AN ASYMMETRIC B-MESON FACTORY AT PEP

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Abstract

A preliminary design for a B-factory has been made using asymmetric collisions between positrons in the PEP storage ring and electrons in a new, low-energy ring. The design utilizes small-aperture, permanent-magnet quadrupoles close to the interaction point (IP). Optimization of optical and beam parameters at the IP will be discussed, as well as the lattice design of the interaction region and of the rings.

Introduction

To create large numbers of B-mesons in a way to facilitate separation of the two B-mesons created, an interesting possibility is to make electron positron collisions at unequal energies between an existing storage ring, such as PEP, and a new lower-energy ring. Collisions between unequal energy beams complicates the choice of interaction point parameters; however, if one makes a few plausible assumptions, such as complete beam overlap and equal beam-beam tune shifts, the situation is greatly simplified. After a few basic parameters are chosen, such as the energies, currents and the lowest β-function value at the IP, most other parameters follow, including the luminosity.

Based on known properties and limitations of PEP, reasonable assumptions on the low-energy ring, and the above considerations on beam parameters, a preliminary design for a 12 GeV × 2 GeV B-factory has been made, called Apiary I.[1] This design, which will be described here, gives the rather modest luminosity of 0.5 $\times 10^{33}$ cm^{-2}sec^{-1}. A major limitation was the power that can be absorbed by the PEP vacuum chamber. By going to a more symmetrical system such as 9 GeV × 3 GeV, it may be possible to go to almost a factor of four higher luminosity. A consistant set of IP parameters of this type will be given. A design study based on this second set of parameters is now in progress.

Interaction Point Parameters

The choice of beam parameters is based on the following simplifying assumptions:

- The horizontal and vertical beam-beam tune shifts of both beams should be equal to a single specified value, ξ.
- The beams should exactly coincide at the IP.

From these assumptions three important relations between the energy, intensity, emittance and β-function values can be derived, and explicit expressions for emittance and luminosity obtained.

Equal beams

The first assumption gives a relation between the horizontal and vertical β-function and emittance values. If the beams are identical the tune shifts are

$$\Delta\nu_i = \frac{r_e \beta_i N}{2\pi\gamma\sigma_i(\sigma_x + \sigma_y)}$$

where r_e is the classical electron radius, N the number of particles per bunch, γ the relativistic energy, $i = x, y$ and $\sigma_i = \sqrt{\epsilon_i \beta_i}$, (at the IP). Equating the tune shifts: $\Delta\nu_x = \Delta\nu_y$, gives the first rule:

$$\beta_y/\beta_x = \epsilon_y/\epsilon_x = \sigma_y/\sigma_x = r, \tag{1}$$

where r is a constant.

Unequal beams

Two unequal beams, designated by superscripts $j = 1, 2$, have beam sizes $\sigma_i^j = \sqrt{\epsilon_i^j \beta_i^j}$. Setting $\sigma_i^1 = \sigma_i^2$ gives the second rule:

$$\beta_i^1/\beta_i^2 = \epsilon_i^2/\epsilon_i^1 = b, \tag{2}$$

where $i = x, y$ and b is a second constant. The tune shifts are given by

$$\Delta\nu_i^j = \frac{r_e \beta_i^j N^k}{2\pi\gamma^j\sigma_i^k(\sigma_x^k + \sigma_y^k)},$$

where $j = 1, 2$; $k = 2, 1$. Equating the four tune shifts, $\Delta\nu_i^1 = \Delta\nu_i^2 = \xi$, $i = x, y$, gives the third rule:

$$b = \beta_i^1/\beta_i^2 = (\gamma^1/\gamma^2)\ (N^1/N^2). \tag{3}$$

Emittance

An explicit formula for emittance is obtained from the tune-shift formula and replacement of σ_i^k by σ_i^j:

$$\epsilon_x^j = \frac{r_e N^k}{2\pi\xi\gamma^j(1+r)}, \qquad \epsilon_y^j = r\epsilon_x^j \tag{4}$$

Luminosity

The luminosity for equal beam sizes is given by $\mathcal{L} = cN^1N^2/4\pi S_B\sigma_x\sigma_y$, where S_B is the bunch spacing. Substituting $\sigma_x\sigma_y = \beta_y\epsilon_x$, using the above emittance formula, and replacing N by the current $I = \epsilon cN/S_B$, we get

$$\begin{aligned}\mathcal{L} &= \frac{\xi(1+r)}{2er_e}\left(\frac{I\gamma}{\beta_y}\right)^{1,2} \\ &= 2.167\times10^{34}\xi(1+r)(IE/\beta_y)^{1,2} \quad \text{cm}^{-2}\text{sec}^{-1}\end{aligned} \tag{5}$$

where I is in Amperes, E in GeV, and β_y in cm.

The above relations have been obtained independently by a group at DESY.[2] They can be used to produce self-consistant sets of parameters; but which ones should be chosen and which ones derived is somewhat arbitrary. The approach here is to pick the energies, currents, aspect ratio r, and β_y of the low energy beam.

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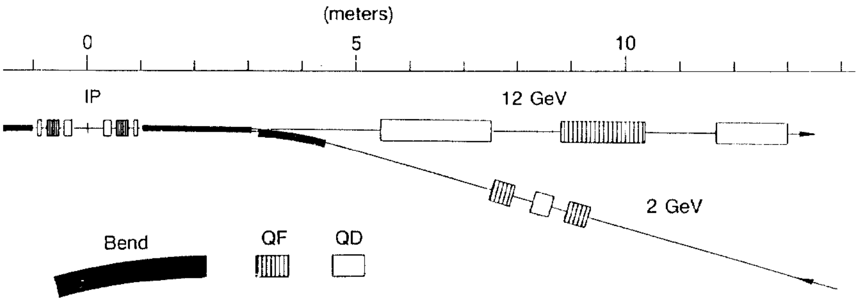

Figure 1. Interaction region of Apiary I B-Factory design.

Apiary I

Parameters

A first attempt at a complete design was made with PEP at 12 GeV and the low-energy ring at 2 GeV. The current in PEP, 0.267 A was based on the power deposition on the vacuum chamber wall; that in the 2 GeV ring was taken to be twice as high, since this was within the range of existing rings such as the NSLS VUV ring and BESSY. Since the PEP bunch length is about 2 cm, we set β_y for the 2 GeV ring to 2.5 cm, and then took an aspect ratio $r = 0.1$, in accord with normal PEP operation. The tune shift limit was set at $\xi = 0.05$, since that value had been achieved in PEP. With these choices, the relations of the previous section yield the parameters of Table I. This table also includes a few other parameters, such as the bunch spacing, which was chosen partly in view of the length needed to separate the two beams.

Table I APIARY I Parameters

		Beam 1	Beam 2	
Energy	E	12.	2.	GeV
Bunch spacing	S_B	27.2	27.2	m
Particles/bunch	N_B	1.51×10^{11}	3.02×10^{11}	
Current	I	0.267	0.535	A
Emittances	ϵ_x	0.105	0.315	μm
	ϵ_y	0.0105	0.0315	μm
β-functions at IP	β_x^*	76.2	25.4	cm
	β_y^*	7.62	2.54	cm
Dispersion at IP	η^*	0.	0.	m
Beam-beam tune shifts	$\Delta\nu_x$	0.05	0.05	
	$\Delta\nu_x$	0.05	0.05	
Luminosity	$\mathcal{L}$	0.5×10^{33}		cm^{-2}s^{-1}
Circumference	$2\pi R$	2200.	163.	m

Lattice

A schematic diagram of the interaction region is shown in Figure 1. The beams collide head-on at the IP in a beam pipe of about 1 cm radius, to allow the detectors to be as close as possible. After transversing a 30 cm drift space, the beams go through a triplet of permanent-magnet quadrupoles that focus the low-energy beam to zero slope and minimize its size there. After the triplet the two beams go through a 2 m long low-field dipole that begins to separate the beams. It is followed by a septum magnet that acts on the low-energy beam only and completes the separation. A simpler alternative is to replace the septum by a strong dipole acting on both beams; however, this might not be feasible due to synchrotron radiation from the high energy beam.

The complete optics of the 2 GeV ring is shown in Figure 2. After the dipole and septum magnet, a quadrupole triplet and a doublet match the beams into the arc. The complete ring has a racetrack shape, with two semicircular arcs and two straight sections. The number of cells and their phase advances were chosen to achieve the design emittance.

Figure 3 shows a half sextant of the superperiod that contains the B-factory interaction region. After the triplet and low-field bend common to both beams, the rest of the IR is similar to that used now in PEP. The arc cells are tuned to produce the design emittance, the main triplet and the first few arc quadrupoles match the beam between the IP and the arc.

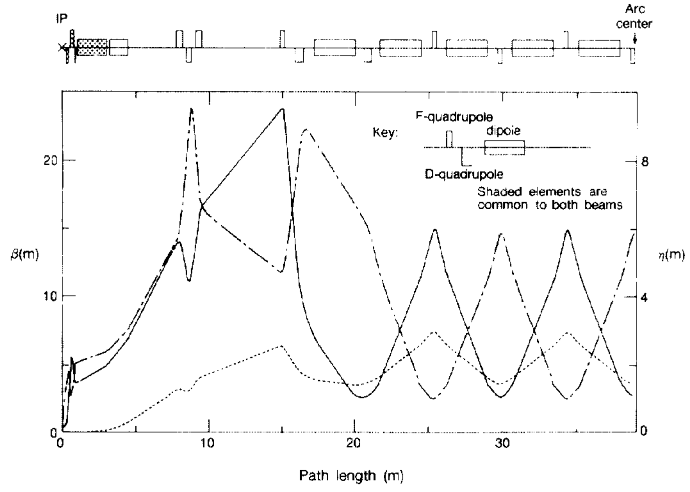

Figure 2. One quadrant of the low-energy ring.

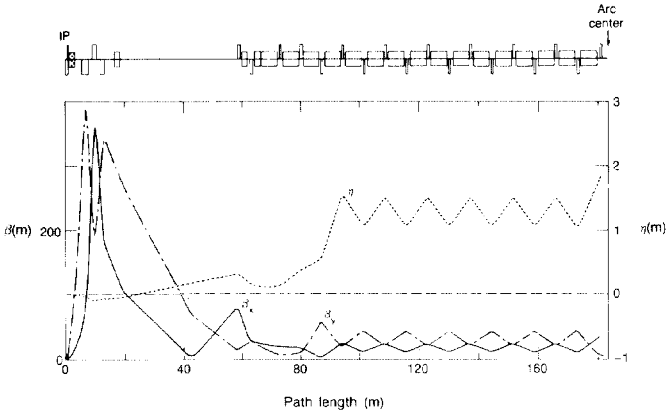

Figure 3. Half of the PEP sextant containing the B-Factory IR.

Beam current limitations

The Apiary I parameters have been examined briefly for possible beam current limitations by use of the ZAP program.[3]

Single-Bunch Thresholds

Single-bunch limitations arise from the longitudinal microwave and transverse mode-coupling instabilities. The former instability does not cause beam loss but could lead to a decrease in luminosity through bunch lengthening. In contrast, the mode-coupling threshold is a hard limit. For PEP, we take $|Z/n| = 3\Omega$ for the microwave instability and the same value, scaled to $Z \perp$, for mode coupling. This value is roughly compatible with experimental results for both phenomena.[4]

At 12 GeV, we expect the single-bunch current of 3.3 mA to be below the microwave threshold, so the rms bunch length will remain at its natural value, i.e., below 2 cm. The mode-coupling should not be a problem since the observed threshold in PEP at 14 GeV ranges from 8 to 14 mA.[5]

For the low-energy ring, assuming an impedance (including that from the RF) of 1.75 ohms, bunch lengthening about 10% beyond the natural value is expected, but this will not jeopardize the luminosity. Furthermore, transverse mode coupling should not be a problem. In the ALS, a similar ring, the calculated limit is 44 mA per bunch.

Lifetime

For PEP, the high beam energy makes the Touschek scattering process unimportant. For the low energy ring, the Touschek lifetime is estimated to be more than 10 hours.

Coupled-Bunch Instabilities

Wakefields induced by a circulating electron or positron beam in high-Q resonant structures, i.e., the RF cavities, can couple different bunches and induce unstable motion either longitudinally or transversely. For electron storage rings having high beam currents and short bunches, the growth rates can be quite fast – well beyond that of the counteracting radiation damping process. Estimates have been made for both rings, based on available information on the PEP RF cavity higher-order modes. It is assumed that the present RF frequency of PEP, 353 Mhz, will be used in the two rings.[6]

For PEP the predicted growth times for the longitudinal case are below 0.1 ms for the fastest-growing dipole (a=1) modes. Transverse growth is somewhat slower, 0.1-1 ms for the fastest-growing rigid dipole (a=0) modes. Both rates far exceed the radiation damping rates (about 8 ms and 16 ms for the longitudinal and transverse planes, respectively). Thus, some combination of mode damping, feedback and/or a modified RF system is clearly called for.

In the low energy ring – where there are fewer bunches and much less RF hardware is required – the story is similar but less severe. Predicted growth times in this case, based on PEP-like RF higher-order modes, are about 1 ms for the longitudinal instability (a=1) and about 10 ms for the transverse instability (a=0). It is likely that growth times on this order could be easily controlled with a suitable combination of feedback and damping.

Future possibilities

It is intended to seek a path to even higher luminosity. A large step can be made by reducing the energy asymmetry from 12 GeV × 2 GeV to 9 GeV × 3 GeV. The reduced separation of the decay B-mesons should be acceptable. The luminosity can then be significantly improved, mainly because the current in PEP can be increased a factor of three without exceeding the vacuum chamber wall-heating limit. With round rather than flat beams one can seek to exploit the $(1+r)$ factor in the luminosity formula (5). The round beams may cause an increase of the peak β-function value in PEP. However the Apiary I value is lower than present PEP operational values. Furthermore, by retuning the other five IRs, the present chromaticity can probobly be maintained. Parameters based on these considerations, which are being used in a new design study, are shown in Table II:

Table II Proposed new PEP B-factory parameters

		Beam 1.	Beam 2	
Energy	E	9.	3.	GeV
Bunch spacing	S_B	13.6	13.6	m
Particles per bunch	N_B	2.4×10^{11}	2.4×10^{11}	
Current	I	0.85	0.85	A
Emittances	ϵ_x	0.061	0.183	μm
	ϵ_y	0.061	0.183	μm
β-functions at IP	β_x^*	9.	3.	cm
	β_y^*	9.	3.	cm
Dispersion at IP	η^*	0.	0.	m
Beam-beam tune shifts	$\Delta\nu_x$	0.05	0.05	
	$\Delta\nu_x$	0.05	0.05	
Luminosity	$\mathcal{L}$	1.84×10^{33}		cm^{-2}s^{-1}
Circumference	$2\pi R$	2200.	299.	m

Further improvements require hardware changes, such as modifying the vacuum chamber and lowering the impedence from the RF. Further improvements require hardware changes, such as modifying the vacuum chamber and lowering the impedence from the RF. It should be noted that Porter has used a similar energy asymmetry in his parameter study.[7]

Acknowledgments

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