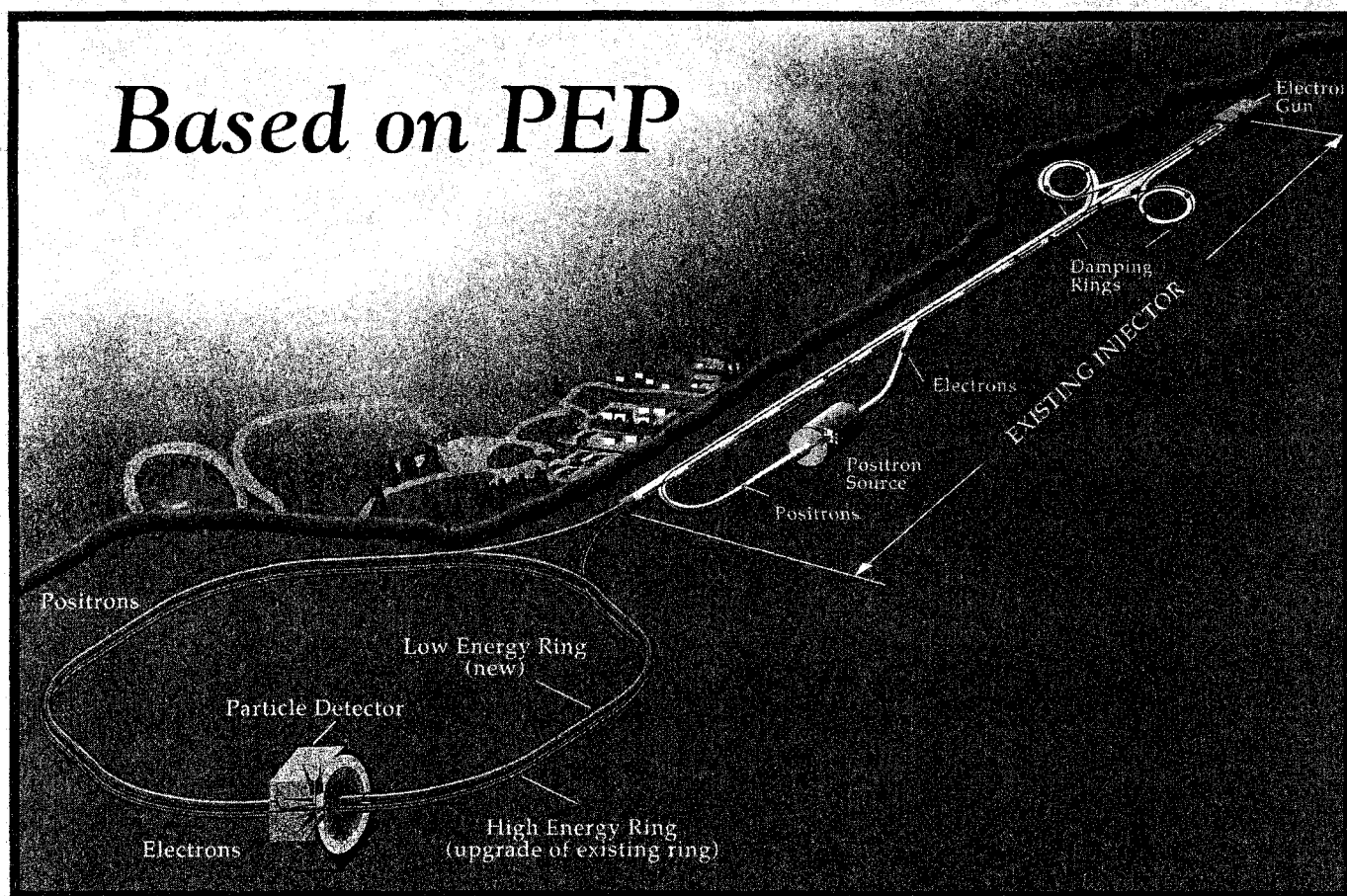


An Asymmetric B Factory

Based on PEP



Conceptual Design Report

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1.

OVERVIEW

IT has become increasingly apparent in recent years that systems containing b quarks offer unique opportunities for studying the theoretical edifice of particle physics, the so-called "Standard Model." Although measurements with these b -quark systems offer a host of possibilities, the one that has riveted the attention of the particle physics community worldwide is the potential for understanding the origin of the phenomenon of CP violation—a small deviation in Nature's otherwise symmetric order that has been clearly observed but whose origins remain a mystery. The phenomenon of CP violation has cosmic consequences; in particular, it played a crucial role in the formation of our Universe. Thus, to understand it is one of the central goals in our quest to comprehend the orderly foundations of the natural world. The program of CP violation studies that we envision has great discovery potential; should the measurements disagree with predictions of the Standard Model, the observed pattern of CP violation will provide substantial and specific clues as to how the model should be extended.

Capitalizing on recent advances in detector technology and newly acquired information on the properties of the b quark, it is now widely accepted that a high-luminosity, asymmetric e^+e^- collider offers an ideal platform for an exhaustive study of CP violation. This fact was forcefully endorsed last year by HEPAP through the deliberations and recommendations of its subpanel on the U.S. High Energy Physics Research Program for the 1990s (the Sciulli panel, DOE/ER-0453P and the accompanying transmittal letter, April 1990). The thrust of HEPAP's recommendations was that the physics program of a B factory was compelling and that, given a technically sound proposal for construction of a machine, funds for such a facility should be sought with high priority.

While CP violation is the main motivation for the construction of a B factory, such a facility will also host a very exciting and broad-based program of bottom quark, charm quark, τ , and two-photon physics. Important tests of the Standard Model are possible in this program and many gaps in our knowledge are sure to be filled in. Because the number and range of distinct topics is very large, an asymmetric B factory will be an ideal facility for the training of young physicists, and we envisage more than 200 Ph.D. theses during the lifetime of the program (conservatively estimated at 15 years). The specific machine implementation discussed here has a single interaction region, though flexibility exists to expand this to two interaction regions, and therefore two detectors, should the user community consider this important enough to provide the extra funds. A

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parasitic program of synchrotron radiation physics and nuclear physics would also be possible with additional funds.

A very large international particle physics community is committed to physics studies at an asymmetric e^+e^- B factory. A group of physicists numbering more than 150 Ph.D.'s has been involved with the PEP-based B Factory, both in developing the physics arguments and in designing an appropriate detector. This group includes investigators from more than 20 U.S. institutions, as well as physicists from Canada, Europe, Japan, and Israel. There are an equal number involved in other B factory efforts worldwide.

In early 1989, a group of accelerator and particle physicists from Caltech, LBL, SLAC, and the University of California began a study of the feasibility of an asymmetric e^+e^- collider based on an upgrade of the PEP storage ring at SLAC. A parallel study was conducted to examine in detail the physics capabilities of such a facility and to specify the luminosity required for a broad-based program aimed at understanding the origins of CP violation. The feasibility studies indicated that, with appropriate care, PEP could be upgraded to achieve the required luminosity of $3 \times 10^{33} \text{ cm}^{-2} \text{ s}^{-1}$. In November 1989, the SLAC Experimental Program Advisory Committee agreed that the B Factory program was indeed very compelling and encouraged the Directors of SLAC and LBL to move from a feasibility study to a conceptual design phase. It is the result of that conceptual design study that is contained in these pages. The Asymmetric B Factory design proposed here serves as a direct and wholly satisfactory response to the challenge set down by the Sciulli subpanel.

The goal of the conceptual design was to be a machine that would be both responsive to the physics needs and conservative in its approach to achieving high luminosity. The Asymmetric B Factory design we propose meets this goal. The facility consists of two independent storage rings, one located atop the other in the PEP tunnel. The high-energy ring, which stores a 9-GeV electron beam, is an upgrade of the existing PEP collider; it reutilizes all of the PEP magnets and incorporates a state-of-the-art copper vacuum chamber and a new RF system capable of supporting a stored beam of very high current. The low-energy ring, which stores 3.1-GeV positrons, will be newly constructed. Its design takes advantage of many of the machine component designs that have already proved successful at PEP.

Our approach to reaching the required luminosity of $3 \times 10^{33} \text{ cm}^{-2} \text{ s}^{-1}$ is to use, in each ring, high circulating currents (approximately 2 A) separated into more than 1600 bunches. An advantage to this approach is that the parameters of individual bunches (current, length, emittance, etc.) are quite conventional and have been demonstrated in numerous successful colliders over many years. Thus, the design challenges are restricted to the high-current and multibunch arenas. These, in turn, are mainly engineering challenges, and—although they are by no means easy—they are amenable to standard engineering tools and approaches that assure us that the proposed solutions are workable, reliable, and conservative.

The PEP site offers an ideal location for the B Factory. SLAC has the world's most powerful positron injector, and the availability of the large 2.2-km-circumference tunnel greatly eases the problems associated with handling the intense synchrotron radiation power emitted by the high-current beams. This approach is not unique to the SLAC project; both DESY and KEK have now moved away from earlier plans to employ small storage rings and have adopted machine designs that place both rings in their large-radius

PETRA (2.3 km) and TRISTAN (3 km) tunnels. Moreover, the parameters of the B Factory high-energy ring match almost perfectly those of the present PEP; the project can benefit from the existing PEP infrastructure so that no conventional construction is required on the SLAC site.

SLAC and LBL have a long and very successful history of design, construction, and operation of e^+e^- storage rings. The original PEP project was a joint endeavor of these two laboratories. The staffs of both laboratories are enthusiastic about the prospect of an upgrade to this facility. Much of the expertise that conceived and built SPEAR and PEP remains within the laboratories, and new additions to the staff (for example, the team that is now completing construction of the ALS at LBL) have enhanced these strengths. The addition of LLNL as an institutional collaborator further strengthens the team that will build the Asymmetric B Factory.

In summary, we believe that the SLAC site is an ideal location for the construction of an Asymmetric B Factory that will provide the platform for a crucial component of the U.S. high-energy physics base program. The design presented here is flexible and fully capable of meeting the demands of a physics program that will exhaustively examine the question of CP violation. As soon as funds are available, we are ready to begin the construction and commissioning of this exciting facility and then to embark on studying one of the most important topics in high-energy physics today.

2.

INTRODUCTION

ON the following pages, we give an overview of the physics motivation for the Asymmetric B Factory. The overview includes a discussion of the advantages of the e^+e^- environment and a menu of the physics achievable at the B Factory. This chapter also offers a justification for the design luminosity for the machine and the asymmetric aspect of the collider, and it outlines a list of constraints on the machine design that arise from the physics goals (that is, tolerable background levels, maximum beam pipe radius, etc.).

2.1 OVERVIEW

We propose to construct a high-luminosity electron-positron colliding-beam accelerator that will operate in the 10-GeV center-of-mass energy ($E_{c.m.}$) regime; the majority of the physics running will be at the $\Upsilon(4S)$ resonance ($E_{c.m.} = 10.58$ GeV). The machine described in the following chapters has the novel feature of unequal beam energies, a configuration we call *asymmetric*. The luminosity goal is $3 \times 10^{33} \text{ cm}^{-2} \text{ s}^{-1}$; the electron and positron beam energies were chosen to be 9 and 3.1 GeV, respectively.

The main physics motivation for the B Factory is a full and exhaustive study of CP violation, using the rich spectrum of B meson decays. The goal is not simply to measure, for the first time, CP violation in the B meson system, but to mount a program sufficiently diverse to examine the more crucial issue of what constitutes the *origin of CP violation*. Such a program requires a machine that produces in excess of 10^7 neutral B mesons (B^0 's) per year. The goal for the machine described in this proposal is 3×10^7 neutral B mesons per year.

The 10-GeV region was chosen so as to exploit the copious and exclusive production of B mesons at the $\Upsilon(4S)$ resonance; the level of asymmetry was chosen to optimize the measurement of CP -violating asymmetries in the decays of the B mesons. The full time-evolution of this phenomenon can be exposed by the use of the asymmetry, with the time-evolution measurements providing a comprehensive set of systematic cross-checks for the CP violation measurements.

The e^+e^- 10-GeV region has proved to be an ideal environment for the study of b quark physics. The $\Upsilon(4S)$ offers special advantages for the study of B hadron (meson and baryon) decays. The production of B hadrons at the $\Upsilon(4S)$ constitutes fully one-third of

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the available cross section, and the availability of kinematic constraints further permits exceptionally clean isolation of the B physics. The background rejection is sufficient to allow a wide range of B meson decays, even decay modes with small branching fractions (10^{-4} – 10^{-5}), to be reconstructed with high efficiencies and large signal-to-noise ratios. These include decay modes of high multiplicity and those that include final state π^0 's. The ability to use the sign of the electric charge of both leptons and kaons to establish, accurately and with high efficiency, the difference between a B and a $\bar{B}$ meson is very powerful. These characteristics are especially advantageous for the study of CP violation. Programs at CESR and DORIS have provided a large amount of data for a detailed characterization of the T region. This, coupled with the rather simple nature of the e^+e^- environment, makes it possible to simulate the physics processes very reliably. Hence, one can attach considerable confidence to the estimates of the physics capabilities calculated for the B Factory. Indeed, as discussed below, the present proposal is based on very detailed modeling of the physics.

Besides bottom quark production, the B Factory will produce very large samples of charm quarks and τ leptons. The environment again favors high-efficiency, low-background studies of important physics processes associated with these fundamental constituents. Hence, the B Factory is more correctly viewed as a *Heavy Constituent Factory*.

Rounding out the possibilities offered by the B Factory is an exciting program of two-photon physics and the study of the spectroscopy of the T resonances. This spectroscopy reflects the underlying strong force that binds the quarks together and offers an opportunity for detailed and essential studies of this fundamental force.

Details of this compelling physics program are given below. As a measure of the power of the B Factory, we have tabulated in Table 2-1 the yields for $B\bar{B}$ and T that exist worldwide today and that will be available in a one-year run at the B Factory. Also tabulated are the annual yields of D mesons and τ pairs expected at the B Factory. The increase in statistical power is itself very impressive; what is not evidenced by the relative numbers is the level of accessibility to crucial physics that can only come with the Asymmetric B Factory.

The B Factory also offers the opportunity for an exciting parasitic program of synchrotron radiation and nuclear physics studies. The very high circulating current will generate x-ray beams of unprecedented brightness, permitting some experiments that will not be accessible even at the next generation of advanced light sources. Likewise, for certain QCD studies, a heavy-element gas-jet target intercepting the electron beam, along the lines proposed by the PEGASYS experiment [Van Bibber, 1989], would reach regions of phase space inaccessible at any other facility.

The U.S. is currently embarked on the SSC program, which will begin producing physics at the end of this decade. The U.S. particle physics program is in great need of additional facilities, particularly in the intervening years, both to maintain a balanced and vibrant program and to keep young people in the field. In this regard, the B Factory offers the nation an ideal opportunity. The SLAC site, with its existing powerful injector and large-circumference machine (PEP), provides a natural site for a high-luminosity Asymmetric B Factory. The B Factory constitutes an upgrade of the existing SLAC facility, with no conventional construction required. This has the advantage of saving both money and time. With proper financial planning, the U.S. program could have the

Table 2-1. Bottom, T , charm, and τ yields (1 yr = 10^7 s).

Channel	World sample (Jan. 1991)	B Factory $\mathcal{L} = 3 \times 10^{33}$ (per yr)
$B\bar{B}$	1×10^6	3×10^7
$T(1S)$	3.5×10^6	5×10^8
$T(2S)$	8.5×10^5	2×10^8
$T(3S)$	4.9×10^6	1×10^8
D^0	—	6.9×10^7
D^+	—	3.3×10^7
D_s	—	2.3×10^7
$\tau^+\tau^-$	—	2.8×10^7

SLAC-based B Factory operational for physics in 1996. The program has an expected lifetime for compelling physics of at least 15 years. While the SSC challenges the Standard Model by vigorously pursuing an understanding of the Higgs sector, the B Factory would provide a complementary pursuit of the Standard Model through the study of CP violation and the pattern of heavy-constituent decays. The B Factory physics program is exceedingly diverse, and the number of fully independent physics topics that can be studied is very large. This fact, coupled with the compelling nature of the physics, has brought together a very large community pushing for such a facility. (Based on current attendance at workshops and discussions with members of the worldwide community, we estimate that 300 particle physics Ph.D.'s will work at the B Factory.) The majority of this community has worked in e^+e^- collisions for many years and has a demonstrated ability to produce high-quality physics results. In addition, we envisage the B Factory as providing an exceptional training ground for young physicists: The number of interesting thesis topics far exceeds one hundred.

The rest of this chapter is organized to provide background for the nonspecialist; a more detailed discussion of physics measurements resumes in Section 2.3.4. Section 2.2 discusses the characteristics of the 10-GeV center-of-mass region as seen in e^+e^- collisions. Section 2.3 then discusses the physics motivation, including an outline of the Standard Model (Sections 2.3.1 through 2.3.3), a discussion of how CP asymmetries are measured at the $T(4S)$ (Section 2.3.4), a justification of the machine asymmetry and luminosity (Sections 2.3.5 and 2.3.6), a discussion of sensitivity to non-Standard Model explanations for CP violation (Section 2.3.7), and outlines of B physics exclusive of CP violation, together with charm, τ , T , and two-photon physics (Sections 2.3.8 through

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2.3.12). The chapter concludes with a discussion of the constraints imposed by the physics on the machine design and an outline of the likely scenario for choosing the operating energy of the machine.

2.2 CHARACTERISTICS OF THE 10-GEV REGION—THE UPSILON FAMILY

The cross section for producing hadrons in electron-positron collisions in the 10-GeV region is shown in Fig. 2-1. The rich resonance structure above the b quark threshold is called the Υ (upsilon) system. The first three prominent resonances are the lowest-lying S states of a bound $b\bar{b}$ quark system. These states are analogous to the bound states in an atomic system (such as positronium); in this case, however, it is the strong (color) force that provides the binding energy for the two constituents. The narrowness of the resonances reflects their stability against strong decays; the states have insufficient energy to decompose into a pair of mesons, each carrying a b quark. The fourth state, $\Upsilon(4S)$, has just sufficient energy to decay to a pair of B mesons (B and $\bar{B}$); this decay totally dominates the disintegration of the $\Upsilon(4S)$. The $\Upsilon(4S)$ is thus an ideal laboratory for the study of B decays, having the following important features:

- The $\Upsilon(4S)$ decays almost exclusively to pairs of B mesons. There are thus no extraneous particles that would provide background and reduce the sensitivity of the measurements.
- Since the $\Upsilon(4S)$ decays to only two particles, the daughter B mesons have a unique momentum in the $\Upsilon(4S)$ center-of-mass frame. In addition, the fraction of all events that contain a $B\bar{B}$ pair is 30%, significantly greater than at higher energies or in proton collisions. These two effects greatly limit contamination from backgrounds from the continuum of physics channels (non- b quarks) that accompany the $\Upsilon(4S)$.
- When the $\Upsilon(4S)$ decays, the two B mesons are coherently produced in a P -wave state. This guarantees that the two B mesons are nonidentical; that is, the one is a B^0 while the other is a $\bar{B}^0$. This feature is particularly advantageous for CP violation studies.
- The multiplicity of hadrons in the $\Upsilon(4S)$ decay is relatively small. When combining particles to reconstruct B meson states, this low multiplicity keeps combinatorial backgrounds at a reasonable level.

The B mesons produced in $\Upsilon(4S)$ decay (B_u , B_d) comprise a b quark and a lighter quark, either an up (u) or down (d) quark. It is also of considerable interest to study the decays of B mesons that contain a strange (s) quark (B_s). These studies must be done at the $\Upsilon(5S)$ resonance (see Fig. 2-1).

The majority of the B Factory program will be spent at the $\Upsilon(4S)$. As we have seen, this choice of energy provides a copious source of B_u and B_d mesons. Accompanying the resonant production of B mesons is the so-called continuum physics, the roughly 2.5 nb of cross section that comprises e^+e^- annihilation into pairs of light quarks (u , d , and s), pairs of light leptons (e^+e^- and $\mu^+\mu^-$), pairs of heavy quarks (charm quarks), and pairs of heavy leptons ($\tau^+\tau^-$). The light quark and lepton events are of little interest (save for

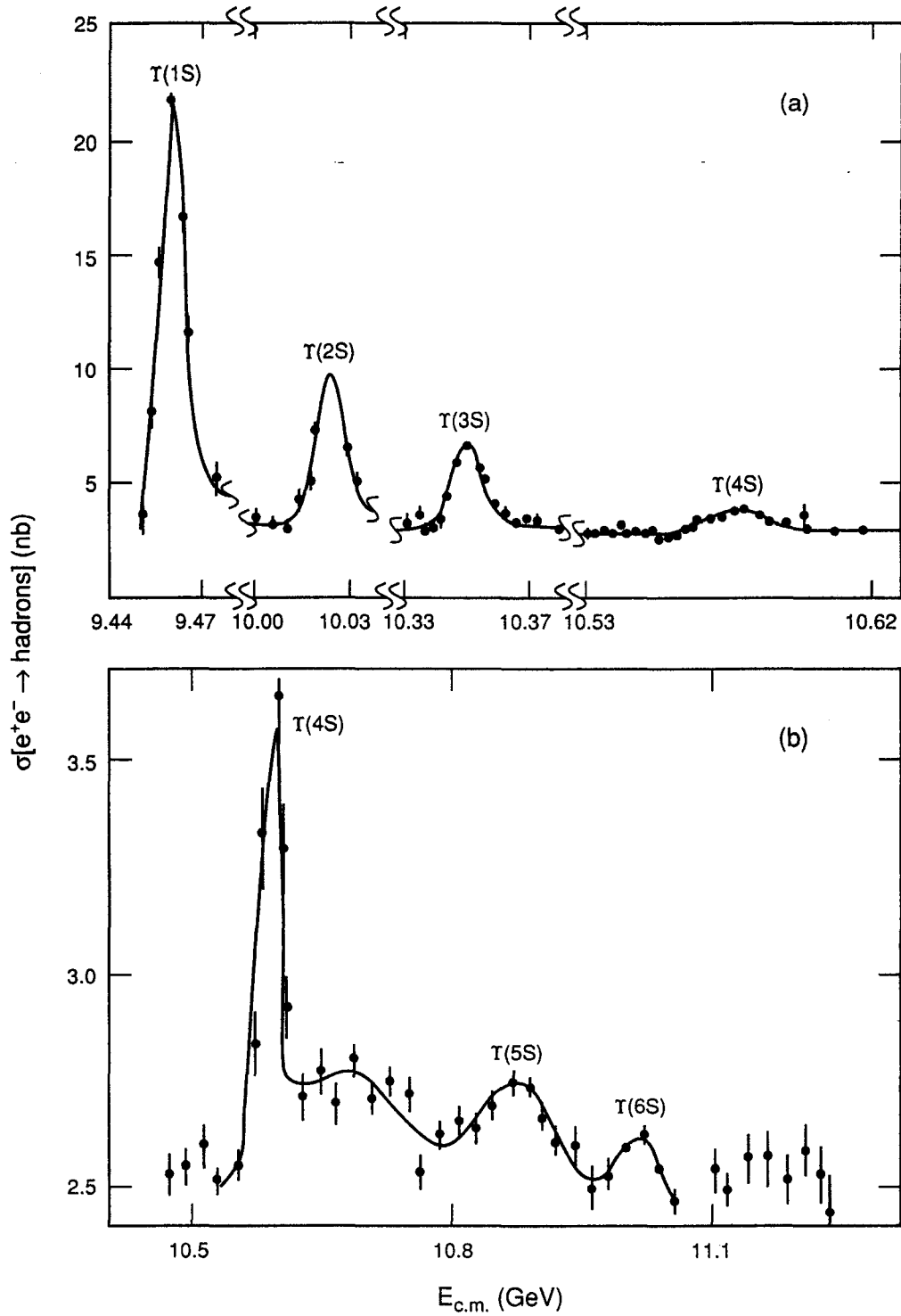


Fig. 2-1. The cross section for the production of hadrons in e^+e^- collisions in the center-of-mass energy region near 10 GeV. The data are characterized by a series of resonances, the Υ family, which herald the onset of the b quark threshold. The data in (a) are from the CUSB detector group; the data in (b) are from the CLEO detector group.

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normalization of the experiment), but the heavy-constituent events are of considerable interest. The B Factory will produce very large samples of these heavy constituents, thereby assuring an interesting and diverse physics program.

2.3 PHYSICS MOTIVATION

We turn our attention now to the details of the particle physics program and how it relates to specifying the goals for the B Factory. We have studied this physics program very extensively and with great attention to detail in a series of workshops held over the past two years. The interested reader is encouraged to consult the proceedings of these workshops [Hitlin, 1989 and 1991] for more details. The earlier workshop covered the full spectrum of available physics (except two-photon physics), whereas the more recent one dealt much more extensively with the study of CP violation and also covered two-photon physics. The machine design goals all come from the B physics program and are dominated by the requirements for studying CP violation. [A rather similar set of goals arises from the study of B_s mixing, although, in this case, the experiment is done at the T(5S).] Happily, the requirements for the CP violation program do not conflict in any way with those of the rest of the physics program.

2.3.1 The Standard Model of Particle Physics

Our understanding of the interactions among Nature's basic building blocks, the quarks and leptons, is described by a theory called the *Standard Model*. This model successfully explains all experimental measurements as they pertain to the three forces seen by the constituents, the strong force, the electromagnetic force, and the weak force. There are no verified experimental anomalies between experiment and the Standard Model—a situation of unprecedented success. However, as a complete model of Nature, the Standard Model has several crucial shortcomings, and most particle physicists believe that it must one day be superseded by a more complete theory. It is widely acknowledged that progress toward this more satisfactory theory will almost certainly have to come from experiment (as opposed to new theoretical insights); the field is therefore greatly in need of verifiable data that is in solid *conflict* with the Standard Model.

Among the unsatisfactory elements of the Standard Model are its inability to predict many important numbers (such as the masses of the constituents, the masses of the force mediators, etc.) and the rather ad hoc (often called “unnatural”) manner in which it handles certain essential elements, the leading example being the way particle masses are generated (the Higgs phenomenon). Whereas the well-established phenomenon of CP violation has a natural place within the Standard Model, it in no sense has an explanation. One of the strengths of the B Factory heavy-constituent program is the broad range of measurements that will directly confront the validity of the Standard Model. Many ways can be imagined in which this program could provide the first indication of where the Standard Model fails—in this sense, it provides possibly the best window to new physics of any currently proposed facility. Understanding the Higgs mechanism supplies the justification for the SSC; likewise, understanding the origin of CP violation is the central driving force for the construction of the B Factory.

The Standard Model describes the interactions of the building blocks of matter, the six quarks and the six leptons. These spin 1/2 constituents interact via three forces, each of which is mediated by spin 1 force carriers such as the photon (electromagnetic); the Z , W^+ , and W^- (weak); and the gluons (strong). With these twelve constituents (and their antiparticles) and the force carriers, all physical phenomena are explainable (we ignore gravity in this discussion). The constituents come in three generations, or families. The lightest generation (the up and down quarks, the electron and the electron neutrino) plays a special role in our universe: All stable matter is made up of these four constituents. Yet, for reasons we do not understand (another shortcoming of the Standard Model), Nature has chosen to make two replicas of this lightest generation (see Table 2-2). The clearest distinction among the generations is the increase in mass; the higher the generation, the larger the constituent masses (save for the neutrinos, which so far appear massless). Hence, the τ lepton is the heaviest charged lepton, the top quark (as yet undiscovered, with a mass in excess of 90 GeV) is the heaviest charge 2/3 quark, and the b quark is the heaviest charge -1/3 quark. Whereas we do not understand the replication of the lowest-lying generation, there is no denying the existence of the second and third generations. Indeed, it is the richness of the quark generations that most likely holds the key to expanding beyond the Standard Model.

2.3.2 The Pattern of Quark Decays—The CKM Matrix

To understand this last statement, we must delve more deeply into the pattern of constituent decays. Here the apparently symmetrical role of the quarks and leptons breaks down. The lepton generations are distinct: No interactions couple them. In any physical process, lepton number is conserved separately *for each generation*. Thus, in the decay of a muon, three particles materialize: a muon neutrino, an electron, and an electron antineutrino. The first-generation lepton number is conserved by the balance of the electron and its antineutrino, while the muon neutrino is needed to balance the second-generation lepton number. This absence of cross-generation coupling appears to be absolute in the lepton sector, but not in the quark sector. Indeed, the s and b quarks would be entirely stable if they could not couple to quarks of a lower generation. Thus, quark decay involves a coupling of the generations: A b quark can cascade down to the charm quark (which is its predominant choice) or, less likely, to the up quark. This intergenerational mixing is summarized by the so-called Cabibbo-Kobayashi-Maskawa (CKM) matrix. This matrix represents the fact that the weak interaction does not couple directly to the quark mass eigenstates; rather the weak eigenstates (which couple to the W 's) are admixtures of the mass eigenstates, the exact admixture being given by the elements of the CKM rotation matrix. The richness of the quark decay spectra is represented by the elements of the matrix:

$$\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

Table 2-2. The particles of the Standard Model.

Leptons			
Name	Symbol	Mass (GeV)	Electric charge
Electron	e^-	0.000511	-1
Electron neutrino	ν_e	0	0
Muon	μ^-	0.106	-1
Muon neutrino	ν_μ	0	0
Tau	τ^-	1.784	-1
Tau neutrino	ν_τ	0	0
Quarks			
Name	Symbol	Mass (GeV)	Electric charge
Up	u	0.31	+2/3
Down	d	0.31	-1/3
Charm	c	1.50	+2/3
Strange	s	0.51	-1/3
Top	t	>90	+2/3
Bottom	b	5.0	-1/3
Carriers of force			
Force (carrier)	Symbol	Mass (GeV)	Electric charge
Electromagnetism (photon)	γ	0	0
Weak (weak vector bosons)	Z^0	92	0
	W^+	81	+1
	W^-	81	-1
Strong (gluon)	g	0	0
Higgs			
Name	Symbol	Mass	Electric charge
Neutral Higgs	H^0	?	0
Charged Higgs	$H^\pm$	?	± 1

The CKM matrix can be completely characterized by four parameters: three real numbers and one complex phase. A commonly used parametrization is that due to Wolfenstein:

$$\begin{pmatrix} 1 - \lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1 - \lambda^2 & A\lambda^2 \\ A\lambda^3(1 - \rho - i\eta) & -A\lambda^2 & 1 \end{pmatrix}$$

where A , λ , ρ , and η are real parameters. When $\lambda = 0$, this matrix becomes the unit matrix, and there is no coupling among generations.

If the Standard Model were truly a complete theory of Nature, the CKM mechanism would have arisen naturally in the model, and all the values of the elements of the matrix would be specified. Instead, these numbers must be measured, and self-consistency must be established to check the validity of the model. *It is for this reason that the pattern of quark decays offers a powerful window onto the validity of the Standard Model.* In particular, the heavy-quark decays (those of charm and bottom, which are so profuse and so readily studied at the B Factory) provide a wealth of data for testing the Standard Model.

2.3.3 CP Violation in the Standard Model

We will now focus on the phenomenon of CP violation. The origin of CP violation has been one of the defining mysteries of particle physics since the violation was first discovered in the Nobel Prize-winning work of Cronin, Fitch, and collaborators [Christenson et al., 1964]. While the physical manifestations of this asymmetry are tiny, its ramifications are cosmic. Indeed, without the presence of this phenomenon, we would be hard-pressed to explain the presence of our universe. In the absence of CP violation, the equations that govern the behavior of particles created in the Big Bang are matter-antimatter symmetric. Under such circumstances, particle-antiparticle annihilation should have dominated, and no stable universe should have resulted. Yet we find ourselves living in a stable, matter-dominated universe. The tiny anisotropy generated by CP violation, the only known physical process that allows for an *absolute* determination of the sign of the electric charge, was sufficient to tip the balance away from total annihilation and permit the creation of a stable universe.

The lack of CP symmetry is experimentally well-demonstrated in the decays of K mesons. However, an explanation for the origin of the violation remains no more than conjecture; the K meson system provides too limited a set of measurements to fully fix the appropriate CKM parameters or to distinguish between competing models of the mechanism. It is the inclusion of the complex element (the phase η in the Wolfenstein representation) that provides a *mechanism* for CP violation in the Standard Model. It should be emphasized that CP violation is not a necessary consequence of the Standard Model; it is merely allowed. We have no experimental evidence for or against the idea that this mechanism of CP violation is in fact the correct one. Studies of CP violation in the decays of the B meson system, unlike those in the K meson system, provide the

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diversity needed to over-constrain the Standard Model and hence establish once and for all whether this mechanism is correct.

Using the data from K meson measurements and the framework of the Standard Model, predictions for the size of the CP asymmetries in B meson decays can be made. Because our understanding of quark decays is not perfect, the size of these CP -violating effects cannot be precisely pinpointed; rather, a range of validity is predicted. Despite this uncertainty, for certain decays ($B^0 \rightarrow J/\psi K_s$ being the most studied), the Standard Model makes an unambiguous prediction of a large CP -violating asymmetry, in the range of 10–60%. (This can be contrasted with the asymmetries in the K meson system, which amount to two parts per thousand.) The physical effect we seek is thus large and easily measured, provided that sufficient events can be accumulated in the appropriate B meson decay modes. The branching fractions for these CP -violating decay modes tend to be small (typically 10^{-4} – 10^{-5}), hence one needs to produce of the order of 10^7 – 10^8 B mesons to make statistically significant measurements of CP asymmetries. The desire to confront CP violation in this complete manner is what leads to the requirement of a very large integrated luminosity.

We shall now explore the range of the Standard Model predictions more quantitatively, because, if we are to fully test the validity of the Standard Model, we need to construct a machine capable of producing sufficient luminosity to cover this range completely. The CKM matrix is unitary, and therefore the following requirement must hold:

$$V_{ud} V_{ub}^* + V_{cd} V_{cb}^* + V_{td} V_{tb}^* = 0$$

This equation can be viewed as the closure of a triangle (the “Unitarity Triangle”) in the complex (ρ, η) plane. Using the Wolfenstein representation, the triangle is as shown in Fig. 2-2. If CP violation in the B meson system were absent, then η would be zero and the triangle would collapse to a line on the real axis. As we stated above, the Standard Model predicts a range of CP -violating asymmetries in B decays and therefore a range of allowable angles α , β , and γ . This range is shown in Fig. 2-3 as a function of the t quark mass. It is this range of values that we must be capable of measuring if we are to ascertain whether the Standard Model can accommodate B meson CP asymmetries and

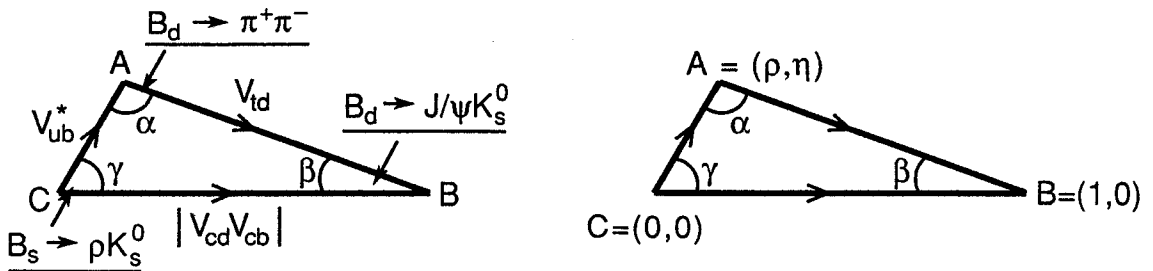


Fig. 2-2. The “Unitarity Triangle,” along with definitions of the angles α , β , and γ and the prototypical self-conjugate CP eigenstates that are used to measure these angles. Closure of this triangle in the complex plane represents the unitarity of the CKM matrix. The parameters ρ and η , which appear in the Wolfenstein parametrization of the CKM matrix, are also shown here.

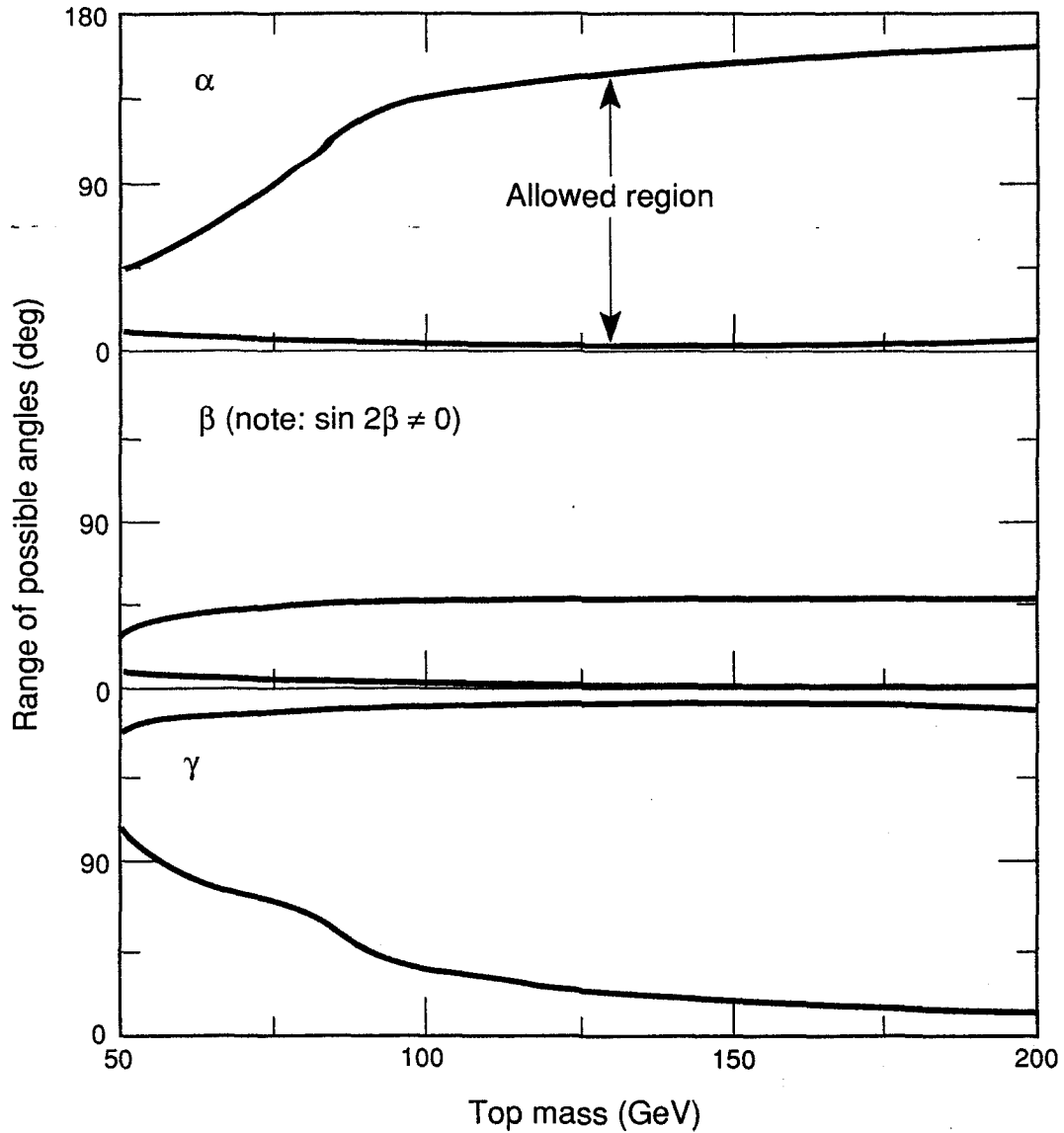


Fig. 2-3. The range of the unitary triangle angles allowed by the Standard Model (under reasonable assumptions for the model parameters), as functions of the top mass, currently thought to be above 90 GeV. Since the allowed range of β is never zero, the Standard Model unambiguously predicts finite asymmetries in decays characterized by $\sin 2\beta$ (like $J/\psi K_S$).

whether it is self-consistent. As indicated in Fig. 2-2, α , β , and γ are directly measurable from specific B meson decays to CP eigenstate final states, respectively indicated by a set of prototypical decays $B_d \rightarrow J/\psi K_S$, $B_d \rightarrow \pi\pi$, and $B_s \rightarrow \rho K_S$.

2.3.4 How CP Asymmetries Are Measured

To understand how the asymmetries are measured, we now return to our discussion of the $T(4S)$ system and its decay into a $B^0\bar{B}^0$ pair. These B mesons are fairly long-lived (the B

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meson lifetime is about 1 ps) and will propagate a measurable distance before they decay. The first B (we assume it to be a B^0 ; the argument is just reversed if it is a $\bar{B}^0$) will decay at time t_1 and, by the coherence referred to earlier, will force the second B to be a $\bar{B}^0$. This second B meson propagates further in time before it decays at time t_2 . However, during the time interval $t_2 - t_1$, the $\bar{B}^0$ can change itself into a B^0 via the phenomenon of mixing. In fact, the Argus Group at DESY [Albrecht et al., 1987] first showed that mixing of neutral B_d mesons is large. Hence, it is possible to end up with either a $B^0\bar{B}^0$ final state or a B^0B^0 final state, depending on whether the second B meson has mixed or not. If we now arrange to detect one of the B's decaying to a CP self-conjugate eigenstate (like $J/\psi K_s$ or $\pi\pi$) and the other in a decay that distinguishes between a B^0 and a $\bar{B}^0$ (such as the sign of the charge of a lepton or kaon), it is possible to measure a CP asymmetry. The asymmetry arises from the fact that mixing has allowed two separate routes from the initial B meson to the final CP self-conjugate state (see Fig. 2-4), one without intermediate mixing and the other with mixing. If the interference between these two separate paths is different, depending on whether one starts from a physical B^0 or $\bar{B}^0$, a potentially measurable asymmetry is generated. The decay rate (Γ) of a time-evolved, initially pure $B^0\bar{B}^0$ into a B^0 ($\bar{B}^0$) and a self-conjugate CP eigenstate f_{CP} is given by

$$\Gamma(B^0\bar{B}^0 \rightarrow B^0 f_{CP}) \propto e^{-\Gamma\Delta t} [1 + \sin 2\phi \sin \Delta m(t_2 - t_1)]$$

$$\Gamma(B^0\bar{B}^0 \rightarrow \bar{B}^0 f_{CP}) \propto e^{-\Gamma\Delta t} [1 - \sin 2\phi \sin \Delta m(t_2 - t_1)]$$

where Δm is the $B^0\bar{B}^0$ mass difference, $\Delta t = t_2 - t_1$, and ϕ is α , β , or γ , depending on whether the CP eigenstate observed is $J/\psi K_s$, $\pi\pi$, or ρK_s .

There are four different measurable configurations:

$$n_1: f_B(t_1)f_{CP}(t_2)$$

$$n_2: f_{CP}(t_1)f_B(t_2)$$

$$n_3: f_{\bar{B}}(t_1)f_{CP}(t_2)$$

$$n_4: f_{CP}(t_1)f_{\bar{B}}(t_2)$$

where f_B signifies a B^0 tag, $f_{\bar{B}}$ signifies a $\bar{B}^0$ tag, and f_{CP} signifies a CP eigenstate. *CP violation produces a distribution in $t_2 - t_1$ that is different for n_1 and n_4 from that for n_2 and n_3 .* In the absence of CP violation, the n_i distributions would be exponentials; in the presence of CP violation, they are measurably distorted by a sinusoidal oscillation with amplitude $\sin 2\phi$ and frequency Δm , as shown in Fig. 2-5.

A measurable asymmetry results from a proper summation of the number of events of each type:

$$A_{CP} = (n_2 + n_3 - n_1 - n_4)/(n_1 + n_2 + n_3 + n_4)$$

It is this asymmetry, as well as the detailed time distributions, that will be measured at the Asymmetric B Factory. As seen from Fig. 2-5, the advantage of the B Factory is the availability of the time-evolving distributions. Not only does this exhibit the CP

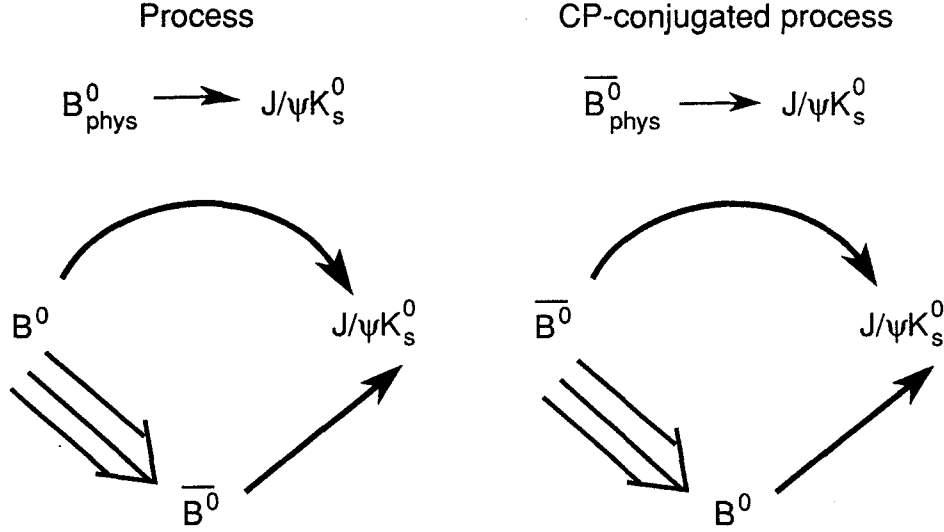
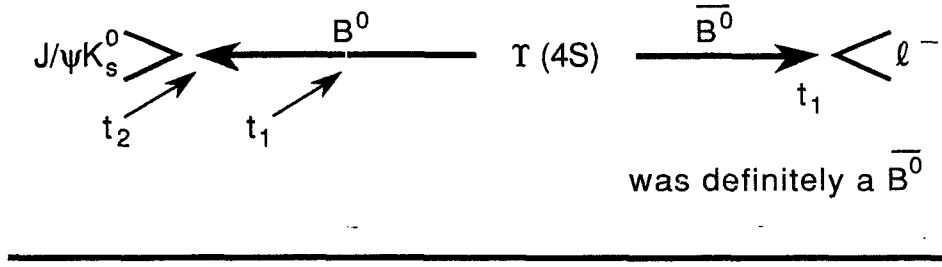


Fig. 2-4. An artist's rendition (upper diagram) of the topology used for measuring CP violation effects at the T(4S). One of the neutral B's is reconstructed in a CP self-conjugate state (the $J/\psi K_s$), while the identity of the other B (B^0 or $\overline{B}^0$) is established from the sign of the charge of a lepton (or K meson). The lower diagram illustrates how mixing is used to project out the CP violation effects. The B^0 can decay to $J/\psi K_s$ (bottom left) via two routes, one direct and one involving mixing. These two amplitudes will interfere, and this interference has a different magnitude when one begins with the CP-conjugated state $\overline{B}^0$ (bottom right). Thus, final states involving $J/\psi K_s/B^0$ and $J/\psi K_s/\overline{B}^0$ can be used to measure CP asymmetries.

violation to its fullest extent, but also the four time-evolved spectra provide two pairwise identical distributions, and the sum of the integrals under the four distributions should be zero (another way of saying that the time-integrated asymmetry must be identically zero). These constraints provide a valuable set of cross-checks on the correctness of the measurements.

The asymmetry A_{CP} is directly related to the angles of the Unitarity Triangle, according to

$$A_{CP} = \frac{x_d}{(1 + x_d^2) \sin 2\phi}$$

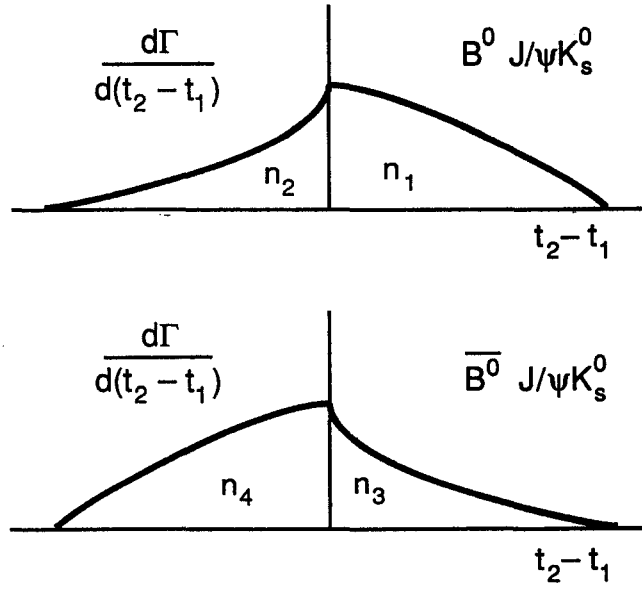


Fig. 2-5. The time-evolved decay distributions that are measured to yield the CP asymmetries. The n_i signify four different final-state topologies, as outlined in the text. It is the distortion of these spectra from exponentials that provide the information for measuring CP violations.

where ϕ is α , β , or γ , depending on whether the CP eigenstate observed is $J/\psi K_s$, $\pi\pi$, or ρK_s . Here x_d represents the strength of the B^0 mixing (measured to be 0.71), hence the dilution factor relating the measured asymmetry to the unitarity angle is known.

To summarize, then, the experiment involves measuring the time difference between the decay points of the two B mesons produced in the decay of the $\Upsilon(4S)$. In addition, one of the B final states must be established as a CP eigenstate, and the other must be tagged as either a B^0 or a $\bar{B}^0$. Establishing the identity of the two B mesons is readily done; this has a significant impact on the design of the detector but relatively little impact on the design of the accelerator. The time-difference measurement is faithfully represented by the measurement of the difference in the positions of the two decay points of the B mesons; it is the need to measure this difference that is responsible for the energy asymmetry of the accelerator.

2.3.5 Justification for the Energy Asymmetry

As suggested above, the crucial experimental ingredient is the ability to accurately measure the distance between the decay points of two B mesons. With modern vertex detectors using silicon technology, one is able to measure this distance with a resolution of about $50 \mu\text{m}$. If a B meson facility is run with equal beam energies, the $\Upsilon(4S)$ is produced at rest in the laboratory and the two mesons do not propagate very far before they decay. The typical distance between the B meson decay points in this equal-beam-energy geometry would be about $30 \mu\text{m}$, a distance too small to discern with today's detectors. The solution to this dilemma, first proposed by Oddone [1987], is to boost the

T(4S) in the laboratory frame by running the storage ring with *unequal beam energies*, hence the name Asymmetric B Factory. The asymmetry denotes the difference in energy between the electron and positron beams. For example, if one chooses 9 and 3.1 GeV for the two beam energies [$E_{\text{c.m.}}^2 = 4E_{\text{low}}E_{\text{high}}$; the center-of-mass energy is thus that of the T(4S)], then the average distance between the two B meson decays becomes $180 \mu\text{m}$. Figure 2-6 shows the results of a detailed simulation (see Hitlin [1989], pp. 69–83) of a measurement of $\sin 2\beta$, using the CP eigenstate $J/\psi K_s$ and kaons and leptons as tags. The distortion of the exponential decay distributions, arising from CP violation, is readily seen.

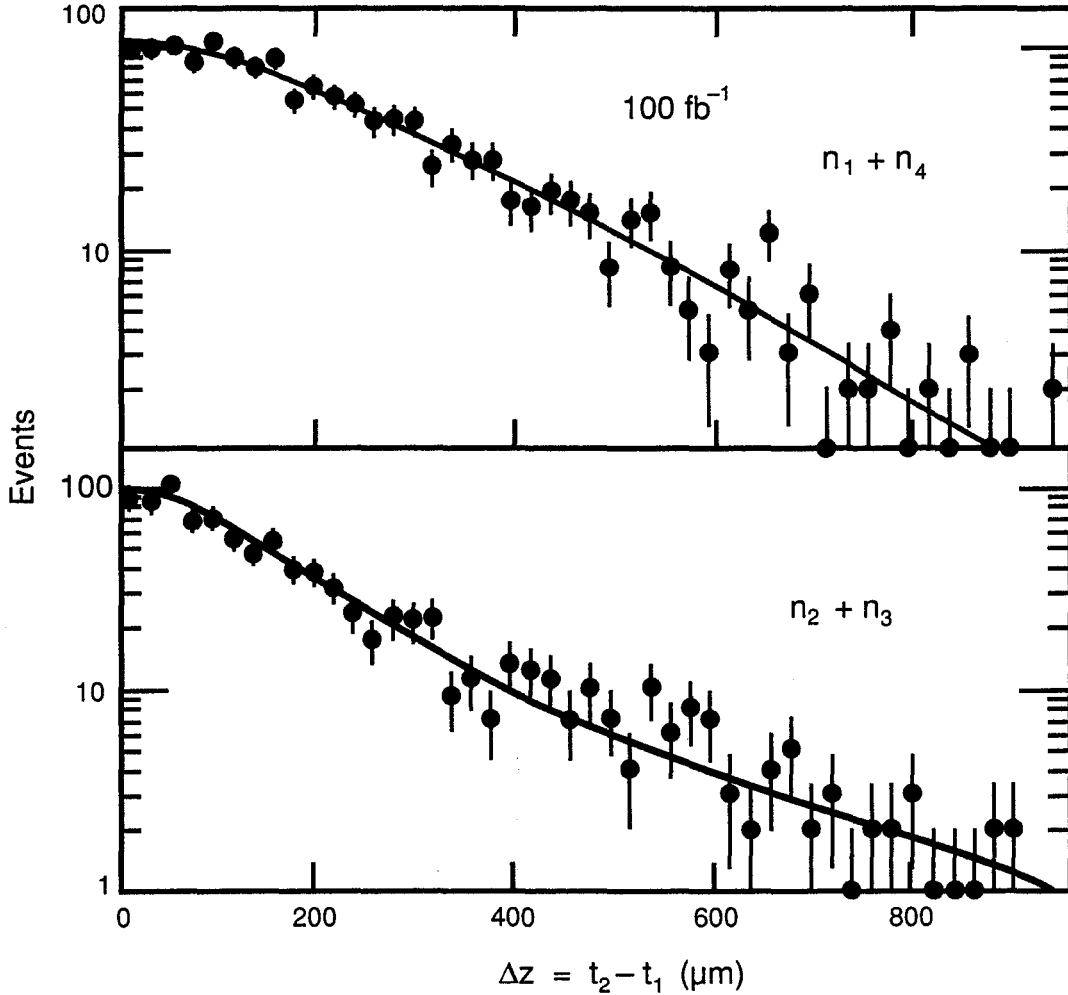


Fig. 2-6. A simulation of the decay length distributions for two classes of events. The upper plot includes events where the first B decays to $J/\psi K_s$ and the second B is tagged as a B^0 , or the first B is tagged as a $\bar{B}^0$ and the second B decays to $J/\psi K_s$ (n_1 and n_4); the lower plot has the two complementary topologies (n_2 and n_3). For details, see Hitlin [1989], pp 69–83. The input value was $\sin 2\beta = -0.4$; a fit to the data yielded $\sin 2\beta = -0.408 \pm 0.023$ for the assumed 100 fb^{-1} of data.

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The justification for an asymmetry in the beam energy is now clear: It is required to give the $\Upsilon(4S)$ system a sufficient Lorentz boost to provide a measurable $t_2 - t_1$ distribution. But how large does the asymmetry need to be? Figure 2-7 shows a simulation of the measurement error for $\sin 2\beta$ as a function of the energy of the high-energy beam. One sees a precipitous dependence on the asymmetry for energy choices below 8 GeV. To remain safely above this region, and to protect against a less optimal set of experimental conditions than those assumed in the simulation, we chose to set the high-energy beam energy at 9 GeV. This choice guarantees the full benefit of the asymmetric geometry.

2.3.6 Justification for the Design Luminosity

We now turn to the issue of what the machine design luminosity ought to be if we are to fully constrain the Standard Model within a reasonable period of time. A decision requires doing very detailed simulations of the measurements of CP asymmetries, using a realistic detector. Accordingly, simulations have been performed [Hitlin, 1989 and 1991] for a wide variety of final states. It turns out that it is possible to employ many more B^0 final states than the CP self-conjugate ones referred to above. A number of impressive studies have now shown that these final states also have measurable asymmetries, comparable to those expected for $J/\psi K_s$ and $\pi\pi$. These states are those of mixed CP , such as $J/\psi K^*$ and $D^{*+}D^{*-}$, as well as states that are not CP eigenstates, such as $\rho\pi$ or $a_1\pi$. Figure 2-8 shows the range of sensitivity to the angles α and β for an integrated

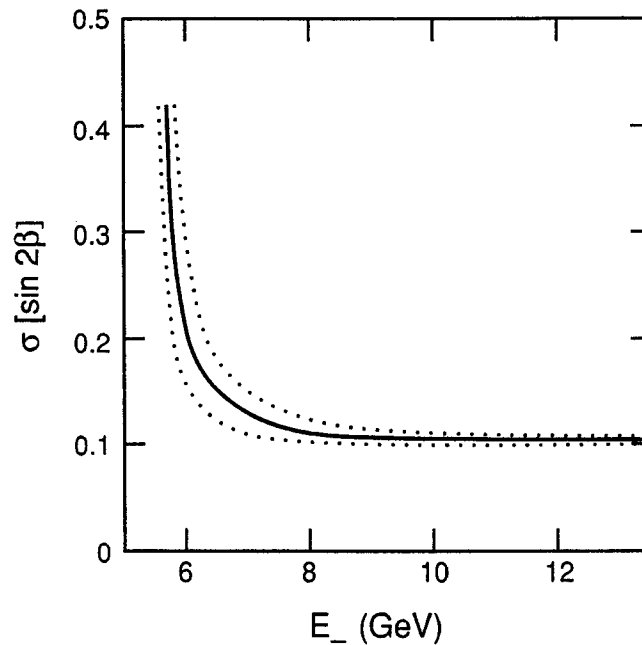


Fig. 2-7. The resolution for measuring $\sin 2\beta$ as a function of the energy of the electron (high-energy) beam. The upper (lower) dotted curve assumes a vertex resolution of 120 μm (50 μm); the solid line assumes 80 μm .

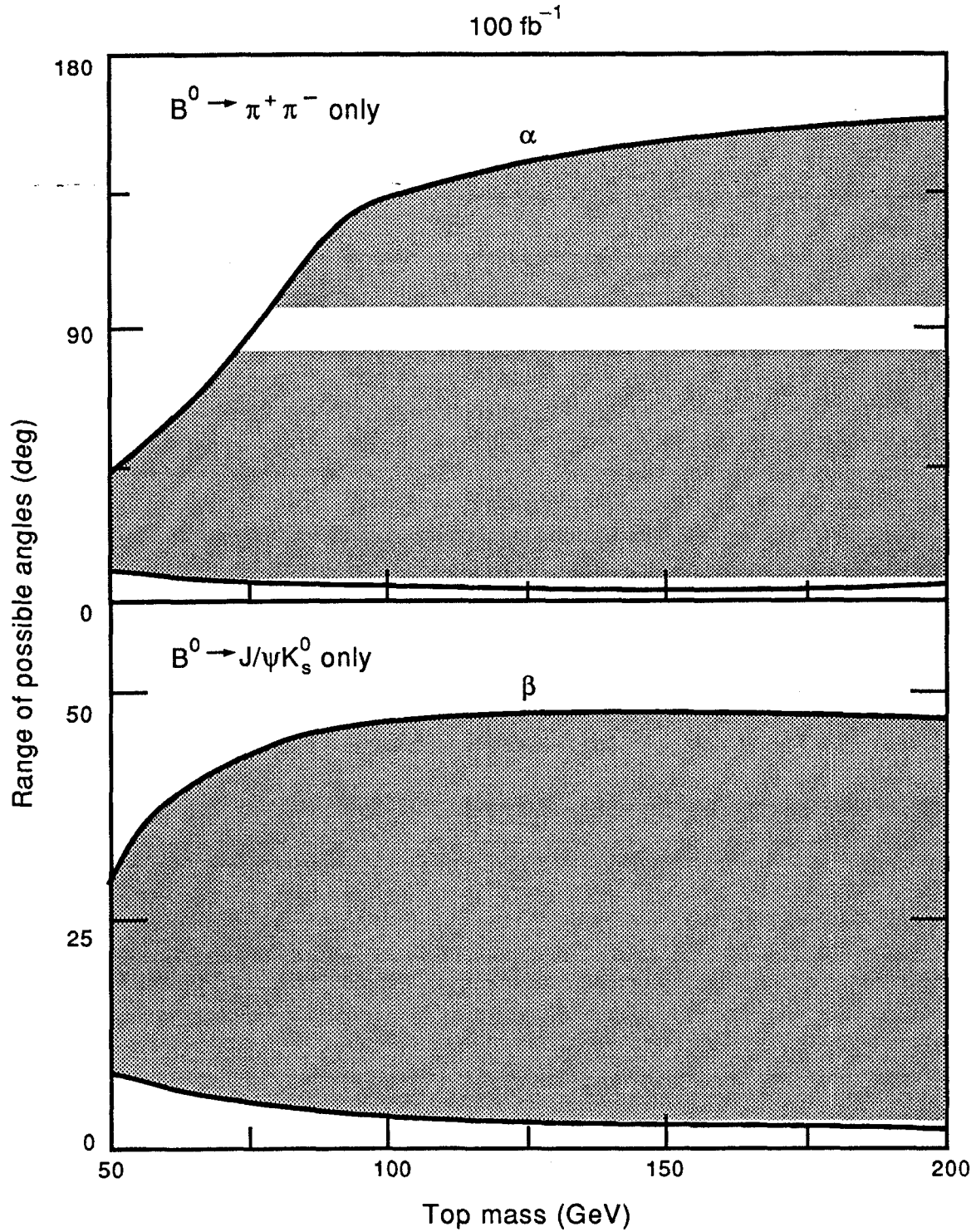


Fig. 2-8. The range of the Standard Model predictions for α and β . The shaded region represents the portion of this range covered (with 3σ precision) by measurements using the CP decay modes $J/\psi K_s$ (for β) and $\pi\pi$ (for α). A data set of 100 fb⁻¹ was assumed.

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luminosity of 100 fb^{-1} , using only the CP eigenstates $J/\psi K_s$ (for β) and $\pi\pi$ (for α). A data set of this size gives excellent coverage of the range of parameter space allowed by the Standard Model. Figure 2-9 shows what can be accomplished using the additional modes in Table 2-3, using a data set of 30 fb^{-1} .

It is important to emphasize here that the large integrated luminosities shown in Figs. 2-8 and 2-9 arise from the need to cover essentially the entire range of Standard Model predictions. It is entirely possible that a significant measurement of a CP violation asymmetry could be established with far less data. For instance, if the angle β were in the middle of the predicted Standard Model range, $\sin 2\beta = -0.4$, a 3σ measurement would be obtained with only 3 fb^{-1} . Likewise, if the Standard Model were wrong, and $\sin 2\beta$ were positive, a clear indication of such an effect would require relatively little data. It is for “less favorable” scenarios that the high luminosity is necessary.

Based on Figs. 2-8 and 2-9, we have concluded that an accelerator that delivers 30 fb^{-1} per calendar year has spectacular discovery potential and will cover the complete range of Standard Model predictions in a period of a few years. This then becomes the design goal for the storage ring. To convert this into a design luminosity for the B Factory, we use the “Snowmass convention” that a year has 10^7 seconds, taking into account accelerator and detector efficiencies and the difference between peak and average luminosities. We thus require a peak luminosity of $3 \times 10^{33} \text{ cm}^{-2} \text{ s}^{-1}$ to log 30 fb^{-1} in one calendar year.

Information gathered at the $T(5S)$ resonance on the angle γ is complementary to the measurements of α and β , but very large samples (several hundred fb^{-1}) are required to match the precision of the measurements done at the $T(4S)$. For details, see Hitlin [1989], pp. 84–91.

2.3.7 Sensitivity to Nonstandard Origins for CP Violation

So far we have restricted ourselves to the use of CP asymmetries in the context of verifying the Standard Model. The asymmetries are actually much more powerful: They can provide deep insights in the event that the Standard Model proves to be incorrect.

The simplest statement that can be made is that, a priori, there is no reason to expect the Standard Model range for $\sin 2\beta$, namely $-1 \leq \sin 2\beta \leq -0.08$, to be any more probable than the rest of the physical range ($-0.08 \leq \sin 2\beta \leq 1$). Establishing that the Standard Model is wrong is therefore very direct and could take relatively little running time, even at luminosities significantly below the design level.

The B^0 meson CP laboratory is considerably richer than even this statement would suggest, as has been outlined by Nir and collaborators [1990a, b, and c]. When we make the predictions about CP asymmetries discussed above for the Standard Model, we make several essential assumptions. We assume, for instance, that the nontagging B^0 decay has contributions from only one W -mediated quark subprocess. Multiple subprocesses (such as penguin contributions) could significantly change the predictions of the Standard Model. (It is fortunate that this assumption is reliable for the prototypical decay $B^0 \rightarrow J/\psi K_s$, where contaminations are considered to be below the few percent level.) We also assume that both $K-\bar{K}$ and $B-\bar{B}$ mixing proceed via the Standard Model mechanism of a “box diagram.” Both of these assumptions enter the calculations of the asymmetries in a

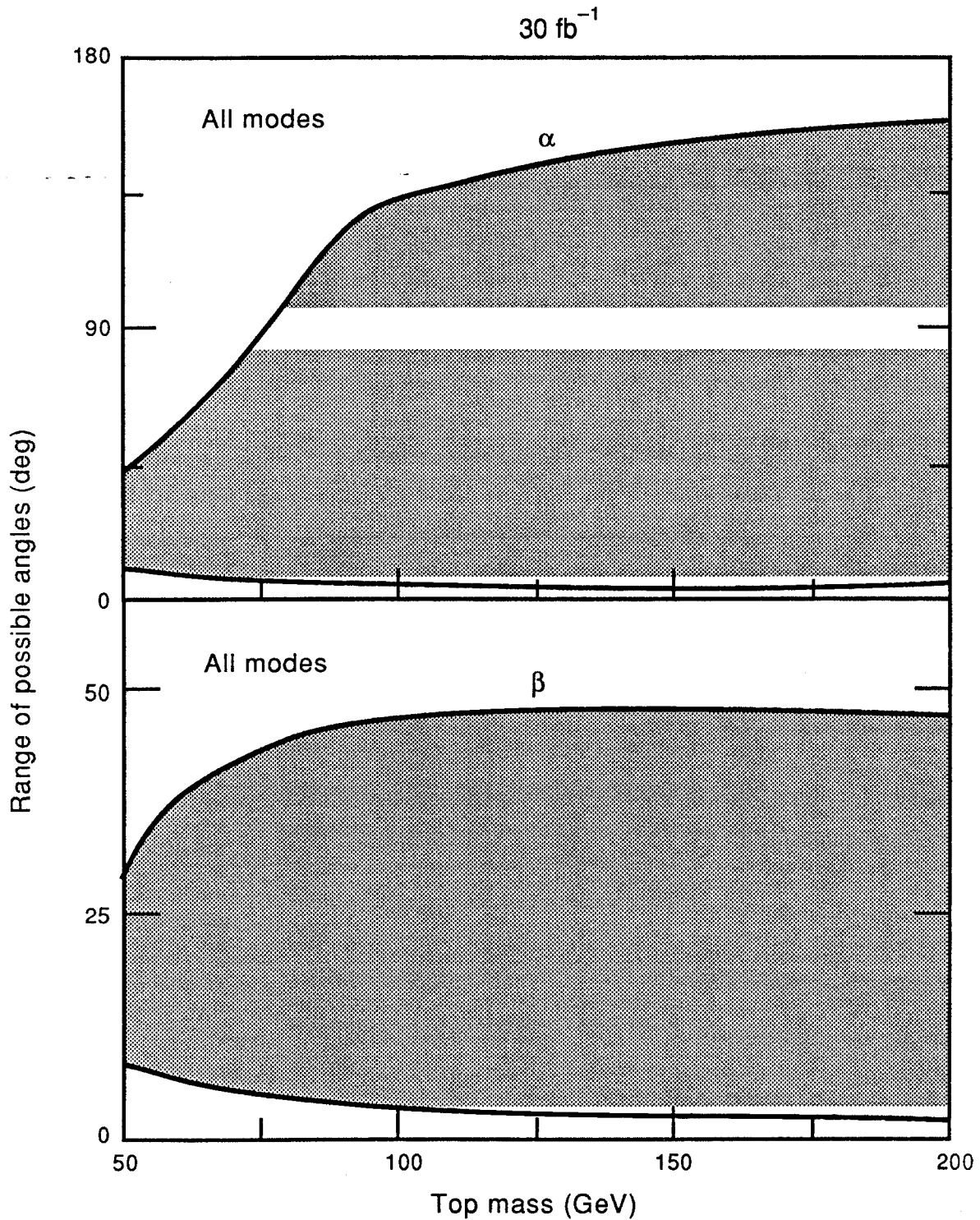


Fig. 2-9. The range of α and β predicted by the Standard Model that can be covered (3σ) by a 30-fb^{-1} data set, using a spectrum of CP decay modes (see Table 2-3).

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Table 2-3. Summary of the assumptions used in the simulations of Fig. 2-9 to establish the measurement errors for $\sin 2\alpha$ and $\sin 2\beta$ (here generalized as $\sin 2\phi$). In addition, we have used as input a wrong-sign fraction of 8%, a $B\bar{B}$ cross section of 1.2 nb, and a neutral B fraction of 0.5.

Mode	Assumed branching fraction	Tagging efficiency (%)	Reconstruction efficiency (%)	$\sigma (\sin 2\phi)$ (30 fb ⁻¹)
$B^0 \rightarrow J/\psi K_s$	7.4×10^{-4}	45	58	0.077
$\rightarrow D^+ D^-$	6×10^{-4}	45	46	0.14
$\rightarrow J/\psi \bar{K}^{*0}$	12.5×10^{-4}	45	30	0.17
$\rightarrow D^{*+} D^{*-}$	16×10^{-4}	45	28	0.08
Combined (2β)				0.050
$B^0 \rightarrow \pi^+ \pi^-$	2×10^{-5}	45	43	0.18
$\rightarrow \rho^\pm \pi^\pm$	6×10^{-6}	37	58	0.12
$\rightarrow a_1^\pm \pi^\pm$	6×10^{-5}	32	60	0.18
Combined (2α)				0.086

central way. What Nir and collaborators have shown is that experiments performed at the Asymmetric B Factory can, through a specific set of measurements, pinpoint directly which of these underlying assumptions is breaking down. For instance, in the Standard Model, the asymmetry measured in $B^0 \rightarrow J/\psi K_s$ must have the same value as that measured in $B^0 \rightarrow D^+ D^-$: If these do not agree, the problem is uniquely with the assumption that $K-\bar{K}$ mixing proceeds via the box diagram. It has also been shown [Nir, 1990c] that in a model in which $B-\bar{B}$ mixing is predominantly due to Z-mediated flavor-changing neutral currents (rather than the familiar box diagram), the predictions for α and β can be completely different from those in the Standard Model; in fact, in this model, the Unitarity Triangle is actually a quadrangle. All these eventualities lead to striking departures from the Standard Model predictions—and they are all readily measurable at the Asymmetric B Factory.

It should also be reiterated that backgrounds in the reconstruction of B mesons in the T(4S) environment are small, making it uniquely suited to the reconstruction of a large number of B^0 decay modes with measurable CP asymmetries, even those of higher multiplicity and those that involve final state π^0 's (see Table 2-3). This gives us the ability to make important cross-checks, as well as to reduce the luminosity required for the asymmetry measurements. Our simulations demonstrate that, for all the modes studied, large detection efficiencies are possible, with excellent signal-to-noise ratios.

2.3.8 Other B Physics

As outlined in Hitlin [1989], data taken at the T(4S) yield a rich B physics program beyond the area of CP violation. The production of several hundreds of millions of B mesons permits a sensitive search for rare and unexpected B decays. These rare decays also provide an important window to violations of the Standard Model. Processes involving yet-unseen penguin diagrams (an example of which is the decay $B^0 \rightarrow K^* \gamma$) will be accessible. It may also be possible to observe the decay $B^0 \rightarrow \tau \nu_\tau$, which would yield a measurement of the B decay constant f_B , a fundamental parameter. The B Factory will permit the search for rare decays at the level of 1 part in 10^8 .

As pointed out earlier, the patterns of the heavy-quark decays are basic to an understanding of the weak interaction, and they determine directly the elements V_{ij} of the CKM matrix. A wide variety of $b \rightarrow c$ and $b \rightarrow u$ hadronic decays are available for study, as are $b \rightarrow c$ and $b \rightarrow u$ semileptonic decays.

Whereas we have measured mixing in the B_d^0 sector, mixing in the B_s^0 sector has not yet been observed. The mixing is expected to be more rapid: x_s is expected to be in the range 3–20 (compared with x_d , which is 0.71). Observing this mixing is a high-priority measurement. We have simulated a measurement of x_s using same-sign dilepton events observed in the decay of the T(5S). Requiring 10% measurement precision, x_s is measurable up to a value of 15 in a run of 30 fb^{-1} . This result assumes that the energy asymmetry at the T(5S) would be the same as at the T(4S); one gains rapidly in precision by increasing the energy asymmetry. In all likelihood, the T(5S) running will be a second-round experiment, following the first round of CP violation measurements done at the T(4S). It would seem prudent, then, when moving the energy up to the T(5S), to also reoptimize the interaction region geometry to provide a larger asymmetry. The machine design allows for such a change.

2.3.9 Charm Quark Physics

There is a long list of important topics in charm physics accessible at the B Factory by virtue of its high luminosity.

Mixing in the $D^0\text{--}\bar{D}^0$ system can be measured at a level several times smaller than the Standard Model prediction for this phenomenon. The expected limit on the mixing for a 30 fb^{-1} run at the T(4S) is less than 6×10^{-5} , compared with the Standard Model prediction of about 10^{-4} or larger. This means that if the Standard Model prediction is wrong the B Factory will have adequate sensitivity to establish this fact. The same measurement will yield information about CP violation in D decay, which is expected to be very small in the Standard Model. In a 30 fb^{-1} run at the T(4S), we will be able to search for CP -violating effects in the decays $D^0 \rightarrow K^+ K^-$ and $D^0 \rightarrow \pi^+ \pi^-$ at the 1% level. An effect this large would be uncommonly interesting, but is rather unlikely.

As with bottom quark decays, charm quark decays provide valuable input for the CKM matrix. Definitive measurements of both Cabibbo-allowed and Cabibbo-suppressed semileptonic decay modes are possible.

Two new areas of interest in charm physics are the spectroscopy of the $L = 1$ D^{**} meson resonances and charmed baryons. This area of study has recently been initiated by CLEO and ARGUS with small numbers of events. There are 12 D^{**} $L = 1$ states. Because this system is composed of one heavy and one light object (much like the hydrogen atom), the energy levels are sensitive to the details of the long-range (scalar) part of the potential. Mass splittings between the states are due to the spin-orbit interaction, rather than the more familiar spin-spin interaction. A large number of events are required to measure the masses, widths, spins and splittings in this system. Estimates have been made (see Hitlin [1989], Table 9.1, p. 236) of the number of events that would be observed in these 12 states. For a 30-fb^{-1} run, these numbers range from 700 to 20,000, with typical signal-to-noise ratios of better than 1 to 1. There is also a rich spectroscopy of charmed baryon states, few of which have been observed. The same 30-fb^{-1} run would yield thousands of these events per mode (see Hitlin [1989], Table 9.2, p. 239), with a signal-to-noise ratio of about 1 to 1.

2.3.10 Tau Physics

As far as we can discern, the τ lepton is a heavier version of the muon and electron, all three having properties strikingly consistent with the predictions of the Standard Model. The level of certainty of this statement is, however, experimentally not as great in the case of the τ as it is for the two lighter leptons, as our studies of τ decay involve statistical samples many orders of magnitude smaller. There are, in fact, several inconsistencies in the measurements of τ branching fractions. The B Factory will provide an increase in statistical power, relative to present studies, of about two orders of magnitude, thus allowing much more thorough tests of the sequential lepton hypothesis for the τ .

Many specific measurements have been considered in detail. The limit on the τ neutrino mass (currently less than 30 MeV) can be lowered to a few MeV. The Cabibbo angle in τ decay can be measured far more accurately than the current $\pm 20\%$. Searches for second-class currents are possible at a level below the expectations of the Standard Model. Rare decays can be searched for at the 10^{-8} level. The structure of the τ -W- ν_τ vertex can be studied in detail. Both τ branching fractions and the τ lifetime can be measured with exquisite precision; these can then be combined to yield absolute decay widths. The current branching fraction puzzle in τ decays will either be resolved or shown to be an anomaly. The precision with which these measurements can be made is summarized in Table 2-4.

2.3.11 Upsilon Physics

Quarkonia, bound states of quark and antiquark, provide us with an excellent testing ground for QCD, both perturbative and nonperturbative. Bottomonium ($b\bar{b}$), the heaviest known system, is the most amenable to theoretical interpretation, as both relativistic corrections and higher-order QCD effects are much smaller than in the lighter quarkonia. The spectrum of bottomonium states is very rich, and although many of the states have been observed, a number of important spectroscopic measurements remain to be made.

Table 2-4. Summary of τ physics measurements.

Physics topic	$\int \mathcal{L} dt$ (fb $^{-1}$)	Sensitivity	Backgrounds	Systematics
M_{ν_τ}	100	3 MeV @ 95% CL	None found	1.1 MeV; hadronic mass scale & M_τ
Cabibbo angle	30	0.5%	Small; from $\tau^+\tau^-$	0.4%; from background and cuts
Second-class currents	30	5σ signal if BF = 3×10^{-5}	From $\tau^+\tau^-$	
Rare decays ($\tau^+ \rightarrow \mu^+\mu^+\mu^-$)	100	BF $\leq 3 \times 10^{-7}$ @ 95% CL	Dominantly $\tau^+\tau^-$	
B_e/B_μ	30	0.2%	Dominantly $\tau^+\tau^-$	0.4%; from background
τ lifetime	30	0.14%	1%; from $q\bar{q}$	0.25%; from vertex detector position
Branching fracs ($\tau \rightarrow e \nu \bar{\nu}$)	30	0.3%	2%; from $q\bar{q}$	0.2%; from background
τ -W- ν_τ structure	30	ρ, η $O(0.1\%)$ ξ, δ $O(1\%)$		

Much of this physics is only accessible with statistical samples of the size to be available at the B Factory.

Among these measurements, we single out a few for illustration. Transitions from the $T(3S)$ and $T(2S)$ states to the singlet S states (η_b) and to the lowest singlet P state could lead to the discovery of the pseudoscalar and pseudovector states and measurements of the hyperfine splittings. Detailed studies of the known triplet P states are needed. Enhanced studies of hadronic transitions between the T family are also much needed. High-statistics studies of radiative transitions will be performed, including searches for nonstandard Higgs particles. The T system can yield precise determinations of the strong coupling constant α_s from comparisons of B meson branching fractions to different final states.

These studies require that the machine be run at energies other than that of the $T(4S)$. Relatively short runs (5–10 fb $^{-1}$) easily suffice to provide more than sufficient data for

these channels. These dedicated runs will be interspersed with T(4S) running: The accelerator will have sufficient energy tunability to allow movement among the T resonances.

2.3.12 Two-Photon Physics

The study of final states produced in e^+e^- reactions via the two-photon reaction (in contrast to the more prevalent one-photon exchange) has been actively pursued over the last ten years. Two-photon physics is now one of the primary sources of information about meson spectroscopy and QCD, and it serves as a unique laboratory for exotic meson searches. While a second generation of experiments is currently accumulating data, the much higher integrated luminosities available at the B Factory will make it an ideal place to study two-photon physics and will extend the range of results considerably beyond what could otherwise be achieved in the next few years.

The two-photon reaction permits detailed studies of the properties of charge-conjugation $C = +1$ mesons, which are not directly accessible in one-photon annihilation. The environment has many advantages for establishing the quantum numbers of these states; in the special case of spin 1 particles, the TPC group at PEP has demonstrated a unique method for determining the spin and parity of the states. The two-photon reaction probes the quark content of hadrons in a manner different from that of one-photon annihilation. The former has a rate proportional to the fourth power of the quark charges, whereas the latter has a rate proportional to the second power. This enhances sensitivity to the mesons containing up and charm quarks.

Two-photon reactions provide an ideal hunting ground for exotic meson states, those that cannot be formed by pairs of quarks. Such states might include four-quark states, states made from two quarks and a gluon, etc. Here, as with the $C = +1$ mesons, the high luminosity of the B Factory will provide sensitivity to particle masses well above anything current experiments will achieve.

The measurement of exclusive and inclusive hadron production in two-photon reactions allows access to many aspects of QCD that remain difficult to probe in other ways. Reaction rates and kinematic distributions yield important information on the distribution of quarks and gluons inside hadrons. One can probe regions of high Q^2 and large two-photon center-of-mass energy, where reliable perturbative QCD predictions exist. The total cross section yields information about the hadronic nature of the photon, while photon structure function measurements permit a definitive test of perturbative QCD.

2.4 CONSTRAINTS IMPOSED ON THE ACCELERATOR BY THE DETECTOR

The detector required for this physics program imposes certain constraints on the accelerator design, in addition to those of the energy asymmetry and the required luminosity. The main constraints involve requirements of solid angle coverage, the radius of the beam pipe, and the reduction of backgrounds.

The detector will closely resemble a conventional 4π detector for e^+e^- annihilation. It will not be inherently asymmetric, but there will be a premium on good charged-particle

and photon detection in the forward direction. Sensitivity to CP asymmetries suffers significantly if the solid angle for tracking is reduced, for example, from 95% to 85%. This leads to a requirement that the machine components not encroach beyond a ± 300 -mrad cone, measured relative to the beam direction. This stay-clear region must be maintained to a distance of ± 2 m along the beam axis.

One would expect that an experimental program that depends so heavily on vertex detection for its success would require that a layer of vertex detector be at the smallest possible radius. There are many reasons for a small beam pipe radius, such as reducing the cost and improving many physics measurements, but they must be balanced against the fact that the detector backgrounds improve with a larger beam pipe radius. It is therefore fortunate that the measurement of the CP -violating asymmetries, which is the experiment motivating the entire facility, does *not* depend critically on this radius. Figure 2-10 shows the relative error on the measurement of $\sin 2\alpha$ (using $B^0 \rightarrow \pi\pi$), as a function of the radius of the first vertex detector layer. One sees that providing a beam pipe with a radius in the region of 2–4 cm maintains resolution close to the best case, assuming an energy asymmetry of 3.1 on 9 GeV. (For B_s mixing, the story is somewhat different: Here it is indeed best to have the smallest possible beam pipe radius.)

Detector backgrounds have two deleterious effects: radiation damage to the devices and unacceptable occupancy levels. We have carefully studied the tolerance level for these two effects on the main elements of the detector. These backgrounds arise from two sources, namely, synchrotron radiation photons and lost particles ($e^\pm$)—either direct sources of electrons and positrons or those resulting from photon conversions

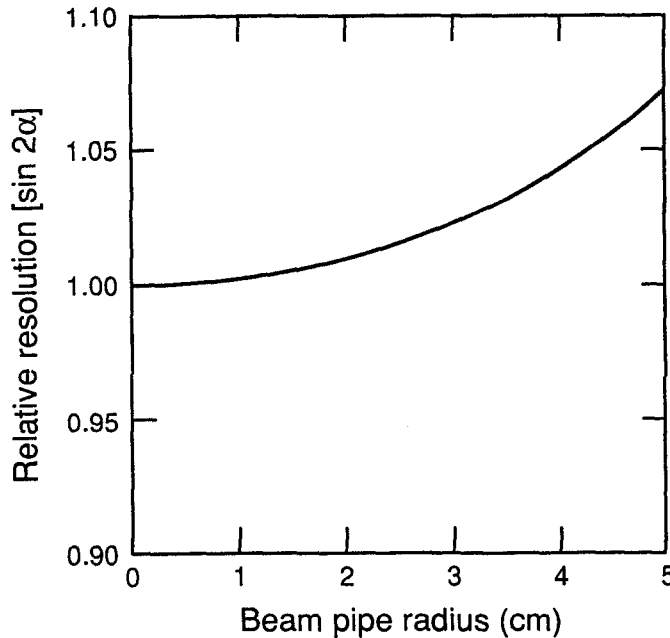


Fig. 2-10. The sensitivity of the measurement error for $\sin 2\alpha$, as a function of the radius of the beam pipe. The resolution worsens slowly as the beam pipe radius (that is, the radius of the first vertex detector layer) increases.

INTRODUCTION

(independent of whether the photons are from synchrotron radiation or bremsstrahlung). Our detailed synchrotron radiation calculations were based on the appropriate photon spectrum, as generated in the background studies (see Section 4.2). Energy-loss mechanisms in the devices were also accounted for.

Tables 2-5 and 2-6 show the tolerance levels of the silicon vertex detector and the central drift chamber for these sources, as they pertain to detector occupancy and radiation damage. For the silicon, we assumed a radiation limit of 100 krad/yr, and for the occupancy limit, we assumed 10% in four strips. For the drift chamber, we took the radiation limit to be 0.5 C/cm of sense wire, and for the occupancy limit, we used 10%. For the calorimeter, we used the most conservative estimate available of radiation

Table 2-5. Silicon vertex detector background limits.

Source	Limit	Flux (particles/cm ² μs)	Rate (particles/μs)
Synchrotron radiation photons	Occupancy	2	400
	Radiation damage	3	600
Lost particles (e [±])	Occupancy	1	200
	Radiation damage	0.1	20

Table 2-6. Drift chamber background limits.

Source	Limit	Flux (particles / cm ² μs)	Rate (particles/μs)
Synchrotron radiation photons	Occupancy	1.0	30,000
	Radiation damage	2.0	60,000
Lost particles (e [±])	Occupancy	0.0003	11 (1st sense wire layer)
	Occupancy	0.0003	28 (middle sense wire layer)
	Radiation damage	0.002	50 (1st sense wire layer)

damage limits for CsI: 5 krad/yr. For this limit, the corresponding guideline is to keep the radiation below 10^4 MeV/ μ s in the barrel region. We see that, in reality, the calorimeter radiation requirements are less stringent than those for the other two devices.

It is against these criteria that the estimates of backgrounds in Section 4.2 must be measured.

2.5 RUNNING SCENARIOS

It is worthwhile in conclusion to summarize the energy settings for the machine that we envision providing the proper balance for the physics program.

The physics running will commence at the $\Upsilon(4S)$; most of the running in the first few years will be at this energy. This running will be interspersed with short (1–3 month) runs on the $\Upsilon(1S)$, $\Upsilon(2S)$, $\Upsilon(3S)$, and $\Upsilon(5S)$ resonances. After sufficient data have been accumulated to establish the CP program, a dedicated one-year program could be run at the $\Upsilon(5S)$, the primary motivation being to measure B_s mixing. The interaction region components will likely be reoptimized for this run, so as to obtain a smaller beam pipe radius and perhaps a larger energy asymmetry.

3.

GENERAL DESCRIPTION AND PARAMETER CHOICES

IN this chapter, we give a general overview of the Asymmetric B Factory collider. First, we summarize the performance goals of the collider, based on the physics considerations outlined in Chapter 2. Then, we briefly describe a design that meets these requirements. To carry out the physics program of a B Factory, the luminosity of the facility must be improved by a factor of 30 over that of currently operating e^+e^- colliders. It is clear, of course, that this is a challenging goal, and one that is inherently at odds with maintaining a “conservative” design in all areas. On the other hand, we are convinced that a successful project must take seriously the concept of a “factory,” that is, the machine must be designed—insofar as possible—to be highly reliable.

As might be imagined, there are various possible machine configurations that could be considered to achieve our performance goals. Therefore, it is necessary to make certain choices from the outset to focus the design process. Such choices might be based on the advantages (or disadvantages) of a particular site, on the experience and expertise of the design team, or on judgments about the degree of reliability and/or flexibility inherent in particular approaches. To put our parameters in context, we include in this chapter a discussion of the rationale for each of the major choices made in arriving at the B Factory configuration described in this report.

We have restricted ourselves to consideration of a B Factory based upon storage ring technology. At the present time, alternative approaches, such as linac-on-linac or linac-on-storage-ring scenarios, are felt to be more speculative than the approach taken here. For example, the technology of high-power, high-repetition-rate, high-brilliance linacs is still in its infancy. Moreover, it does not appear that these alternative approaches offer significant advantages over the more straightforward approach of extrapolating the relatively well-understood performance of storage rings. This outlook is clearly shared by many other groups worldwide that have actively pursued the design of a B Factory collider, all of whom have based their work on asymmetric storage rings [Funakoshi et al., 1990; Hartill, 1990; Rivkin, 1990; Zholents, 1990].

3.1 DESIGN OVERVIEW

The primary performance goals for the collider, based on the discussion in Chapter 2, are as follows:

- Achieving a peak luminosity of $3 \times 10^{33} \text{ cm}^{-2} \text{ s}^{-1}$ in a reliable fashion
- Operating with an energy asymmetry of about 1:3 in the vicinity of the $\Upsilon(4S)$ resonance, $E_{\text{c.m.}} = 10.58 \text{ GeV}$
- Storing high beam currents (1–2 A) stably and with adequate lifetime
- Maintaining acceptable detector background conditions
- Providing flexibility to accommodate both modifications to the assumed beam-beam interaction parameters and optics changes near the interaction point required by background considerations

The Asymmetric B Factory design described in this report meets all of these requirements. Key features of the design are summarized below:

- Low β_x^* values at the interaction point
- Head-on collisions
- Flat beams ($\sigma_x/\sigma_y = 25$)
- Many bunches ($k_B = 1658$ in each ring)
- Two rings (9-GeV e^- in PEP; 3.1-GeV e^+ in a new low-energy ring)
- Well-cooled, low-impedance vacuum chambers
- Wigglers to control the emittance and damping time of the low-energy ring
- Single-cell, room-temperature RF cavities
- Feedback systems for controlling multibunch instabilities
- A powerful injection system (the SLC linac)

The B Factory collider is an upgrade of the existing PEP (“Positron-Electron Project”) collider at the Stanford Linear Accelerator Center (SLAC); its major parameters are collected in Table 3-1. To optimize the physics potential of the facility, we have adopted an *asymmetric* design in which a high-energy electron beam of 9 GeV collides with a low-energy positron beam of 3.1 GeV. We thus require a two-ring configuration, where each beam circulates in its own vacuum chamber and is controlled by independent optical elements, except in the interaction region (IR) where the beams collide. The high-energy beam will circulate in the (upgraded) PEP ring; the low-energy beam will circulate in a newly constructed ring.

Both the high-energy ring (HER) and the low-energy ring (LER) are located in the existing PEP tunnel; a site plan for the facility is shown in Fig. 3-1. The tunnel has a hexagonal geometry and accommodates a ring having a circumference of 2200 m. The

Table 3-1. Main B Factory parameters.

	Low-energy ring	High-energy ring
Energy, E [GeV]	3.1	9.0
Circumference, C [m]	2199.32	2199.32
Emittance, ϵ_x/ϵ_y [nm-rad]	96.5/3.9	48.2/1.9
Beta function, β_x^*/β_y^* [cm]	37.5/1.5	75.0/3.0
Beam-beam tune shift, $\xi_{0,x}/\xi_{0,y}$	0.03/0.03	0.03/0.03
RF frequency, f_{RF} [MHz]	476	476
RF voltage, V_{RF} [MV]	9.5	18.5
Bunch length, σ_t [cm]	1.0	1.0
Number of bunches, k_B	1658	1658
Bunch separation, s_B [m]	1.26	1.26
Damping time, τ_E/τ_x [ms]	18.4/36.4	18.4/37.2
Total current, I [A]	2.14	1.48
Synch. rad. loss, U_0 [MeV/turn]	1.24	3.58
Luminosity, $\mathcal{L}$ [cm ⁻² s ⁻¹]	3×10^{33}	

six straight sections in the PEP tunnel are each 110 m long; this provides generous space not only for the IR but also for the various utility functions (RF, injection, etc.).

Because the PEP tunnel was originally sized to house a second (proton) ring, there is ample room for the LER to be mounted above the HER, as illustrated in Fig. 3-2. This design choice, which leads to equal circumferences for the LER and HER, has several advantages. First, it eliminates the need for the major conventional construction that would result if a smaller-circumference LER were chosen. Second, it permits the same number of beam bunches in each ring, thus avoiding possible concerns about coherent beam-beam instabilities. Finally, the large circumference increases the luminosity lifetime, compared with that in a smaller ring, by storing more particles (which are lost at a constant rate in the beam-beam collisions) for a given luminosity. (To take full advantage of the last benefit, it must be possible to fill the large ring quickly. As we will discuss below, the linac injector available at SLAC is ideal for this purpose.)

Reutilizing the PEP tunnel has the added benefit of making many of the installed utilities available for the B Factory, including power and water distribution, cable ways, etc. This is advantageous not only in terms of costs, but also in terms of minimizing the construction time for the facility. We also intend to reuse essentially all of the existing

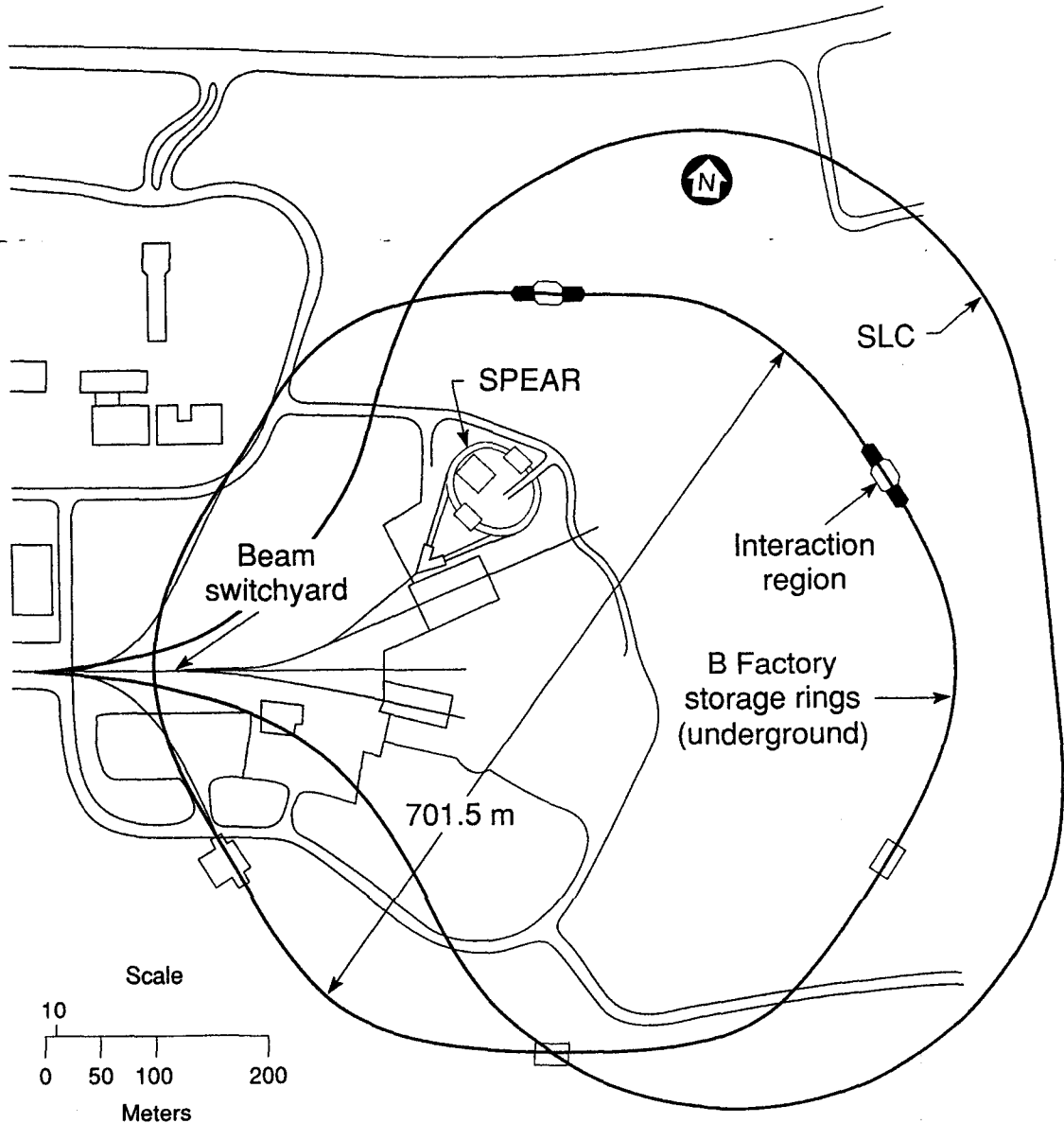


Fig. 3-1. SLAC site plan showing the general configuration of the B Factory. The linac beam enters the rings from the beam switchyard at the left. The SLC arcs are at a different elevation from the PEP tunnel and thus do not intersect it.

PEP magnets for the HER. This too will yield significant cost and schedule benefits, with no compromise on the performance of the B Factory.

PEP was built to operate at beam energies up to 18 GeV; therefore, its magnet parameters are fully compatible with the requirements for the HER of the Asymmetric B Factory collider. For example, the PEP bending magnets have a magnetic radius of $\rho = 165$ m at 9 GeV, which considerably reduces the synchrotron radiation power emitted by the high-energy beam in the B Factory, compared with that from a smaller ring. Thus, we will be able to maintain a high beam current and a suitable asymmetry without prohibitively high synchrotron radiation power losses. The natural emittance required for

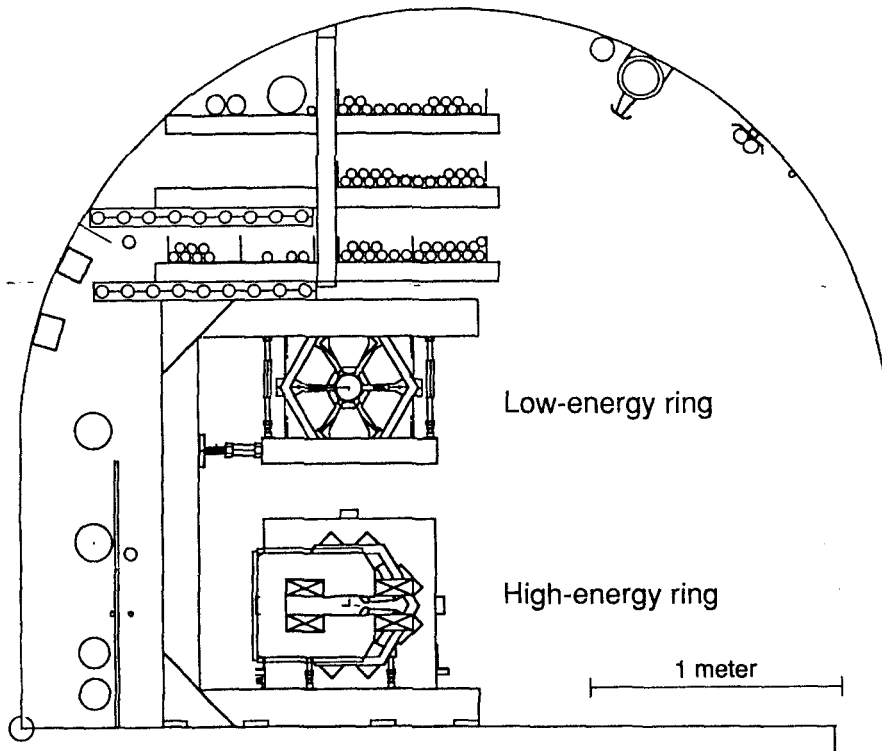


Fig. 3-2. Cross section of the PEP tunnel, showing the locations of the two B Factory rings and installed utilities.

the B Factory HER is essentially that of the standard PEP lattice. Moderate adjustments to the emittance, such as might be dictated by beam-beam considerations, can be accommodated either by mismatching the dispersion function or by trimming the phase advance in one or more sextants of the ring.

In the case of the LER, relatively short (1 m) bending magnets having a magnetic radius of $\rho = 30.5$ m are used. Despite this choice, the natural emittance generated in the ring dipoles alone would be considerably lower than the emittance called for in Table 3-1. To handle this, we make use of wigglers in two straight sections to give us independent control of emittance and damping times. This approach provides a great deal of flexibility to select the operating parameters of the LER in an optimum fashion.

The injection system for the collider is based upon the existing SLC linac injector, as illustrated in Fig. 3-3. It is assumed here that the SLC experimental program will be completed prior to the time the B Factory becomes operational, although it is likely that the injector complex will still play a part in various R&D activities (for example, as injector for the Final Focus Test Beam or, possibly, for a test section of the so-called Next Linear Collider), in addition to its primary role as the B Factory injector. Thus, the SLC damping rings and positron-production target will be available for the B Factory. We will see in Chapter 6 that this combination is very powerful and provides an ideal injector for the B Factory. With the injection system operating at only 10% of routine SLC intensity, the top-up time for *both* collider rings is about 3 minutes.

To summarize, we note that from many viewpoints the PEP site at SLAC is an ideal location for the construction of an Asymmetric B Factory collider:

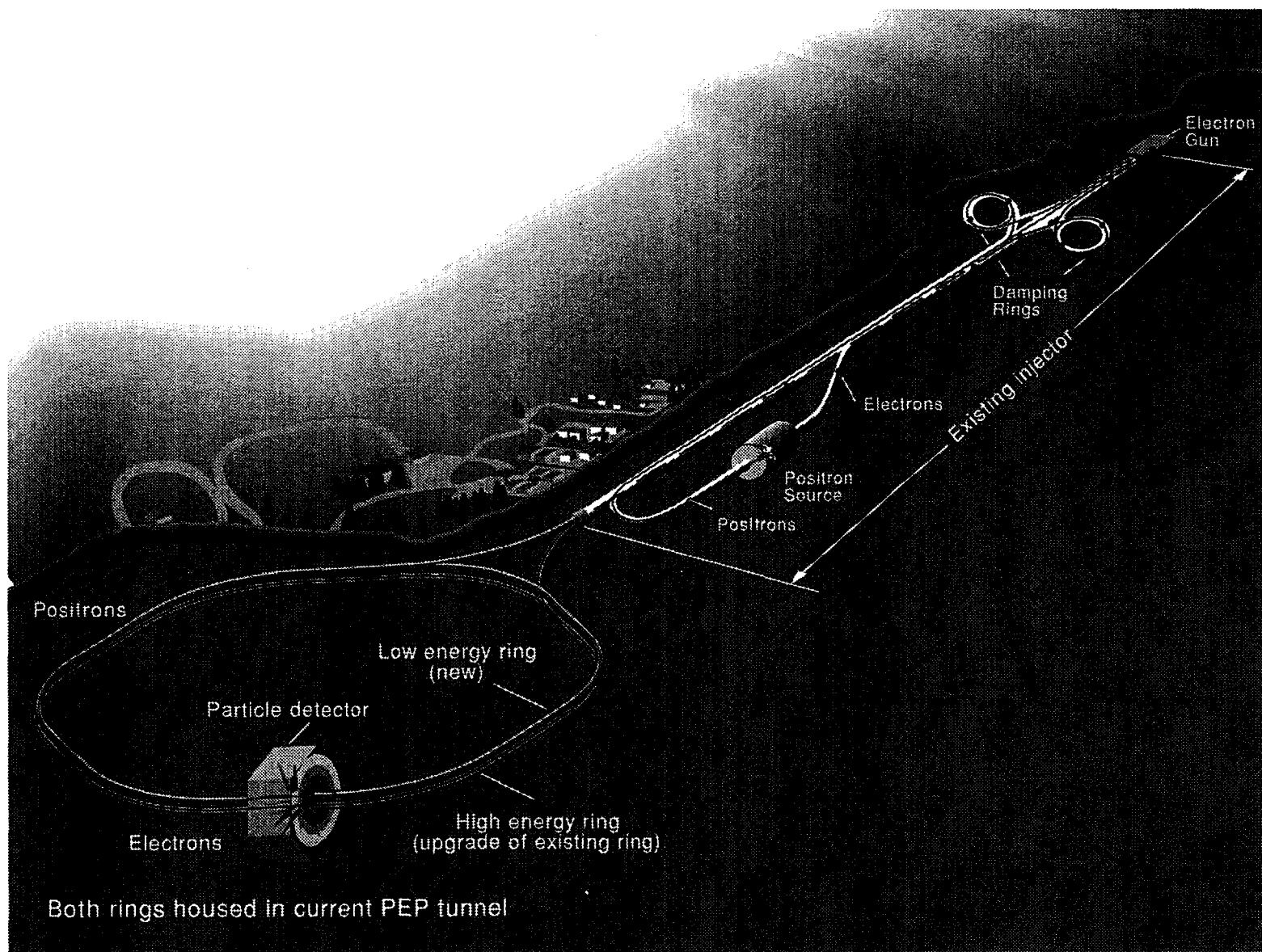


Fig. 3-3. Schematic illustration of the B Factory, showing the existing injector system.

- The availability of a large-circumference tunnel offers maximum flexibility in the choice of collider parameters.
- The existence of a powerful positron injector facilitates rapid commissioning and ensures a high *integrated* luminosity.
- The existing PEP infrastructure permits the rapid construction and commissioning of the facility.

In addition, the considerable accelerator design expertise and engineering strengths of SLAC, LBL, and LLNL will ensure the successful and reliable operation of the facility at its design luminosity.

3.2 LUMINOSITY CONSIDERATIONS

The first four of the key B Factory design features listed earlier are dictated primarily by the luminosity limitations associated with the beam-beam interaction. The physics issues will be discussed in detail later (in Section 4.4), but here we will introduce the topic in the context of parameter choices for the B Factory.

The general expression for luminosity in an asymmetric collider is cumbersome, involving various parameters of both beams at the interaction point (IP). To simplify the choices and to elucidate the general issues of luminosity for any B factory, it is helpful to write the luminosity in an energy-transparent way. In this section, we express the luminosity in terms of a single beam-beam tune shift parameter ξ , common to both beams, along with a combination of other parameters taken from *either* the high-energy (e^-) or low-energy (e^+) ring, irrespective of energy.

With a few plausible assumptions (for example, complete beam overlap at the IP and equal beam-beam tune shifts for both beams in both transverse planes), such parameters as energy, intensity, emittance, and the values of the beta functions at the IP may be constrained to satisfy certain scaling relationships. (Details of this approach are presented in Section 4.4.) It then becomes possible to express luminosity in a simple, energy-transparent form [Garren et al., 1989]:

$$\mathcal{L} = 2.17 \times 10^{34} \xi (1 + r) \left(\frac{I \cdot E}{\beta_y^*} \right)_{+,-} [\text{cm}^{-2} \text{s}^{-1}] \quad (3-1)$$

where

- ξ is the maximum saturated dimensionless beam-beam interaction parameter (taken to be the same for both beams, and for both the horizontal and the vertical transverse planes).
- r is the aspect ratio characterizing the beam shape (1 for round, 0 for flat).
- I is the average circulating current (in amperes).
- E is the energy (in GeV).
- β_y^* is the beta function at the IP (in cm).

The subscript on the combination $(I \cdot E / \beta_y^*)_{+,-}$ means that it may be evaluated with parameter sets taken from either ring.

The scaling relations derived in Section 4.4 were used to produce a self-consistent set of parameters that have been used in this report. After a few basic parameters are chosen, such as the energies, the currents, the aspect ratios, and the lowest beta value at the IP for each ring, most of the other parameters, including the luminosity $\mathcal{L}$, follow. To a certain extent, the choice of which parameters are specified and which are derived is arbitrary. Nonetheless, as discussed below, there are many practical considerations that limit the degrees of freedom in maximizing the luminosity.

Energy. The energies $E_{+,-}$ are not entirely free parameters; they are constrained kinematically. To take advantage of the cross section enhancement at the $T(4S)$ resonance, the collider center-of-mass energy must be 10.58 GeV. Precise determination of the decay vertices with a reasonable detector geometry then limits the energy ratio to the range of about 1:3 to 1:5. Simulations of the beam-beam interaction (both our own and those of others [Hirata, 1990]) argue for approximately equal damping times per collision ("damping decrement") in the two rings, which is more easily accomplished when the energy asymmetry is reduced. On the other hand, magnetic separation becomes easier when the energy asymmetry increases. Taken together, these considerations lead to an optimum energy of the high-energy beam of $E \approx 8\text{--}12$ GeV, and the corresponding energy of the low energy beam is thus $E \approx 3.5\text{--}2.3$ GeV. For the B Factory design, we have adopted energies of $E_- = 9$ GeV and $E_+ = 3.1$ GeV.

Beam-beam tune shift. The beam-beam tune shift parameter ξ is not really a free parameter; it is determined intrinsically by the nature of the beam-beam interaction. The range of maximum beam-beam tune shifts achieved in existing equal-energy e^+e^- colliders is $\xi \approx 0.03\text{--}0.07$. We chose a moderate value of $\xi = 0.03$ as the basis of our nominal luminosity estimates. (For simplicity, we assume at this point that the ξ values of both beams, in both transverse planes, are equal. Less restrictive assumptions would lead to a parameter dependence similar to that in Eq. 3-1, as discussed in Section 4.4.) Insofar as considerably higher tune-shift values than this have already been observed at PEP—even with multiple IPs—we consider the value of 0.03 to be reasonable for estimating the performance of an asymmetric collider.

One implication of the tune-shift limitation is that increased luminosity must perforce come from decreasing the bunch spacing s_B , that is, increasing the number of bunches. The push toward small bunch spacing has a significant impact on the design of the IR, which must separate the beams sufficiently to avoid unwanted collisions. (As will be discussed in Section 4.4, including the effects of parasitic crossings makes the ξ value we have adopted less conservative.) The close spacing also exacerbates the problem of controlling coupled-bunch beam instabilities, because it increases the bandwidth requirements of the feedback systems.

There is evidence from computer simulations [Krishnagopal and Siemann, 1990] that the maximum achievable ξ may depend on the beam aspect ratio: $\xi = \xi(r)$. This is a controversial issue, now being debated, but it is known that an enhancement in ξ (for round beams) of at best a factor of two can be obtained. As will be discussed below, there are significant difficulties associated with round beams, having nothing to do with the beam-beam interaction, that make this option unattractive even if the tune-shift enhancement proves to be correct.

Beam Aspect Ratio. The aspect ratio r is free to the extent that one can create round beams. However, the physics of the beam-beam interaction is sensitive to the method (coupling resonances, wigglers, etc.) used to make the beams round. Although the use of coupling resonances is a straightforward way to obtain a round beam, it is not clear that applying such a constraint in tune space—where the nonlinear effects of the beam-beam interaction manifest themselves—is the best thing to do. The use of wigglers or phase-plane rotators offers the potential advantage of producing round beams via a noiselike excitation that should not correlate with the subtleties of the nonlinear tune-space behavior.

In the LER, one could imagine the use of wigglers to create a large vertical emittance corresponding to $r = 1$. In the case of the HER, where the synchrotron radiation emission in the horizontal bending magnets is already very large, the addition of sufficient wigglers (in an intentionally created vertically dispersive region) to produce a round beam is nontrivial, although it is certainly conceptually possible. This technique may, however, be impractical from the viewpoint of synchrotron radiation power. Therefore, optics changes (via skew quadrupoles) would likely be the preferable way to create round beams in the HER.

If there is no increase in the beam-beam tune shift, the maximum enhancement from the use of round beams is a factor of two, that is, $r = 1$ gives $(1 + r) = 2$ in Eq. 3-1. (As discussed below, however, the limit on β_y^* is lower in the flat-beam case, so the geometrical gain does not appear to be realizable in practice.) If the tune shift itself increases, a luminosity improvement by another factor of two might result. Such enhancements potentially permit the same luminosity to be reached with a twofold or fourfold decrease in the required beam current.

The fundamental disadvantage of round beams lies in the optics required to focus them. Near the IP, very strong quadrupoles are required. Because of the magnetic separation scheme, at least one of the beams must be off-axis in the quadrupoles, which results in the production of copious synchrotron radiation very close to the detector. In our earlier attempts [*Feasibility Study for an Asymmetric B Factory Based on PEP*, 1989; *Investigation of an Asymmetric B Factory in the PEP Tunnel*, 1990] to explore the round-beam case, up to 750 kW of synchrotron radiation power was emitted within a few meters of the IP. To handle this power, and the photon background that comes with it, in such a spatially constrained region appears at best to be very difficult.

Flat-beam optics, in contrast, produce an order-of-magnitude less synchrotron radiation power near the IP. In this case a masking and cooling scheme is practical, though still difficult. The flat-beam solution we adopted is described in detail in Section 4.2. It is worth noting here that, even taking account of the possible reductions in beam current enhancements from the use of round beams, the synchrotron radiation power near the IP in the round-beam case would be at least twice that of the flat-beam solution adopted here.

For the flat-beam case, there are some constraints on how low the aspect ratio can be. In the LER, the need to displace the beam vertically in the IR contributes to vertical emittance. For the HER, there is no such limit. In any case, we are concerned that the independent optics in the two rings could lead to a tilt of the two “ribbon beams” at the IP, such that the luminosity degrades quite substantially. The beam separation scheme gets easier if the aspect ratio of the beams is large (due to the lower angular spread of the

beams at the IP), so it is to the designer's advantage to postulate as large a ratio as possible. The Asymmetric B Factory design is based upon an assumed aspect ratio of $r = 0.04$; this value, conservative from the standpoint of ensuring a good collision geometry, makes the requirements on beam separation more stringent. (Because the limit associated with the weak LER vertical bends is only $r = 0.001$, we have considerable margin for improvement. This has *not* been taken into consideration in assessing the efficacy of the separation scheme discussed in Section 4.2.)

Beam Intensity. The average beam current I is a relatively free parameter, but not absolutely so. It is determined by various current-dependent coherent effects. The storage rings must accept the chosen currents, given certain impedances in the paths of the beams. There are several intensity-dependent issues with which we must be concerned:

- Longitudinal microwave instability, which causes individual beam bunches to grow both in length and in momentum spread; both the increased bunch length and the increased center-of-mass energy spread can reduce the effective luminosity
- Transverse mode-coupling instability, which limits the maximum current that can be stored in a single beam bunch
- Touschek scattering, which causes particle loss (from large-angle intrabeam scattering) and reduces the beam lifetime
- Coupled-bunch instabilities, which, unless controlled by feedback, can lead to unstable longitudinal or transverse motion and thus to either beam loss or luminosity loss
- Synchrotron-radiation-induced gas desorption, which can lead to very high background gas pressure and thus to beam losses from gas scattering
- Synchrotron radiation heating of the vacuum chamber wall, which can lead to melting of the chamber if the power density is sufficiently high

As will be discussed in Section 4.3, for our chosen parameters, the first three issues listed above are not expected to limit the performance of the B Factory. Based on our present estimates, the issues of most concern to the B Factory design are coupled-bunch instabilities (driven by parasitic higher-order modes of the RF system), synchrotron radiation heating, and synchrotron-radiation-induced gas desorption. Means to deal with the first issue are discussed in Sections 5.5 and 5.6. Problems arising from the synchrotron radiation emission require innovations in vacuum chamber design; our approach, based on a copper vacuum chamber, is described in Section 5.2. To provide a safety margin and to permit some room for future improvements, we have considered a maximum beam current of 3 A in the design of the vacuum systems for both the HER and the LER.

Beta Function at the IP. The beta function at the IP, β_y^* , is a free parameter and is easily variable down to a few centimeters, subject to the bunch-length condition $\sigma_z \leq \beta_y^*$ that arises from considerations of the beam-beam interaction. (Specifically, we wish to avoid luminosity loss resulting from either the increase in beam size away from the IP or the excitation of synchrotron resonances.) As the beta functions are reduced, of course, it becomes difficult to reduce the bunch length accordingly. Either the RF

voltage becomes excessive or the IR optics become unmanageable owing to the increased chromaticity. We have taken a bunch length of $\sigma_L = 1$ cm, which then restricts the value of β_y^* to the range of 1–3 cm.

It turns out that, for round-beam optics, the chromaticity tends to be about twice that of flat-beam optics. Thus, whatever chromaticity is tolerable in the round-beam case can be reached equivalently with flat-beam optics in which the β_y^* value has been reduced by a factor of two. This means that, in practice, the factor of two increase in luminosity implied by Eq. 3-1 is largely illusory.

From Eq. 3-1, it is clear that the luminosity is maximized with high currents and low β_y^* . What are the implications regarding these parameters for a luminosity goal of $3 \times 10^{33} \text{ cm}^{-2} \text{ s}^{-1}$? Following a conservative route, we use a typical low β_y^* of a few centimeters (1.5 cm in the LER, 3 cm in the HER), $\xi \approx 0.03$, and flat beams ($r = 0.04$). These choices imply an average circulating current I of several amperes (2.14 A in the LER, 1.48 A in the HER). As mentioned above, those portions of the vacuum chambers that would be difficult to upgrade later in the project have been designed to handle up to 3 A of beam current.

As a final point, we note that, for the initial phase of the project, we have adopted a design based upon a head-on collision geometry. This configuration has been employed successfully in many colliders and is therefore felt to be a prudent choice. It is likely, however, that detector backgrounds could be reduced by going to a nonzero crossing angle geometry in which the bunches are tilted transversely with respect to their direction of motion (a so-called “crab-crossing” scheme) to avoid the excitation of synchrotron resonances. To permit reaching higher luminosity values in the future, therefore, we do not wish to preclude this alternative now. Fortunately, because the separation scheme adopted here operates in the horizontal plane, the proposed layout lends itself quite well to later modification to a crab-crossing scheme. This possibility, discussed in Appendix B.2, is *not* part of the present project but could be considered as a future upgrade.

3.3 RF CONSIDERATIONS

There are two important choices to be made in the design of the RF system: frequency and technology (room temperature vs superconducting). The issues involved are discussed below.

3.3.1 Choice of Frequency

The choice of frequency is influenced by a number of intertwined issues. We have already discussed the need for obtaining short bunches, $\sigma_L = 1$ cm, to avoid a loss in luminosity. To obtain short bunches, it is necessary to increase the longitudinal focusing of the RF system, which can be accomplished with either additional voltage or higher frequency. Indeed, in the limit where the applied voltage is large compared with the synchrotron radiation energy loss (that is, $\cos \phi_s \rightarrow -1$), the two parameters are essentially equivalent and $\sigma_L \propto (V_{\text{RF}} f_{\text{RF}})^{-1/2}$.

The aperture of the accelerating cavities must be sufficient to avoid reducing the beam lifetime and to avoid introducing excessive transverse beam impedance into the ring. In practice, these constraints limit the choice of frequency to only a few frequency “islands” ($f \approx 350$ MHz and 500 MHz) for which high-power (1 MW) klystrons are commercially available. Because we must provide 1-cm bunches, we find that—even with equal apertures—the upper frequency range, near 500 MHz, offers lower power and lower cost; it is thus the preferred choice.

To pick the exact frequency, we must bring in additional considerations. The injection system timing requirements are best handled by having the linac and storage ring RF systems phase-locked, which is most easily accomplished if the two frequencies are harmonically related. The advantage of phase-locking the two RF systems is expected to show up primarily in the feedback system requirements. Any phase jitter at injection will initiate oscillations that must be controlled by the longitudinal feedback system. Such injection jitter can easily dominate the feedback system design, in the sense of determining the power required by the system. Because the SLAC linac operates at a frequency of 2856 MHz, the possible harmonically related choices are 357 MHz and 476 MHz. As mentioned, we prefer a higher frequency to reduce the voltage requirement, so we have adopted 476 MHz for the Asymmetric B Factory RF system.

3.3.2 Choice of Technology

The choice of room-temperature or superconducting RF is also a complicated issue. Given the parameters of the Asymmetric B Factory, superconducting technology would not be of much benefit in reducing the power requirements of the facility. Even for room-temperature cavities, only about one-third of the RF power will be dissipated in the walls, and the power associated with cryogenics for a superconducting RF system would consume a significant fraction of the potential savings. Thus, the choice is not dominated by operating cost considerations.

The potential benefit of a superconducting RF system is that it can provide a high voltage with relatively few cavities. This is important because the most serious beam instabilities in the B Factory (the coupled-bunch instabilities; see Section 4.3) are driven primarily by the higher-order-mode (HOM) impedance of the RF cavities. Reducing the number of cavities lowers the instability growth rates proportionately, which in turn reduces the feedback system power requirement quadratically (unless the power is already limited by injection jitter).

As mentioned, in the case of a B Factory, the RF power requirements are dominated by beam loading; that is, the majority of the power put into a cavity goes to the beam itself, even in the case of a room-temperature system. The limit on the number of cavities, then, is dictated by the power-handling capability of the RF input coupler. In the B Factory design, a 20-cavity room-temperature RF system requires nearly 500 kW per cavity, of which about two-thirds goes into the beam. If the difficulty of designing a reliable high-power input coupler were the same in a superconducting environment as it is in a room-temperature environment, then the number of cavities could possibly be reduced by one-third in the superconducting case. A moderate derating of the input

power capability in the (presumably more difficult) superconducting case, however, would lead to roughly equal numbers of cavities in the two scenarios.

A difficulty with superconducting cavities that requires new technology arises from the need to remove the HOM power deposited in the cavity by the high-current beam. For the room-temperature case, solutions for this problem have been demonstrated in test cavities and can be implemented in a reasonably straightforward manner (see Section 5.5). The problem of removing hundreds of kilowatts from the cryogenic environment, however, has not been solved. At present, the Cornell RF group [Padamsee et al., 1990] is working on this problem, and it may be solvable with suitable R&D.

On balance, superconducting RF technology for a high-luminosity collider seems to require a significantly larger performance extrapolation than does room-temperature technology, and it is not judged by us to be a sufficiently mature platform on which to base a “factory” at present. Therefore, the present proposal is based on a conventional room-temperature RF system, as described in Section 5.5.

3.4 RELIABILITY CONSIDERATIONS

The physics requirements for the Asymmetric B Factory are associated with a large *integrated* (as opposed to peak) luminosity. Therefore, it will be necessary to pay attention to reliability issues from the outset. Several approaches can be used to improve the reliability of the facility:

- Provide safety margins in the initial design parameters
- Design the control system to facilitate failure diagnosis
- Design the hardware in a modular fashion to facilitate repairs
- Maintain adequate spares
- Use a powerful, fully automated injection system to recover quickly from beam loss
- Design the detector for rapid turn-on and turn-off during injection

All of these approaches will be taken for the B Factory collider. As a goal, the collider will be designed to be in collision mode 85% of its scheduled operating time. Initial guidelines for the allocation of operating time are as follows:

Filling or top-up	5%
Detector switch-on, switch-off, tune-up	5%
Scheduled and unscheduled maintenance	5%
Collisions	85%

While we recognize that it will not be possible to reach this goal immediately, it is clear that highly reliable operation of a B Factory mandates a careful and conservative design approach. This has been our guideline for the design presented here.

4.

COLLIDER DESIGN

IN this chapter, we describe the physics designs of the two storage rings that make up the B Factory. The concepts described here have evolved over the past several years and are based on numerous interactions among the lattice designers, detector designers, and engineering staff. More than has been true for most past colliders, the B Factory design has, from the outset, focused heavily on the issues of flexibility and reliability. In addition, it was recognized that the success of the B Factory project, measured in terms of its ability to produce the requisite physics data, would depend on special attention being paid to the machine-detector interface. The issue of background suppression is so central to the project that it quite strongly influenced the lattice design.

In what follows, we first describe the lattice designs themselves and the beam focusing and separation solutions we have adopted. Thereafter, we describe the detailed background and masking studies we have undertaken. The design we have arrived at has considerable safety margin in terms of expected vs tolerable background levels, based on careful and systematic examination of all background sources. Because of the high beam intensity required for the B Factory, it is important to examine the influence of collective effects on the ring performance. These are discussed in Section 4.3. Our choice of many relatively low-current bunches results in there being no single-bunch thresholds that lead to performance limitations. Coupled-bunch instabilities are important, however. We have developed means to deal with this problem by damping the cavity HOMs and by feedback. These solutions are described in Sections 5.5 and 5.6. Beam lifetimes have been examined for both rings and found to be acceptably long. Because we wish to achieve a very high luminosity, we have looked carefully at the performance limitations imposed by the beam-beam interactions. Detailed results of our simulations appear in Section 4.4.

4.1 LATTICE DESIGN

4.1.1 High-Energy Ring

The design of the lattice for the high-energy ring (HER) has been influenced by the following criteria:

- It must meet all the conditions necessary to obtain the desired luminosity of $3 \times 10^{33} \text{ cm}^{-2} \text{ s}^{-1}$. These conditions require that the beta functions at the collision point be correct; that the horizontal emittance, energy spread, and momentum compaction factor be brought to their proper values; and that the dynamic aperture of the ring be adequate.
- It must fit in the PEP tunnel, leaving space for existing services and enough aisle space for the passage of magnet trolleys, etc., and it must have the correct circumference for the chosen RF frequency and harmonic number.
- It must be arranged in the tunnel such that it is easily supported and aligned.
- It should be designed such that existing PEP components and services are used as much as possible (provided that the design is not compromised by doing so).

The lattice we have adopted meets all the criteria outlined above. In Fig. 4-1 we show a layout of the PEP tunnel. The straight sections of the hexagonal ring are labeled according to the clock. (The straight sections have even numbers, and the arcs connecting them are odd-numbered regions.) Figure 4-2 shows the lattice functions of the HER, β_x , β_y , and D_x , starting and ending at the center of the straight section in region 8. Collisions take place in the center of the straight section of region 2, which is shown in the center of the figure. In the straight section of region 8 (and also in region 6) the beta functions are seen to be somewhat uneven. This is because these straights are used to adjust the betatron tunes of the lattice. In arcs 9, 5, 7, and 11, the horizontal dispersion function is mismatched. This (controllable) mismatched dispersion function is used to adjust the horizontal emittance of the beam. Region 10 is the injection straight where the beta functions are tailored to optimize the injection process. Arcs 1 and 3 have a regular dispersion function to make it easier to match the chromatic properties of the interaction region by adjustment of sextupoles. The design of the lattice is modular, and the individual modules can be adjusted with little or no effect on the remainder of the lattice. The basic modular building blocks of the lattice are regular arcs, dispersion suppressors, and straight sections. Details of each of these lattice modules are discussed below.

4.1.1.1 Choice of Cell Length. Before design can start in earnest, the length of the standard arc cell must be chosen. One obvious choice of cell length would have been to leave the layout of the ring components exactly as it is in PEP, so that PEP essentially becomes the HER. Consideration of this possibility, however, showed that such a layout

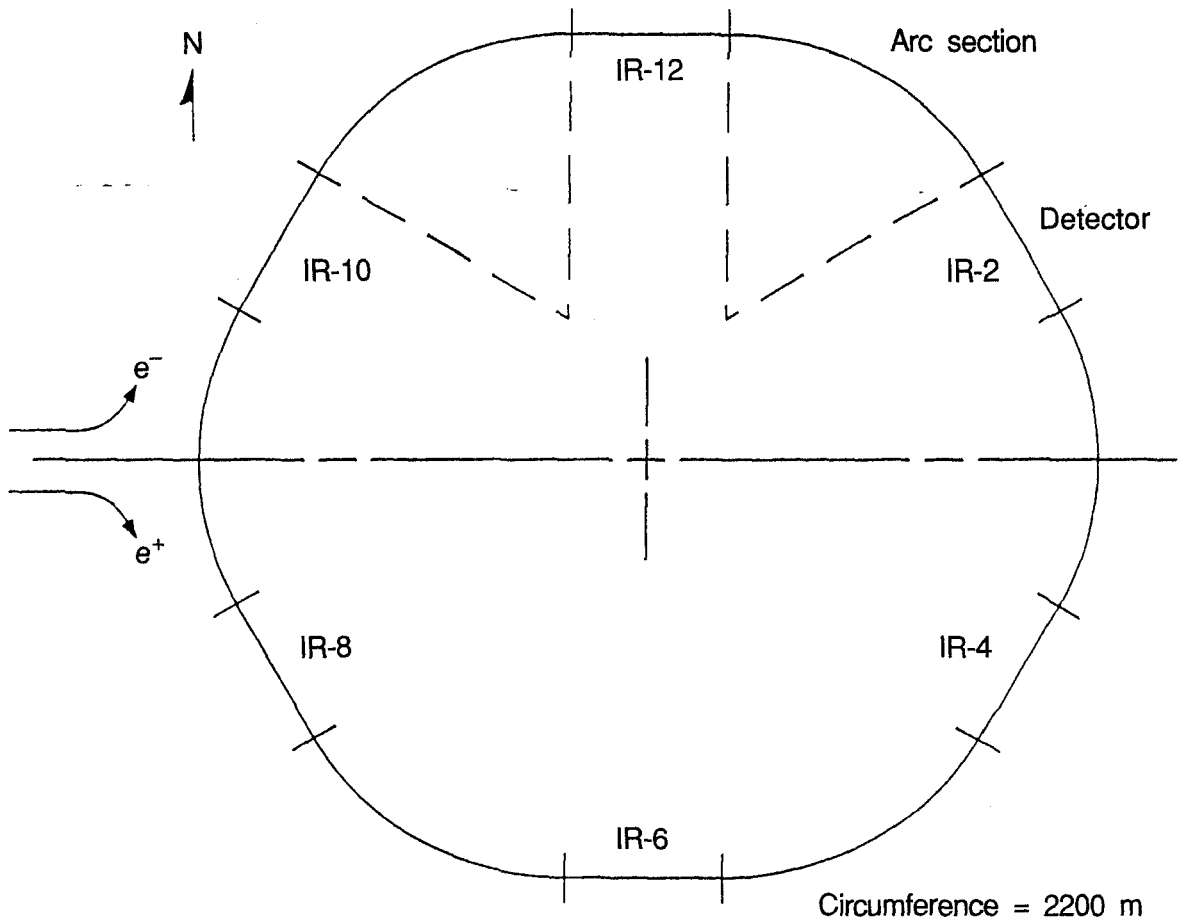


Fig. 4-1. Layout of the PEP tunnel. The numbering system follows the clock, with the straight sections being even numbers; IR = interaction region.

would not suffice and that the cell length would have to be changed. There are three factors that enter:

- The HER is located closer to the tunnel floor than the PEP ring, so that the low-energy ring (LER) can be mounted above it while still providing sufficient space for cable trays, etc. Therefore, the present support structure will have to be replaced.
- The circumference of the ring has been changed to match the new RF frequency chosen for the B Factory. The circumference of PEP is 2200.0004 m, whereas the B Factory HER circumference will be 2199.318 m. The harmonic number of the HER is 3492, compared with 2592 for PEP.
- The new (copper) vacuum chambers cannot be fabricated in sections as long as the PEP (aluminum) chambers, so extra space is needed for additional flanges. Therefore, the cell length must be longer than the present 14.35 m of the PEP cell.

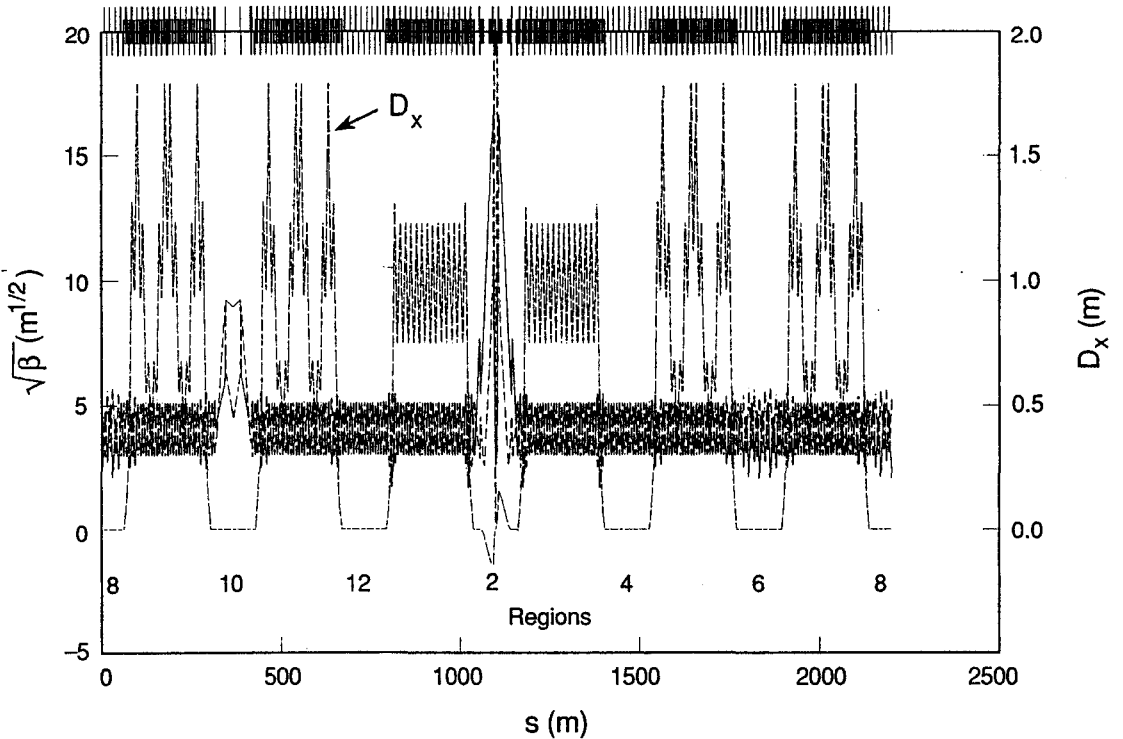


Fig. 4-2. Lattice functions $\sqrt{\beta_x}$, $\sqrt{\beta_y}$, and D_x (horizontal dispersion function) for the complete HER, starting at region 8. The collision region (region 2) is shown in the center of the figure.

To accommodate the longer cell, we must remove the short (symmetry) straight sections located at mid-arc in the present PEP lattice. A half-sextant of PEP is made up of a long straight section of just over 60 meters, followed by an arc section and terminated by a short straight section of about 2.5 meters. This short straight section was used as a utility straight and was tailored to the needs of PEP. For the B Factory, however, the utilities are more usefully placed in the long straight sections.

PEP has 192 main dipole magnets, 16 in each half-arc, 2 per standard FODO cell. Keeping this structure, a range of cell lengths was investigated for two different types of dispersion suppressor. The missing-magnet type of dispersion suppressor was found to be unsuitable for the HER, because the "gap" in the bending makes the central orbit too different from the present PEP central orbit, giving layout problems in the tunnel. A dispersion suppressor consisting of two cells, each of approximately 90° phase shift gave an acceptable geometry for the beam orbit. These cells must be slightly longer than the regular cells to match both the beta functions and dispersion function properly.

A computer code was developed to plot the deviation of the central orbit of the beam relative to the central orbit of a smooth version of PEP. (A "smooth PEP" consists of straight sections of the appropriate lengths sandwiching an arc of constant radius.) The results of the survey of cell lengths are shown in Fig. 4-3.

In Fig. 4-3, three parameters are plotted as a function of cell length: The straight lines, labeled "mid-arc" and "mid-straight," show the deviation of the orbit from the smooth PEP orbit at the symmetry point (mid-arc) and at the original PEP interaction

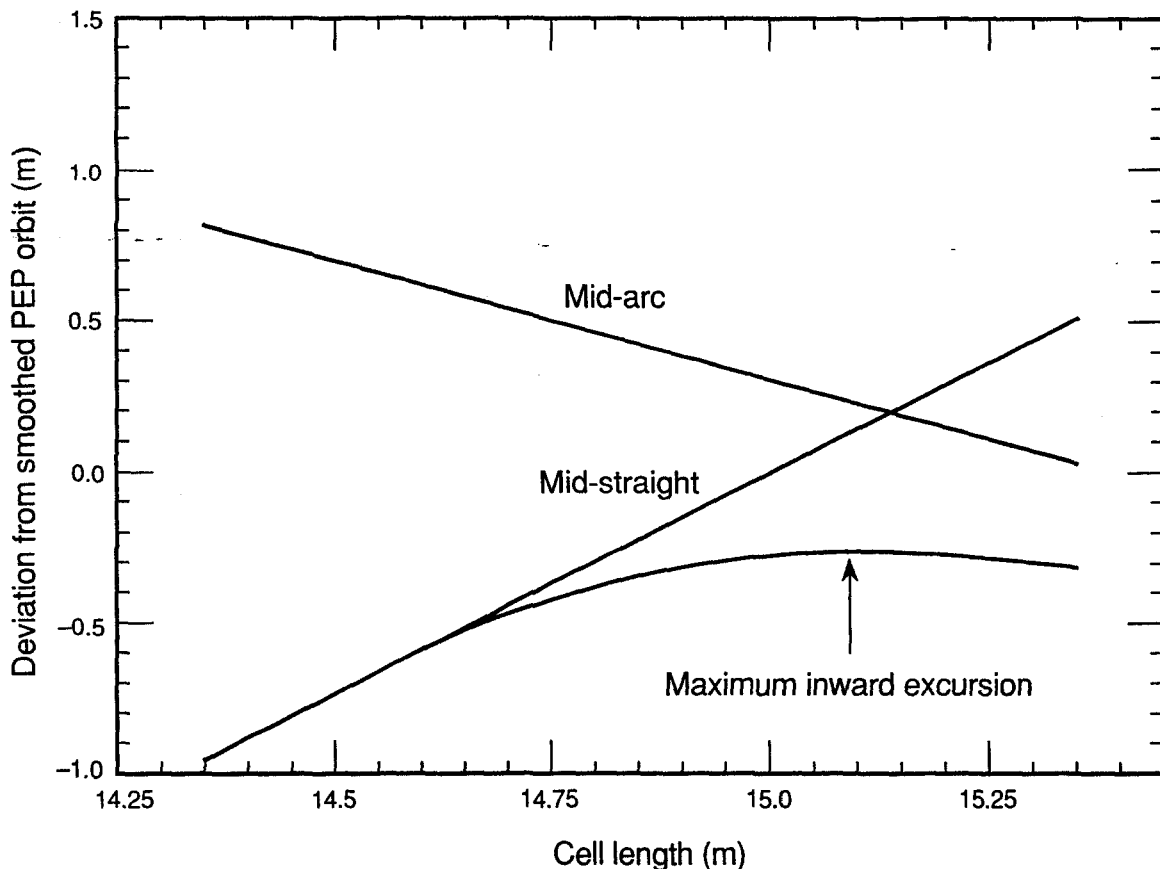


Fig. 4-3. Results of computations to find the optimum length for the regular arc cells. The radial displacement from the smooth PEP orbit is plotted as a function of cell length. The displacement is plotted for mid-straight, mid-arc, and the greatest excursion inside the PEP orbit.

point (IP, in the center of a long straight section). The curve shows the maximum deviation of the orbit in the arc toward the inside of the smooth PEP orbit. It is seen that a cell length of 15.125 m gives an orbit closest to the original PEP orbit and thus minimizes layout problems in the tunnel. This cell length is also long enough to meet the spatial requirements given by mechanical engineering considerations and is thus a good choice on that basis as well.

With this choice of cell length, the long straight sections can be segmented into eight cells of the same length as the regular arc cells. The various cell lengths of the HER modules are summarized in Table 4-1.

The geometry of a normal sextant of the HER is shown in Fig. 4-4, where the ordinate denotes the radial position of the beam orbit relative to the smooth PEP orbit. The curve close to the zero position is the actual PEP orbit, the small wiggles being due to the nonuniform bending in a PEP cell (due in turn to the fact that the dipoles occupy most, but not all, of the length). The other curve shows the deviation of the orbit of the HER from the smooth orbit. At the ends (symmetry points in the arcs), the HER orbit is just over 20 cm outside of the smooth orbit; in the long straight section (center section of the plot), the orbit is just less than 20 cm outside the PEP orbit; and in the arcs, the orbit

Table 4-1. Lengths of HER lattice modules.

Module	Cell length (m)
Arc	15.125
Straight section	15.125
Dispersion suppressor	16.013

comes inside the PEP orbit by about 26 cm. With this layout for the HER, there is enough clearance on the inside for the existing PEP services, and there is enough space in the outer aisle for magnet trolleys to pass.

4.1.1.2 Normal Sextant. A phase shift of 60° per cell was chosen to obtain a beam emittance slightly below the emittance required for the design luminosity. As will be

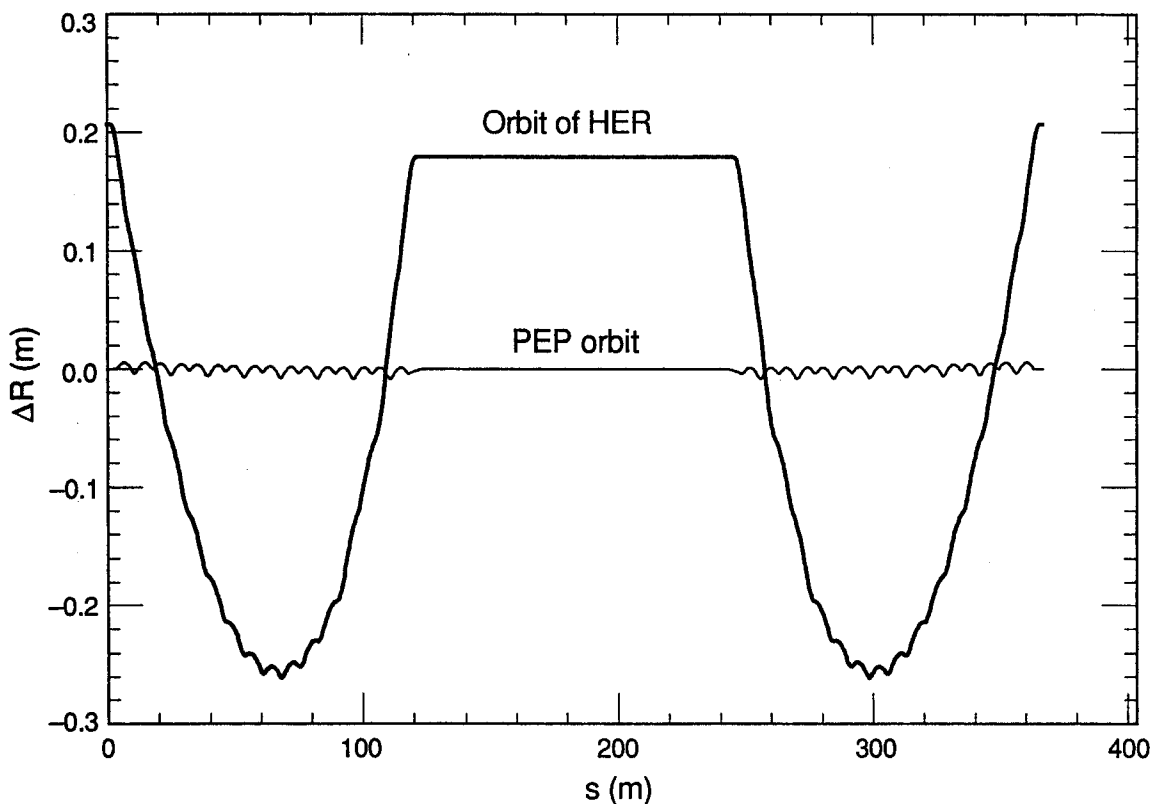


Fig. 4-4. Geometry of the HER orbit in the PEP tunnel relative to that of a smooth PEP orbit. The radial displacement of the orbit is plotted as a function of distance along the orbit from mid-arc to mid-arc. Negative ΔR values correspond to being inside the smooth PEP orbit. A different geometry applies in the special case of the collision sextant (cf. Fig. 4-13).

discussed shortly, the emittance can be changed, in a controlled fashion, above and below the design value. The phase advance of 60° per cell is also optimal for the control of the chromatic properties of the lattice by sextupole compensation. The lattice functions for a normal sextant are shown in Fig. 4-5. It can be seen that the lattice is quite well-matched; the dispersion function is zero in the straight section and the beta functions are regular throughout, except for a small beating in the dispersion suppressor cells. Beta function values are moderate in the straight section, making it a suitable place for locating the RF accelerating cavities.

4.1.1.3 Emittance Control Sextant. The HER beam emittance is controlled by adjusting the dispersion function at the position of the main dipoles, where most of the synchrotron radiation is generated. It is, of course, possible to have a portion of the lattice with a phase shift per cell different from 60° . (As the phase shift per cell decreases, the dispersion function increases and therefore the emittance increases.) Adjustment in this fashion is workable, but has the disadvantage of increasing the

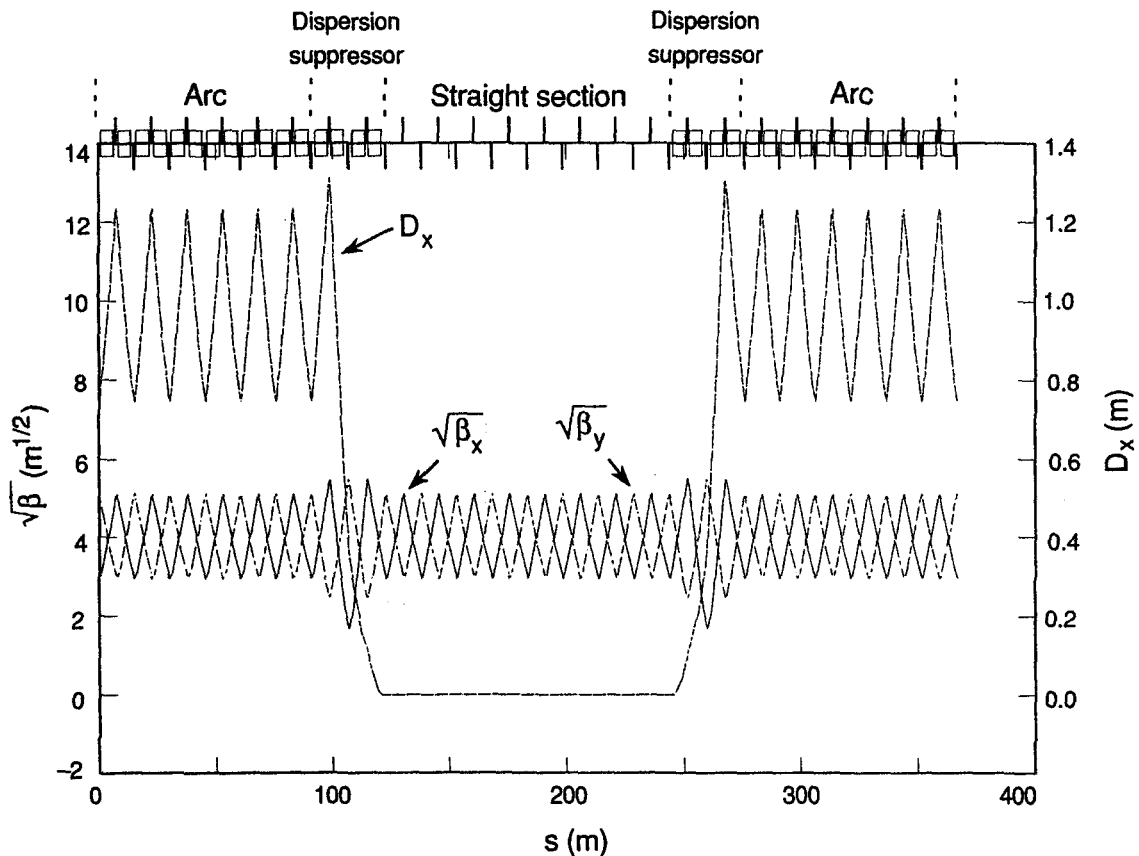


Fig. 4-5. Lattice functions for a normal sextant of the HER, plotted as a function of position in the sextant, from mid-arc to mid-arc. Dispersion is matched to zero in the straight sections.

momentum compaction factor α . This means that additional RF accelerating voltage would be needed to maintain the desired 1-cm bunch length. Instead of this phase adjustment, we have chosen to use a mismatched dispersion function in the arcs of four of the six sextants. Similar to an orbit bump, the dispersion mismatch is confined to the arc, with the dispersion in the adjoining straight sections remaining at zero. Although the average value of D remains unchanged by this modulation, it is the square of the dispersion function that determines the increase in emittance. Figure 4-6 shows an emittance control sextant that is mismatched sufficiently to increase the emittance from 40 nm rad to 48 nm rad. (In reality, there is no sextant exactly like the idealized version in Fig. 4-6, because the straights adjoining these arcs are all special.) The modularity of our lattice design allows “plugging in” sections in a mix-and-match manner without having to do any lattice rematching, apart from possibly having to restore the betatron tune.

4.1.1.4 Injection Sextant. The injection sextant provides lattice functions suitable for the injection scheme presently envisaged, and it provides great flexibility in adjusting the lattice functions to whatever is required to optimize the injection process. Figure 4-7 shows a nominal design having beta functions of 80 m in the horizontal plane and 20 m in

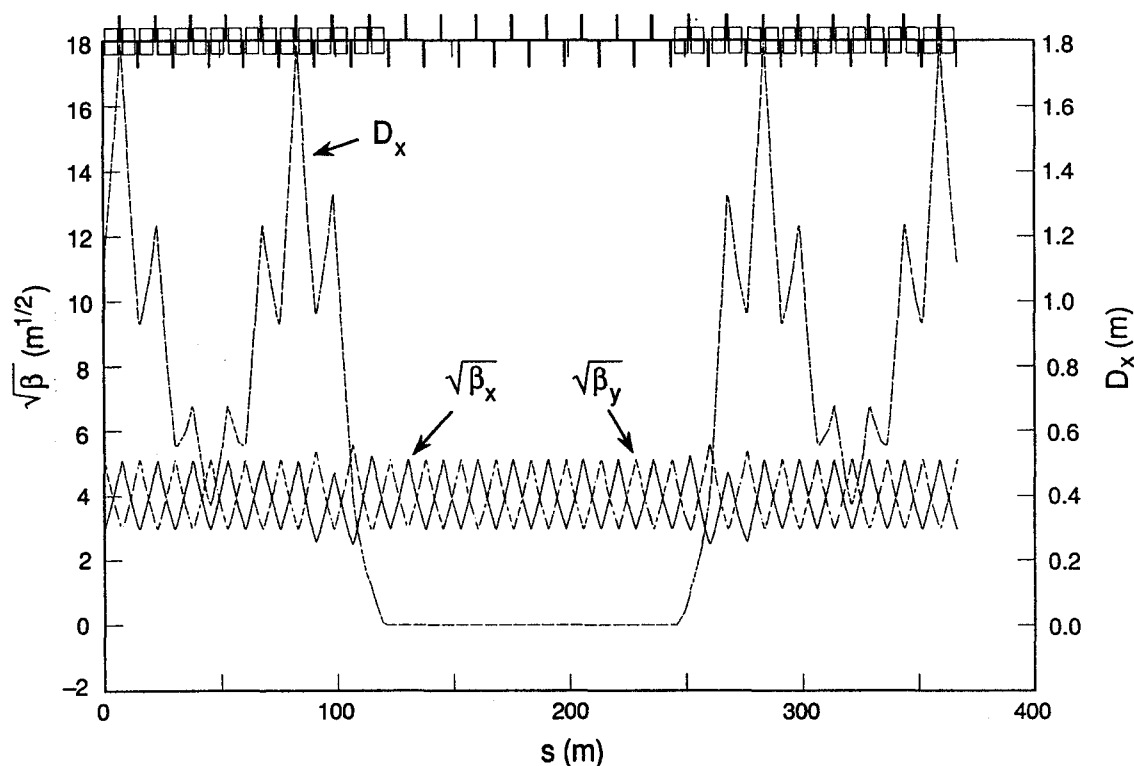


Fig. 4-6. Lattice functions for an emittance control sextant of the HER. The dispersion function mismatch is confined to the arcs, the dispersion function being zero in the straight section.

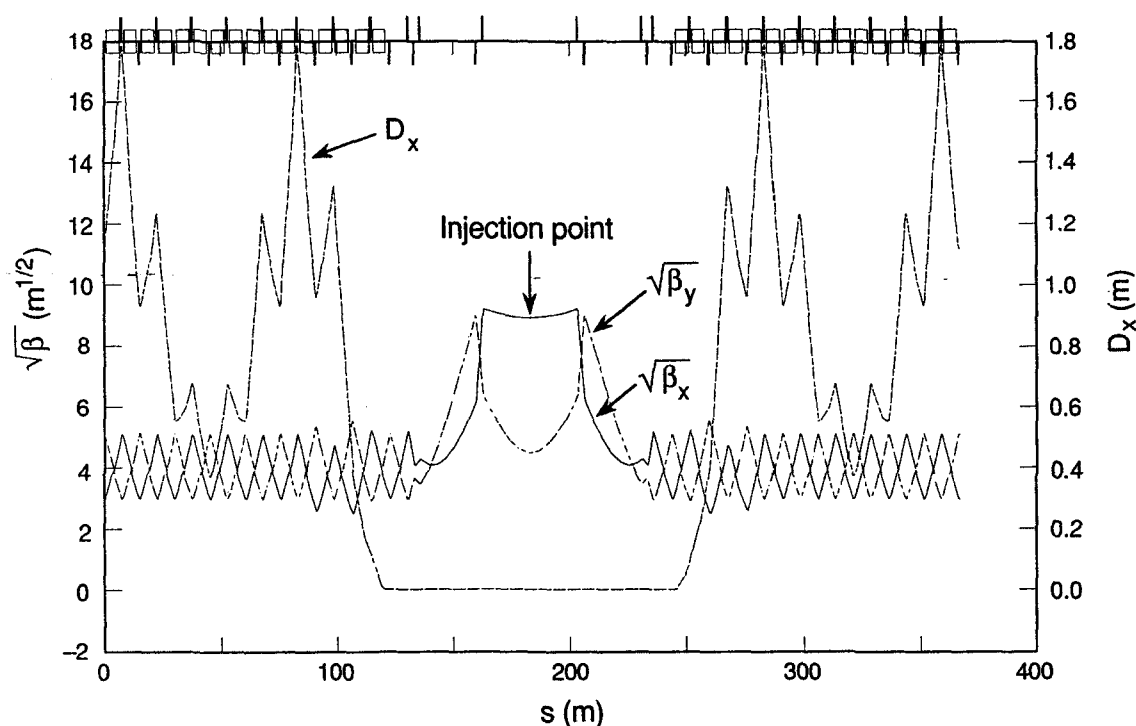


Fig. 4-7. Lattice functions for the injection sextant of the HER. The beta functions at the injection point in the center of the straight section are adjustable. Nominal values correspond to $\beta_x = 80$ m, $\beta_y = 20$ m.

the vertical plane. If another injection scheme were considered, the appropriate lattice module could be very quickly fitted into the straight section.

4.1.1.5 Phase Control Sextant. The straight sections of two sextants will be used to change the betatron tune of the HER. Even a single phase-control sextant would probably have enough range to be acceptable, but the choice of two sextants improves the beta functions at the extremes of the required tune range. The phase control straight sections are located in regions 6 and 8. The optical functions of a phase control sextant are shown in Fig. 4-8.

4.1.1.6 Interaction Region Sextant. The IR sextant is very special and is considerably more complicated than the other sextants. The IR, described in Section 4.1.2, is at its center. The arcs on either side have matched dispersion functions so as to facilitate the correction of chromatic aberrations produced by the IR focusing. Between the IR and the arcs are the matching elements. The matching of the HER is fairly simple owing to the fact that the ring lies in a plane (that is, there are no vertical bends). The lattice functions for the collision sextant and right-hand half-sextant are shown in Figs. 4-9 and 4-10, respectively. In Fig. 4-9 notice the antisymmetry of the dispersion function caused by the S-bend geometry.

Figure 4-11 shows the first 10 m from the interaction point (IP). The dipole B1 initiates the separation of the beams, the separation being aided by the offset quadrupoles

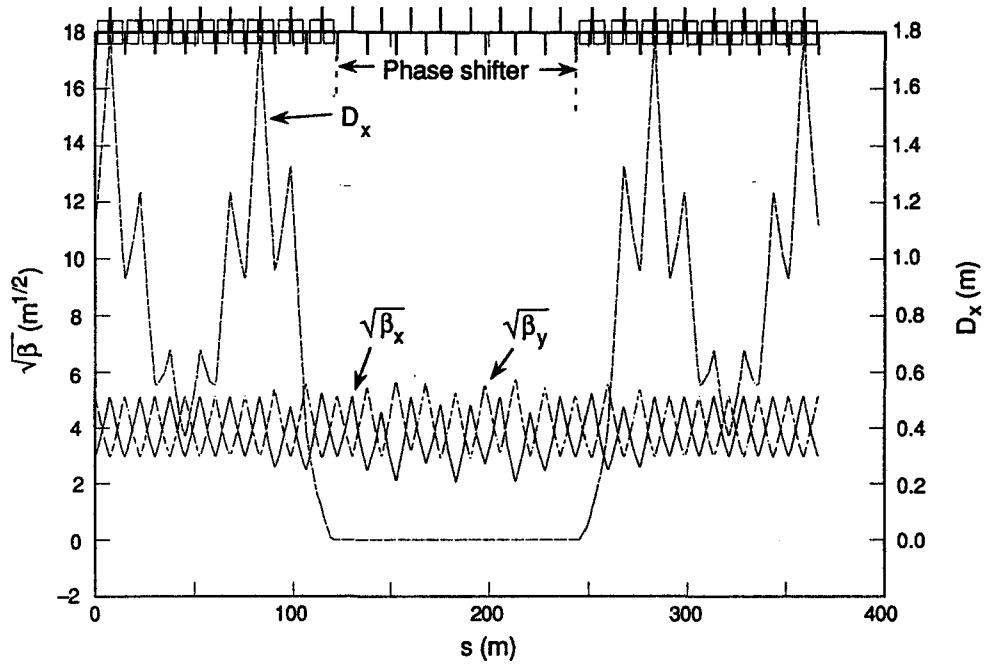


Fig. 4-8. Lattice functions for the phase control sextant of the HER. The beta functions are almost regular in the straight section where the phase shifter is located.

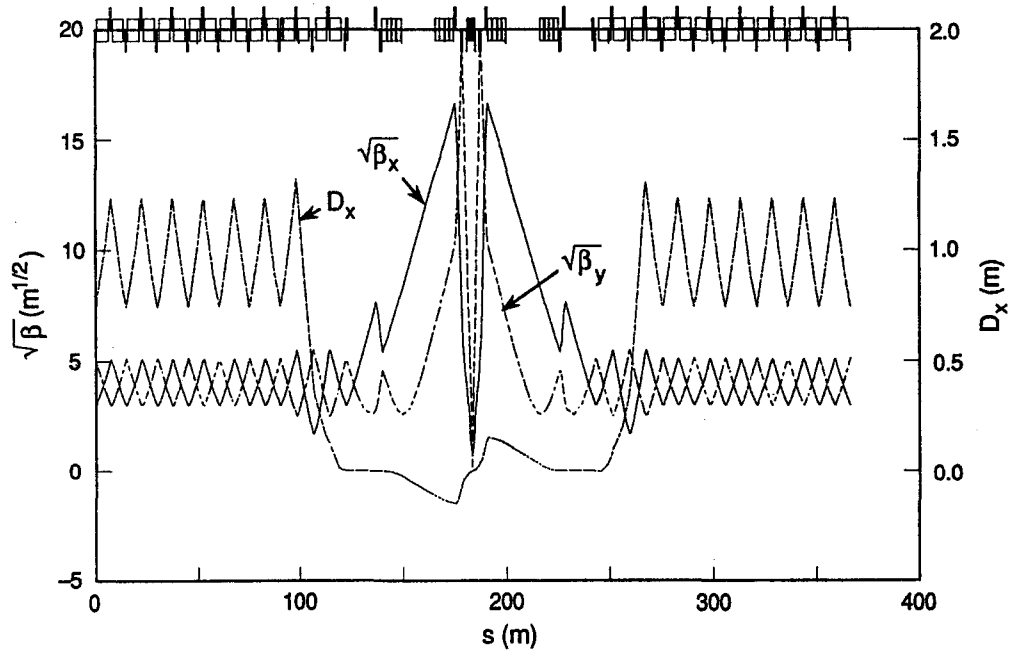


Fig. 4-9. Lattice functions for the collision sextant of the HER. Note the symmetry of the beta functions and the antisymmetry of the dispersion function in the straight section.

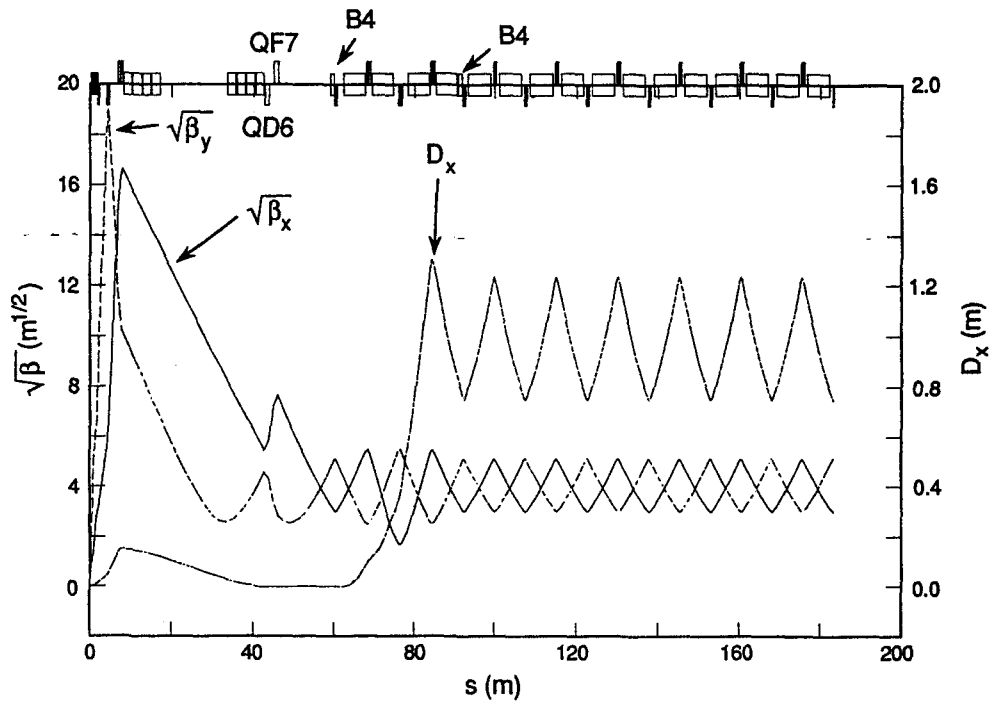


Fig. 4-10. Lattice functions for the right-hand half of the collision sextant of the HER. The B4 magnets that steer the orbit into the arcs are shown here.

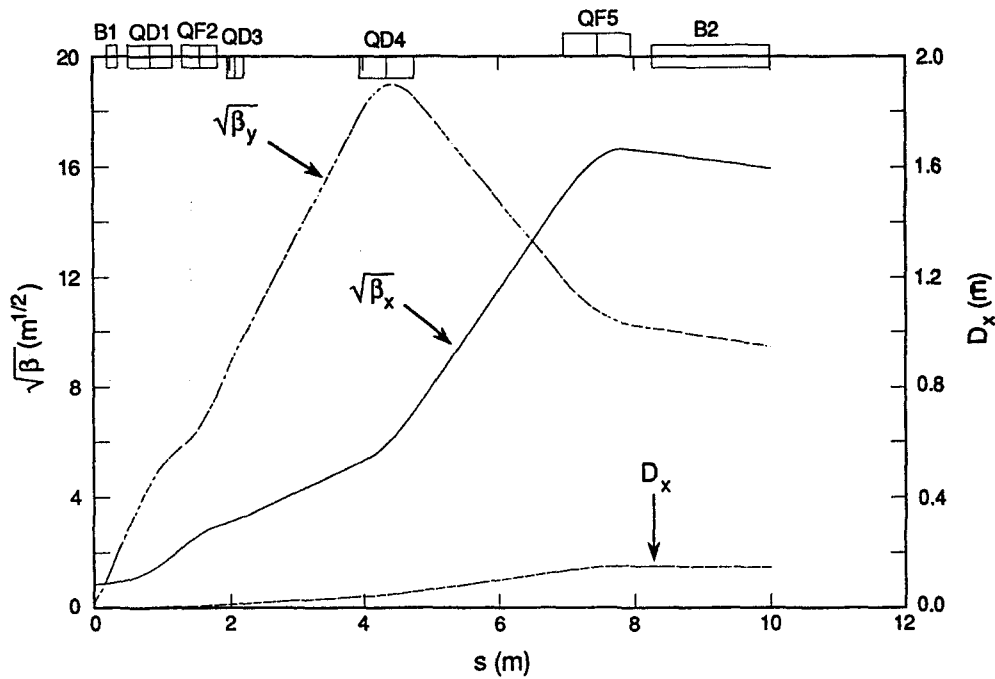


Fig. 4-11. Lattice functions for the first 10 m of the IR straight section of the HER. Note the prefocusing of the beta functions of the HER by the first triplet.

QD1 and QD3. Quadrupole QF2 actually hinders the separation somewhat, but is necessary for the horizontal focusing of the low-energy beam. Quadrupole QF2 is centered on the low-energy beam and thus acts as a combined-function dipole for the high-energy beam; it is thus shown in the figure as a dipole. Quadrupole QD1, although centered on the high-energy beam, is tilted with respect to it and therefore bends the beam slightly (essentially a mini-S bend). As a consequence, it too is shown as a dipole. The quadrupoles QD1, QF2, and QD3 are common to both beams. Their primary purpose is to focus the low-energy beam, but they also have a quite useful focusing effect on the high-energy beam, reducing considerably the beta functions at the high-energy beam focusing elements QD4 and QF5, compared with the values they would have had in the absence of the prefocusing.

QD4 is the first of the high-energy beam focusing elements. It is a septum quadrupole, vertically focusing for the high-energy beam while acting as a field-free region for the low-energy beam. This is a strong quadrupole with a large aperture requirement. Both a superconducting and a conventional design are being considered, as discussed in Section 5.1.3.

As Fig. 4-11 shows, QD4 and QF5 serve to turn over the beta functions coming from the IR and reduce the slope of the dispersion function to near zero. The dispersion function produced by the bending in the IR should be corrected before matching the IR into the arc region. (Strictly speaking, this is not necessary, but to keep the design modular it is advantageous to insist on it.)

Figure 4-12 shows the 60 m from the IP to the start of the arc (that is, to the entrance of the dispersion suppressor). The dispersion function and its slope are brought to zero

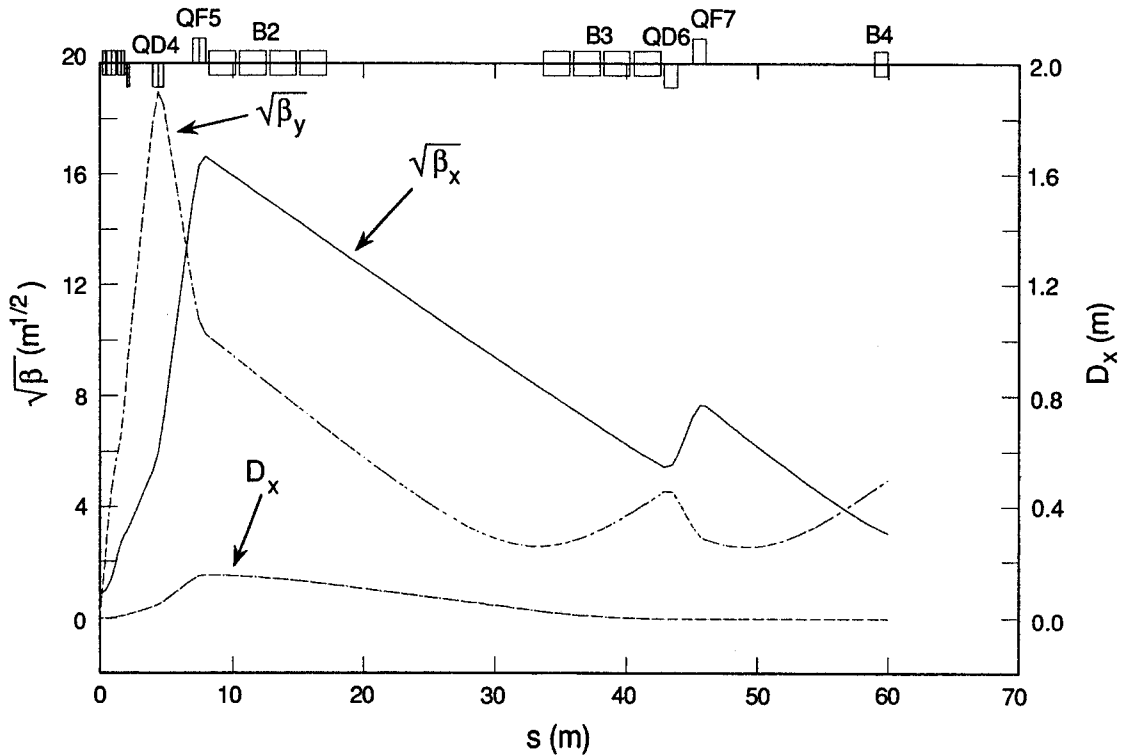


Fig. 4-12. Lattice functions for the first 60 m of the IR straight section of the HER. The B2 and B3 dipoles match the dispersion function to zero.

by the dipole combination B2 and B3. These are very weak dipoles, each made up of four of the PEP low-field bends. The bending is purposely kept very weak to avoid problems with synchrotron radiation shining into the IR. The dipoles B2 and B3 are followed by a pair of matching quadrupoles QD6 and QF7 that, in conjunction with QD4 and QF5, match the beta functions into the dispersion suppressor.

The dispersion suppressors in the arcs adjacent to the IP are slightly different from the others. There is a pair of small dipoles, B4, situated 180° apart in betatron phase (see Fig. 4-10), that match the angles of the orbits from the IP to the arcs. These pairs of dipoles on the two sides of the IP are powered antisymmetrically, as is the B1 dipole. The quadrupoles QD1, QF2, and QD3 are also offset antisymmetrically. The B4 dipoles make an adjustment to the beam trajectory such that the center of the IP lies at the point where the center of the straight section of a normal sextant would be. The angle of the high-energy beam at the IP is not zero with respect to this line, however. The LER has to match the angle of the low-energy beam to this same angle, 13.5 mrad. The IR geometry is illustrated in Fig. 4-13.

4.1.1.7 Dispersion Suppressors. The dispersion suppressors consist of two 90° cells, each slightly longer than the regular cells. All five quadrupoles of the suppressor are independently adjustable to give flexibility in matching, although two pairs are almost identical in strength. As mentioned, the dispersion suppressors surrounding the IR have additional dipoles B4 in them to adjust the position of the IP. Dispersion suppressors in

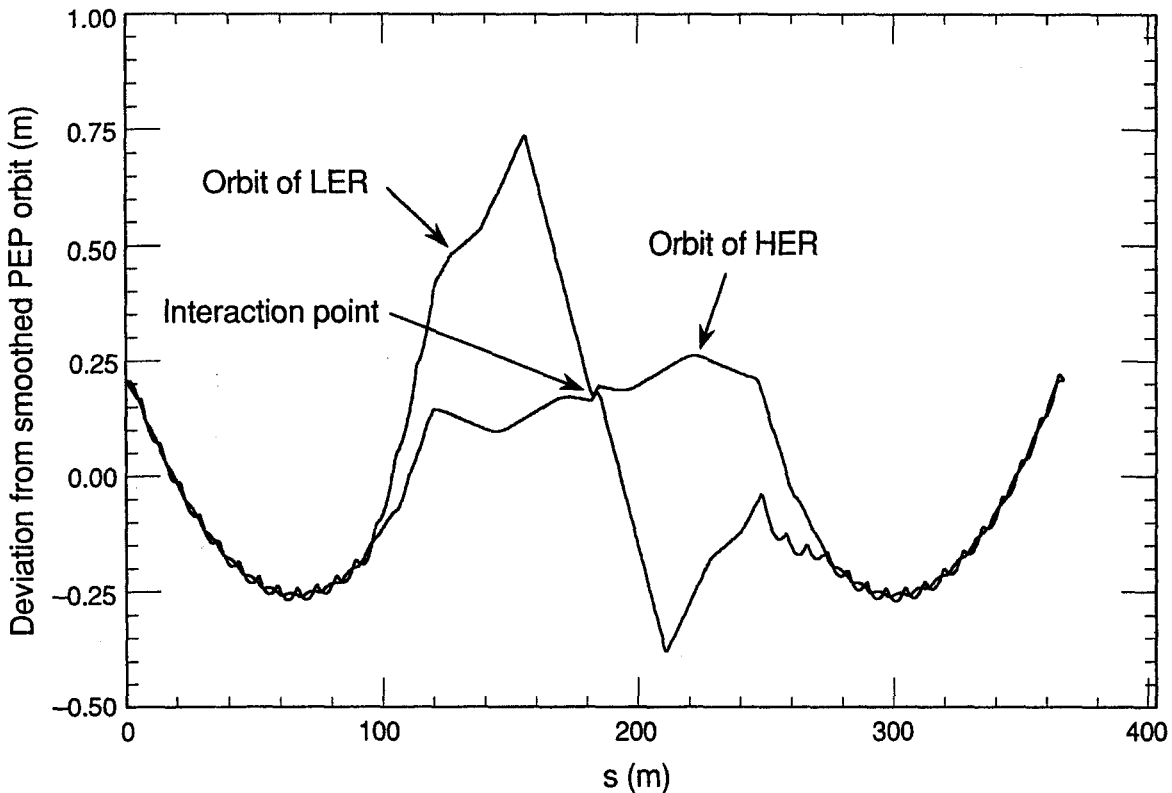


Fig. 4-13. Geometry of the collision sextant, showing how the orbits of the LER and HER deviate from the orbit of PEP. The orbits at the collision point are tilted 13.5 mrad with respect to the straight-section axis.

the emittance control sextants are the same as those for the normal sextants, but they have their quadrupoles powered differently to produce the dispersion function mismatch in the arcs. To match so that the dispersion function is zero in the arcs for this mismatched dispersion case, it is necessary to adjust the strength of the first QF quadrupole in the regular arc cells. This causes only a minor perturbation to the sextupole correction scheme for the achromats in the arcs.

4.1.2 Low-Energy Ring

The LER is designed to satisfy the design parameters discussed in Chapter 3. Key features of the LER include

- Head-on collision optics
- Flat beams with 25:1 horizontal-to-vertical aspect ratio and $\beta_y^* = 1.5$ cm
- Zero dispersion in both planes at the IP
- Bunch separation of 1.26 m
- Beam separation in the IR first horizontally and then vertically
- Wigglers to permit adjustments of emittances and damping times

4.1.2.1 Overall Ring Configuration. The LER has a circumference of 2199.318 m and is designed to operate at 3.1 GeV. As illustrated schematically in Fig. 4-14, the ring has the hexagonal shape of PEP, with six long straight sections and six arcs. One of the long straight sections contains the IR with its low-beta optics; on the opposite side of the ring, the straight section is configured for injection. Two straight sections contain wigglers; two others, one containing the RF cavities, are used for tune adjustment. Figure 4-15 shows the layout and lattice functions of the LER. The beam circulates in a counter-clockwise direction as seen from above the ring. (Note, however, that the optics figures, such as Fig. 4-15, are arbitrarily drawn in the clockwise direction.)

The LER is situated 89.5 cm above the HER in the PEP tunnel, except in the IR straight section, where the two beams collide head-on. There are small radial offsets of the two rings in the arcs, and in the RF and injection straight sections, and larger offsets in the IR and wiggler straight sections.

4.1.2.2 Arcs. The six arcs of the LER are identical. Each contains nine regular FODO cells in the center and has a dispersion suppressor at each end, consisting of 3-1/2 cells with modified gradients. The ring circumference is quantized with two distinct half-cell lengths: that of the regular cells, $LC_{1/2} = 7.5625$ m, and that of the two suppressor cells closest to the straight section, $LD_{1/2} = 8.00625$ m. Each long straight section has a half-length equal to that of four regular cells: $LS_{1/2} = 8$ $LC_{1/2} = 60.5$ m. As described in Section 4.1.1, the HER circumference is divided in exactly the same way. The overall geometrical layouts of the two rings are rather close, but there are notable differences in the optics.

Each FODO half-cell in the LER contains one 1-m dipole, one 0.726-m quadrupole, and one sextupole, and has length $LC_{1/2} = 7.5625$ m. The optics of one cell, shown in

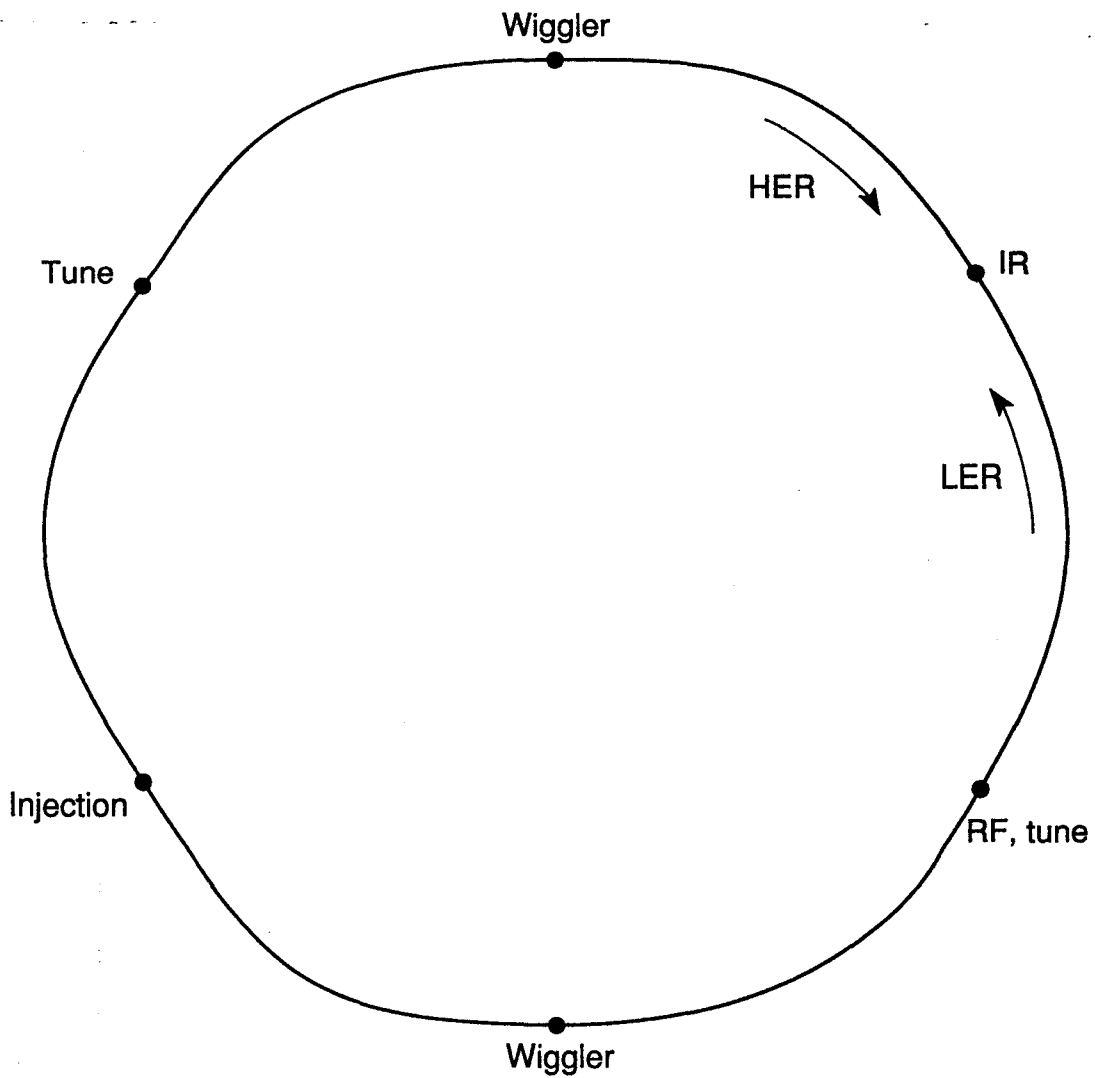


Fig. 4-14. Schematic layout of the LER, which will be located above the HER in the sixfold symmetric PEP tunnel.

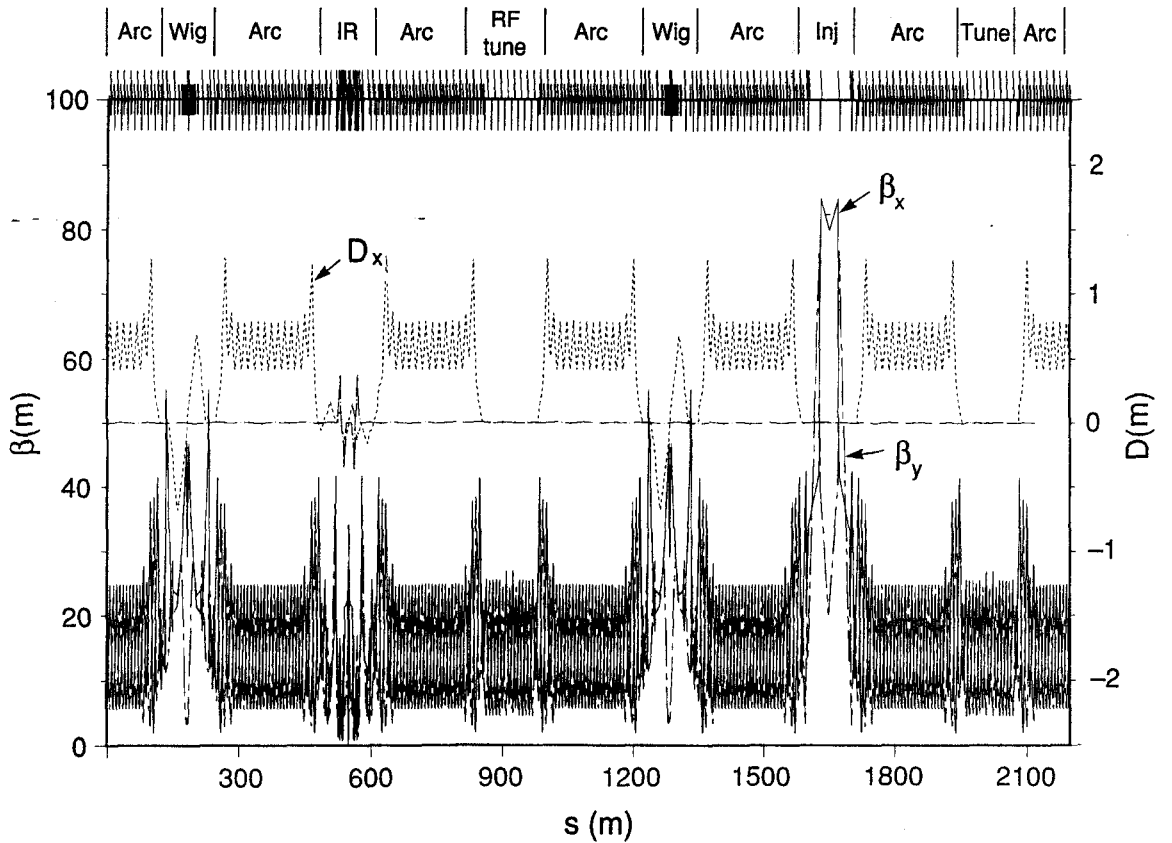


Fig. 4-15. Layout and optics functions for the LER. The lattice for the full ring is shown, starting and finishing at mid-arc in region 11.

Fig. 4-16, are adjusted to give a phase advance of 80° in each transverse plane; hence, the nine regular cells constitute an achromat with a tune of two units. The dipoles are offset 2.24 m upstream from the half-cell center, both to prevent the synchrotron radiation generated by them from striking the adjacent magnets and to facilitate the mechanical support system of the two rings. In plan view, the arc quadrupoles of the LER are almost coincident with those of the HER. The reason the cell phase advance is higher in the LER than in the HER (where it is 60°) is to avoid having too large a value for the momentum compaction factor α . If α gets too large, a very large RF voltage is required to hold the bunch length to a value consistent with the low value of β_y^* . Unfortunately, for geometrical reasons, this difference in phases prevents use of the more elegant type of dispersion suppressor used in the HER.

4.1.2.3 Dispersion Suppressors. The dispersion suppressors on the left and right sides of the long straight sections (or right and left sides of the arc) are shown in Figs. 4-17 and 4-18. As shown in Fig. 4-17, the left suppressor is bordered on the left by the regular cells and on the right by the long straight section. It has seven half cells, the first three of which are the same as those of the regular cells except that the quadrupole gradients are different and the sextupoles are missing, while the last four half cells have the length $LD_{1/2} = 8.00625$ m. The gradients are irregular in these longer half cells as well, and

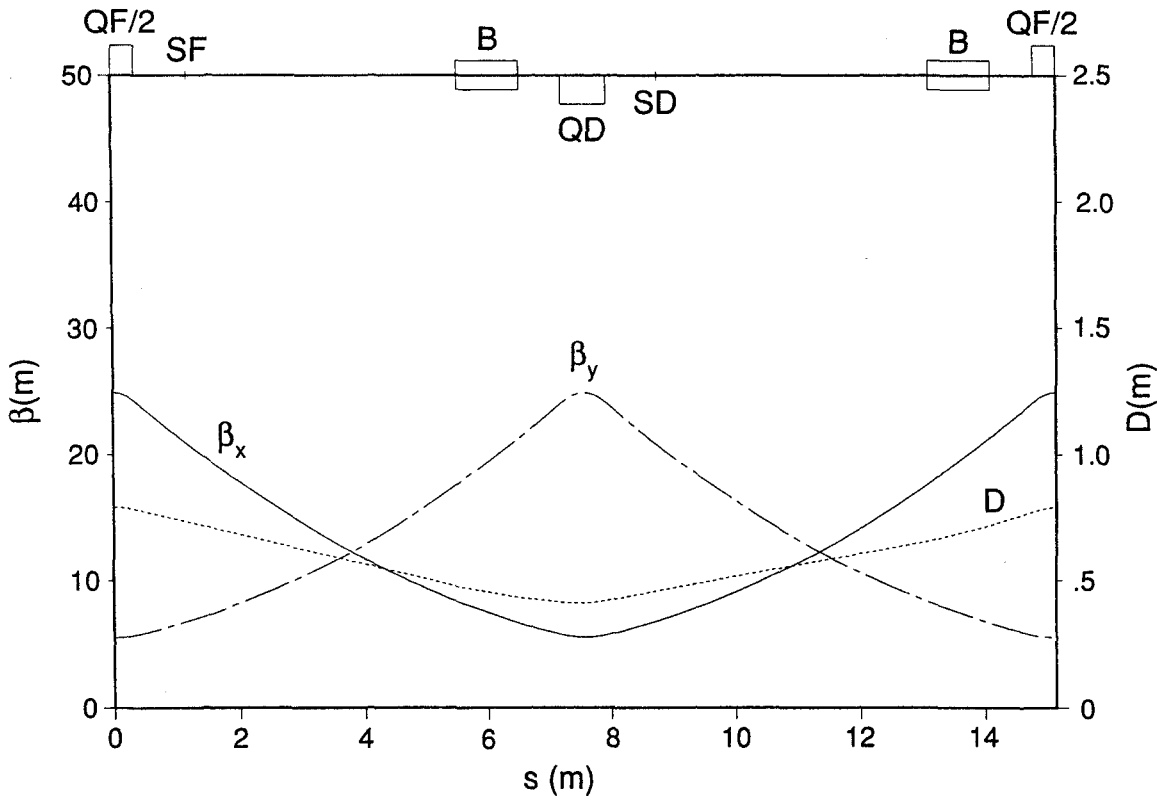


Fig. 4-16. Layout and optics functions for the standard arc cell of the LER. The dipoles B are offset from the center of the half cells so that synchrotron radiation from the beam, traveling from right to left, is absorbed in the longer straight sections between B and QF or B and QD.

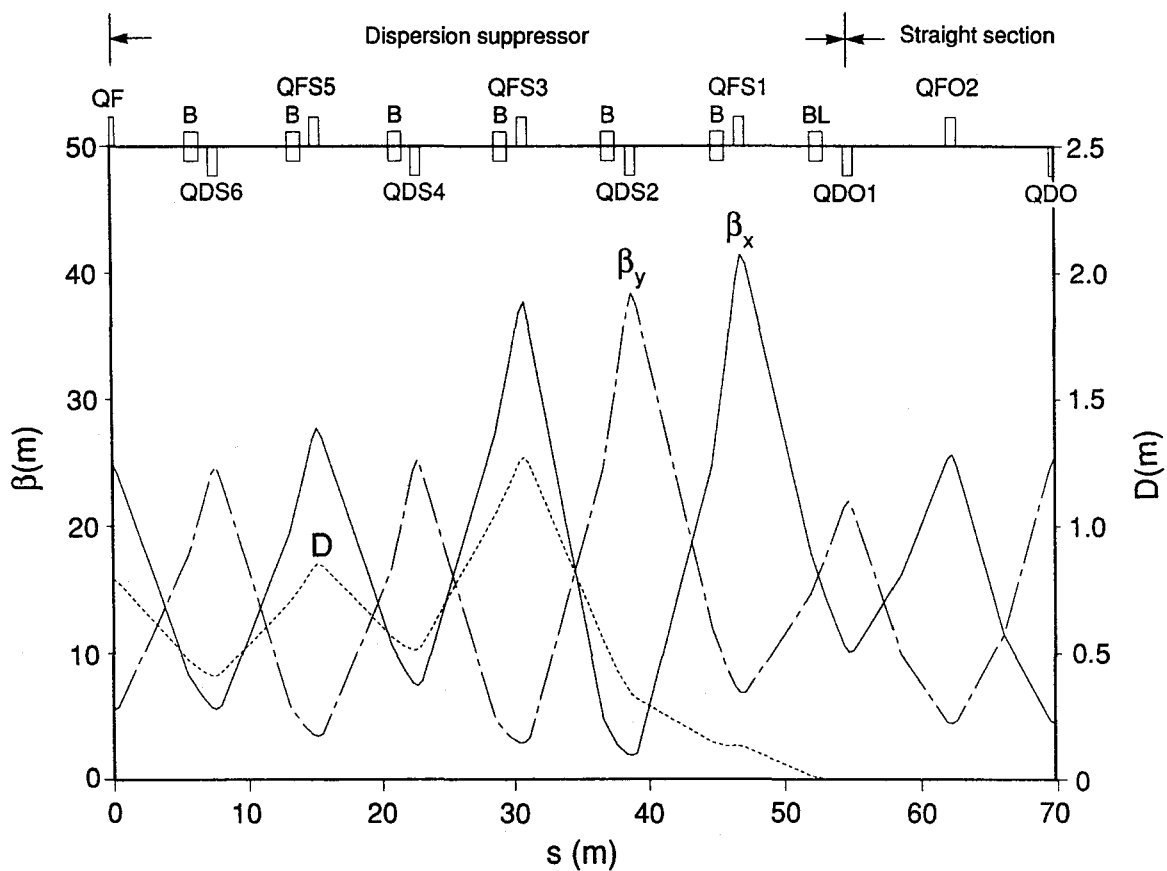


Fig. 4-17. Layout and optics functions for a left-hand dispersion suppressor of the LER. The strength and position of the dipole BL compensates for the fact that the LER dipoles are not symmetric about the arc center. It steers the orbit to the center of the straight section.

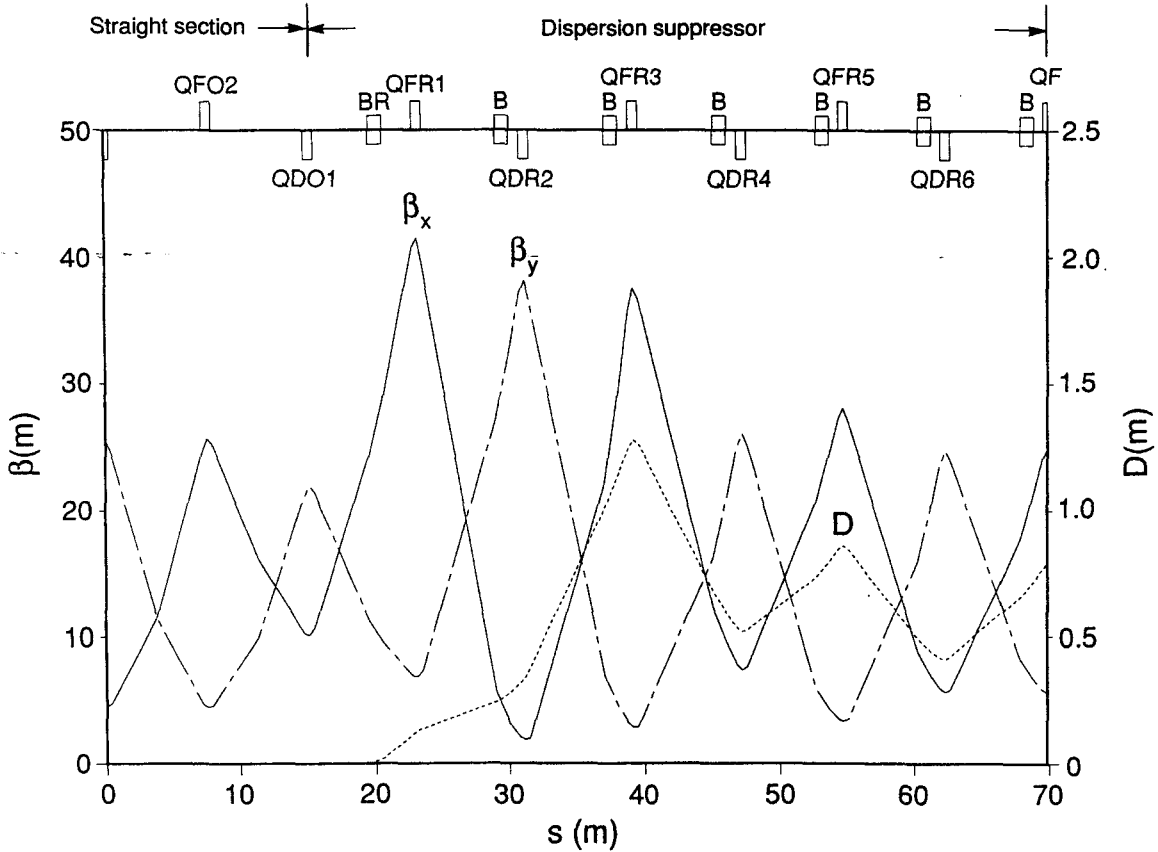


Fig. 4-18. Layout and optics functions for a right-hand dispersion suppressor of the LER. The dipole BR corresponds to BL in Fig. 4-17.

their dipole longitudinal offsets are scaled with the half-cell length in order to keep the quadrupoles lined up vertically with those of the HER. The dipoles in the suppressor cells are the same as those of the regular cells, except for those immediately adjacent to the long straight section, which are adjusted in position and strength in such a way as to steer the LER beamline into horizontal coincidence with that of the HER in the long straight sections.

Each suppressor is matched optically at one end to the orbit functions of a regular cell in the center of a QF quadrupole, and at the other end to those of a 90° normal-length cell without dipoles, with the dispersion being zero at that end. Because the dipole positions do not have reflection symmetry between the left and right suppressors, the quadrupole gradients are slightly different in the two cases.

4.1.2.4 Normal Sextants. We consider each sextant to begin and end at the center of an arc; that is, the long straight section lies in the center of the sextant. There are four straight section types and four corresponding types of sextant. The normal long straight section consists of eight 90° normal-length FODO cells without dipoles; the last two quadrupoles at the ends of each straight section (QDO1, QFO2) have different gradients and are actually part of the dispersion suppressor matching system. The optics and lattice arrangement of a normal long straight section with its adjacent dispersion suppressors are

shown in Fig. 4-19. A normal sextant is shown in Fig. 4-20. The near geometrical coincidence of the HER and LER in plan view, achieved by the dipoles BL (see Fig. 4-17) and BR (see Fig. 4-18), is shown in Fig. 4-21, which shows the radial offset of the two rings from the PEP centerline.

The two normal straight sections are used for adjustment of the global betatron tunes; one also houses the RF system. For the former purpose, the seven quadrupoles in the center of the straight section are varied symmetrically in such a way as to change the two tunes independently, while preserving the beta-function matching to the regular empty (dipole-free) cells. Figure 4-22 shows a normal long straight section with such a "phase trombone" activated.

4.1.2.5 Wiggler Straight Sections. Two of the long straight sections contain wiggler magnets, which are used to adjust the emittance of the LER and also to permit the damping time of the LER to be reduced to a value as low as that of the HER, if desired. Figure 4-23 shows the layout and optics of a wiggler straight section. Four blocks of 6-m wigglers are placed in each wiggler straight section along the length of a horizontally tilted line. The zig-zag beamline pattern serves both to deflect the synchrotron radiation away from the main beamline and to increase the dispersion in the wigglers (which in

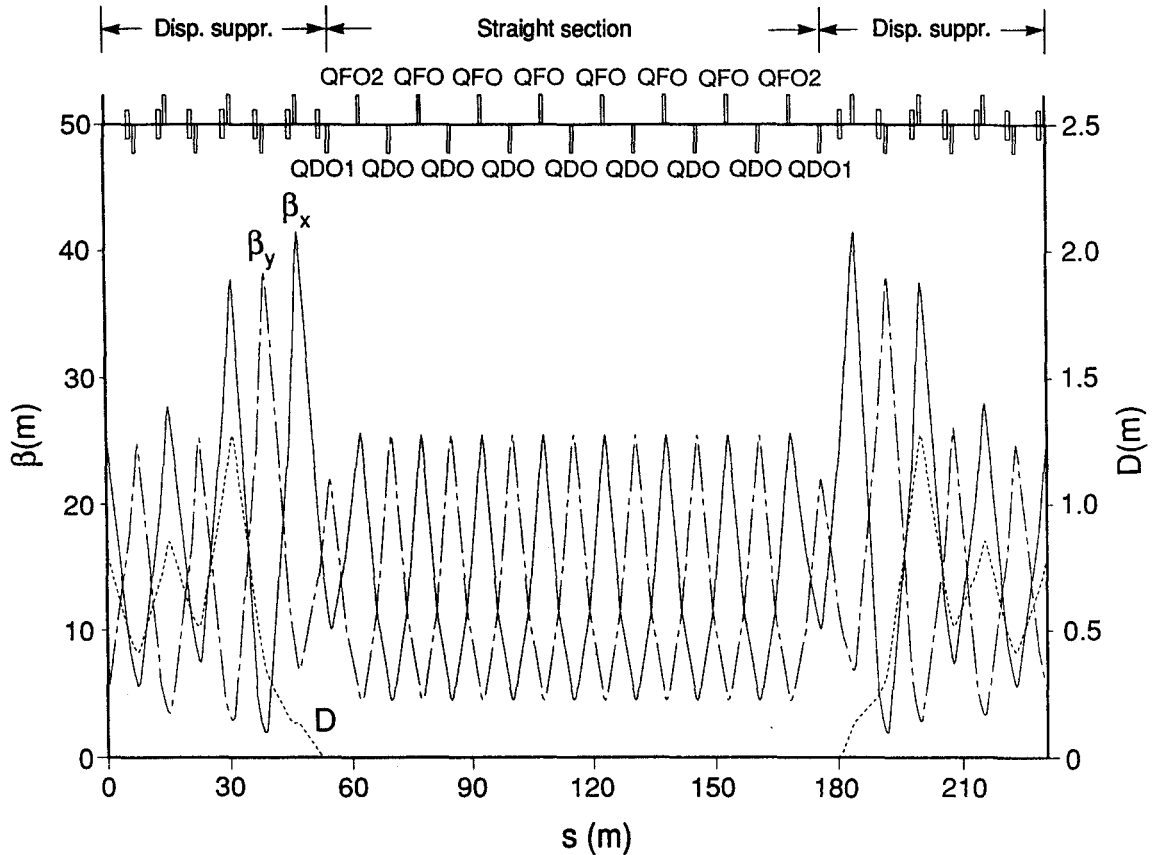


Fig. 4-19. Layout and optics functions for a normal long straight section of the LER.

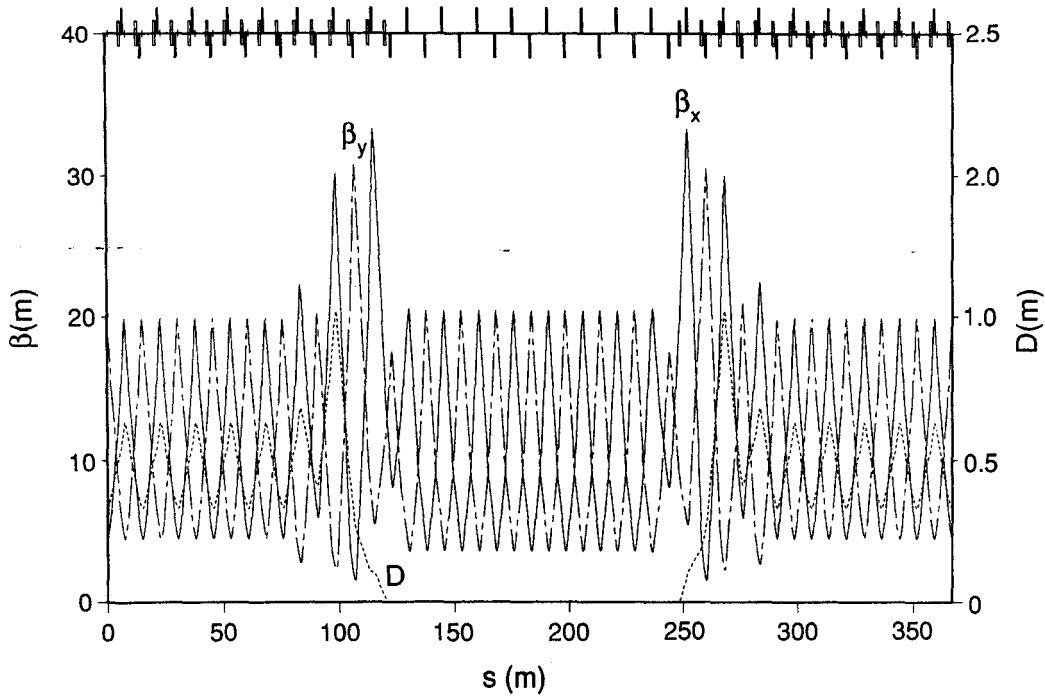


Fig. 4-20. Layout and optics functions for a normal sextant of the LER.

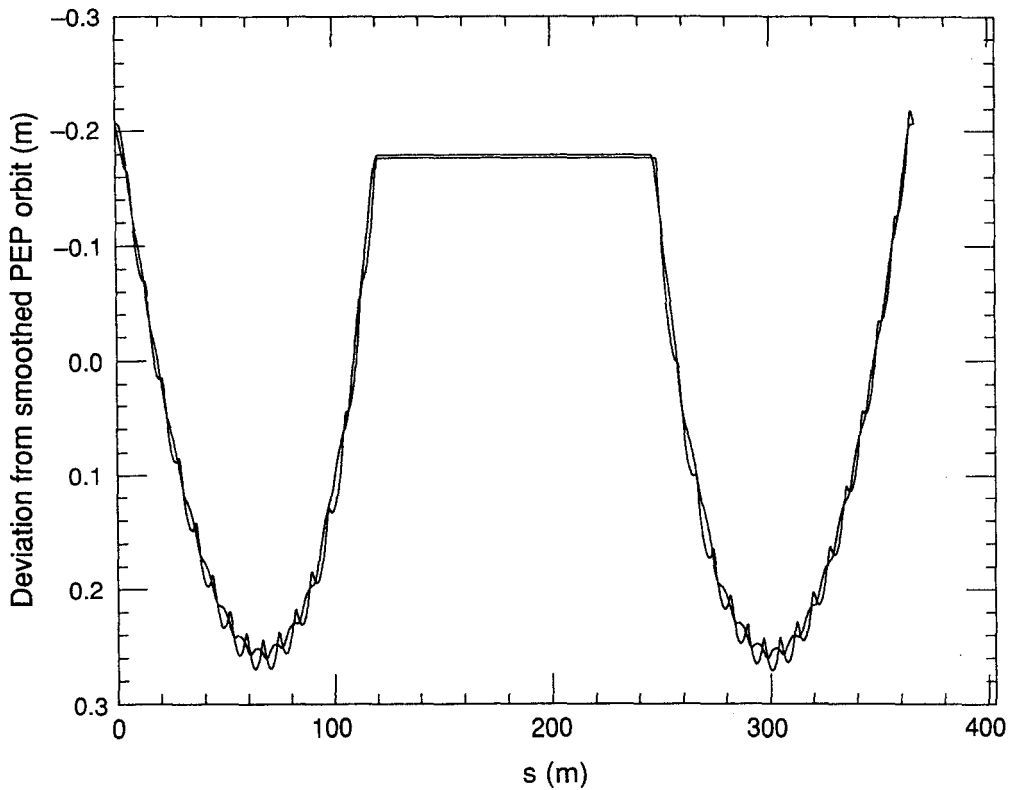


Fig. 4-21. Plot showing the radial offsets of the LER and HER in a normal sextant, with respect to the PEP centerline. The maximum excursions, 26 cm to the inside and 21 cm to the outside of the PEP orbit, fit well in the PEP tunnel.

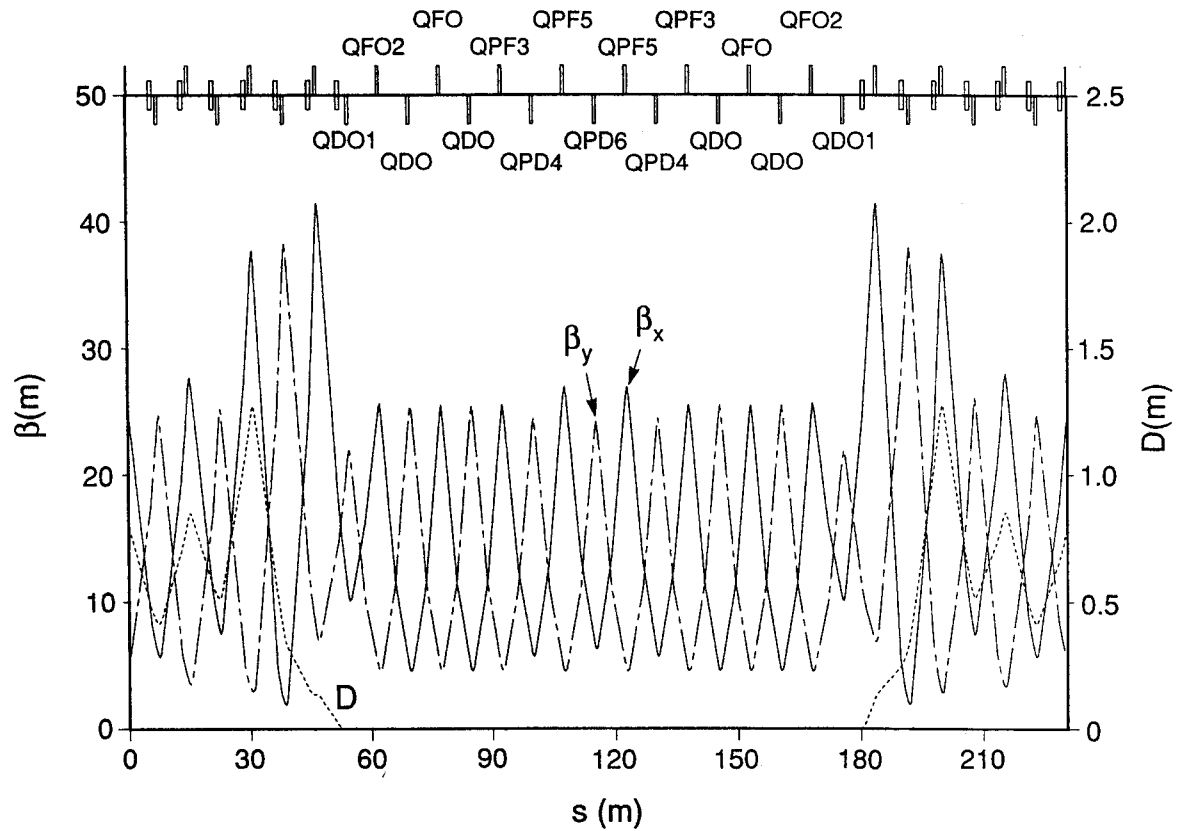


Fig. 4-22. Layout and optics functions for a phase control straight section containing “phase trombone” quadrupoles. The many independently adjustable quadrupoles permit smooth beta functions in a region where RF cavities may be placed.

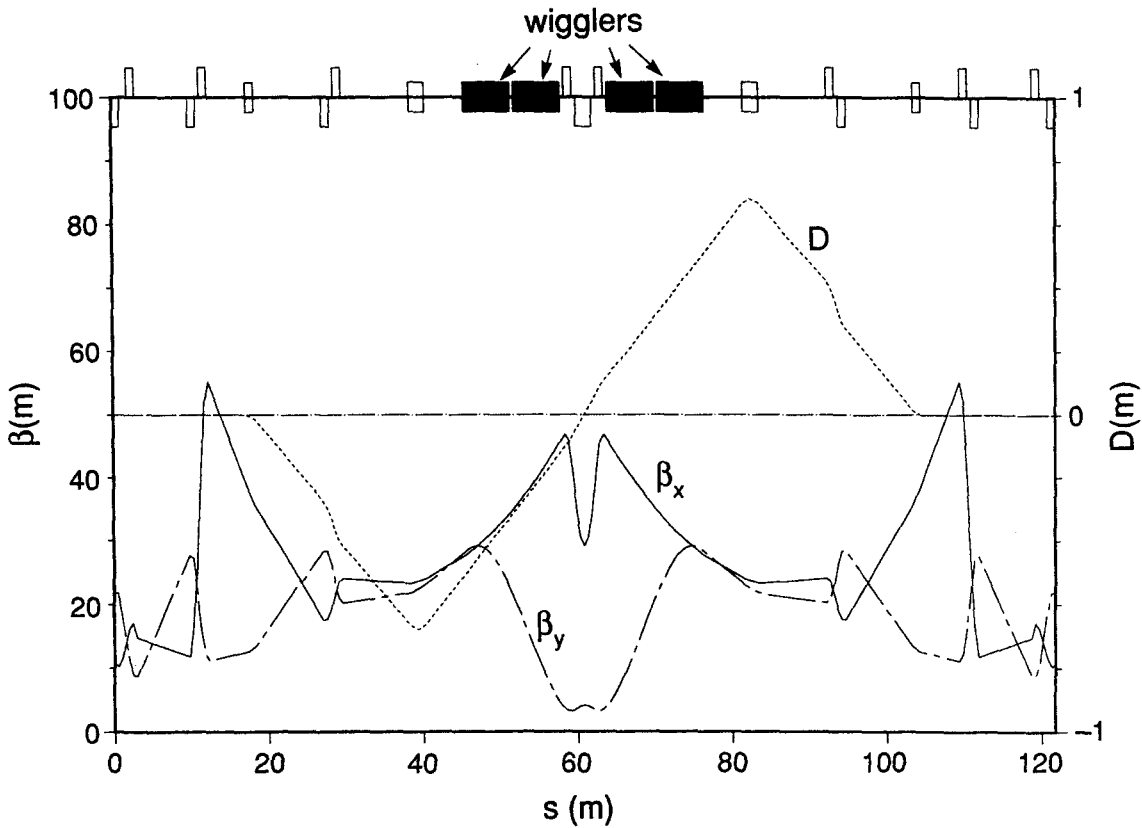


Fig. 4-23. Layout and optics functions for the wiggler straight sections of the LER. In conjunction with the dispersion function D , and its derivative, the wigglers increase the emittance of the low-energy beam. In addition, the wigglers can decrease the damping time of the low-energy beam so that it is equal to that of the high-energy beam.

turn causes a growth of horizontal emittance). By adjusting the strength of the bends that constitute the dogleg, the emittance is brought to the design value.

The optics shown in Fig. 4-23 correspond to the case where the damping times of the two rings are equal. Each 6-m block contains nine wiggler periods, each 60% full of 1.63-T dipoles. Figure 4-24 shows the radial offset of the two rings in a wiggler sextant and shows that the radiation is directed from right to left radially outward. The optics of the wiggler straight is symmetric. Seven independent quadrupoles produce a beam waist at the center and bring the dispersion to zero there, causing both the dispersion and its slope to be zero at either end of the straight section.

4.1.2.6 Injection Straight Section. The straight section opposite the IR straight section is used for injection into the LER. It is configured in the same way as that of the HER, with a 40-m-long free space in the center having $\beta_x = 80$ m. The layout and optics of this straight section are shown in Fig. 4-25.

4.1.2.7 Interaction Region and Beam Separation. The most difficult part of the design of a collider is that of the IR, and that is especially true in the case of a high-luminosity

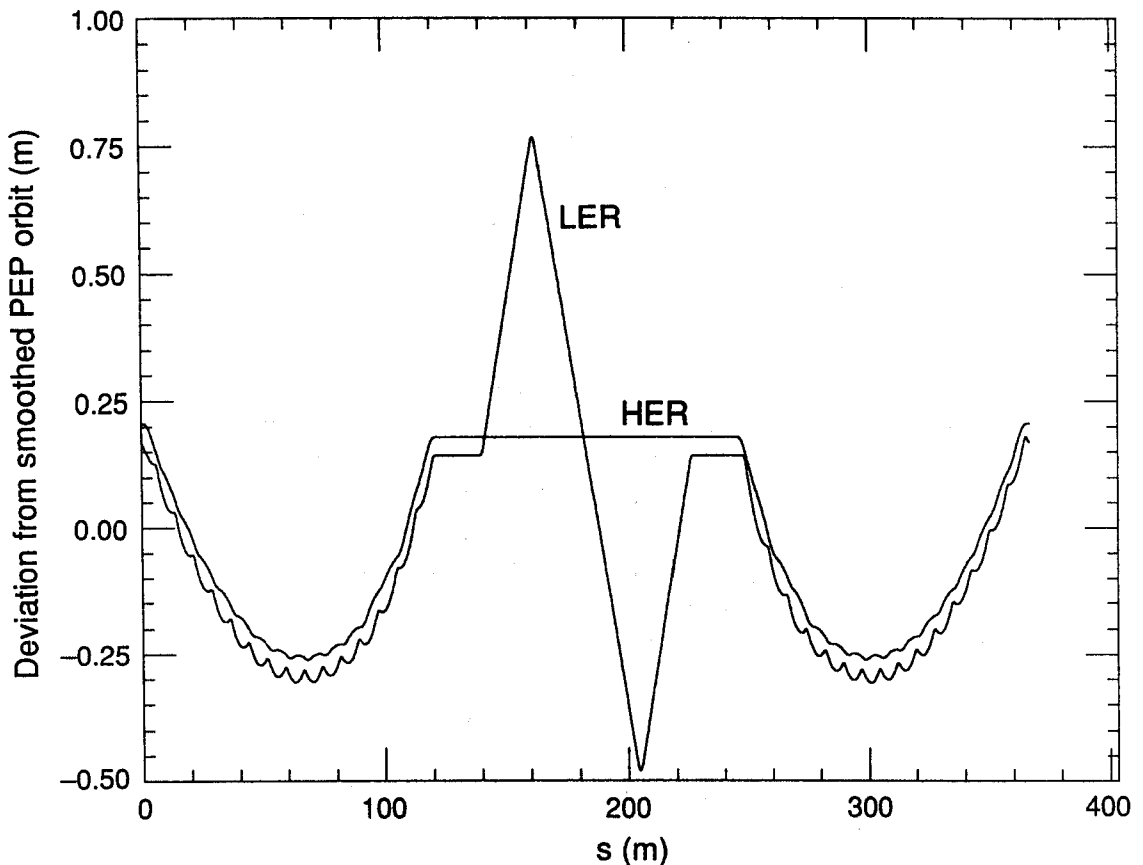


Fig. 4-24. Plot showing the radial offsets of the LER and HER in the sextant containing the wigglers, with respect to the PEP centerline. Note that, with the low-energy beam traveling from right to left, synchrotron radiation from the wigglers is directed to the outside of the ring.

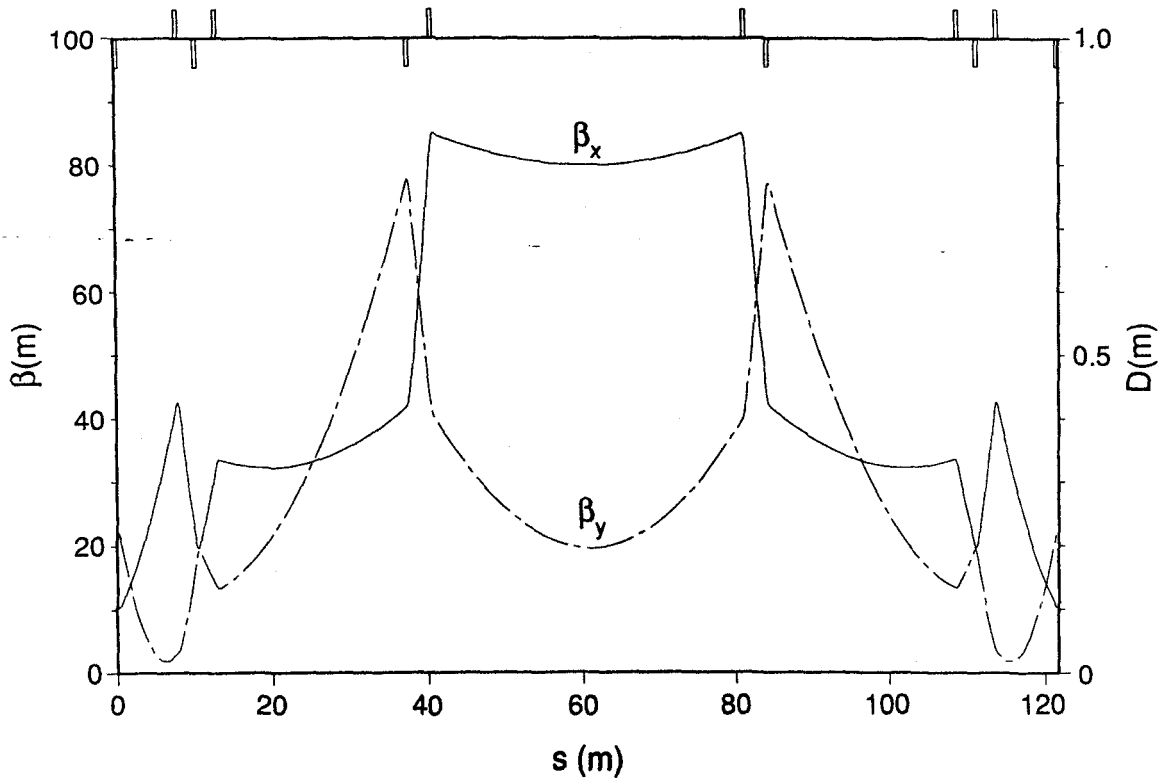


Fig. 4-25. Layout and optics functions for the injection straight section of the LER. The injection point is at the center of the figure, in the middle of the long straight section. Beta functions in this region are easily adjustable to match injection requirements.

asymmetric machine. The energies and beta functions of the two rings are different, the bunches are closely spaced, and the synchrotron radiation from the magnetic separation is large. Optics, separation, masking, and experimental detectors must all coexist in a very small region, so that neat, modular designs are elusive or nonexistent.

As discussed earlier, the scheme adopted for this design is horizontal separation using a separating dipole, a quadrupole triplet common to both beams (with offsets to enhance the separation), a septum quadrupole to focus the high-energy beam, followed by a vertical septum magnet that begins the step that brings the LER beamline 89.5 cm above that of the HER. The horizontal bending pattern is antisymmetric about the IP, which produces an S-bend beamline—a geometry that is conducive to extracting the synchrotron radiation. Figure 4-26a shows an anamorphic diagram of the IR in plan view. The beamlines are shown solid, and the $15\sigma_x$ envelopes are dashed. The polarities of the quadrupoles are indicated, as usual, by the names QF or QD, and (H) or (L) indicates that the magnet is centered on the HER or LER beamline, respectively.

The horizontal separation is produced by B1 and the common triplet QD1, QF2, QD3 with the offsets shown in the figure. These are permanent magnets. The separated beams then traverse the septum quadrupole QD4H, which focuses the high-energy beam only. Figure 4-26b shows the displacements of the low-energy beam from the IP through the horizontal and vertical separation systems. The low-energy beam is transported from the

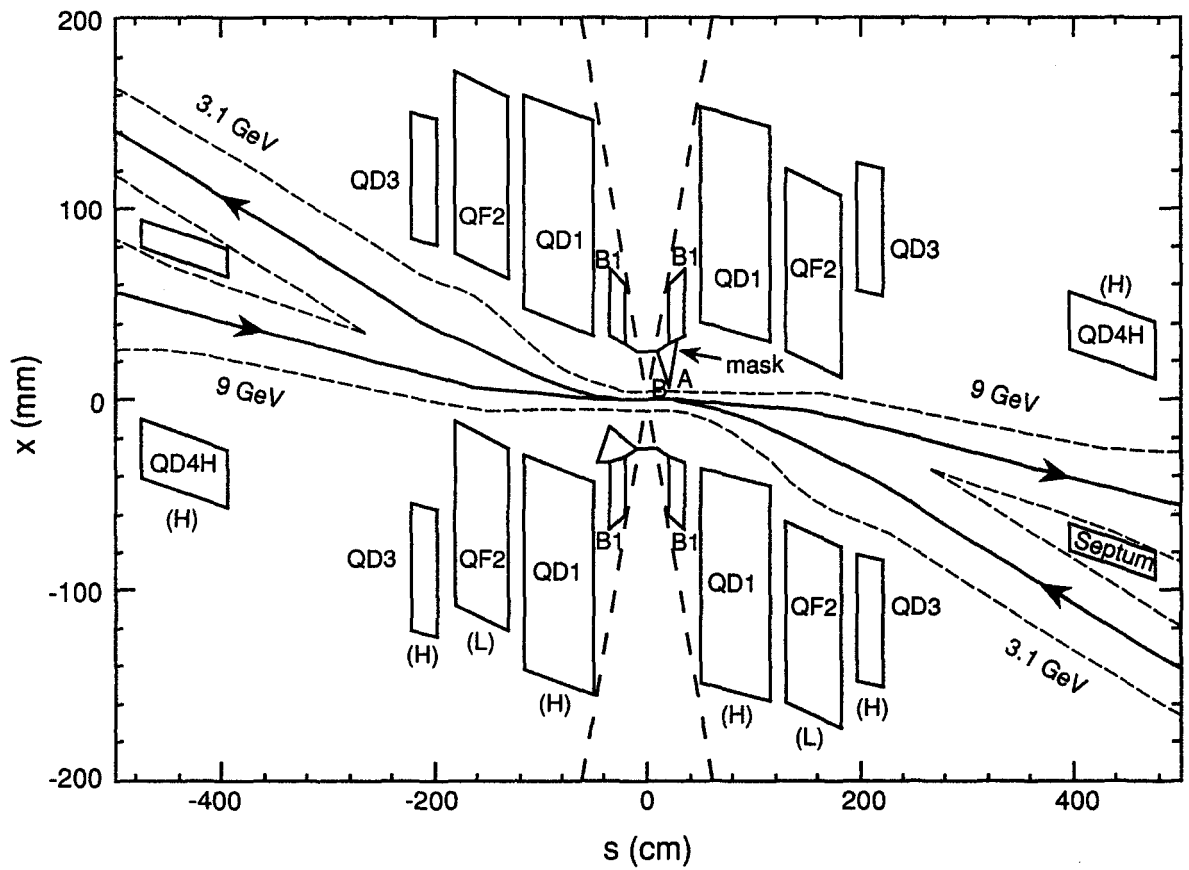


Fig. 4-26a. Anamorphic plan view of the IR.

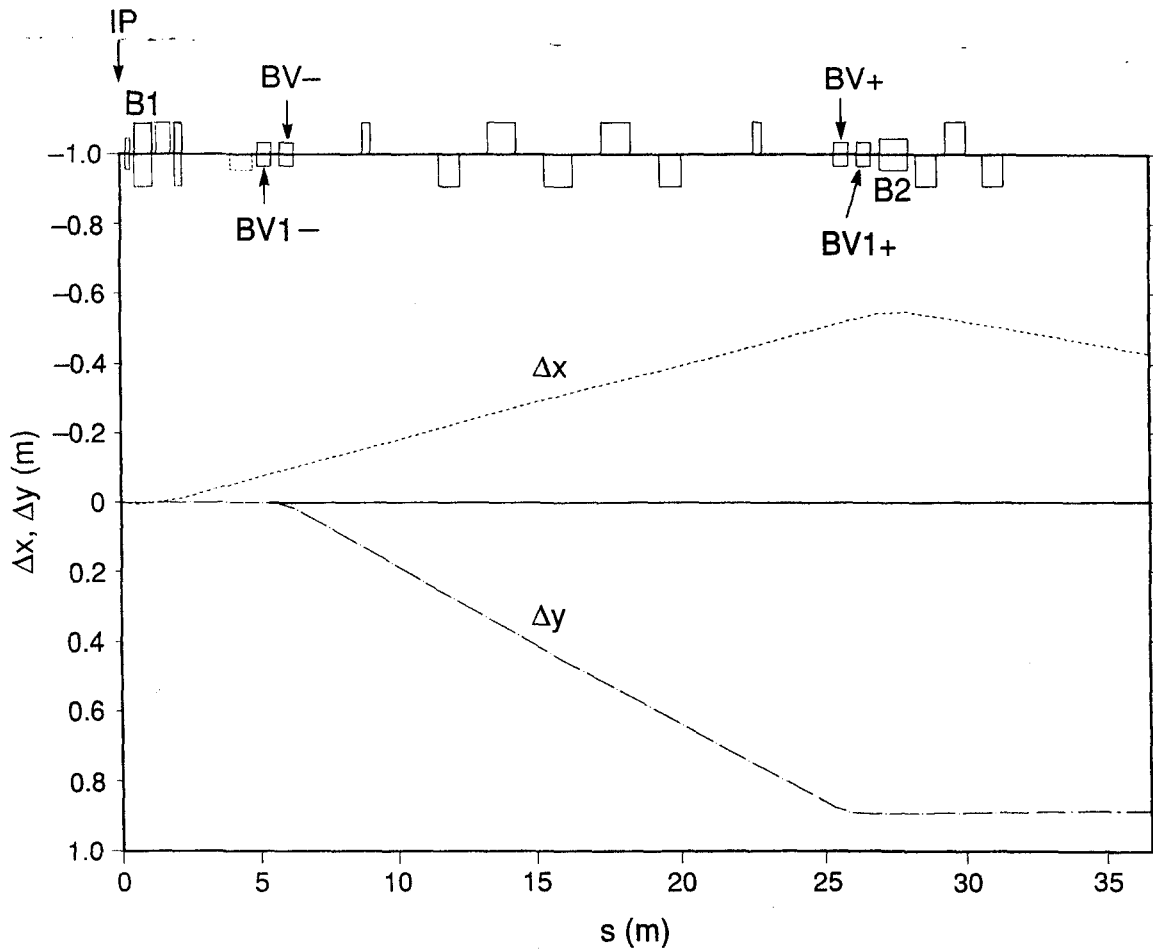


Fig. 4.26b. Plot showing the horizontal and vertical displacements of the low-energy beam in the separator systems. Note the inverted scale for Δx and Δy . The dashed quadrupole represents QD4H, which acts only on the high-energy beam.

collision plane to one 89.5 cm above by the action of the four vertical bending magnets BV1-, BV-, BV+, BV1+, the first of which is a Lambertson septum magnet.

The optics of the LER in the horizontal separation region is shown in Fig. 4-27. The low-energy beam proceeds from a waist at the IP with $\beta_x^* = 37.5$ cm, $\beta_y^* = 1.5$ cm. The first parasitic bunch-crossing point occurs 0.63 m from the IP, just inside of QD1, where the beamlines are separated by $7.5\sigma_x$. The quadrupole apertures allow for $15\sigma_x$ and $15\sigma_y$ beams (the fully coupled vertical emittance is used to calculate the vertical beam size), plus 5 mm for the beam pipe and trim coils and a 2-mm closed-orbit distortion allowance, as well as the additional aperture required by the synchrotron radiation fans. These factors set the inner radii; the outer radii are controlled by the need to maximize the detector solid angle. These dimensions, and an assumed remanent field of 1.05 T give the gradients. The lengths are then adjusted to achieve the desired low-energy beam optical behavior, as shown in Fig. 4-27. Although many iterations were needed to make this process self-consistent, the outcome of these iterations was a conservative and robust design. The discussion of the background issues is covered in Section 4.2. It is worth reiterating here that the high-energy beam benefits significantly from the focusing

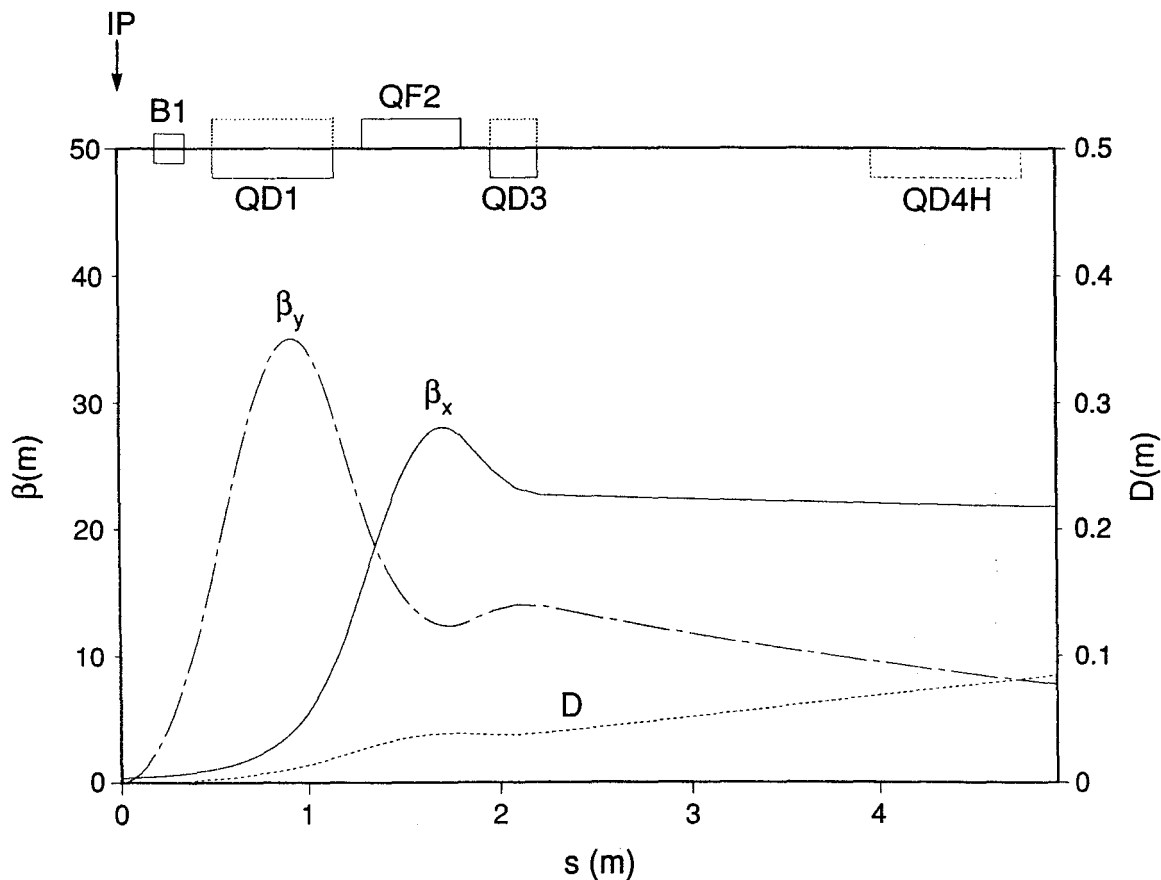


Fig. 4-27. Layout and optics functions for the horizontal separation region of the LER. The dipole B1 and the offset quadrupoles of the triplet, QD1 and QD3, separate the beams. The triplet focuses the low-energy beam to a nearly parallel condition; it then passes through the field-free region of the HER quadrupole QD4H.

of the triplet. Although substantial focusing of the high-energy beam takes place mainly in QD4H, the $\beta_{y,-}$ value in this quadrupole is sufficiently low that the resultant chromaticity contribution to the HER is actually lower than that of the corresponding quadrupole at PEP.

The optics through the horizontal and vertical separation regions is shown in Fig. 4-28. The common triplet is adjusted to produce a beam waist at the entrance to QF4 and a low enough β_x value to permit the low-energy beam to clear the septum in QD4H. The seven quadrupoles, which are located symmetrically about the center of the vertical step, are adjusted to bring D_y and its slope to zero at the end of BV1+, to bring D_x to zero in the center of B2, and to prevent large beta values in between. The B2 dipole is centered on the point where D_x is brought to zero by the quadrupoles to its left; as part of the design process, its strength was initially adjusted to bring both D_x and the slope of D_x to zero at the end of B2. Later, its strength was incremented, along with those of the dipoles B3–B6, in such a way as to steer the low-energy beam from the arc to the IP with the correct radial position and slope, while preserving the dispersion matching.

The remaining optical matching of the IR straight section is shown in Fig. 4-29. It is done with the quadrupoles QD8 through QF13, which produce the characteristic β and α functions at the center of the QDO1 quadrupole. This point marks the beginning of the

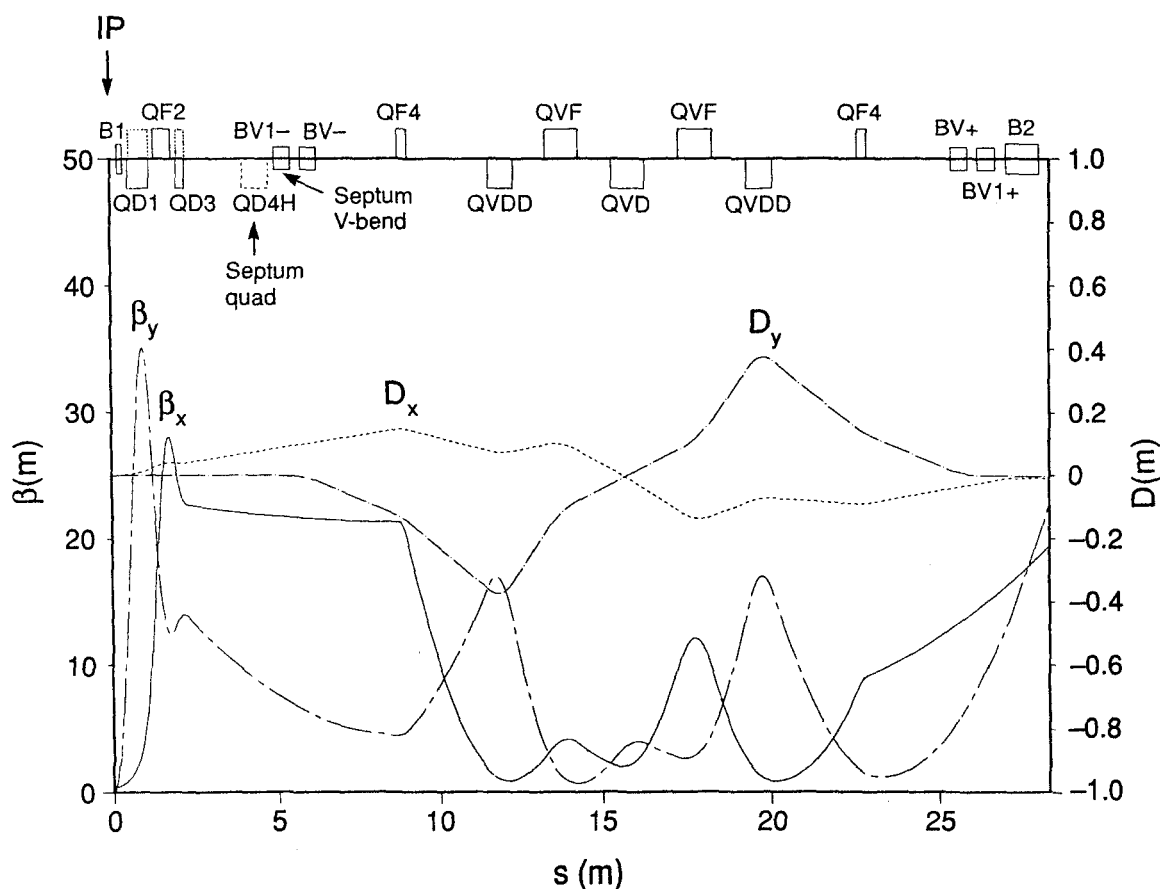


Fig. 4-28. Layout and optics functions for the horizontal and vertical separation regions of the LER. To avoid coupling of the horizontal and vertical motion, the vertical bending is confined to a region that is free of horizontal bends.

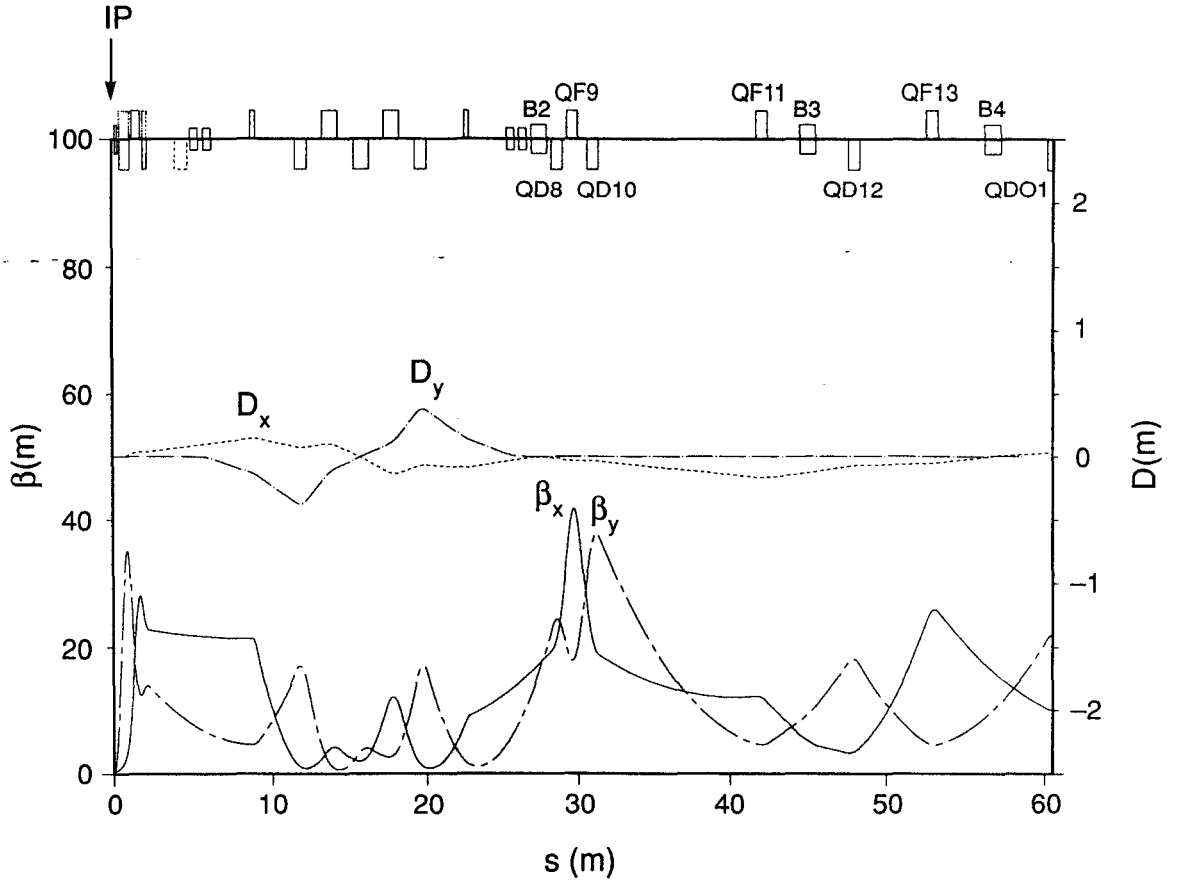


Fig. 4-29. Layout and optics functions for the right-hand half of the IR straight section of the LER. The quadrupoles QD8 through QF13 match the beta functions into the dispersion suppressor.

arc. Figure 4-30 shows the optics from the IP, through the right half of the IR straight section and the right dispersion suppressor, to the beginning of the regular cells. In this figure the bends B2–B6 are set as described above. The radial displacement of the LER compared with that in a normal sextant is shown in Fig. 4-31, while Fig. 4-13 shows both the LER and HER displacements relative to PEP in the IR sextant. Figures 4-32 and 4-33 show the optics of the right side and of the complete IR sextant of the LER. The maximum beta functions generated by these optics, even with $\beta_y^* = 1.5$ cm, are quite moderate.

4.1.3 Tracking Studies

4.1.3.1 High-Energy Ring. Here we present results of the dynamic aperture studies for the B Factory HER. The lattice actually studied is a slightly earlier version of the lattice presented in Section 4.1.1. At present, only a single tune configuration, $\nu_x = 25.29$, $\nu_y = 24.19$ has been analyzed.

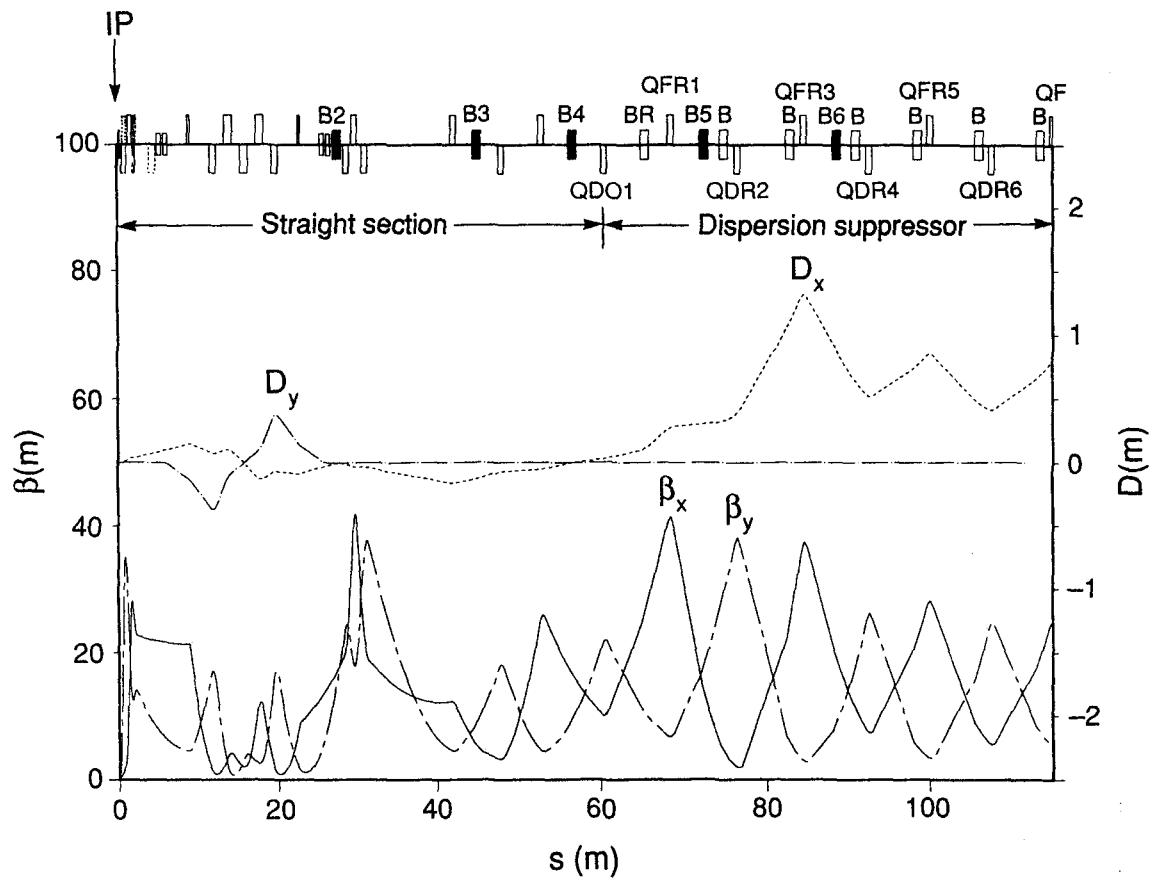


Fig. 4-30. Layout and optics functions from the IP to the beginning of the normal cells of the LER. The dipoles B2 through B6 correct the horizontal dispersion function and steer the beam into the arcs. The steering is needed to place the IP at the center of the straight section and to match the beam angle at the IP to that of the high-energy beam.

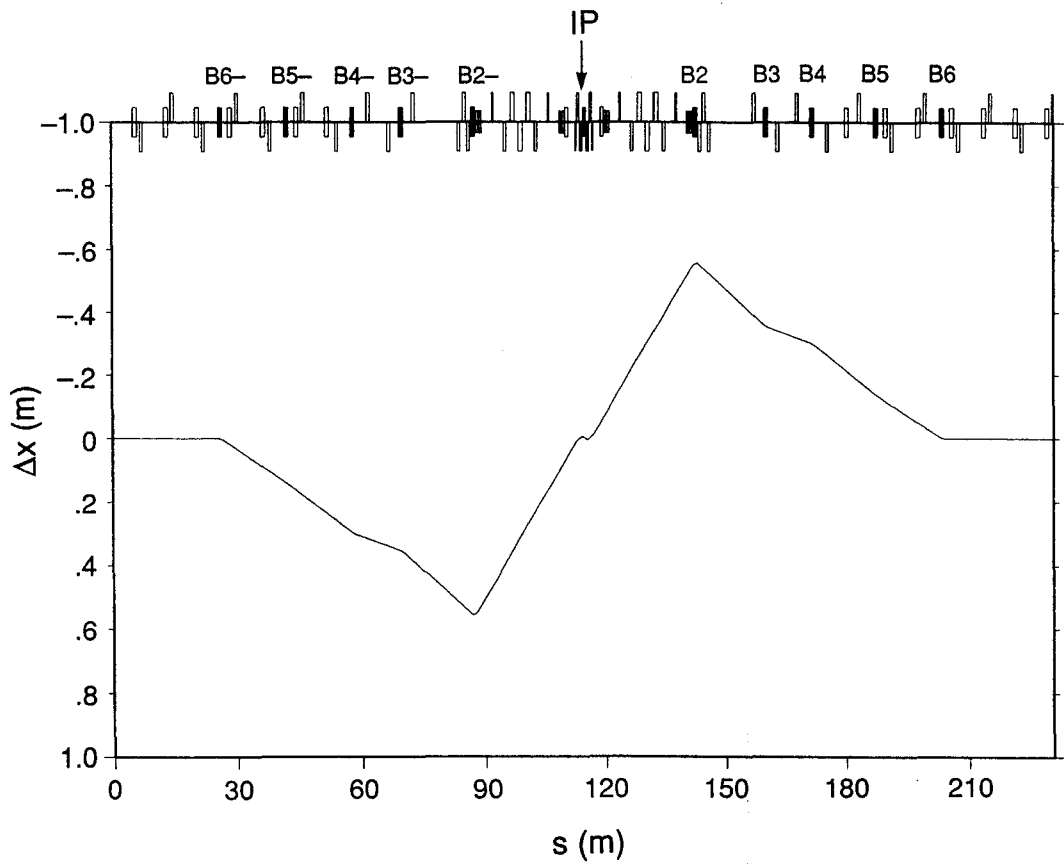


Fig. 4-31. Radial displacement of the low-energy beam in the IR sextant, compared with that in a normal sextant.

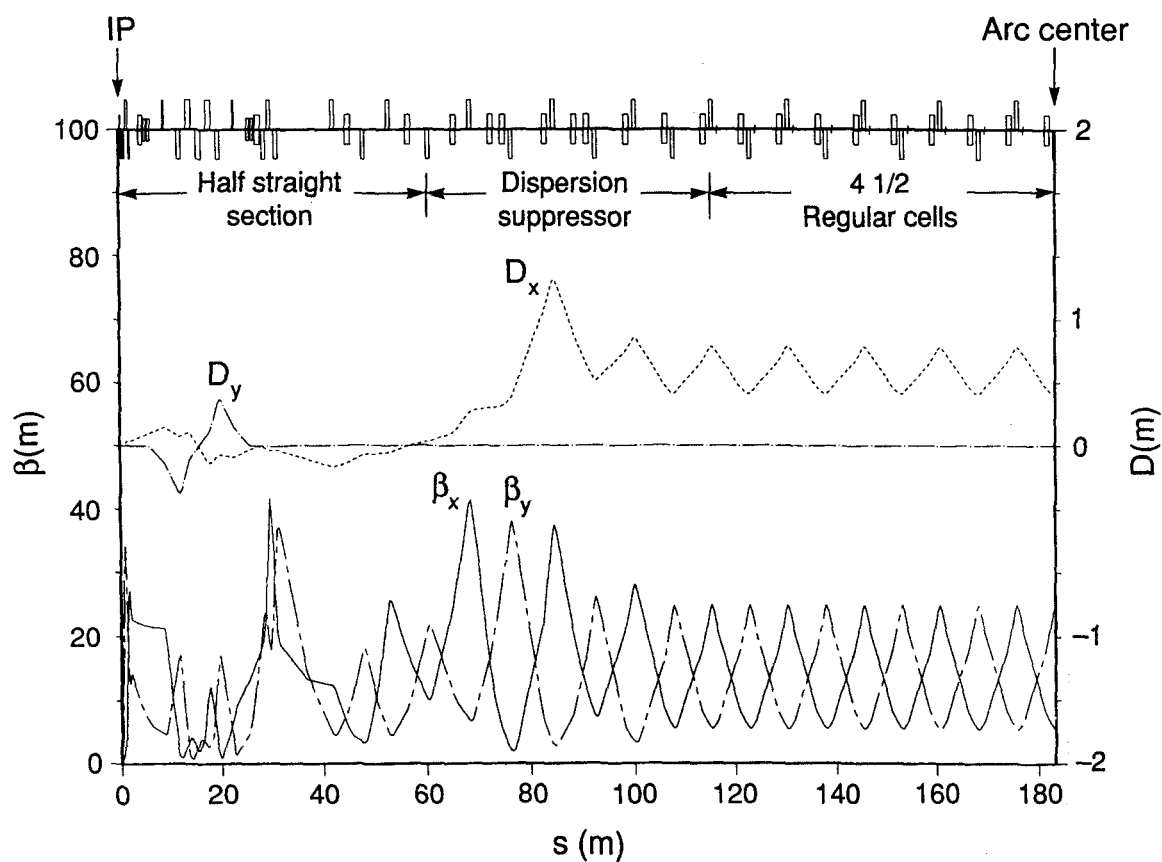


Fig. 4-32. Layout and optics functions for the right-hand side of the IR sextant in the LER.

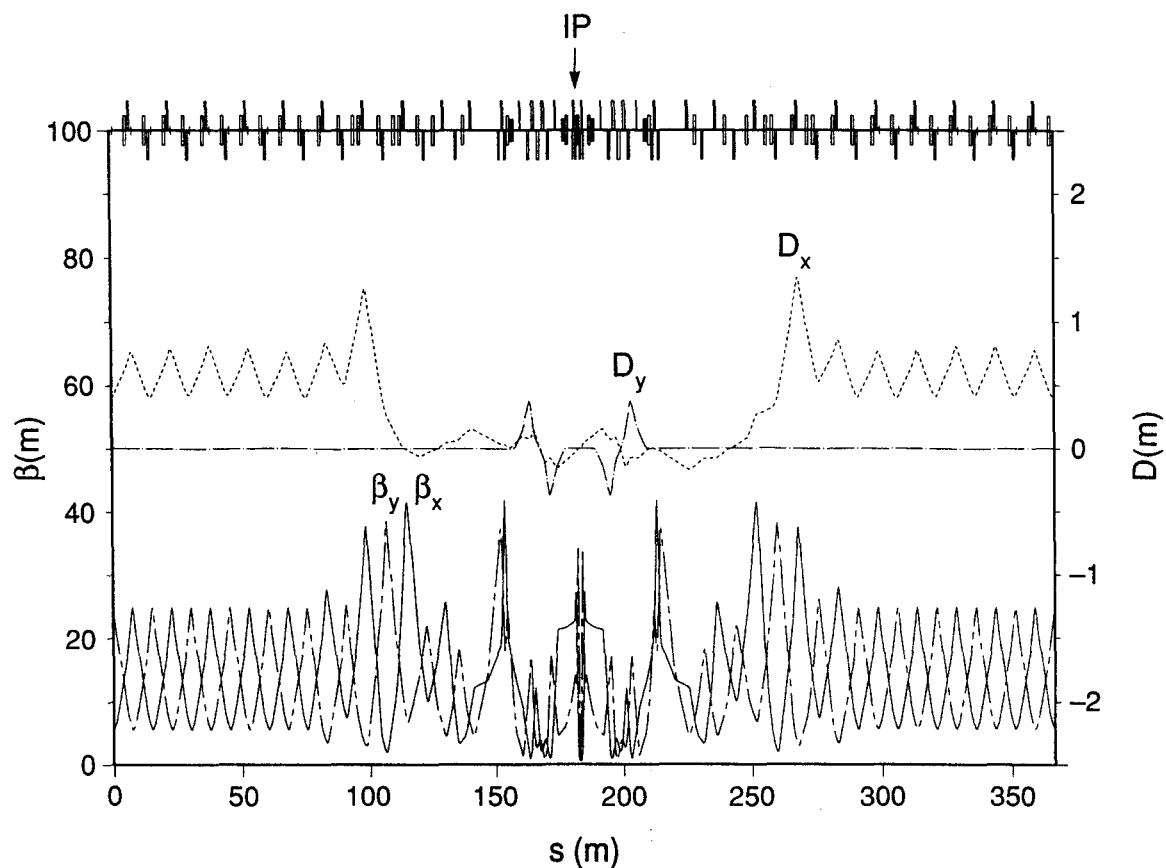


Fig. 4-33. Layout and optics functions for the complete IR sextant in the LER. Note the symmetry of the vertical dispersion function and the antisymmetry of the horizontal dispersion function.

Chromatic Correction Scheme. For this study we adopted a rather straightforward chromatic correction scheme. First, one family of sextupoles for each plane (SFA, SDA) was distributed inside the pseudo-achromats in the arcs. This accounts for 12 sextupoles of each family in each regular arc section and eight per family in the emittance control arcs. These sextupoles are set to completely correct the chromaticity of the entire ring.

Then four sextupoles, SD1, and two sextupoles, SF1, replace selected SDA and SFA sextupoles in the two pseudo-achromats that surround the IR. The sextupoles SDA, SFA, SD1, and SF1 are then set to completely correct both the chromaticities and the momentum dependence of the beta function ($d\beta/d\delta$) at the IP. The positions of the SD1 and SF1 sextupoles are chosen to minimize the sextupole strengths required.

Alignment Tolerances. The alignment errors taken for the magnetic elements are summarized in Table 4-2. For the present study, the errors for the IR quadrupoles were taken as 100 μm transverse error and a field error of 0.0001. This aspect will be revisited after the detailed designs of the IR magnets are available.

For tracking purposes, sets of horizontal and vertical correctors and beam position monitors were distributed around the ring to provide a closed-orbit correction scheme. The scheme chosen works well, although it is not necessarily the one that will be adopted on the real machine. After correction, the rms orbit errors were 650 μm in both planes, with a maximum displacement below 2 mm. In the orbit-correction procedure, it was assumed that BPMs had rms errors of 300 μm in displacement and 1 mrad in roll angle.

Magnetic-Field Errors. Dipole field errors are based on measurements of prototype PEP magnets and include only multipoles up to sextupole. As part of the removals process, a number of actual magnets will be measured to provide additional input for future tracking studies. The values used in the present case are given in Table 4-3.

For the arc quadrupoles, errors are available as values of b_n/b_1 at a radius of $r = 0.05652$ m, where b_n is the multipole n -field and b_1 is the quadrupole field at that radius. The k_n and k_1 are defined by:

$$k_n = \frac{b_n}{B\rho \cdot r^n} \quad (4-1)$$

Table 4-2. Positioning and strength errors taken for tracking runs. All errors are rms values, truncated at 2σ .

Transverse displacements	$\Delta x = 300 \mu\text{m}; \Delta y = 300 \mu\text{m}$
Longitudinal displacement	$\Delta z = 1 \text{ mm}$
Roll angle (quadrupoles)	$\Delta\theta = 1 \text{ mrad}$
Field setting error (dipoles)	$\Delta B/B = 0.001$
Gradient error	$\Delta k/k = 0.001$

from which it follows that

$$\frac{k_n}{k_1} = \frac{b_n}{b_1} \frac{1}{r^{n-1}} \quad (4-2)$$

Table 4-4 summarizes the systematic and random values of b_n/b_1 used in the tracking.

Table 4-3. Dipole field errors; tabulated values are rms errors, truncated at 2σ .

Multipole	Systematic	Random
Quadrupole, k_1 [m^{-2}]	0	1.1×10^{-5}
Sextupole, k_2 [m^{-3}]	2×10^{-4}	3×10^{-4}

Table 4-4. Summary of multipole errors in quadrupoles; tabulated values are rms errors, truncated at 2σ .

n	(b_n/b_1) (systematic)	(b_n/b_1) (random)
2	1×10^{-3}	0.5×10^{-3}
3	2×10^{-4}	1×10^{-4}
4	1.5×10^{-4}	0.75×10^{-4}
5	1×10^{-3}	—
6	0.5×10^{-4}	0.25×10^{-4}
7	1.5×10^{-5}	0.75×10^{-5}
8	2.5×10^{-5}	1.25×10^{-5}
9	5.0×10^{-4}	—
10	2×10^{-5}	1×10^{-5}
11	1.5×10^{-5}	0.75×10^{-5}
12	1.5×10^{-5}	0.75×10^{-5}
13	5×10^{-5}	—
14	1×10^{-5}	0.5×10^{-5}

The quadrupole data come from the measurement of one prototype magnet. Allowed harmonics were assumed to have no random component; for nonallowed multipoles, the measured values were (arbitrarily) ascribed to be half random, truncated at 2σ . During the disassembly of PEP, we will measure a sample of quadrupole magnets to obtain a better estimate of the errors for future tracking studies. These selected magnets will be measured again after reassembly to ensure that no changes have taken place.

Dynamic aperture runs were made with varying amplitudes for these errors. Multiplicative factors f_s and f_r were used to adjust (independently) the systematic and random errors, respectively.

Dynamic Aperture Determination. The HER dynamic apertures were determined by tracking particles for 1000 turns. The basic rms emittance values were taken as $\epsilon_x = 50 \times 10^{-9}$ m-rad and $\epsilon_y = 25 \times 10^{-9}$ m-rad, the latter corresponding to a fully coupled beam in the vertical plane. Particle starting amplitudes of 10, 15, 20, 23, 26, and 28σ in both planes were tracked. A summary of the results for the working point $\nu_x = 25.29$, $\nu_y = 24.19$ is presented in Table 4-5.

For the canonical error values $f_s = f_r = 1$, the dynamic aperture remains quite large. However, the present set of errors is relatively small and, for example, does not contain information in the higher multipoles in the dipoles. When either f_s or f_r is set to 20, the dynamic aperture collapses to well below 10σ . On the other hand, it is worth pointing out that the quadrupole errors are measured at a radius of 56 mm, whereas the 30σ beam envelope in the HER is only about 30 mm. Thus, the beam does not really experience the high-order multipole components of the field very strongly. The results obtained here are consistent with this consideration.

Table 4-5. Dynamic apertures, given in units of the normal rms beam size.

$\delta p/p$ (10^{-3})	$f_s = 1$ $f_r = 0$	$f_s = 1$ $f_r = 1$	$f_s = 1$ $f_r = 10$	$f_s = 10$ $f_r = 1$	$f_s = 5$ $f_r = 10$
0	28	28	26	15	15
2	28	28	23	15	15
-2	28	28	20	15	15
4	28	28	23	15	15
-4	28	28	23	15	20
6	28	28	23	15	15
-6	28	28	23	15	20
8	20	28	23	15	20
-8	23	15	26	23	23

No assessment has yet been made of the field quality needed for the IR quadrupoles. Insofar as the beta functions here are lower than now used at PEP, it is likely that tolerances will be relaxed compared with the present PEP IR quadrupole tolerances, but the degree to which this is true must be determined.

We conclude from the work to date that the HER ring can operate satisfactorily with the existing PEP magnets.

4.1.3.2 Low-Energy Ring. An initial study of the LER lattice has been carried out based on the same errors (summarized in Tables 4-3 and 4-4) used for the HER results quoted above. The phase advance adopted here, 80° , was selected after earlier investigations of an LER lattice with strings of 12 cells tuned to 90° . The on-momentum dynamic aperture in that case was found to be near $10\sigma_x$; this left us with a very small safety margin for the errors.

A lattice with 90° phase advance per cell is often selected when chromatic effects are to be minimized. To maximize the dynamic aperture, the cells with sextupoles are put together in groups of four, which produces a second-order achromat. To be more technical, one can say that the map for four cells will contain only second-order terms generating chromaticities and quadratic momentum compaction. However, the cubic part of the map can be more of a problem in a 90° lattice than in a 60° lattice, for example. Indeed, the cubic part will generate potentially harmful resonances, such as the $4\nu_x$ and the $2\nu_x + 2\nu_y$ resonances, in addition to the tune shifts and the $2\nu_x - 2\nu_y$ resonance found in the 60° lattice.

The dynamic aperture of the 80° ideal lattice adopted for the B Factory LER is shown in Fig. 4-34. The tracking runs were carried out with a fully six-dimensional code, including synchrotron oscillations.

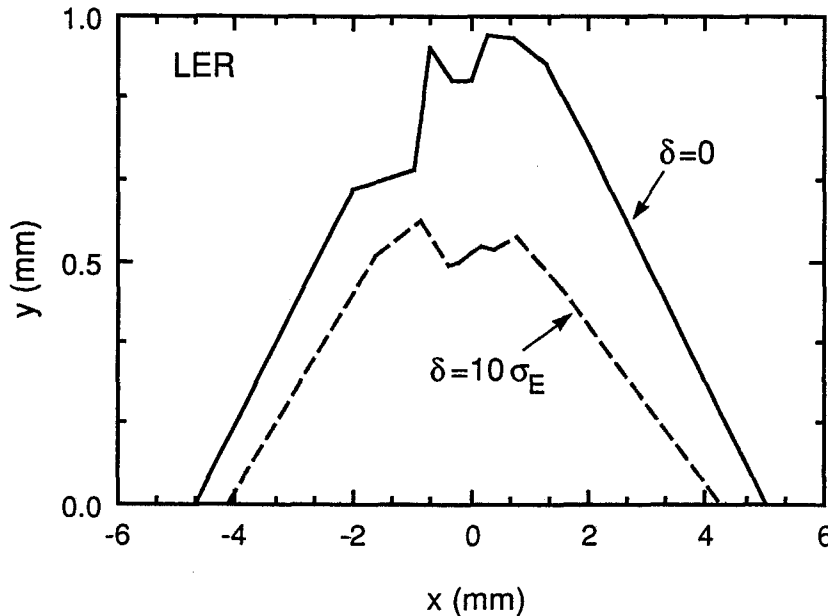


Fig. 4-34. Dynamic aperture of the 80° ideal lattice for the LER. At the tracking point, $\sigma_x = 0.2$ mm, $\sigma_y = 0.03$ mm, the vertical beam size being evaluated with the fully coupled vertical emittance.

It is clear that the LER lattice ($v_x = 32.29$, $v_y = 35.19$) provides a good starting point. At present only two families of sextupoles are being used, and these were always adjusted so that the chromaticities were near zero (within a unit). Particles are launched at the IP with initial conditions of the form $(x, 0, y, 0, 0, \delta)$ and tracked for 400 turns.

Simulations with Errors. Next we introduced errors into the ideal lattice. For technical reasons having to do with the present status of the simulation code, we did not correct the closed-orbit distortions. Instead, the errors were reduced so as to produce an average distortion around a few tenths of a millimeter, typical of an orbit after proper correction. The multipole errors used are given in Tables 4-3 and 4-4. These were applied to all magnets in the lattice, including the permanent magnet quadrupoles in the IR. Strength errors of $\Delta B/B = 0.001$ for dipoles and $\Delta k/k = 0.001$ for quadrupoles and sextupoles, and a roll angle of 1 mrad were also included in the simulations. The resulting dynamic aperture is given by Fig. 4-35. Although there is some loss compared with the ideal lattice, the apertures are still quite acceptable.

To get a feeling for the tolerance of this 80° lattice, we augmented first the random and then the systematic multipole errors by a factor of 10. Figure 4-36 shows the dynamic aperture for the case of amplified random errors. Even in this case, the apertures are still quite large. This gives us some confidence that the lattice behavior is acceptable, despite the preliminary nature of these simulations. Figure 4-37 shows the aperture for the case of amplified systematic errors. For this case, the $10\sigma_E$ particle has a significantly reduced aperture; it is likely that this can be improved by using additional sextupole families, as was done for the HER. Even if the systematic errors turn out to be small,

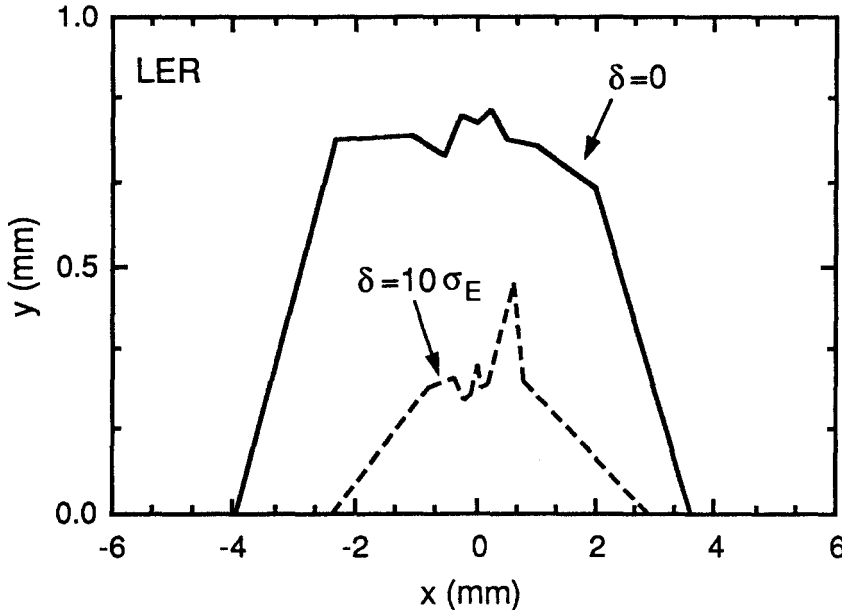


Fig. 4-35. Dynamic aperture of the LER lattice, with multipole errors included in the simulation.

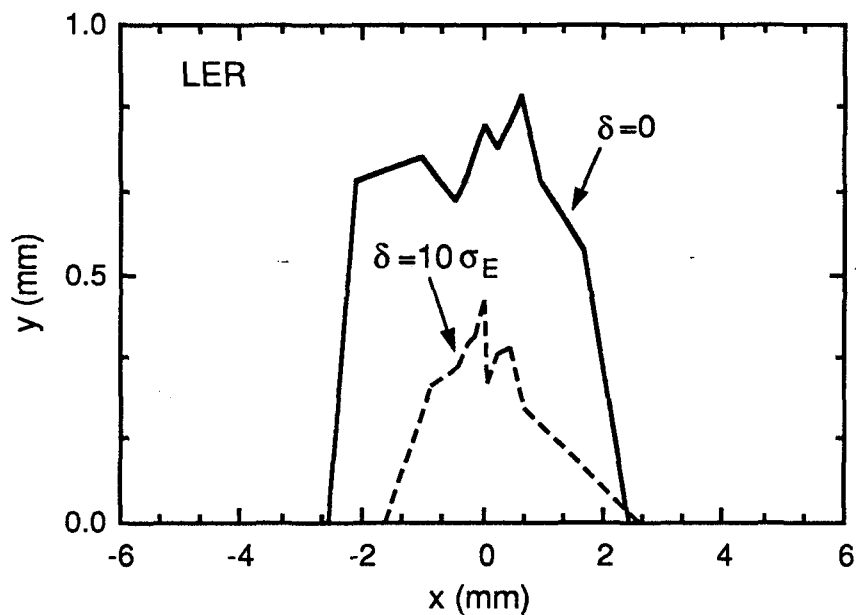


Fig. 4-36. Dynamic aperture of the LER lattice with amplified random errors.

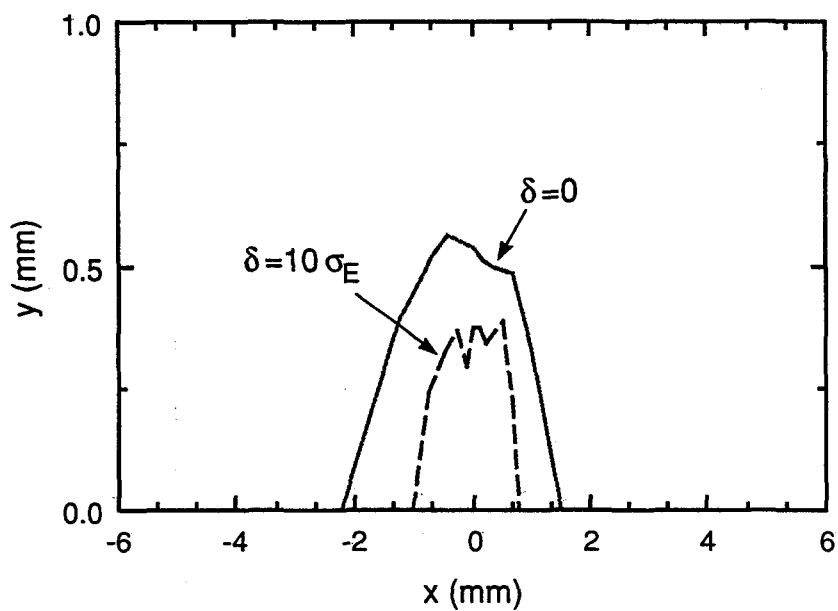


Fig. 4-37 Dynamic aperture of the LER lattice with amplified systematic errors.

future simulations done in conjunction with the beam-beam studies might lead us to modify the tunes and the chromatic behavior of the linear lattice functions. This can be accomplished with the use of additional families of sextupoles distributed, for example, as described earlier for the HER.

Initial tracking studies for both rings, based on errors from prototype PEP magnets, show that the dynamic aperture is adequate for injection and beam lifetime. Future work, using more realistic errors and possibly additional sextupole families is expected to improve the dynamics further.

4.1.3.3 Injection Studies. In many present-day colliders, much of the total radiation damage to the detector components comes during the injection process. For example, it has been estimated by Billing [1990] that at CESR about half of the total radiation dose to the detector occurs during injection. Because the B Factory will undergo injection relatively often, albeit for short periods of time, we have adopted a “graded-aperture” approach to the IR design.

As described in Section 4.2, the B Factory rings have been designed such that the beam-stay-clear aperture near the detector is given by $15\sigma + 2$ mm, whereas it is limited to 10σ elsewhere in the arc sections by means of movable collimators. (To be safe, the horizontal beam-stay-clear aperture is evaluated with the uncoupled emittance and the vertical beam-stay-clear aperture is evaluated with the fully coupled emittance.) These aperture choices are meant to ensure that the limiting aperture occurs at a well-defined location that is far away from the detector. To explore the efficacy of this graded approach, we have performed tracking studies of the injection process to see where the lost particles are stopped. Thus far, only the LER has been studied, but it is clear that the behavior of the HER will be similar.

Injection takes place in the middle of a special high-beta injection straight section, as discussed in Section 6 (see Figs. 4-25 and 6-8). For the purposes of tracking, we have kept the septum location fixed at $10\sigma_x$, that is, at 27 mm; this serves to define the limiting aperture of the ring. (In the actual design, specially designed movable collimators located upstream of the injection septum define the limiting aperture.)

In the initial simulations, we tracked the phase-space distribution of particles (at the injection point) shown in Fig. 4-38. The nominal launch point of the injected beam is at $8\sigma_x = 21.6$ mm from the closed orbit of the stored beam, so the phase-space distribution is centered at this location. For each initial condition, particles were launched with energy offsets (shown from left to right in each triplet of points) of $\delta = -1\%$, 0 , and $+1\%$. As in the dynamic aperture studies discussed in Section 4.1.3.2, particles were tracked in six dimensions, that is, including synchrotron oscillations. The errors used were the same as those listed in Tables 4-3, and 4-4. To permit realistic long-term tracking, radiation damping effects were also included, using damping coefficients of $\alpha_x = \alpha_y = 2 \times 10^{-4}$ turn⁻¹ and $\alpha_E = 4 \times 10^{-4}$ turn⁻¹. The aperture limitation in the arcs was taken as $x = \pm 40$ mm and $y = \pm 25$ mm; near the IP, we took the limiting aperture to be $x = y = \pm 25$ mm, and in the straight sections, we used $x = y = \pm 50$ mm.

The results are summarized in Fig. 4-38, where particles that survived for 20,000 turns are represented by filled circles and lost particles by open circles. All particles with an energy offset of $\delta = +1\%$ were lost in the first turn at a high-dispersion point, for

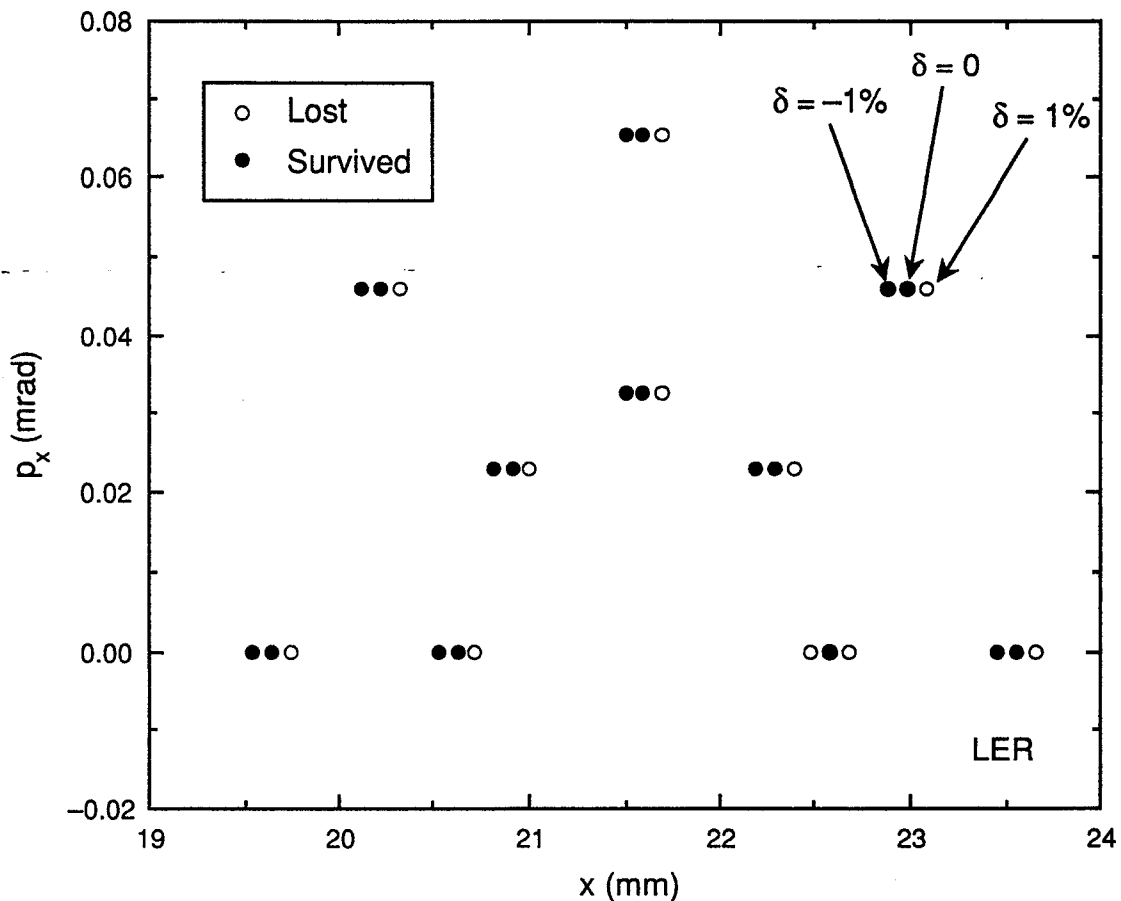


Fig. 4-38. Phase-space distribution at the injection point of particles tracked in the injection simulations with nominal lattice errors. Particles that survived for 20,000 turns are indicated by filled circles; lost particles are represented by open circles. Each triplet of points represents three different energy offsets, as indicated. The normal injection point, corresponding to $8\sigma_x$, is 21.6 mm. All lost particles stopped at a high-dispersion point, and none was lost near the IP.

example, the QFR3 quadrupole (see Fig. 4-30). Only one of the particles launched with $\delta = -1\%$ was lost, and it was lost at the $10\sigma_x$ aperture limitation represented by the septum. Although the physical aperture near the IP is smaller than in the arcs, no particle was lost in this region after 20,000 turns.

To ensure that this result is not strongly influenced by the choice of errors, we repeated the study for a lattice having large errors; these were obtained by increasing both the random and systematic errors by a factor of 10 from their nominal values. The resultant dynamic aperture (projected to the standard tracking point at the IP) is shown in Fig. 4-39. For on-momentum particles, the dynamic aperture has decreased below $10\sigma_x$; for off-momentum particles, the degradation is even more severe, down to about $5\sigma_x$.

To determine where the on-momentum particles are lost, starting amplitudes of the tracked particles were increased to cover a larger range, as shown in Fig. 4-40. For completeness, both positive and negative p_x values were tracked. Again, we indicate the surviving particles (followed for 20,000 turns) with closed circles and the lost particles

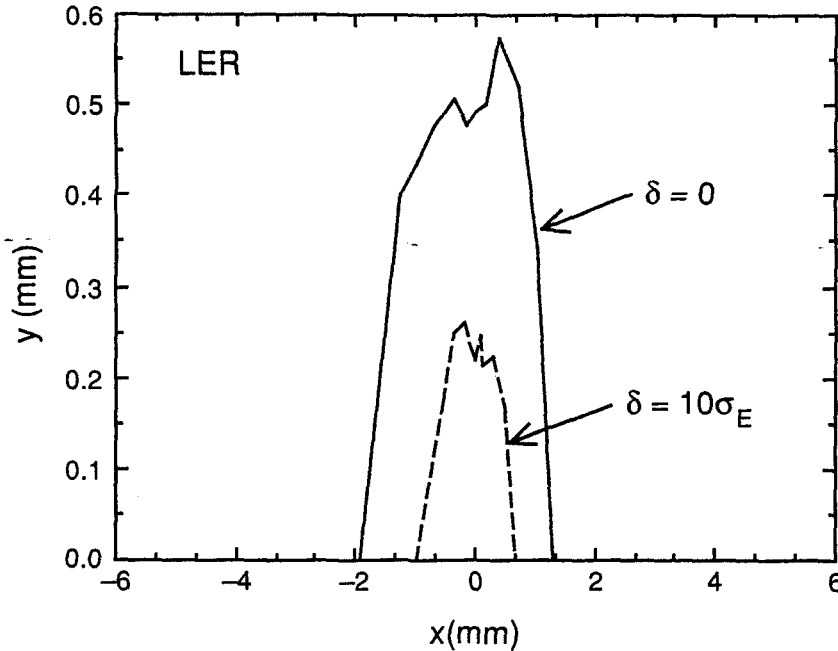


Fig. 4-39. LER dynamic aperture (at the IP) corresponding to the enhanced errors used in the injection simulation shown in Fig. 4-40.

with open circles. Despite the increased errors and larger starting amplitudes, we still see that most of the on-momentum particles survive. Of those that do get lost, all are stopped at the $10\sigma_x$ aperture, and none is lost near the IP. Results for the off-momentum particles remain the same as before; that is, they are lost in the dispersion suppressor in the region near QFR3.

From these studies, we see that a collimator located in the dispersion suppressor cell downstream of the injection point suffices to stop the off-momentum lost particles. On-momentum lost particles can be stopped in the injection straight section itself, using a collimator located upstream of the septum at a $10\sigma_x$ aperture. In reality, of course, all lost particles will not be stopped cleanly by a single collimator. At least one additional collimator will be located at a suitable distance downstream from the primary collimator to deal with edge-scattered particles.

To summarize, we conclude from this initial investigation that the use of a larger effective aperture in the IR than in the arcs ($15\sigma_x$ compared with $10\sigma_x$) is successful in eliminating the loss of particles near the IP during the injection process.

4.1.3.4 Compensation of the Detector Solenoid. One aspect of the lattice design not covered elsewhere is that of compensating for the optical effects of the detector solenoid. To explore the feasibility of restoring the ring optics in the presence of the solenoidal field from the detector, we performed a series of calculations for the LER lattice. For this purpose, it suffices to use a rather simple model of the solenoid. We therefore considered a constant-field solenoid set at $B_z = 1$ T for our initial study. If we denote the map of a solenoid of length l and field B by $S(l, B)$, then we can create a zero-length insertion, $I(l, B)$, by using the elements $I(l, B) = S(-l/2, 0) S(l, B) S(-l/2, 0)$.

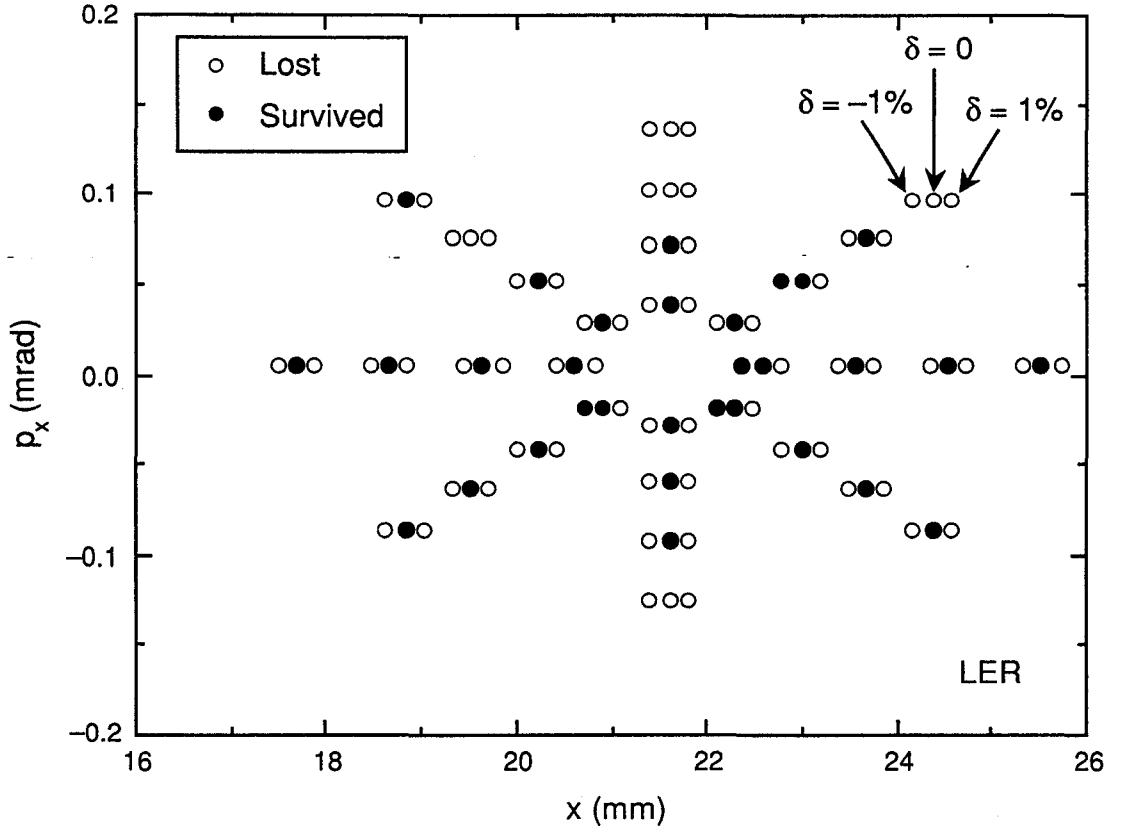


Fig. 4-40. Phase-space distribution at the injection point used in the injection simulations with enhanced errors. On-energy lost particles were stopped at a 10σ aperture; off-energy particles were stopped at a point of high dispersion in the dispersion suppressor cells. No particles were lost near the IP after 20,000 turns.

In the actual calculations, we used this approach to mimic the effect of the solenoid over an extended region near the IP by utilizing four such insertions $I(l, B)$ with $l = 0.5$ m and $B = 1$ T, located as follows (see Fig. 4-27 for the layout; all drifts are not identical):

QD4H, drift, $I(l, B)$, drift, QD3, drift, QF2, drift, QD1, drift, B1, $I(l, B)$, drift
+ mirror symmetric beamline

Because a 4×4 symplectic matrix can be generated by a quadratic Hamiltonian having four variables, we require 10 adjustable parameters to match the transverse optics. In other words, with 10 “knobs” we can restore a coupled, mismatched map to its original conditions. As a first attempt to do this, we placed correctors as close as possible to the IP without encroaching on the solenoid region itself. The setup employed is denoted symbolically as follows (where underlined quadrupoles are normal elements and quadrupoles marked with an asterisk have an adjustable skew component as well; again, all drifts are not identical):

QVD, drift, QVE, drift, QVD*, drift, QVF*, drift, QVD*, drift, QF4*, drift,
 BV-, drift, BV1-, drift, QD4H, drift, $I(l,B)$, drift, QD3, drift, QF2, drift, QD1,
 drift, B1, $I(l,B)$, drift, IP
 + mirror symmetric beamline

With these magnets, the map was restored to its original value, that is, one without a solenoidal field. Unfortunately, this approach does not suffice to restore the beam conditions at the IP; beam sizes in both transverse planes were roughly double their original values. An examination of the beam behavior in the rematched lattice indicates why this occurs: It is due to the fact that the dispersion has not been properly rematched by this technique. The resultant mismatched dispersion propagates around the lattice and is large enough in the wiggler sections to give rise to considerable growth in beam emittance.

We conclude from this attempt that it is not sufficient merely to reduce the dispersion at the IP to a low value. It is also necessary to match the dispersion and its slope in each transverse plane, which requires an additional four adjustable parameters. Therefore, we must add another set of quadrupoles, located in a dispersive region, to our matching parameters. After doing so, we found that the resultant solution works perfectly. With additional quadrupoles in the dispersion suppressor cells adjacent to the IP, we were able to fully restore the optics in the presence of the solenoidal field. Although we have not yet attempted to optimize the correction scheme, we conclude from the work to date that it is possible to provide sufficient parameters to do so.

4.1.4 Energy Tunability

Because the LER optics are based on permanent magnet technology and are thus not easily adjustable, some care must be taken to ensure suitable optics flexibility.

The majority of running at the B Factory will be at the $T(4S)$ resonance. This is where the CP violation physics is done; the remaining physics topics, except for the T resonance and B_s mixing studies, are also best done at the $T(4S)$. It will nevertheless be desirable to intersperse short runs (1–3 months) at the other resonances, the $T(1S)$, $T(2S)$, $T(3S)$, and $T(5S)$ (see Fig. 2-1). For such studies, these short runs will generate enormous increases (factors in excess of 100; see Table 2-1) over the size of data-sets currently available. In addition to a short run at the $T(5S)$, a longer dedicated run (on the order of 30 fb^{-1}) will be needed for studies of B_s mixing; for this, it may well be prudent to reoptimize the IR region, increasing the machine asymmetry and reducing the radius of the first layer of the silicon vertex detector. This experiment is not foreseen early in the program; it will commence after a comprehensive CP violation program has been established.

The Asymmetric B Factory has been designed to accommodate this program. The collision energy is tunable over the full range of energies from the $T(1S)$ to the $T(5S)$. The strategy for covering the range from the $T(2S)$ to the $T(5S)$ is to change both the electron and positron beam energies, keeping their ratio constant. Scaling the fields in the accelerator lattice magnetic elements and in the trim coils (see Section 5.1.3) of the samarium-cobalt IR magnets accordingly ($\pm 4\%$), the particle orbits are kept identical and the change is transparent to the accelerator environment.

To run at the $T(1S)$, the positron energy is kept constant at 2.942 GeV and the electron energy is lowered by 11% to 7.6 GeV. The currents in all the magnets in the HER are scaled in proportion to the electron beam energy. The trajectories are restored to within a few millimeters of their nominal positions by adjusting the magnetic field in B1, the position and angle of the incoming beams, and the position of the IP itself. We have assured ourselves that the beam trajectories in this case—as at higher center-of-mass energies—remain within our conservatively defined stay-clear region of $15\sigma + 2$ mm.

The B Factory has been designed to deliver a luminosity of $3 \times 10^{33} \text{ cm}^{-2} \text{ s}^{-1}$ at the $T(4S)$. It is, of course, desirable to maintain this maximum luminosity for the short T -physics runs; by the very nature of the large increase in statistics these runs will bring, however, moderate reductions in machine luminosity pose no problems.

The luminosity of the B Factory at different center-of-mass energies can be derived in a straightforward way from the scaling of a single-ring circular collider. In going from the $T(4S)$ to the $T(5S)$, the beam energies must be raised by 2.4%. In a conventional electron-positron collider, most of the RF power is devoted to producing the cavity voltage at the design energy. Above this energy, the voltage required is proportional to the synchrotron radiation loss (the well-known γ^4 law), so the cavity dissipation scales as γ^8 . Since the tune shift is proportional to γ , the luminosity scales as γ^7 . In the case of the B Factory, the cavity wall losses are only about one-third of the total power; the existing spare capacity can therefore be used to keep the luminosity approximately constant up to the $T(5S)$.

In the regime below the nominal energy, and with fixed optics, the beam dimensions are proportional to γ . (In this regime, the RF power needed to restore synchrotron radiation is always less than at the design energy.) The current per beam is then limited by the beam-beam tune shift equation, scaling as γ^3 . The luminosity then scales as γ^4 . In the B Factory, as in most modern storage rings, the emittance can be optimized by using wigglers or dispersion mismatching. In this case, it is possible to keep the beam dimensions constant as the energy varies. Under these conditions, the luminosity varies as γ^2 , giving a 10% reduction in luminosity at the $T(1S)$.

4.2 ESTIMATION OF DETECTOR BACKGROUNDS

The problem of machine-related backgrounds is one of the leading challenges in the B Factory project: The detector must be sufficiently well-protected to prevent either excessive component occupancies or deterioration from radiation damage. In effect, what is required is to achieve background rates similar to those of existing colliders, but at beam currents an order of magnitude higher. There are three primary sources of backgrounds:

- Synchrotron radiation photons produced in the machine magnetic elements
- Off-energy electrons and photons produced in bremsstrahlung interactions with background gas molecules
- Elastically (Coulomb) scattered, off-angle electrons produced in interactions with background gas molecules

These background sources can give rise to primary particles that can either enter the detector directly or generate secondary debris that ultimately reaches the detector.

We have carefully simulated, in great detail, the effects of these backgrounds. It is probably fair to say that the interaction of machine backgrounds and the detector environment has never been so exhaustively studied for any previous accelerator. This level of detail is mandatory in the case of a B Factory design, because the consequences of underestimating the effects of the background are so serious. Thus, we view the considerations described in this section to be the *sine qua non* of the Asymmetric B Factory design.

In what follows, we try to convey the breadth of the considerations and the level of detail that were incorporated in the simulations. Before delving into the details of the calculations, however, it is useful to provide an overview that describes the thrust of our approach to the machine optimization.

The attraction of head-on collisions and magnetic separation of the heteroenergetic beams was discussed in Chapter 3. As indicated there, we believe that this strategy provides the most conservative approach to achieving high luminosity in an asymmetric collider. Magnetic separation (as opposed to using a nonzero crossing angle) does come at a price, however. The separating elements (dipoles and quadrupoles) generate high levels of radiated power and consequently a large flux of synchrotron radiation photons. Two issues thus dominate the optimization of the interaction region (IR) optical design: controlling the resultant backgrounds and effectively managing the absorption of the power. Achieving these goals simultaneously is quite difficult. Indeed, we generated many attractive IR geometries that were ultimately rejected because one or both of these criteria could not be met.

It is also crucial to subject each promising design to the stringent test of a realistic engineering solution for the IR elements (magnets, masks, etc.). Both the limiting of backgrounds and the ability to engineer all the beamline elements in the IR must be demonstrated before the design can be deemed acceptable. We believe that what follows in this section (management of backgrounds) and the detailed engineering considerations

for all the IR mechanical elements, covered in Sections 5.1.3 and 5.2.7, represent a robust and completely satisfactory solution.

Our design strategy was to choose the placement and apertures of the IR magnetic elements in such a way as to ensure that most (about 90%) of the radiated power produced close to the interaction point (IP) is absorbed on downstream surfaces far away from the detector. This is the key ingredient in the success of the design, because it ensures that local sources of secondary interactions are greatly limited. Our strategy requires a careful evaluation of all the material required for the machine elements and for their support, as well as a generous space allowance between the radiation fans and any such material. Realistic evaluations of the space required for the IR elements have been based on the detailed engineering designs discussed in Section 5.1.3; appropriate clearances, including an allowance for displacement of the beam orbit, have been incorporated. It has also proved important to provide a low gas pressure (1 nTorr) in the section of beam pipe in each ring that immediately precedes the IR. Because this region is relatively free of machine components, this vacuum requirement is not technically difficult.

In addition to paying attention to these engineering details, sufficient care must also be taken with the simulations of the absorption, scattering, and reemission of radiation incident on masks, beam pipe walls, magnets, etc. In our simulations, all primary sources (both electrons and photons) were propagated from their creation to the point where they are intercepted by a machine element. For charged particles, the effects of all magnetic elements were taken into account. The EGS electromagnetic shower simulation code was used to track the debris of the showers. This code includes the material properties appropriate to each intercepting element, the incidence angle and energy of the showering particle, and the geometry of the scatterer (particularly thin, sharp edges or “tips”). The shower process is followed until an inventory, in terms of both energy and number, of all electrons, positrons, and photons hitting each detector element has been established. The appropriate material, geometry, and magnetic effects of the detector are incorporated in establishing this inventory.

In what follows, we turn first to the details of the synchrotron radiation backgrounds (Section 4.2.1), next to the inventory of where all the synchrotron radiation power is deposited (Section 4.2.2), and finally to the consideration of lost-particle backgrounds (Section 4.2.3). We will see that the design we adopted provides a considerable safety margin between the occupancy and radiation-tolerance levels of the detector components and the estimated levels of detector backgrounds.

4.2.1 Synchrotron Radiation Backgrounds

Several sources must be considered in the investigation of synchrotron radiation backgrounds:

- Direct synchrotron radiation (primary masks must be placed to prevent such radiation from striking the detector beam pipe, at the same time keeping the number of photons striking their tips to an acceptable level)
- Photons that scatter through a mask tip

- Sources of synchrotron radiation from elements far upstream of the IP
- Sources of backscattered photons from downstream surfaces

These issues are taken up here, along with a discussion of the calculational procedure used for predicting detector backgrounds. Our conclusions are that synchrotron radiation background rates are 100 times lower than the allowable detector occupancy and radiation damage limits.

A detailed tracing of all the synchrotron radiation power must also be undertaken to make sure that no background problems arise from surfaces where the power is absorbed. This study is described in Section 4.2.2.

Separating the unequal-energy beams by the use of bending magnets and offset quadrupoles generates several fans of synchrotron radiation. The geometry of the IR optics, however, is designed to minimize the amount of synchrotron radiation that strikes nearby surfaces. In particular, the "S-bend" geometry of the beamlines (see Fig. 4-41)

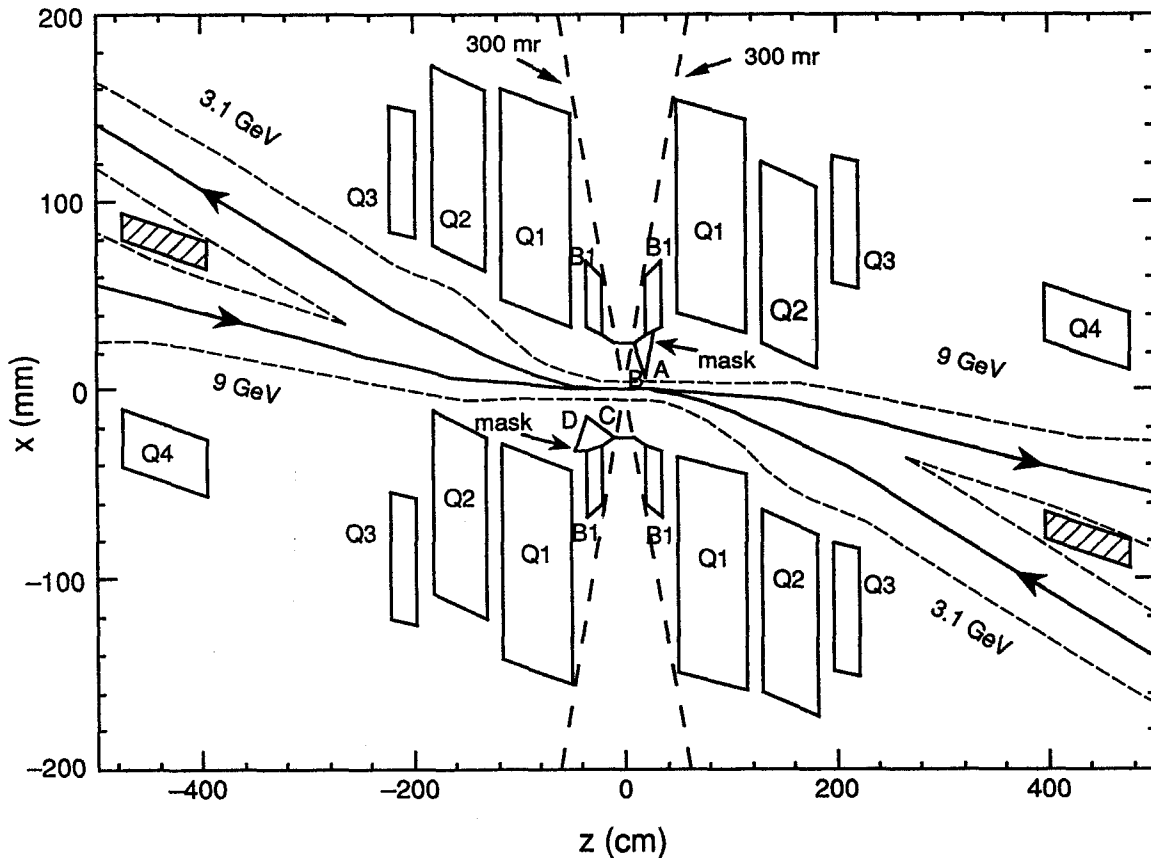


Fig. 4-41. General layout of the interaction region. The vertical scale is highly exaggerated. The dashed lines are the beam-stay-clear envelopes. The masks labeled AB and CD shield the detector beam pipe from direct synchrotron radiation. The mask surfaces A and D are sloped so that incoming photons striking these surfaces cannot scatter directly onto the detector beam pipe.

allows most of the synchrotron radiation generated by magnetic elements upstream of the IP to pass through the detector region without hitting local surfaces.

For this discussion, synchrotron radiation generated by beam particles is separated into two categories:

- Radiation generated by a beam passing through a bending magnet or an offset quadrupole; this is referred to as *fan radiation*. The intensity and power density of the fan radiation are high, because all of the beam particles contribute.
- Radiation generated by a beam that is on-axis as it travels through a quadrupole; this is referred to as *quadrupole radiation*. The intensity and power density of quadrupole radiation are much lower than for fan radiation, because the radiation is dominated by beam particles that are some distance away from the beam centerline, usually by three or more rms beam widths ($\sigma_{x,y}$).

In general, quadrupole radiation contributes only about 1% of the power generated by fan radiation, and the power is spread out over a much larger surface area. All calculations of detector backgrounds reported here include both fan and quadrupole radiation. Power calculations and estimates of photon power density on surfaces, described in Section 4.2.2, include only fan radiation. Both types of calculations are based on the nominal beam currents: 1.48 A for the high-energy beam (HEB) and 2.14 A for the low-energy beam (LEB).

As shown in Fig. 4-41, the LEB is centered in the Q2 quadrupole, and the HEB is centered in both the Q1 and Q3 quadrupoles. This combination of offsets maximizes the separation of the beams as they travel through these magnets. The Q1 and Q3 quadrupoles are horizontally defocusing. Therefore, offsetting the LEB in these magnets produces substantial beam deflection. Because Q2 is horizontally focusing, offsetting the HEB in this quadrupole helps the beam separation by minimizing the beam deflection.

The apertures of the separation dipole magnet B1 and the quadrupoles Q1, Q2, and Q3 are large enough to accommodate at least 5 mm of radial space for a beam pipe and trim coils, while still maintaining 2 mm of free space between the beam pipe and either the synchrotron radiation fans or the 15σ envelope of the beam. (For determining beam-stay-clear apertures, we use the *uncoupled* horizontal emittance and the *fully coupled* vertical emittance, as discussed in Section 5.2.)

4.2.1.1 Synchrotron Radiation Fans. The LEB generates synchrotron radiation fans as it passes through the Q3, Q1, and B1 magnets on its way to the IP. Figure 4-42 shows the LEB radiation fans near the IP. The mask labeled AB in Figs. 4-41 and 4-42 is designed to prevent any of the synchrotron radiation (either fan or quadrupole) generated by the upstream magnets from directly striking the detector beam pipe. Surface A of mask AB is sloped such that incoming photons striking it cannot scatter into the detector beam pipe. To clear the radiation that goes by the AB mask tip, the Q1 magnet on the downstream side of the IP for the LEB, though centered on the high-energy beamline, is rotated with respect to the HEB axis by 22 mrad. As can be seen in Fig. 4-42, the AB mask absorbs all of the fan radiation from the upstream Q3 magnet. The fans generated by the two B1 magnets and by the downstream Q1 and Q3 magnets pass through the IR without striking any surfaces. The first surface that intercepts these fans is the “crotch mask” in front of the Q4 septum quadrupole, located 3.96 m from the IP (see Fig. 4-41).

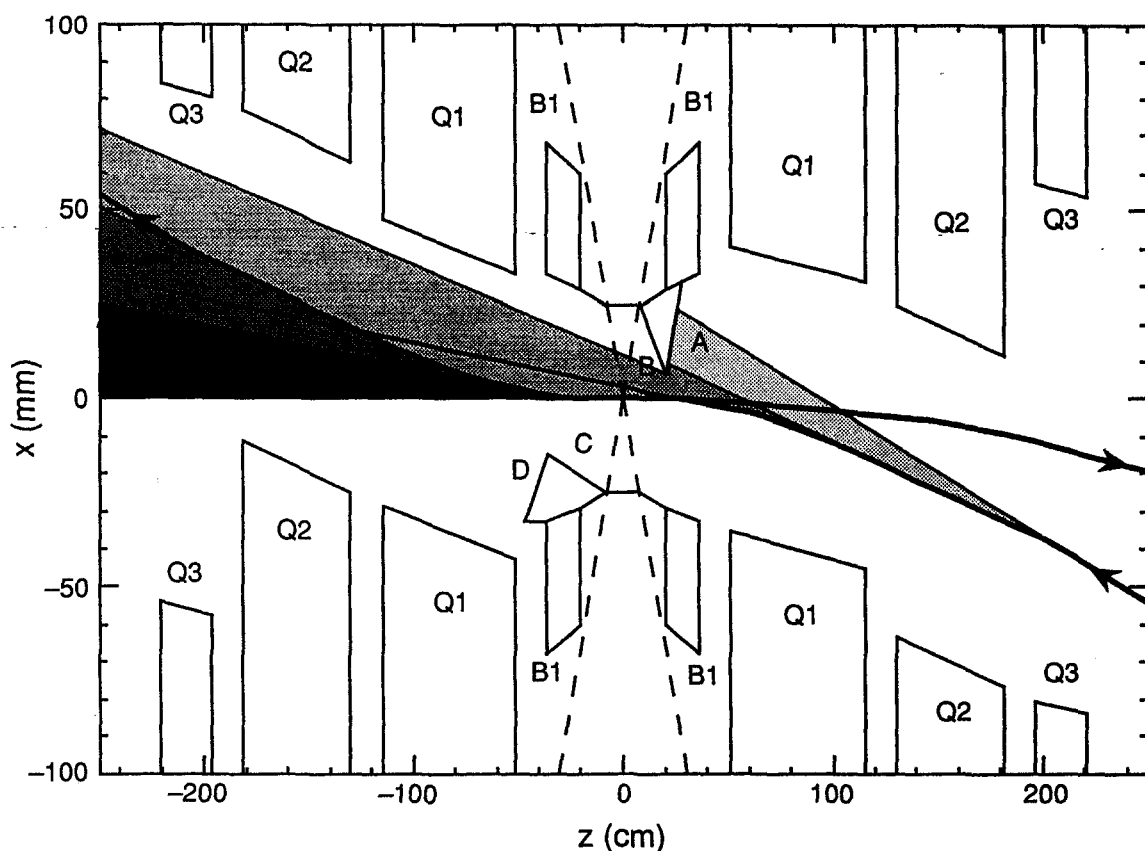


Fig. 4-42. Detail of the IR geometry, showing the radiation fans from the low-energy beam. The density of shading gives a crude indication of the relative photon intensity from the various radiation fans.

About 400 W of power is deposited on this mask from both of the LEB Q1 fans. Table 4-6 summarizes some of the properties of the LEB and HEB radiation fans.

The synchrotron radiation fans generated by the HEB as it passes through the Q2 and B1 magnets also pass through the detector region without striking any surfaces. Figure 4-43 shows the HEB radiation fans near the IP. The mask labeled CD in Figs. 4-41 through 4-43 is located to prevent quadrupole radiation produced by the HEB in Q5 and Q4 (the last major focusing elements for the HEB before the collision point) from directly striking the detector beam pipe. Again, surface D of mask CD is sloped such that scattered photons cannot reach the detector beam pipe. The CD mask tip is positioned 2 mm outside the Q2 radiation fan that passes through the IR. The first surface struck by the upstream Q2 fan is the crotch mask in front of the Q4 septum quadrupole (see Fig. 4-44). This crotch mask must be capable of absorbing 4.3 kW of power; a satisfactory design is described in Section 5.2.7.

Again, the Q1 magnet downstream of the IP for the HEB is tilted with respect to the HEB axis by 15 mrad, so it clears the synchrotron radiation fan generated by the upstream Q2 magnet.

As can be seen in Table 4-6, most of the synchrotron radiation power is generated by the HEB, and all but 4.3 kW of this power passes through the IR without striking any

Table 4-6. General properties of the fans of synchrotron radiation generated by the B1 magnets and the offset beams in the quadrupoles within ± 3 m of the IP. The values are based on the nominal beam currents of 1.48 A for the HEB and 2.14 A for the LEB.

Magnet	Fan power (kW)	N_γ (10^{10})	ϵ_{crit} (keV)
LEB:			
Upstream Q3	0.84	3.1	2.3
Upstream Q1	0.83	5.4	1.3
Upstream B1	2.39	4.2	4.8
Downstream B1	2.39	4.2	4.8
Downstream Q1	0.96	5.2	1.4
Downstream Q3	0.91	3.1	2.4
Subtotal	8.3	13	
HEB:			
Upstream Q2	28.3	7.5	32.1
Upstream Q1	2.3	2.7	7.3
Upstream B1	13.8	2.9	40.4
Downstream B1	13.8	2.9	40.4
Downstream Q1	1.1	1.8	5.1
Downstream Q2	26.1	7.3	30.5
Subtotal	85.4	25	
Total	93.7	38	

local surfaces. A complete inventory of synchrotron radiation power striking various surfaces near the IP is presented in Section 4.2.2.

4.2.1.2 Detector Backgrounds from Synchrotron Radiation. To evaluate detector backgrounds from synchrotron radiation, a series of programs was used. A flow diagram corresponding to the description below is shown in Fig. 4-45. As a first step, a machine lattice file is produced in which magnet positions, lengths, and strengths are specified, as well the position of each beam in each magnet. This information is fed into two programs, MAGBENDS and FINBETAS. The MAGBENDS code produces a beamline geometrical layout and calculates the fan power distribution. The FINBETAS code is used to calculate beta functions, beam sigmas, and beam-stay-clear envelopes for both beams. Information from both of these programs is used to produce pictorial layouts of the IP region. In addition, outputs from these two programs are used to make the input file for SYNC_BKG, an enhanced version of the code QSRAD that was originally written to study synchrotron radiation backgrounds at PEP and that has also been used to model backgrounds at the final focus of the SLC.

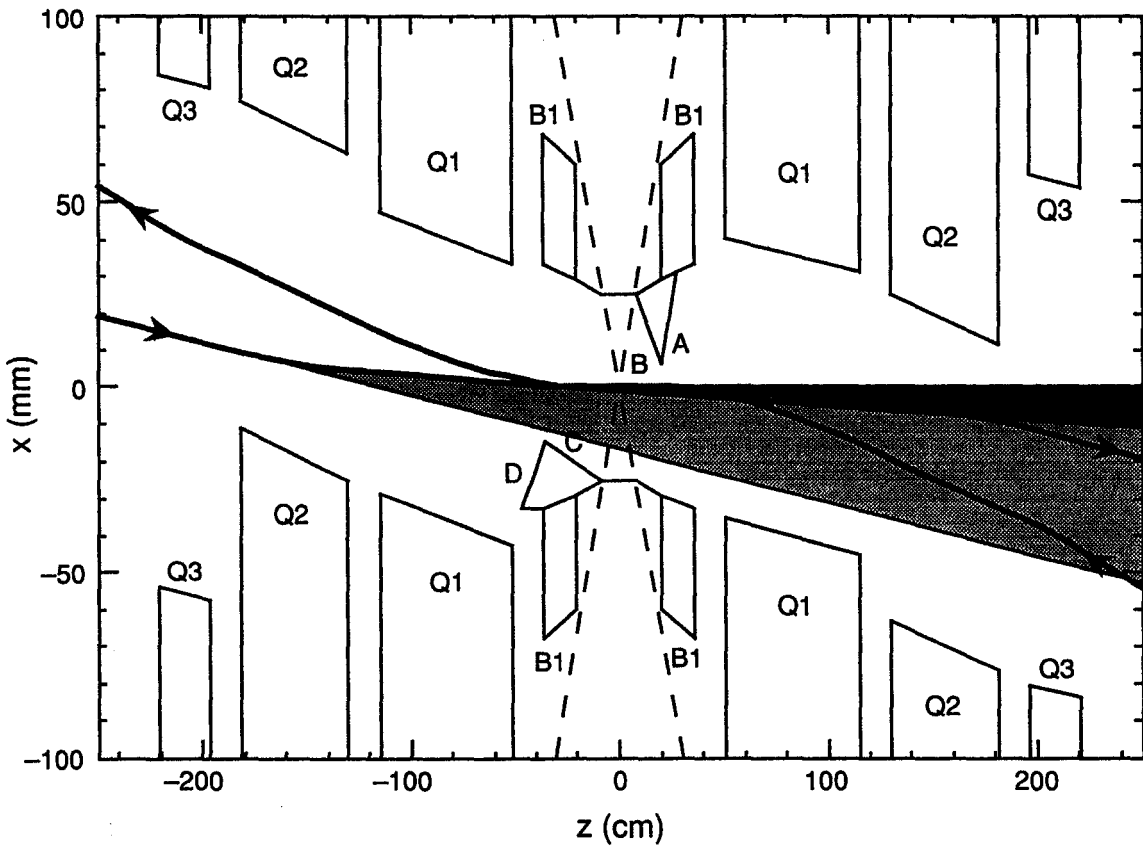


Fig. 4-43. Detail of the IR geometry, showing the radiation fans from the high-energy beam. The density of shading gives a crude indication of the relative photon intensity from the radiation fans. The tip of the CD mask is at least 2 mm outside the fan of radiation generated by the HEB as it goes through Q2.

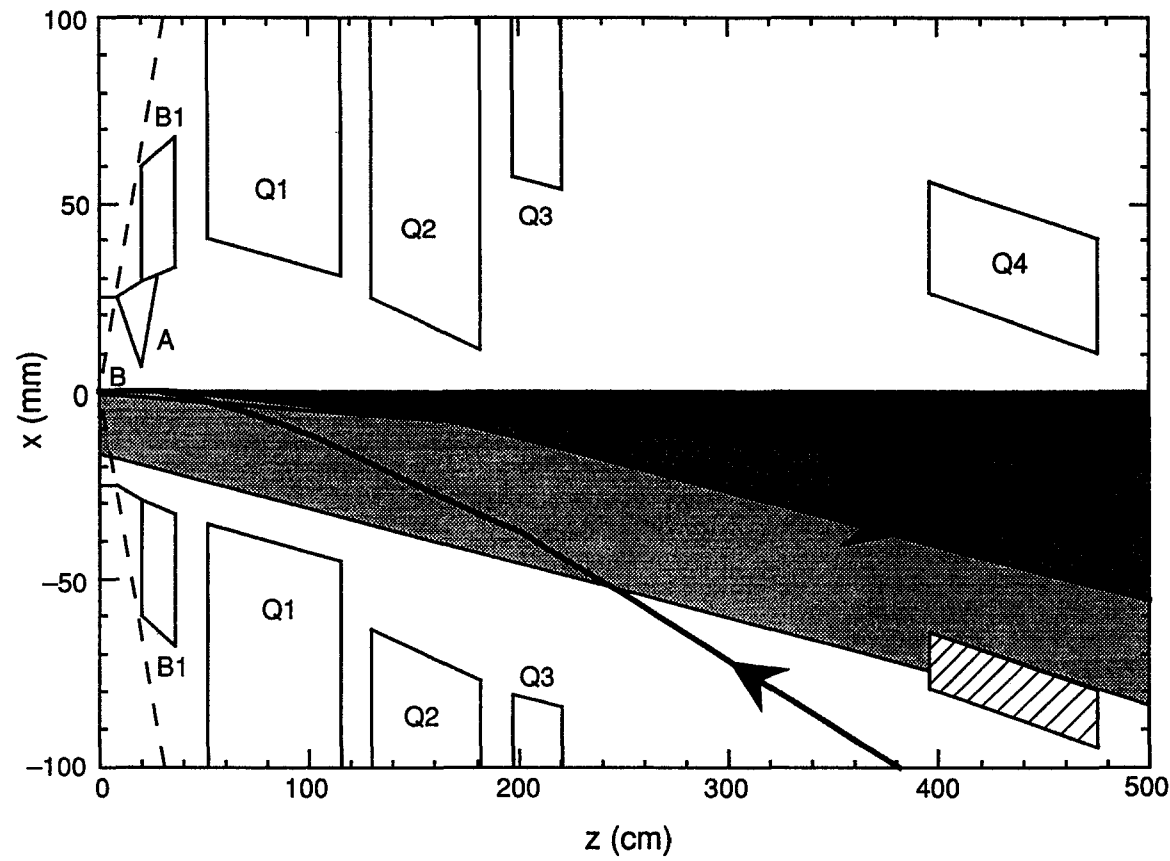


Fig. 4-44. The HEB synchrotron radiation fan from the upstream Q2 magnet that strikes the crotch mask (not shown) in front of Q4. The Q4 crotch is shown crosshatched.

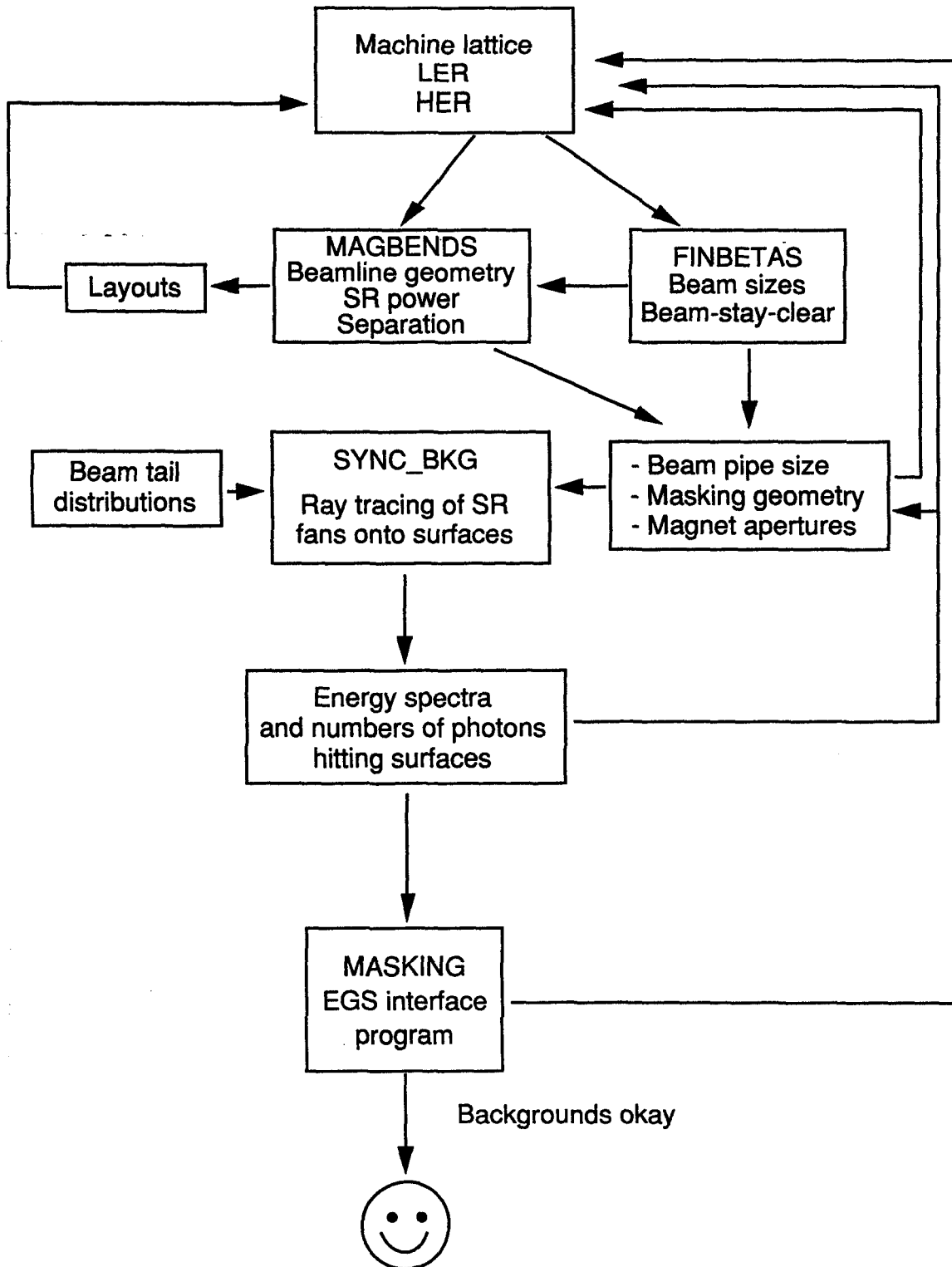


Fig. 4-45. Flow diagram of the procedure for calculating detector backgrounds from synchrotron radiation. At various stages in the procedure, a problem can be uncovered that forces a change in either the lattice or the masking geometry. This is represented by the various arrows returning to the lattice and masking geometry boxes. For any single design, many trips around these internal loops are needed before the design is either accepted or rejected.

The SYNC_BKG program traces rays for the entire beam profile through quadrupoles and produces synchrotron radiation fans that are "scored" on various user-supplied mask surfaces. SYNC_BKG tallies both the number of photons striking each surface and the photon energy distribution. In the case of the B Factory, the masking and beam pipe surfaces are designed so that the only nearby sources of photons that can reach the detector beam pipe are the tips of the masks AB and CD.

In addition to the beam pipe and masking geometry, SYNC_BKG also receives information about the transverse profile of the beam. Although its exact shape is not easily predicted, a non-Gaussian beam profile might result from, say, the beam-beam interaction. We include this possibility in our calculations by introducing a second Gaussian that has a larger rms width (σ) and a lower amplitude than that of the nominal beam core. Adding these two distributions together produces a non-Gaussian beam profile, with enhanced particle densities at large amplitudes. This parametrization of the beam tail yields two variables, the amplitude A of the distribution and the scaling factor S for the beam tail width. Figure 4-46 shows the beam distributions and the values of A and S used in this study; these values result from a previous study of synchrotron radiation backgrounds at PEP. To ensure that detector background rates are acceptable under all conditions, the beam-tail distributions are traced out to the limiting aperture of the ring. In the case under study, this means $10\sigma_{x0}$ and $35\sigma_{y0}$. We determined that our masking design is insensitive to the exact beam-tail distribution. Removing the tail distribution completely results in a very small (about 1%) change in detector background rates.

The information from SYNC_BKG is fed into an EGS [Nelson et al., 1985] interface program called MASKING. As indicated in Fig. 4-47, for a given incident photon energy spectrum, this program produces reflected, transmitted, and absorbed photon energy spectra. (A large selection of elements and compounds is available for the intercepting materials.) The EGS package includes K -shell photon fluorescence and Rayleigh scattering, but does not have provision for L -shell fluorescence. (Calculations of L -shell fluorescence suggest only small increases in the synchrotron radiation background rates we have computed.) MASKING uses an infinite-slab geometry to calculate the spectrum of photons that reflect from a surface or that penetrate through materials (for example, a beam pipe). In addition, a finite-slab geometry is available to study tip scattering. The files of reflection, transmission, and absorption coefficients thus produced are collected by another program (PHTALLY) and folded together to produce the background rates for various detector elements. These are displayed in Table 4-7. For comparison, Tables 2-5 and 2-6 indicate the maximum numbers of photons/ μ s that are permissible in terms of detector occupancy and radiation damage considerations. Figures 4-48 and 4-49 show the photon energy spectra for the HEB and LEB, respectively.

4.2.1.3 Tip Scattering. The scattered photons incident on the detector beam pipe are those that scatter through the tips of masks AB and CD. Figure 4-50 illustrates the mechanism of tip (as opposed to surface) scattering. The coordinate system in Fig. 4-50 is based on the direction-cosine axes for the incident photons. The tip-scattering effect is modeled by uniformly generating the incident photons along a line perpendicular to the edge of the material. The angular distribution of tip-scattered photons is azimuthally uniform in the UV plane (see Fig. 4-50a), but there is a preference for photons to scatter

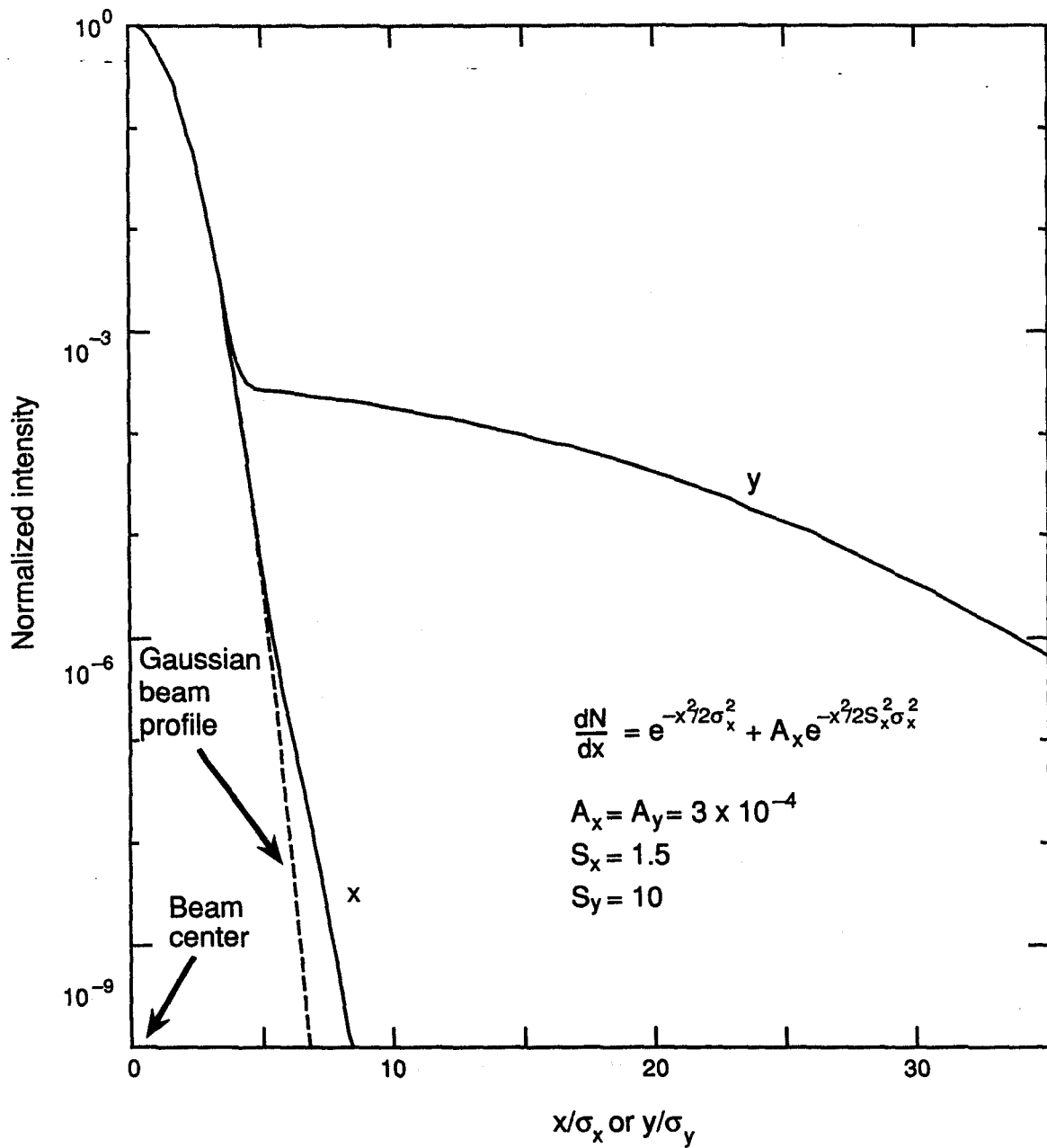


Fig. 4-46. Plot of the beam profiles assumed for the calculation of detector backgrounds due to synchrotron radiation. The integral of the background Gaussian is about 0.25% of the main beam Gaussian.

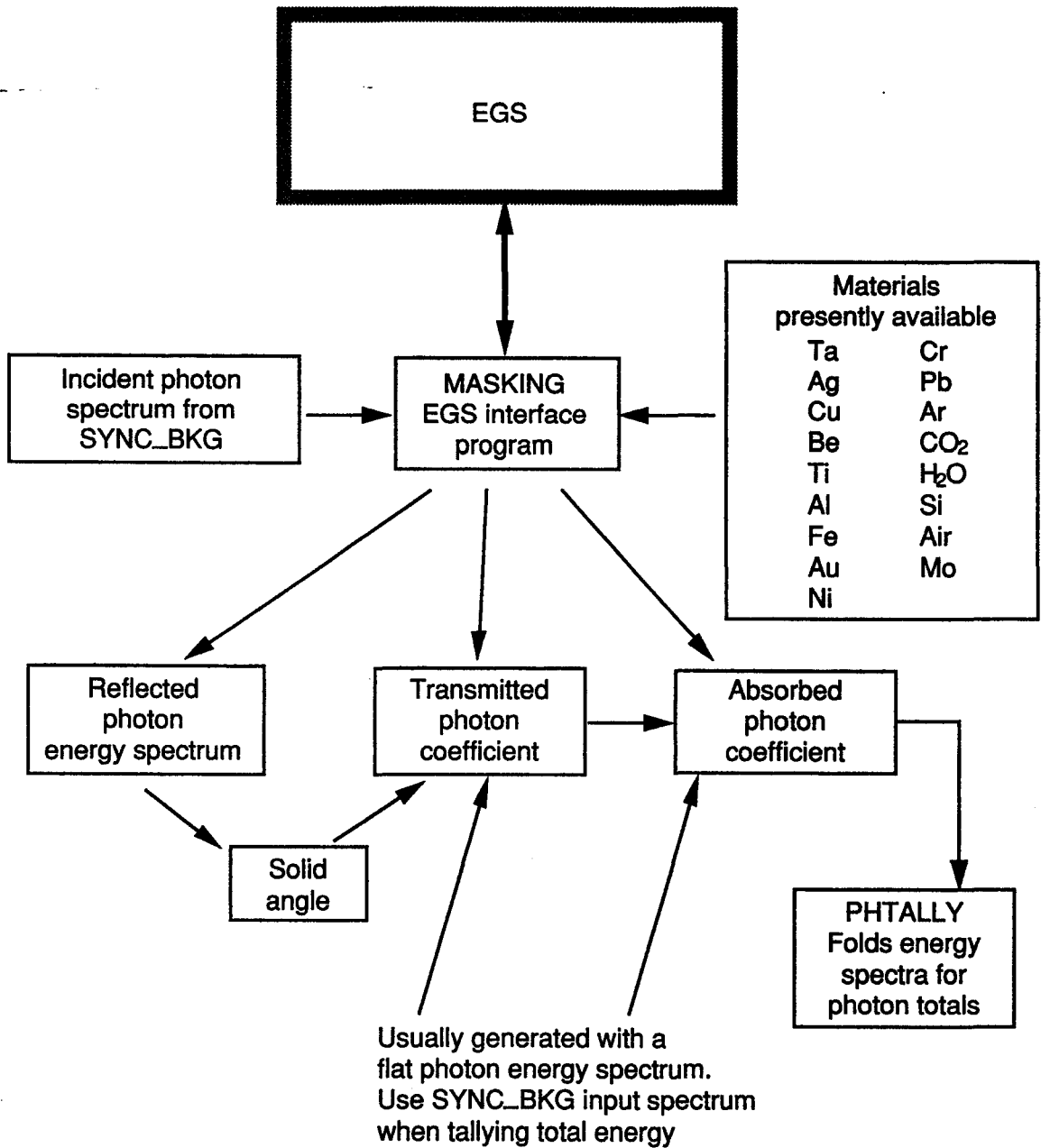


Fig. 4-47. Flow diagram of the procedure for producing reflection, transmission, and absorption coefficients and final photon spectra.

Table 4-7. Synchrotron radiation detector background predictions. The numbers are for each crossing. Multiply by 2.38×10^8 to get photons per second. The energies refer to the total energies of the indicated photons. The beam pipe materials are 25 μm of Cu and 1 mm of Be. The beam pipe inner radius is 2.5 cm with a 17-cm length for the Be section. The average angle of incidence is 100 mrad for the radiation striking the beam pipe from the tip of the CD mask and 200 mrad for the radiation striking the pipe from the AB mask tip. The silicon layers are 300 μm thick. The number of photons per crossing penetrating the beam pipe and incident on the first layer of silicon is 0.038. The total energy of these photons is 1.19 keV.

	Incident on Be pipe	Absorbed in first Si layer	Absorbed in second Si layer	Absorbed in third Si layer	Incident on drift chamber
3.1-GeV beam					
4 < E_γ < 100 keV:					
Number of photons	0.39	1.0×10^{-3}	3.9×10^{-6}	3.4×10^{-7}	1.8×10^{-9}
Energy (keV)	2.48	9.4×10^{-3}	3.8×10^{-5}	3.4×10^{-6}	1.9×10^{-8}
4 < E_γ < 20 keV:					
Number of photons	0.39	1.0×10^{-3}	3.9×10^{-6}	3.4×10^{-7}	1.8×10^{-9}
Energy (keV)	2.48	9.4×10^{-3}	3.8×10^{-5}	3.4×10^{-6}	1.9×10^{-8}
9.0-GeV beam					
4 < E_γ < 100 keV:					
Number of photons	0.65	0.017	6.6×10^{-4}	6.0×10^{-4}	1.5×10^{-4}
Energy (keV)	10.0	0.48	0.03	0.03	7.8×10^{-3}
4 < E_γ < 20 keV:					
Number of photons	0.52	6.4×10^{-3}	3.2×10^{-5}	9.4×10^{-6}	2.1×10^{-7}
Energy (keV)	5.20	0.075	4.1×10^{-4}	1.4×10^{-4}	3.7×10^{-6}
Totals					
4 < E_γ < 100 keV:					
Number of photons	1.04	0.018	6.6×10^{-4}	6.0×10^{-4}	1.5×10^{-4}
Energy (keV)	12.5	0.49	0.03	0.03	7.8×10^{-3}
4 < E_γ < 20 keV:					
Number of photons	0.91	7.4×10^{-3}	3.6×10^{-5}	9.7×10^{-6}	2.4×10^{-7}
Energy (keV)	7.68	0.084	4.5×10^{-4}	1.4×10^{-4}	3.7×10^{-6}

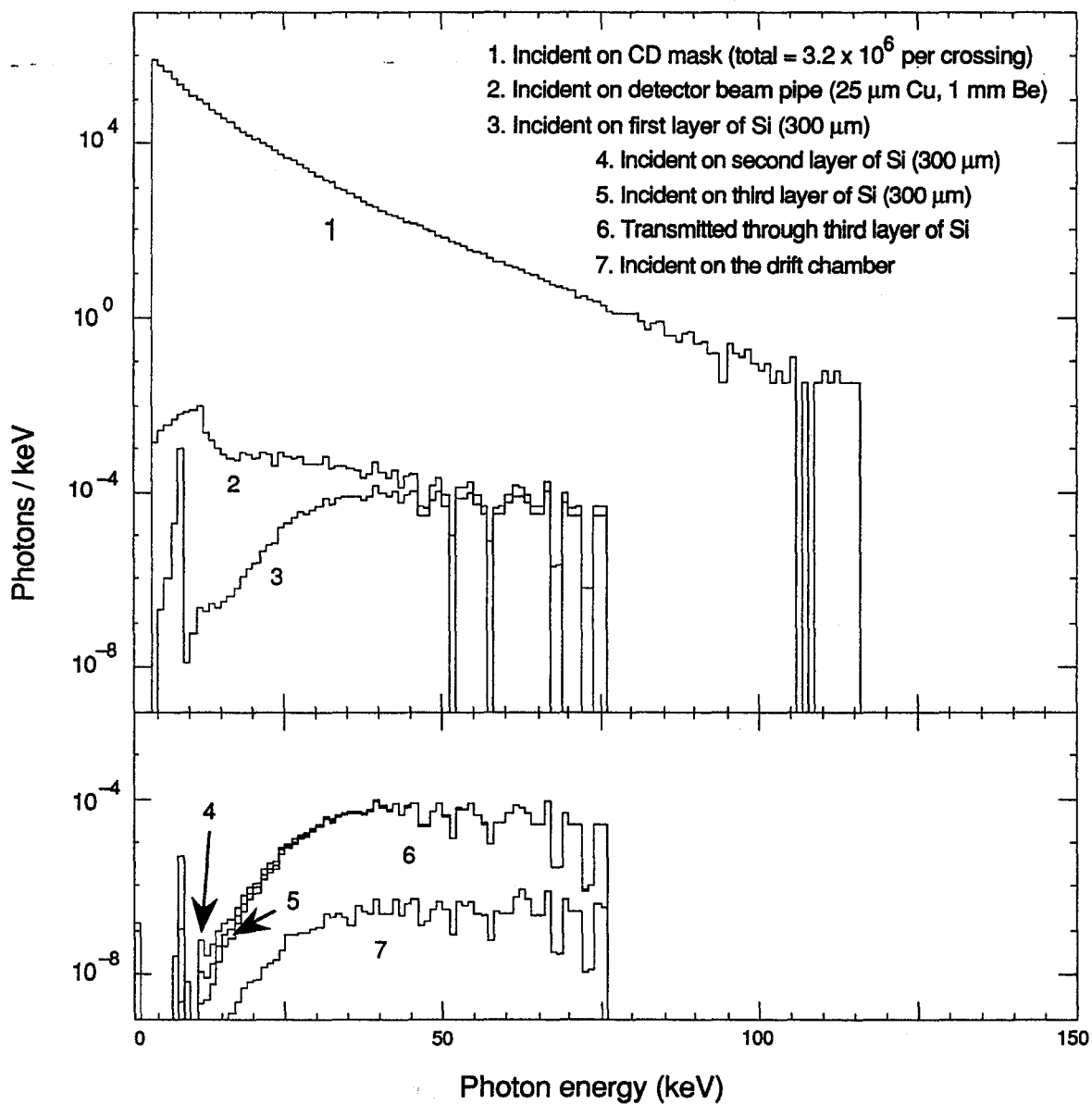


Fig. 4-48. Final photon spectra for the HEB. The initial photon spectrum is incident on the 500 μm of the CD mask nearest the edge. The second spectrum results from photons that have scattered through the tip of the CD mask.

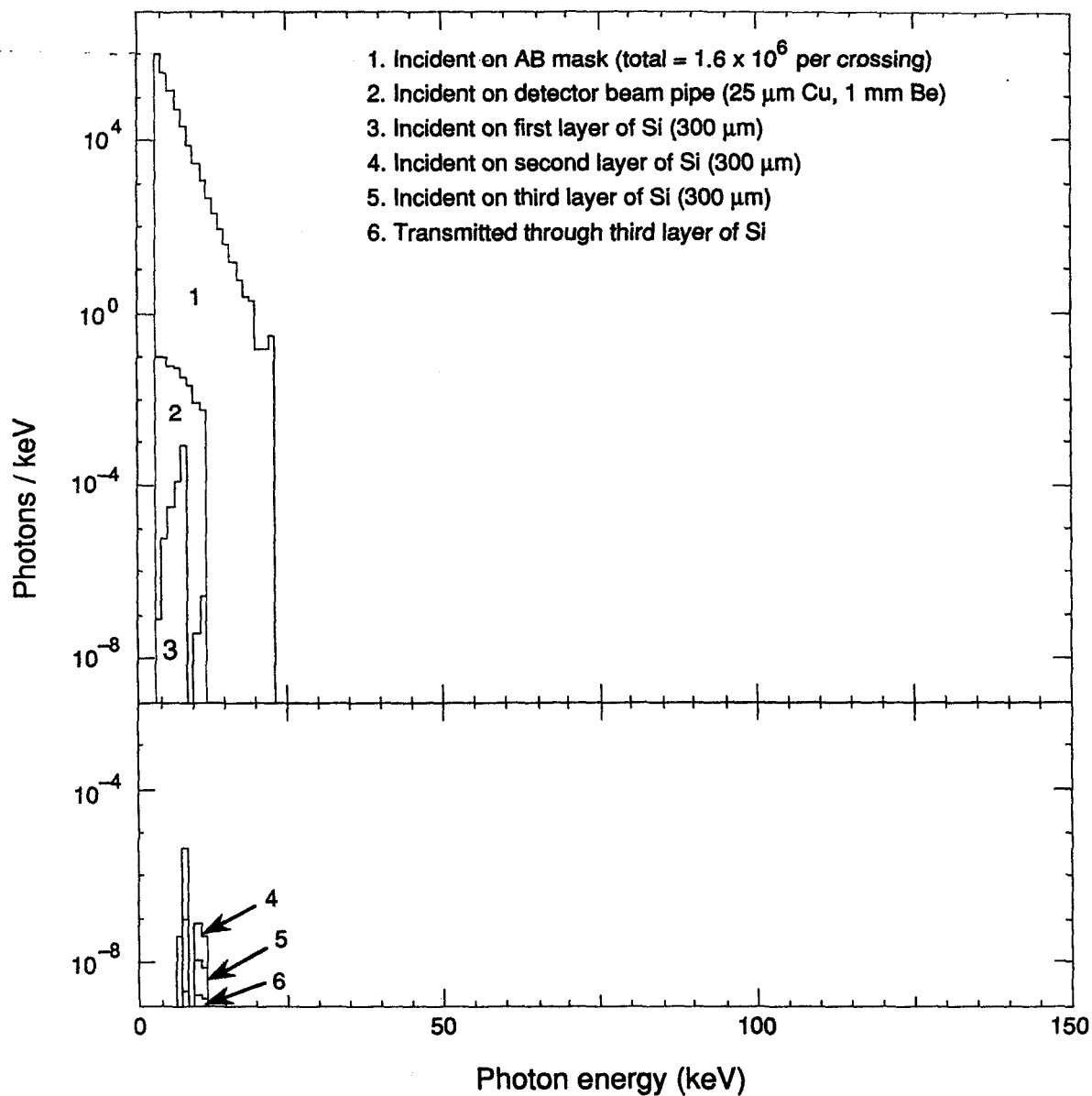


Fig. 4-49. Final photon spectra for the LEB. The initial photon spectrum is incident on the 500 μm of the AB mask nearest the edge. The second spectrum results from photons that have scattered through the tip of the AB mask.

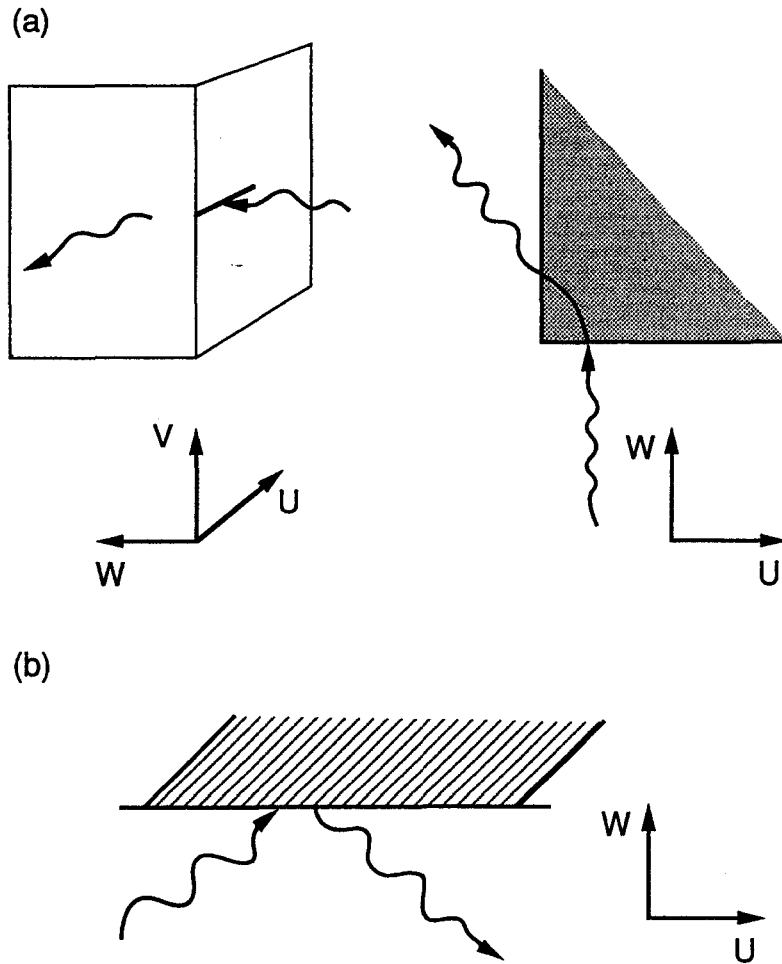


Fig. 4-50. Schematic illustration depicting the mechanisms of (a) tip scattering and (b) reflected scattering from a surface.

forward, thereby enhancing the number of photons with a direction-cosine close to that of the incident photon direction-cosine. Figure 4-51 is a plot of the distribution of W direction-cosines for photons that scatter through a mask tip when the incident-photon direction-cosine is equal to 1. The shaded region of the plot is the approximate angular region of the detector beam pipe seen from the mask tips. The number of photons in this forward direction is about 2.5 times higher than would result from an isotropic distribution. This increase is taken into account for determining photon rates that come from the mask tips.

Figure 4-52 shows a plot of the distribution of photons that scatter through a mask tip of gold, as a function of the distance from the edge of the mask. Nearly half of the scattered photons result from incident photons that are less than $1\text{ }\mu\text{m}$ from the edge. This calculation assumes a perfectly sharp mask edge; however, an actual mask tip will be somewhat rounded. Photons that strike the rounded surface can also reflect directly, as illustrated in Fig. 4-53; indeed, this direct reflection is more likely than tip scattering through the mask. If we assume that the corner of the mask has a $1\text{-}\mu\text{m}$ radius (which is

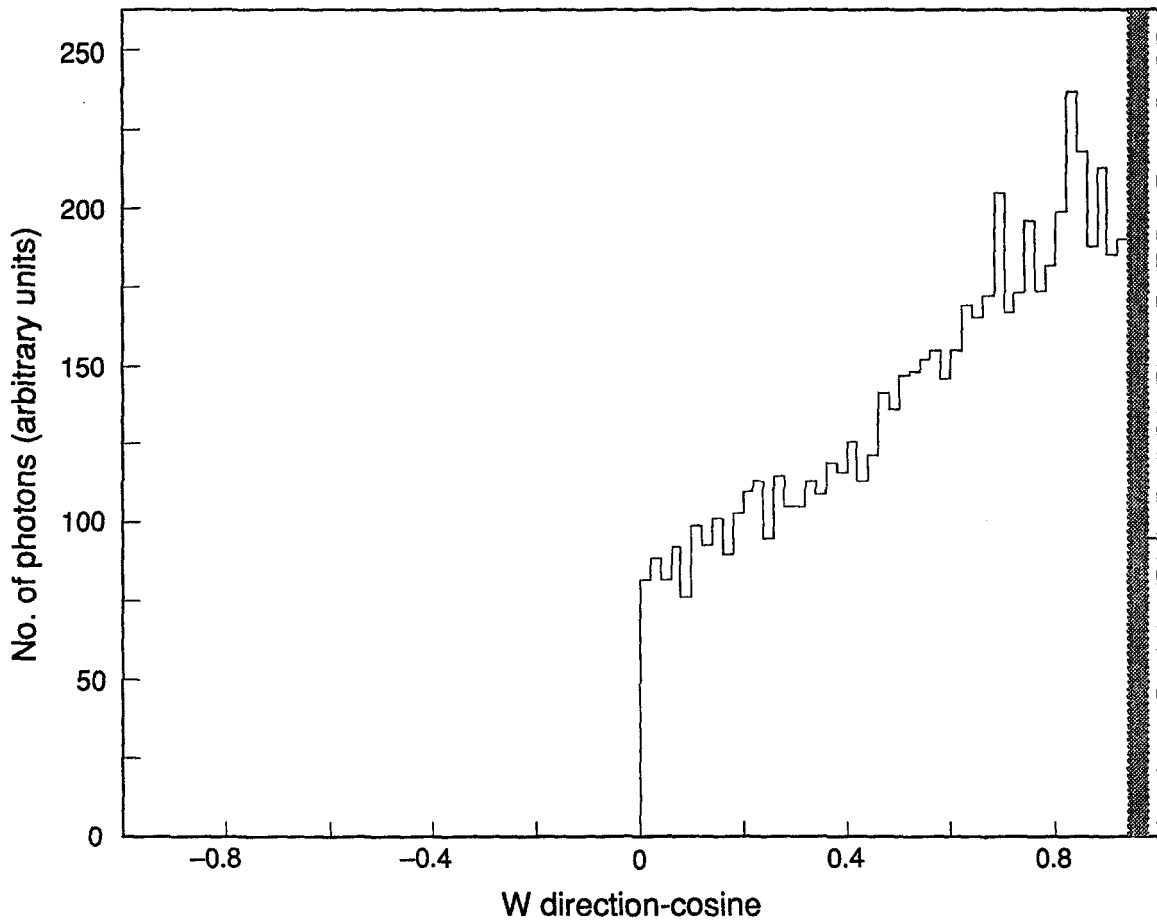


Fig. 4-51. Plot of the *W* direction-cosines for photons that scatter through the CD mask tip with an initial *W* direction-cosine of 1. The shaded region represents the approximate angular region occupied by the detector beam pipe.

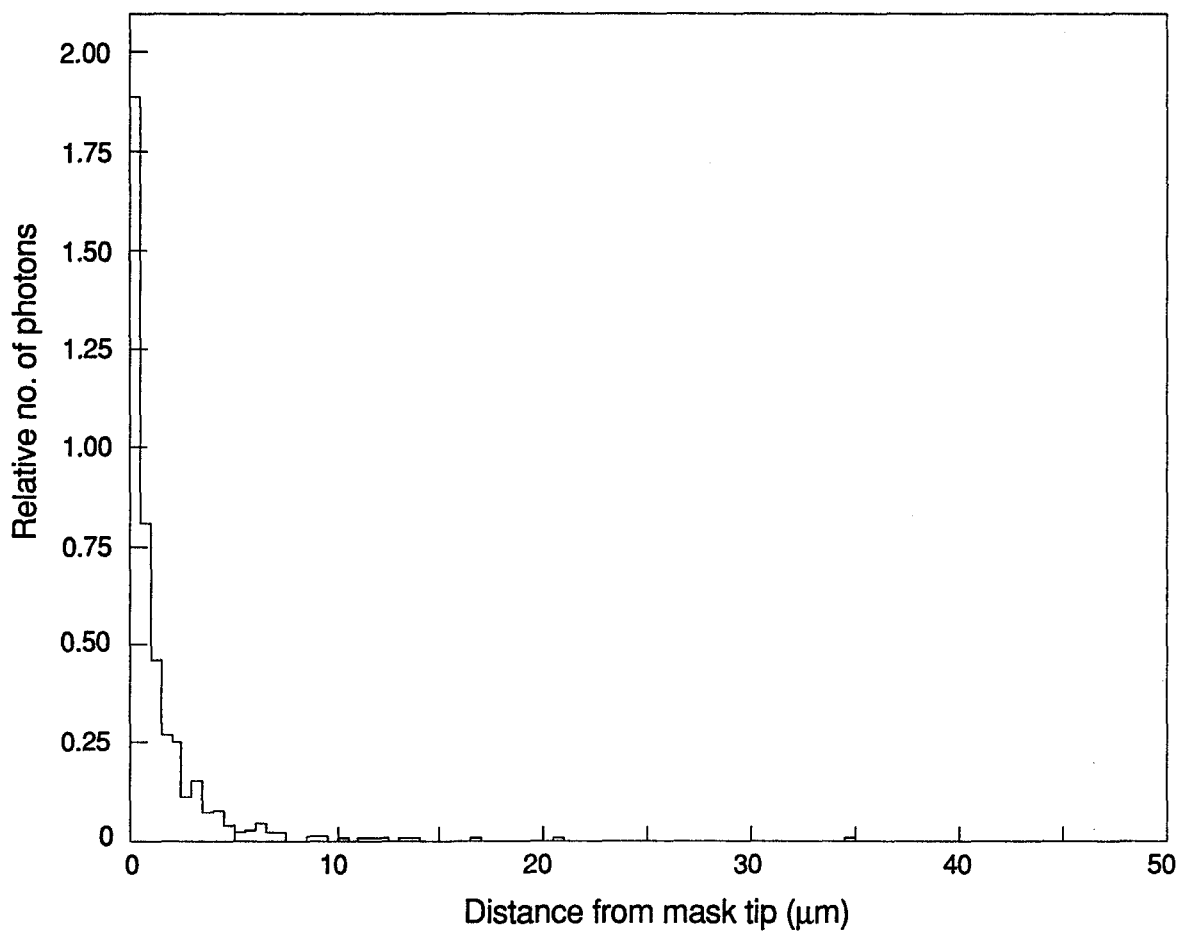


Fig. 4-52. Plot of the distribution of photons that scatter through a gold mask tip, as a function of the incident distance from the mask tip, for the CD mask.

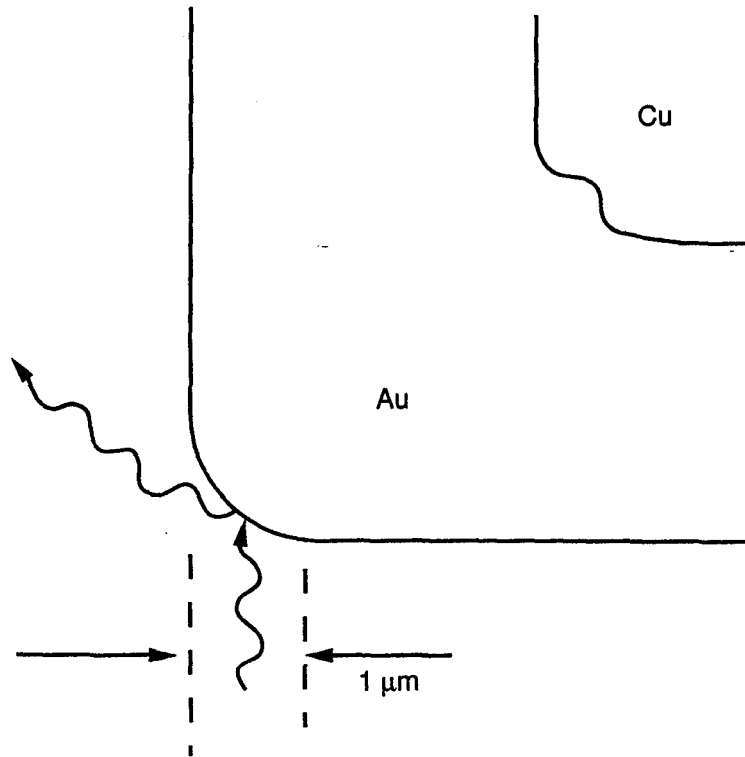


Fig. 4-53. Schematic illustration of direct reflection from a rounded mask tip.

not difficult to achieve), then, for the 9-GeV radiation on the tip of the CD mask, we can estimate the number of photons per crossing incident on the detector beam pipe from this source of background by taking the product of the number of incident photons/ μm (above 4 keV), the surface-scattering probability of the mask material, and the solid-angle fraction subtended by the detector beam pipe:

$$6400 \text{ photons}/\mu\text{m} \times 0.007 \text{ (for Au)} \times 0.014 = 0.63 \text{ photons per crossing}$$

Similarly, for the 3.1-GeV radiation on the rounded AB mask tip we have

$$3200 \text{ photons}/\mu\text{m} \times 0.0016 \text{ (for Au)} \times 0.095 = 0.49 \text{ photons/crossing}$$

We therefore find that the background rates from a tip with a $1\text{-}\mu\text{m}$ radius and that from a perfect tip are comparable (see Table 4-7, which assumes a perfect tip).

4.2.1.4 Other Upstream Sources of Synchrotron Radiation

High-Energy Beamline. There are two bending magnets (B2 and B3, located 11 m and 40 m from the IP) in the high-energy beamline that generate radiation fans passing through the IR. These are very low-field, long bending magnets ($\epsilon_{\text{crit}} = 1 \text{ keV}$), but they nonetheless produce a large number of low-energy photons that strike the B side of the AB mask. The total synchrotron radiation power from these two magnets striking the AB

mask is 130 W, corresponding to 1.1×10^{10} photons per crossing. The low critical energy of these photons means that only 9.5×10^8 photons have an energy greater than 1 keV. Of these, 7.9×10^5 reflect from the mask surface. With a detector beam pipe solid-angle fraction of 0.019, we have 1.5×10^4 photons above 1 keV incident on the beam pipe. Fortunately, the energy spectrum of these photons is so soft that only 1.1×10^{-2} photons per crossing are transmitted through the beam pipe and are incident on the first layer of the silicon vertex detector. This compares with 3.8×10^{-2} photons per crossing incident on the first layer of silicon from the tip-scattered photons. All of the photons transmitted through the beam pipe are completely absorbed in the first layer of silicon and do not increase the detector occupancy.

Low-Energy Beamline. There are two bending magnets in the low-energy beamline that bend the beam vertically into the horizontal plane upstream of the magnetic elements near the IP. Figure 4-54 shows elevation views of the LEB as it enters and leaves the IP region. The first vertical bending magnet, BV-, produces about 7.5 kW of synchrotron radiation power, but this is absorbed in a mask that spreads the power out over 2 m. None of this radiation reaches the detector beam pipe. The second vertical bending magnet, BV1, is a weaker magnet ($\epsilon_{\text{crit}} = 1$ keV). It deposits about 100 W of power on the A side of the AB mask. Again, none of the photons from this source strikes the detector beam pipe.

4.2.1.5 Downstream Secondary Sources of Synchrotron Radiation. The radiation fan generated by the HEB as it passes through the upstream Q2 magnet strikes the downstream crotch mask in front of the Q4 septum quadrupole. Roughly 1×10^{10} photons per crossing strike this mask. Photons that backscatter out of the crotch mask have no direct line-of-sight to the detector beam pipe: The AB mask shields the beam pipe from this source of photons. Nonetheless, the intensity of this photon source is sufficiently high that one must ascertain that photons bouncing off the intervening beam pipe do not cause a background problem.

The mechanism of the "double bounce" of photons onto the detector beam pipe is illustrated in Fig. 4-55a. The simplified geometry shown in Fig. 4-55b permits the calculation of solid-angle fractions for various cylindrical sections of beam pipe between the detector beam pipe and the source. A calculation of the solid-angle fraction of the detector beam pipe seen by each cylindrical section of beam pipe can also be made. Summing the products of these two solid-angle fractions yields the probability that a photon can backscatter from the crotch mask and strike the detector beam pipe. The solid-angle fractions, along with their products, are displayed in Fig. 4-56; Table 4-8 lists the numerical solid-angle values.

As can be seen, the largest contribution to the solid angle comes from those beam pipe surfaces near the detector beam pipe and near the source. Assuming 1×10^{10} photons per crossing incident on a copper mask located 3 m from the IP, and assuming that the intervening beam pipe is coated with a high-Z element such as gold, then the number of photons per crossing incident on the detector beam pipe is given by the product of the photons per crossing incident on the mask, the reflectivity of the mask material, the solid angle for a double bounce, and the reflectivity of the beam pipe coating:

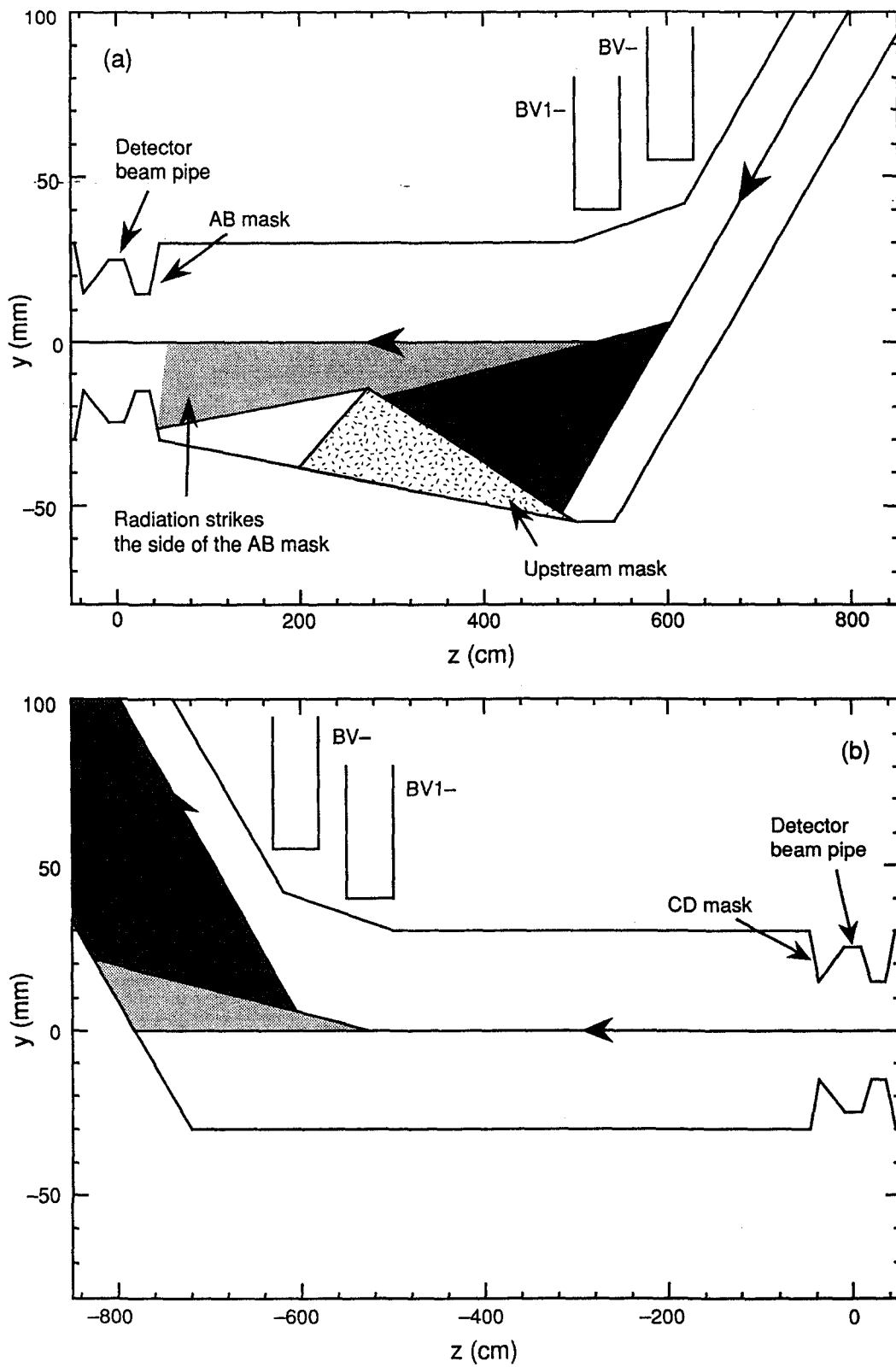


Fig. 4-54. Elevation views of the LEB as it (a) enters and (b) leaves the IR.

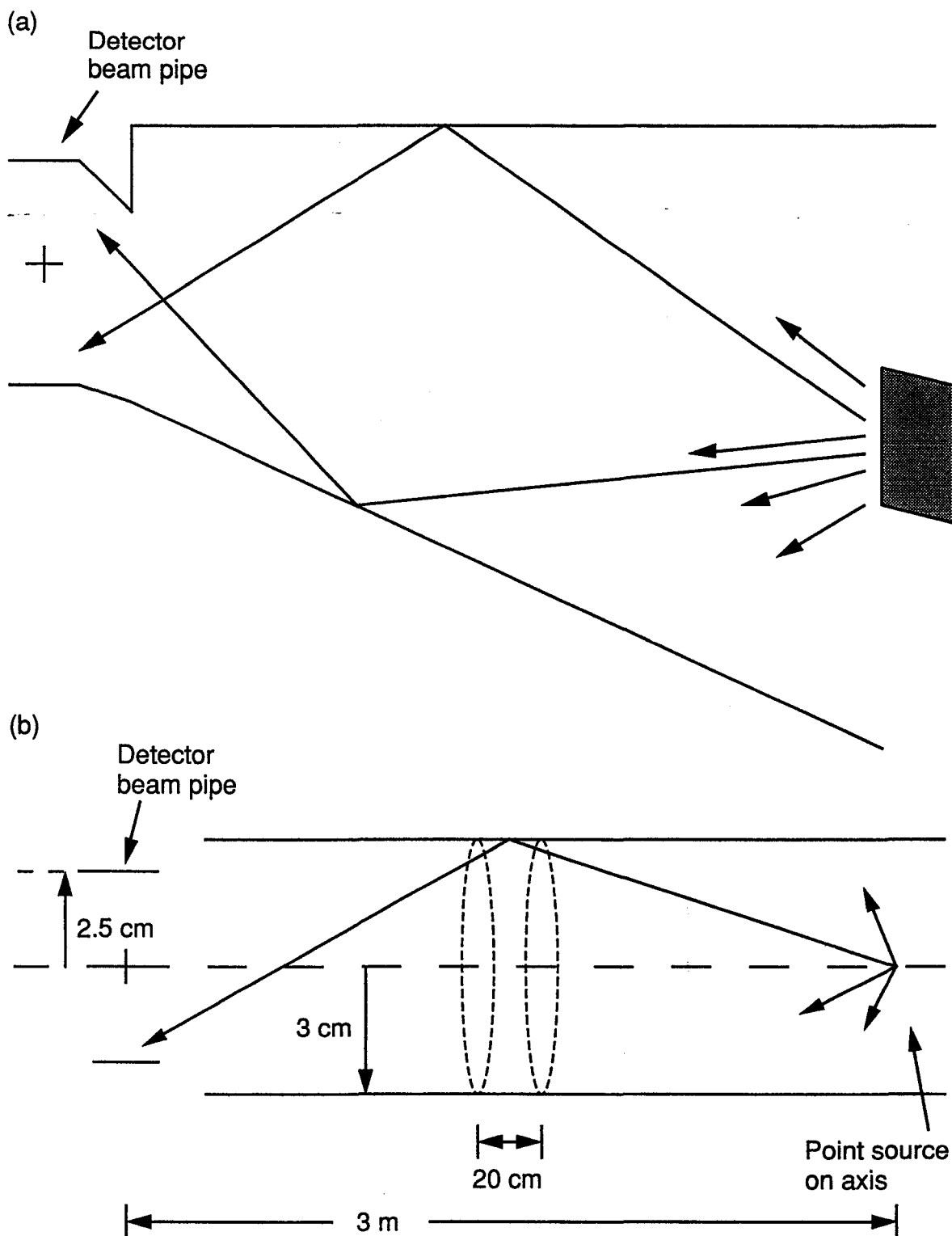


Fig. 4-55. (a) Schematic illustration of photons "double bouncing" to the detector beam pipe from a source of synchrotron radiation, and (b) a simplified geometry for the double-bounce problem. The typical dimensions shown in (b) were used to generate Table 4-8.

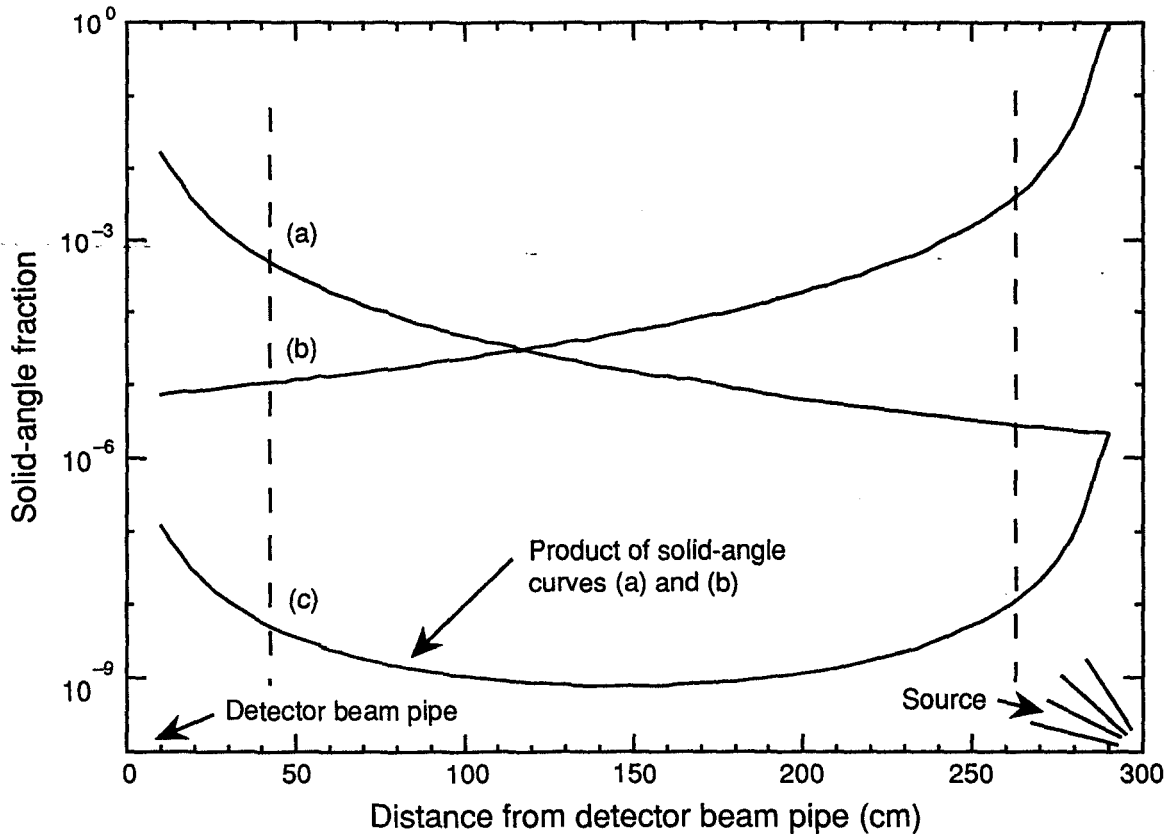


Fig. 4-56. Plot of (a) the solid-angle fraction of detector beam pipe as seen from the main beam pipe, (b) the solid-angle fraction of intervening beam pipe as seen from the source of radiation, and (c) the product of (a) and (b); the abscissa represents the distance from the detector beam pipe.

$$(1 \times 10^{10}) \times 0.06 \text{ (for Cu)} \times (2.2 \times 10^{-6}) \times 0.007 \text{ (for Au)} = 10 \text{ photons per crossing}$$

The AB mask effectively shields most of the detector beam pipe from photons reflected from the nearby portion of the intervening beam pipe. In addition, care has been taken to ensure that regions of the beam pipe within 50 cm of the source and within 50 cm of the detector beam pipe do not have any line-of-sight to the detector beam pipe. This reduces by two orders of magnitude the probability of backscattered photons striking the detector beam pipe (see Table 4-8). Furthermore, most of the photons that do strike the detector beam pipe have a very small angle of incidence (<25 mrad), which further reduces the probability that photons from this source will penetrate the detector beam pipe. Taken together, these factors make double-bounce photons from the crotch mask a negligible source of detector background.

Still another possible source of detector background is backscattered photons coming from the dump downstream of the IP in which most of the synchrotron radiation power from the IR is absorbed. These photons may backscatter directly onto the detector beam pipe. To estimate this effect, we assumed that the entire synchrotron radiation power is absorbed in a dump located 12 m from the IP. The solid-angle fraction of the detector

Table 4-8. Solid-angle fractions from a double-bounce source. The numbers between the two dashed lines correspond to the double-bounce solid angle for the 2 m of beam pipe centrally located between the source and the detector beam pipe.

Distance from detector beam pipe to intervening beam pipe (cm)	SA fraction of detector beam pipe as seen from intervening beam pipe segment (a)	SA fraction of intervening beam pipe segment as seen from source (b)	Product (c)
290	2.14×10^{-6}	0.9557	2.05×10^{-6}
270	2.64×10^{-6}	8.26×10^{-3}	2.18×10^{-8}
250	3.30×10^{-6}	1.55×10^{-3}	5.12×10^{-9}
230	4.21×10^{-6}	5.45×10^{-4}	2.29×10^{-9}
210	5.49×10^{-6}	2.53×10^{-4}	1.39×10^{-9}
190	7.34×10^{-6}	1.37×10^{-4}	1.01×10^{-9}
170	1.10×10^{-5}	8.28×10^{-5}	8.36×10^{-10}
150	1.45×10^{-5}	5.38×10^{-5}	7.80×10^{-10}
130	2.19×10^{-5}	3.69×10^{-5}	8.08×10^{-10}
110	3.52×10^{-5}	2.64×10^{-5}	9.29×10^{-10}
90	6.20×10^{-5}	1.95×10^{-5}	1.21×10^{-9}
70	1.25×10^{-4}	1.48×10^{-5}	1.85×10^{-9}
50	3.11×10^{-4}	1.16×10^{-5}	3.61×10^{-9}
30	1.18×10^{-3}	9.17×10^{-6}	1.08×10^{-8}
10	1.60×10^{-2}	7.40×10^{-6}	1.18×10^{-7}
Total			2.22×10^{-6}
Total for central 2 m			1.98×10^{-8}

beam pipe seen from this source is 6×10^{-8} . (This calculation assumes that there is no intervening AB mask to shield most of the detector beam pipe.) There are about 5×10^{10} photons per crossing incident on the dump mask. Taking a reflection coefficient for the dump mask material of 0.007, we get 22 photons per crossing incident on the detector beam pipe. In reality, the AB mask shields at least 90% of the detector beam pipe from this source. The small region of detector beam pipe still exposed can be easily shielded by a small lip (about 1 mm) near the edge of the beam pipe. In addition, the very small

angle of incidence on the beam pipe (about 2 mrad) eliminates the high-power downstream dump as a possible source of detector background.

4.2.1.6 Sensitivity of Backgrounds to Misalignments. The following misalignments were evaluated for their effects on detector backgrounds:

- Displacing the Q4 magnet ± 1 mm in x and y for the HEB
- Displacing the Q2 magnet ± 1 mm in x and y for both beams
- Displacing the Q1 magnet ± 1 mm in x and y for both beams
- Displacing Q1, Q2, Q3, and Q4 ± 3 mm in x for the HEB; this corresponds to a displacement of about 1σ for the beam
- Displacing Q1, Q2, and Q3 ± 1.5 mm in x for the LEB; this also corresponds to about a 1σ beam displacement

The LEB background is the more sensitive to misalignments such as these. We see a 2.5-fold increase in the background rate for a 1-mm excursion in y for both Q1 and Q2. Likewise, the LEB background rate increases by a factor of about 2.25 for a 1-mm excursion in x for Q1 and Q2, and for a 1.5-mm displacement in all three inner magnets. The rest of the misalignment checks produced small ($<25\%$) increases in backgrounds, with some settings producing rates that are actually below the nominal background rate.

4.2.2 Survey of Synchrotron Radiation Power in the Interaction Region

Here we discuss the power levels on all the surfaces near the IP. An extensive analysis of all sources of fan radiation that either travels through or comes close to the IP is included. The analysis follows the fan from each source of radiation, and a tally of all surfaces the fan strikes is maintained. Table 4-9 summarizes the power deposited on various surfaces near the IP. The letters in the table that identify the various surfaces are also shown in Figs. 4-57 through 4-60. As mentioned earlier, the power values are calculated using the nominal beam currents: 1.48 A for the HEB and 2.14 A for the LEB.

There are fourteen radiation fans, ten of which are produced within 3 m of the IP and four of which originate from upstream bending magnets. The radiation fans can be conveniently separated into four categories: upstream LEB sources, downstream LEB sources, upstream HEB sources, and downstream HEB sources.

4.2.2.1 Upstream LEB. These sources of radiation include two bending magnets, BV– and BV1–, and three magnets near the IP, Q3, Q1, and B1. As described earlier, the synchrotron radiation fan from BV– is stopped in a 2-m-long mask located well upstream of the IP (see Fig. 4-54a); the total power from this fan is 7.5 kW. The fans from BV1– and Q3 and part of the fan from Q1 strike the AB mask, giving a total power of 1.15 kW. Some of the Q1 fan strikes the downstream Q4 crotch mask, depositing 186 W. The rest of the Q1 fan goes into dumps located about 6 m from the IP in the LER beam pipe and 12–15 m from the IP in the HER beam pipe. The downstream dump in the HER beamline is referred to as the high-power downstream dump (HPDD). The B1 fan misses

Table 4-9. Power on surfaces near the IP. Each surface is identified by letter in Figs. 4-57 through 4-60. Radiation fans that strike a surface do not necessarily overlap; the surface power summary for each surface is the maximum power density for that surface. Quadrupoles Q1 and Q2 were split into pieces (A and B) to reflect the changing power levels as the offset beams travel through these magnets.

	Source	Surface power (W/mm)	Total power (W)
<i>Surface struck:</i>			
a. Beam pipe between Q4 and Q5 (4.76 – 5.25 m)	B3B	0.03	17
	B2B	<u>0.13</u>	<u>65</u>
		0.16	82
b. Bore of Q4, HEB side (3.76 – 4.76 m)	B3B	0.03	16
	B2B	0.04	35
	Q1A downstream	<u>0.1</u>	<u>105</u>
		0.17	156
c. Crotch mask, HEB side (3.76 m)	Q1A upstream	1.2	186
	Q1A downstream +	1.7	75
	Q1B downstream	<u>1.1</u>	<u>122</u>
		2.9	383
d. Beam pipe between Q3 and Q4, HEB side (2 – 3.76 m)	B3B	0.03	52
e. CD mask, D side (0.35 m)	B3B	0.36	9
	Q4 + Q5 quad. rad.	<u>—</u>	<u>16</u>
		0.36	25
f. AB mask, B side (0.2 m)	B3B	0.29	29
	B2B	<u>0.84</u>	<u>99</u>
		1.13	128
f. AB mask, A side (0.2 m)	BV1–	2.8	225
	Q3	17.	901
	Q1B	<u>17.</u>	<u>138</u>
		17.	1264
g. Crotch mask, LEB side (3.76 m)	B2A	0.9	99
	Q2B	<u>41.</u>	<u>4330</u>
		41.9	4429

all nearby surfaces and is absorbed entirely in the HPDD. The total B1 fan power is 2.4 kW. These radiation fans are shown as shaded regions in Fig. 4-57.

4.2.2.2 Downstream LEB. Three fans are generated by the downstream elements B1, Q1, and Q3. The B1 fan again misses all nearby surfaces and is absorbed in the HPDD (with a power of 2.4 kW). Part of the downstream Q1 fan strikes the crotch mask on the Q4 septum quadrupole, depositing 200 W of power, and some is deposited inside the beam pipe in Q4 (giving a power of 100 W over 0.8 m of length). The rest of the Q1 fan is absorbed in the HPDD and in the corresponding LER beamline dump. The Q3 fan is also absorbed in the LER dump. Figure 4-58 shows as shaded regions the fans generated by the downstream LEB elements.

4.2.2.3 Upstream HEB. For the HEB, there are four upstream sources of radiation fans, as shown in Fig. 4-59: Two emerge from the upstream B3 and B2 bending magnets and two from the Q2 and B1 magnets near the IP. Weak radiation fans ($\epsilon_{\text{crit}} = 1$ keV) from the B2 and B3 bending magnets located at 11 m and 40 m, respectively, sweep through the entire IR. The B3 fan strikes the beam pipe between Q4 and Q5 (with 17 W of power), the inside of the Q4 beam pipe (16 W), the beam pipe between Q3 and Q4

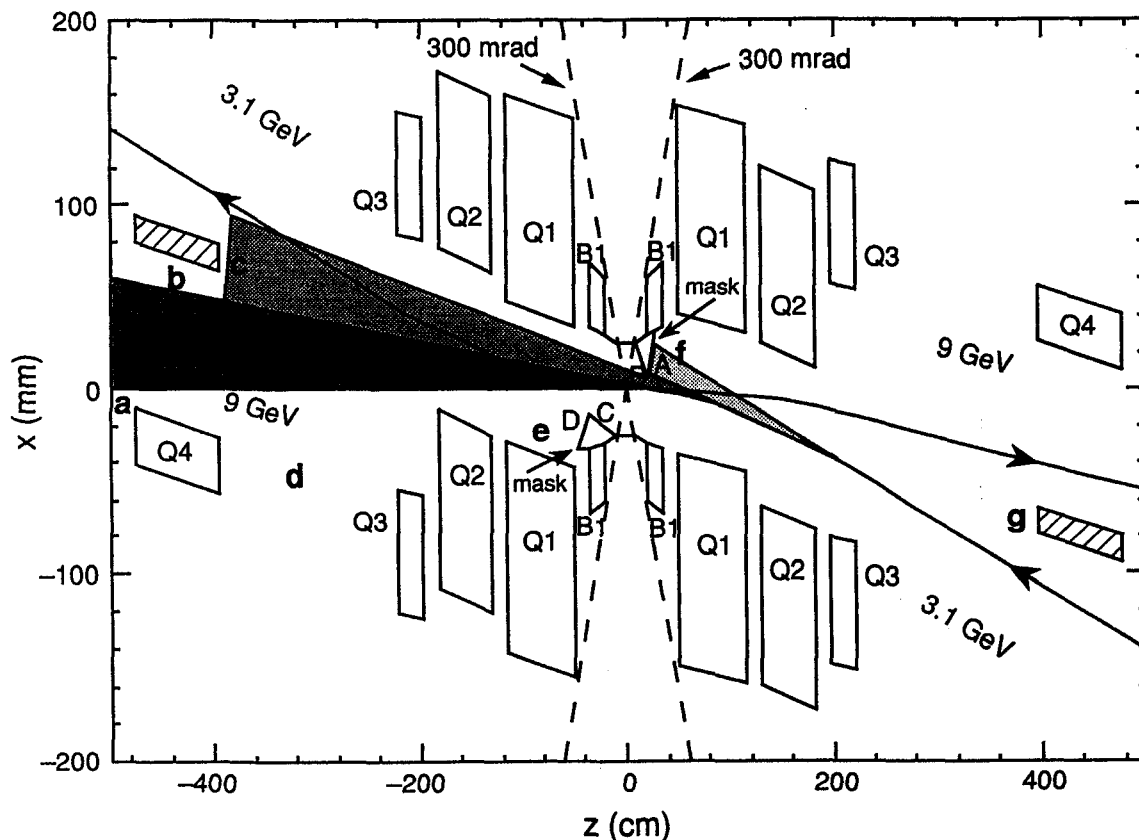


Fig. 4-57. LEB radiation fans produced upstream of the IP. The fan generated by the upstream Q3 magnet is absorbed by the AB mask. The lower-case lettering refers to surfaces in Table 4-9 that are struck by synchrotron radiation.

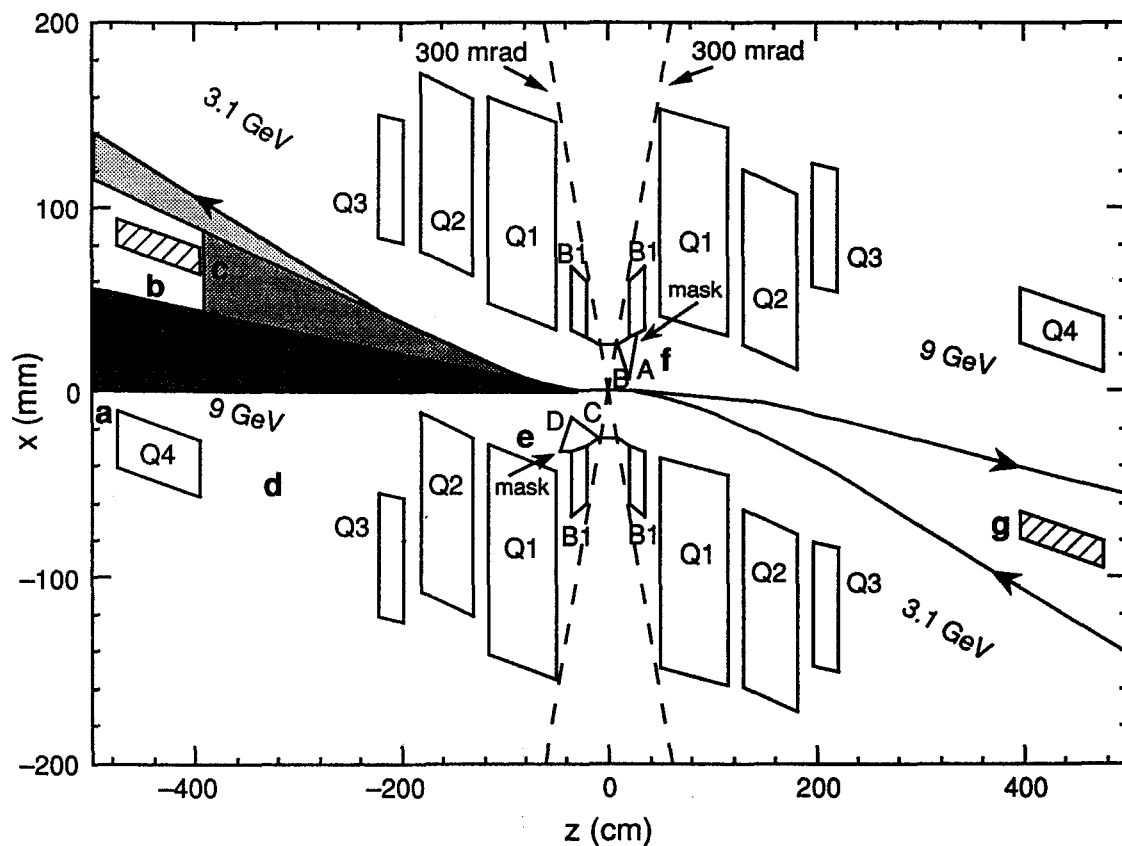


Fig. 4-58. LEB radiation fans produced downstream of the IP. The radiation fans from the downstream B1 and Q1 magnets overlap the upstream B1 and Q1 radiation fans (see Fig. 4-57).

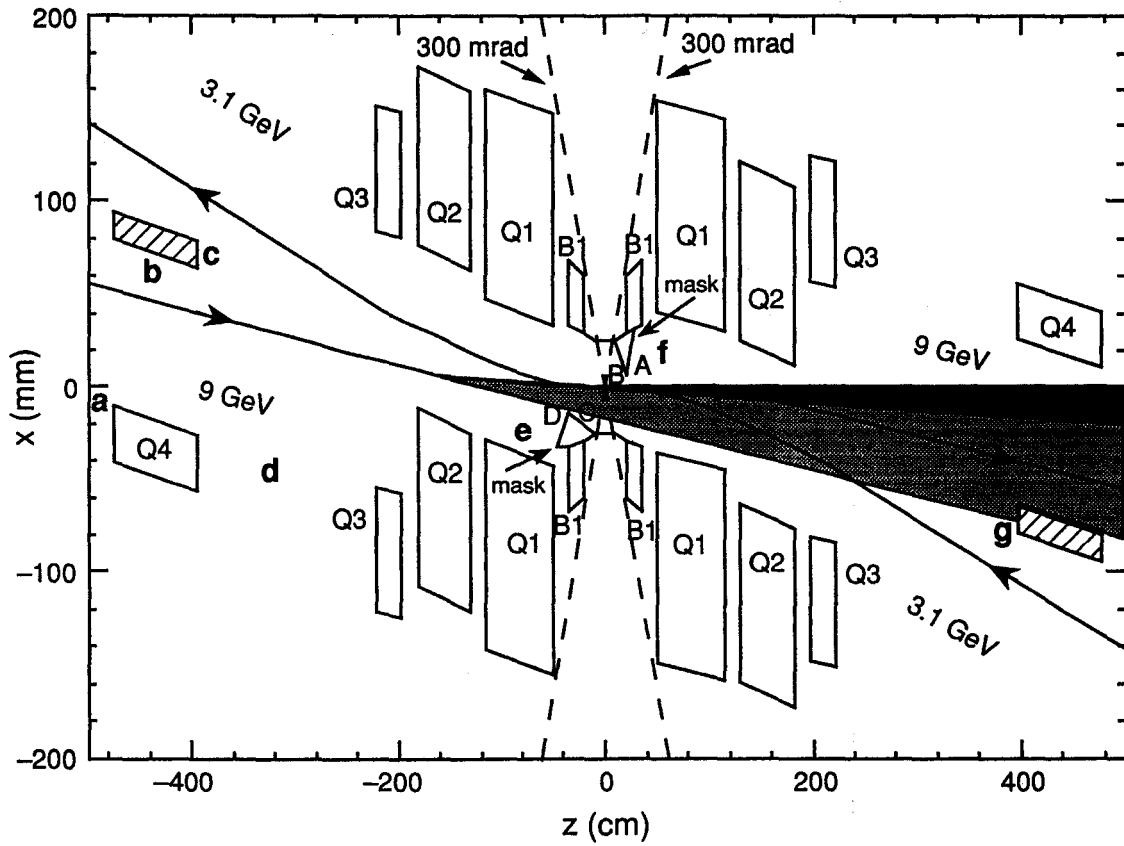


Fig. 4-59. HEB radiation fans produced upstream of the IP. The upstream Q2 fan strikes the downstream crotch mask in front of the Q4 septum, depositing about 4.5 kW of power.

(52 W), the CD mask (9 W), and the AB mask (29 W). The B2 fan strikes the beam pipe between Q4 and Q5 (65 W), the inside of Q4 (35 W), the AB mask (99 W), and the downstream Q4 crotch mask (99 W). Part of the intense fan of photons coming from the Q2 magnet strikes the downstream crotch mask in front of the Q4 septum quadrupole. A power of 4.33 kW is deposited on this mask, with the rest of the fan power going down the HER beam pipe, where it is absorbed by the HPDD. The B1 fan misses all nearby surfaces and is absorbed in the HPDD.

4.2.2.4 Downstream HEB. The two radiation fans from downstream HEB elements B1 and Q2 miss all nearby surfaces (see Fig. 4-60) and are absorbed in the HPDD.

The total amount of power that is absorbed in the upstream 12-m region of the HEB is 5.6 kW, and the HPDD absorbs 84 kW of power. The power absorbed in the downstream dump in the LER is 1.2 kW. No power is seen in the upstream beamline of the LER. In summary, nearly 90% of the synchrotron radiation power is absorbed in downstream dumps and thus causes no increase in detector background, either from backscattered photons or from beam-gas interactions. Of the remaining 10.5 kW, 5.6 kW are absorbed

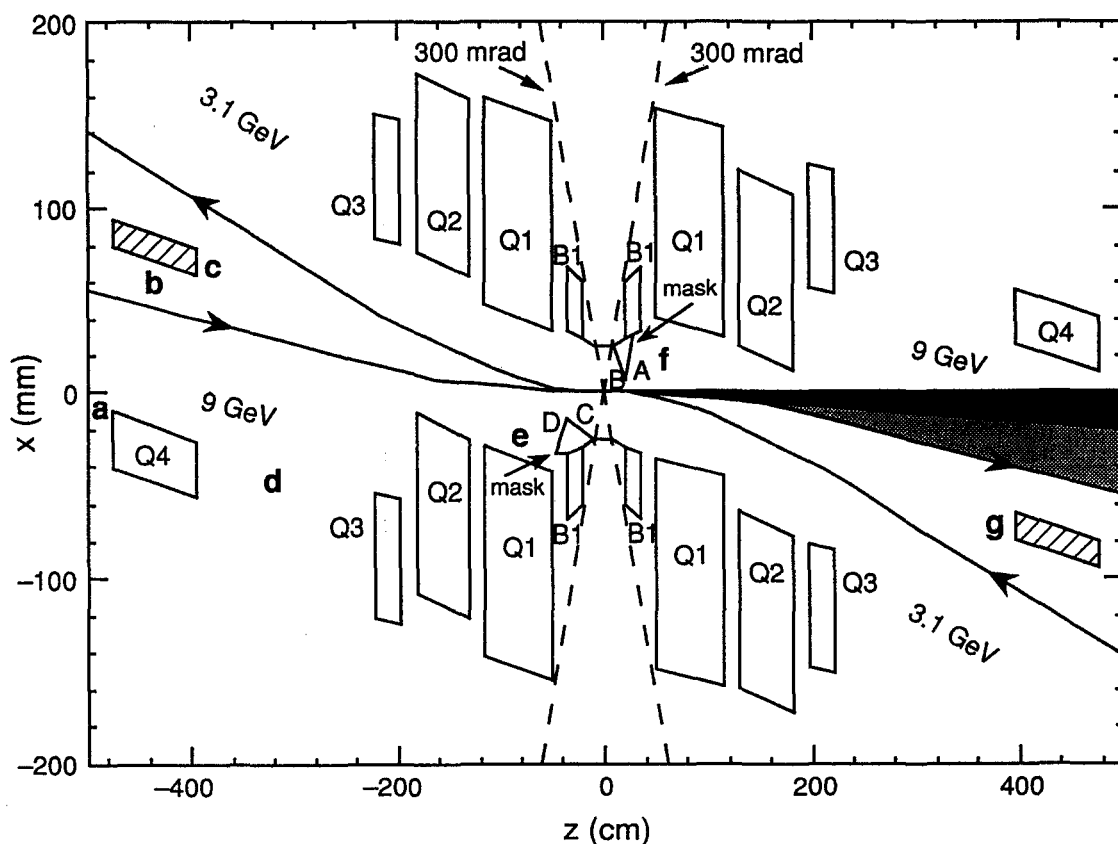


Fig. 4-60. HEB radiation fans produced downstream of the IP. The radiation fans from the downstream B1 and Q2 magnets overlap the upstream B1 and Q2 radiation fans (see Fig. 4-59).

in an upstream region of the HER 12 m from the IP, and most of the rest is absorbed on the crotch mask at Q4 and on the AB mask.

4.2.3 Detector Backgrounds from Lost Beam Particles

Bremsstrahlung and Coulomb scattering of beam particles from residual gas molecules in the beam pipe can lead to high-energy electrons and photons striking masks and the beam pipe near the IP. The resulting electromagnetic showers can cause excessive detector occupancy and lead to radiation damage. Here we discuss the methods used to simulate this process, the rates and locations of lost-particle hits, and the resulting detector backgrounds. Calculated rates are found to be 25–100 times lower than the acceptable limits (see Section 2.4, Tables 2-5 and 2-6) in the silicon microvertex detector and the CsI calorimeter, and about 15 times lower in the drift chamber.

In calculating the rates of bremsstrahlung and Coulomb scattering, both the high- and low-energy lattices are simulated for a distance of 185 m upstream of the IP (halfway around the arc). Bremsstrahlung scattering produces an electron and a photon whose combined energy is equal to the beam energy. The photon energy is restricted to a range between 0.02 and 0.99 of the beam energy; scattering events with a lower photon energy are found to contribute less than 1% to the energy deposited near the IP. Coulomb scattering gives an off-axis electron at the nominal beam energy; the scattering angle is restricted to lie between 1 and 500 mrad. (Electrons scattered at lower angles do not strike the beam pipe.)

The pressure in the beam pipe is assumed to be 1 nTorr of N_2 within 30 m upstream of the IP and 5 nTorr elsewhere.

The analysis was carried out using DECAY TURTLE [Carey et al., 1982], a modified version of TRANSPORT [Brown et al., 1977]. In this program, rays are scattered and transported until they either strike an aperture or pass through the IR. The location and direction of rays that strike near the IP are stored, together with a weighting factor corresponding to the probability of that scattering process occurring per beam crossing, for later use in a detailed EGS model. Approximately 230 beam crossings occur per microsecond; this is the relevant time interval, because 1 μ s is typical of the live-time of most detector elements.

The rate of rays striking near the IP is reduced by the use of upstream masks at points of high dispersion. The masks are elliptical, with half-apertures in x and y given by the larger of 8 mm or $15\sigma_{x,y} + 2$ mm, where $\sigma_{x,y}$ is the transverse beam size at that point in the lattice. The dispersion in x and y of each beam and the location of the masks are shown in Fig. 4-61. These masks completely shadow the IR from LEB bremsstrahlung scattering events upstream of the outboard vertical bend (30 m upstream of the IP). Particles from upstream Coulomb scattering do strike the detector, but at a low rate. The masking is not quite as successful for the HEB. Figure 4-62 shows the energy of the scattered electrons that strike near the IP as a function of the bremsstrahlung scattering location (in meters upstream of the IP). There is a “window” for electrons having energies between 8.5 and 9 GeV that scatter 85–90 m upstream to hit the region near the IP. However, these rays constitute only 14% of the energy from the HEB deposited near the IP and thus do not dominate the background. A more sophisticated masking scheme

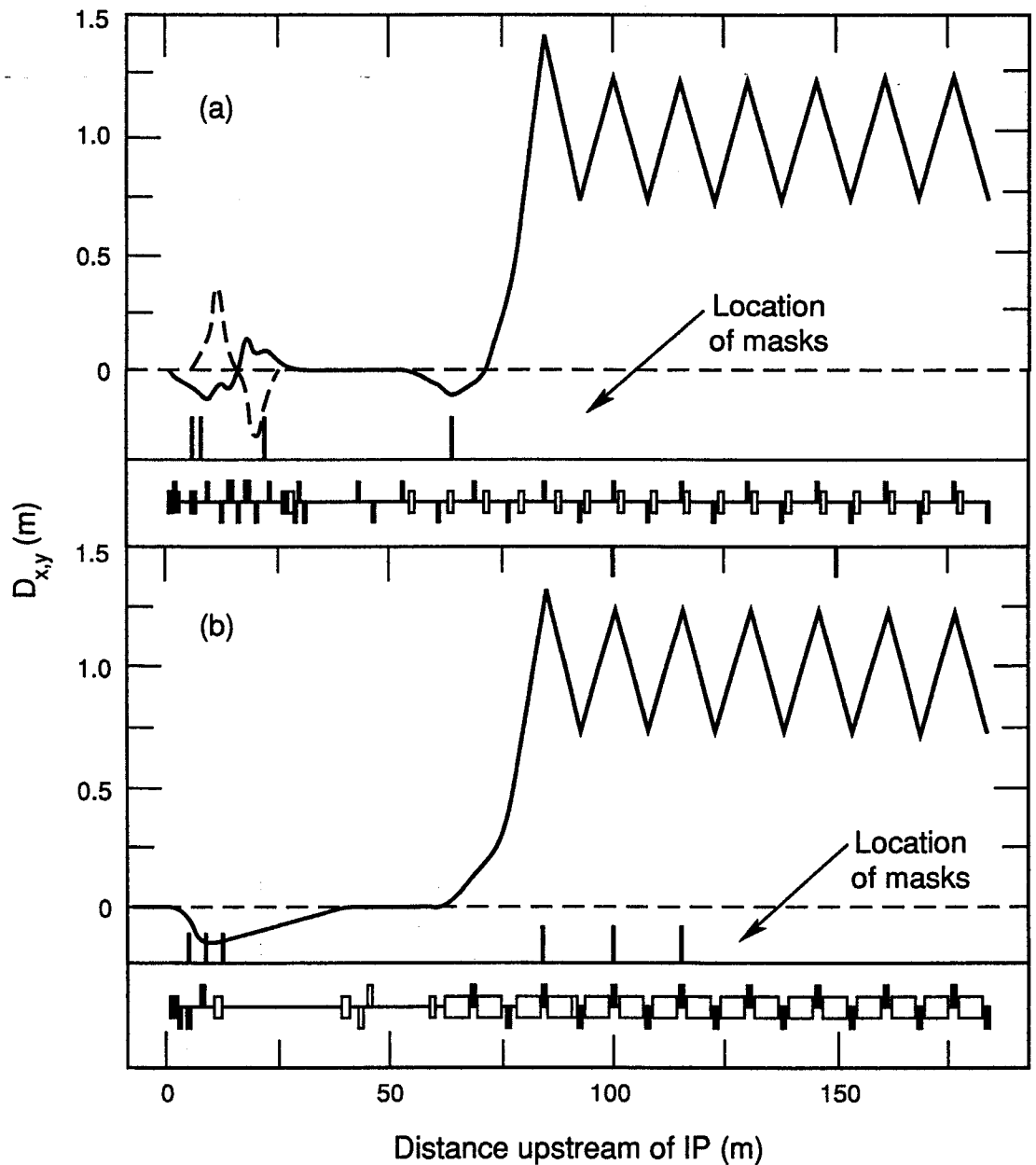


Fig. 4-61. Plots showing the dispersion and location of masks for (a) the low-energy beam and (b) the high-energy beam: solid line, horizontal dispersion; dashed line, vertical dispersion. The HER lies in a horizontal plane and therefore has no vertical dispersion.

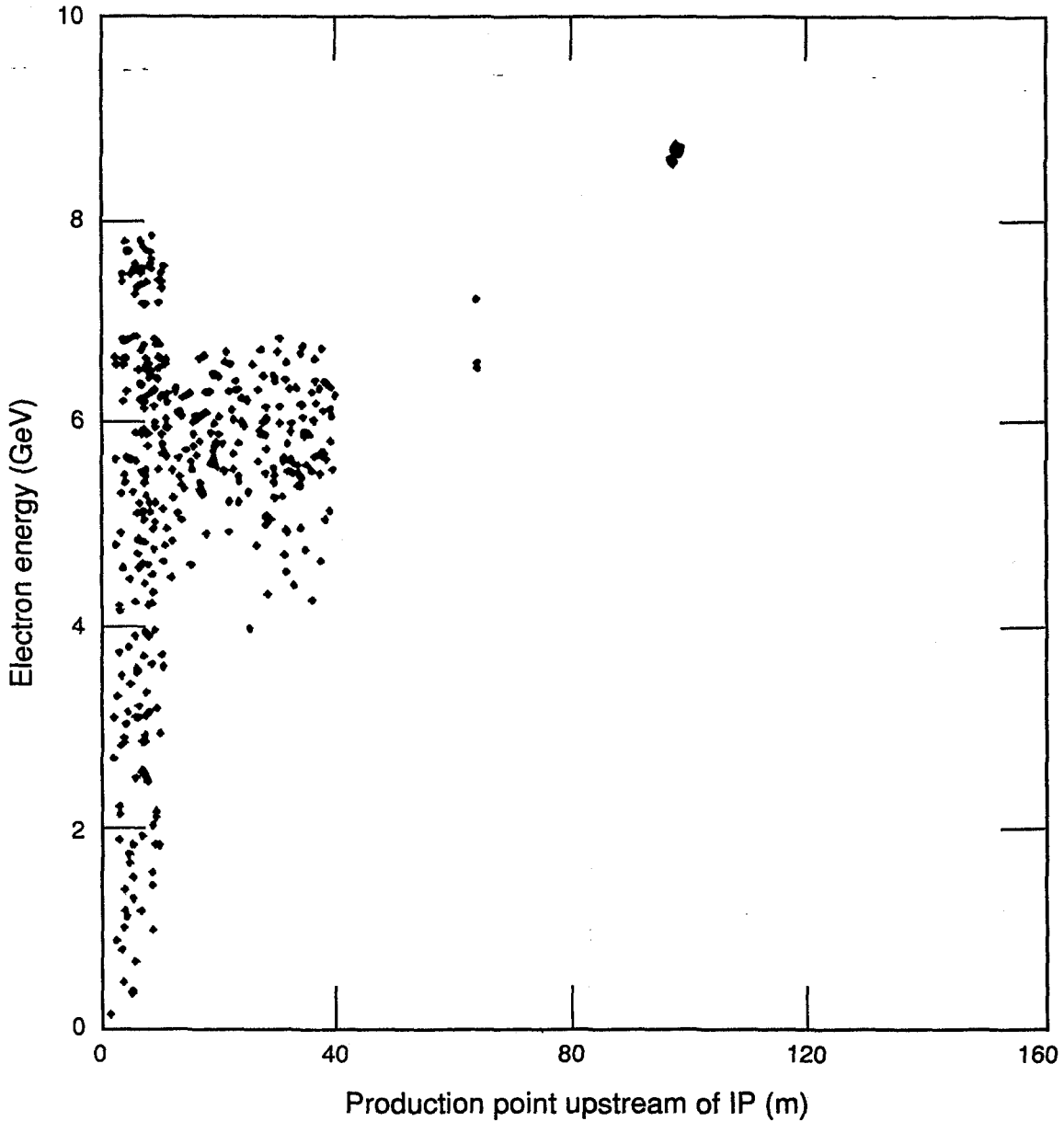


Fig. 4-62. Plot of the energy of bremsstrahlung-scattered electrons striking near the IP, as a function of the location of the scattering point (distance upstream of the IP), for the HEB. Scattering events 85–90 m upstream with $8.5 < E < 9.0$ GeV are not completely masked.

could probably eliminate them. Coulomb scattering events of the HEB that take place more than 30 m upstream do not strike near the IP.

Because shower debris is expected to be roughly proportional to the incident energy, the rate of energy deposition on each aperture in the IR is given in Table 4-10 for each source and is displayed graphically in Fig. 4-63. For both the HEB and the LEB, the dominant sources of detector background are bremsstrahlung electrons deflected by the B1 magnet that strike the downstream synchrotron radiation mask. Note that Coulomb scattering contributes less than 6% of the deposited energy. Overall, a total energy of 5.7 GeV, from 3.1 rays per microsecond, is deposited near the IP from the LEB, while 19 GeV, from 4.4 rays per microsecond, originates from the HEB.

In our analysis, all rays that strike the IR were passed to an EGS simulation code that includes the geometry and material type of the beam pipe, masks, magnets, and detector components, as well as the final-focus optics and detector magnetic fields. The number of showers generated per incident ray is determined by its weighting factor from DECAY TURTLE. For the LEB backgrounds, 250,000 beam crossings (1100 μ s of running) were simulated; 70,000 crossings (300 μ s) were used for the HEB backgrounds. The EGS total energy cutoffs were 0.7 MeV for electrons and 0.01 MeV for photons.

All objects in the simulation are constructed from cylinders parallel to and centered on the z axis. The geometry is therefore specified by the extent in z and the inner and outer radii of each object (see Table 4-11). Note that the synchrotron radiation masks (masks AB and CD) were divided into five cylinders to better represent their tapered shape. The composition of each object is also shown in Table 4-11. Figure 4-64 shows the detector and IR geometry incorporated into the EGS simulation.

The actual layout of the IR (corresponding to the geometry used by TRANSPORT) is not cylindrically symmetric about the z axis. This is particularly true of the masks. Therefore, TRANSPORT rays are mapped from the correct geometry to the cylindrically symmetric EGS geometry [Nelson et al., 1985]. This is done so as to preserve the incident angle of the particle with respect to the surface, the azimuthal angle of the point of impact, and the distance (δ) of the impact point from the edge of the struck mask. Figure 4-65 shows an example of this mapping.

The EGS calculation finds the energy deposited in, and the number of photons and electrons entering, each object. Electrons are counted each time they loop through an object in the solenoid field. For this reason, the drift chamber is divided into a series of thin cylinders so that the number of electron crossings at each radius is accurately counted. Electrons produced by photon interactions in the gas are scored as electrons when they subsequently enter a new object (a drift chamber scoring cylinder, for example). The results of the EGS calculations for the B Factory IR are summarized in Table 4-12 for the LEB and HEB, both separately and combined.

Four plots characterizing the backgrounds in the drift chamber from the LEB are shown in Fig. 4-66. The backgrounds in the drift chamber are due primarily to low-energy photons from rays striking the HEB synchrotron radiation mask (CD); Fig. 4-67 shows the z location at the beam pipe of photons that enter the drift chamber. Backgrounds from the HEB are qualitatively similar, except that the LEB synchrotron radiation mask (AB) is the primary source. The probability that a photon interacts in the

Table 4-10. Number of rays and energy (given in parentheses in GeV) deposited on IR area apertures per microsecond.

Aperture	Coulomb	Brem e^-	Brem γ	All rays
<i>Due to LEB:</i>				
Q3	0.0 (0.0)	0.0 (0.0)	0.2 (0.07)	0.2 (0.07)
Q2	0.0 (0.04)	0.1 (0.31)	0.0 (0.0)	0.1 (0.35)
Q1	0.0 (0.02)	0.0 (0.02)	0.0 (0.01)	0.0 (0.05)
HEB SR mask	0.0 (0.04)	0.9 (2.39)	0.0 (0.0)	0.9 (2.43)
IP	0.0 (0.0)	0.0 (0.08)	0.0 (0.0)	0.0 (0.08)
LEB SR mask	0.0 (0.05)	0.0 (0.06)	0.8 (0.50)	0.8 (0.610)
B1	0.0 (0.0)	0.0 (0.02)	0.3 (0.15)	0.3 (0.18)
Q1	0.0 (0.01)	0.4 (1.16)	0.1 (0.07)	0.5 (1.24)
Q2	0.0 (0.01)	0.3 (0.65)	0.0 (0.01)	0.3 (0.68)
Q3	0.0 (0.0)	0.0 (0.01)	0.0 (0.0)	0.0 (0.01)
Total	0.0 (0.17)	1.7 (4.70)	1.4 (0.81)	3.1 (5.70)
<i>Due to HEB:</i>				
Q3	0.0 (0.0)	0.0 (0.01)	0.0 (0.0)	0.0 (0.01)
Q2	0.0 (0.05)	1.1 (6.3)	0.0 (0.0)	1.1 (6.35)
Q1	0.0 (0.01)	0.1 (0.24)	0.0 (0.0)	0.1 (0.25)
HEB SR mask	0.0 (0.01)	0.0 (0.20)	0.2 (0.44)	0.2 (0.66)
IP	0.0 (0.0)	0.0 (0.02)	0.0 (0.0)	0.0 (0.02)
LEB SR mask	0.0 (0.42)	0.5 (3.39)	2.1 (4.1)	2.6 (7.92)
B1	0.0 (0.0)	0.0 (0.0)	0.0 (0.0)	0.0 (0.0)
Q1	0.0 (0.0)	0.0 (0.07)	0.0 (0.07)	0.0 (0.07)
Q2	0.1 (0.59)	0.3 (2.78)	0.0 (0.0)	0.4 (3.37)
Q3	0.0 (0.0)	0.0 (0.0)	0.0 (0.0)	0.0 (0.0)
Total	0.1 (1.07)	2.0 (13.01)	2.3 (4.61)	4.4 (18.63)
<i>Due to both beams:</i>				
Q3	0.0 (0.0)	0.0 (0.01)	0.2 (0.07)	0.2 (0.08)
Q2	0.0 (0.09)	1.2 (6.61)	0.0 (0.0)	1.2 (6.70)
Q1	0.0 (0.03)	0.0 (0.26)	0.0 (0.01)	0.0 (0.30)
HEB SR mask	0.0 (0.05)	0.9 (2.59)	0.2 (0.44)	1.1 (3.03)
IP	0.0 (0.0)	0.0 (0.1)	0.0 (0.0)	0.0 (0.11)
LEB SR mask	0.0 (0.47)	0.5 (3.45)	2.9 (4.6)	3.4 (8.53)
B1	0.0 (0.0)	0.0 (0.02)	0.3 (0.15)	0.3 (0.18)
Q1	0.0 (0.01)	0.4 (1.23)	0.1 (0.14)	0.5 (1.31)
Q2	0.1 (0.6)	0.6 (3.43)	0.0 (0.01)	1.7(4.05)
Q3	0.0 (0.0)	0.0 (0.01)	0.0 (0.0)	0.0 (0.01)
Total	0.1 (1.24)	3.7 (17.71)	3.7 (5.42)	7.5 (24.33)

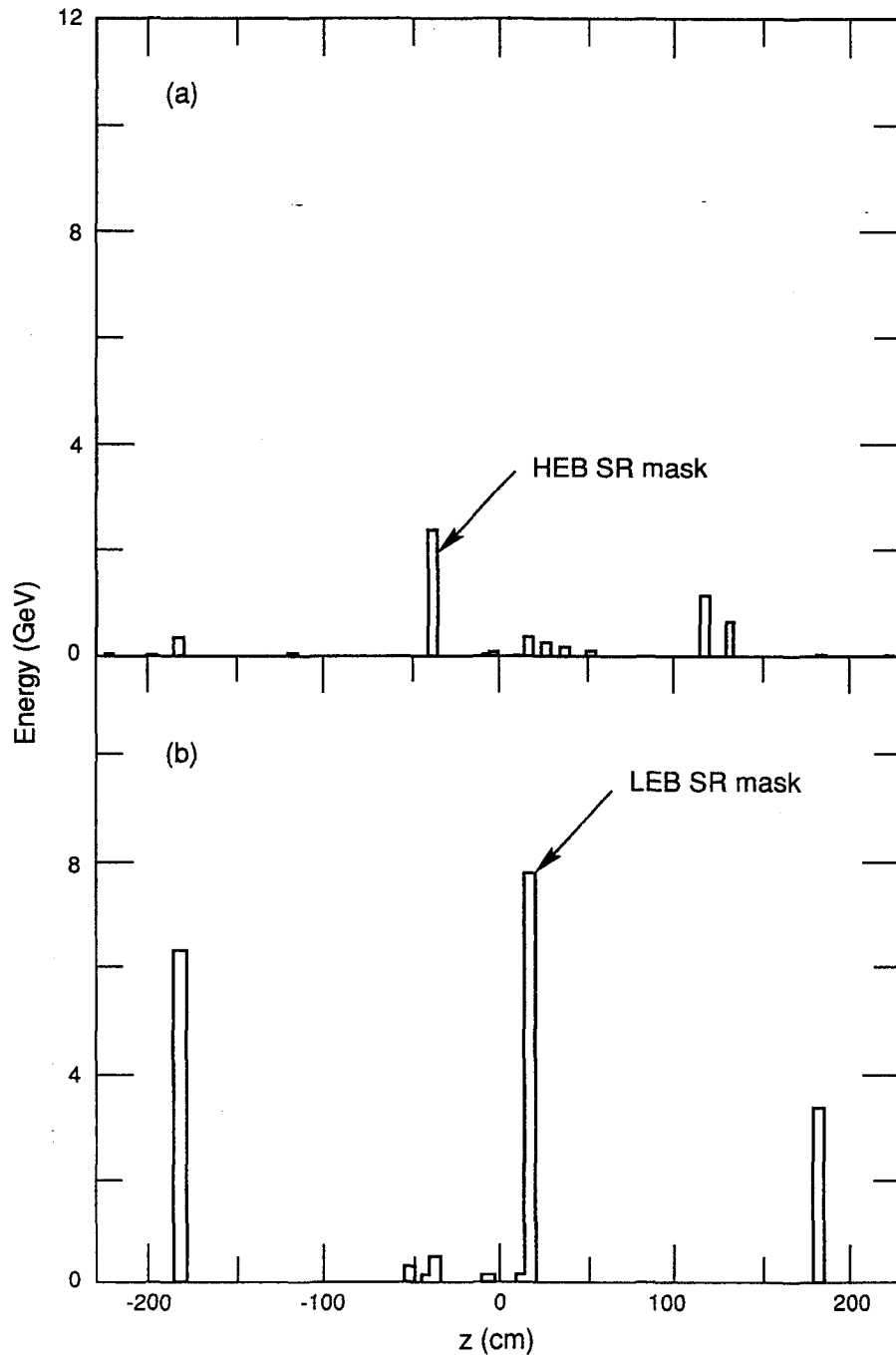


Fig. 4-63. Energy per microsecond incident on the IR due to scattering from (a) the low-energy beam and (b) the high-energy beam, as functions of location. The location plotted corresponds to the point where the ray strikes an aperture. The HEB travels in the direction of increasing z . The drift chamber covers the region $-150 < z < 150$ cm.

Table 4-11. Geometry and materials used in EGS simulation.

Object	Material	z (cm)	r (cm)
Support 2	Al	± 60 to ± 900	16.8 to 18.0
Q3	Sm ₂ Co ₁₇	± 196.8 to ± 220.8	6.1 to 13.2
Q2	Sm ₂ Co ₁₇	± 130.2 to ± 181.8	3.6 to 11.0
Q1	Sm ₂ Co ₁₇	± 51.0 to ± 115.2	3.3 to 14.6
B1	Sm ₂ Co ₁₇	± 20.0 to ± 36.0	2.6 to 6.1
Beam pipe 3	Al	± 115.2 to ± 181.6	3.5 to 3.6
Beam pipe 4	Al	± 181.8 to ± 900	6.0 to 6.1
End cap	CsI	± 150.0 to ± 187.0	45.0 to 100.0
End cap shield 1	Pb	± 187.0 to ± 197.0	45.0 to 100.0
End cap shield 2	Pb	± 150.0 to ± 197.0	35.0 to 45.0
Mask E	W	± 14.9 to ± 20.0	2.6 to 4.6
Beam pipe 1	Be	-40.3 to $+36.0$	2.5 to 2.6
Beam pipe 2+	Al	$+36.0$ to $+115.2$	3.2 to 3.3
Beam pipe 2-	Al	-115.2 to -40.3	3.2 to 3.3
Mask A ₁	Ta	$+19.37$ to $+20.51$	1.50 to 1.70
Mask A ₂	Ta	$+18.11$ to $+21.53$	1.70 to 1.90
Mask A ₃	Ta	$+16.85$ to $+22.55$	1.90 to 2.10
Mask A ₄	Ta	$+15.59$ to $+23.57$	2.10 to 2.30
Mask A ₅	Ta	$+14.33$ to $+24.59$	2.30 to 2.50
Mask C ₁	Ta	-35.59 to -32.37	1.75 to 1.90
Mask C ₂	Ta	-36.77 to -27.11	1.90 to 2.05
Mask C ₃	Ta	-37.95 to -21.85	2.05 to 2.20
Mask C ₄	Ta	-39.13 to -16.59	2.20 to 2.35
Mask C ₅	Ta	-40.31 to -11.33	2.35 to 2.50
Mask F	W	-40.31 to -36.0	2.6 to 6.1
Support	Carbon fiber	-60.0 to $+60.0$	16.8 to 18.0
Si layer 1	Si	-4.5 to $+4.5$	2.80 to 2.83
Si layer 2	Si	-9.0 to $+9.0$	5.10 to 5.13
Si layer 3	Si	-9.0 to $+9.0$	7.40 to 7.43
Si layer 4	Si	± 11.0 to ± 11.03	2.80 to 8.50
Si layer 5	Si	± 14.0 to ± 14.03	2.80 to 8.50
DC inner wall	Al	-150 to $+150$	18.0 to 18.2
DC score 1	He/CO ₂ /Iso	-150 to $+150$	18.2 to 18.4
DC score 2	He/CO ₂ /Iso	-150 to $+150$	18.4 to 18.6
DC score 3	He/CO ₂ /Iso	-150 to $+150$	18.6 to 18.8
DC score 4	He/CO ₂ /Iso	-150 to $+150$	18.8 to 19.0
DC score 5	He/CO ₂ /Iso	-150 to $+150$	19.0 to 19.2
DC score 6	He/CO ₂ /Iso	-150 to $+150$	19.2 to 19.4

Table 4-11 continued.

Object	Material	z (cm)	r (cm)
DC score 7	He/CO ₂ /Iso	-150 to +150	19.4 to 19
DC score 8	He/CO ₂ /Iso	-150 to +150	19.6 to 19.8
DC score 9	He/CO ₂ /Iso	-150 to +150	19.8 to 20.0
DC score 10	He/CO ₂ /Iso	-150 to +150	20.0 to 20.2
DC score 11	He/CO ₂ /Iso	-150 to +150	20.2 to 20.4
DC score 12	He/CO ₂ /Iso	-150 to +150	20.4 to 20.6
DC other 1	He/CO ₂ /Iso	-150 to +150	20.6 to 30.0
DC score 13	He/CO ₂ /Iso	-150 to +150	30.0 to 30.2
DC other 2	He/CO ₂ /Iso	-150 to +150	30.2 to 40.0
DC score 14	He/CO ₂ /Iso	-150 to +150	40.0 to 40.2
DC other 3	He/CO ₂ /Iso	-150 to +150	40.2 to 50.0
DC score 15	He/CO ₂ /Iso	-150 to +150	50.0 to 50.2
DC other 4	He/CO ₂ /Iso	-150 to +150	50.2 to 60.0
DC score 16	He/CO ₂ /Iso	-150 to +150	60.0 to 60.2
DC other 5	He/CO ₂ /Iso	-150 to +150	60.2 to 70.0
DC score 17	He/CO ₂ /Iso	-150 to +150	70.0 to 70.2
DC other 6	He/CO ₂ /Iso	-150 to +150	70.2 to 79.3
DC score 18	He/CO ₂ /Iso	-150 to +150	79.3 to 79.5
DC outer wall	Al	-150 to +150	79.5 to 80.0
CRID	Vacuum	-150 to +150	80.0 to 94.0
Calorimeter	CsI	-150 to +150	94.0 to 131.0

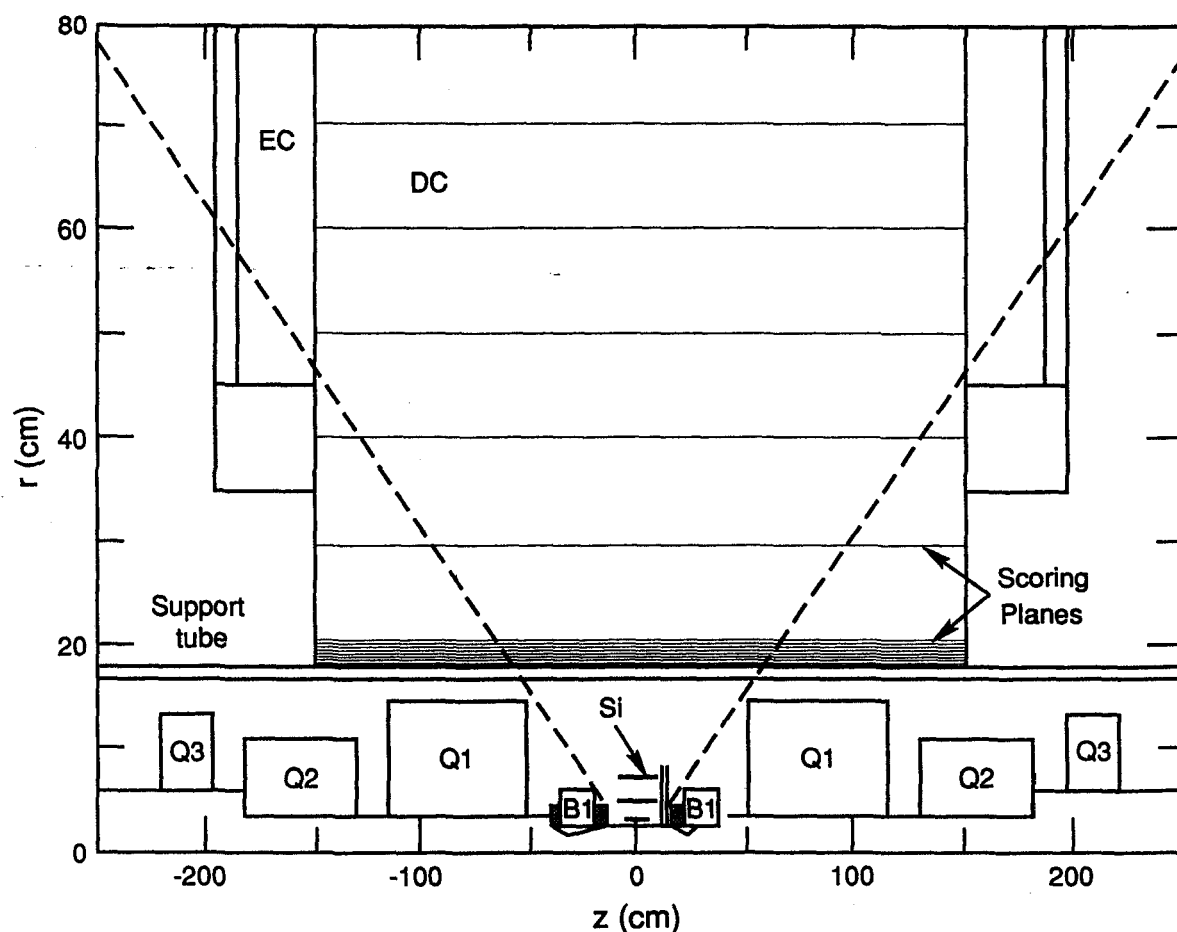


Fig. 4-64. Schematic of the detector and IR geometry used by EGS.

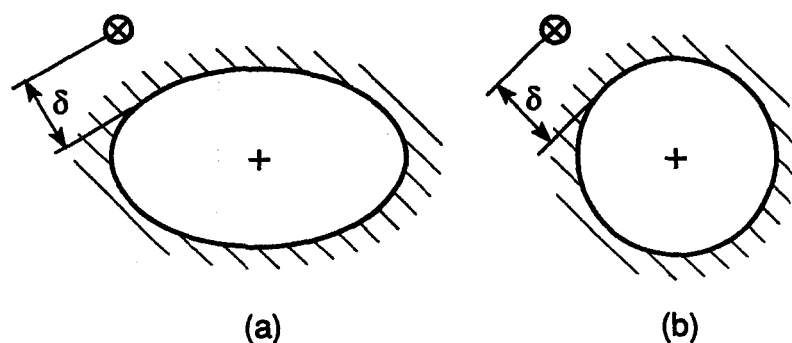


Fig. 4-65. Representation of the mapping of a noncylindrical geometry to the cylindrically symmetric EGS geometry. A ray striking a mask in DECAY TURTLE (a) is represented in EGS by a ray striking a cylinder (b). The distance δ is the same in both cases.

Table 4-12. Rate of energy deposition (in MeV/ μ s) as determined by EGS simulation.

Object	Energy deposited by LEB	Energy deposited by HEB	Total energy deposited
+z support 2	2.8	275.9	278.7
+z Q3	26.1	150.2	176.3
+z Q2	661.6	2251.3	2912.9
+z Q1	1788.5	933.9	2722.4
+z B1	119.1	860.5	979.6
+z beam pipe 3	35.2	78.7	113.9
+z beam pipe 4	1.0	44.8	45.8
+z end cap	2.2	38.2	40.4
+z end cap shield 1	0.03	0.41	0.44
+z end cap shield 2	3.6	26.1	29.7
+z mask E	52.3	1056.9	1109.2
-z support 2	38.9	10.3	49.2
-z Q3	4.4	37.5	41.9
-z Q2	18.9	6063.8	6082.7
-z Q1	300.0	334.5	634.5
-z B1	249.4	143.8	393.2
-z beam pipe 3	1.4	158.0	159.4
-z beam pipe 4	2.8	1.08	3.9
-z end cap	14.0	4.90	18.9
-z end cap shield 1	0.04	0.16	0.20
-z end cap shield 2	2.8	36.4	39.2
-z mask E	77.6	18.1	95.7
Beam pipe 1	8.6	84.0	92.6
Beam pipe 2+	23.8	41.5	65.3
Beam pipe 2-	13.2	13.8	27.0
Mask A ₁	3.6	116.0	119.6
Mask A ₂	9.0	283.6	292.6
Mask A ₃	6.3	583.9	590.2
Mask A ₄	11.4	767.3	778.7
Mask A ₅	13.0	1175.2	1188.5
Mask C ₁	252.5	132.8	385.3
Mask C ₂	570.9	194.8	765.7
Mask C ₃	617.4	131.4	748.8
Mask C ₄	306.5	96.9	403.3
Mask C ₅	163.0	86.7	249.7
Mask F	123.9	140.4	264.3
Support 1	0.54	1.16	1.70
Si layer 1	0.089	0.17	0.26

Table 4-12 continued.

Object	Energy deposited by LEB	Energy deposited by HEB	Total energy deposited
Si layer 2	0.063	0.21	0.27
Si layer 3	0.055	0.098	0.15
Si layer 4	0.024	0.088	0.11
Si layer 5	0.018	0.078	0.10
DC inner wall	2.5	5.69	8.2
DC score 1	0.0026	0.0059	0.0085
DC score 2	0.0025	0.0061	0.0086
DC score 3	0.0019	0.0047	0.0066
DC score 4	0.0019	0.0035	0.0054
DC score 5	0.0012	0.0033	0.0045
DC score 6	0.0011	0.0027	0.0038
DC score 7	0.0005	0.0024	0.0029
DC score 8	0.0005	0.0033	0.0038
DC score 9	0.0010	0.0014	0.0024
DC score 10	0.0007	0.0024	0.0031
DC score 11	0.0010	0.0008	0.0018
DC score 12	0.0010	0.0017	0.0027
DC other 1	0.033	0.134	0.167
DC score 13	0.0001	0.0019	0.002
DC other 2	0.036	0.118	0.154
DC score 14	0.0004	0.0008	0.0012
DC other 3	0.033	0.078	0.111
DC score 15	0.0010	0.0031	0.0041
DC other 4	0.038	0.044	0.082
DC score 16	0.0003	0.0006	0.0009
DC other 5	0.028	0.076	0.104
DC score 17	0.0007	0.0019	0.0026
DC other 6	0.025	0.070	0.095
DC score 18	0.0002	0.0008	0.0010
DC outer wall	4.39	10.32	14.71
CRID	0.0000	0.0000	0.0000
Calorimeter	102.9	230.2	333.1

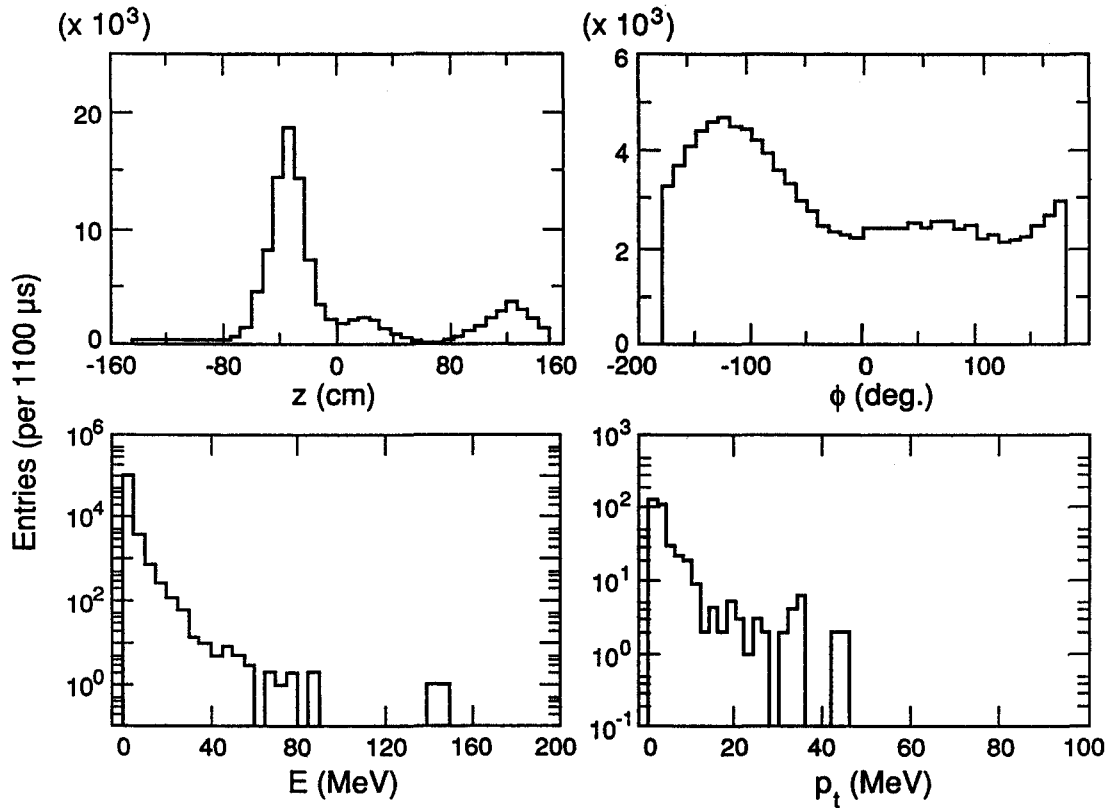


Fig. 4-66. Backgrounds due to the LEB in the first sense wire plane of the drift chamber ("drift chamber score 8" in Tables 4-11 through 4-13): (a) z ; (b) the azimuthal angle ϕ , (c) energy of photons entering the scoring plane; and (d) the transverse momentum p_t of the electrons. The vertical scale represents entries per 1100 μ s of running.

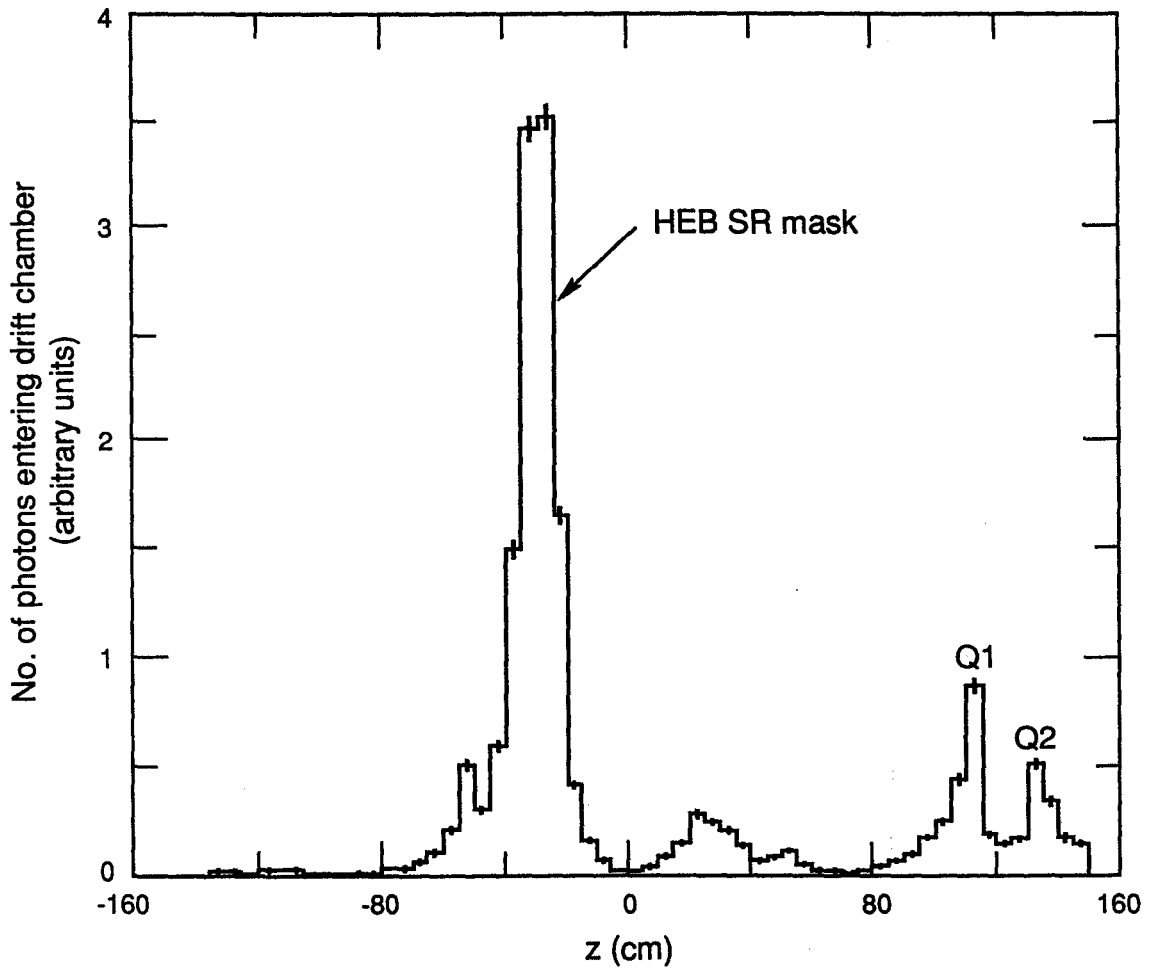


Fig. 4-67. Plot showing the origin of photons that enter the drift chamber due to beam particles lost from the LEB. The largest peak is due to showers originating at the synchrotron radiation mask CD.

drift chamber is of the order of 5×10^{-3} . The electrons entering the innermost drift chamber scoring layers are due to photon conversions in the inner wall. At larger radii—roughly 2–3 cm from the inner wall—the electrons are due to photon conversions in the gas. A low-density gas (He, 78%; CO₂, 15%; C₄H₁₀, 7%) is used. The number of photons, and hence the number of electrons, crossing each radius is essentially constant with radius (see Fig. 4-68). The number of electrons per area therefore falls as $1/r$. Note that the points in Fig. 4-68 have large statistical fluctuations, because a single electron can be counted as many as 100 times due to looping. Electrons deposit 3.0 keV per cm of path length in the gas. The average path length of an electron traversing a 2-mm-thick scoring cylinder is 5.2 mm. (Similarly, the path length of an electron traversing a 0.3-mm-thick silicon vertex detector layer is 0.8 mm.) Backgrounds elsewhere in the detector are similar to those in the drift chamber; that is, they are characterized by low-energy photons and low- p_t electrons.

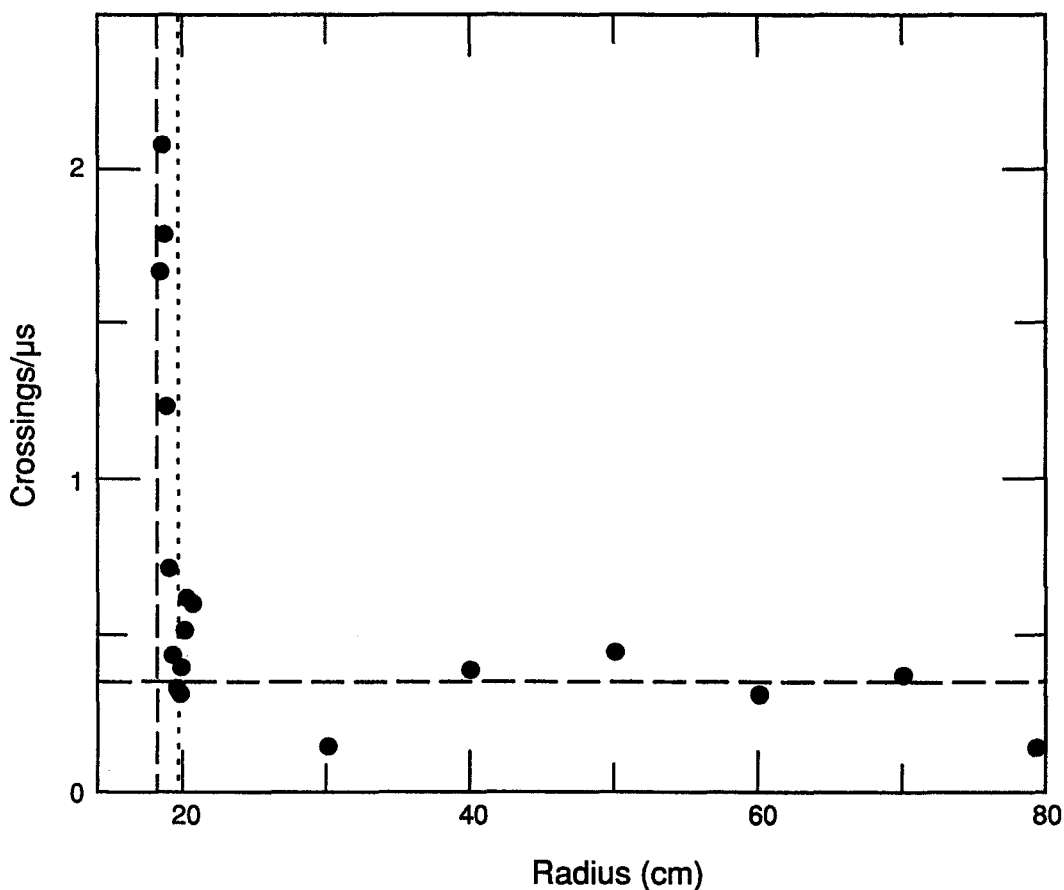


Fig. 4-68. Number of electrons crossing each drift chamber scoring plane as a function of radius. Electrons looping in the solenoid field are counted each time they cross the plane; electrons from photon conversions are counted as electrons. The peak at the inner wall (dashed line) is due to conversions in the wall. Charge deposited in the first centimeter beyond the wall will drift to the z strips rather than the first sense wire (dotted line).

Table 4-13 lists the calculated backgrounds in several detector components from the LEB and the HEB, along with the estimated allowable rates (see Chapter 2). The most stringent limit on silicon backgrounds comes from an allowed radiation dose of 100 krad in a 10^7 -second operating year, rather than occupancy considerations. In the drift chamber, the most stringent limiting factor is the 10% occupancy allowed; the radiation damage limit of 0.5 C/cm is six times higher. In the calorimeter, the limit results from a radiation dose of 5000 rads per 10^7 -second operating year.

We therefore see from comparing the calculated rates with the limits imposed by detector considerations (see Section 2.4) that, on average, the drift chamber dose is a factor of fifteen lower than the most stringent limit. Even the worst case, for the first sense wire, is a factor of six below the limit. Safety factors in the silicon vertex detector and the calorimeter are even better.

4.2.4 Summary

The B Factory lattice and masking designs produce detector synchrotron radiation backgrounds that are more than 100 times below the specified limits for radiation damage and detector occupancy. The design allows most of the synchrotron radiation to pass through the IR without striking any nearby surfaces. Backgrounds are insensitive to the beam-particle distribution at large amplitudes, making the design insensitive to details of the beam-beam interaction. The primary masks, labeled AB and CD in Fig. 4-41, shield the detector beam pipe from direct synchrotron radiation. Detector backgrounds result from photons that scatter through the tips of these masks. A careful analysis of tip-scattered photons using a realistic (rounded) tip edge shows that the background levels

Table 4-13. Summary of detector backgrounds per microsecond, due to lost beam particles; energy is given in MeV.

		Limits				
		LEB	HEB	Total	Occupancy	Radiation
Si 2	Energy	0.06	0.21	0.27	—	—
	$e^\pm$	0.20	0.61	0.81	200	—
	γ	1.9	10.1	12.0	—	—
	rads/yr	250	880	1130	—	10^5
DC 8 1st sense	Energy	0.0005	0.0033	0.0038	—	—
	$e^\pm$	0.32	1.5	1.8	11	50
	γ	95	191	286	—	—
DC 15 $r = 50$ cm	Energy	0.0010	0.0031	0.0041	—	—
	$e^\pm$	0.45	0.44	0.9	28	127
	γ	95	202	297	—	—
Barrel calorimeter	Energy	103	230	333	—	—
	γ	84	176	260	—	—
	rads/yr	2	4	6	—	5000

are essentially the same as those of a mask with a perfect tip. Sources of synchrotron radiation farther upstream (beyond 5 m) were also investigated. These sources do not increase detector occupancy and only increase the amount of energy absorbed in the first layer of silicon by 50%. A substantial amount of synchrotron radiation power strikes surfaces downstream of the IP. Photons that backscatter from these surfaces were studied and found not to contribute to detector background levels. The sensitivity of detector backgrounds to reasonable beam misalignments (± 1 mm) is small (about a factor of two).

We made an exhaustive study of all radiation fans generated near the IP. Care was taken to ensure that all of this miscellaneous synchrotron radiation does not increase detector backgrounds. Nearly 90% of the 97 kW of power is absorbed in downstream dumps. This causes no increase in detector backgrounds, either from backscattered synchrotron radiation photons or from beam-gas interactions.

A detailed study of lost-particle backgrounds in the detector was also carried out. The dose in the drift chamber was found to be a factor of fifteen below its limit, on average, and a factor of six below its limit at the worst location (the first sense wire). For the silicon vertex detector and the calorimeter, even larger safety factors are available. Thus, the configuration adopted here is safely and conservatively designed from the viewpoint of detector backgrounds.

4.3 COLLECTIVE EFFECTS

In Chapter 3 we discussed the alternatives that might be considered in the design of a high-luminosity B Factory, and indicated the reasons for the choices we have made. The lattice design presented in Section 4.1 is based on these choices. Having fixed these parameters, it is necessary to investigate the influence of the various intensity-dependent effects on the actual performance of the accelerator.

The main parameters we must achieve in the B Factory include:

- Beam energies of 9 GeV (HER) and 3.1 GeV (LER)
- Beam currents of 1.48 A (HER) and 2.14 A (LER)
- Bunch length of 1 cm
- Beam emittances of approximately 50 nm-rad (HER) and 100 nm-rad (LER)
- Beam energy spread of $\sigma_E/E \leq 1 \times 10^{-3}$

In terms of collective effects, the dominant issue is the relatively high beam current that must be supported in each ring. As was discussed briefly in Chapter 3, and as will be covered in more detail in Section 4.4, this constraint is associated mainly with the fact that the beam-beam tune shift parameter is taken to be a design limit, which means that the high luminosity must come mainly from the combined benefits of low beta functions and high currents.

A beam circulating in a storage ring interacts with its surroundings electromagnetically by inducing image currents in the walls of the vacuum chamber and other “visible” structures, such as beam position monitor electrodes, kickers, RF cavities, bellows, valves, etc. This interaction leads, in turn, to time-varying electromagnetic fields that act on the beam and can give rise to instabilities. In most electron-positron colliders, single-bunch effects are the primary concern. However, different beam bunches can communicate through the narrow-band impedances in the ring, producing coupled-bunch instabilities.

The issues with which we must deal for the B Factory fall into the broad categories of single-bunch and multibunch phenomena. Single-bunch phenomena include:

- Longitudinal and transverse single-bunch instabilities
- Beam loss from intrabeam (Touschek) or beam-gas scattering
- Beam loss from beam-beam (Bhabha) scattering
- Higher-order-mode (HOM) heating
- Ion trapping

Multibunch phenomena can also be a serious issue. Wakefields deposited in various high- Q resonant objects can influence the motion of following bunches and can cause the motion to become unstable if the beam currents are too high. This effect is one of the most serious issues for a B Factory design.

For our B Factory design, we have opted for a situation in which the nominal beam currents of 1.48 A in the HER and 2.14 A in the LER are distributed in many (1658) bunches. Our reasoning is as follows: The multibunch instabilities are mainly driven by the total beam current, with little regard to how it is distributed in the ring. That is, once the bunch separation is small enough for bunches to fully see wakefields left by preceding bunches, the growth rates are independent of the details of the bunch pattern. Thus, if a high beam current is needed, coupled-bunch instabilities become almost unavoidable. If we choose a relatively small number of bunches to make up the high current, we do little to improve the situation with regard to coupled-bunch instabilities and simply make the single-bunch phenomena harder to manage—in effect requiring the accelerator designers to wage a two-front war. (This usually translates into impedance requirements for the ring that are difficult to meet.) It is true, of course, that the bandwidth requirements of a feedback system to deal with coupled-bunch motion are eased if the bunch spacing increases. However, we do not feel that this is a major limitation (see Section 5.6 for details) and it should not dominate the design decisions.

Given our decision to utilize many bunches, the parameters of the single bunches (emittances, bunch length, intensity) are not unusual—they are in the parameter regime in which PEP and many other colliders have run successfully for many years. This, in turn, means that heroic efforts at impedance reduction are not required to avoid problems with single-bunch effects.

4.3.1 Single-Bunch Issues

In this section, we focus on the issues of single-bunch instability thresholds, beam lifetime, and heating of the chamber due to parasitic HOM losses. We also discuss the issue of ion trapping and the means available to avoid or eliminate it. Before beginning, we digress briefly to define the beam impedances that drive the various instabilities.

4.3.1.1 Impedances. Beam instabilities can occur in either the longitudinal or transverse phase planes. Longitudinal instabilities are driven by voltages induced via interactions of the beam with its environment. The strength of the interaction can be characterized by the ring impedance $Z_{\parallel}(\omega)$, in ohms, which is defined by

$$V_{\parallel}(\omega) = -Z_{\parallel}(\omega) I_b(\omega) \quad (4-3)$$

where $V_{\parallel}(\omega)$ is the longitudinal voltage induced in the beam per turn arising from a modulation of the beam current $I_b(\omega)$ at some particular angular frequency ω .

Transverse instabilities arise from the transverse dipole wake field, which gives a force that increases linearly with transverse distance from the electromagnetic center of the vacuum chamber and is antisymmetric in sign about that center. The transverse impedance (in Ω/m) is defined by

$$Z_{\perp}(\omega) = \frac{-i \int_0^{2\pi R} F_{\perp}(\omega, s) ds}{e \Delta I_b(\omega)} \quad (4-4)$$

where $F_{\perp}$ is the transverse force, integrated over one turn, experienced by a charge e having transverse displacement Δ . Explicitly, $F_{\perp}$ is given by

$$F_{\perp} = e \hat{\theta} (E_{\theta} + B_r) + e \hat{r} (E_r - B_{\theta}) \quad (4-5)$$

In a typical storage ring, the impedance seen by the beam can be loosely characterized as being either broadband or narrow-band. Sharp discontinuities in the vacuum chamber act as local sources of wakefields. These fields have a short time duration, which means that they include many frequency components, and we refer to the corresponding impedance as broadband.

For instability calculations performed in the frequency domain (for example, with ZAP), such impedances are typically represented with a so-called $Q = 1$ resonator, whose analytical form is given below for the longitudinal and transverse cases, respectively:

$$Z_{\parallel}^{\text{BB}}(\omega) = \frac{R_s}{\left[1 + i \left(\frac{\omega_c}{\omega} - \frac{\omega}{\omega_c} \right) \right]} \quad (4-6)$$

$$Z_{\perp}^{\text{BB}}(\omega) = \left(\frac{\omega_c}{\omega} \right) \frac{R_T}{\left[1 + i \left(\frac{\omega_c}{\omega} - \frac{\omega}{\omega_c} \right) \right]} \quad (4-7)$$

This representation has convenient analytical properties and qualitatively exhibits the correct behavior for the actual impedance of a storage ring. In particular, the modulus of the longitudinal impedance, $|Z_{\parallel}|$, is proportional to frequency up to a cutoff frequency ω_c , after which it falls off as $1/\omega$ with increasing frequency. In the calculations of longitudinal instabilities described below, we make use not of $|Z_{\parallel}|$ but of the related quantity $|Z_{\parallel}/n|$, where $n \equiv \omega/\omega_0$ is the harmonic of the revolution frequency ω_0 . This quantity remains essentially constant up to the cutoff frequency, beyond which it decreases as $1/\omega^2$. (The fall-off with frequency for the $Q = 1$ resonator is now believed to be somewhat more rapid than is true for the actual storage ring impedance. Nonetheless, a $Q = 1$ resonator impedance model is typically used for calculational convenience. In the B Factory parameter regime, the differences are not expected to be large.) As can be seen from inspection of Eq. 4-7, the frequency dependence of the transverse impedance follows that of $|Z_{\parallel}/n|$.

The other category of impedance-producing objects in a typical storage ring consists of cavitylike objects. Such objects can trap electromagnetic energy and exchange it with the beam. The wakefield from a cavity oscillates for a long time and thus gives a narrow

spectrum in the frequency domain. These impedances are represented in calculations as narrow-band (that is, high- Q) resonators:

$$Z_{\parallel}(\omega) = \frac{R_s}{\left[1 + iQ\left(\frac{\omega_r}{\omega} - \frac{\omega}{\omega_r}\right)\right]} \quad (4-8)$$

$$Z_{\perp}(\omega) = \left(\frac{\omega_r}{\omega}\right) \frac{R_T}{\left[1 + iQ\left(\frac{\omega_r}{\omega} - \frac{\omega}{\omega_r}\right)\right]} \quad (4-9)$$

Typical values for Q lie in the range of 10^2 – 10^5 , with parasitic modes of the RF cavities being closer to the upper end of the range (unless special procedures, such as those discussed in Section 5.5, are used to de- Q them). As a result of the relatively long duration of these wakefields, trailing beam bunches feel the effects of the bunches that preceded them. The motion of the many bunches in the ring thus becomes coupled and can become unstable for certain patterns of relative phase between bunches. This topic is discussed in Section 4.3.2.

4.3.1.2 Longitudinal Microwave Instability. The first instability we consider is the longitudinal microwave instability, sometimes referred to as turbulent bunch lengthening. This instability, which has been seen in numerous proton and electron storage rings, is not a “fatal” instability, in the sense that it does not lead to beam loss. Instead, the instability causes an increase in both the bunch length and the momentum spread of a bunched beam. Its threshold (peak) current is given by

$$I_p = \frac{2\pi|\eta|(E/e)(\beta\sigma_p)^2}{\left|\frac{Z_{\parallel}}{n}\right|_{\text{eff}}} \quad (4-10)$$

where $|Z_{\parallel}/n|_{\text{eff}}$ is the effective broadband impedance of the ring and $\eta = \alpha - 1/\gamma^2$ is the phase-slip factor.

We refer to an “effective” impedance here to account for the fact that the bunch samples the storage ring impedance weighted by its power spectrum $h(\omega)$, which is the square of the Fourier spectrum of the bunch. As was shown by Zisman [1990a], a short bunch—one having a frequency spectrum that extends well beyond the cutoff frequency of the broadband impedance—does not sample the impedance fully. This reduction in effective impedance can be modeled in calculations by making use of the “SPEAR Scaling” ansatz [Chao and Gareyte, 1976] for $\sigma_l < b$:

$$\left|\frac{Z_{\parallel}}{n}\right|_{\text{eff}} = \left|\frac{Z}{n}\right|_0 \left(\frac{\sigma_l}{b}\right)^{1.68} \quad (4-11)$$

where b is the chamber radius. (In terms of the discussion above, the dependence on b in Eq. 4-11 results from our estimate of the cutoff frequency of the broadband impedance to

be $\omega_c = c/b$.) The result of the impedance roll-off for short bunches is that the bunch lengthening threshold increases. It is worth noting that the expression given in Eq. 4-11, which was determined phenomenologically, is in reasonable agreement with the behavior expected from a simple $Q = 1$ resonator.

As mentioned, the actual broadband impedance in a storage ring is not exactly a $Q = 1$ resonator shape, and so the actual roll-off of the broadband impedance in any ring depends on the details of the particular vacuum chamber hardware. Indeed, in modern storage rings that are specifically designed to minimize the broadband impedance, it may well be that the impedance is dominated by a few discrete items, making the concept of an amorphous broadband impedance somewhat suspect.

To estimate the growth from the longitudinal microwave instability, we must assume a value for the broadband impedance of the ring. For the B Factory HER, this value—usually dominated by the RF system in a high-energy storage ring—is expected to be lower than the value of $|Z/n| = 3 \Omega$ obtained from measurements at PEP [Rivkin, 1987].

The equivalent broadband contribution to the impedance seen by the beam can be estimated, for a given RF system, following the approach of Zisman et al. [1986]. Basically, this involves estimating the frequency shift that would be induced in a long beam bunch by the aggregate of the many cavity HOMs, and then determining the strength of a $Q = 1$ broadband resonator that would produce the same effect. That is, we take

$$\left| \frac{Z_{\parallel}}{n} \right|_{\text{BB,RF}} = \sum_{\text{HOMs}} \left| \frac{Z_{\parallel}}{n} \right|_j = \sum_j \left(\frac{R_s \omega_0}{Q \omega_R} \right)_j \quad (4-12)$$

where R_s , ω_R , and Q are the shunt impedance, resonant angular frequency, and quality factor, respectively, of the j th HOM, and ω_0 is the particle (angular) revolution frequency. With this approach, we find that the present PEP RF system contributes an equivalent broadband component of $|Z/n| \approx 0.026 \Omega/\text{cell}$. Applying the same prescription to the B Factory RF cavity (described in Section 5.5) yields an equivalent broadband contribution of $|Z/n| \approx 0.01 \Omega$ for the first few trapped modes. If additional higher-frequency modes were included in our estimate, it is likely that the broadband impedance *per cell* would not differ markedly from PEP.

A more significant gain is made by producing the required voltage and providing the required power to the beam (to replenish the losses to synchrotron radiation) with many fewer RF cells than the 120 used now at PEP. In the design described in Section 5.5, the voltage is provided by only 20 RF cells in the HER or 10 cells in the LER. This decrease in the number of cells reduces, by about a factor of six, the broadband impedance in the ring that stems from the RF system (estimated in PEP to be about two-thirds of the total). Thus, we expect to reduce the RF contribution to the broadband impedance to about 0.3Ω . Clearly, however, the broadband impedance from the other components in the beam path (valves, bellows, BPMs, etc.) must contribute to the total seen by the beam, and there will be additional hardware in the B Factory ring (for example, more powerful feedback kickers) that will have an effect.

A preliminary investigation of the impedance contributions from the various components in the rings was carried out by Heifets [1990b]. The results of this

investigation, summarized in Table 4-14, indicate a small impedance contribution from the non-RF hardware. Nonetheless, the actual PEP chamber has a broadband impedance of about $1\ \Omega$, and it is prudent, for now, to take the larger value to account for those things that have not been considered yet. With this in mind, we have adopted a total broadband impedance of $|Z/n| = 1.5\ \Omega$ for the HER—half that of PEP. As we will see, even this fairly conservative assumption does not lead to any difficulties in the parameter regime in which the B Factory rings are designed to operate. Although the LER has less RF hardware than does the HER, we have assumed for simplicity that it is also characterized by a broadband impedance of $1.5\ \Omega$.

Table 4-14. Preliminary B Factory impedance budget.

Item	Broadband impedance contribution (Ω)
Bellows	0.012
Clearing electrodes	0.072
Transition tapers	0.18
Feedback system	0.05
Interaction region	0.015
Total	0.35

To maintain bunch lengths in both rings that are short compared with the small β^* value of 1.5 cm in the LER, we adopt an RF voltage in the HER of 18.5 MV. As shown in Fig. 4-69, this voltage gives an rms bunch length of $\sigma_z = 1$ cm at the required single-bunch current of 0.9 mA. For the LER (see Fig. 4-70), a 1-cm bunch at the design current of 1.3 mA can be obtained with a voltage of 9.5 MV.

The expected bunch lengthening beyond threshold is shown in Fig. 4-71 for the HER, based on the threshold formula given in Eq. 4-10. We remain well below the threshold at the required single-bunch current of 0.9 mA. The situation for the LER is shown in Fig. 4-72; again we are well below threshold at the nominal 1.3 mA/bunch value. The curves in Figs. 4-71 and 4-72 are based on the so-called SPEAR Scaling ansatz, mentioned earlier. It is worth noting here that we have estimated the natural momentum spread of the low-energy beam to be 9.5×10^{-4} . This relatively large value is associated with the significant amounts of "extra" synchrotron radiation (generated in the wigglers) needed to achieve the proper emittance and to preserve the ability to reach equal damping decrement if need be.

Because the collider must be able to accommodate some energy variability, we have also considered the effects of moderate changes from the nominal operating energies of 9

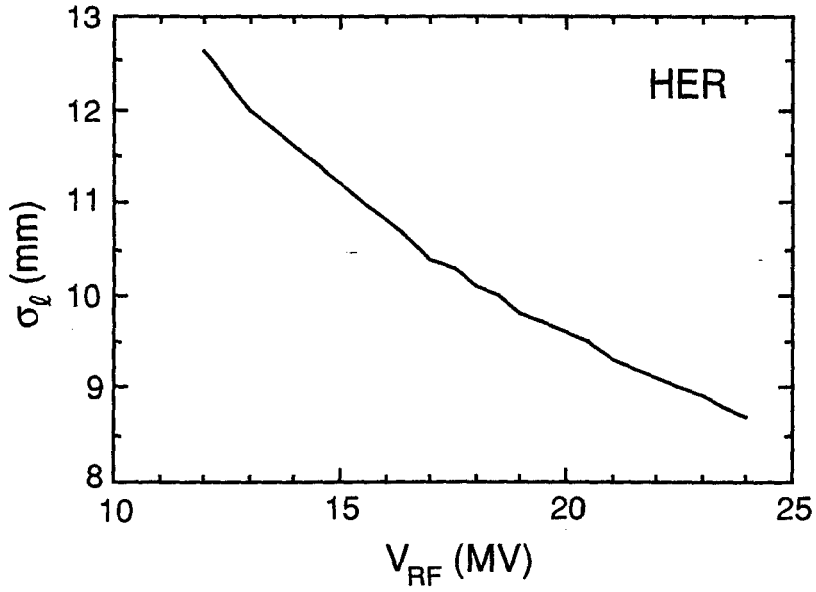


Fig. 4-69. Plot of HER bunch length as a function of RF voltage. A 1-cm bunch requires $V_{RF} = 18.5$ MV.

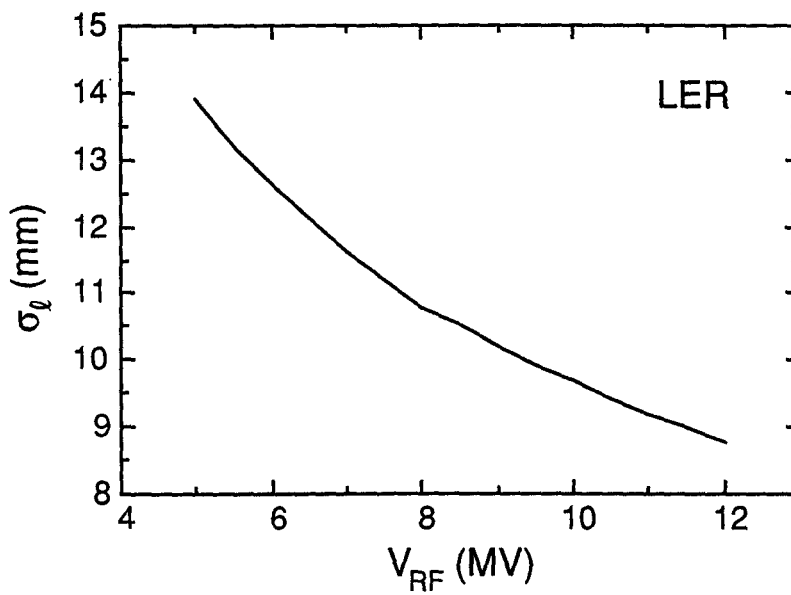


Fig. 4-70. Plot of LER bunch length as a function of RF voltage. A 1-cm bunch requires $V_{RF} = 9.5$ MV.

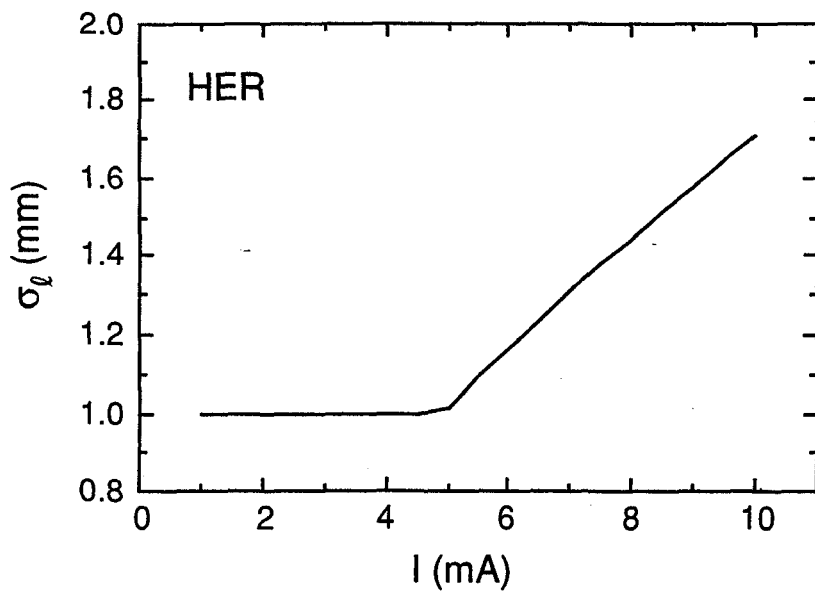


Fig. 4-71. Plot of HER bunch length as a function of current, showing the onset of bunch lengthening. Even above threshold, the bunch length increases only slowly with current.

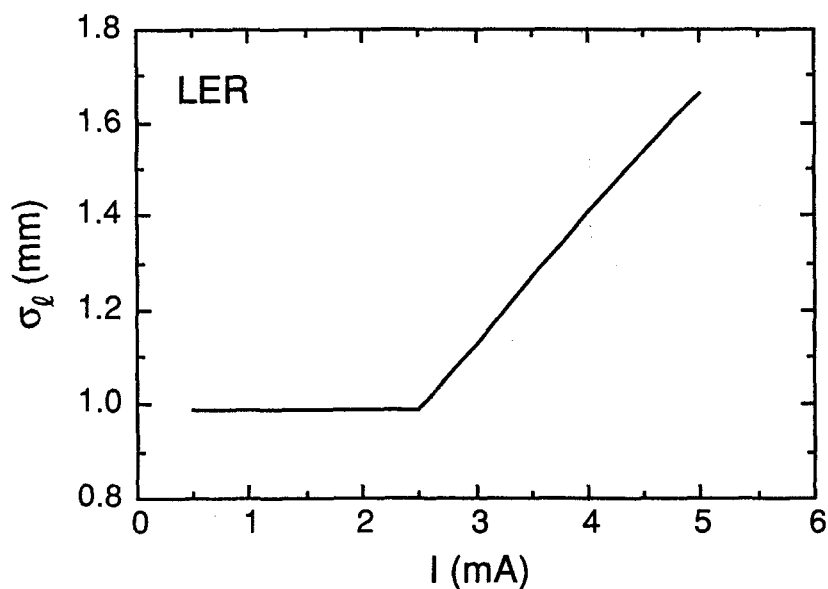


Fig. 4-72. Plot of LER bunch length as a function of current, showing the onset of bunch lengthening. The bunch length increases slowly with current above threshold.

GeV (HER) and 3.1 GeV (LER). In Figs. 4-73 and 4-74, we show the energy dependence of the microwave threshold current at the specified operating voltages for the two rings. The steepness of these curves is mainly due to the increase in natural momentum spread with energy (see Eq. 4-10). The dependence of the threshold current on voltage is shown for several different energies in Fig. 4-75 (HER) and 4-76 (LER). The preference for higher voltage is a consequence of the decrease in effective impedance as the bunch length decreases.

In our calculations we have ignored the effect of potential-well distortion, which—for short bunches—is predicted to reduce the bunch length; this effect is expected to be minor.

From these estimates, we conclude that there are no problems associated with the longitudinal microwave instability, provided the broadband impedance of each ring can be kept at or below 1.5Ω .

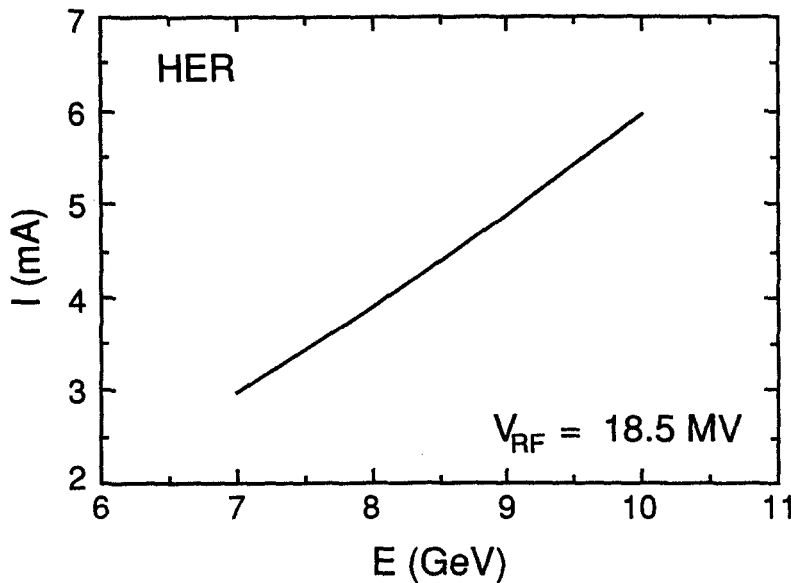


Fig. 4-73. Plot of the microwave threshold current in the HER as a function of energy, for $V_{RF} = 18.5$ MV. The required single-bunch current of 0.9 mA is well below the instability threshold in this energy range.

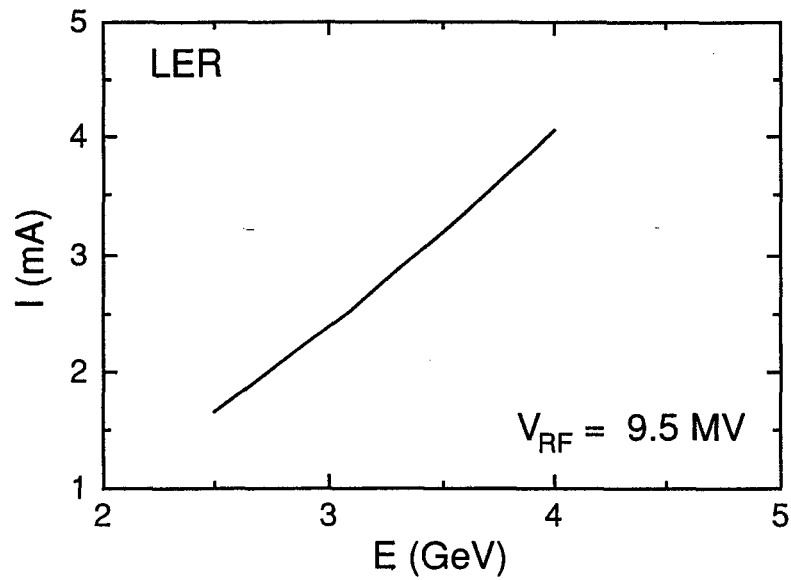


Fig. 4-74. Plot of the microwave threshold current in the LER as a function of energy, for $V_{RF} = 9.5$ MV. The required single-bunch current of 1.3 mA is below the instability threshold in this energy range.

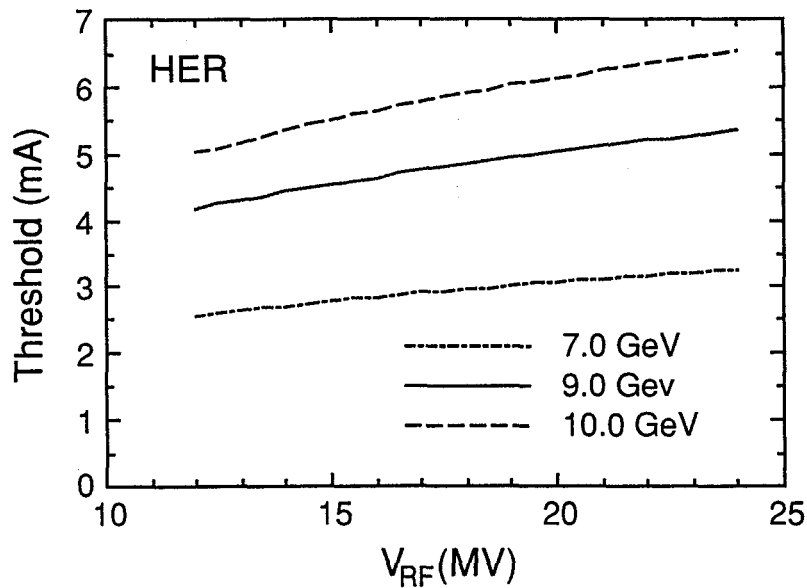


Fig. 4-75. Plot of the microwave threshold current in the HER as a function of RF voltage, for several energies. Throughout this parameter range, the threshold current is well beyond the required 0.9 mA.

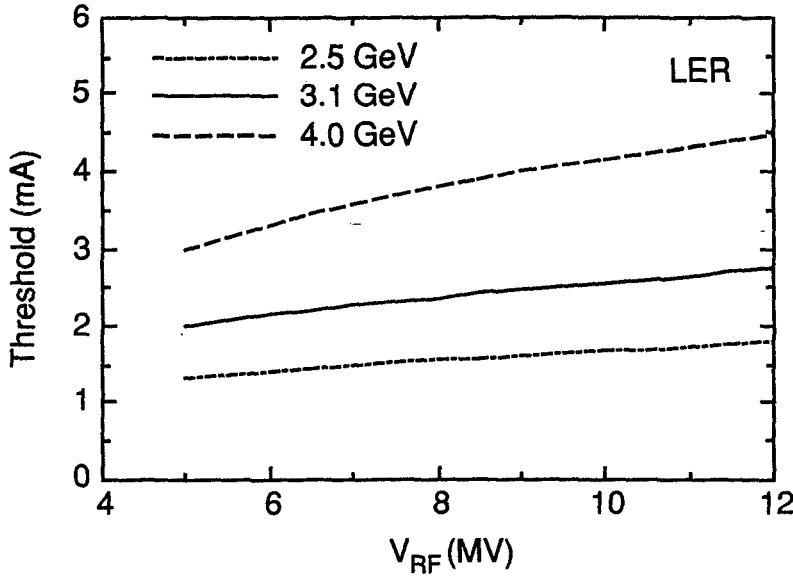


Fig. 4-76. Plot of the microwave threshold current in the LER as a function of RF voltage, for several energies. Only for the lowest energy and lowest voltage does the threshold current approach the required operating value of 1.3 mA.

4.3.1.3 Transverse Mode-Coupling Instability. Because the ring is large, we must also consider the transverse mode-coupling instability, which is known [Zisman et al., 1988] to limit the single-bunch current in PEP. This instability arises when the imaginary part of the transverse impedance $Z_{\perp}$ couples the frequency of the $m = 0$ and $m = -1$ synchrotron sidebands. For long bunches, the threshold is expected to scale as

$$I_b = \frac{4(E/e) v_s}{\langle \text{Im}(Z_{\perp}) \beta_{\perp} \rangle R} \frac{4\sqrt{\pi}}{3} \sigma_t \quad (4-13)$$

where v_s is the synchrotron tune, $\beta_{\perp}$ is the beta function at the location of the impedance, and R is the average ring radius. Although the transverse impedance is expected to decrease for very short bunches [Zisman 1990a], we are operating in a regime where the mode-coupling threshold is more or less independent of bunch length. For the impedance presently expected for the HER, a simple scaling from measured PEP data based on Eq. 4-13, shown in Table 4-15, suggests that the transverse mode-coupling threshold should be somewhat higher for the B Factory than for PEP, even though both the HER and LER will have a lower beam energy than does PEP. The scaled threshold value for the LER, nearly 14 mA/bunch, is well beyond the required single-bunch current of 1.3 mA and should pose no problem.

To estimate the transverse mode-coupling threshold in each ring more reliably, we used the code MOSES [Chin, 1988]. Initially, we considered a $Q = 1$ resonator impedance having a cutoff frequency of 1 GHz and a transverse impedance of 0.5 M Ω /m.

Table 4-15. Scaling comparison for transverse mode-coupling threshold.

	Low-energy ring	PEP	High-energy ring
E [GeV]	3.1	14.5	9.0
$\beta_{\perp}$ [m]	20	87	20
R [m]	350	350	350
v_s [10^{-2}]	5.0	4.6	5.3
$Z_{\perp}$ [M Ω /m]	0.5	0.8	0.5
Relative factor ^a	1.6	1	5.0
Observed [mA]	—	8.5	—

$$^a \text{Factor} = \frac{Ev_s}{Z_{\perp}\beta_{\perp}R}$$

The calculations take into account the effect of bunch lengthening at high currents, which is ignored in the simple scaling arguments presented in Table 4-15. The threshold currents, corresponding to the crossing of the mode $m = 0$ and mode $m = -1$ frequencies, are 37 mA for the HER (Fig. 4-77) and 10.6 mA for the LER (Fig. 4-78), in good agreement with the scaling estimates.

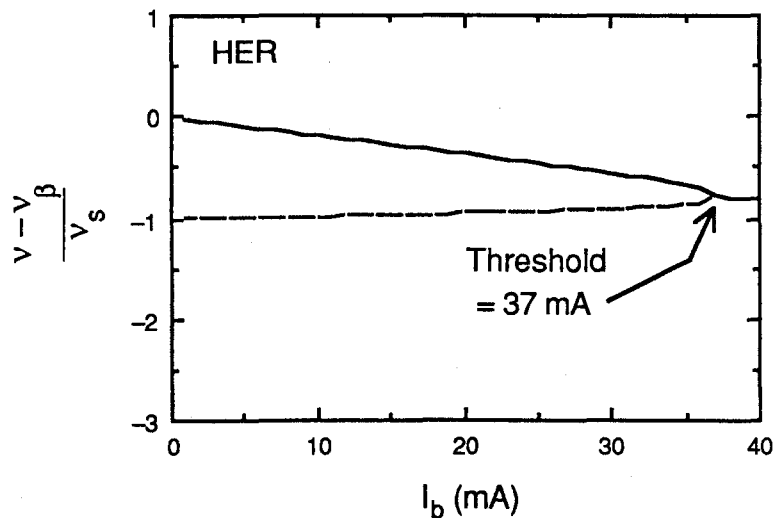


Fig. 4-77. Calculation of transverse mode-coupling instability threshold for the HER, assuming $Z_{\perp} = 0.5$ M Ω /m. The instability sets in when the $m = 0$ and $m = -1$ frequencies merge. This calculation represents a limitation in the horizontal plane; the vertical limitation is lower (see text).

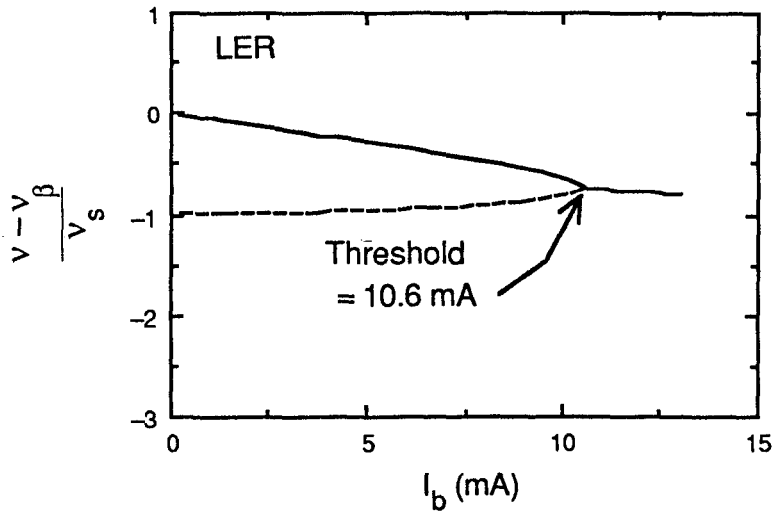


Fig. 4-78. Calculation of transverse mode-coupling instability threshold for the LER, assuming $Z_{\perp} = 0.5 \text{ M}\Omega/\text{m}$. The instability sets in when the $m = 0$ and $m = -1$ frequencies merge. This calculation represents a limitation in the horizontal plane; the vertical limitation is lower (see text).

Because the RF cavities are no longer expected to be the dominant impedance source, we have also considered the situation in which the transverse impedance comes mainly from the arc vacuum chamber hardware. In this case, the cutoff frequency for $Z_{\perp}$ increases to 1.9 GHz, and the strength of the impedance (weighted by the fraction of the circumference that consists of arc chambers, roughly 70%) increases to about 1.3 M Ω/m . For these parameters, MOSES predicts the transverse thresholds to be 6.5 mA for the HER and 2.2 mA for the LER.

To put these results in context, we note that the maximum allowable single-bunch current in the B Factory rings is 1.8 mA, corresponding to 3 A in 1658 bunches. Thus, the transverse mode-coupling instability is not expected to limit the performance of the B Factory.

Although the RF cavities are not the dominant contributors to the transverse impedance, it is still best to “hide” them in a low-beta region of the ring. This should be more easily accomplished in the B Factory HER than in PEP, because the total length of RF structure will be considerably shorter. Indeed, it would be possible, in principle, to adapt the focusing of the RF straight sections to permit very low beta functions in both planes.

4.3.1.4 Intrabeam Scattering. Although we are considering beams of fairly high energy, the requirements for relatively short bunches and relatively high peak currents make emittance growth from intrabeam scattering (IBS) a possible concern. IBS collisions occur because, in the bunch rest frame, not all particles are moving in the same direction. In general, the temperatures in the transverse phase planes (x and y) are higher than in the longitudinal plane. This results in small-angle multiple scattering occurring mainly in such a way as to transfer momentum from the transverse to the longitudinal plane. However, in dispersive regions of the lattice, this momentum change results in the

excitation of a betatron oscillation and thus gives rise to an increase in horizontal emittance.

To be sure this is not a concern, we performed calculations on each of the rings at the lowest energy now being considered: 7 GeV for the HER and 2.5 GeV for the LER. In the HER case, our estimates indicate that no growth is expected. In the LER case, the lower beam energy enhances the IBS growth rates, and the single-bunch current is higher than for the high-energy beam, so we might expect an observable growth. However, in the LER these aspects are compensated by the larger transverse emittance values. Thus, even here we predict no emittance growth from intrabeam scattering.

4.3.1.5 Beam and Luminosity Lifetime. For a high-energy electron beam, there are four main processes that lead to beam loss: Touschek and gas scattering for the single beams, and Bhabha ($e^+e^- \rightarrow e^+e^-$) and radiative Bhabha ($e^+e^- \rightarrow e^+e^-\gamma$) interactions for the beams in collision. For single beams at the B Factory, the first of these effects is not generally important, but the second one is. For the colliding beams, the radiative Bhabha interactions dominate the luminosity lifetime. Lifetimes presented in this section are quoted as mean (that is, $1/e$) values.

Touschek Scattering. The Touschek scattering mechanism is related to the IBS mechanism described above. The main difference is that we are concerned now with large-angle, single-scattering events that change the scattered particle's momentum sufficiently to make it fall outside the momentum acceptance of the accelerator.

The limit on the tolerable momentum deviation from the design value can come from several sources. There is a longitudinal limit from the potential well ("RF bucket") provided by the RF system. Particles deviating in momentum from the nominal value by more than this amount do not undergo stable synchrotron oscillations and are lost. There can also be a transverse limit on momentum acceptance, arising from the excitation of a betatron oscillation when the Touschek scattering event takes place in a dispersive region of the lattice. For large momentum deviations ($\delta p/p \approx$ several percent), the resultant betatron oscillation can either hit the vacuum chamber wall elsewhere in the lattice (physical aperture limit) or exceed the dynamic aperture of the machine. Because the lifetime for Touschek scattering increases approximately as $(\Delta p/p)^3$, where $(\Delta p/p)$ is the limiting momentum acceptance value, there is the potential for a strong degradation if the acceptance is too low.

For detector background reasons, we envision the possibility of installing collimators in the arcs that would restrict the particle amplitudes to about $10\sigma_x$ motion. To see how this affects the various lifetimes, ZAP has been modified to include this option.

The RF voltage in the HER, selected to be 18.5 MV so as to produce short beam bunches, actually provides too large an acceptance ($\Delta p/p = 1\%$) compared with the estimated limitation from the physical aperture ($\Delta p/p = 0.7\%$). This is not beneficial to the lifetime, since it results in a higher bunch density and thus a higher collision probability; this is the price we must pay to obtain short bunches. Fortunately, the Touschek lifetime is not a major concern in this parameter regime, as shown in Fig. 4-79. At 9 GeV, a Touschek lifetime of 870 hours is predicted for the HER based on the physical aperture limit. If a 10σ limit is applied, however, the lifetime decreases to 188 hours.

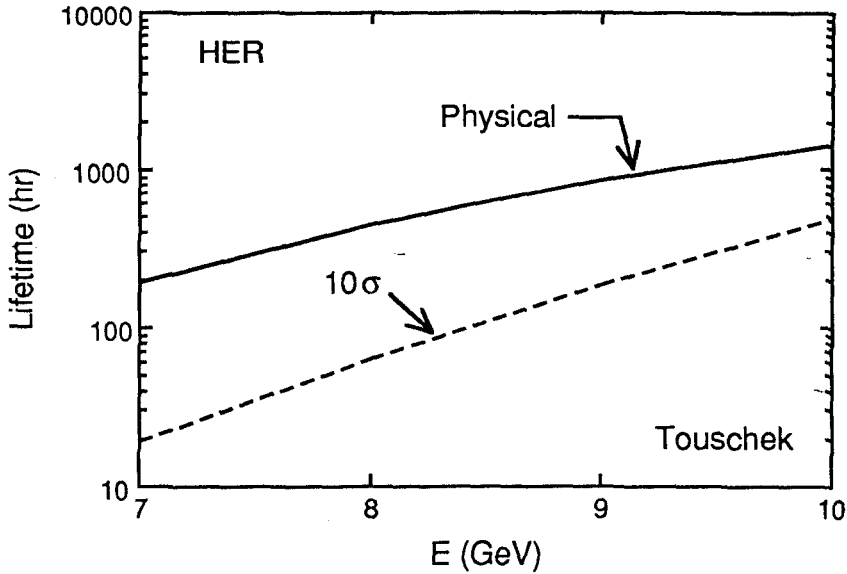


Fig. 4-79. Plot of Touschek lifetime as a function of beam energy in the B Factory HER. The solid line corresponds to taking the physical aperture of the vacuum chamber as the transverse limitation; the dashed line assumes a 10σ aperture restriction in the injection straight section.

In the LER, the physical momentum acceptance limit, $\Delta p/p \approx 1.3\%$, is almost the same as that of the RF bucket ($\Delta p/p \approx 1.7\%$). Although the energy is lower than in the HER, the large acceptance makes the Touschek lifetime about 270 hours, and thus not of concern. With a 10σ aperture restriction, the lifetime drops to 65 hours, which is still quite comfortable. We see (Fig. 4-80) that a 10σ aperture becomes quite noticeable at the lower energies, where the lifetime drops to below 10 hours.

Gas Scattering. Gas scattering involves collisions with residual gas nuclei present in the vacuum chamber. Such collisions can be either elastic or inelastic (bremsstrahlung). In the former case, particle loss results from the excitation of a betatron oscillation that exceeds the physical or dynamic aperture of the ring; in the latter case, the loss results from a momentum change that exceeds the momentum acceptance of the ring (see discussion above).

The HER must accommodate 1.48 A of circulating beam to reach a luminosity of $3 \times 10^{33} \text{ cm}^{-2} \text{ s}^{-1}$. This high beam current will give a large desorbed-gas load, and substantial pumping speed is needed to maintain a background gas pressure below 10 nTorr in the ring. The B Factory vacuum system is designed to produce a pressure of 5 nTorr under these conditions, so we base our lifetime estimates on this value (N_2 equivalent).

For the HER (see Fig. 4-81), the estimated lifetime from gas scattering—dominated by the bremsstrahlung process—is six hours at a pressure of 5 nTorr. This beam loss process is much more severe in its effects than the Touschek scattering process; therefore, we have placed great emphasis (see Section 5.2) on a vacuum system design capable of maintaining a good pressure in the presence of a large gas load from synchrotron-radiation desorption. It is worth noting here that our lifetime estimates are somewhat

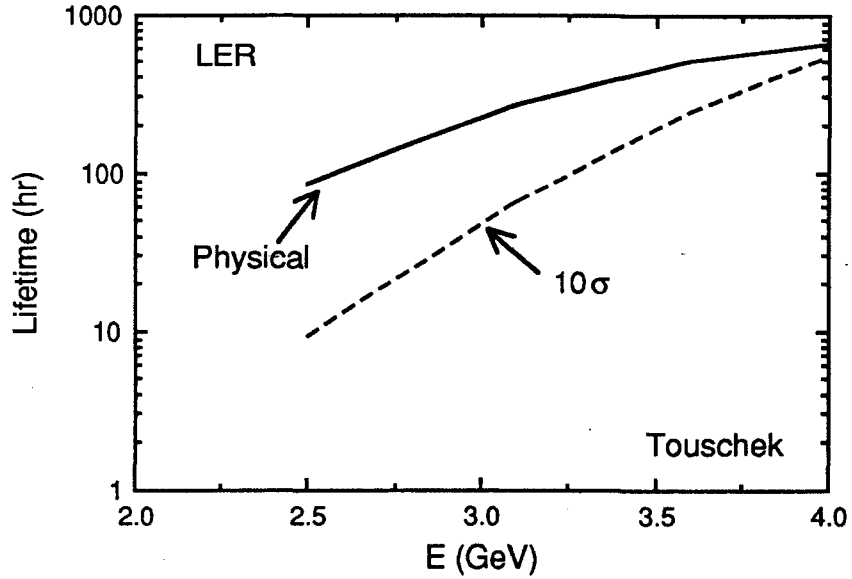


Fig. 4-80. Plot of Touschek lifetime as a function of beam energy in the B Factory LER. The solid line corresponds to taking the physical aperture of the vacuum chamber as the transverse limitation; the dashed line assumes a 10σ aperture restriction in the injection straight section.

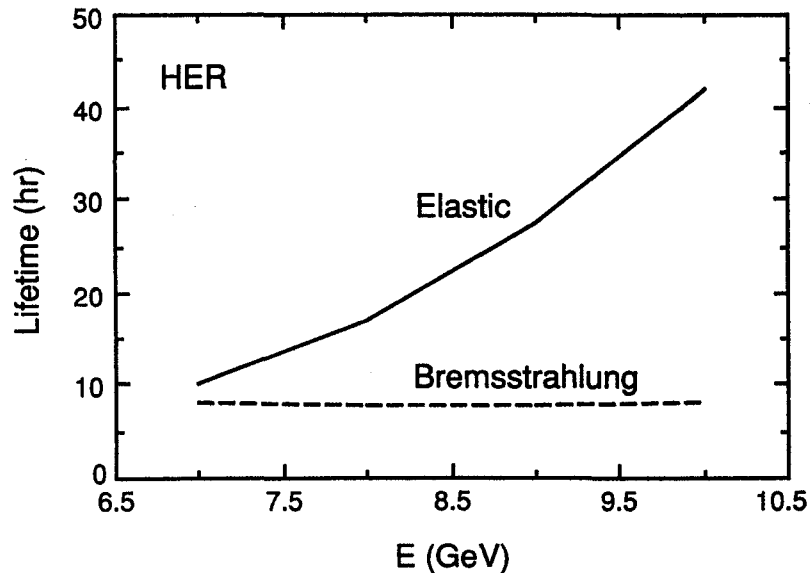


Fig. 4-81. Plot of gas-scattering lifetime as a function of beam energy for the HER. For the elastic scattering (solid line), an aperture restriction of 10σ was taken in each plane, with the vertical σ being calculated with the fully coupled vertical emittance. An average pressure of 5 nTorr (N_2 equivalent) was assumed.

pessimistic in that they are based on a fixed gas pressure. In reality the pressure will decrease as the beam current decreases, making the lifetimes longer than the values quoted here.

For the LER at a gas pressure of 6 nTorr (N_2 equivalent), the lifetime is roughly equally matched between elastic scattering and bremsstrahlung losses (see Fig. 4-82); the overall beam lifetime is 3.6 hr. Even for the LER, special care must be taken in the design of the vacuum chamber; this topic is discussed in Section 5.2.

Luminosity Lifetime. A potentially important contribution to beam lifetime is the loss of particles due to interactions between the individual particles in the two beams. In particular, we consider the loss of particles due to $e^+e^- \rightarrow e^+e^-$ and $e^+e^- \rightarrow e^+e^-\gamma$ interactions that scatter beam particles outside the accelerator acceptance.

If the e^+e^- cross section leading to loss of a particle from beam i is σ_i , then the loss rate depends on the luminosity according to

$$\frac{dN_i}{dt}(t) = -\sigma_i \mathcal{L}(t) \quad (4-14)$$

Each beam may consist of a number of bunches (not including gaps), n_{bi} with a number of particles per bunch, $N_{bi}(t)$. The subscript b is used to indicate that this is a quantity for a single bunch, and the subscript i refers to the beam ($i = +, -$). The total number of particles in a given beam is $N_i = n_{bi}N_{bi}$. We introduce the notation $N_{0,i} \equiv N_i(0)$, and we also use $\mathcal{L}_0 \equiv \mathcal{L}(0)$ to denote quantities evaluated at $t = 0$.

To determine the beam and luminosity lifetimes for the processes of interest, we need to know how the luminosity depends on the beam currents. This dependence is

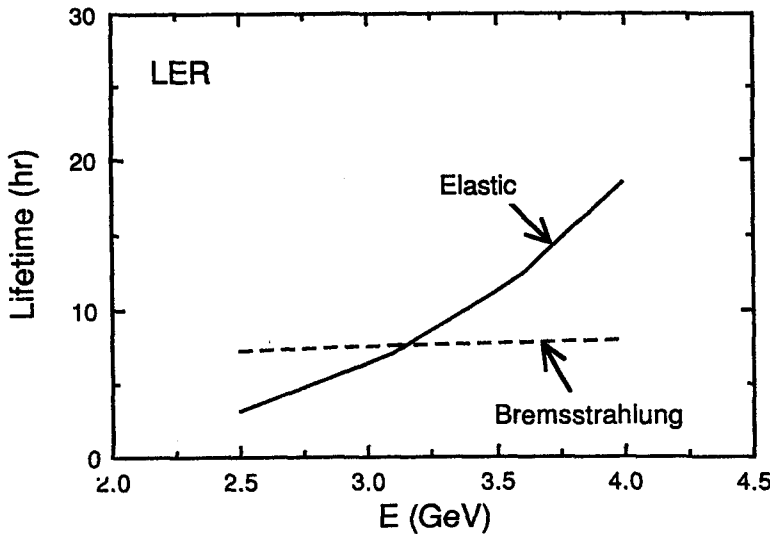


Fig. 4-82. Plot of gas-scattering lifetime as a function of beam energy for the LER. For the elastic scattering (solid line), an aperture restriction of 10σ was taken in each plane, with the vertical σ being calculated with the fully coupled vertical emittance. An average pressure of 6 nTorr (N_2 equivalent) was assumed.

determined to some extent by the operation of the storage ring. We adopt here a conservative model which assumes that the bunch sizes do not vary with time. Then the luminosity is given by

$$\mathcal{L}(t) = \frac{N_{b+}(t)N_{b-}(t)n_b f_i}{2\pi\sqrt{(\sigma_{x,+}^{*2} + \sigma_{x,-}^{*2})(\sigma_{y,+}^{*2} + \sigma_{y,-}^{*2})}} \quad (4-15)$$

The $\sigma_{x,\pm}^*$ and $\sigma_{y,\pm}^*$ in this equation are the transverse rms spot sizes at the interaction point (IP). All time-dependent terms are explicitly indicated. It is assumed that the bunches are distributed such that all bunches meet opposing bunches at the IP (that is, bunches meet bunches and gaps meet gaps), hence $n_{b+}f_+ = n_{b-}f_-$ is the bunch collision frequency. Here, f_i is the revolution frequency for beam i . We also assume that any modifications to the above formula from considerations such as finite bunch lengths and nonzero crossing angles are time independent.

Equations 4-14 and 4-15 lead to two coupled differential equations in the beam currents:

$$\begin{aligned} \frac{dN_+}{dt} &= -k\sigma_+N_+N_- \\ \frac{dN_-}{dt} &= -k\sigma_-N_+N_- \end{aligned} \quad (4-16)$$

where

$$k \equiv \frac{\mathcal{L}_0}{N_{0,+}N_{0,-}} \quad (4-17)$$

The solution is

$$\begin{aligned} N_+(t) &= N_{0,+} \frac{1-r}{e^{Gt}-r} \\ N_-(t) &= N_{0,-} \frac{1-r}{1-re^{-Gt}} \end{aligned} \quad (4-18)$$

where

$$G \equiv \mathcal{L}_0 \left(\frac{\sigma_+}{N_{0,+}} - \frac{\sigma_-}{N_{0,-}} \right) \quad (4-19)$$

and

$$r \equiv \frac{N_{0,+}\sigma_-}{N_{0,-}\sigma_+} \quad (4-20)$$

The $1/e$ beam lifetimes are given by

$$\begin{aligned}\tau_+ &= \frac{1}{G} \ln [e + r(1 - e)] \\ \tau_- &= -\frac{1}{G} \ln \left[\frac{1}{r} (1 - e + re) \right]\end{aligned}\quad (4-21)$$

The time-dependence of the luminosity is

$$\mathcal{L} = \mathcal{L}_0 e^{Gt} \left(\frac{1 - r}{e^{Gt} - r} \right)^2 \quad (4-22)$$

We define the luminosity lifetime τ to be the time it takes the luminosity to reach $1/e$ of its initial value:

$$\tau = \frac{1}{G} \ln \left\{ \frac{e}{2} \left[(1 - r)^2 + 2r/e + (1 - r) \sqrt{(1 - r)^2 + 4r/e} \right] \right\} \quad (4-23)$$

The more important mechanism of the two Bhabha processes considered here is loss due to bremsstrahlung ($e^+e^- \rightarrow e^+e^-\gamma$) of a photon, which can change the energy of a beam particle sufficiently to put it outside the energy acceptance of the accelerator. An excellent approximation for the cross section to lose a particle from beam i due to bremsstrahlung is [Altarelli and Buccella, 1964]

$$\sigma_{\text{brems } i} \approx \frac{16\alpha r_e^2}{3} \left[\left(\ln \frac{E_{\text{c.m.}}^2}{m_e^2} - \frac{1}{2} \right) \left(\ln \frac{E_i}{k_{\min i}} - \frac{5}{8} \right) + \frac{1}{2} \left(\ln \frac{E_i}{k_{\min i}} \right)^2 - \frac{3}{8} - \frac{\pi^2}{6} \right] \quad (4-24)$$

In this expression, $k_{\min i}$ is the minimum energy of a radiated photon that causes loss of a particle from beam i . Thus, $k_{\min i}/E_i$ can be taken as the fractional energy aperture of the machine for beam i . This cross section depends slowly on the energy aperture and on $E_{\text{c.m.}}$.

Table 4-16 shows the bremsstrahlung beam loss cross section calculated according to Eq. 4-24 for the Asymmetric B Factory. The fractional energy aperture is limited by the transverse aperture rather than by the RF voltage—we have used a value corresponding to ten times the rms energy spread of the beam.

The $1/e$ time for the low-energy beam is infinite; that is, the high-energy beam is completely destroyed before the low-energy beam drops by $1/e$ from its initial value. The asymptotic current in the low-energy beam is roughly 40% of its initial value. The instantaneous loss rate at $t = 0$ for the low-energy beam would correspond to a $1/e$ beam lifetime of 36 hours if the rate were constant.

We note that the large circumference of the B Factory rings (2200 m) helps to produce a comfortably large luminosity lifetime from this source. Even if future upgrades result in a higher luminosity, we do not have a problem. For example, suppose we anticipate a luminosity of $1 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$. As a “worst case,” suppose further that

Table 4-16. Bremsstrahlung luminosity lifetime calculation.

Parameter	Symbol	High-energy ring	Low-energy ring
Fractional energy aperture	f_E	0.0061	0.0095
Min. energy in brems. integral [MeV]	$k_{\min}$	55.0	29.7
Brems. cross section for particle loss [cm ²]	$\sigma_{e^+e^-\gamma}$	3.0×10^{-25}	2.7×10^{-25}
Bremsstrahlung beam lifetime [hr]	$\tau_{Br\ i}$	27.3	—
Bremsstrahlung luminosity lifetime [hr]	τ_{Br}	17.2	

this gain is achieved at the same beam currents as in our nominal design, either by reaching higher tune shifts or by focusing more strongly. In this case, the luminosity lifetime is inversely proportional to the luminosity, so 17.2 hours at $3 \times 10^{33} \text{ cm}^{-2} \text{ s}^{-1}$ becomes 5.2 hours at $10^{34} \text{ cm}^{-2} \text{ s}^{-1}$. This would still be acceptable, although it would then be comparable to the beam-gas luminosity decay rate.

Another loss mechanism, typically not as important as the bremsstrahlung considered above, is the loss due to Bhabha ($e^+e^- \rightarrow e^+e^-$) scattering at sufficiently large angles to escape the acceptance of the machine. To a good approximation for the small angles and high energies that we consider, the cross section to lose a particle from beam i is

$$\sigma_{\text{Bhabha } i} \approx \frac{8\pi\alpha^2}{E_{\text{c.m.}}^2} \frac{E_j}{E_i} \left(\frac{1}{\theta_{\min x;i}^2} + \frac{1}{\theta_{\min y;i}^2} \right) \quad (4-25)$$

where $\theta_{\min x,y;i}$ is the minimum horizontal or vertical scattering angle in the laboratory frame leading to particle loss, and $j = (-,+)$. Cross sections in units of GeV^{-2} may be converted to cm^2 by multiplying by $3.89 \times 10^{-28} \text{ GeV}^2 \text{ cm}^2$.

Table 4-17 summarizes the calculation for the present B Factory design. For the minimum angles, we have made our usual assumption that the limiting aperture is 10σ (using the uncoupled horizontal and the fully coupled vertical beam sizes). Because the Bhabha cross section to lose a beam particle is substantially smaller than the cross section in our earlier bremsstrahlung loss example, this is not a significant lifetime consideration.

We conclude that the luminosity lifetime from $e^+e^- \rightarrow e^+e^-$ and $e^+e^- \rightarrow e^+e^-\gamma$ will not be a significant limitation for the B Factory at a luminosity of $\mathcal{L} = 3 \times 10^{33} \text{ cm}^{-2} \text{ s}^{-1}$. Even at a luminosity of $1 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$, the large circumference (and hence large number of particles per unit of beam current) of the B Factory rings ensures that these sources of beam loss will not seriously degrade the lifetime.

4.3.1.6 Higher-Order-Mode Losses. A complete specification of the thermal loading in the vacuum chamber must take into account the localized heating of beamline

Table 4-17. Bhabha luminosity lifetime calculation.

Parameter	Symbol	High-energy ring	Low-energy ring
Minimum angle in Bhabha integral [rad]	$\theta_{\min x}$	2.59×10^{-3}	5.17×10^{-3}
Minimum angle in Bhabha integral [rad]	$\theta_{\min y}$	9.14×10^{-3}	1.83×10^{-2}
Bhabha cross section for beam loss [cm ²]	$\sigma_{e^+e^-}$	2.60×10^{-28}	5.44×10^{-28}
Bhabha beam lifetime [hr]	$\tau_{Bh i}$	90000	24000
Bhabha luminosity lifetime [hr]	τ_{Bh}	13373	

components due to the absorption of power generated by the beam in the form of HOM losses. We estimate the HOM power as

$$P_{\text{HOM}} = 1.6 \times 10^{-10} N_b I k_l \text{ [kW]} \quad (4-26)$$

where N_b is the number of particles per bunch, I (in A) is the total current, and k_l (in V/pC) is the loss factor for the ring due to its broadband impedance. For the design parameters of the B Factory, the HOM power in the HER is given by [Heifets, 1990a]

$$P_{\text{HOM}} = 10 k_l \text{ [kW]} \quad (4-27)$$

The equivalent value for the LER is

$$P_{\text{HOM}} = 20 k_l \text{ [kW]} \quad (4-28)$$

To estimate the loss factor, we consider a broadband impedance of the form

$$\frac{Z(\omega)}{n} = \begin{cases} \frac{Z}{n} & \text{for } \omega \leq \omega_c \\ \frac{Z}{n} \left(\frac{\omega_c}{\omega} \right)^{3/2} & \text{for } \omega > \omega_c \end{cases} \quad (4-29)$$

This form of broadband impedance has a frequency dependence similar to that of the commonly used $Q = 1$ resonator (see Eq. 4-6) at low frequencies, but it falls off more slowly above the cutoff frequency $\omega_c = c/b$, where b is the beam pipe radius. The loss factor is defined as

$$k_l = \frac{1}{\pi} \int_0^\infty Z(\omega) e^{-(\omega \sigma_t/c)^2} d\omega \quad (4-30)$$

For the impedance of Eq. 4-29, the loss factor is dominated by the contribution from the high-frequency tail and has been estimated by Heifets [1990a] to be

$$k_\ell = \frac{1}{6000} \left(\frac{Z}{n} \right) \left(\frac{R}{b} \right) \frac{R}{\sqrt{b\sigma_\ell}} \left[\frac{R}{\text{pC}} \right] \quad (4-31)$$

where (Z/n) is the broadband impedance (in Ω), R is the mean ring radius (in meters), b is the chamber height (in meters), and σ_ℓ is the rms bunch length (in meters). For $(Z/n) = 1 \Omega$, we find from Eq. 4-31 that k_ℓ is about 60 V/pC. If we evaluate the loss factor numerically, however, we find that Eq. 4-31 overestimates its value by about 50%. Thus, a better estimate is $k_\ell = 40$ V/pC for a 1- Ω broadband impedance. It is worth mentioning here that the impedance in Eq. 4-29 results in a considerably higher loss factor than would be calculated using an equivalent $Q = 1$ resonator impedance, for which the loss factor is only $k_\ell = 16$ V/pC for $(Z/n) = 1 \Omega$.

The HOM heating resulting from our choice of broadband impedance is $P_{\text{HOM}} = 400$ kW for the HER and $P_{\text{HOM}} = 800$ kW for the LER. We expect this power to be generated mainly at the various tapers in the rings, as these have the highest loss factors [Heifets, 1990a]. In addition to these losses, there will be HOM power deposited in the RF cavities. Taking the equivalent broadband impedance of the RF system into account, we expect this additional loss in each ring to be about 130 kW.

Based on the work of Heifets, we can estimate the overall loss factor for the various components close to the IP as $k_\ell = 0.06$ V/pC, which gives $P_{\text{HOM}} = 1.8$ kW for the high- and low-energy beams together. Of this, about 90 W is expected to be deposited in the beryllium beam pipe at the IP. The means to remove this power is described in Section 5.2.7.6.

4.3.1.7 Ion Clearing. The trapping of positively charged ions produced by collisions between electrons in the beam and background gas molecules has degraded the performance of many electron storage rings. The present theory of ion trapping is quite simple. When one of the electron beam bunches passes near an ion, the ion experiences a restoring force towards the beam axis. This force results in a change in the transverse velocity of the ion. Between bunch passages, the transverse velocity produces a change in the transverse position of the ion. This pattern is repeated for each passage of an electron bunch.

To estimate the ion motion, it is useful to consider the case in which the transverse charge density of the electron beam is uniform inside an ellipse with rms width and height σ_x and σ_y , respectively. Because the width of the beam is much greater than its height, ion trapping can be described by the motion of the ion in the vertical plane only; this is the motion we consider here.

The equation of motion for an ion in the electron bunch is given by

$$\ddot{y} + \hat{\omega}^2 y = 0 \quad (4-32)$$

where

$$\hat{\omega}^2/c^2 = \frac{4\hat{I}}{I_p A \sigma_y (\sigma_x + \sigma_y)} \quad (4-33)$$

with $\hat{I}$ the peak current in the bunch, c the speed of light, $I_p = m_p c^3/e = 3.1 \times 10^6$ A the Budker current of the proton, and A the ion mass number. The bunch cross section varies around the ring, but for purposes of estimation, we can take $\sigma_x = 1$ mm, $\sigma_y = 0.2$ mm, an ion mass of 20, and a peak current of 100 A. This yields $\omega = 5 \times 10^8$ rad/s. The bunch length τ and the interbunch spacing Δt are 30 ps and 4.2 ns respectively. Since both the quantities $\omega\tau$ and $\omega^2\tau\Delta t$ are much less than one radian, we can neglect the bunch structure of the beam, and the average ion motion can be obtained from Eq. 4-32 by replacing the peak current in Eq. 4-33 by the average current $\bar{I} = 1.48$ A. The ion effectively sees a continuous electron beam and oscillates with an average frequency of $\bar{\omega} = 6 \times 10^7$ rad/s. For a continuous bunched beam, the ions will be trapped in the electron beam unless measures are taken to remove them.

One method of removing trapped ions that has been used effectively is to turn on a fast kicker or “pinger” for a few turns and allow the ions to escape while the beam is moved away. However, the ionization rate is such that to reach a few percent neutralization again takes only of the order of milliseconds, so the beam would need to be kicked at a rate of nearly 1 kHz to keep it free of ions. If this method of ion clearing were used, the lifetime of the colliding beams and the detector backgrounds could be seriously affected.

Another method often used to clear the ions is to periodically excite the electron beam near the ion frequency. However, the ion frequency depends upon the amplitude of ion motion as well as upon the average current and transverse size of the electron beam, both of which vary around the ring and change during colliding beam running. This technique would potentially require a complicated control system to be useful during colliding beam conditions, and it might have a detrimental effect upon the beam lifetime and detector backgrounds. Moreover, the success of this method has been mixed.

A vertical DC electric field also may be used to clear the ions. The vertical clearing field E_c must be greater than the trapping field, that is,

$$E_c > \frac{Z_0 \bar{I}}{\pi (\sigma_x + \sigma_y)} \quad (4-34)$$

where $Z_0 = 377 \Omega$ is the impedance of free space and $\bar{I}$ is the average beam current. For an average current of 1.48 A, this would require a clearing field in excess of 1.4 kV/cm. While this is a possible solution, it has the drawback of requiring additional electrodes in the vacuum chamber structure. These increase the impedance seen by the beam and therefore increase the difficulty of controlling beam instabilities. In addition, it will not be possible to have the transverse electric field everywhere around the circumference of the ring, so there could still be pockets of trapped ions.

The most desirable solution—and the one that we have chosen to use—is to leave a gap in the electron bunch train. This gap need only be a few percent of the total ring

circumference, so that only a small increase in the single-bunch current is necessary to achieve the same luminosity obtained for the continuous bunch train. An ion will be linearly unstable whenever the gap satisfies the following condition:

$$\Delta T > \frac{2}{\bar{\omega}} \cot \left[\frac{\bar{\omega} (T - \Delta T)}{2} \right] \quad (4-35)$$

where T is the revolution period and ΔT is the gap period. For $T = 7 \mu\text{s}$, the total ion oscillation during the passage of the bunch train is given by $\bar{\omega} (T - \Delta T) \approx 400 \text{ rad}$, and a gap of a few percent is sufficient to allow the ions to be cleared.

There is the worry that for a particular combination of current, beam cross section, and ion mass, the ion would perform nearly an exact number of half-integer oscillations during passage of the bunch train. This would result in a large value for the cotangent on the right-hand side of Eq. 4-35. Because the beam cross section varies around the ring, there may be locations where ions can be trapped. These locations would move as the current decays and the beam cross section changes. Similarly, the alternating magnetic fields in the wigglers could produce a “magnetic bottle” that can trap ions. We do not expect such localized pockets to contain sufficient ions to disturb the electron beam. This view is supported by the observation that many storage rings have demonstrated the ability to eliminate ion trapping problems by having a beam gap such as we envision. The more serious question, which we are now investigating with simulations, is how the amplitude dependence of the ion oscillation frequency affects the ion trapping, for example, whether an ion that is linearly unstable remains unstable at a large amplitude.

One of the disadvantages in this method of ion clearing is that the use of a gap in the bunch train will have an effect upon the control circuitry of the RF system. However, this is a problem that needs to be considered anyway, since the RF system must be designed to function with uneven bunch population during the filling process. The solution to this problem is discussed in Section 5.5.4.

4.3.2 Coupled-Bunch Instabilities

As mentioned earlier, wakefields in high- Q resonant structures in a storage ring cause different beam bunches to interact. In general, such high- Q resonances result from the HOMs of the RF cavities. For certain values of relative phase between bunches, the coupled-bunch motion can grow and become unstable, leading to beam loss. In addition to the relative phase between bunches, the instabilities are characterized by their motion in longitudinal (synchrotron) phase space. Longitudinally, the $a = 0$ mode (corresponding to no motion) cannot be unstable, so the lowest longitudinal instabilities are characterized by $a = 1$ (dipole) synchrotron motion. In the *transverse* case, the $a = 0$ motion can also become unstable (referred to as “rigid-dipole” motion).

In the case of the B Factory, we require a relatively large number of RF cells, both to generate the voltage needed to produce the short bunches and to replace the beam power lost to synchrotron radiation each turn. Combined with the required very high average beam currents, the substantial RF system can produce extremely rapid growth of coupled-bunch instabilities. In the cases studied here, the most severe growth comes from the

lowest modes, that is, $a = 1$ longitudinally and $a = 0$ transversely.

We have estimated the growth rates for both longitudinal and transverse instabilities for typical B Factory parameters, that is, 1746 bunches having a total current of 1.48 A (HER) or 2.14 A (LER). This bunch number, which ignores the gap for clearing ions, is necessary for calculations performed with ZAP in the frequency domain.

Two different cases, based on the cavity design described in Section 5.5, were studied:

Case A: Undamped cavities; 20 cells (HER) or 10 cells (LER)

Case B: As in A, but with HOMs damped to $Q = 70$; 20 cells (HER) or 10 cells (LER)

In Case A, we examined the behavior of a standard B Factory cavity with no HOM damping. This cavity has a high shunt impedance for the fundamental while having reasonable values for the HOMs. Case B represents what happens when the higher-order RF modes of the single-cell system are heavily de-Qed by external means, such as the waveguides described in Section 5.5.

Predictions of longitudinal growth times (for the fastest-growing mode) for both RF scenarios considered are summarized in Tables 4-18 and 4-19. The undamped cavity (Case A) gives $a = 1$ growth times below 0.1 ms. Substantial de-Qing (Case B) does help slow down the growth considerably, to times on the order of 5 ms. Note that the feedback system power required to counteract these instabilities will scale as the square of the growth rate, so the change associated with damping the cavity HOMs is very significant.

Although not shown in Tables 4-18 and 4-19, we have also observed that the fundamental mode of the RF system is capable of causing instability for selected coupled-bunch normal modes. This problem is handled via feedback on the cavity itself, as

Table 4-18. Longitudinal coupled-bunch growth times for the B Factory HER (9 GeV; $\tau_E = 18.4$ ms) at a beam current of 1.48 A.

(A) Undamped		
	$\tau_{a=1}$	0.04 ms
	$\tau_{a=2}$	1.3 ms
(B) Damped to $Q = 70$		
	$\tau_{a=1}$	5.1 ms
	$\tau_{a=2}$	242 ms

Table 4-19. Longitudinal coupled-bunch growth times for the B Factory LER (3.1 GeV; $\tau_E = 18.4$ ms) at a beam current of 2.14 A.

(A) Undamped		
	$\tau_{a=1}$	0.03 ms
	$\tau_{a=2}$	1 ms
 (B) Damped to $Q = 70$		
	$\tau_{a=1}$	3.8 ms
	$\tau_{a=2}$	180 ms

described in Sections 5.5 and 5.6. Transverse results, summarized in Tables 4-20 and 4-21, are similar to those for the longitudinal case. Here too, we find for Case A that the two lowest synchrotron modes, $a = 0$ and $a = 1$, have growth times much shorter than the radiation damping time. We again note the benefits of substantial de- Q -ing (Case B) in slowing down the growth rates to more manageable levels.

Although the feedback system design (Section 5.6) is based on detailed simulations of the multibunch growth rates, the simple estimates made here already justify the effort that has gone into designing an effective HOM damping system for the RF cavities (described in Section 5.5).

4.3.3 Summary of Findings

Total beam current limitations in both rings will depend upon the ability of the vacuum system to maintain an acceptable pressure, about 5 nTorr, in the presence of about 2 A of circulating beam. Neither bunch lengthening and widening due to the longitudinal microwave instability (which places a limit on the allowable broadband impedance), nor

Table 4-20. Transverse coupled-bunch growth times for the B Factory HER (9 GeV; $\tau_x = 37.2$ ms) at a beam current of 1.48 A.

(A) Undamped		
	$\tau_{a=0}$	0.2 ms
	$\tau_{a=1}$	8.4 ms
 (B) Damped to $Q = 70$		
	$\tau_{a=0}$	1.1 ms
	$\tau_{a=1}$	302 ms

Table 4-21. Transverse coupled-bunch growth times for the B Factory LER (3.1 GeV; $\tau_x = 36.4$ ms) at a beam current of 2.14 A.

(A) Undamped		
	$\tau_{a=0}$	0.1 ms
	$\tau_{a=1}$	4.8 ms
 (B) Damped to $Q = 70$		
	$\tau_{a=0}$	0.65 ms
	$\tau_{a=1}$	184 ms

current limitations arising from the transverse mode-coupling instability are predicted to be constraints in the multibunch scenario considered here.

We have seen here that the performance of both high- and low-energy rings is likely to be limited mainly by coupled-bunch instabilities. Our choice of specially designed single-cell RF cavities helps to reduce the longitudinal HOM impedance by permitting the voltage to be produced with relatively few cells and by permitting the cavity HOMs to be effectively damped. Feedback systems able to deal with the remaining growth have been designed; they are described in Section 5.6.

4.4 BEAM-BEAM ISSUES

As discussed in Chapter 3, the desire to achieve high luminosity leads one naturally to specify high currents and/or small beam sizes. These tend to make the beam-beam interaction stronger, which, in turn, may lead to beam blowup, coherent oscillations, or fast particle losses that could defeat the purpose of the initial specification.

If the beam-beam interaction is sufficiently weak, the beams behave as if there were no collisions, and the performance is controlled by the single-beam parameters of the two rings. This condition implies a relative simplicity in the operation of the collider, because the two beams are effectively decoupled. The price one must pay for this simplicity is that, in order to achieve a specified luminosity, the weakness of the beam-beam interaction must be compensated by using large beam currents distributed over many bunches, or over few bunches with a large beam emittance. Either of these approaches can become a problem for other aspects of the design, such as the vacuum system, RF system, etc., and can also lead to various kinds of beam instabilities.

If the beam-beam interaction is significant, the beam parameters generally are modified from their nominal values. A strong beam-beam interaction naturally tends to imply a high luminosity, but it entails the potential for the problems mentioned above. In addition, the operation becomes relatively more complicated because the two beams are effectively coupled.

Obviously the desired luminosity performance of the collider implies specifications on the dynamical quantities. The nominal quantities, on the other hand, imply specifications on the individual rings. If the beam-beam dynamics were well-understood, it would be possible to translate specifications from dynamical to nominal quantities, and then to proceed to the design of the two rings individually. Unfortunately, our understanding is incomplete. This is particularly true for asymmetric colliders, which involve the additional complication of having two separate rings. Furthermore, all beam-beam simulation tools in existence take nominal parameters as input and produce dynamical quantities as output. Therefore, the understanding obtained from beam-beam simulations proceeds, in some sense, "in reverse." In practice, therefore, the only way to arrive at a specification of nominal beam parameters is to proceed by iterations.

The basic strategy we adopt for the B Factory is to choose values for the nominal quantities (including the beam-beam parameters ξ_0) to achieve a certain (nominal) luminosity, and then to verify by simulations that the dynamical behavior is close to nominal. If the dynamical results are substantially different from the nominal expectations, we change the nominal parameters and try again until an acceptable solution is found. Ideally, we wish to obtain the highest luminosity with acceptable beam lifetime and also with the highest reliability and flexibility of operation.

In this section, we present one set of parameters that strikes a balance between these conflicting requirements. This solution is not necessarily optimal, but it is an existence proof that a luminosity of $3 \times 10^{33} \text{ cm}^{-2} \text{ s}^{-1}$ is an achievable goal. Although substantial detailed work remains to be done, we are confident that the solution we propose will lead to a productive B Factory, and we further expect that improved solutions can be found by modest modifications of various parameters.

4.4.1 Nominal and Dynamical Beam Quantities

In the absence of the beam-beam interaction, the beam parameters are determined by the lattice, the energy, and the RF parameters of each ring. In particular, this is true of the emittances and therefore the beam sizes at the interaction point (IP). From these one can compute the beam-beam parameters and the resultant luminosity in the limit that the beam-beam interaction does not change them; the quantities calculated in this limit are referred to here as *nominal* and are indicated by a subscript 0. As an example of our notation, the nominal vertical beam size at the IP, $\sigma_{0y,+}^*$ and beam-beam parameter $\xi_{0y,+}$ of the positron beam, and the nominal luminosity $\mathcal{L}_0$ are given by

$$\sigma_{0y,+}^* = \sqrt{\epsilon_{0y,+} \beta_{y,+}^*} \quad (4-36a)$$

$$\xi_{0y,+} = \frac{r_0 N_- \beta_{y,+}^*}{2\pi \gamma_+ \sigma_{0y,-}^* (\sigma_{0x,-}^* + \sigma_{0y,-}^*)} \quad (4-36b)$$

$$\mathcal{L}_0 = \frac{N_+ N_- f_c}{2\pi \sqrt{(\sigma_{0x,+}^{*2} + \sigma_{0x,-}^{*2})(\sigma_{0y,+}^{*2} + \sigma_{0y,-}^{*2})}} \quad (4-36c)$$

where $\beta_{y,+}^*$ and $\epsilon_{0y,+}$ are the vertical beta function at the IP and the nominal emittance of the positron beam, the $N_{\pm}$ are the number of particles per bunch, r_0 is the classical electron radius, and f_c is the bunch collision frequency. We assume here that the bunches collide head-on, that they have elliptical Gaussian transverse profiles with common axes, and that they have lengths comparable to or smaller than their transverse beta functions. In this case the so-called “hourglass” reduction effect is small [Furman, 1991a]. There are three more beam-beam parameters, whose expressions are obtained from the above by the replacements $x \leftrightarrow y$ and/or $+ \leftrightarrow -$. If the bunches are evenly spaced by a distance s_B , the bunch collision frequency is, in the relativistic approximation, $f_c = c/s_B$, where c is the velocity of light.

Once the beams are brought into collision, the emittances inevitably deviate from their nominal values and, as a result, so do all quantities involving the beam sizes, including the beam-beam tune shift and the luminosity. These are the *dynamical* quantities, denoted without the subscript 0; the dynamical quantities corresponding to those in Eqs. 4-36 above are given by

$$\sigma_{y,+}^* = \sqrt{\epsilon_{y,+} \beta_{y,+}^*} \quad (4-37a)$$

$$\xi_{y,+} = \frac{r_0 N_- \beta_{y,+}^*}{2\pi \gamma_+ \sigma_{y,-}^* (\sigma_{x,-}^* + \sigma_{y,-}^*)} \quad (4-37b)$$

$$\mathcal{L} = \frac{N_+ N_- f_c}{2\pi \sqrt{(\sigma_{x,+}^{*2} + \sigma_{x,-}^{*2})(\sigma_{y,+}^{*2} + \sigma_{y,-}^{*2})}} \quad (4-37c)$$

In this discussion, we assume that the beam-beam interaction does not induce coherent oscillations or a relative displacement of the closed orbits at the IP. This is discussed in greater detail when we describe our simulation results in Section 4.4.5.

4.4.2 Transparency Symmetry

The fact that an asymmetric collider necessarily consists of two rings enlarges the beam dynamics parameter space considerably relative to a single-ring, symmetric collider. The bunches in the two rings see different RF systems, different lattice functions, and different magnetic fields. Even the simplest beam-beam dynamics study requires, at a minimum, the specification of the following quantities:

- Two values for the number of particles per bunch, $N_{\pm}$
- Six beam sizes (two transverse and one longitudinal for each beam)
- Four beta functions at the IP (one vertical and one horizontal for each beam)
- Six tunes
- Two damping decrements

In general, the four beam-beam parameters are different, as can be seen from Eqs. 4-36.

Because no asymmetric colliders exist at present, and because the consequences of the beam-beam interaction are not completely understood for intense beams, it has been argued [Chin, 1990] that a cautious approach might be to require that the beam dynamics of an asymmetric collider resemble as closely as possible the dynamics of a symmetric one. In this way, the design can draw upon the valuable experience gained from single-ring colliders. This is the so-called “transparency symmetry” condition; it is reached by imposing constraints on the parameters of the two rings according to the following:

- (i) Pairwise equality of nominal beam-beam parameters: $\xi_{0x,+} = \xi_{0x,-}$ and $\xi_{0y,+} = \xi_{0y,-}$
- (ii) Pairwise equality of nominal beam sizes: $\sigma_{0x,+}^* = \sigma_{0x,-}^*$ and $\sigma_{0y,+}^* = \sigma_{0y,-}^*$
- (iii) Equality of damping decrements of the two rings
- (iv) Equality of the tune modulation amplitudes due to synchrotron oscillations: $(\sigma_l v_s / \beta_{x,y}^*)_+ = (\sigma_l v_s / \beta_{x,y}^*)_-$, where σ_l is the bunch length and v_s is the synchrotron tune

An immediate consequence of the transparency symmetry is a significant reduction in the number of free parameters, which is certainly a practical advantage for beam-beam studies. On the other hand, it has been argued on general grounds [Tennyson, 1990] that, given an asymmetric machine design, the beam-beam limit (maximum luminosity with acceptable beam lifetime), subject to certain constraints, can only be achieved with

asymmetric beam dynamics parameters. Thus, the transparency symmetry might preclude reaching the actual beam-beam limit. It is possible that the ultimate beam-beam limit in an asymmetric collider can be achieved only at the price of relinquishing too much flexibility and therefore operational reliability, or of undesirably tight tolerances. Furthermore, it is not known at present how different the luminosity at the beam-beam limit would be compared with what could be achieved in a given transparent case. These are matters that deserve careful investigation in the near future. As will be discussed in more detail in the following sections, for now we adopt an approximate transparency symmetry as a prudent starting point.

Another advantage of transparency symmetry is that the luminosity can be very simply and conveniently expressed in terms of a single beam-beam parameter. First, we note that condition (ii) above implies that there is a single nominal aspect ratio r :

$$\left(\frac{\sigma_{0y}^*}{\sigma_{0x}^*} \right)_+ = \left(\frac{\sigma_{0y}^*}{\sigma_{0x}^*} \right)_- \equiv r \quad (4-38)$$

and that the expression for the nominal luminosity simplifies to

$$\mathcal{L}_0 = \frac{N_+ N_- f_c}{4\pi \sigma_{0x}^* \sigma_{0y}^*} \quad (4-39)$$

By combining conditions (i) and (ii), we have [Chin, 1990; Furman, 1991b]

$$\frac{\beta_{x,-}^*}{\beta_{x,+}^*} = \frac{\beta_{y,-}^*}{\beta_{y,+}^*} = \frac{(EI)_-}{(EI)_+} \quad (4-40)$$

One also finds that there is a single beta-function ratio (rather than two) and a single nominal emittance ratio:

$$\frac{\beta_{y,+}^*}{\beta_{x,+}^*} = \frac{\beta_{y,-}^*}{\beta_{x,-}^*} \equiv r_\beta \quad \text{and} \quad \frac{\varepsilon_{0y,+}}{\varepsilon_{0x,+}} = \frac{\varepsilon_{0y,-}}{\varepsilon_{0x,-}} \equiv r_\varepsilon \quad (4-41)$$

so that the beam-size ratio becomes

$$r = \sqrt{r_\varepsilon r_\beta} \quad (4-42)$$

The nominal beam-beam tune shift parameters are related to r_β and r_ε by

$$\frac{\xi_{0y}}{\xi_{0x}} = \sqrt{\frac{r_\beta}{r_\varepsilon}} \quad (4-43)$$

and the nominal luminosity is

$$\mathcal{L}_0 = K(1+r)\xi_{0y}\left(\frac{EI}{\beta_y^*}\right)_{+,-} \quad (4-44)$$

where the subscript $+,-$ means that the expression in parentheses can be taken from either beam, because of Eq. 4-40. The constant K is

$$\begin{aligned} K &= \frac{1}{2er_0mc^2} \\ &= 2.17 \times 10^{34} \left[\text{cm}^{-2} \text{s}^{-1} \right] \cdot \left[\frac{\text{cm}}{\text{GeV A}} \right] \end{aligned} \quad (4-45)$$

where mc^2 is the rest energy of the electron and e is its charge. Therefore, if we express the energy E in GeV, the current I in A, and the beta function in cm, we obtain

$$\mathcal{L}_0 = 2.17 \times 10^{34} (1+r)\xi_{0y}\left(\frac{EI}{\beta_y^*}\right)_{+,-} \left[\text{cm}^{-2} \text{s}^{-1} \right] \quad (4-46)$$

Note that ξ_{0y} cannot be varied independently of the other parameters, since it is related to them through Eqs. 4-42 and 4-43. It is also worth commenting that Eq. 4-46 can be rewritten, if desired, in terms of horizontal, rather than vertical, parameters by making the replacements $y \rightarrow x$ and $r \rightarrow 1/r$.

In contrast, the nominal aspect ratio r , the beta function ratio r_β , and the nominal emittance ratio r_ϵ are free parameters, except that they are related by Eq. 4-42.

If, in addition to the transparency symmetry condition (i), we impose the extra requirement that *all four* beam-beam parameters should be equal, that is

$$\xi_{0x,+} = \xi_{0y,+} = \xi_{0x,-} = \xi_{0y,-} \equiv \xi_0$$

as we will in our simulations presented below, then one finds the additional equality $r = r_\beta = r_\epsilon$ or, explicitly,

$$\frac{\sigma_{0y,+}^*}{\sigma_{0x,+}^*} = \frac{\sigma_{0y,-}^*}{\sigma_{0x,-}^*} = \frac{\beta_{y,+}^*}{\beta_{x,+}^*} = \frac{\beta_{y,-}^*}{\beta_{x,-}^*} = \frac{\epsilon_{0y,+}}{\epsilon_{0x,+}} = \frac{\epsilon_{0y,-}}{\epsilon_{0x,-}} = r \quad (4-47)$$

The formula for the luminosity reads the same as the previous case, Eq. 4-46, except that now the beam-beam parameter carries no index y .

4.4.3 Physics of the Simulation Codes

For our simulations, we employ two distinct codes (by H. Yokoya and J. Tennyson) that are similar, but not identical. Each of these codes represents a beam bunch by a collection of many (we have used up to 300) “superparticles.” Initially, these

superparticles have a Gaussian distribution in phase space. At the IP, the rms beam sizes σ_x and σ_y are calculated from the superparticle distribution at every turn. Although the shape of the distribution deviates from Gaussian as time progresses, for the purposes of computing the beam-beam kick, it is a good approximation to retain the Gaussian shape, albeit with time-dependent σ_x and σ_y . From these distributions, the beam-beam force on each superparticle of the opposing bunch is computed by means of the well-known expression for the transverse electric field in terms of the complex error function [Bassetti and Erskine, 1980]. Deviations from a Gaussian shape are monitored; if the dynamic distribution differs substantially from Gaussian, one has reason to doubt the results, owing to the lack of self-consistency.

Each beam is transported through the rest of the machine by a linear matrix; that is, no lattice nonlinearities are considered. Synchrotron radiation and damping are included and are represented by localized kicks. The RF system is also represented by a localized kick. Typically, the beams are tracked for three to five damping times to verify that an equilibrium situation has been reached. (For the specific set of parameters studied here, we have verified that five damping times is long enough to yield stable results and that three damping times is often adequate.)

The electromagnetic fields produced by relativistic particles are Lorentz-contracted into a thin disk perpendicular to the direction of motion. As a consequence, the force on a single particle due to the opposing bunch is, to a good approximation, strictly transverse; longitudinal forces can be neglected. (Indeed, the integrated longitudinal force is *exactly* zero in the case when the beta function is constant during the collision.) What cannot be neglected, however, is the fact that the opposing bunch has a finite longitudinal extent.

Near the IP, the vertical beta function is small and the betatron phase of a particle changes rapidly. Consequently, the net force due to the opposing bunch (that is, the beam-beam interaction) is distributed over a wide range of betatron phase. Because most beam-beam limiting phenomena are resonant in nature, this feature, called phase averaging, is important and must be incorporated into beam-beam calculations and simulations. [Krishnagopal and Siemann, 1990].

Phase averaging thus emphasizes the importance of the longitudinal extent of the beam-beam interaction. A Hamiltonian analysis that includes this feature predicts resonance strengths that are smaller than those calculated by models in which the beam-beam interaction is approximated by a single kick (impulse approximation). This also implies that resonance overlap, and the stochastic motion that results from it, set in at higher currents than would be estimated in the impulse approximation.

In the simulation results presented here, we allow for phase averaging by dividing the bunch longitudinally into several slices. Typically, five slices are used, although spot-checks with nine slices have sometimes been made. Both codes distribute the slices evenly along the length of the bunch and symmetrically about its center. However, the slices farthest away from the center are located in different places in the two codes. In Yokoya's code, the outermost slice is located at a distance $s = \pm 2\sigma_z$ from the bunch center, regardless of the number of slices. In Tennyson's code (TRS), the corresponding outermost distance is $s = \pm[1 + (n - 3)/12]\sigma_z$, where n is the total number of slices. Thus, the two codes have identical slicing algorithms only when 15 slices are used; for fewer slices, Tennyson's code concentrates the slices closer to the center of the bunch than does

Yokoya's code. As the bunches pass through each other during the collision, the beta functions seen by the different slices are different, since the slices collide at points away from the IP. In the neighborhood of the IP, we take the s -dependence of the beta functions to correspond to that of a drift.

Besides the distinctions discussed above, the codes also differ in technical details having to do with the way certain quantities are averaged from turn to turn in order to smooth out statistical fluctuations associated with the relatively small number of superparticles.

The lattice design described in Section 4.1 has head-on collisions at the IP, with magnetic separation of the beams. However, the beams go into their own vacuum pipes only after traveling about 4 m away from the IP; as a result, they experience several grazing collisions on their way into and out of the IP. There are six such "parasitic" crossings on either side of the IP. These parasitic crossings couple the dynamics of all bunches, so a completely faithful simulation of the B Factory beam-beam dynamics would require 1658 bunches per ring, along with a gap equivalent to 88 bunches. Since this is an impractical requirement for any present-day simulation, we make two simplifying approximations: (i) We consider only the first parasitic crossing on either side of the IP and (ii) we use only one bunch per ring, which is "reused" (so that this bunch collides three times per turn—two parasitic crossings plus the main collision at the IP—with the same partner in the other beam).

The first approximation is quite reasonable, since, as discussed in more detail below, the effect of the first parasitic crossing overwhelms all the others. The second approximation rests on the sensible assumption that, in reality (or in a faithful simulation), the particle distributions are not expected to differ much from bunch to bunch, especially when the bunches interact at a distance, as is the case at the parasitic crossings.

Given the complicated process that is being simulated, it is natural to test the predictions of the simulation codes against known experimental results. As an example, we have studied the particular PEP configuration summarized in Table 4-22 with Yokoya's code. We find that the luminosity prediction agrees with the measured value to within 10%. In fact, the simulation result is actually slightly *pessimistic*, since it is 10% below the observed luminosity. We also predict from the simulations that there will be no saturation of the dynamic beam-beam tune-shift parameter ξ up to a beam current of 30 mA—again in agreement with experimental observations. Calculations for other PEP configurations yield more or less equivalent agreement with the observed luminosities.

We have also tested Tennyson's code for the case of PEP, for a different configuration from that above, including the effect of the parasitic crossings in the arcs. The comparison with experiment is summarized in Fig. 4-83. In this comparison, too, we find reasonable agreement with experiment. Again, we note that the code tends to underestimate the luminosity.

Insofar as the simulation results in both cases are consistent in trend with the actual PEP observations, we feel that the predictions derived from these codes are reasonable guides for the design of the B Factory. Implied in this statement is the assumption that there is no new physics that enters into the beam-beam interaction due to the asymmetric collisions. At the present time, we have every reason to believe that this assumption is valid.

Table 4-22 PEP parameters used in simulation comparison.^a

Betatron tunes		
Horizontal		21.2962
Vertical		18.2049
Beta functions at IP		
Horizontal [m]		1.342
Vertical [m]		0.053
Dispersion at IP		
Horizontal [m]		0.00049
Emittances		
Horizontal [nm·rad]		99.6
Vertical [nm·rad]		3.96
Synchrotron tune		0.043
Beam current [mA]		18.85
Nominal beam-beam parameter, ξ_0		
Horizontal		0.04653
Vertical		0.04653
Luminosity		
Nominal [cm ⁻² s ⁻¹]		5.07×10^{31}
Observed [cm ⁻² s ⁻¹]		4.80×10^{31}
Simulation [cm ⁻² s ⁻¹]		4.34×10^{31}
^a Data from E. Bloom and M. Donald		

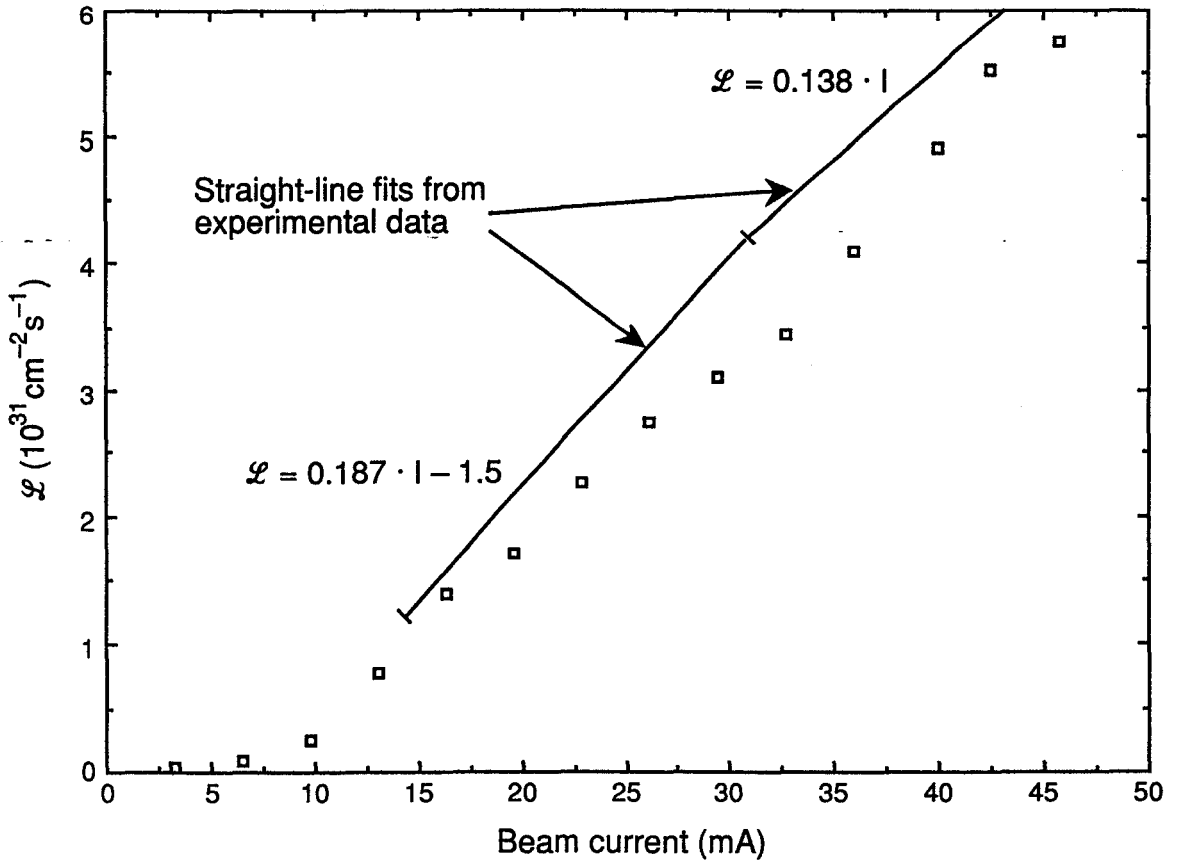


Fig. 4-83. Plot of observed luminosity at PEP and the simulation results from Tennyson's code. The tune values used in the simulation were slightly different from those used in the experiment itself; preliminary results show that the agreement improves when the tunes are the same.

4.4.4 Beam Dynamics Studies

The primary parameters that determine the strength of the beam-beam interaction are the four nominal beam-beam parameters, $\xi_{0x,\pm}$ and $\xi_{0y,\pm}$. If these are small enough, and if the working point of the ring is not too close to the integer tunes, ξ_0 is equal to the nominal tune spread induced by the beam-beam interaction. We adopt, as a starting point, the fully symmetric condition

$$\xi_{0x,+} = \xi_{0y,+} = \xi_{0x,-} = \xi_{0y,-} = 0.03 \quad (4-48)$$

The specification of $\xi_0 = 0.03$ is intended to be conservative, insofar as existing machines have already achieved substantially higher values of ξ_0 [Rice, 1989 and 1990; Seeman, 1985]. As mentioned, this strategy of setting the beam-beam interaction to be reasonably weak has the desirable consequence that the beam behavior will be close to nominal. This has the advantage of preserving operational flexibility, because the closer to nominal the beam-beam dynamics is, the more controllable is the machine

performance. (Clearly, in an operating collider, the machine parameters will be adjusted to maximize the luminosity. The idea here is not to limit the machine performance, but rather to leave room for subsequent improvements.)

Our basic strategy is first to choose nominal parameters, and then to verify that the beam-beam interaction does not cause significant deviations from them. If the beam dynamics is substantially different from nominal (for example, if beam blowup is too large or beam lifetime too short), we change the nominal parameters and try again until an acceptable solution is found. In more detail, this strategy is divided into several steps:

(i) *Set nominal parameters.* Our design goal is to reach a nominal luminosity of $\mathcal{L}_0 = 3 \times 10^{33} \text{ cm}^{-2} \text{ s}^{-1}$. From this requirement and other considerations, a complete set of parameters for both rings can be derived (see Appendix A). For the purposes of this section, however, we show only an abbreviated list in Table 4-23. Further, because the collider design has evolved in parallel with the simulation study, some of the final parameters in Appendix A differ slightly from those in this section. The parameters indicated in Table 4-23, however, are the values used in the simulation study.

In Table 4-23, E is the beam energy, s_B is the bunch spacing, and f_c is the bunch collision frequency at the IP ($f_c = c/s_B$); V_{RF} , f_{RF} , and ϕ_s are the RF voltage, frequency, and synchronous phase, respectively; α is the momentum compaction factor; ν_s is the synchrotron tune; σ_L is the rms bunch length; and τ_x and τ_y are the horizontal and vertical damping times, respectively. The other parameters are the emittances ϵ , beta functions β , and nominal rms beam sizes σ_0 at the IP.

The above parameters are consistent with Eq. 4-48 and our stated luminosity goal, as can be easily verified. Their values do not, however, correspond exactly to the requirements of transparency symmetry, on account of the difference in the amplitudes of the tune modulation:

$$\begin{aligned} \left(\frac{\sigma_L v_s}{\beta_x^*} \right)_+ &= 1.07 \times 10^{-3}, & \left(\frac{\sigma_L v_s}{\beta_x^*} \right)_- &= 6.93 \times 10^{-4} \\ \left(\frac{\sigma_L v_s}{\beta_y^*} \right)_+ &= 2.69 \times 10^{-2}, & \left(\frac{\sigma_L v_s}{\beta_y^*} \right)_- &= 1.73 \times 10^{-2} \end{aligned} \quad (4-49)$$

(ii) *Select a working point.* Only the primary collisions at the IP are considered in this step. The choice of tunes can be made quite effectively with “weak-strong” beam-beam simulations, in which the high-energy beam is forced to remain undisturbed while the low-energy beam is studied dynamically. (For the B Factory, we are confident that this approximation is reasonable, because more realistic “strong-strong” simulations show that there is little or no beam blowup for the high-energy beam in our design.) This more approximate type of simulation has the advantages that it is relatively fast and that the effects of resonances, such as synchrotron sidebands, are clearly seen (thus allowing, in principle, a theoretical understanding of the underlying beam dynamics). The main figure-of-merit that we use in this study is the beam blowup factor of the low-energy beam.

In general, the resonance density in the tune diagram is lowest close to the integer tune, so we have begun by performing a tune scan close to the lower left corner of the

Table 4-23. Main B Factory parameters used in the beam-beam simulation studies.

	LER (e ⁺)	HER (e ⁻)
E [GeV]	3.1	9
s_B [m]	1.26	1.26
f_c [MHz]	238	238
V_{RF} [MV]	8.0	18.5
f_{RF} [MHz]	476.0	476.0
ϕ_s [deg]	170.6	168.7
α	1.15×10^{-3}	2.41×10^{-3}
ν_s	0.0403	0.0520
σ_t [cm]	1	1
N_b	5.61×10^{10}	3.88×10^{10}
ϵ_{0x} [nm-rad]	92	46
ϵ_{0y} [nm-rad]	3.6	1.8
β_x^* [cm]	37.5	75.0
β_y^* [cm]	1.5	3.0
σ_{0x}^* [μ m]	186	186
σ_{0y}^* [μ m]	7.4	7.4
τ_x [turns]	4400	5014
τ_y [turns]	4400	5014

tune plane. The beam-beam interaction causes a tune spread because particles of different betatron amplitude experience different tune shifts. This causes the beam to have a characteristic "footprint" that extends diagonally upward from the working point. Figure 4-84 shows the vertical and horizontal blowup factors of the low-energy beam for each working point scanned. Figure 4-85 shows the same portion of the tune plane, with even-order resonance lines through sixth order. The results in Fig. 4-84 can be interpreted by assuming that the large blowup points, indicated by darker shading, are caused by synchrotron sidebands of the fourth order and the integer resonances.

While a comprehensive scan of the entire tune square remains to be carried out, for the present limited purpose of studying the beam-beam dynamics, we selected the fractional tunes to be $\nu_x = 0.09$ and $\nu_y = 0.05$ (both beams). For these tunes, the blowup factor is 10% or less, as can be seen from Fig. 4-84. Other considerations, such as dipole error sensitivity, may well dictate working points further away from the integer.

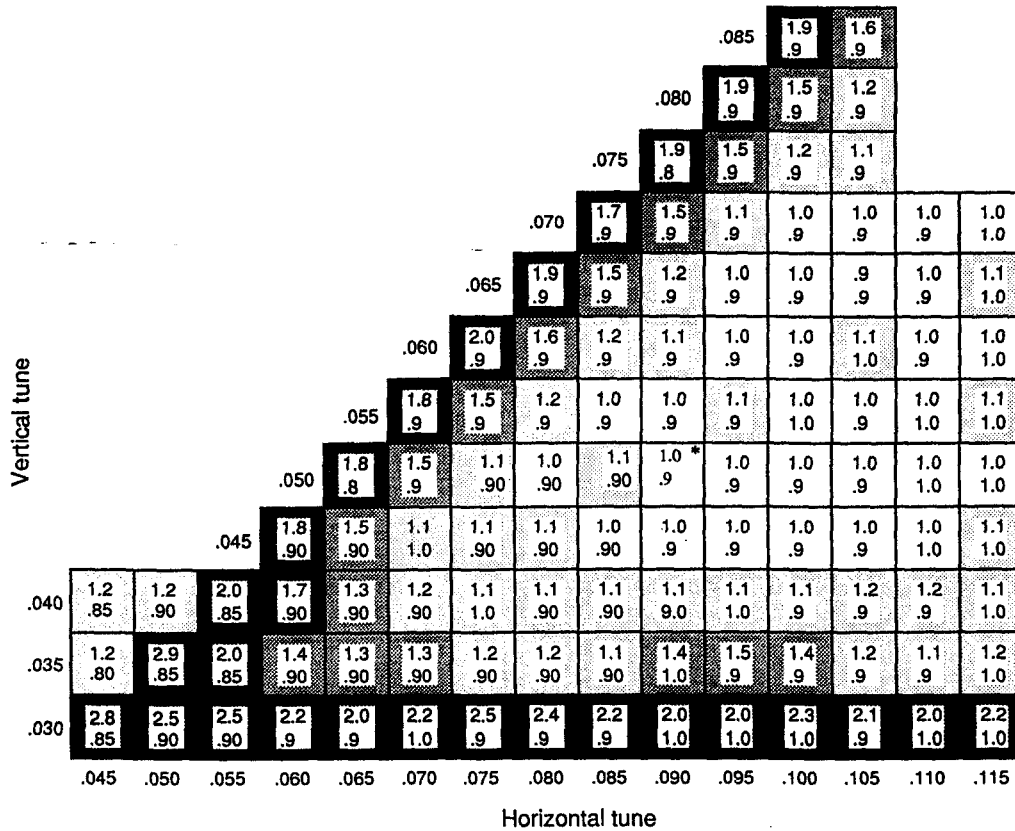


Fig. 4-84. Low-energy beam blowup factors (σ/σ_0) for various working points. The numbers in each box are the vertical and horizontal blowup factors at that particular working point. Our choice at (0.09, 0.05) is indicated by an asterisk. The shading in each box is indicative of the blowup: the darker the shading, the larger the vertical blowup.

Nevertheless, at least some existing machines [Rice, 1989 and 1990; Seeman, 1985] operate in this general area of the tune plane. Figure 4-86 shows the beam footprint extending away from this working point.

(iii) *Verify the behavior of the beam-beam interaction.* The next step is to check that the beam-beam interaction remains reasonably weak in the fully coupled beam-beam calculations. This is done with “strong-strong” simulations, in which both beams are allowed to vary dynamically according to their mutual beam-beam interaction. At this stage, the study is still done with only the primary collisions at the IP. This type of simulation is time-consuming, but it is necessary because it is the only way to compute dynamical quantities, such as actual beam blowup and luminosity, and because it can reveal coherent oscillations, closed-orbit distortion, and particle losses. As a check on the robustness of our chosen parameters and working point, we have considered values of ξ_0 much higher than the nominal value of 0.03 in the simulations. This is shown in Fig. 4-87, which gives the calculated blowup factors of all four beam sizes vs ξ_0 , and Fig. 4-88, showing the corresponding luminosities. In both Figs. 4-87 and 4-88, we maintain the equality of all four ξ_0 values (which are varied by simply increasing the number of

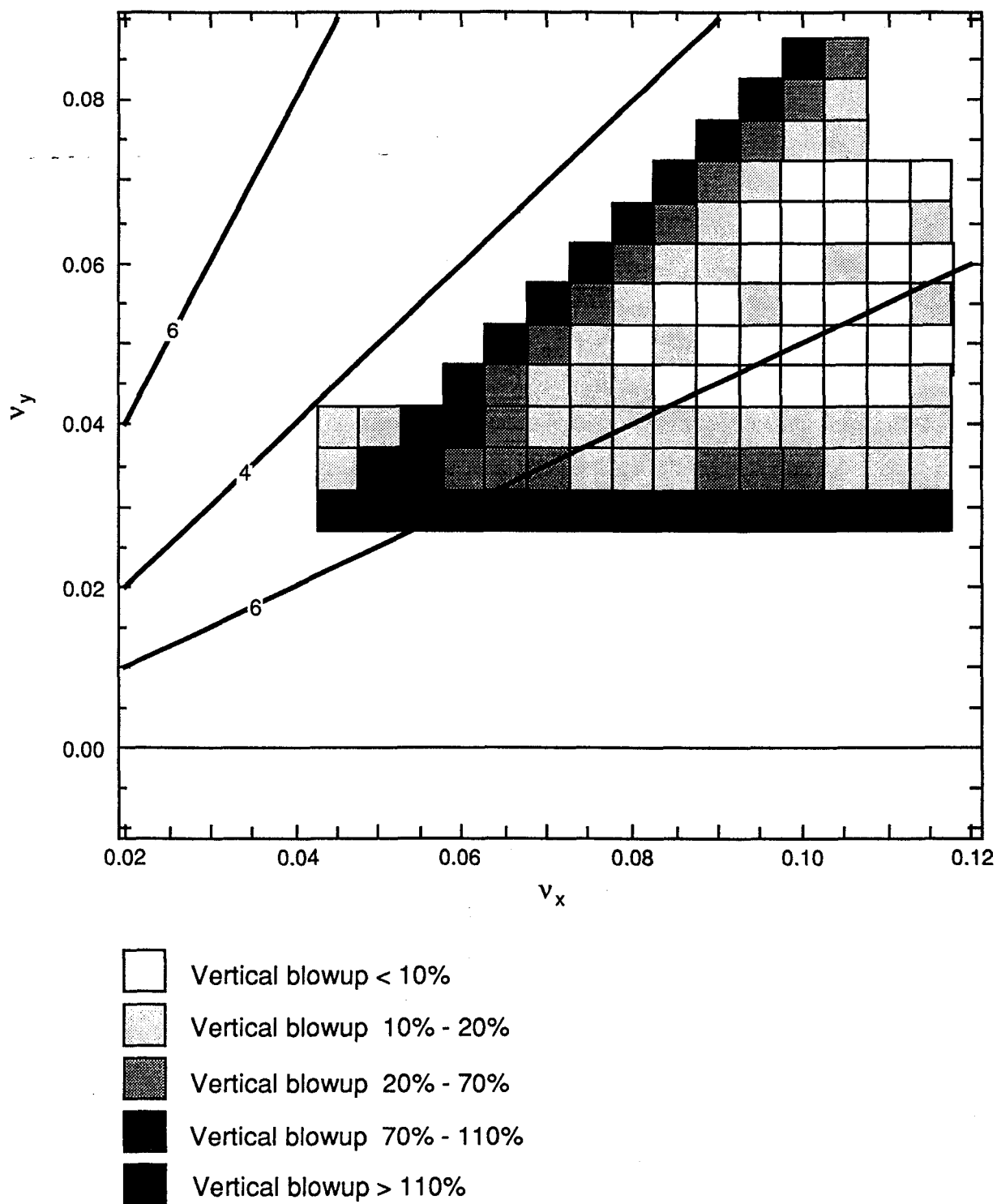


Fig. 4-85. Tune plot with even-order resonance lines through sixth order. This is the same portion of the tune plane as in the previous figure.

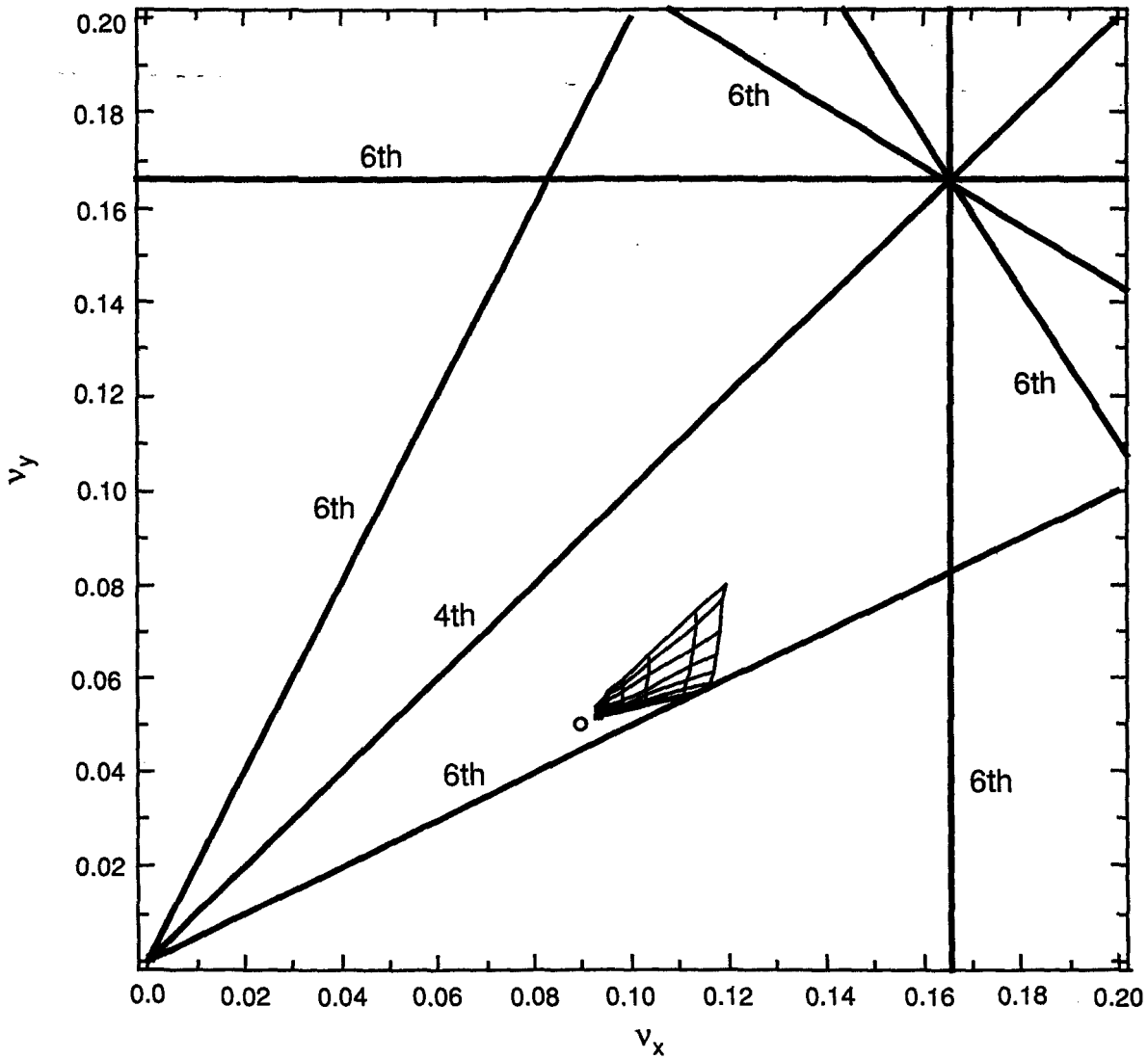


Fig. 4-86. Tune plot and beam footprint. The tune plane shows the working point (circle) and the beam footprint caused by the beam-beam tune spread. The lines in the footprint correspond to particles with amplitudes with constant σ_x or constant σ_y , from 0 to 7σ in steps of 1σ . The particle closest to the working point has the largest amplitude, $7\sigma_x$ and $7\sigma_y$. The particle furthest away is at the center of the bunch.

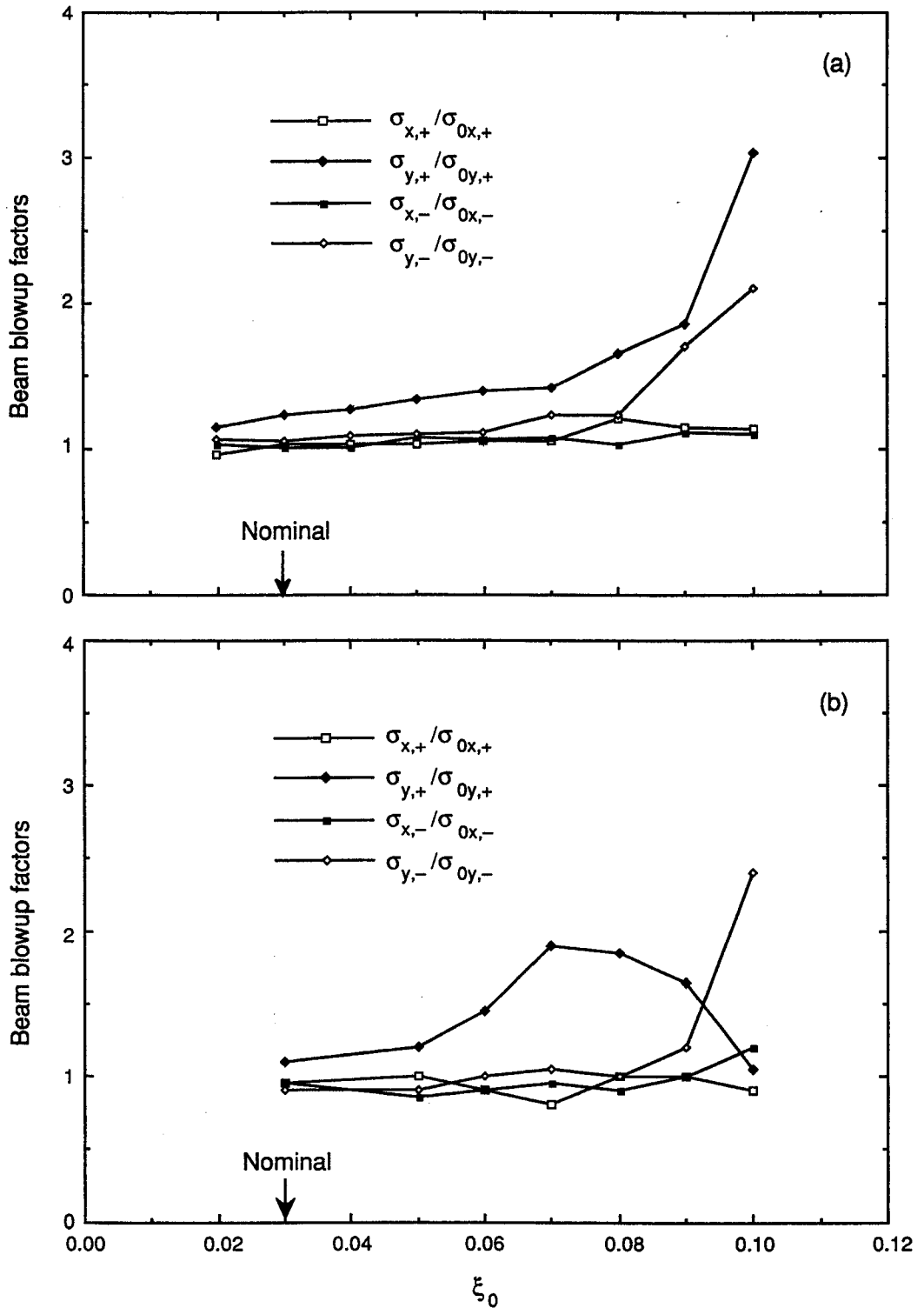


Fig. 4-87. Beam blowup factors vs ξ_0 . These are the results for the dynamical beam size over nominal beam size for both beams, from both simulation codes: (a) Yokoya's and (b) TRS. The parameter ξ_0 is increased by increasing the number of particles per bunch in both beams, with fixed nominal emittance.

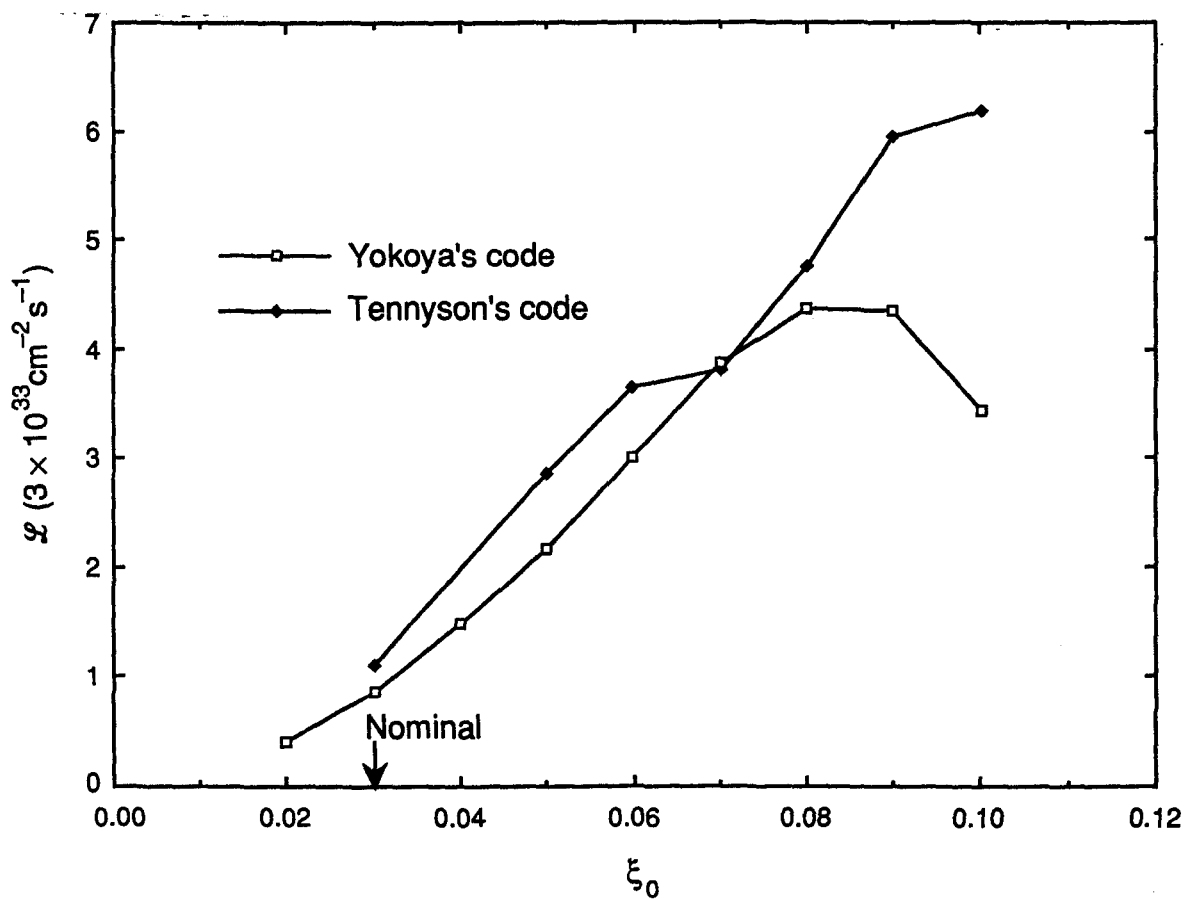


Fig. 4-88. Luminosity vs ξ_0 corresponding to the blown-up beam sizes in Fig. 4-87.

particles per bunch). In general, the two codes predict reasonably similar dynamical behavior.

Because the various beam sizes change differently, the dynamical beam-beam parameters also become different from each other. This means that the transparency symmetry is inherently broken by the dynamics, although not to a great extent. This is shown in Fig. 4-89.

- - (iv) *Verify that the results are maintained when parasitic crossings are included.* Although the beams collide head-on at the IP, the bunches experience grazing collisions on their way into and out of the region within ± 4 m of the IP, where both beams travel in a common pipe. We must assess the effect of these parasitic crossings on the performance. This is done with strong-strong simulations. Parasitic crossings have a potentially detrimental effect on beam blowup, because they induce odd-order resonances and because the vertical beta function is sufficiently high at the crossing points that the long-range tune shift is comparable to the head-on tune spread at the IP. This also means that the parasitic crossings induce significant horizontal-vertical coupling. Taken together, these effects make it harder to find an optimum working point in the tune plane.

There are six parasitic crossings symmetrically located on either side of the IP. For the purposes of studying the beam-beam dynamics, the first parasitic crossing (that is, the one closest to the IP on either side) overwhelms the others on account of the small separation, together with the large vertical beta function. The strength of the long-range beam-beam kick at this first parasitic crossing is much greater than those of all the remaining crossings combined. This justifies our considering only this first parasitic crossing in our present calculations. Table 4-24 shows the relevant parameters for the primary and the first parasitic crossing for the B Factory.

In Table 4-24, Δs is the distance from the IP to the parasitic crossing point along the beam trajectory; $2\pi\Delta v_x$ and $2\pi\Delta v_y$ are the phase advances from the IP to the parasitic crossing; d is the separation between the two closed orbits at the parasitic crossing; and d/σ_{0x} is a measure of the extent of the overlap between the two bunches at the parasitic crossing point. The nominal emittances and number of particles per bunch are listed in Table 4-23. The parasitic crossings induce a tune shift and an amplitude-dependent tune spread in the particles due to the mutual interaction of the two bunches. It can be shown that the incoherent tune shifts experienced by a particle at the center of the positron bunch from a single parasitic interaction point are, to lowest-order approximation, given by [Tennyson, 1991a]

$$\begin{aligned}\Delta v_{x,+} &= -\frac{r_0 N_- \beta_{x,+}}{2\pi\gamma_+ d^2} \\ \Delta v_{y,+} &= +\frac{r_0 N_- \beta_{y,+}}{2\pi\gamma_+ d^2}\end{aligned}\tag{4-50}$$

with the corresponding expressions for the electron bunch obtained by exchanging the indices + and - in Eq. 4-50. In these expressions, $\beta_{x,y}$ are the beta functions at the parasitic crossing location. The negative sign in Δv_x arises from the fact that the horizontal force is a decreasing function of separation at the parasitic crossing (the

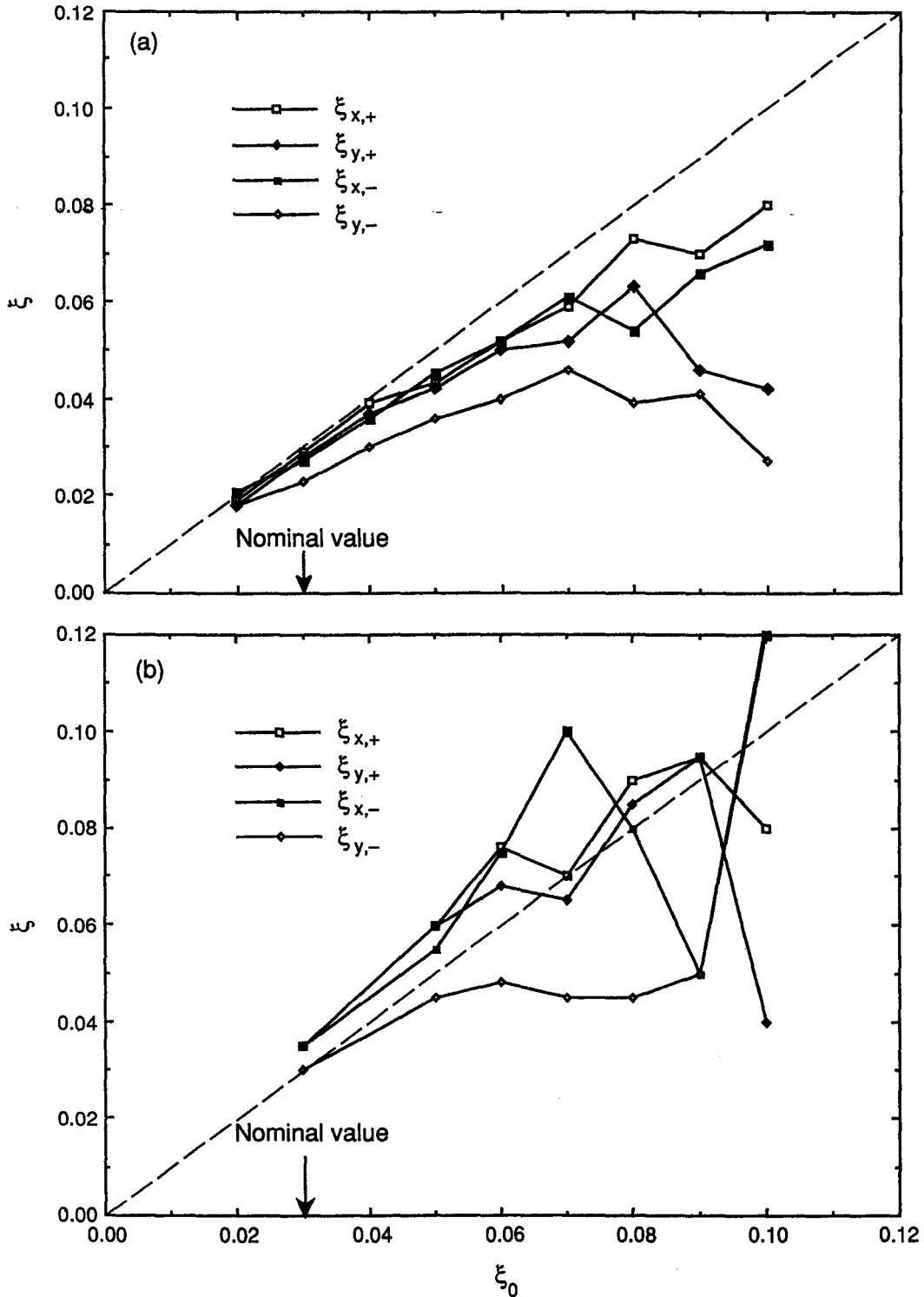


Fig. 4-89. Dynamical beam-beam parameters ξ vs ξ_0 corresponding to the blown-up beam sizes of Fig. 4-87: (a) Yokoya's code and (b) TRS. If the behavior were nominal, all four lines would coincide with the dashed main diagonal.

Table 4-24. B Factory nominal parameters at the IP and first parasitic crossing.

	LER (e ⁺)		HER (e ⁻)	
Δs [cm]	63			
d [mm]	2.82			
	IP	1st PC	IP	1st PC
Δv_x	0	0.1643	0	0.1111
Δv_y	0	0.2462	0	0.2424
β_x [cm]	37.5	151	75	130
β_y [cm]	1.5	2,523	3	1,301
α_x	0	-2.42	0	-1.06
α_y	0	-29.25	0	-18.74
σ_{0x} [μm]	186	373	186	245
σ_{0y} [μm]	7.4	302	7.4	153
d/σ_{0x}	—	7.56	—	11.5

“background” force induced by the closed-orbit separation is subtracted out in arriving at the above expressions). Using the numerical values for the parameters given in Table 4-24, we obtain

$$\begin{aligned}
 \Delta v_{x,+} &= -0.001, & \Delta v_{x,-} &= -0.0002 \\
 \Delta v_{y,+} &= +0.009, & \Delta v_{y,-} &= +0.002
 \end{aligned}
 \tag{4-51}$$

which shows that each of the first parasitic crossings contributes a vertical tune shift of almost one-third of the nominal IP tune shift of 0.03 in the positron beam. The remaining parasitic crossings contribute negligibly to the tune shifts.

A tune shift by itself is not detrimental, since it can be compensated by a shift in the working point. However, as mentioned above, the amplitude dependence causes a tune spread, which is more problematic. This spread, which can be calculated by appropriate numerical integration [Tennyson, 1991a], causes a distortion of the beam footprint, as shown in Fig. 4-90. Such a distortion makes it more difficult to find a good working point; for our present simulation purposes, we have maintained the original working point, $v_x = 0.09$, $v_y = 0.05$.

As implied by the above, the parasitic crossings produce horizontal-vertical coupling that can cause beam blowup. Obviously if the separation d were large enough, all effects of the parasitic crossings would disappear altogether. To assess this effect, we have carried out simulations in which we vary the separation d and keep all other parameters fixed. Figure 4-91 shows the beam blowup factors vs $d/\sigma_{0x,+}$ for $\xi_0 = 0.03$ and 0.05. Figure 4-92 shows the corresponding luminosity vs $d/\sigma_{0x,+}$ for $\xi_0 = 0.03$ and 0.05.

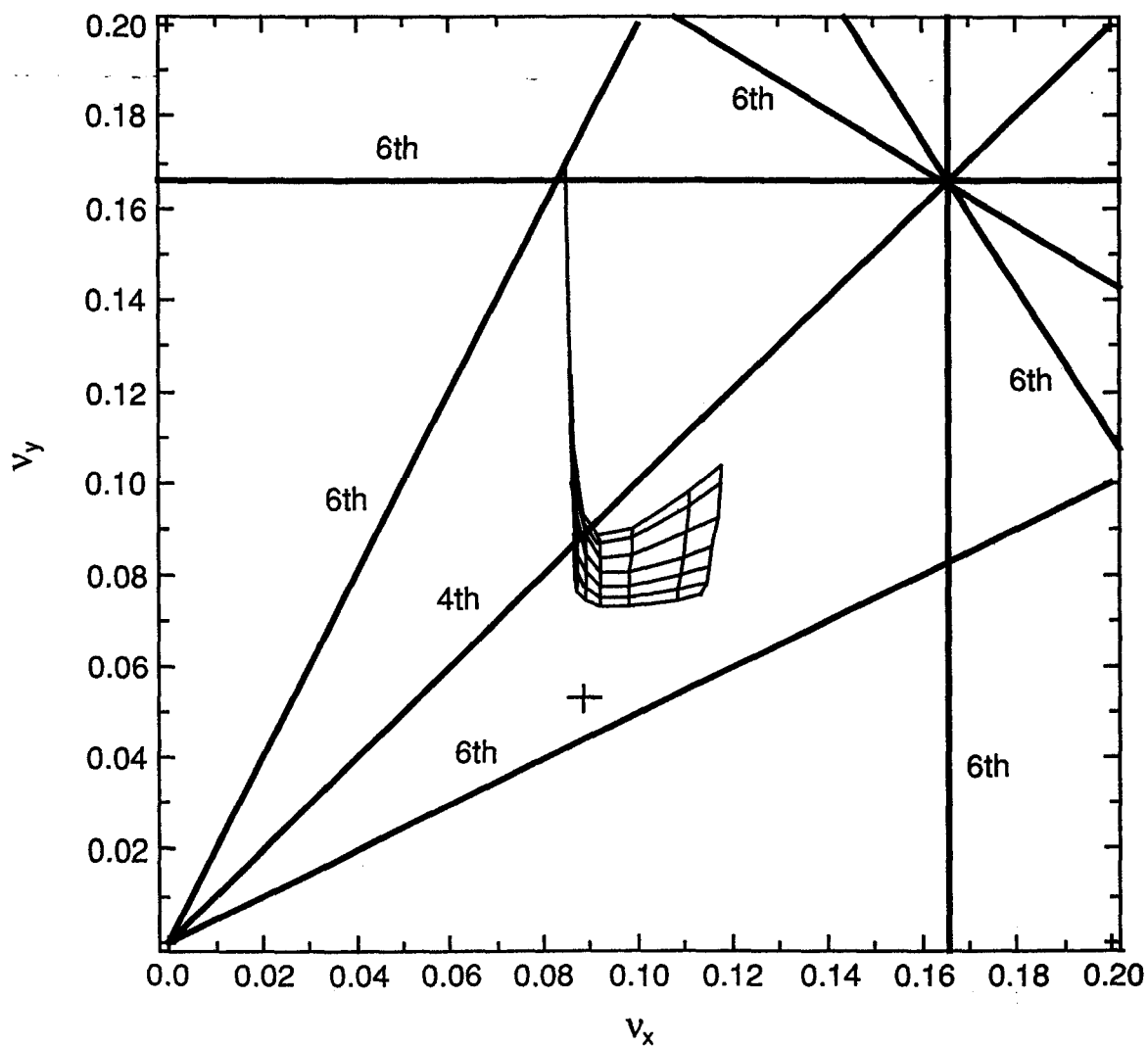


Fig. 4-90. Beam footprint, including the effect of the parasitic crossings. The large-amplitude distortion of the footprint produced by the long-range collision is apparent (see Fig. 4-86 for a comparison).

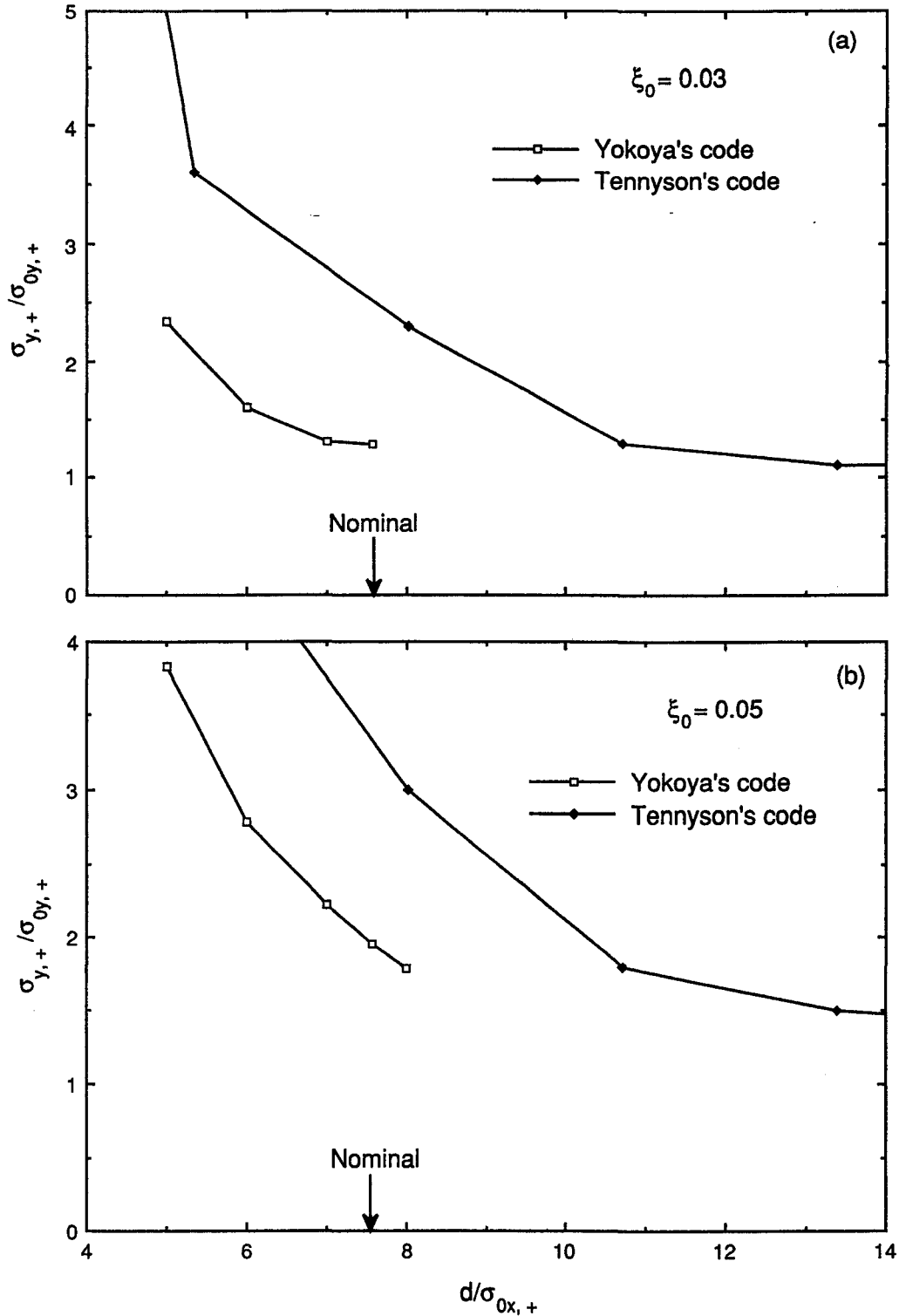


Fig. 4-91. Vertical beam blowup factor for the low-energy (positron) beam vs $d/\sigma_{0x,+}$ for the B Factory design, for (a) $\xi_0 = 0.03$ and (b) $\xi_0 = 0.05$. The nominal beam separation at the parasitic crossing, indicated by the arrow, corresponds to $d/\sigma_{0x,+} = 7.56$. The remaining three beam sizes are not shown because they exhibit blowup (or contraction) factors of 10% or less in all cases, except at very low values of $d/\sigma_{0x,+}$. This feature is qualitatively similar to what is shown in Fig. 4-87.

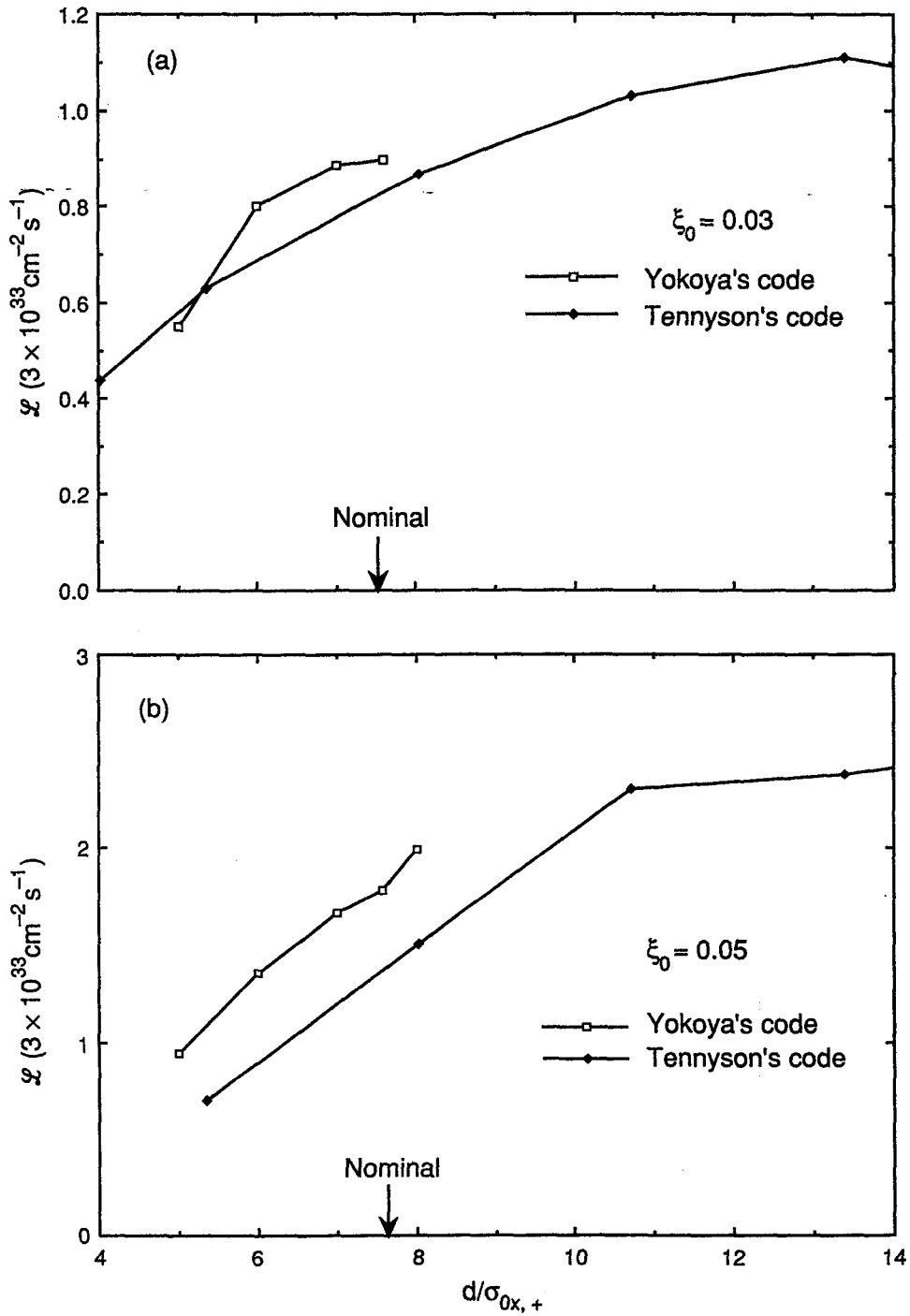


Fig. 4-92. Luminosity vs $d/\sigma_{0x,+}$ for the B Factory design, for (a) $\xi_0 = 0.03$ and (b) $\xi_0 = 0.05$, corresponding to the blown-up beam sizes shown in Fig. 4-91. Note that, for $\xi_0 = 0.05$, the nominal value of the luminosity is $8.3 \times 10^{33} \text{ cm}^{-2} \text{ s}^{-1}$.

4.4.5 Discussion

Figure 4-88 shows that, if only the IP were considered, nominal behavior for the working point chosen would persist up to values of ξ_0 much larger than 0.03. However, the parasitic crossings induce significant blowup in the vertical size of the low-energy beam. Even so, Fig. 4-92a shows that the luminosity is only reduced by about 15% from its design value for $\xi_0 = 0.03$. For the higher value of $\xi_0 = 0.05$, the luminosity degradation from its nominal value ($\mathcal{L}_0 = 8.3 \times 10^{33} \text{ cm}^{-2} \text{ s}^{-1}$) is more significant, but the absolute luminosity still increases roughly linearly with beam current.

Although the two codes show good agreement in the absence of parasitic crossings, the agreement is less good when the parasitic crossings are included, especially for the larger value of ξ_0 . We have not yet resolved this discrepancy. Qualitatively, however, both codes show the same features. For example, both indicate that it is the low-energy beam vertical blowup that is responsible for the luminosity degradation. This result means that the transparency symmetry is broken substantially by the dynamics.

The asymmetric behavior in the simulations suggests two approaches to try to improve the situation: Either make the nominal design truly conform to transparency symmetry or abandon the transparency symmetry approach altogether. The fact that the low-energy beam blows up suggests that, in the latter approach, one should probably lower its specified tune-shift value and raise the values of the other three beam-beam parameters. It is worth exploring the consequences of both routes in the future, as part of an expanded exploration of parameter space.

For now, however, we have adopted a more limited approach in order to examine other possibilities for luminosity improvement, by changing the nominal parameters slightly from those specified above, a few at a time. The first such exploration is to see the effect of a larger $\beta_{x,+}^*$ and $\beta_{y,+}^*$. The idea is to try to make the tune modulation amplitude closer to the transparency condition, as defined in Eq. 4-49. In order that the nominal luminosity and the four nominal beam-beam parameters remain constant at their original values, this change in $\beta_{x,+}^*$ and $\beta_{y,+}^*$ requires an increase in the emittances of the high-energy beam, $\epsilon_{0x,-}$ and $\epsilon_{0y,-}$, and in the number of particles per bunch of the low-energy beam, N_+ , all in the same proportion as the increase in $\beta_{x,y,+}^*$. The result of the simulation, which does not include parasitic crossings, is shown in Figs. 4-93 and 4-94, where we compare the old result, corresponding to $\beta_{x,+}^* = 37.5 \text{ cm}$, $\beta_{y,+}^* = 1.5 \text{ cm}$, with the result for a new set of values, 33% larger, $\beta_{x,+}^* = 50 \text{ cm}$, $\beta_{y,+}^* = 2 \text{ cm}$. We see that the behavior is better in the sense that the luminosity is closer to its nominal value.

The penalty in this case is a larger low-energy beam current, which approaches 3 A on account of the increase in N_+ . However, a beneficial effect of increasing the beta function at the IP is that the beta function at the first parasitic crossing decreases. This serves to make the bunches smaller, therefore increasing $d/\sigma_{0x,+}$, and also to reduce the tune shift produced at the parasitic crossing. At present, simulations including the parasitic crossings have not been done to test the effect of this reduction.

Another way of making the tune-modulation-amplitude parameters closer to the transparency condition is by decreasing the bunch length $\sigma_{L,+}$ of the low-energy beam in such a way that the synchrotron tune ν_s remains constant (see Eq. 4-49). This requires changing the momentum compaction factor α and the RF voltage V_{RF} . The result of the

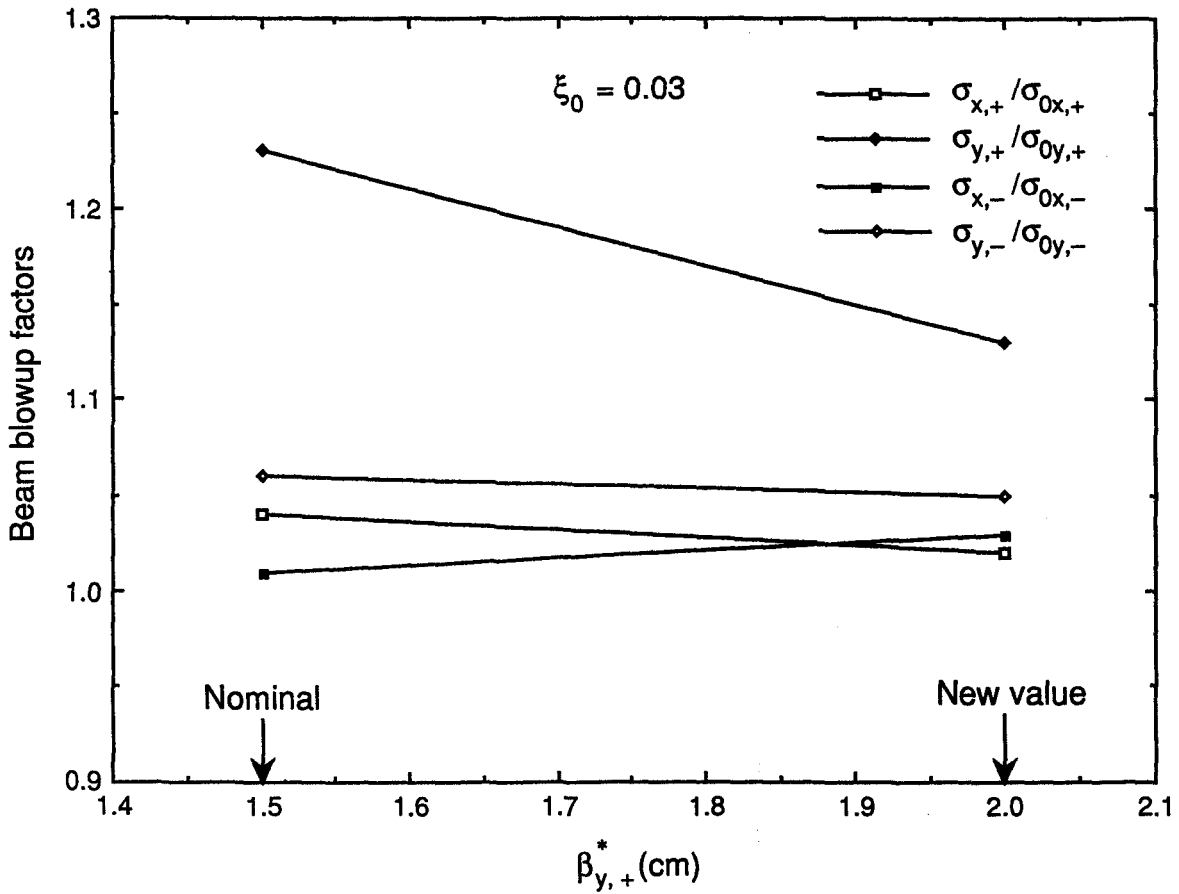


Fig. 4-93. Beam blowup factors vs $\beta_{y,+}^*$ for the B Factory design. Only the IP collision is considered ($\xi_0 = 0.03$, Yokoya's code). Other parameters were changed along with the beta function; see text.

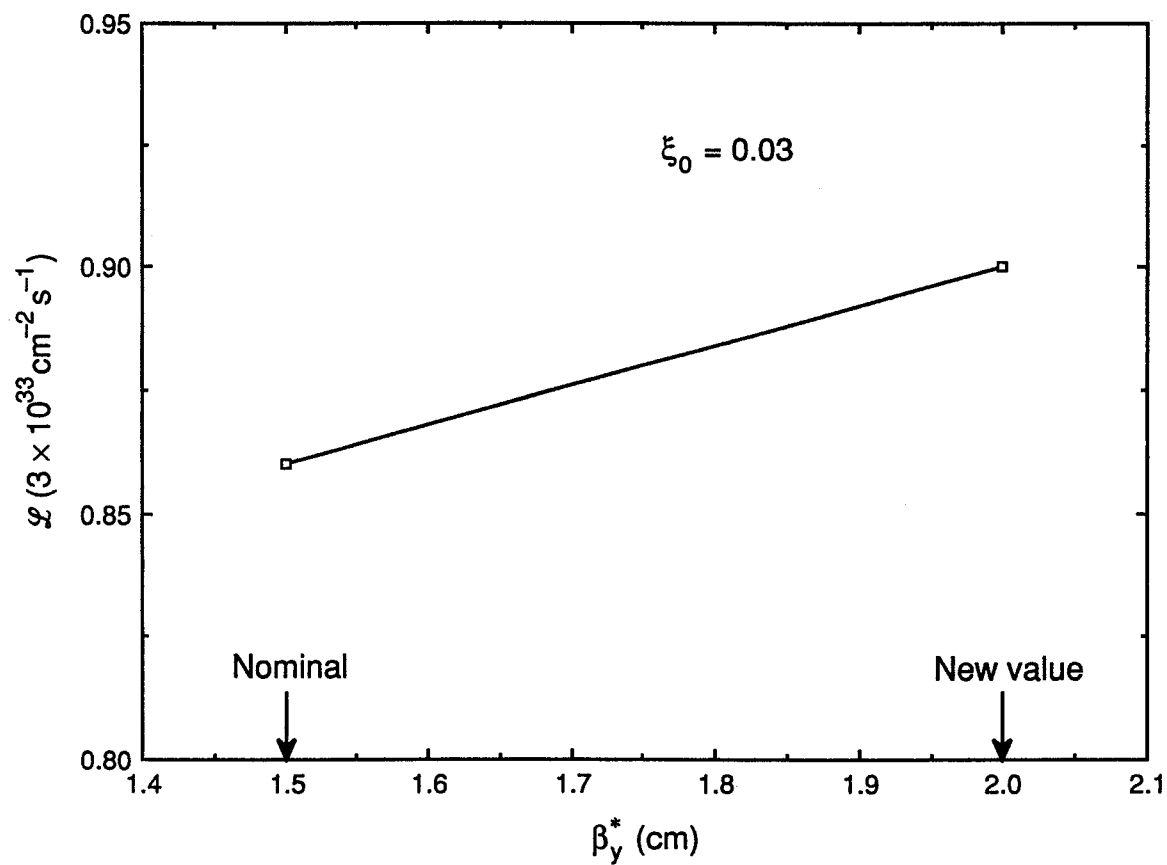


Fig. 4-94. Luminosity vs $\beta_{y,+}^*$ for the B Factory design. This corresponds to the blown-up beams of Fig. 4-93.

simulation, which again does not take into account parasitic crossings, is shown in Figs. 4-95 and 4-96. We see that the beam blowup is smaller and that the luminosity loss is quite small.

Finally, a third approach to making the beam dynamics closer to nominal is to increase the bunch spacing s_B by 50%, from 1.26 m to 1.89 m, by filling the rings with bunches every third RF bucket rather than every second bucket. The idea is to push the parasitic crossings farther away from the IP, so that the bunch separation is

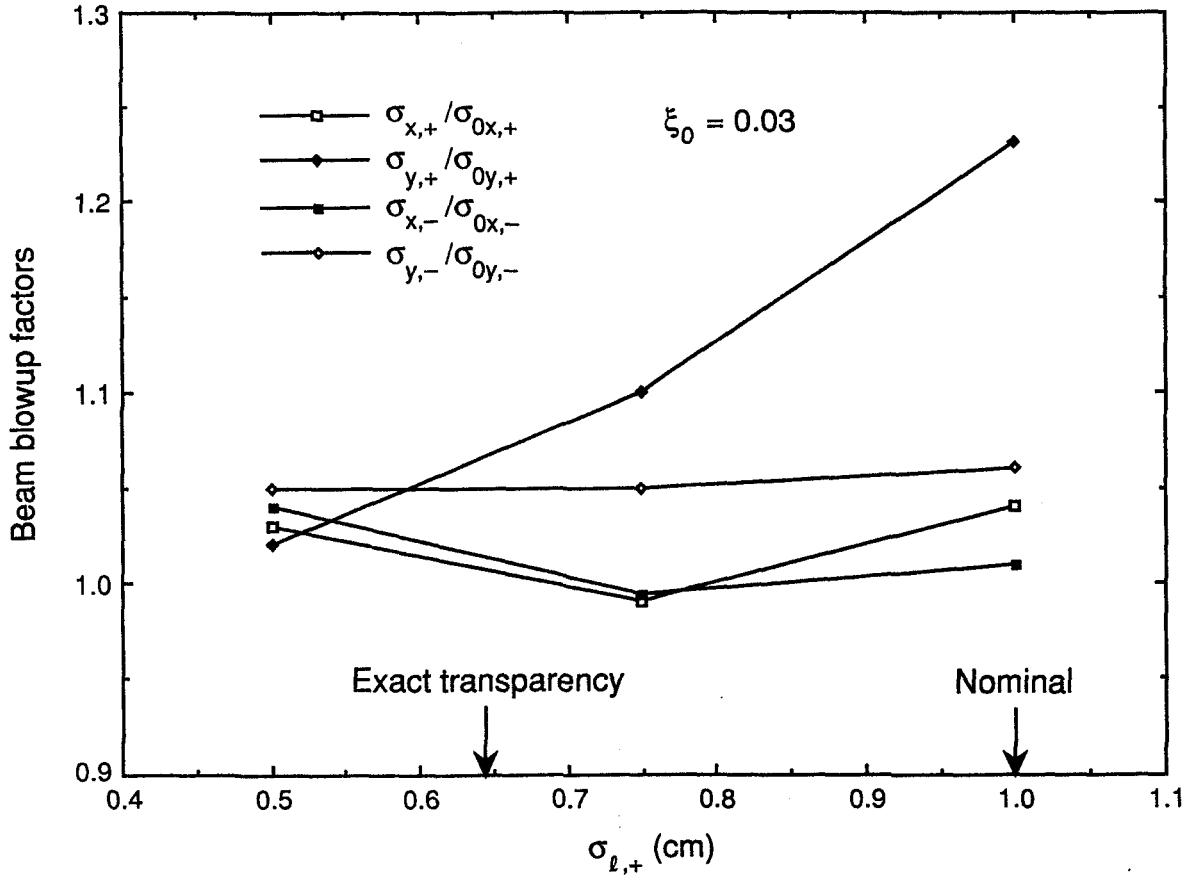


Fig. 4-95. Beam blowup factors vs $\sigma_{l,+}$. Only the IP collision is considered ($\xi_0 = 0.03$, Yokoya's code). The arrow labeled "exact transparency" indicates the value of $\sigma_{l,+}$ for which the amplitudes for the tune modulation due to synchrotron oscillations are the same in both beams. Other parameters are changed along with the bunch length; see text for details.

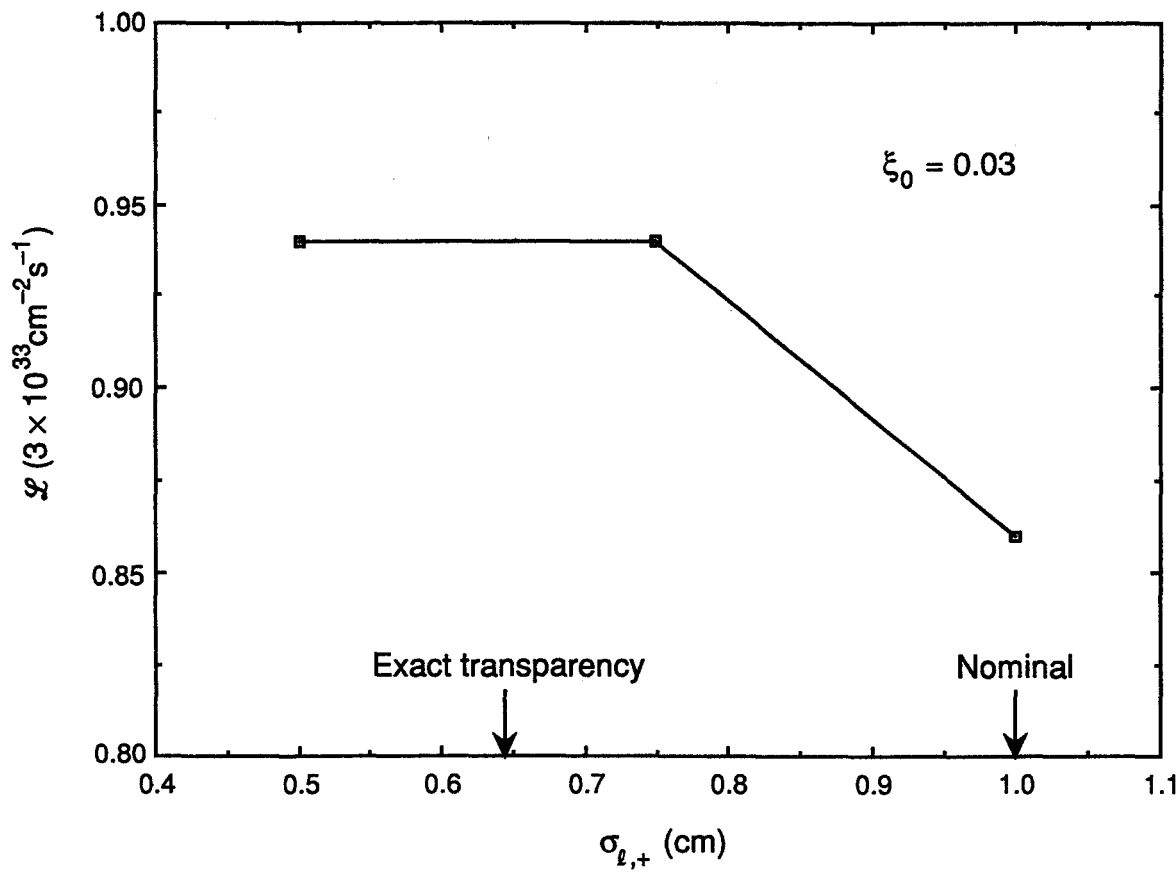


Fig. 4-96. Luminosity vs $\sigma_{l,+}$ for the B Factory design. This corresponds to the blown-up beams of Fig. 4-95.

correspondingly larger. In order to maintain ξ_0 and $\mathcal{L}_0$ at their original values of 0.03 and $3 \times 10^{33} \text{ cm}^{-2} \text{ s}^{-1}$, respectively, we require that the numbers of particles per bunch and the emittances also be increased by 50%. The resulting lattice parameters and nominal beam parameters are listed in Table 4-25.

Note that the bunch separation d at the first parasitic crossing is now 7.41 mm rather than the old value of 2.82 mm. The parameter $d/\sigma_{0x,+}$ is now a more comfortable 9.16 instead of the original value of 7.56. The resulting simulation results are shown in Figs. 4-97 and 4-98.

By comparing Fig. 4-97 with the previous case, Fig. 4-91, we can see a substantial improvement. The behavior is now very close to nominal.

Table 4-25. B Factory nominal parameters at the IP and the first parasitic crossing with increased bunch separation (every third bucket filled).

	LER (e ⁺)		HER (e ⁻)	
Δs [cm]	94			
d [mm]	7.41			
N_B	8.42×10^{10}		5.82×10^{10}	
ϵ_{0x} [nm·rad]	138		69	
ϵ_{0y} [nm·rad]	5.4		2.7	
	IP	1st PC	IP	1st PC
Δv_x	0	0.1844	0	0.1403
Δv_y	0	0.2478	0	0.2453
β_x [cm]	37.5	474	75	241
β_y [cm]	1.5	3,265	3	2,449
α_x	0	-9.20	0	-2.60
α_y	0	8.68	0	-15.95
σ_{0x}^* [μm]	228	809	228	408
σ_{0y}^* [μm]	9.00	420	9.00	257
d/σ_{0x}	0	9.16	0	18.2

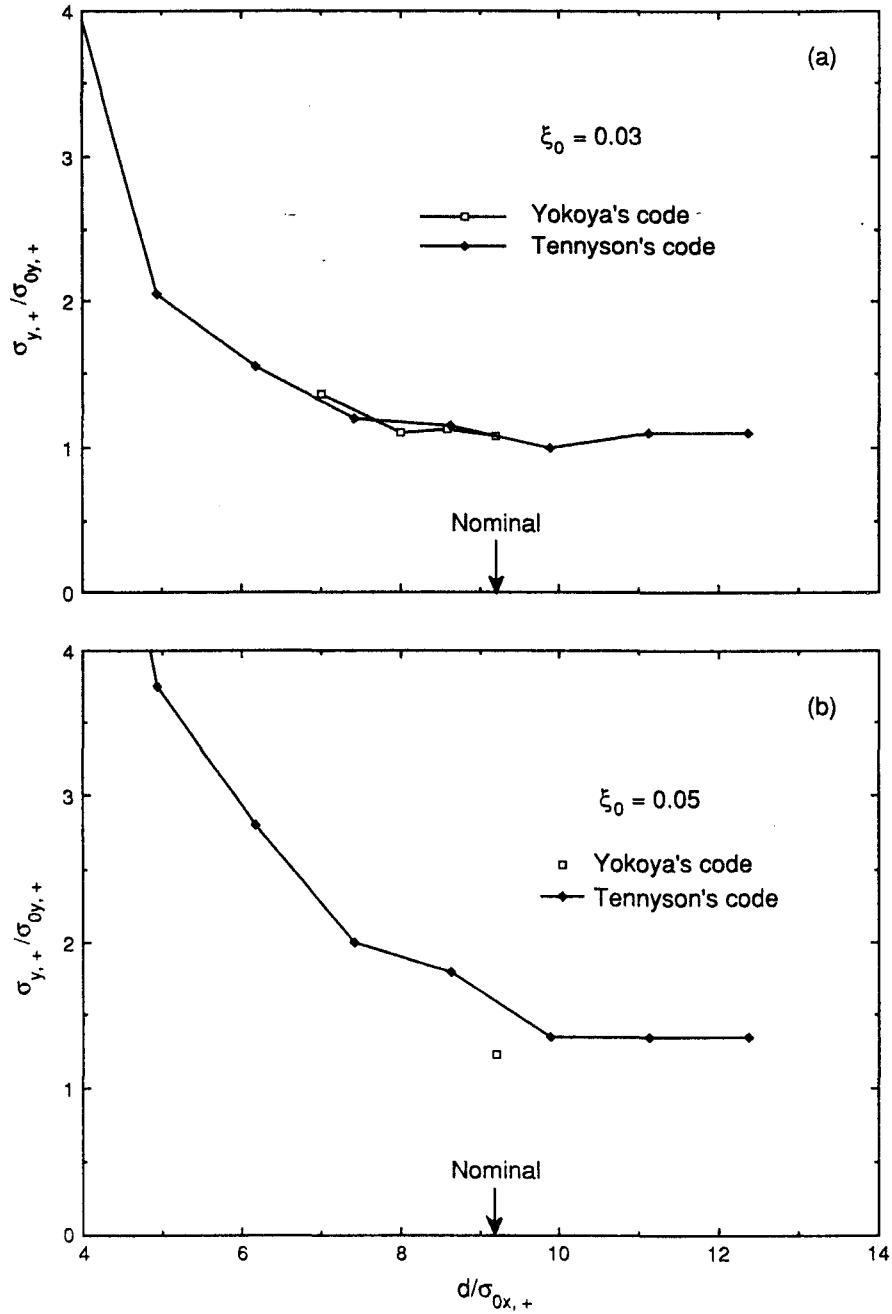


Fig. 4-97. Vertical beam blowup factor for the low-energy (positron) beam vs $d/\sigma_{0x,+}$ for the B Factory design, in the case where the bunches are filled every third bucket instead of every second bucket, for (a) $\xi_0 = 0.03$ and (b) $\xi_0 = 0.05$. The nominal beam separation at the parasitic crossing, indicated by the arrow, corresponds now to $d/\sigma_{0x,+} = 9.16$. The bunches have 50% more particles and 50% larger emittances than in the every-second-bucket filling scheme so that the nominal luminosity and beam-beam parameters retain their original values. The remaining three beam sizes are not shown, because they exhibit blowup (or contraction) factors of 20% or less in all cases, except at very low values of $d/\sigma_{0x,+}$. This feature is qualitatively similar to what is shown in Fig. 4-91.

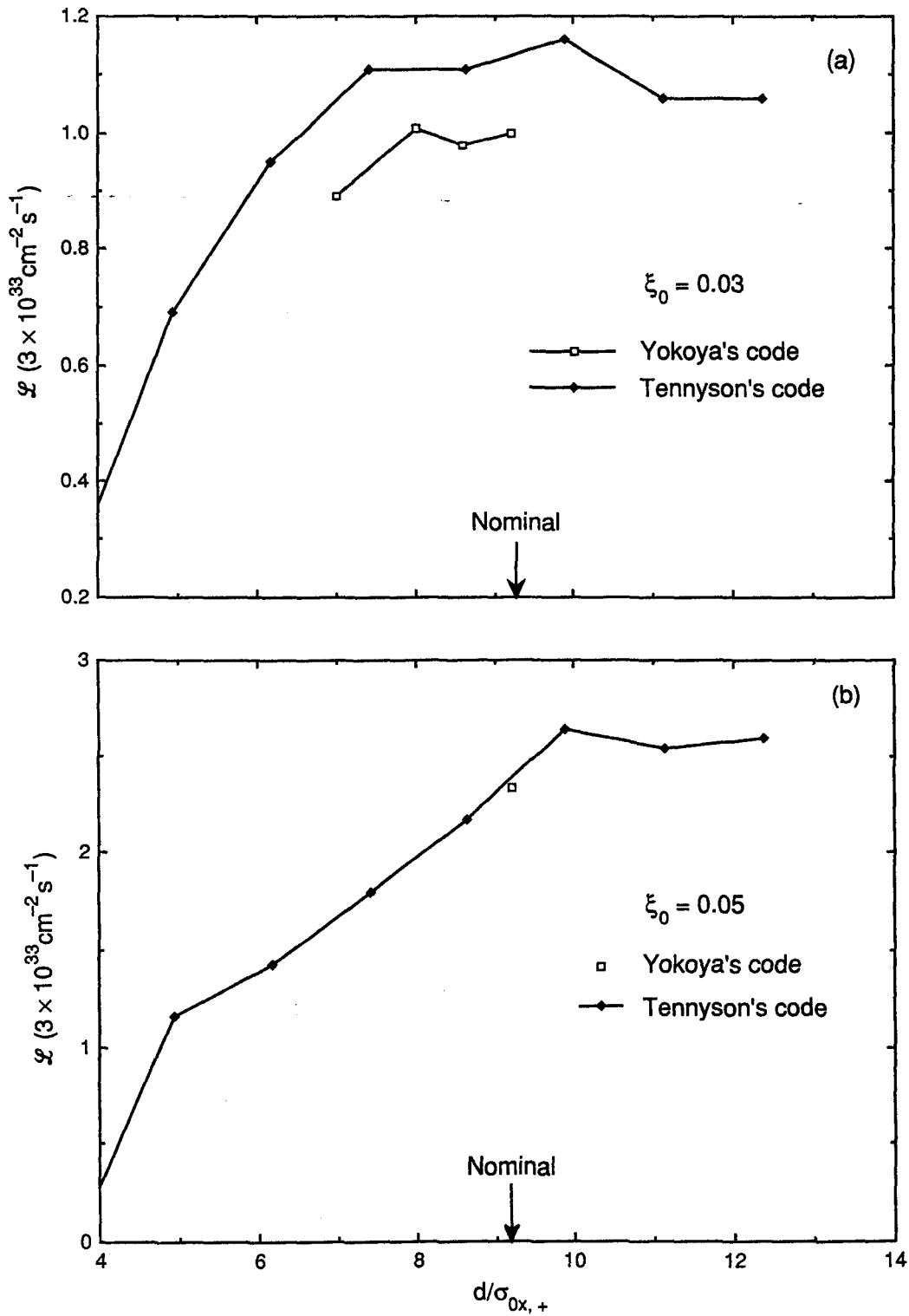


Fig. 4-98. Luminosity vs $d/\sigma_{0x,+}$ for the B Factory design, in the case where the bunches are filled every third bucket instead of every second bucket, for (a) $\xi_0 = 0.03$ and (b) $\xi_0 = 0.05$, corresponding to the blown-up beam sizes of Fig. 4-97.

4.4.6 Conclusions

Our results to date show that, without the parasitic crossings, the beam dynamics performance of the machine is quite close to nominal, up to values of ξ_0 substantially higher than the design specification of 0.03. Although we have shown this to be the case only for a working point just above the integer, we have preliminary evidence that this feature remains qualitatively valid for other working points as well [Tennyson, 1991b]. Another important issue that we are beginning to study in detail is that of beam lifetime. This is the most expensive and difficult part of beam-beam simulations; for this reason, we have concentrated our effort thus far on finding solutions with acceptable luminosity.

The parasitic crossings introduce a substantial horizontal-vertical coupling due to the large value of the vertical beta function. This has the effect of increasing the vertical size of the low-energy beam substantially, with a corresponding lowering of the luminosity. However, because the other three transverse beam sizes are not changed much, the luminosity degrades no more than 15% from its nominal value for $\xi_0 = 0.03$. For $\xi_0 = 0.05$, the relative degradation is larger, of the order of 40–50%; however, since the nominal luminosity is larger in this case ($\mathcal{L}_0 = 8.3 \times 10^{33} \text{ cm}^{-2} \text{ s}^{-1}$), the *absolute* value of the luminosity is about $5 \times 10^{33} \text{ cm}^{-2} \text{ s}^{-1}$, which exceeds the nominal specification. Although the resultant performance is still deemed completely acceptable, we intend to seek improvements by exploring alternative parameters that entail less blowup at the larger value of ξ_0 . Some possibilities, which are either in progress or as yet untried, are

- Make the machine designs more symmetric from the point of view of tune modulation due to synchrotron motion (for example, increase $\beta_{x,y,+}^*$, or decrease the bunch length $\sigma_{l,+}$)
- Leave the design of the collider as it is (slightly asymmetric), but introduce a slight asymmetry in the nominal beam parameters in such a way as to compensate the asymmetry (for example, increase $\xi_{0,-}$ and decrease $\xi_{0,+}$)
- Increase the bunch spacing from $2\lambda_{\text{RF}} = 1.26 \text{ m}$ to $3\lambda_{\text{RF}} = 1.89 \text{ m}$, with a concomitant increase in emittances and numbers of particles per bunch, so that the total beam current, nominal beam parameters, and nominal luminosity remain unchanged
- Introduce a slight horizontal crossing angle, so that the beams are farther apart at the first parasitic crossing

So far we have tried only the first and third possibilities in any detail, with encouraging preliminary results that show dynamical behavior noticeably closer to nominal.

Because of this, and because of the other possibilities for improvement mentioned above, we are confident that a solution with a luminosity of $3 \times 10^{33} \text{ cm}^{-2} \text{ s}^{-1}$ is entirely feasible. While many issues remain to be studied in much more detail, such as beam lifetimes, choice of working point, effect of magnet errors on beam dynamics performance, etc., it seems clear that a more comfortable, even conservative, solution is possible with relatively modest changes to the present design. Even without these improvements, the B Factory will be able to meet its luminosity goals with the addition of slightly more beam current in each ring.

5.

COLLIDER COMPONENTS

IN Chapter 4 we presented the physics design of the Asymmetric B Factory. The parameters we have adopted to achieve a luminosity of $3 \times 10^{33} \text{ cm}^{-2} \text{ s}^{-1}$, and the beam separation scheme we have arrived at (driven mainly by background considerations), impose many requirements on the various technical components of the project. In this chapter, we describe these technical components, paying particular attention to those aspects that are most crucial to reaching the high luminosity we have specified. In general, the challenges to be met are associated with the high beam currents that must be stored in the two rings, 1.48 A in the high-energy ring (HER) and 2.14 A in the low-energy ring (LER). In all cases, we have designed the hardware to have adequate operating margin to ensure reliability, and we have employed proven design concepts wherever possible.

In Section 5.1 we describe the magnets and supports. In the case of the HER, nearly all of these magnets are existing PEP magnets, but we describe them briefly for completeness. Though the LER magnets will be newly constructed, they are based in large measure on proven PEP designs and are therefore straightforward to design and build. Magnets in the interaction region (IR), however, are technically quite challenging and are the key to the successful implementation of the beam separation scheme; these are described in Section 5.1.3.

The vacuum systems for the two rings are described in Section 5.2. The design challenges here are to provide a low background gas pressure in the face of copious synchrotron-radiation-induced photodesorption and to manage the high thermal loads associated with many megawatts of synchrotron radiation power. We have adopted a copper chamber for our design, based on its desirable properties in both these regards. In this section, we also describe the design and cooling for the various IR hardware components, such as the synchrotron radiation masks, the beam dumps, and the vertex detector beam pipe.

The other technically challenging aspects of the B Factory design include the RF cavities (Section 5.5) and the feedback system (Section 5.6). The RF cavities must be designed to dissipate approximately 150 kW of power and to permit the effective damping of dangerous higher-order modes (HOMs) to Q values of about 70. This

damping is accomplished with an innovative design in which three waveguides are attached to the body of the room-temperature cavity to remove the HOM power. The feedback system utilizes a bunch-by-bunch approach that is designed to handle the full bunch repetition rate of 238 MHz; the system employs a novel digital processing scheme that is very flexible and can accommodate both injection and colliding-beam conditions. Detailed simulations of system performance have demonstrated the efficacy of the design. The remaining design aspects covered in Chapter 5—survey and alignment (Section 5.3), power supplies (Section 5.4), instrumentation (Section 5.7), and control system (Section 5.8) are relatively straightforward. Here too we have paid attention to providing flexibility and reliability in all components to ensure that the B Factory will indeed function as a “factory.”

5.1 MAGNETS AND SUPPORTS

The magnet system in the B Factory provides the guide fields that bend and focus the charged particles, electrons in the HER and positrons in the LER. In the case of the HER, the lattice is designed to make use of most of the existing PEP magnets. The LER is an entirely new ring for which all magnets must be newly constructed.

Because PEP was designed to operate at 18 GeV, whereas the B Factory HER need operate at only 9 GeV, the PEP magnets are very conservatively designed for their new function. As discussed in Section 7.2, it is prudent to inspect the magnets when they are removed from the tunnel; as needed, the magnet coils will be refurbished to ensure their reliability for long-term B Factory service. In addition, the magnets will be measured after reassembly to ensure that their fields remain the same.

We plan to reuse all of the PEP dipoles and quadrupoles for the B Factory HER. Because the HER lattice uses more quadrupoles than did PEP, additional magnets must be fabricated. In the case of the dipoles, we need 192 regular bending magnets and an additional 16 PEP low-field bending magnets, for a total of 208 PEP dipoles; four short LER-style dipoles will also be used, making a grand total of 212 dipoles for the HER. All 144 sextupoles are available from PEP. For completeness, however, we describe the existing PEP magnets briefly in Section 5.1.1.

The quadrupole and sextupole magnets for the LER are designed to have the same aperture as the present PEP magnets. This is justified because the required beam-stay-clear aperture in the LER is almost identical to that of the HER, as discussed in Section 5.2.1. Basing the LER designs on PEP magnets minimizes the engineering and design efforts required, because the already-optimized pole profiles of the PEP magnets can be used without modification. The LER dipoles are much shorter than the PEP dipoles (1 m compared with 5.4 m for PEP) but can nevertheless make use of the same pole profile. Design details for the LER magnets are presented in Section 5.1.2.

5.1.1 HER Magnets

As mentioned above, most of the magnets for the HER are existing PEP magnets. The only exception is the quadrupoles. Additional quadrupoles are needed for the HER

because the FODO focusing structure (see Section 4.1) will be maintained throughout the straight sections, except the IR-2 straight that houses the detector.

5.1.1.1 Dipoles. The main parameters of the laminated PEP dipoles are summarized in Table 5-1 for conditions corresponding to the nominal B Factory operating energy of 9 GeV. Physical dimensions of the magnet are shown in Fig. 5-1. Each magnet has a magnetic length of 5.4 m (212.607 in.) and weighs 7.4 tons. The coils, located above and below the midplane, are constructed of water-cooled aluminum, insulated with Mylar and fiberglass tape and vacuum potted in an alumina-based epoxy. All dipoles will be disassembled and will have their coil insulation inspected and refurbished to ensure reliable service in the B Factory. After reassembly, a sample of magnets will be remeasured to ensure the constancy of their magnetic properties. To provide horizontal orbit correction, backleg windings are employed. Windings from a pair of dipoles on either side of a focusing quadrupole will be ganged together to form a single corrector.

5.1.1.2 Quadrupoles. As with the dipole magnets, all existing PEP quadrupoles will be reused for the HER. Altogether, 272 magnets are required for the B Factory HER, of which 204 are available from PEP. The additional magnets will be fabricated using the same pole-tip profile developed for PEP, thus avoiding the need to develop a new design. Dimensions of a typical quadrupole magnet are shown in Fig. 5-2. The electrical characteristics of the existing quadrupoles, together with the new magnets, are summarized in Table 5-2. As is the case for the dipoles, the conductor for the quadrupoles is an aluminum extrusion. The insulating procedure used for the dipoles, employing Mylar, fiberglass tape, and alumina-loaded epoxy, will also be used for the quadrupole magnets.

5.1.1.3 Sextupoles. For chromaticity correction in the B Factory HER, 144 sextupoles are required; all are available from PEP. The nominal operating point of the HER is quite similar to that of PEP, and since the sextupoles were designed for 18-GeV operation, they have ample margin for any reasonable HER operating parameters. The dimensions of the sextupole are shown in Fig. 5-3, and the electrical characteristics for the various sextupole types at the nominal HER energy are summarized in Table 5-3. Coil design and insulation are the same as for the dipoles and quadrupoles, discussed above.

5.1.2 LER Magnets

All magnets for the LER will be newly constructed. However, the beam-stay-clear aperture requirements for the LER are sufficiently similar to those of the HER (and PEP) that it is justifiable to use the same magnet aperture dimensions. (It is worth noting here that a review of the anticipated gas loads in both the HER and the LER indicates very little difference between the two; this argues for the choice of a vacuum chamber of similar cross section in the two rings.)

The main benefit of keeping the same magnet aperture is that the new LER magnets can take advantage of the well-proven pole-tip profiles developed for PEP and PETRA (using the computer program POISSON); that is, the magnets can be very similar to PEP magnets, with only the external dimensions changed to reflect the lower field

Table 5-1. HER dipole parameters. All are refurbished PEP dipoles.

Magnet designation	2.8C212	2.8C40	5.25C80	5.25C80
Number of magnets	192	4	8	8
Field @ 9 GeV [T]	0.1819	0.0356	0.0166	0.0214
Integrated field @ 9 GeV [T·m]	0.9824	0.0356	0.0332	0.0428
Pole width [in.]	8.425	7.5	5.9	5.9
Gap height [in.]	2.787	2.787	5.276	5.276
Core length [in.]	209.820	36.583	73.622	73.622
Magnetic length [in.]	212.607	39.370	78.740	78.740
Width of useful field, 0.1% [in.]	4.725	4.00	3.15	3.15
Lamination height [in.]	15.433	16	13.38	13.38
Lamination width [in.]	18.19	17.8	10.47	10.47
Packing factor, minimum [%]	96	96	NA	NA
Core weight [lb]	14,168	2,000	1,500	1,500
Amp turns per pole @ 9 GeV	5,279	1,007	469	605
Turns per pole	8	15	1	1
Pancakes per pole	1	1	1	1
Conductor dimensions [in.]	2.4 × 0.7	2.0 × 0.3125	2.4 × 0.7	2.4 × 0.7
Cooling hole diameter [in.]	0.25	0.1875	0.25	0.25
Conductor cross section [in. ²]	1.59	0.60	1.59	1.59
Current @ 9 GeV [A]	659.9	67.1	469.4	605.2
Resistance @ 40°C [mΩ]	5.5	7.2	0.362	0.362
Power @ 9 GeV [kW]	2.39	0.03	0.08	0.13
Voltage drop @ 9 GeV [V]	3.63	0.48	0.17	0.22
Coil weight [lb]	585	200.00	40.00	40.00
Number of water circuits	2 @ 0.6 gpm	2 @ 0.6 gpm	2 @ 0.6 gpm	2 @ 0.6 gpm
Water flow rate [gpm]	1.2	1.20	1.20	1.20
Water pressure drop [psi]	50	100	50	50
Temperature rise [°C]	7.6	0.1	0.3	0.4
Total power, magnets and buss [kW]	545.5	0.1	0.6	1.1
Total voltage, magnets and buss [V]	736.4	1.9	1.4	1.8
Total system water requirements [gpm]	230.4	4.8	9.6	9.6

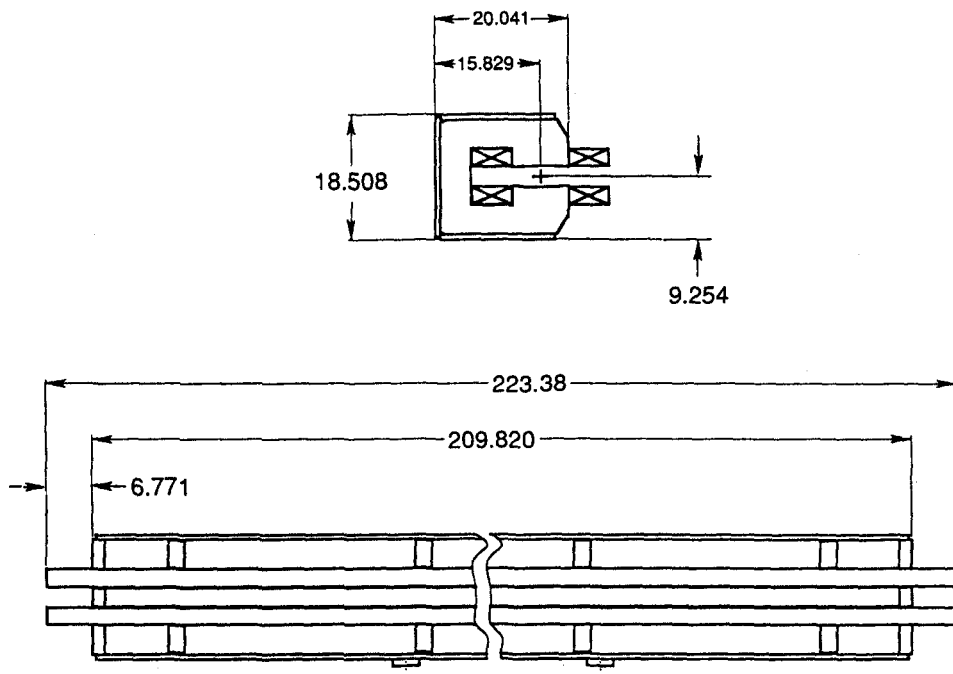


Fig. 5-1. End and side views of the HER bending magnet. Dimensions are given in inches.

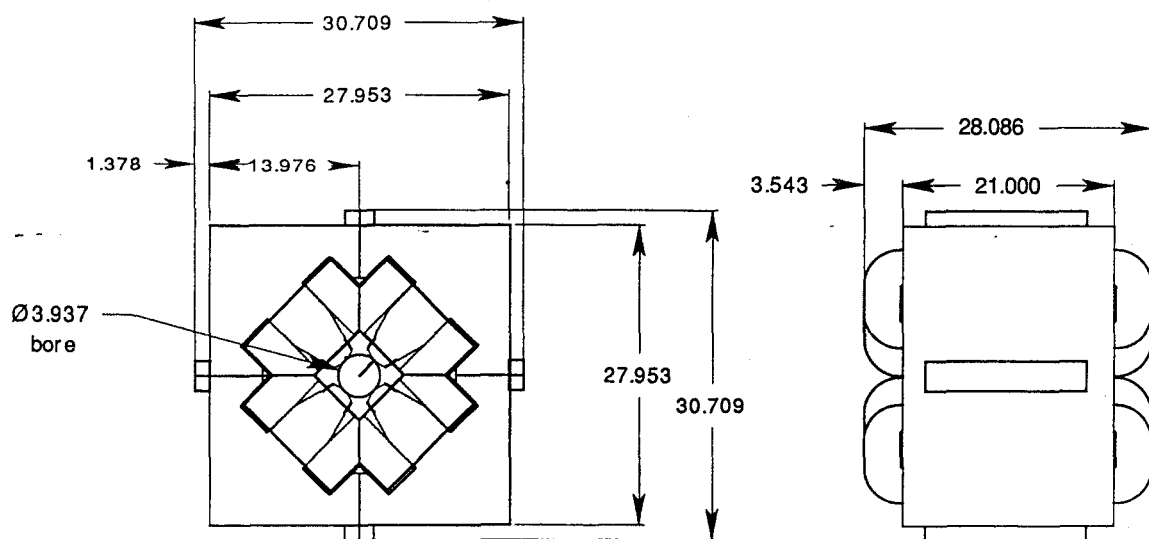


Fig. 5-2. End and side views of an HER quadrupole magnet. Dimensions are given in inches.

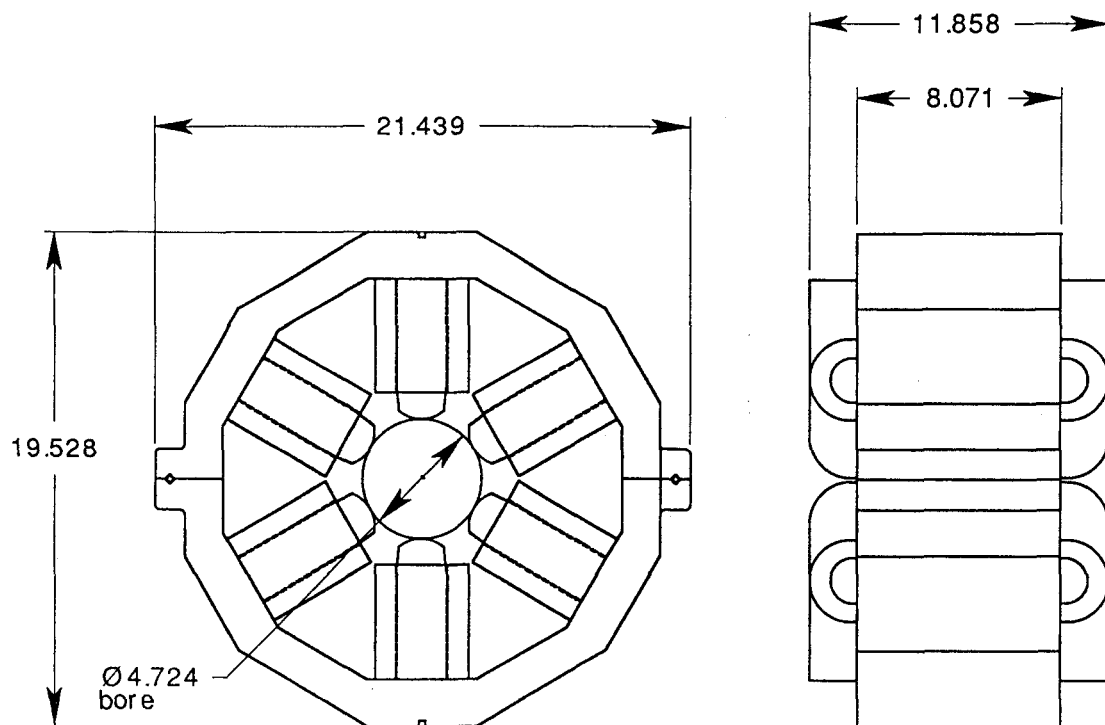


Fig. 5-3. End and side views of a PEP/HER sextupole magnet. Dimensions are given in inches.

Table 5-2a. HER quadrupole parameters. The column heads indicate whether the magnets are refurbished PEP quadrupoles or newly constructed magnets.

	PEP	PEP	PEP	New	PEP	PEP
Magnet designation	4Q21	4Q29	4Q39	4Q39L	4Q21	4Q29,
Location in ring	QD Sup	QD Sup	QF Sup	Straights	QD arc	QF arc
Number of magnets	24	12	24	60	66	72
Operating gradient [T/m]	7.99	5.59	5.39	4.05	7.29	5.58
Pole tip field @ operating gradient [T]	0.399	0.279	0.270	0.203	0.364	0.279
Gradient length product [T]	4.460	4.095	5.386	4.053	4.070	4.090
Inscribed radius [in.]	1.968	1.968	1.968	1.968	1.968	1.968
Minimum gap [in.]	1.457	1.457	1.457	1.457	1.457	1.457
Core length [in.]	21.00	27.87	38.35	38.39	21.00	27.86
Magnetic length [in.]	21.98	28.85	39.33	39.37	21.98	28.85
Lamination height [in.]	13.98	13.98	13.98	10.50	13.98	13.98
Lamination width [in.]	13.35	13.35	13.35	10.50	13.35	13.35
Packing factor, minimum [%]	98	98	98	98	98	98
Core weight [lb]	2882	3825	5264	3455	2882	3824
Amp turns per pole @ 9 GeV	7937	5552	5357	4027	7243	5546
Turns per pole	56	56	56	37	56	56
Pancakes per pole	1	1	1	1	1	1
Conductor cross-sectional area [in. ²]	0.197	0.197	0.197	0.197	0.197	0.197
Conductor dimensions [in.]	0.5×0.5	0.5×0.5	0.5×0.5	0.5×0.5	0.5×0.5	0.5×0.5
Cooling hole diameter [in.]	0.25	0.25	0.25	0.25	0.25	0.25
Current @ 9 GeV [A]	142	99	96	109	129	99
Resistance @ 40°C [mΩ]	72.7	91.8	121.45	80.24	72.7	91.8
Power @ 9 GeV [kW]	1.46	0.90	1.11	0.95	1.22	0.90
Voltage drop @ 9 GeV [V]	10.30	9.10	11.62	8.73	9.40	9.09
Coil weight [lb]	233	308	396	396	233	308
Number of water circuits	1	1	1	1	1	1
Water flow rate [gpm]	0.65	0.55	0.50	0.50	0.65	0.55
Water pressure drop [psi]	150	150	150	150	150	150
Temperature rise [°C]	8.5	6.2	8.4	7.2	7.1	6.2
Total power (magnets and buss) [kW]	35.1	10.8	26.7	57.0	80.3	64.8
Magnet system water requirements [gpm]	15.6	6.6	12	30	42.9	39.6

Table 5-2b. HER special quadrupoles.

	NEW	NEW	PEP	PEP	PEP	NEW	NEW
Magnet designation	4Q39	4Q39	6Q60	6Q60	6Q60	4Q39	4Q39
Transport name	QFi1	QDi2	QFi3	QDi4	QFi5	Qd6	Qf7
Location in ring	Inj	Inj	Inj	Inj	Inj	IR	IR
Number of magnets	2	2	2	2	2	2	2
Operating gradient [T/m]	3.43	3.96	0.86	2.52	3.14	5.16	4.04
Pole tip field @ operating gradient [T]	0.172	0.198	0.069	0.201	0.251	0.258	0.202
Gradient length product [T]	3.431	3.962	1.309	3.833	4.784	7.871	6.155
Inscribed radius [in.]	1.968	1.968	3.1496	3.1496	3.1496	1.968	1.968
Minimum gap [in.]	1.457	1.457	1.457	1.457	1.457	1.457	1.457
Core length [in.]	38.39	38.39	58.43	58.43	58.43	59.02	59.02
Magnetic length [in.]	39.37	39.37	60.00	60.00	60.00	60.00	60.00
Lamination height [in.]	10.50	10.50	13.98	13.98	13.98	10.50	10.50
Lamination width [in.]	10.50	10.50	13.35	13.35	13.35	10.50	10.50
Packing factor, minimum [%]	98	98	98	98	98	98	98
Core weight [lb]	2882	2882	16148	16148	16148	2882	2882
Amp turns per pole @ 9 GeV	3409	3937	2186	6401	7989	5132	4013
Turns per pole	37	37	13	13	13	37	37
Pancakes per pole	1	1	1	1	1	1	1
Conductor cross-sectional area [in. ²]	0.197	0.197	0.197	0.197	0.197	0.197	0.197
Cooling hole diameter [in.]	0.25	0.25	0.25	0.25	0.25	0.25	0.25
Conductor dimensions [in.]	0.5 × 0.5	0.5 × 0.5	0.5 × 0.5	0.5 × 0.5	0.5 × 0.5	0.5 × 0.5	0.5 × 0.5
Current @ 9 GeV [A]	92	106	168	492	615	139	108
Resistance @ 40°C [mΩ]	72.7	72.7	72.7	72.7	72.7	72.7	72.7
Power @ 9 GeV [kW]	0.62	0.82	2.06	17.62	27.45	1.40	0.86
Voltage drop @ 9 GeV [V]	6.70	7.73	12.22	35.79	44.67	10.08	7.88
Coil weight [lb]	233	233	955	955	955	233	233
Number of water circuits	1	1	1	1	1	1	1
Water flow rate [gpm]	0.65	0.65	0.65	0.65	0.65	0.65	0.65
Water pressure drop [psi]	150	150	150	150	150	150	150
Temperature rise [°C]	3.6	4.8	12.0	103.0	160.5	8.2	5.0
Total power (magnets and buss) [kW]	1.2	1.6	4.1	35.2	54.9	2.8	1.7

Table 5-3. HER sextupole parameters.

Magnet designation	10 D	10 F	10D1	10 F1	10 D2	10 F2
Number of magnets	56	64	8	4	8	4
Operating gradient [T/m ²]	73.04	44.67	104.41	66.57	33.61	22.81
Pole tip field @ operating gradient [T]	0.131	0.080	0.188	0.120	0.060	0.0411
Integrated strength @ 9 GeV [T/m]	18.63	11.39	26.63	16.98	8.57	5.817
Aperture inscribed radius [in.]	2.362	2.362	2.362	2.362	2.362	2.362
Core length [in.]	8.071	8.071	8.071	8.071	8.071	8.071
Magnetic length [in.]	10.041	10.041	10.041	10.04	10.041	10.041
Core weight [lb]	170.	170.	170.	170.	170.	170.
Amp turns per pole	2081	1273	2974	1896	957	650
Turns per pole	24	24	24	24	24	24
Pancakes per pole	1	1	1	1	1	1
Square conductor dimensions [in.]	0.375	0.375	0.375	0.375	0.375	0.375
Cooling hole diameter [in.]	0.125	0.125	0.125	0.125	0.125	0.125
Conductor cross-sectional area [in. ²]	0.127	0.127	0.127	0.127	0.127	0.127
Current @ 9 GeV [A]	-86.7	-53.0	-123.9	-79.0	-39.9	-27.1
Coil length/pole [ft]	70.0	70.0	70.0	70.0	70.0	70.0
Resistance @ 40°C [mΩ]	44.25	44.25	44.25	44.25	44.25	44.25
Power @ 9 GeV [kW]	0.33	0.12	0.68	0.28	0.07	0.03
Voltage drop @ 9 GeV [V]	3.84	-2.35	5.48	-3.50	1.77	-1.20
Coil weight [lb]	200	200	200	200	200	200
Number of water circuits	2	2	2	2	2	2
Water flow rate [gpm]	0.25	0.25	0.25	0.25	0.25	0.25
Water pressure drop [psi]	150	150	150	150	150	150
Temperature rise [°C]	5.1	1.9	10.3	4.2	1.1	0.5
Total magnet power [kW]	18.6	8.0	5.4	1.1	0.6	0.1
Total voltage [V]	214.8	-150.2	43.9	-14.0	14.1	-4.8
Total system water requirements [gpm]	14.0	16.0	2.0	1.0	2.0	1.0

requirements at the nominal 3.1-GeV operating point. In this way, we substantially reduce our R&D and engineering costs.

The design of the new magnets will be optimized by minimizing the sum of the installed capital cost plus ten years of operating cost at the design energy. This means that prudent attention is paid to reducing power consumption. Despite this, the LER magnets use proportionately more power than the PEP/HER magnets. This comes about because the PEP magnets were optimized for 18-GeV operation, where the operating costs are higher than at 9 GeV.

5.1.2.1 Dipoles. The design of the LER dipoles was dictated by several considerations. First, the LER magnets must be mounted above the HER. To minimize the weight that must be rigidly supported, it is important to reduce the size of the dipoles considerably, compared with the PEP design. Second, the problems with synchrotron-radiation-induced gas desorption are eased considerably if the dipole is kept short enough to permit its synchrotron radiation fan to exit the magnet completely (as discussed in detail in Section 5.2). Finally, the lattice parameters of the LER call for a relatively high emittance and short damping times, compared with what would result from a low-field bending magnet lattice. Although we have chosen to provide wigglers to adjust these parameters, the choice of a short, higher-field dipole helps to reduce the demands on the wigglers and to spread the synchrotron radiation power around more of the ring.

The LER arc dipole magnet physical dimensions are shown in Fig. 5-4. The key dimensions are the length of 36.583 in. and the gap of 2.787 in. The electrical properties of the LER dipole at its nominal operating energy of 3.1 GeV are summarized in Table 5-4.

To reduce production costs and to maximize magnet-to-magnet uniformity, the main ring magnets for the LER are of laminated construction. The dipole magnets will be constructed of one-piece laminations, 1/16-in. thick, punched from a decarburized, annealed, low-carbon steel sheet, such as Armco special magnet steel. This material—which has been used successfully for many accelerator applications, including those at PEP and Fermilab—exhibits high saturation induction, modest coercive force, and low remanent field. The estimated steel weight to manufacture the required 208 bending magnets is 350 tons.

Laminations will be punched with built-in fiducials to provide convenient external references for alignment, as discussed in Section 5.3. In addition, for reasons explained below, new witness marks will be introduced into the die at each heat-change to ensure magnet uniformity. Particular attention will be paid to the wear on the die. The vendor will be required to keep track of the number of laminations punched between die sharpenings and to provide SLAC with sample laminations on a regular basis, so that in-house inspections can be made to ensure that undue wear (>0.0005 in.) has not taken place on the critical surfaces (thereby producing out-of-tolerance laminations).

The vendor responsible for stacking the laminations will be required to deburr and then stack them, using laminations from consecutive heats. If this is done, the pattern generated by the witness marks will be obvious upon visual inspection. If the observed pattern is regular, the core will be acceptable, whereas an irregular pattern will indicate a lack of quality control on the part of the manufacturer and will be sufficient cause for rejecting the magnet core.

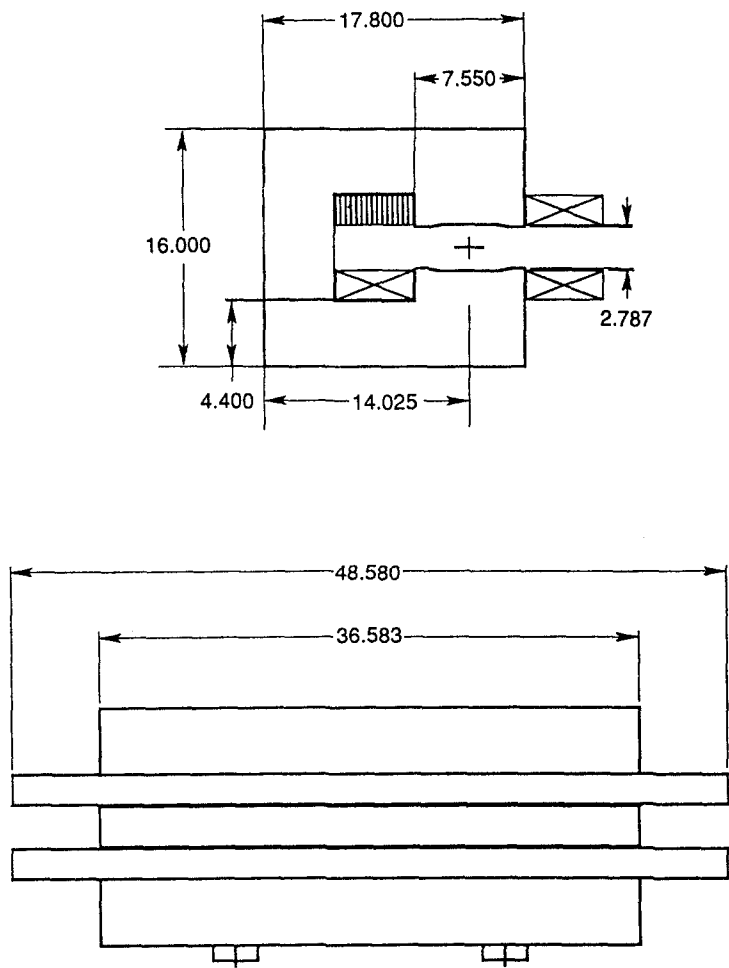


Fig. 5-4. End and side views of the LER bending magnet. Dimensions are given in inches.

Table 5-4. LER dipole parameters.

	2.8C40	2.8C20	2.8C20	2.8C40	2.8C40	2.8C40	2.8C80
Magnet designation	2.8C40	2.8C20	2.8C20	2.8C40	2.8C40	2.8C40	2.8C80
Bending angle [deg]	1.875	1.300	0.750	2.5	1.078	0.176	3.000
Location in ring	Arc	Vert bend	Vert bend	IR	IR	IR	Wiggler
Number of magnets	192	4	4	2	1	1	4
Field [T]	0.33948	0.47074	0.27158	0.45264	0.19518	0.03187	0.27158
Integrated field [T·m]	0.33948	0.23537	0.13579	0.45264	0.19518	0.03187	0.54317
Pole width [in.]	7.5	7.5	7.5	7.5	7.5	7.5	7.5
Gap height [in.]	2.787	2.787	2.787	2.787	2.787	2.787	2.787
Core length [in.]	36.583	16.898	16.898	36.583	36.583	36.583	75.953
Magnetic length [in.]	39.370	19.685	19.685	39.370	39.370	39.370	78.740
Width of useful field, 0.1% [in.]	4.00	4.00	4.00	4.00	4.00	4.00	4.00
Lamination height [in.]	16	16	16	16	16	16	16
Lamination width [in.]	17.8	17.8	17.8	17.8	17.8	17.8	17.8
Packing factor, minimum [%]	96	96	96	96	96	96	96
Core weight [lb]	2,000	1,000	1,000	2,000	2,000	2,000	3,000
Amp turns per pole	9,600	13,313	7,680	12,801	5,520	901	7,680
Turns per pole	15	15	15	15	15	15	15
Pancakes per pole	1	1	1	1	1	1	1
Conductor dimensions [in.]	2.0×0.3125	2.0×0.3125	2.0×0.3125	2.0×0.3125	2.0×0.3125	2.0×0.3125	2.0×0.3125
Cooling hole diameter [in.]	0.1875	0.1875	0.1875	0.1875	0.1875	0.1875	0.1875
Conductor cross section [in. ²]	0.60	0.60	0.60	0.60	0.60	0.60	0.60
Conductor length/pole [ft]	150	150	150	150	150	150	150
Current [A]	640.03	887.51	512.02	853.37	367.97	60.08	512.02
Resistance @ 40°C [mΩ]	7.2	7.2	7.2	7.2	7.2	7.2	7.2
Power [kW]	2.96	5.70	1.90	5.27	0.98	0.03	1.90
Voltage drop [V]	4.63	6.42	3.70	6.17	2.66	0.43	3.70
Coil weight [lb]	200.00	150.00	150.00	200.00	200.00	200.00	300.00
Number of water circuits	2 @ 0.6 gpm	2 @ 0.6 gpm	2 @ 0.6 gpm	2 @ 0.6 gpm	2 @ 0.6 gpm	2 @ 0.6 gpm	2 @ 0.6 gpm
Water flow rate, total [gpm]	1.20	2.40	1.20	1.20	1.20	1.20	1.20
Water pressure drop [psi]	100	100	100	100	100	100	100
Temperature rise [°C]	9.4	9.0	6.0	16.7	3.1	0.1	6.0
Total power (magnets and buss) [kW]	593.3	22.8	7.6	10.5	1.0	0.0	7.6
Total voltage (magnets and buss) [V]	1014.6	35.7	24.8	19.8	7.7	5.4	24.8
Total system water requirements (gpm)	230.4	9.6	4.8	2.4	1.2	1.2	4.8

Laminations will be rotated after stacking each (approximately) 4-in. segment of the core. In this way, errors due to the slight variation in the thickness of the laminations will be eliminated. (This thickness error, referred to as "crowning," is well-known to occur in flat rolled sheet due to curvature in the rollers caused by forces generated during the production of the sheet.) The precise number of laminations that are stacked before performing such a rotation, which can only be determined when the number of heats is known, will be sufficient to ensure that the regular periodicity of the witness marks is retained.

The magnets run at low fields, well below saturation, and thus are more sensitive to core length than to the density of the lamination packing. Therefore, to maximize magnet-to-magnet reproducibility, particular attention will be paid to the length of the core (rather than its packing factor).

The magnet end-plates will be manufactured by numerically controlled mills and will contain the necessary holes for mounting coil retainers and other such devices. Angle plates welded to both the end-plates and the laminations will provide the torsional rigidity necessary to stabilize the cores and prevent twisting or bending.

Magnet coils will be of water-cooled aluminum, extruded from billets using porthole dies to provide continuous lengths up to several thousand feet. This technique obviates the need to make joints in the coil, thus eliminating the possibility of leaks. The length of a typical coil is about 150 ft, so there will be minimal waste at the end of each reel of conductor. The estimated weight of one dipole, including coils, is 2200 lb.

5.1.2.2 Quadrupoles. The standard LER quadrupole has a length of 20.0 in. and a bore diameter of 3.937 in.; its physical dimensions are shown in Fig. 5-5. The electrical properties of the quadrupoles corresponding to the nominal energy are summarized in Table 5-5.

The LER quadrupoles will be constructed, and the laminations handled, in the same manner described for the dipole magnets, except that they will use four-piece construction. The anticipated weight of steel is larger than that for the dipoles, about 550 tons, thus requiring more heats (about eight rather than five).

The design will include numerically machined end-plates with predrilled holes to mount the beam position monitors. These end-plates will be used to sandwich the laminations together. As with the dipoles, angles welded to the corners of the laminations will provide the required torsional rigidity and stiffness. Four cores, fitted with water-cooled aluminum coils approximately 180 ft long and extruded by the same technique as used for the bending magnets, will be bolted together to form one quadrupole weighing an estimated 2000 lb.

5.1.2.3 Sextupoles. The LER sextupole physical dimensions are shown in Fig. 5-6. These magnets have a length of 8.071 in. and a bore of 4.724 in. Their electrical properties, corresponding to the nominal energy are summarized in Table 5-6.

The LER sextupoles will be identical to the present PEP short (8 in.) sextupoles. This will permit us to interchange magnets between the LER and HER, if necessary, and minimizes the required number of spares. Manufacturing techniques will be the same as those described above for the LER dipoles and quadrupoles, although the anticipated steel requirement of about 50 tons will come from only a single heat. For this reason, witness

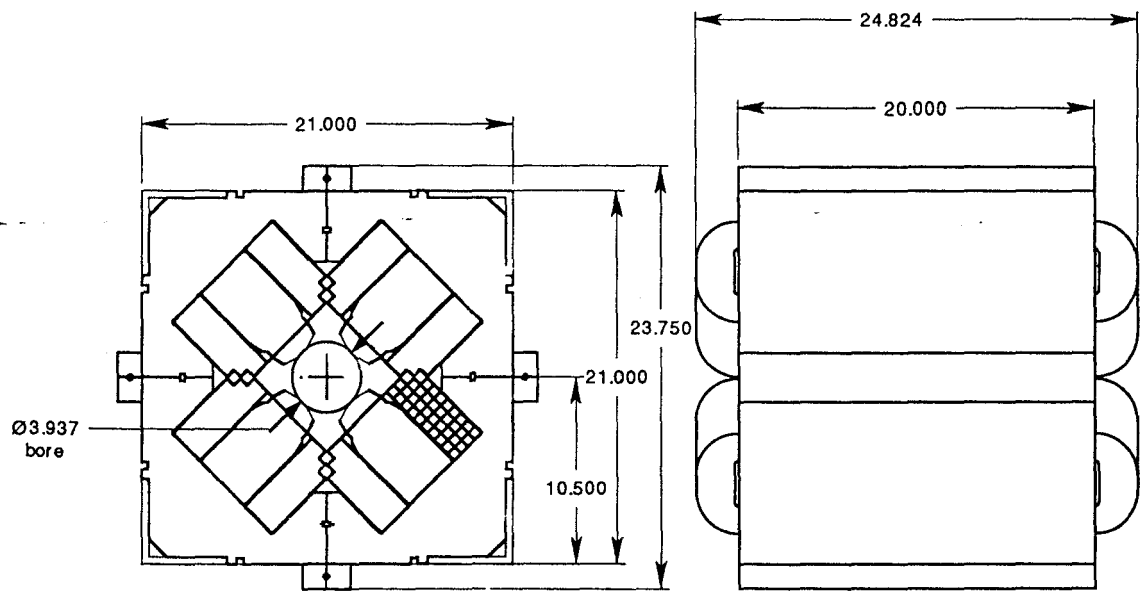


Fig. 5-5. End and side views of an LER quadrupole magnet. Dimensions are given in inches.

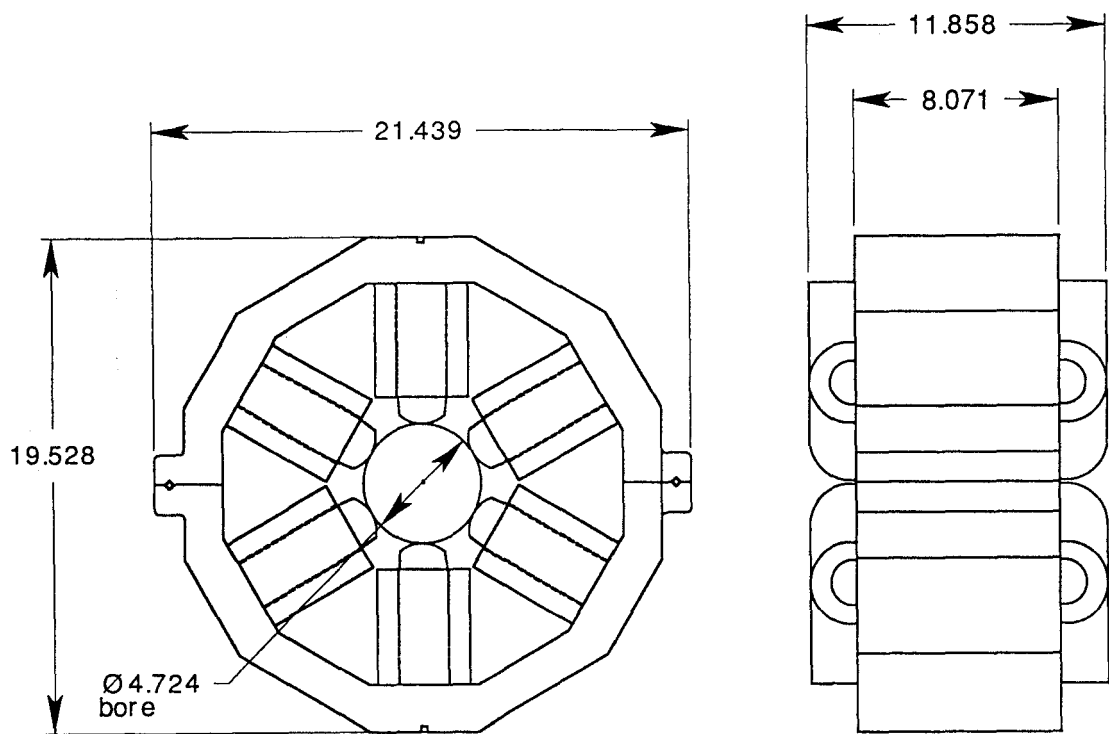


Fig. 5-6. End and side views of the LER sextupole magnet. Dimensions are given in inches.

Table 5-5. LER quadrupole parameters.

Magnet designation	4Q20	4Q13	4Q28	4Q40	4Q21	4Q21	4Q21
Location in ring	Arc & SS	IR	IR	IR	IR	IR	Wiggler
Number of magnets	264	4	4	6	12	4	6
Operating gradient [T/m]	2.499	10.340	8.980	8.980	11.350	3.410	4.500
Pole tip field @ operating gradient [T]	125	0.517	0.449	0.449	0.568	0.171	0.225
Gradient length product [T]	1.36	3.10	6.91	8.98	6.13	0.92	1.21
Inscribed radius [in.]	1.968	1.968	1.968	1.968	1.968	1.968	1.968
Minimum gap [in.]	1.457	1.457	1.457	1.457	1.457	1.457	1.457
Core length [in.]	20	10.354	28.8579	37.913	19.8028	9.1729	9.1729
Magnetic length [in.]	21.457	11.811	30.315	39.37	21.2598	10.6299	10.6299
Lamination height [in.]	10.5	10.5	10.5	10.5	1.968	1.968	1.968
Lamination width [in.]	10.5	10.5	10.5	10.5	1.457	1.457	1.457
Packing factor, minimum [%]	98	98	98	98	98	98	98
Core weight [lb]	1800	932	2597	3412	1782	826	826
Amp turns per pole	2484	10279	8927	8927	11283	3390	4473
Turns per pole	37	37	37	37	37	37	37
Pancakes per pole	1	1	1	1	1	1	1
Conductor cross-sectional area [in. ²]	0.197	0.197	0.197	0.197	0.197	0.197	0.197
Cooling hole diameter [in.]	0.25	0.25	0.25	0.25	0.25	0.25	0.25
Conductor dimensions [in.]	0.5 × 0.5	0.5 × 0.5	0.5 × 0.5	0.5 × 0.5	0.5 × 0.5	0.5 × 0.5	0.5 × 0.5
Conductor length/pole [ft]	180	180	180	180	180	180	180
Current [A]	67	278	241	241	305	92	121
Resistance @ 40°C [mΩ]	52.6	52.6	52.6	52.6	52.6	52.6	52.6
Power [kW]	0.237	4.06	3.06	3.1	4.9	0.4	0.8
Voltage drop [V]	3.5	14.6	12.7	12.7	16.0	4.8	6.4
Coil weight [lb]	151	151	151	151	151	151	151
Number of water circuits	1 @ 1 gpm	1 @ 1 gpm	1 @ 1 gpm	1 @ 1 gpm	1 @ 1 gpm	1 @ 1 gpm	1 @ 1 gpm
Water flow rate [gpm]	0.5	0.5	0.5	0.5	0.5	0.5	0.5
Water pressure drop [psi]	150	150	150	150	150	150	150
Temperature rise [°C]	0.00	0.03	0.02	0.02	0.04	0.00	0.01
Total magnet power [kW]	62.6	16.2	12.3	0.0	0.1	0.0	0.0
Total magnet water requirements [gpm]	132	2	2	3	6	2	3

Table 5-6. LER sextupole parameters.

Magnet designation	4.5S10
Number of magnets	144
Operating gradient [T/m ²]	36.07
Pole tip field @ operating gradient [T]	0.065
Integrated strength [T/m]	9.20
Aperture inscribed radius [in.]	2.362
Core length [in.]	8.071
Magnetic length [in.]	10.041
Core weight [lb]	170.
Amp turns per pole	1027.64
Turns per pole	24
Pancakes per pole	2
Conductor cross-sectional area [in. ²]	0.127
Cooling hole diameter [in.]	0.125
Conductor dimension [in.]	0.375 × 0.375
Current [A]	43.5
Resistance @ 40°C [mΩ]	62
Power [kW]	0.1
Voltage drop [V]	2.69
Coil weight [lb]	200
Number of water circuits	2 @ 0.125 gpm
Water flow rate [gpm]	0.25
Water pressure drop [psi]	150
Temperature rise [°C]	1.8
Total magnet power [kW]	16.9
Total system water requirements [gpm]	36.0

marks will not be needed for the sextupoles. Laminations will still be reversed periodically, however, to account for the crowning referred to above.

5.1.3 Interaction Region Magnets and Supports

5.1.3.1 Permanent Magnets. The final triplet of focusing quadrupoles, Q1, Q2, and Q3, and the magnetic separation dipoles B1 are located within 2 m of the IP. At these close distances, they will be inside the detector and immersed in its solenoidal magnetic field. The only viable magnet technologies for such an environment are superconducting or permanent magnets. A conventional electromagnet with iron pole tips would have its field distorted by the detector field. For the IR magnets, required field strengths and apertures are within the reach of modern rare-earth-cobalt (REC) alloys, and superconducting technology is not demanded. For the B Factory, the choice of a permanent magnet design was based on the following characteristics of such magnets:

- They avoid the complexity, cost, and reliability problems inherent in cryogenic operation.
- They are compact and avoid cryogenic plumbing and cryostats, both of which would significantly reduce the detector acceptance solid angle.
- They are nearly free of fringe fields that could otherwise complicate particle tracking.
- They avoid the safety aspects of superconducting systems; they will not quench—a possible advantage in a high-current storage ring.

There are also drawbacks to our choice of permanent magnet technology. Foremost among these is the fact that permanent magnets offer only a limited adjustment capability. In our design, we have added trim windings on all four pairs of permanent magnets in the IR to alleviate this lack of flexibility. Other issues include the following:

- The field quality of a REC magnet depends on accurate magnetization of its constituent blocks; special techniques and equipment must be developed to measure block magnetization, and to assemble and adjust blocks.
- Strong demagnetizing external fields and high temperatures must be avoided if field quality is to be preserved. Quadrupole and dipole fields are assembled from sector-shaped REC blocks arrayed in a circle around the magnet aperture [Halbach, 1981]. Each block is magnetized in an appropriate direction so that the magnetic field varies approximately as $\cos N\theta$ around the bore, where $N = 1$ for dipoles, $N = 2$ for quadrupoles, etc. The optimal compromise between the number of blocks, M , and the field quality is to use $M = 16$ for a quadrupole and $M = 8$ for a dipole. These configurations are shown in Fig. 5-7.

The magnetic and mechanical properties of the B Factory IR magnets are summarized in Table 5-7.

For quadrupoles ($N = 2$) the magnetic field at the aperture radius, $B(r_1)$, is related to the inner and outer radii, r_1 and r_2 , by

$$B(r_1) = 2C_N B_r \left(1 - \frac{r_1}{r_2}\right) \tag{5-1}$$

where B_r is the remanent field of the permanent magnet material and

$$C_N = \frac{\cos^N\left(\frac{\pi}{M}\right) \sin\left(\frac{N\pi}{M}\right)}{\frac{N\pi}{M}} \tag{5-2}$$

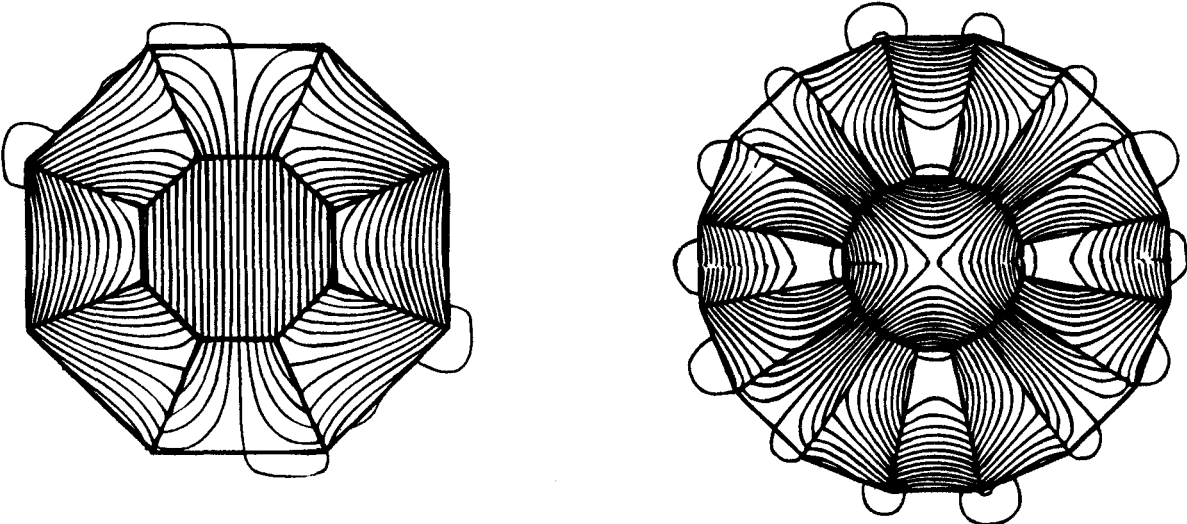


Fig. 5-7. Field lines for an 8-block permanent magnet dipole (left) and a 16-block quadrupole (right).

Table 5-7. Magnetic and mechanical dimensions for the IP permanent magnets.

	$B(r_1)$ [T]	Gradient [T/m]	r_1 [cm]	r_2 [cm]	L [cm]	Weight [kg]
B1	0.75	—	2.4	5.3	16.0	9.4
Q1	1.47	38.84	3.8	15.1	64.2	362.0
Q2	1.35	30.70	4.4	14.0	51.6	240.5
Q3	0.97	14.04	6.9	13.6	24.0	87.0

Choice of Material. The B Factory magnets will be assembled from $\text{Sm}_2\text{Co}_{17}$, a material having a high remanent field ($B_r = 1.05$ T). Figure 5-8 shows the B - H curves of some of these materials. Commercial grades of $\text{Sm}_2\text{Co}_{17}$ are available.

The B - H relation for a candidate material, R26HS (see Table 5-8), shows a linear $\mu_r \approx 1$ for the entire second quadrant. An external demagnetizing H field must actually exceed B_r/μ_0 of the material before nonlinearities and hysteresis develop, causing permanent demagnetization of the material. For lower external fields, simple linear superposition of fields holds. Since the detector axial solenoidal field is nearly orthogonal to the transverse field of the beamline magnets, the two fields are not expected to interact. The high Curie temperature of $\text{Sm}_2\text{Co}_{17}$ allows this material to be used at temperatures up to 500°C , and its low temperature coefficient should preserve field quality. Lastly, the chosen material has good radiation-resistance properties, so its performance is not expected to degrade in the relatively harsh environment of the B Factory IR.

Permanent Magnet Assembly. Taken together, fabrication of the IR magnets will involve thousands of precisely machined and magnetized blocks of $\text{Sm}_2\text{Co}_{17}$. The field quality of the resulting magnets depends critically on their precise magnetization. The magnitude, direction, and uniformity of the magnetization $\mathbf{M}$ will therefore be held to tight tolerances inside each block. In addition, variations can, to some degree, be accommodated by selective assembly and adjustment of final block positions. In any case, block magnetization will be measured before assembly. Even perfectly magnetized blocks do not produce simple, uniform $\mathbf{B}$ fields. Figure 5-9 shows the $\mathbf{B}$ field pattern for two typical uniform magnetizations of a block. The $\mathbf{B}$ field is related to block magnetization by

$$\mathbf{B}(\mathbf{r}) = \mu_0 \mathbf{M}(\mathbf{r}) + \frac{\mu_0}{4\pi} \left[\int_S \mathbf{M} \cdot \mathbf{n} \frac{(\mathbf{r} - \mathbf{r}')}{|\mathbf{r} - \mathbf{r}'|^3} da' - \int_V \nabla \mathbf{M} \frac{(\mathbf{r} - \mathbf{r}')}{|\mathbf{r} - \mathbf{r}'|^3} dV \right] \quad (5-3)$$

If the block has perfectly uniform magnetization ($\nabla \mathbf{M} = 0$), then $\mathbf{B}$ and $\mathbf{M}$ differ only by a surface integral over the shape of the block. Using the above relation, the internal magnetization field of a block can be inspected by making measurements of $\mathbf{B}$ over its surface. Figure 5-10 illustrates this inspection procedure.

Table 5-8. Properties of R26HS magnetic material.

Material	B_r [T]	Temperature coefficient [%/ $^\circ\text{C}$]	Curie temperature [$^\circ\text{C}$]	Density [g/cm ³]
R26HS	1.05	-0.03	820	8.4

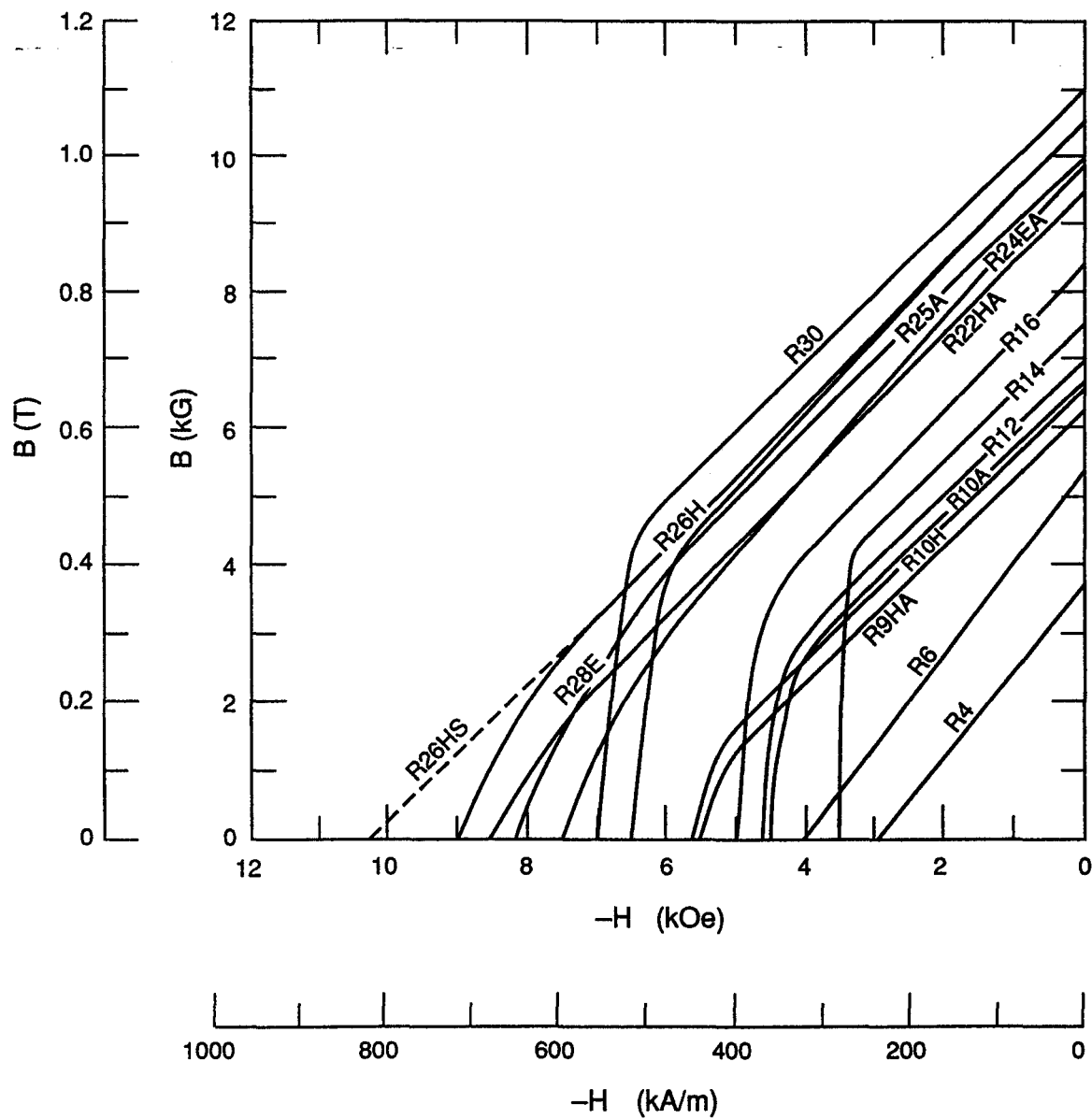


Fig. 5-8. B-H curves for various permanent magnet materials.

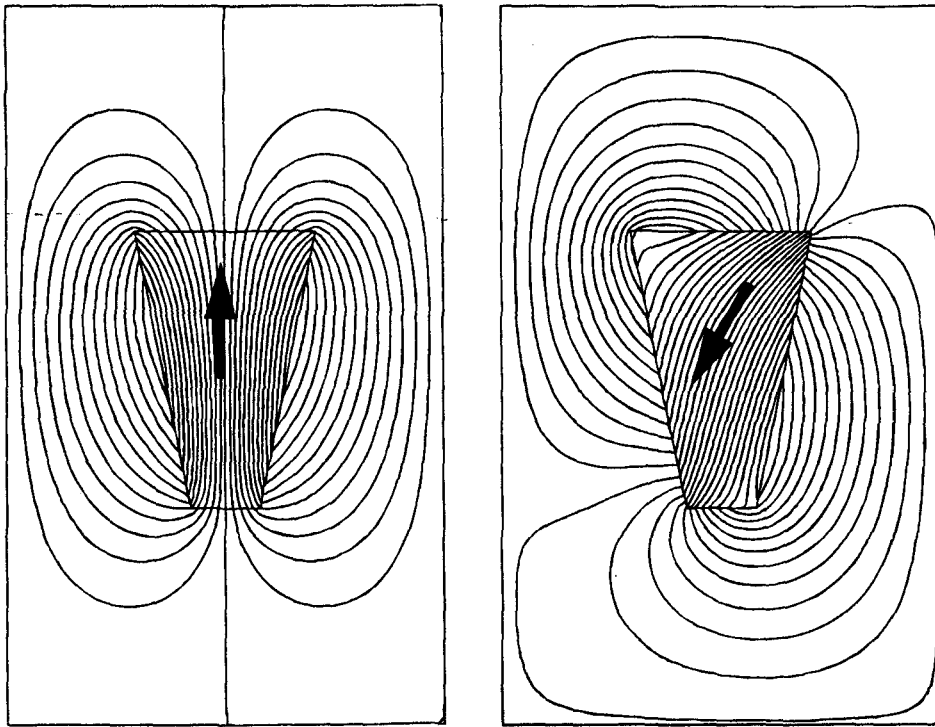


Fig. 5-9. Field patterns for two typical uniform magnetizations of permanent magnet material blocks.

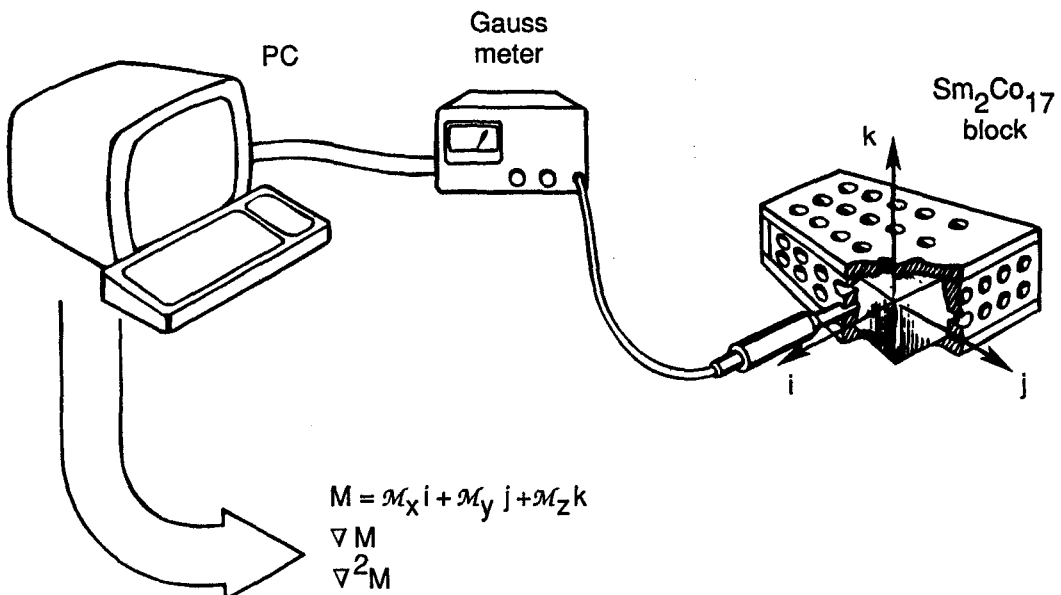


Fig. 5-10. Schematic representation of a procedure to inspect permanent magnet blocks before assembly.

A simple jig will be used to determine the coordinate frame and measurement points on the surface at which the normal component of $\mathbf{B}$ is measured. These data will then be used to calculate the magnitude and direction of $\mathbf{M}$ inside the block. Estimates of the uniformity of $\mathbf{M}$ can also be computed. If magnetic tolerances can be tightly held by this inspection procedure, it may be possible to avoid adjustment of individual block positions in the finished magnets. This would greatly reduce the time involved in this labor-intensive fabrication step.

Permanent magnets have already been successfully applied to storage rings at SLAC [Spencer, 1985] and elsewhere [Herb, 1987]. We consider the technology to be a mature one, well-suited to this application.

5.1.3.2 IP Support Barrel. The B Factory poses difficult support and alignment problems for the final magnetic elements near the interaction point (IP). Bunch spacing is only 1.26 m and requires magnetic separation of the two beams to begin at ± 20 cm from the collision point. The final quadrupole triplets are completely buried inside the detector. Previous storage rings have placed the equivalent magnets on separate individual supports, cantilevered in from the detector entrance. Unfortunately, such a support is difficult to make rigid, and the relative alignment of the magnets is not easily measurable once they are installed.

As shown in Fig. 5-11, for the B Factory we intend to avoid this limitation by using a single support "barrel" through the detector, from one end to the other, to carry all magnets. In addition to carrying the beam separation dipoles B1 and the final permanent magnet quadrupole triplets, Q1, Q2, and Q3, the support barrel carries the central vertex detector. Other equipment carried inside the barrel includes the water-cooled masks AB and CD (see Sections 4.2 and 5.2.7), radial ion pumps, and BPMs. Plumbing and cabling

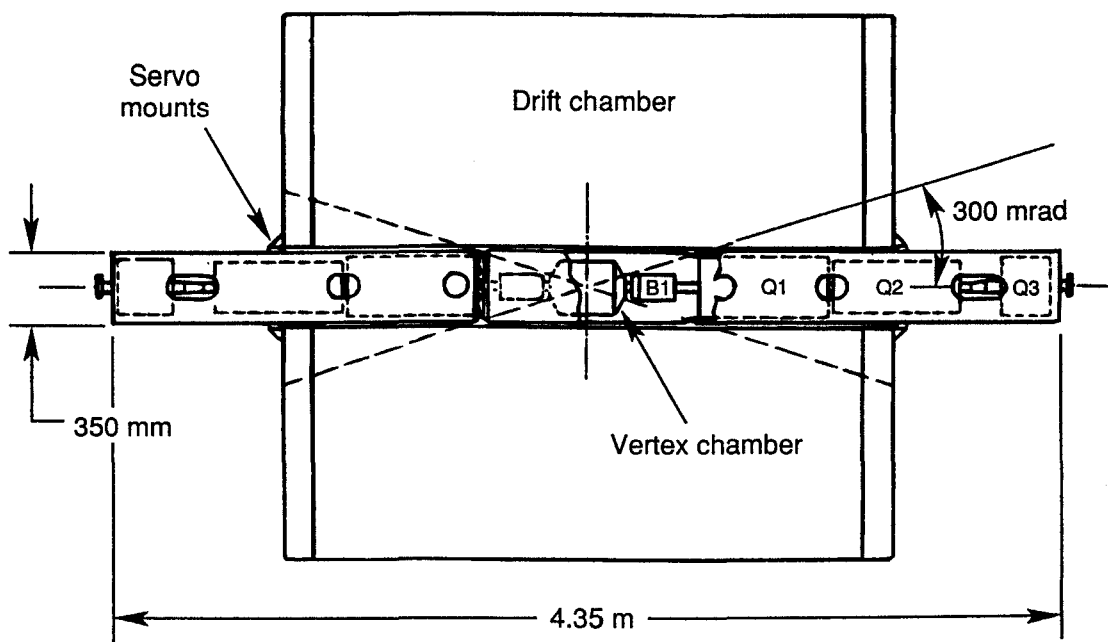


Fig. 5-11. Tube or barrel to support the permanent magnets, beam pipe, and vertex detector inside the drift chamber.

for this equipment passes through the barrel, while vertex detector cabling is carried on the outside.

Our choice of a single support barrel has two important advantages over previous designs:

- Magnetic elements on each side of the IP are directly connected by a rigid structure that maintains their relative alignment.
- All components can be preassembled and aligned in the barrel outside the detector, where precise and effective survey techniques can be employed.

Barrel Mounts. The barrel is supported from the detector drift chamber end-plates. These support locations are approximately at the quarter points of the barrel, thus balancing end and midpoint deflections. This reduces deflection by nearly 50-fold compared with a simple end support, and raises the natural frequency of the structure by a factor of 7. The barrel rests on roller cams (consisting of a spherical roller that bears on a shaft with 1.5-mm eccentric journals; see Fig. 5-12) at each end of the drift chamber. Two roller cams locate the barrel axis at one end, and three roller cams fix the axis and roll at the other end, as shown in Fig. 5-13. During operation, only the eccentric shaft rotates, displacing the outer bearing race. The race remains in fixed contact with its barrel support pad, so no sliding motions are involved; only rolling motion occurs. All five roller cams are driven by stepper motors through gear reducers, allowing five-axis remote positioning of the barrel; that is, the barrel position can be adjusted by ± 1.5 mm in x and y , along with pitch, roll, and yaw, during beam operation.

With this technique, positioning of the support barrel to an accuracy of a few micrometers is practical. Because excursions are cyclic and naturally limited by cam lift, no limit switches are needed to protect against damage. Except for a fixed z restraint at

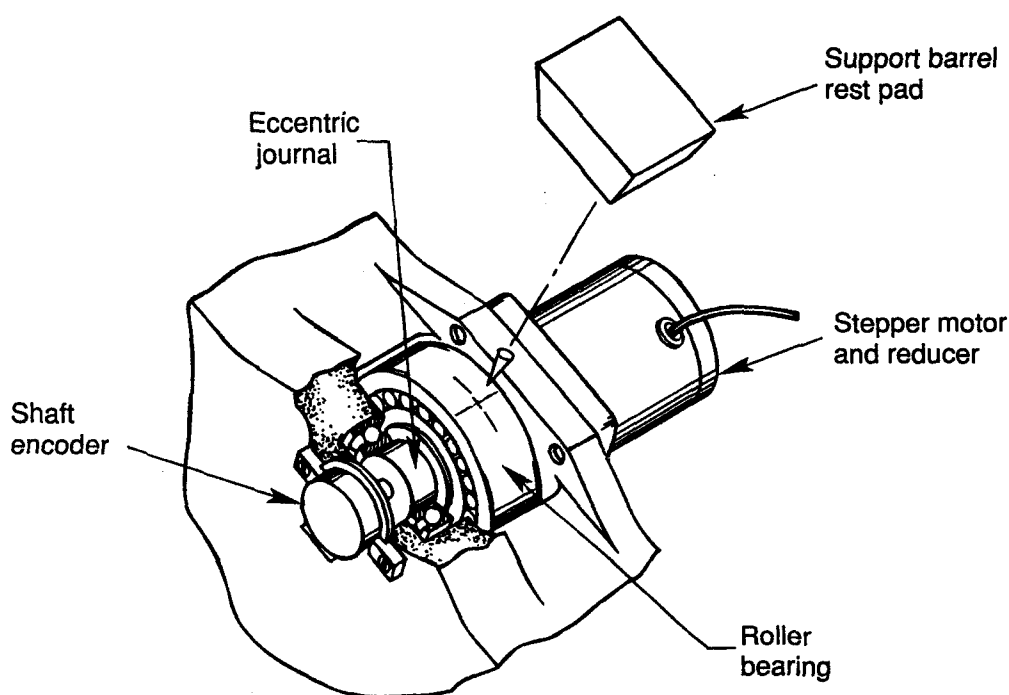


Fig. 5-12. Detail of roller cam for supporting and adjusting the support barrel.

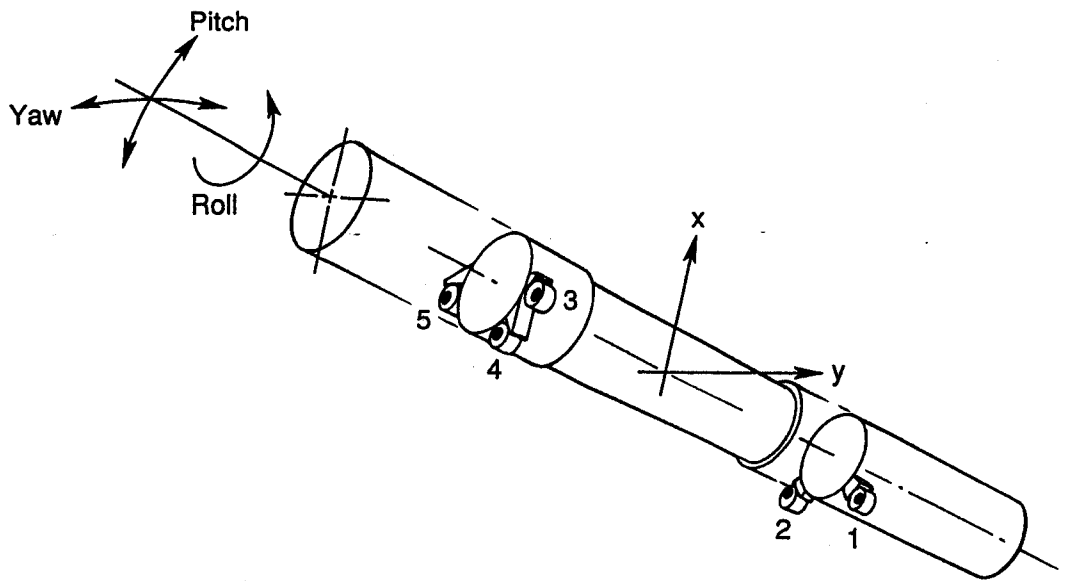


Fig. 5-13. View of the support barrel, showing its five remotely adjusted roller cams.

one end, the barrel mount is fully kinematic and free of any over-constraints that might distort internal alignment. A similar remote-positioning mount design is being used successfully for the final triplets in the SLC interaction region [Bowden and Putallaz, 1985].

Barrel Construction. The support barrel consists of three separable sections. The two outboard ends, which carry the heavy quadrupole triplets, are made from 0.75-in.-wall aluminum pipe. Access ports and magnet mounting points will be machined into the walls. The middle barrel section is of sandwich construction, with carbon-fiber facings and a foam core. This section must be nearly transparent to radiation and insensitive to thermal distortion, while supporting the peak mid-span bending moments (87.3×10^3 in. lb). Figure 5-14 shows the barrel construction details.

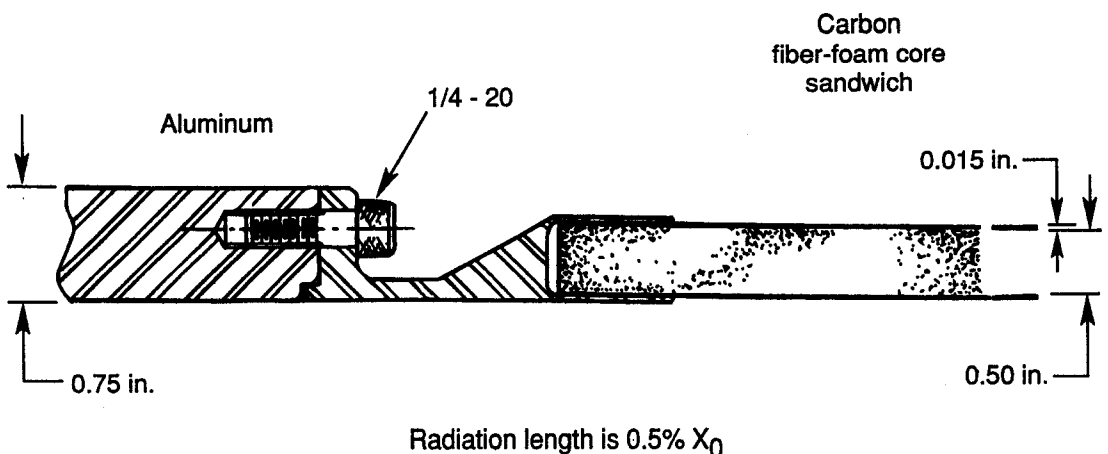


Fig. 5-14. Detail of joint between the thin inner section of the support barrel and the outer aluminum section.

The most damaging thermal distortion is bending of the barrel due to transverse temperature gradients. Expansion of the warmer top of the barrel and contraction of the cooler bottom would cause the barrel to arch upward, as shown in Fig. 5-15. Because carbon fibers shorten slightly with increasing temperature (see Table 5-9), the center barrel section can be compensated to approximately zero expansion, either by balancing the fiber pitch helix angle against the high expansion coefficient of the resin matrix, or by cladding the fiber layers (which have a negative expansion coefficient) with a thin (say, 10 μm) layer of a material having a positive expansion coefficient, such as aluminum. Because the two outer aluminum ends of the barrel are only about one-third of the total length L , it should be possible to hold the total distortion δ (defined in Fig. 5-15), below 25 μm per $^{\circ}\text{C}$. In addition to the protection afforded by our fabrication method and materials, the barrel will be well-sealed from natural convection by the detector, and water cooling of local heat sources will prevent asymmetric heating from causing temperature differences greater than 1°C .

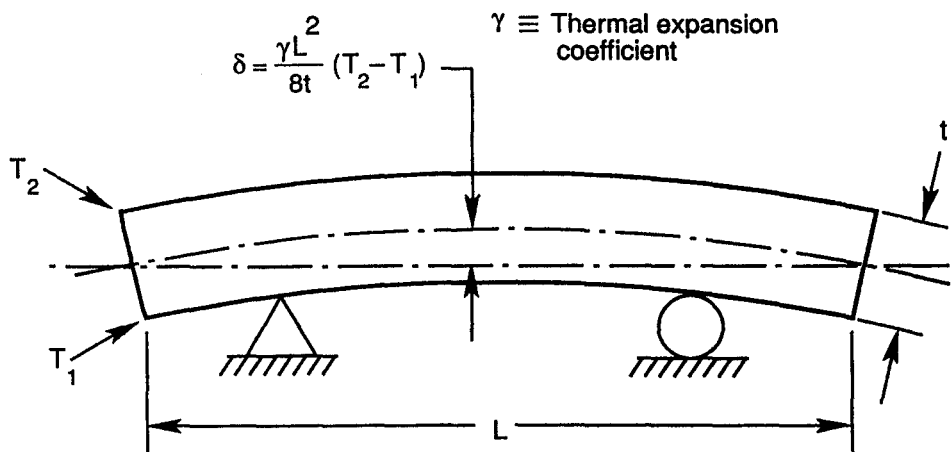


Fig. 5-15. Curvature of support barrel resulting from a temperature difference between its top and bottom.

Table 5-9. Thermal expansion coefficients and deflection of the materials that make up the 4.35-m barrel.

Material	γ [$\Delta L/L$ per $^{\circ}\text{C}$]	δ [μm per $^{\circ}\text{C}$]
Aluminum	2.3×10^{-5}	153.0
Carbon fiber 0°	-5.6×10^{-7}	-3.7
Carbon fiber 90°	3.6×10^{-5}	235.0

Ground Motion. Because the B Factory consists of two independent storage rings, microseismic ground motion could possibly interfere with beam collisions. The spectrum of ground motion measured at SLAC [Bowden, 1985] is shown in Fig. 5-16, along with its amplitude distribution. Most ground motion is found in the 1- to 10-Hz band, whereas the barrel resonant frequency is about 30 Hz; therefore, no strong coupling will occur. The vertical beam-spot size is $7\text{ }\mu\text{m}$ in the B Factory, about 100 times the amplitude of the average microseismic noise. Quadrupole amplification will use up some, but not all of the available margin. Further, because the barrel ensures a smooth fundamental-mode response to the vibration modes, the relative motions of the quadrupoles will be much smaller than the vibration amplitude of the barrel itself. Previous measurements at SLAC of mechanical noise from cooling-water flow have shown that this source usually does not make a significant contribution. Thus, we conclude that mechanical vibration will not be a serious problem for the barrel support.

Barrel Assembly and Component Alignment. The technical difficulties of assembling 4 m of heavy and delicate beamline equipment in a close-fitting support barrel has already been solved for the SLC final triplets, as demonstrated in Fig. 5-17. A similar technique will be employed for the B Factory. All beamline components are built up and checked out on a tracked assembly stand. Each magnet is equipped with small wheels that roll on the assembly stand rails, which are linked to rails on the inner walls of the support barrel. The train of magnets, along with a preinstalled vacuum pipe, ion pumps, BPMs, cabling, etc., is then pulled off the assembly stand into the support barrel. Once in place, magnets are temporarily supported on bolts screwed up from the barrel bottom while the rails are removed.

Magnet mounts are installed and adjusted from the outside of the barrel. Magnets are clamped near their ends by shimmed bolts through the barrel wall, as shown in Fig. 5-18. Bolts work in four opposing pairs. The position of one bolt in each pair is fixed by a replaceable shim washer. The opposing bolt preloads the magnet mount through a spring-loaded pusher. The amount of preload is set by a second shim under this bolt. Adjustment of the alignment is made by changing shim thicknesses. Whenever a fixed bolt shim is changed, the corresponding preload shim is changed to maintain the nominal preload. In this way, forces and deflections are held constant during the alignment procedure. Adjustment of one magnet position does not affect another, and the tightening torque on the support bolts does not affect magnet position. When this technique was

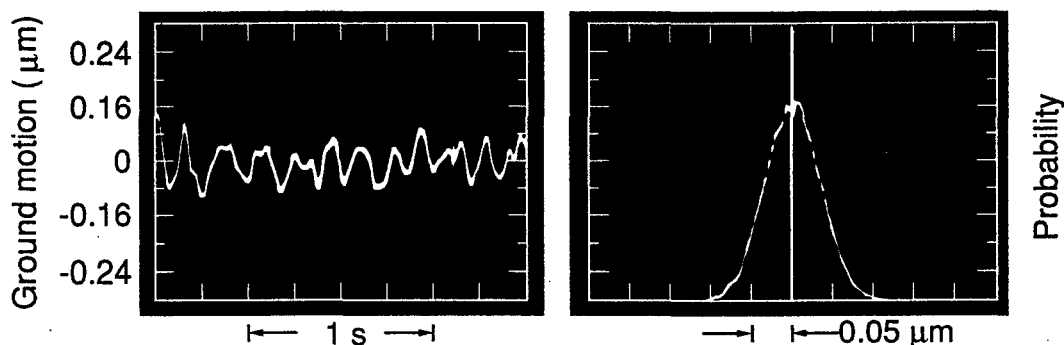


Fig. 5-16. Ground motion measured at SLAC.

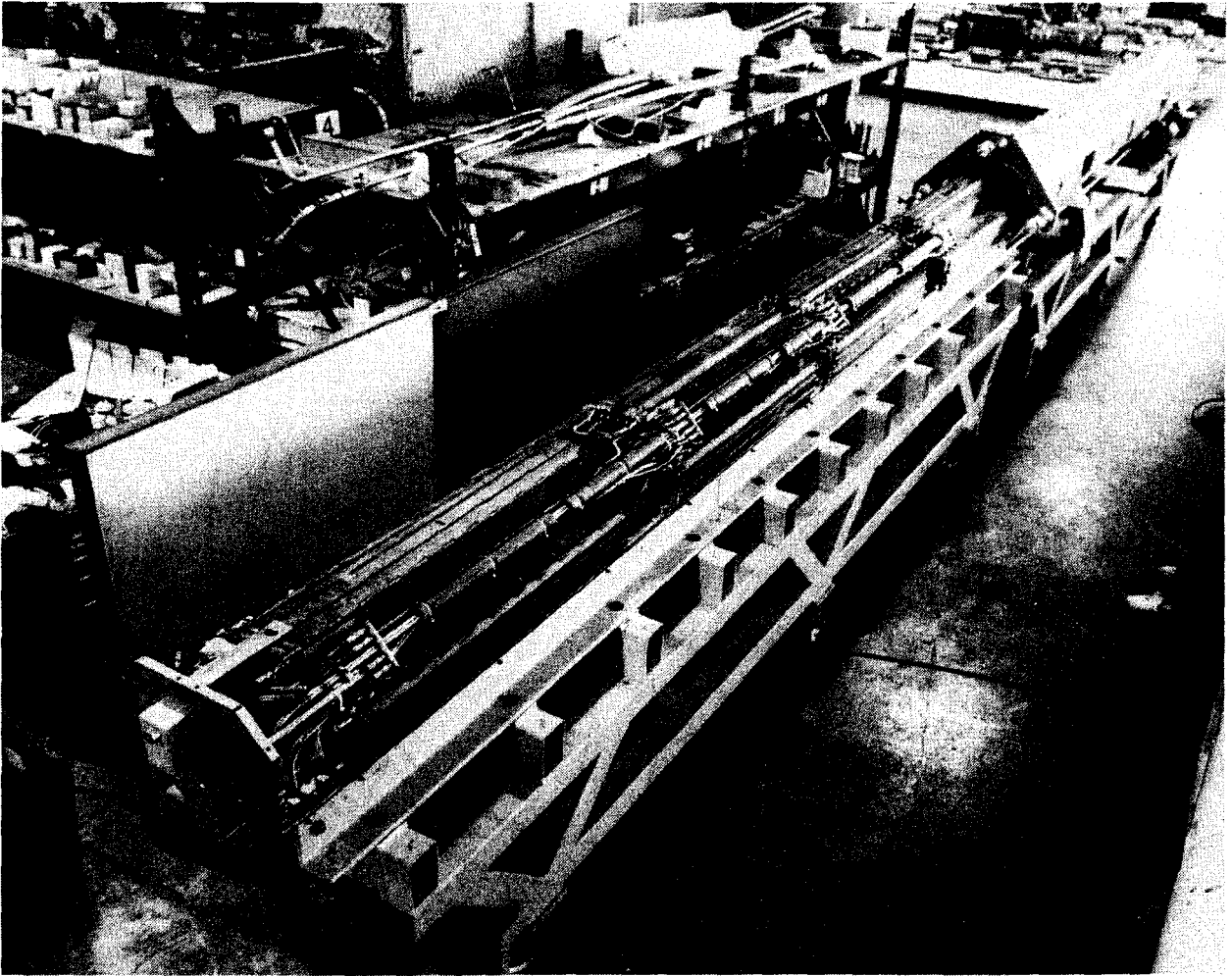


Fig. 5-17. Illustration showing the assembly technique for the SLC final focus triplet barrel.

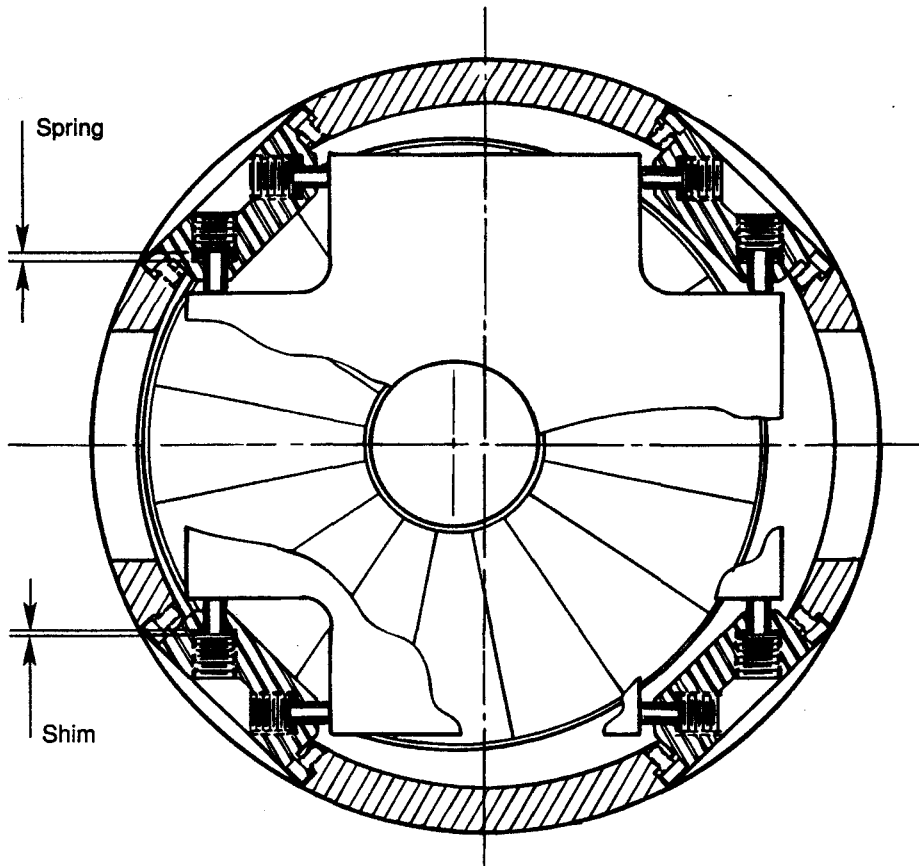


Fig. 5-18. Section through SLC final focus triplet barrel, showing magnet-positioning technique.

used on the SLC final triplets, alignment by shim changes converged in two iterations. This method is well-matched to modern survey procedures based on computer-linked theodolites and sophisticated survey software, of the type described in Section 5.3.

A major reason for building all IR components into a common support barrel is to allow prealignment of beamline components prior to assembly into the detector. Once hidden inside the detector, magnets cannot easily be surveyed from the outside. The support barrel allows this alignment to be done in the laboratory under optimal conditions; Fig. 5-19 illustrates the procedure.

During alignment the barrel will be supported in mounts identical to those to be used on the actual detector. In this way, all deflections are accurately reproduced. Access ports for either directly viewing magnet fiducials or attaching extended targets are provided on the support barrel. Magnet survey is done with computer-linked theodolites using many redundant observations to obtain a strongly over-constrained fit on the relative positions of all fiducials. A length standard is set in clear view of all theodolite locations. The raw survey data consist of precision-encoded angle measurements. All

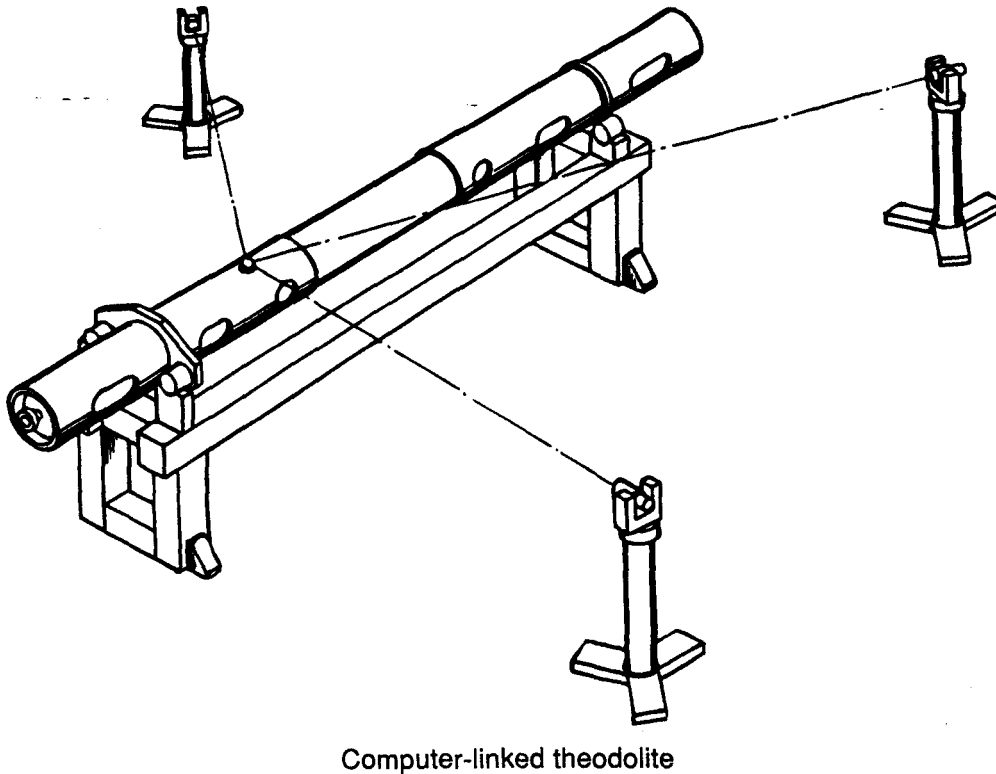


Fig. 5-19. Illustration of a method for prealigning elements inside the support barrel before installation in the detector.

measurements are then computer processed to reconstruct the relative magnet positions. The overall resolution of such a modern system is $25\ \mu\text{m}$ over 5 m. Positioning the barrel components with respect to the rest of the storage ring is straightforward. After installation into the detector, barrel-end fiducials will be clearly visible from the standard survey stations used to align other external beamline components. Furthermore, the remote positioning mounts will allow fine adjustment of the barrel position during beam operation.

5.1.3.3 Permanent Magnet Trim Coils. To tune the collider beam optics and to permit shifting of the ring energies to reach different T resonances, Q1, Q2, Q3, and B1 will require trim coils with a 4% adjustment range. These coils, which line the bores of the permanent magnets, must be of compact design because the bore increases needed to accommodate them reduce the magnetic field strength. Moreover, small increases in the aperture of the inner bore require large increases in the outer diameter of the permanent magnet assembly to recover the lost strength.

Owing to the severe radial space limitations, conventional coils wound from hollow water-cooled conductor are not practical. Therefore, the trims will be single-layer coils

attached in good thermal contact to a highly conductive beam pipe made from high-strength GlidCop. The beam pipe will have single-pass water cooling coils brazed to it along the inner edges of each coil and will thus serve as a thermal sink to cool the coil. The layout we have adopted (see Fig. 5-20) allows parallel water channels for coil cooling. Dimensions shown are for Q1. The other magnets, B1, Q2, and Q3, have similar or more relaxed requirements.

- Although an ideal quadrupole field requires a $\cos 2\theta$ distribution of current density, this can be well approximated by a uniform coil subtending 0.5 rad (28.65°). For weak trim fields, the harmonic purity of this coil form is more than adequate.

For Q1 a 4% trim requires maximum fields of 0.055 T at the 35.3-mm mean trim-coil radius. Five turns of wire carrying 310 A will produce this field. The total power dissipated per coil is 1.4 kW (assuming that insulation and winding reduce the actual copper density in the coil to 80% of the overall cross section). Heat must be conducted from the middle of the coil to the cooled edge and then across the cooling-water boundary film. Conduction through the coil and to the beam pipe wall is reduced somewhat by electrical insulation. A worst-case estimate of this temperature rise gives $\Delta T = 20^\circ\text{C}$ at full power. The multitube cooling channel carrying 1.2 gpm will have an outlet temperature rise of $4\text{--}5^\circ\text{C}$. The water film drop is 8°C using a film coefficient of $5 \text{ W/in.}^2 \text{ per } ^\circ\text{C}$. These temperature drops sum to 33°C , which is high but manageable.

5.1.3.4 Septum Quadrupole (Q4). The Q4 septum quadrupole is the last magnet in the HER before the high- and low-energy beam trajectories merge into a common vacuum pipe on their way to and from the IP. It is located about 4 m from the IP, and is the last storage ring magnet before the beamline “disappears” into the detector.

Although the two Q4 magnets focus only the incoming and outgoing high-energy beam (HEB), the low-energy beam (LEB) is separated from the HEB trajectory by only 6.5 cm at the front face of Q4. Figure 5-21 shows the dimensions of the beam-stay-clear envelopes, as well as the synchrotron radiation fans from the B1 bending magnets and from Q2, at the front face of Q4.

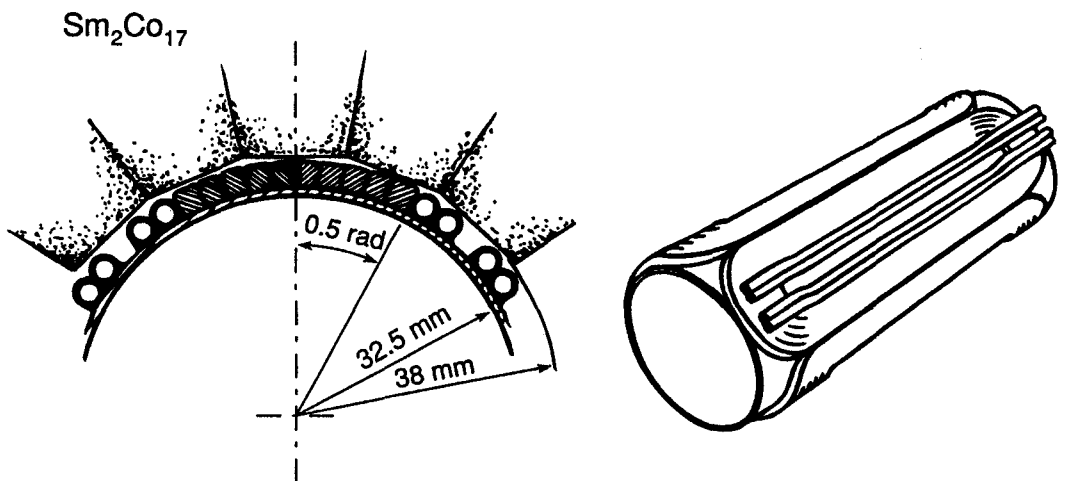


Fig. 5-20. Cross section and perspective view of the permanent magnet trim coils.

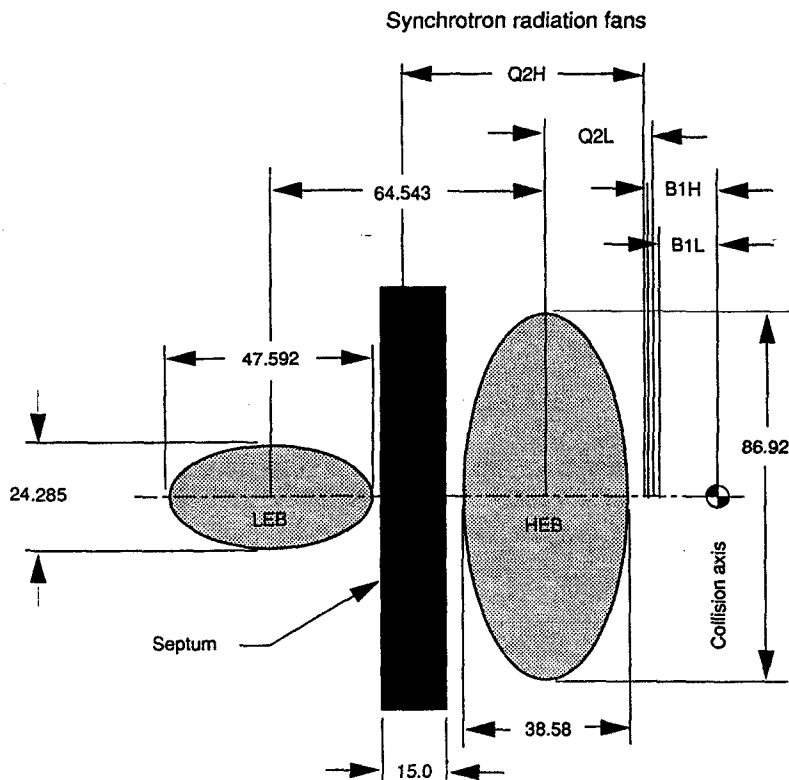


Fig. 5-21. Dimensions (in millimeters) of the beam-stay-clear envelopes and locations of the synchrotron radiation fans from the B1 and Q2 magnets.

Producing a pure quadrupole field centered on the HEB, while still leaving a clear field-free channel for the LEB only 6.5 cm to the side, is a formidable magnet design problem. (Only 21.4 mm of clearance exists between the two beam-stay-clear ellipses here.) The problem is compounded by the need to pass synchrotron light fans in the horizontal midplane. These fans carry 90 kW of radiation away from the region near the IP and, as shown in Fig. 5-21, extend in angle all the way out to the collision axis. Furthermore, the HEB requires a large, vertically elongated magnet aperture.

Ideally, the solution would be some type of septum quadrupole having a quadrupole field pattern sharply cut off by a septum separating the HEB from the LEB. Several designs have been considered.

The most obvious candidate is the Panofsky quadrupole, formed from a rectangular enclosure of current sheets. To pass the midplane synchrotron radiation fan, a large, nearly square aperture is required, with the quadrupole center offset to the side; in essence, this corresponds to a quadrupole with a superimposed dipole field. Panofsky quadrupoles are usually enclosed in an iron box to confine the external field, but their field shape is dominated by the current distribution rather than by the iron. By imbalancing the right-left symmetry of the currents, a dipole field can be created to shift the quadrupole magnetic axis. External iron is crucial in shielding the path of the low-energy beamline just outside the magnet. Magnetic flux in the midplane iron return path is large but tolerable. It is worth noting that pushing the quadrupole magnetic center toward this side of the aperture (by imposing a large dipole field) has the beneficial effect

of reducing this midplane flux.

Several estimates of a Panofsky style Q4 using conventional conductors have been made. The required gradient is about 15 T/m over an 80-cm length. Such a magnet requires high current densities, over 5 kA/cm², and would dissipate between 150 and 200 kW; cooling would therefore be a serious problem. Furthermore, conventional coils would be rather thick compared with the idealized current sheets required for pure quadrupole fields, which means that field quality would suffer. Designed as a superconducting magnet, these problems disappear. Such a design alternative is discussed below. We note here that Q5 must also be a nonstandard quadrupole, but its design is much less exacting than that of Q4, and it has not yet been studied at the same level of detail.

Superconducting Panofsky Quadrupole. A superconducting septum quadrupole Q4 consists of a square Panofsky quadrupole and a dipole, with the geometrical center of the magnet offset by 19 mm from the HEB center (Fig. 5-22). The dipole field is used to offset the quadrupole field such that the resulting quadrupole field is centered on the HEB.

The Q4 magnet has a gradient of 15.2 T/m and a magnetic length of 800 mm; the distance between the front face of the magnet and the IP is 3.96 m. The positions of the two beams, which lie in the same horizontal plane, are given in Table 5-10. As indicated in Fig. 5-22, the two beams diverge with an angle of 20 mrad.

The iron yoke is square and is everywhere 25 mm thick, except in the region between the two beams, where the thickness tapers to a minimum of about 2.3 mm near the end of the magnet closer to the IP. Because the magnet has a minimum distance between the inside of the two beam pipes of 13.55 mm (the “septum thickness”), the LEB vacuum pipe is supported by the same iron yoke. The bore tube inner radius is 45 mm for the HEB and 25 mm for the LEB. As mentioned, the dipole field strength is adjusted to offset the center of the quadrupole field by 19 mm from the center of the HEB bore tube.

The septum wall (Fig. 5-23) has the following elements:

- 1-mm-thick stainless-steel bore tube (HEB)
- 1.8-mm-thick multilayer insulation (MLI)
- 0.2-mm clearance
- 1.5-mm-thick stainless-steel vacuum pipe
- 3.25-mm-thick superconducting coils and electrical insulation
- 2.3-mm-thick iron
- 0.75-mm-thick stainless-steel vacuum pipe
- 1.8-mm-thick MLI
- 0.2-mm clearance
- 0.75-mm-thick stainless-steel bore tube (LEB)

The quadrupole coils are wound on four quadrants. These are then assembled around the outer diameter of a vacuum pipe that is separated from the bore tube by multilayer

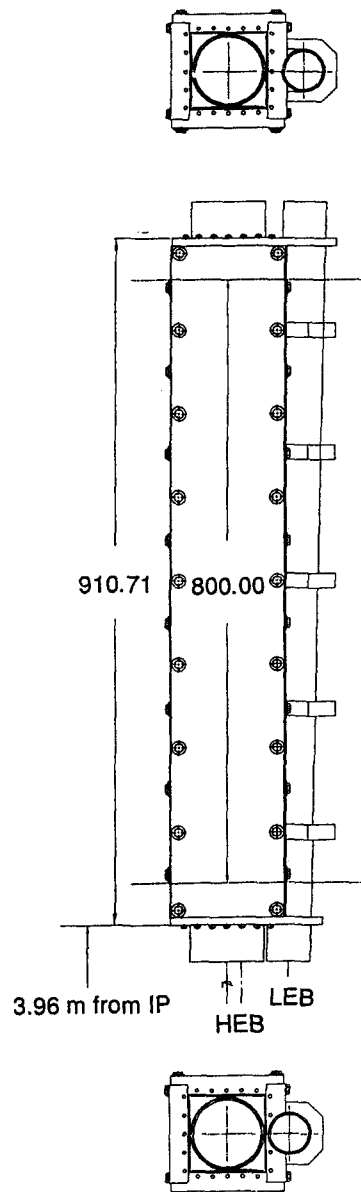


Fig. 5-22. Top and end views of the superconducting septum quadrupole Q4. Dimensions are in millimeters. The septum itself is shadowed with the Q4 crotch mask, described in Section 5.2.7.

Table 5-10. Positions of the beam along along the magnet.

Distance from IP (m)	HEB position (mm)	LEB position (mm)
3.96	40.29	104.84
4.76	51.95	132.69

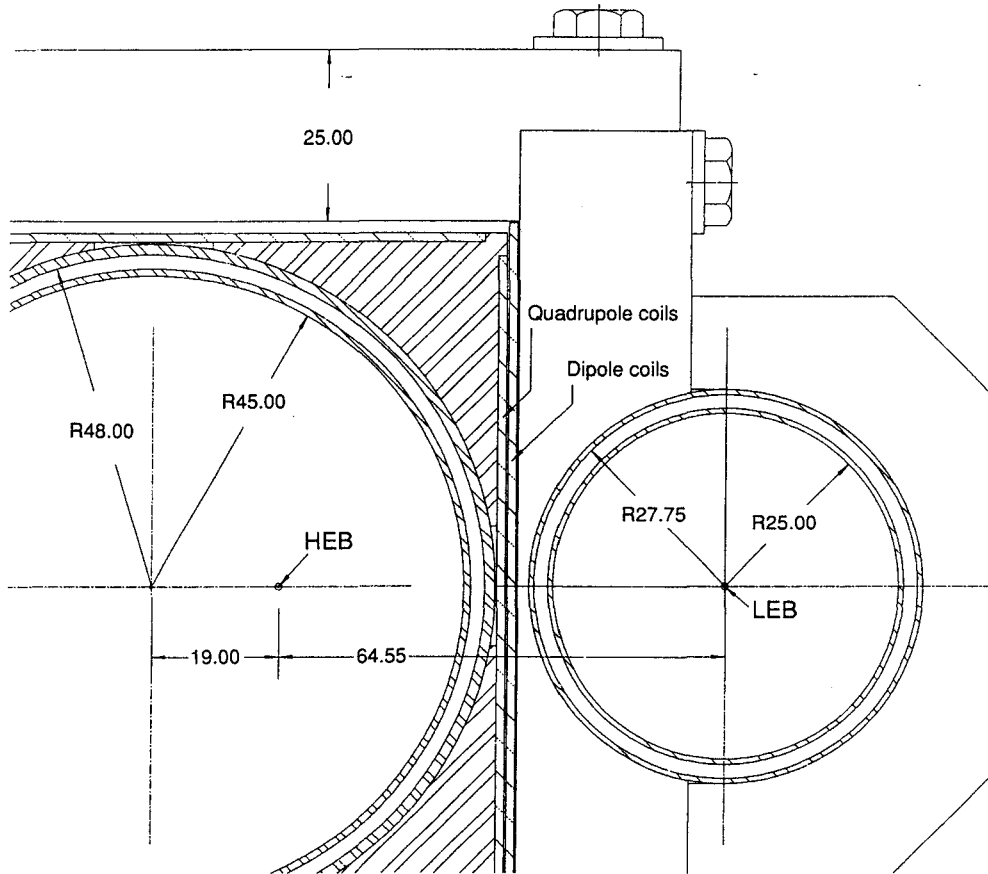


Fig. 5-23. Detail of the superconducting septum quadrupole Q4. Dimensions are in millimeters.

insulation. Next, the dipole coils are wound and assembled over the quadrupole coils. Finally, an iron yoke is put in place that completely covers the coils. The superconducting wire used in this magnet is a monolithic, square multifilamentary Nb-Ti superconductor in a copper matrix.

The Q4 field quality has been computed analytically considering the real coils and their images reflected in the iron yoke. The uniformity of the magnetic field is expressed in the usual multipole coefficients. The multipole coefficients of the magnetic field are shown in Tables 5-11, through 5-13; the coefficients are calculated at a radius of 10 mm centered around the bore tube ($x = 0$) and around the HEB axis ($x = 19$ mm). If need be, these multipole coefficients could be further reduced by using an appropriate nonuniform spacing of the wires in the coils.

A two-dimensional finite-element analysis using ANSYS and POISSON, and considering the real B - H curve for the iron (see Fig. 5-24), has confirmed that there is no saturation in the iron yoke and that the maximum field in the yoke is 1.37 T, as shown in

Table 5-11. Multipole coefficients for the Q4 quadrupole component only. A "unit" is $10^4 \times b_n(\text{T/cm}^n - 1)/b_2$.

	Multipoles at $x = 0$ mm	Multipoles at $x = 19$ mm
b1	0	-0.2884 T
b2	-0.1518 T/cm	-0.151807 T/cm
b3	0	0.50 units
b4	0	0.25 units
b5	0	0.05 units
b6	0.007 units	-0.002 units

Table 5-12. Multipole coefficients for the Q4 dipole component only.

	Multipoles at $x = 0$ mm	Multipoles at $x = 19$ mm
b1	0.288392 T	0.288527 T
b2	0	0.000148 T/cm
b3	-2.35 units	-2.9 units
b4	0	-0.16 units
b5	-0.035 units	0.008 units
b6	0	0.01 units

Table 5-13. Multipole coefficients for the combined Q4 quadrupole and dipole components.

	Multipoles at $x = 0$ mm	Multipoles at $x = 19$ mm
b1	0.288392 T	0.0001 T
b2	-0.1518 T/cm	-0.15166 T/cm
b3	-2.35 units	-2.4 units
b4	0	0.09 units
b5	-0.035 units	0.058 units
b6	0.007 units	0.008 units

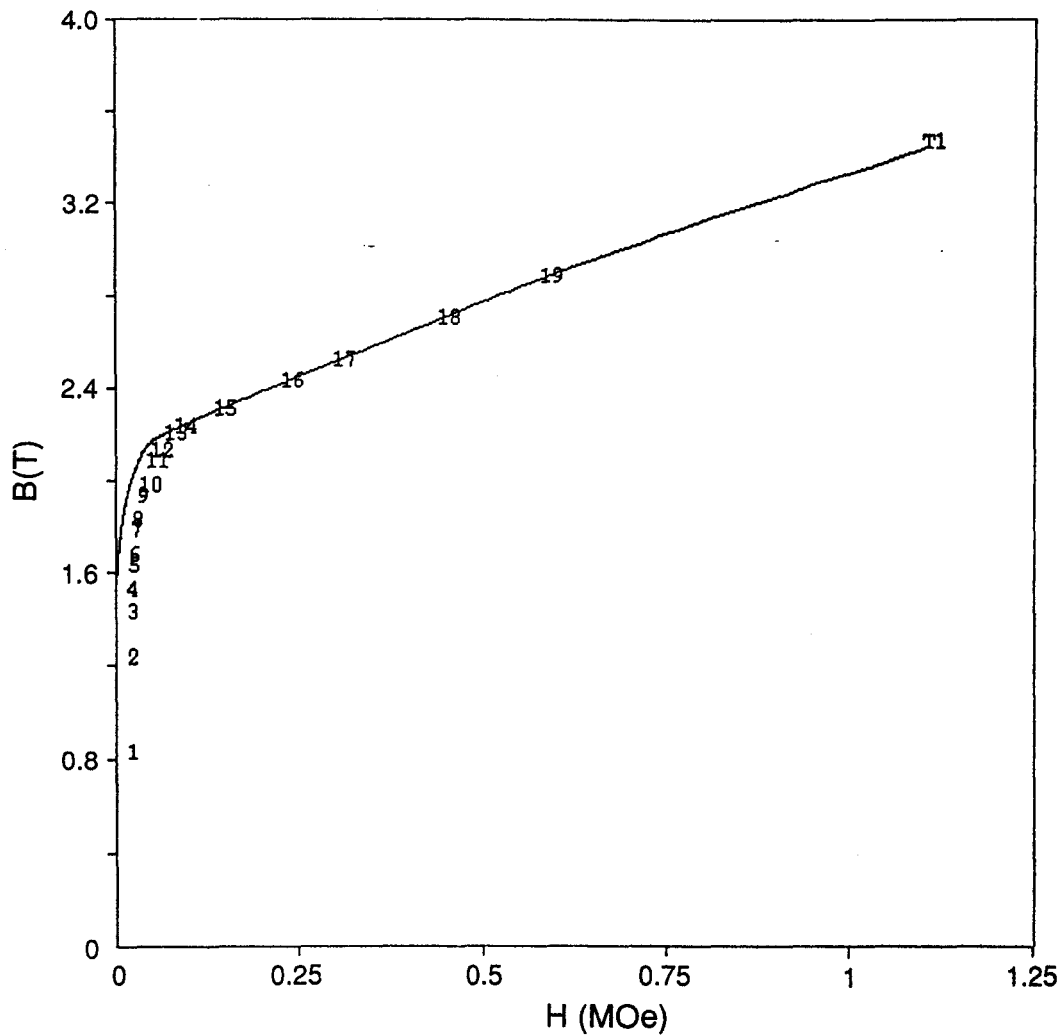


Fig. 5-24. *B-H curve of the Q4 iron.*

Fig. 5-25). This two-dimensional analysis was performed using the geometry of the magnet cross section at the magnetic center of the return end (that is, the end nearer the IP). Flux lines of the magnetic induction B are shown in Fig. 5-26. The maximum field in the coil region is at the quadrupole coil and is 1.253 T (see Fig. 5-27).

Because the magnet is required to have a wall thickness of 13.55 mm at the return end, the iron yoke has a circular cut to accommodate the beam pipe for the LEB. In this region the yoke thickness is reduced to 2.3 mm at the magnetic center of the return end (and to 1.6 mm at the physical end). However, in this region there is only a small magnetic flux because the dipole and quadrupole fluxes very nearly cancel each other. Nonetheless, this region of iron is required in order to close the magnetic flux and screen the LEB.

In Figs. 5-28 and 5-29, the Lorentz forces acting on the coils are shown; these values are summarized in Table 5-14. The Lorentz forces squeeze the quadrupole and dipole coils together and compress them along their main dimension. There is everywhere a force between the coils and the adjacent iron yoke face. The prestress required to maintain compressive loading of the coils during excitation is less than 8 N/mm². This

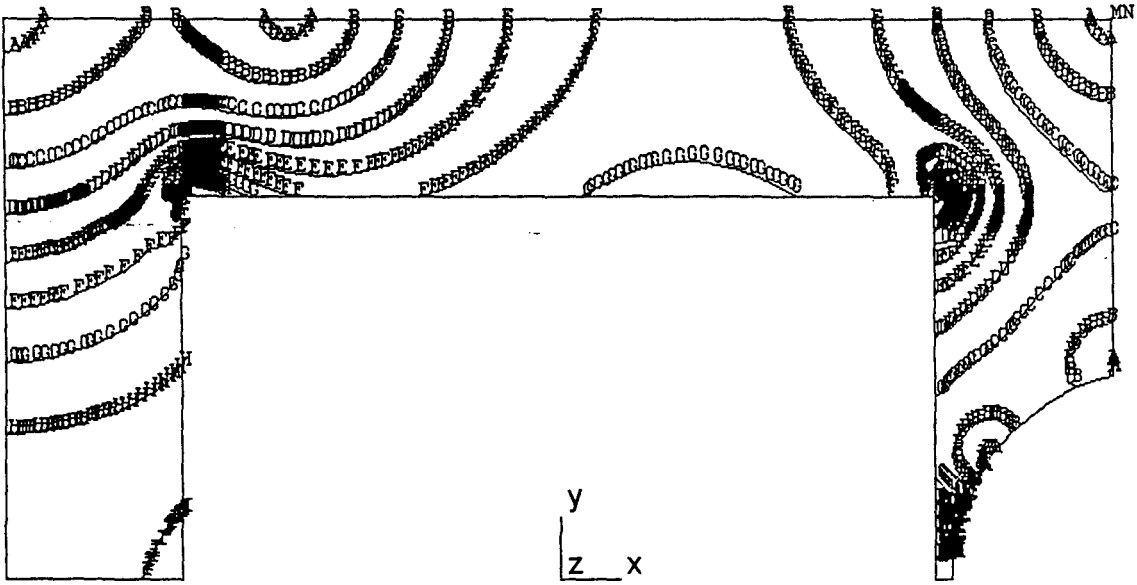


Fig. 5-25. Magnetic induction B in the $Q4$ iron yoke; $B_{max} = 1.37$ T.

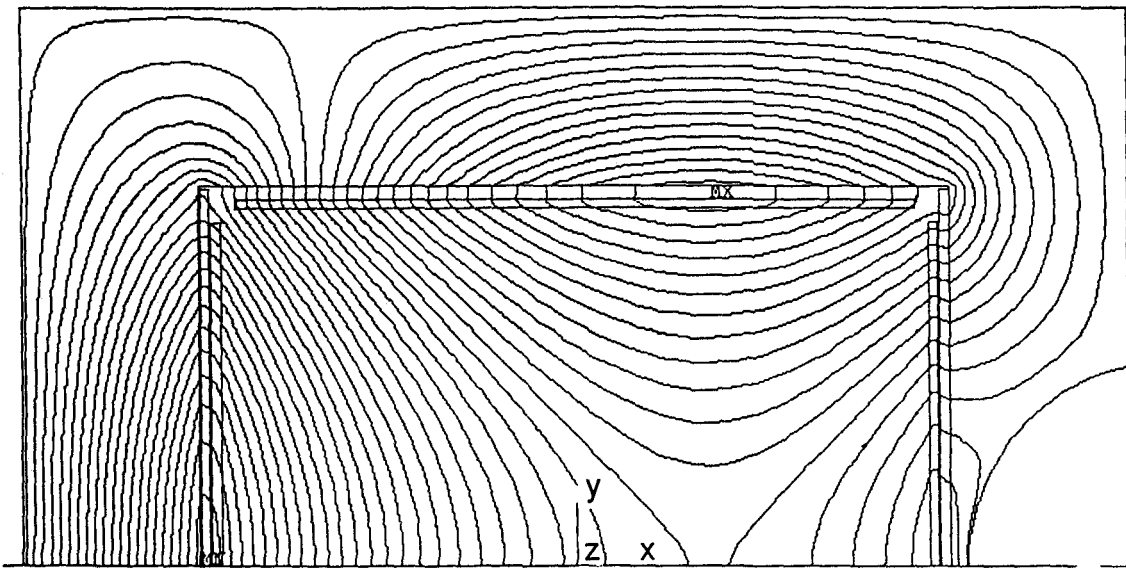


Fig. 5-26. Flux lines of the magnetic induction B for the $Q4$ quadrupole. Note the offset of the quadrupole center due to the superimposed dipole fold.

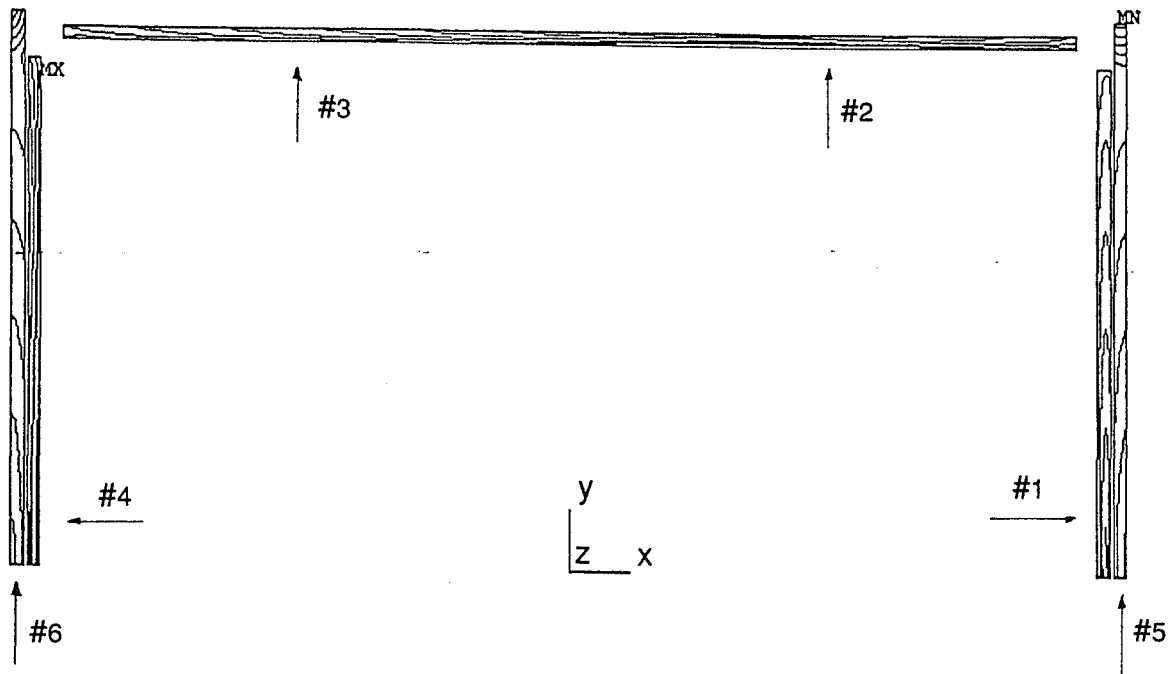


Fig. 5-27. Magnetic induction B in the $Q4$ coils; $B_{max} = 1.253\text{ T}$.

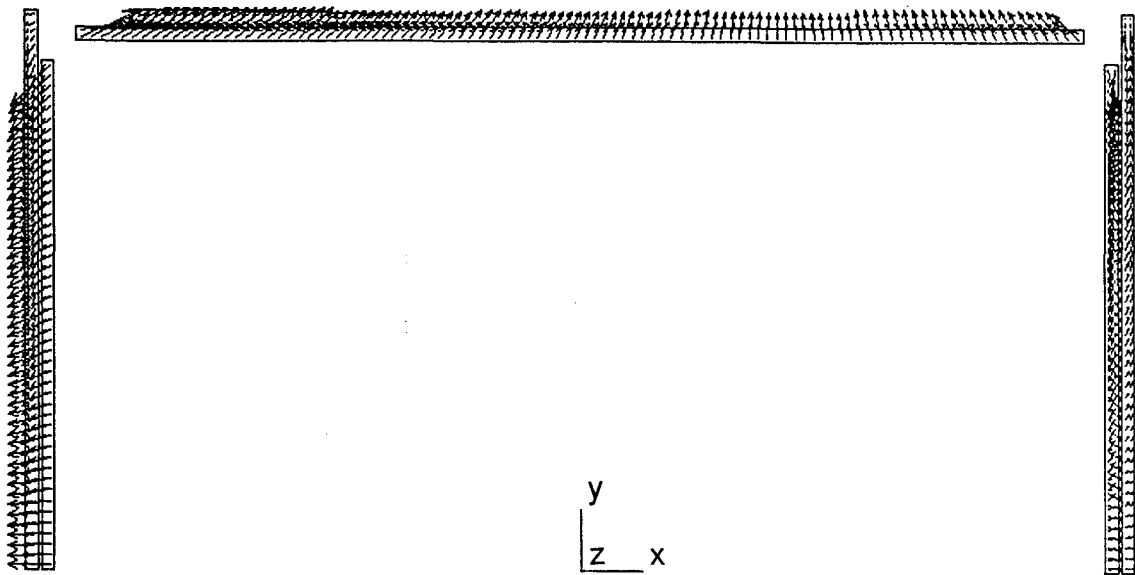


Fig. 5-28. Lorentz forces acting on the coils.

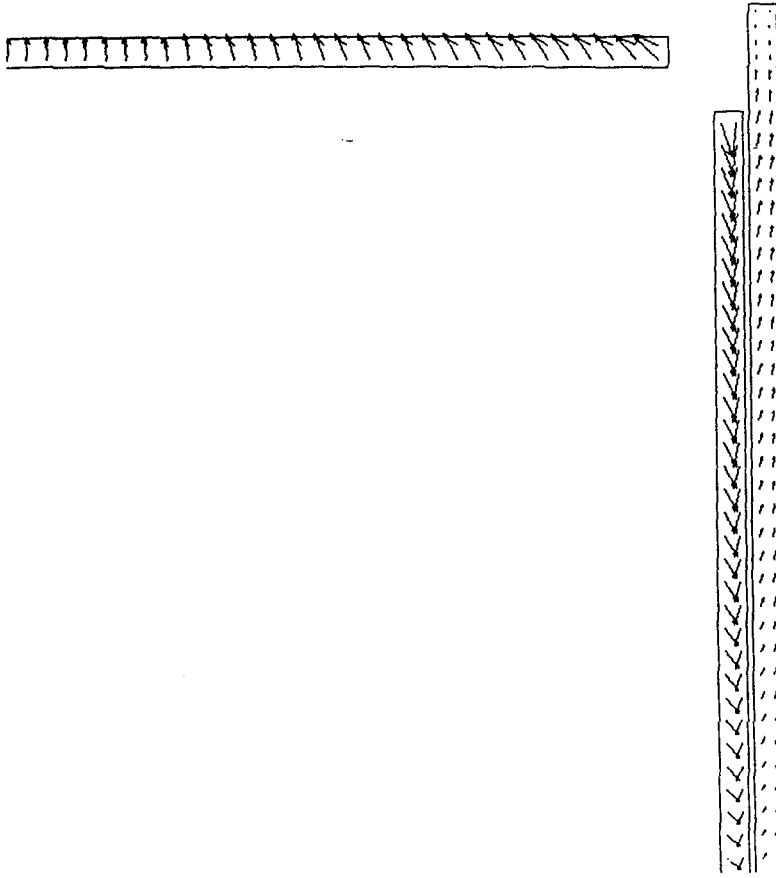


Fig. 5-29. Detail of the Lorentz forces acting on the coils.

Table 5-14. Lorentz forces acting on the coils.

Coil number ^a	F_x (N/mm)	F_y (N/mm)
1	2.5	-11.1
2	-2.7	11.1
3	19.7	11.1
4	-19.6	-11.3
5	1.7	4.3
6	-1.7	-4.3

^aSee Fig. 5-27.

prestress is applied during coil assembly by properly shimming the coils and assembling the four-piece iron yoke around the coils with an "interference" fit.

The overall current density in the dipole is $J_0 = 179 \text{ A/mm}^2$, and in the quadrupole, it is $J_0 = 511 \text{ A/mm}^2$. The critical curve B - J_{sc} for the superconducting material is obtained from the following expression:

$$J_{sc\text{-critical}}(T, B) = p_1 \left(1 - \frac{T - T_0}{p_2 - p_3 B} \right) (1 + p_4 B) \quad (5-4)$$

with $p_2 = 7.81042 \text{ K}$, $p_3 = 0.778448 \text{ KT}^{-1}$, $p_4 = -0.0996643 \text{ T}^{-1}$, and $T_0 = 4.22 \text{ K}$. We assume a superconductor having $J_{sc}(T = 4.22 \text{ K}, B = 5 \text{ T}) = 2750 \text{ A/mm}^2$, which gives $p_1 = 3192 \text{ A/mm}^2$. The assumed packing factor of the conductor is 0.64 and the Cu:SC ratio is 3.0.

Because the operating current density is $J_{sc} = J_0(1 + 3)/0.64 = 3192 \text{ A/mm}^2$ and the operating temperature is 4.22 K, then $J_{sc\text{-critical}} = 4513 \text{ A/mm}^2$ and $B_{\text{critical}} = 1.77 \text{ T}$. The operating margin, defined as $(J_{sc\text{-critical}} - J_{sc})/J_{sc}$ is 41% (Fig. 5-30).

The configuration used for the magnet ends is the "Lambertson" end [Laslett, et al., 1987], with an angle of 60° (see Figs. 5-31 and 5-32). These ends have the same integrated multipoles as found in the central cross section of the magnet, and this design eliminates the need for spacers between the wires. The physical length of the coils is 860 mm. Axial compression is obtained from the end-plates that are fixed to the iron yoke.

In the 1.8-mm space between the bore tube and the vacuum pipe, multilayer insulation is used. The assumed apparent conductivity is $k_a = 1 \times 10^{-4} \text{ W/m/K}$ and the heat transfer from the two room-temperature bore tubes to the LHe-cooled vacuum pipes is $\sim 7 \text{ W}$. The leads carry 800 A for the quadrupole and 280 A for the dipole. The heat flow into the helium is $\sim 1 \text{ W/kA}$ per lead; the four leads (two for the dipole and two for the quadrupole) contribute a heat load of about 2 W. The total heat to be extracted, then, is about 9 W; this is easily manageable.

The cryostat for the Q4 quadrupole, shown in Fig. 5-33, is a conventional assembly, typical of many others now in use with superconducting magnets (such as the three spin-rotator superconducting solenoid magnets now installed at SLAC). It has a diameter of about 46 cm and a length of 150 cm. The magnet cold mass is supported and aligned by vertical and horizontal fiberglass-reinforced plastic straps (similar to the designs used at DESY and SLAC). Both beam tubes are at room temperature and are shielded from the liquid-helium wall with superinsulation.

The cryostat has two dipole current leads (280 A each) and two quadrupole current leads (800 A each). Two bayonet connections, for liquid-helium supply and for liquid-nitrogen supply (to the heat shields), are indicated in Fig. 5-33. Static heat loads, including current leads, are estimated at 1.5–2 L/hr of liquid helium. A 50-L storage volume will provide 24-hour operation between liquid-helium fills. The liquid helium will be supplied by 500-L dewars fed from the SLAC central liquefiers (as is now done for the three spin-rotator solenoid cryostats).

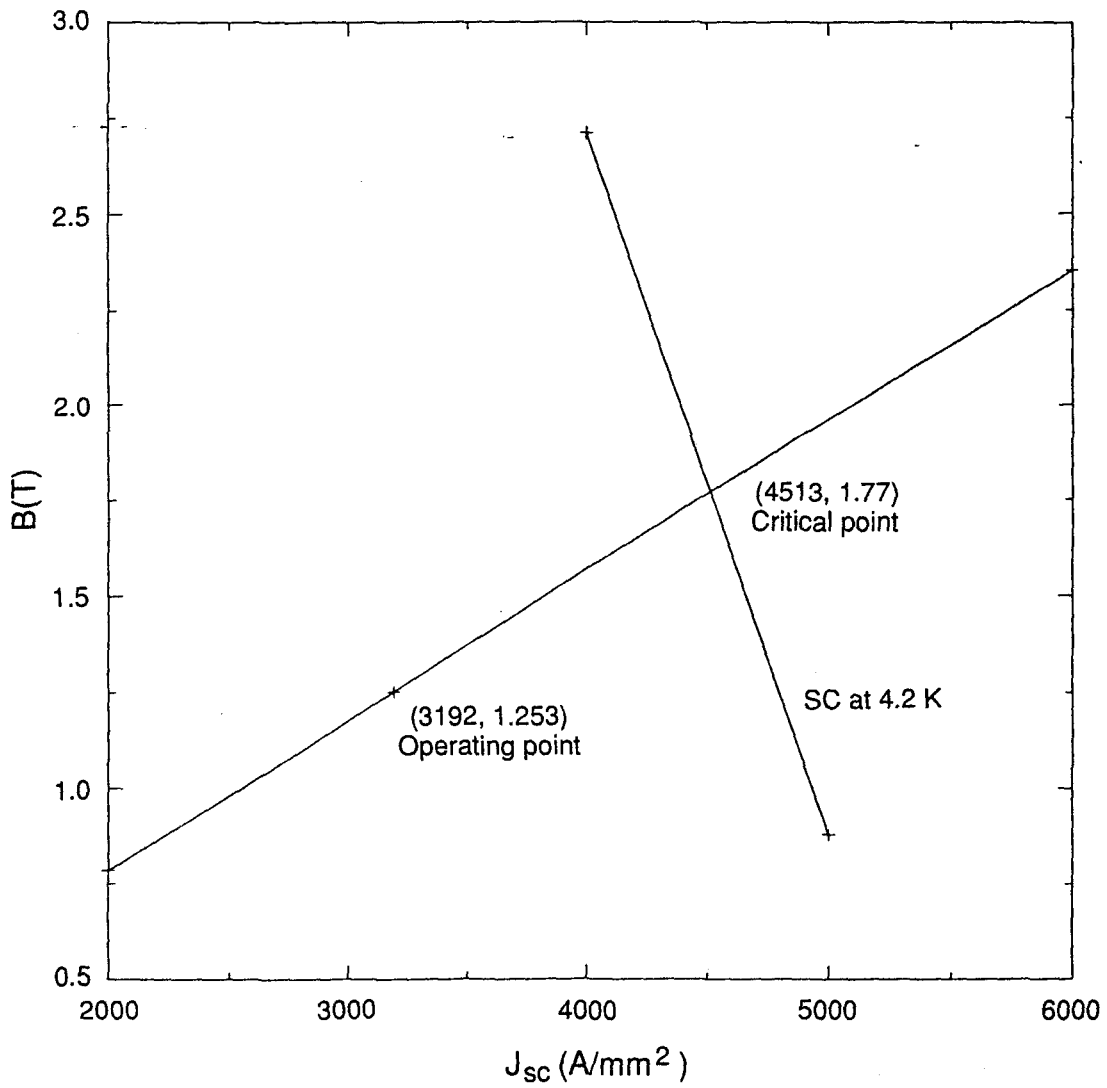


Fig. 5-30. Operating point of the magnet Q4 and critical curve B - J for the superconductor.

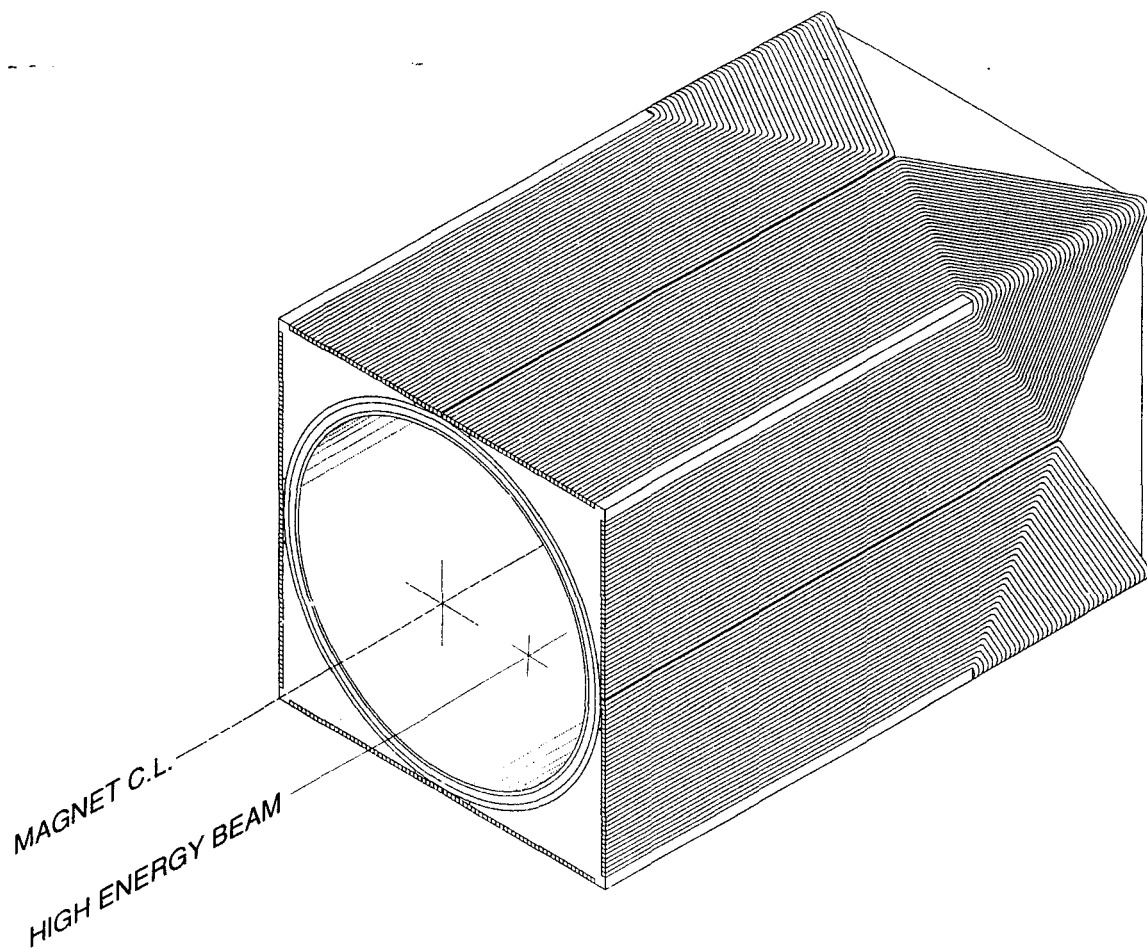


Fig. 5-31. View of the Lambertson end termination for the Q4 quadrupole coils.

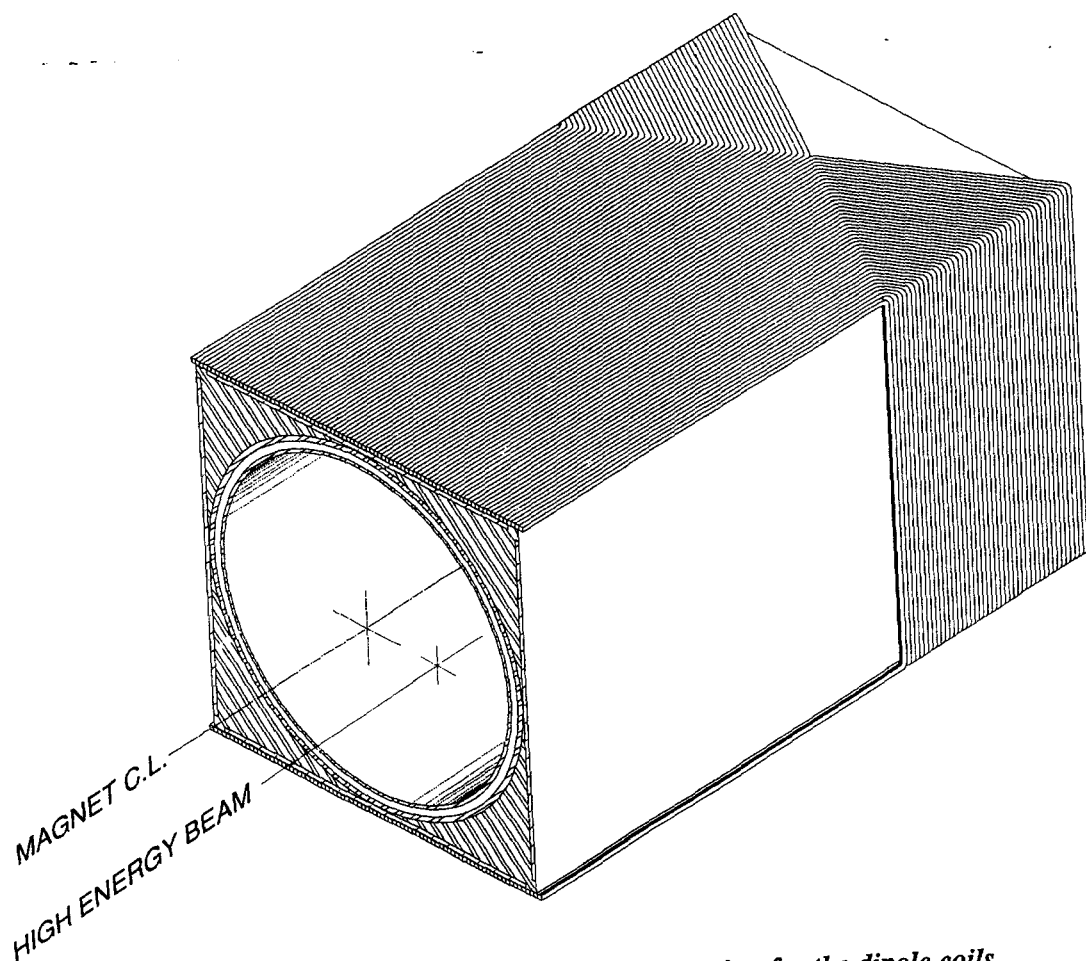


Fig. 5-32. View of the Lambertson end termination for the dipole coils.

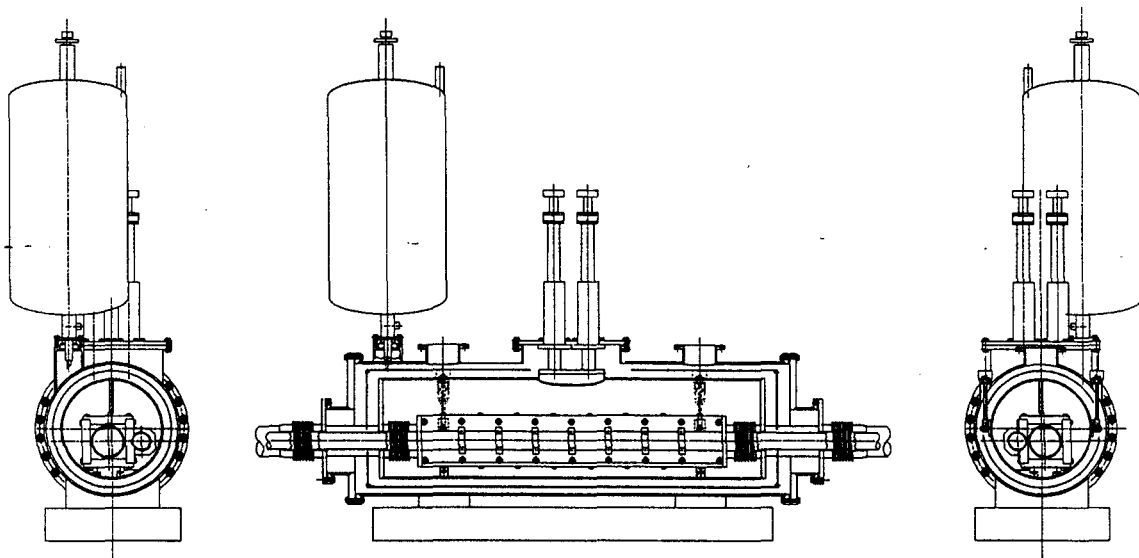


Fig. 5-33. End and cutaway views of Q4 cryostat.

Room-Temperature Alternative. Given the large amount of synchrotron radiation in this part of the lattice, it is clearly worthwhile to consider the possibility of a conventional, rather than a superconducting, Q4. An example of such an alternative concept would be to design a conventional quadrupole and then provide a flux-free channel for the LEB inside the magnet. A conventional quadrupole in the Collins form, with a figure-eight field pattern, has a natural coil-free midplane to pass the synchrotron light fan on one side. The low-energy beamline vacuum pipe is located in the midplane between the other two poles. An iron pipe of sufficiently high permeability and a sufficiently thick wall will screen out the field at the LEB beamline, but by itself would cause large distortions in the quadrupole field sampled by the HEB. A way around this difficulty has recently been discussed by Herrmann and Szyszko [1989]. A current sheet on the outer surface of the magnetic shield can, in principle, completely correct the external distortions introduced by the shield tube. Figure 5-34 shows the resultant field patterns.

On the left in Fig. 5-34 is the desired quadrupole field without a flux shield pipe. The center plot shows the distortion caused by the iron flux shield tube alone. The right-hand field plot shows the effect of the correcting current sheet. To match the original field pattern, the distribution of corrector currents must vary around the perimeter of the shield. The general rule for determining the required surface current elements di is

$$di = -\frac{\mathbf{B} \cdot d\mathbf{s}}{\mu_0} \quad [\text{A}] \quad (5-5)$$

Here $d\mathbf{s}$ is a vector tangent to the outer surface of the iron shield and $\mathbf{B}$ is the undistorted magnetic field at that surface. In this approach, all magnetic flux that would otherwise have passed through the LEB beam-stay-clear aperture must now be channeled around in the iron beam pipe walls. The peak current densities in the corrector current

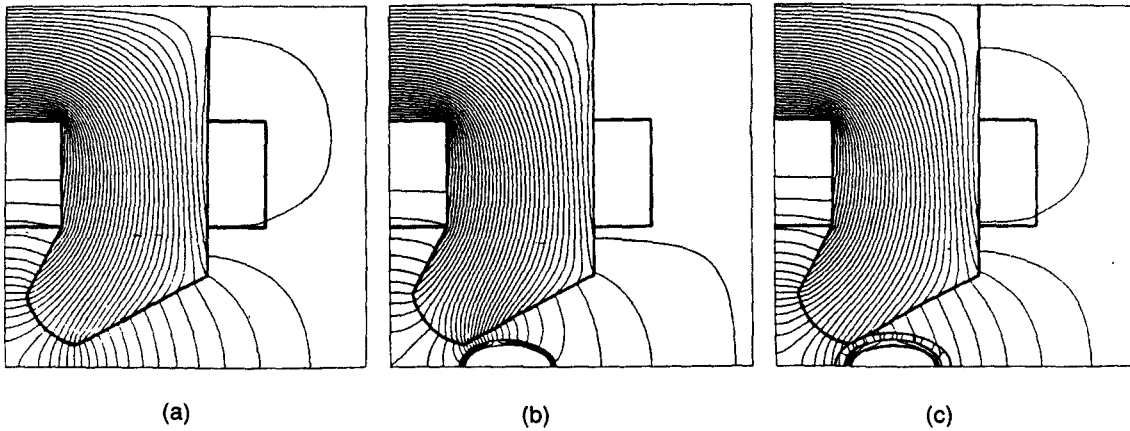


Fig. 5-34. Example of field lines for a Collins quadrupole design. The left picture is a single magnet, the center picture shows the field perturbations introduced when an iron pipe for the LEB is inserted, and the right picture shows the restored field when the proper current sheets are used to shield the LEB pipe.

sheath located at the midplane are $4\text{--}5\text{ kA/cm}^2$, just as in the Panofsky septum designs. However, there are several important advantages to the design of a quadrupole with flux shield:

- Quadrupole magnet and flux shield are two distinct, decoupled design problems.
- No extra dipole field is required to offset the quadrupole center to create clearance for the synchrotron radiation fan. A gap for the fan is intrinsic to the standard quadrupole geometry. Total field energy is much lower for the flux shield approach.
- A conventional quadrupole can have standard low-current-density coils for low power consumption (10 kW or less).

Although a high current density (5 kA/cm^2) would still be required for a portion of the shield, the top and bottom surfaces of the elliptical flux shield, where the field strikes at almost normal incidence, would require only hundreds of A/cm of surface-current-density. The total flux shield power could be as low as 10 kW.

The integrated current density around the perimeter of the flux shield is zero. Shaping the conductor cross sections or winding densities may make it possible to power the flux shield from a single supply. The wall thickness of the iron shield in any actual design would be adjusted around the perimeter to match the local flux and thus prevent saturation.

Simulations indicate that the remaining field inside the LEB beam pipe would be about 0.006 T. A second, floating magnetic-shield layer of high-permeability material lining the inner surface could reduce this further, if necessary. The particular Collins quadrupole design illustrated in Fig. 5-34 has a pole-tip bore radius of 3.12 cm and requires about 7000 A turns per coil to reach a field gradient of 17 T/m.

During the detailed design stage, studies will be carried out to see if the field quality expected from the superconducting design can also be achieved with a conventional magnet design. The design will ultimately depend on both performance and reliability considerations.

5.1.4 Magnetic Measurements

Five stations will be constructed for magnetic measurements, each having a computer. The computer will serve for data storage and data handling, and will also permit a comparison between the new magnetic measurements made on the refurbished PEP magnets and the original data taken at the time of their manufacture. A standardization procedure for each particular type of magnet will be stored in the computer so that it can be performed automatically prior to the commencement of measurements. The software will also prompt the operators to enter serial numbers, attach cables and water hoses, etc. Variables such as water flow, terminal voltage, and temperature rise will all become part of the database. This will ensure quality control and provide a complete pedigree for each magnet.

The choice of five stations will permit us to handle the five different types of magnets: HER dipoles, HER quadrupoles, LER dipoles, LER quadrupoles, and HER/LER sextupoles. This number of stations is perceived to be a minimum, based on the number of magnets to be tested and their different configurations. In particular, the HER dipoles present a challenge, owing to their 5.4-m length. The long coil required for these magnetic measurements will be unique. The LER bends are only 1 m long, so a relatively short coil can be used. Both HER and LER quadrupoles could be measured at a single station, but it is prudent to have a degree of redundancy and to avoid the possibility of bottlenecks. Because the HER and LER sextupoles are identical, the same station will be used, irrespective of the final destination of the magnet.

Magnetic measurements will be conducted using standard rotating-long-coil techniques. This method gives the integrated strength of the magnet, either $\int B \, dl$ or $\int G \, dl$, including end effects. In the case of quadrupoles, the rotating-coil measurement is a convenient way of determining the magnetic center, since a zero dipole signal occurs at this location. This measurement will provide a convenient check on the accuracy of the external fiducials built into the laminations at the time of stamping. Furthermore, the rotating-coil technique permits a determination of the higher-multipole content of the field, which is the true measure of magnet quality. Measurements will be conducted at different current settings, corresponding to the operating energies envisioned. This will provide a polynomial fit that will permit the magnets to be set accurately at any required field strength.

Magnetic tolerances for both the HER and the LER are similar to those for PEP and can be summarized as follows: The sum of all higher multipoles over the required beam-stay-clear region should be less than 0.1% of the main field component of the magnet over this same region.

5.1.5 Supports

Considerable thought has been given to the support and alignment of the two rings of the B Factory. Because of the large mass of the PEP components, which are to be reused in the HER, the HER will be mounted below the LER. A side elevation of the standard HER and LER cells and a cross-sectional view of the PEP tunnel are shown in Figs 5-35 and 5-36, respectively. An artist's conception of the overall layout of the two rings is shown in Fig 5-37.

Once the PEP tunnel has been emptied, a rough alignment procedure (see Section 5.3) will locate the anchors for the lower legs of the support structures. These support structures will be placed at the quarter-points of the HER dipole magnets, as was done in PEP, to maintain the alignment and minimize sag and twist of these long laminated magnets. The four feet necessary to adjust and maintain the alignment of the bending magnets will be mounted on these horizontal legs.

To facilitate installation, the quadrupole-sextupole pairs for the HER will be mounted on a rigid box-frame, or raft, and aligned in a temperature-controlled facility using high-precision optical benches. In this manner, component-to-component misalignment is kept to a minimum. The vacuum spool piece for this section will be installed along with the vacuum chamber support, which must be capable of locating and fixing the associated beam position monitor with an accuracy of about 0.1 mm with respect to the magnetic center of the adjacent quadrupole. This requirement justifies our plan to prealign the individual components on a monolithic, stress-relieved frame that will avoid costly in-field alignment (which historically has proved to be more expensive and less accurate than prealignment in the laboratory).

In the tunnel, precision alignment will locate the base support on which the doublet rests. The base will have dowel pins identical to those at the alignment stations. Thus, when the magnetic components and base are taken to the tunnel, these pins will enable us to place the doublet accurately. Although the base itself will be provided with adjustments having six degrees of freedom, we believe that it will be unnecessary to provide individual adjustment for all the raft components. The technique outlined here has been employed successfully at SLAC on several other projects, including the damping rings, the SLC arcs, and the final focus beamline.

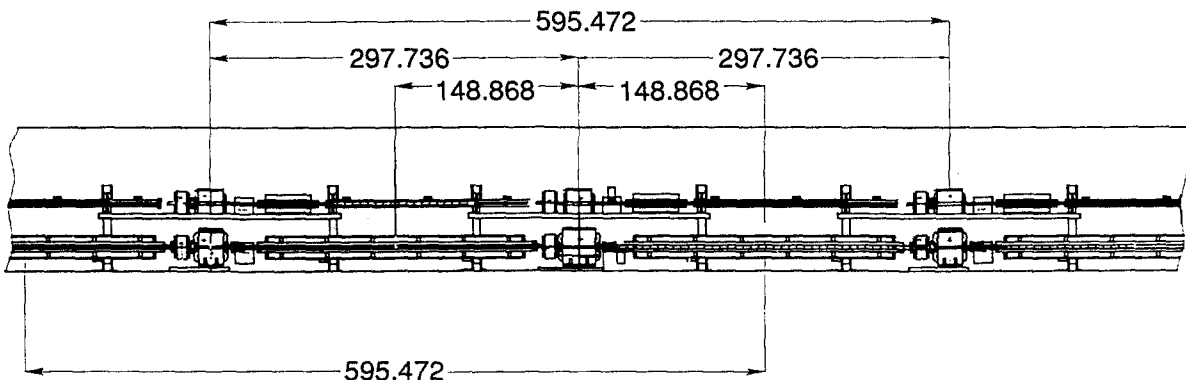


Fig. 5-35. Side elevation of a standard HER cell.

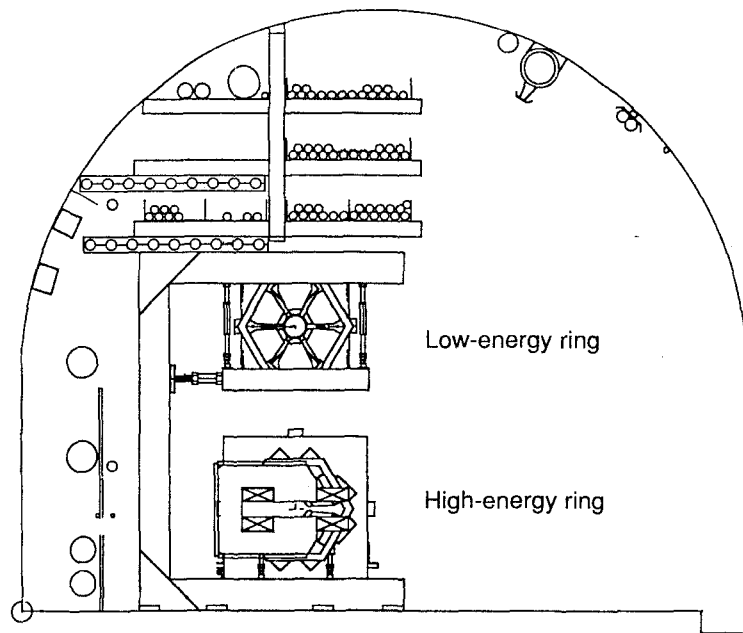


Fig. 5-36. Cross-sectional view of the PEP tunnel, showing the locations of utilities and the high- and low-energy rings.

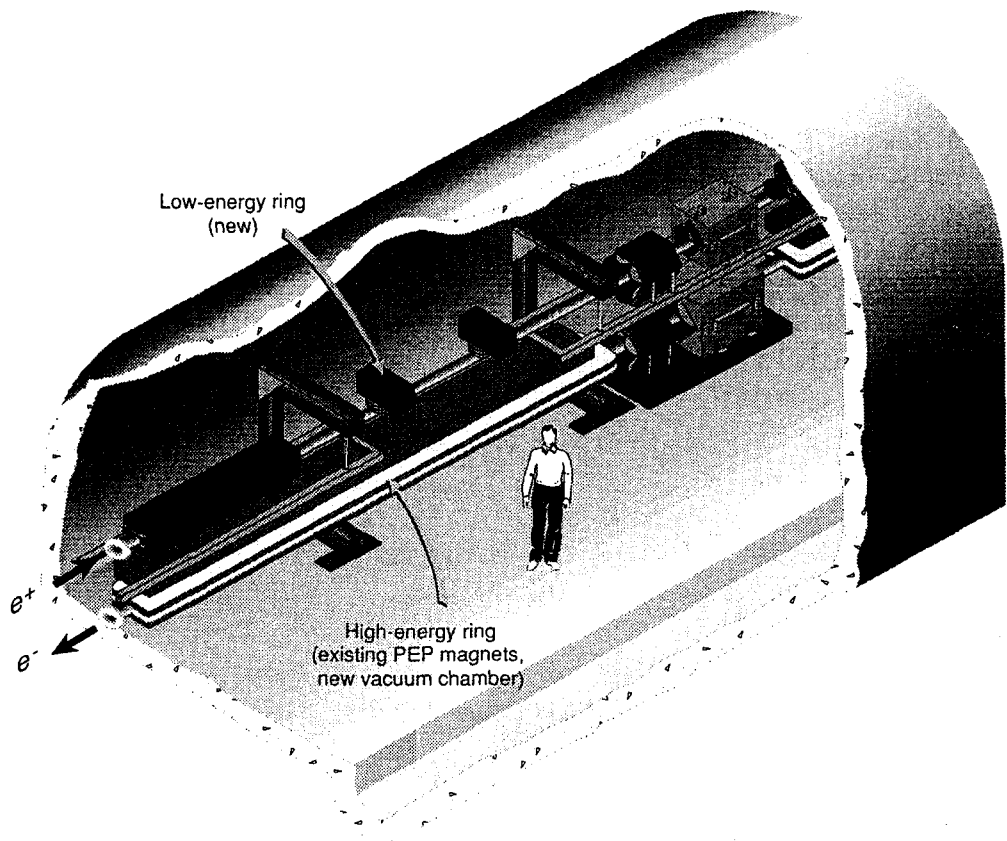


Fig. 5-37. Artist's conception of the high- and low-energy rings in the PEP tunnel.

After the main components of the HER ring are in place, the LER components will be installed above them. Once again, we will take the approach of using a raft or strong frame and prealigning the LER components in the laboratory. Because of their smaller size and lighter weight, we expect to be able to support and align the magnetic components of an entire half-cell (including a sextupole, a quadrupole, a bending magnet, and either a steering magnet or beam position monitor, together with the vacuum chamber and associated pumps) on one raft. As with the HER, the raft itself will be provided with six degrees of controlled freedom. We believe that it will be unnecessary to provide easy adjustments for individual raft components.

To facilitate alignment, the LER will be suspended above the HER such as to leave about an 8-in. component-free zone between the two rings for unobstructed line-of-sight. As discussed in Section 5.1.3, extensive ground-motion measurements were made at SLAC prior to building the SLC, since that accelerator was expected to be very sensitive to small, steady-state ground motions or noise. These measurements indicated which site-wide excitation frequencies are a problem. Our supports will be designed to avoid unwanted resonances.

Because the two rings are independently supported, at different heights in the tunnel, it is clear that changes in temperature within the tunnel can cause relative motion between them. Fortunately, time constants for such motion will be slow, of the order of hours, and steering corrections can be made in the IR to compensate for the resultant beam drifts.

5.2 VACUUM SYSTEM

The vacuum system of the B Factory collider presents a technical challenge beyond that of any existing electron-positron collider. Each technical subsystem must meet demanding design criteria to satisfy the overall system requirements. These subsystems for the high-energy (electron) and low-energy (positron) rings (HER and LER, respectively) include vacuum chambers, pumps, cooling, and special components, such as bellows, beam position monitors (BPMs), valves, etc.

In the case of the B Factory design, the high- and low-energy rings will have circulating beam currents of 1.48 and 2.14 A, respectively, to reach the design luminosity of $3 \times 10^{33} \text{ cm}^{-2} \text{ s}^{-1}$. We refer to these as the “nominal” or “design” currents. The nominal beam currents are at least an order of magnitude beyond the typical values for today’s colliders and, as such, present an appreciable challenge to the vacuum system designer. To provide for possible upgrades, and for luminosity “breathing room,” we also specify a *maximum allowable* current in each ring of 3 A. Because the vacuum system is generally difficult to upgrade after the collider is operating, we have chosen in some instances to allow for the 3-A capability from the outset. In cases where the initial configuration can be upgraded and does not require the extra capability, it is sufficient simply to provide the means for future upgrades—for example, by having unused ports to which additional pumps could be attached later.

Note that, in this section, we will use the term “electrons” in its generic sense, that is, to refer to either electrons or positrons.

5.2.1 General Issues and System Requirements

A well-designed vacuum chamber is the key to providing a suitable beam environment. In particular, the chamber design should have the following attributes:

- Adequate beam-stay-clear aperture for injection and for stored-beam lifetime
- Low impedance to avoid beam instabilities and to minimize higher-order-mode (HOM) power dissipation
- Sufficient pumping speed to maintain a low pressure in the face of substantial synchrotron-radiation-induced gas desorption
- Sufficient cooling to safely dissipate the heat load associated with both synchrotron radiation and HOM losses
- Capability to shield external ring components from synchrotron radiation

Most of these requirements are fairly obvious and do not differ from those of existing colliders. The main distinction in the case of the B Factory is associated with the required beam currents, which are much higher than those in present-day colliders.

Depending on the magnitude of the dynamic gas load due to photodesorption, the chamber could have a conventional elliptical shape or it could exploit differential pumping via an antechamber arrangement. In the B Factory parameter regime, use of a conventional chamber shape is acceptable, provided that the material is chosen to have a low photodesorption coefficient. If the chamber material is suitably chosen, the chamber walls will also serve as the primary shield for the synchrotron radiation that would otherwise damage magnets and other beamline components. Basically, this consideration implies the use of a high-Z material such as copper or stainless steel, rather than the more easily fabricated aluminum. (If aluminum were chosen, the shielding would have to be provided by an additional layer of material—for example, lead—to absorb the radiation passing through the chamber walls. While this is possible, it is an undesirable complication.)

Included as integral parts of the chamber are several special sections and components, such as cross-section transitions, pumping ports, bellows, and BPMs. The high peak and average beam currents in the B Factory demand that the electromagnetic environment presented by the vacuum chamber and its special components satisfy a strict impedance budget for the ring. It is known that the present PEP vacuum chamber provides a sufficiently low broadband impedance ($|Z/n| \approx 1 \Omega$) to be acceptable for the B Factory [Rivkin, 1987; Zisman, 1990b]. Thus, we are assured that standard care in the design of the vacuum chamber will permit us to reach our impedance goal.

The pumping subsystem of the collider must maintain the specified operating vacuum under conditions of a large dynamic photodesorption gas load caused by the intense synchrotron radiation bombardment of the chamber walls. In high-energy, high-current electron rings, thermal outgassing is generally a small contribution to the gas load that mainly determines the base pressure in the absence of beam. In addition to handling the gas load during routine operation, the pumping must also be sufficient to allow for rapid initial commissioning (cleaning) of the vacuum chamber. The *system requirements* for the vacuum system during collider operation are as follows:

- ≤ 10 nTorr in the arcs
- ~ 3 nTorr in the straight sections
- ~ 1 nTorr in the two half straight sections upstream of the detector
- ~ 0.1 nTorr base pressure due to thermal outgassing under no-beam (static load) conditions

(Note that pressure requirements are quoted here as N_2 -equivalent values.) We have generally designed the vacuum systems to reach these goals even at the maximum allowable beam current of 3 A. Thus, at the nominal operating currents, we expect to do better than the requirements listed above. In this sense, the design is conservative and should operate very reliably. Moreover, the additional pumping capability will be of great benefit in reducing the conditioning time for the system.

An electron beam circulating in a storage ring subjects the vacuum chamber walls to copious synchrotron radiation. As the spatial extent of the incident radiation is small, the associated thermal flux is generally high enough to require considerable cooling of the chamber wall. The cooling subsystem is designed to remove the waste heat safely under conditions of high radiation flux. As is typical, cooling is accomplished by water flowing

in channels outside the chamber. In addition to ensuring the mechanical stability of the chamber under thermal loads that could reach 10 MW in the HER, maintaining the chamber wall at a relatively low temperature serves to reduce the gas load due to thermal desorption.

5.2.2 Determination of Vacuum Chamber Aperture

The size requirements of the beam chambers are determined by the beam emittances and energy spreads and by the optical functions of the HER and LER lattices. To ensure adequate quantum lifetime, the chamber was designed to accommodate the *uncoupled* horizontal emittance and the *fully coupled* vertical emittance. It is also desirable to keep the cross section of the chamber constant throughout the arc sections to minimize the impedance contribution from shape transitions. Consequently, we considered the maximum values of the beta functions in determining the chamber sizes.

For determining the required chamber aperture, we took the uncoupled emittance value for each ring to be twice the value required for the nominal operating configuration. This will provide considerable flexibility to adjust the ring parameters as dictated by operational needs. Thus, the chamber of the HER was designed for 100 nm-rad uncoupled horizontal emittance, and the LER chamber was designed for 200 nm-rad. In the absence of wigglers, the relative energy spread of the beam in the HER should be close to its natural value of 6.1×10^{-4} . To be conservative, we took a value of 1×10^{-3} for estimating the required chamber size. For the LER, we envision that the natural energy spread of 3.5×10^{-4} will be increased by means of wigglers to a value closer to 1×10^{-3} , which we again adopted as a design specification for evaluating aperture requirements. Since the HER optics are similar to PEP, the closed-orbit allowances were taken to be the same as those adopted for the original PEP design; these values were also assumed for the LER.

Emittance and beta function values used to evaluate the required apertures for the HER and LER are summarized in Table 5-15.

The horizontal beam-stay-clear half-aperture is evaluated as

$$\text{BSC}_x = 10 \sqrt{\epsilon_{x0} \hat{\beta}_x + \hat{D}^2 \left(\frac{\sigma_E}{E} \right)^2} + \text{COD}_x \quad (5-6)$$

Similarly, the vertical beam-stay-clear is

$$\text{BSC}_y = 10 \sqrt{\epsilon_{y0} \hat{\beta}_y} + \text{COD}_y \quad (5-7)$$

Using the values in Table 5-15 and including allowances for fabrication and mechanical positioning errors, we obtain the minimum chamber (inner) half-apertures:

$$\text{HER: } \text{BSC}_x \times \text{BSC}_y = 45 \text{ mm} \times 25 \text{ mm}$$

$$\text{LER: } \text{BSC}_x \times \text{BSC}_y = 40 \text{ mm} \times 25 \text{ mm}$$

The HER chamber dimensions can be accommodated by the present PEP magnets.

Table 5-15. Parameters used to evaluate vacuum chamber dimensions for the high- and low-energy ring arcs.

Beam parameter	HER	LER
Max. uncoupled horizontal emittance, ϵ_{x0} [nm]	100	200
Max. fully coupled vertical emittance, ϵ_{y0} [nm]	50	100
Max. horizontal beta in arcs, $\widehat{\beta}_x$ [m]	25.6	26
Max. vertical beta in arcs, $\widehat{\beta}_y$ [m]	32.9	26
Max. dispersion, $\widehat{D}$ [m]	1.86	0.7
Max. energy spread, σ_E/E	1×10^{-3}	1×10^{-3}
Horizontal closed-orbit allowance, COD_x [mm]	10	10
Vertical closed-orbit allowance, COD_y [mm]	5	5

It is worth noting that the corresponding conductances of a section of beam pipe of the above dimensions are 35 L/s per meter and 30 L/s per meter for the high- and low-energy rings, respectively. These relatively small values have a considerable influence on the choice of pump sizes and locations, as discussed below.

5.2.3 Synchrotron Radiation and Vacuum

As mentioned earlier, two design issues follow from the copious production of synchrotron radiation in a high-intensity storage ring: (i) heating of the vacuum chamber walls owing to the high thermal flux density and (ii) radiation-induced gas desorption (both photodesorption and thermal desorption). In this section, we quantify these effects and evaluate their impact on collider performance. As we shall see, despite the difficulties associated with the high beam currents in the B Factory storage rings, handling the large synchrotron radiation power is amenable to standard engineering solutions in a beam chamber of elliptical cross section, without requiring a more exotic approach based on an antechamber design.

5.2.3.1 Wall Heating. At the design luminosity of $3 \times 10^{33} \text{ cm}^{-2} \text{ s}^{-1}$, each ring will contain a beam current more than an order of magnitude higher than that typical in existing high-energy storage rings; the associated heat load is, therefore, quite high. The technical difficulty is not the total synchrotron radiation power per se, but rather the linear thermal flux. Thus, contrary to intuition, a small-circumference ring is more difficult to cool and pump than a large ring. Were a very small circumference to be chosen for the LER, thermal management would be considerably more difficult than in

the HER, despite the fact that the total synchrotron radiation power would be considerably lower in the LER. By adopting a design in which the LER has a circumference equal to that of the HER, such concerns are eliminated (except for the damping wiggler regions). For this reason, our estimates in this section will focus on the parameters of the HER. The wiggler section of the LER lattice is discussed in Section 5.2.6, below.

- - To estimate the heat load, we start from the well-known expression [Sands, 1970] for the synchrotron radiation power (in kW) emitted by an electron beam in uniform circular motion:

$$P_{\text{SR}} = \frac{88.5 E^4 I}{\rho} \quad (5-8)$$

where E is the total energy (in GeV), I is the total beam current (in A), and ρ is the bend radius of the dipoles (in meters). The linear power density (in W/cm) radiated along the circumferential path length is given by

$$P_L = \frac{10 P_{\text{SR}}}{2\pi\rho} = \frac{885 E^4 I}{2\pi\rho^2} \quad (5-9)$$

For a 9-GeV beam in the HER ($\rho = 165$ m) at the maximum allowable current of 3 A, we find from Eq. 5-9 a linear power density of $P_L = 102$ W/cm. At the nominal operating current of 1.48 A (corresponding to the design luminosity of $3 \times 10^{33} \text{ cm}^{-2} \text{ s}^{-1}$), the linear power density is reduced to 51 W/cm.

In reality, the arcs are not exactly circular in either ring—the dipoles in each cell are connected by short straight sections a few meters in length. These straight regions serve to spread out the radiation flux. Consequently, Eq. 5-9 gives the worst-case value of the linear power density anywhere in the ring. For the purposes of designing the cooling system, we have used this worst-case value at the maximum allowable current. Thus, we have ample reserve cooling capacity at the nominal operating current.

The vertical (half) angular spread (in radians) of the synchrotron radiation fan containing ~85% of the radiation is given approximately by

$$\psi \approx \frac{m_0 c^2}{E} = \frac{1}{\gamma} \quad (5-10)$$

which, for a 9-GeV beam, is $\psi = 0.06$ mrad. Although it is not strictly true (see Section 5.2.6), we assume the power to be uniformly distributed over this angular extent. Including the finite size and angular divergence of the electron beam, the height of the vertical band illuminated by the synchrotron radiation fan is

$$h = 2 \left[\sigma_y^2 + d^2 (\sigma_y^2 + \psi^2) \right]^{1/2} \quad (5-11)$$

where σ_y is the rms beam height, σ_y' is the rms angular spread, and d is the tangential distance from the beam orbit to the chamber wall. The value for d can be easily calculated from the geometry shown in Fig. 5-38, where $w/2$ is the transverse distance from the beam orbit to the outer wall of the vacuum chamber:

$$d = \sqrt{\left(\rho + \frac{w}{2}\right)^2 - \rho^2} \quad (5-12)$$

For the HER, with a chamber of half-width equal to 4.5 cm and a 165-m bending radius, we obtain $d = 3.85$ m, with a maximum angle of incidence given by $\alpha = d/\rho = 23$ mrad.

To be conservative in estimating the power density, we have ignored the contribution to the height of the synchrotron radiation fan from the finite beam emittance; that is, we take $\sigma_y = \sigma_y' = 0$ in Eq. 5-11, and we assume that all the radiation falls between $\pm\psi$. Thus, the height of the illuminated strip is $h = 2\psi d = 0.44$ mm. The corresponding maximum thermal flux density at a beam current of 3 A is then $P_A = P_L/h = 2.3$ kW/cm². If need be, this value could be reduced by a factor of two by inclining the wall at 30°.

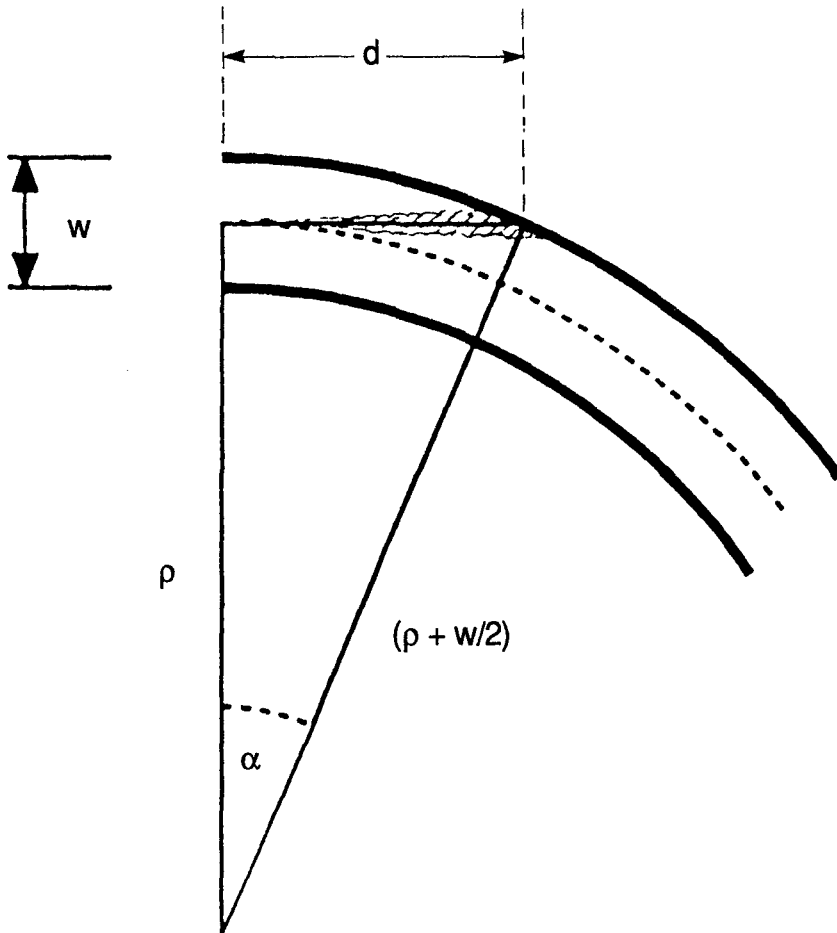


Fig. 5-38. Geometry of the synchrotron radiation fan hitting the vacuum chamber wall (not to scale).

The above estimate of power density applies to a photon beam incident on the HER vacuum chamber wall at a shallow angle ($\alpha = 23$ mrad). The worst case, however, is that of an object *normal* to the radiation fan, such as a flange or radiation mask, for which the density would increase in the ratio $\sin(\pi/2)/\sin \alpha \approx 43$, giving $P_A = 98$ kW/cm²—a high value, but one still within the standard operating range for properly engineered masks.

Having calculated the thermal flux density produced by the synchrotron radiation, we can estimate the temperature drop ΔT across the vacuum chamber wall, using a thermal relaxation program. With this approach, it is possible to model the influence of wall thickness, fins, and cooling tubes to obtain an optimized design. Typical results for copper and aluminum chambers of simple geometry, with cooling water at 22°C, are shown in Fig. 5-39. Details of the thermal response of the HER chamber with a copper cooling bar are given in Section 5.2.4.

In addition to the synchrotron radiation heating, we must also consider the heat loads from HOM losses. These were estimated in Section 4.3.1.6 to be 400 and 800 kW for the HER and LER, respectively. This power will be distributed roughly uniformly around the ring, leading to an additional 1.8-W/cm thermal load for the HER and twice this for the LER. For the LER, this value is only about 20% of the peak synchrotron radiation load in the arcs, so HOM heating represents only a small additional burden for the cooling subsystem. In the HER, the additional heat load from HOM losses is only about 4% of that from synchrotron radiation.

Tables 5-16a and 5-16b summarize both the nominal-current and maximum-allowable-current cases for the LER and HER, respectively, compared with values from PEP. We see that the wall temperature is below the original design specification for the PEP chamber in all cases.

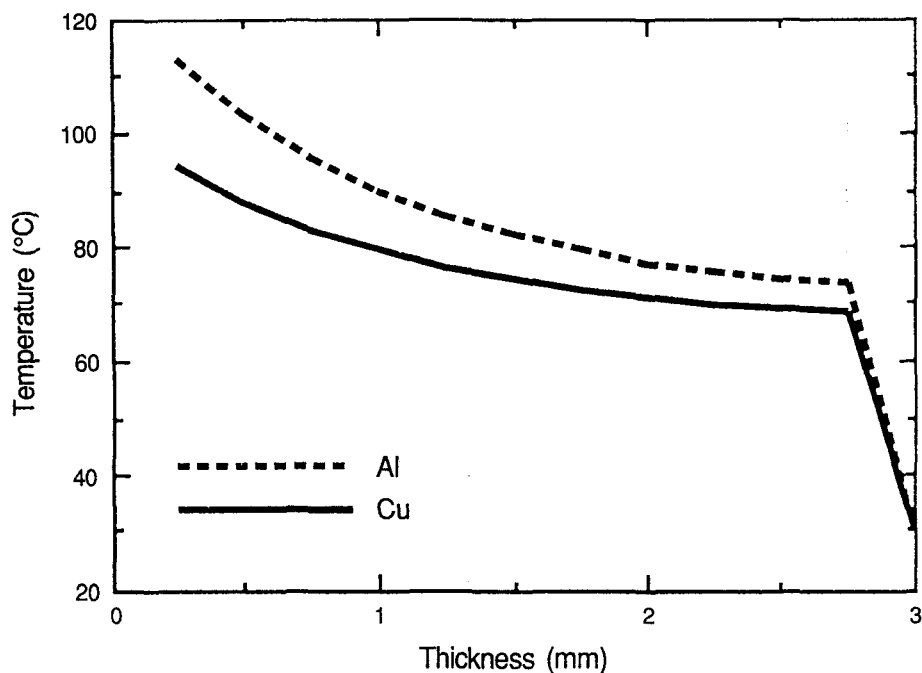


Fig. 5-39. Temperature distribution for the vacuum chamber wall, computed by a thermal relaxation code. Results for aluminum and copper are quite similar.

Table 5-16a. Comparison of radiation loads and heat fluxes in PEP and the B Factory LER. For PEP an aluminum chamber is used; the B Factory estimates assume a copper chamber and are computed as described by Alexandrov et al. [1990].

Parameter	PEP	B Factory	
		LER nominal current	LER maximum current
Magnetic radius [m]	165.00	30.56	30.56
Bending magnet field [T]	0.3033	0.3395	0.3395
Energy [GeV]	15.00	3.11	3.11
Current [mA]	200	2140	3000
Power [kW]	5,436	580	812
Peak chamber wall lin. flux [W cm^{-1}]	52	21	30
Beam divergence, 2θ [mrad]	0.07	0.33	0.33
Min. tangential distance, d [m]	4.06	1.35	1.35
Max. angle of incidence, α [mrad]	24.62	44.3	44.3
Minimum beam height [mm]	0.277	0.445	0.445
Linear flux on masks at 90° [W cm^{-1}]	2130	681	955
Wall heat load [kW cm^{-2}]	1.89	0.68	0.95
Heat load on masks at 90° [kW cm^{-2}]	77	15	21
Wall thickness [cm]	0.92	1.0	1.0
ΔT across wall [$^\circ\text{C}$]	61	12	21
ΔT , chamber to water [$^\circ\text{C}$]	35	14	24
ΔT , total, inner wall to water [$^\circ\text{C}$]	96	26	45
Inlet water temperature [$^\circ\text{C}$]	22	22	22
Water temperature rise [$^\circ\text{C}$]	9	2	4

Table 5-16b. Comparison of radiation loads and heat fluxes in PEP and the B Factory HER. For PEP an aluminum chamber is used; the B Factory estimates assume a copper chamber. Temperatures are illustrative for a planar geometry. Actual values appear in Fig. 5-57.

Parameter	PEP	B Factory	
		HER nominal current	HER maximum current
Magnetic radius [m]	165.00	165.00	165.00
Bending magnet field [T]	0.3033	0.1820	0.1820
Energy [GeV]	15.00	9.00	9.00
Current [mA]	200	1500	3000
Power [kW]	5,436	5,424	10,567
Chamber wall linear flux [W cm^{-1}]	52.43	50.9	101.92
Beam divergence, 2θ [mrad]	0.07	0.11	0.11
Tangential distance, d [m]	4.06	3.85	3.85
Angle of incidence, α [mrad]	24.62	23.4	23.4
Beam height [mm]	0.277	0.44	0.44
Linear flux on masks at 90° [W cm^{-1}]	2130	2125	4140
Wall heat load [kW cm^{-2}]	1.89	1.14	2.29
Wall thickness [cm]	0.92	1.0 ^a	1.0 ^a
ΔT across wall [$^\circ\text{C}$]	61	36	73
ΔT , chamber to water [$^\circ\text{C}$]	35	31	62
ΔT , total, inner wall to water [$^\circ\text{C}$]	96	67	135
Inlet water temperature [$^\circ\text{C}$]	22	22	22
Water temperature rise [$^\circ\text{C}$]	9	6	13

^aConsists of 0.5 cm Cu-Sn wall, plus 0.5 cm pure Cu cooling bar.

5.2.3.2 Gas Desorption. The gas load in electron storage rings arises from two processes: thermal outgassing and synchrotron-radiation-induced photodesorption. Thermal outgassing is common to all vacuum systems and occurs in the absence of synchrotron radiation; that is, it contributes mainly to the base pressure of a ring in the absence of circulating beam. In all high-energy electron storage rings, thermal outgassing is negligible when compared with the dynamic gas load from photodesorption. Thus, the dynamic gas load due to synchrotron radiation actually determines the operating pressure of the ring.

To estimate the desorption rate, we follow the approach of Gröbner et al. [1983]. After taking the spectrum of the synchrotron radiation photons into account, we can express the photon flux in the spectral interval $(0, x)$ in the form

$$\dot{N}(x) = \frac{\sqrt{3} r_e F(x) E I}{e \hbar c} \quad (5-13)$$

where

$$x = \frac{\epsilon}{\epsilon_{\text{crit}}} = \frac{\epsilon}{\left(\frac{3\hbar c}{2}\right)\left(\frac{\gamma^3}{\rho}\right)} \quad (5-14)$$

with ϵ being the photon energy and ϵ_{crit} being the critical energy of the radiation in the dipoles. In practical units,

$$\epsilon_{\text{crit}} = 2.218 \frac{E^3}{\rho} \text{ [keV]} \quad (5-15)$$

$F(x)$ is the integral over the modified Bessel function:

$$F(x) = \int_0^x \int_u^\infty K_{5/3}(y) dy du \quad (5-16)$$

For large values of x , $F(x) \rightarrow 5.23$. After rearranging terms and inserting appropriate values for the constants, we obtain a photon production rate of

$$\dot{N} = 8.08 \times 10^{20} E I \text{ [photons/s]} \quad (5-17)$$

where E is in GeV and I is in A.

At the design current of 1.48 A, the synchrotron radiation load in the HER is 1.1×10^{22} photons per second, or a maximum of 1.0×10^{19} photons/s/m. As the height of the synchrotron radiation fan in the HER is only 0.44 mm, the maximum photon flux on

the walls is 2.4×10^{18} photons/cm²/s. For later use in computing the photon dose on the chamber walls, we note that in the HER 1 A hr corresponds to 2.5×10^{22} photons/m.

Gas molecules are desorbed from the walls in proportion to the photon flux; that is, the number of molecules produced per incident photon is

$$\dot{N}_{\text{Mol}} = 8.08 \times 10^{20} E I \eta \text{ [molecules/s]} \quad (5-18)$$

The ideal gas law relates the number of molecules to a gas load in Torr·L via a conversion factor of 3×10^{-20} Torr·L/molecule. In these units, the effective gas load due to photodesorption is found to be

$$Q_{\text{gas}} = 24.2 E I \eta \text{ [Torr·L/s]} \quad (5-19)$$

The photodesorption coefficient η is a property of the chamber that depends on several factors:

- Chamber material
- Material fabrication and preparation
- Amount of prior exposure to radiation
- Photon angle of incidence
- Photon energy

In light of these complexities, it seems better to regard η as an effective engineering value that accounts for the differential illumination of the chamber walls by both direct (beam-produced) and diffusely scattered (secondary) photons, rather than considering the photodesorption coefficient to be a fundamental material property. Using a single value of η in Eq. 5-19 yields only a rough estimate of the actual dynamic gas load but one that is nonetheless useful in setting the scale of the engineering task, as well as in choosing the chamber material.

5.2.3.3 Choice of Chamber Material. Experimental measurements of η [Gröbner et al., 1983; Foerster et al., 1990; Ueda et al., 1990; Mathewson et al. 1990] for well-exposed samples of aluminum, stainless steel, and oxygen-free, high-conductivity copper indicate minimum values of η ranging from less than 2×10^{-6} for copper and stainless steel up to 2×10^{-5} for aluminum. Although the gas-scattering lifetimes in storage rings with lower critical photon energies than the B Factory suggest that aluminum chambers may eventually develop an effective $\eta \approx 10^{-6}$, we believe a more reliable design procedure is to adopt copper or stainless steel as the chamber material, despite their higher cost per kilogram. Because the data of Ueda et al. indicate that clean, machined, oxygen-free copper can attain $\eta = 2 \times 10^{-6}$, we have chosen this value as the design basis. Such a low photodesorption coefficient allows us to design the B Factory vacuum chamber with a conventional elliptical shape instead of being driven to adopt an antechamber design that is more difficult and expensive to fabricate. The apparent cost disadvantage of copper or stainless steel vis-à-vis aluminum is more than offset by the relative simplicity of the

chamber shape, by the reduction in the amount of pumping needed, and by the shortening of the vacuum commissioning time.

As shown below, copper and stainless steel also have the considerable advantage of being fully self-shielding and thus can protect the magnets and other hardware from radiation damage caused by the hard component of the synchrotron radiation. The need for lead shielding, which would be required to accompany an aluminum chamber, is completely eliminated. In that the chamber walls are subjected to very high thermal loads, copper, with its excellent thermal conductivity, appears to be the preferred material, despite the paucity of experience in building large copper vacuum chambers.

For a copper chamber with a desorption coefficient of $\eta = 2 \times 10^{-6}$, the dynamic gas load is

$$Q_{\text{gas}} = 4.84 \times 10^{-5} EI \text{ [Torr}\cdot\text{L/s]} \quad (5-20)$$

In Tables 5-17a and 5-17b, we use Eq. 5-20 to estimate the gas loads in the low- and high-energy rings. Maintaining a pressure of 10 nTorr in the LER requires a total

Table 5-17a. Comparison of vacuum loads and pumping speed requirements in PEP and the B Factory LER.

Parameter	PEP	B Factory	
		LER nominal current	LER maximum current
Gas load [Torr·L s ⁻¹ mA ⁻¹]	5.5×10^{-6}	1.5×10^{-7}	1.5×10^{-7}
Total photon gas load [Torr·L s ⁻¹]	1.1×10^{-3}	3.2×10^{-4}	4.5×10^{-4}
Assumed desorption coefficient, η	1.5×10^{-5}	2.0×10^{-6}	2.0×10^{-6}
Photon gas load [Torr·L s ⁻¹ m ⁻¹]	1.05×10^{-6}	1.68×10^{-6}	2.35×10^{-6}
Base pressure required [nTorr]	10	10	10
Distributed pumping [L m ⁻¹ s ⁻¹]	105	—	—
Total distributed pumping [L s ⁻¹]	109,080	—	—
Thermal desorption coef. [Torr·L cm ⁻²]	1.0×10^{-11}	1.0×10^{-11}	1.0×10^{-11}
Calculated wall temperature [°C]	123	89	115
Thermal desorption [Torr·L °C ⁻¹ cm ⁻²]	8.2×10^{-11}	5.9×10^{-11}	7.7×10^{-11}
Total perimeter of ring [m]	2200	2200	2200
Calculated thermal load [Torr·L m ⁻¹]	2.5×10^{-7}	1.8×10^{-7}	2.3×10^{-7}
Total calculated thermal load [Torr·L]	5.4×10^{-4}	3.9×10^{-4}	5.1×10^{-4}
Total gas load [Torr·L]	1.6×10^{-3}	7.1×10^{-4}	9.6×10^{-4}
Total pumping [L s ⁻¹]	163,182	95,660	95,660

Table 5-17b. Comparison of vacuum loads and pumping speed requirements in PEP and the B Factory HER.

Parameter	PEP	B Factory	
		HER nominal current	HER maximum current
Gas load [Torr·L s ⁻¹ mA ⁻¹]	5.5×10^{-6}	4.3×10^{-7}	4.3×10^{-7}
Total photon gas load [Torr·L s ⁻¹]	1.1×10^{-3}	6.6×10^{-4}	1.3×10^{-3}
Assumed desorption coefficient, η	1.5×10^{-5}	2.0×10^{-6}	2.0×10^{-6}
Photon gas load [Torr·L s ⁻¹ m ⁻¹]	1.1×10^{-6}	6.3×10^{-7}	1.2×10^{-6}
Base pressure required [nTorr]	10	5	10
Distributed pumping [L m ⁻¹ s ⁻¹]	105	125	125
Total distributed pumping [L s ⁻¹]	109,080	1.3×10^5	1.3×10^5
Thermal desorption coef. [Torr·L cm ⁻²]	1.0×10^{-11}	1.0×10^{-11}	1.0×10^{-11}
Calculated wall temperature [°C]	130	67	109
Thermal desorption [Torr·L °C ⁻¹ cm ⁻²]	8.7×10^{-11}	4.5×10^{-11}	6.0×10^{-11}
Total perimeter of ring [m]	2200	2200	2200
Calculated thermal load [Torr·L m ⁻¹]	2.6×10^{-7}	1.3×10^{-7}	1.8×10^{-7}
Total calculated thermal load [Torr·L]	5.7×10^{-4}	2.9×10^{-4}	3.9×10^{-4}
Total gas load [Torr·L]	1.7×10^{-3}	5.3×10^{-3}	1.0×10^{-2}
Total pumping [L s ⁻¹]	166,219	1.7×10^5	1.7×10^5

pumping speed of ~64,000 L/s at the maximum allowable current of 3 A. To put this requirement into perspective, we note that it is less than 1/15 of the pumping speed (per meter of ring circumference) being installed on the ALS ring at LBL [*1-2 GeV Synchrotron Radiation Source Conceptual Design Report*, 1986]. The HER requires about three times the pumping speed of the LER, which is still much less than the ALS specifications.

5.2.3.4 Evaluation of Gas Load Profile. To proceed beyond the estimates of the previous section to an engineering design of the vacuum system, it is necessary to specify the actual distribution of radiation along the arc, $\dot{N}(s)$, taking into account the presence of short straight sections between the dipoles. Following the prescription of Alexandrov et al. [1990], we computed the distributions shown in Figs. 5-40a and 5-40b for the HER and LER, respectively.

Naively, one might think to compute the distributed gas load in the arcs by applying Eq. 5-19 directly to the profiles given in Fig. 5-40, with the adopted value of η . This procedure would, however, neglect the strong variation in η with material exposure.

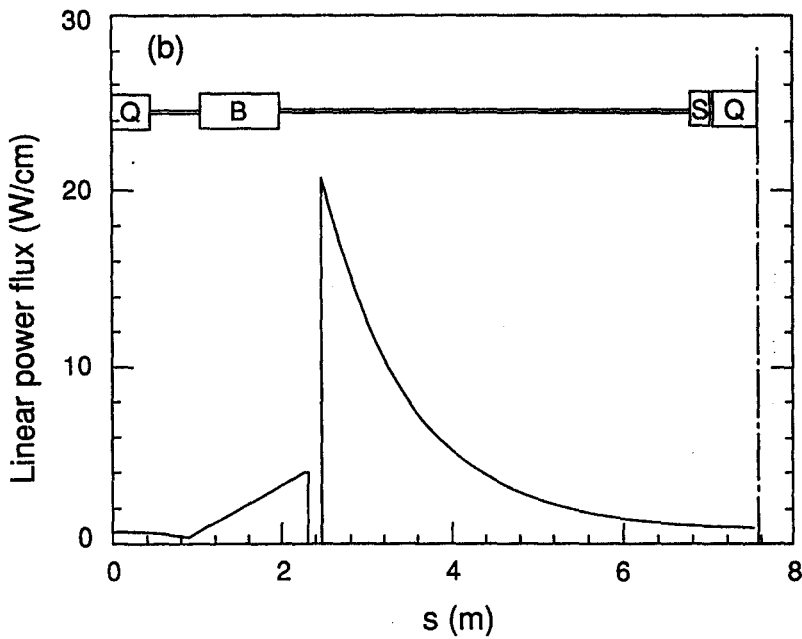
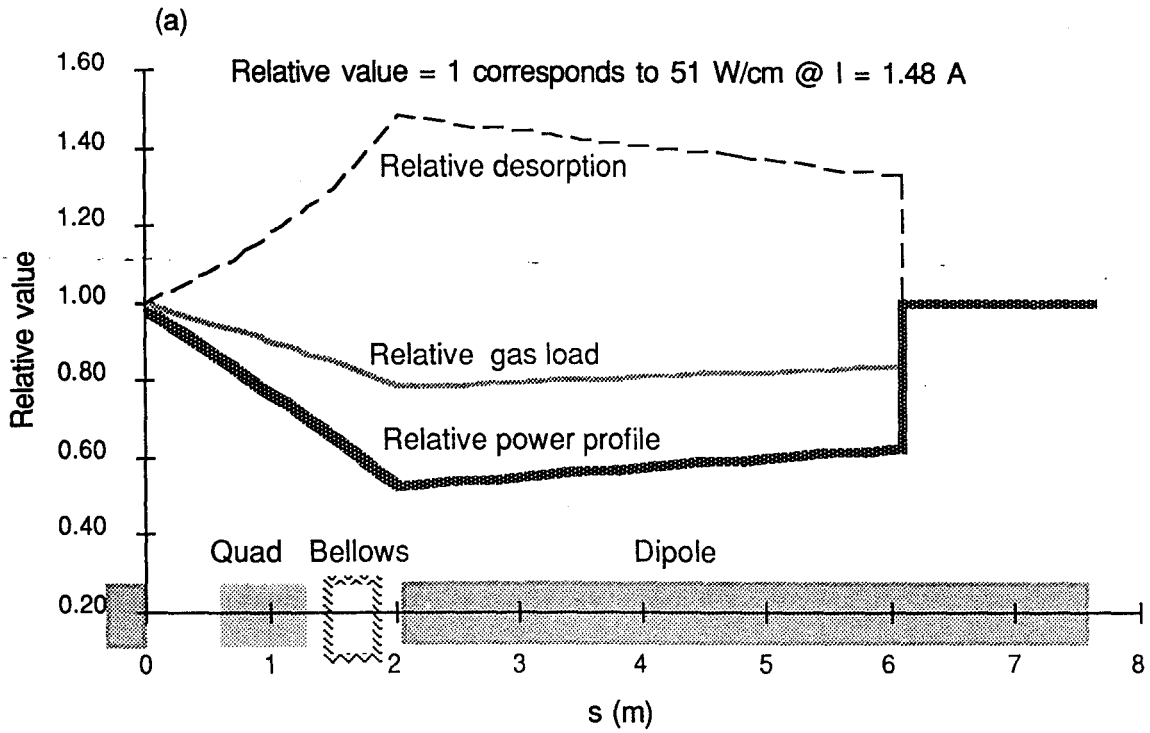


Fig. 5-40. (a) Radiation distribution along a half-cell of the HER arc at the design current of 1.48 A. (b) Radiation distribution along a half-cell of the LER arc at the design current of 2.14 A.

From a typical set of data, such as that reproduced in Fig. 5-41 [Foerster et al., 1990], we observe that, for large exposures, η tends to follow a power law dependence on dose; that is,

$$\eta \propto (It + t_0)^{-p} \tag{5-21}$$

where I is the beam current, t is the exposure time, and p is between 0.4 and 0.7 (depending on choice of material and preparation). The constant t_0 is chosen to yield the correct initial value of η . Assuming that $p = 0.6$ for copper, we can compute a local value of $\eta(s)$ along the beamline. Then the gas load at a position s is given by a generalization of Eq. 5-19:

$$Q_{\text{gas}}(s) = \eta(s)\dot{N}(s) \tag{5-22}$$

The effect of the differential exposure of the chamber is to level the gas load along the beamline and thus to require more pumping capacity than would be needed if Q_{gas} were a

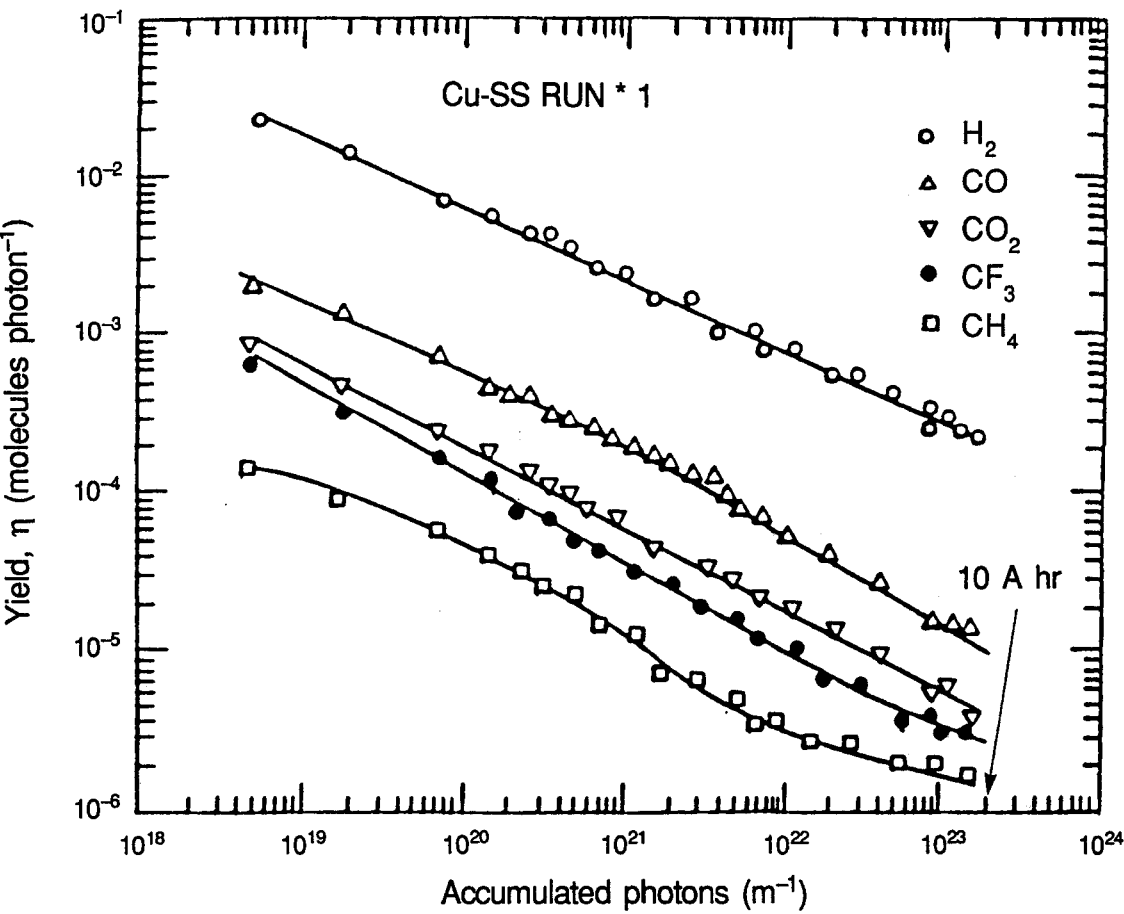


Fig. 5-41. Data from Foerster et al. [1990] showing the variation of the photodesorption coefficient η with material exposure.

constant multiple of the photon flux. By assuming that the value of η is 2×10^{-6} where $\dot{N}(s)$ assumes its *maximum* value, we compute the gas load along a half cell of the arc as shown in Fig. 5-42. This gas profile becomes a system specification for the vacuum engineer.

Using the data of Ueda et al. [1990], we have estimated that for copper with an initial desorption rate of 10^{-3} molecules/photon, the sections of the chamber will reach $\eta \approx 2 \times 10^{-6}$ after a photon exposure of about 100 A hr. Based on the pumping scheme described in Section 5.2.4 (which provides 125 L/s/m distributed in the dipoles), the vacuum-conditioning scenario can be computed as a function of the initial photodesorption rate. Such calculations are displayed in Fig. 5-43.

5.2.3.5 Validation Test Program. The data of Ueda et al., on which the above calculations are based, were taken with a photon beam incident normal to the surface and having $\epsilon_{\text{crit}} = 4.5$ keV. In the HER, the critical energy is nearly 10 keV and photons will strike the surface at a shallow angle. The data of Foerster et al. [1990], though taken at a shallow angle, used a photon beam of $\epsilon_{\text{crit}} = 500$ eV and were not generally carried to such large exposures as to actually observe photodesorption coefficients as low as 10^{-6} . Therefore, our design assumption of $\eta \approx 2 \times 10^{-6}$ must be viewed as an extrapolation of the experimental database. Although designing the pumping system to handle a photodesorption coefficient of roughly 2×10^{-6} from a copper chamber represents a reasonable extrapolation of that database, it is nonetheless prudent to carry out a series of validation experiments using the specific alloys, photon incidence angles, and preparation procedures that will actually be employed in the design. Fortunately, appropriate photon sources with which to make measurements on short sections of test chamber are available at several laboratories in the U.S., Europe, and Japan. We plan an experimental validation program as an essential component of the engineering design process. The experimental setup will follow closely the procedures that have been described extensively in the literature [Foerster et al., 1990; Ueda et al., 1990; Gröbner et al., 1983; Mathewson et al., 1990]. The primary quantity to be measured will be the specific pressure rise $\Delta P/I$, which is of most direct relevance to the engineering design of the B Factory vacuum system.

5.2.3.6 Shielding of Synchrotron Radiation. The HER of the B Factory, running at an energy of 9 GeV, generates the synchrotron radiation spectrum shown in Fig. 5-44a. It has been contemplated that the B Factory HER might also run at 12 GeV (though this is not part of the present design), in which case it would produce the harder spectrum shown in Fig. 5-44b. Depending upon beam pipe material and thickness, some of this radiation may escape and deposit energy in the surrounding material. This was originally pointed out during the design of PEP [Nelson et al., 1975] and subsequently verified by measurements both at PEP and at PETRA. Of most concern to the B Factory is magnet insulation, although other nearby materials, such as wire insulation and cooling-water hoses, are even more sensitive to radiation.

Radiation damage to magnets depends strongly on the type of material used in the potting compound. PEP magnets, which will be used for the HER of the B Factory, are insulated with an epoxy whose composition is given in Table 5-18. It is estimated that

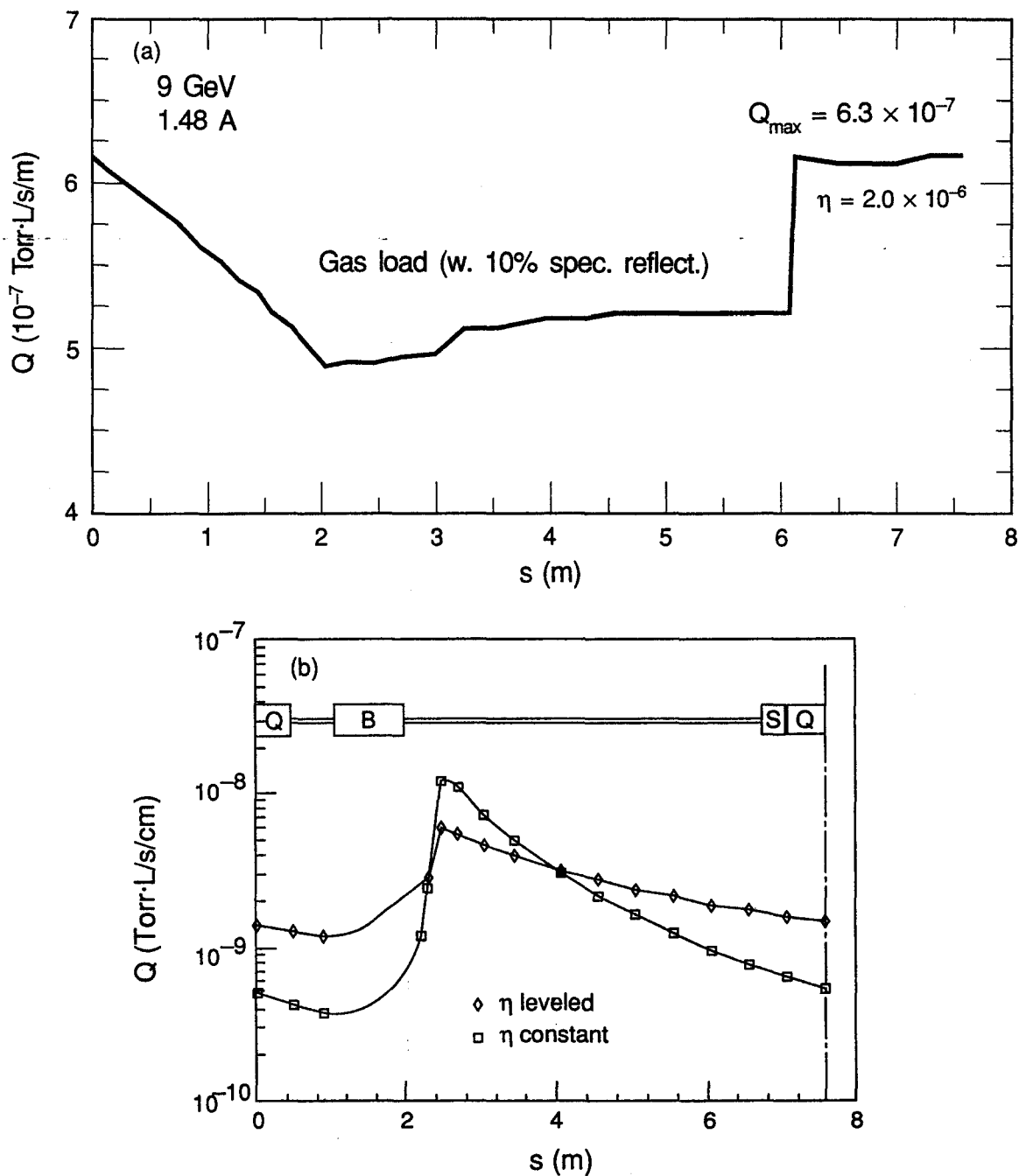


Fig. 5-42. (a) Gas load along a half cell of the arc in the HER at the design current of 1.48 A. The desorption coefficient was assumed to scale with the power profile and was normalized such that $\eta = 2 \times 10^{-6}$ molecules/photon at the location of maximum power. A contribution of 10% from reflected photons was included in the estimate of the gas load. (b) Gas load along an arc in the LER for two assumptions regarding the desorption coefficient: (i) constant value of $\eta = 2 \times 10^{-6}$ molecules/photon (squares), and (ii) "leveled" photodesorption accounting for the variation in exposure along the arc (diamonds). In the latter case, $\eta = 1 \times 10^{-6}$ at the peak power density.

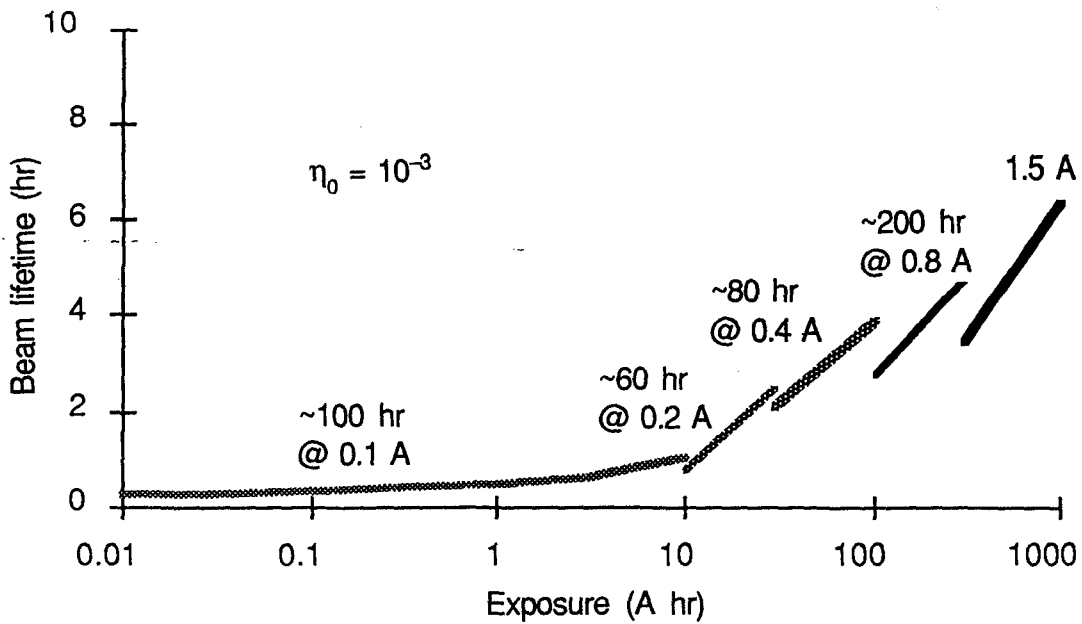


Fig. 5-43. Calculated beam lifetime in the HER as a function of exposure during initial commissioning of the collider.

this epoxy compound should tolerate doses of the order of 10^{10} rads without degradation of its properties. However, the exact damage threshold is not known, so we rely upon other sources to set a criterion. CERN used 3×10^9 rads as the dose criterion for the LEP magnets [CERN 85-02, 1985]. They note that using fiberglass insulation tape gives a factor of ten higher tolerance to radiation damage (up to the 10^{10} -rad region). To be conservative, we have elected to use 3×10^9 rads as a criterion for the B Factory magnet insulation. Stated another way, the criterion will be 10^8 rads/yr; this should give a magnet lifetime of 30 years or more. (Here, we ignore doses already received by the magnets from PEP running to date. These exposures are small compared with the doses expected from B Factory operation.)

To estimate the annual radiation dose, we take 1.48 A for a 6000-hr operating year, giving roughly 9000 A·hr/yr. The radiation strikes the wall at a 23-mrad angle of incidence. The absorbed dose D must remain below 4.9×10^{-19} rads/electron, corresponding to 10^8 rads/yr. This criterion is used when considering output from the program EGS4, which gives results *per incident electron*, either in terms of fluences, energy deposited, or rads (using appropriate conversion factors). Various user codes have been developed specifically to study such problems. These codes all generate the synchrotron radiation spectrum both analytically and from a sampling algorithm, with scoring done in the regions outside the beam pipe. A fluence-to-dose conversion, using the surface dose numbers of Rogers [1984], modified for the SLAC epoxy compound, is performed within the code each time the epoxy region is entered. Details of the calculations can be found in Jenkins et al. [1990].

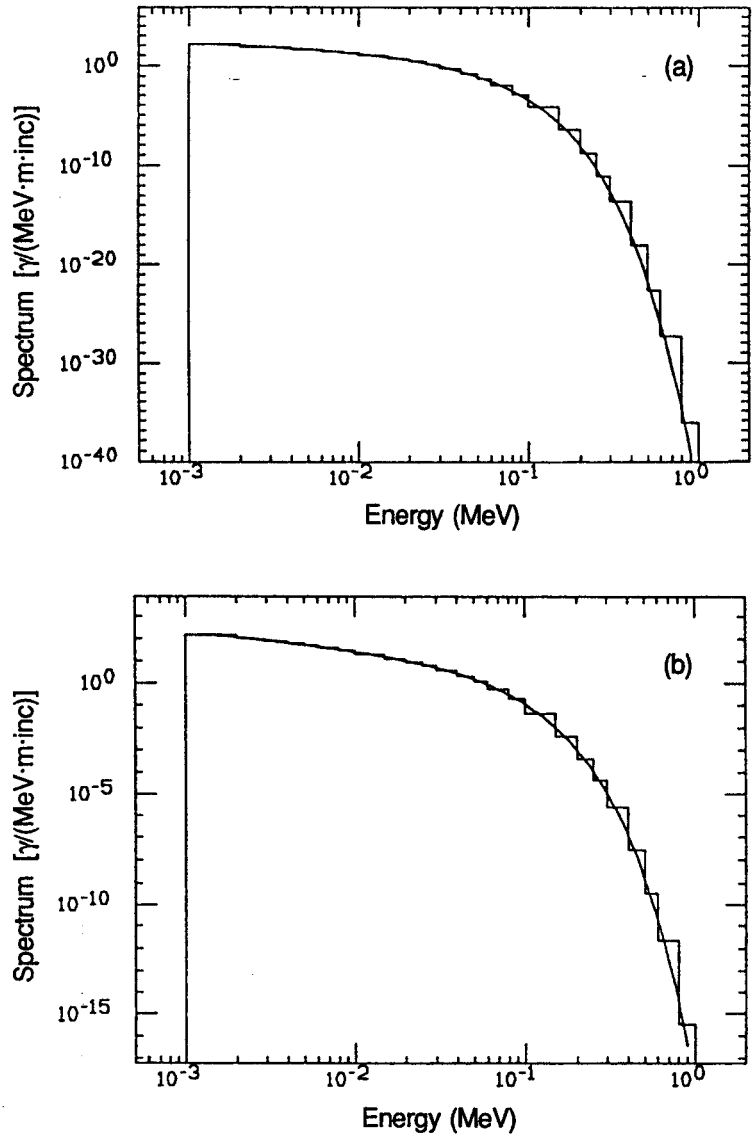


Fig. 5-44. Synchrotron radiation spectrum produced by (a) 9-GeV operation at PEP and (b) 12-GeV operation at PEP; solid line, analytic; histogram, EGS sampled spectrum.

Table 5-18. Chemical makeup and mass of the epoxy used in the PEP magnets.

Material	Composition	Mass ^a (g)
DER 332—epichlorohydrin + bisphenol A	$C_{21}H_{24}O_4$	851
DER 732—epichlorohydrin-polyglycol	$(C_3H_6O)_n C_6H_{10}O_3$	1049
NMA—nadid methyl anhydride	$C_9H_8O_3$	1832
Aluminum oxide	Al_2O_3	4252

^aWeight fractions of the elements in the epoxy (for EGS4 purposes) are hydrogen, 2.6%; oxygen, 38.4%; carbon, 30.7%; aluminum, 28.3%.

Calculations are based on the configuration of the present PEP ring, assuming a maximum energy of 12 GeV and a nominal energy of 9 GeV. Only the HER is considered; synchrotron radiation will not penetrate the beam pipe of the LER, which runs at 3.1 GeV.

For this study, a new EGS4 data set was generated, including photon energies down to 1 keV and electron energies down to 10 keV (521-keV total energy). For most calculations, however, the actual cutoffs used were 10 keV (photons) and 1 MeV (electrons). Upper energies for both electrons and photons were 10 MeV, which is adequate because the spectra are essentially zero above a few MeV for both the 9- and 12-GeV electron energies. The photon spectrum was sampled uniformly within an energy range from $0.1\epsilon_{crit}$ to $10\epsilon_{crit}$. A weight was carried along with each photon (and its progeny) for scoring purposes. The final results were later normalized per incident beam electron.

The B Factory beam pipe geometry is similar to the existing PEP beam pipe, with some minor differences. First, the vacuum pumping channel is separate from the beam channel for most of the ring (the arc regions), with horizontal slots joining the two channels. Details of the chamber configuration are described in Section 5.2.4. The chamber material assumed for these calculations is copper; stainless steel would give essentially the same results.

A curve of the maximum dose versus copper thickness for an octagonal chamber cross section is shown in Fig. 5-45. Points for a chamber with a rectangular cross section are included for comparison. This figure shows the benefits of an octagonal geometry over a rectangular geometry, given the same wall thickness.

To summarize the results of our calculations, for an octagonal beam pipe, 0.7 cm of copper is needed at the point of maximum dose for 12-GeV operation to reach our dose criterion. For 9-GeV operation, an octagonal copper pipe need only be 0.25 cm thick. Clearly, with a copper chamber, a beam pipe 0.5 cm thick (required for structural reasons) is more than adequate, as shown in Fig. 5-46. By way of comparison, an

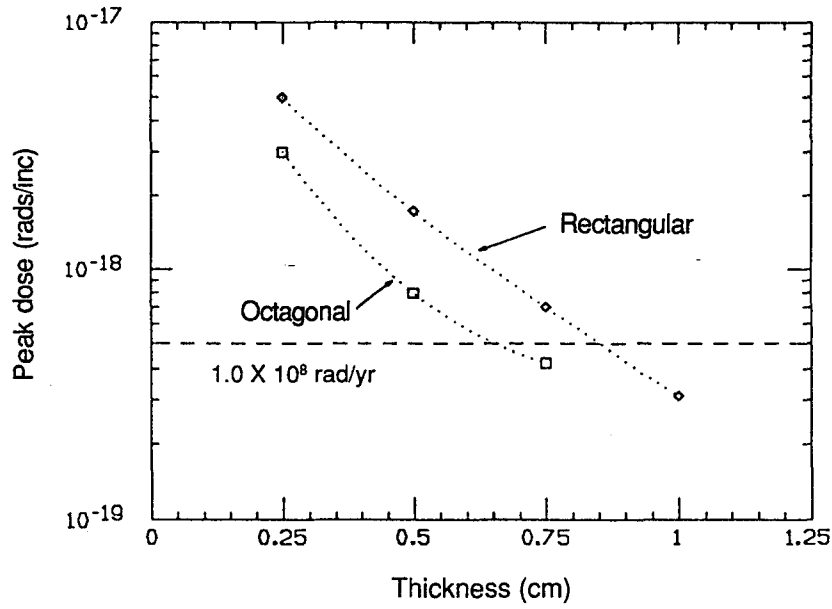


Fig. 5-45. Radiation dose to the magnet windings through a 0.5-cm-thick copper beam pipe having an octagonal cross section and a vacuum channel, computed for 12-GeV operation. A rectangular chamber of the same wall thickness does not provide as effective shielding. The dose corresponding to 1×10^8 rads/yr is shown by the dashed line.

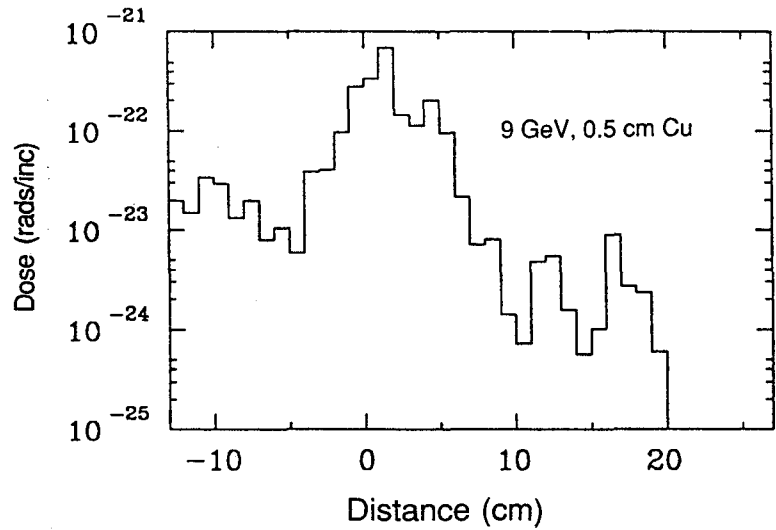


Fig. 5-46. Radiation dose to the magnet windings through a 0.5-cm-thick copper beam pipe with no liner, computed for 9-GeV operation. The radiation dose limit corresponds to 5×10^{-19} rads/inc electron, well above the calculated values.

octagonal aluminum chamber that is 0.5 cm thick would also need 0.3 cm of lead on the outside to reach the same dose criterion for 12-GeV operation. Even for 9-GeV operation, an aluminum pipe would require a lead liner. The liner would be needed only at the point of maximum dose (top and bottom of the beam pipe); the rest of the pipe could be thinner.

5.2.4 HER Vacuum Components

The configuration of the HER is shown schematically in Fig. 5-47. Figure 5-48 shows both the high- and low-energy rings in the tunnel, with the LER positioned above the HER. The overall circumference of the rings is 2200 m, and their geometries have been adjusted to fit in the existing PEP tunnel, as described in Section 4.1.

The vacuum system for the HER is designed to handle the large gas loads anticipated from photon-induced gas desorption and to carry away the large amount of power deposited on the outer chamber wall by the synchrotron radiation. The pressure requirements—quoted as N_2 -equivalent values—were described in Section 5.2.3.

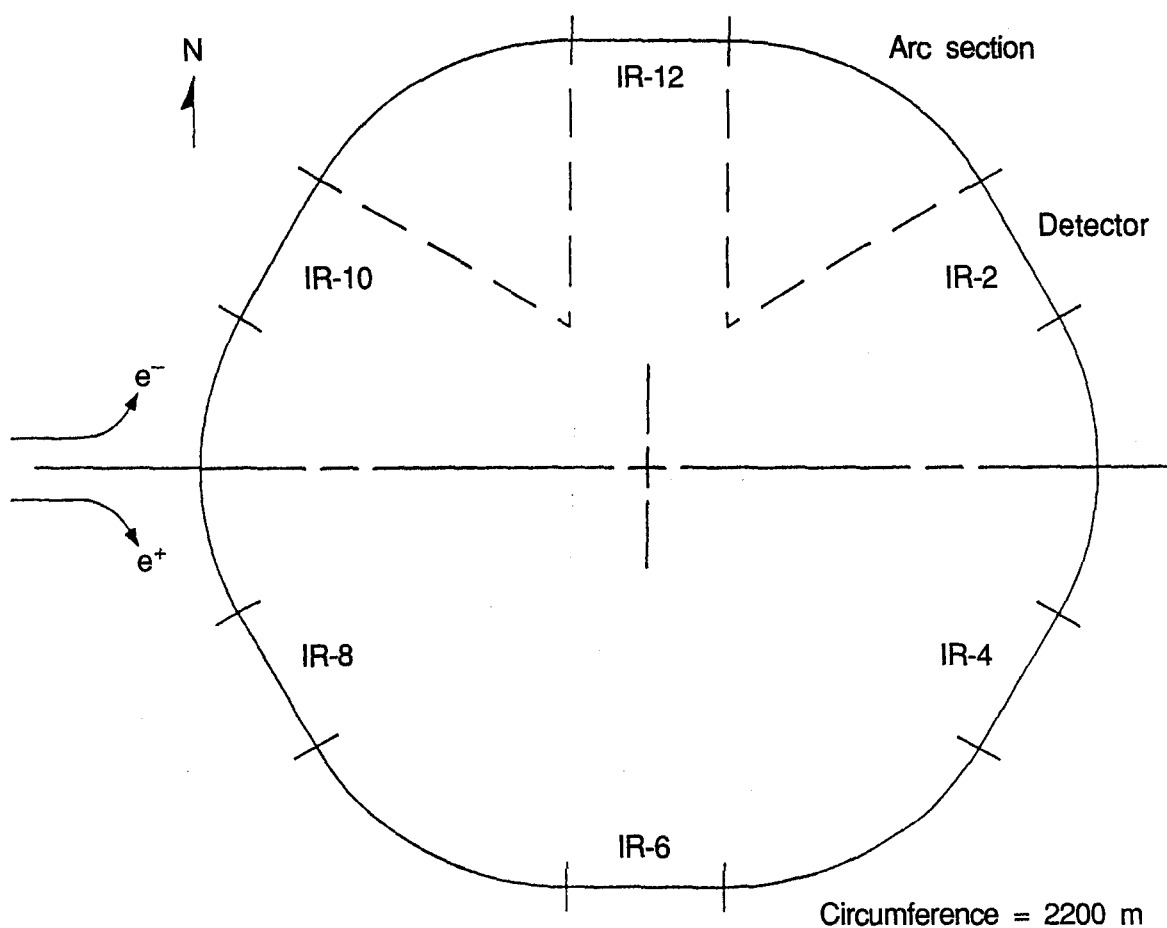


Fig. 5-47. Schematic of the B Factory storage ring layouts.

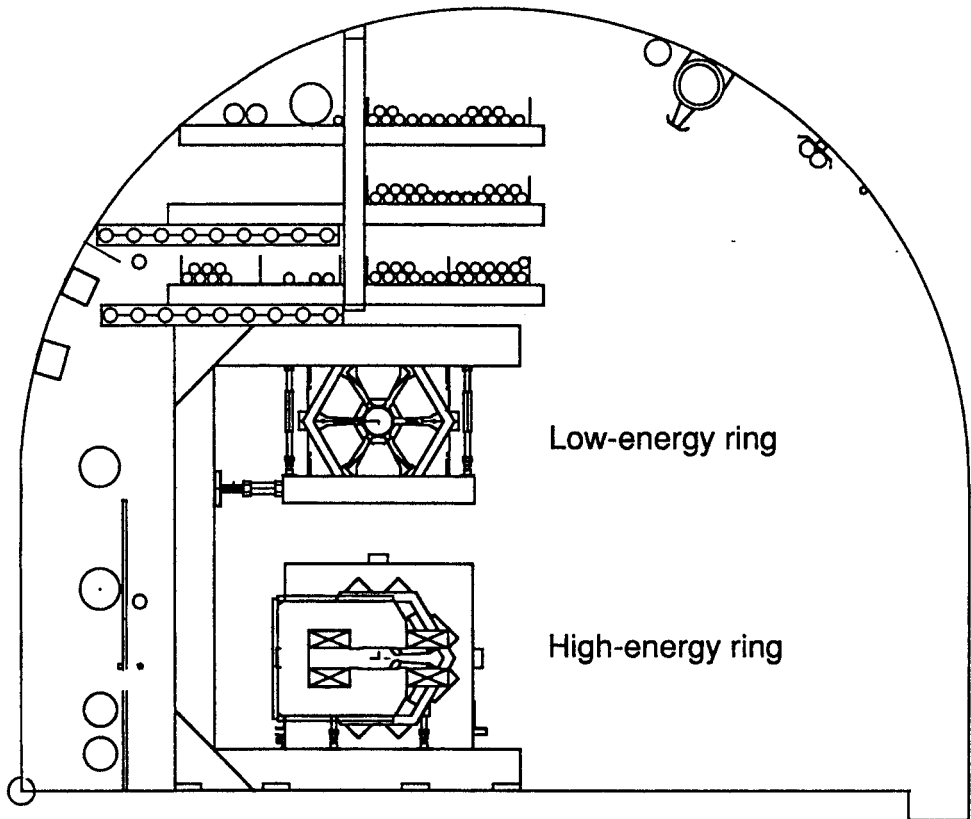


Fig. 5-48. Cross section of the PEP tunnel, showing the arrangement of the high- and low-energy rings of the B Factory.

The HER, illustrated in Fig. 5-49, contains 40 empty FODO cells grouped in 5 straight sections (the remaining straight section houses the interaction region) and 96 regular FODO cells in the arcs. As discussed above, copper was chosen for the vacuum chamber in the arcs because of its low photon-induced gas desorption coefficient, its high thermal conductivity, and its large absorption coefficient (which obviates the need for adding lead shielding). Vacuum chambers in the straight sections will be fabricated from stainless steel.

5.2.4.1 Arc Sections. Each arc section consists of 4 dispersion-suppressor cells of length 16.013 m and 12 regular cells of length 15.125 m, giving an overall arc length of 245.6 m. All-metal isolation valves are located at each end of the arc sections. The magnet arrangement in each of the regular cells consists of a defocusing quadrupole with sextupole, a dipole, a focusing quadrupole with sextupole, and finally a second dipole. The cell vacuum chamber will be constructed of extruded copper in four sections to facilitate fabrication and assembly in the PEP tunnel. Chamber sections are joined at the ends with 8-in., stainless-steel Conflat flanges; a bellows section is located in the vicinity of the focusing quadrupole.

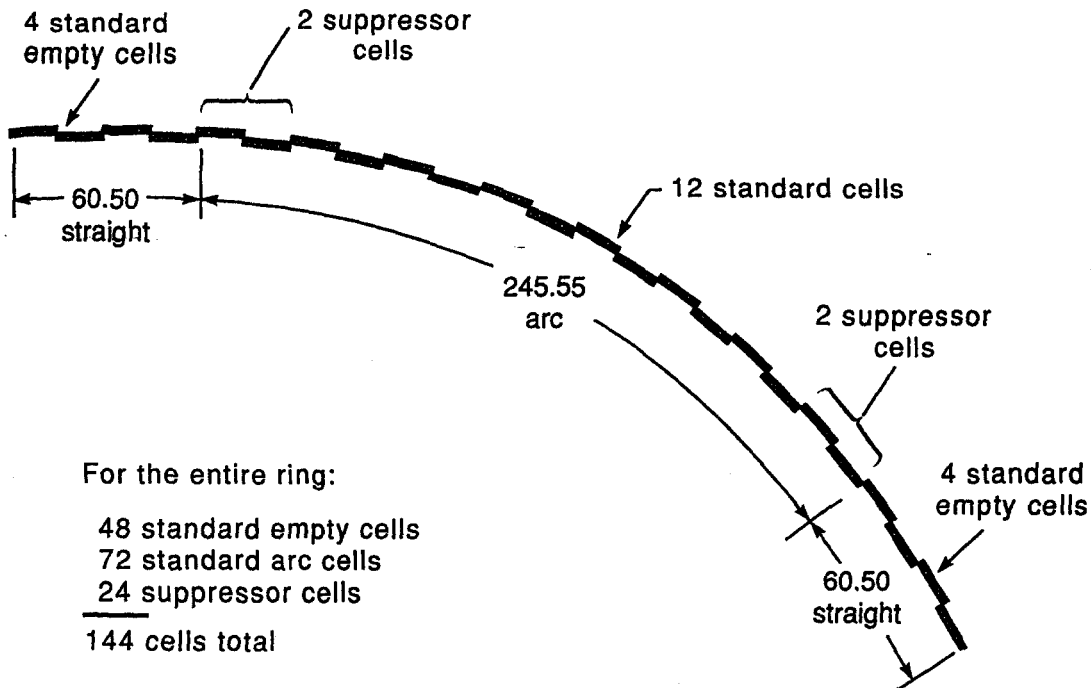


Fig. 5-49. Schematic of one sextant of the B Factory HER.

Cross sections of the vacuum chamber at the dipoles and quadrupoles are shown in Figs. 5-50 and 5-51, respectively. The beam tube of octagonal cross section is 100 mm wide (OD) by 60 mm high (OD), with a uniform wall thickness of 5 mm. The pumping channel for the distributed ion pumping has an inner size of 61 mm wide by 50 mm high. Slots in the septum between chambers are designed to provide a conductance of about 500 L/s/m. Both the beam tube and the pumping channel will be fabricated from a copper alloy having 2% tin (to maintain stiffness following an 800°C furnace braze). A cooling bar located on the outer wall of the beam tube carries away the heat produced by synchrotron radiation hitting the chamber wall. The bar will be fabricated from an oxygen-free copper alloy having a thermal conductivity of 93% International Annealed Copper Standard. Each of the quadrupoles in the arc cells has a pair of distributed ion pumps in stainless-steel housings, one located below and one to the side of the beam tube. The pumping slots between the beam tube and stainless-steel housing are arranged similarly to those in the dipoles. Lumped ion pumps are provided at each of the quadrupole spaces, as shown in Fig. 5-52; pressure gauges and pump-down connections are also located there.

5.2.4.2 Straight Sections. A standard cell in the straight sections is 15.125 m in length (as in the arcs) but contains no dipoles. The vacuum pipe is a 10-cm-diameter, stainless-steel tube of circular cross section, sized to clear the 100-mm bore of the quadrupole magnets. To produce an average pressure of less than 3 nTorr in the straight sections, lumped sputter-ion pumps rated at 230 L/s will be installed with a spacing of approximately 8 m. The pump size and spacing were calculated on the basis of a thermal

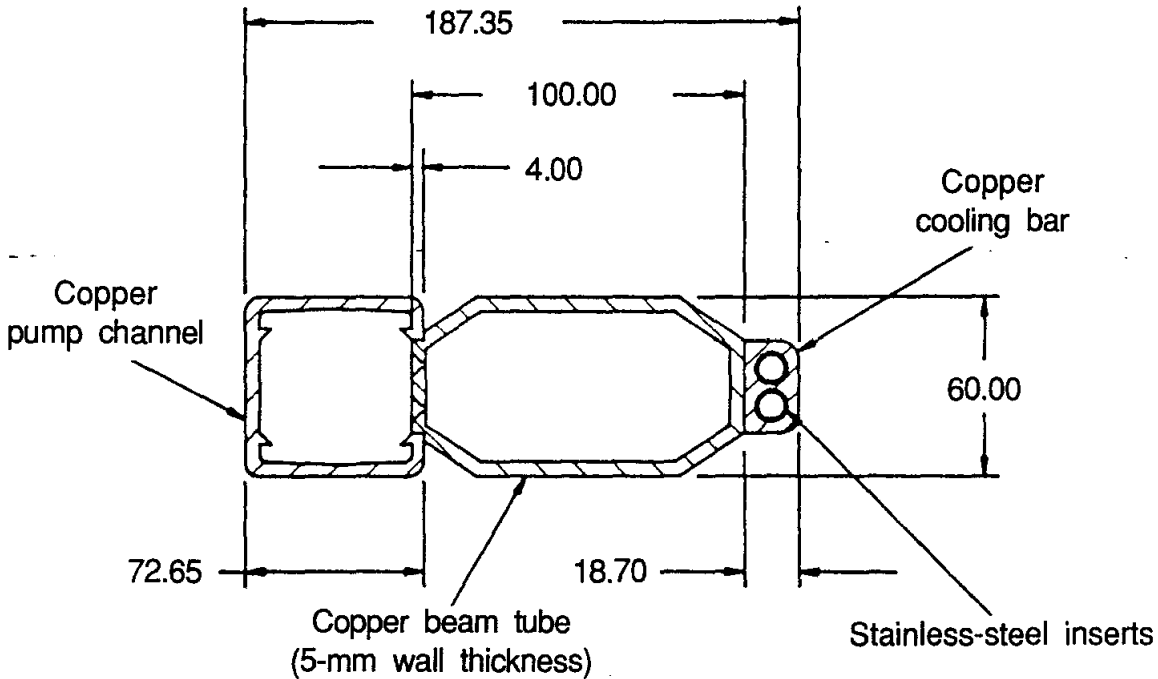


Fig. 5-50 Vacuum chamber cross section at a dipole; dimensions are in millimeters.

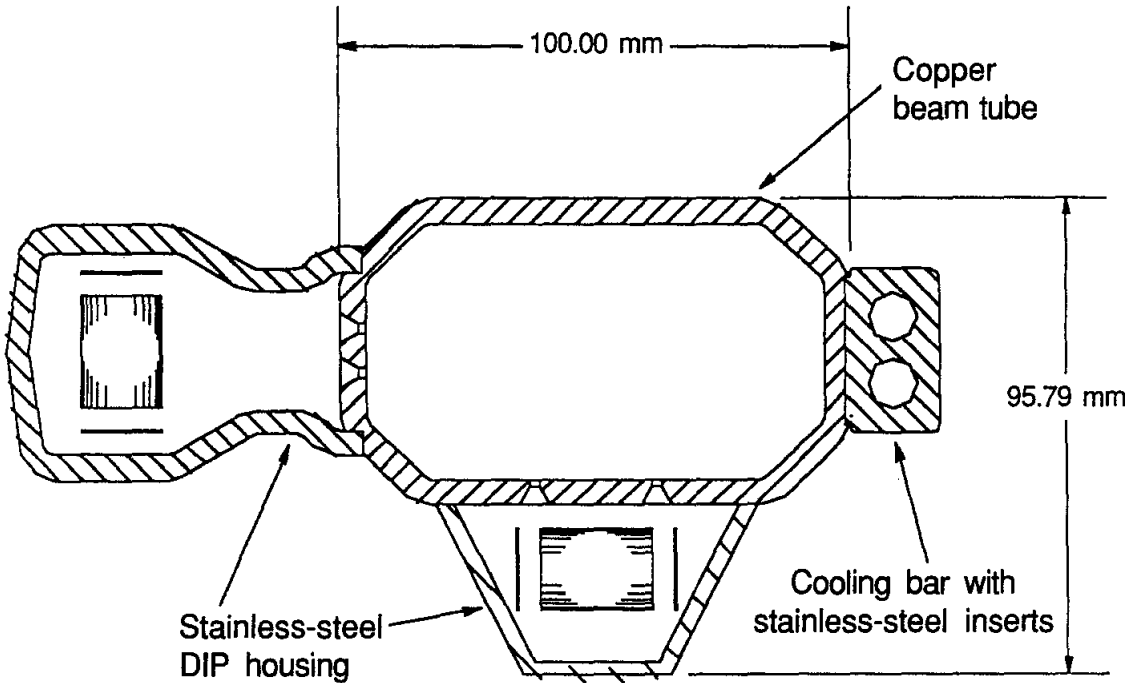


Fig. 5-51. Vacuum chamber cross section at a quadrupole (DIP, distributed ion pump).

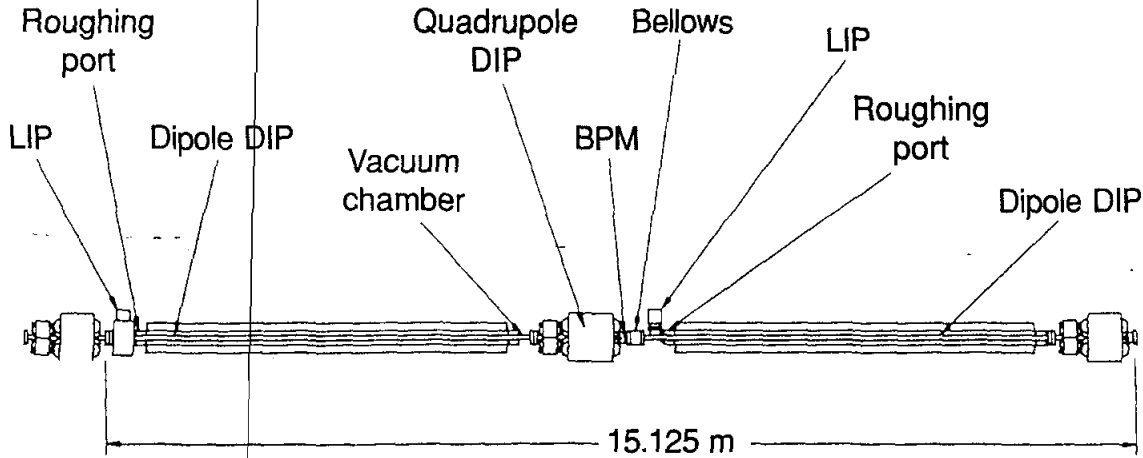


Fig. 5-52. Illustration showing locations of lumped ion pumps (LIPs) in the HER arc cells.

outgassing rate of 1×10^{-11} Torr·L cm⁻² s⁻¹ and a required base pressure in the beam tube of 0.5 nTorr. In situ baking compatibility to 300°C (150°C without opening the chambers) will be provided to reduce the initial outgassing rate and thus to allow for base pressures in the 0.1-nTorr range, should the need arise. A diagram of a straight-section cell is shown in Fig. 5-53.

5.2.4.3 Special Components. The bellows, which are designed to permit a 130°C thermal expansion, aid in the assembly of the ring. In their extended position (at room temperature), the bellows are 22.9 cm (9 in.) long, as shown in Fig. 5-54. They can compress about 4 cm at 150°C, the maximum temperature at which the ring can be baked in situ without disassembly. The inner bellows, which carries the surface currents, is fabricated as one piece, with formed convolutions in the plane of the beam tube flats; it has narrow slits at the intersecting corners to permit axial movement. To carry away the thermal load, a narrow slit at the outer beam tube wall permits synchrotron radiation to shine through to a thick-walled, water-cooled, copper absorber cantilevered from the bellows flanges.

Each arc cell contains a beam position monitor (BPM) located at, and anchored to, the defocusing quadrupole. The design chosen for the B Factory, shown in Fig. 5-55, follows the HERA design, with a few minor modifications. The housing will be accurately machined from a solid copper block. The block will have recesses on the end faces to index the beam tube ends for alignment during brazing. Cooling on both sides will preclude any temperature asymmetry.

Changes in cross section between the arc chambers of octagonal cross section and the straight section chambers of circular cross section are made with tapered transition elements. To keep the impedance contribution from the transitions low, the taper angle is less than 10°.

The system of supports for the arc cell vacuum chamber consists of a fixed support near the midpoint and flex supports at each end. Within the dipoles, slider supports are spaced at about 1.0-m intervals.

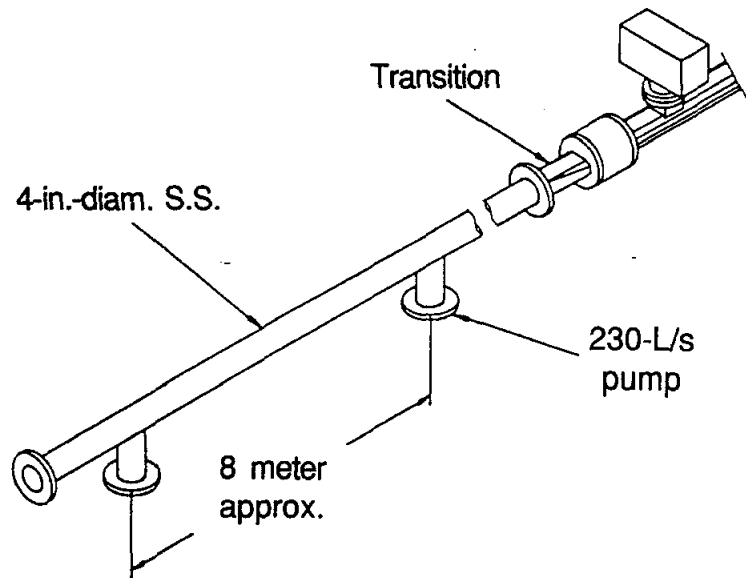


Fig. 5-53. Perspective view of straight-section vacuum chamber.

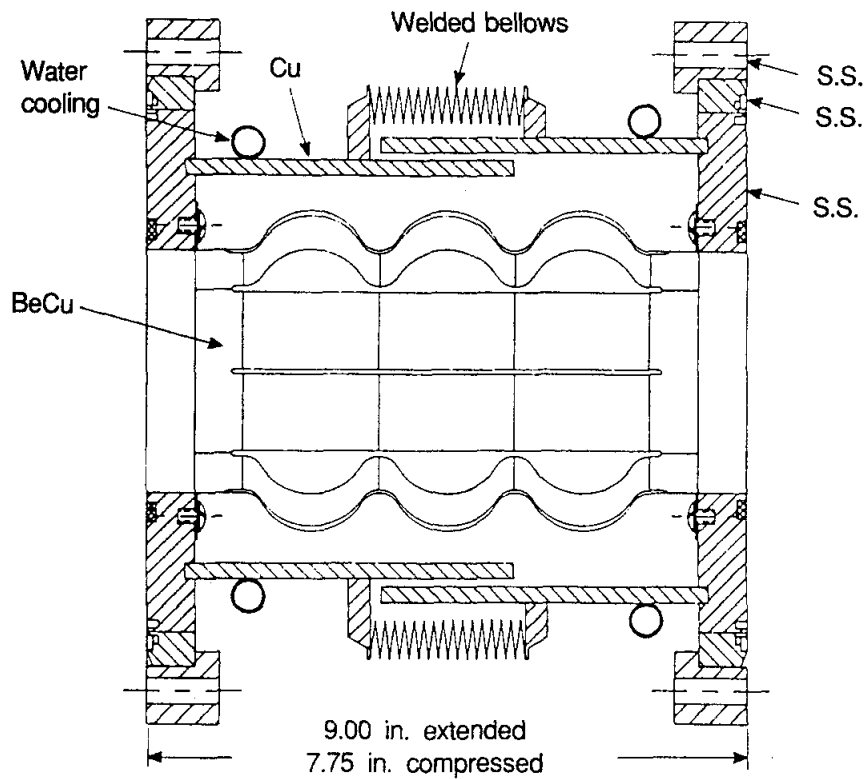


Fig. 5-54. Cross section of the vacuum chamber bellows.

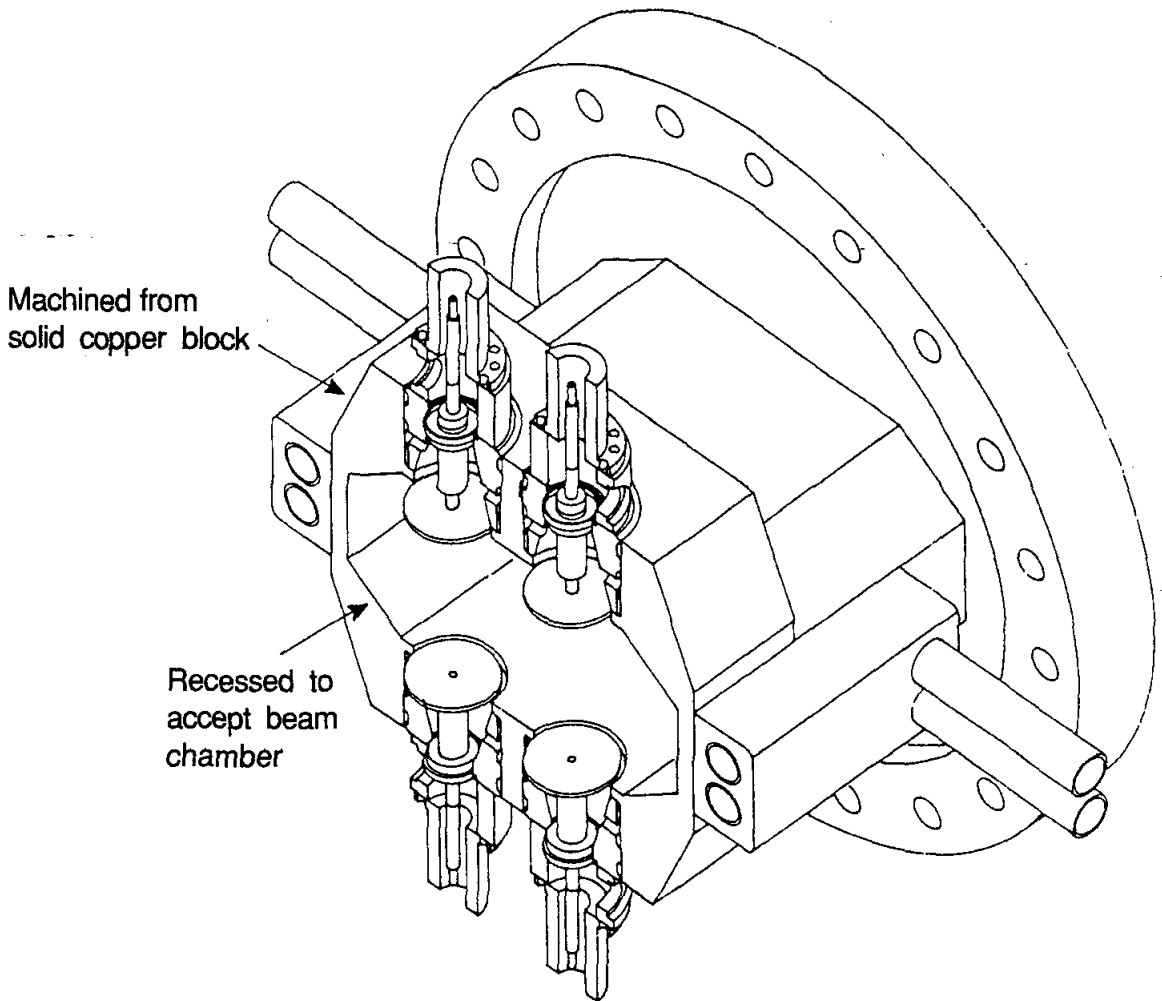


Fig. 5-55. Cutaway view of a B Factory beam position monitor.

5.2.4.4 Heat Load and Thermal Response. As described in Section 5.2.3, a maximum thermal load of 2.3 kW/cm^2 will be incident on a strip less than 0.5 mm high. A two-dimensional thermal analysis of the response of the vacuum chamber was performed using the output from EGS4 runs to specify the correct distribution of energy deposited along the interior walls of the beam tube. Examination of the EGS4 data shows that 99.9% of the energy is deposited locally at the radiation impact point. Figure 5-56 shows that the maximum temperature produced in the beam pipe wall is 160°C . In this calculation, the water in the cooling tubes enters at 30°C and flows with a velocity of 3 m/s . The two-dimensional stress analysis displayed in Fig. 5-57 shows a maximum thermal stress of 90 MPa , which exceeds the yield stress of the copper-tin alloy. We note that the major stress component occurs along the chamber length (perpendicular to the cross section), because in our calculation the thermal stress was not allowed to be

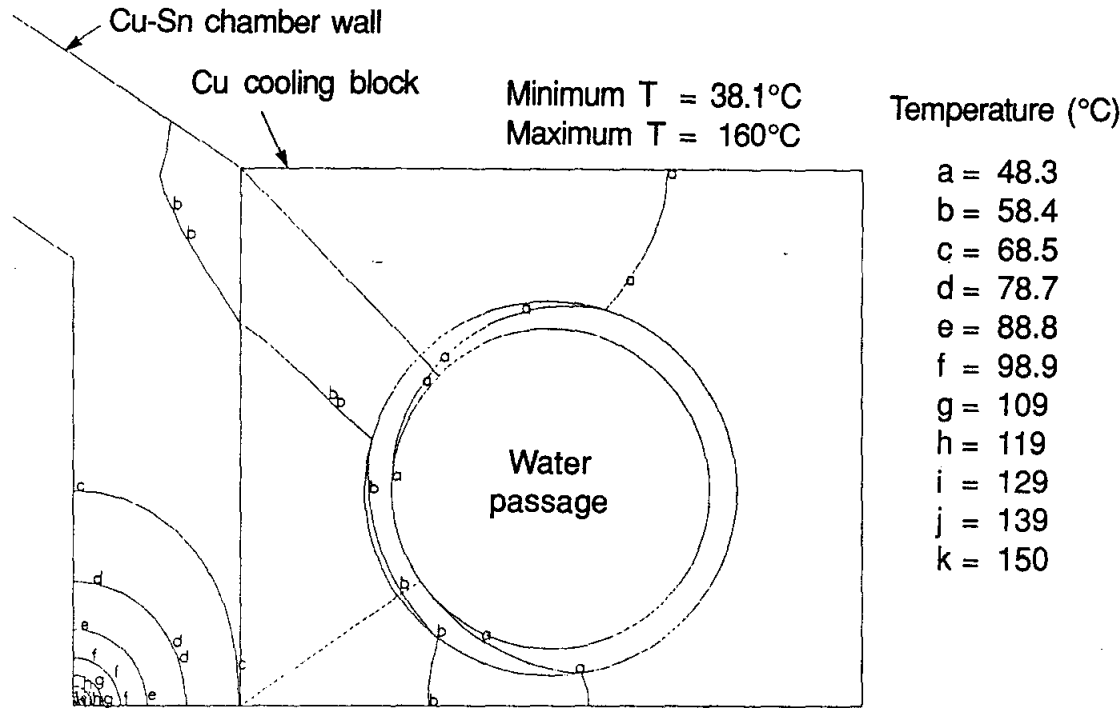


Fig. 5-56. Computed temperature distribution in the beam pipe wall and cooling bar of the B Factory HER.

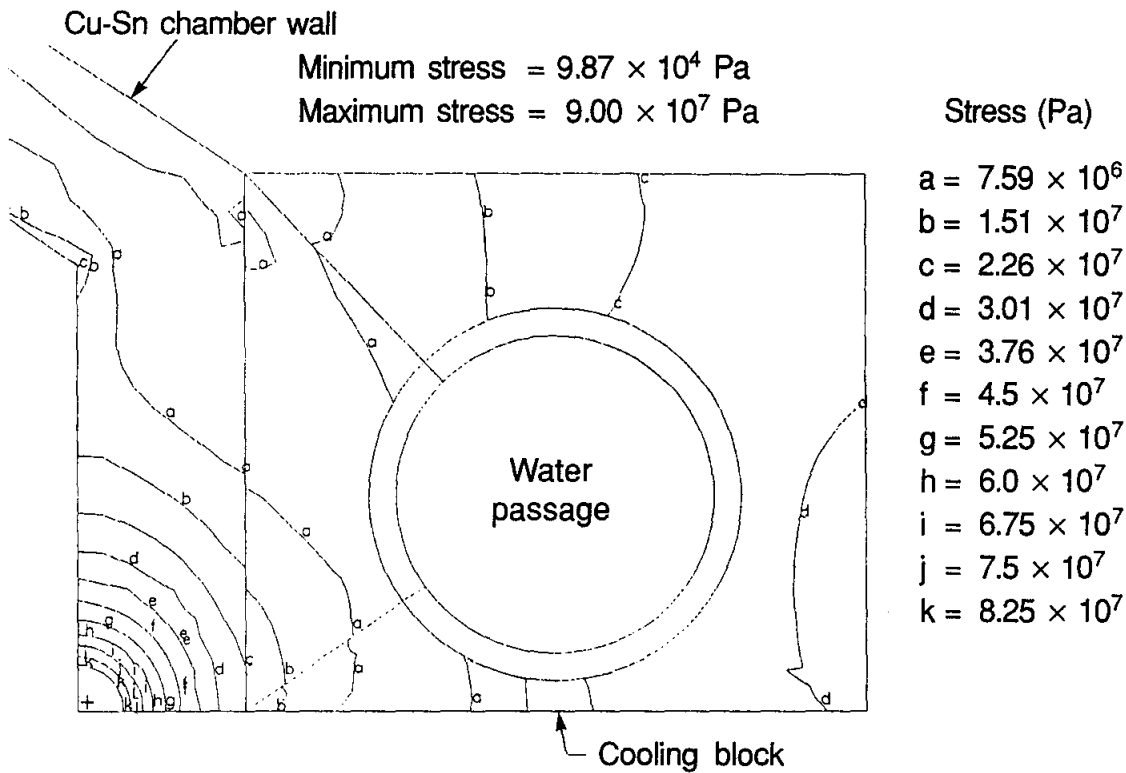


Fig. 5-57. Computed effective stress in the beam pipe wall and cooling bar of the B Factory HER.

relieved by expansion in that direction. Figure 5-58 shows that the maximum effective plastic strain is 0.1%. It is confined to the small area of synchrotron radiation impact and is not seen as a problem. Both these results were obtained using a two-dimensional plane-strain model with the thermal stress problem being started at the average steady-state cross section temperature. That is, the length was allowed to accommodate the average temperature of the cell because of the bellows. This calculation is overly conservative, since it does not account for the stress relief that will be obtained through bending. We therefore believe that the copper-tin alloy will actually have sufficient yield strength for the thermal load imposed by the radiation. Indeed, calculations done at CERN indicated that copper-tin alloy can tolerate more than twice the thermal stress to be encountered at the B Factory [Nakada, 1990].

A three-dimensional analysis is being made to evaluate the effects of bending. If the three-dimensional results also indicate that the material yields, a cyclic fatigue analysis will be made to determine if there is a structural problem. Examining the deflections of the structure in Fig. 5-59, we see that a maximum vertical deflection of 0.023 mm occurs in the horizontal flat faces of the beam tube, which is acceptable. Figure 5-60 shows the displaced shape, with vertical displacements multiplied by 100 for visibility.

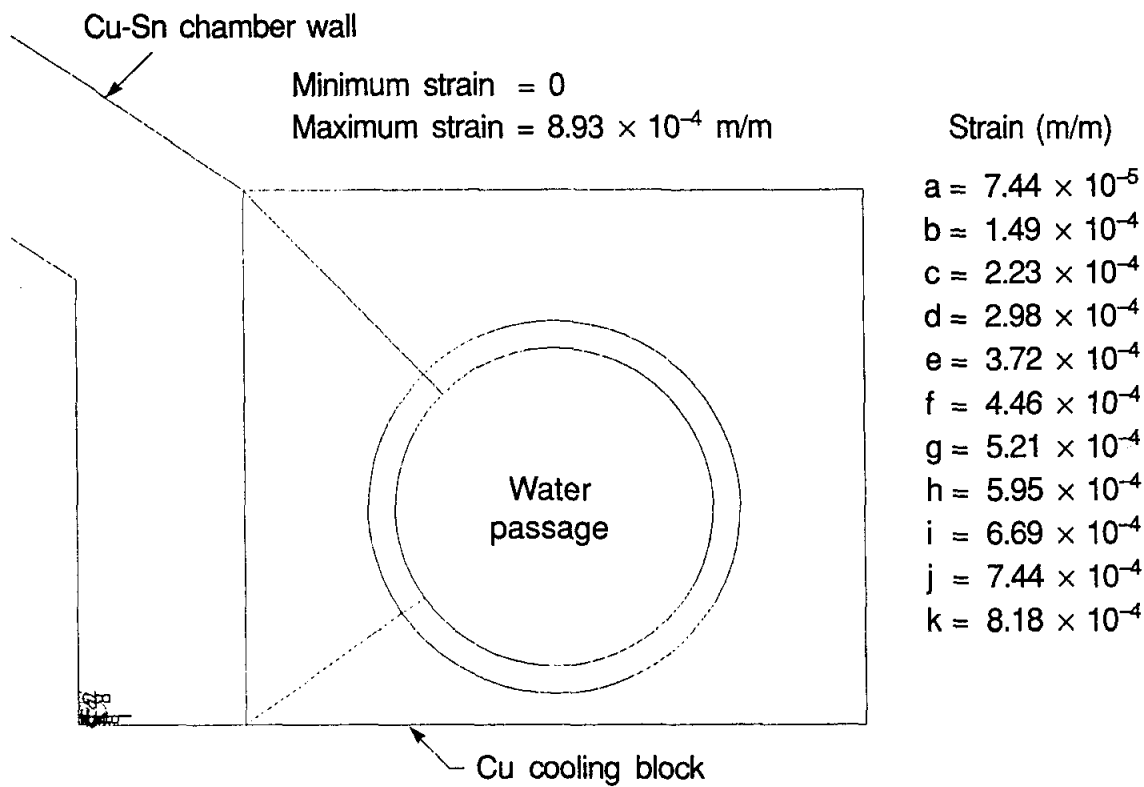


Fig. 5-58. Computed plastic strain in the beam pipe wall of the B Factory HER.

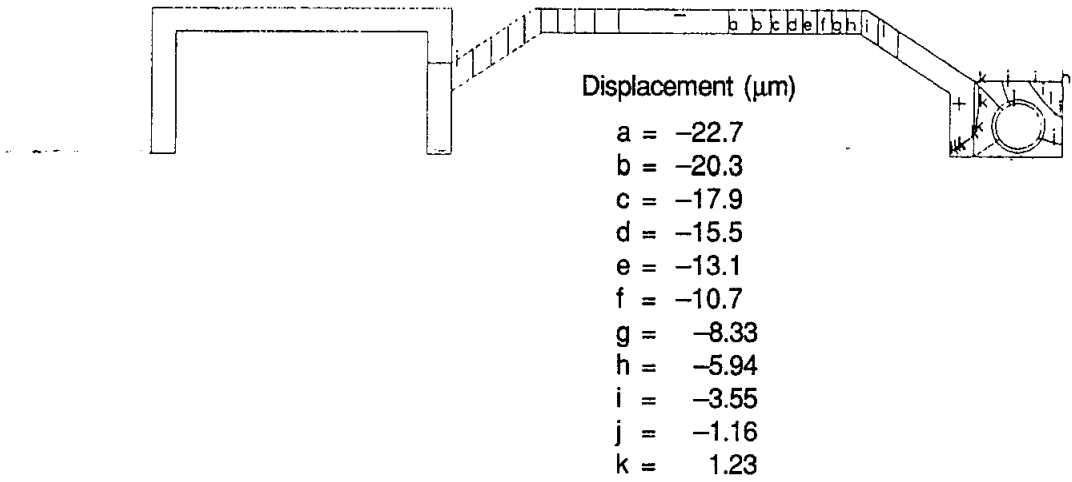


Fig. 5-59. Vertical deflections computed for the beam pipe wall and cooling bar of the HER, as a consequence of thermal stress.

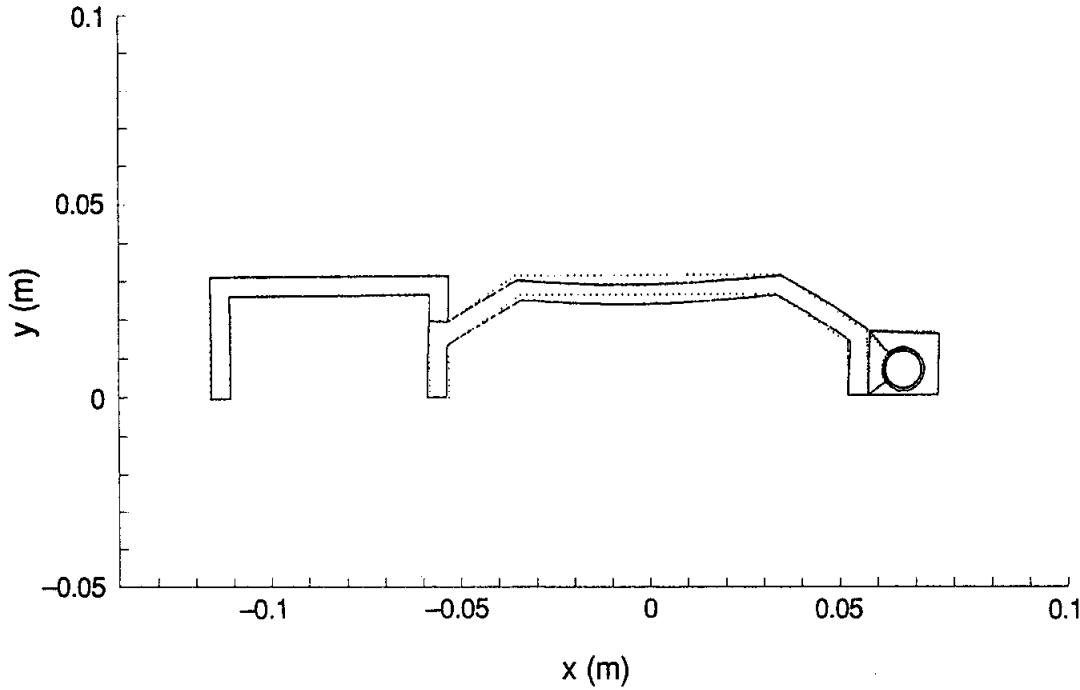


Fig. 5-60. Displaced shape computed for the beam pipe wall of the HER, as a consequence of thermal stress. The vertical scale is exaggerated by a factor of 100.

5.2.4.5 Vacuum Pumping Design. To satisfy the design criteria for adequate beam lifetime and low background rate, we chose to design the distributed pumping in the arcs to produce an average pressure of less than 5 nTorr at the nominal operating current of 1.48 A. The peak gas load corresponding to operation at the design luminosity has already been shown in Fig. 5-42.

We selected a design based entirely on sputter-ion pumps to handle this gas load. An inventory of pumping capacities for each pumping element in a typical cell is shown in Table 5-19. During 1.48-A operation, the desired average pressure (5 nTorr) can be maintained with distributed pumping of 125 L/s/m.

To achieve these pumping speeds, the distributed ion pumping in the dipoles was redesigned to operate in a 0.18-T field, about half of the 0.3-T field used normally in PEP. The anode diameter was maintained at 1.59 cm, but as seen in Fig. 5-61, an additional row has been added, increasing the number of anodes by about 50%, with a packing factor of about 90%. As mentioned, distributed ion pumping has also been included at the quadrupoles, located to one side of the beam tube and below, but not on the top, to preclude particles dropping into the beam chamber. Anode sizes for these pumps were scaled to fit into the very restrictive space available. The calculated pumping speed in the beam tube will be about 75 L/s/m from each of the stainless-steel housings shown in Fig. 5-62. However, the total pumping speeds for the defocusing and focusing quadrupoles will be different, owing to their differing magnetic lengths. To augment the distributed pumping, we have added 60-L/s lumped ion pumps in the spaces adjacent to each of the quadrupoles in the cells (see Fig. 5-52). Given the low conductance of the beam pipe, larger pumps would not improve system performance. In

Table 5-19. Available pumping in a typical cell.

2 dipole pumps at	800 L/s =	1600 L/s
1 quad pump at	110 L/s =	110 L/s
1 quad pump at	82 L/s =	82 L/s
2 LIP pumps at	60 L/s =	120 L/s
	Total =	1912 L/s
	or	125 L/s/m

For a gas load of 6.3×10^{-7} Torr·L/s/m,

$$P = 5.0 \text{ nTorr}$$

For a gas load of 1.26×10^{-6} Torr·L/s/m,

$$P = 10 \text{ nTorr}$$

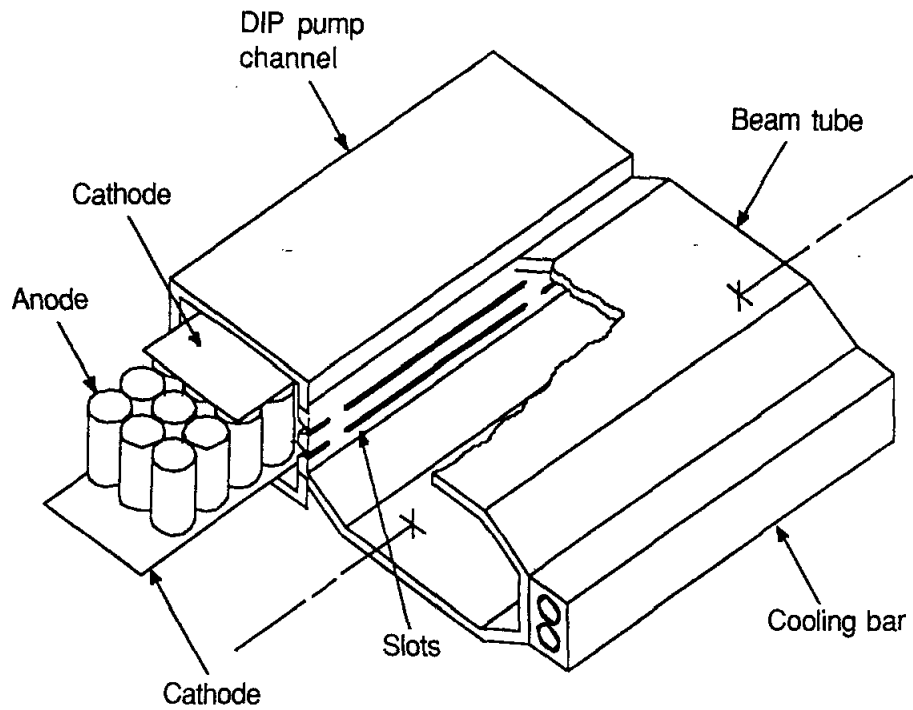


Fig. 5-61. Distributed ion pumping arrangement for the dipoles of the HER.

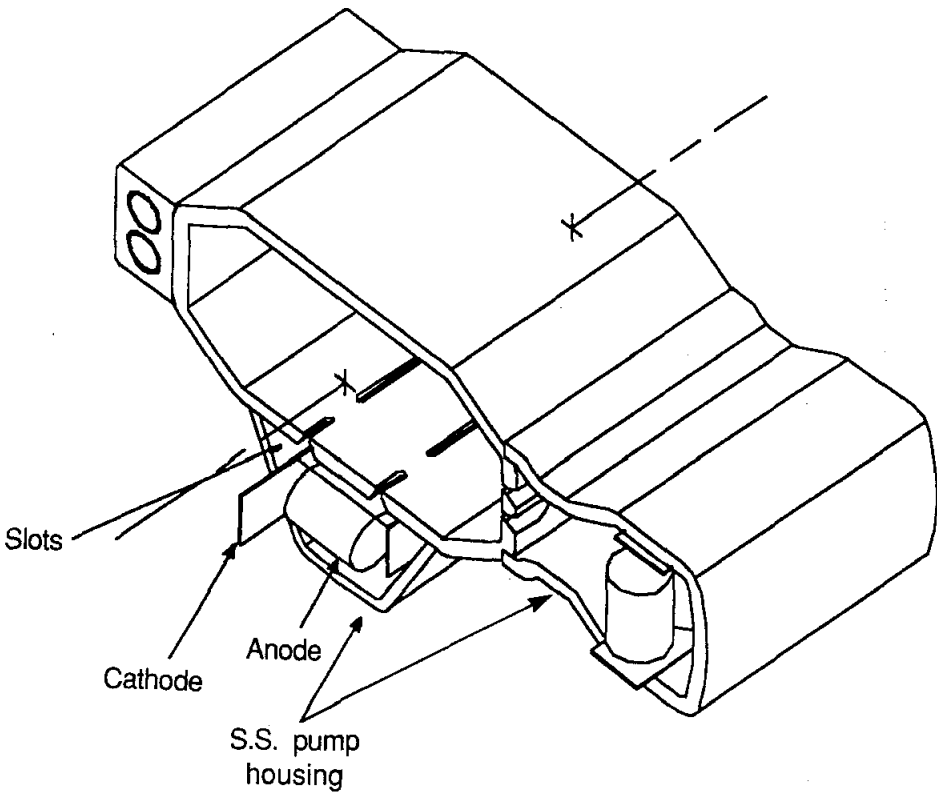


Fig. 5-62. Distributed ion pumping arrangement for the quadrupoles of the HER.

addition, the ports are designed to accommodate additional pumps, should the need arise. To keep the impedance contribution of the ports to a negligible level, they will be shielded with a perforated screen having longitudinal slots 10 cm in length.

The slots between the pumping chamber and beam tube are in rows, 9 cm long by about 0.2 cm wide, at a pitch of 10 cm, similar to the HERA machine; this gives a conductance of about 500 L/s/m. These slots contribute negligibly to the impedance.

The calculated pressure profile achieved with this configuration of pumps is shown in Fig. 5-63.

5.2.4.6 Fabrication. Several different fabrication methods will be utilized in the construction of the vacuum chambers for the HER. Vacuum chambers in the straight sections will be fabricated of stainless steel, using well-known and well-established welding methods to produce vacuum-tight assemblies. The copper vacuum chamber components in the arc sections will be joined almost entirely by brazing operations. Although long used for constructing small components, the brazing technique will, in this case, be applied to a much larger task, namely, producing approximately 400 vacuum chamber sections that vary in size from less than 2 m to approximately 6 m in length. Joints will also be required between stainless steel and copper.

For those B Factory fabrications involving copper components, we will use the same brazing steps, methods, and techniques established at DESY in constructing the vacuum chambers for HERA [Ballion et al., 1989]. This technology includes cleaning methods,

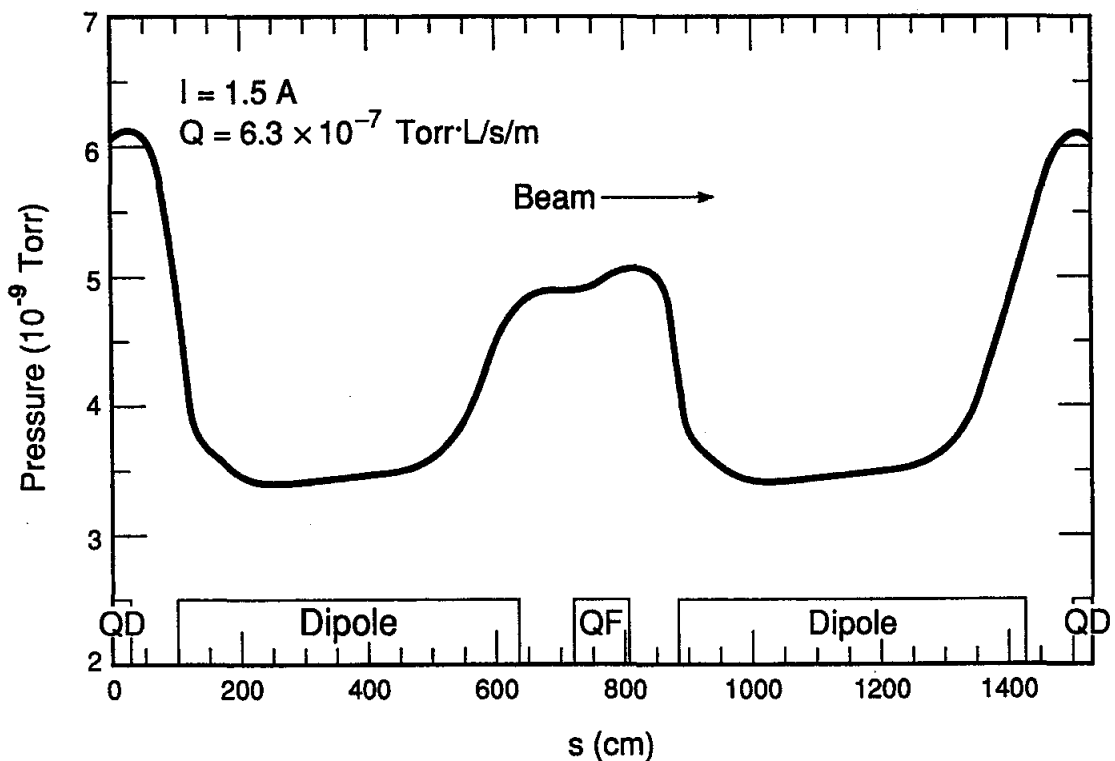


Fig. 5-63. Calculated beam pipe pressure profile of the B Factory HER.

fixturing, brazing alloys, furnace environments, heating schedules, and brazing steps at 1000°C and 800°C. Nonetheless, we recognize the necessity of prototyping these brazing processes in developing the required methods, materials, procedures, and specifications for our application, to ensure that appropriate fabrications can be made in a timely manner.

Cleaning. Techniques were developed at DESY to provide clean brazing surfaces and to obtain good vacuum properties on the chamber surfaces. The particular method chosen depends on the nature of the component being cleaned. Small stainless-steel parts are washed in an alkaline detergent and then rinsed in a dilute citric acid solution, followed by rinsing in distilled water at approximately 90°C. Small copper parts, following machining, are cleaned in the same manner, except that the detergent is only slightly alkaline and the process temperature is reduced to about 40°C. Large copper parts are assumed to be supplied by the vendor precleaned of production-process residues. Following machining, the parts are degreased in a slightly alkaline, 10% detergent bath, followed by rinsing in distilled water. Next, the parts are etched in a nonferrous-metal etch solution containing 83 parts water by volume, 10 parts concentrated sulfuric acid, 5 parts 35% hydrogen peroxide, and 2 parts stabilizer. After a rinse in distilled water, pickling is performed in warm water with 10% citric acid. Finally, the parts are rinsed in distilled water and dried.

Brazing. Brazing will be performed in two steps. The first step produces subassemblies of stainless-steel and copper parts. In the second step, only copper-to-copper brazing is performed. Brazing between stainless-steel and copper parts, which is required for the end-flanges, the lumped-pump ports, and the stainless-steel housings for distributed ion pumps in the quadrupoles, will be done in a small vacuum-furnace at 1000°C, using L-CuSn12 braze material. In the final braze assembly process, these subassemblies will be brought together with the beam tube, the pumping channel and cooling bar extrusions, the lumped-ion-pump manifolds, the BPM housings, and end-flanges, to form a complete chamber section that will be brazed at 800°C. For this brazing step, DESY used both brazing wire and a film of L-Ag72. We will use similar brazing alloys. This final brazing was made in a horizontal furnace in an atmosphere of 93% Ar and 7% H₂. This technique permitted rapid and uniform heating of the chamber assemblies and enabled 8-hour brazing cycles to be obtained. For the B Factory, leak checking will be performed after each brazing step, and completed chamber sections will be sealed and backfilled with dry nitrogen for storage and shipping to a preassembly site prior to installation.

Chamber Assembly. Assembly work on the vacuum chamber sections will include forming the chambers to contour; installing the dipole and quadrupole distributed ion pump hardware; making the vacuum seals for these chamber spaces; leak checking; installing the support-bracket plates, water connections, and BPM electrodes; performing mechanical and electrical checkouts (including dimensional checks); and carrying out a bakeout to 100°C above the ambient temperature. Completed assemblies will again be backfilled with dry nitrogen while awaiting installation. At this point, all necessary work will have been completed except for that required for actual installation in the tunnel.

5.2.5 LER Vacuum System

The operating pressure requirements for the LER are the same as those for the HER. In addition, the periodic layout of the lattice is similar: The cells of the two rings are the same length and stacked one atop the other. Major differences between the two rings, however, are the length and placement of the dipoles. The LER configuration, in the arcs, is shown in Fig. 5-64.

The synchrotron radiation photon flux in the LER will be four times that in PEP. Therefore, as already discussed, copper was chosen as the most suitable material for fabrication of the vacuum chambers in the arcs. In the straight sections, where the synchrotron radiation is minimal, the vacuum chambers will be fabricated from stainless steel.

5.2.5.1 Vacuum System Design. As shown in Fig. 5-65, the LER beam chamber cross section in the arc regions is identical to that of the HER, except for the omission of the pump channel. The inner dimensions accommodate the beam-stay-clear region required by beam dynamics and allow for the unavoidable errors in fabrication and mechanical positioning. A standard FODO cell contains the following elements: (i) defocusing sextupole, (ii) defocusing quadrupole, (iii) corrector, (iv) bending magnet, (v) drift, (vi) focusing sextupole, (vii) focusing quadrupole, (viii) bending magnet with corrector winding, and (ix) drift.

These two "sets" of magnets are grouped together on support rafts, with the bending magnet placed downstream of the other elements. The length of the bending magnet was chosen such that all of the synchrotron radiation it produces strikes the vacuum chamber

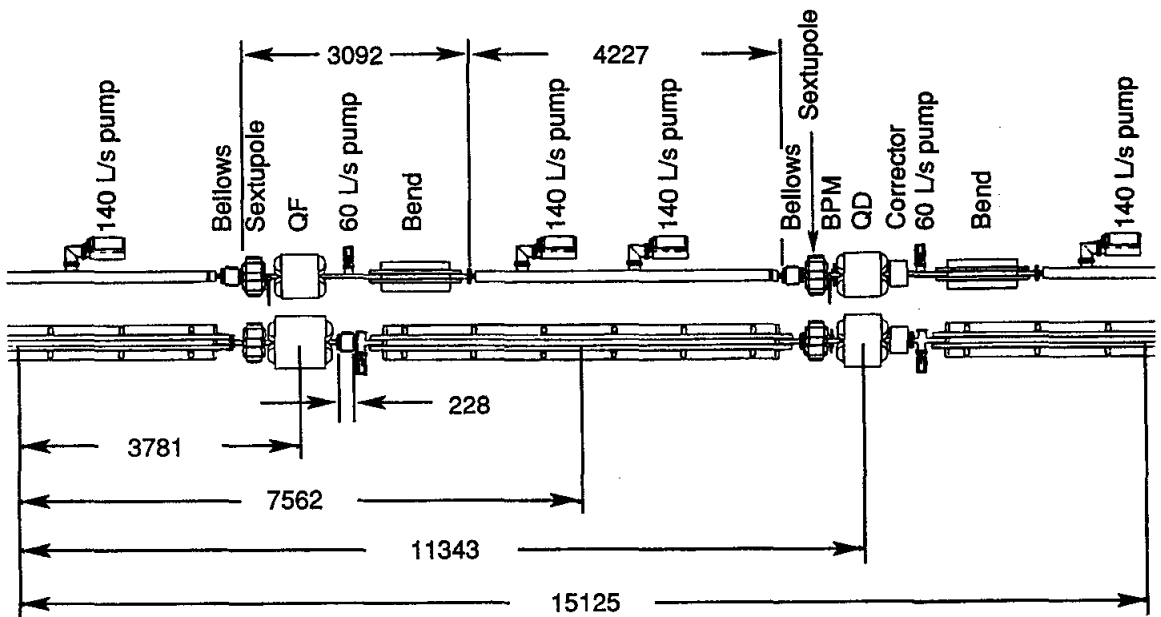


Fig. 5-64. Layout of a single arc cell of the LER of the B Factory; dimensions are in millimeters

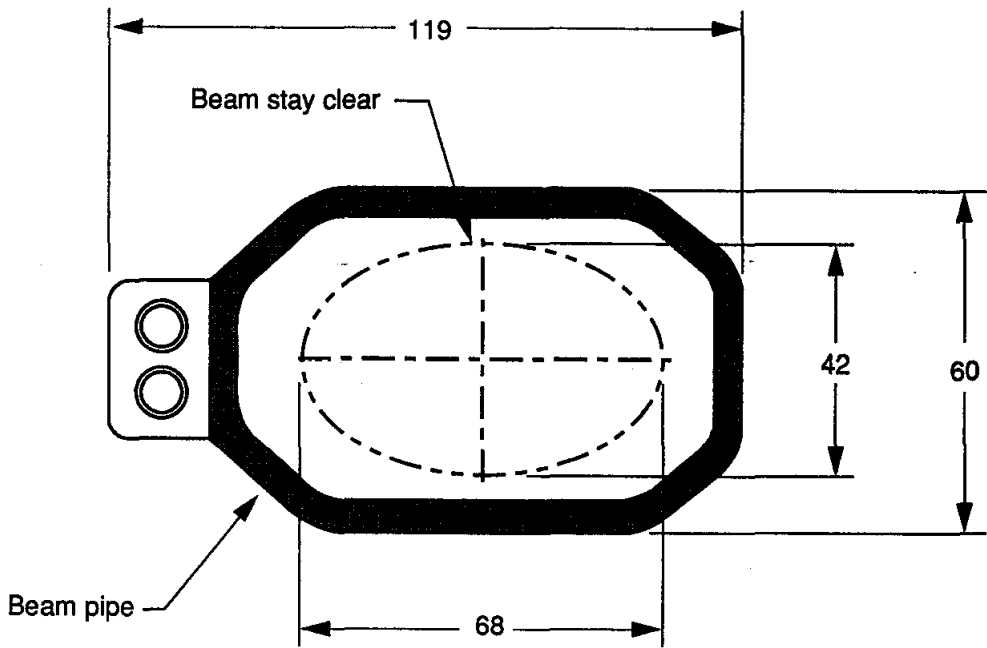


Fig. 5-65. Cross section of the LER vacuum chamber in the arcs; dimensions are in millimeters.

wall beyond the magnet (see Fig. 5-66), where vacuum pumps can be easily located to remove the desorbed gas. Distributed ion pumps inside the bending magnet are thus unnecessary. As is typical of storage rings, the beam chamber, which is of continuous cross section through the arc, is vacuum-conductance limited. Our solution for pumping the system (without using distributed ion pumps) is implemented in the sections of vacuum chamber downstream of the bending magnets. Here the conductance is doubled by enclosing the beam chamber itself within a tubular vacuum manifold.

Each of the six straight sections has a length corresponding to eight standard cells. Included in these sections are the RF cavities, the injection septa, beam pickups and kickers, horizontal and vertical beam scrapers, and BPMs. One of the straight sections houses the common interaction region for the B Factory and thus has a unique layout. There are also 28 empty FODO cells in the ring. The diameter for the beam pipe in the straight sections is 100 mm. Existing 152-mm-bore isolation valves from PEP will be used where possible; 100-mm-bore valves will be used elsewhere.

All pumping of the system is by means of lumped sputter-ion pumps. To provide stable argon pumping speed (in case of small air leaks), one pump in each cell will have "differential cathodes" (of titanium and tantalum). The pumping speed requirements are discussed below.

Experience from SPEAR and PEP has demonstrated the wisdom of installing a large vacuum system with flanged rather than welded interconnections. Standard stainless-steel Conflat flanges with copper gaskets will be used, as these have proved very reliable in the past.

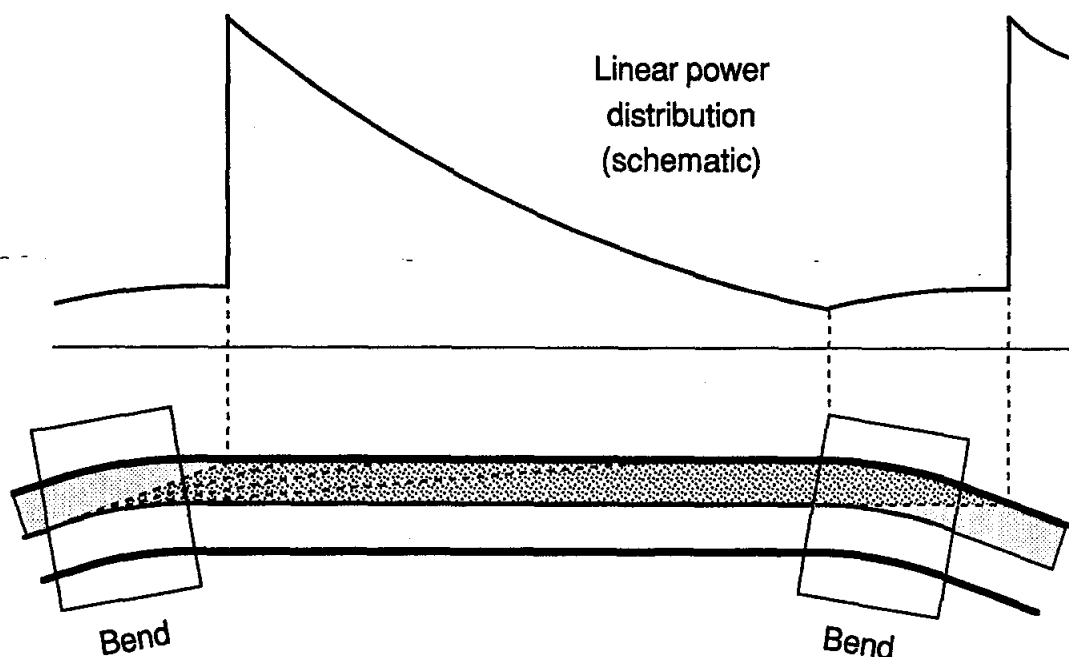


Fig. 5-66. Schematic illustration showing the distribution of synchrotron radiation power striking the LER vacuum chamber.

As in the HER, HOM losses will be kept to a minimum by keeping a uniform chamber cross section where possible. Tapered transitions smoothly blend the unavoidable changes in cross section. Ports on the beam chamber are shielded by screens. Copper rings between the flanges provide a smooth electrical path and will eliminate RF losses.

In the interest of reducing the number of different components, LER and HER vacuum systems will be standardized wherever possible. An example is the expansion bellows used to accommodate misalignment and to allow for thermal expansion of the vacuum chamber. Also interchangeable will be the isolation valves, pump-out valves, vacuum gauges, and ion pumps with their associated controls.

The vacuum system will be equipped to accommodate an in situ bakeout to 120°C. Thermal insulation of the bending magnet chamber will be provided by a permanently installed wrapping consisting of a powdered oxide pressed between glass fiber. Hot water circulated through the low-conductivity water (LCW) system will supply the heat.

5.2.5.2 Arcs. The layout of one standard cell is shown in Fig. 5-64. There are six beam chamber components per cell: bending magnet chamber, pumping chamber, bellows, bending magnet chamber with BPM, pumping chamber, and bellows.

The bending magnet chamber, shown in Fig. 5-67, is a 3.09-m-long, water-cooled copper brazement that passes through the sextupole, quadrupole, and bending magnets. It is rigidly attached to the support girder between the sextupole and quadrupole, at the location of the BPM. (Only alternate bending magnet chambers in the cell will require a BPM, namely, those near the defocusing quadrupole magnets.) Flex plates at the ends of

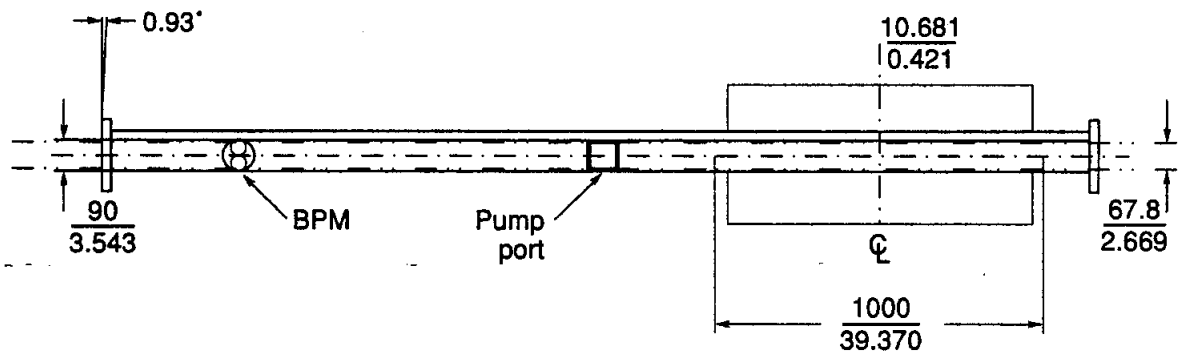


Fig. 5-67. Schematic of a bending magnet vacuum chamber for the LER.

the chamber will hold its lateral position while allowing thermal expansion. A pump port is provided between the quadrupole and bending magnets.

BPMs will be of the "button-electrode" type, modeled after the LEP design. They will be calibrated by a noninvasive technique, thus avoiding the threading of an antenna through the beam chamber and allowing the buttons to be located at any point along the beam pipe.

Most of the synchrotron radiation power is absorbed in the pumping chamber, which is 4.227 m long and is located immediately downstream of the bending magnet. The B Factory design, shown in Fig. 5-68, incorporates a water-cooled copper beam chamber,

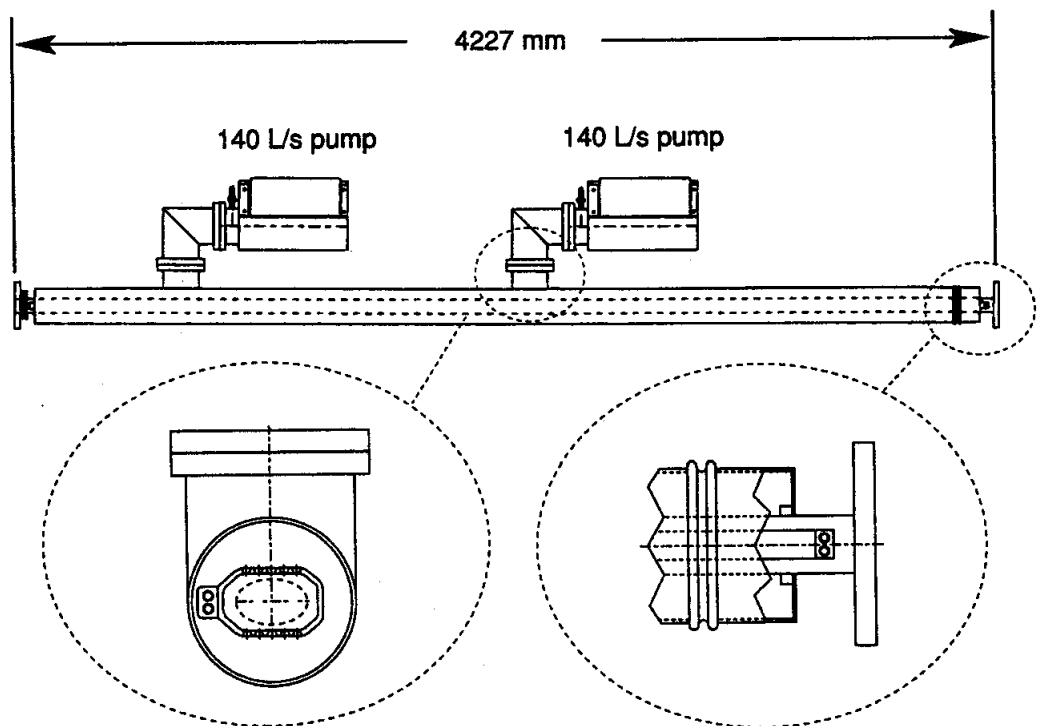


Fig. 5-68. Schematic of a pumping chamber for the LER.

with end flanges for interconnection. The chamber is slotted top and bottom over most of its length and surrounded by a 152-mm-diameter vacuum manifold. A short bellows at the end nearer the bending magnet allows the flexibility necessary for alignment. The longer bellows module at the downstream end of the pumping chamber provides the necessary space for installation and accommodates thermal expansion. Differential thermal expansion within the chamber is accommodated by a bellows on the manifold. Connections to the LCW system are external to the vacuum system, thus eliminating water-to-vacuum welds that might develop leaks.

5.2.5.3 Straight Sections. A typical straight section cell, fabricated from 100-mm-diameter stainless-steel tube, is shown in Fig. 5-69. Isolation valves are located in the straight sections at the end of each arc. To protect the RF cells in the event of an accidental vent to air and to facilitate their conditioning, additional valves are also provided to isolate them.

5.2.5.4 Synchrotron Radiation. At a beam energy of 3.1 GeV, the critical energy of the synchrotron radiation is 2.2 keV. In this photon energy regime, almost all the power is absorbed on the inside wall of the vacuum chamber. At 3.1 GeV, assuming 2.14 A of stored beam, the total power radiated in the arcs is 580 kW, giving 6.04 kW per cell. The power distribution is plotted in Fig. 5-40b. The peak power, 21 W/cm, is deposited approximately 40 cm beyond the bending magnet exit; thereafter, the power decreases rapidly along the cell.

Given this distribution of synchrotron radiation, the temperature differential across the water-cooled metal wall of the chamber is approximately 12°C; across the surface film in the water, it is 14°C. At the required flow rate of 10 gpm, the bulk temperature rise per cell is 2°C.

Within each cell, LCW from the supply header will flow out, in both directions, from the center of the cell through the LER bending magnet chambers. At the ends, the water will be directed to the HER chambers, through which it will flow back to the center. The two circuits then merge and pass into the return header through a flow switch that monitors for low flow (see Fig. 5-70). This design ensures that all cells are uniformly cooled.

A second consequence of synchrotron radiation is photodesorption. The gas load produced by this mechanism is plotted in Fig. 5-42b, assuming a value for the photodesorption coefficient equal to 1×10^{-6} molecules/photon at the maximum value of P_{SR} . The arrangement of sputter-ion pumps in the arc cells is shown in the layout of Fig.

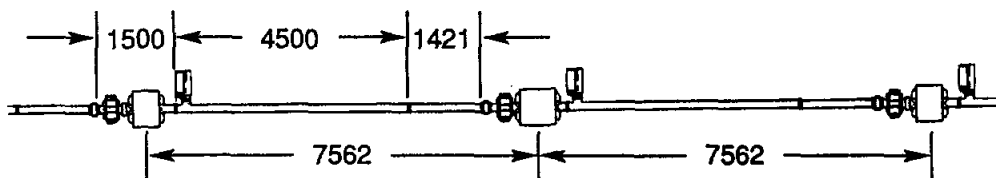


Fig. 5-69. Schematic of the vacuum chamber for an LER straight section.
Dimensions are in millimeters.

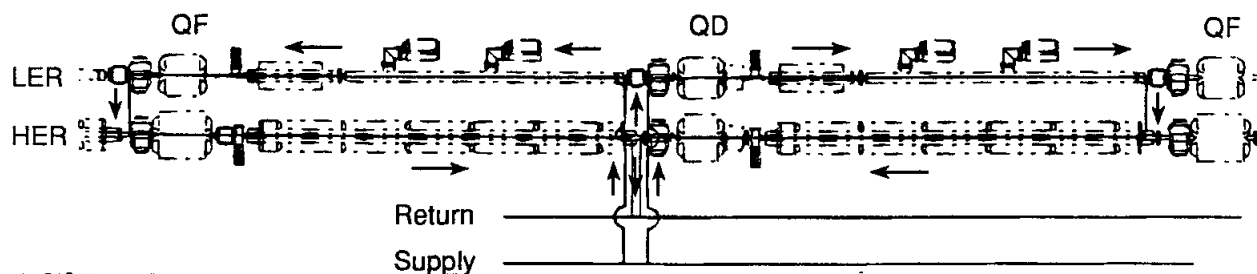


Fig. 5-70. Schematic of the cooling water system for the high- and low-energy-rings.

5-64. The total pumping speed per cell is 680 L/s. The pressure distribution calculated on this basis is shown in Fig. 5-71. Based on the above estimate of the desorption coefficient, the average pressure in the arcs during operation with a beam current of 2.14 A will be about 7.5 nTorr.

In the straight sections, the design pressure of 3 nTorr will be maintained by installing 220-L/s sputter-ion pumps at intervals of 7.56 m (that is, two per cell). Based on experience at SLAC, we have assumed a thermal outgassing rate of 1×10^{-11} Torr-L/s/cm². For the region immediately upstream of the interaction region, 220-L/s pumps will be installed at intervals of 3.8 m to obtain the operating pressure of 1 nTorr. With these values, the average pressure around the LER circumference is 6 nTorr. This pressure was used in the lifetime estimate discussed in Section 4.3.

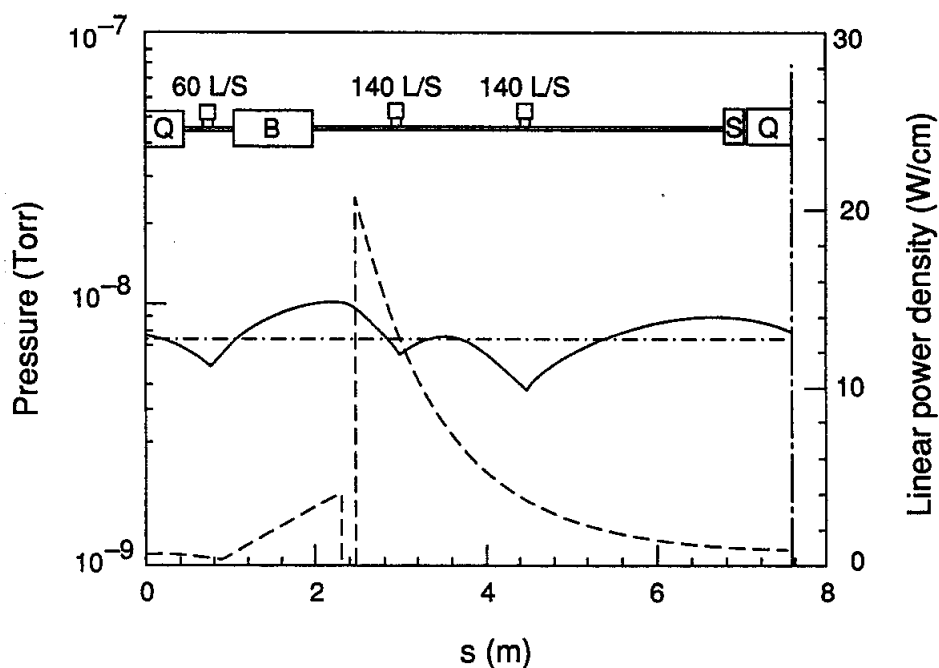


Fig. 5-71. Plot of the pressure distribution along an arc of the LER (solid line). The dashed line is the linear power density on the wall.

5.2.6 Radiation from Wigglers

To provide acceptable beam-beam tune shifts, the natural emittance of the LER must be increased considerably beyond that resulting from the arc dipoles alone. In addition, we have discussed in earlier reports [*Feasibility Study for an Asymmetric B Factory Based on PEP*, 1989; *Investigation of an Asymmetric B Factory in the PEP Tunnel*, 1990] the potential advantages of having equal damping decrements in the high- and low-energy rings to minimize the effects of the energy asymmetry on the beam-beam interaction. For these reasons, wigglers will be used to create additional energy loss in the LER.

The damping decrement for a storage ring can be written as

$$\lambda = \frac{T_0}{\tau_x} = \frac{U_0}{2E} \quad (5-23)$$

from which it is clear that, for equal damping decrements, the required synchrotron radiation energy loss per turn for the high- and low-energy rings must simply scale proportionately to the beam energy in the ring.

In the high-energy lattice ($\rho = 165$ m; $E = 9$ GeV), the total energy loss, which is dominated by the normal bends, is $U_0 = 3.58$ MeV/turn. For equal damping decrements, then, we need an energy loss in the LER of

$$U_{0,+} = U_{0,-} \frac{E_+}{E_-} = 3.58 \left(\frac{3.1}{9.0} \right) = 1.24 \text{ [MeV/turn]} \quad (5-24)$$

In the LER, we have a bend radius of $\rho = 30.6$ m. The energy loss from the horizontal bends can be estimated as

$$U_0 = 0.0885 \frac{E^4}{\rho} \text{ [MeV/turn]} \quad (5-25)$$

giving $U_0 = 0.27$ MeV/turn, that is, only about one-fifth of the requisite amount. (To create the matched damping decrement from the bending magnets alone would require a bend radius of 6.75 m, which would be, at best, inconvenient in terms of thermal power density.) In addition to the contribution from the horizontal bends, we must take account of the synchrotron radiation emission in the vertical bends used to steer the low-energy beam into the arc sections (which lie above the plane of the HER). The energy loss from the two sets of vertical separation magnets in the IR can be calculated from

$$U_{0,V} = 1.266 \times 10^{-3} E^2 B^2 L \text{ [MeV/turn]} \quad (5-26)$$

where E is in GeV, B is the dipole field in T, and L is the total bend length in meters. This gives a total contribution from the vertical bends of 0.014 MeV/turn. Thus, the lattice itself contributes a total energy loss of 0.28 MeV/turn from the bending and separation magnets.

To reach equal damping decrements, then, we must produce an additional energy loss of 0.96 MeV/turn. This will be accomplished by including wiggler magnets in two of the LER straight sections. As already mentioned, these wigglers also serve as a means of emittance adjustment for the LER; this adjustment works by creating a dispersion “bump” at the wiggler locations. By locating the wigglers in shallow chicanes off the principal axis of the straight section, the rms dispersion in the wiggler can be controlled externally to the wiggler. This additional degree of freedom extends the range of allowable wiggler characteristics. It also allows us to project the radiation into a distant photon dump. The bend magnets used to divert the beam into the chicanes contribute an additional 0.03 MeV/turn of energy loss.

Four wigglers, with nine periods of $\lambda_w = 0.67$ m, are included in each of two utility straight sections, as discussed in Section 4.1. The total length of wigglers is thus 48 m and the magnetic length is 28.8 m. A schematic drawing of the layout is shown in Fig. 5-72. For a wiggler composed of alternating-field dipoles, the total radiated power in MeV/turn is again given by Eq. 5-26. A wiggler field of $B = 1.63$ T is therefore needed to provide the additional 0.93 MeV/turn to fully equalize the damping decrements.

At the nominal current of 2.14 A, each wiggler will produce about 1 MW of synchrotron radiation power, with a critical energy of 10.4 keV. Most of this power will be dealt with externally to the ring vacuum chamber in specially designed photon beam dumps. However, some of the power will be deposited on the side walls of the vacuum chamber in the vicinity of the wiggler. To compute the power density at the dump and on the walls, we must estimate the angular distribution of the radiation. A precise description of radiation from a nonsinusoidally varying wiggler in the near field is not given in the literature, but we can modify the far-field description for standard wigglers given by Kim [1986] and apply it to segments of the wiggler to evaluate the resultant vacuum system requirements [Barletta and Garren, 1991].

Denoting the horizontal angle by θ and the vertical angle by ψ , we can write the power density in W/mrad² as

$$\frac{dP}{d\Omega}(\theta, \psi) = \frac{21\gamma^2}{16\pi K} U_{0,w} I N_w G(K) f_K(\gamma\theta, \gamma\psi) \quad (5-27)$$

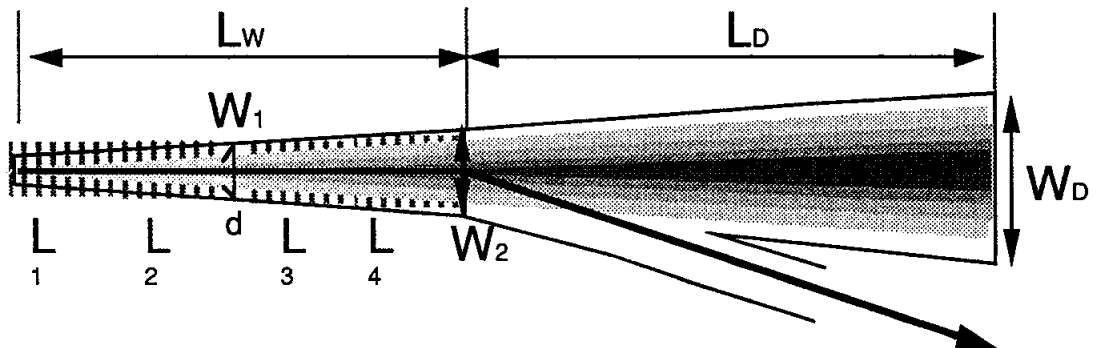


Figure 5-72. Schematic representation of the vacuum chamber in the region of the LER damping wigglers.

where $U_{0,w}$ is the synchrotron radiation loss in one wiggler period, I is the beam current in A, N_w is the number of wiggler periods, and G and f_K are universal functions. For the bend-drift configuration, $U_{0,w}$ is given by Eq. 5-26, where the wiggler magnetic length is substituted for L . For a standard wiggler, K is the usual wiggler parameter defined (for B in T and λ in cm) by

$$K = 0.934 B_w \lambda_w \quad (5-28)$$

The normalization factor $G(K)$ is

$$G(K) = K \frac{\left(K^6 + \frac{24}{7} K^4 + \frac{16}{7}\right)}{(1 + K^2)^{7/2}} \quad (5-29)$$

For $K \gg 1$, $G(K) \rightarrow 1$; moreover, the angular distribution is sharply cut off in the wiggler bend plane. In the limit $K \rightarrow \infty$, the normalized angular distribution function $f_K(\gamma\theta, \gamma\psi)$ is given by

$$f_K(\gamma\theta, \gamma\psi) = \sqrt{1 - (\gamma\theta/K)^2} \left\{ \frac{1}{[1 + (\gamma\psi)^2]^{5/2}} + \frac{5(\gamma\psi)^2}{7[1 + (\gamma\psi)^2]^{7/2}} \right\} \quad (5-30)$$

From Eq. 5-30 one sees that the radiation is spread over a horizontal angle $2\theta_w$, where

$$\theta_w = \frac{K}{\gamma} \quad (5-31)$$

For the bend-drift configuration, θ_w is the bend angle in a single dipole. In that case Eq. 5-31 becomes the defining relation for an effective K value, K_{eff} . Given this K_{eff} , we apply the formalism for the standard wiggler. In the nonbend (vertical) plane, the rms angle of the radiation is

$$\psi_w = \left(\frac{\varepsilon_y}{\beta_y} + \frac{0.63}{\gamma^2} \right)^{1/2} \quad (5-32)$$

At 3.1 GeV, the second term in Eq. 5-32 is dominant, and $\psi_w \approx 1/\gamma = 0.13$ mrad to a good approximation. At the nominal operating current of 2.14 A, each wiggler generates 42 kW/m. The opening half-angle of the radiation is 15.8 mrad. Therefore, if the vacuum chamber is to intercept less than 20% of the radiation generated (to avoid an impractically high power loading on the crotch and on the side walls), the enclosure needs to be quite wide. By integrating Eq. 5-27 over ψ for K_{eff} , one can determine the power density on the side walls of the enclosure.

With regard to pumping requirements, there is a weak trade-off between increasing the static load from widening the chamber and minimizing the dynamic load by avoiding

the photon fan. In the wiggler region, which occupies only 2% of the circumference of the ring, we have relaxed the required operating pressure to 10 nTorr.

As discussed in Section 4.1, we have opted for a quadrupole triplet located between wiggler segments L_2 and L_3 to provide flexibility to tune the lattice. This configuration suggests the use of a tapered stainless-steel chamber, as illustrated in Fig. 5-72. The photodesorption coefficient of the chamber is assumed to be 2×10^{-6} . The width W_1 should be as narrow as possible to maintain a practical quadrupole design. With this constraint in mind, the required pumping, which ranges from about 115 L/s/m in L_2 to about 160 L/s/m in L_4 , is obtained for $W_1 = 24$ cm and $W_2 = 40$ cm. The corresponding thermal loads range from 3.2 to 5.1 kW/m, respectively, on each side wall of the wiggler enclosure.

From Eq. 5-27, we can estimate that, at 2.14 A, the power density in the forward direction will be 1.6×10^5 W/mrad². We also find that 80% of the radiation is emitted into 8.1 mrad². Hence, we can compute the distance from the end of the wiggler to the photon dump, such that the power density is limited to a maximum value of 1 kW/cm². The distance from the wiggler to the dump, L_D , can be foreshortened by tilting the dump at an angle of about 20° with respect to the vertical. For a tilted dump, L_D should be about 44 m. Although roughly 20% of the power will actually be deposited on the walls of the wiggler chamber, we estimate the gas load at the dump assuming that all the power is incident there. We find that, for a copper dump with a photodesorption coefficient of 2×10^{-6} , the gas load at the dump is $Q_{\text{dump}} = 1.1 \times 10^{-4}$ Torr·L/s.

By considering the flared vacuum chamber from the wiggler to the dump to be a long, differentially pumped manifold, we can allow the pressure at the dump to rise to a much higher value than that required in the beam pipe. At the dump, the maximum horizontal extent of the radiation fan is 2.15 m, whereas the vertical extent of the radiation is only 2.0 cm. To lower the conductance of the photon channel, we take the chamber height to be 8 cm; baffles will also be added as needed to reduce the vacuum conductance into the wiggler straight section to 250 Torr·L/s.

The minimum total pumping of the dump plus photon channel is obtained by choosing the pressure to be 60 nTorr. This pressure requires 2000 L/s of pumping at, or near, the dump. This could be provided, for example, by installing large cryopumps. At a distance $L_D/2$, 700 L/s of pumping will reduce the pressure to 45 nTorr. Distributed pumping of 50 L/s/m along the first third of the photon channel reduces the pressure to 10 nTorr at the exit of the wiggler. More novel approaches, such as having the radiation fan strike NEG panels, are under study [Halama and Guo, 1990].

A C-frame bending magnet 5 m downstream from the wiggler exit bends the positron beam out of the radiation fan and into the straight beamline. The crotch can thereby be located away from the radiation fan of the wiggler. The straight beam pipe leaving the crotch is a special section of stainless-steel pipe, with a restricted aperture of less than 3 cm. Lumped ion pumps, providing 100 L/s of pumping speed in the region starting 10 m beyond the crotch and extending 5 m downstream of it, will reduce the pressure to 3 nTorr. At this point, a transition section will match the beam pipe dimensions to the standard straight-section vacuum chamber cross section.

5.2.7 Interaction Region Considerations

The interaction region is the heart of the entire B Factory facility. Because the detector is located in the IR, and because the separation of the two beams takes place here, there are a number of special requirements and special constraints that must be accommodated by the hardware. The design issues that must be considered are mainly those associated with the need to protect the detector from backgrounds. As discussed in Section 4.2, various masks are used in this region to protect the detector components and other sensitive equipment from the synchrotron radiation emitted as the beams are being magnetically separated, and these masks perforce intercept some of the synchrotron radiation power. The issues that we consider here include:

- Local pumping to deal with the photodesorption from those mask surfaces hit by the synchrotron radiation fans
- Cooling of the detector beam pipe masks to remove the synchrotron radiation power
- Cooling of the so-called “crotch masks” that shield the septum quadrupole (Q4) from the high-power synchrotron radiation fans
- Cooling of the very thin beam pipe in the center of the detector to remove the power due to wall-current and HOM heating.

5.2.7.1 Local Pumping. The pressure requirements inside the detector in the region upstream of the permanent-magnet quadrupoles are set by beam-gas bremsstrahlung events leading to lost beam particles. Within about ± 20 cm of the interaction point (IP), the limitation arises from electron-nucleus events leading to spurious triggers. For beam-gas interactions, we would like a pressure of 1 nTorr or lower outboard of the upstream Q2 magnet (for each beam). Near the IP, estimates based on calculations [Lightbody and O’Connel, 1988] indicate that some tens of nanotorrs should suffice, although measurements with MkII at PEP suggest a more stringent limit. For the B Factory, a precise calculation requires more knowledge of the detector and trigger design than is now available, so the simple estimates must suffice.

Pumping inside the detector is provided by radial ion pumps between the permanent magnets, for example, between B1 and Q1. These pumps utilize the 1-T field of the detector solenoid. It seems feasible to provide pumps with 150 L/s effective speed, including the conductance of the RF screen required to isolate the pump structure from the beam [Hartwig and Kouptsidis, 1974].

The principal gas load comes from photodesorption by the synchrotron radiation hitting masks AB and CD inside the B1 magnets. To estimate the magnitude of the gas load, we use a desorption coefficient of 2×10^{-6} molecules/photon and a thermal outgassing coefficient of 1×10^{-11} Torr-L/s/cm². With these parameters, it will be possible to achieve the desired pressures.

5.2.7.2 LEB Beam Pipe Mask (Mask AB). The vertex detector vacuum chamber must be protected from incident synchrotron radiation. Without a mask, portions of the synchrotron radiation fans generated by the incoming low-energy beam (LEB) as it

passes through BV1–, Q3, and Q1 would be incident on the vertex detector vacuum chamber. With our geometry (see Fig. 4-41), a mask that shields the vertex detector chamber from this radiation protrudes sufficiently into the beam pipe to intercept on its inboard (B) face some synchrotron radiation generated by the incoming high-energy beam (HEB) as it passes through B3 and B2. Characteristics of those portions of the synchrotron radiation fans that hit the mask are listed in Table 5-20.

As this table shows, the total heat deposited in the mask is 1273 W; this value was used in calculating the water temperature rise. A thermal analysis was performed only for the outboard (A) side of the mask, since the heat input and linear flux on the inboard side are very low. Because it is a small part of the total heat input, and because the source is so far away (making the fan very diffuse), the BV1– linear flux was also ignored in the analysis. As shown in Fig. 5-73, synchrotron radiation fans from Q1 and Q3 do not overlap; the two fans form a single continuous fan with a normal linear flux of 55 W/mm (although the σ_y values of the two fans differ by a factor of three). To reduce the synchrotron radiation background (see Section 4.2.1.1), the outboard side of the mask is sloped at 3.2:1, thereby reducing the surface linear flux to 17 W/mm. Using the lower σ_y value to be conservative, the peak heat flux normal to the surface is calculated to be 35 W/mm².

Two-dimensional spread-sheet analyses were carried out to determine the peak mask temperature and the maximum metal-to-water surface temperature for various distances between heated surface and cooling passage. Thermal stress was then estimated from the peak temperature results. Peak metal temperature, thermal stress, and cooling-surface maximum temperature are shown as functions of thickness, for the two σ_y values of interest, in Figs. 5-74, 5-75, and 5-76, respectively. As is true for the HEB crotch mask (see below), there is a trade-off between maximum cooling-surface temperature (peak heat flux) and thermal stress.

Furnace brazing the mask will subject it to a temperature of the order of 800°C. The yield strength of a dispersion-strengthened copper such as GlidCop, after being subjected

Table 5-20. Synchrotron radiation power on the AB mask.

	Source	Power (W)	Normal linear flux (W/mm)	σ_y^a (mm)
Side A (outboard; from LEB radiation)				
1	BV1–	106	8	—
2	Q3	901	55	0.5
3	Q1	138	55	15
Side B (inboard; from HEB radiation)				
4	B3	29	2	—
5	B2	99	8	—

^aNormal to radiation fan

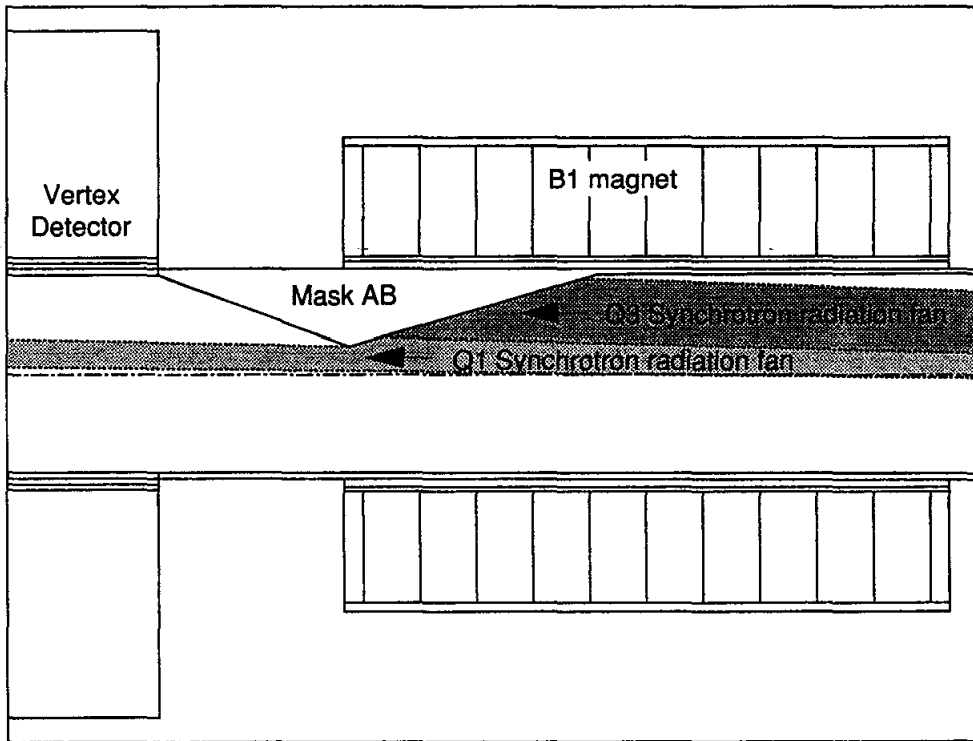


Fig. 5-73 Synchrotron radiation fans incident on the outboard side of the AB mask.

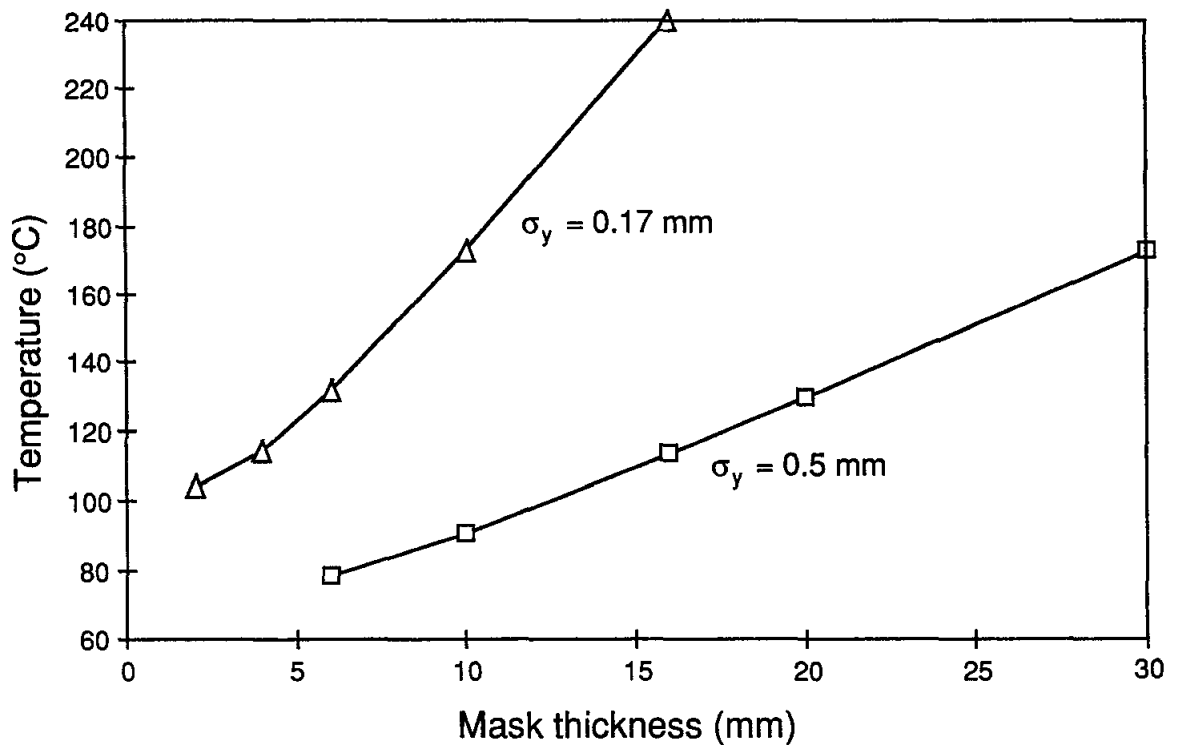


Fig. 5-74. Peak metal temperature on the AB mask as a function of thickness, for two values of σ_y .

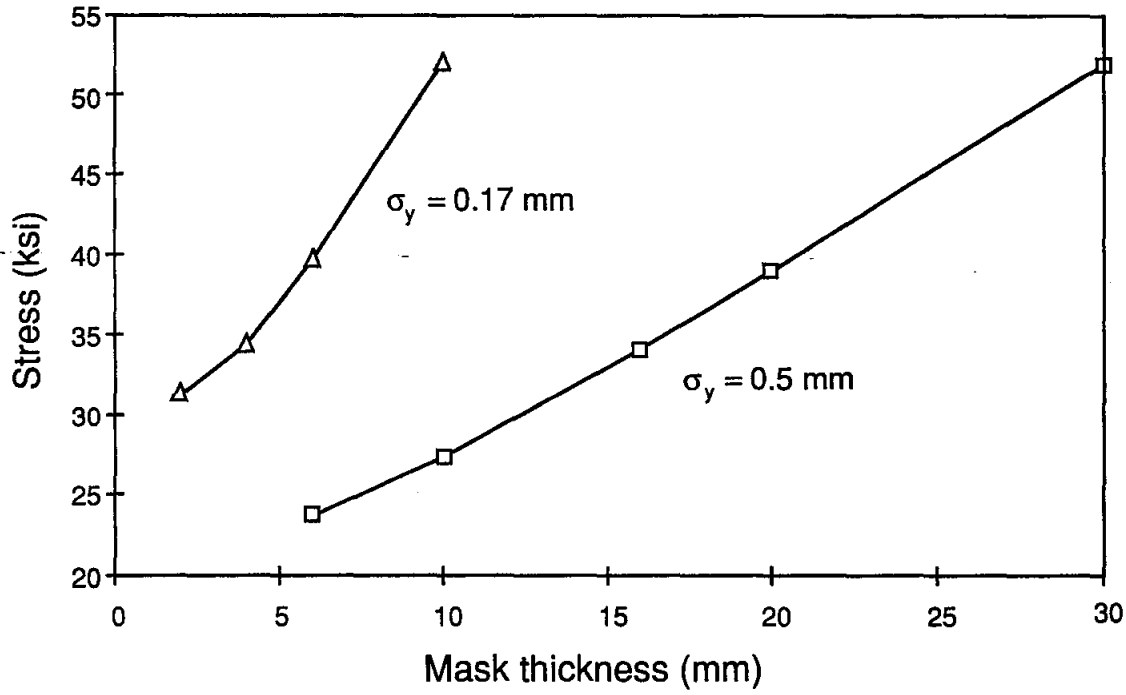


Fig. 5-75. Thermal stress at the AB mask as a function of thickness, for two values of σ_y .

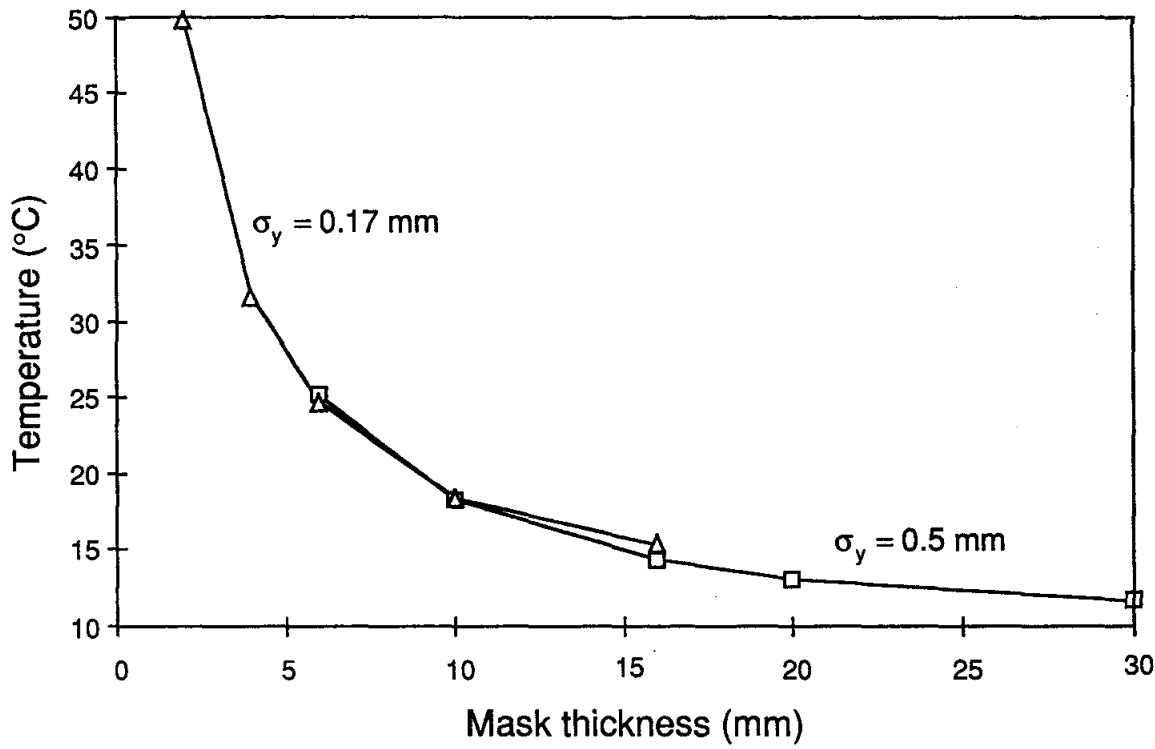


Fig. 5-76. Maximum cooling-surface temperature at the AB mask as a function of thickness, for two values of σ_y .

to such a temperature, is around 49,000 psi (see Fig. 5-77). If we desire to keep the peak stress to 75% of the yield strength, or 37,000 psi, then the distance from heated surface to water surface should not exceed 17 mm for the case of $\sigma_y = 0.5$ mm. For $\sigma_y = 0.17$ mm, the material thickness should not exceed 5 mm. In both cases, the maximum cooled-surface temperature is sufficiently low to avoid boiling. For long-term reliability, the vacuum-to-water wall thickness should not be less than 2 mm, and even at this thickness, the cooled-surface temperature is sufficiently low to avoid boiling (see Fig. 5-76).

Based on the two-dimensional analysis, the design shown in Fig. 5-78 will work well. During the detailed design phase, a three-dimensional analysis will be performed to verify these two-dimensional results for temperatures and stresses. The portion of the mask that forms the vacuum envelope is made of a single piece of GlidCop. As is normal practice, there will be no water-to-vacuum joints. Coolant passages will be drilled or milled from the outside (air side) of the mask. Covers that form the water-to-air seals will be brazed in place. Water is fed to the mask in a slot running from the outboard end

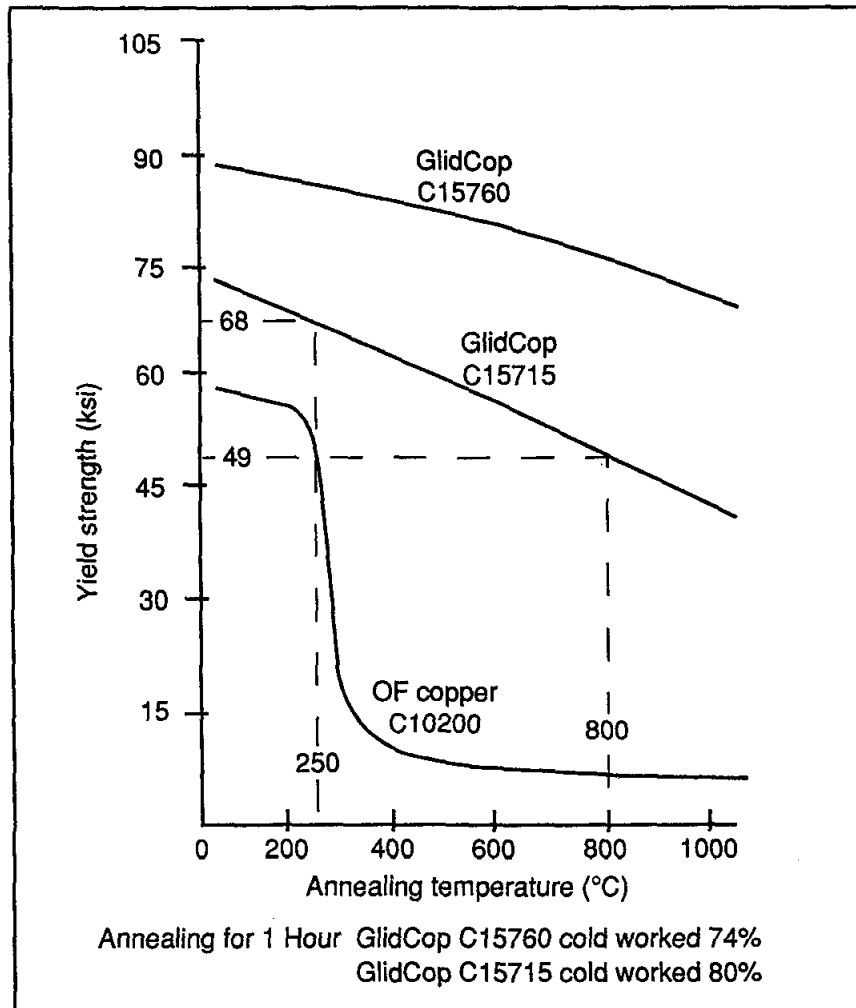


Fig. 5-77. Plot of the yield strength of a dispersion-strengthened copper, as a function of annealing temperature.

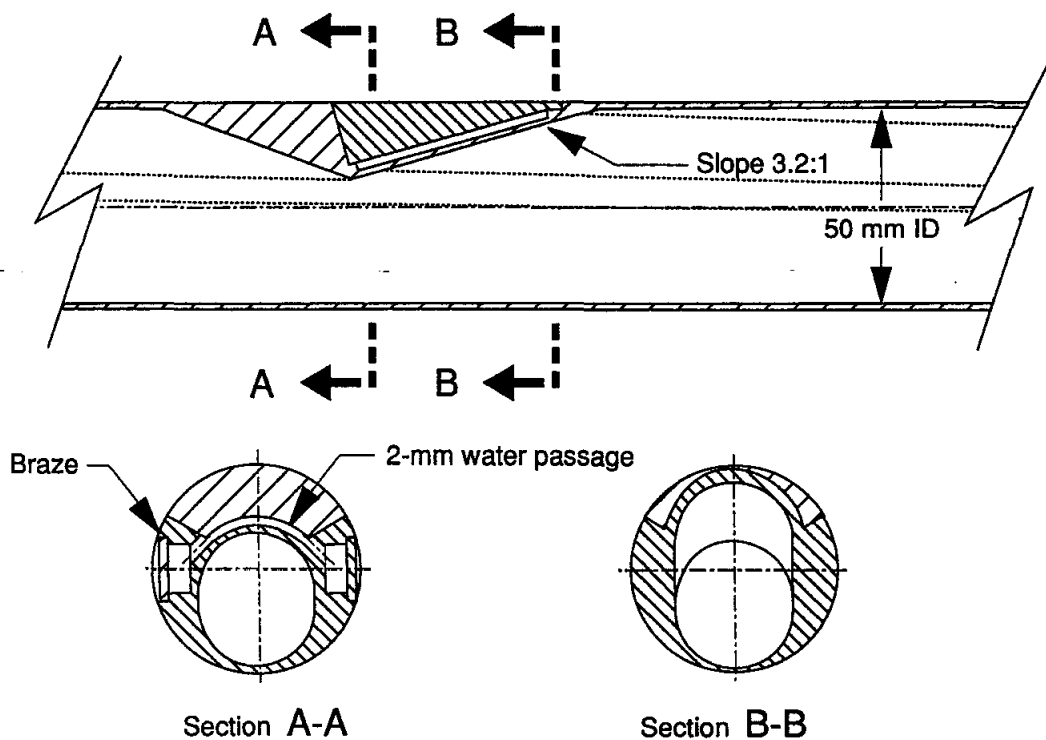


Fig. 5-78. Schematic showing the design of mask AB.

of B1; it returns via a similar slot on the other side of the mask body. With a total water flow rate of 1 gpm, the water-temperature rise will be 4.8°C.

5.2.7.3 HEB Beam Pipe Mask (Mask CD). Synchrotron radiation heat fluxes incident on both sides of mask CD (located on the incoming HEB side) are extremely low. Synchrotron radiation fan sources and their characteristics are listed in Table 5-21. The total heat deposition is only 36 W. With a surface slope of 6:1, the highest normal synchrotron radiation flux density is just 1 W/mm. Furthermore, σ_y values here are large, of the order of 3 mm or more. Thus, this mask will not present any thermal or stress problems.

5.2.7.4 High-Energy Beam Crotch Mask. The vacuum wall at the Q4 crotch must be protected from HEB synchrotron radiation by a mask, which we refer to as the HEB crotch mask. This crotch mask, located just ahead of Q4 on the incoming low-energy beam side of the IR, intercepts very strong synchrotron radiation generated by the HEB as it passes through the Q2 and B2 magnets, both on the incoming HEB side. Characteristics of the synchrotron radiation fans that hit the mask are summarized in Table 5-22.

The total power deposited in the mask is 4429 W. The fan from Q2 covers 7.6 mm of the 11-mm-wide mask; the B2 fan covers this same area plus another 0.3 mm. For the thermal and stress analyses, we assumed a total power input of 4430 W over a 7.6-mm width of the mask, giving a linear power density of 580 W/mm. The σ_y values in Table

Table 5-21. Synchrotron radiation power on the CD mask.

	Source	Power (W)	Normal linear flux (W/mm)
Side C (inboard; from LEB radiation)			
1	BV1	11	6
Side D (outboard; from HEB radiation)			
2	B3	9	2
3	Q4 + Q5	16	—

Table 5-22. Summary of synchrotron radiation power on the HEB crotch mask.

	Source	Power (W)	Normal linear flux (W/mm)	σ_y (mm)
1	Q2, incoming HEB side	4330	570	0.5
2	B2, incoming HEB side	99	13	>1.0

5-22 are for a zero-emittance beam, as this yields the most pessimistic result; the combined synchrotron radiation stripe was assumed to have $\sigma_y = 0.5$ mm. The vertical power distribution used in the analyses is shown in Fig. 5-79. The heat flux near the peak is 420 W/mm².

The above linear power density and heat flux are much too high for normal incidence, so the mask surface must be sloped relative to the incoming synchrotron radiation fan. Several slopes, ranging from 10:1 to 20:1 were investigated. A slope of 14:1 was ultimately selected and found to give reasonable temperatures and stresses. At a slope of 14:1, the linear power density becomes 42 W/mm, and the peak heat flux becomes 30 W/mm².

Initially, an uncooled tungsten mask was considered. However, it was found that the peak temperature on a mask that would fit into the available space was in excess of 2600°C. At that temperature, tungsten has a vapor pressure of about 10⁻⁴ Torr, and the evaporation rate is 0.6 μ m/hr. Needless to say, radiation cooling was not considered further.

The mask design ultimately chosen and the synchrotron radiation orientation are shown in Fig. 5-80. Note that the leading edge (tip) of the mask must be tapered to avoid violating the beam-stay-clear region of the incoming low-energy beam. Because there is not room to locate the cooling water directly behind the heated surface, the mask must be edge cooled, with cooling tubes at the top and bottom. Figure 5-81 shows the mask in more detail. The mask will be fabricated of a dispersion-strengthened copper, such as GlidCop C15715. This material was selected because it has a high yield strength, while retaining a high thermal conductivity—only 7% lower than that of OFE copper. Yield

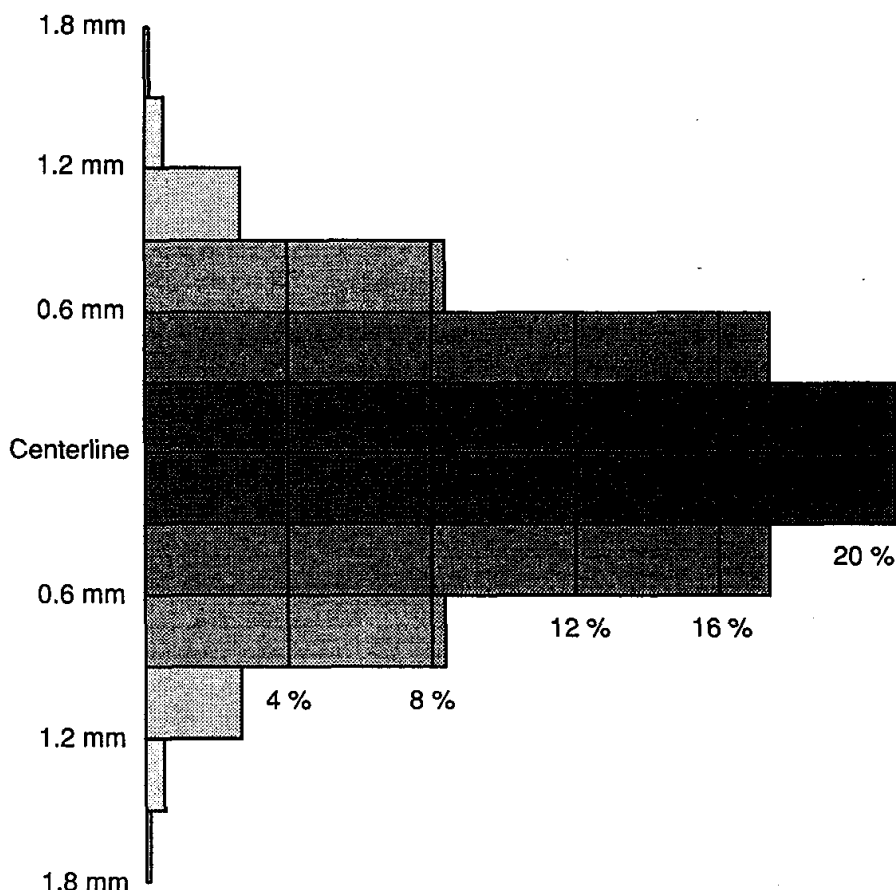


Fig. 5-79. Vertical synchrotron radiation power distribution assumed in thermal and stress analyses of HEB crotch mask.

strength is shown as a function of annealing, or operating, temperature in Fig. 5-77. Although the GlidCop yield strength is not as strong a function of temperature as is that for copper, its strength is somewhat (adversely) affected by temperature. Therefore, we plan to fabricate the mask from "as worked" material, without exposing the bulk of the material to brazing temperatures.

The mask and cooling passages will be machined from a single block of work-hardened GlidCop. Openings required to drill the cooling passages will be plugged, and cooling supply and return lines attached, by TIG brazing with an alloy such as Nicoro80. Using a TIG torch to braze allows the application of heat very locally at the braze joint, without subjecting the entire part to brazing temperatures. Sample TIG brazes have been made and found to be strong and vacuum leak tight. As mentioned above, double joints have been designed so that each vacuum joint has air rather than water on the outside. A second joint then separates water from air.

Two-dimensional spread-sheet analyses of mask temperatures were carried out to determine the feasibility of edge cooling. Various mask thicknesses and cooling-tube separations were studied. It was found that the maximum temperature dropped sharply

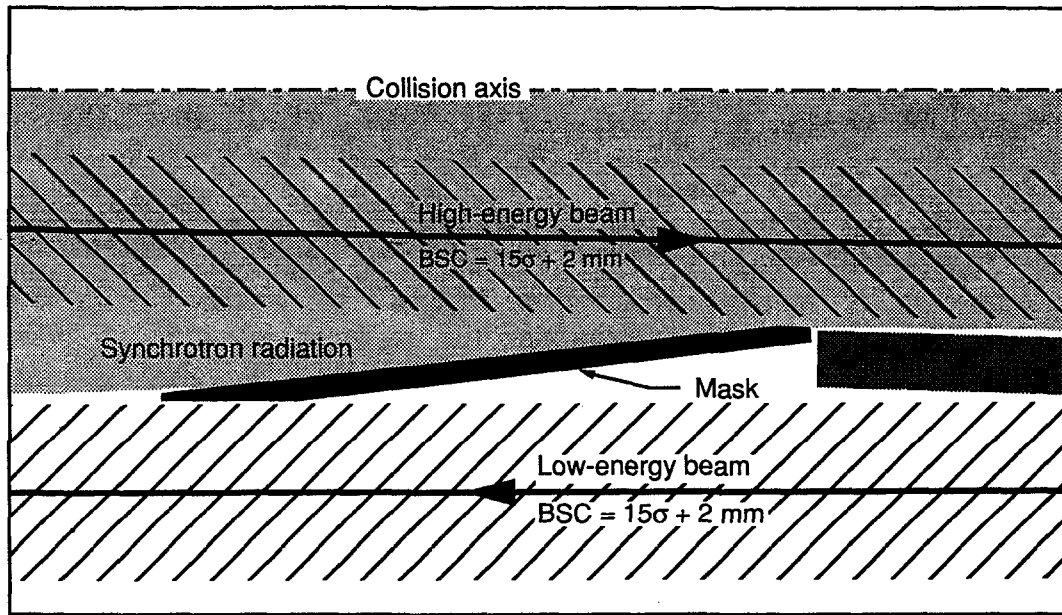


Fig. 5-80 Position of HEB crotch mask relative to impinging fan of synchrotron radiation. Beam-stay-clear areas are indicated by cross-hatching.

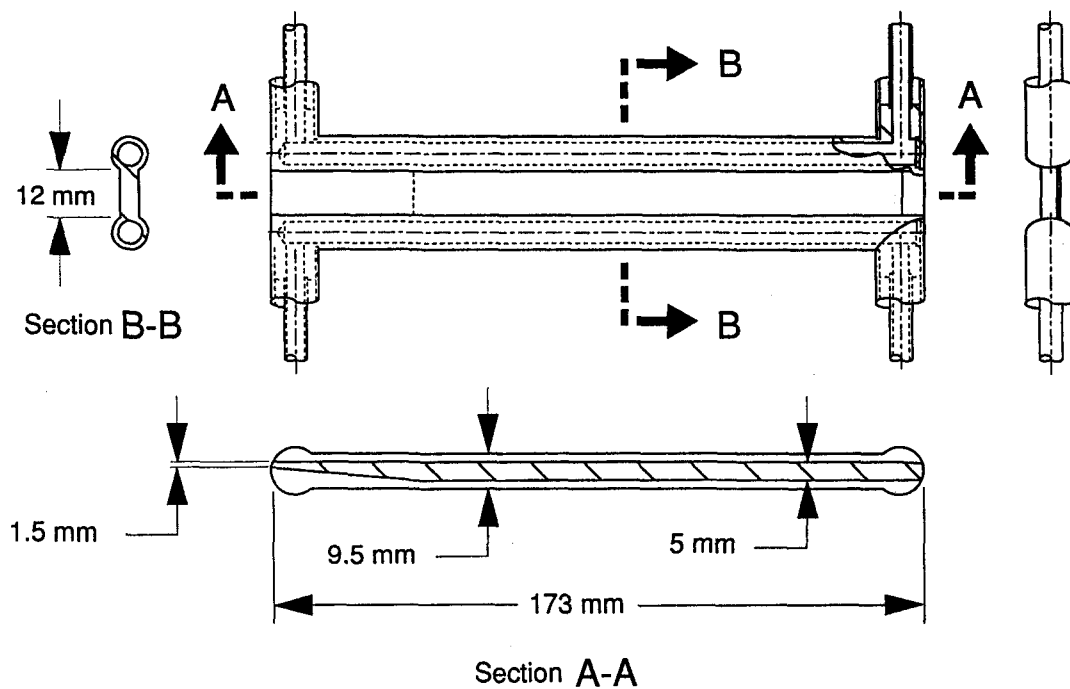


Fig. 5-81. Detail of HEB crotch mask.

with increasing mask thickness at thicknesses below 2 mm. Above 5 mm, however, added thickness actually increases the maximum temperature gradually. The results are plotted in Fig. 5-82. A 5-mm thickness gives both a maximum surface temperature that is near the minimum possible, and a reasonable interface temperature. Cooling-tube separation needs to be ± 6 mm or greater to provide adequate clearance for the electron and positron beam-stay-clear regions.

A mask thickness of 5 mm and a distance of ± 6 mm from beam centerline to water-cooling surface were chosen for a three-dimensional analysis using ANSYS. These results (see Fig. 5-83) show a maximum temperature of 253°C , which occurs on the beam centerline, approximately 9 mm beyond the edge of the synchrotron radiation fan, where the mask tapers to about a 3-mm thickness. Figures 5-83 and 5-84 show the geometry of the top half of the front portion of the mask used in the three-dimensional analysis. The top and bottom halves are mirror images, with the symmetry plane at the midplane of the synchrotron radiation fan. Highest temperatures and stresses occur in the tapered portion of the mask, near the front edge. The maximum stress is a compressive stress of 48,900 psi. It occurs on the beam centerline, approximately 11 mm from the fan edge. A maximum tensile stress of 18,400 psi occurs on the outside surface of the cooling channel at the end of the tapered section. The stress distribution is shown in Fig. 5-84.

The proposed design should be straightforward to fabricate. The vapor pressure of copper at 250°C is negligible, and the GlidCop yield strength at 250°C is 68,000 psi, well above what is required.

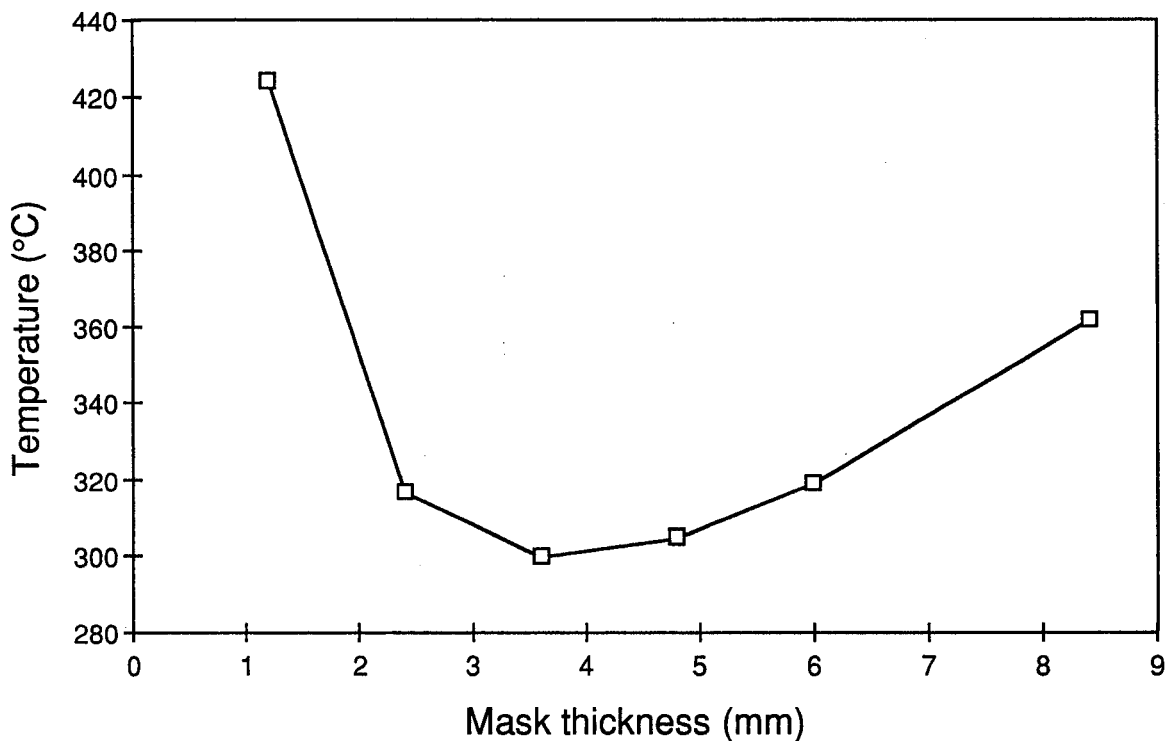


Fig. 5-82. Maximum HEB crotch mask temperature as a function of metal thickness.

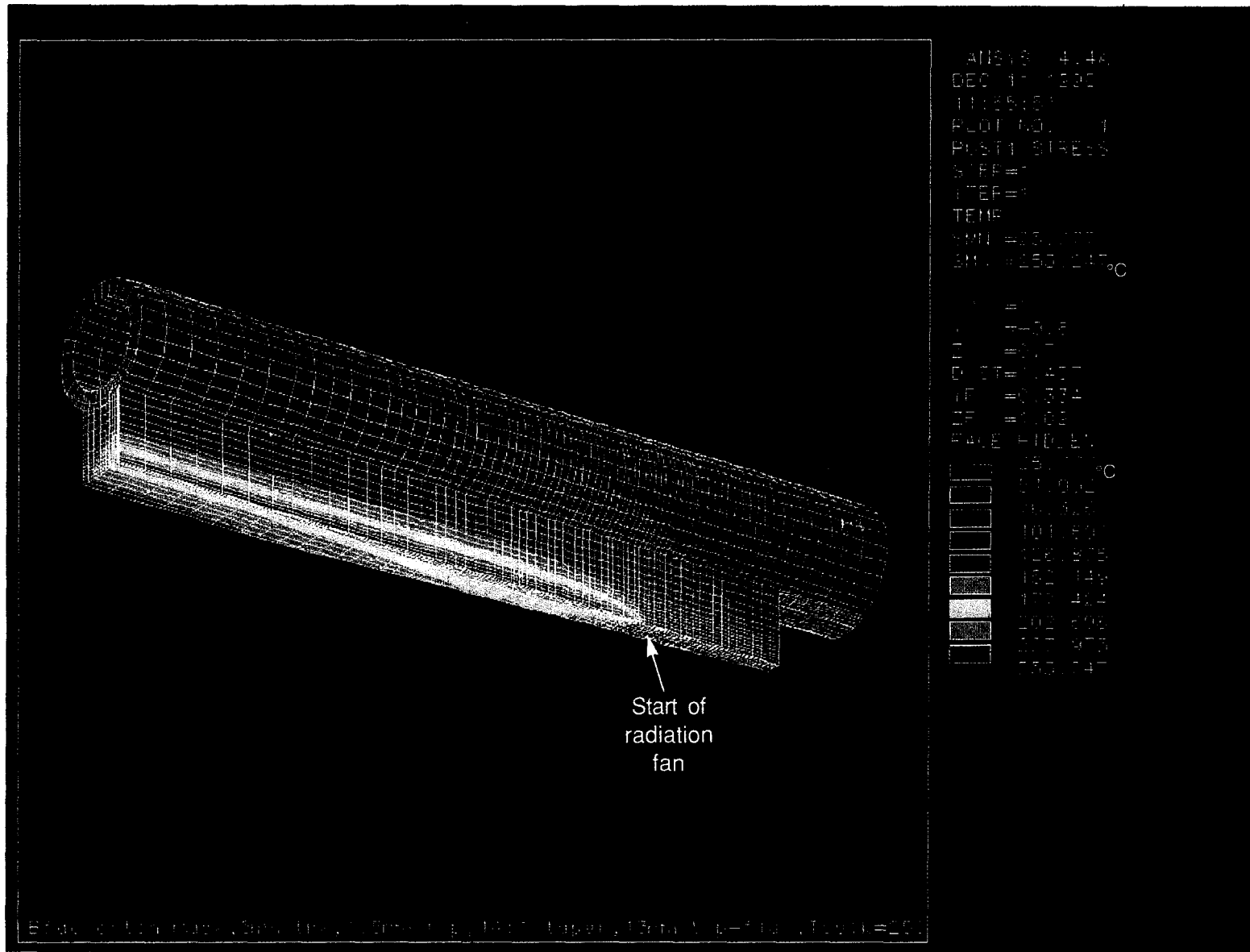
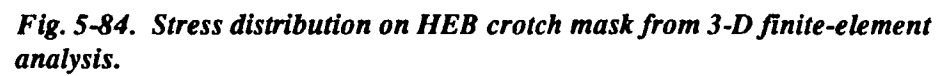


Fig. 5-83. Temperature distribution on HEB crotch mask from 3-D finite-element analysis.



It is important to remember that the maximum temperature, and therefore the stress, rise rapidly with decreasing thickness below 2 mm (see Fig. 5-82). Therefore, the synchrotron radiation fan must not be allowed to strike too near the tip of the tapered portion of the mask (where the mask is thinner). In particular, the tip of the mask must be out of the radiation fan. A temperature-sensor located in the tip of the mask and connected to a beam abort system is provided to protect the mask from overheating.

A convection conductance h of 0.028 W/mm² per °C was used in all the analyses. A relatively high water velocity, 12 ft/s, is needed to reach such a value. To attain this water velocity in the two 7-mm-diameter cooling passages requires a total flow of about 4 gpm. At this flow rate, the water temperature rise will be about 4°C.

5.2.7.5 Low-Energy Beam Crotch Mask. The crotch ahead of Q4 on the incoming HEB side of the IR sees synchrotron radiation generated by the LEB as it passes through the Q1 magnets on both sides of the IP. The vacuum chamber wall at the crotch must therefore be protected from synchrotron radiation. Characteristics of the portions of the synchrotron radiation fans that hit the mask are summarized in Table 5-23.

The total power deposited in the mask is 383 W. The synchrotron radiation fan from source 1 in Table 5-23 covers the entire crotch width. The synchrotron radiation fan from source 2 covers 3.1 mm of the 11-mm-wide crotch, and the fan from source 3 covers the remaining 7.9 mm. For thermal and stress analyses, we assumed the sum of sources 1 and 2 to be the worst case, and then applied this power across the entire mask width. On this basis, the linear flux density is 41 W/mm. To be conservative, we assumed also that the beam σ_y is 0.8 mm for both fans. This value is a worst-case estimate based upon the assumption of a zero-emittance positron beam.

The above linear power density is about the same as that normal to the surface of the HEB crotch mask (at a 14:1 slope). The rms beam size here is 1.6 times that on the HEB side. We conclude, therefore, that the LEB mask need not be sloped. Its face can be normal to the synchrotron radiation fan. The mask geometry is shown in Fig. 5-85. The mask material is a dispersion-strengthened copper, such as GlidCop, because thermal stress levels preclude the use of oxygen-free copper.

A two-dimensional spread-sheet analysis of mask temperatures indicates that the mask should be at least 8 mm thick to give a maximum temperature at the copper-water interface that will avoid any possibility of boiling. Thickness, in this case, refers to the

Table 5-23. Summary of synchrotron radiation power on LEB crotch mask.

	Source	Power (W)	Normal linear flux (W/mm)	σ_y (mm)
1	Q1, LEB side	186	17	1.14
2	1st half Q1, HEB side	75	24	0.8
3	2nd half Q1, HEB side	122	15	0.7

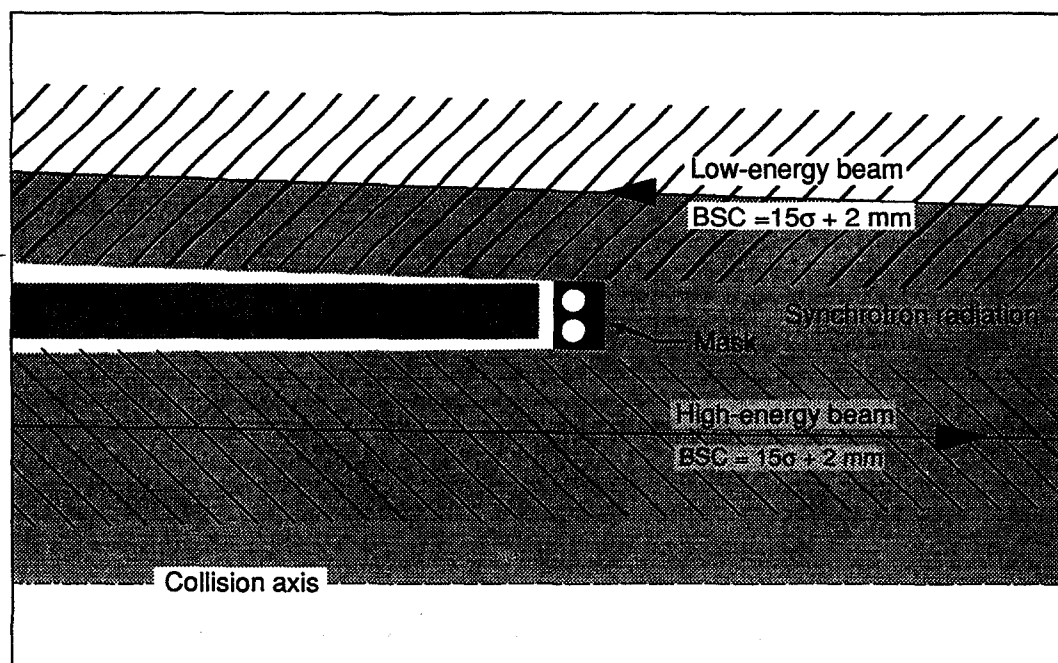


Fig. 5-85. Position of LEB crotch mask relative to impinging fan of synchrotron radiation. Beam-stay-clear areas are indicated by cross-hatching.

distance from the heat-absorbing face to the water-cooled face. The thicker the mask, the lower the maximum interface temperature, as can be seen in Fig. 5-86. However, as shown in Figs. 5-87 and 5-88, the thicker the mask, the higher the maximum temperature and therefore the stress. In this case, stress was determined by a simple calculation, assuming that $\sigma = E\alpha\Delta T$ at the maximum temperatures calculated above. Note that the above results are for oxygen-free copper; temperatures for GlidCop will be slightly higher and stresses about 5% higher.

The yield strength of GlidCop near 200°C (see Fig. 5-77) is about 69 ksi. If the stress is to be kept below 75% of yield, the thickness should not exceed about 10 mm. At 10 mm, the maximum temperature is about 170°C, and the stress is 50 ksi (72% of yield). To retain high yield strength, the mask will be fabricated from "as worked" material, and joints will be made by TIG brazing, as for the HEB crotch mask.

The peak heat flux is 1.5 W/mm². Such a value is manageable without boiling by maintaining a high water velocity (say, 12 ft/s) over the cooled surface. If the cooling passage inner diameter is 7 mm, a flow of 2 gpm is needed to attain this velocity. At such a flow, the water temperature will rise by only 0.7°C.

5.2.7.6 Vertex Detector Vacuum Chamber. The vertex detector vacuum chamber must be designed to be compatible with the detector requirements. This means that it must

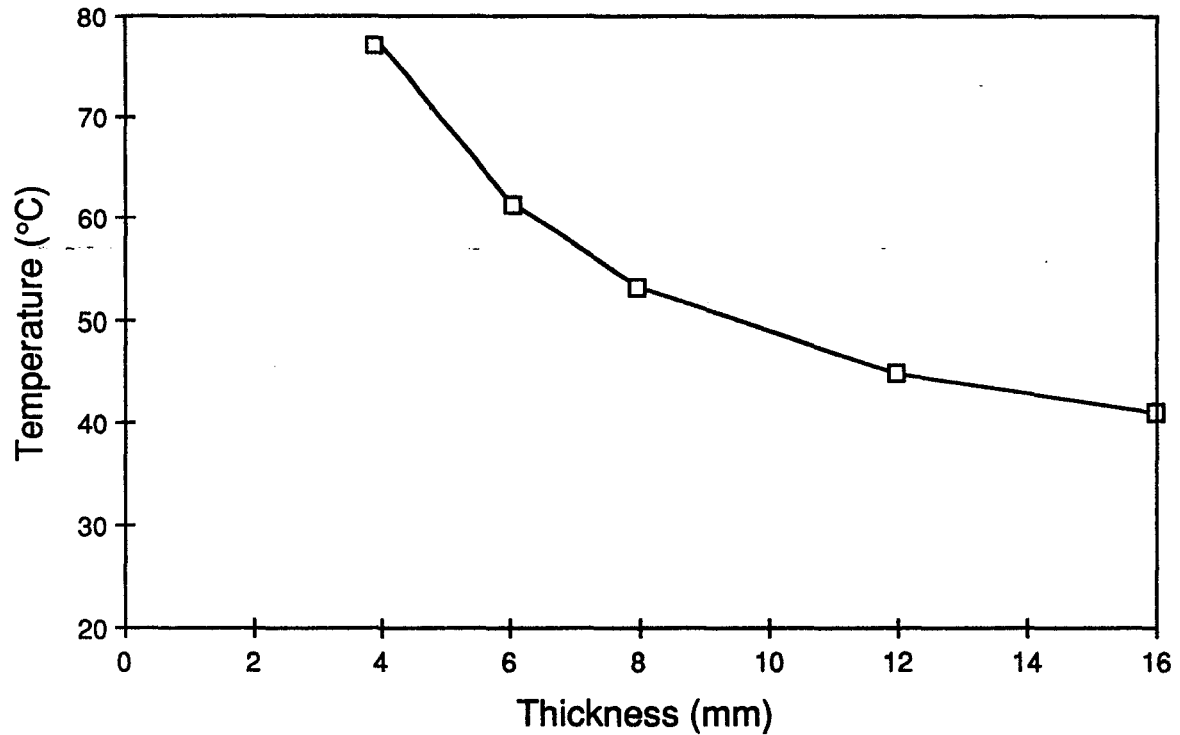


Fig. 5-86. Maximum cooling-surface temperature for the LEB crotch mask as a function of metal thickness.

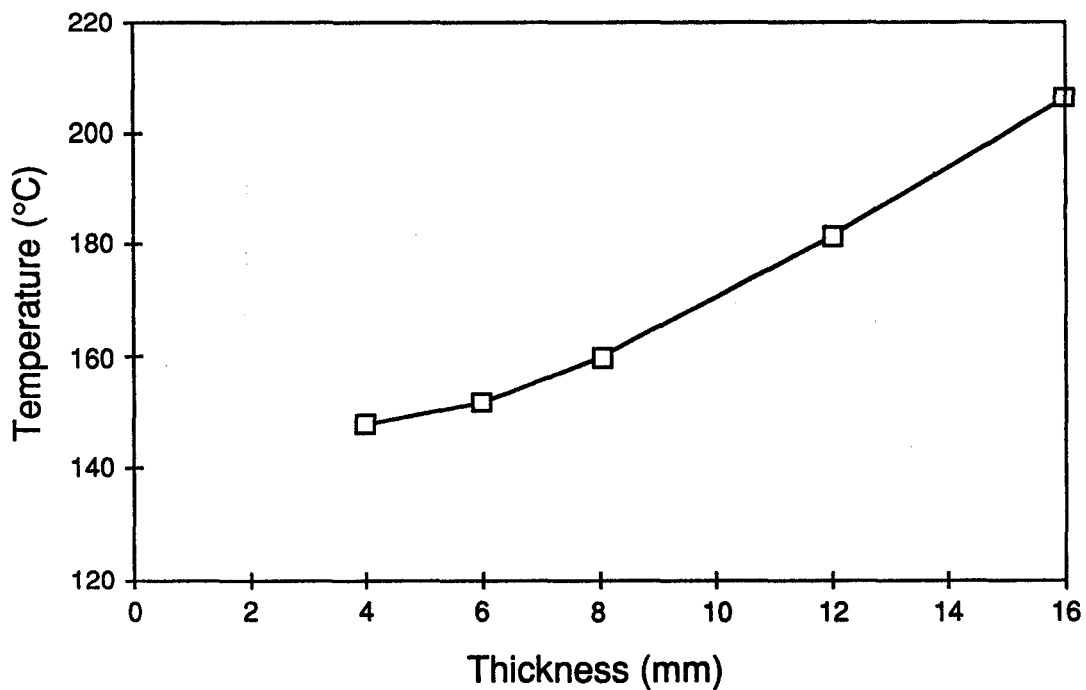


Fig. 5-87. Peak metal temperature on the LEB crotch mask as a function of metal thickness.

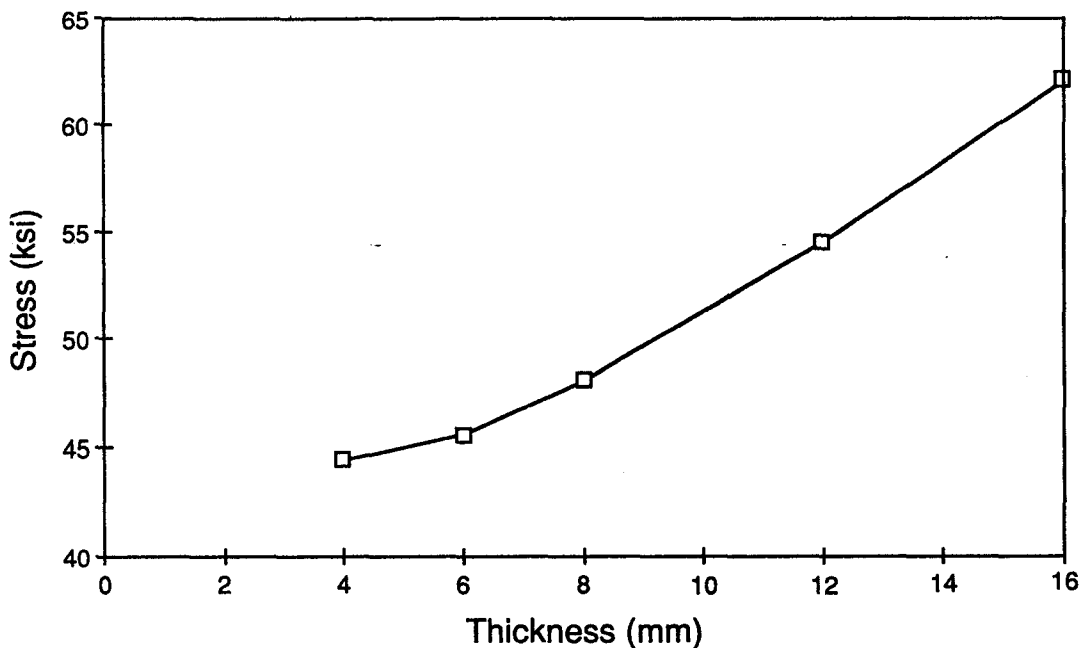


Fig. 5-88. Peak thermal stress on the LEB crotch mask as a function of metal thickness.

have the following features:

- It must be as transparent as possible to outgoing particles and photons from the collisions.
- It must have as small an outside diameter as possible.
- It must have an inside diameter of 50 mm or less.
- It must be approximately 300 mm long.

Because heat deposited in the chamber by HOM heating and resistive heating will be about 200 W, the vertex detector vacuum chamber must also be cooled.

Beryllium was chosen for the chamber wall material because of its low Z and relatively high strength. The possibility of a beryllium tube cooled only at its ends was considered, but a double-walled tube with a cooling fluid in the annular space was found to be a more transparent and more efficiently cooled design. An illustration of the chamber concept is shown in Fig. 5-89. The ends of the beryllium tubes are brazed to stainless-steel ends. A spacer ring between the inner and outer tubes at each end maintains concentricity between the tubes to form an annular cooling passage 2 mm wide. The stainless-steel ends are welded to the spacer ring to seal the ends of the passage. Stainless-steel-to-beryllium joining technology that was used in the construction of the SLD beryllium vertex chamber will be used. Figure 5-90 is a photograph of the SLD chamber.

The outer wall thickness of the vertex detector chamber pipe is 0.4 mm, and its inner wall has a thickness of 0.8 mm. Both will withstand a pressure of about 50 atm. Coolant pressure will be considerably lower than this, so the safety margin is substantial. Indeed,

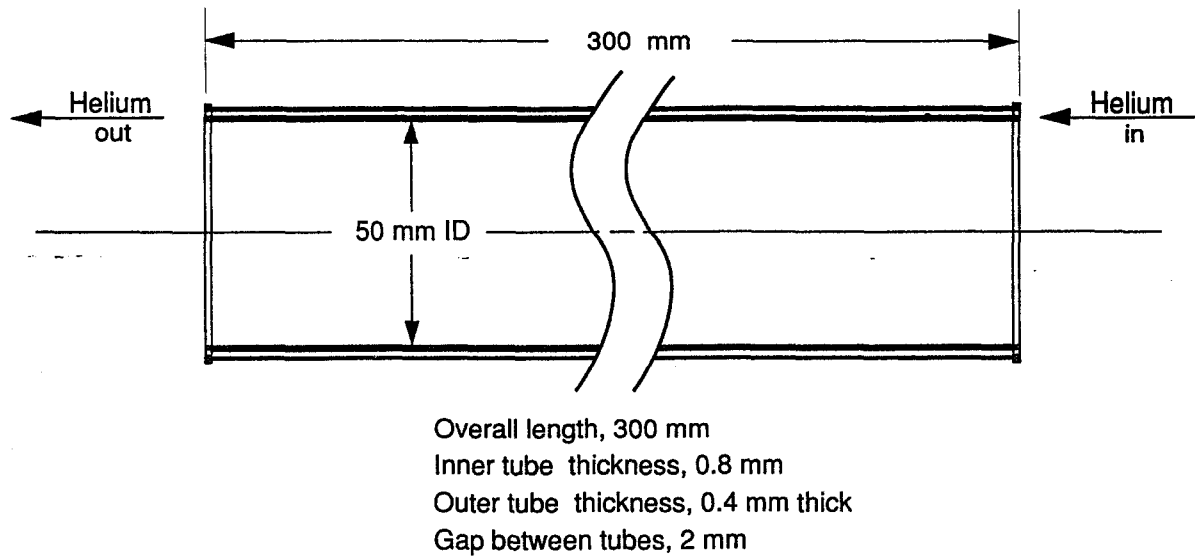


Fig. 5-89. Design for the double-walled beryllium vacuum chamber for the vertex detector. Helium at 2 atm is used as the coolant.

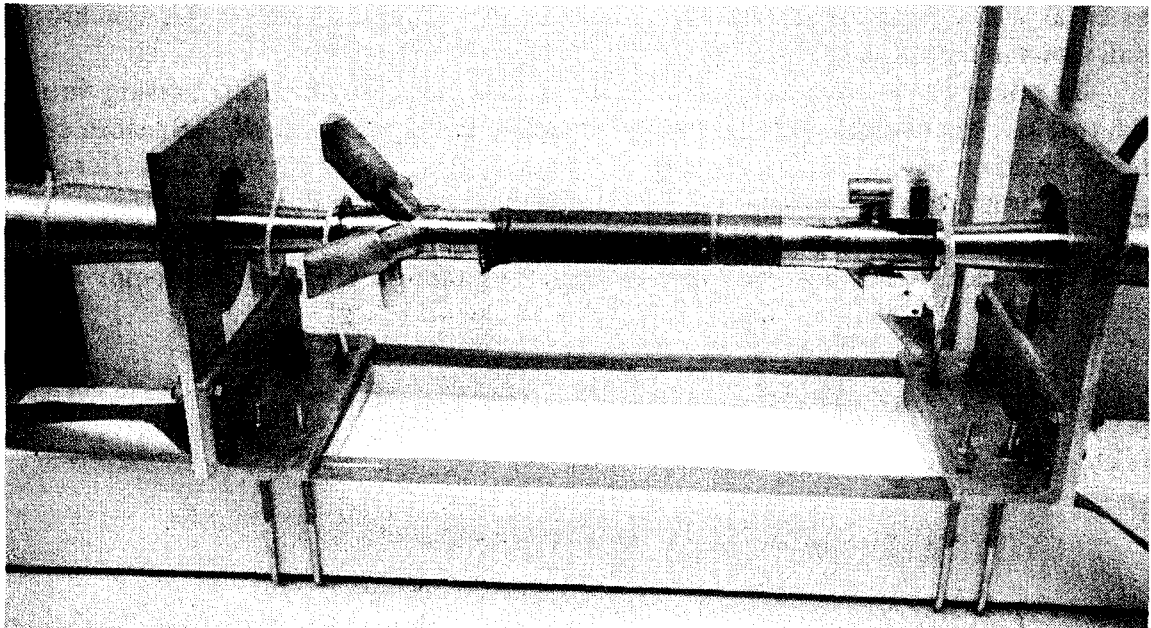


Fig. 5-90. Photograph of SLD vertex chamber.

the thickness was chosen primarily to make the chamber more rugged and to minimize chances of damage in handling.

Helium, hydrogen, and water were all considered as possible coolants. Although helium is not quite as good a coolant as either water or hydrogen, the fact that it is inert led to its being the coolant of choice. Beryllium and water appear to be compatible, but some beryllium would certainly enter the water and be carried by it. Concern about leaks and spills, and the resulting possibility of contamination, thus ruled out water. Hydrogen should be compatible with beryllium, but was ruled out because of its flammability.

Helium pressurized to 2 atm is quite adequate as a coolant. A flow of 22 g/s (Mach number = 0.2) gives a helium temperature rise of 1.1°C and a film temperature drop of 2°C for a 200-W heat input. Thermal stresses are quite low at these temperature differences. At least twice as much heat could be removed by the above flow should it prove necessary. Furthermore, the wall thicknesses adopted would allow the use of higher-pressure helium in the event that still more heat needed to be removed. Thus, the vertex chamber beam pipe is very reliably and conservatively designed for use in the B Factory.

5.2.7.7 Synchrotron Radiation Dumps. The synchrotron radiation fans created by the HEB passing through the two B1 and the two Q2 magnets carries some 80 kW of power. To keep IR backgrounds low and to allow the synchrotron radiation fans to spread, the bulk of the HEB synchrotron radiation fan is dumped at a location 12–15 m away from the IP. At 12 m, the synchrotron radiation fan linear power density from the two B1 magnets is 580 W/mm. The linear power density from the two Q2 magnets is only slightly lower. At 12 m from the IP, the fans have spread vertically to $\sigma_y = 1.2$ mm.

If the vacuum chamber wall has a slope of 11:1 relative to the fan, the radiation is absorbed over a length of about 2 m. The maximum linear power density is about 55 W/mm. This power is removed by a longitudinal cooling-water line that is brazed to the external wall of the copper vacuum chamber, just outside of where the synchrotron radiation fan strikes.

The power carried by synchrotron radiation fans created by the LEB passing through the two B1, the two Q1, and the two Q3 magnets is only about 8 kW. Because of the lower beam energy, vertical spreading will be even greater than for the HEB. Here also, the synchrotron radiation fans will be absorbed on the water-cooled vacuum chamber wall starting about 12 m from the IP.

Clearly, heat removal will not be a problem for either the HEB or LEB dump.

5.3 SURVEY AND ALIGNMENT

The primary goal of the survey and alignment activity for the Asymmetric B Factory is to align the lattice components along a "smooth" curve. This should be done in such a way that the rms deviations of components from this curve do not exceed $150\text{ }\mu\text{m}$ and that the resulting circumference is within 5 mm of its design value. Overall tolerances for the alignment of the various ring components are summarized in Table 5-24. As can be seen from this table, the most important alignment criterion is the *relative* accuracy requirement. Consequently, long-period systematic effects on the measurements and computations can be neglected. This means that we need not be concerned about effects like geoid undulations, deflections of the vertical, earth tides, site-wide water table changes, etc.

For the installation of the machine, modern computer-aided methods and procedures, which have been tested and proved at SLC, HERA, and LEP, will be applied to perform the alignment. The specific alignment tasks that are required include the following, each of which is taken up in a subsequent section:

- Support the component fiducialization effort
- Align modules and girder components in the alignment laboratory
- Perform "blue-line" survey of anchor bolt positions for supports
- Rough-align the supports
- Rough-align the components
- Final-align (smooth) the components
- Align the interaction region components
- Perform quality control surveys

5.3.1 Preliminary Considerations

Before expanding on specific tasks, some fundamental alignment requirements must be introduced.

5.3.1.1 Fiducialization. The virtual magnetic axis of each component must be related to external fiducial marks. Since the fiducialization error is budgeted as part of the overall alignment error, it should be kept very small. Otherwise, it will dominate the alignment error budget, thereby eliminating most of the allowable error margin for the positioning of the fiducial relative to the traverse monuments. In general, the fiducialization error should be kept below $50\text{ }\mu\text{m}$ to facilitate a successful alignment.

Because the low-energy ring (LER) is mounted above the high-energy ring (HER), there is inadequate space to mount alignment equipment on top of the HER magnets. Consequently, placement of permanent alignment fiducials on the tops of magnets is impractical. Therefore, we plan to incorporate reference grooves in the magnet

Table 5-24. B Factory alignment tolerances.

Global tolerances	
Horizontal and vertical positioning of quadrupoles (rms) [mm]	1.5
Horizontal and vertical positioning of sextupoles (rms) [mm]	1.5
Horizontal and vertical positioning of dipoles (rms) [mm]	4
Roll angle of quadrupoles (rms) [mrad]	1
Roll angle of sextupoles (rms) [mrad]	1
Roll angle of dipoles (rms) [mrad]	0.3
Circumference [mm]	5
Component-to-component tolerance	
Sextupole to quadrupole within a module (rms) [mm]	0.10
Horizontal and vertical position of quadrupoles and sextupoles in injection coast line [mm]	0.5
Smoothness tolerance	
Quadrupole-sextupole pair to quadrupole-sextupole pair (rms) [mm]	0.15

laminations that will allow alignment reference fixtures to be mounted on the aisle side of the components.

5.3.1.2 Coordinate System. Before performing the survey and alignment procedure, we must first define a coordinate system in which all measurements will be reported. For a machine of this size, the fact that the local shape of the earth is not planar, but somewhat spherical, must be taken into consideration. If the primary datum of the coordinate system is defined such that it coincides with the center of the ring, then, at least to a first approximation, the machine is built in a common tangential plane. This means that the horizontal direction with respect to gravity is also “horizontal” in the layout coordinate system, within the required accuracy. However, this horizontal plane is inclined with respect to the common SLAC coordinate system. With this in mind, the B Factory alignment coordinate system will have the following properties:

- Right-handed system
- Primary datum at the center of the ring
- Y-axis parallel to gravity at datum point
- Z-axis perpendicular to Y, along the SLAC linac axis, with the downstream direction of the linac defined as positive
- X-axis perpendicular both to Y and Z.

A rotation matrix will be defined to perform transformations between the local B Factory coordinate system, as defined above, and the global SLAC coordinate system.

5.3.1.3 Control Networks. Computer simulations have shown that the global tolerances for the positioning of the lattice components can be met without the supporting framework of a surface network. However, it was assumed that the tunnel control traverse can be measured all around the ring in one survey. The B Factory tunnel horizontal net will be established as a traverse with stations every 7.54 m, that is, adjacent to the middle of the HER bending-magnets. As floor marks, we will use a new design of three-dimensional "reference cups," a design adopted from the ALS now under construction at LBL. This design, combined with the new ALS "monopod" instrument stand, is highly efficient and accurate; it virtually eliminates the task of centering instruments and targets over monuments. Furthermore, the elevation of the instrument above the three-dimensional reference cup is known very accurately, which facilitates three-dimensional mapping with theodolites. The traverse layout will be modified as necessary to accommodate the bridging of interaction halls and to provide for the subsequent alignment of the interaction region components.

The fact that the PEP tunnel lies in a horizontal plane makes a liquid-leveling system practical and efficient. We will therefore refurbish and reinstall the existing PEP liquid-leveling system. The primary upgrade will involve replacing the present copper tubing with stainless steel. The tie to the linac and the SLAC-wide elevation datum will be made using differential-leveling procedures.

5.3.2 Survey and Alignment Tasks

5.3.2.1 Girder and Module Alignment in the Laboratory. The HER quadrupole-sextupole pairs will be aligned with each other in the laboratory and thereafter treated as a module; that is, their relative alignment will not be adjusted in the tunnel. The dipole-quadrupole-sextupole-BPM modules on each LER girder will also become a laboratory-aligned unit whose relative alignment will not be adjusted in the field. Traditional optical-tooling techniques can provide the 0.1-mm relative alignment required for this procedure.

5.3.2.2 Blue-Line Survey. In preparation for the installation of the support systems, a blue-line survey will be performed to lay out the anchor bolt positions. This will be done from the tunnel traverse points using intersection methods. An accuracy of 5 mm, which is more than sufficient, can be easily achieved.

5.3.2.3 Rough Alignment of Supports. After the blue-line survey, the anchors and support systems will be installed, but with the anchor bolt nuts only hand tight. At this point, the adjustment systems for the components are already mounted on the supports and adjusted to a midrange position. Using laser theodolites (set up on traverse points) and inclinometers as control instruments, the supports will be tapped into position to an accuracy of about 5 mm. This is especially important for the C-frame supports, because a small roll displacement will have a large correlated horizontal (x) effect for the LER components. If not controlled, this type of support misalignment could easily exceed the adjustment mechanism range of individual components.

5.3.2.4 Rough Alignment of Components. After the magnets are installed, they will be positioned relative to the traverse monuments to an accuracy of about 0.3 mm. This will be done with a two-step procedure:

- Bring the magnets to their ideal elevations and set their pitch and roll values to zero, using differential-leveling techniques
- Map the horizontal positions of quadrupole-sextupole pairs relative to the traverse points, using triangulation methods

The mapped positions will be compared with their ideal values to determine the required mechanical adjustments. The subsequent application of adjustments will be controlled using digital indicators. Two iterations should yield the desired accuracy. For the injection lines in the linac, traditional optical tooling techniques will be used. The linac tooling reference holes, after they have been mapped using the linac Fresnel lens alignment system, will provide the necessary tunnel control.

After the quadrupoles are aligned, the horizontal positions of the HER dipoles will be set using the HERA CCD-theodolite technique. Fixtures are attached to neighboring quadrupoles such that one supports a theodolite equipped with a CCD camera and the next a special target. The theodolite is aimed at the target, and another target is mounted on the dipole between the two quadrupoles. The surveyor then watches a video screen while moving the dipole to determine when it is properly aligned.

The alignment of the matching sections, the barrel, and the detector will lend itself to the standard rough alignment technique. Fiducials on the outermost magnets of the barrel will be visible from the aisle. These fiducials will be used to align the barrel.

5.3.2.5 Smoothing of Quadrupoles and Sextupoles. The “smoothness” of a beamline refers to the quality of the relative positioning of a number of adjacent beam-guiding components. The fact that smoothness is of the highest importance in terms of positioning magnets can be judged from the relative tolerances imposed by the beam optics (see Table 5-24). The benefits of the smoothing technique are that it eliminates the effects of unknown systematic errors and that it minimizes the number and size of magnet movements necessary to reach the final alignment criterion.

The observation plan best suited for this method is a three-dimensional traverse measured directly over the components to be smoothed. Unfortunately, for the B Factory design, there are constraints that make this scenario impossible. To have unobstructed lines-of-sight from one magnet to two adjacent ones in both directions, the measurements must be performed either on top of the magnets or on the side nearer the center of the ring. Because of the vertical arrangement of the two rings, there is no room on top, as mentioned above. In addition, the magnets are located near the wall closer to the center of the ring, so there is not enough room for measurements there either. Therefore, the observations must be carried out from the traverse stations on the aisle side.

From the aisle-side traverse stations, horizontal and vertical direction sets will be measured to the four nearest quadrupole-sextupole pairs. To strengthen the network, distances will be measured from station to station. One important difference from the rough positioning step described earlier is that the traverse stations will only be treated as tie points; that is, we will not introduce their known coordinates into the least-squares

adjustment, but rather treat them as unknowns. Repeated test smoothings carried out in the SLC arcs and Final Focus beamline have shown that 150- μm smoothness can be obtained in one iteration; a second iteration will improve this to better than 100 μm . (Note that we refer here to the rms value of the residual magnet fiducial displacement relative to a smooth curve, without including any fiducialization error.) The matching sections and the barrel will be included in the smoothing procedure, as will the NIT and SIT parts of the injection lines. The alignment tolerances of the injection bypass lines (the injection transport lines in the linac tunnel) do not warrant smoothing.

5.3.2.6 Quality Control. After completing the final smoothing step, the positions of all components will be mapped one more time to confirm that the alignment tolerances have been met.

5.4 POWER SUPPLIES

In this section we describe the power supplies required for the B Factory. For both the HER and LER, many of the supplies are very similar in function. These are described together in Section 5.4.1. In the common interaction region of the two rings, there are a number of special magnets that serve to focus and to separate the two beams. Power systems for these magnets are discussed in Section 5.4.2. Finally, in Section 5.4.3 we discuss the power supplies required for the injection system. Most of these supplies—along with the magnets they power—are already in existence. The primary exceptions to this are the supplies for the interaction region.

5.4.1 HER and LER Power Supplies

The HER and LER power supply systems are divided into a number of independent supply strings, as listed in Table 5-25 for the HER and Table 5-26 for the LER. Since the strings for the two rings are identical in most respects, save only their detailed electrical characteristics, they are described together in the following paragraphs.

5.4.1.1 Bending Magnet Strings. The HER utilizes a single bending magnet string of 192 dipoles, connected in series (see Fig. 5-91a) by existing water-cooled aluminum cables. The LER requires a similar string but, in this case, only 180 dipoles are on the main bus. One dipole at each end of each LER arc, denoted BL (left of straight, see Fig. 4-17) and BR (right of straight, see Fig. 4-18), is powered differently from the main string; these magnets are on independent busses as shown in Fig. 5-91b. The magnet connections consist of a supply cable and a return cable, with the turnarounds at IR-2 and the supplies at IR-8 (see Figs. 5-91a and 5-91b). Supply and return cables are arranged to cancel the residual field due to the high cable currents. Supply and return cable connections alternate every sector or half-sector to minimize the voltage to ground and to cancel current differences in the bending magnets that would otherwise develop as a result of current leakage to ground through cooling hoses or stray capacitance. The HER bending magnets require a maximum of 660 A, regulated to 0.01%; the main bending magnet string is supplied by two 500-V power supplies connected in series and located at IR-8. For the LER, the maximum current is 850 A, regulated to 0.01%; the main bending magnet string is supplied by four 500-V power supplies, also connected in series and located at IR-8. Two more supplies with the same rating are used for the offset dipole (BL and BR) strings. All these supplies will be refurbished PEP chopper-type supplies, upgraded with new power hardware and controls.

5.4.1.2 Quadrupole Magnet Strings. The quadrupole magnets of both rings fall into three main functional groups: arc quadrupoles; dispersion-suppressor quadrupoles; and straight-section quadrupoles. The straight-section quadrupoles further subdivide into quadrupoles for “normal” straights, injection straights, phase-trombone straights, wiggler straights and the collision straight.

Table 5-25. HER power supplies. In some cases the string voltage is dominated by cable voltage drop.

Magnet string name	Number of magnets	Current per magnet (A)	Voltage per magnet (V)	String voltage (V)	Number of supplies	Power supply rating
Bending magnets	192	660	3.63	457	2	500V/850A
Arc quadrupoles QF	60	100	9.1	280	2	500V/140A
Arc quadrupoles QD	66	140	9.9	338	2	500V/140A
Straight quadrupoles QF	16	110	8.7	70	2	80V/140A
Straight quadrupoles QD	14	110	8.7	62	2	80V/140A
Phase trombone quads QF	16	110	8.7	9	16	15V/140A
Phase trombone quads QD	14	110	8.7	9	14	15V/140A
Suppressor quadrupoles QF	36	95	11.6	17	36	15V/140A
Suppressor quadrupoles QD	36	129	9.4	9	36	15V/140A
Injection quadrupoles QF1	2	95	6.7	13	1	15V/140A
Injection quadrupoles QD2	2	106	7.7	15	1	15V/140A
Injection quadrupoles QF3	2	140	6.5	13	1	15V/140A
Injection quadrupoles QD4	2	500	35.8	99	1	500V/850A
Injection quadrupoles QF5	2	620	44.6	123	1	500V/850A
IR4-IR12 sextupoles SF	48	54	2.4	124	1	500V/140A
IR4-IR12 sextupoles SD	48	90	3.9	202	1	500V/140A
IR12-IR4 sextupoles SF	24	128	5.7	6	24	15V/140A
IR12-IR4 sextupoles SD	24	128	5.7	6	24	15V/140A
Dipole trims	96	12	25	25	96	40V/12A
Corrector vertical bends	144	6	20	20	144	±40V/6A
Corrector horizontal bends	48	6	20	20	48	±40V/6A
IR skew quadrupoles	8	12	25	27	8	40V/12A
Skew quadrupoles	12	12	25	26	12	40V/12A

Table 5-26. LER power supplies. In some cases the string voltage is dominated by cable voltage drop.

Magnet string name	Number of magnets	Current per magnet (A)	Voltage per magnet (V)	String voltage (V)	Number of supplies	Power supply rating
Bending magnets	180	822	6.0	335	4	500V/850A
Offset magnets BL	6	580	4.2	120	1	500V/850A
Offset magnets BR	6	1060	7.8	221	1	500V/1200A
Arc quadrupoles QF	60	87	4.6	290	1	500V/140A
Arc quadrupoles QD	54	87	4.6	263	1	500V/140A
Straight quadrupoles QF	32	87	4.6	161	1	500V/140A
Straight quadrupoles QD	28	87	4.6	143	1	500V/140A
Phase trombone quads QF	16	87	4.6	5	16	15V/140A
Phase trombone quads QD	14	87	4.6	5	14	15V/140A
Suppressor quadrupoles QF	36	87	4.6	5	36	15V/140A
Suppressor quadrupoles QD	48	87	4.6	5	48	15V/140A
Injection quadrupoles QF1	2	31	2.2	5	1	15V/140A
Injection quadrupoles QD2	2	35	2.6	6	1	15V/140A
Injection quadrupoles QF3	2	56	4	9	1	15V/140A
Injection quadrupoles QD4	2	164	11.9	26	1	30V/200A
Injection quadrupoles QF5	2	200	13	29	1	30V/200A
Wiggler quadrupoles QF	8	140	7.8	10	8	15V/140A
Wiggler quadrupoles QD	7	130	7	9	7	15V/140A
IR4-IR12 sextupoles SF	48	56	3.5	177	1	500V/140A
IR4-IR12 sextupoles SD	48	56	3.5	177	1	500V/140A
IR12-IR4 sextupoles SF	24	56	3.5	4	24	15V/140A
IR12-IR4 sextupoles SD	24	56	3.5	4	24	15V/140A
Wiggler magnets	4	1800	300	602	2	620V/1800A
Wiggler bend magnets	8	750	5.4	40	2	40V/800A
Dipole trims	96	12	25	26	96	40V/12A
Corrector vertical bends	144	6	20	22	144	±40V/6A
Corrector horizontal bends	48	6	20	22	48	±40V/6A
IR skew quadrupoles	8	12	25	26	8	40V/12A
Skew quadrupoles	12	12	25	26	12	40V/12A

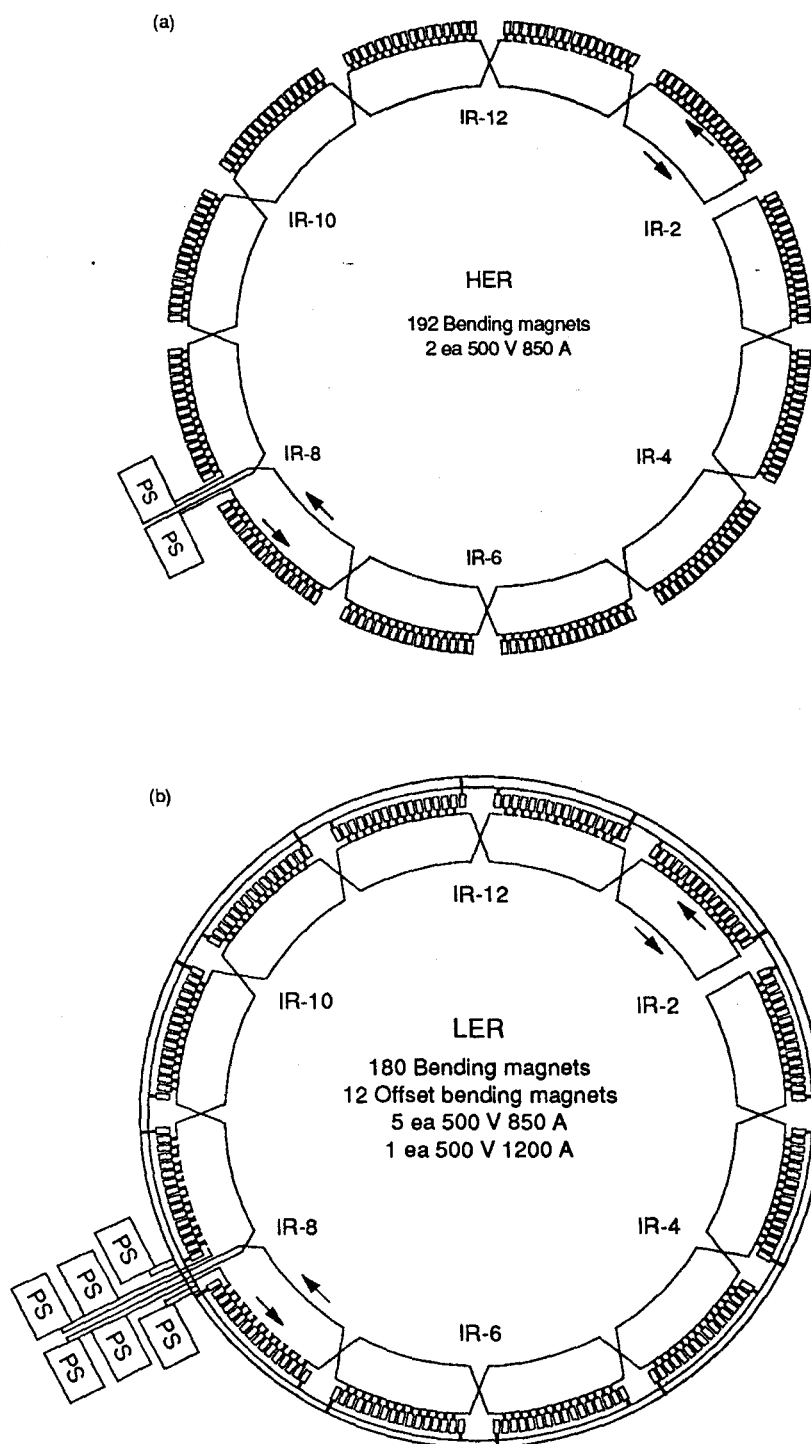


Fig. 5-91. Schematic of magnet and power supply connections for (a) the HER and (b) the LER bending magnet strings.

Arc Quadrupoles. The six arcs of each ring each have 12 horizontally focusing quadrupoles, QF, and 11 vertically focusing quadrupoles, QD, giving 72 QF and 66 QD quadrupoles in total. To help in tailoring the arc dispersion function in the HER, one QF quadrupole at each end of each arc needs to be independently powered. For similar reasons, in the LER there is one QF quadrupole and one QD quadrupole at each end of each arc that is independently powered. Figure 5-92a shows the circuits for the 60 QF and 66 QD magnets of the HER arc strings. Figure 5-92b shows the circuit powering the 60 QF and 54 QD quadrupoles of the LER that are on the main bus.

The main quadrupole busses for the two rings will use existing aluminum cables and do not require water cooling. The two cables will be powered with current flowing in opposite directions so as to help in cancellation of stray magnetic fields. The main arc quadrupoles require an operational current of 140 A (for the HER) and 90 A (for the LER), regulated to 0.01%, at a maximum of 350 V. These supplies will be refurbished PEP choppers, operating from the same DC supply as the bending magnet supplies. The independently powered quadrupoles at the ends of the arcs in the HER and LER are included in the dispersion-suppressor quadrupoles (see below).

Dispersion-Suppressor Quadrupoles. For the HER, the dispersion suppressors at both ends of each of the six arcs contain 6 quadrupoles, three vertically focusing and three horizontally focusing, giving 36 QD and 36 QF quadrupoles in all. Each of these magnets is powered by an independent 140-A power supply, regulated to 0.1%. The supplies are switching-type DC-to-DC converters, each locally mounted on the magnet girder and powered from a ring DC cable. Existing aluminum cables will be used for the DC source and will be powered from current-limiting regulated supplies (Fig. 5-93a) in buildings at IR-12, IR-8 and IR-4.

In the LER, the dispersion suppressors must occupy three full cells at each end of the arcs. (This is why the main LER quadrupole strings, QF and QD, have only 10 and 9 magnets per arc, respectively, or 60 and 54 magnets in all.) The LER dispersion suppressor quadrupoles, 36 QF and 48 QD magnets, have independent power supplies similar to those in the HER (see Fig. 5-93b).

Straight-Section Quadrupoles. The quadrupoles in the normal straight sections of the HER are arranged into FODO cells similar to those of the arcs (that is, they have the same cell length and phase advance, but the dipoles are absent). In the HER, normal straight sections are in regions 12 and 4 (these regions being where the RF for the HER will be located). The LER has no normal straights as such—every straight is required for some special purpose. The normal straight sections for the HER each utilize 8 QF and 7 QD quadrupoles (see Fig. 5-94a). The QF and QD magnets are connected in two strings, each powered in series from a supply having an operating current of 140 A, regulated to 0.01%, at a maximum of 70 V. These commercially procured, current-regulated supplies will be installed in the IR-12 and IR-4 support buildings.

The injection straight sections are in region 8 (for the LER, Fig. 5-94b) and region 10 (for the HER, Fig. 5-94a); they are configured identically for both rings. Each is symmetrical about its center, having a triplet structure (QF1, QD2, QF3) close to the arc and a doublet structure (QD4, QF5) nearer the center. Each of the five independent supplies for one ring feeds one pair of magnets located symmetrically on the two sides of

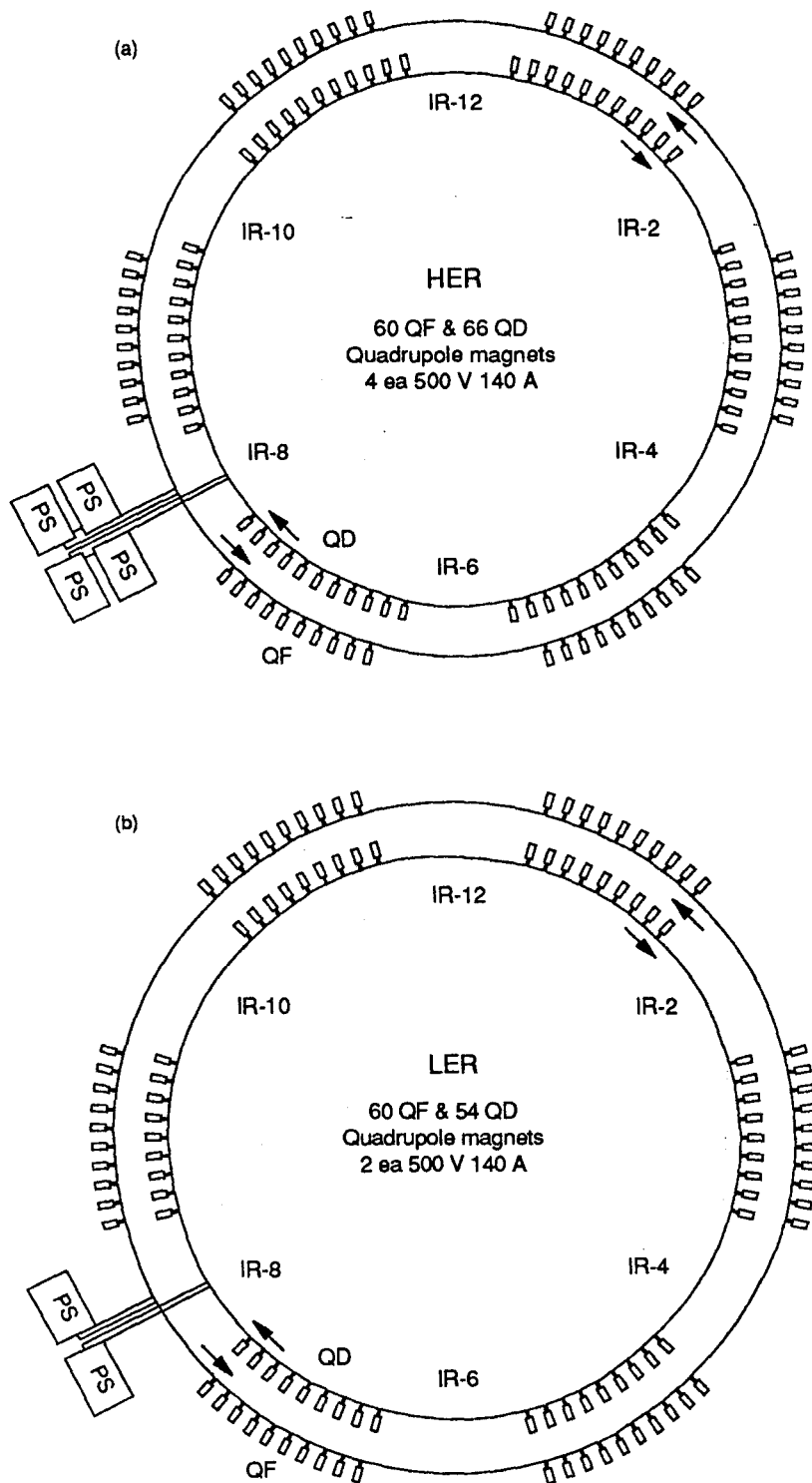


Fig. 5-92. Schematic of magnet and power supply connections for (a) the HER and (b) the LER arc quadrupole magnet strings.

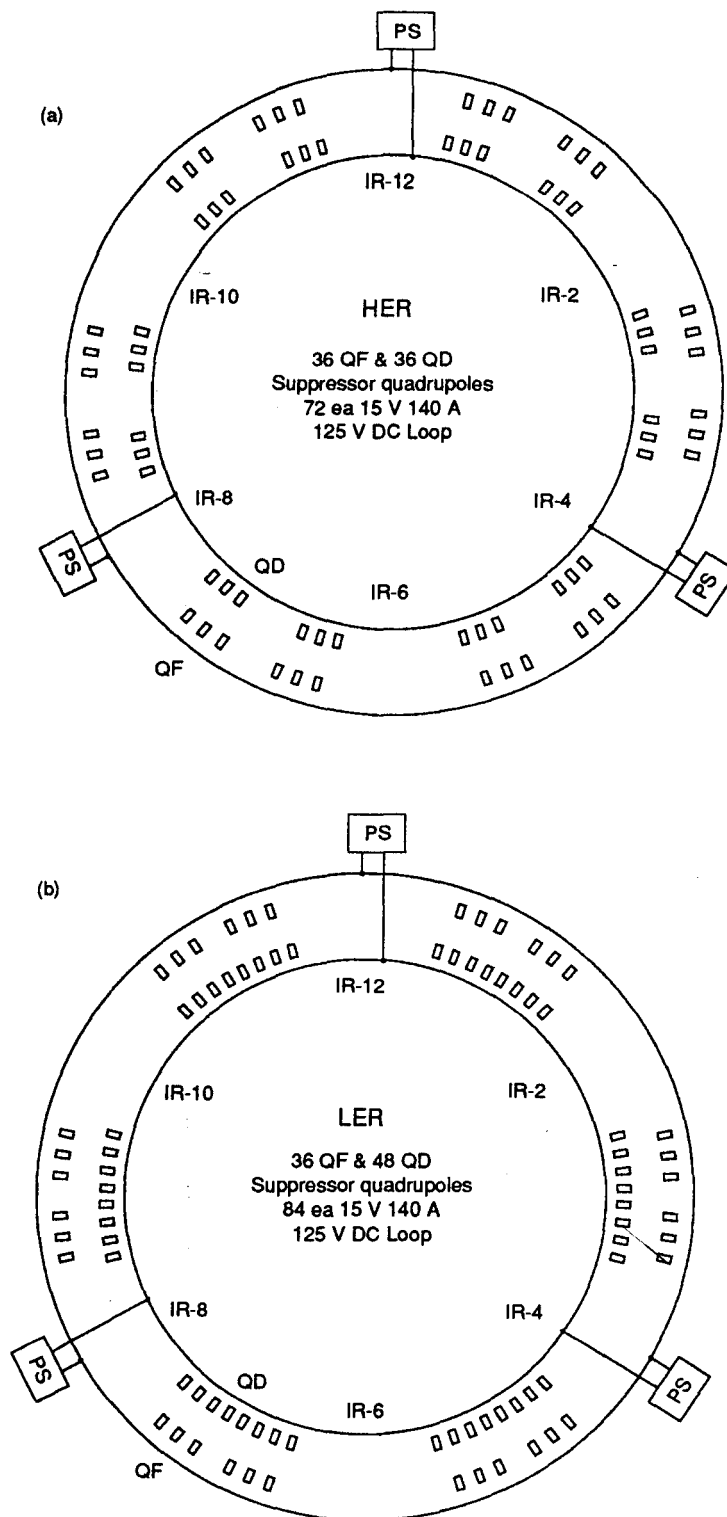


Fig. 5-93. Schematic of magnet and power supply connections for (a) the HER and (b) the LER suppressor quadrupole magnet strings.

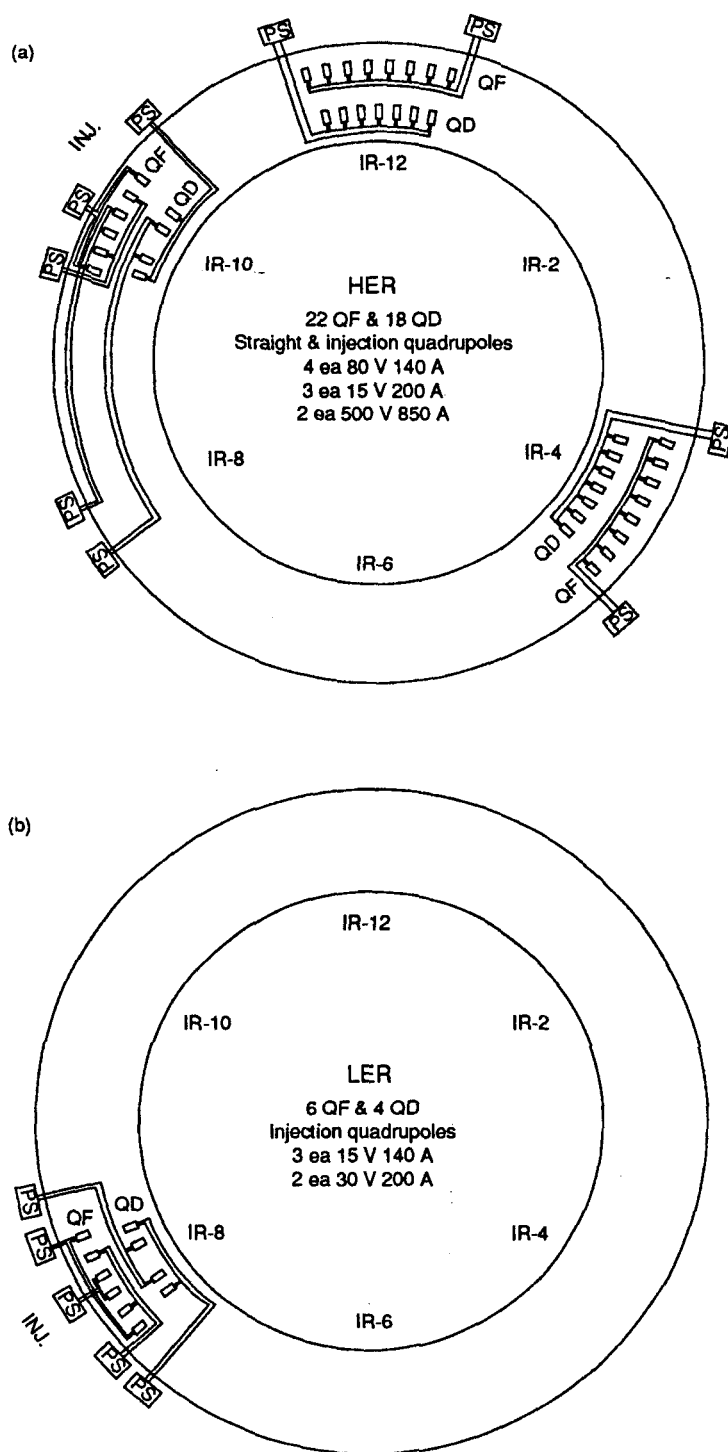


Fig. 5-94. Schematic of magnet and power supply connections for (a) the HER straight-section and injection quadrupole magnet strings and (b) the LER injection quadrupole strings.

the straight. The triplets will be powered by commercially procured, current-regulated supplies, regulated to 0.01%, that will be installed in their respective injection IR service buildings. The QD4 and QF5 quadrupoles will be connected to refurbished PEP chopper supplies (located in IR-8) in the same way as the arc quadrupoles. Existing cable (that will not need water cooling) between IR-8 and IR-10 will be used for the QD4 and QF5 quadrupoles in the HER injection straight section.

Each ring has two straight sections devoted to changing the betatron tunes of the machine. These "phase trombones" are located in regions 6 and 8 for the HER, and in regions 4 and 10 for the LER. (The LER RF cavities will share region 4 with the LER phase trombone.) The phase trombones consist of regularly spaced quadrupoles, as in the normal straights, but with each having an independent power supply identical to those for the dispersion-suppressor quadrupoles. There are then 15 power supplies for a total of 8 horizontally focusing and 7 vertically focusing quadrupoles in each region, as shown in Figs. 5-95a and 5-95b. Because one of the phase-trombone sections of the LER must coexist with the RF cavities, it is important to ensure smooth beta functions in this region.

In addition to the above functions, the LER has two straight sections (regions 6 and 12) devoted to control of beam emittance and damping via strings of wiggler magnets. A pair of dipoles on each side of the straight section, powered antisymmetrically about its center, provides the orbit dogleg and dispersion function for the emittance control (see Sections 4.1.2.5 and 5.2.6). Fifteen independently powered quadrupoles provide the necessary control of the beta functions (Fig. 5-96).

5.4.1.3 Sextupole Magnet Strings. The sextupoles of the HER comprise two sets, one between IR-4 and IR-12 and a second centered around the interaction region at IR-2. The first set of sextupoles is connected in two strings, one of 48 focusing sextupoles and a second of 48 defocusing sextupoles; these are shown in Fig. 5-97. The nominal operating current for these sextupole families is 130 A, regulated to 0.1%, at approximately 300 V per magnet string. The supplies will be refurbished PEP choppers operating from the same DC supply used for the bending magnets. The second set of sextupoles, which occupies arcs 1 and 3, includes 24 focusing and 24 defocusing magnets, each powered by an independent 140-A power supply (see Fig. 5-98). These supplies are switching-type DC-to-DC converters, each locally mounted and powered from a ring DC cable, just like those for the quadrupole DC-to-DC converters.

In particle tracking simulations done so far, the sextupoles of the LER have been grouped into just two families, consisting of 54 focusing and 54 defocusing sextupoles. To preserve flexibility, we plan to provide power supplies for the LER sextupoles just as described for the HER. For the LER, however, the nominal operating current of the sextupoles is only 60 A at 130 V.

5.4.1.4 Trim Magnet and Corrector Strings. Each bending magnet incorporates backleg windings, 96 of which are powered in each ring by backleg trim power supplies. The powering requirements for the backleg windings are less than 12 A, regulated to 0.1%, at approximately 25 V. There will be an induced voltage of not greater than 10 V on the backleg trim supplies when the bending magnets are energized or deenergized. The trim supplies are switching-type unipolar supplies, mounted in the tunnel in groups of eight or more independent supplies per cabinet. Control is supplied by way of a single

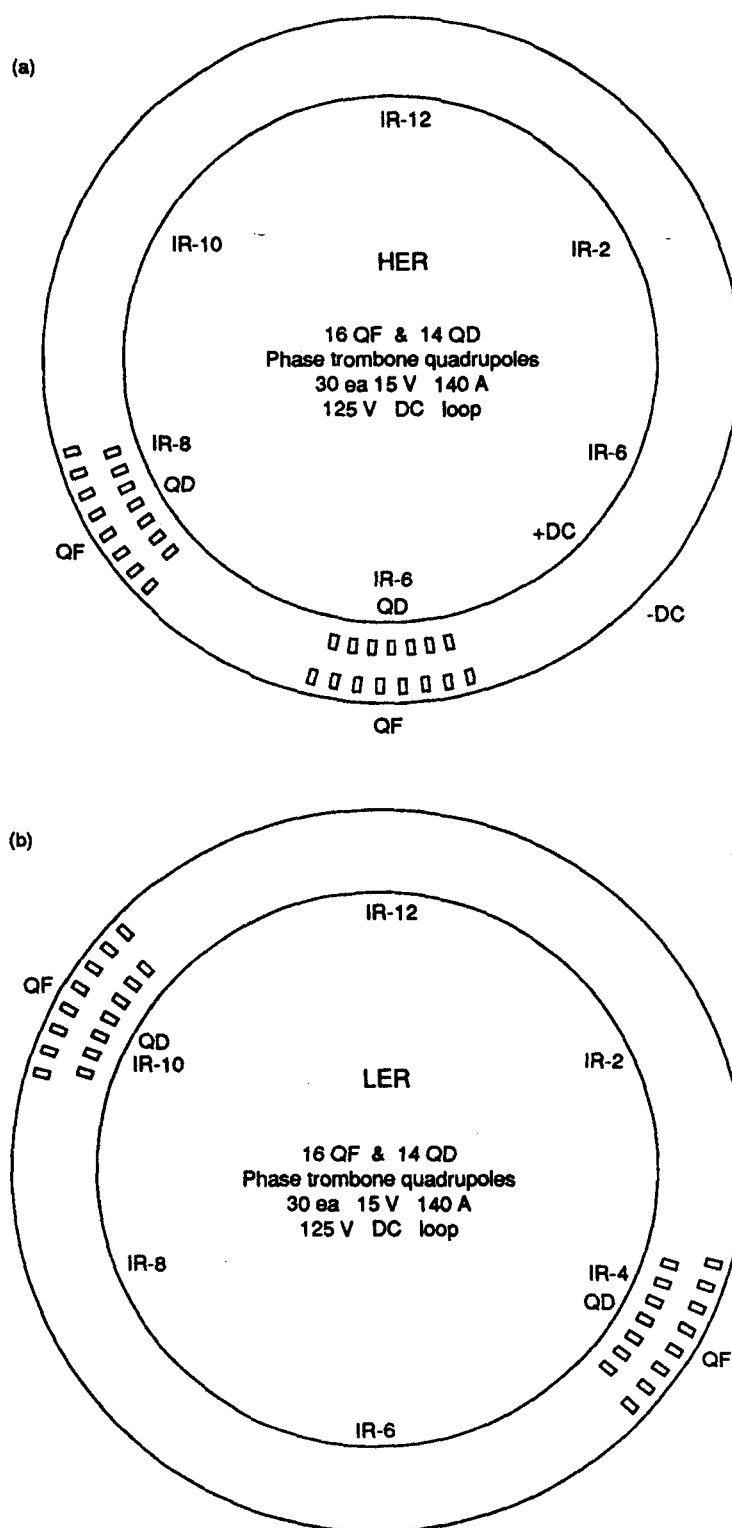


Fig. 5-95. Schematic of magnet and power supply connections for (a) the HER and (b) the LER phase trombone quadrupole magnet strings.

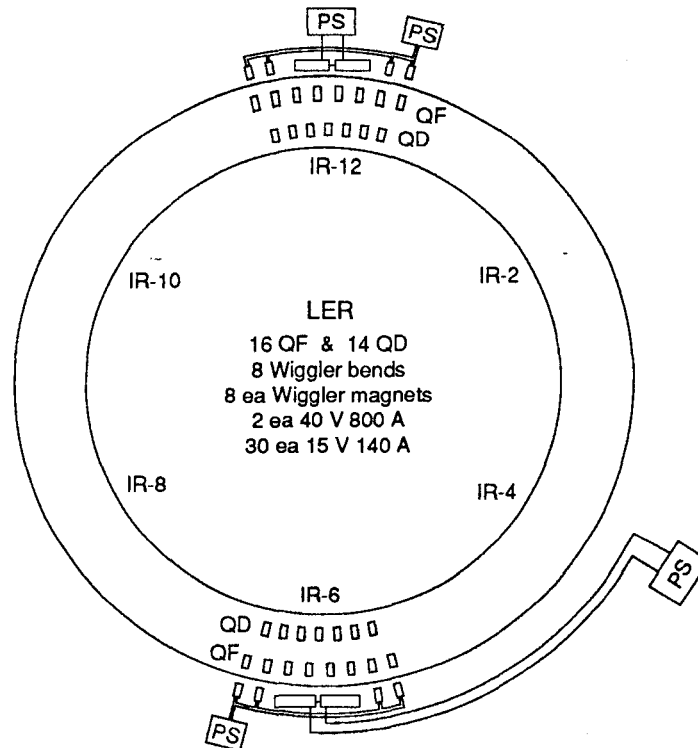


Fig. 5-96. Schematic of magnet and power supply connections for the LER wiggler, wiggler bending magnet, and wiggler quadrupole strings.

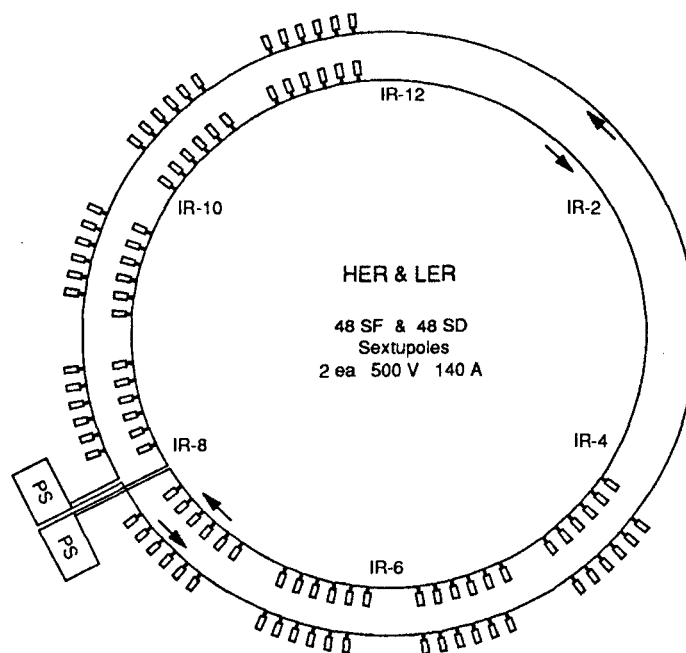


Fig. 5-97. Schematic of magnet and power supply connections for the normal sextupole magnet strings of both the HER and LER.

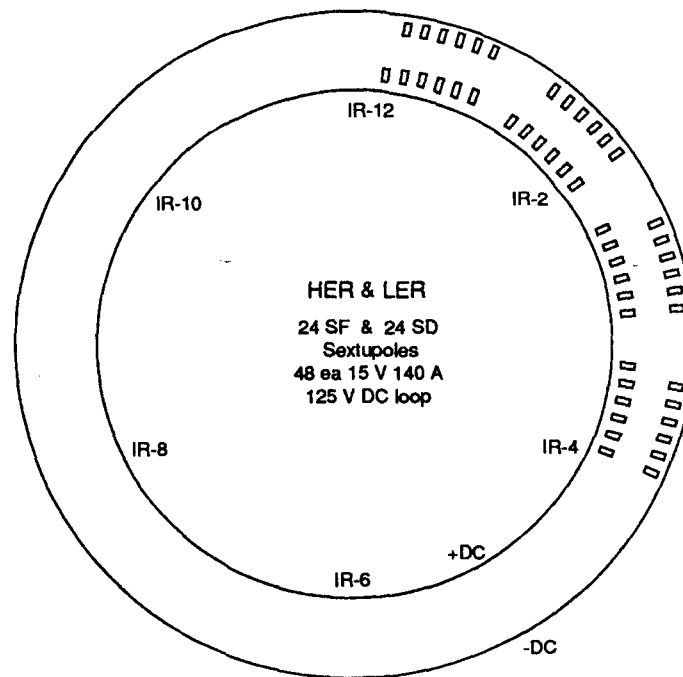


Fig. 5-98. Schematic of magnet and power supply connections for the sextupole magnet strings surrounding the IR, for both the HER and LER.

serial transmission line around the ring. The supplies are DC-to-DC converters, obtaining their power from a DC cable loop around the ring, powered in turn by current-limiting supplies in buildings at IR-12, IR-8, and IR-4 (see Fig. 5-99). Additional trim supplies are used to power 20 skew quadrupoles distributed around each ring.

There are also 144 vertical corrector magnets and 48 horizontal corrector magnets in each ring. The corrector supplies are switching-type, bipolar, two-quadrant supplies, powered from the same DC cable loop and mounted in the same enclosure as the trim supplies. The magnet requirements are ± 6 A, regulated to 0.1%, at 20 V maximum. Control is as described for the trim supplies.

5.4.1.5 Wiggler Magnets. The LER will have four wiggler magnets located in IR-6 and IR-12. These magnets will require 1800 A at 300 V (Fig. 5-96). The two booster supplies for the PEP bending magnets will be reworked in the same way as the bulk supplies for the choppers and used to power the wiggler magnets. The supplies are located in IR-12 and IR-4. Existing water-cooled aluminum cables will be used to power the wigglers.

5.4.1.6 Refurbishing the PEP Chopper Supplies. The existing PEP chopper power system will be reworked for use in the B Factory. The 12-kV switchgear, rectifier transformers, and SCR-controlled DC converters will be reused, after being totally reconditioned. All equipment will be thoroughly inspected and cleaned, connections will be remade, and all parts subject to aging will be replaced. The controls of the DC supplies will be redesigned and rebuilt. The chopper supplies themselves will be redesigned and refurbished to make them more reliable and accessible, and where

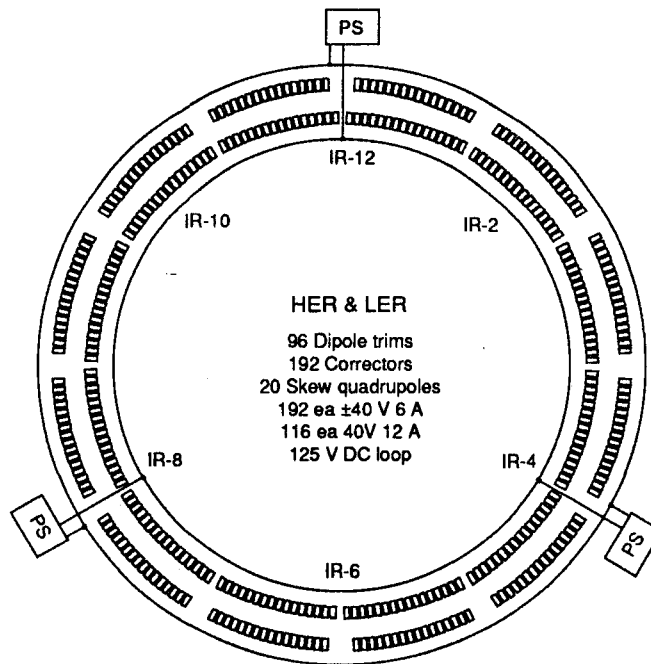


Fig. 5-99. Schematic of magnet and power supply connections for the trim dipole, skew quadrupole, and corrector strings for both the HER and LER.

practical they will be built with redundancy. The present SCR switches will be upgraded with modern switching devices, and the chopping frequency will be increased to improve the overall performance. Where practical, more than one chopper will be operated in parallel, designed and rated such that a single-point failure of power equipment or controls will not result in equipment shutdown.

The possibility of on-line replacement of failed equipment will be investigated to determine if it is practical and safe to incorporate this feature into the design, to improve the up-time of the supplies. Improved EMI filtering will be incorporated into the supplies to reduce noise. The choppers will be redesigned with all-digital computer controls to enhance performance and flexibility. The B Factory requires two sizes of chopper: one rated at 500 V (maximum) at 850 A (maximum) for the bending magnets and a second rated at 500 V (maximum) at 140 A (maximum) for the quadrupoles and sextupoles.

5.4.1.7 Quadrupole and Sextupole DC-to-DC Supplies. A DC-to-DC power supply will be developed for the quadrupoles and sextupoles that are to be operated individually. The supplies will be rated for 15 V at 140 A and will operate from a DC cable of approximately 120 V DC. The supplies will be designed to operate with a switching frequency greater than 20 kHz and will incorporate step-down transformers for magnet ground isolation and DC breakers for DC source isolation and protection. The supplies will be installed individually in the tunnel at locations adjacent to the magnets being supplied. There will be more than one switching system operating in parallel, such that in the event of a single-point failure the supply will continue to operate without interruption. The supplies will be designed to be readily replaceable, to reduce downtime. All-digital microcomputer controls will be connected in a serial transmission line running around the

tunnel for control and monitoring of the individual supplies. Each supply will have a local current monitor and regulator.

5.4.1.8 Trim and Corrector DC-to-DC Supplies. Trim and corrector DC-to-DC switching-type power supplies will also be developed (see Fig. 5-99). The trim supplies are unipolar, rated for 12 A at 40 V maximum. The bipolar, two-quadrant corrector supplies are rated for 6 A at 40 V. Both the trim and the corrector supplies operate from a DC cable of approximately 120 V DC. The supplies will be designed to operate with a switching frequency above 20 kHz and will incorporate an isolation step-down transformer for magnet ground isolation. The supplies will be installed in clusters of eight or more, and will be distributed around the tunnel at locations selected to minimize cabling costs. The supplies will be mounted in cabinets that will service both the HER and LER. Supply clusters will have DC breakers for DC source isolation and protection. The supplies will be plug-in types to allow easy replacement and thus reduce facility downtime. All-digital microcomputer controls will be connected to a single serial transmission line running around the tunnel for control and monitoring of the individual supplies.

5.4.2 Interaction Region Power Supplies

The magnetic devices at the heart of the interaction region are made of permanent magnet material and require no power supplies. To permit energy variations, however, there will be trim windings associated with these magnets (B1, Q1, Q2, Q3) that will require small supplies. The septum quadrupoles of the HER (QD4 and QF5), which focus the high-energy beam, are special magnets with special power supplies. The remaining IR power supply requirements for the HER are relatively straightforward. One supply powers the string of B2 weak bends on each side of the IP and another supply powers a similar string of B3 bends, each string (see Fig. 4-12) having four magnets. One supply powers the two B4 dipoles on each end of the straight, and two supplies are needed for the single QD6 and QF7 quadrupoles on each side of the IP (see Fig. 4-10).

The LER is much more complicated and power supplies are needed for many quadrupole and dipole magnets, including the vertical bending magnets and the horizontal magnets to align the collision axis. The complete list of power supplies for the interaction region is shown in Table 5-27. Supplies will all be installed in the existing IR-2 service building, where sufficient AC power is available. With the exception of those for the correctors and trims, all supplies will be commercially obtained and will be regulated to 0.01%. Supplies will be controlled remotely from the B Factory control system. The trim and corrector supplies will be of the type described in Section 5.4.1.8, and will be installed in the tunnel and controlled in the same manner.

5.4.3 Injection Power Supplies

The injection system for the B Factory utilizes the existing SLAC linac to produce positrons and electrons. We expect that no power supply modifications will be required to the present linac to accommodate the new injection system. Most of the linac power

Table 5-27. Interaction region power supplies. In some cases the string voltage is dominated by cable voltage drop.

Magnet string name	Number of magnets	Current per magnet (A)	Voltage per magnet (V)	String voltage (V)	Number of supplies	Power supply rating
HER dipoles B2	8	910	1.0	26	1	30V/1000A
HER dipoles B3	8	910	1.0	26	1	30V/1000A
HER dipoles B4	4	67	0.5	3	1	15V/140A
HER quadrupoles Q4	2	800	14	36	1	40V/800A
HER quadrupoles Q5	2	800	14	36	1	40V/800A
HER quadrupoles Q6	2	212	17	36	1	80V/250A
HER quadrupoles Q7	2	166	13.3	28	1	80V/250A
LER bend BV1	4	146	1.1	7	1	30V/200A
LER bend BV	4	731	5.3	36	1	40V/800A
LER bend B2	2	652	4.7	22	1	40V/800A
LER bend B3	2	139	1.0	5	1	15V/140A
LER bend B4	2	107	0.8	4	1	15V/140A
LER bend B5	2	25	0.2	2	1	15V/140A
LER bend B6	2	171	1.3	13	1	30V/200A
LER quadrupoles QF4	4	147	7.7	32	1	80V/250A
LER quadrupoles QVDD	4	158	12.7	52	1	80V/250A
LER quadrupoles QVF	4	219	17.5	72	1	80V/250A
LER quadrupoles QVD	4	219	17.5	72	1	80V/250A
LER quadrupoles QD8	2	164	8.5	19	1	30V/200A
LER quadrupoles QF9	2	164	13.2	27	1	30V/200A
LER quadrupoles QD10	2	105	9.7	20	1	30V/200A
LER quadrupoles QF11	2	76	4.5	9	1	15V/140A
LER quadrupoles QD12	2	116	5.1	11	1	15V/140A
LER quadrupoles QF13	2	105	5.6	12	1	15V/140A
Corrector vertical bend	16	6	20	20	16	±40V/6A
Corrector horizontal bend	16	6	20	20	16	±40V/6A
Quadrupole trims	11	12	25	18	15	40V/12A

supplies were either installed or upgraded during construction of the SLC. In addition, power supplies will be available from the SLC final focus and arc systems for the B Factory. The available supplies comply with SLC standards and are of the same age and condition as the rest of the SLC linac. We will therefore recondition and reuse as many of the SLC final focus and arc supplies as possible for the B Factory injection system. Power supply requirements for the injection system are listed in Table 5-28.

The B Factory injection power supply system can be divided into five parts: electron extraction, positron extraction, beam transport, NIT and SIT lines, and the kicker system. All of the power supplies except those for the kickers will be installed in the klystron gallery and will be controlled and operated by the SLC control system. Standard SLC equipment and procedures will be used throughout.

5.4.3.1 Electron Extraction System. The electron extraction system consists of two pulsed bending magnets connected in series, two bending magnets at the entrance to the NIT line, and 24 quadrupole magnets. The pulsed bending magnets require approximately 250 A at 750 V. The present SLC pulsed dump supplies are available for these magnets. The two-dipole string that directs the electron beam to the NIT line operates at 110 A; available SLC final focus supplies will be used for these magnets, along with existing SLC control interface equipment. There will be two strings of 8 quadrupoles, each operating from its own 6-A, 300-V supply. In addition, there will be two groups of 4 individually powered quadrupoles supplied by standard SLC power supplies (available from the final focus).

5.4.3.2 Positron Extraction System. The positron extraction system includes a bending magnet chicane composed of five bending magnets connected in series, a two-bending-magnet string, and 24 quadrupoles. The five-dipole string requires approximately 110 A at 120 V; the two-dipole string also operates at 110 A. For these strings, available SLC final focus supplies will be used with existing SLC control interface equipment. There will be two strings of 8 quadrupoles, each operating from its own 6-A, 300-V supply. In addition, there will be two groups of 4 individually powered quadrupoles supplied by standard SLC power supplies (available from the final focus).

5.4.3.3 Beam Transport. The positron beam transport system, consisting of two strings of 26 quadrupoles, connected in series, requires 6 A at 150 V per string. Available commercial power supplies, interfaced to the SLC control system, will be used. Requirements and provisions for the electron beam transport system, consisting of two strings of 22 quadrupoles, are identical. In addition, the beam transport systems include 120 individually controlled trim magnets, operating at 6 A maximum at approximately 12 V. The necessary supplies are available from the SLC final focus and are interfaced to the SLC control system.

5.4.3.4 NIT and SIT Lines. The NIT and SIT lines will be electrically connected as they were for PEP; however, all power supplies will be replaced by supplies available from the SLC final focus and arcs. A small number of the NIT supplies now located in Buildings 685 and 705 will be relocated to Sector 30, so that all of the NIT and SIT supplies can be easily controlled by the SLC control system.

Table 5-28. Injection power supplies.

Magnet string name	Number of magnets	Current per magnet (A)	Voltage per magnet (V)	String voltage (V)	Number of supplies	Power supply rating
Positron chicane bend magnets	5	110	23	127	1	150V/200A
Positron down bend magnets	2	110	23	51	1	80V/375A
Positron quadrupoles	16	6	10	100	2	300V/6A
Positron quadrupoles	8	6	10	11	8	SCOR6,25A
Electron pulsed bend magnets	2	250	750	1500	1	Dump pulser
Electron up and top bend magnets	2	110	22	48	1	80V/375A
Electron down bend magnets	2	110	23	51	1	80V/375A
Electron quadrupoles	16	6	10	100	2	300V/6A
Electron trims	8	6	10	11	8	SCOR6,25V
Bypass positron quadrupoles	52	6	5	143	2	250V/20A
Bypass electron quadrupoles	44	6	5	121	2	250V/20A
Bypass trim dipoles	120	6	10	11	120	HCOR12,35A
NIT electron bend magnets	11	570	5	12	5	30V/800A
NIT quadrupoles	24	62	7.1	62	3	100V/200A
NIT vertical bends	1	75	13	14	1	50V/200A
NIT dipole trims	16	14	16	18	16	HCOR12,35A
NIT new quadrupoles	4	62	7.1	8	4	20V/125A
NIT trim dipoles	4	6	12	13	4	SCOR6,25V
NIT septum	1	600	40	44	1	100V/600A
HER kicker magnets	2	1100	11 kV	11 kV	2	
HER pulsed septum	1	1100	18.2 kV	18.2 kV	1	
SIT positron bend magnets	10	230	2	4	5	45V/450A
SIT quadrupoles	24	25	2.8	25	3	30V/100A
SIT vertical bends	1	30	5.2	6	1	30V/100A
SIT dipole trims	16	5.8	6	7	16	SCOR6,25V
SIT new quadrupoles	4	25	2.8	3	4	20V/90A
SIT trim dipoles	4	6	12	13	4	SCOR6,25V
SIT septum	1	600	40	44	1	100V/600A
LER kicker magnets	2	600	5.8 kV	5.8 kV	2	
LER pulsed septum	1	600	9.7 kV	9.7 kV	1	

5.4.3.5 Injection Kicker System. The PEP kicker magnet modulator supplies will be redesigned and rebuilt at SLAC for the HER and LER. The kicker system for each ring consists of three kicker magnets. The current rise time for the magnet must be less than 200 ns, and the fall time less than $1.5 \mu\text{s}$. Two of the kickers will operate at the same amplitude, while the third will be adjusted independently. Therefore, only two independent kicker modulators are required for each ring.

The kicker modulator design uses a capacitor that is pulse-charged to the required 10–20 kV, then discharged into the kicker magnet by use of a thyatron. A terminating resistor is provided to damp the discharge and thus avoid ringing in the magnet. The kicker modulator will be connected to the kicker magnets by coaxial cables with an impedance of approximately 12Ω . This type of kicker modulator is currently being used in the SLC final focus dump system. The kickers will be controlled by the B Factory control system.

5.5 RF SYSTEM

The design of the B Factory RF system is governed by the requirement that the system be as conservative and reliable as possible, despite the increased demands associated with the high luminosity. In this section, we describe the design for the RF system and indicate the basis for our technical choices.

The B Factory RF system must fulfill the following requirements:

- Provide sufficient voltage to maintain acceptable quantum lifetime and suitable bunch length
- Provide sufficient power to compensate for the losses due to synchrotron radiation and losses into higher-order modes (HOMs)
- Provide a suitable low-impedance environment for the beam

All of these requirements are common to every collider and storage ring RF system and do not in themselves drive us into uncharted territory as far as RF system design is concerned. The noteworthy difference in the case of the B Factory is associated with the very large beam current that must be supported—an order of magnitude higher than in present colliders.

The choice of frequency is driven by the need to produce short bunches and the availability of high-power RF sources. To minimize injection jitter, we have also specified that the storage ring RF systems be harmonically related to the 2856-MHz SLAC linac, which serves as the B Factory injector. We selected a frequency of 476 MHz to meet these needs. This choice provides the required 1-cm bunches with moderate voltage and is a convenient subharmonic of the linac frequency. Moreover, klystrons capable of providing in excess of 1 MW of CW power are available, or can be easily modified to work at this frequency. Because the frequency range near 500 MHz is a common choice for storage rings, it is also a good starting point for the design of the RF cavity, as discussed below.

To provide adequate lifetime, the RF system momentum acceptance $\Delta p/p$ (the “bucket height”) should be of the order of $10\sigma_E/E$. For our parameters (see Table 4-1), this calls for a bucket height of 0.6% in the HER and 1% in the LER. A more stringent voltage requirement arises from the need to provide short bunches, $\sigma_z = 1$ cm, to avoid luminosity losses associated with the beam-beam interaction (for example, excitation of synchrotron resonances, as discussed in Section 4.4). This requires a voltage of 18.5 MV for the HER and 9.5 MV for the LER at our chosen frequency of 476 MHz.

The power requirements are most severe for the HER. Here, the energy loss per turn due to the emission of synchrotron radiation is 3.58 MeV. At the nominal operating current of 1.48 A, the total power that must be provided to the beam is 5.3 MW; miscellaneous losses, such as resistive-wall heating and HOM losses, add to this value. If the number of cavities were not a concern, the power could simply be distributed over sufficiently many RF cells that it did not become a technology issue.

Unfortunately, the RF cells contribute considerable impedance to the ring and can lead to either single-bunch or coupled-bunch instabilities, as discussed in Section 4.3.

Although single-bunch instabilities are not predicted to limit the performance of the B Factory collider, HOMs of the RF cavities, driven by the intense beams, are expected to give rise to wakefields that cause potentially severe longitudinal and transverse coupled-bunch instabilities. This aspect could easily limit the performance of the B Factory and must be avoided, or at least mitigated, in the design of the RF system.

In practice, this means that the total impedance presented by the RF cavities should be kept as low as possible. To minimize the HOM impedance, we keep the number of cavities small and we adopt single-cell cavities, rather than multicell structures of the type used in PEP. (In multicell structures, the number of possible modes is multiplied by the number of cells, as compared with the modes of a single cell.) In consequence, the single cells must operate at high accelerating fields to provide the required voltage and must provide high power to the beam. Even with these precautions, the cavity HOMs must be damped substantially to reduce their shunt impedance to acceptably low values, and a number of feedback systems must be employed to combat the effects of the coupled-bunch instabilities.

The B Factory RF system could employ either room-temperature or superconducting cavities. Because about 60% of the RF power is delivered to the beam, only a small reduction of installed RF power could be realized by using superconducting technology (at the cost of increased complexity associated with the required cryogenic systems). Furthermore, the technology of providing a large input power and removing a large HOM power in a superconducting environment is not yet in hand. For these reasons, and because the expertise at SLAC and LBL is mainly in conventional room-temperature RF systems, an approach using copper cavities was chosen.

The filling pattern adopted for our collider design places the beam bunches in every other RF bucket throughout 95% of the circumference, with a 5% gap in the bunch train to avoid trapping ions in the HER beam. Thus, out of the 3492 possible RF buckets in each ring, 1658 are filled with beam. The same filling pattern for both rings minimizes asymmetries in the beam-beam collisions, but it may be desirable to add bunches in the positron beam to equalize transients induced in the two RF systems by the beam gaps.

5.5.1 RF System Choices and Requirements

The design of the RF systems is based on the following input parameters for the HER and LER:

- The high luminosity of $3 \times 10^{33} \text{ cm}^{-2} \text{ s}^{-1}$ requires high beam currents: 1.48 A (HER) and 2.14 A (LER).
- The lattice design and beam current determine the power to be delivered to the beam: 6 MW (HER) and 3 MW (LER).
- The low vertical beta functions of 3 cm (HER) and 1.5 cm (LER) at the interaction point require a bunch length of 1 cm, which, in turn, requires a large overvoltage.

Two frequency regimes, 350 MHz and 500 MHz, were initially considered because 1-MW CW klystrons are commercially available at these frequencies. Cavity designs also exist at both frequencies, namely, PEP, LEP, and APS cavities at 350 MHz, and Daresbury, KEK, and ALS cavities at 500 MHz. Because the required overvoltage to

achieve the design bunch length is reduced at higher frequencies, the higher-frequency regime was selected.

As mentioned above, to allow for stable injection with small phase deviations, 476 MHz, a subharmonic of the SLAC linac frequency, was established as the operating frequency for the RF systems of both rings. Contacts with klystron manufacturers indicate that the existing 508-MHz klystron design can be easily modified to operate at 476 MHz.

The cavity design was strongly influenced by the requirement to load HOMs to a very low shunt impedance for beam stability reasons, while simultaneously maintaining a high shunt impedance for the fundamental mode. The scheme for loading the HOMs is a further development of that employed at Daresbury [Corlett, 1989, and Corlett and Hill, 1989] and the ALS [Jacob et al., 1990], and analyzed by Conciauro and Arcioni [1990]. The technique consists of suitably positioning three waveguides on the wall of the cavity, with the waveguides dimensioned to be below cutoff for the fundamental mode while transmitting all unwanted HOMs into dissipative loads. This method of HOM impedance reduction does not restrict the cavity shape in other respects, leaving the designer free to maximize the shunt impedance of the fundamental mode (using a reentrant cavity shape). Thus, a cavity shape similar to the ALS cavity can be used, as shown in Fig. 5-100. The calculated shunt impedance of this ALS-type cavity is $5.3 \text{ M}\Omega$, but, considering all the ports and wall-heating effects, a lower value, say, $3.5 \text{ M}\Omega$, is a more reasonably achievable fundamental-mode shunt impedance in an actual cavity.

The chosen RF system configuration requires each cavity to handle a maximum wall loss of about 150 kW at an accelerating gradient of 4.5 MV/m. It also requires the input

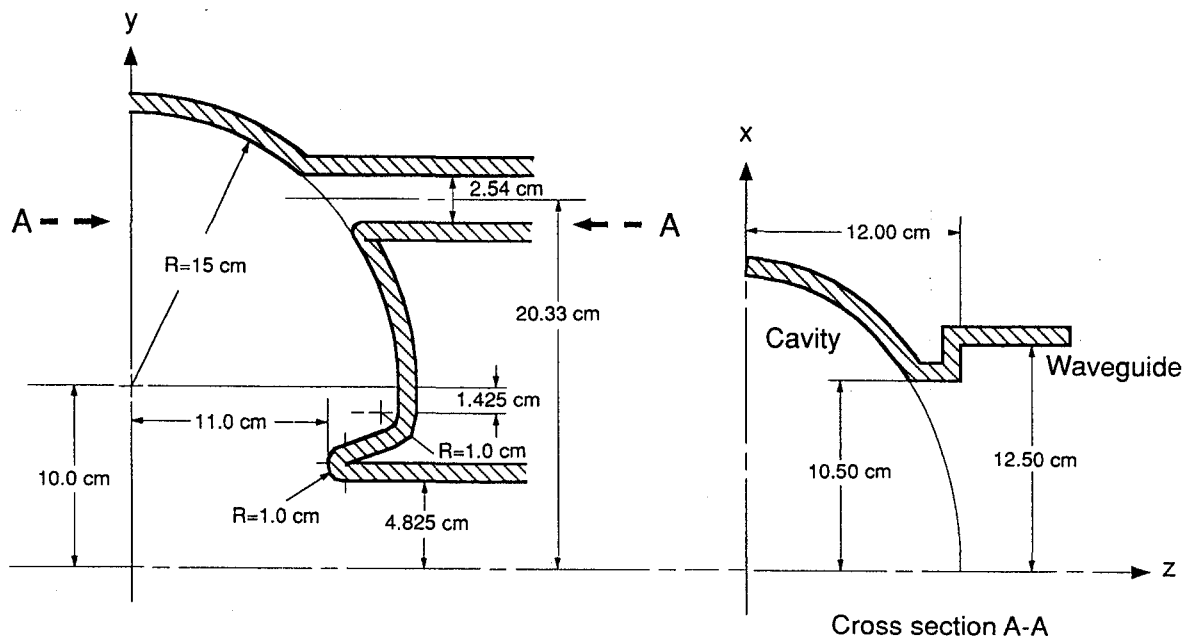


Fig. 5-100. Schematic of a quadrant of the B Factory RF cavity.

window and coupling network for each cavity to carry a power load of almost 500 kW. Both requirements are challenging and will be discussed further in the context of the cavity description. The klystron output power is assumed to be 90% of saturated power to accommodate a capability for overdrive needed by some of the feedback circuits.

Based on the above considerations, the B Factory RF system can meet all requirements with 10 klystron stations, driving 20 cavities, in the HER, and 5 klystron stations, driving 10 cavities, in the LER. The parameters for the RF systems for both rings are summarized in Table 5-29.

5.5.2 Cavity Design

The large synchrotron radiation losses mean that the RF cavities and conventional circuit components, such as windows and couplers, must deliver very high power throughput to the beam. In addition, the large circulating currents make it imperative to keep the HOM impedance as low as possible to avoid uncontrollable coupled-bunch instabilities. Thus, the number of cavities must be a compromise between their power-handling capability and the total beam impedance. The power-handling capability of existing (or reasonably extrapolated) window and coupler technology, and the problem of heat dissipation in the cavity walls and apertures, ultimately limit the power into each cell and thus determine the minimum number of cells that can be used reliably.

5.5.2.1 Choice of Cavity Shape. Preliminary optimization of the cavity shape was done using the URMEL-T code (triangle mesh version). Initially, the mode patterns of open, or “bell-shaped” (Fig. 5-101a), and reentrant (Fig. 5-101b) cavities having the same beam pipe radius and fundamental-mode frequencies were compared. The results clearly demonstrate that, for conventional copper construction, there is no advantage to the open shape as far as the HOM impedances are concerned—in fact quite the opposite. (For superconducting cavities, where the fundamental-mode shunt impedance is very high in any case, there are other advantages to the smooth shape—for example, to reduce the problems of field emission and multipactoring.) With this in mind, we adopted a reentrant cavity design with nose cones, patterned after those used at Daresbury, the Photon Factory, and the ALS.

5.5.2.2 Cavity Parameters. URMEL calculates the transit-time-corrected shunt impedance $R_s (= V^2/2P)$ for the basic reentrant geometry to be about 5.3 M Ω , with an unloaded Q of 45,000 and R_s/Q of 116 Ω . In a real cavity, this impedance is degraded by the addition of ports and damping waveguides and by the effect of increased temperature on the conductivity of the copper. Using MAFIA and ARGUS to compare the fundamental-mode properties with and without damping waveguides suggests a loss of about 10–12% in R_s and Q due to these structures, while R_s/Q stays about constant. Experience with other designs suggests a further 10% will be lost by the addition of the tuner, drive, and other ports.

The degradation due to thermal effects is determined by the effective wall temperature for the maximum power of 150 kW dissipated in the cavity. Extrapolation from existing designs (see Table 5-30), and studies using MAFIA and ARGUS outputs in a thermal model with the ANSYS code, suggest the average temperature rise may be as

Table 5-29. RF system parameters for the B Factory high- and low-energy rings.

Parameter	HER	LER
RF frequency, f_{RF} [MHz]		476
Harmonic number, h		3492
RF voltage, V [MV]	18.5	9.5
Beam current, I [A]	1.48	2.14
Energy loss/turn [MeV]	3.58	1.24
Synchrotron radiation power, P_{SR} [MW]	5.30	2.65
HOM power (est.) [MW]	0.53	0.93
Cavity wall loss, total [MW]	2.44	1.3
Klystron power, total [MW]	10.00	5.0
Number of klystrons	10	5
Klystron power, P [MW]		1.0
Number of cavities	20	10
Shunt impedance/cavity, ^a R_s [M Ω]		3.5
Gap voltage/cavity [MV]	0.93	0.94
Accelerating gradient [MV/m]	4.20	4.3
Wall loss/cavity [kW]	122	130
Coupling factor without beam, β	3.7	3.8
Unloaded Q of cavity		30000
Synchrotron frequency [kHz]	7.1	7.0
Natural bunch length, σ [cm]	1.0	1.0
^a $R_s = V^2/2P$		

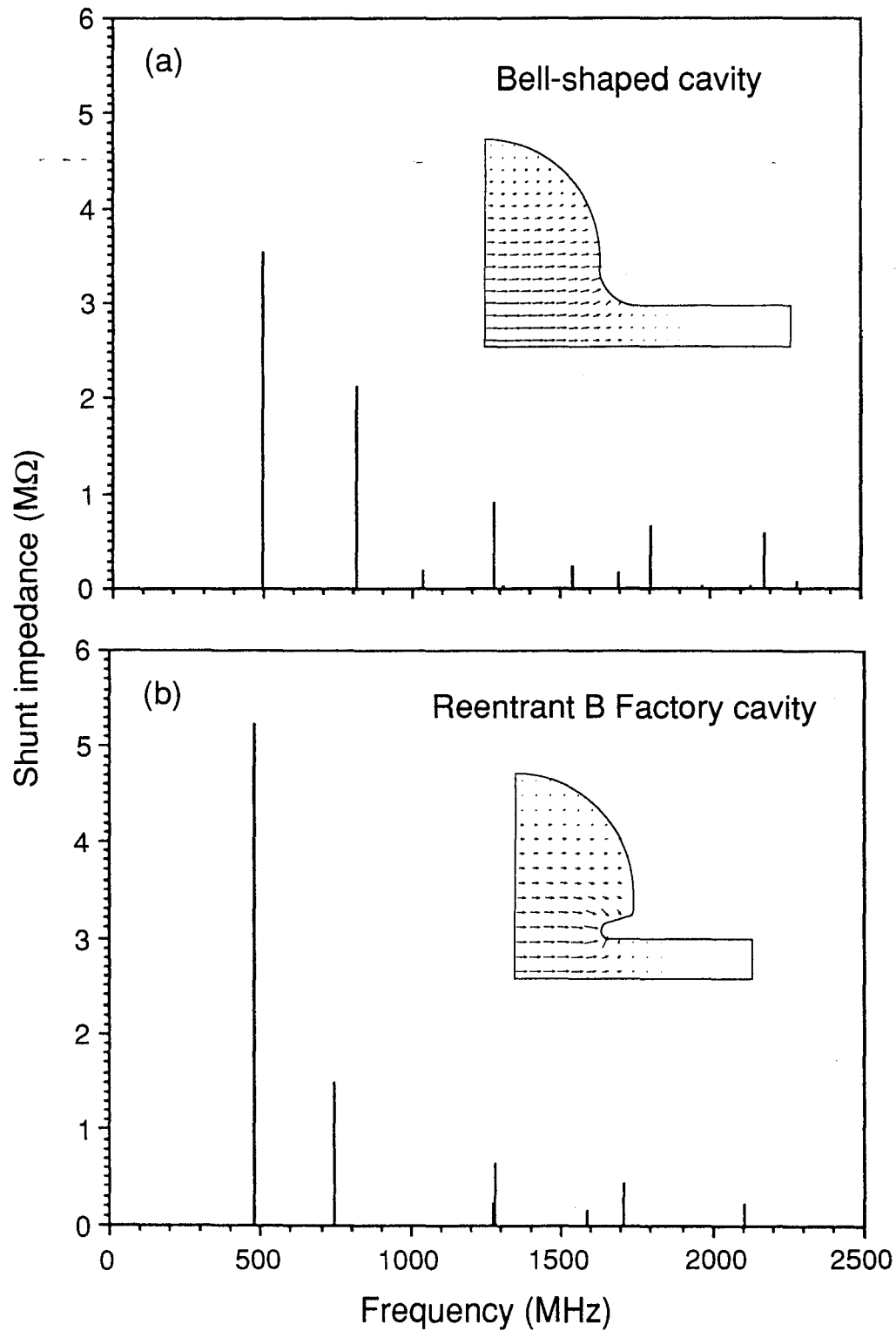


Fig. 5-101. Mode pattern calculated for (a) an open, or "bell-shaped," cavity and (b) a reentrant cavity shape

Table 5-30. Temperature comparison of existing and proposed cavities.

System	Frequency (MHz)	Power (kW/cell)	T_{inlet} (°C)	$\Delta T(\text{H}_2\text{O})$ (°C)	$\Delta T(\text{Cu})$ (°C)	$\Delta T(\text{total})$ (°C)	R_s loss (%)
PETRA cavity ^a	500	24	45	10	18	53	23.3
PEP cavity (Al)	350	50	35	10	15	40	23
LEP cavity ^b	350	25	20	9	12	21	4.2
ALS cavity ^c	500	70	40	3	18	41	~9
B Factory cavity	476	150	35	10	31	56	14

^aGaede et al., 1980^bHenke and Wilson, 1981^cTaylor, 1990

much as 56°C. This would give rise to an additional loss of about 14% in R_s and Q . Lowering the input water temperature by the use of chillers could reduce this, but may not be cost-effective. The result of these cumulative losses is to reduce the practical shunt impedance to about 3.5 M Ω , with a Q of about 30,000.

The coupling to the waveguide is such that a good match can be obtained at the nominal operating currents of 1.48 A (HER) and 2.14 A (LER). This requires a coupling factor β of about 3.7 and results in a loaded $Q_L = Q_0/(1 + \beta)$ of approximately 7000. Both loop- and aperture-type couplers were considered. The loop coupler has the advantage that the coupling may be adjusted mechanically by rotating it, but it is a more complicated structure that must be water-cooled because of the very high surface-current density. An aperture coupler, on the other hand, has the advantages of simplicity and lower surface-current density but has a fixed coupling factor. The usual method of achieving a match with an aperture coupler is to use a tuning stub in the waveguide, usually a sliding short-circuit device. Unfortunately, this may cause practical problems. Therefore, a loop-type coupler was ultimately chosen for the B Factory because of the possible variation in beam currents that must be handled.

Either coupling device requires the use of a vacuum window at some point. At lower power levels, previous designs have incorporated ceramic windows in the construction of the coupler (sometimes with disastrous results), either in the coaxial part of the loop or as a disk filling the coupling aperture. Neither of these designs is suitable for very high power applications, where it is necessary to locate the window well away from the harmful heating of the cavity standing-wave fields. These may penetrate into the waveguide near the coupling point, so it is prudent to locate the window a safe distance away in the waveguide. Such a window then need only survive the heating due to the traveling wave that carries power to the cavity. Designs of this type are currently being

developed by commercial sources. Remote location of the vacuum window requires that the waveguide adjacent to the cavity be part of the cavity vacuum system, which may lengthen the conditioning time and increase pumping requirements. The ceramic window must still be protected against multipactoring, which can be done by using a low-secondary-emission surface coating.

5.5.2.3 HOM Damping. The high beam currents, and therefore the potential for very high coupled-bunch instability growth rates, require that special attention be paid to the HOM impedances of the cavities. To reduce the growth rates to a level where they can be controlled by a technically (and economically) feasible feedback system required careful attention to the issue of HOM damping at an early point in the cavity design. Externally applied damping techniques using tuned couplers have not proved effective enough in existing applications to meet the requirements of the B Factory. Damping waveguides were therefore included in the initial design of the cavity. These waveguides are designed to propagate at the HOM frequencies and are positioned to offer the maximum coupling to the most troublesome HOMs, while being below cutoff and offering minimal perturbation at the fundamental-mode frequency.

The effect of the size, shape, and location of these coupling apertures has been studied experimentally on a simple pillbox structure and computationally using the three-dimensional code MAFIA on both the simple pillbox shape and the B Factory cavity shape. MAFIA results for the B Factory cavity have also been verified by comparison with the ARGUS code where possible. The waveguide apertures will be fabricated by electroforming (along with the tuner, drive, and other coupling ports) when the cavity is constructed. Cooling channels will be added to the outside of the cavity, with particular attention paid to the heat concentration around the orifices of these various structures.

Calculation of the damping effect of these waveguides was carried out with MAFIA, making use of the Kroll-Yu method [Kroll and Yu, 1990]. This method involves calculating the frequencies of the cavity modes modified by waveguides having short-circuits placed at various lengths. This technique is necessary because MAFIA is not capable of solving the complex eigenvalue problem that arises when significant losses are introduced into the model. The validity of this method was demonstrated experimentally by using a pillbox-shaped cavity, to which three waveguides were attached. The results for this pillbox are given in Table 5-31, which shows strong damping of all troublesome higher modes to Q values less than 60. These results agree very well with calculations, especially considering that our terminating loads on the waveguides were less than ideal. Calculations for a similar damping scheme applied to the proposed B Factory cavity shape (see Table 5-32) also produced acceptable reduction of the HOM Q values (for example, the Q of the TM₀₁₁ mode was reduced to 30), with tolerable losses of fundamental-mode impedance and Q (about 12%). If verified by experiment, this HOM damping will result in instability growth rates well within the capability of a reasonable feedback system (see Section 5.6).

The first calculated example of waveguide damping applied to the B Factory cavity shape uses shallow rectangular waveguides with a cutoff frequency of about 600 MHz; this choice allows all of the HOMs to propagate. The first and strongest longitudinal HOM has an unloaded frequency of around 750 MHz, and the cutoff frequency of the damping waveguide must be sufficiently far below this to allow for the frequency drop

Table 5-31. Damping of an aluminum pillbox cavity by three 1 in. $\times$ 6 in. waveguides ($f_c = 786.8$ MHz).

Mode	No waveguides (MAFIA)			Three waveguides				
	Frequency (MHz)	Q	RT^2 (M Ω)	MAFIA/Kroll			Experiment	
				Frequency (MHz)	Q	dQ (%)	Frequency (MHz)	Q
TM010 monopole	617.2	36150	1.66	611	33400	8	609.5	649 ^b
TM011 monopole	868.4	29500	0.88	841	17	(large)	836.2	31
TE111 dipole	711.6	42100	1.29 (M Ω /m) ^a	708	39300	7	704.2	676 ^b
TM110 dipole	909.6	38400	1.34 (M Ω /m) ^a	906	55	(large)	898.8	37
TM111 dipole	1027.2	28000	6.97 (M Ω /m) ^a	1020	28–35	(large)	(not visible)	
TE211 quadrupole	959.9	38400	—	957	54–58	(large)	(not visible)	
TM211 ^c quad	1366.2 (URMEL)	36800	—	—	—	—	1365.8	152

^a R/kr^2 , where r is the beam pipe radius, 0.04825 m [URMEL gives $(R/Q)/(kr_0)^{2m}$].

^bWaveguide load sees evanescent fields of trapped mode.

^cIdentification uncertain.

caused by external loading. The choice of 600 MHz is very conservative, because it also allows the very weak transverse TE mode at 685 MHz to propagate. The required width of this waveguide, 25 cm, is too large to cut directly into the cavity, so a smaller aperture (21 cm) was used, forming an iris into the waveguide (see Fig. 5-100). This solution may lead to practical problems of cooling the surfaces around the iris, where the current density is high. This can be reduced, to some extent, by smoothly blending the edges of the waveguide and iris to remove sharp corners or by using a slightly ridged waveguide design, which can be narrower for the same cutoff frequency, thus eliminating the need for an iris. First indications regarding the feasibility of the second approach are encouraging: The smooth, ridged waveguide solution has a lower fundamental-mode perturbation (about 7%) than does the square guide with the iris, while still offering good coupling to the HOMs.

Table 5-32. Damping of the copper B Factory cavity by three 1 in. $\times$ 10 in. waveguides; $f_c = 599.6$ MHz.

Mode	No waveguides (MAFIA)				Three waveguides (MAFIA/Kroll)					
	Frequency (MHz)	Q	RT^2 (M Ω) ^a	RT^2/Q (Ω)	Frequency (MHz)	Q	dQ (%)	RT^2 (M Ω) ^a	dR (%)	RT^2/Q (Ω)
TM010 monopole	479.9	40003	4.71	117.73	474.6	35248	-12	4.12	-12	117.00
TM011 monopole	750.0	33270	1.35	40.67	745	30	(large)	—	—	—
TE111 dipole	684.5	54844	0.191 (M Ω /m) ^b	—	680	~65	(large)	—	—	—
TM110 dipole	794.3	57762	18.3 (M Ω /m) ^b	—	~795	~73	(large)	—	—	—
^a MAFIA shunt impedance (transit time corrected) ^b R/kr^2 , where r is the beam pipe radius, 0.04825 m										

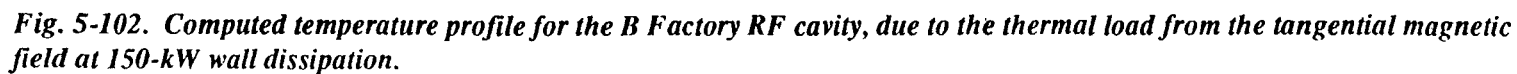
Evanescent penetration of the cavity fundamental mode into the damping waveguides and other apertures gives rise to the possibility of multipactoring. Increasing the number of ports may therefore require a longer conditioning time before the cavity can take full power, and, in some places, the use of low-secondary-emission coatings may be appropriate. A full-power test of a model cavity will be conducted to prove the effectiveness of the damping and cooling schemes under realistic conditions.

5.5.2.4 Mechanical Design. The cavity geometry, including the size and shape of the HOM loading waveguide holes, will be optimized during the final design phase for the B Factory, but proof-of-concept thermal calculations have been carried out with parameters that are considered realistic, and in some cases overly pessimistic. The results clearly indicate that the general design is workable and that, with detailed engineering, a practical cavity will evolve from our present design.

The cooling scheme chosen for the RF cavity is patterned after the ALS cavity; this basically involves two concentric shells, with the space between them serving as the cooling passage. Fins protrude from the surfaces of the shells into the water and thus channel the flow. Based on a bulk temperature rise of 10°C, with 150 kW of power dissipated in the walls, the cooling passage must be able to transport 57 gpm (= 3.6 kg/s) of water without an excessive pressure drop. Because of the relatively large size of the cavity and cooling channels, this is not a difficult criterion. We have calculated the temperature rise and thermal stress due to a thermal load distribution that arises from the tangential magnetic field at the surface of the cavity. The surface temperature, assuming a bulk water temperature of 45°C, is shown in Fig 5-102. Also calculated were the thermal stresses and the stresses induced by atmospheric pressure loading: The maximum combined stress was 3850 psi. The stress analysis showed that the cavity was mechanically strong enough to withstand the combined atmospheric and water pressure load for reasonable pressure drops through the cavity. Note that the water temperature of 45°C is the design value for the outlet water temperature. Figure 5-102 shows that even with this conservative choice of water temperature and with little effort made to mitigate the heating of the nose cone, the present cavity design is a good starting point for further optimization.

Because of the ports for the HOM loading waveguides, there will be concentrations of wall currents, and hence increased thermal loads, around the periphery of the ports. We have conservatively calculated the thermal loads in these locations. (We believe the results to be pessimistic, as they come out of three-dimensional electromagnetic codes that utilize rectangular blocks of material to model the cavity. Such codes therefore model extremely sharp corners and breaks in the wall currents.) Calculations are under way to analyze the stresses and temperature profiles in this region. The present model treats the intersection of the rectangular waveguide with a plane representing the cavity wall. This simple model is a reasonable approximation near the corner because the radius of curvature is large compared with the wall thickness.

The resultant temperature distribution, with an assumed bulk water temperature of 40°C, is shown in Fig. 5-103. The two hot spots correspond to the two local maxima in thermal loading. The hottest spot, at 129°C, corresponds to a thermal load of 50 W/cm². The reasons for this are twofold: First, the acute angle formed by the waveguide and cavity wall creates a long thermal path for the heat to travel, and second, the model is



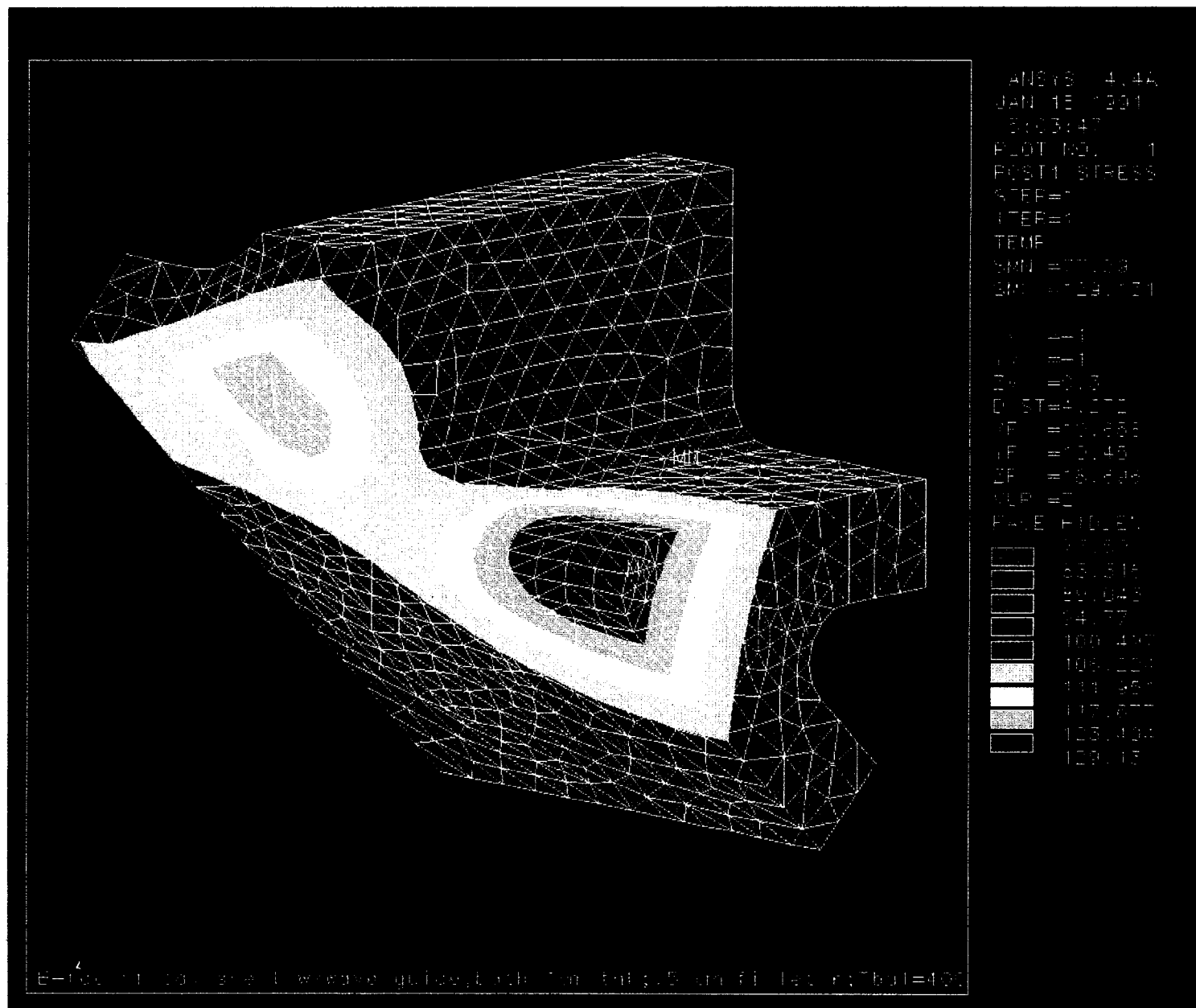


Fig. 5-103. Computed temperature profile in the region of the HOM-loading waveguide ports at 150-kW wall dissipation.

terminated at this point and no heat is allowed to flow across a model boundary. Adjusting the angle of the waveguide-cavity intersection to be 90° (whereby the waveguide extends from the cavity radially) will eliminate the first of these causes. The second can be addressed simply by extending the model. The hotspot located on the vertical wall corresponds to the maximum heat deposition of 80 W/cm^2 . Available methods of reducing the temperature in this area include cooling channels, bored cooling passages in the copper, and a reduction in the wall thickness (if it is mechanically feasible). It would also be possible, though not desirable, to add a separate cooling circuit in this region, thereby reducing the bulk water temperature used to cool the region by $5\text{--}10^\circ\text{C}$. Here again, the simulations have revealed the scope of the problem and have shown that the present cavity design is a good starting point for further optimization. In summary, we expect that, following a detailed analysis of the final cavity design, the wall heating problem will yield to present-day cooling technology.

5.5.2.5 Cavity Tuning. The tuning of the cavity will be accomplished with a PEP-style tuner, that is, a 10-cm-diameter plunger with about 10 cm of travel (see Fig. 5-104). Estimates predict a 1.1-MHz tuning range, which is sufficient to cover a temperature-related detuning of 400 kHz per 50°C , as well as a 130-kHz detuning to compensate for beam loading, or a 240-kHz detuning to “park” an idling cavity. This type of tuner uses carbon brushes to prevent HOM power from entering the space within the bellows. The handling of the higher power, compared with the PEP case, will be further evaluated.

5.5.2.6 Input Coupler. An input coupling network using loop coupling from a 6-in. coaxial line is planned. It may be necessary to go to a 9-in. coaxial line if field calculations or multipactoring evaluations indicate an advantage for the larger size. The coupling factor can be varied between 3 and 8 by rotating the loop (a coupling factor of 8.3 would be needed in the high-current, 3-A upgrade case). The coupling network will

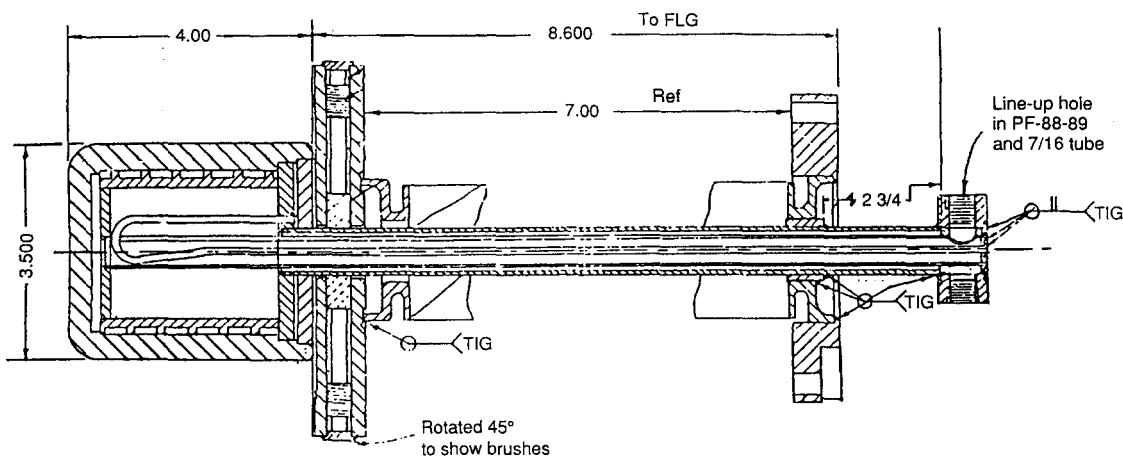


Fig. 5-104. Cross-sectional view of an all-copper PEP cavity tuner.

have to transmit up to 500 kW of RF power. The design provides for vacuum pumping ports at the input coupling network.

5.5.2.7 Input Window. The window must also transmit up to 500 kW of CW RF power. Four configurations are possible (see Fig. 5-105):

- *Coaxial window:* These are used in European and Japanese 1- to 1.2-MW klystrons as output windows, with air cooling on one side. The characteristic impedance is 50 Ω , thus presenting lower voltage across the ceramic, compared with the 300- Ω characteristic impedance of the waveguide. However, the coaxial window is mechanically more difficult to realize than the other types of windows.
- *Ceramic cylinder at the coaxial-line-to-waveguide transition.* This design has been used extensively at SLAC (500 kW per klystron, 300 kW per 5-cell cavity), at LEP (125 kW per cavity), and at CESR (400 kW per cavity under continuous operation, window failure observed at 970 kW, trickle cooling with trichloroethane and trifluoroethane).
- *Ceramic disk in waveguide.* This approach is commercially available and specified at 500 kW per cavity CW, but not yet tested at this power level. This design, using alumina or beryllia disks, is very promising and will be studied carefully for the B Factory.
- *Ceramic cylinder in the waveguide with aperture coupling.* This method is used for the ALS cavity, designed to operate at 70 kW. No operating and power handling experience has been gained yet. Because the ceramic is fairly close to the cavity, it may cause difficulties in the presence of beam-induced fields.

We expect to design a ceramic cylinder or ceramic disk window and also to purchase a commercially available window with a ceramic disk in a waveguide. We will make calculations to determine the field pattern and field stress areas to help in the choice of a promising window design. After a window design is selected, tests are planned in which two such windows will be mounted back-to-back, with adjustable vacuum between them, then run at 500 kW into a load. Extensive monitoring will be provided for these tests in the form of infrared detectors, arc detectors, voltage standing-wave detectors, etc.

5.5.3 RF Station

Each RF station will consist of one klystron powering two cavities; a block diagram is shown in Fig. 5-106. The power is distributed through a WR1800 waveguide and a Magic Tee. Reflected power from the cavities is combined in the Magic Tee and directed back toward the circulator; only imbalance power shows up at the load at the fourth port of the Magic Tee. A 300-kW load at this port is sufficient.

A circulator is required to absorb either the reflected power or the considerable beam-induced power; its presence serves to guarantee stable klystron operation under such conditions. Circulators with 1 MW of CW power capability, both forward and reflected, have been produced in connection with recently developed 1-MW klystrons, and they are

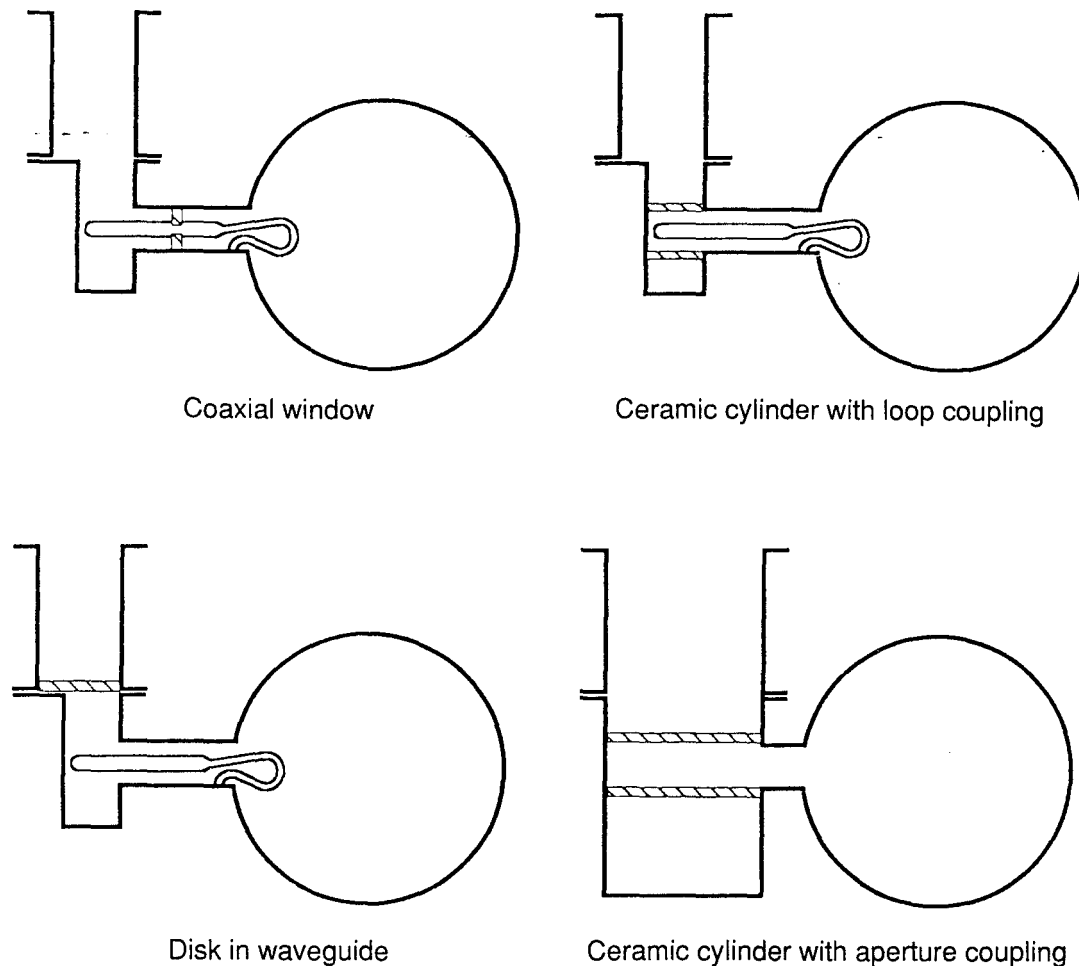


Fig. 5-105. Schematics of four window and coupling network configurations.

commercially available. Reflected power is of the order of 125 kW when there is no beam in the cavities, but beam-induced power can be as high as 1 MW in the case of the klystron tripping off at full beam, and this must be absorbed by the circulator load. The 1-MW condition need only be tolerated for the time it takes to detune the cavities, which is about 1–2 seconds. A 1-MW load at the circulator is planned. Loads with this power-handling capability are now used on klystron test stands.

The klystron is of the modulating-anode type, with an output of greater than 1 MW. A 476-MHz version can be developed in a straightforward manner by scaling from klystrons that are commercially available from several different manufacturers.

A high-voltage power supply provides 80 kV and 20 A, unregulated, with some filtering to a 1% ripple at 720 Hz. This high-voltage ripple causes a 15° phase ripple in the klystron, but this can be regulated out in the low-level RF system. To allow soft turn-

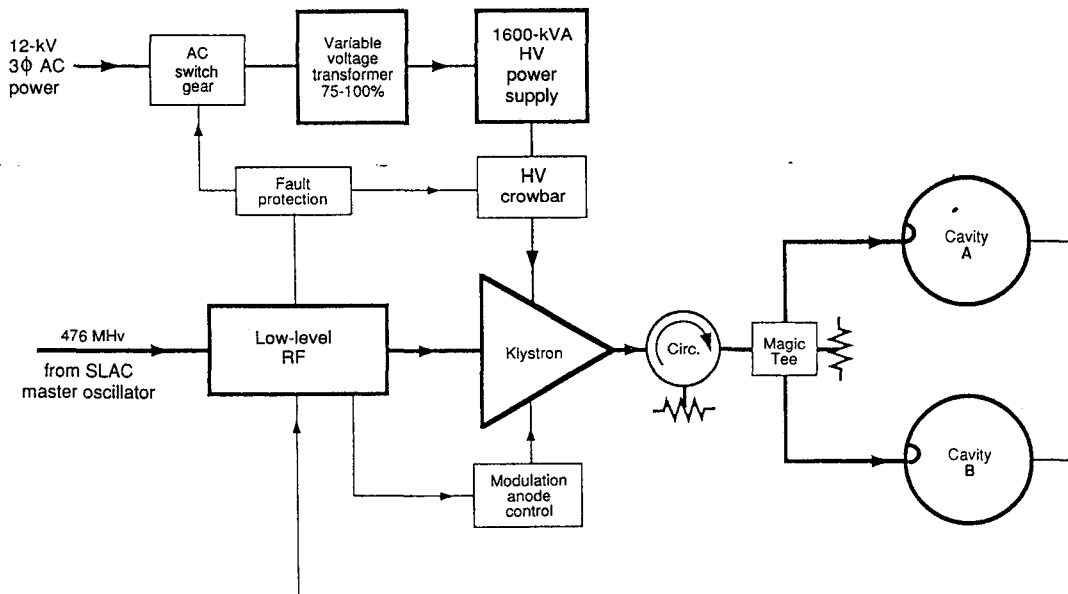


Fig. 5-106. Block diagram of a single B Factory RF station.

on of the klystron, a variable input transformer, 75–100%, is used. Standard fault-protection circuitry, with a crowbar and RF drive removal, is planned to protect the klystron.

5.5.4 Low-Level Controls

The low-level RF system consists of six types of feedback loops, along with the usual controls, interlocks, and protection systems. The various low-level RF system feedback loops are described functionally below and depicted schematically in Fig. 5-107. During the detailed design phase, the stability of the whole system will be calculated and simulated.

Tuning Loop. Two loops of this type, one per cavity, keep the cavities tuned by compensating for either detuning by the beam or temperature effects. Each loop measures phase across its cavity and moves the corresponding tuner. Bandwidth is limited by the stepping motor response to 1 Hz.

RF Feedback Loop. This feedback loop is required to reduce the cavity impedance for the first few coupled-bunch modes, which will interact with the cavity strongly owing to the detuning of the cavity away from 476 MHz. This loop also aids in regulating the cavity reaction to the 5% gap in the beam. Two types of feedback loops are under study. The first is a voltage-follower approach in which the cavity voltage is sampled, shifted to the proper phase, summed with the reference drive signal, and then fed to the klystron

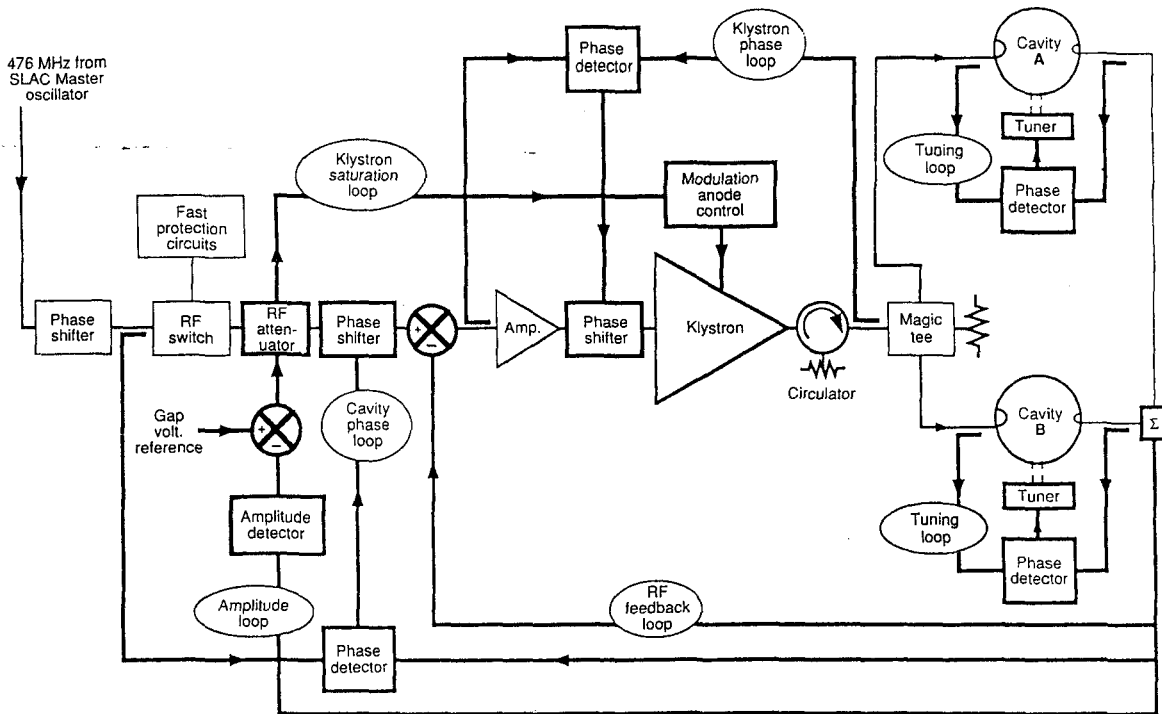


Fig. 5-107. Block diagram of the low-level RF feedback loops.

with the proper amount of gain. The bandwidth of this type of feedback is limited by the total amount of loop delay. Open-loop simulations indicate that a unity-gain bandwidth of 1.1 MHz can be achieved for a system delay of 300 ns. If the delay is 500 ns, the bandwidth is reduced to 700 kHz. A second approach involves sampling the cavity field, picking out only the harmonics of the revolution frequency with a comb filter, delaying the signal to a total delay of one revolution period ($7.3\mu\text{s}$) before summing with the reference signal and driving the klystron with the correct amount of loop gain. While this RF feedback loop reduces the impedance that drives coupled-bunch modes, additional feedback of bunch phase will be needed to stabilize the beam motion. These phase signals will be supplied by the longitudinal feedback phase detection and applied to the klystron input. Each of these two feedback schemes will be analyzed in detail to establish the one with the best performance. Studies will include merging the control loops into the storage ring simulation code now used for development of the longitudinal feedback system. Actual performance tests can also be done on the existing PEP RF stations.

Klystron Phase Loop. This is implemented to reduce the phase ripple of 15° associated with the 1%, 720-Hz ripple on the klystron high-voltage power supply. Bandwidth of this loop can be as much as 10 kHz.

Cavity Phase Loop. This loop keeps the phase of the vector sum of the fields in two cavities constant, compared with a reference signal (shifted by a station phase shifter) from the SLAC master oscillator. This will be a relatively slow loop, with a bandwidth of about 1 kHz limited by the synchrotron frequency of the beam.

Cavity Amplitude Loop. In a similar fashion to the phase loop, the amplitude loop keeps the gap voltage constant by measuring the magnitude of the cavity field and comparing it to a reference voltage. The loop then adjusts a variable attenuator in the RF reference to the RF feedback loop to keep the gap voltage constant. Bandwidth of this loop will also be of the order of 1 kHz.

Klystron Saturation Loop. To keep the klystron operating efficiently, this loop adjusts the modulation anode for operation at about 90% of saturation. (The klystron will need to be operated at about 90% of saturation to ensure reserve power for RF feedback.) The loop response time should be slow, of the order of seconds. The klystrons will be specified to provide the required power under these operating conditions.

If an RF station trips off, the circulating beam will induce a field in the cavities comparable to the normal operating field. This will not only produce similar wall losses in the cavities, it will also generate 1 MW of power traveling towards the circulator to be absorbed by its load. This will be a temporary condition, because the low-level RF system will move the tuners to a predetermined "park" position corresponding to tuning the cavities about 240 kHz below the nominal frequency of 476 MHz. This tuner position will reduce beam-induced power, while still operating the cavity at a point on the resonance curve that produces Robinson damping. After detuning, the power to be absorbed by the circulator load will be reduced to about 280 kW in the LER and 110 kW in the HER. A monitor will measure the beam-induced power and dump the beam should a potentially dangerous power level be reached. This could happen if, with klystron drive removed, a cavity were accidentally tuned to resonate at 476 MHz.

5.5.5 General Layout

There are three RF buildings available at the PEP site, located in regions 4, 8, and 12 (Fig. 5-108). Each building can accommodate up to six RF stations, for a total of 18. For the initial operation of the B Factory, fifteen stations will be installed, six each in regions 4 and 8, and three in region 12. The RF building layout shown in Fig. 5-109 indicates how the 476-MHz klystrons could be arranged. A profile view of an RF building and a section of the tunnel is shown in Fig. 5-110.

5.5.6 Expandability

Ultimately, we envision one backup station for each B Factory ring — to ensure a full complement of stations for the required luminosity, even if one RF station is down. As discussed in Section 5.5.4, the cavities of an inoperative station would see considerable beam-induced power, and would have to be tuned off-resonance to reduce that power to

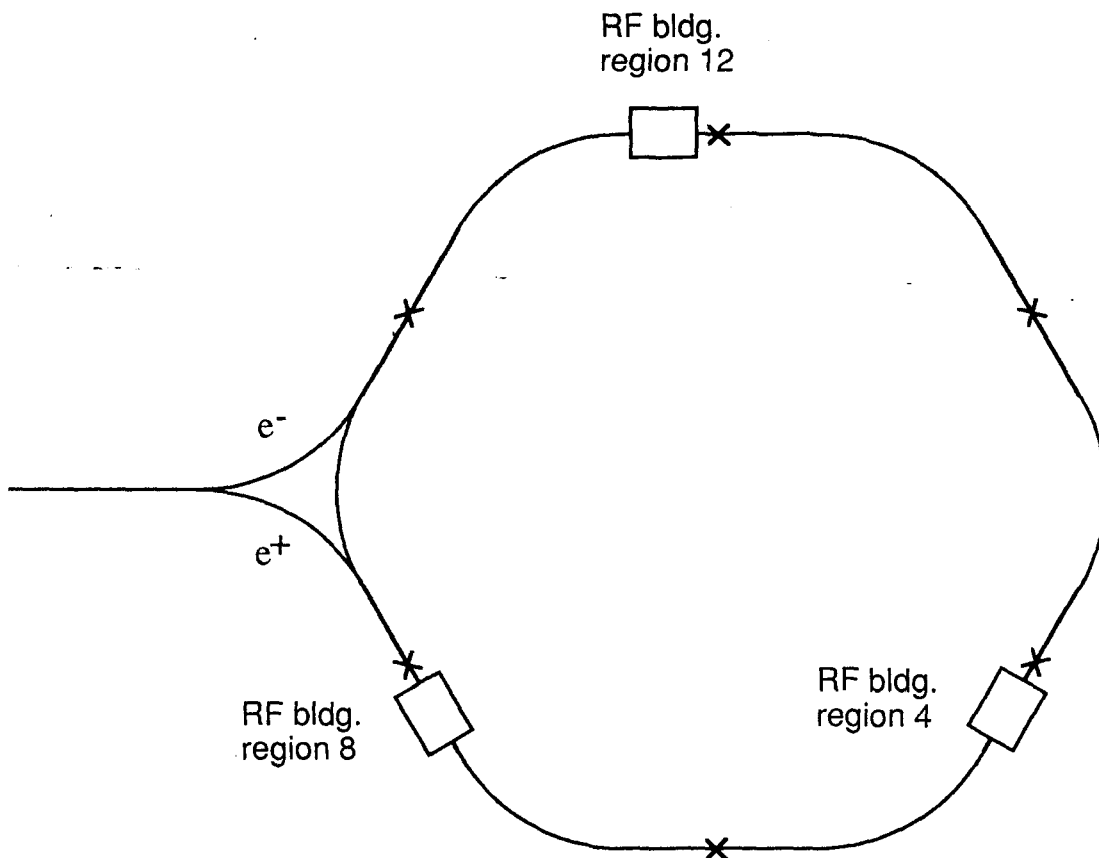


Fig. 5-108. Layout of the B Factory, showing the locations of RF buildings.

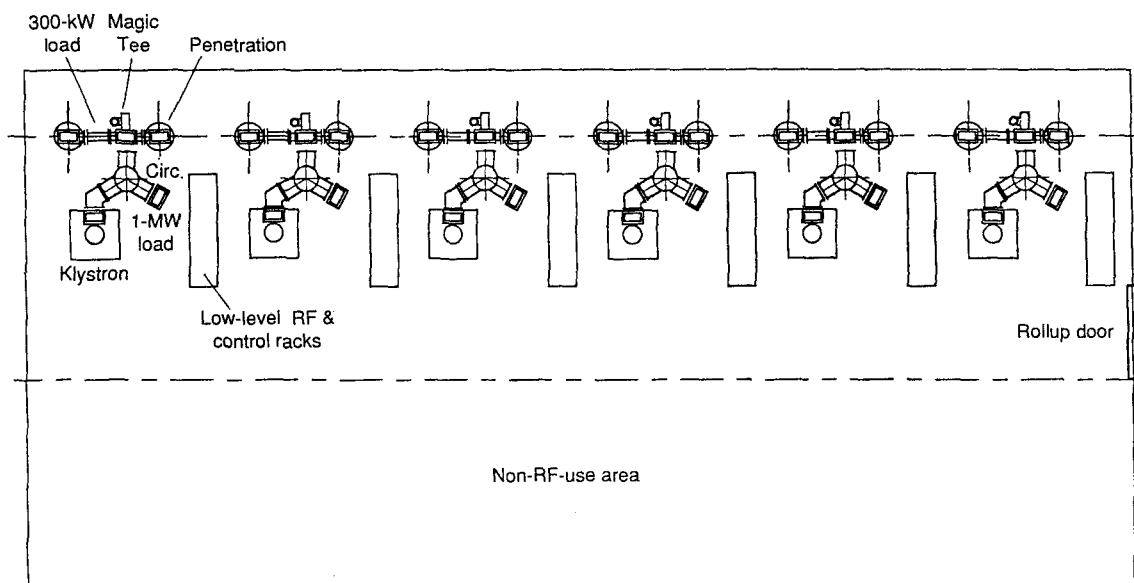


Fig. 5-109. Plan view of an existing RF building, showing the arrangement of six RF stations.

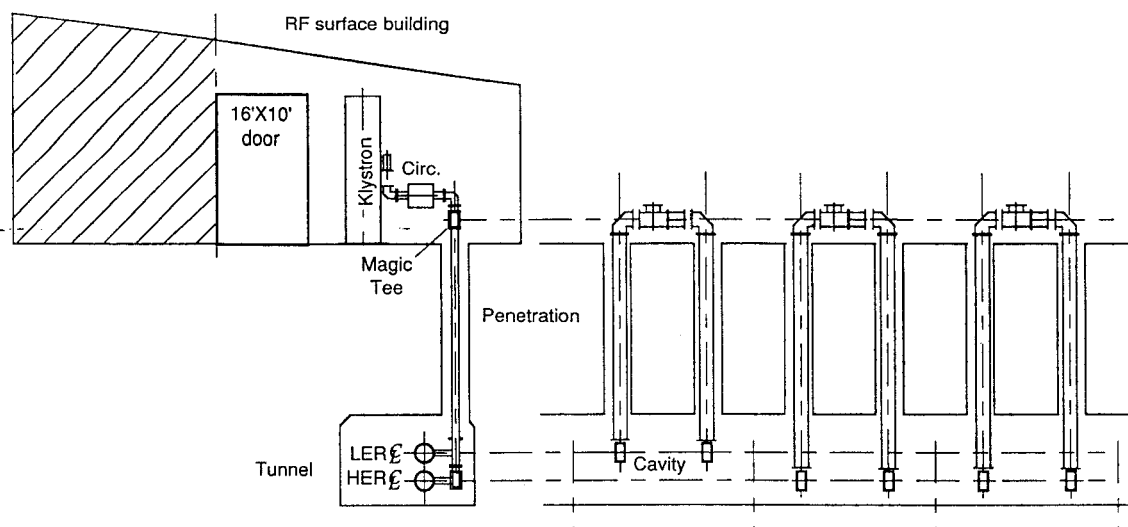


Fig. 5-110. Cross-sectional view showing an RF station and a section of the PEP tunnel.

manageable levels. It will not be possible to change a klystron while a beam is circulating, but maintenance or repair work on the low-level RF modules could be performed when a station is in the off position.

If the B Factory current were increased to 3 A in each ring, additional RF stations would be installed; the number of stations would rise to 15 in the HER and 6 in the LER, and the number of cavities would increase to 30 in the HER and 12 in the LER. The wall loss in each cavity in this scenario would decrease. The coupling factor for each cavity would have to be increased to 8.3, because more power must be delivered to the beam. An additional surface building would also be required to house the three RF stations that could not be accommodated in the present RF buildings.

5.5.7 Summary

Considerable effort has gone into the choice and design of the B Factory cavities. A cavity shape with nose cones provides a maximum shunt impedance at the cavity fundamental mode, while HOMs are heavily damped by three HOM loading waveguides. The 150 kW of wall dissipation requires a careful design of the cooling of the cavity. A drive network with a window capable of delivering 500 kW of RF power to the cavity must also be developed. We believe the proposed designs to be within the realm of present-day technology, but further simulations, as well as actual tests under full power, will be conducted to verify their performance.

We chose an RF system design that uses two single-cell cavities with each 1-MW klystron. This combination can provide the required gap voltage and deliver the needed power to the beam, using the relatively small number of 20 cavities in the HER and 10 in the LER. The low-level RF system, besides providing conventional control and feedback, will also be required to help in the damping of beam-induced instabilities with

direct RF feedback loops. The stability of such loops needs further investigation and performance tests. The planned RF system has the advantage of using existing conventional facilities and can be implemented without any structural changes. All components of the system can be used in a future upgrade to a 3-A machine, with only minor adjustments and the addition of a small number of RF stations.

5.6 FEEDBACK SYSTEMS

As pointed out in the discussion of beam instabilities (see Section 4.3), the high beam currents in the B Factory rings can provide strong excitation of any resonator to which they can couple. The voltages that arise drive coupled-bunch instabilities, and active feedback systems are required to prevent the growth of longitudinal and transverse bunch oscillations. In practice, it is the high- Q resonators associated with the parasitic higher-order modes (HOMs) of the RF cavities that are the main culprits, hence the considerable effort to damp these modes, as described in Section 5.5.

To control the oscillations, the corrective kicks that the feedback system applies to the bunches must be at least as large as the induced resonator voltages minus the effective "voltage" due to the radiation damping. Because the induced voltages are proportional to the shunt impedances of the resonators, the technique of passive damping of HOMs in the RF cavities greatly reduces the feedback voltages required. On the other hand, a single HOM that has been broadened in frequency by damping can potentially cause instability in perhaps 100 coupled-bunch modes of the beam. Therefore, one expects many beam modes to require feedback stabilization.

In most operating accelerator rings, coupled-bunch damping has been applied selectively to the few observed unstable modes. The traditional method has been to extract the beam signal and feed it back at these few unstable mode frequencies. For the B Factory, damping must be provided to suppress many modes, and the systems must be designed in advance, before details of the particular modes that are unstable are known. For both these reasons, we have decided to damp bunch motions with systems that feed the signals detected from each oscillating bunch back to that same bunch. Such *bunch-by-bunch* feedback has the additional advantages of suppressing other disturbances, such as motions driven by the beam-beam interaction, and it is very effective in damping transients introduced by the injection of a small fraction of the stored beam. Systems of this type are now operating at PETRA [Heins et al., 1989].

Although we must deal with a relatively short bunch spacing of 4.2 ns, the electronics required for the prompt processing of such signals is now available. It is also worth noting that, for many-mode operation, the bandwidth required in the power amplifier and kicker would be the same for either mode-filtered or bunch-by-bunch feedback, namely,

$$\Delta f \geq \frac{1}{2} B_0 f_0 = \frac{1}{2} (1746) (136.7 \text{ kHz}) = 119 \text{ MHz} \quad (5-33)$$

It is this bandwidth that makes the power capability costly and emphasizes the importance of an efficient kicker design.

While instabilities driven by HOMs of the cavities are to be controlled by the bunch-by-bunch feedback, there are three longitudinal coupled-bunch modes in each B Factory ring that are driven even more strongly by the off-resonance response of the principal, accelerating RF mode. For these unstable coupled-bunch modes, the RF cavity itself is the most efficient kicker to employ for feedback. Accordingly, narrow-band signals to suppress each of these modes will be fed to the beam through the bandpass of the RF amplifiers.

5.6.1 Longitudinal Damping

The damping applied by the bunch-by-bunch feedback must be capable of opposing the shunt impedance of the strongest cavity HOM, at 750 MHz. As noted in Section 5.5, strong reduction of the Q of this HOM by passive damping has already been demonstrated. Although we have observed a reduction to $Q \approx 30$, we have specified a more conservative value of $Q = 70$ for the feedback system design described here. The various parameters that define the task of the longitudinal feedback system are given in Table 5-33 for both rings. In what follows, the HER will be used to illustrate the feedback system design and expected performance; extension of the design to the LER is straightforward.

The required system gain and kick amplitude are determined by the excitation of the strongest longitudinal resonance, a mode near 750 MHz having phase amplitude $\Delta\phi_0 = 0.03$ rad (at the RF frequency of 476 MHz). For short bunches this voltage is

$$V = j I_0 R_s \frac{\omega_{\text{res}}}{\omega_{\text{RF}}} \Delta\phi_0 \quad (5-34)$$

where $R_s = 20 (R/Q)Q = (20) (41) (70) = 57 \text{ k}\Omega$ for the HER. From Eq. 5-34 and the parameters of Table 5-33, we find that the damping voltage must be at least 4 kV/turn. Although radiation damping will provide about one-third of the required damping, we ignored this contribution in our design. That is, the contribution from radiation damping is considered a safety factor, and we have designed the feedback kickers to be capable of 4 kV/turn in the HER (or 2.9 kV/turn in the LER).

Table 5-33. Parameters used for feedback system design.

	HER	LER
Average current, I_0 [A]	1.48	2.14
Number of cavities	20	10
Strongest HOM frequency [MHz]	750	
R/Q per cavity [Ω]	41	
Q	70	
Maximum mode amplitude [ps/rad]	10/0.03	
Injection scheme	1/5 bunch at 60 pps	
Assumed injection errors [$(\delta E/E)/\text{ps}$]	0.002/100	

Errors in the energy and/or timing of the injected beam will combine to produce a phase error that is about 14 times as large as the 0.03-rad excitation considered from the 750-MHz HOM. However, the small quantity of charge injected with this large deviation can excite the resonators to only about 3.4 kV. Therefore, if the low-level circuits of the feedback system are designed to limit the kicker output to 4 kV in response to phase excursions greater than 0.03 rad, transients and growth at injection will still be controlled. This action is clearly illustrated by our numerical simulations, shown later in this section.

5.6.1.1 RF Feedback. For the B Factory, the usual practice of detuning the frequency of the cavity accelerating mode to compensate beam loading stabilizes the coupled-bunch mode $m = 0$ (Robinson damping), but leads to difficulties. This is because the detuning must be quite large to account for the beam loading, with the result that the detuned fundamental mode drives bunch modes $m = -1, -2$, and -3 more strongly than can be counteracted by the damping provided by the bunch-by-bunch feedback system. To deal with this, these few particular modes will be damped by signals at the appropriate mode frequencies that are extracted from the detected beam phase signals and fed back through the RF amplifiers and cavities. To ensure that mode $m = -1$ can be damped in this manner, narrow-band active damping circuits around the cavities and drivers will be used to suppress the shunt impedance 130 kHz (that is, f_0) away from 476 MHz. This suppression will be sufficient to reduce the potential growth rate to less than the synchrotron frequency. The effective impedances with and without this suppression are given in Table 5-34. Also listed are the effects of the amplified phase signals for the mode amplitude of 0.03 rad.

5.6.1.2 System Overview and Principle of Operation. The bunch-by-bunch feedback system will measure the instantaneous phase of each bunch with respect to the ring master oscillator and provide a correction voltage for each bunch via a kicker structure. The large number of bunches (1658) and the interbunch time interval of only 4.2 ns require a wideband processing system, with the front-end and power-amplifier stages operating at a 238-MHz clock rate. The processing of the phase information from each bunch can be performed at a lower rate. Our feedback system design therefore employs common wideband front-end and power-amplifier stages, with many processor channels operating in parallel, at a slower rate, to generate the correction signal for each bunch.

Table 5-34. Damping of the $m = -1$ coupled-bunch mode.

	HER	LER
Effective R [$M\Omega$]	5.85	10.0
Reduced R for $1/t = f_s$ [$M\Omega$]	3.7	1.22
Reduction by active damping system [$M\Omega$]	3.6	1.2
Feedback kick [kV/turn]	162	79

We decided upon a digital signal-processing approach to convert the bunch-phase information into a correction signal. This digital-filter approach permits the use of a matched-filter feedback algorithm and takes advantage of recent commercial activity in the digital signal processing (DSP) field. The programmable nature of this scheme provides flexibility and allows us to implement compactly a nonlinear (soft-limiting) feedback system. It is also possible to program several operating modes into such a system—for example, to distinguish injected bunches from stored bunches, should this be necessary or desirable.

There are two possible approaches to the measurement of longitudinal motion: (i) direct measurement of the phase of each bunch and (ii) measurement of the transverse displacement of each bunch in a region of the storage ring with nonzero dispersion. The second approach requires signal processing to separate the betatron motion from the transverse displacement due to longitudinal motion, and can give problems with synchro-betatron coupling. Furthermore, this approach does not relax any of the timing or bandwidth constraints compared with a phase-measurement-based system. Therefore, we selected the direct phase-measurement approach for our design, which means that the phase of each bunch is our control variable.

5.6.1.3 System Design. Figure 5-111 presents a block diagram of the B Factory longitudinal feedback system, showing its essential elements. The bunch phase signal is derived from a beam pickup structure, which generates a short coherent tone burst for each bunch passage. The phase of this burst is compared with a master oscillator

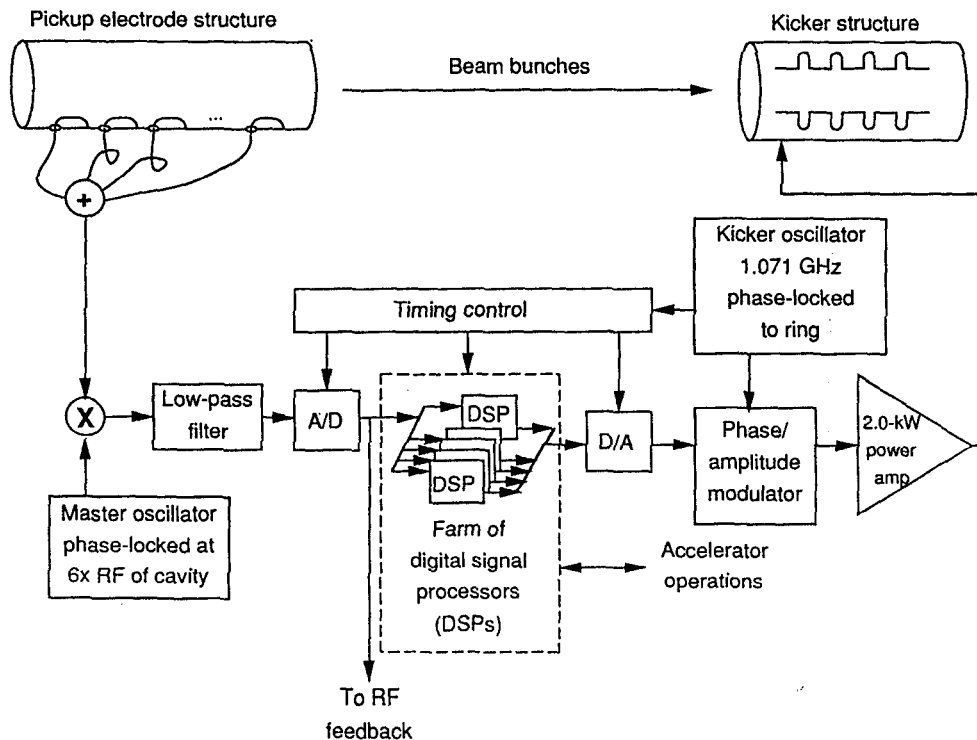


Fig. 5-111. Block diagram of the B Factory longitudinal feedback system.

synchronized to the ring RF system, and the phase-error signal is digitized at the bunch crossing rate. Digital processing of the phase-error signals is performed in an array of microprocessors (the DSP farm). This approach allows parallel processing of the phase-error signals and thus reduces the processing rate needed in each DSP block. The computed correction signals are recombined into a wideband correction signal and converted back to analog form. Finally, the feedback loop is closed via a power amplifier and a kicker structure that applies the correction voltage to each bunch. The constituents of the various functional units in Fig. 5-111 are described below.

Beam Pickup. The beam pickup generates a short (less than 4 ns) tone burst at the sixth-harmonic of the ring RF (that is, at 2856 MHz). We use a periodic coupler structure that generates a burst, rather than a tuned resonant structure, to avoid coupling between adjacent bunches. The burst of RF carrying the signature of the arrival time of the bunch can be generated in several different ways, using stripline pickups, power dividers and combiners, or delay lines. To simulate such a burst in the laboratory, we have performed measurements in which a narrow pulse is launched into a transmission line, coupled to an array of directional couplers evenly distributed along it, with all the coupler outputs added with a power combiner. As an alternative approach, we have also built another passive structure with periodically coupled microstrips. The advantage of this latter approach is that it minimizes the number of RF connections and, for the case of a beam-coupled structure, it would also minimize the number of vacuum feedthroughs.

As depicted in Fig. 5-112, we envision a pickup electrode structure made out of four transmission lines coupled to the beam through slots. The slot width can be adjusted to

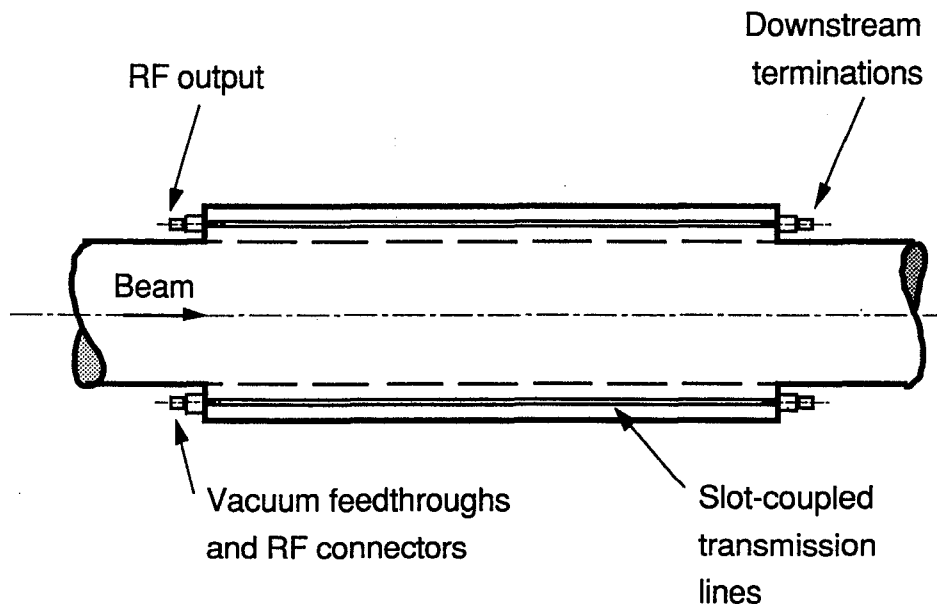


Fig. 5-112. Structure of a pickup electrode. Four transmission lines are coupled to the beam through slots. The pitch of the slots along the beam trajectory determines the tone burst frequency.

control the power coupled to the transmission lines, and the slot periodicity along the beam axis determines the frequency of the output waveform. As mentioned, we plan to operate at 2856 MHz and with 8–10 RF periods in the burst, so the structure length will be nearly 1 m.

Phase Detector. Phase detection is implemented in a double-balanced mixer. A master oscillator, phase-locked to the ring RF, generates a stable 2856-MHz signal for the phase reference. A filter on the output of the mixer eliminates the 2ω term and limits the bandwidth of the signal for noise reduction.

The choice of a 2856-MHz operating frequency is a trade-off between sensitivity and dynamic range. It allows a phase-processing range of $\pm 15^\circ$ at the 476-MHz frequency of the RF system, with a phase measurement resolution of better than 0.5° . This value is adequate for the linear damping range of the system, but it is important that the phase detector limit cleanly for excursions greater than $\pm 15^\circ$, because such a condition is likely at injection. Another attribute required in this block is an automatic gain control (AGC) loop to allow the system to operate over a wide range of beam currents. This loop will control an attenuator between the beam pickup and subsequent processing electronics.

Phase Digitizer. The digitizer converts the phase-error signal from the mixer into an 8-bit signal. It operates at the 238-MHz beam crossing rate and provides a unique measurement at each bunch crossing. Components are available commercially to implement this digitizer.

DSP Farm. The DSP farm includes wideband multiplexing and demultiplexing circuits to convert the sequential 238-MHz data stream into several slower parallel streams. An array of commercial DSPs receives these signals. These processors (which are all identical and execute identical programs) treat each bunch as an individual oscillator and combine information from several sequential crossings of a particular bunch to compute a correction signal on each turn. We intend to use a finite-impulse response (FIR) matched filter for the feedback algorithm. This filter generates the required 90° phase shift and also provides some noise reduction (processing gain) on the raw error signals.

The DSP farm implements the limiting functions mentioned earlier and handles the special out-of-range conditions generated during injection. Before finalizing the design, we will also examine the performance of alternative feedback algorithms, especially a two-coefficient infinite-impulse response (IIR) filter, suggested recently by F. Pedersen. This more compact filter algorithm has the potential to reduce the size of the DSP farm by a factor of ten, but it might have the disadvantage of being less sensitive to the phase signal and more sensitive to electronics systematics and noise.

The analog-to-digital (A/D) phase digitizer produces a digitized sample every 4.2 ns, and the kicker requires a correction signal at this same 4.2-ns interval. Each physical DSP node receives data for several bunches from the A/D and transmits the corresponding correction signals to the digital-to-analog converter (DAC) within the $7.33\text{-}\mu\text{s}$ revolution period of the beam. The design of this system presents a high-speed distribution problem of the scatter-gather type, which can be solved in several ways. Here, we outline one solution as an example. In Fig. 5-113, a demultiplexer follows the

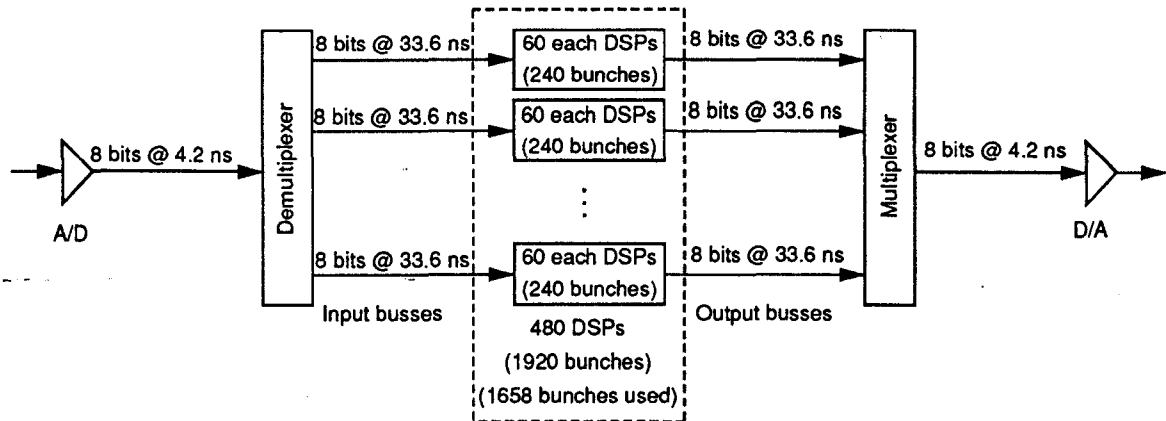


Fig. 5-113. Schematic of one scheme for digital signal distribution for the longitudinal feedback. The bandwidth of the input and output streams is far greater than the throughput of a single DSP. The input stream must therefore be scattered to many DSPs, whose outputs must then be gathered to form the output stream.

A/D and scatters groups of eight sequential samples onto eight 8-bit parallel input busses. A multiplexer precedes the DAC and gathers groups of eight sequential responses from eight 8-bit parallel output busses. On the parallel busses, data move at the rate of one byte every 33.6 ns. Each physical DSP node connects to one input and one output bus and accommodates four bunches. With this architecture, each processor executes at most 80 multiply-accumulate instructions and four groups of I/O and clipping operations per bunch revolution period. Available commercial processors meet this performance requirement.

We anticipate packaging four to eight DSP processors on a VME or VXI module. The digital signal processing for the longitudinal feedback system would then comprise 50 to 100 modules that would be mounted in 3–5 crates. Such a hardware assembly would occupy a standard 19-in. rack and would consume approximately 1–5 kW of power.

Output D/A and Amplifier. This block converts (at a 238-MHz rate) the correction signal stream from the output multiplexer into an analog level suitable for driving subsequent stages. It is an 8-bit system.

Power Amplifier. The longitudinal feedback system uses commercial RF power amplifiers and modulators to provide the signal for the output kickers. The operating frequency is 1.071 GHz at a power level of 2.0 kW. The power amplifiers will be configured in a modular fashion. This allows a soft-failure mode, that is, operation at reduced power levels, should components fail.

Beam Kicker. The beam kicker converts the output signal from the power amplifier into a longitudinal E field to correct the energy of each bunch. A periodic coupler provides the bandwidth required to prevent bunch-to-bunch coupling, along with a small voltage gain. To reduce the broadband power required, four separate kickers are used in

the HER to deliver the 4-kV (maximum) acceleration to the bunches. As illustrated in Fig. 5-114, each kicker will consist of an array of four quarter-wavelength drift tubes, joined in series by half-wavelength delay lines (at the operating frequency of 1.071 GHz). The kicker is constructed as a transmission line (with a characteristic impedance of $25\ \Omega$) made up of several segments in series and parallel. The transmission line is divided into two $50\text{-}\Omega$ lines at the ends; these connect through vacuum feedthroughs to the driver at the downstream end and terminating loads upstream. Transitions between the drift tubes and the delay lines between them must be well-matched to avoid reflections that will introduce losses and spurious responses. Initial modeling of series-electrode structures has verified the expected bandwidth; evaluation of the strength and some details of the response is under way.

Each kicker presents to the beam an impedance band that is about 250 MHz wide, with a maximum value of $400\ \Omega$. Such an impedance is too broadband to drive coupled-bunch instabilities and contributes negligibly to the broadband impedance of the ring as well. The power this impedance extracts from the beam, about 800 W per kicker, is dissipated in the terminating loads.

To deliver a different voltage to each passing bunch, the allowed kicker length is limited by the combination of its filling time, the transit time of the passing bunch, and the rise time of the driving amplifier. The characteristics for each four-element kicker unit are summarized in Table 5-35. There are four of these kickers. The use of four units in the HER provides redundancy and a safety margin; the LER uses three identical units.

The 2.0-kW power amplifier required at the 1.071-GHz operating frequency is available from several commercial vendors. These solid-state amplifiers are modular, and typically include low-level drive electronics and power supplies.

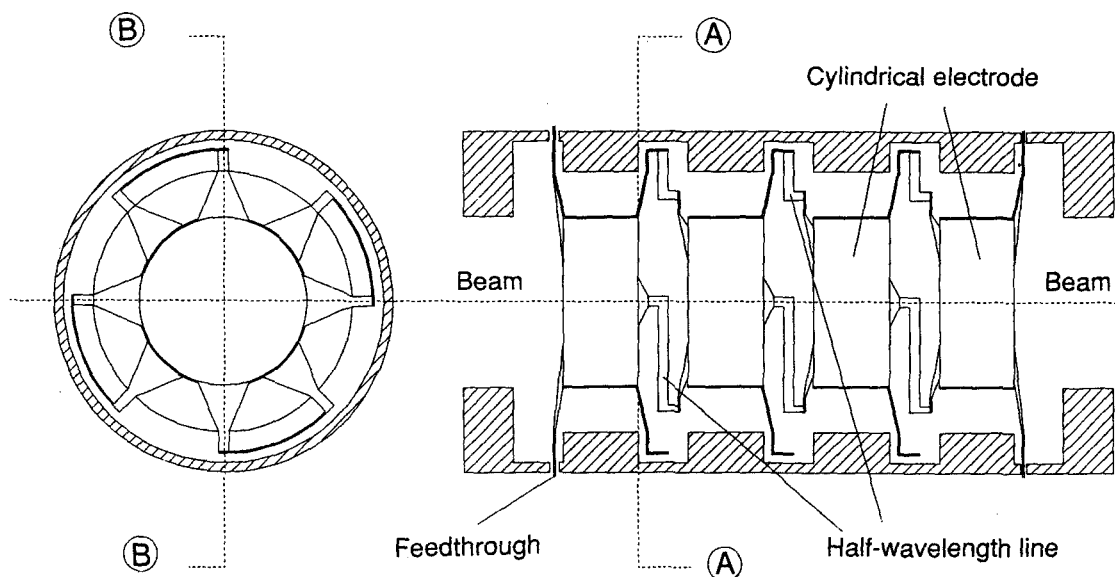


Fig. 5-114. Beam kicker for longitudinal feedback.

Table 5-35. Characteristics of longitudinal feedback kicker units.

Length [cm]	32
Frequency [GHz]	1.071
Kicker bandpass [MHz]	241
Driver bandwidth [MHz]	357
Shunt impedance [Ω]	1600
Power for 1 kV/unit [W]	313
Driver power rating [W]	500

5.6.1.4 System Summary. Table 5-36 provides a summary of the technical specifications proposed for the longitudinal feedback system. Laboratory measurements of a prototype feedback front-end processing system are already under way, and our initial results are quite encouraging. The prototype system has been shown to detect the phase of simulated bunches with a resolution better than the required 0.5° and thus demonstrates the level of performance needed for use at the B Factory.

5.6.1.5 Overview of the Simulation. We have studied the behavior of the proposed longitudinal bunch-by-bunch feedback system with a computer model of the HER. The simulation includes a ring model, along with an electronic model of the bunch-by-bunch feedback system shown in Fig. 5-101. The simulation code calculates the longitudinal motion of the bunches in the ring and their interactions with the RF cavities. It determines the bunch phase at the pickup electrode structure, adds the appropriate kick

Table 5-36. Longitudinal feedback system specifications

RF frequency [MHz]	476
Bunch interval [ns]	4.2
Beam pickup central frequency [MHz]	2856
Phase detector dynamic range (at 476 MHz)	$\pm 15^\circ$
Phase detector resolution (at 476 MHz)	0.5°
Bunch-to-bunch signal isolation [dB]	>26
Kicker structure operating frequency [GHz]	1.071
Output power [kW]	2.0

from the kicker structure (as determined by the electronic model), and propagates the bunches through the ring and cavities.

The electronic model includes

- The transfer function of the feedback system
- The feedback algorithm that processes the signals from the pickup electrode structure before sending them to the longitudinal kicker
- The properties of the phase detector, the low-pass filter, the front-end A/D, the DSP farm, and the kicker
- Parameters to simulate input noise, gain and offset errors, bandwidth limitations, and the effects of the limited dynamic range of the analog components

The model of the DSP farm emulates a 20-tap FIR filter. The coefficients ξ_j of the taps comprise a sinusoid with a longitudinal oscillation period of 19.3 turns, that is,

$$\xi_j = A_{\text{DSP}} \sin\left(2\pi \frac{j-1}{19.3}\right)$$

$$j \in \{1, \dots, n_{\text{samples}}\}$$
(5-35)

Given measures $x_i(k)$ of the phase of bunch i on successive turns as input, the result of the DSP algorithm is the output

$$y_i(k) = \sum_{j=1}^{n_{\text{samples}}} \xi_j x_i(k-j)$$
(5-36)

This result is clipped to an 8-bit signed integer, which is used to inform the kicker of the proper phase of the kicker oscillator for that bunch on that turn. The kicker model is implemented as a phase-modulated RF kicker with a nominal 4-kV maximum output amplitude.

The simulation model assumes that the measurement of bunch phase is independent of bunch charge. This corresponds to the case where the front-end circuits include an AGC loop or where a separate measurement of bunch charge is available for normalization. A propagation delay of at least one turn (7.33 μs) is enforced in the feedback transfer function.

5.6.1.6 Ring Simulation. In the ring simulation code, the bunch phases ϕ_i are taken with respect to the zero crossing of the RF waveform. We assume that a discrete kick is given to each bunch at a single point in the ring; that is, the system is modeled as though there were a discrete change in energy at a single point on each turn. This simplification is justified, because the synchrotron frequency is small compared with the revolution frequency. The motion of bunch i on one turn is divided into two parts:

- Propagation around the ring, outside the kick point:

$$\begin{aligned}\phi_i &\rightarrow \phi_i + T_0 \dot{\phi}_i \\ \dot{\phi}_i &\rightarrow \dot{\phi}_i\end{aligned}\tag{5-37}$$

- The kick given to the bunch at the kick location:

$$\begin{aligned}\phi_i &\rightarrow \phi_i \\ \dot{\phi}_i &\rightarrow \dot{\phi}_i + \Delta \dot{\phi}_i\end{aligned}\tag{5-38}$$

The kick given to bunch i includes several components, corresponding to the various contributions that produce an energy change in bunch i on one turn:

- The RF generator voltage in the cavity at the time bunch i passes through. We represent this as $\hat{V}_g \sin \phi_i + V^{\text{cav.fbk}}$, where the second term corresponds to the RF cavity feedback needed to control beam loading at the fundamental.
- The wakefields (both the fundamental mode and HOMs) ringing in the cavity.
- The synchrotron radiation loss per turn, U_0 , which actually occurs throughout the ring, but is lumped into the kick in the simulation.
- The voltage V_i^{fdbk} applied to bunch i by the bunch-by-bunch feedback system.

The equation for the total kick is:

$$\Delta \dot{\phi}_i = -\frac{\alpha \omega_{\text{RF}}}{E_0/e} \left[\hat{V}_g \sin \phi_i + V^{\text{cav.fbk}} - \frac{U_0}{e} + V^{\text{wake}} + V_i^{\text{fdbk}} \right] - \frac{2T_0}{\tau_E} \dot{\phi}_i \tag{5-39}$$

where α is the momentum compaction factor, E_0 is the nominal energy for a particle on the design orbit, ω_{RF} is the RF frequency, T_0 is the revolution period, and τ_E is the longitudinal radiation damping time.

Cavity Wakefield. In computing V^{wake} , we keep track of the (complex) wake voltage in each cavity mode k . This voltage gets a discontinuous increment each time a bunch passes through the cavity, and it rotates in phase and attenuates (since ω_k is complex) between bunch passages. Note that according to the fundamental theorem of beam loading, a bunch sees half the wake voltage it induces during its present passage.

Cavity Feedback. Because the beam loading in the fundamental cavity mode is very heavy, RF cavity feedback will be necessary to compensate it. The response at coupled-bunch frequencies that fall within the bandwidth of the fundamental mode will require special feedback. In simulations to date, we have assumed that the compensation is perfect, that is, that $V^{\text{cav.fbk}}$ exactly cancels the fundamental mode of the wakefield in the cavity. In reality, the situation is more complicated (involving the cavity phase loop, amplitude loop, tuning loop, localized impedance reduction, and bunch motion feedback), and the compensation will not be perfect. We are now studying an improved

representation that includes the response of the cavity, the feedback of the phases of nearby beam modes, and the effect of the gap in the bunch train.

5.6.1.7 Simulation Parameters. We start a given simulation run with specified initial conditions ϕ_i and $\dot{\phi}_i$ for each bunch. A typical initial condition we have studied is that of an injected bunch with a relatively large offset from the average synchronous phase, while the remaining bunches are close to the synchronous phase. All bunches, including the injected bunch, begin at the nominal energy, and the charge in all bunches is taken to be equal and to remain constant. (Although not yet implemented, the simulation is structured such that it will be straightforward in the future to include the addition of charge to bunches during injection.)

When the simulation begins, there are no wakefields present in the cavities. As noted above, the present simulations then assume that the wakefield at the fundamental (accelerating) mode is fully compensated; that is, only the effect of the HOM wakefields is included. The present simulations include only the single dominant HOM at 750 MHz, whose properties are included in Table 5-33.

Parameters used in the simulation results shown below are as follows:

- Bunch charge $N_b = 4 \times 10^{10}$
- 1658 bunches (corresponding to a harmonic number of 3492, with every other bucket filled, except in a 5% gap)
- Total current of 1.48 A
- $R/Q = 33 \Omega$ per cavity for the single strongest HOM (which is assumed to be damped to $Q = 70$)
- 20 RF cavities
- Starting phase for bunch #5 is $\phi_5 = 0.2915$ rad (that is, a 0.1-rad offset from the synchronous phase of $\phi_s = 0.1915$ rad); the remaining bunches start at the synchronous phase
- $U_0 = 3.52$ MeV/turn
- $\alpha = 0.00241$
- $\hat{V}_g = 18.5$ MV

(In some cases, these parameters are slightly different from those finally adopted for the B Factory, but the simulation results reported below are not strongly influenced by these minor differences.)

5.6.1.8 Simulation Results. We show an example with *no* bunch-by-bunch feedback in Fig. 5-115, which is a plot of the maximum bunch offset ϕ_i reached in 3000 turns for the first 100 bunches after the gap. (Note that the time between injection pulses is 1/60 second, which corresponds to about 2300 turns.) We see that the disturbance due to the offset of a given bunch does not propagate very far back in the bunch train during this time, even *without* a feedback system. However, in the absence of a feedback system, the disturbance would continue to grow and would ultimately propagate further in the bunch train.

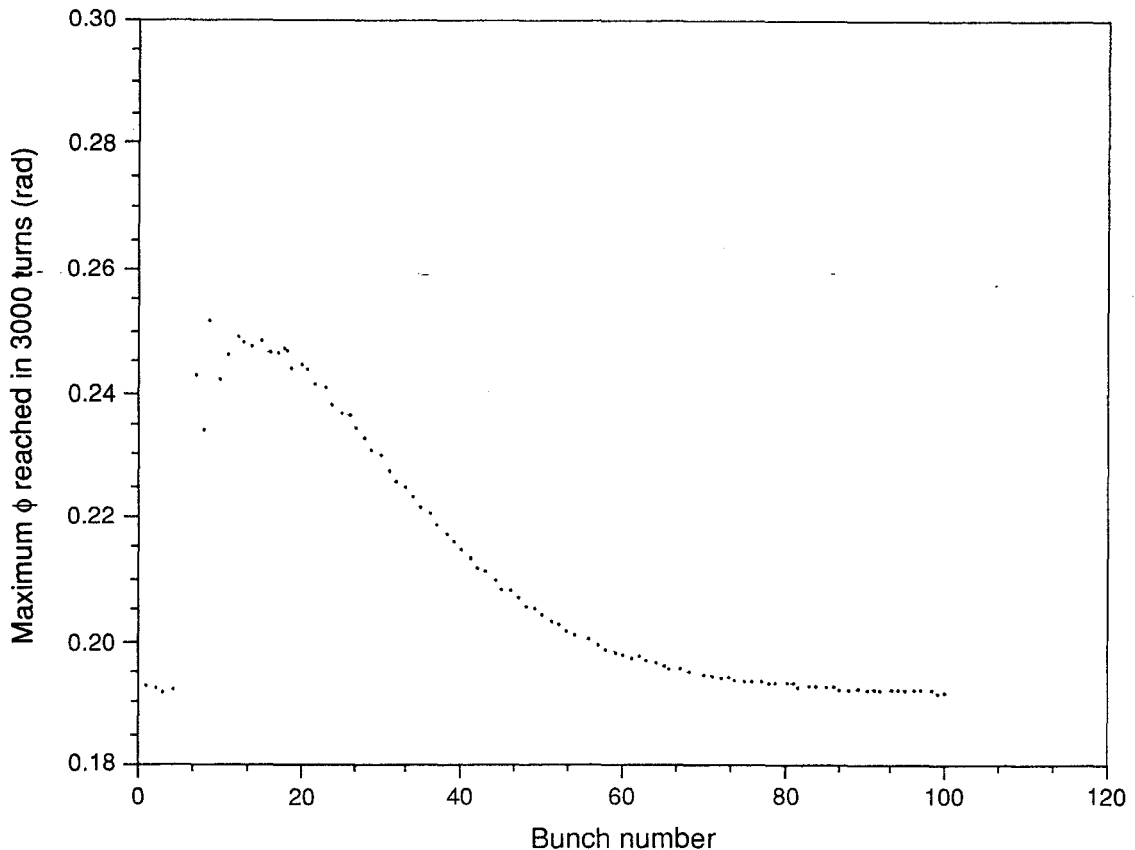


Fig. 5-115. Plot of the maximum bunch offset reached in 3000 turns for the first 100 bunches after the gap, in the absence of feedback.

Next we consider results that include the effects of bunch-by-bunch feedback. In these simulations, the kicker output is limited to 4 kV/turn. Only the first ten bunches after the gap are included, because the coupled-bunch excitation does not extend beyond a very few bunches with the feedback system turned on. These simulations were again run for 3000 turns. To observe the characteristic behavior in fewer turns, the feedback gain in the results described below is increased to correspond to reaching the 4-kV maximum kicker amplitude at a phase offset of 5 mrad rather than 30 mrad.

Figure 5-116 shows the longitudinal phases of the injected bunch (#5) and the bunch immediately following (#6), vs turn number. The envelope of the phase of the injected bunch damps linearly even though the kicker saturates, and the phase of the following bunch grows quickly to its maximum value near 400 turns and then slowly damps. The system limits the excitation of the bunch following the injected bunch and strongly suppresses the excitation of subsequent bunches.

Figure 5-117 exhibits the input and output of the DSP model for bunches #5 and #6 shortly after injection. We see that the DSP output saturates for bunch #5, but maintains the proper 90° phase lag. Benign saturation behavior of this type is difficult to realize with conventional analog approaches.

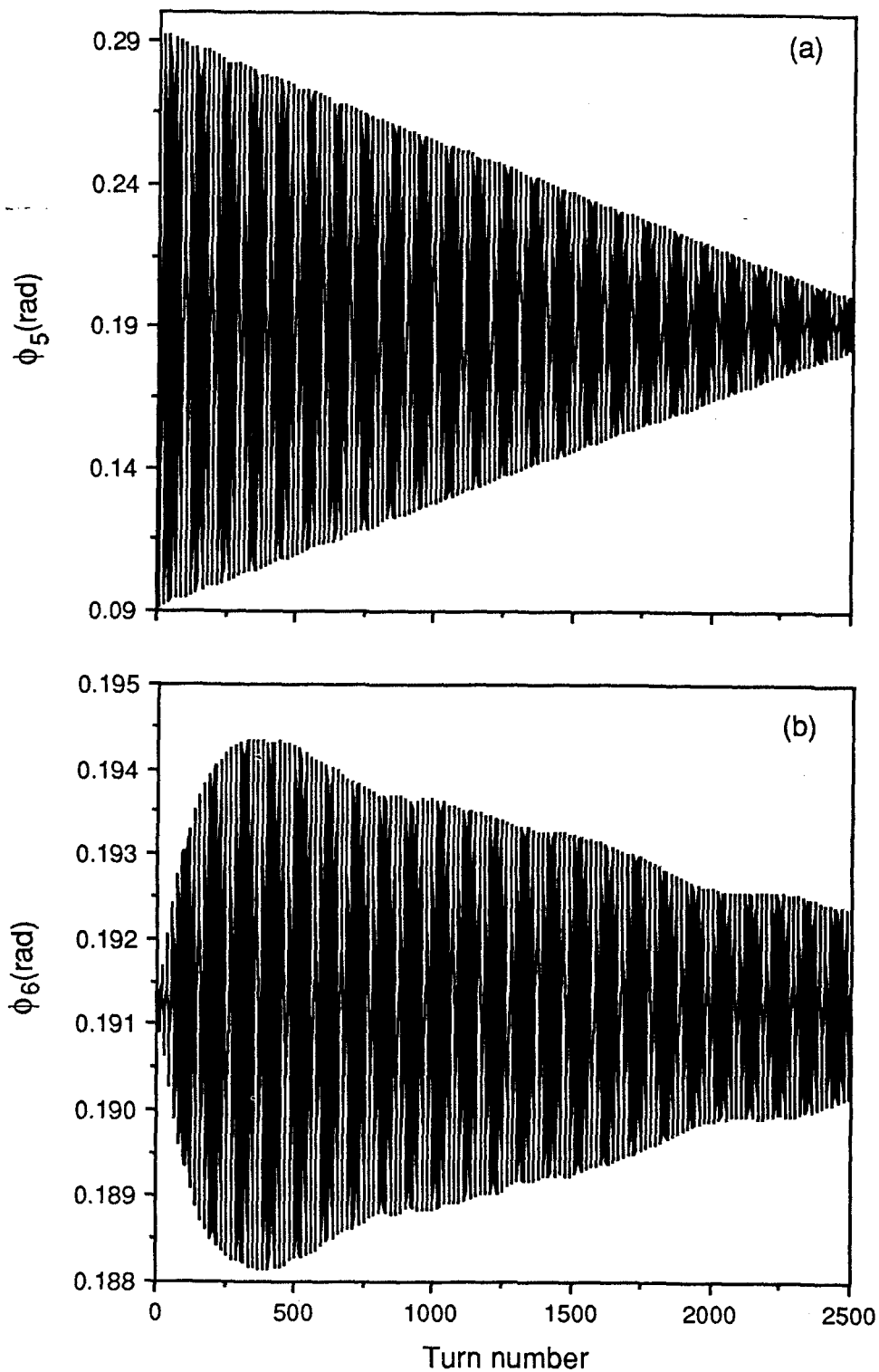


Fig. 5-116. Plots of the longitudinal phases of (a) the injected bunch (#5) and (b) the bunch immediately following (#6), vs turn number, in the presence of a longitudinal feedback system. Note the expanded vertical scale for (b).

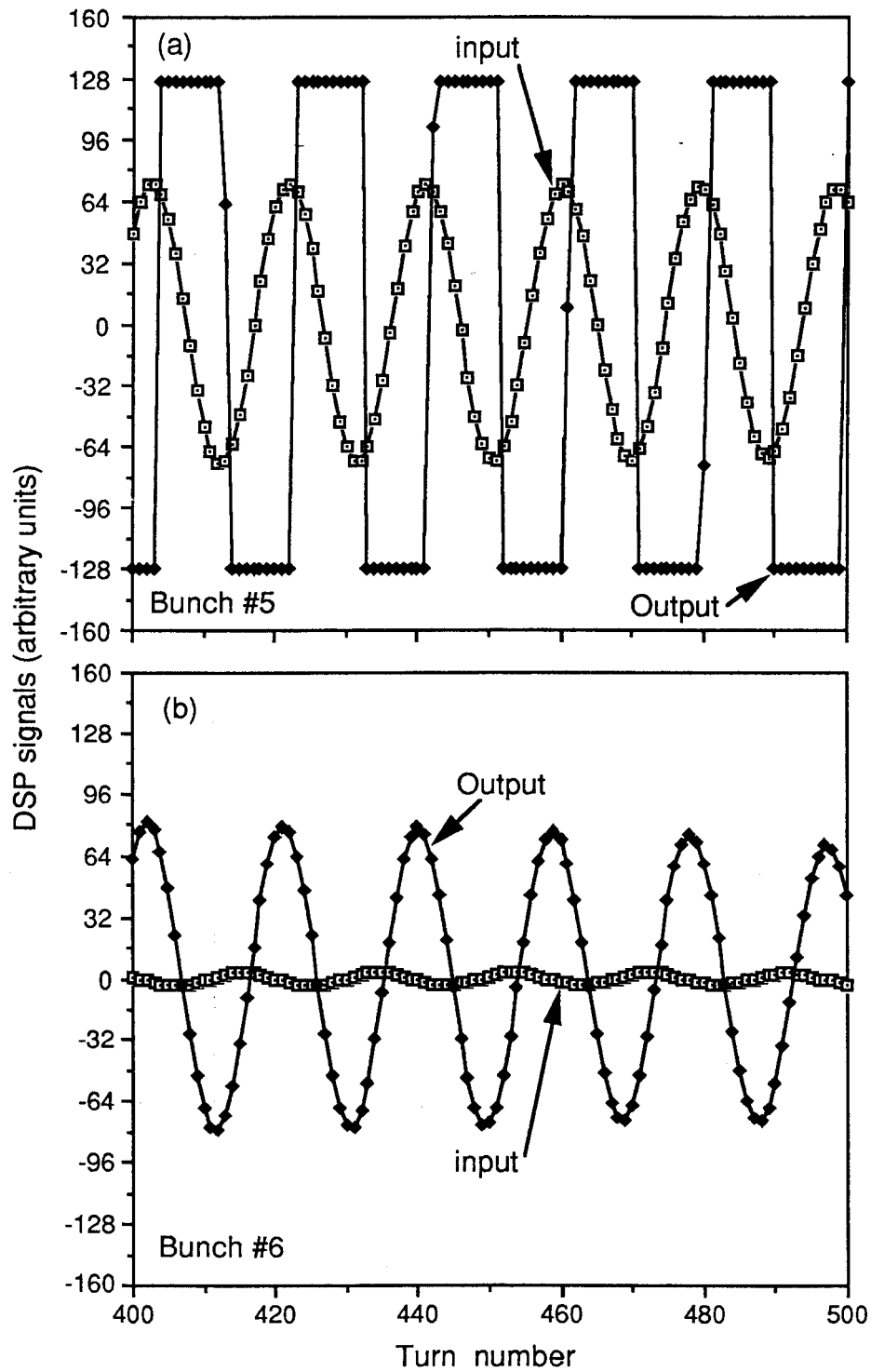


Fig. 5-117. Plots of the input and output of the DSP model for (a) bunch #5 and (b) bunch #6, shortly after the injection of bunch #5.

Figure 5-118a shows the amplitude of the phase-space error vs turn number for the injected bunch (#5). (The phase-space error is defined as the result of adding the error in phase and the error in energy in quadrature, expressed in radians.) We see the amplitude decreasing linearly during the time when the kicker limits at ± 4 kV per turn. After coming out of saturation, the amplitude of the injected bunch falls exponentially. The amplitude of the following bunch (#6) is plotted on the same scale. Figure 5-118b shows the behavior of the injected bunch as it leaves the regime of kicker saturation. The decrease in amplitude changes from linear to exponential. Note that the transition from saturation does not perturb the following bunch. Figure 5-118c shows the phase-space error amplitudes for the two bunches immediately following the injected bunch. With bunch-to-bunch coupling in the electronics set to zero, the rates of rise agree with calculations.

Figure 5-119a compares the amplitude of the injected bunch for two values of gain in the DSP model. The lower gain corresponds to our specified value of 4 kV at a phase offset of 30 mrad. The higher gain, used for the simulations that produced Figs. 5-116 through 5-118, corresponds to 4 kV at a 5-mrad offset. Figure 5-119b shows the amplitude of the following bunch at each gain value. Lower gain results in larger excursions of amplitude and slower recovery, as expected. The only penalty of higher gain is a smaller linear regime.

Figure 5-120 shows the amplitudes of the injected bunch (#5) and the two following bunches, with a 10% bunch-to-bunch coupling in the front-end electronics and a 3% coupling in the kicker. In this case, bunch #6 suffers a much greater excursion from equilibrium, but still damps. Bunch #7 suffers only slightly. We conclude from this that our system design is tolerant of a reasonable amount of bunch-to-bunch coupling in the analog components.

5.6.1.9 Conclusions of Simulation Study. In this simulation study of the B Factory longitudinal bunch-by-bunch feedback, we have determined that the system proposed is a reasonable point of departure for a more detailed design effort. We have found that 4 kV/turn is sufficient to damp both an injected bunch and the perturbed stored beam, in the presence of the expected HOM strength. We have set an upper bound on the number of DSPs required for bunch-by-bunch longitudinal feedback, and we have shown that the system performance is insensitive to nonidealities in the electronics. The simulation tools that have been developed for these studies can be adapted to further investigations.

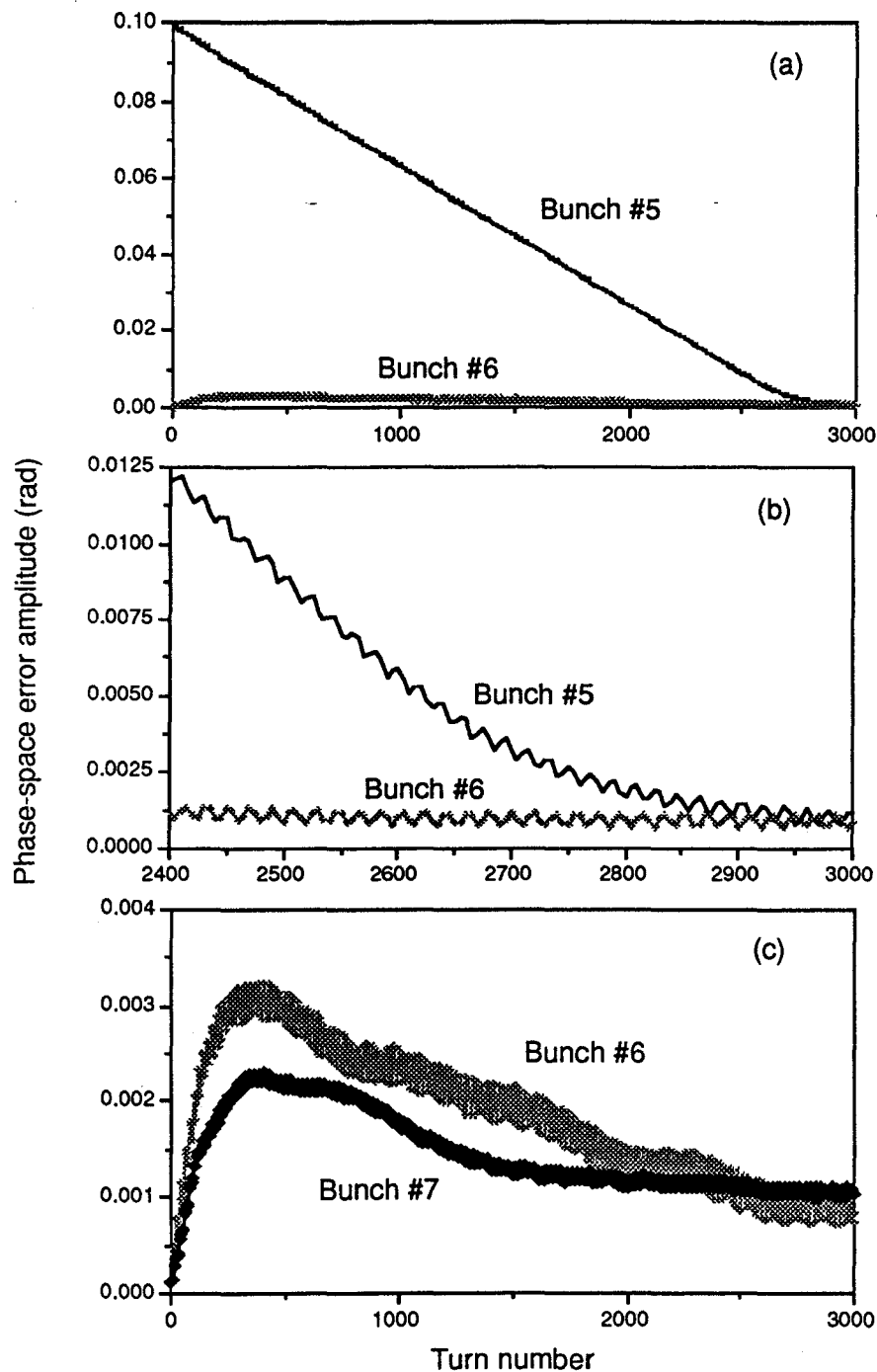


Fig. 5-118. Plots of the phase-space error amplitudes for (a) bunches #5 and #6 for the first 3000 turns, (b) bunches #5 and #6 in the region where the kicker comes out of saturation, and (c) bunches #6 and #7 for the first 3000 turns. In (b) we see that the trailing bunch is undisturbed as the kicker comes out of saturation. The rise times shown in (c) agree with calculated values when no bunch-to-bunch coupling in the electronics is assumed.

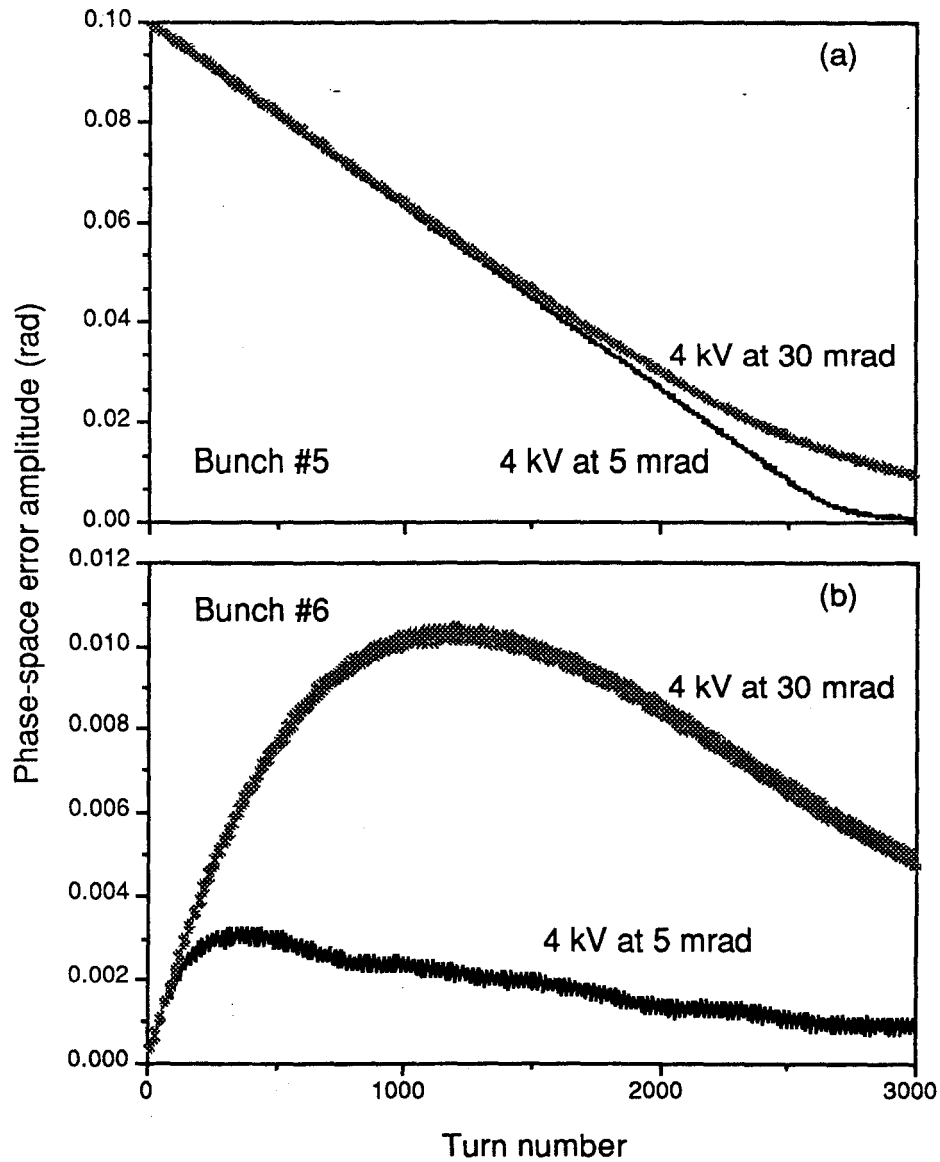


Fig. 5-119. Plots of the phase-space error amplitude for (a) the injected bunch and (b) the following bunch, for two values of the gain: 4 kV at phase offsets of 30 and 5 mrad. The higher gain was used for the simulation results shown in Figs. 5-116 through 5-118. The lower gain corresponds to the actual B Factory hardware specifications.

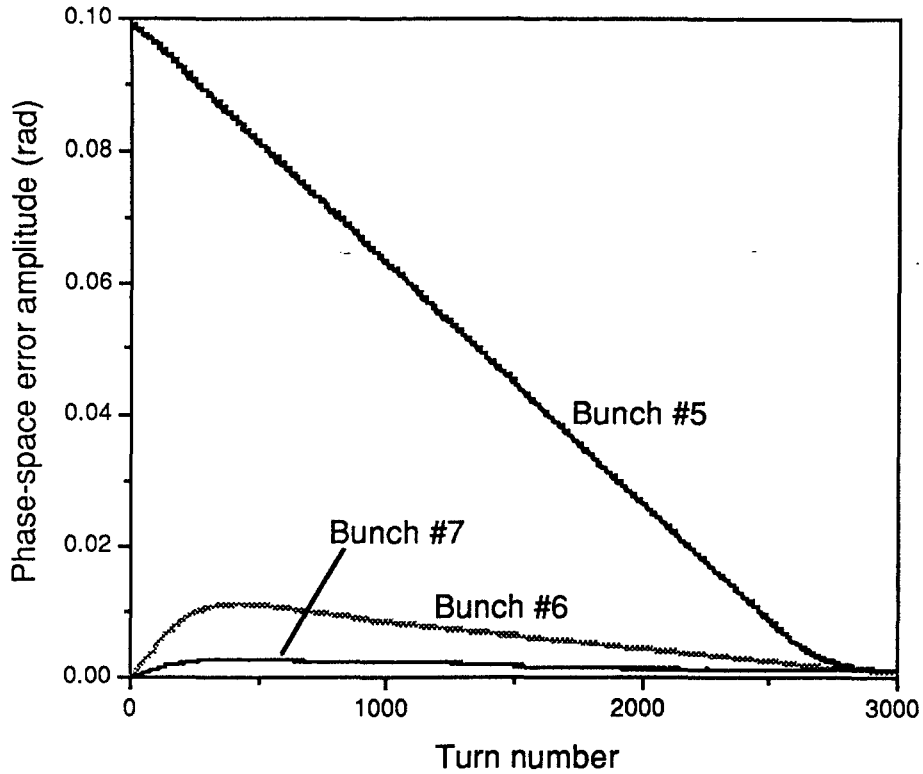


Fig. 5-120. Plot of the phase-space error amplitude for the injected bunch (#5) and the two following bunches, with a 10% bunch-to-bunch coupling in the front-end electronics and a 3% coupling in the kicker.

5.6.2 Transverse Damping

The feedback systems to stabilize transverse coupled-bunch oscillations are similar in principle and architecture to the longitudinal system. Detection of transverse excursions is simpler, and optimization of the kicker calls for a lower operating frequency. The strongest resonance and other parameters for the transverse cases are given in Table 5-37. Again the value $Q = 70$ has been taken for the damped HOM.

For the HER, the highest shunt impedance, $R_{\perp}$ is $20 (R_{\perp}/Q)Q = (20) (640) (70) = 900$ k Ω /m. The transverse impulse induced in this impedance by the 1-mm oscillation amplitude Δx is

$$V_{\perp} = j 2I_0 R_{\perp} \Delta x = 2.8 \text{ kV/turn} \quad (5-40)$$

If the kickers that oppose this were located at a point in the ring where the beta function is larger than at the cavities, the required kicker strength would be reduced. Such a reduction has not been utilized at this point in the design development; the kickers are therefore designed to provide up to 2.8 kV/turn at the bunch repetition rate.

Table 5-37. Parameters used for transverse feedback design.

	HER	LER
Average current, I_0 [A]	1.48	2.14
Approximate betatron tune	20	37
Number of cavities	20	10
HOM frequency [MHz]		1060
R/Q per cavity [Ω/m]		640
Q		70
Maximum oscillation amplitude at cavities [mm]		1
Injection scheme	1/5 bunch each 1/60 s	
Injection error [mm]		10

As for the longitudinal case, the injection of a small charge with larger amplitude produces a modest excitation of the cavities, in this case 1.1 kV transversely. The resulting transient will be controlled by the bunch-by-bunch feedback system with amplitude-limiting of its output.

The signal processing required for the transverse feedback system is similar to that proposed for the longitudinal system. As shown in Fig. 5-121, a beam pickup structure (utilizing button or stripline electrodes, or possibly a slotted coupler as in the longitudinal design) is used to generate horizontal and vertical position signals. The horizontal and vertical signals are detected and a fast A/D system converts the position information at the 238-MHz bunch rate. The signal processing required to compute the transverse correction voltages is less complex than in the longitudinal case, requiring fewer DSP modules. We anticipate using much of the same processing hardware as for the longitudinal system, and the systems can share a common timing and control path. An output multiplexer combines the correction voltage signals from the DSP farm and a fast D/A converts the information to an analog correction signal. The feedback loop is closed via commercial power amplifiers and modulators, operating in the 180- to 270-MHz band, which drive horizontal and vertical beam kicker structures.

Each transverse kicker unit consists of a pair of stripline electrodes; each electrode is a segment of a cylinder that covers one-third of the perimeter of a 10-cm-diameter aperture. These electrodes have a length of 31.5 cm (one-quarter wavelength at 238 MHz) and have a characteristic impedance $Z_{\perp} = 50 \Omega$. The kicker must handle mode frequencies in the range 114–235 MHz. We find the transverse shunt impedance using

$$R_{\perp} = 2Z_{\perp} \left(g_{\perp} \frac{l}{b} \frac{\sin kl}{kl} \right)^2 \quad (5-41)$$

with $g_{\perp} \approx (4/\pi) \sin 60^\circ$; at the midpoint of the frequency range, this is 2.95 k Ω .

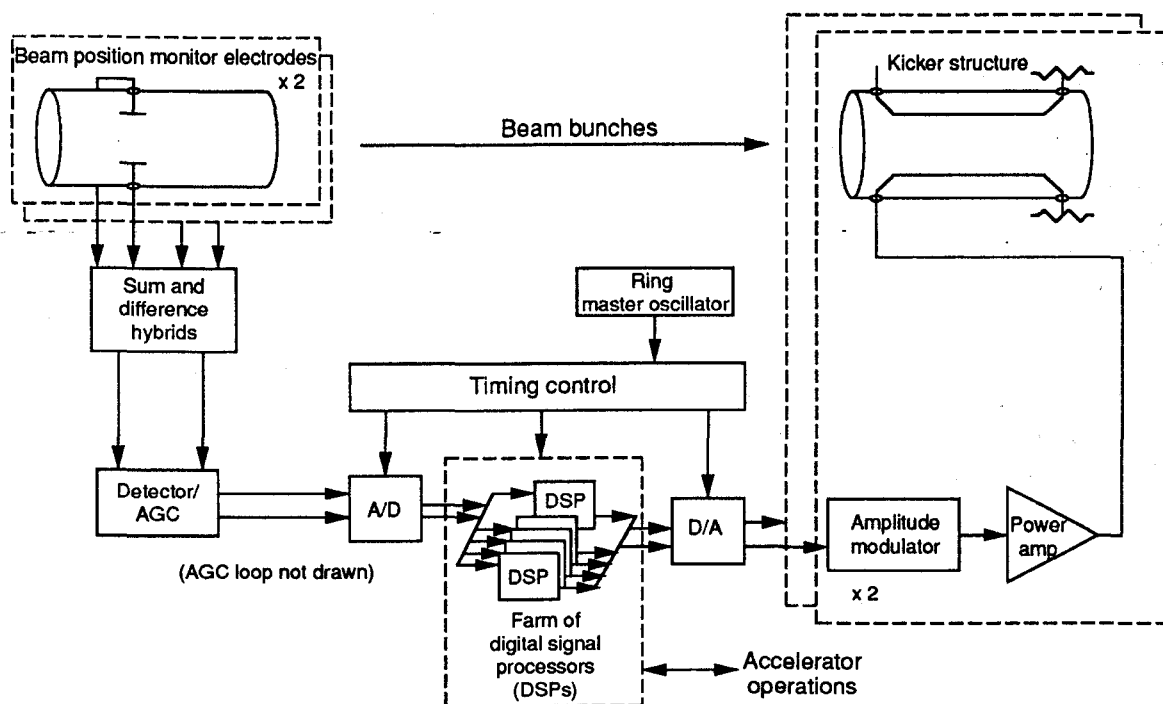


Fig. 5-121. Block diagram of the transverse feedback system.

In the HER, two units will be used, each requiring power $V^2/2R_{\perp}$. With $V = 1.4$ kV, the power is 332 W per kicker; a 400-W driver is specified. Good isolation between kicks to successive bunches requires that the driver cover the approximate bandwidth of 180–270 MHz. The required complement of transverse kickers is given in Table 5-38.

Table 5-38. Transverse kickers and drivers.

	HER	LER
Number of kickers	2	1
Power per kicker [W]	332	678
Driver rating [W]	400	800

5.6.3 Conclusions

The proposed detection and processing system has been shown to damp excitations from off-energy injected bunches and from the excitation of HOM resonances in the accelerating cavities. Laboratory measurements of prototype front-end detection and digitizing circuitry have demonstrated performance consistent with B Factory requirements. The simulation tools we have developed and the simulation results already obtained provide a solid base for the detailed system design and optimization of the longitudinal and transverse damping systems. Finally, and most importantly, the feedback system output power requirements are relatively modest, and the electronics systems are based on existing commercial technology. We conclude, therefore, that B Factory feedback systems based on the approach outlined here are entirely feasible.

5.7 INSTRUMENTATION AND ELECTRONICS

Most storage rings are equipped with a standard package of instrumentation and electronics designed to speed up injection, optimize the lattice parameters, monitor the beams orbits, and improve the luminosity. The two rings of the B Factory will be no exception, and a full set of diagnostic tools is planned for each ring.

The injection transfer lines will be monitored with instrumentation similar to that currently used at PEP, namely, stripline position monitors, current monitors (resonant toroids), wire scanners, and injection screens (with TV transmission). Also similar to current PEP hardware will be the tune measurement system (with the addition of an X-Y pinger), a direct current transformer, stoppers and scrapers, and profile monitors (UV telescope, vertical beam profile x-ray imaging system, and, for single-bunch operation, a streak camera). However, because of the very high bunch frequency, there will be some systems quite different from those now in operation at PEP. These are

- Beam position monitors (BPMs; button type)
- Bunch-by-bunch current monitor system (for injection control)
- Feedback system to maintain the beams in collision

The last three of these systems, the third of which is altogether new and unique to the operation of the B Factory, are described below.

5.7.1 Beam Position Monitors

The term "beam position monitor" can refer to a piece of vacuum chamber fitted with pickup electrodes, processing electronics and the associated cable plant, or even a special computer code designed to interpret the data produced by this system. We are concerned here only with the processing electronics; the pickup electrodes are described in Section 5.2, and the computer control system that will handle the data processing is covered in Section 5.8.

The position monitors now in place in each half sextant of PEP have their four electrode signals multiplexed onto a single transmission line by means of an arrangement of coaxial relays. The pulses from a single bunch of the stored beam are isolated by a gate, and their amplitude is measured in a relatively narrow bandwidth, with a synchronous detector operating at the revolution frequency of the ring (136 kHz). A sequential detection of the four pickup electrodes at each monitor yields the complete closed orbit in about 30 seconds. However, because of the above-mentioned relays, the four signals are not simultaneously available, and the beam position cannot be obtained for a single turn, as is desirable during commissioning or for certain machine physics experiments.

In contrast with PEP, the high bunch frequency of the B Factory makes it difficult to isolate one bunch (the bunch spacing is 4.2 ns), and the most straightforward approach to a closed-orbit measurement is to detect the fundamental frequency of the train, that is, 238 MHz. All channels of the processing electronics must then be calibrated at this

frequency. On the other hand, it is impractical to distribute such a calibration signal to all the multiplexer relays; consequently, the B Factory will employ a different type of multiplexer, and each monitor will be fitted with a matched set of four cables. Besides eliminating the need for the distribution of a calibration signal, this cable plant will also allow the measurement of single-turn trajectories in a snapshot manner, since now the four electrode signals are simultaneously available for each beam pass.

Each ring of the B Factory includes 144 BPMs; their instrumentation will be divided into 12 identical subsystems. Figure 5-122 depicts the general configuration of the cable plant for one-twelfth of a single ring. Advantage will be taken of the existing instrumentation and controls (I&C) alcoves at ground level, thus avoiding electronics in the tunnel and saving the cost of constructing radiation-proof alcoves. This plan entails a 200-ft increase in the length of each monitor cable and requires a careful trimming of its electrical length, as well as a periodic check of the differential attenuation of each set. One type of coaxial line appropriate for this application is a solid-copper, semirigid cable with an outside diameter of 0.375 in. and a low-density foam dielectric. This type of cable has been shown to resist radiation better than cables with solid polyethylene insulation. The specified attenuation is 2 dB/100 ft at 250 MHz; it remains stable as long as moisture is kept from contaminating the foam dielectric.

The RF multiplexer will be based on PIN diode switches, with which SLAC has had successful experience during the past eight years. (Recent advances in the development of GaAs switches make this alternative very attractive as well. The technology actually used will depend on evaluations during the final design phase.) For the processing electronics themselves, the design for the BPMs of the Advanced Light Source at LBL will be adapted, with the operating frequency changed from 500 to 238 MHz. The ALS package includes one intelligent local controller for each BPM. Four such packages will be required for each half-sextant of each B Factory ring.

In addition, it is worth mentioning that, in contrast to the present position monitor system at PEP, the B Factory design does not require any timing signals for its operation. Even in the single-turn mode, digitization will be initiated with beam-derived triggers, as they are at SLC. This has the effect of confining triggers and timing logic to the main control room, where they will be dedicated to the injection system.

5.7.2 Bunch-by-Bunch Current Monitor

There are two compelling reasons for wishing to operate each ring with an equal population in all its bunches (with the exception of an unpopulated gap for ion clearing). First, one can imagine that the optimization of the beam-beam tune shift will be difficult in the event of nonuniform bunch currents (even though it is desirable to operate with different total currents in the individual rings). Second, equal bunch currents make it easier to control the stability of individual bunches.

This requirement places additional demands on the injection system (see Chapter 6) and suggests that a means of monitoring the intensity of individual bunches is necessary. The two key components of this monitoring system are a fast analog-to-digital converter and a programmable trigger delay generator (see Fig. 5-123). The ADC is a 500-megasample/s track-and-hold circuit, followed by an 8-bit flash converter; both units are

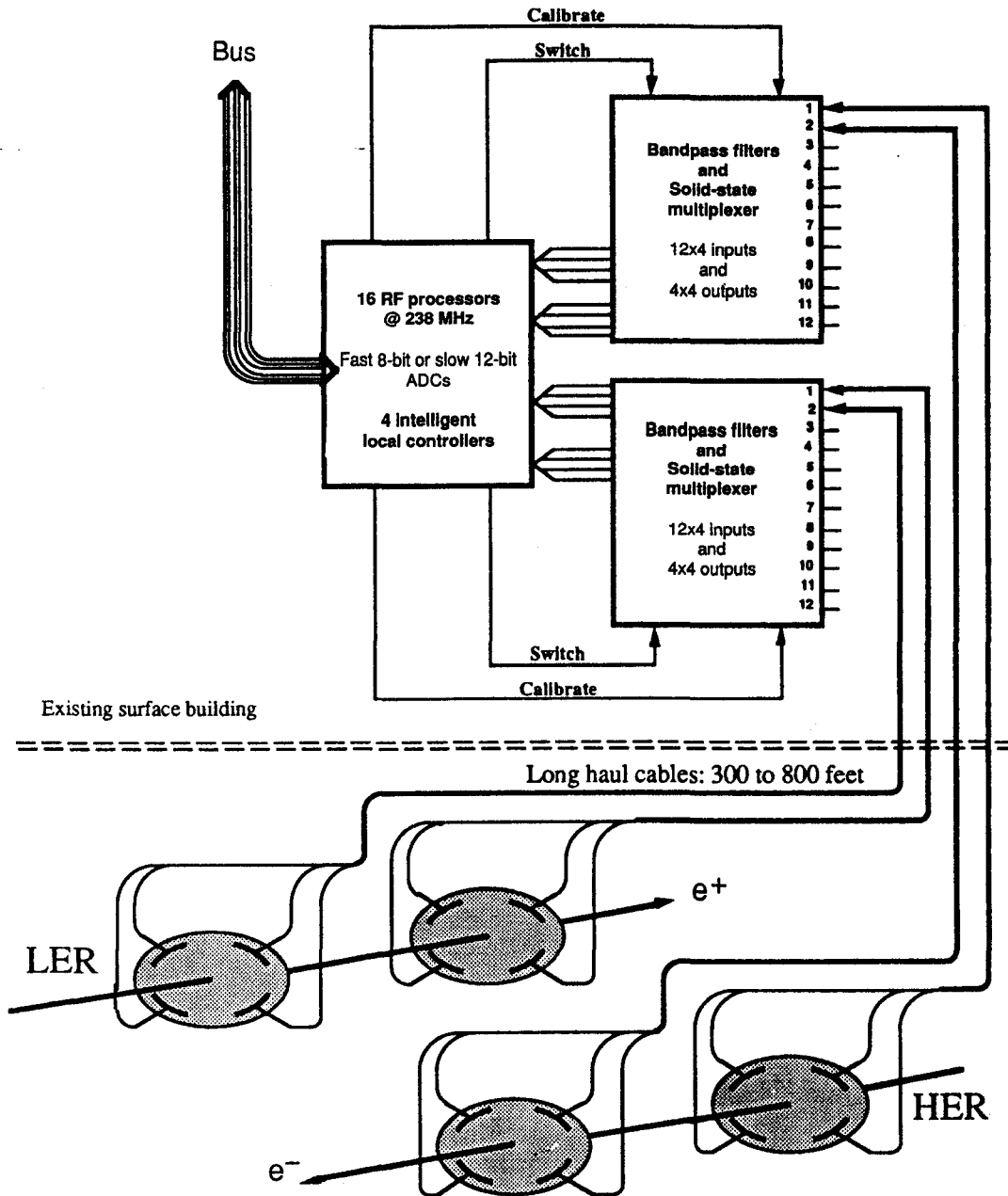


Fig. 5-122. Schematic of a single BPM subsystem, to be installed in existing I&C alcoves. For each ring, the multiplexer addresses two BPMs at a time, thus allowing single-turn measurements for commissioning or for machine physics studies.

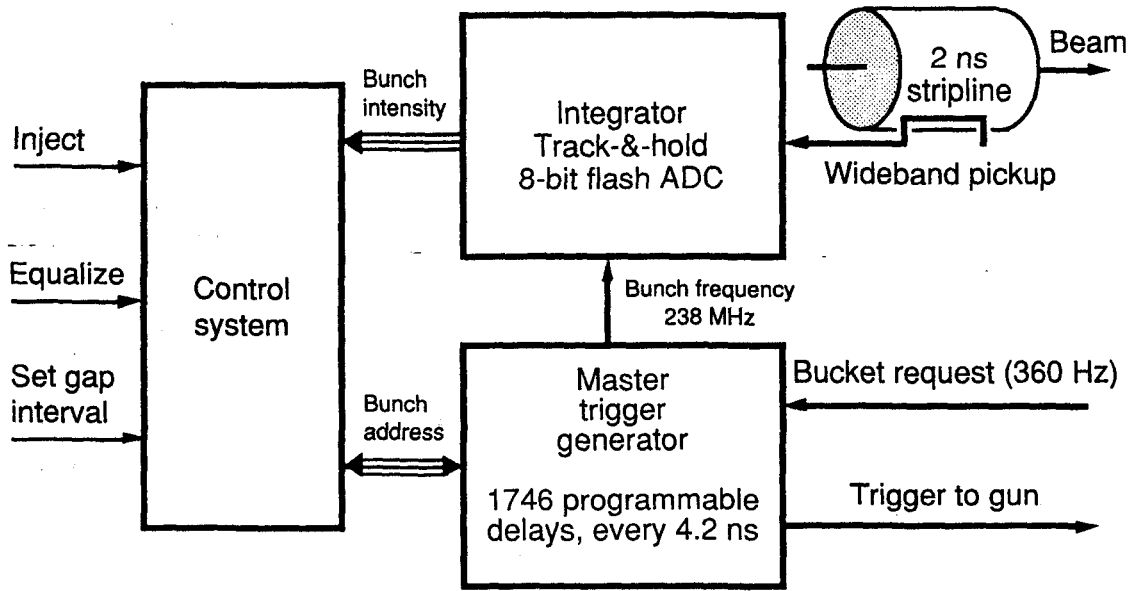


Fig. 5-123. Block diagram of the bunch-by-bunch current monitor. The injector trigger delay is programmed as a function of the bunch address.

now commercially available and sold as a single circuit board. We have evaluated this product in conjunction with the feedback system front end (see Section 5.6). This circuit can be implemented in a straightforward fashion with 100K-series emitter-coupled logic. With both bunch intensity and bunch address data, the control system should be able to devise any injection pattern and monitor its orderly development by interrupting the gun trigger at the proper time and shifting its delay to aim at the next desired bucket. The master trigger generator of PEP will be redesigned to accommodate not only the new requirements of input-output address data, but also the new RF frequency.

For the bunch intensity measurement, we expect a resolution of about 1%. (Injection is planned in steps of 20% up to 80% of full intensity, followed by 5% steps; the residual imbalance in bunch population will be kept below the 5% level.) We anticipate injection trigger jitter of about 50 ps, comparable to that at PEP; this amounts to a phase error of less than 10° at the RF frequency.

5.7.3 Feedback System to Maintain the Beams in Collision

As part of the design effort for the B Factory, we have studied means of monitoring and controlling the beams in collision. Indeed, residual orbit shifts in both rings will have to be corrected with a pair of steering dipoles on each side of the interaction point, for each beam and in both planes. Figure 5-124 depicts an open-loop method of setting these steering dipoles. The hardware normally used for the measurement of the betatron tunes is connected so as to excite one beam and detect the response of the other to this excitation. We expect a strong coupling of the beams when they are colliding; however, this method does not lend itself to automatic control.

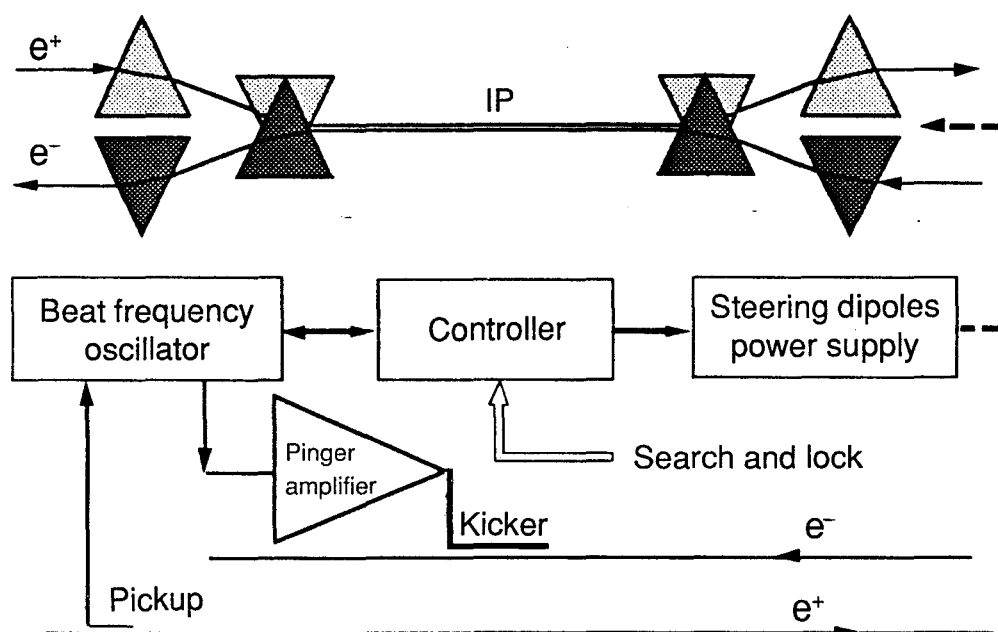


Fig. 5-124. Block diagram of a system for bringing beams into collision, based on the measurement of one beam's response to excitation of the other.

Alternately, the scheme illustrated in Fig. 5-125, involving a rapid count of Bhabha events, could be implemented. Owing to the high luminosity of the B Factory and its relatively low beam energies (the cross section for Bhabha scattering is proportional to $1/E^2$), it should be possible to monitor changes of the order of 1% in luminosity in a few minutes (for instance, at $\mathcal{L} = 10^{31} \text{ cm}^{-2} \text{ s}^{-1}$ and a beam energy of 14 GeV, the count rate of the PEP luminosity monitor is of the order of 30 counts per second). We envision a system whereby the beams are brought into collision with the help of a raster scan excitation of the set of dipoles for one beam. After freezing the dipole settings, the system control is then turned over to a surveillance program. After the detection of a small drop in luminosity, a "miniscan" is initiated and the dipoles are reset to optimize the collision rate.

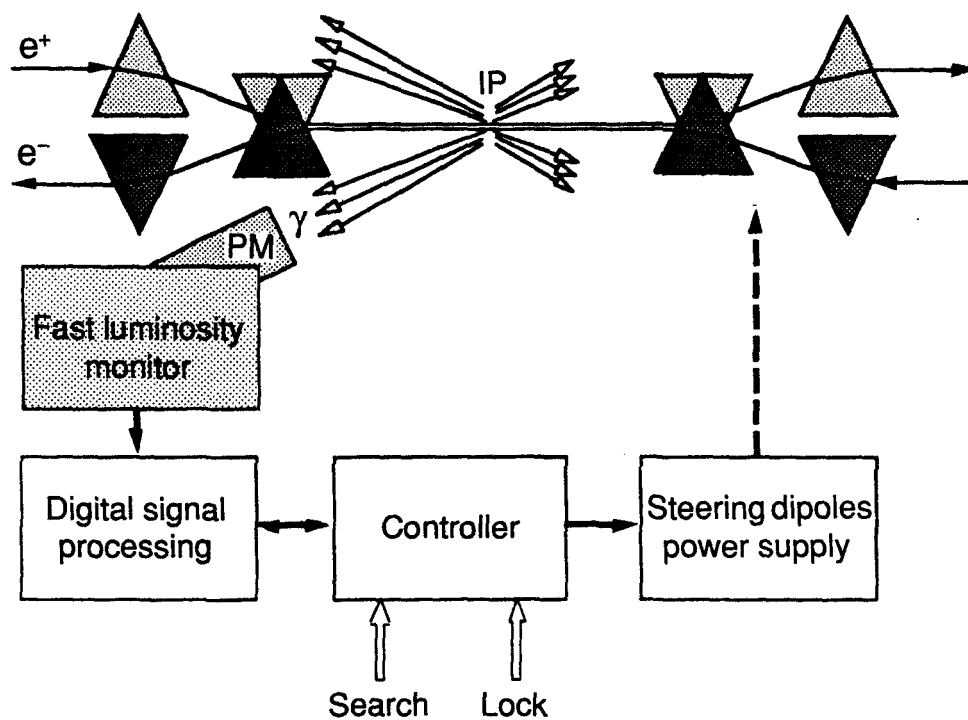


Fig. 5-125. Block diagram of a system for keeping the beams in collision, based on luminosity monitoring.

5.8 CONTROL SYSTEM

The control system for the B Factory comprises two separate systems, one for the linac injector and the other for the storage rings. The two systems are separate but closely integrated, owing to their common architecture and their hardware links.

Since the SLC linac will be used as the B Factory injector, the control system currently running the SLC facility will be retained essentially unchanged. The two injection lines (for electrons and positrons) will be operated through the SLC control system, using an SLC control console located in the B Factory control room.

The SLC control system distributes control functions among a supervisory mainframe, remote consoles for human interface, and remote microcomputers for actual hardware control. A more detailed discussion of the SLC control system can be found in Phinney [1985] and Phinney and Shoaee [1987].

The control system for the HER and LER will be new, but its design is patterned after the SLC control system (see Figs. 5-126 and 5-127). It consists of a multitiered distributed intelligence system. Supervisory control is provided by a pair of mainframes. Normally, one is used for on-line control and the other for software development and off-line monitoring. However, the second computer can be used as a backup should the primary mainframe go down. This redundancy has proved useful with the SLC and will be even more important in a facility serving as a particle "factory." Multiple workstation consoles, networked to the mainframe, provide the interface that allows operators and machine physicists to control and monitor the machine. Also connected to the mainframe are a group of microcomputers, linked by a separate, dedicated high-speed network. These microcomputers will be responsible for the actual machine-control and data-acquisition functions. The microcomputers will be logically organized on a geographical, rather than a functional, basis, thus reducing cabling costs and simplifying the software design, given the database structure described below.

The control systems for the injector and the storage rings are linked in two ways. First, the supervisory mainframes of both systems are networked to allow database exchange, hence streamlining coordination of the operating conditions of the two machines. Second, certain time-critical information will be passed directly from injector microcomputers to storage ring microcomputers via data paths already established for the SLC control system.

The storage ring control system will control and/or monitor the power supplies, vacuum system, RF system, beam position and luminosity monitors, machine protection system, and personnel protection system (status only). Based on experience at PEP, we expect this system to handle approximately 30,000 signals. The control of these functions will be governed by a run-time database in much the same way that the SLC control system now operates. The database will contain all the information needed to describe the machine, including control connections, device characteristics (for example, magnetization polynomial fits), and present configuration (for example, magnetic fields). This allows all devices of similar types to be controlled by the same software utilities, with references to different entries in the database. The database, managed by a standard relational database package, will be maintained by B Factory operations staff.

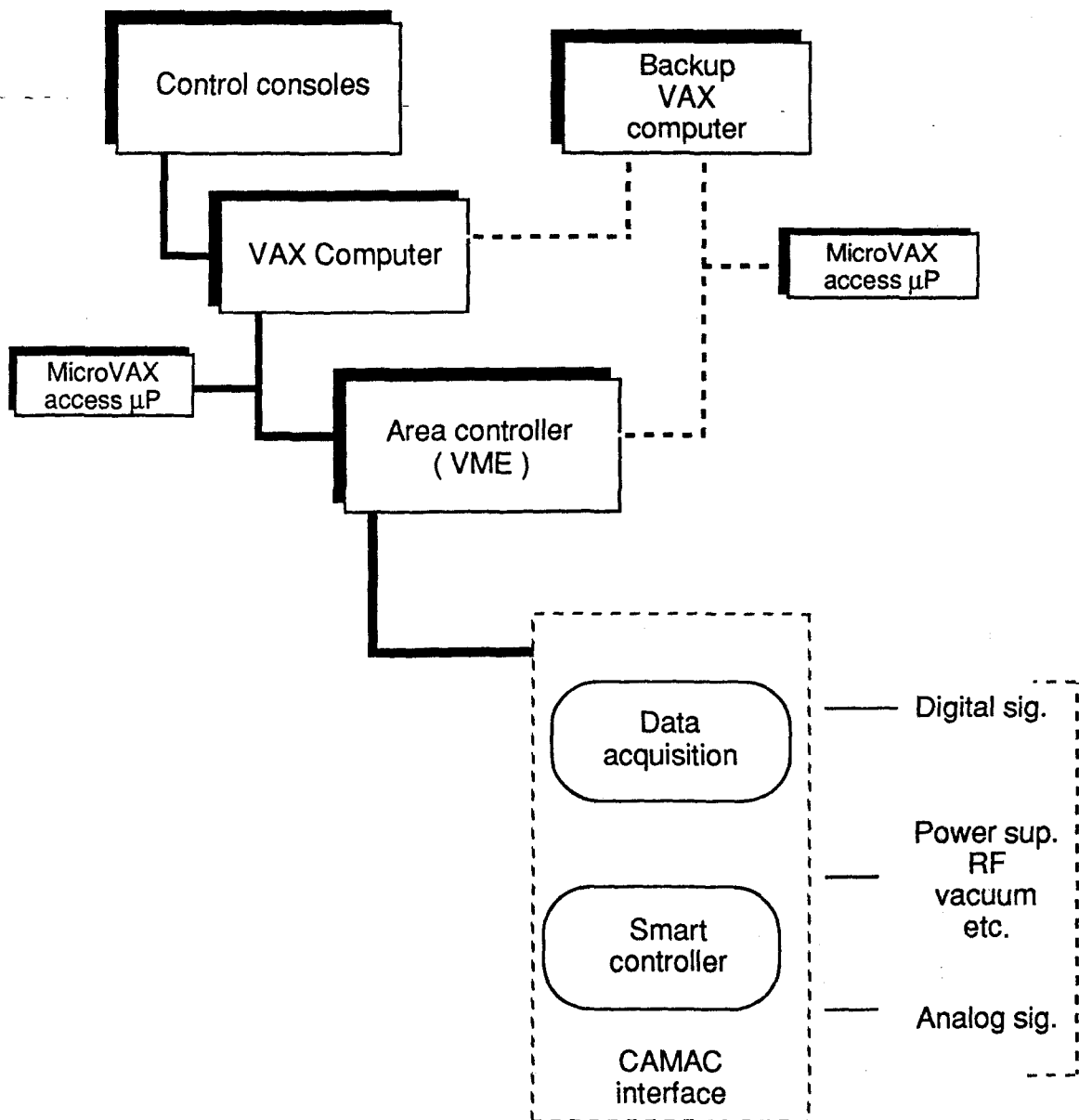


Fig. 5-126. Architecture of the B Factory distributed control system.

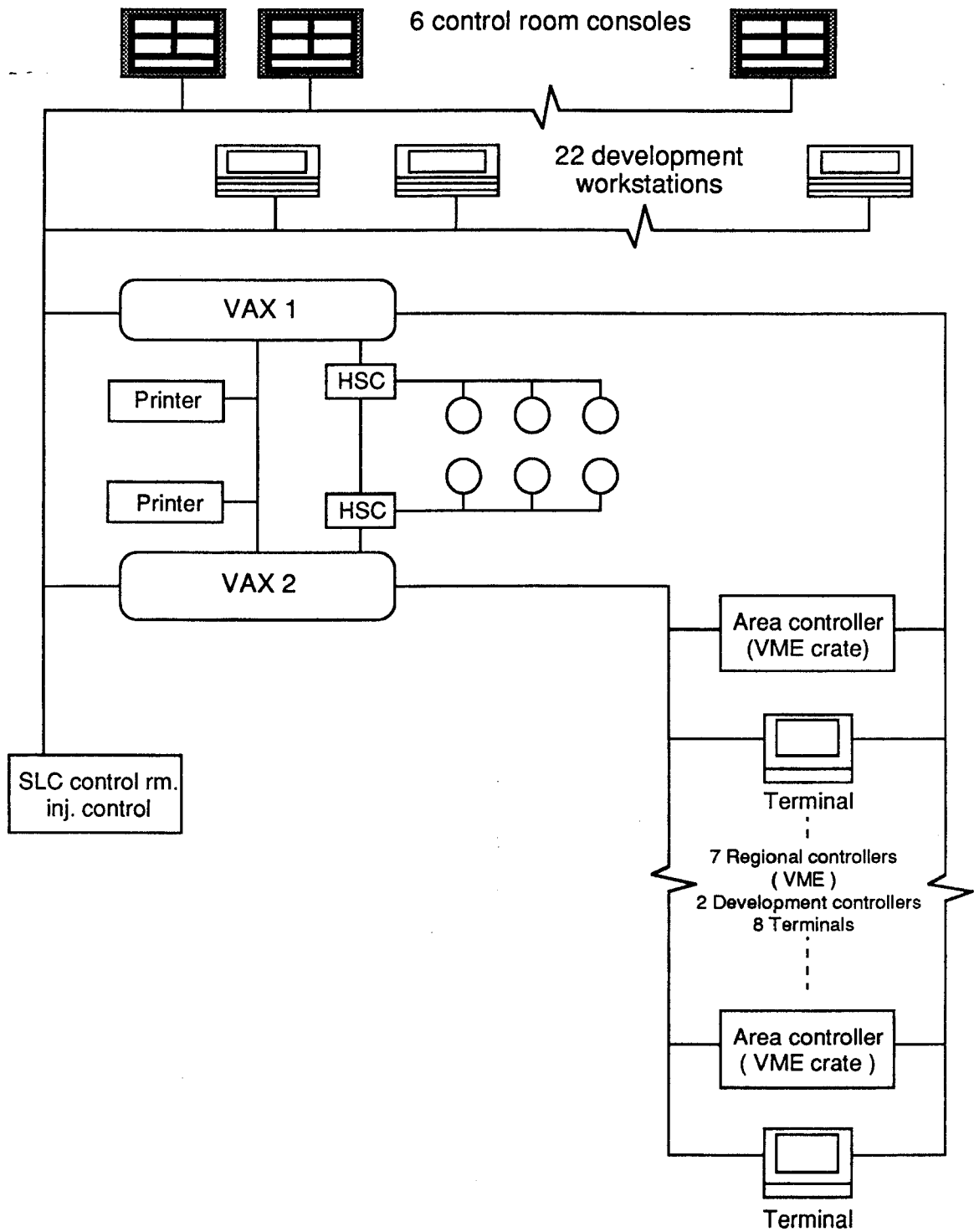


Fig. 5-127. Schematic layout for the B Factory control center.

The database-driven architecture of the control system will also facilitate the use of monitoring and analysis tools already available within the SLC control system. These include historical data regarding machine conditions and correlation analyses of multiple machine parameters. These tools have proved very important in the commissioning and running of the SLC.

5.8.1 Control Center

5.8.1.1 Consoles and User Interface. The control consoles in the control room will be developed in keeping with the philosophy that the operator interfaces must be easy and convenient to use, and must contain graphically presented information rather than a profusion of unprocessed data (see Fig. 5-128). Overview large-screen display systems having color and symbolic representations will be used to monitor machine operating parameters, operational processes and procedures, machine subfunctions, and safety systems.

These facilities will be implemented using industry standard X-Windows graphics systems, so as to separate software packages from the underlying hardware platforms. The hardware will support popular user-interface devices (track-ball, mouse, digitizing pad, etc.) and standard network and connectivity protocols, and will incorporate the flexibility needed to allow future, software-independent development.

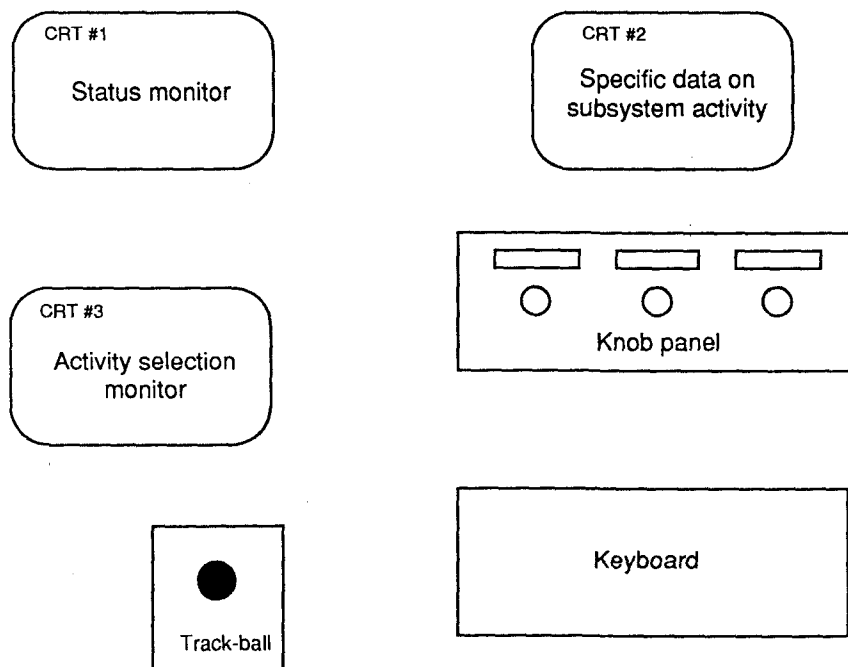


Fig. 5-128. Components of a B Factory control console.

The software will take advantage of the graphics facilities to provide symbolic representations of the machine and its elemental components. This approach guarantees that operators and other users will get a visual image of the present state of the machine. These facilities will be integrated in such a way as to be independent of the underlying hardware.

The operator-control consoles will be implemented in such a way that multiple operators can work separately or in unison on the same or related machine subsystems from identical consoles. This will require two- or three-screen consoles so that operators have a screen for data selection and one or more screens for data or status representation. In addition, summary status displays must be visible around the control room and in remote areas, so that all affected personnel are kept aware of information they need. Some consoles will be located in remote areas to aid commissioning and to provide emergency backup.

5.8.1.2 Database Facility. The database facility includes the data acquisition and control database that describes the characteristics and the operating parameters and limits for all real-time storage ring subsystems. It also includes the server functions that allow noncontrol software to collect and manipulate stored data. The database will be distributed such that local databases maintain and use local data to operate local equipment, whereas critical elements that must be available in multiple databases are broadcast across the entire computer system. This arrangement will minimize data-path bandwidth requirements between operating nodes, while maximizing local data availability, utilization, and manipulation.

These real-time databases will be built up and organized by a readily available relational database that draws on standardized device data structures and device characteristics. This approach will allow automated generation of run-time structures by personnel not familiar with the hardware and will ensure that the proper relationships exist among distributed elements of the database so as to provide updated real-time data to the right software applications on the correct hardware platforms.

5.8.1.3 Model Driver. Accelerator operation and performance will be very closely coupled to a real-time, on-line simulation model of the injector, transport lines, and accelerator optics. This has been done at the SLC, and the same model software can be adapted to the B Factory environment. The model provides expected values when the machine parameters are changed and provides a diagnostic facility when expected and actual values differ.

5.8.1.4 Program Development Facility. The software development environment will be composed of a second large VAX processor, clustered with the primary control VAX and with limited but compatible access to machine networks and systems. The program development system will have access to the operational database and accelerator facilities via the cluster, and it makes available a backup processor to operate the accelerator if the primary computer fails. This secondary operations role requires that the development machine be of similar size to the on-line machine.

The software will be written in such a way as to be database-driven and layered so that elements of the code or hardware configurations can be changed without complex or

extensive rework in the programming. To the extent possible, driver-style interfaces will be used to bridge the system to specific classes of devices or systems so that these elements can be upgraded to keep pace with advances in technology without unreasonable software modifications. Structured analysis and design tools will be used to improve the flexibility, modularity, and reusability of the code, so that generic software can be applied to a wider range of uses. These tools bridge well to modern structured languages, which provide greater software portability across hardware platforms. Software development will be accomplished on workstations with VAX compatibility. This approach makes it possible to control, test, and debug hardware and software from workstations throughout the VAX systems.

5.8.2 Control Distribution

The control system will have its processes distributed spatially and functionally. The SLC injector will continue to use its own control system and will additionally control the injector beam transport lines, while the B Factory control system will run the storage rings and their associated equipment. Consoles for the SLC system will reside in the B Factory control room. Functionally, the control processes will be distributed across the master VAX cluster, the microprocessors in the ring alcoves, and the smart controllers in the power supplies and RF systems. The VAX cluster will deal with the user interface, user analysis and data manipulation, network control, and the run-time database for all physical devices in the system. The alcove microprocessors will be responsible for data acquisition and control forwarding. The smart device controllers will deal with functional control, backup safety monitoring, and calibration of the individual devices. The processors will be linked by standard networks or custom high-speed communication links, depending on their functions. This will allow functionality to be pushed down to the level where the actual control takes place or where data are manipulated.

5.8.2.1 Computers. The centralized computer will be a large VAX-cluster paired processor, with shadowed disks for redundancy and speed. This machine will be a multiple-processor machine with 100 megabytes of main memory. The alcove microprocessors will be 32-bit diskless processors with hardware math support and approximately 4 megabytes of main memory. These units will be RAM based and will receive their systems and database-executable images from the centralized cluster or the network server, depending on the final detailed design. These units could be RISC- or CISC-based processor architectures, depending on the technology available at the time.

The device controllers will be relatively simple and can be implemented with highly integrated controller-oriented chips in either an 8- or 16-bit architecture. The controlling factor in this case will be the availability of software development and maintenance environments.

5.8.2.2 Networks. To the extent possible, general-purpose networks employed at the higher levels of the system will be standard "off-the-shelf" facilities to enhance connectivity and maximize flexibility. These networks, which could be implemented with Ethernet, are consistent with the notion that intelligence should be located where it can be useful, then laced loosely throughout a network.

Special-purpose networks will be required in some data paths, owing to particularly large data bandwidths or requirements for very fast response times. Systemwide networks will be implemented on fiber optics using standard T3 technology, while fast point-to-point links will be established with custom protocols on top of readily available transport hardware. These connections will exist at multiple levels: between large machines, between microcomputers, and between microcomputers and mainframes.

Standard networks utilize standard software, supported industry-wide across hardware platforms, and they are also layered so that the systems in general are extensible. Current technology provides a wide range of server and network-bridge functionality to permit the intelligence centers to operate at the subsystem level, without overloading the network bandwidth.

5.8.2.3 Device Interface. Device interfaces will be implemented around a layered, driver-oriented architecture, so that functional software can relate in a standard way to the driver, thus requiring no interaction or detailed familiarity with the actual physical devices. This approach will allow the use of more generic software and will allow the hardware specifics to change as the technology evolves. The system architecture will involve smart control nodes or clusters around the machine, tied to relatively less smart input-output facilities located adjacent to the equipment being controlled or monitored. Standard data conversion cards, bus structures, and communications facilities exist to support this approach.

5.8.2.4 Timing Systems and Synchronization. Software currently exists in the linac control system to operate the injector and the transport lines to the rings. Synchronizing injector beams with the fill timing of the rings will be straightforward. The timing required for kickers and BPMs already exists. Although there is no need for timing and frequency control to ramp the energy of the rings during operation (because the beams are injected at full energy), provision must be made in the system design to allow slight energy changes to tune to the exact $T(4S)$ energy. This capability requires a facility to synchronize the alcove microprocessors and their associated control crates.

5.8.2.5 Access Procedures. Machine configuration changes, made before and after access is permitted to the machine structures and tunnels, will be controlled from the machine control rooms. This access control system will monitor and manage the hardware Personnel Protection Systems, although it will not supplant the hardware for that protection interlock system (see Chapter 8).

Specifically, the computer-controlled ring access control systems will manage the ramp-up, ramp-down, standardization, and calibration tasks associated with turning equipment off or returning it to ready status. These processes will also keep track of personnel in the tunnels during limited access periods to minimize the equipment restoration necessary for turn-on. The processor responsible for this function will be slaved to the database and control activator paths, but will be a separate physical processor, so that the main computer system can be repaired or tested without losing lockup security throughout the facility.

5.8.3 Special Control Zones

5.8.3.1 Injector. There will be two beam transport lines from the injector to the rings, one line for electrons and one for positrons. Both lines will require large numbers of quadrupole and trim magnets for optical changes and steering. All these will be controlled by existing microcomputers in the SLC control system.

5.8.3.2 Interaction Point. The interaction point requires controls to handle the superconducting focusing magnets, as well as some fast-feedback control software to maintain the beam spots at the maximum luminosity. The feedback control loops will run on an interaction area microprocessor and will implement the beam-on-beam scans to measure the beam size, as well as control the beam wiggler magnets to keep the beams in collision at maximum luminosity.

5.8.4 Control System Functionality

5.8.4.1 Problem Reporting. Fault reporting and management will be configured so that the systems identify and report the specific device that failed or indicated an unsafe condition. These faults will be monitored by a separate machine protection system (MPS) that is capable of shutting down the system. Recovery from fault conditions will be automatic.

Diagnostic panels will display equipment or computer system problems through the MPS or computer error log system and will be linked to the run-time database, so that the device or system is correctly identified and located, and the faulty characteristic or parameter described. Such faults can be automatically logged into the existing CATER maintenance-reporting system as well. This system, developed for the SLC, will be responsible for logging and cataloging faults, the urgency of repair, and the responsible support groups. This system will help ensure that support and maintenance work is done on a priority basis and that problems are not lost, only to be rediscovered later.

5.8.4.2 Data Collection and Retention. As part of the B Factory control system, history buffers will sample device status on a periodic basis, so that the configuration and status of the machine can be reviewed in detail later. Configurations can be archived for all or parts of the machine so that the machine can be restored to a known state and optimal orbits replicated.

5.8.4.3 Data Analysis. History plot facilities will be used to review trends or specific events over time. Such facilities are useful in correlating faults, detecting the onset of problems, and identifying optimal operational configurations. Correlation plot facilities will be used to correlate a wide range of data elements with one another to learn more about the interrelationships of machine parameters.

6.

INJECTION SYSTEM

THE basic method proposed to fill the B Factory rings with electrons and positrons is to use the SLC linac, including its damping rings and positron source. Given that the B Factory luminosity lifetime will be of the order of a few hours, our goal is to complete the injection cycle for both electrons and positrons within a few minutes. As will be shown below, the SLC linac (with a few modifications and simplifications) is ideally suited for this function.

By the time the B Factory is operational, it is assumed that the SLC will be nearing the end of its usefulness for high-energy physics research. Even so, it is worth noting that the modifications that will be implemented for the B Factory will not eliminate the independent utility of the SLC. For example, the straight-ahead Final Focus Test Beam area will remain usable for accelerator research. The same will be true of the traditional SLAC fixed-target areas, such as End Station A and the test beam areas. The so-called Nuclear Physics Injector (NPI), located at the beginning of linac Sector 25 and capable of producing 2- to 10-GeV electron beams at the end of the linac for nuclear physics research, will be operable simultaneously with the B Factory injection system, without any interference.

6.1 OVERALL APPROACH AND SPECIFICATIONS

The basic approach adopted for the B Factory injection system is illustrated schematically in Fig. 6-1, and the overall injection specifications and relevant parameters are given in Table 6-1. The fundamental simplification, compared with the SLC, results from the use of two bypass lines, one for nominally 3.1-GeV positrons, the other for nominally 9-GeV electrons. These positron and electron bypass lines start near the end of linac Sectors 3 and 7, respectively, and run to the end of the linac at Sector 30. Once extracted at the correct energies, the beams never reenter the linac, thereby avoiding emittance growth from wakefields in the disk-loaded waveguide and eliminating the need for deceleration (as was used for SPEAR and PEP injection). That portion of the linac downstream of Sector 19 could be used for the acceleration of other beams to higher energies, or for

INJECTION SYSTEM

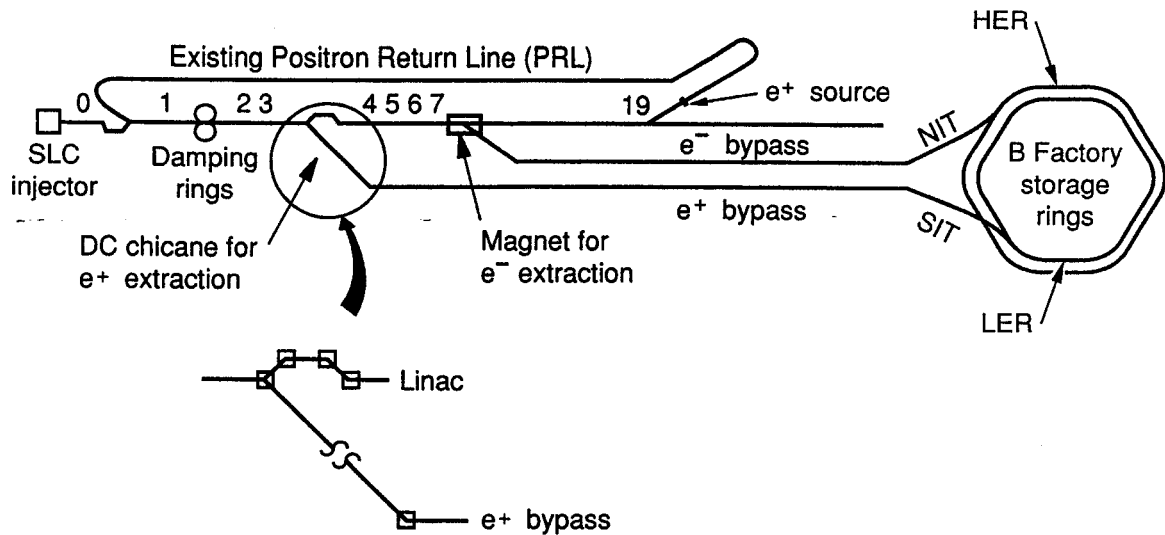


Fig. 6-1. Schematic of the B Factory $e^\pm$ injection system, based on use of the SLC linac with bypass lines. The numbers along the linac indicate the location (not to scale) of each sector. Each of the 30 sectors is 100 m long.

separate operation with the NPI, but will be turned off when not needed, to reduce power consumption.

The bypass lines, much like the existing Positron Return Line (PRL) from Sector 19, are located above the existing linac, suspended in the tunnel just below the ceiling. They consist of two parallel and independent FODO arrays. At the end of Sector 30, just before the beam switchyard, each bypass line is directly connected to its corresponding (north or south) injection transport line (NIT or SIT) leading to the B Factory tunnel. The existing NIT and SIT lines will undergo only minor modifications (see below). Injection into the high- and low-energy rings (HER and LER, respectively) will take place in the long straight sections of IR-10 (e^-) and IR-8 (e^+). For both the HER and LER, injection will occur in the horizontal plane, utilizing a combination of DC bumps and pulsed kickers.

The injection scenario proposed here was selected after considering other alternatives, including (i) using only the last one-third of the linac and building a new in-line positron source, (ii) using the NPI injector for electrons only, while using the SLC for positrons, and (iii) keeping a system very similar to the one now used to fill SPEAR and PEP with the SLC, where the low-energy $e^\pm$ beams (2.8–10 GeV) are obtained by deceleration downstream of Sector 19. Some of the reasons for ultimately rejecting these alternatives include:

- A new positron source would be very costly and would complicate the transmission of SLC-type beams to the Final Focus Test Beam or End Station A.

Table 6-1. B Factory injection specifications and parameters.

Beam energy	
High-energy ring (e ⁻) [GeV]	9 [range: 8–10]
Low-energy ring (e ⁺) [GeV]	3.1 [range: 2.8–4]
Beam current	
High-energy ring [A/10 ¹⁰ e ⁻]	1.48/6777
Low-energy ring [A/10 ¹⁰ e ⁺]	2.14/9799
Particles per bunch	
High-energy ring [10 ¹⁰ e ⁻]	4.1
Low-energy ring [10 ¹⁰ e ⁺]	5.9
Linac repetition rate [pps]	60 or 120
Linac current [10 ¹⁰ e [±] per pulse] ^a	0.2–1
Invariant linac emittance [m·rad]	5 × 10 ⁻⁵
Normal filling time ^b	
Topping-off (80–100%) [min]	3
Filling time (0–100%) [min]	6
Magnet standardization time [min]	15
Ring circumference [m]	2199.318
Revolution period [μs]	7.336
Revolution frequency [kHz]	136.311
Bunch frequency [MHz]	476/2 = 238
Time between bunches [ns]	4.20
Harmonic number	3492
Number of bunches ^c	1746 – 5% = 1658
Horizontal damping time	
High-energy ring [ms]	38
Low-energy ring, with wigglers [ms]	36
Low-energy ring, without wigglers [ms]	150
Nominal horizontal beam emittance [nm·rad] ^d	
High-energy ring, horizontal/vertical	48/1.9
Low-energy ring, horizontal/vertical	96/3.8

^aThe SLC routinely delivers 1.5×10^{10} e⁺ and 3×10^{10} e⁻ per bunch on each linac pulse.

^bElectron and positron bunches are injected on alternate pulses at 60 pps, in which case both rings can be topped-off in 3 minutes.

^cFor filling purposes, the rings will be divided into nine zones of equal length. The 5% gap leaves one zone partially unfilled.

^dStorage ring emittances are quoted here, and elsewhere in this document, as unnormalized, or geometrical, values.

- NPI-type beams, for electrons only, downstream of Sector 19 would either have bunch currents lower by two orders of magnitude (that is, about 10^8 electrons) or would require upgrading the NPI to SLC standards, a costly operation that would not, in any case, yield SLC-quality emittances without damping rings.
- Multibunch electron injection, that is, with a train of bunches 4.2 ns apart, would only pay off if the linac were not operated with SLED, so that a long pulse train of at least 200 bunches (about 840 ns) could be accelerated and stored. This would require a costly move of the NPI to about Sector 20 to obtain the required 9–10 GeV, and would mean tying up that entire part of the linac solely for this purpose. Furthermore, this approach would not permit single-bunch electron filling and would make the electron injection scheme very different from, and less flexible than, positron filling—an undesirable feature per se. Finally, this filling method is undesirable for the storage ring feedback systems, which benefit from a scheme in which the injected beam comes in small increments, as discussed in Section 5.6.
- Using the SLC in the “SPEAR-PEP” filling mode would have all the disadvantages of back-phasing the latter part of the linac and simultaneously having to handle beams of 3.1 and 9 GeV of opposite charges.

A slightly less costly implementation for the proposed bypass scheme might be to use a single, common line for both positrons and electrons beyond Sector 7. Such a scheme could be made to work with a weaker focusing system for the electrons but with twice as many correctors and beam position monitor (BPM) electronic processing systems. Moreover, it would require a second chicane at the Sector 9 junction point, larger-aperture quadrupoles and BPMs, and a method of separating the unequal-energy beams at the end of the linac into the NIT and SIT lines. These complications would likely lead to operational difficulties arising from steering and instrumentation problems. The resulting compromises would almost inevitably lead to inefficiencies and an overall decrease in the robustness of the injection system.

After considering the various scenarios, we adopted the more flexible and reliable scheme described here, with independent bypass lines. As outlined in Section 6.5, the optimum injection pattern involves “topping-off” the rings approximately once every hour, so the operational benefits of having a robust injection scheme are extremely important.

As shown in Table 6-1, the bypass lines are designed to accommodate an energy range of 2.8–4 GeV for positrons and 8–10 GeV for electrons. When filled to the nominal operating point (corresponding to the design luminosity of $3 \times 10^{33} \text{ cm}^{-2} \text{ s}^{-1}$), the LER will have a current of 2.14 A, or roughly 6×10^{10} positrons per bunch, and the HER will have a current of 1.48 A, or about 4×10^{10} electrons per bunch. The normal filling process will consist of topping-off the rings when the stored currents drop to 80% of these values. Thus, the topping-off operation will consist of delivering roughly 10^{10} particles to each of the 1658 bunches in each ring. For each bunch, this will be accomplished in five (nonconsecutive) linac pulses, at a rate of 60 pps. Currently, the SLC routinely delivers 3×10^{10} electrons and 1.5×10^{10} positrons per pulse to the rings. It will be extremely easy to deliver less than one-fifth of this charge per pulse to the rings.

At 60 pps (interleaved) for both e^- and e^+ , the filling operation should take $(1658/60) \times 5 = 140$ seconds, that is, less than 3 minutes.

When filling from zero (empty rings), the linac will be run with roughly $10^{10} e^\pm/\text{pulse}$, and all of the 1658 bunches will be filled to about 80% of their final charge. This operation will also take about four or five linac pulses, or less than 3 minutes, to fill both storage rings; an additional 3 minutes will then be needed to top-off, giving a total filling time of 6 minutes.

Another great simplification will result from making the ring RF frequency 476 MHz (that is, exactly one-sixth of the 2856-MHz linac frequency). The drive system along the 3-km linac already operates at 476 MHz, and extending it to the B Factory (or vice-versa) will be very easy. With this choice, all the key RF frequencies (the damping rings at 714 MHz, the linac at 2856 MHz, and the two collider rings at 476 MHz) will be harmonically related. For proper spacing around the rings, every second bucket (4.20 ns apart) will be filled, giving a bunch repetition frequency of 238 MHz. With a harmonic number of 3492 ($= 2^2 \times 3^2 \times 97$) and a 5% gap for ion control, there will be 1658 filled buckets. As explained later, for filling purposes each ring will be divided into nine equal "zones," of which one will be left half empty to avoid ion trapping in the HER. By filling the bunches in sequential zones, the time that elapses between each individual bucket fill will be 27.6 seconds.

In the following sections, we describe the elements of the proposed injection system.

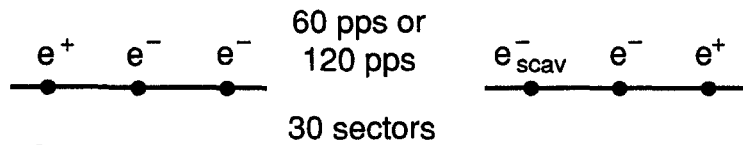
6.2 SLC MODIFICATIONS

As illustrated in Fig. 6-1, positrons will be extracted from the linac near the end of Sector 3 and electrons near the end of Sector 7. These choices provide considerable latitude in obtaining the desired energies, as the linac can provide roughly 1.8 GeV per sector with SLED. At each extraction point, a segment equivalent to one linac girder (about 12 m) will be cleared for new equipment. The lengths of the positron and electron bypass lines are 2.7 and 2.3 km, respectively.

6.2.1 Extraction Method

To understand the pulse sequence and method of extraction from the linac, we must first review how the SLC currently functions (see Fig. 6.2a). For the SLC, two electron bunches and one positron bunch are accelerated with each linac macropulse. Two of the bunches are used for the electron-positron collisions in the SLC arcs, while the extra ("scavenger") electron bunch is used to create the positron bunch for the next pulse. To accomplish this, at 60 or 120 pps, Sectors 2 through 30 are pulsed essentially simultaneously (with just enough delay to accommodate the 10- μs particle transit time) and Sectors 0 and 1, upstream of the damping rings, are pulsed roughly 12 μs later to receive the positrons generated at Sector 19, which return via the PRL. In Sectors 2 through 19, the positron bunch comes first, followed approximately 60 ns later by the first electron bunch and another 60 ns later by the second electron bunch. Both of these electron bunches are extracted (with some difficulty) on the same pulse from the north damping ring. As mentioned, the second bunch is normally redirected by a pulsed

(a)



(b)

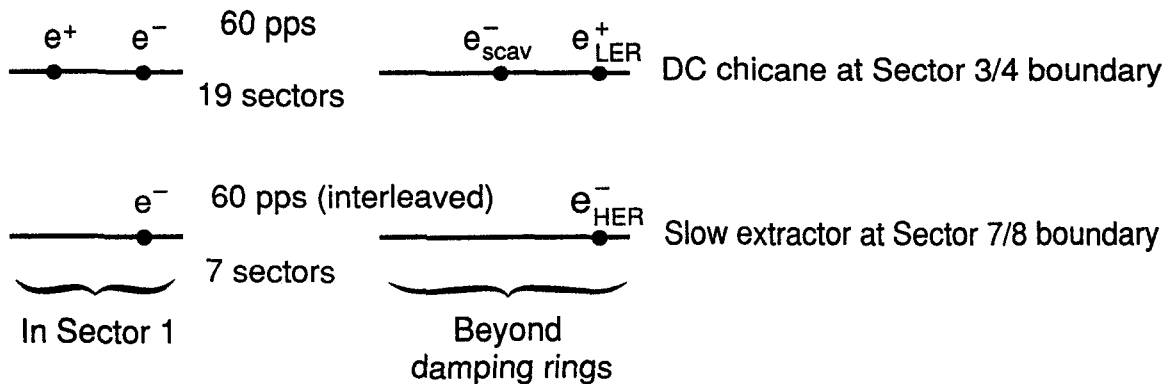


Fig. 6-2. Linac pulse and bunch sequence for (a) typical SLC operation and (b) injection into the B Factory.

magnet and Lambertson septum in Sector 19 to produce the positrons in the positron alcove, while the first electron bunch goes on to the SLC north arc. In Sectors 0 and 1, the order of the bunches is inverted (for beam-loading reasons) and the newly generated electron bunches from the injector gun are placed ahead of the bunch returning from the positron source. The spacing between the three bunches is dictated by the almost diametrically opposite positions that they occupy in the damping rings, and by the maximum appropriate distances at which they can ride on the SLED wave to acquire the proper energies in the linac.

There are a number of different ways in which the SLC pulse sequence could be modified to fill the B Factory, but probably the simplest is shown in Fig. 6-2b. Here, at the end of Sector 3, a DC chicane (see Fig. 6-1) set for an energy of about 3.1 GeV extracts the positrons and reinjects the electrons into the linac. On one 60-pps time slot, the positron bunch comes first and the second bunch is the scavenger electron bunch, which makes the positrons. (We define a 60-pps time slot as a set of 60 pulses synchronized with one 60-cycle phase. When the accelerator runs at 120 pps, it uses two such slots, equally spaced in time.) Only one electron bunch is in the north damping ring at a time, and this considerably eases the difficulty of extraction compared with present SLC operation. To let the scavenger electron bunch reach Sector 19, the pulsed magnet at the end of Sector 7 is turned off during this time slot. When the positron bunch returns via the PRL, only one electron bunch is generated at the gun and stored in the north

damping ring, while the positron bunch is stored in the south damping ring. The electron bunch is ejected from the north damping ring and accelerated to the end of Sector 7, 8.3 ms (1/120 of a second) later. This time, the extractor magnet is turned on and the electron bunch is launched into the electron bypass line. After 12 μ s, the injector gun generates a new electron bunch that is stored in the north damping ring to become the next scavenger bunch, 8.3 ms later. Subsequently, the whole pattern is repeated.

Note that in this mode of injection there is no need for any new fast-pulsed magnet: The chicane is DC and the magnet at the end of Sector 7 is on and off during successive pulses. Sectors 8 through 19 run at 60 pps and Sectors 1 through 7 run at 120 pps. Total power consumption for these linac pulses is less than 10 MW AC.

6.2.2 Bypass Lines

Let us now consider the bypass lines. These are simple FODO arrays, suspended from the ceiling. We envision a pair of 4-in.-diameter beam pipes located roughly 25.5 in. above the linac. The positron bypass line reaches its final elevation in Sector 5 (approximately 32 in. to the south of the linac axis); the electron bypass line arrives at the same elevation in Sector 9 (approximately 18 in. to the south of the linac axis). To achieve this, the first chicane magnet (see Fig. 6-3) at the end of Sector 3 will be installed at a tilt of 51° with respect to the vertical. This will permit the positron beam to reach the bypass line after deflection in a single plane. A second magnet of the pair (see Fig. 6-1) straightens out the beam in the line. Meanwhile, three similar magnets bend the electron beam back and reinsert it into the linac. At the end of Sector 7, two pulsed magnets extract alternate electron bunches at 35° with respect to the vertical (see Fig. 6-3). (These magnets will be very similar to the 40 PM1 and 40 PM2 magnets now used for PEP.) The pulsed magnets are followed by a DC dipole to increase the upward kick and a slightly stronger DC reverse-bend magnet to direct the electron beam into its bypass line.

The bypass lines will be fabricated from 4-in. seamless aluminum tube with stainless-steel transitions at the ends for flanges. The 4-in.-diameter tube provides sufficient pumping conductance, but every 50 m it is necked down to about a 1-in. diameter to allow for small-bore quadrupoles. Where the two lines are parallel (from Sector 9 through 30), they are cross-connected for common pumping. For each line, every 100-m length (one FODO cell) has two quadrupoles, two BPMs (each with a readout in a single plane), two corresponding correctors for steering, and one 120-L/s pump. Isolation valves and roughing connections are provided every 200 m. Matching quadrupoles at both ends of the bypass lines need individual power supplies, but in the long FODO array, the quadrupoles are powered in series, in two strings each, to reduce costs. Profile monitors are provided to check emittance and beam shape along the way. A list of bypass line components is shown in Table 6-2. Relevant beta and dispersion functions for the positron beam, as it is extracted from the linac and injected into the bypass line, are shown in Fig. 6-4. The corresponding functions for the electron beam are similar.

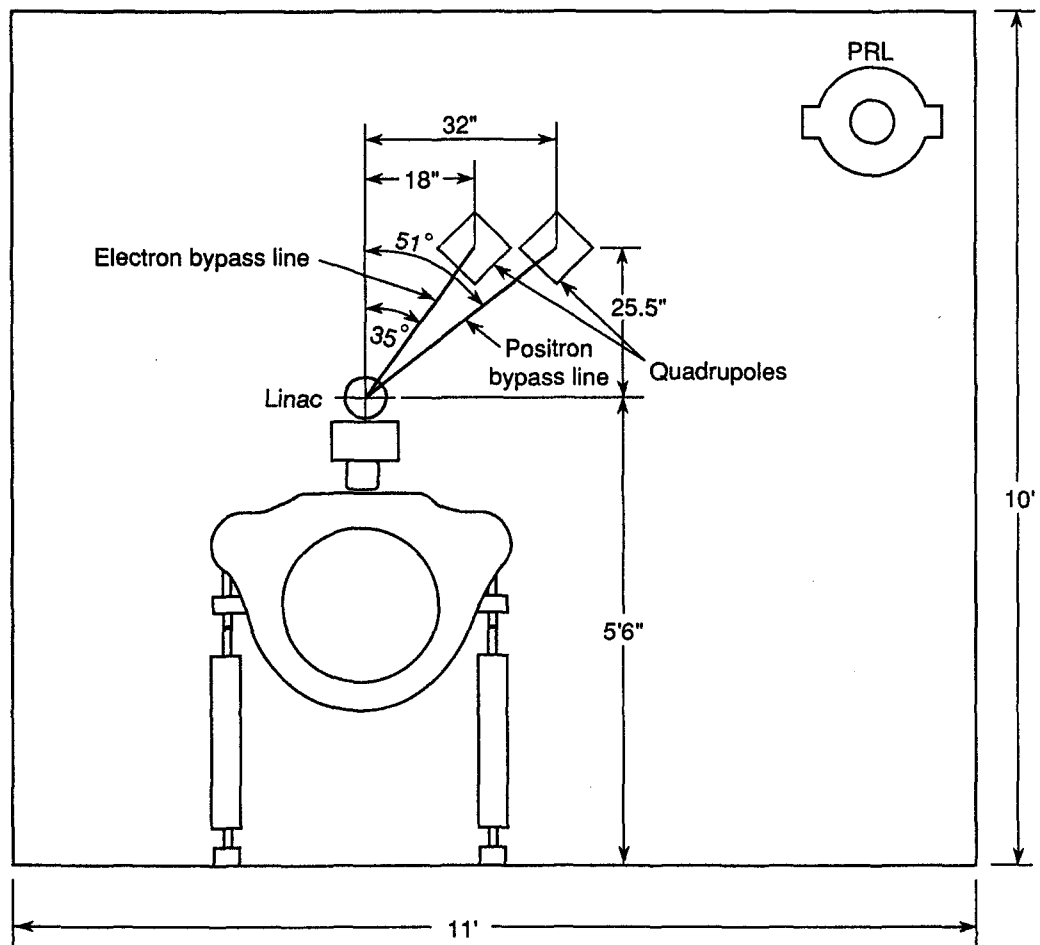


Fig. 6-3. Cross section of linac housing showing the location of the electron and positron FODO array quadrupoles. Note the tilts of the extraction planes.

Table 6-2. Linac bypass line components and specifications.

	Positron line	Electron line
Length [km]	~2.6	~2.2
Energy [GeV]	2.8–4	8–10
No. of quadrupoles		
Matching	24	24
FODO array	52	44
Steering correctors	64	56
Beam position monitors	64 (32 readouts)	56 (28 readouts)
Profile monitors	2	2
Pumps (120 L/s)	29	23
Vacuum roughing connections	29	23
Fast valves	1	1
Isolation valves	14	13

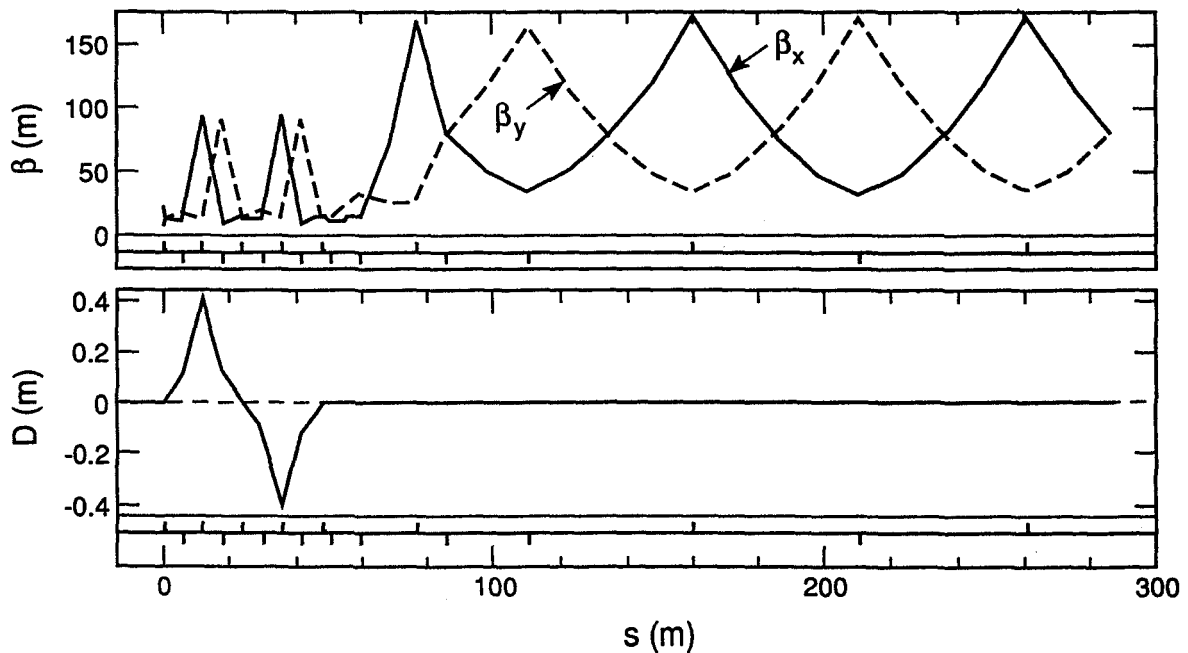


Fig. 6-4. Optical functions β_x , β_y , and D in the first magnet of the chicane, the diagonal extraction line, the matching section, and the first 200 m of the bypass line.

6.3 UPGRADE OF THE NIT AND SIT LINES

Except for a few modifications and improvements, the existing NIT (e^-) and SIT (e^+) lines, shown in Fig. 6-5, will be used in their entirety. At the end of Sector 30, the in-line equipment used for PEP will be removed and the bypass lines connected to the NIT and SIT lines upstream of the existing B3 magnets. Three new DC dipoles in each line are necessary to obtain the proper bends upstream of the B3 magnets, and these will be slightly rotated to align the beam trajectory properly.

We now briefly review the NIT and SIT optics, the magnets and power supplies, the instrumentation, and the vacuum systems.

6.3.1 Optics

Figure 6-5 indicates the arrangement of bending magnets, focusing magnets, and instrumentation elements for the identical NIT and SIT lines. Each consists of 11 bending magnets (of which B1 and B2 will be replaced) and 24 quadrupoles, making up three 360° achromats (the first two in the horizontal plane, the third in the vertical plane). The beam transport system is designed to accept an energy spread of $\pm 0.8\%$ and has a momentum resolution of better than $\pm 0.1\%$. The design apertures are ± 25 mm for the horizontal good-field region in the quadrupoles and ± 10 mm vertically. The periodic FODO array is designed for a phase shift of 90° per cell.

When the lines were properly set up for PEP, beam transmission and monitoring presented no major difficulties. One improvement that will be implemented for the B Factory is to install additional BPMs (see below) at the end of each bypass line and to use feedback to correct the beam position and angle at that point. If the beam then moves in the Q4 dispersive region, it will be because of energy drift and jitter, which will be corrected separately. Currently, because the lines are achromatic at the injection septum, energy jitter in the linac does not move the beam (and thus cannot be discerned) at that point. Injection into the HER and LER, much like PEP, will likely be quite sensitive to linac energy variations, and it will clearly be beneficial to observe beam energy drift or jitter and to correct it.

Since injection into the HER and LER will take place in the middle of IR-10 and IR-8, respectively, the ends of the NIT and SIT lines will be extended about 40 m from their present termination points, and four additional quadrupoles (similar to the existing ones), with corrector windings and built-in position monitors, are added. The elevations of these parts of the NIT and SIT lines will be somewhat different from those of the present layouts, because the elevations of both the HER and LER will differ from that of the present PEP ring.

6.3.2 Magnets and Power Supplies

Details of the magnets can be found in the Injection Section of the *PEP Design Handbook* [1977]. The present injection line magnets can be used without modification,

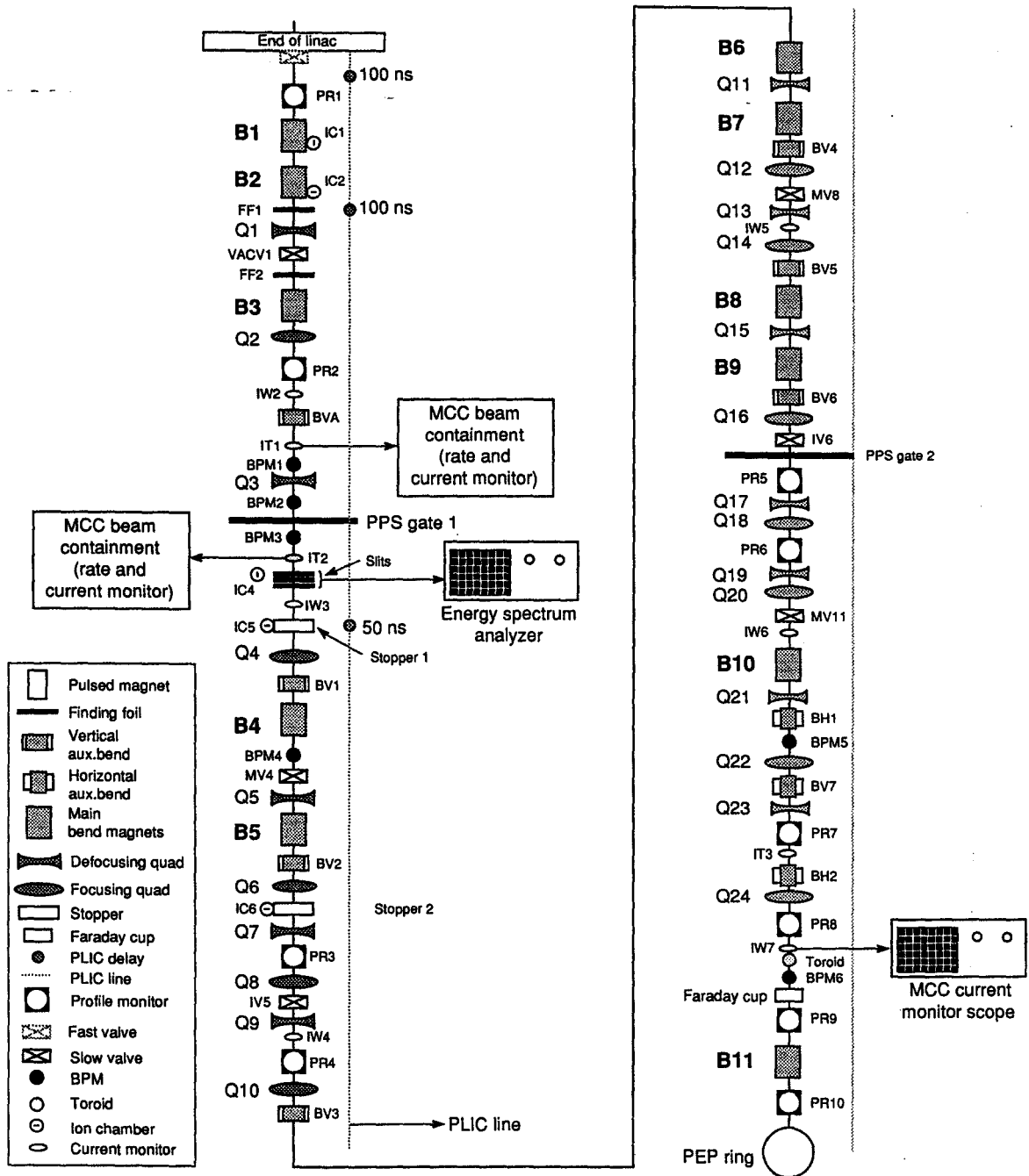


Fig. 6-5. Schematic layout of the identical NIT and SIT lines. For the B Factory, magnets B1 and B2 will be replaced.

but they must be slightly repositioned. The present power supplies will be upgraded, and their control, presently performed by a PDP-11 system, will be switched to a modern unified control system.

6.3.3 Instrumentation

Most of the instruments shown in Fig. 6-5 are satisfactory and will remain in place. Originally, beam position and shape were measured at 10 locations along each injection line, using scintillation screens. Over the past few years, six additional SLC-type stripline BPMs, also indicated in Fig. 6-5, have been installed in both the NIT and SIT lines. These BPMs are considerably larger than the standard SLC BPMs, but they use the same readout electronics. The first four BPMs are located in the region of maximum dispersion, and the last two are located close to the injection septum to allow both (x, x') and (y, y') to be determined for the beams just before injection into the rings. To implement the improvements in monitoring capability referred to above, and thus to achieve better overall control of the orbits, an additional 10 BPMs will be installed in each line, located in or near the quadrupoles; these provide beam position information approximately every 90° in betatron phase. Beam current is now measured by toroids installed in the NIT and SIT lines, as shown in Fig. 6-5. The operation of these devices is satisfactory, and they will be retained.

6.3.4 Vacuum Systems and Beam Pipes

The vacuum systems and beam pipes for the NIT and SIT lines are described in the *PEP Design Handbook* [1977]. The present design produces a pressure of about 100 nTorr, which has proved satisfactory in all respects.

6.4 INJECTION INTO THE HER AND LER

In contrast to the single PEP ring, for which the injection lines come down vertically into the plane of the ring and are tangent to the inside, the HER and LER injection lines will be brought down on the outside of the two rings—into the plane of the HER at IR-10 and into the plane of the LER at IR-8. The method of injection we have adopted is very similar to the one used in PEP. It assumes $\beta_x = 80$ m and $\beta_y = 20$ m in the 40-m-long injection regions, as shown in Fig. 6-6 and described in Section 4.1.

Horizontal injection occurs as shown in Fig. 6-7. The closed orbit of the stored beam is distorted by means of four DC bump magnets (not shown) and three kickers. Details of the horizontal phase space (x, x') for the stored and injected beam are shown in Fig. 6-8 at three consecutive points in time following the turn-on of the DC bump magnets:

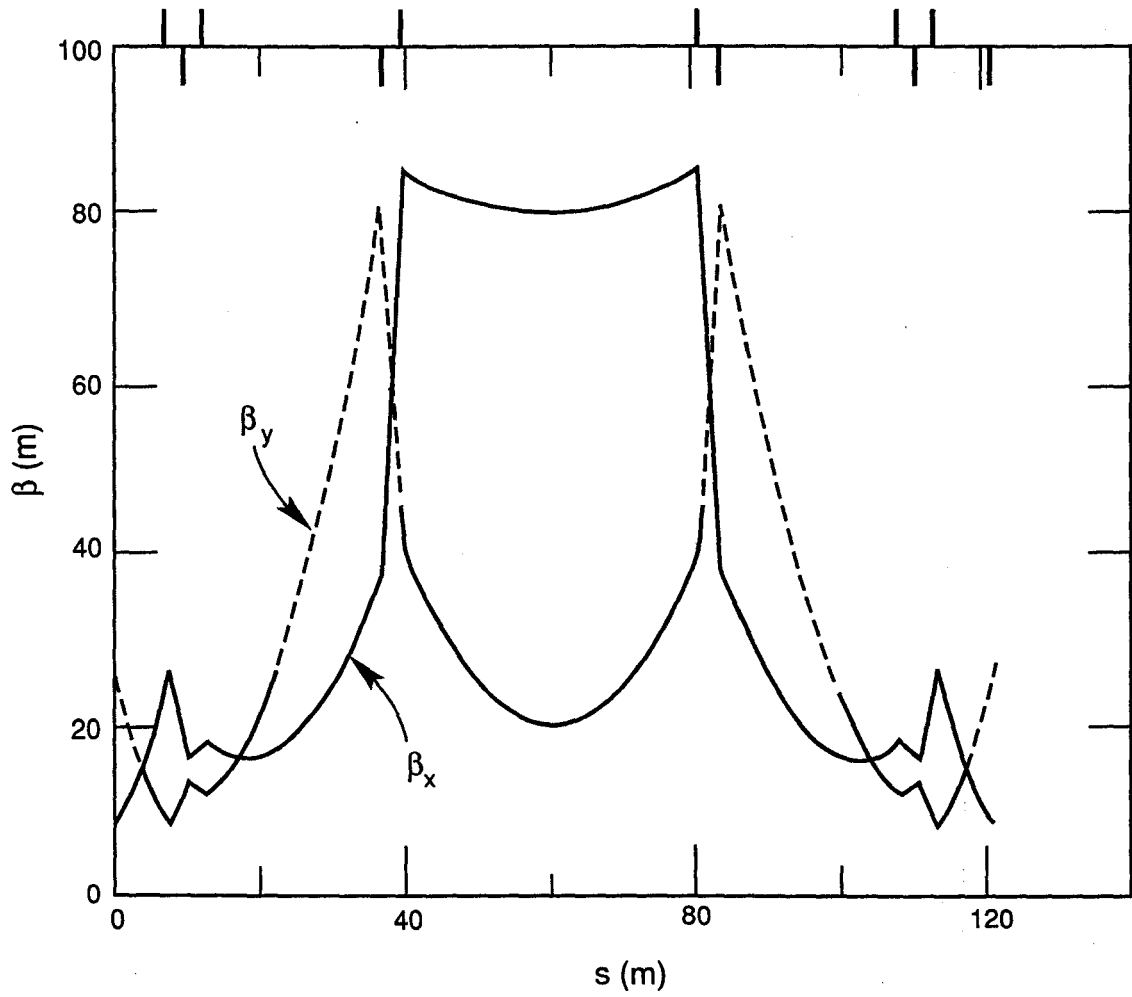


Fig. 6-6. Twiss parameters β_x and β_y in the injection straights of the HER or LER.

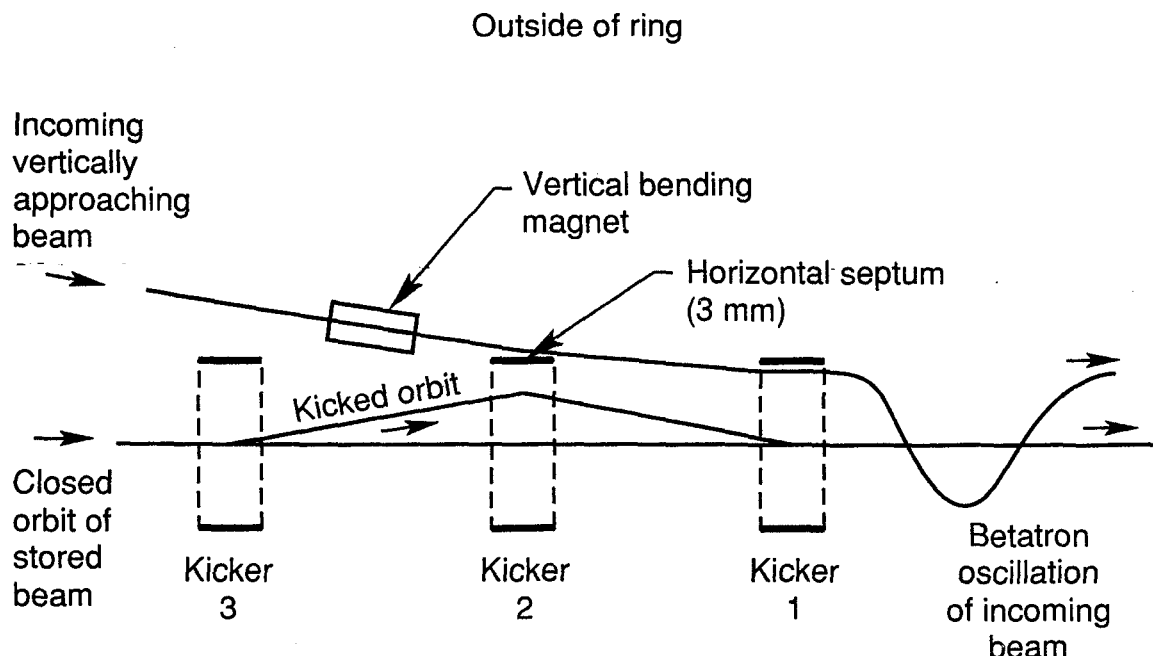


Fig. 6-7. Schematic of the horizontal injection scheme (DC bump magnets not indicated), showing closed and kicked stored orbits, and incoming injected beam (HER or LER). Note that kicker 2 kicks the stored and injected beams in opposite directions.

- (i) Stored beam is moved to DC bumped position, $10\sigma_x$ away from the inner edge of the 3-mm septum.
- (ii) Stored beam is kicked within $6\sigma_x$ of the septum inner edge; incoming beam from the linac is tangent to the stored-beam orbit and within $2\sigma_i$ of the outer septum edge.
- (iii) Four turns later, the stored beam is back to its DC bumped orbit; the incoming beam is inside the ring within $2\sigma_x$ of the inner septum edge, ready to damp and merge with the stored beam.

In Fig. 6-8, it is assumed that the injected beam has $\beta_x = 30$ m. As shown in Fig. 6-6, in the vertical plane, the beams go through a waist. Typical characteristics of the kicker magnets and their power supplies are summarized in Table 6-3; these parameters will be optimized during the detailed design stage of the project.

For injection purposes, each ring is divided into nine "zones" of equal length. A zone has a length of about 244 m (or 815 ns) and contains 194 bunches. One of these zones in each ring will remain about half empty to leave a gap for ion control. We describe here the process for filling the LER at a 60-Hz rate; the HER is filled in a similar way. The transverse damping time for the HER is 37 ms. If the damping contribution of the wigglers in the LER is ignored—a worst-case situation in terms of injection—then the LER has a damping time of 150 ms.

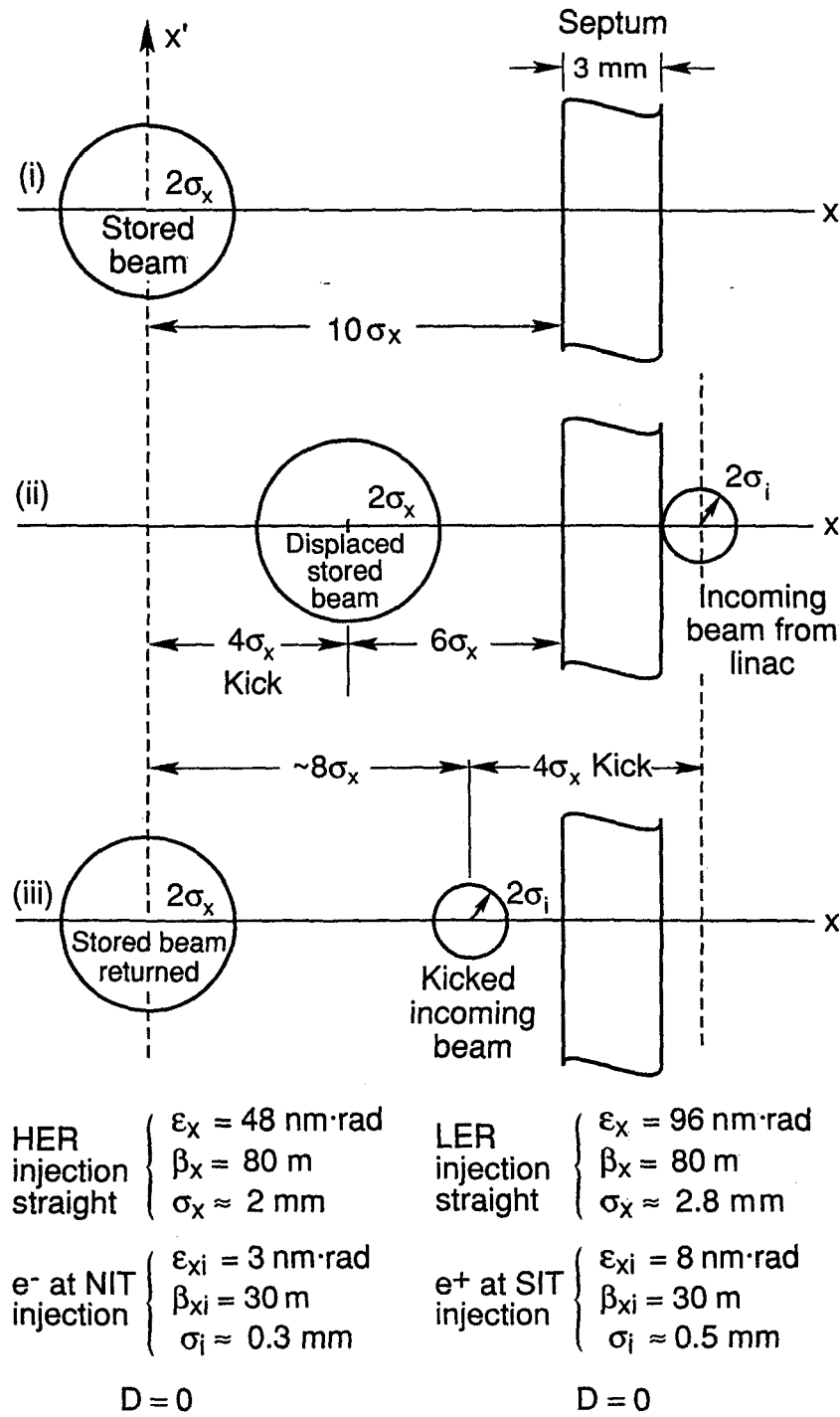


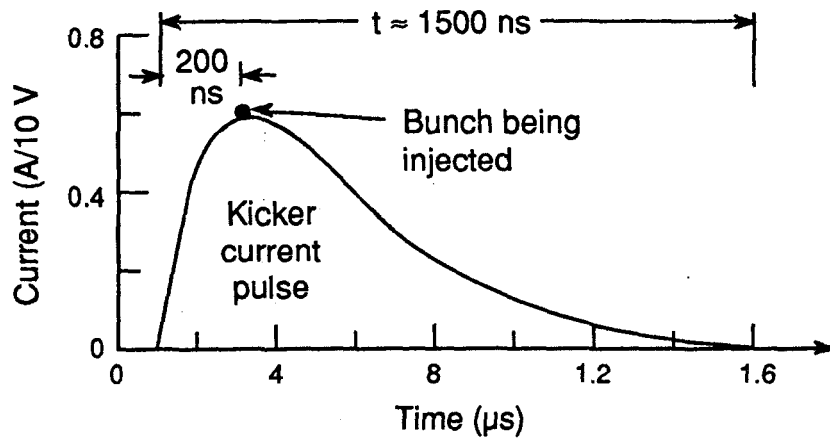
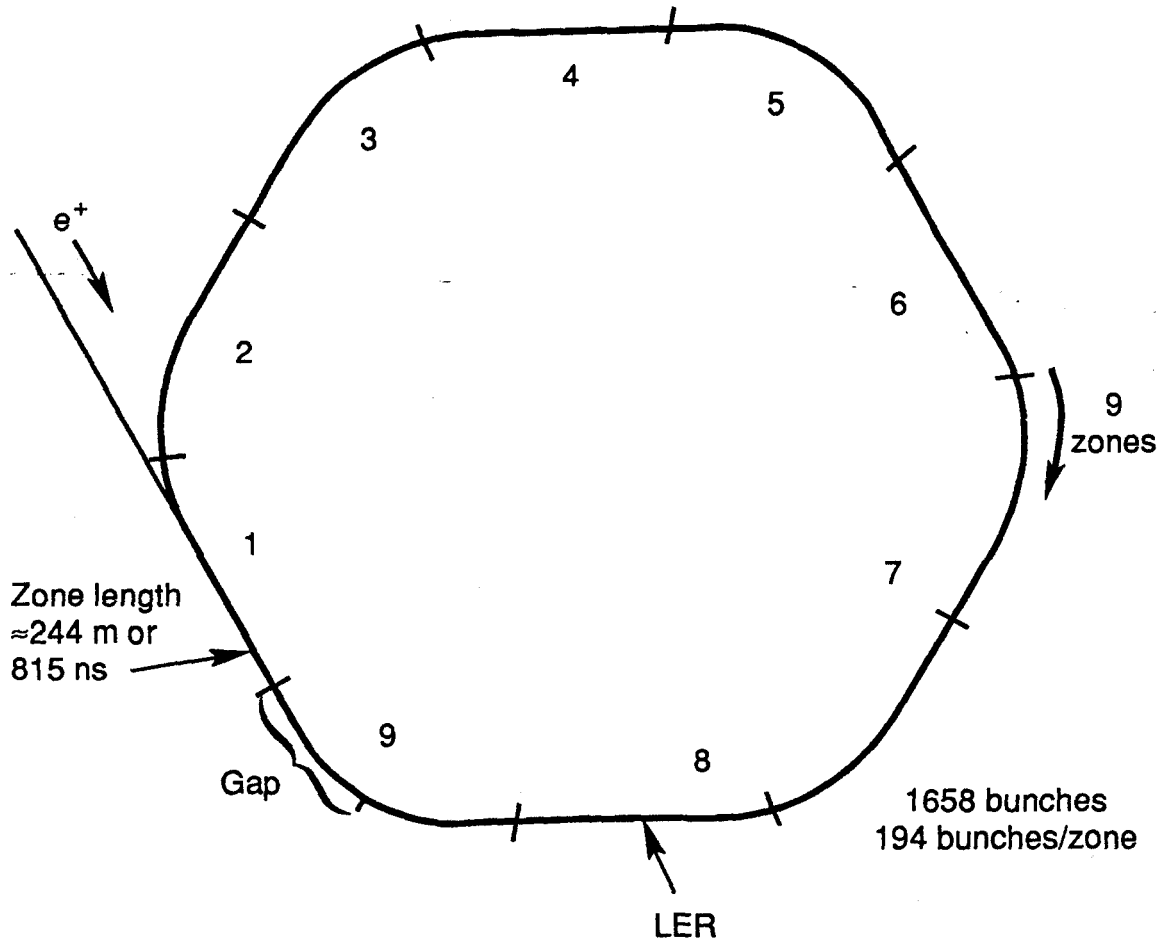
Fig. 6-8. Horizontal transverse phase space (x, x') of stored and incoming beams during three successive steps of the injection process (HER and LER). The position of the stored beam is shown after it has been moved to the right by roughly 0.5 cm by the DC bump magnets. The diameters of the stored and incoming beams are not drawn to scale.

Table 6-3. Examples of characteristics of K1, K2, and K3 kicker magnets and pulsters.

Aperture dimensions (cm)	Total inductance ^a (μ H)	Length (m)	Damping (Ω)	Current, $I_{\max}$ (kA)	Voltage (kV)
Magnet:					
LER K1 or K3					
6.4 $\times$ 6.4	0.93	1	7.5	0.57	5.8
LER K2 (septum)					
6.4 $\times$ 6.4	1.56	2	12.5	0.57	9.7
HER K1 or K3					
4.8 $\times$ 4.8	0.93	2	7.5	1.1	11
HER K2 (septum)					
8 $\times$ 8	1.56	4	12.5	1.1	18.2
^a Kicker is housed in a pipe of radius r equal to aperture width. Connections inductance, assumed to be 0.3 μ H, is included. The connections inductance does not enter into the magnetic field calculations.					

As shown in Fig. 6-9, the beginning of each zone is determined by the time onset of the kicker current pulses. All three kicker pulsters are identical, consisting of critically damped RLC circuits that rise and fall to practically zero within less than 1500 ns. The first bucket to be filled in zone n is located roughly 200 ns after the beginning of the kicker pulse so as to ride on the flat top where sensitivity to time jitter is minimized. Since the rise time of the pulse is much shorter than the fall time, bunches recently stored in zone $n - 1$ are unaffected. Bunches in zone $n + 1$ (at least 815 ns later) are kicked slightly, but since they have been in the ring for the longest time, their orbits are almost fully damped, and, to the extent that the kickers are matched, these bumps are closed. Thus, single buckets in zones 1 through 9 are filled in succession, after which, 9 times 1/60th of a second, or 150 ms, later (that is, one damping time in the LER in the absence of wigglers), the next adjacent buckets (4.2 ns later) in each zone are filled, and so on. With this method, damping in the LER, even without wigglers, is adequate.

The entire filling sequence of the 1658 bunches will be computer controlled and automated. Computer control of the process, in conjunction with the proper triggers (synchronized through the 476-MHz clock and countdown electronics) will be simpler and more straightforward than that in PEP, where the RF frequency is not harmonically related to that of the linac.



Zone filling sequence: 1,2,3,...,9(partially),1,...

Fig. 6-9. Azimuthal zone filling sequence for the LER, showing nine zones. The kicker current pulse shown (equal for all kickers) was computed by assuming a charged, critically damped RLC circuit [$R = 2 (L/C)^{1/2}$] in which the current reaches its maximum at $t = 2 L/R$ after a thyatron is fired and allows the circuit to be discharged.

6.5 OPTIMUM TIME BETWEEN FILLS

As part of the design for the injection system, it is useful to estimate the optimal time between injection cycles (fills). By “optimal” we mean the filling pattern that maximizes the average luminosity. Clearly, this optimal value depends on the time course of the luminosity following injection, which will be determined to some extent by the details of storage ring operation. Still, it is useful here to get a sense of the likely interval between fills. Our assumptions, stated below, are intended to err on the side of conservatism, thus yielding a worst-case estimate (smallest value) for this interval. In particular, we have taken a simple model in which the bunch sizes do not vary with time. The appropriate luminosity formula is then

$$\mathcal{L}(t) = \frac{N_{b1}(t)N_{b2}(t)n_{bi}f_i}{2\pi\sqrt{(\sigma_{x1}^{*2} + \sigma_{x2}^{*2})(\sigma_{y1}^{*2} + \sigma_{y2}^{*2})}} \quad (6-1)$$

All time-dependent terms are indicated explicitly in Eq. 6-1. The σ_{xi}^* and σ_{yi}^* are the transverse rms spot sizes at the interaction point (IP). We assume here that

- Bunches are distributed such that every bunch meets an opposing bunch at the IP. Thus, $n_{b1}f_1 = n_{b2}f_2$ is the bunch collision frequency, where f_i is the revolution frequency and n_{bi} is the number of bunches for beam i .
- All bunches in a given beam have the same number of particles (N_{bi} for beam i).
- Any modifications to the above formula from beam-beam considerations, finite bunch lengths, and nonzero crossing angles are independent of time.

To the extent that the individual beams decay according to exponential decay laws, the luminosity will also decay exponentially, and the desired optimization is straightforward. However, the beams are not expected to decay in a purely exponential way. For example, in beam-gas collision processes, the loss rate is proportional to the gas pressure, which in turn depends on the beam current. For the present calculations, we make the pessimistic assumption that the pressure does not decrease as the current decreases. Then beam-gas losses yield an exponential time dependence. In addition, beam-beam scattering losses, notably $e^+e^- \rightarrow e^+e^-\gamma$ do not give an exponential luminosity dependence. However, it can be shown [Porter, 1990] that if we make the exponential approximation, with a time constant given by the exact $1/e$ decay time, then the error is at most a few percent for times of interest to us. Thus, we start with a luminosity that depends on time according to

$$\mathcal{L}(t) = \mathcal{L}_0 e^{-t/\tau} \quad (6-2)$$

The decay time τ is dominated in the present design by the bremsstrahlung and Coulomb beam-gas scattering. Including these and additional losses due to beam-beam bremsstrahlung and elastic scattering, and those due to Touschek scattering, gives $\tau = 1.9$ hr, with the assumptions discussed above.

The scenario we envision is that a data-taking period T for the experiment is long compared with the injection time and the stored-beam time (that is, there are many such fills in a data run). In this case, it is sufficient to replace the actual distribution of injection times with a single average injection time, which we call t_I . We further assume that we take data for a fixed time interval t_c following injection, prior to beginning the next injection, and that each fill begins with the same initial luminosity ($\mathcal{L}_0$). Finally, we assume that no useful data are accumulated during injection. Given this scenario, we wish to find the optimal value for t_c .

The total integrated luminosity accumulated during our data run is given by

$$\int_0^T \mathcal{L} dt = n \int_0^{t_c} \mathcal{L}_0 e^{-t/\tau} dt \quad (6-3)$$

where $n = T/(t_c + t_I)$ is the number of injection-coast cycles in the run. The ratio of the actual integrated luminosity to that obtained if the machine were capable of running the entire time at its peak luminosity is then

$$\frac{1}{\mathcal{L}_0 T} \int_0^T \mathcal{L} dt = \frac{\tau}{t_c + t_I} (1 - e^{-t_c/\tau}) \quad (6-4)$$

This quantity (and hence the actual integrated luminosity) is maximized when t_c is chosen to satisfy the condition

$$\frac{t_c + t_I}{\tau} = e^{t_c/\tau} - 1 \quad (6-5)$$

Thus, the maximum average luminosity possible is

$$\langle \mathcal{L} \rangle_{\max} = \mathcal{L}_0 e^{-t_c/\tau} \quad (6-6)$$

with t_c given by Eq. 6-5.

For simplicity, we assume that the injection time required is independent of the coast time t_c . For our parameters, this is a good approximation. Thus, we assume a fixed injection time of six minutes: approximately three minutes of overhead to change both accelerator and detector states between injection and stored-beam conditions, plus about three minutes for the actual top-off.

Solving Eq. 6-5 then gives an optimal time between fills of about 35 minutes. This yields an average luminosity of 74% of the peak luminosity. We note that the injection conditions are nearly optimum over a rather broad range; changing the stored-beam time from its optimal value of 40 minutes to 60 minutes reduces the average luminosity by only a few percent. It is somewhat more important to keep the injection time small; increasing the average injection time to 10 minutes reduces the average luminosity to 68% of its peak value.

6.6 SUMMARY

With minor modifications, the SLC linac will serve as a well-optimized and powerful injector for the B Factory. The ability to fill the storage rings rapidly will be of great benefit not only for the operational stage, but also for the earlier commissioning stage in which the vacuum chamber walls must be scrubbed by synchrotron radiation. As discussed in Section 5.6, there are also advantages to the single-bunch filling scheme adopted here. This approach lessens the power demands on the feedback system, which might otherwise be dominated by considerations of injection jitter.

7.

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SINCE the B Factory will occupy the existing PEP tunnel and make use of the existing SLC linac, no conventional construction is required. However, modifications will be necessary to mechanical and electrical facilities, as described below. This chapter also describes necessary removals, including the steps to be followed in disassembling and refurbishing the magnets. Finally, in Section 7.2.3, the installation procedure for the new facility is given in broad outline.

7.1 SITE AND UTILITIES

7.1.1 PEP Buildings and Underground Structures

The PEP conventional facilities consist of all beam housings (bored and cut-and-cover tunnels), research halls, support buildings, roads, earthwork, fencing, landscaping, AC power, mechanical utilities, and sewers and drainage facilities (see Fig. 7-1). The only changes to these facilities that will be needed to accommodate the B Factory are modifications of the cooling water system and the electrical distribution system.

An Environmental Impact Statement (EIS) for PEP was issued by the Energy Research and Development Administration in 1976. There will be no changes to the PEP conventional facilities that will affect the conclusions of the PEP EIS.

The PEP tunnel, above-ground structures, and utility structures were designed to withstand a major earthquake. Accordingly, they are expected to suffer only minor or moderate damage in an earthquake that will cause widespread devastation in the surrounding region [Savage, 1990, and references therein; Earth Sciences Associates, 1982]. The earthquake on October 17, 1989, which was not very severe locally, caused no damage to the PEP tunnel, buildings, or utilities. There was, however, some permanent displacement of the PEP tunnel, and the PEP ring magnets moved enough to require realignment [Fischer, 1989].

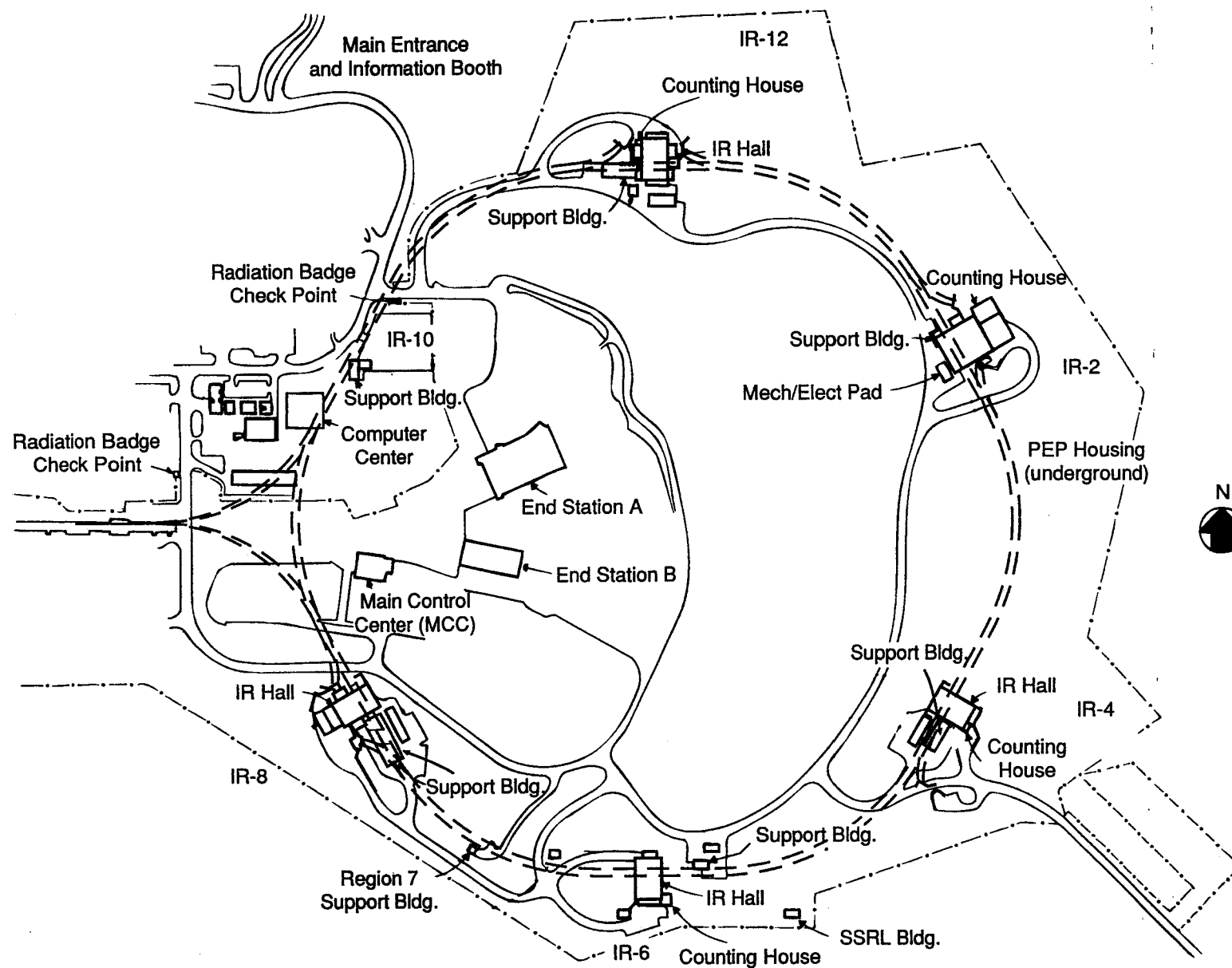


Fig. 7-1. Site map of the PEP facility.

7.1.1.1 Beam Housings. Beam housings include the PEP main ring tunnel, ring access tunnels, injection beam tunnels and their junctions with the accelerator housing and the storage ring, and all penetrations into the tunnels. Where deep underground, the underground structures were built by tunneling methods; elsewhere cut-and-cover methods were used. Beam housings are concrete lined, painted white, and continuously ventilated. Telephone service is provided. The tunnels are protected from fire by detection and sprinkler systems.

Water seepage in the PEP tunnel in the vicinity of IR-10 has been a nagging problem for many years. The seepage water is corrosive and attacks iron, aluminum, and some plastics. It also supports the growth of algae. The water has a high mineral content, which produces deposits that can block drainage pipes and clog drainage channels and gutters. Rather than stopping water seepage, a program of water management has been used in the vicinity of IR-10. Covers were installed over equipment, water was diverted, and grooves were cut into the concrete floor to channel the water to the drainage gutter. Domestic water has been introduced to maintain the flow, dilute the groundwater to prevent precipitation of minerals, flush out solids, and discourage the growth of algae. These measures have been fairly successful: *Water seepage has never caused an interruption of PEP operations.*

This same method of water management will be used for the B Factory. Prior to installation of the machine components, the affected area will be thoroughly cleaned. Protective covers will be installed over all B Factory equipment in the leaky sections of the tunnel, and provisions will be made for guiding leakage into the drainage gutters. Regular maintenance will be provided to keep drains and gutters clear and pumps running.

7.1.1.2 Support Buildings. Support buildings are provided for instrumentation and controls (I&C) equipment at IR-2 and IR-6; for RF, I&C, and magnet power supplies at IR-4 and IR-12; and for RF, I&C, magnet power supplies, and overall operational control of the storage ring at IR-8. Additional special support buildings are located at region 7 and IR-10.

7.1.2 Mechanical Facilities

7.1.2.1 PEP Site Cooling Water. The machine components in the storage rings and the detector will be cooled by closed-loop low-conductivity water (LCW) systems. These are, in turn, cooled by a cooling tower water (CTW) system. Existing PEP systems will be used wherever possible.

A four-cell cooling tower, rated at 21 MW, is located near the Main Control Center. The CTW is distributed around the PEP ring to equipment pads at PEP regions 2, 4, 6, 8, and 12. At IR-4, IR-8, and IR-12, closed-loop cooling water systems circulate LCW to cool PEP equipment. Each system has a heat exchanger that is cooled by CTW. The PEP water systems are (i) the klystron tube and ring magnet cooling systems, (ii) the RF cavity and vacuum chamber cooling systems, and (iii) the experimental equipment cooling systems. Regions 2 and 6 each have an experimental equipment cooling system. Currently, CTW is circulated through the system by four pumps located at the south side

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of the existing cooling tower. The pumps are rated at 3800 gpm, so four pumps are required to be in operation. One additional pump will be installed to provide an installed backup.

The present cooling tower capacity is inadequate for the B Factory, which will require 32 MW of cooling; an additional 5 MW will be required for SPEAR and the research yard. We assume that the beam switchyard, SLD, and the SLC collider hall will require only house power by the time the B Factory is commissioned. Accordingly, the following modifications of the existing cooling tower cells will be made to provide the required 37-MW capacity: The existing fill will be replaced with new high-performance PVC fill; the drift eliminators will be replaced with new PVC drift eliminators; and the distribution system laterals and nozzles will be replaced with bigger laterals and large-orifice nozzles. These changes will not affect the size or external appearance of the towers. The CTW piping to the PEP ring is adequate to handle the higher flow.

The total cooling load for the B Factory is higher than the PEP load, and the distribution of loads between the LCW systems, above and below ground, is different from that at PEP. The PEP heat exchangers will be replaced with new, larger, plate-type heat exchangers. The LCW system pumps will be replaced with pumps of larger capacity. In addition, piping will be rearranged to better match the heat exchangers to the loads. The loads will be segregated so that copper and aluminum items are not in the same loops.

The LCW systems will be connected to B Factory loads as described in the following paragraphs. (The names used for the cooling systems below correspond to their current functions.)

IR-12. The RF-vacuum cooling system will supply cooling water to six RF cavities and one-third of the vacuum chambers. The experimental equipment cooling system will supply cooling water to the three IR-12 klystrons and to one of the LER wiggler synchrotron radiation dumps. The klystron-magnet cooling system will supply cooling water to the power supplies, IR-12 RF circulators and tees, and one-third of the ring magnets.

IR-2. The B Factory detector will be installed at IR-2. The cooling water for the 3-MW detector magnet will be provided by the IR-2 experimental equipment cooling system.

IR-4. The RF-vacuum cooling system will supply cooling water to six RF cavities and one-third of the vacuum chambers. The experimental equipment water system will supply cooling water to four of the IR-4 klystrons, circulators, and tees and to six RF cavities. The klystron-magnet cooling system will supply cooling water to the magnet power supplies, two of the IR-4 klystrons and circulators, and one-third of the ring magnets.

IR-6. The experimental equipment water system will supply cooling water to one of the LER synchrotron radiation dumps.

IR-8. The RF-vacuum cooling system will supply cooling water to six RF cavities and one-third of the vacuum chambers. The experimental equipment water system will supply cooling water to four of the IR-8 klystrons and six RF cavities. The klystron-magnet water system will supply cooling water to the magnet power supplies, two of the IR-8 klystrons, circulators, and tees, and one-third of the ring magnets.

7.1.2.2 Cooling Water for Injection System Components. The magnets for the injection system for the B Factory will be supplied with cooling water from existing headers in the accelerator housing and the NIT and SIT tunnels. Magnet power supplies will be located above ground and will be supplied with cooling water from existing headers.

7.1.3 Electrical Facilities

SLAC receives power from two sources: A 230-kV line with a 300-MW capacity and a standby 60-kV line with an 18-MW capacity. The two sources are asynchronous and cannot be operated in parallel. The master substation is located at Sector 30 on the south side of the linac. No expansion of the high-voltage feeders or the master substation is required for the B Factory.

The maximum electrical power demand for the B Factory ring and experimental apparatus will be 32 MW. The anticipated load is broken down by region in Table 7-1.

Electrical power to the B Factory ring and the detector in IR-2 will be distributed at 12.47 kV through the PEP ductbank to the six regional substations at regions 2, 4, 6, 8, 10, and 12.

The distribution of the RF klystrons and cavities around the ring was chosen to match the availability of power. There will be three 1.1-MW klystrons and six 500-kW cavities at IR-12, and six klystrons and twelve cavities at both IR-4 and IR-8. It will be necessary to install additional cables to IR-2, IR-4, and IR-8 to match the B Factory loads in these regions. The cables will be installed in the existing PEP ductbank.

Table 7-1. Anticipated electrical loads for the B Factory.

Region	Anticipated loads	
	in kW	in kVA
2	4,580	5,720
4	10,260	14,900
6	560	700
8	9,890	13,700
10	760	700
12	6,000	7,500
Total	32,050	43,220

High-voltage disconnect switches will be installed at 22 locations on the electrical equipment pads at regions 4, 8, 10, and 12 to make it possible to work on electrical equipment without shutting down the entire electrical distribution system.

The power supplies for the B Factory injection system will be located above ground; power will be supplied by existing circuits.

7.1.4 Interaction Region

PEP has five interaction halls suitable for the assembly and operation of a large particle detector. Current plans are to install a detector in IR-2 for the B Factory.

The IR-2 experimental hall is 20 m wide in the beam direction and 32 m long. It is equipped with a 50-ton overhead crane. The beam height is 4 m above the floor. The building can be divided into two spaces by a shielding-block wall, which makes it possible to work on a detector when it is off the beamline and beams are circulating. There is a two-story counting house on the north side of the experimental hall with 370 m² of floor space. Five megawatts of AC power will be available at IR-2. The cooling water system will be expanded to handle this load by the addition of a heat exchanger.

7.2 REMOVALS AND INSTALLATIONS

7.2.1 Space Requirements

Construction of the B Factory requires that the PEP tunnel be cleared of all existing magnets and related components. Table 7-2 summarizes the components to be removed.

Table 7-2. Summary of components to be removed from the PEP tunnel.

Component	Number	Weight (tons)
Bending magnets	192	1,416
Low-field bends	24	18
Quadrupoles	216	405
Insertion quads	24	207
Miscellaneous quads	48	60
Sextupoles	192	33
Concrete rafts	216	925
Miscellaneous supports	400	32
Total		3,096

The storage and refurbishing space required for these and other components is shown in Table 7-3. These requirements have been minimized by assuming that unwanted components (for example, the concrete rafts) will be discarded. Recent tests, conducted throughout PEP, showed no residual radioactivity above background in the rafts. They can thus be disposed of in a conventional manner. With the 32,100 ft² of crane-covered space already identified at SLAC (Table 7-4), and with additional space to be made available at other collaborating laboratories, no additional buildings will be required at SLAC during construction of the B Factory.

7.2.2 Disassembly and Removals

7.2.2.1 Main Tunnel. PEP disassembly will commence with the bending magnets in the water-affected area in regions 9 and 11 (see Fig. 7-1). The removal rate of these components will be two magnets or three rafts per day. At this rate, the PEP tunnel can be cleared in approximately nine months. Fixtures used for disassembly and removal will be designed to ensure that previously obtained alignment information for the bending magnet cores will be preserved.

Once removed from the tunnel, the main coils, trim coils, and other ancillary equipment will be removed from the cores. The coils will be inspected for possible radiation damage and will receive an approved water-sealing coating. The cores will be inspected for damage and will be repainted. New trim coils will be wound and installed, and the magnet then reassembled. To assure the magnetic quality of these refurbished magnets, each one will be mechanically checked for twist, roll, and gap. Previous measurements at SLAC using this technique have shown that magnetic measurements are necessary only on a sample basis, provided that mechanical measurements are completed on each magnet. This procedure will be followed for the refurbished magnets.

The quadrupole-sextupole raft structure will be removed after the main bending magnets. With the bending magnets removed, the unwanted aluminum vacuum chamber will be exposed, which will allow cutting adjacent to the quadrupole-sextupole pairs. This will decrease the total time for raft removal, since the quadrupoles and sextupoles will not have to be opened in the tunnel. Careful attention will be given to those components that can be reused, namely, beam position monitors, bellows, ion pumps, and flanges. After the quadrupole-sextupole pairs are removed from the tunnel, they will be transported to a refurbishing area where they will be opened and the vacuum components removed. Tests will be made to determine the extent of radiation damage to the coils. If undamaged, they will be removed from the cores and resealed. The cores will then be repainted prior to reassembly.

Since the quadrupole magnets underwent magnetic measurements prior to PEP installation, it may not be necessary to remeasure each magnet again. Previous data have shown that the magnetic characteristics of the magnet can be duplicated, provided good mechanical measurements are taken and specific reassembly techniques are used. With the previous PEP magnetic information at hand, sample tests can be performed to ensure that the magnetic properties are preserved. The refurbished magnets can then be mounted on a new support and rough-aligned using gauges and fixtures. When the vacuum chambers and beam position monitors become available, the cores will be opened and the

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Table 7-3. Space required for preinstallation, PEP disassembly, and B Factory component assembly.

Component	Space requirement (ft ²)
PEP disassembly	
Bending magnets	10,000
Quadrupole/sextupole pairs	2,500
Rafts	10,000
Miscellaneous magnets	1,500
Miscellaneous supports	2,000
Vacuum components	2,000
Miscellaneous	1,000
HER assembly	
Bending magnet assembly	1,000
Quadrupole assembly	600
Quadrupole fabrication	600
Sextupole fabrication	600
Sextupole assembly	600
Support assembly	600
Mechanical measurement	1,000
Mechanical alignment	1,000
Magnetic measurement	3,000
Coil storage	1,000
Hose factory	500
Miscellaneous storage	500
LER assembly	
Bending magnet assembly	1,000
Quadrupole assembly	500
Sextupole assembly	500
Support assembly	500
Mechanical measurement	500
Mechanical alignment	750
Magnetic measurement	1,000
Coil storage	500
Miscellaneous storage	250
Total	45,500

Table 7-4. Crane-covered SLAC space available for B Factory construction activities.

Area	Space available (ft ²)	Current use
Light assembly	11,500	SLD
Heavy fabrication (center bay)	7,500	Storage
IR-6	4,500	SLD
IR-8	4,500	SLD
IR-12	4,100	SSRL
Total	32,100	

chamber package installed. At this time, precision mechanical alignment will be accomplished. This alignment process will be completed in a temperature-controlled area, using precision optical alignment docks to ensure that the beam position monitors and magnet components are aligned to within a few thousands of an inch.

Generally, much of the existing PEP cable plant will be used for the HER and LER. For example, all of the vacuum system cables will remain in place and will be connected to new equipment in locations nearby. In some instances, splicing and other means may be needed to make up the required lengths. Unneeded cabling will be removed and, in some cases, stored for later reuse.

To ensure adequate documentation and control during disassembly and subsequent reassembly, travelers will be attached to each component for tracking. Databases will be set up to ensure that other information regarding these components is readily available. Data taken during PEP construction regarding mechanical and magnetic measurements can be retrieved in such a way as to allow comparison of these properties.

With the tunnel housing empty, the floor will be cleared of all attachments used for PEP. New support points for the B Factory rings will be accurately placed by an alignment team. Surveys are currently under way to determine what other equipment, such as utilities, must be modified and installed once the alignment process is complete in a given section of the tunnel.

7.2.2.2 Interaction Regions. In addition to the beamline components, existing experiments at PEP will require removal. Means will be sought for these experiments to be used by others prior to B Factory construction, but if no satisfactory alternatives are suggested, these experiments will be dismantled or moved to other areas to allow B Factory operation.

PEP IR-2—Time Projection Chamber (TPC). The TPC Facility will be removed from PEP to allow installation of the new B Factory experiment.

PEP IR-4—MAC. Since the MAC detector is capable of moving off-line within a short period, it will be moved from the interaction area to the assembly area. This will

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permit this detector to be evaluated by others for possible use elsewhere and places it in an area that is not fully utilized.

PEP IR-6—HRS. The detector iron will be relocated from the IR to the rear IR hall assembly area. This places the detector in an area where it will not interfere with activities in the main assembly area, and which has been identified as a possible work and storage area for the B Factory.

PEP IR-8—DELCO. This detector has been removed from PEP, but support structures used for this detector are within the IR, as are some detector parts. These items will be removed and pose no significant space demands. This IR hall has also been identified as a possible storage and working area for the B Factory.

PEP IR-12. The Mark 2 detector has been removed from this region, which is currently being used by SSRL as an assembly area. This hall has been identified as a storage and working area for the B Factory.

7.2.3 Installation

7.2.3.1 High-Energy Ring. Installation of the HER components (Table 7-5) will begin after alignment teams have located support points. Anchor bolts will be installed for the bending magnet supports, which will be the first components to be reinstalled for the B Factory. After the supports are grouted and aligned, the bending magnets will be installed using new installation fixtures. Caution will be taken to ensure that all magnets are handled in an approved manner. The quadrupole-sextupole pairs on their prealigned supports will be installed in a similar way. After this, the vacuum chamber will be placed in the bending magnets and the fixed flanges made up. The final connection will be the HER flexible bellows unit. During the entire installation process, quality control

Table 7-5. Inventory of HER components.

Component	Quantity	Total weight (tons)
Bending magnets	212	1,433
Quadrupoles	272	514
Sextupoles	144	26
Bending magnet supports	192	36
Quadrupole/sextupole supports	192	8
Quadrupole supports	96	6
Total		2,023

measures will be undertaken to ensure that each component is installed according to written procedures. Documentation regarding the installation, fabrication, and refurbishing process of the B Factory components will also be filed according to written procedures.

7.2.3.2 Low-Energy Ring. The LER components (Table 7-6) will become available after the HER is installed, owing to the fact that they must all be fabricated. Accordingly, since these magnets are installed above the HER, they will be installed on the "C" support structure as a prealigned unit. Quality control and documentation measurements will be taken, as described for the HER.

7.2.3.3 Cable Plant Installation

Raceways. Cables will run in 4-in.-deep, ladder-type steel cable trays, conduits, and wireways from points of origin to terminations. Instrumentation and DC cables will extend in the air from the cable trays to the devices served. Long runs will be supported. Barriers in the cable trays or separate cable trays will be used to carry conductors for different functions (for example, DC, instrumentation, AC power, etc.). AC cables extended from cable trays to equipment will be run in rigid conduit, flexible conduit, or other approved raceways.

Cables between the klystron gallery and the accelerator tunnel will be run in conduits in the existing 30-in. vertical penetrations between the two areas. Cable grips will support the vertical load of cables at the point of entry into the conduits.

All raceways will be bonded for electrical continuity.

Additional cable trays will be installed in the accelerator tunnel and the klystron gallery to support cables.

Existing cable trays in the PEP housing will be utilized for the new cable systems. Additional trays will be installed in the existing interaction halls to carry cables for components in the halls. New cable trays will be installed in the RF areas of the support buildings to support the cable plant.

Large DC Cables. Existing DC circuits in the PEP ring are capable of supplying both the HER and the LER large magnet circuits. There are twenty-one 1-in.-OD, PVC-

Table 7-6. Inventory of LER components.

Component	Quantity	Total weight (tons)
Bending magnets	208	227
Quadrupoles	298	289
Sextupoles	144	26
Dipole/quadrupole/ sextupole supports	192	77
Quadrupole supports	96	17
Total		636

jacketed, water-cooled cable circuits, extending completely around the ring, with taps to power supplies and magnets served, utilizing air-cooled conductors to bridge the gap. In addition, 6 air-cooled 350-MCM aluminum cables run through the same route. Existing circuits will be modified to reach the new magnet locations. Modifications will consist of jumpers in locations no longer served and additional taps into existing cables for new magnet locations. Water cooling will no longer be required, owing to the lower magnet currents.

Many of the existing power supplies will be reassigned or removed. Changes to the existing large DC cables will be made as appropriate.

Power supplies for the injection system magnets will be located in the klystron gallery. Cables will run from power supplies in the klystron gallery, in cable trays and through penetrations, to the accelerator housing. They will exit the penetrations to a cable tray and will be routed to the magnets served.

Trim and Steering Circuits. Existing trim and steering cables will be disconnected from the PEP magnets and removed to the terminal cabinets that formerly served them. New trim and steering circuits will be fed from a power supply utilizing one of the former large power supply circuits for its main power distribution. Separate DC-to-DC converters will serve local magnet trim circuits. As with the large DC cables, trim and steering cables for the injection lines will originate at power supplies in the klystron gallery.

Instrumentation and Control Cables. A wide variety of cable types will be utilized for the I&C systems. Where practical, cables will be preassembled with connectors, as complete units. In many cases, cable connectors will be installed in the field. Multiconductor I&C cable will be type TC (tray cable), with overall shield. Safe High-Voltage (SHV) connectors will be utilized where required. High-voltage circuits will be run separately from other circuits.

New I&C cables in the injection system will be routed through cable trays to vertical penetrations and then to cable trays in the accelerator tunnel, and hence to the instruments served.

AC Circuits. The existing AC distribution system for ring components, removed to allow the dismantling of the PEP ring, will be reinstalled in appropriate locations. New AC systems will be provided for all I&C racks, power supplies, and other components not presently served. Rigid steel conduits or cable trays will be used for 480-V circuits; 208Y/120-V circuits will be run in EMT or other suitable raceways. Wireways will be used for 480-V and 208Y/120-V circuits where required.

Grounding. All elements of the new rings, the IR, and the injection beamlines will be grounded to the existing SLAC ground system. Connections will be made by clamp-type connectors, for easy removal. The grounding connectors will be carefully torqued.

8.

SAFETY AND QUALITY ASSURANCE

FROM a safety standpoint, the B Factory does not present any significant new problems. All of the anticipated hazards are ones that SLAC has faced during previous construction or experimental activities and for which programs are in place to protect the environment and the health and safety of workers and others.

Installation of the B Factory in the existing PEP tunnel at SLAC will enable us to take advantage of a number of existing, proven safety features and systems. The fact that these features are already present and operational in the tunnel will provide an extra measure of safety during the decommissioning of PEP and the installation and commissioning of the B Factory.

The SLAC safety organization will ensure that all safety aspects of the design, installation, testing, and operational phases of the project are reviewed and approved by the cognizant SLAC safety committees, including the Safety Overview Committee, the Hazardous Experimental Equipment Committee, the Radiation Safety Committee, the Electrical Safety Committee, the Non-Ionizing Radiation Safety Committee, and the Earthquake Safety Committee [SLAC Environment and Safety Office, 1987].

8.1 FIRE SAFETY

The existing fire safety system in the PEP tunnel and experimental areas will remain operational throughout the installation, commissioning, and operation of the B Factory. All areas are classified as Ordinary Hazard, Group I. The tunnel sections, interaction region halls, and support building are protected by automatic wet sprinkler systems and smoke detectors. The sprinkler systems are designed for a coverage of 0.15 gpm/ft². The ring is divided into twelve zones, each with its separate water supply. Six of these zones supply water to the centers of the curved sections of the tunnel. The remaining six supply water to the interaction regions (IRs). The counting houses and control room are protected by a smoke detector that actuates a pre-action, air-supervised sprinkler. The substation is protected by a heat detector that actuates a deluge system. The smoke detectors are of a high-voltage type that is no longer manufactured. These will be replaced with low-voltage components to facilitate system maintenance.

With the exception of regions 8 through 12, each curved section of the PEP tunnel has three fans: two intake and one exhaust. Owing to the presence of above-ground structures above regions 8 through 12, the ventilation configuration there is somewhat different, with a total of five fans: two intake and three exhaust, including one double-volume exhaust fan. The fans automatically stop operating when the fire alarm sounds. The Fire Department then has the option of restarting any of the fans to provide fresh air or to exhaust smoke. The Fire Department's controls for this purpose are located on above-ground pedestals.

SLAC contracts with the Palo Alto Fire Department to provide an on-site fire station and emergency response services. The Palo Alto Fire Department also provides ongoing fire safety inspections of SLAC facilities, as well as personnel training.

8.2 RADIATION SAFETY

The design and operation of all facilities at SLAC are governed by the ALARA (as low as reasonably achievable) policy. Thus, SLAC has always maintained radiation dose limits below the maximum allowed by regulation.

8.2.1 Radiation Shielding

Shielding for the B Factory will conform to the Design and Control section of DOE Order 5480.11, Section 9(J) [*SLAC Radiation Safety Procedures*, 1990]. The design criterion will be 1 rem/yr at the shield surface for normal beam losses. This assumes a 2000-hr working year and an occupancy factor of 1. In addition, SLAC internal design criteria will require that (i) the boundary dose be limited to 5 mrem/yr for 6000-hr beam operation and (ii) a maximum radiation level of 25 rem/hr be allowed at the outer surface of the shield from an accidental beam loss.

The PEP tunnel was originally designed for 200-GeV protons. Since the shielding requirements for protons are far more stringent than those for electrons, present shielding is more than adequate for 18-GeV electrons and will also be adequate for the B Factory, assuming maximum values for energies and currents.

The IRs in PEP were originally designed for about 20 kW of injected power at 18 GeV, though injection was always limited to 1 kW. Radiation has never been a problem at these low power levels. The B Factory design calls for typical injection power levels of $3.2 \text{ nC/pulse} \times 60 \text{ pps} \times 9 \text{ GeV} = 1.7 \text{ kW}$, well below the original design criterion for the IRs. (Even at the highest conceivable injection power of $8 \text{ nC/pulse} \times 120 \text{ pps} \times 10 \text{ GeV} = 9.6 \text{ kW}$, there is a factor of two safety margin compared with the original PEP shielding design.) Thus, we expect little or no radiation in these areas during normal B Factory operation.

The loss of the circulating beams in the case of the thinnest shielding (that is, a curtain wall in an IR) would result in an integrated dose-equivalent of less than 75 mrem. Since the total energy of the two circulating beams, at their maximum allowable currents of 3 A, is only 253 kJ, the potential for activating air, ground, or beamline components is very low. Operational experience with PEP and SPEAR indicates that air, ground, and beamline component activation are not major radiological problems.

8.2.2 Personnel Protection System

The Personnel Protection System (PPS) currently in place in the PEP tunnel is designed to protect personnel from radiation, electrical, and RF hazards. This is accomplished through a system of electronically interlocked gates, lights, alarms, and operator displays and controls [Constant et al., 1977; Smith and Constant, 1981]. (See below for further discussion of electrical and RF safety considerations.) With installation of the B Factory in the tunnel, the PPS will undergo necessary upgrades and enhancements to address the new facility and operating conditions, but will remain largely the same in terms of its overall design and function. The five existing access states, as shown in Table 8-1, will be retained, as will the lighting controls and audio signals that alert personnel to a change in access state.

Because the B Factory high- and low-energy rings (HER and LER) will be assembled within the existing PEP housing structure and because their injection lines will occupy the existing north and south injection transfer (NIT and SIT) lines, the present PPS perimeter control and interlock facility can be utilized with some modification and upgrades. The perimeter access points into the housing tunnels from all the IR halls and the personnel and equipment tunnel access gates can be fully utilized as part of an upgraded distributed PPS system. All displays and remote control functions available in the PEP control room will be retained. In addition to interfacing with the existing hardware panels, the upgraded system will provide software-driven CRT displays and touch-panels from a dedicated distributed PPS controller system. Personnel badge reading and monitoring capability will be utilized for access control.

Table 8-1. Access states of the current PEP Personnel Protection System [SLAC Radiation Rule Book, 1990].

NO ACCESS	Beam on or potential for beam to be on.
RESTRICTED ACCESS	Similar to CONTROLLED ACCESS, but electrical hazards and x-rays from the RF system may be present. Because of additional hazards, access is allowed only as necessary to knowledgeable persons.
CONTROLLED ACCESS	Beam off. Electrical and RF hazards off. Zone has been searched. Persons are identified, are logged in and out, and must carry a key from the keybank.
IN SEARCH	Beam off. Electrical and RF hazards off. Doors electrically locked until search completed.
PERMITTED ACCESS	Assurance that beam and RF hazards cannot come on. All door releases are enabled (doors are "open").

The PPS stopper logic will be modified to accommodate the new HER, LER, NIT, and SIT configurations. The emergency-off button configuration will remain the same. In general, the new ring configurations will not impose any major new PPS logic requirements. Tone loop systems will be reconfigured to be compatible with the upgraded distributed controller logic.

Existing doors and gates will be upgraded to improve reliability. The current system provides seven complete access modules located at or near the five IR halls. Each entry module includes keybanks, video cameras, and direct voice communications via intercom and telephone. In addition, five equipment/personnel entry points are located around the periphery of the PEP ring, together with 13 additional key-operated personnel access/egress points. All of these points can be "crashed" for emergency exit.

There are 15 zone barrier gates in the PEP tunnel that require "access state" compatibility to allow passage in either direction. These zones will be retained for the B Factory, and logic requirements will not change. RF areas will continue to be located at the IR halls 4, 6, and 8. The four NIT/SIT barrier gates between the beam switchyard and the PEP tunnels will also remain.

The current PPS safety system interface (SSI) provides for electrical and RF hazard safety interlocks distributed throughout the PEP ring and at IR halls 4, 6, and 8. The input interface to this system will be expanded to accommodate additional RF and magnet power supply requirements, and the control logic will be upgraded to a distributed control interface that will be compatible with the PPS technology.

8.2.3 Beam Containment System

The redesigned NIT/SIT lines will be monitored by toroid current monitors located at their entry portals and will be instrumented in much the same way as are the existing beamlines [Constant et al., 1977]. Each beamline (NIT and SIT) will have two toroids that feed wideband balanced-input preamps located near the beamlines. These preamps will drive fan-out distribution amplifiers in the main control room area. These, in turn, will distribute the beam-induced current signals to average-current monitors, repetition-rate monitors, and pulse-to-pulse peak-current monitors. Each current-monitoring device will generate test signals between beam pulses that will be redistributed to the beamline toroids and fed back to the processing electronics to provide a closed-loop test capability.

The existing Beam Containment System (BCS) is primarily analog in nature and requires many careful setup adjustments to achieve the operational protection limits required by these beamlines. The present BCS will therefore be upgraded, utilizing digital processing techniques to capture beam-pulse information and generate the necessary interlocks. The upgrade will include the use of state-of-the-art wideband preamps, flash ADCs, serial data links, digital discrimination logic, and intelligent processors. The B Factory BCS will utilize this design upgrade in the implementation of its required interlocks, thereby providing rapid setup, flexibility, and improved reliability.

8.2.4 Radiation Safety Training

In accordance with SLAC's implementation plan for DOE Order 5480.11 (Radiation Protection for Occupational Workers), all regular SLAC employees and any persons who work at the laboratory longer than one month must receive training in radiation fundamentals. In addition, those workers whose assignments make it likely that they will receive a total occupational radiation dose greater than 100 mrem in one year receive extensive radiation safety training and are required to pass an examination. The latter class of workers is recertified by examination every two years.

8.3 NONIONIZING RADIATION SAFETY

The radio-frequency (RF) energy system for the B Factory will incorporate all the safety measures that are currently in place at PEP [Allen and Karvonen, 1978]. These include the use of pressurized waveguides and strict procedures for mechanical assembly and inspection.

Each waveguide network will be pressurized with regulated 0.25-psig instrument air. Since the volumetric supply rate is limited, a leak in the waveguide will cause a drop in pressure, actuation of a pressure switch, and shutdown of the rings. After the leak is repaired, a field measurement will be made to check for RF leakage. Normal ring operation may resume when the pressure in the waveguide is restored and the RF field survey is completed.

Pressurization guards mainly against operation with a missing piece of waveguide or an improperly assembled flanged joint. Although the most likely cause of RF leakage under operating conditions is that a waveguide joint has been left open, it is possible that the system could be gas-leak-tight and not RF-leak-tight. This could occur, for example, if the flange bolts are not tightened enough to fully compress the rubber gas seal. Thus, proper torquing of the flange bolts is necessary to prevent possible RF leakage at the flange joint.

During assembly and installation of the waveguide components, all flange bolts will be torqued and all field-assembled waveguide joints will be tested by pressurization and checked for bubbles. Joints must be free of visible bubbles. After installation, an inspector will measure the torque on a minimum of six bolts chosen at random on each flange. If the torques exceed specified levels, the inspector will then initial and date the flange joint, thus indicating that the joint is acceptable. If the joint is not acceptable, all the bolts on the flange must be retorqued and remeasured.

After the requirements for gas leak checking and bolt torquing are satisfied, a check for RF leakage around each accessible flanged joint will be made. If the test is satisfactory, an adhesive label with the inspector's initials and the date will be applied across each joint. An intact and signed label on each waveguide joint is always a prerequisite to operational transmission of RF through a waveguide network. The coaxial connectors at the final drive amplifier and at the input to the klystron will also be surveyed for possible leakage.

When a klystron is disconnected from the waveguide between the klystron and the circulator, a cover will be bolted over the open end of the waveguide on the cavity side. The cover will be inspected and labeled and the waveguide pressurized before any beam can be stored in the ring. Also, a pressure switch interlock in the waveguide close to the klystron will prevent high voltage from being applied to a klystron when it is disconnected from the waveguide feeding its cavities.

B Factory operations staff will conduct RF radiation hazard surveys at least every 90 days to ensure that the RF leakage level is less than 1 mW/cm².

8.4 ELECTRICAL SAFETY

It is SLAC policy that every necessary precaution is taken in the performance of work to protect all persons on the site from the risk of electrical shock and to minimize the probability of damage to property due to electrical accidents. This policy is implemented by assigning responsibility and adhering to basic safety principles, as stated in the *SLAC Electrical Safety Policy* [1990] and the *SLAC Electrical Safety Standards* [1990], and by complying with regulations and procedures appropriate to each operation. A 4-hour electrical safety training course is provided by the Laboratory for those workers who are likely to be exposed to high-voltage hazards.

Several B Factory subsystems will employ high voltages. For example, voltages in the detector subsystems used to achieve gas amplification could reach 7 kV DC. The controls and work procedures necessary to ensure safe work on these systems are well-understood. The interlocking of these systems will implement SLAC's established procedures for lockout and tagout and for working on energized equipment only under very limited and controlled conditions to ensure safe operation.

Special procedures are in place to permit authorized personnel to occupy areas adjacent to energized hazardous magnets. These procedures are called RASK, for "Restricted Access Safety Key." Under these procedures, a special RASK authorization form must be filled out to obtain a key that enables the hazardous supply under test. Testing is done in accordance with written procedures. The emergency-off buttons remain active and will crash off the power supply when pushed. The RASK system will remain operational during construction of the B Factory. Thus, we will have the advantage of having this safety system in place during installation and testing of the magnets.

During the life of the PEP tunnel, there has been some damage to junction boxes and conduit due to water seepage near IR-10. Owing to the difficulty in obtaining a tight water seal in the shotcrete-lined tunnel, water flow has been managed through a series of efforts, including covering vulnerable equipment and installing drainage gutters to channel the flow of water [Weidner, 1990; see also Section 7.1.1]. No electrical accidents have occurred as a result of the water seepage. To address this continuing problem over the life of the B Factory, additional improvements to the drainage system are planned, as described in Chapter 7. Further, the entire electrical distribution system now in place will be inspected, and any elements of the system that are damaged or vulnerable to damage will be replaced and maintained in a manner that will ensure safe

operation. All new electrical installations will be in accordance with current applicable codes and requirements.

8.5 CONSTRUCTION

The SLAC Environment Safety and Health (ES&H) Division has primary responsibility for overseeing safety compliance by construction contractors. This responsibility, which is carried out in concert with SLAC plant engineers, contract administrators, and line supervisors, includes

- Apprising contractors of SLAC and DOE safety criteria prior to construction
- Conducting periodic inspections of contractor construction areas to evaluate the quality of the contractor's safety compliance program
- Receiving contractor accident reports and compiling information for reporting to DOE

8.6 EMERGENCY PREPAREDNESS

Like all experimental equipment at SLAC, the B Factory will be designed, constructed, and operated in a manner that minimizes the risk of injury to property or personnel as a result of a natural disaster or other emergency situation. In the event of any abnormal condition, the interlock system will automatically shut the machine down until the situation is diagnosed and corrected. The formal emergency planning system described in the *SLAC Emergency Planning Booklet* [1988] will help to ensure a logical, organized, and efficient response to any emergency. It sets forth specific steps to deal with various emergency conditions, identifies the appropriate personnel to act as resources, and provides a chain of command for responding to unplanned events.

The emergency situation most likely to arise at SLAC is an earthquake. As indicated in Section 7.1.1, the PEP tunnel and related structures are designed to withstand the effects of a major earthquake. In addition, all mechanical components of the B Factory will be secured to protect persons working nearby. This will be assured by a review of the design and installation of the experimental equipment by the SLAC Earthquake Committee, as mandated by the *SLAC Safety Program* [SLAC Environment and Safety Office, 1987]. Further, as with all activities at SLAC, operation of the B Factory will be covered by the *SLAC Earthquake Emergency Plan* [1987], which outlines the procedures to be followed in the event of an earthquake severe enough to cause possible structural damage or personal injury.

8.7 ENVIRONMENTAL PROTECTION

8.7.1 Disposal of PEP Components

Decommissioning PEP and making room in the tunnel for installation of the B Factory will require the removal of 925 tons of concrete rafts and hundreds of tons of other materials. The concrete rafts have been surveyed and found to be free of radioactivity other than background activity from radon (^{214}Bi , ^{214}Pb) and ^{40}K . The concrete may therefore be disposed of as nonhazardous waste. All other items will be surveyed before they are removed from the tunnel and will be handled in a manner appropriate to the level of residual radioactivity present. Those materials that may be reused in the B Factory will be held in a secure area until they are reinstalled. All scrap will be disposed of in accordance with approved procedures.

8.7.2 Ongoing Environmental Protection Activities

In accordance with 29 CFR 1910.1200 (the OSHA hazard communication standard), SLAC has developed a *SLAC Hazard Communication Program* [1986]. Under this program, SLAC conducts regular inventories of hazardous materials, makes Material Safety Data Sheets (MSDSs) available to all employees, ensures appropriate labeling of hazardous materials, trains employees to identify and control hazards in the workplace, and informs users, contractors, and temporary employees of the hazards that may be encountered at SLAC.

Construction and operation of the B Factory is not expected to cause any additional impact on the groundwater at SLAC. Preservation of groundwater quality is ensured through implementation of the groundwater monitoring program [Earth Sciences Associates, 1991], which SLAC has instituted in compliance with DOE Order 5400.1.

8.8 DETECTOR SAFETY ISSUES

A separate CDR and safety evaluation will be prepared and submitted for the B Factory detector. This discussion is intended merely to summarize the safety and environmental hazards posed by the detector and to describe the means proposed to mitigate them.

The detector for the B Factory will be similar, from a safety point of view, to particle physics detectors at many other storage rings. It is therefore possible to evaluate with some confidence potentially hazardous conditions that must be protected against. The detector systems may employ gases with a small but significant flammable component. This is also a standard situation. Safety procedures in this case involve (i) the proper venting of gases in such a way as to prevent the accumulation of explosive concentrations, (ii) the placement and proper maintenance of flammable-gas detectors on the detector itself and in the regions of gas storage and mixing, (iii) the proper siting and installation of pressure vessels, (iv) the interlocking of high voltages so as to prevent

sparks that could ignite the mixture, and (v) the training of operators regarding proper safety procedures.

The final potential safety hazard is the cryogenic system associated with the superconducting solenoidal magnet. This system must handle liquid helium to cool the magnet. Safety considerations here mainly involve prevention of spills of cryogenics (liquid helium and liquid nitrogen), which could cause injury by freezing or by creating an oxygen-deprived atmosphere upon evaporation. This will be done by engineering the system such that large liquid spills can be prevented, even in the event of a major line rupture; by the installation of low-oxygen detectors; by the proper engineering of pressure vessels and attendant systems; and by extensive training of the system operators and maintenance personnel. If a superconducting Q4 magnet is chosen for the B Factory, these measures will be applied to it as well. Further, the volume of cryogenics will be much smaller for the Q4 magnet.

8.9 QUALITY ASSURANCE

The B Factory management is strongly committed to the implementation of a quality assurance (QA) program for the design, construction, and operation of the B Factory. A dedicated QA manager, reporting directly to the B Factory project leader, is planned. Working together with QA staff at SLAC and the various B Factory subsystem managers, the B Factory QA manager will develop and implement a QA plan that will ensure that the B Factory is built to applicable SLAC, LBL, government, and industry standards and codes. The QA plan will include, at the minimum, consideration of

- Purchased material controls
- Design controls
- Drawings, procedures, standards, and databases
- Document control
- Controls for fabrication, assembly, installation, and operation
- Inspection and testing
- Internal and external audits
- Quality reports

We plan to institute a flexible database management program (we foresee using ORACLE along the lines followed by the LEP project at CERN), which will allow us to keep track of every component of the machine for the full duration of the project. In this way, for every machine component, all items of an historical and/or characterization nature, be they documentation, vendor, maintenance history, etc., will be encoded and cross-linked. This system will also provide a unique, modifiable means of maintaining the machine parameters that will allow the engineering staff easy and accurate access to any parameter they need, and will avoid the promulgation of out-of-date parameters.

In addition to the salary for a QA manager, the budget presented in Chapter 9 includes considerable funds for engineering staff who will perform QA tasks for each

individual subsystem. Funds have been included for inspection at both on-site and off-site (that is, vendor) facilities.

Project management is committed to an ongoing process of subsystem review. These reviews will be staffed by a combination of in-house and outside experts, whose job will be to provide technical input for all phases of the project. Part of their function will be to ensure that proper standards of quality are maintained at all times. This process of expert review has already been used on the project; four in-depth reviews were held to solicit a candid technical evaluation of the critical items of the design presented in this report. The review teams were asked to draw attention to any design features that would lead to unreliable or poor-quality machine operation. The reports from these four review teams, along with supporting documentation, are available in a companion document.

9.

COST AND SCHEDULE

THE Asymmetric B Factory project involves an upgrade of the SLAC accelerator complex. This upgrade includes construction of the high- and low-energy rings in the existing PEP tunnel and construction of bypass lines for the electrons and positrons in the existing linac enclosure. Many PEP components will be reused, and additional savings will accrue from the reuse of hardware from SLAC installations other than PEP. Although no conventional construction is required, minor modifications to the electrical and cooling-water systems are included in the project scope. The cost estimate presented here includes only the construction activities and does not include either the costs of preconstruction R&D or the preoperations costs associated with project commissioning.

9.1 COST ESTIMATE

The B Factory cost estimate was generated, and will be subsequently monitored, through a work breakdown structure (WBS), described in Section 9.3. The total construction cost, in FY 1991 dollars, is \$167.2 million. This estimate is presented in Table 9-1; the associated schedule (see Section 9.2) assumes an optimum funding profile.

Contingency is an explicit line item that was determined after a detailed analysis of each of the major subsystems. The contingency varies from system to system, depending upon the complexity of the system and the details of our understanding. In those cases where PEP components are being duplicated, we have felt justified in assigning a lower-than-average contingency. The percentage of contingency varies between 20% (for a well-defined and well-understood magnet system) and 60% (for the less well-defined interaction region components). The overall contingency for the project is 26%. Table 9-1 includes the individual contingency assigned to each subsystem.

An associated schedule for preconstruction R&D (not shown here) has been used to ensure a realistic construction schedule. That is, the schedule presented in Section 9.2 takes proper account of the time required for R&D activities prior to detailed design and hardware fabrication.

Table 9-1. Estimated cost, in FY91 dollars, of the Asymmetric B Factory.

WBS code	System	Cost (FY1991 K\$)	Contingency	
			(%)	(FY1991 K\$)
1	Asymmetric B Factory	129,844	26	33,559
1.1	High-Energy Ring	58,525	25	14,748
1.1.1	High-Energy Ring Magnets	3,127	20	625
1.1.2	Magnet Power Supplies	2,381	20	476
1.1.3	RF System	20,350	25	5,088
1.1.4	Vacuum System	21,547	25	5,387
1.1.5	Feedback System	2,586	40	1,034
1.1.6	Instrumentation and Electronics	1,944	25	486
1.1.7	Installation	5,415	26	1,417
1.1.8	Alignment	1,175	20	235
1.2	Low-Energy Ring	41,425	24	10,069
1.2.1	Low-Energy Ring Magnets	10,564	20	2,113
1.2.2	Magnet Power Supplies	1,953	20	391
1.2.3	RF System	10,180	25	2,545
1.2.4	Vacuum System	12,767	25	3,192
1.2.5	Feedback System	2,200	40	880
1.2.6	Instrumentation and Electronics	1,859	25	465
1.2.7	Installation	1,520	27	407
1.2.8	Alignment	382	20	76
1.3	Interaction Region	4,376	39	1,706
1.3.1	Interaction Region Magnets	1,583	60	950
1.3.2	Power Supplies	605	20	121
1.3.4	IR Vacuum System	836	25	209
1.3.6	Instrumentation and Electronics	316	45	142
1.3.7	Installation	1,036	27	284
1.4	Injection System	8,242	25	2,045
1.4.1	Injection System Magnets	1,951	25	488
1.4.2	Magnet Power Supplies	1,234	20	247
1.4.4	Vacuum System	1,322	25	331
1.4.6	Instrumentation and Electronics	615	25	154
1.4.7	Installation	2,641	28	729
1.4.8	Alignment	479	20	96

Table 9-1 continued

1.5	Control System	8,890	33	2,961
1.5.1	System Engineering	4,737	32	1,508
1.5.2	Hardware	4,153	35	1,453
1.6	Conventional Facilities	5,480	26	1,449
1.6.1	Electrical Utilities	3,549	20	710
1.6.2	Mechanical Utilities	1,763	40	705
1.6.3	Site Work	168	20	34
1.7	Safety and Protection	606	20	121
1.8	Management	2,300	20	460
1.8.1	Administration	1,500	20	300
1.8.2	Quality Control & Quality Assurance	200	20	40
1.8.3	Planning and Scheduling	200	20	40
1.8.4	Budget	200	20	40
1.8.5	Office Staff	200	20	40
	Indirects	3,820		0
	Incremental Indirects	2,820		0
	University Indirects	1,000		0
PROJECT TOTAL: 167,223				

Using this construction schedule, we have developed the funding profile shown in Table 9-2. This profile is presented both in constant FY 1991 dollars and in then-year dollars (based on DOE guidelines). The escalation has been done to the midpoint of the project (June 1994) using DOE construction escalation figures of 4.5% (FY 1991), 5.1% (FY 1992), 5.6% (FY 1993), 5.7% (FY 1994). Labor rates used in determining the project costs are summarized in Table 9-3. In some cases—for example, magnet and vacuum systems fabrication—it was assumed that dedicated contract labor shops would be set up. Otherwise, the rates were based on current laboratory shop rates—mostly the shop rates at SLAC.

9.2 CONSTRUCTION SCHEDULE

The overall construction schedule is shown in Figs. 9-1a and 9-1b. This schedule, based on an optimum funding profile, shows that the B Factory can be completed in a 3-1/2 year construction period. If construction begins in FY 1993, the project would be completed during FY 1996.

Table 9-2. Profile for construction funds in FY 1991 and then-year dollars.

	FY 1993	FY 1994	FY 1995	FY 1996	Total
FY 1991 (K\$)	40.0	63.0	47.0	17.2	167.2
Then-year (K\$)	44.6	74.0	58.0	22.0	198.6

Table 9-3. SLAC shop rates used to establish the cost estimate.

Shop Description	Rate (\$/hr)
Mechanical Engineer	53.20
Mechanical Design	37.10
Mechanical Fabrication	56.95
Mechanical Technician	38.75
Mechanical Alignment	51.15
Plating Shop	73.05
Electrical Engineer	47.02
Electrical Design	41.70
Electrical Fabrication Technician	32.00
Plant Engineer	47.85
Plant Engineering Drafting	43.40
Software Engineer	43.33
Software Coordinator	38.52
Davis-Bacon Labor	55.00

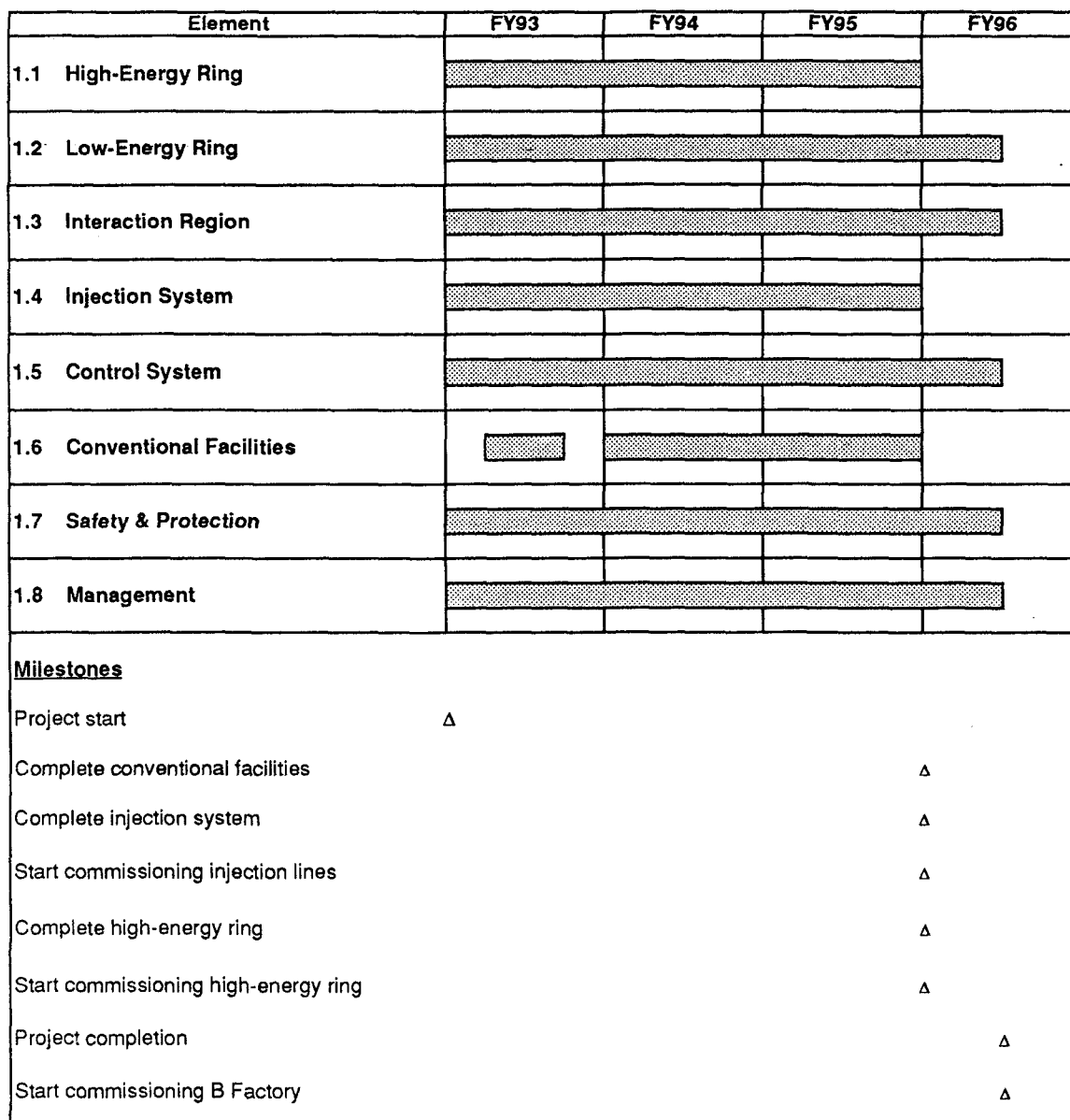


Fig. 9-1a. Overall schedule and project milestones for construction of the Asymmetric B Factory.

COST AND SCHEDULE

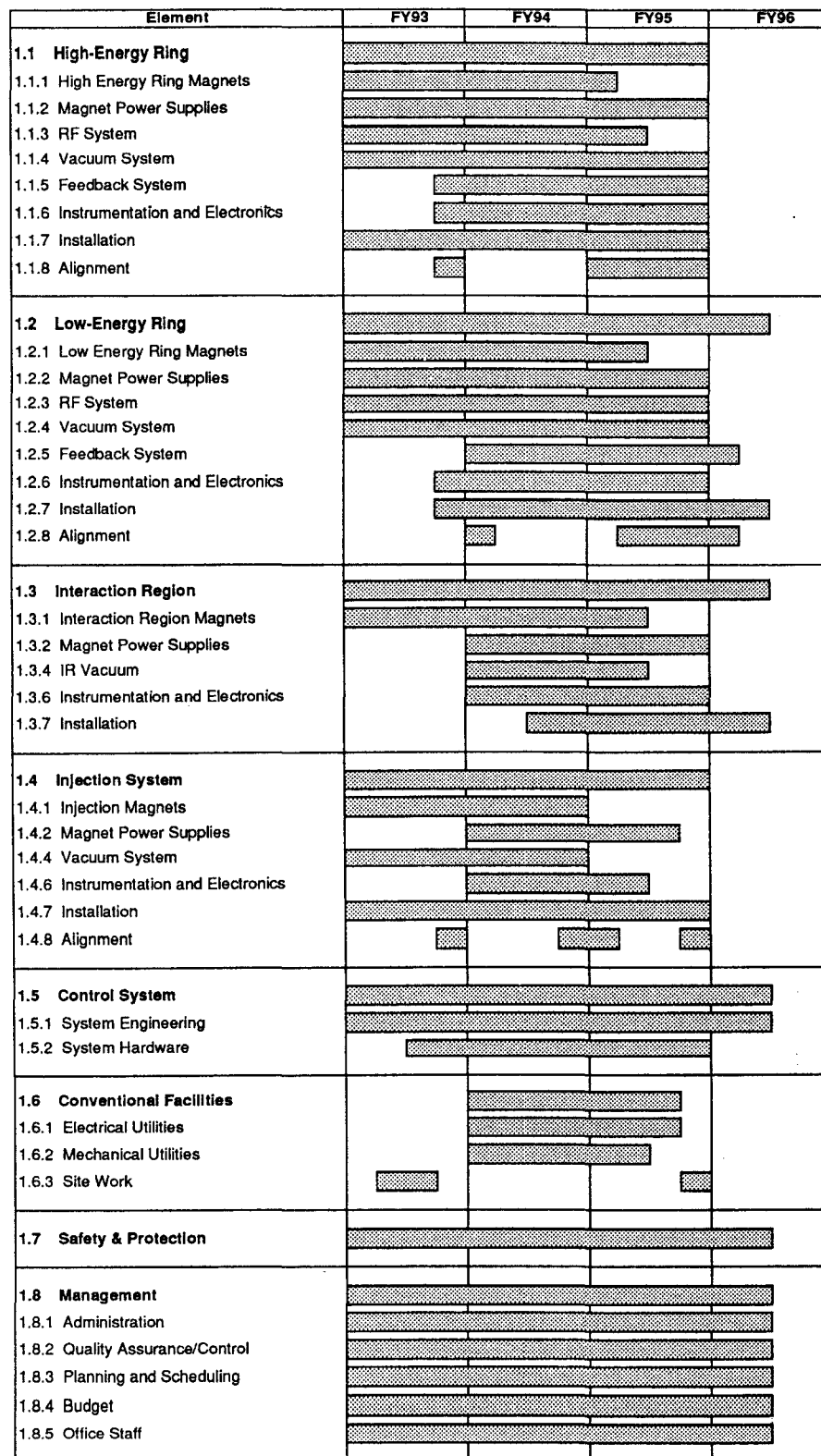


Fig. 9-1b. Project schedule (to WBS level 3) of the Asymmetric B Factory.

9.3 WORK BREAKDOWN STRUCTURE

The work breakdown structure was designed to be consistent with project management's need to track detailed costs of all B Factory subsystems. It conforms to the structure used by the SLAC Accounting Office for reporting costs and commitments to B Factory management. The levels are defined as follows:

- Level 1 = x *Asymmetric B Factory*
- Level 2 = x.x *Major systems*
- Level 3 = x.x.x *Subsystems*
- Level 4 = x.x.x.x *Subsystem detail*

Definitions for levels two and three of the WBS for the Asymmetric B Factory are given below.

- 1.1 High-Energy Ring. The B Factory utilizes a reconfigured and refurbished PEP storage ring, operating at 9 GeV, as the high-energy storage ring.

1.1.1 High-Energy Ring Magnets. The existing PEP magnets will be refurbished and reconfigured in the PEP tunnel. Additional quadrupoles will be added to maintain the beam focusing in the long straight sections.

1.1.2 High-Energy Ring Magnet Power Supplies. The existing PEP large power supplies will be refurbished; additional supplies will be acquired as needed for the new magnets. Monitoring systems will be constructed.

1.1.3 High-Energy Ring RF System. New high-power, low-impedance copper cavities, driven by commercially available 1-MW klystrons, will be designed and fabricated or purchased. This system, which is needed for the new operating conditions of the high-energy ring, will be at a higher frequency (476 MHz) than the original PEP RF system (353 MHz).

1.1.4 High-Energy Ring Vacuum System. The high circulating currents of the B Factory result in high synchrotron radiation power on the vacuum chamber wall. The existing PEP vacuum chamber will be replaced with a new copper chamber to provide the appropriate low pressure and thermal management. Costs of installation of the chamber are included here.

1.1.5 High-Energy Ring Feedback System. To control coupled-bunch instabilities in the high-energy ring, one longitudinal and two transverse feedback systems will be employed. These will be wideband, bunch-by-bunch systems, designed and built primarily in-house but using commercially obtained power amplifiers.

1.1.6 High-Energy Ring Instrumentation and Electronics. Beam position monitors, profile monitors, and various other beam diagnostic devices will be designed and fabricated.

1.1.7 High-Energy Ring Installation. The existing PEP storage ring will be disassembled, refurbished, and reassembled into its new configuration for the B Factory high-energy ring. Both RF and electrical installation are included here.

1.1.8 High-Energy Ring Alignment. The reinstallation of the PEP ring in its new configuration will require a realignment of all components.

1.2 Low-Energy Ring. The low-energy ring of the B Factory is a completely new ring having a circumference of 2200 m, to be located atop the high-energy ring in the PEP tunnel. Its nominal operating energy is 3.1 GeV.

1.2.1 Low-Energy Ring Magnets. The magnet system for the low-energy ring is modeled after that of the high-energy ring, with the lengths of some of the components reduced because of the lower energy. Designs and fabrication techniques closely follow those used successfully in the construction of the PEP magnets.

1.2.2 Low-Energy Ring Magnet Power Supplies. The bulk of the power supplies required for the low-energy ring are existing, refurbished PEP and other SLAC supplies.

1.2.3 Low-Energy Ring RF System. New high-power, low-impedance 476-MHz RF cavities, each driven by a commercially available 1-MW klystron, will be fabricated for the low-energy ring. No additional penetrations or surface buildings will be required.

1.2.4 Low-Energy Ring Vacuum System. The vacuum system for the low-energy ring utilizes a copper beam tube in those regions where the photon flux is high (the area just downstream of the bends) and a stainless-steel beam tube elsewhere.

1.2.5 Low-Energy Ring Feedback System. The feedback demands of the low-energy ring are comparable to those of the high-energy ring. These bunch-by-bunch feedback systems will be capable of damping both transverse and longitudinal instabilities.

1.2.6 Low-Energy Ring Instrumentation and Electronics. Beam position monitors, current monitors, profile monitors and other beam-monitoring devices and their associated electronics are included here.

1.2.7 Low-Energy Ring Installation. The low-energy ring magnetic components will be installed on preassembled and prealigned girders. The supports for these girders are an extension of the high-energy ring supports. Both RF and electrical installation are included here.

1.2.8 Low-Energy Ring Alignment. Conventional optical alignment tooling, already available at SLAC, will be modified to align the low-energy ring.

- 1.3 Interaction Region. The B Factory will have one interaction point, located at IR-2.

1.3.1 Interaction Region Magnets. Since the B Factory consists of two separate rings, special magnets are necessary to bring the beams into collision and then to return them to their respective rings. Included are the septum quadrupoles, as well as the permanent-magnet bending and focusing elements and their trim windings.

1.3.2 Interaction Region Power Supplies. Power supplies, as well as current-monitoring equipment are required for the septum quadrupoles, as well as for some conventional quadrupoles located in this area. Power for the permanent magnet trim windings is also included here.

1.3.4 Interaction Region Vacuum System. This includes all vacuum chamber elements in the interaction region, including the special thin-walled beryllium beam pipe for the detector, radial ion pumps, masks, etc.

1.3.6 Interaction Region Instrumentation and Electronics. Special care must be taken to monitor the beam position and measure the luminosity in the interaction region both to maximize the luminosity and to avoid background problems.

1.3.7 Interaction Region Installation. This entry includes the costs associated with the electrical and mechanical installation of the B Factory final focusing elements, including alignment costs. The IR components will be prealigned in a support barrel to ensure proper relative alignment through the detector.

- 1.4 Injection System. The injector for the B Factory is the SLAC linac. Separate bypass beamlines for positrons and electrons will be provided in the linac housing. These beams will be delivered to the NIT and SIT tunnels that now supply beams to PEP, and then transported in new transfer lines to the high- and low-energy ring injection straight sections.

1.4.1 Injection System Magnets. New magnets are required for the transport lines from linac sector 3 to the SIT line (for positrons) and from linac sector 7 to the NIT line (for electrons). Both the NIT and SIT lines will be upgraded at their entrance and exit ends.

1.4.2 Injection System Magnet Power Supplies. The existing NIT and SIT line bending magnet and quadrupole power supplies will be refurbished. New trim dipole power supplies will be added, and the power supply control and monitoring equipment will be upgraded. The positron and electron bypass lines will use existing bending magnet power supplies and new quadrupole supplies. Magnet control and monitoring equipment will be all new.

1.4.4 Injection System Vacuum System. Roughing fingers and necessary valving and piping for the bypass lines and the NIT and SIT lines are included here, as are ion pumps and their controllers.

1.4.6 Injection System Instrumentation and Electronics. New beam position monitors, profile monitors, and wire scanners will be installed in both the bypass lines and the NIT and SIT lines.

1.4.7 Injection System Installation. Two new beam transfer lines must be installed, bypassing the linac, to transport electrons to the NIT line and the positrons to the SIT line. The NIT and SIT lines will be extended by approximately 50 m and partially rebuilt.

1.4.8 Injection System Alignment. The two new bypass lines must be aligned and matched to the extraction from the linac and the injection into either the NIT or the SIT line. The NIT and SIT lines require realignment, as do their injection lines into the high- and low-energy rings.

- 1.5 Control System. The control system for the B Factory is modeled after the existing control system at the SLC.

1.5.1 Control System Engineering. This entry represents the engineering effort necessary to develop control software and hardware to operate the B Factory.

1.5.2 Control System Hardware This item represents the cost of the main control computer and various control consoles, networks, and electronics that link the subsystems to the control computer.

- 1.6 Conventional Facilities. The B Factory utilizes the existing PEP facility. No new conventional construction is required. The PEP electrical distribution system will be modified to accommodate the new load distribution of the B Factory. Similarly, the water system will be upgraded to replace some parts and slightly reconfigured to reflect the new B Factory loads.

1.6.1 Electrical Utilities. This entry reflects the cost of reconfiguring the PEP electrical distribution system to match B Factory requirements. It also includes the cost of upgrading the pumping capacity of the PEP cooling tower.

1.6.2 Mechanical Utilities. This entry represents the costs associated with upgrading the PEP cooling tower pumping system, the replacement of all the PEP LCW heat exchangers, and the modifications to the linac LCW system to accommodate the injector bypass lines.

1.6.3 Site Work. This involves improving the water management within the PEP tunnel. A small portion of the tunnel will be cleaned and water-diverting hardware will be installed.

- 1.7 Safety and Protection. Included here are costs associated with upgrading the fire-protection system and the rework of the personnel protection system. The salary of a full-time safety inspector will also be covered.

- 1.8 **Management.** This entry reflects the costs associated with the overall management of the project, i. e., effort that is not otherwise included in any of the various subsystem costs. (Salaries for lead engineers are associated with the costs of their respective subsystems.) Included are such things as project administration (1.8.1 and 1.8.5), quality control and quality assurance activities (1.8.2), planning and scheduling (1.8.3), and budget-related activities (1.8.4). In addition to the effort called out here, additional effort in some of these areas will be provided through the incremental indirect costs.

10.

SUMMARY

IN this report we have described a design for a high-luminosity Asymmetric B Factory to be built in the PEP tunnel on the SLAC site. This proposal, a collaborative effort of SLAC, LBL, and LLNL, is the culmination of more than two years of effort aimed at the design and construction of an asymmetric e^+e^- collider capable of achieving a luminosity of $\mathcal{L} = 3 \times 10^{33} \text{ cm}^{-2} \text{ s}^{-1}$.

The configuration adopted utilizes two storage rings, an electron ring operating at 9 GeV and a positron ring at 3.1 GeV, each with a circumference of 2200 m. The high-energy ring is an upgrade of the PEP storage ring at SLAC; all PEP magnets and most power supplies will be reused. The upgrade consists primarily of replacing the PEP vacuum chamber and RF system with newly designed versions optimized for the high-current environment of the B Factory. The low-energy ring will be newly constructed and will be situated atop the high-energy ring in the PEP tunnel. Utilities already installed in the PEP tunnel are largely sufficient to operate the two B Factory storage rings.

Siting the Asymmetric B Factory at SLAC offers a number of important advantages. The existing 2200-m-circumference PEP tunnel provides sufficient space to construct the two-ring collider, and it permits a flexible design with conservative parameters. The bending radius accommodated by the arc sections, 165 m, allows the use of low-field bending magnets, thereby keeping the synchrotron radiation power density to reasonable levels (only 5 kW/m at the design current for the high-energy ring). The availability of six long (110 m) straight sections increases the flexibility of the design and easily accommodates the requirements for beam separation, tune control, injection, and the detector. (There is room for a second detector if extra funds become available.) Because the PEP tunnel was originally sized to house two rings, space is also fully adequate for the addition of the B Factory low-energy ring. Indeed, no conventional construction will be necessary for the B Factory at SLAC, saving both cost and time in making the B Factory operational. The tunnel is adequately shielded against the additional radiation that results from high-luminosity operation, and the IR hall is sufficient to accommodate the envisioned detector and its ancillary equipment.

A unique advantage of the SLAC site is the availability of the most powerful positron injection system in the world—the SLC linac. This feature is crucial for the operation of the collider as a “factory,” because maintaining a high average luminosity depends strongly

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on achieving rapid injection. The linac injection system is also the ideal choice in terms of the requirements of the storage ring feedback systems, because it provides a small amount of charge per injection shot, thus ensuring that the feedback systems are not overloaded by injection transients.

The design approach followed here has focused on achieving the performance goals of the B Factory in a reliable manner. This has meant designing the hardware from the outset with sufficient operating margin, as well as providing good diagnostics as part of the design. Where possible, we have adopted parameters consistent with established collider practice. For example, the required beam currents of 1.48 A and 2.14 A in the high- and low-energy rings, respectively, are split into 1658 bunches. Therefore, the single-bunch parameters (length, current, emittance, beam-beam tune shift) are all conventional and do not require any extrapolation from the operating experience of present machines.

Our choice of many low-intensity bunches, as opposed to fewer high-intensity bunches, avoids difficulties associated with single-bunch instabilities, though it does not change the need for a state-of-the-art feedback system to manage coupled-bunch instabilities. In our approach, the design challenges for the Asymmetric B Factory are restricted to a few selected areas. These areas, listed below, are all amenable to attack by standard engineering approaches and, though demanding, can be handled by applying and extending existing techniques in a reasonably well-understood manner.

Based on our studies, we have concentrated the design effort on those aspects where the most difficult technical challenges exist. These include

- Vacuum system
- RF system
- Multibunch feedback system
- Beam separation and detector masking system

For each of these areas, careful and systematic design work has been undertaken to identify the problems (associated mainly with the required high beam currents) and then to solve them. To ensure that our solutions are effective and appropriate, international experts in each of the above areas were brought to SLAC or LBL to review and validate our design concepts. In each case, the outcome of this process was favorable, thereby verifying the basic soundness of our design.

For the vacuum system, we have adopted a copper vacuum chamber patterned after the HERA design. Copper exhibits good thermal properties and a low rate of photon-induced gas desorption, thus ensuring a low pressure in the face of approximately 2 A of beam current in each ring. Detailed estimates of photon desorption and two- and three-dimensional thermal calculations of the chamber have demonstrated that the approach is an effective one.

The RF system is based on a standard room-temperature cavity design that includes waveguides to damp the unwanted higher-order modes of the structure. This approach has been shown (by means of three-dimensional electromagnetic calculations) to reduce the Q values of higher-order modes to very low values that are favorable for the stabilization of coupled-bunch motions. Furthermore, experiments have been performed on a simple pillbox cavity that confirm the results of the calculations and demonstrate the capability of reaching, or even exceeding, the required amount of damping.

The multibunch feedback system is based on a bunch-by-bunch approach. Extensive simulations have shown that the system will perform effectively under either injection or colliding-beam conditions. The feedback system makes use of commercially available wideband power amplifiers and requires a power level of 2 kW for the longitudinal case and even less for the transverse case. An advantage of our approach is that the feedback system will deal with any form of bunch motion, whatever the cause. Thus, even coherent disturbances arising from the beam-beam interaction can be controlled.

We have carefully designed a beam separation scheme to minimize detector backgrounds, and we have invested substantial effort in detailed simulations of the effects on detector background of both synchrotron radiation photons and lost electrons. This aspect is a challenge for the B Factory because we must achieve the same level of background typically found in today's colliders, but at a beam current an order of magnitude higher. Our masking design gives roughly a factor of 100 safety margin with respect to synchrotron radiation background limitations and about a factor of 15 margin with respect to lost particles. We have also shown the system to be stable against reasonable changes in our design assumptions by examining misalignments of magnets and masks.

The construction of the Asymmetric B Factory at SLAC is an ambitious and exciting project, both as an extension of the accelerator builder's art and as a contributor to our understanding of one of the most fundamental questions in our Universe—the origin of *CP* violation. The SLAC site, with its large-circumference tunnel and the world's most powerful positron injector, is an ideal base from which to launch such a project. Moreover, the combination of the three participating laboratories, SLAC, LBL, and LLNL, offers a pool of accelerator physics, high-energy physics, and engineering expertise unmatched anywhere—a team fully capable of dealing with the challenges that the high-luminosity Asymmetric B Factory presents. There is, in addition, a large community of physicists worldwide who eagerly await the exceptional physics opportunities afforded by the B Factory.

The time is at hand to begin the construction of this frontier facility for high-energy physics research. Based on a 3-1/2 year construction schedule, the Asymmetric B Factory could begin operation at the end of FY 1996. Thereafter, we envision a vigorous research effort that will last for at least 15 years and will address with unique efficiency some of the crucial problems in high-energy physics today.

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APPENDIX A:

PARAMETERS

THIS appendix contains a summary of the B Factory accelerator parameters. It is intended to give a self-consistent snapshot of the machine design. As such, values are often given to more precision than would ultimately be relevant (or even measurable) in an operating accelerator. We start with a few specific comments on the tables to follow.

General Machine Parameters. As is conventional, we quote the luminosity at zero bunch length, constrained by design to $3.00 \times 10^{33} \text{ cm}^{-2} \text{ s}^{-1}$. If we take into account the geometric effect of a finite bunch length, the luminosity is reduced by about 5% to $2.83 \times 10^{33} \text{ cm}^{-2} \text{ s}^{-1}$.

The $1/e$ luminosity decay time is estimated under the conservative assumption that the spot sizes remain constant, that is, that the luminosity goes like the product of the two beam currents. It includes beam loss estimated from $e^+e^- \rightarrow e^+e^-$, $e^+e^- \rightarrow e^+e^-\gamma$, beam-gas bremsstrahlung, beam-gas Coulomb, and Touschek intrabeam scattering. These estimates are made for a 10σ limiting transverse aperture (for an uncoupled beam horizontally and fully coupled beam vertically).

Lattice Cell Parameters. There are four “standard straights” in the HER and two in the LER. These include the two phase control straights in each ring. In addition, there is an “injection straight” and an “IR straight” in each ring, and two “wiggler straights” in the LER.

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TABLE A-1
General Machine Parameters

Parameter	Symbol	High energy ring	Low energy ring	Units
Center-of-mass energy	$E_{c.m.}$	10.580		GeV
Beam energy	E	9.000	3.109	GeV
Peak luminosity	L	3.00×10^{33}		$\text{cm}^{-2}\text{s}^{-1}$
1/e luminosity decay time	τ_L	1.92		hr
Number of populated bunches	n_b	1658	1658	
Number of empty bunches	$n_b(\text{gap})$	88	88	
Bunch spacing	s_b	1.2596		m
Machine circumference	L	2199.318	2199.318	m
Horizontal tune	ν_x	25.280	32.280	
Vertical tune	ν_y	24.180	35.180	
Momentum compaction	α_p	.00244	.00149	
Natural energy spread	σ_E	5.50	2.97	MeV
Natural fractional energy spread	δ_E	6.1×10^{-4}	9.5×10^{-4}	
Natural bunch length	σ_t	1.00	1.00	cm
Circulating current	I	1.479	2.140	A
Number of particles/bunch	N_b	4.084×10^{10}	5.911×10^{10}	
Horizontal damping time	τ_x	37.2	36.5	ms
Horizontal emittance	ϵ_x	48.24	96.48	nm-rad
Vertical emittance	ϵ_y	1.93	3.86	nm-rad
Natural chromaticity, Horizontal	ξ_x	-35.662	-51.800	
Natural chromaticity, Vertical	ξ_y	-46.652	-55.114	
Horizontal damping partition number	J_x	0.9914	1.0050	
Vertical damping partition number	J_y	1.0000	1.0000	
Longitudinal damping partition number	J_E	2.0086	1.9950	
Energy variation of J_x	$dJ_x/d \ln E$	-275.36	-7.88	
Energy Variation of J_y	$dJ_y/d \ln E$	0	-0.78	
Energy Variation of J_E	$dJ_E/d \ln E$	275.36	8.66	
Estimated Touschek lifetime	τ_{TB}	188	65	hr

TABLE A-2
Interaction Region Parameters

Parameter	Symbol	High energy ring	Low energy ring	Units
Horizontal beta function at IP	β_x^*	75.00	37.50	cm
Vertical beta function at IP	β_y^*	3.00	1.50	cm
Horizontal dispersion at IP	D_x^*	0.000	0.000	m
Vertical dispersion at IP	D_y^*	0.000	0.000	m
Horizontal spot size at IP	σ_x^*	190	190	μm
Vertical spot size at IP	σ_y^*	7.6	7.6	μm
Beam cross half-angle	θ_x	0.0		mrad
Beam-beam linear tune shift	$\Delta\nu_x$	0.030	0.030	
Beam-beam linear tune shift	$\Delta\nu_y$	0.030	0.030	
$e^+e^- \rightarrow e^+e^-\gamma$ beam lifetime	τ_{Br}	21.9	35.5	hr
$e^+e^- \rightarrow e^+e^-\gamma$ luminosity lifetime	τ_{Br}	17.2		hr
Beam pipe inner radius at IP	r^*	2.50		cm
IP to first magnet distance	d_f	0.200		m
Detector solenoid field	B_{sol}	1.00		T
Detector solenoid length	L_{sol}	4.00		m

TABLE A-3
RF System Parameters

Parameter	Symbol	High energy ring	Low energy ring	Units
Circulating current	I	1.479	2.140	A
Natural bunch length	σ_L	1.00	1.00	cm
RF frequency	f_{RF}	476.0	476.0	MHz
Harmonic number	h	3492	3492	
Synchrotron tune	ν_s	0.0522	0.0498	
Synchrotron frequency	f_s	7.1	6.8	kHz
Energy loss per turn	U_{0i}	3.58	1.24	MeV
Synchrotron radiation power	P_{SR}	5.29	2.66	MW
HOM power	P_{HOM}	0.53	0.94	MW
Cavity wall loss total	P_{Wall}	2.45	1.26	MW
Total RF power	P_{RF}	8.27	4.86	MW
Klystron power total	$P_{tot\ Klys.}$	10.00	5.00	MW
RF voltage	V_{RF}	18.48	9.45	MV
Synchronous phase angle	ϕ_s	167.7	169.8	deg
Fractional energy RF aperture	$f_E(RF)$	0.0105	0.0173	
Fractional energy aperture	f_E	0.0061	0.0095	
Number of klystrons	N_{klys}	10	5	
Power/klystron	P_{klys}	1.00	1.00	MW
Number of cavities	N_{Cavity}	20	10	
Shunt impedance	R_s	3.5	3.5	M Ω
Gap voltage	V_g	0.93	0.94	MV
Accelerating gradient	E	4.20	4.27	MV/m
Wall loss/cavity	P_{Wall}	0.122	0.126	MV
Coupling factor, no beam	β	3.7	3.6	
Unloaded Q	Q	30000	30000	

TABLE A-4
Instrumentation and Feedback

Parameter	Symbol	High energy ring	Low energy ring	Units
Number of BPMs	N_{BPM}	144	144	
Number of BPMs/cell		1	1	
Bunch spacing	t_b	4.202		ns
RF frequency	f_{RF}	476.0	476.0	MHz
Longitudinal feedback system				
Beam pickup central frequency		2856	2856	MHz
Phase detector dynamic range		± 15.0	± 15.0	deg
Phase detector resolution		0.50	0.50	deg
Bunch-to-bunch signal isolation		> 26	> 26	dB
Kicker structure operating frequency	f_{kick}	1.071	1.071	GHz
Number of kicker units	N_{kick}	4	3	
Kicker length	L_{kick}	0.32	0.32	m
Kicker bandpass		241	241	MHz
Kicker shunt impedance	Z_{kick}	1600	1600	Ω
Power for 1 kV		313	313	W
Maximum voltage/turn		4	3	kV
Transverse feedback system				
Number of kicker units	N_{kick}	2	1	
Kicker length	L_{kick}	0.32	0.32	m
Kicker shunt impedance	Z_{kick}	2950	2950	Ω
Power per kicker		332	678	W

TABLE A-5
Vacuum Parameters

Parameter	Symbol	High energy ring	Low energy ring	Units
Vacuum (design):				
Arcs		5×10^{-9}	7.5×10^{-9}	Torr
Straights		3×10^{-9}		Torr
Upstream of IP		1×10^{-9}		Torr
Local maximum at IP		1×10^{-8}		Torr
Value assumed for lifetime		5×10^{-9}	6×10^{-9}	Torr
Horizontal chamber aperture	a_x	9.0	9.0	cm
Vertical chamber aperture	a_y	5.0	5.0	cm
Dipole critical energy	ϵ_{crit}	9.8	2.2	keV
Beam-gas brems. beam lifetime	τ_{BGbrems}	8.0	7.4	hr
Beam-gas Coulomb beam lifetime	τ_{BGcoul}	27.4	6.9	hr
Nominal desorption for Cu	η_{Cu}	2×10^{-6}		$\frac{\text{molecules}}{\text{photon}}$
Pumping speed in arc cell		1912	680	L/s
		125	44	L/s/m
Pumping speed in straight cell		460	440	L/s
		30	29	L/s/m
Pumping speed in RF cavity		500	500	L/s

TABLE A-6
Lattice Cell Parameters

Parameter	Symbol	High energy ring	Low energy ring	Units
Standard arc cells				
Number of cells	N_{cell}	72	72	
Cell Layout		QF-B-QD-B		
Cell length	L_{cell}	15.125	15.125	m
Phase advance	ϕ_c	60.0	80.0	deg
Dipole magnetic length	L_B	5.400	1.000	m
Dipole field at E_{des}	B_B	0.1819	0.3394	T
Bend radius	ρ	165.012	30.558	m
Dispersion suppressor cells				
Number of cells	N_{cell}	24	24	
Cell Layout		QF-B-QD-B		
Cell length	L_{cell}	16.013	16.013	m
Phase advance	ϕ_c	~ 90	~ 90	deg
Dipole magnetic length	L_B	5.400	1.000	m
Dipole field at E_{des}	B_B	0.1819	0.3394	T
Bend radius	ρ	165.012	30.558	m
Standard straight cells				
Number of cells	N_{cell}	32	16	
Cell Layout		QF-O-QD-O		
Cell length	L_{cell}	15.125	15.125	m
Phase advance	ϕ_c	~ 60	~ 90	deg

TABLE A-7
Main Dipole Parameters

Parameter	Symbol	High energy ring	Low energy ring	Units
Magnet designation		2.8C212	2.8C40	
Number of magnets	N_B	192	192	
Dipole field at E_{des}	B_B	0.1819	0.3394	T
Integrated field at E_{des}	$\int B d\ell$	0.9824	0.3394	T-m
Pole width	w_B	8.425	7.500	in
Gap height	h_B	2.787	2.787	in
Core length	$L_{core B}$	209.84	36.58	in
Dipole magnetic length	L_B	212.60	39.37	in
Width of useful field (0.1%)		4.725	4.000	in
Lamination height	h_{lB}	15.433	16.000	in
Lamination width	w_{lB}	18.189	17.800	in
Packing factor (minimum)		96	96	%
Core weight	$m_{core B}$	14168	2000	lb
Ampere-turns per pole at E_{des}		5279	9600	A-turns
Turns/pole		8	15	
Pancakes/pole		1	1	
Conductor width		2.402	2.000	in
Conductor height		0.7087	0.3125	in
Cooling hole diameter		0.25	0.1875	in
Conductor cross section area		1.59	0.60	in ²
Current at E_{des}	I_B	659.9	640.0	A
Resistance	R_B	5.50	7.20	m Ω
Power at E_{des}	P_B	2.40	2.95	kW
Voltage drop at E_{des}	V_B	3.63	4.61	V
Coil weight	$m_{coil B}$	585	200	lb
Number of water circuits		2	2	
Water flow rate		1.2	1.2	gpm
Water pressure drop		50	100	psi
Temperature rise		7.6	9.4	°C

TABLE A-8
Miscellaneous HER Dipole Parameters

Parameter	Value	Units
Magnet designation	2.8C40	
Number-of magnets	4	
Field at E_{des}	0.0356	T
Integrated field at E_{des}	0.0356	T-m
Magnet designation	5.25C80	
Number of magnets	8	
Field at E_{des}	0.0166	T
Integrated field at E_{des}	0.0332	T-m
Pole width	5.9	in
Gap height	5.276	in
Core length	73.622	in
Magnetic length	78.740	in
Magnet designation	5.25C80	
Number of magnets	8	
Field at E_{des}	0.0214	T
Integrated field at E_{des}	0.0428	T-m

TABLE A-9
Miscellaneous LER Dipole Parameters

Parameter	Value	Units
3 degree wiggler dogleg		
Magnet designation	2.8C80	
Number of magnets	4	
Field at E_{des}	0.2716	T
Integrated field at E_{des}	0.5432	T-m
1.3 degree vertical bend		
Magnet designation	2.8C20	
Number of magnets	4	
Field at E_{des}	0.4707	T
Integrated field at E_{des}	0.2354	T-m
0.75 degree vertical bend		
Magnet designation	2.8C20	
Number of magnets	4	
Field at E_{des}	0.2716	T
Integrated field at E_{des}	0.1358	T-m
2.5 degree IR bend		
Magnet designation	2.8C40	
Number of magnets	2	
Field at E_{des}	0.4526	T
Integrated field at E_{des}	0.4526	T-m
1.078 degree IR bend		
Magnet designation	2.8C40	
Number of magnets	1	
Field at E_{des}	0.1952	T
Integrated field at E_{des}	0.1952	T-m
0.176 degree IR bend		
Magnet designation	2.8C40	
Number of magnets	1	
Field at E_{des}	0.0319	T
Integrated field at E_{des}	0.0319	T-m

APPENDIX A

TABLE A-10
Main High Energy Ring Cell Quadrupole Parameters

Parameter	Value						Units
Magnet designation	4Q21	4Q29	4Q21	4Q29	4Q39	4Q39L	
Principal function	QD arcs	QF arcs	QD Sup.		QF Sup.	Straights	
Number of magnets	66	72	24	12	24	60	
Gradient at E_{des}	7.29	5.58	7.99	5.59	5.39	4.05	T/m
Pole tip field at E_{des}	0.3640	0.2790	0.3990	0.2790	0.2700	0.2030	T
Gradient length product	4.070	4.089	4.461	4.096	5.385	4.050	T
Inscribed radius	1.968	1.968	1.968	1.968	1.968	1.968	in
Minimum gap	1.457	1.457	1.457	1.457	1.457	1.457	in
Core length	21.00	27.86	21.00	27.86	38.35	38.39	in
Magnetic length	21.98	28.85	21.98	28.85	39.33	39.37	in
Lamination height	13.98	13.98	13.98	13.98	13.98	10.50	in
Lamination width	13.35	13.35	13.35	13.35	13.35	10.50	in
Packing factor (minimum)	98	98	98	98	98	98	%
Core weight	2882	3824	2882	3824	5263	3455	lb
Amp-turns per pole at E_{des}	7243	5546	7937	5553	5357	4027	A-turns
Turns/pole	56	56	56	56	56	37	
Pancakes/pole	1	1	1	1	1	1	
Conductor width	0.500	0.500	0.500	0.500	0.500	0.500	in
Conductor height	0.500	0.500	0.500	0.500	0.500	0.500	in
Cooling hole diameter	0.250	0.250	0.250	0.250	0.250	0.250	in
Conductor cross section area	0.197	0.197	0.197	0.197	0.197	0.197	in ²
Current at E_{des}	129.3	99.0	141.7	99.2	95.7	108.8	A
Resistance	72.7	91.8	72.7	91.8	121.45	80.24	m Ω
Power at E_{des}	1.22	0.90	1.46	0.90	1.11	0.95	kW
Voltage drop at E_{des}	9.40	9.09	10.30	9.10	11.62	8.73	V
Coil weight	233	308	233	308	396	396	lb
Number of water circuits	1	1	1	1	1	1	
Water flow rate	0.65	0.55	0.65	0.55	0.50	0.50	gpm
Water pressure drop	150	150	150	150	150	150	psi
Temperature rise	7.1	6.2	8.5	6.2	8.4	7.2	°C

TABLE A-11
Miscellaneous HER Quadrupole Parameters

Parameter	Value	Units
QFI1 injection straight (4Q39)		
Number of magnets	2	
Gradient at E_{des}	3.43	T/m
Pole tip field at E_{des}	0.172	T
QDI2 injection straight (4Q39)		
Number of magnets	2	
Gradient at E_{des}	3.96	T/m
Pole tip field at E_{des}	0.198	T
QFI3 injection straight (6Q60)		
Number of magnets	2	
Gradient at E_{des}	0.86	T/m
Pole tip field at E_{des}	0.069	T
QDI4 injection straight (6Q60)		
Number of magnets	2	
Gradient at E_{des}	2.52	T/m
Pole tip field at E_{des}	0.201	T
QFI5 injection straight (6Q60)		
Number of magnets	2	
Gradient at E_{des}	3.14	T/m
Pole tip field at E_{des}	0.251	T
QD6 interaction straight (4Q39)		
Number of magnets	2	
Gradient at E_{des}	5.16	T/m
Pole tip field at E_{des}	0.258	T
QF7 interaction straight (4Q39)		
Number of magnets	2	
Gradient at E_{des}	4.04	T/m
Pole tip field at E_{des}	0.202	T

TABLE A-12

Main Low Energy Ring Cell Quadrupole Parameters

Parameter	Symbol	Value	Units
Magnet designation		4Q20	
Number of magnets	N_Q	264	
Gradient at E_{des}	G_Q	2.50	T/m
Pole tip field at E_{des}	B_Q	0.1250	T
Gradient length product at E_{des}		1.362	T
Inscribed radius	r_Q	1.968	in
Minimum gap	h_Q	1.457	in
Core length	$L_{core\ Q}$	20.00	in
Magnetic length	L_Q	21.457	in
Lamination height	$h_{l\ Q}$	10.50	in
Lamination width	$w_{l\ Q}$	10.50	in
Packing factor (minimum)		98	%
Core weight	$m_{core\ Q}$	1800	lb
Ampere-turns per pole at E_{des}		2484	A-turns
Turns/pole		37	
Pancakes/pole		1	
Conductor width		0.50	in
Conductor height		0.50	in
Cooling hole diameter		0.25	in
Conductor cross section area		0.197	in ²
Current at E_{des}	I_Q	67	A
Resistance	R_Q	52.60	m Ω
Power at E_{des}	P_Q	0.24	kW
Voltage drop at E_{des}	V_Q	3.53	V
Coil weight	$m_{coil\ Q}$	151	lb
Number of water circuits		1	
Water flow rate		0.5	gpm
Water pressure drop		150	psi
Temperature rise		1.8	°C

TABLE A-13
Miscellaneous LER Quadrupole Parameters

Parameter	Value	Units
Interaction straight		
Magnet designation	4Q13	
Number of magnets	4	
Gradient at E_{des}	10.34	T/m
Pole tip field at E_{des}	0.517	T
Interaction straight		
Magnet designation	4Q28	
Number of magnets	4	
Gradient at E_{des}	8.98	T/m
Pole tip field at E_{des}	0.449	T
Interaction straight		
Magnet designation	4Q40	
Number of magnets	6	
Gradient at E_{des}	8.98	T/m
Pole tip field at E_{des}	0.449	T
Interaction straight		
Magnet designation	4Q21	
Number of magnets	12	
Gradient at E_{des}	11.35	T/m
Pole tip field at E_{des}	0.568	T
Interaction straight		
Magnet designation	4Q21	
Number of magnets	4	
Gradient at E_{des}	3.41	T/m
Pole tip field at E_{des}	0.171	T
Wiggler straight		
Magnet designation	4Q21	
Number of magnets	6	
Gradient at E_{des}	4.50	T/m
Pole tip field at E_{des}	0.225	T

TABLE A-14
High Energy Ring Sextupole Parameters

Parameter	Value						Units
Magnet designation	4.5S10						
Principal function	D	F	D1	F1	D2	F2	
Number of main sextupoles	56	64	8	4	8	4	
Gradient at E_{des}	73.04	44.67	104.41	66.57	33.61	22.81	T/m ²
Pole tip field at E_{des}	0.131	0.080	0.188	0.120	0.060	0.041	T
Integrated strength @ E_{des}	18.63	11.39	26.63	16.98	8.57	5.817	T/m
Inscribed radius	2.362	2.362	2.362	2.362	2.362	2.362	in
Core length	8.071	8.071	8.071	8.071	8.071	8.071	in
Magnetic length	10.041	10.041	10.041	10.041	10.041	10.041	in
Core weight	170	170	170	170	170	170	lb
Ampere-turns per pole at E_{des}	2081	1273	2974	1896	957	650	A-turns
Turns/pole	24	24	24	24	24	24	
Pancakes/pole	1	1	1	1	1	1	
Conductor width	0.375	0.375	0.375	0.375	0.375	0.375	in
Conductor height	0.375	0.375	0.375	0.375	0.375	0.375	in
Cooling hole diameter	0.125	0.125	0.125	0.125	0.125	0.125	in
Conductor cross section area	0.127	0.127	0.127	0.127	0.127	0.127	in ²
Current at E_{des}	86.7	53.0	123.9	79.0	39.9	27.1	A
Resistance	44.3	44.3	44.3	44.3	44.3	44.3	mΩ
Power at E_{des}	0.33	0.12	0.68	0.28	0.07	0.03	kW
Voltage drop at E_{des}	3.84	2.35	5.48	3.50	1.77	1.20	V
Coil weight	200	200	200	200	200	200	lb
Number of water circuits	2	2	2	2	2	2	
Water flow rate	0.25	0.25	0.25	0.25	0.25	0.25	gpm
Water pressure drop	150	150	150	150	150	150	psi
Temperature rise	5.1	1.9	10.3	4.2	1.1	0.5	°C

TABLE A-15
Low Energy Ring Sextupole Parameters

Parameter	Symbol	Value	Units
Magnet designation		4.5S10	
Number of main sextupoles	N_S	144	
Gradient at E_{des}		36.07	T/m ²
Pole tip field at E_{des}	B_S	0.0650	T
Integrated strength @ E_{des}		9.20	T/m
Inscribed radius		2.362	in
Core length	$L_{core\ S}$	8.071	in
Magnetic length	L_S	10.041	in
Core weight	$m_{core\ S}$	170	lb
Ampere-turns per pole at E_{des}		1027.6	A-turns
Turns/pole		24	
Pancakes/pole		2	
Conductor width		0.375	in
Conductor height		0.375	in
Cooling hole diameter		0.125	in
Conductor cross section area		0.127	in ²
Current at E_{des}	I_S	42.8	A
Resistance	R_S	62.0	m Ω
Power at E_{des}	P_S	0.11	kW
Voltage drop at E_{des}	V_S	2.65	V
Coil weight	$m_{coil\ S}$	200	lb
Number of water circuits		2	
Water flow rate		0.25	gpm
Water pressure drop		150	psi
Temperature rise		1.8	°C

TABLE A-16
IR Permanent Magnet Parameters

Parameter	Symbol	Value	Units
Magnetic material	$\text{Sm}_2\text{Co}_{17}$ – R26HS		
Remanent field	B_r	1.050	T
Temperature dependence	$\frac{dB_r}{dT}$	-0.03	%/°C
Curie point	T_C	1093	K
Density	ρ	8.4	g/cm ³

B1 H: First separation dipole			
Parameter	Symbol	Value	Units
Field at E_{des}	B_{B1}	0.750	T
Length	L_{B1}	0.160	m
Inner diameter	ID _{B1}	0.048	m
Outer diameter	OD _{B1}	0.106	m
Magnet weight	W_{B1}	21	lb
Trim range (air core coil)		±4	%

IR Permanent magnet quadrupoles					
Parameter	Symbol	Value			Units
Function		Q1 D	Q2 F	Q3 D	
Gradient at E_{des}	G_Q	38.84	30.70	14.04	T/m
Pole tip field at E_{des}	B_Q	1.474	1.351	0.969	T
Length	L_Q	0.642	0.516	0.240	m
Inner diameter	ID _Q	0.076	0.088	0.138	m
Outer diameter	OD _Q	0.302	0.280	0.272	m
Magnet weight	W_Q	798	530	192	lb
Trim range (air core coil)		±4	±4	±4	%

TABLE A-17
IR Septum Quadrupole (Q4)

Parameter	Symbol	High energy beam	Low energy beam	Units
Technology	superconducting			
Number of magnets	N_{Q4}	2		
Distance from IP	d_{Q4}	3.960		m
Beam-beam separation at d_{Q4}		6.46		cm
Magnetic length	L_{Q4}	0.80		m
Gradient	G_{Q4}	15.18		T/m
Bore tube inner radius		4.5	2.5	cm
Beam offset in tube		1.9	0.0	cm

TABLE A-18
Wiggler Parameters (Low energy ring)

Parameter	Symbol	Value	Units
Number of wiggler arrays	N_W	2	
Wiggle plane	Horizontal		
Total length of wigglers	L_W	48	m
Energy loss/turn at E_{des}	$U_{0,W}$	0.95	MeV
Wiggler segments per array	N_S	4	
Segment length	L_S	6	m
Dipole length		0.20	m
Dipole field	B_W	1.63	T
Drift space		0.133	m
Fill factor		60	%
Effective wiggler period		0.666	m

TABLE A-19
Injection Parameters

Parameter	Symbol	High energy ring	Low energy ring	Units
Injection energy	E	9.000	3.109	GeV
Injection energy range		8-10	2.8-4	GeV
Number of populated bunches	n_b	1658	1658	
Number of empty bunches	$n_b(\text{gap})$	88	88	
Bunch spacing	t_b	4.202		ns
Revolution frequency	f_0	136.312	136.312	kHz
Circulating current	I	1.479	2.140	A
Number of particles/bunch	N_b	4.084×10^{10}	5.911×10^{10}	
Horizontal emittance	ϵ_x	48.24	96.48	nm-rad
Horizontal damping time	τ_x	37.2	36.5	ms
Linac repetition rate		60 or 120		s^{-1}
Linac current ($e^\pm$ /bunch/pulse)		$(0.2 - 1.0) \times 10^{10}$		
Linac invariant emittance	$\epsilon_{N \text{ linac}}$	5.0×10^{-5}		m-rad
Ring kicker pulse length	t_{kick}	≤ 1500		ns
Injection top-off time from 80%		3.0		min
Injection time from zero		6.0		min
Magnet standardization time		15		min
Fractional energy tolerance	$\delta E/E$	0.002		
Injection timing tolerance	δt	100		ps
Injection transverse tolerance	δr	10.0		mm

TABLE A-20
Linac Bypass Lines

Parameter	Electron	Positron	Units
Energy range	8–10	2.8–4	GeV
Linac exit sector	7	3	
Bypass line length	2.2	2.6	km
Extraction plane (from vertical)	35	51	deg
e^+ extraction H magnet bend	–	1.25	deg
e^- extraction pulsed magnets	2	–	
Total bend angle	0.55	–	deg
Matching quadrupoles	24	24	
Bypass drift quadrupoles	44	52	
Pole tip field	1.0	0.4	T
Bore	1.085	1.085	in
Spacing	50	50	m
Steering correctors	56	64	
Beam position monitors	56	64	
Readouts	28	32	
Profile monitors	2	2	
Bypass drift ion pumps	23	29	
Pump capacity	120	120	L/s

TABLE A-21
Parameters Relevant to Experiment Design

Parameter	Symbol	High energy ring	Low energy ring	Units
Horizontal spot size at IP	σ_x^*	190	190	μm
Vertical spot size at IP	σ_y^*	7.6	7.6	μm
Natural bunch length	σ_ℓ	1.00	1.00	cm
Beam cross half-angle	θ_x	0.0		mrad
Natural energy spread	σ_E	5.50	2.97	MeV
Natural CM energy spread	$\sigma_{E_{\text{c.m.}}}$	5.992		MeV
Beam pipe inner radius at IP	r^*	2.50		cm
IP to first magnet distance	d_f	0.200		m
Detector solenoid field	B_{sol}	1.00		T
Detector solenoid length	L_{sol}	4.00		m
Beam pipe thickness	$X_{0,\text{pipe}}$	0.0053		X_0
Support tube ID	ID_{tube}	31.19		cm
Support tube OD	OD_{tube}	35.00		cm
Support tube thickness at IP	$X_{0,\text{tube}}$	0.0047		X_0
Support tube length	L_{tube}	4.35		m
Minimum acceptance angle	θ_{min}	0.300	0.300	rad
cos(min. acceptance angle in C.M.)	$\cos \theta_{\text{min}}^*$	0.876	0.984	

APPENDIX B:

FUTURE UPGRADES

B.1 FUTURE LUMINOSITY IMPROVEMENTS

Increasing the luminosity of the B Factory over the lifetime of the machine is a highly desirable goal, and the machine design is such that future upgrades can be accommodated. However, the factors limiting the luminosity are difficult to predict so far ahead, so it is important that the machine be designed with sufficient flexibility to maximize its performance under a variety of operating conditions.

In its simplest form (see Section 4.4) the luminosity can be written as:

$$\mathcal{L} = 2.17 \times 10^{34} (1 + r) \xi \left(\frac{IE}{\beta_y^*} \right)_{+,-} \quad (\text{B-1})$$

where I is the total current (in A), E is the beam energy (in GeV), and β_y^* is the vertical beta function (in cm). In this equation, most of the parameters are limited by other effects and allow little possibility for improving the luminosity. This was discussed in Chapter 3.

The minimum beta value at the interaction point (IP) is limited by chromatic aberrations, and it seems unlikely that a considerable improvement can be obtained over the values reached in other storage rings. The vertical beta values are also bounded by the bunch length, so a value less than about 1 cm seems unlikely. Should it prove possible to reduce the beta functions at the IP, most of the other parameters of the machine would be unaffected. The major impact would be on the background, owing to the increased angular divergence. If it can be shown that the machine can operate well with the decreased beta values, it is probable that a new masking scheme would need to be installed, profiting from the operational experience acquired.

If the beam-beam tune shift is higher than 0.03 in the vertical dimension, a common occurrence in many storage rings, the vertical beam height can be reduced by lowering the coupling with the installed skew quadrupoles. In this case, the luminosity will increase in proportion to $\xi_y^{1/2}$. It is therefore important to design the interaction region for a conservative value of the emittance ratio, to be certain that higher vertical tune shifts can be fully exploited. We have taken a ratio of 25:1 for the nominal design, comfortably below the 40:1 routinely attained in PEP.

If the beam-beam tune shift were higher than 0.03 in both planes (as it always is in PEP), then the emittance will need to be reduced or the number of bunches decreased for the same total current. In this case, the luminosity will increase as $\xi_y^{1/2} \xi_x^{1/2}$. If the same bunch spacing is maintained, and if the beam-beam tune shift were 0.06 in each beam in each plane—a factor of two above nominal, but a value that has been regularly obtained in PEP at higher energies—then the uncoupled horizontal emittance required is 25 nm·rad in the HER and 50 nm·rad in the LER. These values would require increasing the phase

APPENDIX B

advance per cell in the HER, for which there is sufficient flexibility, and reducing the dispersion in the LER wiggler sections, again a straightforward operation. If the bunch spacing were halved, the bunch current would double while the emittance could remain at the nominal value. The bunch current would still remain below the turbulent bunch lengthening threshold.

B.1.1 Increased Current Scenarios

The currents are limited by the amount of RF power available and by the ability to absorb the synchrotron radiation produced. The B Factory has been designed for maximum currents of 3 A in each ring. Although this capability will not be available initially, all distributed components that would be difficult to upgrade without complete replacement will be designed for the eventual maximum current. Those components that can be upgraded easily are designed for the nominal currents.

Components and systems that are already dimensioned for the maximum current include

- The radiation shielding
- The vacuum chambers of both rings
- The LCW cooling water distribution system in the tunnel

Components that would require upgrading or replacing to go to higher currents are discussed below.

B.1.1.1 RF System. The number of RF modules will be increased to a total of 22 in the two rings. This would require an increase in the site electrical power and an extension of one of the RF support buildings. The RF parameters for this case are shown in Table B-1. Because of the modularity of the system, practically all the installed RF components will accept the higher currents without modification. The main exception is that the higher-order-mode losses in the cavities are proportional to the square of the current, so the loads in the damping waveguides may need upgrading.

B.1.1.2 Vacuum Chamber Pumping. Additional pump ports are provided on the chambers so that additional lumped vacuum pumps can be added as necessary. The exact requirements will depend critically on the long-term beam conditioning of the chambers, which is very difficult to predict.

B.1.1.3 Electrical Power Distribution System. Additional feeders must be run to IR-12, where the new RF stations would be installed. The existing duct banks have spare space for these feeders, so no new civil engineering will be required.

Table B-1. Upgraded RF system parameters.

	HER	LER
Frequency [MHz]	476.0	476.0
Harmonic number	3492	3492
Maximum circulating current [A]	3.0	3.0
Number of klystrons	15	7
Power per klystron [MW]	1.0	1.0
Number of cavities	30	14
Shunt impedance per cavity [M Ω]	3.5	3.5
Total shunt impedance [M Ω]	105	49
Field gradient [MeV/m]	2.8	3.0
Synchrotron radiation loss per turn [MeV]	3.58	1.24
HOM energy loss per turn [MeV]	0.79	0.64
Peak cavity voltage [MV]	18.5	9.5
Total RF power [MW]	15.0	7.0
Fundamental cavity dissipation [MW]	1.6	0.9
Synchrotron radiation loss [MW]	10.8	3.7
Power loss to parasitic modes [MW]	2.4	1.9

B.1.1.4 Cooling Capacity. The capacity of the cooling tower would need to be increased by the addition of another cell to the present tower. The existing headers for the cooling tower water are capable of carrying the extra water, but an additional pump would be needed. At IR-12, an additional heat exchanger would be needed, but the other required changes are relatively minor, as the existing low-conductivity water headers can take the increased flow.

B.1.1.5 Collimators and Scrapers. The masking scheme will probably require modification in the light of operational experience (this has been the case with practically every detector ever installed on a collider). Therefore, the masks and collimators are only dimensioned for the nominal current and would be replaced or upgraded as necessary.

B.1.1.6 Feedback Systems. It is likely that the feedback system will need upgrading. The exact requirements will only be determined as the performance limitations of the system become understood. Since the present design is modular, there would be no problem in upgrading the power. If the number of bunches were to be increased, then the rise time of the system might be insufficient and the front-end might need improvements. There is every reason to believe that the faster low-level electronics required for this purpose would be available at the appropriate time. Indeed, similar systems for a 500-MHz bunch repetition rate are now being designed for the ALS.

B.1.2 Exploiting Increased Current

There are three different scenarios for exploiting the increased current, and flexibility is provided for all three. The easiest of the three follows if the tune shift can be increased above the nominal value adopted. In this case, no other changes would be required. The second alternative is to increase the emittance. The vacuum chambers have been dimensioned to accept twice the nominal emittance (that is, to accommodate 100 nm-rad in the HER and 200 nm-rad in the LER), and the techniques for increasing the emittance have already been discussed in Section 4.1. The interaction region masking would need modifying, as discussed above. The final alternative is to increase the number of bunches. This would require an upgrade of the feedback system and, more importantly, would require modifying the interaction region layout. The most likely configuration would be the crab-crossing scheme, which is discussed in Section B.2 of this appendix.

B.1.3 Summary

The design of the B Factory presented in this document incorporates considerable flexibility, which would allow future upgrades of luminosity. Where necessary, provision has been made for the increase in current that will become possible when resources are available for upgrading the RF system and associated services.

B.2 CRAB CROSSING

The present B Factory lattice (see Section 4.1), with head-on collisions, is designed to avoid the excitation of synchrotron resonances, which result when beams collide with a nonzero crossing angle [Piwinski, 1977]. However, the use of a head-on collision scheme requires us to deal with the following issues:

- The two beams must go through common magnetic elements near the interaction region (IR); designing masks to shield the detector from the synchrotron radiation produced by the beams passing through these magnetic elements is difficult.
- The longitudinal spacing of the bunches must be chosen such that the transverse separation of the beams away from the interaction point (IP) is sufficient to reduce the long-range beam-beam effect between bunches in the opposing beams; this limits the total number of beam bunches in each ring.

For the design luminosity of $3 \times 10^{33} \text{ cm}^{-2} \text{ s}^{-1}$, satisfactory solutions have been found for these problems. However, to upgrade the luminosity to significantly higher values, solutions of this type become ever more difficult to obtain.

A configuration that utilizes a crossing angle would allow the longitudinal spacing between bunches to be reduced and would reduce the problem of lost particles from elsewhere in the ring being swept into the detector beam pipe by the separation dipoles (required for head-on collisions) near the IP. Either or both of these advantages may be necessary for a luminosity upgrade. Fortunately, a new idea, the so-called “crab crossing” scheme, allows a nonzero crossing angle at the collision point while avoiding the excitation of synchrotron resonances. In this scheme, shown schematically in Fig. B-1, the bunches still collide head-on, but in a transversely moving reference frame.

The bunches are tilted before the collision by an angle equal to half of the total crossing angle and then tilted back to their original direction after collision. Figure B-2 shows a layout of an IR with a crab-crossing configuration. Because we anticipate modifying the head-on crossing to a crab-crossing layout as a machine upgrade, great

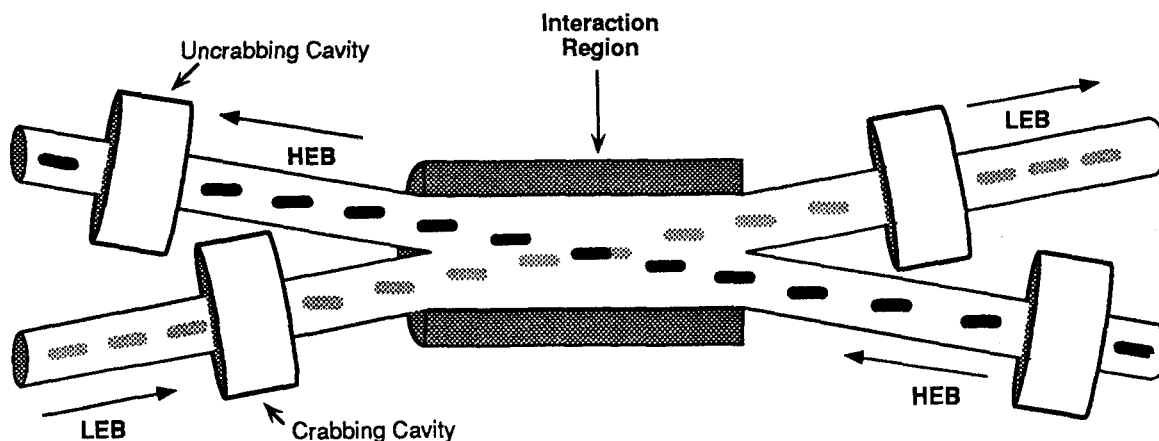


Fig. B-1. Schematic of crab-crossing concept.

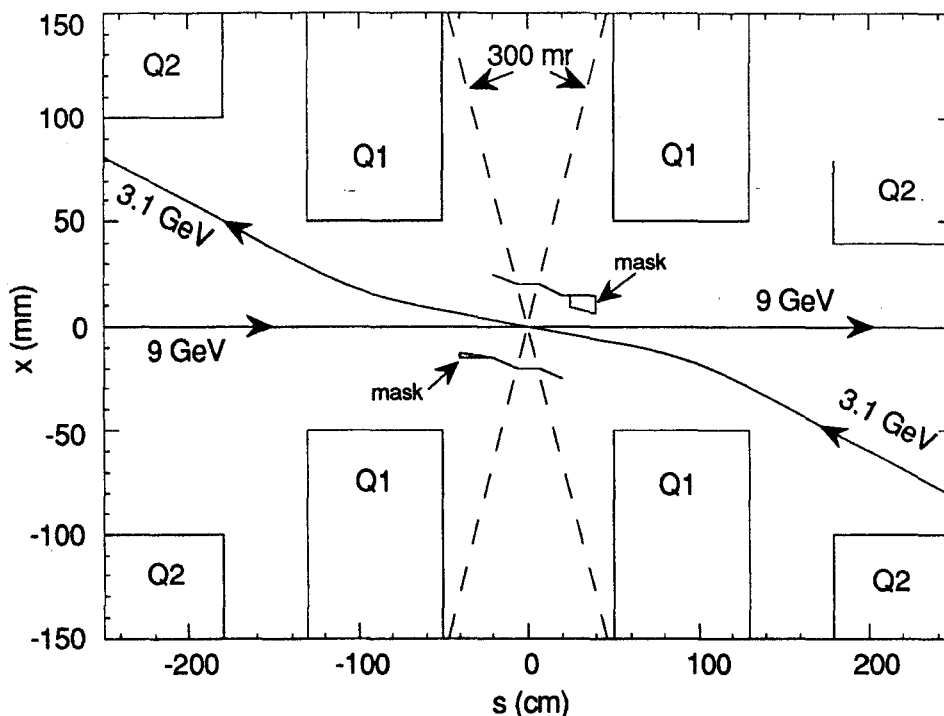


Fig. B-2. Example of a crab-crossing geometry. The total synchrotron power for this geometry, 7.1 kW, is much lower than for the head-on crossing design described in Chapter 4.

care has been taken in all the design choices to ensure the greatest possible compatibility between the two configurations. For example, one of the reasons for the selection of the S-bend geometry of the head-on crossing was that it can be easily converted into a crab-crossing layout. A comparison of the synchrotron radiation power for the head-on and crab-crossing collision scenarios is given in Table B-2. The total synchrotron power is more than an order of magnitude lower in the case of the crab crossing, as might be expected from the discussion above. This is the prime reason for the interest in pursuing this direction.

Crab crossing with transversely deflecting cavities was first proposed as a way to increase the luminosity in linear colliders [Palmer, 1988] and was subsequently proposed for storage rings [Oide and Yokoya, 1989] to suppress synchrotron betatron resonances. For the storage ring case, this scheme requires transversely deflecting cavities at locations of $\pm 90^\circ$ in betatron phase advance away from the IP. The crab-crossing scheme has not yet been tested, and it is difficult to estimate how successful it will ultimately turn out to be. In particular, the tolerances on the various elements used for crab crossing need to be studied both theoretically and experimentally, and the effect on the feedback system to combat coupled-bunch instabilities (due to the additional impedance of the crab cavities) must be assessed. In this section, we report on computer simulations that have been used to address some of the tolerance issues.

There is a second method to produce a tilt of the bunches at the IP that uses *longitudinally* accelerating cavities in a region with a large dispersion [Jackson, 1990]. In

Table B-2. Comparison of synchrotron radiation power near the IP for a head-on and a nonzero-crossing-angle geometry.

Magnet	Fan power from head-on design (kW)	Fan power from crossing angle design (kW)
<i>LEB:</i>		
Upstream Q3	0.84	0.0
Upstream Q1	0.83	3.53
Upstream B1	2.39	—
Downstream B1	2.39	—
Downstream Q1	0.96	3.53
Downstream Q3	<u>0.91</u>	<u>0.0</u>
Subtotal	8.3	7.1
<i>HEB:</i>		
Upstream Q2	28.3	0.0
Upstream Q1	2.3	0.0
Upstream B1	13.8	—
Downstream B1	13.8	—
Downstream Q1	1.1	0.0
Downstream Q2	<u>26.1</u>	<u>0.0</u>
Subtotal	85.4	0.0
Total	93.7	7.1

this case, the phase of the dispersion must satisfy the condition that the derivative of $D_x/\sqrt{\beta_x}$ vanish at a distance of 180° from the IP [Piwinski, 1991]. The position of the cavity is then arbitrary within the straight section, and one can use several cavities distributed over a larger region of betatron phase.

A disadvantage of the longitudinal crab-crossing scheme is that the required longitudinal gradient is larger by an order of magnitude than that needed for the transverse case. The longitudinal and transverse gradients differ by a factor of $\sqrt{\beta_{xt}\beta_{xl}}/D_{xl}$, where D_{xl} is the dispersion at a position where the above-mentioned derivative vanishes, and t and l refer to the transverse and longitudinal cases, respectively. There would be potential advantages to this scheme if the acceleration cavities could be used for the compensation. On the other hand, the disadvantage of a coupling between synchrotron and betatron oscillations is then still present in the longitudinal scheme, due to the large dispersion at the accelerating cavities (which cannot be compensated completely and which can excite all satellite resonances of the integer). Insofar as a solution to this problem is not clear, we focus here on the more commonly considered transversely deflecting cavities.

B.2.1 Simulation Studies

In the double-ring DORIS-I, it was found that a crossing angle excites synchrobetatron resonances that are characterized by

$$kv_\beta + mv_s = n \quad (\text{B-2})$$

where k , m , and n are integers, and v_β and v_s are the betatron tune (in the plane of the crossing angle) and the synchrotron tune, respectively. These resonances are spread over the whole tune diagram and cause beam loss [Piwinski, 1977]. With a crab-crossing scheme, the synchrobetatron coupling vanishes completely. The horizontal kick δx_c given to a particle in a crab cavity must be proportional to its longitudinal position s . The kick causes a displacement at the IP given by

$$\delta x^* = \delta x_c' \sqrt{\beta_{xc} \beta_x^*} \quad (\text{B-3})$$

where β_{xc} and β_x^* are the betatron functions at the crab cavity and at the IP, respectively. The tilt angle $\delta x^*/s$ must be equal to half the crossing angle ϕ in order to get parallel bunches at the IP. The amplitude of the required sinusoidally varying transverse kick is then given by

$$A_{\delta x'} = \frac{\phi \lambda}{2\pi \sqrt{\beta_{xc} \beta_x^*}} \quad (\text{B-4})$$

where λ is the wavelength of the transverse crab-cavity voltage waveform; this should not be smaller than the wavelength of the accelerating voltage in order to avoid deviations from a linear tilt [Piwinski, 1990]. With $\beta_{xc} = 15$ m (15 m), $\beta_x^* = 75$ cm (37.5 cm), and $\lambda = 63$ cm, one obtains a maximum transverse momentum change of 3.6 MeV (1.8 MeV) per cavity for the HER (LER).

Because crab crossing has not yet been verified in an existing storage ring it was initially studied by means of computer simulations for round beams [Piwinski, 1990]. In particular, errors in the strength of the crab cavities and in the betatron phase advance between the cavities and the IP were simulated in order to determine the tolerances for these parameters. Numerical estimates were also made by Kheifets et al. [1989]. For the upgraded B Factory, we have carried out simulations for flat beams with an aspect ratio of 25:1. The coordinate changes due to the crab cavity were calculated from

$$\delta x' = \frac{x \phi \Delta V}{\sqrt{\beta_{xc} \beta_x^*}} \quad (\text{B-5})$$

$$\frac{\delta E}{E} = \frac{x \phi \Delta V}{\sqrt{\beta_{xc} \beta_x^*}} \quad (\text{B-6})$$

where $\Delta V = V/V_0 \neq 1$ describes the deviation from the correct value. The changes of the betatron angles, and of the energy, due to the beam-beam interaction are given by

$$\delta x' = 4\pi \xi_x f_x(x + s\phi, y) \quad (\text{B-7})$$

$$\delta y' = 4\pi \xi_y f_y(x + s\phi, y) \quad (\text{B-8})$$

$$\delta E = \phi E \delta x' \quad (\text{B-9})$$

where ξ_x and ξ_y are the beam-beam space-charge parameters and the functions f_x and f_y are integrals that cannot be expressed by elementary functions but are solved numerically, tabulated, and interpolated linearly for each passage of a particle. As in the rest of the ring, the coordinates between the crab cavities and the IP are transformed linearly. Quantum fluctuations and damping are neglected, because the rise times on a resonance are typically shorter than the damping time. Also, the betatron phase variation seen by a particle due to its longitudinal motion is neglected; that is, it is assumed that the ratio σ_z/β_x^* is small (it is 0.013 and 0.027 for the HER and LER, respectively). This is the worst case, because, for a greater bunch length, the space-charge forces are distributed over a larger betatron phase and the excitation of higher-order resonances will be partially suppressed [Sagan et al., 1990]. Most of the simulations were done for 3000 revolutions and with 98 particles. The synchrotron tune ν_s is 0.06, and ν_y (which has no influence on the horizontal synchrotron resonances) is 0.23. The total crossing angle is $2\phi = 15$ mrad, and the normalized crossing angle ϕ (σ_z/σ_x) is 0.41.

As measurements with DORIS-I and our simulations have shown, the incoherent resonances described by Eq. B-2 influence mainly the beam lifetime and not the beam size and the luminosity. For this reason, many of the present simulations were done for large amplitudes, $6\sigma_x$ and $6\sigma_z$. Particles at these amplitudes must remain stable in order to obtain sufficient lifetime. Figure B-3 shows the increase of the horizontal amplitude as a function of the horizontal betatron tune. For perfect compensation (lower curve) the synchrotron resonances vanish completely. The remaining resonances are the quarter-integer resonance and some others that are excited by the nonlinear beam-beam forces.

Figure B-3 also shows that there are some tune regions that give a relatively small increase of amplitude, for example, that between 0.03 and 0.05. Particles in these tune regions will not be lost if the aperture of the ring is larger than $8\sigma_x$.

Figure B-4 shows, in contrast to Fig. B-3, that the beam size, that is, the rms value of 1200 particles having an initially Gaussian distribution, does not blow up at many resonances. Only at the first satellite of the integer and the two lowest satellites of the

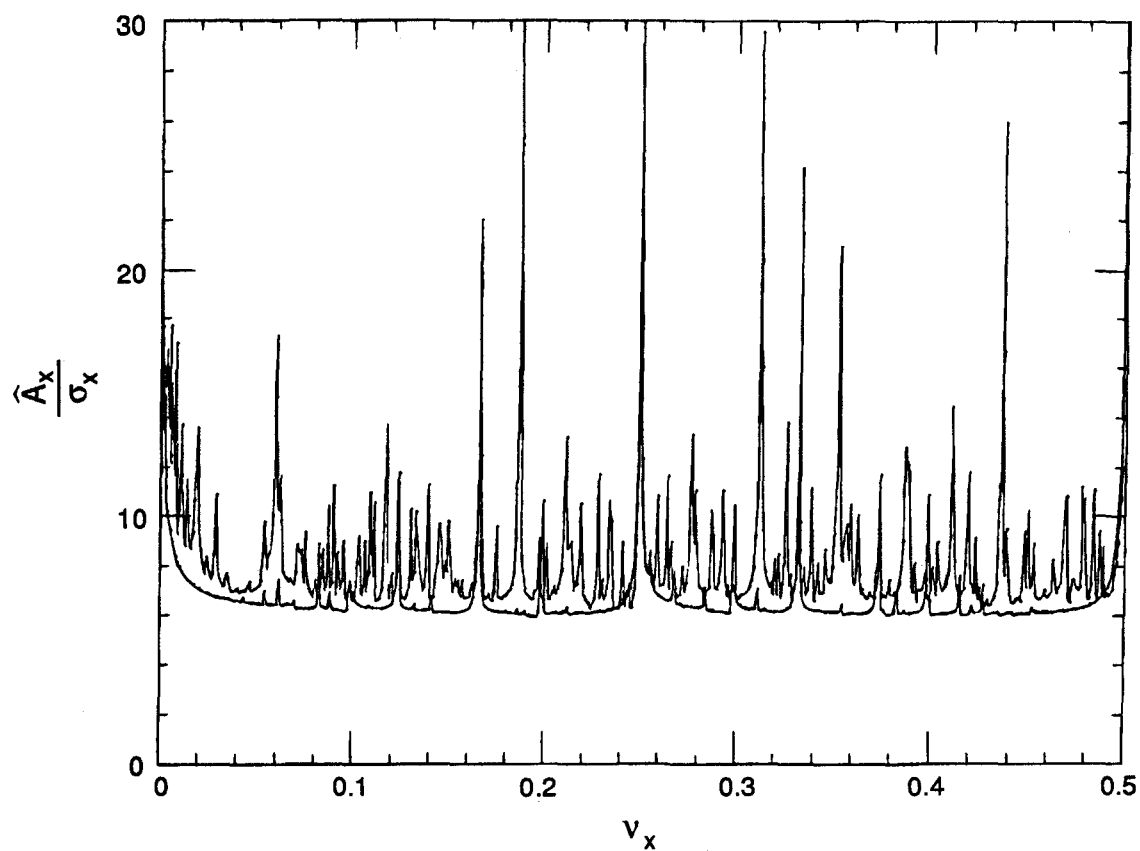


Fig. B-3. Increase of horizontal amplitude as a function of the horizontal betatron tune.

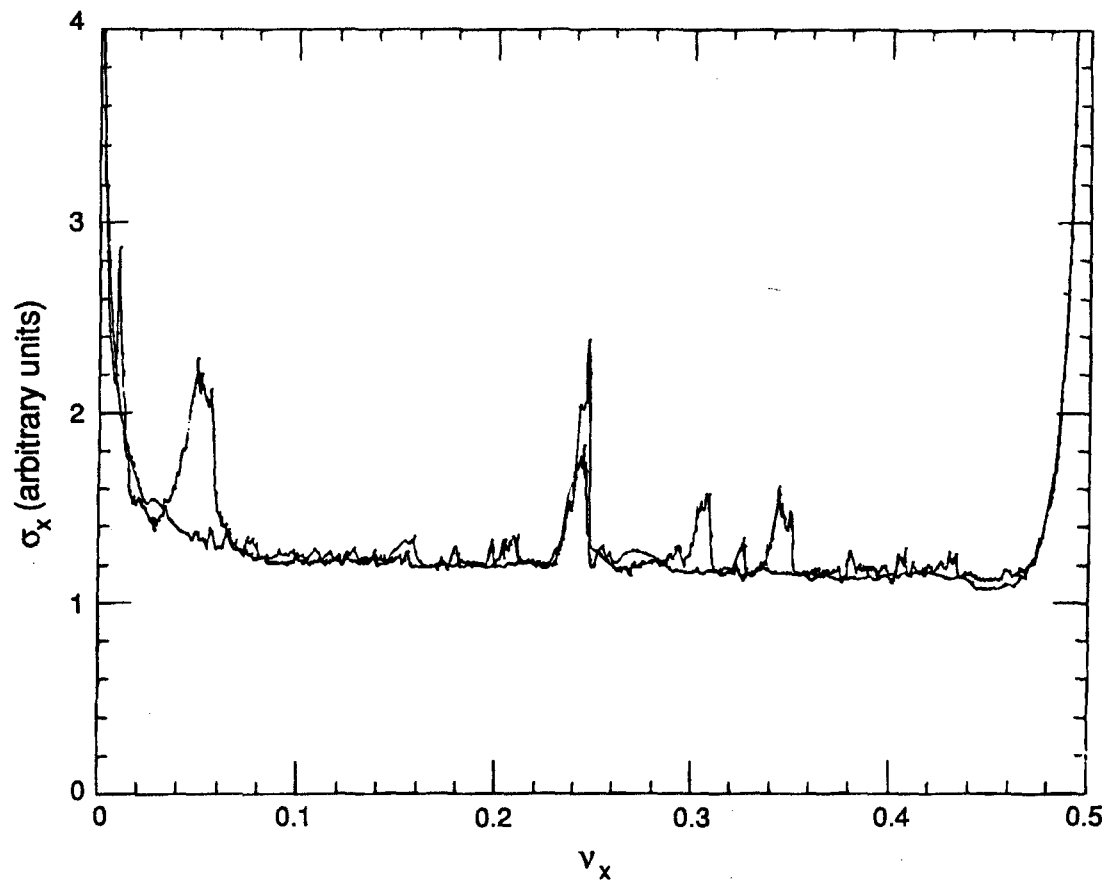


Fig. B-4. The rms value of 120 particles (having an initially Gaussian distribution) vs horizontal tune.

third-order resonance, $\nu_x = (1 \pm \nu_s)/3$ does the beam size increase noticeably. The reason for this behavior is that there are always particles with increasing amplitude and those with decreasing amplitude, depending on the phase between betatron and synchrotron oscillations. For small excitations, the increase and the decrease tend to compensate each other.

Figure B-5 shows the dependence of the maximum amplitude on the voltage error $\Delta V = V/V_0$, at the resonance $3\nu_x - \nu_s = 1$. It was assumed in this calculation that both cavities have the same error, in which case there is a residual angle at the IP whose value is equal to the crossing angle times the relative voltage error. If only one cavity has an error, the residual angle is smaller [Piwinski, 1990], but in this case, a tilt (on the order of the crossing angle times the relative error) will oscillate around the ring. The initial amplitudes for the two curves in Fig. B-5 are $3\sigma_x$ and $6\sigma_x$, respectively. Not surprisingly, the simulation shows that the dependence on the voltage error is stronger for the larger amplitude.

The dependence on phase errors between cavity and IP is shown in Fig. B-6. Here again, equal errors on both sides of the IP was assumed. If the two cavities have position errors, the beams will not only cross at a small angle, but a small tilt angle will also oscillate around the ring. In principle, the error of the tilt at the IP can be compensated by varying the strength of the two cavities; this, however, increases the oscillation of the tilt

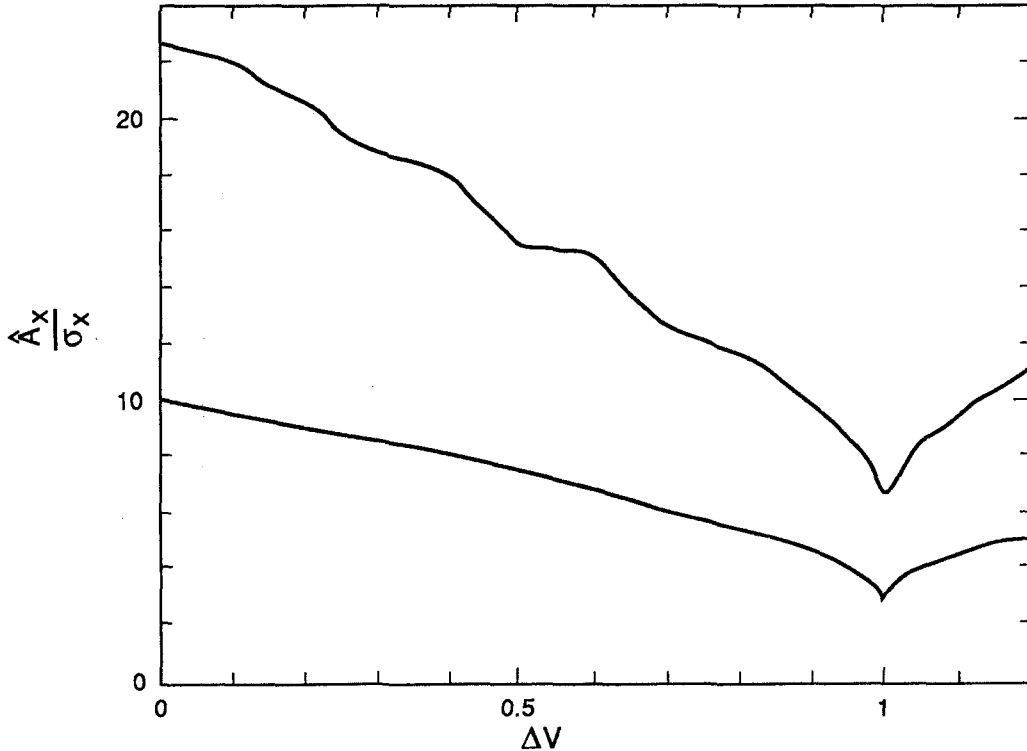


Fig. B-5. Dependence of the maximum amplitude on the voltage error $\Delta V = V/V_0$, at the resonance $3\nu_x - \nu_s = 1$.

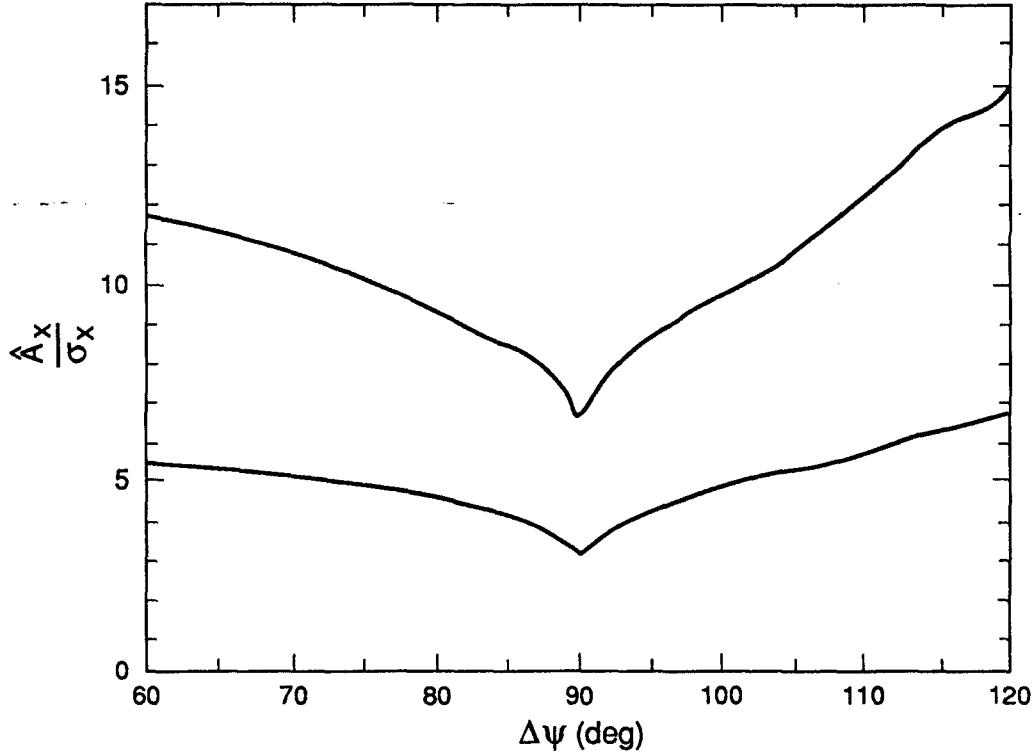


Fig. B-6. Dependence of maximum amplitude on phase errors between crab cavity and IP.

around the ring. Table B-3 shows the tolerable errors of the cavity strength and the phase advance for two synchrotron resonances.

Close to the second resonance, $\nu_x = (1 + 2\nu_s)/6 = 0.1866$, there are a number of other resonances, $\nu_x = (1 - \nu_s)/5 = 0.1880$, $\nu_x = (1 + 5\nu_s)/7 = 0.1857$, $\nu_x = 1/8 + \nu_s = 0.1850$, as well as some higher-order resonances. At those frequencies where several resonances are very close to each other, it is difficult to compensate them; these few frequencies must be avoided.

Phase errors of the crab voltage produce orbit displacements of the whole bunch around the ring with an amplitude

$$\Delta x = (\lambda/2\pi) \sqrt{\frac{\beta_{xc}\beta_x^*}{2 \sin \pi \nu_x}} (dx'/ds) \Delta \psi \quad (\text{B-10})$$

At the IP, the displacement is given by $(\lambda/4\pi)\phi \Delta \psi$ if the voltage in only one cavity has a phase error $\Delta \psi$. To keep the displacement smaller than $\sigma_x^*/10$, $\Delta \psi$ must be smaller than 2.8° .

Table B-3. Increase of amplitudes for different errors of the cavity voltage $\Delta V = V/V_0$ and the phase advance $\Delta\psi$ on two resonances: (a) $3\nu_x - \nu_s = 1$, and (b) $6\nu_x - 2\nu_s = 1$.

$\Delta\hat{x}$	(a) 10%	(b)	(a) 50%	(b)	(a) 100%	(b)
ΔV [%]	2.5	0.5	11	4	35	10
$\Delta\psi$ [deg]	1.5	0.4	2.5	1.5	25	2.5

Dispersion in a crab cavity can give an additional synchrobetatron coupling if it is produced by an error between the crab cavities. If the dispersion is produced outside the crab cavity region, the kicks in the two cavities will compensate each other (because the dispersion oscillates with the betatron phase advance). If a bend between the cavities produces a dispersion of a few centimeters, its effect must be compared with that from the dispersion in the main accelerating cavities (where a spurious dispersion of a few centimeters usually cannot be avoided). Because the synchrobetatron resonance excitation is approximately proportional to the dispersion and to the voltage gradient [Piwinski and Wrulich, 1976], the excitation in the accelerating cavities will be larger than that in the crab cavities by an order of magnitude. In either case, the first satellite of the integer must be avoided.

B.2.2 Summary

The excitation of synchrobetatron resonances causes mainly a reduction in beam lifetime, but it does not generally give rise to beam size blowup or to a loss in luminosity. Three parameters are important: The lifetime is determined by the normalized crossing angle $\phi(\sigma_z/\sigma_x)$, by the beam-beam space charge parameter ξ_x , and by the physical aperture or the dynamical acceptance of the ring. If the first two parameters are not too large ($\phi\sigma_z/\sigma_x \leq 0.5$, $\xi_x \leq 0.03$), and if the acceptance is large enough ($A_x > 15\sigma_x$), it should be possible to avoid beam loss from almost all synchrobetatron resonances with reasonable tolerances for the crab cavities. For some very limited regions in the tune diagram, it may even be possible to operate the machine with a nonzero crossing angle *without* crab cavities. However, more studies must be done for this last possibility to ensure its viability.