Critical Design Issues of e+e− Factories†

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Abstract

The design of a high-luminosity e^+e^- collider, referred to as a "factory," involves significant physics and technology challenges. One category of physics challenges is related to the design of low-beta optics to tightly focus the two beams and steer them into separate rings while maintaining reasonable chromaticity, avoiding problems with parasitic beam-beam collisions, and minimizing detector backgrounds. A second category of physics issues involves beam instabilities associated with producing the required luminosity by means of very high beam currents and many bunches. Technology issues are also important. High beam currents give rise to substantial photodesorption gas loads and, at high energies, substantial thermal loads as well. Providing short beam bunches at very high beam intensities places heavy demands on the RF system. To reduce the growth rates of potentially strong coupled-bunch instabilities, cavities must be designed to provide very low Q factors for the parasitic higher-order modes. Even for a well-optimized RF system, wideband multibunch feedback systems are generally needed to combat longitudinal and transverse coupled-bunch instabilities. Effective approaches to deal with these issues have been developed and representative examples will be described.

1. INTRODUCTION

There has been growing interest in the past several years in the design of a high-luminosity e^+e^- collider, operating at the Υ(4S) resonance, to serve as a "*B* factory." The primary physics motivation for such a facility is to determine the origins of *CP* violation. This phenomenon is expected to be easily observable in the *B* system, and determining its origins will provide a stringent test of the Standard Model. *CP*-violation studies benefit considerably from having a moving center of mass for the $B\overline{B}$ system, so an asymmetric collider is preferred. The physics capability of such a facility is not restricted solely to *CP*-violation studies; rich programs in rare *B* decays, Υ spectroscopy, charm and tau physics, and two-photon physics will also be available.

In recent years, all proposed designs have been storage ring based, so our focus is on this configuration. In particular, both of the recently funded projects PEP-II [1] and TRISTAN-II [2] use this approach.

2. TYPICAL PARAMETERS

To study *CP* violation at the Υ(4S) resonance with an asymmetric collider, a peak luminosity of 3×10^{33} cm^{-2} s^{-1} is taken as a design goal. The actual figure-of-merit for the collider, however, is not peak but *integrated* luminosity, because the physics measurements require the study of an abundant sample of *B* decays to obtain statistically significant results. It is in this sense that we refer to the collider as a "factory."

The luminosity can be expressed in terms of the appropriate collider parameters as [1]

$$\mathcal{L}\left[\mathrm{cm}^{-2}\mathrm{s}^{-1}\right] = 2.17\times10^{34}\xi(1+r)\left(\frac{I\cdot E}{\beta_y^*}\right)_{+,-} \tag{1}$$

where I is the total beam current (A), β_y^* is the vertical beta function at the interaction point (cm), r is the beam aspect ratio (σ_y^*/σ_x^*, i.e., 0 for flat, 1 for round beams), E is the beam energy (GeV), and ξ is the beam-beam tune shift parameter. The subscript on the rightmost factor in Eq. (1) signifies that it can be evaluated using the parameters from either the electron (–) or positron (+) ring. The beam-beam tune shift parameter is not really under our control, and the beam energy is constrained by the need to run at the Υ(4S) resonance, requiring that $E_+ \cdot E_- = 28$ GeV^2.

It is clear from inspection of Eq. (1) that a 15-fold increase in luminosity compared with existing colliders requires high beam currents and small beta functions at the interaction point (IP). The requirement for low beta functions leads to some practical difficulties. For example, low beta functions are produced by strong quadrupoles, and these make the chromaticity correction difficult. Moreover, to take advantage of the low beta functions, there is a concomitant need for short bunches, such that $\sigma_\ell \leq \beta^*$. To produce the short bunches takes a high RF voltage, and thus considerable RF hardware. Taken together, these considerations imply a practical limit corresponding to $\beta_y^* \approx 1$ cm.

Because of the limitation from the beam-beam interaction, that is, the limit on the maximum value of ξ, a large increase in beam current implies the use of many more bunches than typical of today's colliders. (Clearly it is possible to put high current in fewer bunches, but the single-bunch intensity is limited by the transverse mode-coupling instability, and the beam-beam limit pushes the design towards an unreasonably large emittance.) As discussed below, in the absence of experimental guidance from an asymmetric e^+e^- collider, a value of $\xi \approx 0.03$–0.05 is typically adopted as a design parameter. Given little maneuvering room, it is reasonable for the designer to choose the number of bunches to be sufficiently large that *the parameters of a single bunch remain relatively standard.* This is the approach generally followed by *B* factory design groups. Typical parameter ranges for the designs considered here appear in Table 1.

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Table 1.
Typical *B* factory parameter ranges.

Parameter	Value
Total current, I (A)	1–3
Single-bunch current, I_b (mA)	1–5
No. of bunches, k_B	100–2000
Horizontal emittance, ε_x (nm·rad)	100
Bunch length, σ_ℓ (cm)	1
Energy, E_-/E_+ (GeV)	8/3.5 or 9/3.1
Luminosity, $\mathcal{L}$ (cm^{-2} s^{-1})	1–3 × 10^{33}

To stay close to today's experience base, it seems wise to design an asymmetric collider to accommodate head-on collisions. The disadvantage of this choice is that it makes the separation of the two beams more difficult. Encouraging experimental results on colliding equal-energy beams with a few-mrad crossing angle have been obtained at Cornell [3]. Whether a crossing angle is part of the initial design or is viewed as an upgrade is up to the judgment of the designers. It is worth noting, however, that if unexpected difficulties develop in a collider with a crossing angle, it may be difficult to return to a head-on configuration—even for testing purposes—unless the possibility is designed in from the outset.

3. PHYSICS CHALLENGES

The design of a high-luminosity asymmetric *B* factory leads to physics challenges primarily in the areas of lattice design and the beam-beam interaction. In the first area, the issues are related to the production of low β_y^* values, the separation of the two beams, and the design of the masking system. In the second area, the physics issues are centered around the techniques for optimizing the luminosity for the new parameter regime of asymmetric collisions. There is a third category of physics challenges—beam instabilities—associated with the high beam current requirements. This issue is dealt with mainly by means of hardware solutions, and will be discussed in Section 4.

3.1 Lattice Design

Low beta function. To provide the required luminosity, it is necessary to produce low β_y^* values, on the order of 1 cm, without introducing excessive chromaticity into the lattice. To accomplish this, the low-beta quadrupoles must be located as close as possible to the IP, as shown in Fig. 1 for the PEP-II design [1]. As can be seen in Fig. 1, the low-energy ring (LER) focusing does not appear to present a problem, but the high-energy ring (HER) is more difficult. It helps in this case that the common quadrupole is sufficiently strong to provide some focusing for the HER also. This reduces the chromaticity contribution from the more distant HER quadrupoles to a manageable amount. Although the interaction region (IR) quadrupoles for the LER are close to the IP, they nonetheless generate substantial higher-order chromaticity. Dealing with this typically requires additional sextupole (and possibly octupole) families in the lattice. In PEP-II, the LER optics already provide dispersion near the IP, so sextupole families could be installed in the IR straight section itself. This is denoted as "local" chromaticity correction; the scheme is illustrated schematically in Fig. 2.

Because the LER focusing quadrupoles are close to the IP, they lie within the solenoidal field of the detector. This restricts the choice of technology to either permanent magnets or superconducting magnets. Solutions using one or both of these technologies have been adopted by various designers. When using permanent magnets, as in Fig. 1, coupling is compensated with skew quadrupoles located outside the detector region. The placement and dimensions of the low-beta quadrupoles are restricted by the "detector stay-clear" area, usually defined as a 300 mrad cone.

Beam separation. The technique used for beam separation in an asymmetric *B* factory depends in large measure on the design approach. For the head-on collision case, the separation is accomplished by means of dipoles located close to the IP followed by offset quadrupoles. The separation dipoles could

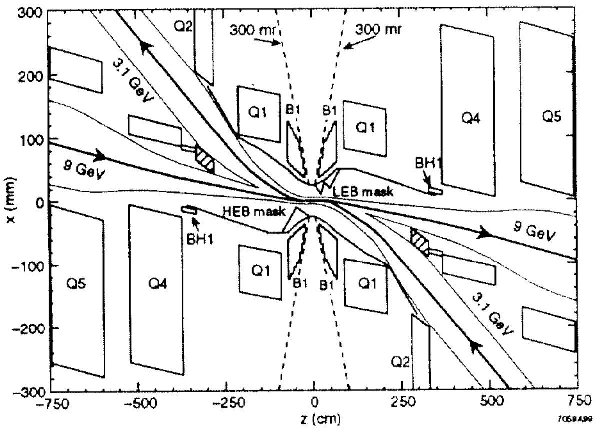

Figure 1. Anamorphic plan view of the PEP-II IR for head-on collisions.

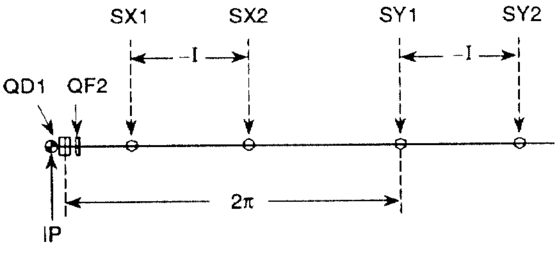

Figure 2. Local chromaticity correction scheme for PEP-II LER.

either be run in a symmetric or an antisymmetric configuration; the latter case, illustrated in Fig. 1, is referred to as an "S-bend" geometry. The advantages of the S-bend geometry are that it decouples the masking solutions for the two rings, and that it permits the synchrotron radiation fans generated by the separation magnets to exit the interaction region without creating severe background problems. It is worth noting here that an S-bend layout such as that shown in Fig. 1 is well suited to being converted into a non-zero crossing angle scheme without major hardware rearrangements.

A major issue in designing a beam-separation scheme is that of parasitic collisions. Both experiments [4] and simulations [1] show that a beam separation in excess of 7σ is required in order to avoid beam blowup and particle loss associated with the parasitic collisions. Because the bunch spacing is small (typically 1–3 m), there is not much space available to separate the beams, so rather strong bending is needed. The IR design in Fig. 1 provides a separation of 11.4σ at the first parasitic collision point (s = 63 cm). The benefit of even a small crossing angle at the IP in increasing the separation is clear, and that is generally what motivates this design choice.

3.2 Beam-Beam Interaction

Choice of Tune Shift. The beam-beam tune shift in the case of an asymmetric collider has not been studied experimentally. In the absence of such data, most design groups have taken guidance from the existing body of data on symmetric collisions [4]. It can be seen from such data that the beam-beam tune shift parameter ξ lies in the range from 0.02 to 0.06 for present colliders. Because most machines have reached $\xi = 0.03$, this value has generally been adopted by *B* factory design groups as a target figure. (The TRISTAN-II design [2] has adopted a larger tune shift value of 0.05, based on their choice to use very short bunches, 0.5 cm.) Note that this value does *not* represent a beam-beam limit, but is merely a design parameter. Beam-beam simulations are carried out to demonstrate that the design choice is a realistic one. Thus far, it is fair to say that no new physics issues have arisen that are related to the energy asymmetry itself.

Crab Crossing. To permit a non-zero crossing angle while avoiding the excitation of synchrobetatron resonances, it is attractive to consider the possibility of crab crossing. This scheme [5] involves the use of a transverse deflecting mode of crab RF cavities, located at a phase difference of $\Delta\phi = (n \pm 1/4)\,2\pi$ from the IP, to rotate the head and tail of the bunches such that they collide head-on at the IP, but in a transversely moving reference frame.

The voltage required to perform the rotation is given by

$$V_c = \frac{(E/e)\phi\lambda_c}{2\pi\sqrt{\beta_{xc}\beta_x^*}} \qquad (2)$$

For typical parameters, V_c is about 2 MV. Simulations done to date [6] suggest that voltage and phase tolerances are reasonable, so the technique should be viable. If one adopts a small crab angle, on the order of 10 mrad, there remains the need for common quadrupoles for the two beams. It is clear that crab crossing is a promising, though untested, technique. Because of the absence of separation dipoles, the synchrotron radiation liberated near the IP is reduced with the crab crossing scheme compared with the head-on case; this may be of benefit in terms of reduced detector backgrounds.

Luminosity Lifetime. In addition to standard studies of the beam cores, the study of the beam tails under the influence of the beam-beam interaction is important. Though the core particles determine the luminosity, it is the tail particles that determine the lifetime and influence detector backgrounds. In a typical simulation with a few hundred superparticles, the tails cannot be studied with any statistical accuracy. However, recently developed algorithms [7] permit such studies to be made efficiently. From such studies it appears that the parasitic crossings do not have a large effect on the beam lifetime. A vertical aperture in excess of $6\sigma_y$ (fully coupled) is required to maintain a 3-hour lifetime when the effects of parasitic collisions are included in the simulations.

4. TECHNOLOGY CHALLENGES

The physics issues discussed in Section 3 make certain implicit assumptions about the hardware capabilities in a *B* factory. For example, beam lifetime estimates assume that the average pressure in the storage rings will remain below about 10 nTorr (N_2 equivalent) despite the high gas loads associated with possibly several amperes of circulating beam. Similarly, luminosity estimates assume that these high beam currents can be supported without melting anything. The assessment of growth times for coupled-bunch instabilities is based on the ability to damp the dangerous HOMs of the RF cavities to $Q \leq 70$. Perhaps most importantly, we assume that the integrated luminosity can be maintained, that is, that the reliability of the components is such that the collider does not "spend all of its time in the shop."

In this section we discuss the technology areas where the main challenges arise. These include the vacuum system, the RF system, and the feedback system. It is worth commenting here that some other items, such as the separation magnets indicated in Fig. 1 (and the equivalent components in the TRISTAN-II IR), are nontrivial engineering tasks as well.

4.1 Vacuum System

The main challenges for a *B* factory vacuum system are:

- withstanding the high thermal flux from the synchrotron radiation
- maintaining a low pressure in the face of considerable synchrotron-radiation-induced gas desorption

The average linear power density for the chamber is

$$P_L = \frac{P_{SR}}{2\pi\rho} \propto \frac{E^4 I}{\rho^2} \qquad (3)$$

This quantity can vary widely among different designs, as it depends on both the beam current and the bend radius of the ring magnets. The linear power density of the PEP-II HER is 3.3 kW/m at its nominal intensity, and that of TRISTAN-II is even lower, 1.5 kW/m. In terms of thermal management, the more important quantity is typically the areal density. The height of the synchrotron radiation fan at the chamber wall is typically about 0.4 mm, in which case the areal power densities range from 0.4 to 0.8 kW/cm^2. Especially for the LER of a *B* factory, the possibility exists of using an antechamber with discrete photon stops (see Fig. 3). With this approach, there is more flexibility in tailoring the power density by adjusting the slope of the photon stop and its distance from the source of synchrotron radiation. Moreover, the photon stop can be fabricated from stronger materials, such as dispersion-strengthened copper.

The photodesorption gas load in the *B* factory rings can be written as

$$Q_{\mathrm{gas}} = 2.42 \times 10^{-2} \, E_{[\mathrm{GeV}]} \, I_{[\mathrm{mA}]} \, \eta \quad [\mathrm{Torr{\cdot}L/s}] \tag{4}$$

where the desorption coefficient, η, represents the number of molecules produced per incident photon. The desorption coefficient depends on the chamber material, its history, and the photon dose to which the material has been exposed. After exposure to about 100 ampere-hours of beam, values of low-to-mid 10^{-6} are observed for a copper chamber or photon stop.

As noted, the two approaches that can be adopted for a *B* factory are a standard chamber shape, with a pumping channel on the inner radius, or an antechamber design in which the synchrotron radiation exits through a slot in the outer wall into an external pumping chamber. For cases where the design pressure can be achieved with a pumping speed S ≈ 100 L/s/m, no antechamber is needed. For cases where S ≥ 500 L/s/m is required, standard distributed ion pumps will not suffice. Then the system of choice is non-evaporable getter (NEG) pumps or titanium sublimation pumps (TSPs). In the case of discrete photon stops, the pumping configuration can take advantage of the localization of the gas source to concentrate high-speed pumping directly there, eliminating the usual problems with conductance limitations.

Most designers favor a chamber made of copper or a copper alloy. In addition to the low desorption coefficient mentioned above (about 10 times lower than for aluminum), copper has good thermal properties and offers better shielding for synchrotron radiation than does aluminum (thus obviating the need for a lead liner on the outside of the chamber). It is worth noting, however, that the shielding requirements in a *B* factory depend on what components need to be shielded. The tolerance of magnet coils to radiation damage is quite high if a radiation-resistant epoxy formulation is used (100 Mrad/yr for 30 years is considered acceptable) but that for beam position monitor electronics or power supplies in the tunnel is much lower (≈1 krad/yr). Thus, if electronics is to be placed in the tunnel, either thick copper or a lead shield is likely to be required.

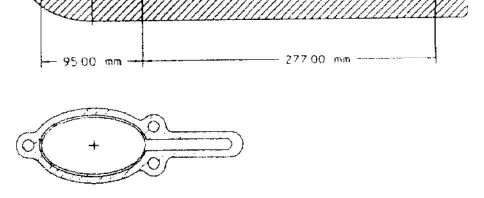

Figure 3. Antechamber vacuum system for PEP-II LER.

In any vacuum chamber design, special care must be taken to avoid shape changes of the beam chamber and to shield all discontinuities in order to minimize beam impedance. Techniques for doing this are now rather well understood and simply require attention to detail. Clearly, the high currents in a *B* factory demand that this be done especially carefully.

4.2 RF System

The main challenges for the RF system include:

- replacing the large synchrotron radiation power loss
- minimizing the total HOM impedance

Synchrotron radiation losses for an 8 or 9 GeV beam in the HER of a *B* factory could be 5 MW at a luminosity of 3 × 10^{33} cm^{-2} s^{-1}. The issue is not the power per se, but is related to the need for controlling the HOM impedance by reducing the number of cavities. This results in a requirement for high input power through the cavity window—up to 500 kW for a room-temperature system. (To put this value in context, it is only half of the power transmitted through the output window of a modern klystron.) Special windows are being designed to handle this power level.

To combat coupled-bunch instabilities, it is important to minimize the HOM impedance of an individual cavity by damping techniques (in order to ensure practical feedback system parameters). Coupled-bunch instabilities result from wakefields resonant in high-Q objects in the ring (usually RF cavities) that are strong enough to deflect the beam and drive it unstable. The strength of the wakefields scales with the beam current; they are nearly unavoidable in the *B* factory parameter regime. The combination of damping the cavity HOMs and providing active feedback is sufficient to handle this problem.

Both room-temperature [1,2] and superconducting [8] cavity designs have been considered for *B* factory use. In the room-temperature case, either single- [1] or three-cell [2] cavities are contemplated. Waveguides or slots in the cavity body are used to couple out the dangerous HOMs. With this technique, damping to a Q of about 30 has been demonstrated (at low power) [9]. It is not possible to use the waveguide technique with superconducting cavities, but in this case it is not necessary to optimize the shunt impedance of the cavity and a large beam aperture is acceptable. In the Cornell approach, the aperture is sufficiently large that HOMs propagate to a room-temperature ferrite load on the inner surface of the beam tube. Measured damping to the level of $Q \approx 70$ was obtained [10].

The choice of superconducting technology would minimize the number of RF cells required. However, in the heavily beam loaded regime of a *B* factory, the advantage is only about 30% (assuming the same limitation on cavity window power as in the room-temperature case). In a design involving crab cavities, the use of superconducting technology would likely be preferred. For this application the requirements—high voltage and low power—match well with the strengths of superconducting RF. To serve as a crab cavity, the cell must be driven at a transverse deflecting mode (TM110) rather than at the fundamental. In this case there is a parasitic "lower-order mode" (the fundamental TM010 mode) to be damped.

4.3 Feedback System

The requirement here is to control the growth of potentially strong coupled-bunch instabilities driven by the HOMs of the RF system. Even for highly damped RF cavities, the high beam current and large number of bunches can give rise to instabilities that grow rapidly ($\approx$1 ms). Because of the closely spaced bunches, the bandwidth requirements are high ($\approx$100–250 MHz). It is worth noting that the response of the feedback system to injection transients may dominate the power requirements. This consideration favors an injection system that is phase-locked to the ring RF systems. It also helps to inject the beam in many small portions rather than injecting large amounts of charge all at once.

A promising approach uses bunch-by-bunch feedback operating in the time domain [11]. Such a system can potentially damp motion from any source, including injection transients and beam-beam disturbances as well as coupled-bunch instabilities. Recent operational tests of such systems have proved their usefulness [12].

5. SUMMARY AND OUTLOOK

The construction of a high-luminosity asymmetric *B* factory provides excellent scientific opportunities, combining first-rate particle physics incentives (to study the origins of *CP* violation) with equally exciting challenges in both the accelerator physics and accelerator technology areas. Challenges in accelerator physics include:

- development of lattices to collide and then cleanly separate two unequal energy beams
- achieving high luminosity in asymmetric collisions

Challenges in accelerator technology include:

- designing vacuum systems capable of handling large thermal loads, providing adequate pumping speed, and having acceptable impedance characteristics
- designing RF systems capable of handling high beam power and providing greatly reduced HOM impedance
- designing wideband bunch-by-bunch feedback systems

Effective approaches to all of these have been identified and R&D activities have been vigorously pursued at many laboratories to optimize designs and finalize design choices. Extensive simulation studies of accelerator physics issues have also been carried out to better understand the beam-beam interaction and beam instabilities.

It is recognized that making a large jump in luminosity is not an easy task. Perhaps the most important ingredient in ensuring the success of a *B* factory—or any high-luminosity e^+e^- collider—will be to remember to treat these challenges with proper respect.

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