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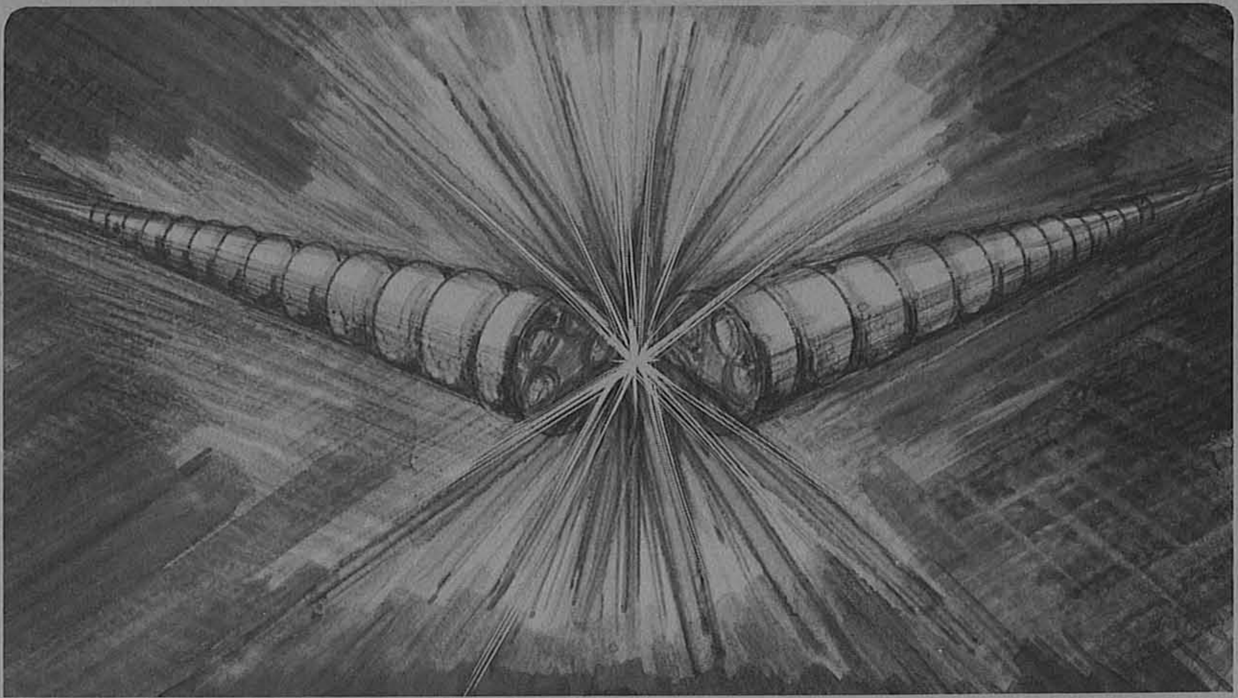

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GENERAL *B* FACTORY DESIGN CONSIDERATIONS†

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Abstract. We describe the general considerations that go into the design of an asymmetric *B* factory collider. Justification is given for the typical parameters of such a facility, and the physics and technology challenges that arise from these parameter choices are discussed. Cost and schedule issues for a *B* factory are discussed briefly. A summary of existing proposals is presented, noting their similarities and differences.

1 Introduction

For the past few years, there has been intense interest [1–8] in the design of a high-luminosity electron-positron collider to serve as a "*B* factory." The primary physics motivation for such a facility is to carry out a detailed and systematic study of the origins of *CP* violation, a phenomenon that is thought to be responsible for the dominance of matter over antimatter in the Universe. It is anticipated that this effect will be large in the $B\overline{B}$ system, making a *B* factory the ideal platform from which to launch such a study.

It was pointed out some years ago by Oddone [9] that the key to studying *CP* violation in the $B\overline{B}$ system was to create a moving center-of-mass. This could be achieved by building a so-called "asymmetric" collider, in which the electron and positron energies are different. With such an approach, the B and $\overline{B}$ decays can be separated spatially with modern silicon vertex detectors, permitting the easy reconstruction of their time difference. To enhance the cross section for producing the particles, we will focus here on colliders designed to operate at the Υ(4S) resonance, requiring a center-of-mass energy of 10.6 GeV. In terms of machine parameters, this requirement means that the product of the two beam energies must be $E_+E_- = 28$ GeV^2. As is obvious, the requirement of asymmetric beam energies dictates a two ring collider. We will see later that other *B* factory parameters also lead to the requirement for two independent rings.

The required energy asymmetry for a *B* factory is a trade-off among competing

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factors. A large energy asymmetry gives a higher boost to the decaying particles and thus makes it easier to separate the decays in the vertex detector. However, the solid angle for detection decreases as the decaying particles are kinematically focused into the forward direction (where it is difficult to detect them due to interference with the collider optical elements and beam pipe). There are equivalent trade-offs to be made in terms of accelerator design. In general, a larger energy asymmetry simplifies the beam separation optics in the interaction region (IR), as discussed in Ref. [10], but makes the beam current requirement more difficult to meet and tends to make the difference in synchrotron radiation damping times between the two beams quite extreme. We will return to these points later when we discuss the parameter choices for a *B* factory. For now, we simply note that the energy asymmetry studied by various designers has ranged from 6.5/4.3 to 12/2.3.

The other parameter we must consider for a *B* factory is the luminosity, $\mathcal{L}$. Based on a number of studies carried out in the past few years [11], it is generally agreed that a peak luminosity of $\mathcal{L} = 3 \times 10^{33}$ cm^{-2} s^{-1} is required for the study of *CP* violation. In reality, however, it is the *integrated* luminosity that is the proper figure-of-merit for a *B* factory. This is because the *CP* violation studies require an abundant sample of $B\bar{B}$ pairs. We consider the luminosity requirement to correspond to an integrated luminosity (over a "standard" year of 10^7 seconds) of:

$$\int_{\text{year}} \mathcal{L} \cdot dt = 3 \times 10^{40}\ \text{cm}^{-2} = 30\ \text{fb}^{-1} \tag{1}$$

This is the meaning—and the challenge—of the "factory" aspect of a *B* factory.

In Section 2 of this paper we discuss the typical parameters of a *B* factory collider and the motivations for them. Section 3 will indicate the design approach that should be followed to achieve high integrated luminosity. In Section 4 we discuss the physics and technology challenges that result from the parameter choices arrived at in Section 2. Section 5 covers the typical construction scenario and cost issues for a *B* factory project. In Section 6 we briefly summarize the present status of existing *B* factory proposals and comment on their similarities and differences. Summary remarks are given in Section 7.

2 Typical Parameters

The luminosity of a *B* factory collider can be expressed in terms of the beam intensities of the electron and positron beams (N_- and N_+, respectively), the collision frequency (f_c), and the cross-sectional area of the beams at the interaction point ($4\pi\sigma_x^*\sigma_y^*$), as:

$$\mathcal{L} = \frac{N_+ N_- f_c}{4\pi\sigma_x^*\sigma_y^*} \tag{2}$$

However, for machine design purposes, we write the luminosity in a different way that calls out explicitly the dependence on machine parameters (the +,– subscripts refer to the e^+ and e^- rings, respectively) with which the accelerator physicist deals:

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

where I is the total beam current in one of the rings, β_y^* is the vertical beta function at the interaction point (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 design value for the beam-beam tune shift.

An important justification for writing the luminosity expression as in Eq. (3) is to call out the dependence on the beam-beam parameter, ξ, which has proved empirically to be a limit in all colliders [12]. In terms of the other beam parameters, the actual expressions for the beam-beam tune shift are:

$$\xi_{y,+} = \frac{r_e N_- \beta_{y,+}^*}{2\pi \gamma_+ \sigma_{y,-}^* \left(\sigma_{x,-}^* + \sigma_{y,-}^* \right)} \tag{4a}$$

$$\xi_{x,+} = \frac{r_e N_- \beta_{x,+}^*}{2\pi \gamma_+ \sigma_{x,-}^* \left(\sigma_{x,-}^* + \sigma_{y,-}^* \right)} \tag{4b}$$

Although we indicated that the various parameters in Eq. (3) are available to be adjusted, in reality a number of them are constrained by other considerations. We have already commented on the accelerator physics limit associated with ξ. The beam aspect ratio, r, is also constrained, in this case by detector background considerations. The potential benefits of using a round beam are twofold. First, it appears by inspection of Eq. (3) that this choice would reduce by a factor of two the beam current required for producing a given luminosity. A second benefit may be an increase in the allowable beam-beam tune shift for round beams. This was predicted by Krishnagopal and Siemann [13], who estimated that $\xi \approx 0.1$ may be reachable. This aspect remains to be confirmed experimentally. Despite the possible advantages, early studies based on a round-beam ($r = 1$) design [14] showed that the required focusing and beam separation optics produced a prodigious amount of synchrotron radiation power (about 0.75 MW) in the region within a few meters of the IP. A masking solution to deal with this problem would be, at best, quite difficult. Furthermore, the assumption of a factor of two reduction in beam current for the same luminosity is predicated on being able to keep the same value for the vertical beta function in the round-beam case. As has been observed by Willeke [15], the total chromaticity that can be handled in the ring is roughly fixed, so the minimum beta that can be tolerated in the standard flat-beam ($r \approx 0$) case will in general be about half that for a round-beam case, eliminating the perceived advantage. For now, it does not seem that the benefits of round beams are sufficient to compensate for the practical difficulties of creating them, and this option has not been followed by any of the *B* factory design teams.

Finally, the beam energies themselves are constrained by the need to operate at the Υ(4S) resonance, as discussed in Section 1. Therefore, the product of the two beam energies is fixed and there is relatively little adjustment possible. Thus, we see that only the beam currents and beta functions are really free parameters in the optimization of luminosity.

At the present time, the beam-beam interaction has not been studied experimentally for the case of asymmetric electron-positron energies. Therefore, lacking data on such collisions, we take our guidance from the observations in symmetric energy colliders [12]. For design purposes, most groups have adopted a beam-beam tune shift value of $\xi = 0.03$ for both beams in both transverse planes. The choice of equal tune shifts for both beams in both planes reduces the number of free parameters but is not otherwise justified on theoretical grounds. It is worth noting, however, that the adopted ξ value should be thought of, at this stage, as a *design value* rather than an actual beam-beam limit.

Most designers have also adopted a head-on collision configuration. Here too, the primary motivation is that this is the configuration we are familiar with from symmetric colliders. Recently, there have been theoretical arguments suggesting that a small crossing angle will not lead to excessive excitation of synchrobetatron resonances and therefore will not reduce the obtainable beam-beam tune shift. Experiments under way at CESR [16] are consistent with only a small decrease in ξ for an uncompensated crossing angle of 2.5 mrad.

A new possible scheme to collide two beams at a non-zero crossing angle without exciting synchrobetatron resonances has been proposed by Palmer [17] for linear colliders and subsequently extended to the circular collider case by Oide and Yokoya [18]. The technique is referred to as "crab crossing." The concept is to apply a transverse kick to each bunch by means of an RF cavity located an odd multiple of $\pi/4$ in phase advance from the IP. If the kick tilts the bunch by $\theta/2$, where θ is the full crossing angle, then the bunches pass through each other head-on in their center-of-mass system and excitation of synchrobetatron resonances is avoided. For a storage ring one uses a pair of transversely deflecting cavities ("crab cavities") located symmetrically about the IP, the first to tilt the bunch and the second to cancel the tilt. Studies of such a system show that the tolerances appear achievable [19] and designs for such cavities are under study at Cornell [20]. Nevertheless, the fact that there is no experience with the technique has convinced most *B* factory design groups to treat crab crossing as a "phase 2" option.

For now, all that can be done to justify the choice of the beam-beam tune shift parameter is to carry out simulations to show that the adopted choice is reasonable. Typical beam-beam simulation results for the PEP-II collider design, taken from Ref. [21], are shown in Fig. 1. It is fair to summarize the present situation by saying that there is no indication of any new physics issues associated with the asymmetric beam energies. It is also noteworthy in this regard that the HERA electron-proton collider, which is exceedingly asymmetric in terms of both energy and damping time, has not shown any surprises in terms of the single-bunch beam-beam behavior [22].

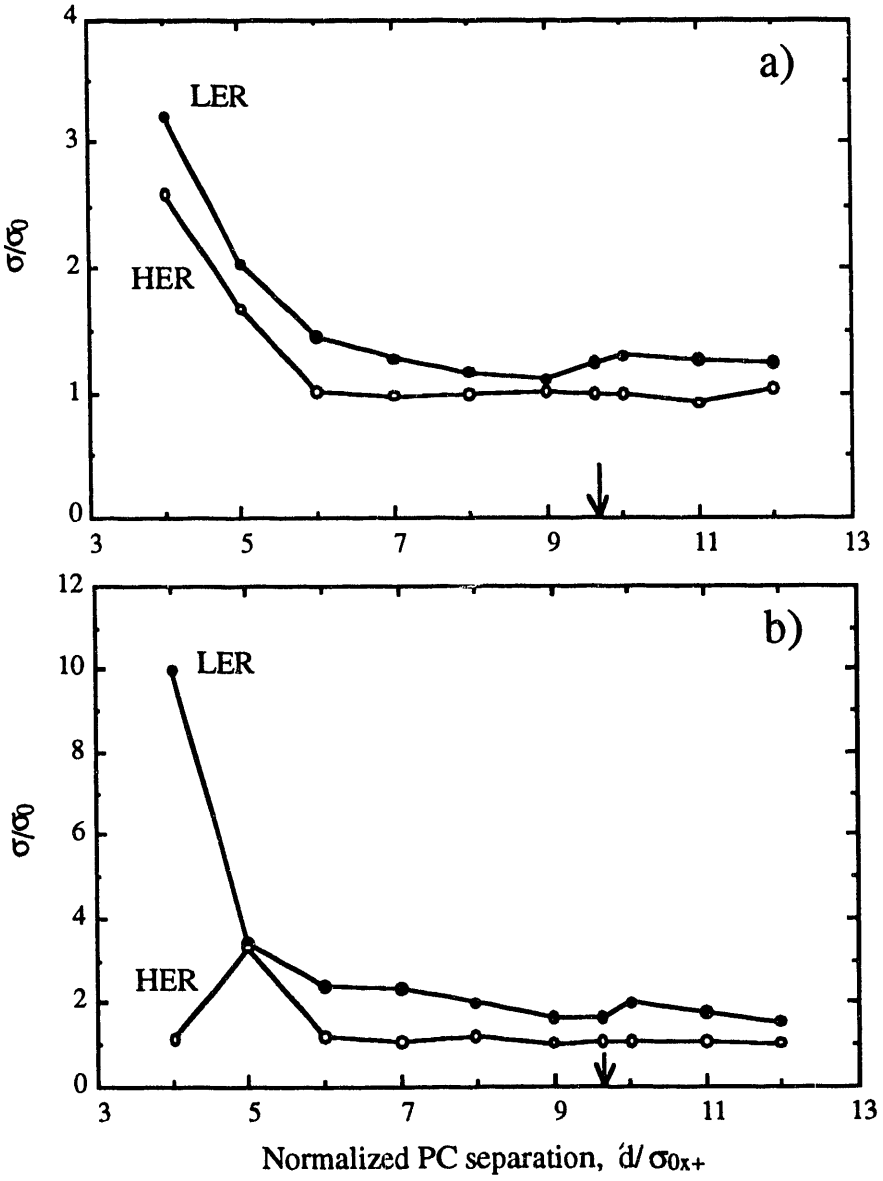

Fig. 1. Beam-beam simulation results for the PEP-II collider, showing vertical beam blowup (horizontal blowup is negligible) as a function of separation distance at the parasitic crossing (PC) points. The nominal separation distance is shown by the arrow. Case a) is for a beam-beam parameter of 0.03 and results in a luminosity of 2.9 × 10^{33} cm^{-2} s^{-1}. Case b) is for a beam-beam parameter of 0.05 and results in a luminosity of 5.7 × 10^{33} cm^{-2} s^{-1}.

As noted in Section 1, to achieve the physics goals of a *B* factory requires a peak luminosity of $\mathcal{L} = 3 \times 10^{33}$ cm^{-2} s^{-1}. This is a factor of about 12 beyond that of today's highest luminosity collider, CESR. We showed above that the constraints on other parameters imply that such a big increase in luminosity can only come from higher beam currents and smaller beam sizes (lower beta functions) at the IP.

The design implications of this conclusion are summarized in Fig. 2. High beam currents give rise to a large gas load arising from synchrotron-radiation-induced photodesorption, and thus to the requirement for a very powerful vacuum system. Given the high current, we must determine how to distribute it into individual beam bunches. There are two issues to consider. The first is that of single-bunch instabilities. Those with which we must be concerned are the "longitudinal microwave" instability and the "transverse mode-coupling" instability.

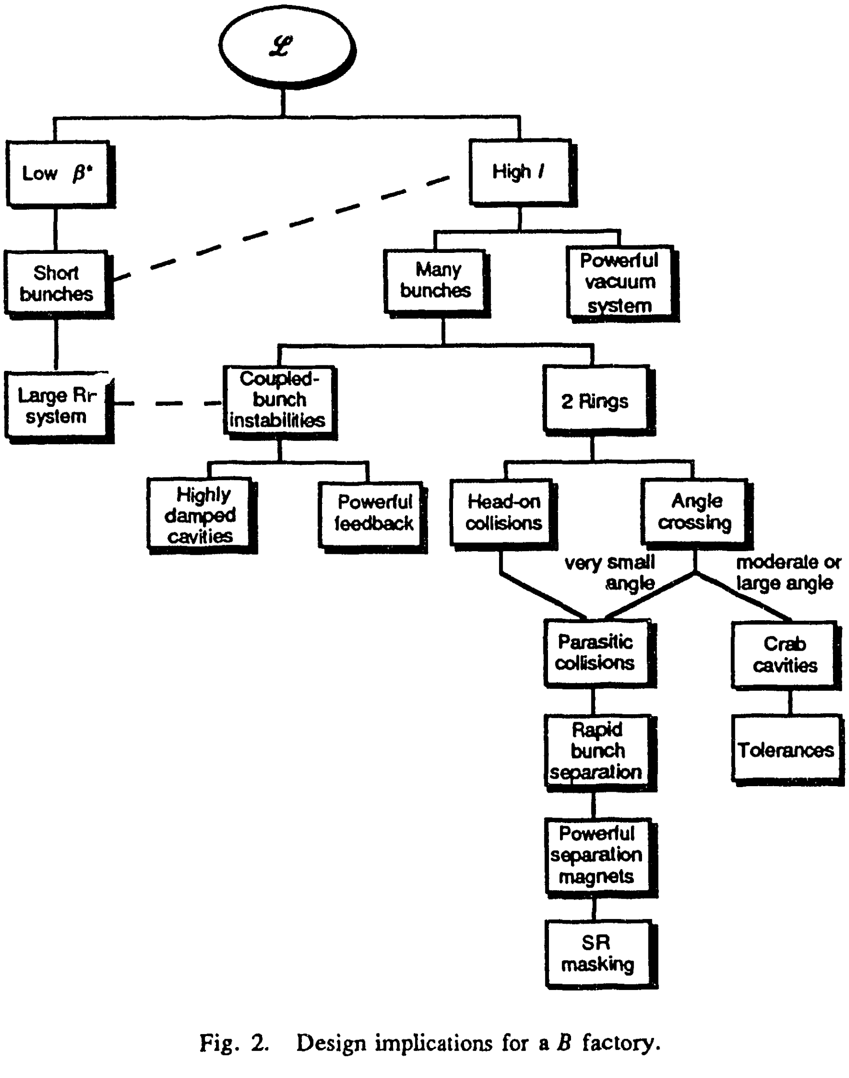

Fig. 2. Design implications for a *B* factory.

The longitudinal microwave instability does not lead to beam loss but to an increase in the bunch length and momentum spread when the single-bunch current exceeds a threshold value [23]. Insofar as we require short bunches to avoid luminosity loss from the hourglass effect [24] and a reasonably small momentum spread to take good advantage of the resonant cross section, it behooves us to keep the single-bunch current below the threshold value. The transverse mode-coupling instability [25] is a more serious constraint, as it limits the current that can be stored in a single bunch.

Although a detailed description of these effects is beyond the scope of the present paper, we note that for either instability the only practical approach to increasing the threshold current is to decrease the broadband longitudinal or transverse impedance of the ring. Given that today's rings are already designed with quite low impedance, reducing the impedance sufficiently to accommodate a factor of 10 increase in single-bunch current is certainly easier said than done. Thus, the single-bunch instabilities in practice preclude a few-bunch, high-current operating mode for a *B* factory and we are led to a many-bunch configuration.

The limitation on the beam-beam tune shift discussed above also means that the luminosity increase must come from more—as opposed to higher intensity—bunches. The reason is that, for a given beam-beam tune shift, the increased current must correspond to an increase in the beam emittance (as implied by Eq. (4)). In today's colliders, the typical beam emittance (limited by reasonable magnet dimensions) is $\varepsilon_x \approx 100$ nm·rad. To increase the beam current by a factor of 10–20 in the same number of bunches would require magnet gaps 3–5 times larger than standard values—an expensive proposition.

It should be clear from the above arguments that a solution with many bunches is inevitable for a *B* factory. This puts us in the regime where coupled-bunch instabilities are of primary concern to the designers. It turns out, however, that the growth rates for coupled-bunch instabilities [26] are determined mainly by the *total* beam current, and depend only weakly on the distribution of that current into different bunch patterns. With this in mind, we are free to choose the number of bunches such that the single-bunch thresholds are not exceeded for reasonable values of broadband impedance. (Increasing the number of bunches is not totally without penalty in terms of coupled-bunch instabilities, because the bandwidth required for a multibunch feedback system increases as the bunch separation decreases, but this is not a significant limitation with modern technology, as will be discussed below.) There is nonetheless a lower limit to the acceptable bunch separation determined by consideration of the parasitic crossings. The general rule-of-thumb is that the beam separation at the parasitic crossing points should be at least 7σ [16]. In present designs, the bunch separation distance, s_B, falls in the range of 0.6–12 m.

The requirement for a low β^* value also implies the need for short bunches ($\sigma_\ell < \beta^*$) to avoid luminosity loss from the hourglass effect [24]. This, in turn, means that a high RF voltage is needed, and thus a large RF system. Because the impedance from the RF cavities is the main driving source for coupled-bunch instabilities, there is an intrinsic conflict between the need for high currents and for short bunches.

Based on the considerations discussed in this Section, we can summarize the typical *B* factory parameter choices as indicated in Table 1.

Table 1. Typical *B* factory parameters for $\mathcal{L} = 3 \times 10^{33}$ cm^{-2} s^{-1}.

ε_x [nm·rad]	100
I_b [mA]	1 – 5
σ_ℓ [cm]	0.5 – 1
I [A]	1 – 3
No. of bunches	100 – 2000

3 Design Approach

Before describing the technical details of a *B* factory, it is worth digressing briefly here to discuss the more "philosophical" issue of the proper way to approach the design of such a facility. The main message to give is that it is important to take the "factory" aspect seriously in order to provide the required integrated luminosity. To do so, it is a reasonable goal to minimize the extrapolations we must make in accelerator design. Clearly, however, this goal will be at odds with the desired extrapolation we wish to make in accelerator *performance*. The reality is that we cannot avoid doing *some* new things in order to provide a high-luminosity asymmetric collider, but we can—and should—pick our spots carefully. That is, we should strive in the design of a *B* factory to avoid problems we already know how to solve and save our strength for the inevitable surprises.

Another important idea is that it is crucial to design in reliability from the outset. This can be accomplished, for example, by making hardware designs modular to facilitate debugging, repair and replacement. Another method to improve reliability is to have in place—at the outset—good diagnostics hardware and a control system that can interpret it. Given a real-world commissioning scenario, it is also crucial to have a powerful injection system that permits quick recovery from the inevitable beam losses.

Lastly, it is important to have a design with sufficient flexibility to maintain "maneuvering room" in parameter space. As examples, it is important to design the vacuum system for beam currents that are higher than nominal, to design feedback systems to cope with expected (or unexpected) instabilities, to design the lattice to permit easy adjustment of the emittance and damping time, and to design the IR layout to accommodate either head-on collisions or a non-zero crossing angle.

In all of the designs discussed in this paper, parameters have been chosen to keep the challenges primarily in the realm of engineering rather than accelerator physics. The reason for this is not so much that the engineering aspects are easy, but that they are more amenable than the physics issues to being verified and optimized via suitable R&D. Put another way, thermal loading on the beam pipe is considerably more reliably estimated than the beam-beam effects.

4 Design Challenges

The design of a high-luminosity *B* factory gives rise to both physics and technology challenges [27]. In practice, the various design choices are interrelated. The proper optimization for a particular site is the "art" of the accelerator design.

4.1 Physics Challenges

We noted earlier that the *B* factory parameter regime of asymmetric energies, high beam currents, and many bunches forces the facility to be a two-ring collider. A two-ring collider leads to physics challenges in several areas.

In terms of lattice design, the issues to be dealt with include:

- providing low $\beta*$ values for both beams while maintaining adequate dynamic aperture
- providing rapid beam separation to avoid luminosity or lifetime degradation
- providing adequate masking both for synchrotron radiation and for lost particles due to beam-gas interactions or injection losses.

These issues are covered in detail in Refs. [10] and [28] and will not be discussed here.

Physics challenges also exist in the area of the beam-beam interaction. In a nutshell, the issue here is how to optimize the luminosity for an asymmetric, two-ring collider. Compared with single-ring colliders, a *B* factory has many more parameters that can be adjusted. In principle, the beam sizes, intensities, aspect ratios, beam-beam tune shift parameters, synchrotron tunes, betatron tunes, bunch lengths, etc., are all independently adjustable in the two-ring case. Optimization of a design in this larger parameter space is just beginning. As a practical matter, most designs have made use of some version of so-called "energy transparency" conditions [29, 30]. These are intended to make the two beams behave symmetrically with respect to the beam-beam interaction, and also serve to limit the parameter choices to a manageable number. In general, the beam-beam tune shifts, fractional betatron tunes, beam sizes at the IP, synchrotron tunes, and aspect ratios are all held equal for the two beams, and the damping decrements (damping rate between collisions) and $\beta*$ values are sometimes made equal as well.

There are two other aspects of *B* factory design associated with the necessity of a two-ring collider. The first is to keep the beams in collision—a condition that cannot be viewed as "automatic" in a case with two independent rings. Effects that can differentiate between the two rings include thermal motion, mechanical vibration, and power supply drifts. Moreover, there is no guarantee that the two relatively flat beams will not be tilted with respect to each other, as illustrated schematically in Fig. 3. As demonstrated in Fig. 4, for a given tilt angle the luminosity decreases rapidly

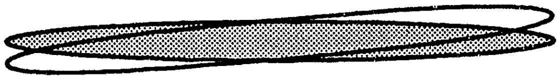

Fig. 3. Schematic illustration of bunches tilted at the IP.

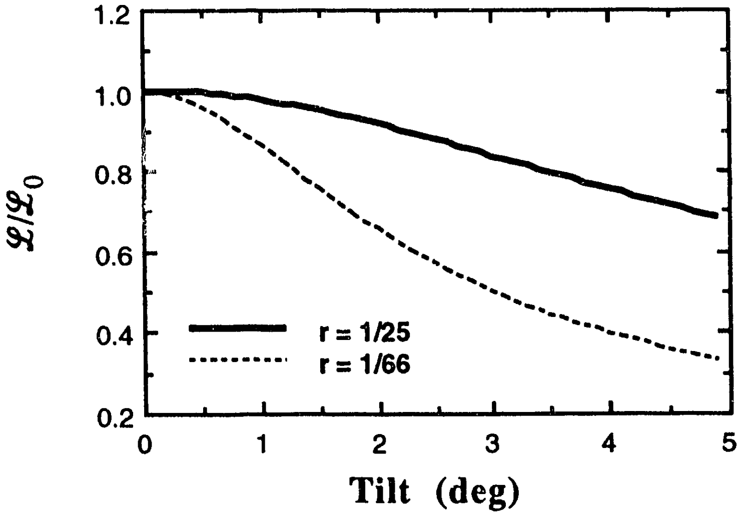

Fig. 4. Sensitivity of luminosity to relative beam tilt illustrated in Fig. 3.

as the aspect ratio of the two beams, *r*, gets smaller. Techniques for utilizing the beam-beam effect to diagnose such alignment problems are being developed [31]. Secondly, we must pay attention to minimizing the deleterious effects of the parasitic crossings. In addition to the obvious approach of increasing the separation distance, a prudent choice of betatron tune can also reduce the effects of the parasitic crossings.

As discussed earlier, *B* factory parameters are invariably chosen such that single-bunch instabilities are not a problem. That is, we use enough beam bunches to keep the single-bunch intensity below the instability thresholds. A broadband longitudinal impedance of $|Z/n| \approx 1\ \Omega$, which requires care—but not heroic effort—in vacuum chamber design, is sufficient. However, coupled-bunch instabilities in a *B* factory are expected to be very severe. The growth rates for coupled-bunch instabilities scale with the *total* beam current, and depend only weakly on the bunch pattern. The impedance that drives these instabilities is due to the trapped higher-order modes

(HOMs) of the RF cavities (of which many are needed to provide the short beam bunches). As will be discussed below, the problem is dealt with via a two-pronged attack wherein the HOMs are damped in the cavities and powerful broadband feedback systems are employed to deal with the remaining instability.

In the *B* factory parameter regime, the luminosity lifetime is limited by two effects: beam-gas bremsstrahlung (a single-beam effect) and radiative Bhabha scattering ($e^+e^- \rightarrow e^+e^-\gamma$, a beam-beam effect). The former effect has a very weak dependence on lattice parameters, and the only means of controlling it is to lower the pressure. The latter effect, which scales with the luminosity itself, will ultimately be dominant in a very high luminosity collider. Because the lifetime from the radiative Bhabha process increases with the ring circumference, a larger ring is an advantage in this regard.

4.2 Technology Challenges

The physics challenges discussed in Section 4.1 make certain implicit assumptions about *B* factory hardware. In a sense, one can summarize the technology challenges implied above by saying that the technology choices should not make liars out of the accelerator physicists. Examples of what is meant by this include:

- beam lifetime and detector background estimates assume a low background gas pressure in the rings, despite the copious photodesorption
- luminosity estimates assume the required high beam currents can be supported without melting anything
- coupled-bunch instability growth rate estimates assume the HOMs of the RF cavities are heavily damped
- performance estimates (in the sense of integrated luminosity) assume the hardware components are sufficiently reliable that the machine does not "spend all of its time in the shop."

For all *B* factory designs, the main technological challenges lie in the areas of vacuum system, RF system, and feedback system design. In addition, the injection requirements for a *B* factory are nontrivial and are worthy of considerable attention.

4.2.1 Vacuum System Challenges

There are two main challenges for the vacuum system of a *B* factory collider:

- withstanding the high thermal flux from synchrotron radiation power
- maintaining a low pressure in the face of severe synchrotron-radiation-induced photodesorption.

The linear thermal power density is given by:

$$P_L = \frac{P_{SR}}{2\pi\rho} \propto \frac{E^4 I}{\rho^2} \qquad (5)$$

This value can reach up to about 25 kW/m in some designs. Most designers choose a copper vacuum chamber, which is better able to dissipate the heat than is the more commonly used aluminum chamber and has other advantages mentioned below.

A B factory vacuum system must maintain a pressure range of 1–10 nTorr at the full beam currents in the rings. The photodesorption gas load is given by:

$$Q_{gas} = 2.42 \times 10^{-2}\, E\, I\, \eta \quad [\mathrm{Torr{\cdot}L/s}] \qquad (6)$$

where E is the beam energy in GeV and I is the beam current in amperes. The photodesorption coefficient, η, which gives the number of gas molecules desorbed per incident photon, depends on the vacuum chamber material, its history (in terms of manufacturing and handling), and the photon dose to which the chamber has been exposed. A typical design value for estimating the required pumping speed is $\eta = 2 \times 10^{-6}$ molecules per photon. This low value requires "scrubbing" the chamber walls with photons until this level of photodesorption is reached. The dependence of the desorption coefficient on photon dose is shown in Fig. 5, taken from Ref. [32]. Note that both the horizontal and vertical scales are logarithmic, so the required dose to reduce η takes progressively longer to reach.

In addition to the functional requirements just discussed, the chamber must be designed in such a way as to minimize the impedance seen by the beam. In essence, this means that the chamber profile should be very smooth. All unavoidable changes in cross section should be done in a gently tapered fashion and any discontinuities (gaps in flanges, bellows, masks, etc.) should be made as smooth as possible. The HOM power lost by the beam scales with the square of the beam current and can be quite high for a B factory.

There are two approaches to the vacuum chamber design that are being pursued by B factory design teams: the standard chamber design (similar to that used for a single-ring collider) and the "antechamber" design. In cases where the parameters are such that a pumping speed on the order of 100 L/s/m is required to achieve the design operating pressure, a standard chamber will suffice. In more extreme cases where much higher pumping speed is required, an antechamber design is called for. For example, both titanium sublimation pumps (TSPs) and non-evaporable getter (NEG) pumps are employed to deliver a pumping speed of 2,500 L/s/m in the hard-bend region of the CESR-B design [4].

As mentioned earlier, most designers favor a copper chamber, similar to that used in the HERA collider [33]. In addition to its excellent thermal properties, copper has a low desorption coefficient, as has been verified in R&D studies (see Fig. 5). Furthermore, in the B factory energy range, copper provides the additional benefit of being self-shielding for the synchrotron radiation emitted by the beam, avoiding the complications of a lead shield on the chamber.

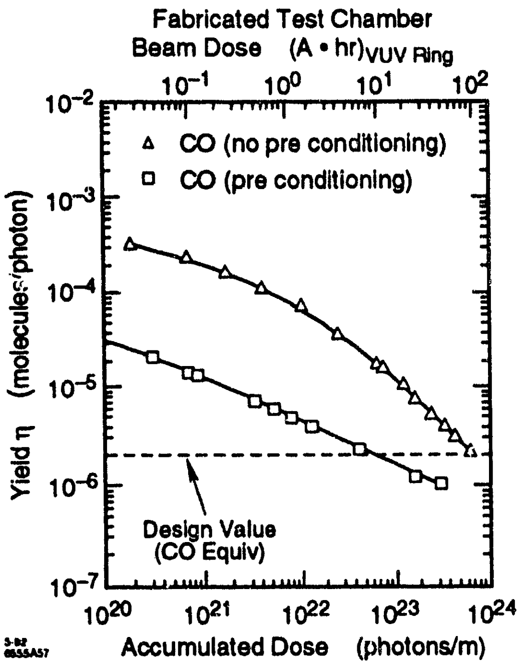

Fig. 5. Photodesorption coefficient for copper vacuum chamber measured at the BNL VUV ring. The PEP-II design goal of $\eta \leq 2 \times 10^{-6}$ is reached at relatively low photon dose. An argon glow-discharge preconditioning further reduces the dose required.

It is worth noting here that the IR is an especially difficult design challenge. On the one hand, there is a special need for low pressure (to minimize lost-particle backgrounds) while, on the other hand, there is a substantial gas source (the masks to protect the detector) combined with little room to install pumps. Innovative solutions are needed here, and all design teams are hard at work to deal with this issue.

4.2.2 RF System Challenges

The main challenges for a *B* factory RF system include:

- providing the large synchrotron radiation power loss
- minimizing the HOM impedance seen by the beam
- managing the transients associated with the gap in the bunch train (used for ion-clearing purposes)

- dealing with very heavy beam loading.

Both room-temperature RF (RTRF) systems and superconducting RF (SCRF) systems are being considered for *B* factory applications. It is fair to say that either technology must be extended from its present state to operate reliably in the *B* factory parameter regime.

The power to be replenished by the RF system is typically on the order of 5 MW for a *B* factory high-energy ring (HER) at a design luminosity of 3×10^{33} cm^{-2} s^{-1}. The difficulty in terms of the RF system is not related to the power *per se*, but results from the need to minimize the HOM impedance by using as few cavities as practical. With this constraint, the power through an individual RF window can be quite high, on the order of 500 kW. To put this value in context, it is only half the power of a typical klystron output window. However, the environment of a cavity window is less well controlled than that of a klystron window, so some caution is warranted. Power levels approaching the required value have been reached at both PEP and CESR, so the extrapolation we require for the *B* factory case is less than a factor of two.

In addition to reducing the HOM impedance by reducing the number of cavities, it is also mandatory to substantially reduce the HOM impedance of the individual cavities to maintain practical parameters for the multibunch feedback system (see Section 4.2.3). In the case of RTRF cavities, the approach adopted (see Fig. 6) is to use waveguides to couple out the dangerous HOMs to damping loads [34]. Damping to *Q* values of about 30 has been demonstrated in tests of a low-power PEP-II cavity and also for the TRISTAN-II cavity prototype. To avoid extra penetrations of the cavity body in the case of SCRF, the approach used (Fig. 7) is to provide a large aperture beam pipe to permit HOMs to propagate to a room-temperature load on the inner surface of the tube. Low-power tests of this scheme have demonstrated roughly the same performance as the RTRF scheme, with *Q* values reduced to about 50.

Those *B* factory designs with a non-zero crossing angle will also need to develop transversely deflecting crab cavities. The design of crab cavities is generally based on SCRF, likely to be a good choice for this application as the requirements are for high voltage but low power. Note that the crab cavities must operate not at their fundamental mode but at the TM110 deflecting HOM.

Especially for RTRF cavities, the transient response of the heavily beam-loaded cavities to the ion-clearing gap in the bunch train is of concern. The issue is not so much that there is a transient, but that the transients must be well matched in the two rings in order to ensure that there is not excessive longitudinal displacement of the IP. As shown by Pedersen [35], it is possible to match the transient responses of the two *B* factory rings quite well by properly tailoring the gap in the positron ring.

Another concern that affects primarily the RTRF system is that of the heavy beam loading. To avoid excessive reflected power, the RF cavity must be substantially detuned in frequency. For a ring with large circumference and high beam current, the required detuning can exceed the rotation frequency. In this circumstance, the cavity fundamental mode strongly drives certain coupled-bunch modes unstable. Because the driving impedance is the fundamental mode itself, we cannot apply the usual trick of simply "de-*Q*ing" the mode. The solution developed [35] involves a special RF

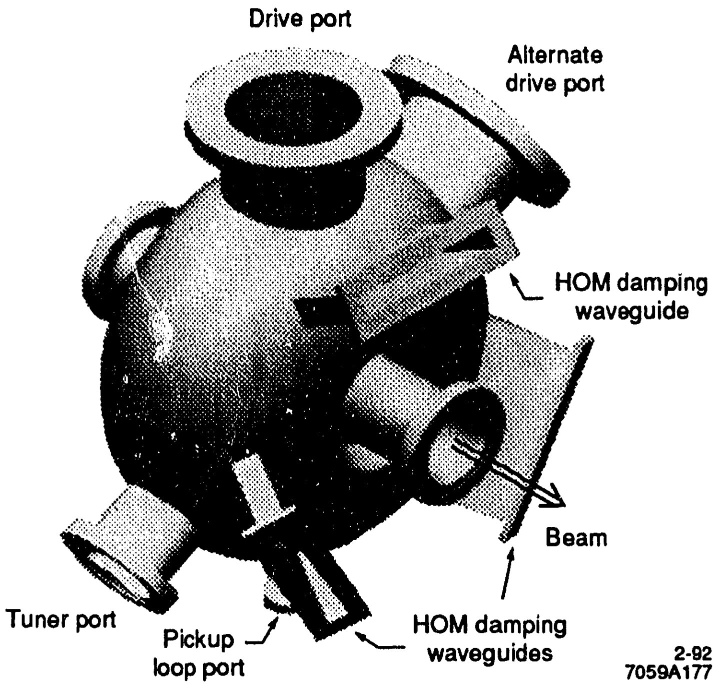

Fig. 6. RTRF cavity design from Ref. [6]. HOM damping loads are placed in waveguides that penetrate the cavity body.

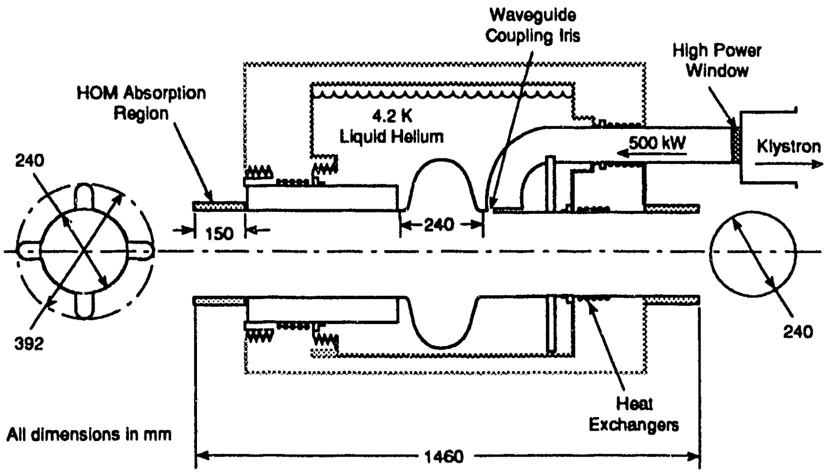

Fig. 7 SCRF cavity design from Ref. [4]. Coaxial HOM damping loads are located on the beam pipe inner surfaces.

feedback system to reduce the cavity impedance at selected frequencies corresponding to the rotation harmonics. To achieve the required amount of impedance reduction, several nested loops are employed. Any residual motion is controlled by using the "normal" multibunch feedback system to operate with the RF cavities as a high-power kicker.

4.2.3 Feedback System Challenges

The challenge of the feedback systems is to control longitudinal and transverse coupled-bunch instabilities with growth times on the order of 1 ms. Studies carried out for the PEP-II project [36] suggest that the power requirements of the feedback system may be influenced mainly by injection errors. With this in mind, there is a preference for an RF system that is phase-locked to the injection system. It is also helpful to inject charge into the rings in small increments.

The preferred feedback approach for a *B* factory is bunch-by-bunch feedback in the time domain [37]. In such a system, the displacement of an individual bunch is detected and the bunch is then kicked back where it belongs. The potential advantage of such an approach is that it is capable of damping bunch motion from *any* source, including injection transients, beam-beam kicks, or coupled-bunch instabilities. Compared with other colliders, the decreased bunch spacing in a *B* factory collider considerably increases the bandwidth requirements of the feedback system. Fortunately, the commercial availability of broadband power amplifiers and fast digital signal processing (DSP) chips makes this approach entirely feasible and tractable for a *B* factory.

4.2.4 Injection System Challenges

As mentioned earlier, the injection system of a *B* factory is a key ingredient for ensuring adequate performance in delivering integrated luminosity. Although it might seem like injection into a storage ring is straightforward, the *B* factory parameter regime places severe demands on the injection system compared with today's colliders. These include:

- minimizing injection transients to avoid excessive power requirements for the feedback system
- providing a uniform fill for hundreds, or thousands, of bunches
- minimizing detector backgrounds arising from the injection process.

We have already referred to the issue of injection transients. In general, we are injecting many bunches in many cycles of the injector and this is not a major problem. With a linac, the bunches are typically injected one at a time, with a fraction of the bunch current in each cycle. Nonetheless, it is important to keep the phase errors to a reasonable value. The uniform filling of the many bunches implies the ability to monitor the charge in each individual bunch at the level of a few percent of the nominal charge. This capability has not been developed in any of the *B* factory designs to date.

The ability to inject the two rings without excessive beam losses in the detector area is of paramount importance. One technique that has been adopted [6] is to use a so-called "graded aperture" in the ring. In this approach, the IR has the largest aperture in the ring (in units of the rms beam size), with progressively smaller apertures farther from the IR.

To optimize the luminosity performance of a *B* factory, it is crucial to be able to inject beam into the rings quickly. It is also beneficial to maintain the highest possible average luminosity, which implies relatively frequent injection (top-off mode). It remains to be seen whether it will be practical to reach the limiting case of continuous injection ("trickle charging"). This decision will require a careful study of detector backgrounds, an analysis of failure modes during injection, and an assessment of whether the injection process can be carried out without any readjustment of beam parameters, that is, with the beams in collision.

5 Cost and Schedule Issues

Clearly, the construction of a *B* factory depends on many considerations, such as:

- site details
- reusability of existing components
- manpower constraints
- funding profile constraints.

It is also important to be aware of a difference in cost accounting for U.S. projects compared with those elsewhere: all labor costs are explicitly included in U.S. cost estimates. (The significance of this accounting difference depends greatly on the amount of the project carried out with in-house personnel. In Japan, for example, many of the technical components are purchased from industry, in which case the labor costs are implicitly included in the overall project budget. In-house personnel, however, are not accounted for in the project cost estimate.) For these reasons, it is difficult to make any sweeping generalizations. Here, we will confine ourselves to those issues that are generally common or relevant to any *B* factory project.

5.1 Schedule

In the U.S., it is becoming more and more difficult to follow an optimum ("technology-limited") schedule. There are several reasons for this, including fluctuations in annual funding levels and the administrative overhead associated with environmental safety and health (ES&H) considerations. Still, it is the technology-limited schedule that is invariably presented at the design stage of a project, as this is the only thing that can be discussed sensibly. Clearly, it is the funding-limited schedule that is actually followed, and the stretch-out in this case can be one or two years.

Most *B* factory projects involve an upgrade of an existing facility. In this case there is little or no conventional construction (tunnels, buildings) required. In addition, there are many technical components (magnets, pumps, injector,...) available for reuse. It is worth commenting here that the equipment to be reused should be carefully inspected—and refurbished as necessary—to ensure its long-term reliability in *B* factory service.

In general, any accelerator project schedule is paced by a few key items. For a *B* factory, the main long-lead items are the vacuum system hardware and the RF system hardware (cavities, klystrons). These are the key to a timely project completion. In addition, there are certain labor-intensive operations that can pace a project schedule, such as installation, survey and alignment, and magnetic measurements, so it is also necessary to ensure that there are adequate resources to achieve the proposed schedule.

For a *B* factory, there are various R&D activities needed to verify design choices and optimize the design. It is important that these activities be fully integrated into the project schedule so that the construction team can decide what to buy or build in a timely way, especially for the long-lead-time items.

Although not a necessity, there are considerable benefits to scheduling the project such that some of the commissioning activities can begin early. One recommendation is to get one of the two *B* factory rings up and running. This will permit important tests of the vacuum system, the RF system, the feedback system, and the injection system. (The disadvantage of this approach is that it almost inevitably causes conflicts between the installation and commissioning teams, but this author is convinced that the advantages far outweigh this inconvenience.) An important point to note is that the detector is an integral part of the collider itself, so its schedule must also be integrated into the overall project schedule. In general, one envisions initial commissioning activities occurring prior to installing the radiation-sensitive portions of the detector. It is an open question whether the detector solenoid, which affects the beam orbit, is required for the initial commissioning.

6 Existing *B* Factory Proposals

In the past few years there have been six *B* factory design initiatives worldwide. A list of these projects is given in Table 2.

A summary of the key parameters for the various *B* factory designs is given in Table 3. It is difficult to make detailed comparisons among the projects, because the design choices are strongly influenced by site considerations. Nonetheless, it is striking in Table 3 that the range of parameters adopted by the design teams is actually rather narrow.

Table 2. List of existing *B* factory proposals.

Country	Laboratory	Project	Status
Germany	DESY	HELENA	Inactive
Japan	KEK	TRISTAN-II	Active (seeking funding)
Russia	INP-Novosibirsk	VEPP-5	Active at low level
Switzerland	CERN/PSI	BFI	Inactive
United States	Cornell	CESR-B	Active (incremental approach)
United States	SLAC	PEP-II	Active (seeking funding)

Table 3. Key parameters for *B* Factory designs.[a]

	PEP-II	CESR-B	BFI	HELENA	TRISTAN-II	VEPP-5
$\mathcal{L}$ (10^{33} cm^{-2}s^{-1})	3	3	1	3	2	5
E (GeV)	9.0,3.1	8.0,3.5	8.0,3.5	9.3,3.0	8.0,3.5	6.5,4.3
C (m)	2200	765	963	2304	3018	714
I (A)	1.5,2.1	0.9,2.0	0.6,1.3	0.7,1.1	0.2,0.5	0.7,1.0
No. of bunches	1658	164	80	640	1024	170
s_B (m)	1.3	3.0	12.0	3.6	3.0	4.2
Separation	magnetic	angle + crab	magnetic	magnetic	magnetic	magnetic
σ_ℓ (cm)	1	1	2	1	0.5	0.8
V_{RF} (MV)	18.0,9.5	33.0,12.0	13.0,2.0	17.0,4.5	47.0,20.0	7.0,4.5
RF technology	RT	SC	RT	RT	RT	RT→SC[b]
Vacuum technol.	DIP	NEG+TSP	NEG	DIP+LIP	DIP+NEG	LIP+TSP
P_L, max. (kW/m)	5.1	46.0	7.6	2.1	1.6	7.3
Pumping (L/s/m)	125	2500	500	670	100	500
$\varepsilon x/\varepsilon y$	25	36	33	20	100	20,16
β_y^* (cm)	3.0,1.5	1.5,1.5	3.0,3.0	2.0,1.0	1.0,1.0	1.0,1.0
D^* (m)	0.0	0.0	0.0	0.0	0.0	0.4
ξ_y	0.03	0.03	0.03	0.04	0.05	0.05
ξ_x	0.03	0.04	0.03	0.04	0.05	0.012

[a] Where two entries are given, they refer to the high- and low-energy ring, respectively. Information summarized here was collected mainly from Siemann, SLAC-PUB-5637, and references contained therein.

[b] Initial operation with RT system; final luminosity makes use of SC system as an upgrade.

In terms of energy asymmetry, the designs based upon a large ring circumference generally favor a higher value. This is because the beam separation is eased in this way and, for a large ring, the countervailing increase in synchrotron radiation power is not an overriding concern. The bunch spacing is usually selected to be a good match to the natural emittance of the HER. As is clear from Table 3, the range of values is not large. Dispersion at the IP is absent in most designs, as conventional wisdom says it should be avoided. The Novosibirsk "monochromatization" scheme takes the opposite tack, making use of a large dispersion and a small beam emittance to decouple the synchrotron and betatron motion. The choice of RF technology (RT or SC) depends mainly on whether the limiting factor is the requirement for high voltage or high power. In the former case SCRF is desirable, whereas the benefits of SCRF are not very significant in the latter case, especially if the voltage requirements are moderate. As mentioned in Section 4.2.2, the HOM damping requirements in either case (to $Q \approx 50$) are essentially the same.

7 Summary

As should be clear from the discussion in this paper, major progress is being made in the various *B* factory R&D programs. The groups are focusing on the proper issues and have successfully eliminated technical uncertainties. To date, no significant new technical issues have arisen. Physics and technology constraints tend to force the various groups to make similar parameter choices (though implementation details often differ), so the ongoing R&D programs are of interest, and have application, to all projects. Indeed, the issues being studied in *B* factory design are of interest to the entire new generation of colliders and storage rings, including Φ and τ-charm factories, hadron colliders (SSC and LHC) and synchrotron light sources.

The excellent combination of physics and accelerator physics makes the *B* factory an important and exciting project. The good mix of accelerator physics and engineering challenges will also make it a fun one! We are all looking forward to the construction start of the first project, hopefully in the next few years.

In closing, it is appropriate to remind the reader that making such a large jump in luminosity will not be an easy undertaking. The key ingredient in ensuring our success will be to remember to treat the challenges with proper respect.

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