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The PEP-II Project: Design Status and R&D Results†

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Abstract

The PEP-II project, a joint proposal of SLAC, LBL, and LLNL, will involve an upgrade of the PEP storage ring at SLAC to serve as an asymmetric *B* factory. The upgrade will involve replacing the vacuum and RF systems of PEP, which will serve as the high-energy ring (containing 9 GeV electrons), along with the addition of a new low-energy ring (containing 3.1 GeV positrons) mounted atop the high-energy ring. The present design status of the project and a summary of recent R&D results are presented here. If approved, the PEP-II project is ready to begin construction in October 1993.

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1 Introduction

The original Conceptual Design Report (CDR) [1] for PEP-II was completed in February, 1991. The project was designed to deliver a peak luminosity of 3×10^{33} cm^{-2} s^{-1} and to operate with an energy asymmetry of 9/3.1. As part of the preparation for the recent Joint DOE/NSF *B* Factory Review Committee (the Kowalski Committee), an updated version [2] of the CDR was prepared. There is also a substantial R&D program under way at the three collaborating laboratories, focused primarily on the key areas of vacuum system , RF system , and feedback system design. Here I summarize the main PEP-II design features and indicate the progress of the R&D program.

Before describing the design of the collider it is worthwhile to put the parameter choices in context by indicating the technical challenges associated with the design of an asymmetric *B* factory. For an asymmetric collider with equal beam sizes at the interaction point (IP) and equal beam-beam tune shifts for both beams in both transverse planes, we can write the luminosity as

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

where I is the total beam current in one ring, β_y^* is the vertical beta function at the IP, $r = \sigma_y^*/\sigma_x^*$ is the beam aspect ratio at the IP, E is the beam energy in GeV, and ξ is the beam-beam parameter. Although it appears that there are five free parameters in Eq. (1), in reality two of them are constrained. The beam aspect ratio, r, is forced to be near zero by detector background considerations—producing a round beam ($r \approx 1$) requires extremely strong focusing near the IP and leads to unreasonable amounts of synchrotron radiation power very near the detector. The beam energy, E, is also constrained due to the fixed $E_{c.m.}$ requirement corresponding to running at the Υ(4S) resonance. Thus, achieving high luminosity requires a high beam-beam tune shift, a low beta function at the IP, and a high beam current.

2 Project Overview

The PEP-II project includes two storage rings, a high-energy ring (HER) containing 9 GeV electrons and a low-energy ring (LER) containing 3.1 GeV positrons. The HER is basically the original PEP ring; it reuses all the PEP magnets but makes use of new RF and vacuum systems. The newly constructed LER is located atop the HER in the PEP tunnel. The main parameters for the two rings are summarized in Table I.

PEP-II uses standard single-bunch parameters (bunch current, emittance, rms bunch length, and beam-beam tune shift) along with a vertical beta function of a few centimeters at the IP. The main increase in luminosity, then, comes from greatly increasing the number of bunches compared with today's colliders. The large increase in beam current implied by this approach means that the vacuum system and RF system must be considerably improved compared with present practice, and that feedback systems to combat coupled-bunch instabilities are needed.

The injection system for PEP-II is based upon the SLC linac, which presently produces ~3×10^{10} electrons or positrons per pulse at 120 pps, compared with the injection requirements for PEP-II of $0.2–1 \times 10^{10}$ electrons or positrons per pulse. The time to top off the operating collider is about 3 minutes, and the time to fill both rings from zero current is about 6 minutes. The PEP-II project is fortunate in this regard—no other injector in the world comes close to being as powerful as the SLC linac, which provides a *demonstrated* capability to fill the rings at a suitable injection rate.

Table I. Main PEP-II Collider Parameters.

	LER	HER
Energy, E [GeV]	3.1	9
Circumference, C [m]	2199.32	2199.32
$\varepsilon_y/\varepsilon_x$ [nm·rad]	2.6/64	1.9/48
β_y^*/β_x^* [cm]	1.5/37.5	2.0/50.0
$\xi_{0x,0y}$	0.03	0.03
f_{RF} [MHz]	476	476
V_{RF} [MV]	5.9	18.5
Bunch length, σ_ℓ [cm]	1	1
Number of bunches, k_B	1658[a]	1658[a]
Bunch separation, s_B	1.26	1.26
Damping time, τ_E/τ_x [ms]	19.8/40.3	18.4/37.2
Total current, I [A]	2.14	0.99
U_0 [MeV/turn]	1.14	3.58
Luminosity, $\mathcal{L}$ [cm^{-2}s^{-1}]	3×10^{33}	

[a]allows for gap of ≈5% for ion clearing

3 Design Details

3.1 Interaction Region Design

The PEP-II interaction region, shown in plan view in Fig. 1, is based upon an "S-bend" geometry; the B1 dipoles that provide the magnetic separation have opposite polarity and are tapered to maximize the solid angle available to the detector. Combined with the bending of the low-energy beam in the Q1 magnets, the horizontal beam separation at the first parasitic collision points (0.63 m from the IP) is $11.8\sigma_x$, more than sufficient to avoid any deleterious effects from the parasitic collisions [2]. Only a single common quadrupole (Q1) is needed; the second IR quadrupole, Q2, is a conventional septum quadrupole that acts only on the low-energy beam.

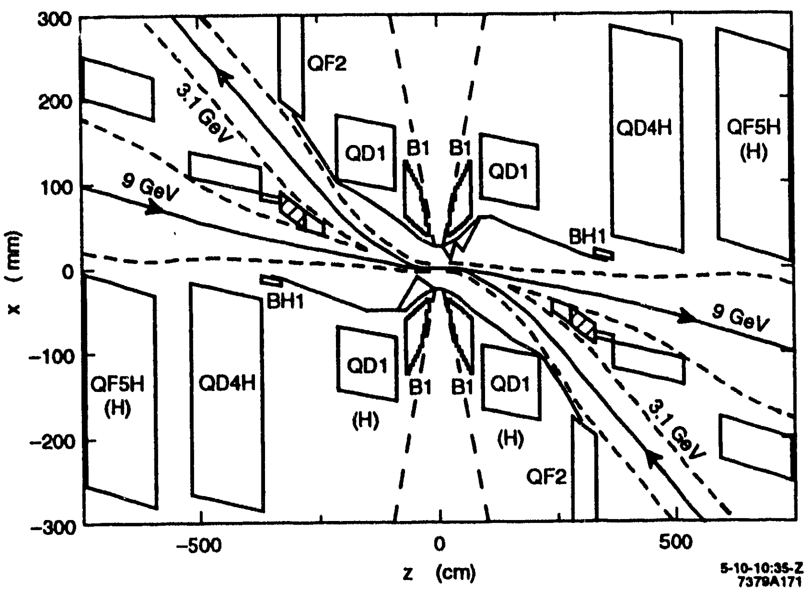

Fig. 1. Anamorphic plan view of PEP-II IR.

As part of the IR design, backgrounds have been studied extensively. We looked at all sources of backgrounds, including synchrotron radiation from the bending magnets and quadrupoles, lost particles from beam-gas interactions, and lost particles during injection. It has been verified that the design shown in Fig. 1 gives adequately low backgrounds. To avoid beam losses near the detector, the storage rings are designed to have a "graded aperture" such that the acceptance in the arcs is restricted to 10σ, that in the IR straight sections is 12.5σ, and that close to the IP is 15σ. Thus, the detector region has the largest acceptance in the ring.

3.2 Lattice Design

The HER lattice is very similar to the successful PEP lattice. It utilizes 96 FODO cells in the six arcs and has six straight sections, each about 120 m long, that provide room for all needed equipment and functions (diagnostics, tune control, injection,...). The lattice is modular, such that tune adjustment, emittance control, and injection are all independent. Based on considerations of the parasitic collisions, we have chosen to inject vertically.

The LER lattice has a similar layout, but its dipoles are quite short to enhance synchrotron radiation damping. As illustrated in Fig. 2, the dipole, quadrupole, steering magnet, and sextupole are mounted on a common support raft that is prealigned prior to installation in the tunnel. To improve the dynamic aperture, a mirror-symmetric layout is used in alternate arcs, that is, D-Q-S in one arc and S-Q-D in the next. To control the emittance and increase the radiation damping rate in the LER, two straight sections contain wigglers. As for the HER, we use vertical injection.

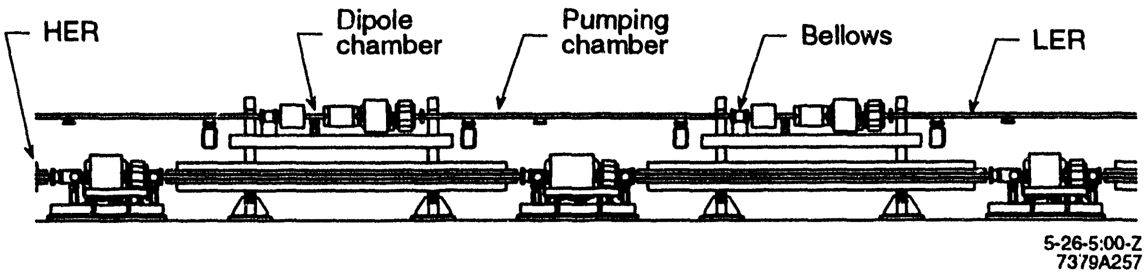

Fig. 2. Side view of HER and LER FODO cells showing magnet layout.

A novel feature of the LER design is the use of a local chromaticity correction scheme to compensate the aberrations generated by the strong IR focusing. The technique requires two pairs of horizontally focusing and two pairs of vertically focusing sextupoles. Tracking studies have been carried out for both rings, including the effects of all magnetic field errors and misalignments. Both rings have more than sufficient dynamic aperture, even for off-energy particles.

3.3 Vacuum System Design

The vacuum system for an asymmetric *B* factory is challenging—it must give a pressure of 10 nTorr in the face of copious synchrotron-radiation-induced gas desorption and it must safely dissipate several megawatts of synchrotron radiation power. For the PEP-II HER, with its large bending radius in the dipoles (ρ = 165 m), this is not hard. At the nominal operating point, the linear power flux is only 3.4 kW/m and the required pumping speed is only 125 L/s/m—a value that can be easily provided with standard ion pumps. An extruded copper chamber of simple cross section is used for the HER. A screen is used to separate the distributed ion pumps (DIPs) from the beam channel.

The vacuum system requirements in the PEP-II LER are similar to those of the HER. However, the short LER dipole means that the synchrotron radiation fan strikes the chamber wall well downstream. For this reason, DIPs are not a viable approach. The solution adopted is to use a large cross section chamber (to give good conductance) and to use lumped ion pumps (LIPs) downstream of the magnets. Special high-power photon dumps, with a differentially pumped chamber, will be used in the wiggler sections.

3.4 RF System Design

The RF system for a high-luminosity collider always presents a challenge, and the requirement for "factory-like" reliability is an additional burden. There are two basic issues that must be addressed for any *B* factory design: (i) handling the high beam current, i.e., heavy beam loading; and (ii) minimizing the cavity higher-order-mode (HOM) impedances that otherwise drive very strong coupled-bunch instabilities.

We have adopted a room-temperature RF (RTRF) system. This technology choice is well matched to the PEP-II rings, which require relatively low voltages (18.5 MV and 5.9 MV for the HER and LER, respectively) to provide 1 cm bunches. RTRF technology is well understood, and is in use at most of today's storage rings. Relatively little R&D effort is needed to design such a system, and standard engineering tools can be applied. Compared with the alternative superconducting RF technology, we believe that RTRF will be more robust because it is less sensitive to its environment (dust, synchrotron radiation, other heat loads) and to mechanical vibrations.

For the PEP-II RTRF system there are two main issues, both associated with the requirement to minimize the HOM impedance. To decrease the HOM impedance, we must reduce the number of RF cavities and also reduce the HOM impedance per cavity. The first approach leads to high voltages in each RF cavity, and thus to a high power load into the cavity wall. For the PEP-II parameters, a cavity voltage of 0.9 MV gives $P_{wall} \approx 120$ kW. For comparison, the RF cavities at the Advanced Light Source (ALS) at LBL have been tested at 70 kW, and those of the Advanced Photon Source at ANL have been tested at 100 kW. The HOM impedance of individual PEP-II cavities must be reduced below 4 kΩ. This is accomplished with three damping waveguides having aperture dimensions that are beyond cut-off for the fundamental (accelerating) mode of the cavity. Each waveguide is terminated with a broadband damping load to absorb the HOM power. The damping technique has been examined via calculations and verified by bench tests of a low-power cavity. To minimize phase jitter during injection, thereby reducing the demands on the feedback system, we have chosen a frequency of 476 MHz. This permits phase-locking of the storage rings to the SLAC linac frequency (2856 MHz).

3.5 Feedback System Design

To combat longitudinal coupled-bunch instabilities that remain even after the cavity modes are damped, and to handle transverse coupled-bunch instabilities driven by the resistive wall of the vacuum chamber, the PEP-II design includes bunch-by-bunch feedback systems for both longitudinal and transverse motion. For the longitudinal case, we employ a very flexible approach [2, 3] based on commercially available digital signal processors (DSPs). The transverse system is simpler to implement, and uses many components common to the longitudinal system. The advantage of the bunch-by-bunch approach is that it is capable of dealing with beam motion of any sort, including damping injection transients. Moreover, the flexibility of the digital architecture permits the design to be usable on many storage rings. The bunch-by-bunch feedback systems for the ALS will be based on the PEP-II designs, as will the system for DAΦNE, now under construction at Frascati.

4 R&D Progress and Plans

In recent years considerable emphasis has been placed on vacuum system R&D. Photodesorption studies have been carried out at BNL [4], initially looking at copper bars to choose acceptable materials and more recently looking at copper chambers to investigate fabrication and cleaning issues. We have also carried out studies of the required fabrication and assembly techniques. This work has culminated in the delivery to SLAC of full-length copper extrusions. Tests of electron-beam welding, attaching the screen for the DIP chamber, and bending the completed chambers to the required 165 m radius have all been completed. We have also carried out a series of DIP tests, under actual PEP-II magnetic field conditions, to optimize the pumping speed of the modules and to verify their performance; design values for the vacuum system were confirmed.

Recent R&D efforts on the RF system focus on the design of a high-power test cavity (similar in shape to the low-power cavity) that will be used to experimentally determine the thermal loads and stresses at power levels up to 150 kW and to test windows up to 500 kW or beyond. A test stand for these purposes, consisting of a 500-kW PEP klystron modified from 353 to 476 MHz and a load, is available. Mechanical design of the cavity, being done in collaboration with Chalk River Laboratories [5], is well under way, and a prototype will be available for testing soon.

The principle of operation of the longitudinal feedback system has been demonstrated in beam tests at both the SPEAR ring and the ALS. As shown in Fig. 3, the system performs as expected under "combat" conditions in the control room of a running accelerator. This gives us full confidence that it will function properly in PEP-II. Design of a full system prototype is now under way, and we plan to test the system at the ALS in late 1993. This is a very stringent performance test for the PEP-II prototype system, as the bandwidth required for the ALS is twice that needed for PEP-II.

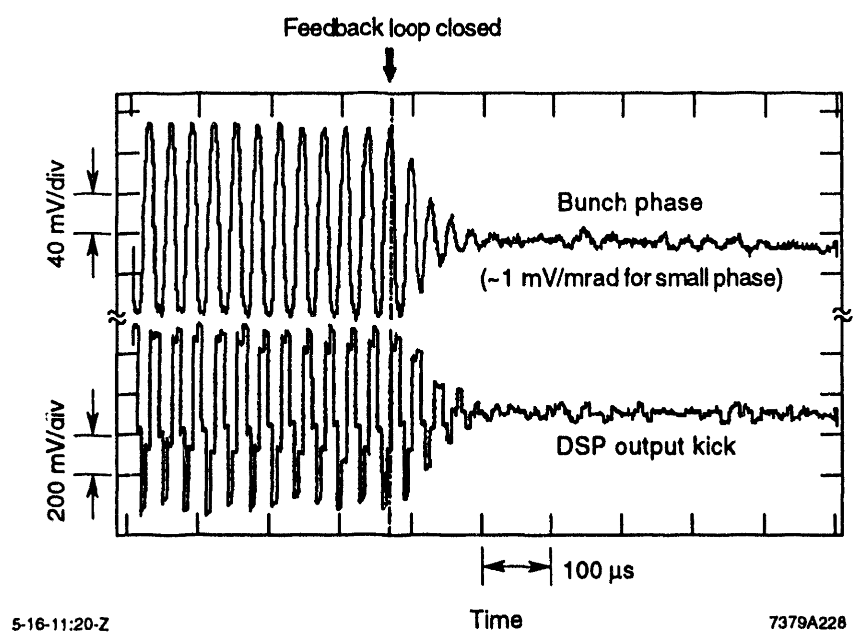

Fig. 3. Bunch phase deviation (upper trace) and DSP output (lower trace) for SPEAR measurements. The bunch is excited with the feedback loop open and then the loop is closed (dashed line), after which the bunch recovers quickly to baseline.

The general goal for this year is to finalize the few remaining R&D issues. For the vacuum system, we plan to complete photodesorption studies on sample extruded chambers using photons of higher critical energy from the XRAY ring at BNL. The design of the DIP modules will be optimized and a finalized version will be fabricated and tested. A full-cell mock-up of the entire vacuum chamber hardware will be built and installed in the existing mock-up of the magnetic components. Finally, sample vacuum chamber components will be measured at LBL to determine their impedance. For the RF system, we intend to measure the behavior of the high-power test cavity, including the properties of the high-power input window and HOM damping loads.

5 Summary

In the past few years there has been major progress on the design of PEP-II. Technical uncertainties have been successfully eliminated and our R&D activities are nearly completed. The PEP-II project has just undergone a joint DOE/NSF review, and we are hopeful of a favorable decision. It is anticipated that the funding will be in place in time for an October, 1993 start. The PEP-II project has a strong design team coupled with an excellent site from which to mount it. We are simply awaiting the go-ahead to begin.

Acknowledgments

The work described here is the product of many dedicated physicists, engineers, and designers from SLAC, LBL, and LLNL. The progress indicated here is a measure of the quality of their work and it is a pleasure to acknowledge it.

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