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Study of Collective Effects for the APIARY Collider*

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Abstract

The design of a high-luminosity electron-positron collider to study B-physics is a challenging task from many points of view. In this paper we consider the influence of collective effects on the machine performance; most of our findings are "generic," in the sense that they depend rather weakly on the details of the machine design. Based upon an example machine design (APIARY-II), we investigate single-bunch thresholds for the longitudinal microwave and transverse mode-coupling instabilities, examine the possibility of emittance growth from intrabeam scattering, calculate the beam lifetime from Touschek scattering and gas scattering, and estimate the growth rates for both longitudinal and transverse coupled-bunch instabilities. We find that the single-bunch instabilities should not lead to difficulty, and that the emittance growth is essentially negligible. At a background gas pressure of 10 nTorr, beam lifetimes of only a few hours are expected, which will place a burden on the injection system if a high average luminosity is to be maintained. Even this lifetime is likely to require an innovative design for the vacuum system to maintain a pressure of 10 nTorr in the presence of a circulating electron or positron beam of approximately 1 A. With a standard PEP-like multicell RF system, multibunch growth rates are very severe, especially in the longitudinal plane. There appear to be significant benefits to a radically different RF system design, either utilizing superconducting single-cell RF cavities, or cavities with equivalent geometrical shapes but operated at room temperature. Even then, a powerful feedback system will likely be required. Nonetheless, it does not appear that there are any fundamental problems that stand in the way of successfully designing and building such a high-luminosity B-Factory.

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INTRODUCTION

In the recent past, there has been a great deal of interest expressed by the high-energy physics community in the possibility of designing a facility for the production of copious quantities of B-mesons, referred to as a "B-Factory." The ultimate purpose of such a facility is to study CP violations, as a means of investigating detailed predictions of the Standard Model. This will require a very high luminosity for the collider, in the neighborhood of $\mathcal{L} = 1 \times 10^{34}$ cm^{-2}s^{-1}. Because such a luminosity is nearly two orders of magnitude beyond the currently achievable value, the design of a suitable collider presents many challenges to the accelerator physics community.

In this paper, we will look at those issues related to the large beam currents required to provide a high-luminosity asymmetric collider, that is, at the *collective effects* of relevance to a B-Factory design. The focus here is on single-ring issues, before the beams are brought into collision. Discussions of the beam-beam interaction—an equally important component of the B-Factory design—will be covered elsewhere in these proceedings.[1] We will first look at single-bunch thresholds, then examine emittance growth from intrabeam scattering (IBS), next estimate beam lifetimes from Touschek scattering, gas scattering, and quantum excitation, and finally consider the growth rates of multibunch instabilities. As we will see below, this last effect is quite severe, and will likely be one of the limitations to the performance of the B-Factory. The results reported here were all obtained with the LBL accelerator physics code ZAP.[2]

Where specific parameters are required, we use the APIARY-II design as an example. This design has evolved from an earlier attempt[3] (APIARY-I) to produce a self-consistent B-Factory design, which was based on using the existing PEP ring (at 12 GeV) colliding with a new low-energy (2.3 GeV) ring. Because APIARY-I gave a luminosity of only 0.5×10^{33} cm^{-2}s^{-1}, the APIARY-II design was upgraded to yield $\mathcal{L} = 1.8 \times 10^{33}$ cm^{-2}s^{-1}. Major parameters for

APIARY-II are summarized in Table I. [Clearly, the APIARY-II design still does not reach our stated luminosity goal. Further enhancements (APIARY-III) are presently under study[4] but will not be reported upon here except to comment that the higher luminosity will require beam currents of about 3 A in both the high- and low-energy rings.] It is worth noting that, at this stage, we try where possible to remain faithful to known constraints of the PEP ring. In particular, we take RF parameters and impedance estimates from the presently used 353-MHz, 120-cell RF system, and we take 3 MW as the maximum acceptable synchrotron radiation power that can be absorbed by the vacuum chamber. Compared with the original APIARY-I design, the increased luminosity of APIARY-II arises from several factors:

- reduced energy asymmetry (9 GeV in PEP, 3.1 GeV in the low-energy ring), which permits more beam current in PEP without violating the 3-MW power limit of the vacuum chamber;
- round beams, which give a twofold (geometrical) improvement in luminosity.

To calculate the design luminosity, we make use of the simplified expression in Eq. (1), taken from Ref. 1:

$$L = 2.2 \times 10^{34}\, \xi\, (1 + r) \left(\frac{I E}{\beta_y^*} \right)_{1,2} \quad \left(\mathrm{cm^{-2}\, s^{-1}} \right) \tag{1}$$

where ξ is the maximum beam-beam tune shift for both beams (and in both transverse planes), r is the beam aspect ratio (r = 0 for a flat beam, r = 1 for a round beam), I is the beam current in amperes, and β_y^* is the beta function at the interaction point (IP) in cm. The subscript in Eq. (1) refers to the fact that the ratio $(I \cdot E/\beta^*)$ can be evaluated with parameters from either beam 1 or beam 2.

The parameters for the low-energy ring were driven primarily by an attempt to achieve more nearly equal damping decrements in the two rings. This feature has been shown in beam-beam simulation studies[5] to be important in obtaining high luminosity.

COLLECTIVE EFFECTS

High-energy Ring

The high-energy ring calculations are based on PEP lattice parameters.[6] The PEP ring has a circumference of 2200 m and an RF frequency of 353.2 MHz, leading to a harmonic number of h = 2592. The required bunch separation for APIARY-II then corresponds to 324 equally spaced bunches in the ring. Although the original APIARY-I design (where PEP was operated at 12 GeV) was constrained by the vacuum chamber power limit of 3 MW to a maximum beam current of 270 mA, the lower PEP energy of 9 GeV chosen for APIARY-II permits an increase in beam current to 850 mA. To maintain bunches that are short compared with the smallest β^* value of 3 cm, we adopt an RF voltage of 25 MV, which gives an rms bunch length of $\sigma_\ell \approx 1$ cm at the required single-bunch current of 2.6 mA.

Thresholds

To estimate the longitudinal growth from the microwave instability, we take a longitudinal impedance of $|Z/n| = 3\ \Omega$. This value, which is heavily dominated by the RF itself, is compatible with existing measurements at PEP.[7] As can be seen in Fig. 1(a), no bunch lengthening is expected unless the beam energy is below 9 GeV. Expected bunch lengthening, and widening, beyond threshold are shown in Fig. 1(b).

Because the ring is large, we must also consider the transverse mode-coupling instability, which is known[8] 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

$$I_b = \frac{4\,(E/e)\,\nu_s}{\langle Im\,(Z_\perp)\,\beta_\perp\rangle\,R}\,\frac{4\sqrt{\pi}}{3}\,\sigma_\ell \qquad (2)$$

where ν_s is the synchrotron tune, $\beta_\perp$ is the beta function at the location of the impedance, and R is the average ring radius. Insofar as the RF is a major contributor to the transverse impedance, it is clear from Eq. (2) that it is best to "hide" it in a low-beta region of the ring. Although the impedance is expected to decrease for very short bunches,[9] we are operating in the regime where the threshold is more or less independent of bunch length. For the same impedance as presently exists in PEP, a simple scaling from existing data suggests that the transverse mode-coupling threshold should increase somewhat for the APIARY-II case, despite the low beam energy.

Intrabeam Scattering

Although we are considering a fairly high energy beam, the requirements for relatively short bunches and relatively high peak currents make emittance growth from intrabeam scattering a possible concern. Intrabeam scattering (IBS) results from the fact that, in the bunch rest frame, all particles are not moving in the same direction, and can thus collide. 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 (regions where the position of a particle depends on its energy deviation) the resultant momentum change is equivalent to exciting a betatron oscillation, and thus causing an increase in horizontal emittance. Fortunately, our estimates for the APIARY-II parameters, shown in Fig. 2, indicate that no growth is expected throughout this energy range.

Beam Lifetime

For a high-energy electron beam, there are three main processes that lead to beam loss: Touschek scattering, gas scattering, and quantum excitation. For the APIARY-II design, we will see below that the first of these effects is not important, but the second one is, and the third one has the potential to be so.

Touschek scattering. The Touschek scattering mechanism is also a single-bunch effect that is related to the IBS mechanism described above. The main difference is that we are concerned now with large-angle, single scattering events that cause the scattered particles' momenta to change sufficiently to 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 it can exceed the so-called "dynamic aperture" of the machine. (The term dynamic aperture refers to the largest betatron amplitudes in the machine that can remain stable, after taking into account the various nonlinear magnetic fields experienced by a particle as it circulates.) 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 of a strong degradation if the acceptance is too low.

As shown in Fig. 3(a), the APIARY-II RF voltage, selected to be 25 MV in order to ensure short beam bunches, actually provides an excessively large acceptance compared with the estimated limitation from the physical aperture. This is not beneficial to the lifetime, since it results in a higher bunch density and thus in a higher collision probability; this is the price we must pay to obtain short bunches. Fortunately, the Touschek lifetime is not a concern in this parameter regime, as can be seen in Fig. 3(b). At 9 GeV, a Touschek lifetime of about 400 hours is expected.

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).

In the case of a ring designed to serve as a high-luminosity B-Factory, we may ultimately[4] have to accommodate up to 3 A of circulating beam. This high beam current will give a large amount of desorbed gas load, and there is a serious question about what background gas pressure can be maintained in the ring. Given that most present colliders operate in the pressure range of about 10 nTorr, we will base our lifetime estimates on this value (N_2 equivalent). It is important to note, however, that achieving such a pressure is not at all trivial even for the APIARY-II beam current of 0.85 A, and quite likely will require an innovative design for the vacuum chamber.

For the APIARY-II high-energy ring, the estimated lifetimes from gas scattering are shown in Fig. 4. This beam loss process is much more severe than the Touschek scattering process. At a pressure of 10 nTorr, the lifetime is expected to be on the order of 2 hours.

Quantum lifetime. It is worth remembering that one must also keep a watchful eye on the quantum lifetime in a high-energy ring. This loss mechanism results from particles being scraped from the tails of the Gaussian distribution that results from the statistical nature of the synchrotron radiation emission process. The lifetime from this effect goes as:[10]

$$\tau_q = \tau_x \frac{e^{\xi^2/2}}{\xi^2} \tag{3}$$

where ξ is the available aperture in units of the rms beam size, σ_x. For an acceptance of $\xi = 6$, the resultant quantum lifetime is about 15 hours, but for $\xi = 5$ the lifetime would be only about 5 minutes. To account for misalignments that can reduce the available aperture, a typical rule of thumb in such machines is to allow for an aperture of about $\xi = 10$ in both planes.

In a high-luminosity collider the required β^* value is only a few centimeters, which can result in very large beta function values ($\beta \approx 1000$ m) in the interaction region (IR) quadrupole triplets, and thus very large rms beam sizes ($\sigma_x \approx 5$ mm). Thus, a quadrupole aperture radius of 3 cm, as was assumed here, is already marginal for the present design.

Presuming that the parameters are suitably chosen to avoid difficulties with quantum lifetime, we can see from the above discussion that the (single-beam) lifetime of the high-energy ring will be dominated by gas scattering, which makes the vacuum system a critical issue. We note that the luminosity lifetime in a high-luminosity collider will also be limited by the beam-beam scattering at the interaction point. Porter[11] has estimated the cross section of this process for a typical B-factory collider design and finds a luminosity lifetime of about two hours. Combining this with the estimates for single-beam loss mechanisms above, suggests that the overall luminosity lifetime will be on the order of 1 hour, which implies the need for a very powerful injection system to maintain an acceptable average value for the luminosity.

Coupled-bunch Instabilities

In a storage ring, wakefields in high-Q resonant structures can cause different beam bunches to interact. In general, the source of such high-Q resonances is the higher-order modes 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, as illustrated schematically in Fig. 5. Longitudinally, the a=0 mode (which corresponds to no motion) cannot be unstable, so the lowest longitudinal instabilities are characterized by the 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 a high-luminosity B-Factory design. we require a large number of RF cells to produce the voltage needed to provide the short bunches and to replace the beam power lost each turn into synchrotron radiation. This fact, combined with the need for very high average beam currents, can lead to extremely rapid growth of coupled-bunch instabilities. In all the cases studied here, the most severe growth comes from the lowest synchrotron modes, that is a=1 and a=2 longitudinally and a=0 and a=1 transversely. Higher synchrotron modes are predicted to be either Landau damped or are growing sufficiently slowly for radiation damping to be effective.

In this paper, we will estimate the growth rates for both longitudinal and transverse instabilities for typical APIARY-II parameters, that is, 324 bunches having a total current of 850 mA. We take the higher-order modes of the existing PEP RF system,[12] which consists of 24 five-cell cavities, i.e., 120 cells. Because this system is capable of providing 39 MV, as opposed to the 25 MV we require for APIARY-II, our calculations are slightly pessimistic (by about 60%). Given the uncertainties in determining the actual higher-order modes for the many PEP RF cavities, which have different beam apertures, it is most sensible to interpret the results shown here "logarithmically." That is, we are interested in seeing whether the fastest growth rates are 1 ms, 0.1 ms, etc., and we should not ascribe too much significance at present to growth rates that differ by a factor of two.

To give a feeling for the range of possibilities, four different cases were studied.

- Case A: PEP RF, 120 cells, no de-Qing
- Case B: PEP RF, 120 cells, Q/5
- Case C: PEP RF, 120 cells, Q/100
- Case D: Superconducting RF, 25 cells

The first case corresponds to the assumption that all PEP RF cells are identical, which (as mentioned above) is unrealistic. Case B is intended to mock up the effect of the mechanical differences between PEP RF cavities by representing groupings of the slightly displaced resonant frequencies in terms of single resonators with a somewhat broader frequency span. The third case represents what might happen if the higher-order RF modes were heavily de-Qed by external means, such as damping antennae. (We note that achieving this level of Q reduction in the PEP five-cell cavities would not be an easy task, to say the least. However, such a drastic reduction in Q might be practical in the case of specially designed single-cell room temperature

RF cells.) Lastly, Case D is intended to show the potential benefits that accrue when a superconducting RF system is employed. For this paper, the RF modes were obtained by simple scaling of a design[13] for a 500-MHz Tristan RF system. Thus, the growth rates calculated are illustrative of the performance of a superconducting RF system, but detailed comparisons must await the modes for a proper 353-MHz single-cell cavity design.

Predictions of longitudinal growth times (for the fastest growing mode) for each of the four RF scenarios considered are summarized in Table II. For the standard PEP RF (Cases A and B), we see that both the a=1 (dipole) and a=2 (quadrupole) modes grow very rapidly compared with the radiation damping time. The predicted rates are so fast that they are comparable to the synchrotron period itself, making the model used to estimate the growth rates suspect. Nonetheless, the calculated values serve as a severe warning. Substantial de-Qing (Case C) does help slow down the growth considerably, and the use of superconducting RF (Case D) is even more helpful. Note that the feedback system power required to counteract these instabilities will scale as the square of the growth rate, so a change of a factor of ten is extremely significant.

Transverse results, summarized in Table III, are similar to those for the longitudinal case, but the predicted growth rates are somewhat lower. Here too, we find that the lowest two synchrotron modes, a=0 and a=1, grow faster than the radiation damping rate. We again note the benefits of either substantial de-Qing (Case C) or, better still, superconducting RF in slowing down the growth rates to more manageable levels.

Investigations done to date indicate that the behavior shown in Tables II and III is insensitive to energy in this regime, so increasing the energy asymmetry by raising the energy of the high-energy ring to 12 or 14 GeV is not especially helpful. We also find that the coupled-bunch growth rates for the case of a high-luminosity collider scale mainly with total current, and do not change significantly if the bunch pattern changes (e.g., choosing half as many bunches, with twice the single-bunch current). Among other things, this means that reaching a luminosity of 1 x 10^{34} $cm^{-2}s^{-1}$ will decrease the growth times calculated here by another factor of three or so.

Low-energy Ring

Major parameters of the low-energy ring considered here are summarized in Table I. The ring was assumed to operate at the same RF frequency (353.2 MHz) as PEP, which leads to a harmonic number of 216. Reaching the desired beam current requires 27 bunches with 31.5 mA/bunch. To maintain equally short beam bunches in this ring (see Fig. 6(a)), the RF system must provide 10 MV; this requires 30 cells of standard PEP RF.

Thresholds

Taking into account the expected[9] impedance roll-off for short beam bunches, the longitudinal microwave instability threshold is shown in Fig. 6(b). For these calculations, each RF cell is estimated to contribute about 0.3 Ω of (low-frequency) broadband impedance, and an additional 1 Ω allowance is made for the vacuum chamber and miscellaneous impedance contributions. Transverse thresholds were predicted to be well beyond the range of interest, and so are of no concern.

Intrabeam Scattering

In this case, the lower beam energy enhances the IBS growth rates, and the single-bunch current is much higher, but these aspects are compensated by the larger transverse emittance values and by the more rapid radiation damping rate. Thus, as seen in Fig. 7, we again predict no emittance growth from intrabeam scattering.

Beam Lifetime

Touschek scattering. As for the high-energy ring, the physical momentum acceptance limit, $\Delta p/p \approx 1\%$ dominates that of the RF bucket (see Fig. 8(a)). Although the lower energy causes the Touschek lifetime to decrease compared with the high-energy case, we see in Fig. 8(b) that the lifetime at 3 GeV, about 100 hours, is still not of concern.

Gas scattering. At a gas pressure of 10 nTorr (N_2 equivalent), the lifetime is predicted to be dominated by the inelastic scattering process, as shown in Fig. 9(a). The overall beam lifetime, shown in Fig. 9(b), again comes mainly from the gas scattering.

Coupled-bunch Instabilities

For the low-energy ring we studied the same four RF scenarios described earlier, with the number of RF cells reduced to be compatible with the lower voltage requirement. The general caveat mentioned earlier about not overinterpreting the results applies equally here. Longitudinal growth times, summarized in Table IV, are more moderate than for the high-energy ring. We again see a strong preference for the superconducting RF scenario. In fact, the Case D result would suggest that feedback for this ring would be unnecessary. The results of Cases A, B, or C, using PEP-like RF cavities, are not unlike those predicted for the Advanced Light Source, now under construction at LBL. Feedback would be required, but the requirements should be manageable.

Similar statements apply to the transverse growth rates, which are summarized in Table V. The preference for the superconducting RF scenario (Case D) is apparent. For this ring, only the a=0 mode is expected to grow fast enough to require feedback, even with the standard RF cases. With sufficient de-Qing (Case C), the a=0 modes are predicted to be Landau damped, so it is possible that no transverse feedback system would be needed for this ring.

SUMMARY

In this paper we have examined the collective effects that influence the performance of a high-luminosity collider that could serve as a B-Factory. Specific numerical examples were based on the parameters of the APIARY-II collider, which is designed to produce a luminosity of about 2×10^{33} cm^{-2}s^{-1}. Design of a refined collider, APIARY-III, that will give $L = 1 \times 10^{34}$

$cm^{-2}s^{-1}$ is presently under way.

We have seen that the performance of the high-energy ring is likely to be limited mainly by coupled-bunch instabilities; the success of APIARY will depend largely on the skills of the feedback system designer. Total beam current limitations in the ring will likely come from the amount of synchrotron radiation power that can safely be absorbed by the vacuum chamber and from the ability of the vacuum system to maintain an acceptable pressure. Single-bunch limitations will arise from the allowable beam-beam tune shift, from bunch lengthening and widening due to the longitudinal microwave instability (which implies a limit on the allowable broadband impedance), and possibly from the transverse mode-coupling instability.

The low-energy ring studied here seems fairly straightforward. Coupled-bunch instabilities are significant here as well, but should be manageable. The total current will be limited by the same issues as for the high-energy ring, but there is an additional complication here because one must be concerned not only with the synchrotron radiation power itself, but with the power *density*. This aspect may well be unmanageable unless the ring size of the low-energy ring is considerably larger than that specified here.

For both rings, we see a preference for the use of superconducting RF cells. This choice tends to reduce the longitudinal impedance by permitting the voltage to be produced with many fewer cells and by permitting the cavity to be more "monochromatic." It also lowers the transverse impedance by permitting a relatively large bore size and by facilitating the location of the RF cells in a low-beta region of the ring. Taken together, these features are expected to lead to a strong reduction in coupled-bunch instabilities and a strong increase in the transverse single-bunch threshold.

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Table I

APIARY-II Major Parameters

		High-energy	Low-energy
E	[GeV]	9	3
C	[m]	2200	183
S_B	[m]	6.79	6.79
N_B	[particles/bunch]	1.2×10^{11}	1.2×10^{11}
I	[A]	0.850	0.850
ε_x	[μm-rad]	0.03	0.09
ε_y	[μm-rad]	0.03	0.09
β_x^*	[m]	0.09	0.03
β_y^*	[m]	0.09	0.03
$\Delta\nu_x$		0.05	0.05
$\Delta\nu_y$		0.05	0.05
$\mathcal{L}$	[cm^{-2} s^{-1}]	1.8×10^{33}	

Table II

Longitudinal Coupled-Bunch Growth Rates for APIARY-II
High-Energy Ring

(9 GeV; τ_E = 19 ms)

(A) PEP, no de-Q	
$\tau_{a=1}$ (ms)	$\tau_{a=2}$ (ms)
0.01	1

(B) PEP, Q/5	
$\tau_{a=1}$ (ms)	$\tau_{a=2}$ (ms)
0.02	1

(C) PEP, Q/100	
$\tau_{a=1}$ (ms)	$\tau_{a=2}$ (ms)
0.3	3

(D) Superconducting	
$\tau_{a=1}$ (ms)	$\tau_{a=2}$ (ms)
0.5	100

Table III

Transverse Coupled-Bunch Growth Rates for APIARY-II
High-Energy Ring

(9 GeV: $\tau_x = 37$ ms)

(A) PEP, no de-Q	
$\tau_{a=0}$ (ms)	$\tau_{a=1}$ (ms)
0.05	0.5

(B) PEP, Q/5	
$\tau_{a=0}$ (ms)	$\tau_{a=1}$ (ms)
0.05	1

(C) PEP, Q/100	
$\tau_{a=0}$ (ms)	$\tau_{a=1}$ (ms)
0.7	20

(D) Superconducting	
$\tau_{a=0}$ (ms)	$\tau_{a=1}$ (ms)
5	1000

Table IV

Longitudinal Coupled-Bunch Growth Rates for APIARY-II
Low-Energy Ring

(3 GeV; $\tau_E = 1.6$ ms)

(A) PEP, no de-Q	
$\tau_{a=1}$ (ms)	$\tau_{a=2}$ (ms)
0.2	10

(B) PEP, Q/5	
$\tau_{a=1}$ (ms)	$\tau_{a=2}$ (ms)
0.05	0.5

(C) PEP, Q/100	
$\tau_{a=1}$ (ms)	$\tau_{a=2}$ (ms)
0.1	1

(D) Superconducting	
$\tau_{a=1}$ (ms)	$\tau_{a=2}$ (ms)
20	2000

Table V

Transverse Coupled-Bunch Growth Rates for APIARY-II
Low-Energy Ring

(3 GeV; $\tau_x = 3.2$ ms)

(A) PEP, no de-Q		(B) PEP, Q/5	
$\tau_{a=0}$ (ms)	$\tau_{a=1}$ (ms)	$\tau_{a=0}$ (ms)	$\tau_{a=1}$ (ms)
1	5	0.1	5

(C) PEP, Q/100		(D) Superconducting	
$\tau_{a=0}$ (ms)	$\tau_{a=1}$ (ms)	$\tau_{a=0}$ (ms)	$\tau_{a=1}$ (ms)
0.5[a)]	10	50[a)]	1000[a)]

[a)]Predicted to be Landau damped.

FIGURE CAPTIONS

1. (a) Predicted bunch lengthening from the longitudinal microwave instability for the APIARY-II high-energy ring with a single-bunch current of 2.6 mA. A low-frequency broadband impedance of $|Z/n| = 3\ \Omega$ was taken, and impedance roll-off according to SPEAR Scaling was assumed.

   (b) Predicted bunch lengthening and widening for the APIARY-II high-energy ring as a function of single-bunch beam current.

2. Predicted emittance growth from intrabeam scattering (IBS) for the APIARY-II high-energy ring, assuming full emittance coupling. The points correspond to the equilibrium values for emittance including the IBS contribution; the dashed line shows the natural emittance, i.e., that due solely to the emission of synchrotron radiation. At these energies, the additional emittance growth from IBS is negligible.

3. (a) Momentum acceptance for the APIARY-II high-energy ring at an RF voltage of 25 MV. Lifetime will be limited by the physical aperture in this case.

   (b) Predicted Touschek lifetime for the APIARY-II high-energy ring, based on the momentum acceptance shown in Fig. 3(a).

4. Predicted gas scattering lifetime for the APIARY-II high-energy ring, assuming a background gas pressure of 10 nTorr (N_2-equivalent). Contributions from elastic and inelastic (Bremsstrahlung) scattering are shown separately, along with the combined lifetime from both processes together.

5. Schematic diagram of the lowest few coupled-bunch synchrotron modes. For longitudinal instability, only modes $a \geq 1$ are possible; transversely, the $a=0$ mode can also be unstable. In the case of APIARY-II, the most troublesome cases are $a=1,2$ longitudinally and $a=0,1$ transversely (see Tables II and III).

6. (a) Predicted natural bunch length for the APIARY-II low-energy ring as a function of RF voltage. To achieve a 1 cm bunch length, at least 10 MV must be provided.

(b) Predicted threshold for longitudinal microwave instability for the APIARY-II low-energy ring. The threshold is above the required single-bunch current throughout this voltage range.

7. Predicted emittance growth from intrabeam scattering (IBS) for the APIARY-II low-energy ring, assuming full emittance coupling. The points correspond to the equilibrium values for emittance including the IBS contribution; the dashed line shows the natural emittance, i.e., that due solely to the emission of synchrotron radiation. The additional emittance growth from IBS is negligible.

8. (a) Momentum acceptance for the APIARY-II low-energy ring at an RF voltage of 10 MV. Lifetime will be limited by the physical aperture in this case.

   (b) Predicted Touschek lifetime for the APIARY-II low-energy ring, based on the momentum acceptance shown in Fig. 8(a).

9. (a) Predicted gas scattering lifetime for the APIARY-II low-energy ring, assuming a background gas pressure of 10 nTorr (N_2-equivalent). Contributions from elastic and inelastic (Bremsstrahlung) scattering are shown separately, along with the combined lifetime from both processes together.

   (b) Predicted total lifetime for the APIARY-II low-energy ring, based on the Touschek and gas scattering lifetimes from Figs. 8(b) and 9(a), respectively. As for the high-energy ring, the gas scattering is dominant.

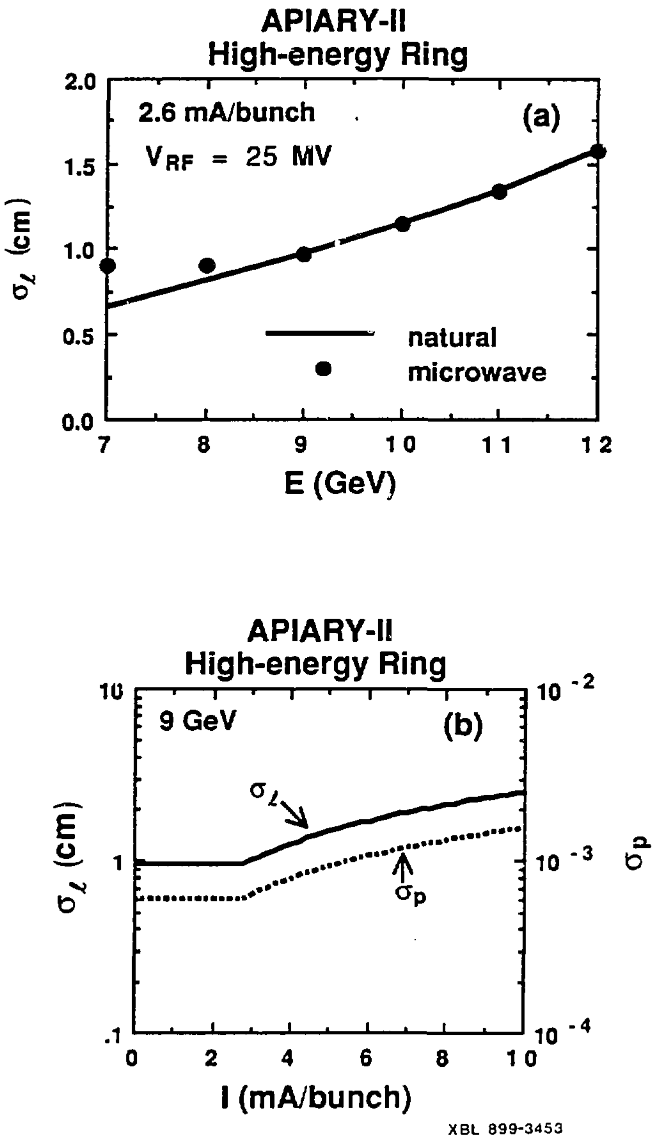
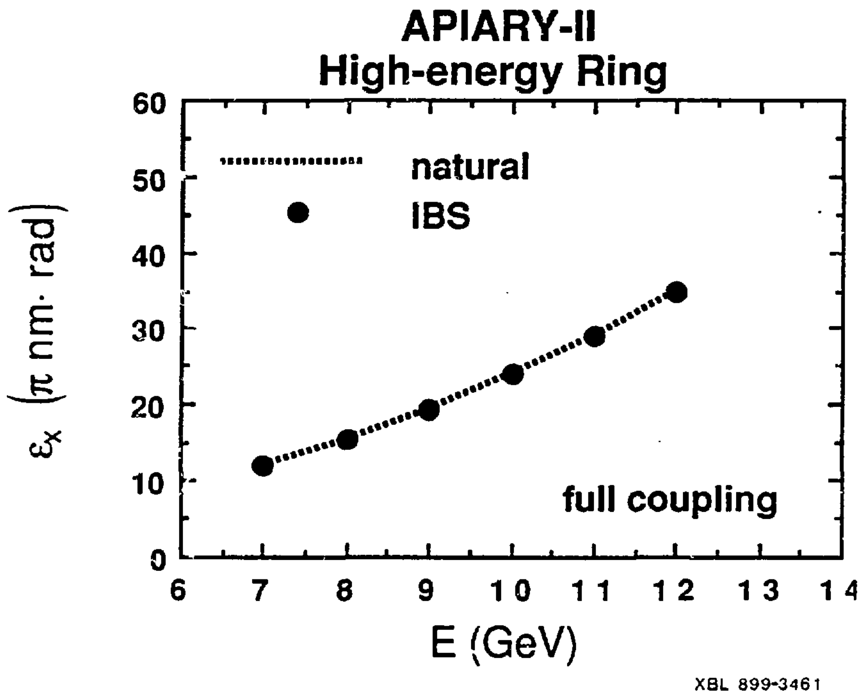
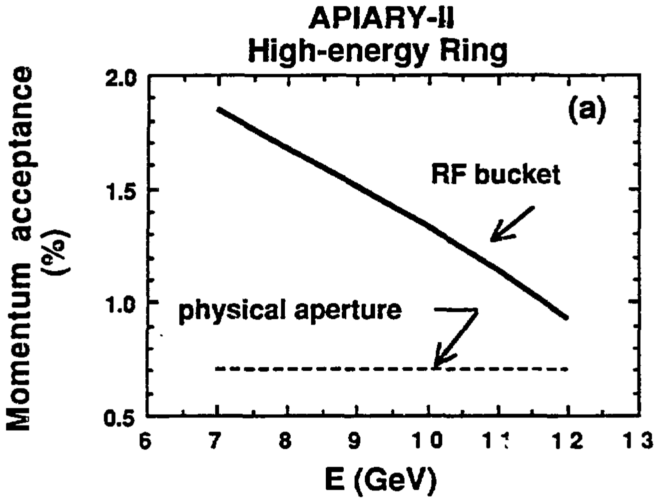

APIARY-II
High-energy Ring
2.6 mA/bunch
V_{RF} = 25 MV
(a)
natural
microwave
σ_ℓ (cm)
E (GeV)
2.0
1.5
1.0
0.5
0.0
7
8
9
10
11
12
APIARY-II
High-energy Ring
9 GeV
(b)
σ_ℓ
σ_p
σ_ℓ (cm)
σ_p
10
1
.1
10^{-2}
10^{-3}
10^{-4}
0
2
4
6
8
10
I (mA/bunch)
XBL 899-3453

Figure 1



APIARY-II
High-energy Ring
natural
IBS
full coupling
60
50
40
30
20
10
0
6
7
8
9
10
11
12
13
14
ε_x (π nm· rad)
E (GeV)
XBL 899-3461

Figure 2


APIARY-II
High-energy Ring
Momentum acceptance (%)
(a)
RF bucket
physical aperture
2.0
1.5
1.0
0.5
6
7
8
9
10
12
13
E (GeV)

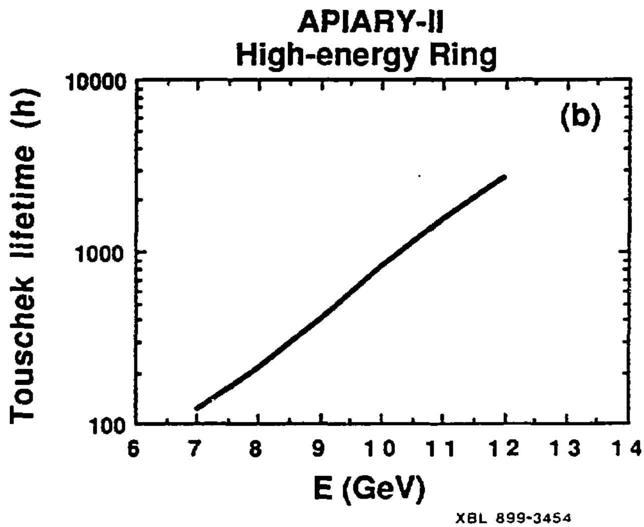

APIARY-II
High-energy Ring
Touschek lifetime (h)
(b)
10000
1000
100
6
7
8
9
10
11
12
13
14
E (GeV)
XBL 899-3454

Figure 3

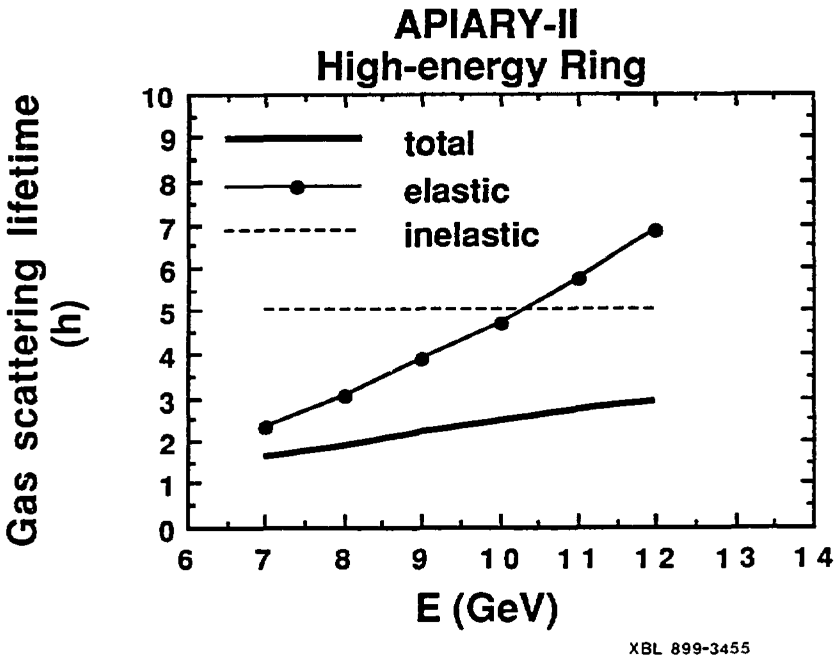

APIARY-II
High-energy Ring
Gas scattering lifetime (h)
10
9
8
7
6
5
4
3
2
1
0
6
7
8
9
10
11
12
13
14
E (GeV)
total
elastic
inelastic
XBL 899-3455

Figure 4

Coupled-bunch Modes

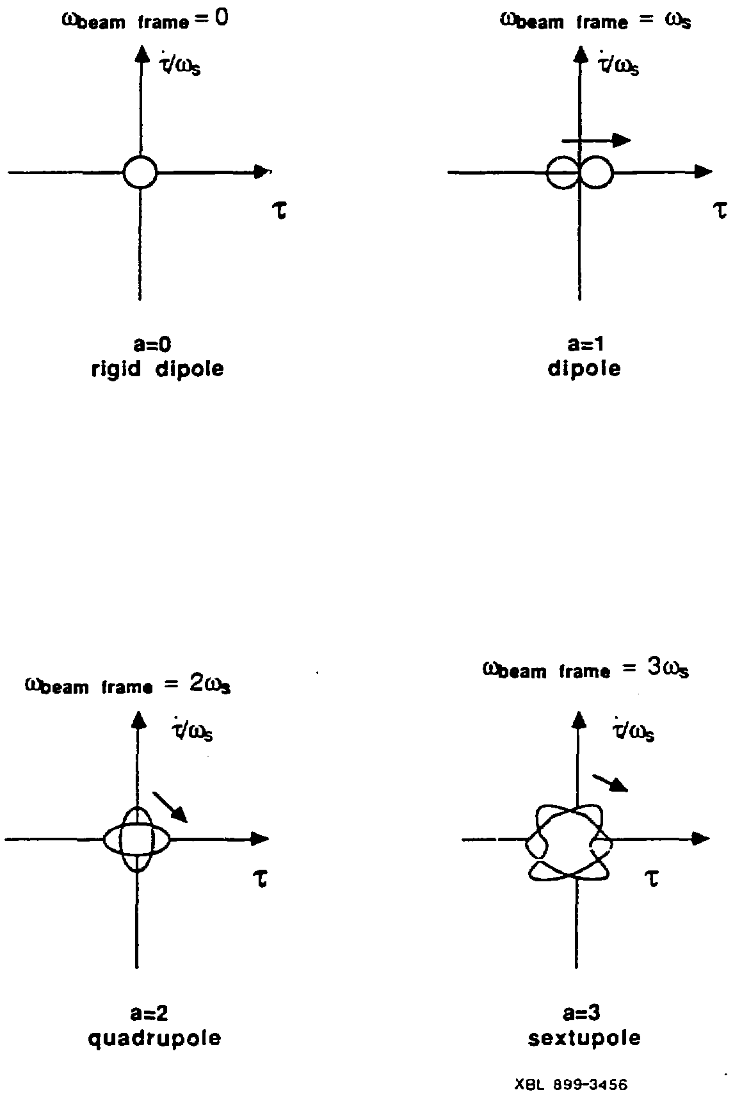


Figure 5

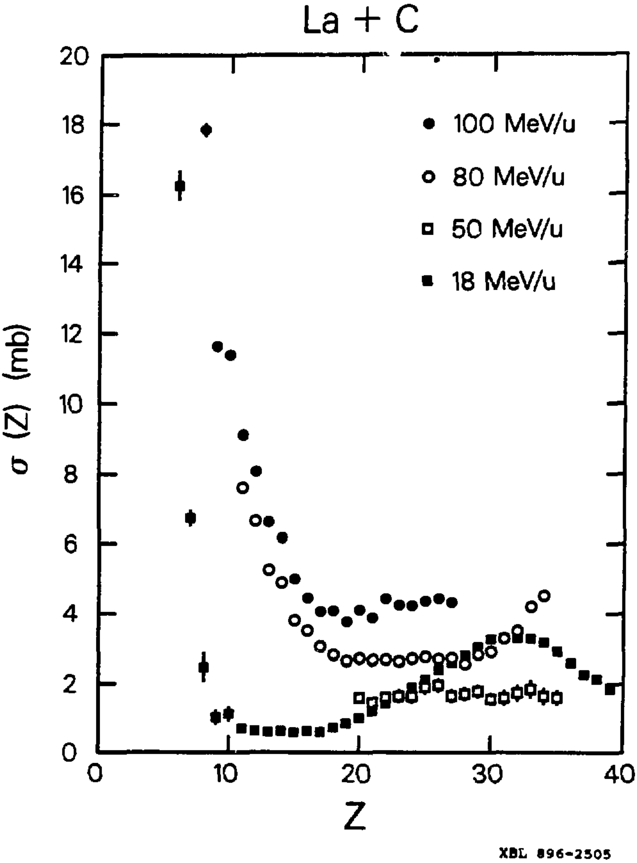


Figure III.18 Angle-integrated cross sections of products in the 18, 50, 80, and 100 MeV/u ^{139}La + ^{12}C reactions. The bars on some of the points are the statistical errors, where bars do not appear the errors are smaller than the size of the data points. The possible systematic errors associated with the absolute beam normalization, target thickness, and the integration procedure are 20 % at 18 MeV/u, 50 % at 50 MeV/u, 20 % at 80 MeV/u and 20 % at 100 MeV/u.

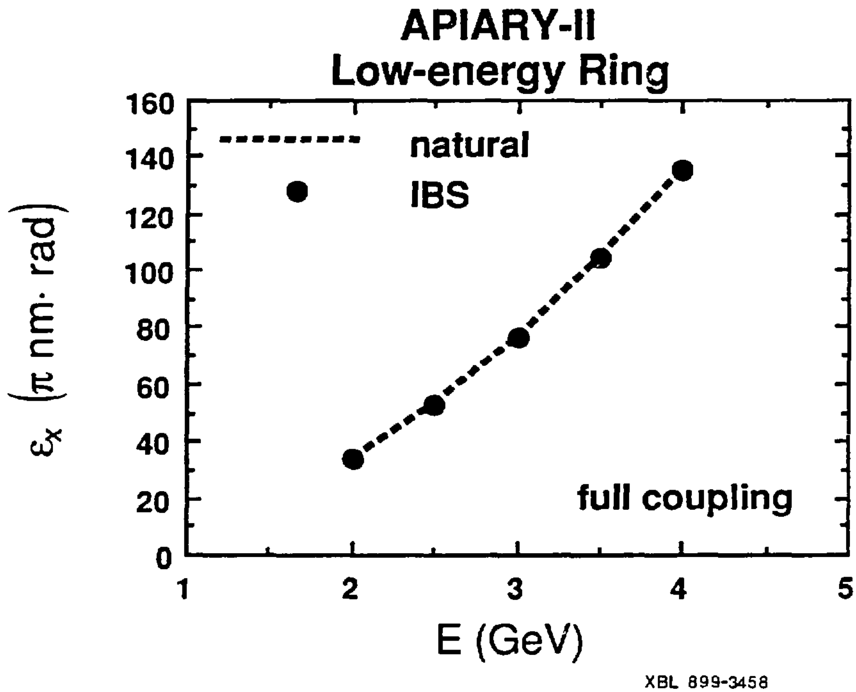

APIARY-II
Low-energy Ring
natural
IBS
full coupling
160
140
120
100
80
60
40
20
0
1
2
3
4
5
E (GeV)
εx (π nm· rad)
XBL 899-3458

Figure 7

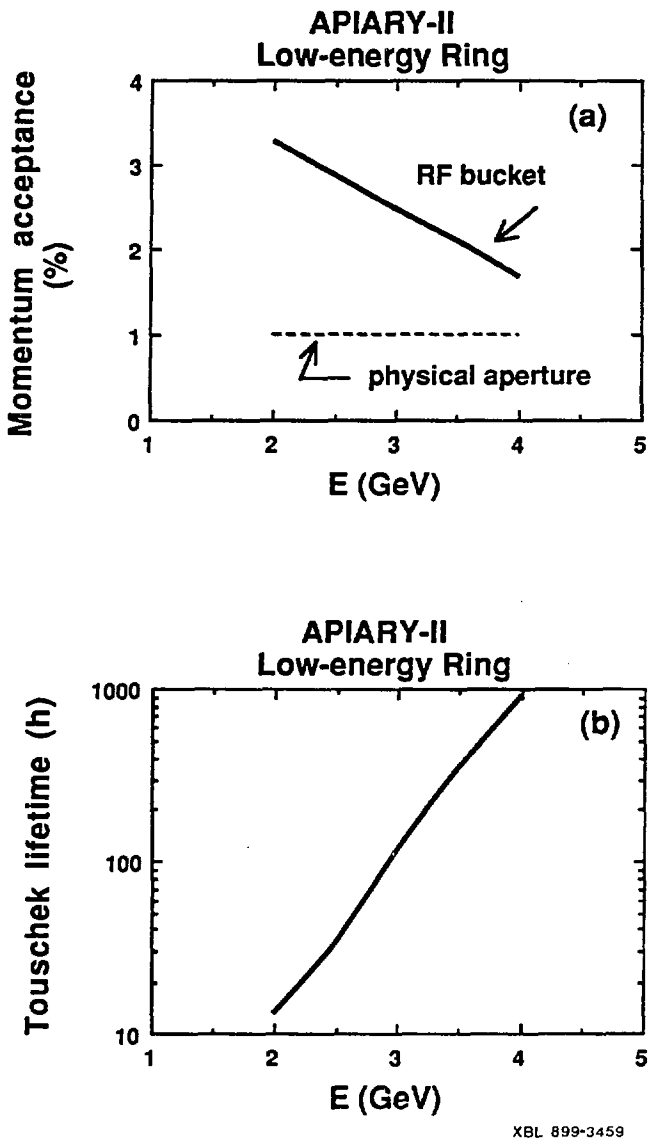

APIARY-II
Low-energy Ring
Momentum acceptance (%)
(a)
RF bucket
physical aperture
E (GeV)
APIARY-II
Low-energy Ring
Touschek lifetime (h)
(b)
E (GeV)
XBL 899-3459

Figure 8

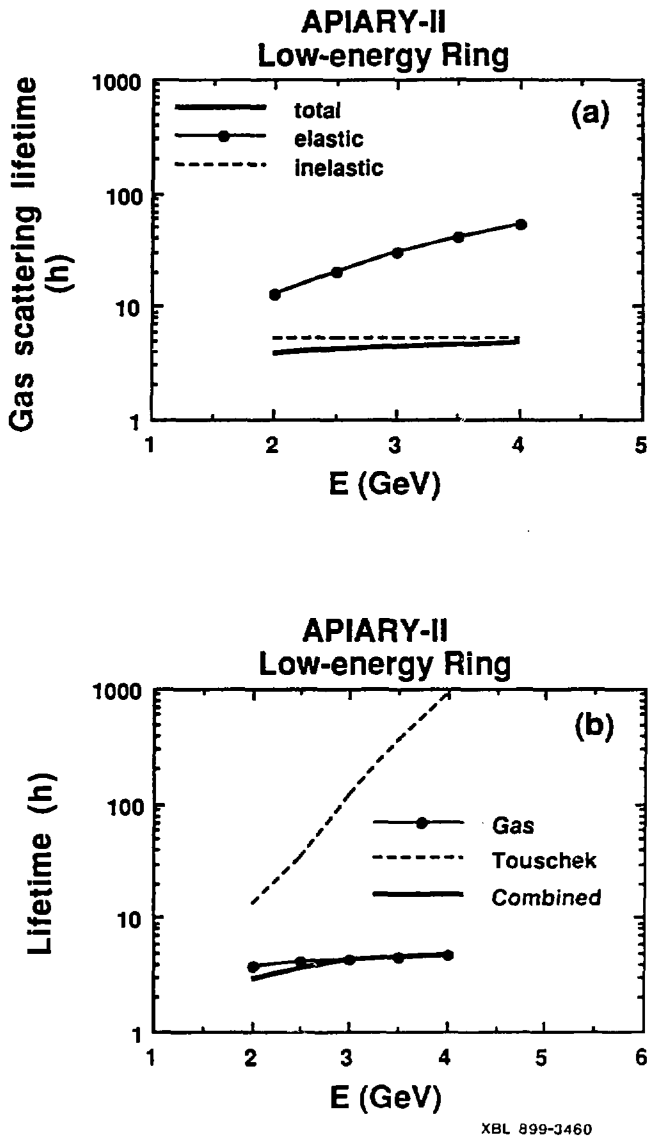

APIARY-II
Low-energy Ring
Gas scattering lifetime (h)
(a)
total
elastic
inelastic
E (GeV)
APIARY-II
Low-energy Ring
Lifetime (h)
(b)
Gas
Touschek
Combined
E (GeV)
XBL 899-3460

Figure 9

DISCLAIMER