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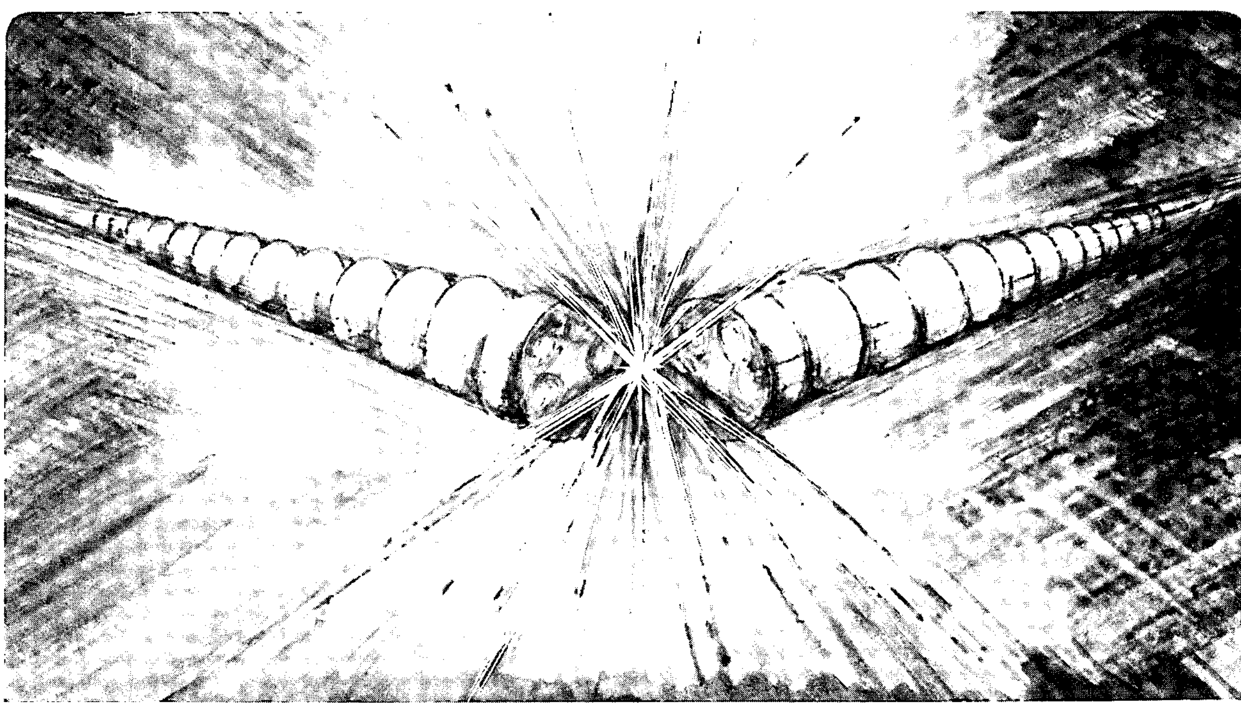

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ELECTRON POSITRON FACTORIES†

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1. Introduction

1.1 General

In the design of an e^+e^- circular collider to serve as a B-factory, a ϕ-factory, or a τ-charm-factory, the beam energies are defined by the resonant nature of the interaction cross section. The challenge in the accelerator design, then, is to push on the *luminosity* frontier rather than the *energy* frontier. Thus, it is issues related to the high beam intensities and the large number of colliding bunches that are paramount.

The goal of all these factories is to achieve luminosity values approximately two orders of magnitude beyond those of existing colliders in the appropriate energy range. In all operating e^+e^- machines, however, there is one characteristic parameter that has proven resistant to large improvements from particular design choices—the beam-beam space charge tune shift parameter, ξ. This parameter—in all operating e^+e^- colliders and in all energy ranges—lies between about 0.02 and 0.06. It does not seem reasonable, then, to base a design on a value for ξ that is well beyond the range that has been seen in experiments over many years and that has resulted from numerous detailed and sophisticated simulation codes.

With this constraint in mind, the design options invariably proceed along two paths, as illustrated in Fig. 1. First, the lattice design is pushed to produce very low values of β_y^*. This choice forces a concomitant reduction in the bunch length to reach the operating regime where $\sigma_L \leq \beta_y^*$, along with a substantial amount of RF hardware to produce the short bunch. Second, achieving high luminosity without a greatly increased ξ value forces the design to one with many bunches (hundreds, or even thousands). To avoid numerous parasitic bunch crossings, and because of the large circulating currents, designs for B- and τ-charm-factories have uniformly adopted a two-ring approach. In a ϕ-factory, such an approach is not mandatory. Subsequent branches in the design logic are indicated in Fig. 1.

The performance criterion of any "flavor factory" is usable integrated luminosity per year. A good duty cycle is required in addition to high peak luminosity. Defining a duty cycle $D \equiv \bar{\mathcal{L}}/\hat{\mathcal{L}}$ over one year of calendar time, present e^+e^- colliders operate at $D \sim 0.25$[1,2]. For a B-factory with $\hat{\mathcal{L}} = 3 \times 10^{33}$, D must be close to 0.4 to ac-

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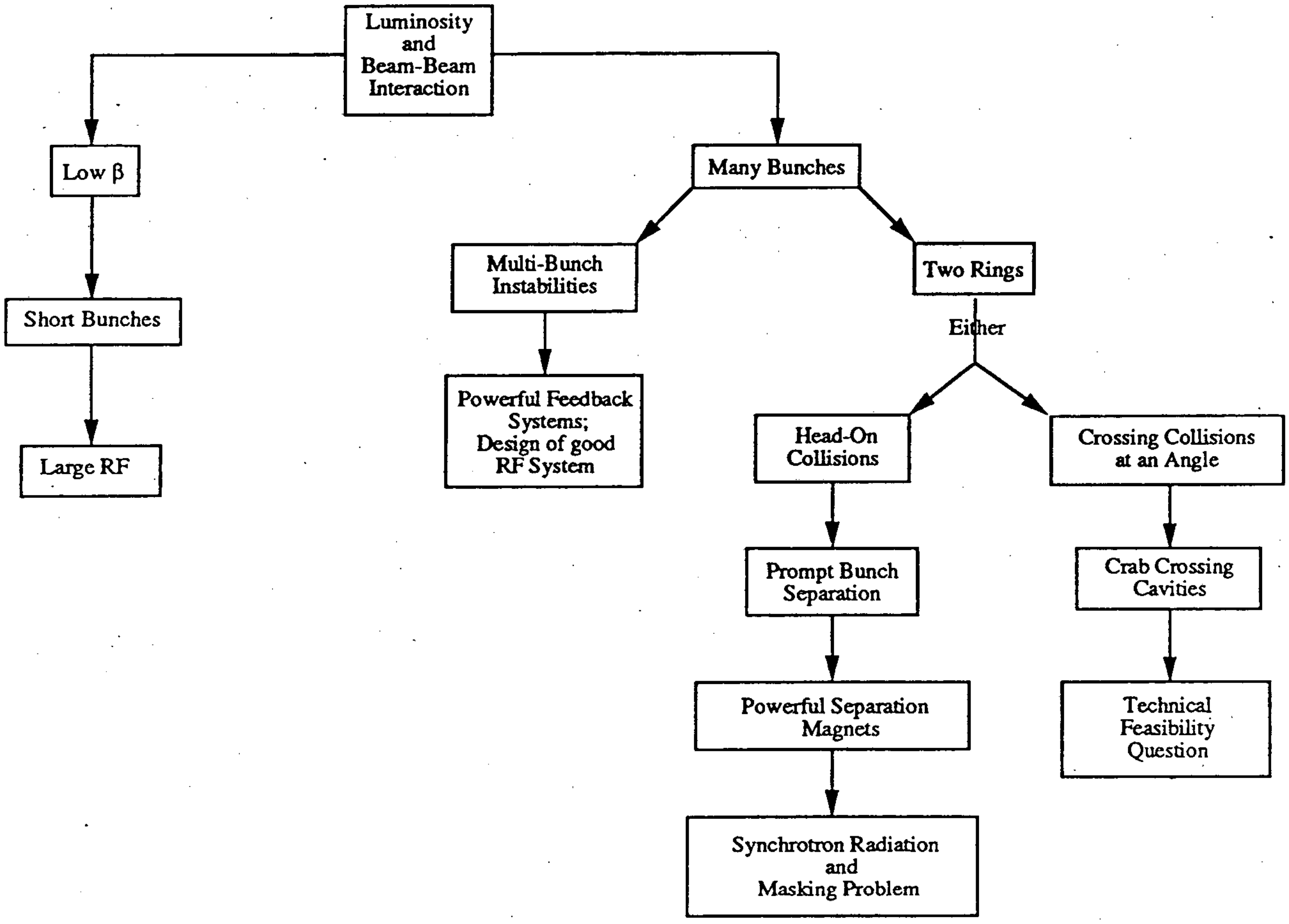

Fig. 1. Illustration of the alternatives that must be considered in the design of a high-luminosity electron-positron factory.

complish the physics goals as we now understand them. One crucial ingredient in improving D will be fast and reliable injection. Beyond this, however, system reliability must be considered at the design stage in order to make at least a factor of two reduction in down time (under "high stress" operating conditions) compared with present machines. To reach this goal, planning must emphasize not only conservative design, but also redundancy. For example, some number of "hot spare" RF stations will be needed to keep the beam in the machine consistently. This type of analysis, which is common in the aerospace industry, may need to be applied to our situation.

In this paper, we will first indicate (Section 2) the key issues in designing a B-factory and a ϕ-factory, and illustrate the approaches that are being followed to address them. In general, reaching the B-factory parameter regime offers the most challenges, so we will emphasize it here. Then we will consider (Section 3) an extrapolation of our present understanding of collider performance and assess the maximum luminosity that could be anticipated. To reach extremely high luminosity, it may be necessary to consider possibilities beyond the scope of "standard" approaches to collider design; a few illustrative examples are outlined in Section 4. For both the present designs and the extrapolated parameters, R&D activities in a few key areas are required; these areas are discussed in Section 5.

1.2 Basic Luminosity Definitions

The luminosity of a particle accelerator is defined as the event rate (per second) of a process with unit cross section:

$$\dot{n} = \hat{\mathcal{L}} \cdot \sigma_T \qquad (1)$$

In terms of machine parameters the luminosity is given by the number of incident particles per second times the effective density of the target or, for a colliding beam accelerator,

$$\hat{\mathcal{L}} = f^* N_1 \cdot \frac{N_2}{A} = \frac{f^* N_1 N_2}{4\pi\sigma_x^*\sigma_y^*} \qquad (2)$$

where f^* is the number of encounters per second, $N_{1,2}$ are the numbers of particles per encounter for the two beams, A is the cross-sectional area (here assumed equal for both beams), and $\sigma_{x,y}^*$ are the rms horizontal and vertical beam sizes, respectively, at the interaction point (IP). Gaussian transverse distributions are assumed.

The transverse deflection given to a particle by the macroscopic electromagnetic field of the opposing bunch is linear for small transverse displacements, Δx, from the bunch center. The effects on beam dynamics of this transverse force are described in terms of a scaling factor, ξ, the beam-beam space charge parameter, defined by

$$\xi_{x,y} \equiv -\frac{1}{4\pi}\frac{\beta_{x,y}^*}{f} = \frac{N_b r_e \beta_{x,y}^*}{2\pi\gamma(\sigma_x+\sigma_y)\sigma_{x,y}} \qquad (3)$$

where $\beta_{x,y}$ is the horizontal or vertical betatron function at the interaction point, f is the focal length of the effective lens created by the opposing bunch, N_b is the number of particles in the bunch, $r_e = 2.8\times10^{-15}$ m, and γ is the relativistic factor.

Because the linear part of this interaction acts like a focusing lens (for oppositely-charged particles), causing a change in the beam's betatron tune, ξ is often referred to as the linear beam-beam tune shift.

1.3 Choice of Beam Parameters

The choice of beam parameters for a typical high-luminosity collider design is based on the following simplifying assumptions:

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

From these assumptions the following well-known relations between the energies E (GeV), intensities I (A), emittances ξ (nm·rad), luminosity $\mathcal{L}$ (cm^{-2}s^{-1}) and beta-function values (cm) at the IP can be derived. In these formulas, given below, r and B are constants, s_B (m) is the bunch spacing, and ξ is the tune shift limit. The beam sizes at the IP of the two beams (designated by $j = 1,2$ or $k = 2,1$) are $\sigma_{j,i} = \sqrt{\epsilon_{j,i}\cdot\beta_{j,i}}$, where $i = x, y$.

$$\beta_y^*/\beta_x^* = \epsilon_y/\epsilon_x = \sigma_y^*/\sigma_x^* = r \qquad (4)$$

$$\beta_{1,i}^*/\beta_{2,i}^* = \epsilon_{2,i}/\epsilon_{1,i} = (E_1/E_2)(I_1/I_2) = b \qquad (5)$$

$$\epsilon_{j,x} = \frac{4.77 s_B I_k}{\xi E_j(1+r)}, \quad \epsilon_{j,y} = r\epsilon_{j,x} \qquad (6)$$

Equations (2) and (3) may be combined, eliminating the beam cross sections σ_x^* and σ_y^*, to explicitly separate luminosity performance into optics parameters $\left[r \equiv \frac{\sigma_y^*}{\sigma_x^*} \text{ and } \beta_y^*\right]$, beam-beam dynamics, (ξ_y), and total current per beam (I):

$$\hat{\mathcal{L}}(\mathrm{cm}^{-2}\mathrm{s}^{-1}) = 2.17\times10^{34}\xi_y(1+r)\left[\frac{IE}{\beta_y^*}\right]_{1,2} \qquad (7)$$

where, as mentioned, E (GeV) is the beam energy, I (A) the total current in one beam, and β_y^* has units of centimeters. This form must be used with caution, since a horizontal beam-beam limit or vertical aperture limit may be implicitly contained in the total beam current, I.

The last parenthetical expression in Eq. 7 can be evaluated using parameters of either one of the two beams, but not both, because of Eq. 6. For a given ξ and r, maximizing luminosity is done by maximizing this bracket, that is, producing high currents and small beta functions. It is worth noting that, to control the beam parameters (emittance, energy spread, damping time) of the low-energy ring in a B-factory, wigglers are often used. This approach gives the designers considerable flexibility in reaching high luminosity at whatever limiting value of ξ can be reached in a given machine.

2. Present Status

2.1 B-Factory Parameter Regime

2.1.1 Beam-Beam Issues

The beam-beam tune shift described above decreases rapidly for particles passing through the opposing bunch with transverse displacements larger than one sigma. A particle's betatron tune is therefore dependent on its betatron amplitude. While the Landau damping introduced by this tune spread can reduce the growth rate of coherent resonances, the resulting spread in tunes can push individual particles onto single-particle resonances[3]. In addition, vertical motion may be driven parametrically by motion in the horizontal plane, which generally has at least an order of magnitude larger emittance. Both these effects increase with the beam-beam parameter, ξ, until σ_y^* or σ_x^* becomes unacceptably large or the beam lifetime becomes unacceptably short.

Although efforts to calculate limits to ξ have had some qualified success, most of our guidance has come from empirical measurements[4], which show a range of 0.02-0.06 for both ξ_x and ξ_y in electron-positron colliders. While several colliders (over a wide range of design energies) have achieved $\xi \sim 0.05$, various operating conditions are known to decrease the attainable tune shift. These include: dispersion at the interaction point, displacement or angle between the two colliding beams, $\sigma_L \geq \beta^*$, and asymmetries in optics between the multiple interaction points of a machine. Furthermore, in a given collider ξ decreases as the operating energy decreases from the maximum design energy[4].

Round beam cross sections may yield more luminosity per unit current. The $(1+r)$ term in Eq. 7 gives a geometrical factor of two. Furthermore, some computer simulations suggest[5] that ξ may be as much as two times higher for round beams than for flat beams. At this time, however, efforts to design interaction region optics for round beams have resulted in β^* values two to three times larger than for flat beams[6], compromising much, if not all, of the potential advantage of round beams. An additional drawback of round beams is that the magnets needed to separate and focus them produce copious amounts of synchrotron radiation power near the interaction point, leading to severe masking and heating problems.

The question, then, is what value of ξ to choose for a B-factory parameter list. Given the lack of experimental data on the effects of unequal energy beams, crossing angles, and wigglers on ξ, some caution is warranted. A value of $\xi = 0.03$ has been the choice of most machine designers. There is good reason to hope that, with experience, ξ may be pushed closer to the value attained by several existing colliders, 0.04-0.05.

2.1.2 Interaction Region Design

2.1.2.1 Minimizing β^*

The smallest β^* values attainable are limited by (i) the need to separate the beams sufficiently to lead them into independent channels (thereby avoiding damaging parasitic beam-beam interactions), (ii) the need to produce the β^* values with quadrupoles that do not cause excessive chromaticity, (iii) the need to do the separation and focusing without producing more synchrotron radiation (SR) than can be absorbed by a masking system, (iv) the need to avoid components that present excessive impedance to the beams, and (v) (but certainly not least) the need to make the design compatible with the detector constraints.

2.1.2.2 Beam Separation

The initial beam separation can be accomplished by crab-cavity assisted crossings, by dipole fields at or near the IP, by the bending action of quadrupoles on off-center beams, or by some combination of these methods. At present, there seems to be a consensus to use off-center quadrupoles in combination either with dipole magnets, with tilted solenoids near the IP, or with a modest crab-type crossing angle. In all of these cases, both beams pass through two or three common quadrupoles on each side of the IP, followed by a special quadrupole that acts only on the high energy beam (or possibly with equal and opposite gradients on both beams). This special quadrupole is followed by a horizontal or vertical septum magnet that completes the separation of the beams and directs them into independent channels.

At present, the two asymmetric B-factory machine designs in the U.S.A. have similar parameters and interaction region concepts, except that one uses dipoles to initiate the separation while the other uses small crab-crossing angles. The common elements are permanent magnets with sufficiently low fields and/or gradients to make synchrotron radiation problems tractable. The other constraints listed above are thought to be satisfied.

Different strategies are being explored for the transverse placement of the common quadrupoles, driven by the conflicting needs to obtain rapid separation and to reduce synchrotron radiation near the IP. It is generally desirable to bring the common elements as close to the IP as possible, consistent with allowing a sufficient solid angle for the detector.

2.1.2.3 Final Focusing System

For the two U.S.A. designs currently envisioned, the first focusing elements proceeding away from the IP comprise a quadrupole doublet or triplet common to both beams, placed either directly after the separating dipole magnet (in the head-on case) or as close to the IP as possible (in the crab-crossing case). These are adjusted primarily to control the rapid rise of the low-energy ring (LER) vertical beta-function. The first quadrupole is vertically focusing, and the others alternate in focusing gradient. The next element is the special quadrupole, vertically focusing, that acts only on the beam in the high-energy ring (HER). After a few meters, another normal HER horizontally-focusing quadrupole brings the beta-functions to their maximum values.

The quadrupoles are typically 40-60 cm long, separated by about 20 cm, and the common elements end two or three meters from the IP. Typical machine parameters are:

$$\begin{aligned} \mathcal{L} &= 3 \times 10^{33}\ \mathrm{cm^{-2}s^{-1}}, \\ s_B &= 1.26\ \mathrm{m}, \\ r &= 0.04, \\ b &= 2\ \mathrm{cm}, \end{aligned}$$

$$\begin{aligned} E_1 &= 9\ \mathrm{GeV}, \\ I_1 &= 1.48\ \mathrm{A}, \\ \beta^*_{1,x} &= 75\ \mathrm{cm}, \\ \beta^*_{1,y} &= 3\ \mathrm{cm}, \\ \epsilon_{1,x} &= 46\ \mathrm{nm\cdot rad}, \\ \epsilon_{1,y} &= 1.8\ \mathrm{nm\cdot rad}, \end{aligned}$$

$$\begin{aligned} E_2 &= 3.1\ \mathrm{GeV}, \\ I_2 &= 2.14\ \mathrm{A}, \\ \beta^*_{2,x} &= 37.5\ \mathrm{cm}, \\ \beta^*_{2,y} &= 1.5\ \mathrm{cm}, \\ \epsilon_{2,x} &= 92\ \mathrm{nm\cdot rad}, \\ \epsilon_{2,y} &= 3.6\ \mathrm{nm\cdot rad}. \end{aligned}$$

The peak beta-function values are about 250 m and 50 m for the high- and low-energy beams, respectively.

2.1.3 Masking and Background Issues

One key issue in B-factory design concerns the interface between the detector and the storage rings. A detailed discussion of these considerations is given as part of the report of the B-Factory Interaction Region Design and Masking group (see report elsewhere in these Proceedings). The interaction region (IR) optics must not only provide low beta functions (strong focusing) and separation of the two beams (as discussed in Section 2.1.2), it must provide low backgrounds in the detector. The backgrounds are of two main types: synchrotron radiation; and scattered-particle backgrounds arising from Bremsstrahlung and beam-gas elastic scattering in the straight sections that precede the IP. Great care is needed to shield against these backgrounds. The optics must be optimized so as to minimize the synchrotron radiation emission from the dipoles and quadrupoles. Even then, the masks must be capable of attenuating the synchrotron radiation by a factor of 10^{10} and dissipating power levels on the order of 100 W/mm^2. Control of scattered particle background levels requires a pressure as low as 10^{-9} Torr in the straight sections in order to satisfy the occupancy and component radiation damage standards of the detector. Both the SLAC/LBL and Cornell groups have done optimization of the IR optics as well as detailed modeling of the backgrounds. In both cases it appears that the backgrounds can be reduced to a level where the detector criteria are satisfied.

There are a number of engineering considerations that are required before the interaction region design can be considered complete. Engineering tolerances on the interaction region elements (masks and magnets) are challenging. For example, the focusing and separation magnets must fit within a roughly 300-mrad cone defined by the detector. Compact permanent magnets may be needed to accommodate both beams. The synchrotron radiation masks must be designed taking into account both the total power loading and the photon energy spectrum. Care must be taken in the choice and mix of materials.

In summary, the interaction region/detector interface for high luminosity e^+e^- machines presents a significant challenge. Most of the problems have been addressed: optics designs are available that provide adequate protection for the detector, but detailed engineering solutions for some beam-line components are still needed. The current outlook is that suitable IR designs are within reach.

2.1.4 Bunch Length Limits

To take advantage of the small β_y^* value required for reaching high luminosity, it is necessary to achieve a bunch length such that $\sigma_L \leq \beta_y^*$. This choice minimizes the influence of synchrotron motion on beam dynamics (betatron tune modulation at the IP) and avoids the luminosity loss associated with the beam size increase near the IP ("hourglass effect").

The straightforward way to obtain short bunches is to use suitable RF parameters, that is, a high voltage and high frequency, since

$$\sigma_L^2 = \frac{(E/e)\eta Rc\sigma_p^2}{V_{RF}f_{RF}} \qquad (8)$$

For a given lattice and beam energy, the numerator in the above equation is a constant, so the bunch length scales inversely with $(V_{RF}f_{RF})^{\frac{1}{2}}$. Taking typical (but not corresponding to any one design) B-factory parameters (see Table I), gives

$$V_{RF}f_{RF} \approx \frac{1}{\sigma_L^2} \qquad (9)$$

where V_{RF} is in MV, f_{RF} is in MHz, and σ_L is in m. At a typical frequency of 500 MHz adopted in most B-factory designs, a voltage of 20 MV is needed to obtain a 1-cm rms bunch length.

To avoid an unwanted increase in the bunch length, the beam current must stay below the longitudinal microwave instability threshold, which can be written in terms of average (single-bunch) current as

Table I
Typical B-Factory Parameters Used for Numerical Estimates

Beam energy, E [GeV]	9.0
Circumference, C [m]	1200.0
Average radius, R [m]	191
Bending radius, ρ [m]	100
Harmonic number, h	2000
Momentum compaction, α	0.002
Bunch length, σ_L [m]	0.01
Relative momentum spread, σ_p	0.001
RF frequency, f_{RF} [MHz]	500
Beam pipe aperture radius, b [cm]	5

$$I_b = \frac{\sqrt{2\pi}|\eta|(E/e)\sigma_p^2\sigma_l}{R\left|\frac{Z}{n}\right|_{eff}} \qquad (10)$$

The only parameter to which we have access in the above equation is the broadband impedance, $|Z/n|_{eff}$. The impedance is "effective" in the sense that the bunch samples the ring impedance weighted by its power spectrum. A short bunch—one having a frequency spectrum extending well beyond the beam pipe cut-off frequency—does not sample the impedance fully[7]; such a reduction in $|Z/n|_{eff}$ has been observed in this bunch length regime at LEP[8].

In many modern storage rings, a typical value of the low-frequency broadband impedance (i.e., the impedance that would be sampled by a long bunch) is 2–3 Ω. Presently in PEP, for example, $|Z/n| \approx 3$ Ω, of which two-thirds is attributed to the RF[9]. Using a modern RF system, we expect that a B-factory ring can be built with $|Z/n| \approx 1.5$ Ω, giving an effective impedance of about 0.1 Ω. The above parameters then correspond to a threshold current of 24 mA—a comfortable value..

With short bunches, non-resonant higher-order mode losses can become significant. These scale as

$$P_{HOM} = 1 \times 10^{12} k(\sigma_L)\frac{I^2}{k_B f_0} \qquad (11)$$

where $k(\sigma_L)$ (in V/pC) is the loss parameter, whose dependence on the bunch length is explicitly called

Table II
Higher-Order Mode Loss Estimates*

Device	# of Units	k_{tot} (V/pC)	P_{HOM} (kW)
RF cavity	20	4.63	74.1
Septa	2	0.27	4.3
Kicker ceramics	4	0.03	0.5
Gate valves	22	0.13	2.1
Sliding joints	100	0.45	7.2
Horiz. scrapers	10	0.01	0.1
Vert. scrapers	8	0.07	1.1
Distributed pumps (per m)	600	0.11	1.8
Lumped pumps	100	0.18	2.9
TOTALS		5.88	94.1

* Loss parameters scaled from CESR hardware, assuming reasonable design improvements. A bunch length of 1 cm and a total beam current of 2 A (in 1000 bunches) were taken.

out by our notation. For the designs under consideration, $I \approx 2$ A, but k_B is also large (≈ 1000). If we scale loss parameters from present CESR hardware, taking account of reasonable design improvements, we obtain the values summarized in Table II. Then we expect typical HOM losses of about 90 kW, which should not be of concern. It is worth noting in Table II that nearly 80% of the total HOM loss is associated with the RF cavities.

2.1.5 RF Parameters

The choice of frequency and voltage are mainly driven by technology considerations. With conventional RF systems, the power requirement scales as V_{RF}^2, so reducing the voltage is beneficial from this viewpoint. Superconducting RF systems, on the other hand, provide higher gradients without a penalty in RF power. In practice, the beam currents in a B-factory are high (1–3 A in each beam), so the RF power requirement is dominated by the need to replenish the beam power lost to synchrotron radiation. Thus, the choice of conventional vs. superconducting RF is not strongly influenced by power considerations.

To obtain the short bunches needed for reaching high luminosity, it is attractive—especially for a conventional RF system—to reduce the voltage requirement by increasing f_{RF}. Restrictions on the choice of frequency arise from two issues. First, the dimensions of the RF structure decrease with frequency, and can give rise to considerable transverse impedance:

$$Z_\perp = \frac{2R}{b^2}\left|\frac{Z}{n}\right| \tag{12}$$

e.g., a scaled 3-GHz structure would have 36 times the $Z_\perp$ of a 500-MHz structure. For large rings, the transverse impedance typically limits the single-bunch current that can be stored. Less fundamental, but perhaps more significant, is the lack of high-power sources at the higher frequencies. Klystrons capable of 1 MW CW power are commercially available only at 350 and 500 MHz, although lower power klystrons at 1 GHz can be obtained. If need be, higher frequency high-power sources could be developed, but the power reduction implied by Eq. (9) does not provide great incentive in a design dominated by beam loading.

To minimize problems with coupled-bunch instabilities, it is necessary to minimize the number of RF cells. For a B-factory, the limit on the number of cells is based on power considerations. The main issues are:

- dissipating the wall power required to develop the voltage; and
- transmitting the total (beam + wall) power through the RF input window.

Single-cell 500-MHz RF cavities have been designed (and are soon to be tested) at $P_W = 60$ kW; an increase in this value by a factor of about two would be desirable for a B-factory.

The total power through the window is also a limitation at present. For the high-energy ring of our "generic" asymmetric B-factory, we need 20 MV to produce a 1-cm bunch. To do this requires $P_W = 0.12$ MW/cell. Including a beam power of 5 MW, the required input power is 0.4 MW/cell. This is higher than what has been routinely demonstrated in an RF cavity, but is well below the capabilities of today's high-power klystrons. Even assuming no improvement in window technology, the power could, in principle, be fed through two windows and recombined. Alternatively, the number of cells could be doubled, which would be undesirable (but not unacceptable) from an impedance standpoint. With superconducting RF, the wall power is negligible so the input power requirement is reduced by about one third. If the window capabilities were the same for the superconducting and room temperature systems, fewer cells would be needed in the former case. Given the significant engineering challenges associated with the superconducting environment, it remains to be seen how much of the potential reduction in RF hardware can be realized with this technology.

Wakefields trapped in high-Q resonant objects can couple the motion of successive bunches in a storage ring and lead to unstable motion that must be controlled with feedback. If the decay time of the wakefields is long compared with the interbunch spacing (as is usually the case), the growth rates scale with total current, and are insensitive to the bunch pattern (Fig. 2). The approach being followed to minimize the coupled-bunch instability problem is to use single-cell cavities with a large-bore radius to minimize the number of trapped modes. Calculations indicate that a 1 MΩ impedance gives a growth rate of about 10^4 s^{-1}. A target value for the growth rate is $1/\tau_g \leq 1000\,s^{-1}$, as this value can be handled with a manageable feedback system[10]. This corresponds to an allowable $R_s \approx 0.1$ MΩ or 5 kΩ/cell. If a typical HOM has $R_s/Q \approx 10$ and Q = 20,000, then we must damp the mode to $Q \leq 500$ without significantly degrading the fundamental. Techniques for achieving this damping, using waveguides on the cavity body to couple out the HOM power, have been shown[10] in low-power tests to give $Q \approx 70$, a comfortable margin.

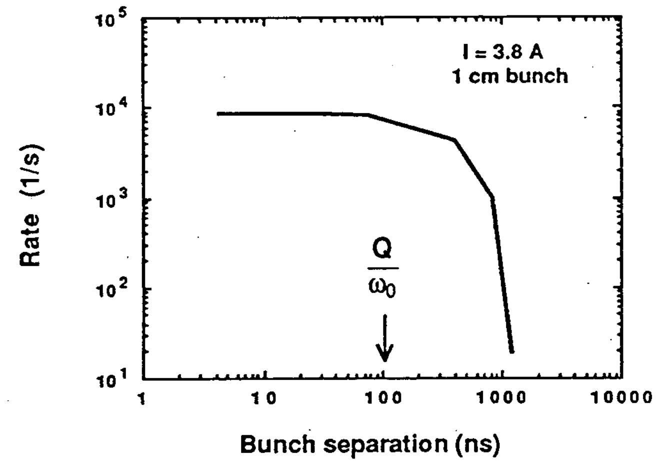

Fig. 2. Dependence of growth rate for longitudinal coupled-bunch instability as a function of the separation between (equally-spaced) bunches. Until the bunch separation time is longer than the typical time for the wakefields to decay, the growth rate is essentially independent of separation.

2.1.6 Feedback System

Because of the significant damping needed to reduce R_s of the HOMs to acceptable values, the modes from the various cells will overlap. In addition, they are sufficiently broad that there is no possibility of "avoiding" them with the beam rotation harmonics. There are several multibunch feedback system options that have been examined and found to be acceptable[11]. For example, one could employ a low-power system, having a bandwidth greater than the required 125 MHz at 1.125 GHz, that is based on 10 kickers, each consisting of four series-connected loops. Total power required is 1.6 kW, which can be provided by ten 160-W solid-state amplifiers. If more power were needed, an alternative system based on 14 stagger-tuned, damped RF cavities could be employed. This system would be powered by commercially available 50 kW UHF TV klystrons. With this latter (albeit costly) approach, much higher power is available, and additional bandwidth can be gained simply by adding more channels. It is worth noting that the power requirements for the feedback system may well be dominated by injection errors, so this aspect must be carefully considered in the system design.

2.1.7 Vacuum System

There are two design issues that must be addressed: heating of the vacuum chamber walls from the synchrotron radiation and photodesorption of gas molecules. For the first issue, the "figure of merit" is the linear power density given by

$$P_L = 8.85 \times 10^4 \frac{E^4 I}{2\pi\rho^2} \quad . \qquad (13)$$

For a beam of 1 A at 9 GeV and $\rho \approx 100$ m, we estimate $P_L = 9$ kW/m compared with 5–10 kW/m for present chamber designs. This value is acceptable for a copper vacuum chamber[12], and is perhaps acceptable for an aluminum chamber if sufficient cooling water passages are provided. However, a higher beam current at this ρ value would almost certainly preclude the use of aluminum. Because of its higher Z, copper is self-shielding for the copious synchrotron radiation produced by the beam and therefore is the favored material for a B-factory vacuum chamber.

The photodesorption rate is given by

$$Q_{gas} = 24.2E_{[\mathrm{GeV}]} \cdot I_{[\mathrm{A}]} \cdot \eta_F \quad \mathrm{Torr} \cdot \mathrm{l/s} \qquad (14)$$

where η_F is the desorption coefficient. A copper surface is expected to behave similarly to stainless steel[13]. Thus, it will take a dose of about 100–1000 A·hr to reach $\eta_F = 2 \times 10^{-6}$ depending on pre-treatment. To reach $P \leq 10$ nTorr, as dictated by lifetime considerations ($\tau_{gas} \approx 3$ hrs), requires a pumping speed of about 100 l/s per meter, which is not too different from that of existing rings. Achieving such low values for η_F requires careful handling of the vacuum system, as has been demonstrated in test samples of stainless steel at BNL[13].

2.1.8 Ion Trapping

The large number of electron bunches in a two-ring collider like a B-factory raises the problem of ion trapping in the potential well of the electron beam. This phenomenon has been seen in all synchrotron radiation sources that utilize electron beams. The most effective cure is to leave a gap in the train of bunches (typically 10–20% of the ring circumference). This remedy should also work with a high-luminosity collider. However, if one relies solely on a gap to suppress ion trapping, the implications of the gap on other systems (e.g. transient beam loading of the crab-crossing or regular RF cavities) needs to be investigated.

Another widely used method for suppressing ion trapping is to install clearing electrodes inside the vacuum chamber. These electrodes typically create a transverse static electric field that drags the ions out of the potential well. The potential across the electrodes is typically on the order of a few kV. A comprehensive theoretical and computational study of ion trapping has shown[14] that the effectiveness of the clearing electrodes can be greatly enhanced by superposing on the static field an electric field oscillating at the natural transverse frequencies of the ion motion. The study also confirms the experimental observation that ions can be trapped in the alternating magnetic field structure of insertion devices. Special care will be required to avoid having damping wigglers in a B-factory low-energy ring become a trap for ions.

2.1.9 Injection System

High-luminosity electron-positron colliders such as B-, ϕ- and τ-charm-factories will require full-energy, low-emittance sources of positrons and electrons suitable for filling the storage rings. The large B-factories may require as much as 10–20 μC each of stored positrons and electrons. In contrast, compact ϕ-factories may contain as little as 40 nC of each species. Ideally, the fill time (or topping-off time) should be much shorter than the beam lifetime of the rings. As the luminosity lifetimes (due to all beam losses) of the proposed colliders are not expected to be much longer than a few hours, such machines should have a powerful, reliable, and dedicated injector to ensure high integrated luminosity.

The fill time of the positron ring will ultimately be limited by the design of the positron production target. Whereas the SLC positron target is designed to operate at 100% duty factor, the target for the high-luminosity colliders considered here need only have a duty factor of several percent. Based on the experience with the SLC positron source, one can expect to generate, damp, and accelerate ≈ 20 nA of positrons per kW of electron beam incident on the production target. Assuming a capture efficiency of 30% for the collider, this rate means that even large B-factory rings can be filled quickly without exceeding the 30 kW (at 100% duty factor) design rating of the new SLC target. Small ϕ-factories, of course, can be filled in a few tens of seconds with only a few hundred watts on the target.

If the aperture of the positron ring is sufficiently large, it may be unnecessary to use an intermediate accumulator or fast damping ring, especially if the injection is accomplished with full-energy linacs that can have repetition rates of hundreds of hertz. This case seems to apply for small ϕ-factories but not for B-factories.

As the luminosity of the collider is increased and the luminosity lifetime falls, present accelerator technology can still meet injection demands if it is possible to "top-off" the ring when the beam intensity falls below, say, 80% of the nominal value. In particular, the positron source is readily scaled to high production rate (by increasing its duty factor) while remaining well within the state-of-the-art. Indeed, the most pressing technical challenge may be the design of a detector that can continue to operate (or cycle rapidly) while the main rings are being "topped-off." This technical challenge is likely to arise first for ϕ-factories, which contain relatively few beam particles and thus have lifetimes strongly limited by beam-beam Bremsstrahlung at luminosities approaching 10^{33} cm^{-2}s^{-1}.

A more conservative, albeit more costly means of providing fast injection is to employ a full energy damping/accumulator ring of the same size as the positron storage ring and to fill the storage ring in a single-turn transfer. In such a scenario, the rings can be thought of as being continually filled. Given such an additional large ring plus continual filling, the transition from the conventional storage ring approach to the quasi-linear collider (in which the interaction region is moved to a bypass outside the positron ring) is readily suggested. The injection difficulty is then transferred from positron production to the generation of low-emittance electron beam pulses at a suitably high effective rate (> 50 kHz). The relevant electron linac technologies are being pursued for TeV linear colliders. Although the required technology is still beyond the state-of-the-art for both the linac and the electron source, research appears promising.

2.2 ϕ-Factory Parameter Regime

There is only one e^+e^-collider operating today at the ϕ energy (1020 MeV c.m.), VEPP2M at Novosibirsk. Its luminosity is approximately 3×10^{30} cm^{-2}s^{-1}. The luminosity needed for a ϕ-factory is $\mathcal{L} \geq 5 \times 10^{32}$ cm^{-2}s^{-1}, about two orders of magnitude larger than that of VEPP2M.

Proposals and studies for ϕ-factories in this luminosity range have been presented recently by groups at Novosibirsk[15], Frascati[16], UCLA[17], NIKHEF[18], and KEK[19].

The Novosibirsk design is aimed at an initial luminosity of 1×10^{33} cm^{-2}s^{-1}, while the others are aimed initially at 10^{32} (or a few times 10^{32}) cm^{-2}s^{-1}, along with plans to increase the luminosity beyond this value as an R&D program. The Frascati and NIKHEF designs are based on two rings, each about 100 m long, and many bunches. The Novosibirsk and UCLA designs use superconducting magnets and one small ring, about 27 m and 15 m long, respectively, and employ only one bunch each of positrons and electrons.

The main luminosity limitations in a ϕ-factory are similar to those of a B-factory and we will follow and use the discussion of Section 2.1. The tune shift can be assumed to be 0.05 in the single bunch design and about 0.025 to 0.03 in the multibunch design.

The bunch length is determined by the microwave instability. In a small ring, it is more difficult to obtain a small value of the longitudinal coupling impedance and, in addition, the vacuum impedance (due to the emission of coherent synchrotron radiation) becomes important. (This is discussed in Sec. 3.1.2 later.) In particular, in the Novosibirsk and UCLA designs this impedance, which can be estimated with the simple formula $300b/R$, where R is the machine radius and b is the vacuum chamber vertical half-aperture, is on the order of 3 Ω. It is then impossible with standard storage ring parameters to obtain a short bunch length and thus to make use of a low β^*. In the UCLA design for example, β^* is 5 cm.

The average current needed for a luminosity of 3×10^{32} cm^{-2}s^{-1} is about 2 A for a β^* of several centimeters. Similar currents have already been obtained in low-energy rings, like the VUV ring at NSLS. Due to the low beam energy, 0.5 GeV, the synchrotron radiation loss is small, 14 keV/turn. In the UCLA case, for a current of 2 A, the synchrotron radiation power loss is only 30 kW. Hence, there is no problem associated with RF power. In the Frascati design, using room temperature magnets, wigglers are added to the ring lattice to increase the synchrotron radiation loss to about 10 keV and reduce the damping time to about 10 ms. One advantage of using superconducting magnets and a small ring is a short damping time of about 2 to 3 ms, which helps to control not only instabilities but effects like intrabeam scattering.

In the UCLA or Novosibirsk designs, the synchrotron radiation power density can be on the order of 10 kW/m, similar to a B-factory. Although we believe it can be handled, the vacuum system will require a careful design.

Multibunch instabilities are expected in the Frascati design but are absent in the UCLA design. They can be controlled with a high-bandwidth feedback system, similar to that of a B-factory but requiring much less power. In fact, the RF system driving the multibunch instability has typically only one cavity in a ϕ-factory, compared with 20 or more cavities in a typical B-factory design.

3. Improvements to Luminosity

In this section we consider extrapolations of the present design strategies to see what gain in luminosity might be possible if we do not confine ourselves to "conservative" parameters.

3.1 B-Factory Parameter Regime

As there are a number of parameters that can be adjusted, some selection process is inevitable. Here we have focused first on the constraints that seem best understood and have left as secondary considerations the resultant parameters insofar as they are not obviously impractical. The logic we apply is as follows:

- Reduce β^* and σ_L to see which is the limiting feature (crab crossing is implicitly assumed to be available).
- Take the beam current limitation to correspond to a vacuum chamber heat load of 20kW/m.
- Take $\xi = 0.05$ to estimate luminosity.
- Take the same f_{RF} (500 MHz) and assume s_B is limited by the longitudinal microwave instability.
- Take superconducting RF, limited by $V_{cell} = 1.6$ MV, to get n_{cell}.
- Check HOM power and vacuum requirements.
- Check (scaled) coupled-bunch instability growth rates against f_s to see if this limits beam current; also look at implications for feedback system.

3.1.1 Interaction Region Modifications

Assuming that the systems outlined in Sec. 2.1.2 perform as planned, what luminosity upgrades can be contemplated? A factor of two increase might be possible by reducing the bunch spacing by a factor of two and increasing the total currents by the same factor. No other IP beam parameters would be changed. However, the magnetic dipole separation scheme would no longer work, because the parasitic crossings would occur in that dipole, before the beams were sufficiently separated. (The crab-crossing scheme, however, would work, although the crossing angle might have to be increased.) The reason for the reduced separation is that the ratio N_σ of beam separation to transverse beam size is nearly constant for distances from the IP greater than twice the β^* value. With the modified bunch spacing, the parasitic crossings will occur at a distance about equal to β_x^*, where N_σ is less. It is thought that safe values of N_σ are in the range of five to seven. Another consequence of the changes is that the SR power will double due to the increase of current.

A further factor of two improvement in luminosity might be achieved by reducing s_B by a factor of two without increasing the currents. The beta functions and emittances would also need to be reduced by the same factor of two, as would the bunch length. This would not alter the separation at the parasitic crossings, but the final focus quadrupoles would have to be scaled down a factor of two in all dimensions and their poletip fields would have to be doubled. This would be difficult with permanent-magnet quadrupoles. Superconducting quadrupoles would probably work but might be too large transversely to fit in the allowed detector solid angle clear space. Moreover, the SR power from the interaction region quadrupoles would double.

Another approach would be to leave the quadrupoles about where they are in present designs, but increase their aperture and length. As the chromatic contributions of the quadrupoles would increase, local chromatic correction sections might be needed to maintain adequate dynamic aperture. Also, the synchrotron radiation fans would increase due to the higher beta-function values in the interaction region quadrupoles. This would require a redesign of the IR masking scheme.

3.1.2 Bunch Length and β^*

At present, lattice designs exist for a β^* value of 1 cm. Present scaling arguments suggest that it will be difficult, even with a crab-crossing scheme, to reduce β^* much below this value if separate optics for the two beams are needed. For this discussion, we will assume a value of $\beta^* = 0.5$ cm to be a plausible lower limit.

With the representative B-factory lattice parameters assumed in Section 2.1, a σ_L of 0.5 cm (requiring $V_{RF} = 80$ MV) would permit $I_b \approx 41$ mA before the bunch stability is limited by $|Z/n|_{eff}$. As the bunch gets shorter, however, there is a new impedance phenomenon that potentially comes into play; the impedance sampled by a short bunch is not expected to continue to decrease at very high frequencies because, in this regime, the process of synchrotron radiation emission itself induces coherence within a bunch and generates a self-impedance. The magnitude of the impedance has been estimated by Bisognano et al.[20] as $|Z/n|_{SI} = 300(b/R)\ \Omega$ where b is the chamber radius and R is the machine radius. This impedance is manifested at quite high frequencies:

$$\omega_{SI} \sim \frac{c}{R}\left(\frac{R}{b}\right)^{3/2} \tag{15}$$
$$= 3.6 \times 10^{11}\ \mathrm{s}^{-1}$$

corresponding to a bunch length of 0.8 mm. Note that, written in terms of average current, the instability threshold, Eq. (10), is independent of the machine radius and depends only on b. With this self-impedance, the threshold is reduced to about 15 mA, but this is still not a performance limitation.

If we restrict the linear power density to 20 kW/m, then for our standard parameters (C = 1200 m) the maximum tolerable current is 1.1 A. Because this is a relatively low current, we have also examined alternative lattice parameters corresponding to a larger ring. In this case (α = 0.001, ρ = 165 m, R = 350 m, $\sigma_p = 6 \times 10^{-4}$), a bunch of 5 mm can be produced with V_{RF} = 27 MV. Now the power density limit corresponds to 5.9 A. The longitudinal microwave instability limit, however, is only 1.9 mA/bunch, so the bunch spacing must be reduced to 0.6 m (every RF bucket). The drawback to this approach for the high-energy ring is that (based on the same beam-beam tune shift in each ring) it implies a beam current of about 17 A in the low-energy ring. For this reason we did not pursue this alternative set of parameters further.

Based on the assumed β_y^* value of 0.5 cm, the luminosity for our original lattice parameters is

$$\mathcal{L} = 2.17 \times 10^{34}(0.05)\left(\frac{1.1 \times 9}{0.5}\right)$$
$$= 2 \times 10^{34}\ \mathrm{cm}^{-2}\mathrm{s}^{-1} \quad .$$

3.1.3 RF Parameters

We require a very high voltage of 80 MV to produce a 5-mm bunch length. Here, we assume a superconducting RF system capable of 1.6 MV/cell, so that 50 cells are used. For a beam power of 12.5 MW, only 0.25 MW/cell is required, and the number of cells is dictated by the voltage requirement.

Assuming similar HOM impedance, the multi-bunch instability growth rates would scale as $\left(\frac{50}{20}\right) \times \left(\frac{1.1}{0.5}\right)$ = 5.5 times the nominal growth rate (i.e., to $1/\tau \sim 5500\ \mathrm{s}^{-1}$). The increase in v_s at the higher voltage will reduce the growth by about a factor of two from this estimate. Overall, then, we would require an eightfold increase in the feedback system power, which in turn might force the use of the high-power staggered klystron approach mentioned in Section 2.1.6. The growth rate is still well below f_s, which ensures the validity of scaling previous results into this parameter regime.

Because of the shorter bunches, HOM power increases in this extended scenario. For our standard parameters, $P_{HOM} \approx 190$ kW is expected; it is nontrivial to handle such power.

3.1.4 Vacuum System

The required pumping speed to maintain a pressure of 10 nTorr is 80 l/s per meter. This value is not cause for concern.

3.1.5 Overview

It is worth taking a critical look at the parameters we have adopted. The reduced β^* value is only a factor of two below present schemes, and conceivably could be pushed even lower. The difficulties here are related to the focusing strength of the quadrupoles, chromaticity correction, and mechanical interferences between quadrupoles for the two rings. In addition, backgrounds under these conditions will require careful evaluation. It is implicitly assumed here that a crab-crossing scheme has been used, as this should minimize both the interference and the background problems.

Issues of RF and feedback system parameters, and of HOM heating, are difficult to examine in detail at a workshop. Although the results here are believed to be reasonable, this would have to be confirmed by actual engineering studies.

An increase in the beam-beam parameter ξ is difficult to justify theoretically, and must be considered as a research topic requiring both experimental and computational efforts. If the original value of 0.03 were retained, the estimated luminosity would drop to 60% of the value quoted in Section 3.1.2, but would remain greater than $10^{34}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$.

3.2 ϕ-Factory Parameter Regime

The high luminosity of the Novosibirsk ϕ-factory is reached using a very short bunch length and a β^* smaller than 1 cm, together with a large beam-beam tune shift (ξ = 0.07). A luminosity improvement in the Frascati approach can be based on the use of crab crossing to reduce the bunch spacing. In the UCLA design, one can use a quasi-isochronous ring configuration[21] to reduce the bunch length and thus make use of a lower β^*. This concept is discussed in Section 4.

With these improvements , one should be able to reach a luminosity of about 10^{33} cm^{-2}s^{-1}. It seems very difficult to push the storage ring technology much above this luminosity. In addition, the beam lifetime due to beam-beam Bremsstrahlung becomes very short at $\mathcal{L} \approx 10^{33}$ cm^{-2}s^{-1}, only a few minutes, requiring very frequent injection and making the ring operation complicated. We believe that to reach luminosities in the 10^{34} cm^{-2}s^{-1} range, new collider concepts need to be developed, such as the quasi-linear collider[22].

4. New Concepts

As discussed previously, the luminosity of a storage ring collider is limited by the beam-beam tune shift, by β^*, and by the allowable beam current. It is worthwhile to discuss possibilities and recent ideas to overcome these limitations. We will try to do so in this section.

Recent work on the physics of the beam-beam interaction and on the importance of effects like non-zero bunch length, round beams, synchro-betatron coupling, etc., is leading to a better understanding of these issues, and may ultimately lead to a better ring design, a higher beam-beam tune shift limit, and higher luminosities.

Several years ago, the Orsay Group proposed a scheme to compensate the beam-beam interaction by colliding four charge-compensated beams, thus reducing the electric and magnetic fields acting on the beams to zero. This was implemented in DCI, but without success, and so DCI was brought back to a standard two-beam configuration. The reason for this failure is still not fully explained and it may be useful to revisit this concept. Either the beam neutralization or the other improvements could lead to a luminosity increase of up to one order of magnitude.

A reduction of β^* is possible only if we can reduce the bunch length below its present typical value of about one centimeter (see the discussion in Section 3.1.2). A proposal to do this using a quasi-isochronous ring has been advanced recently by Pellegrini and Robin[21]. In a quasi-isochronous ring, the linear term of the momentum compaction is made small by using negative dispersion in some of the ring dipoles. How small the linear term can be made is determined by the nonlinear terms of the momentum compaction factor, as discussed, for example, by Chattopadhyay et al[23]. When the momentum compaction is reduced, the threshold condition for the microwave instability decreases; however, the growth rate also decreases such that, at some point, the instability can be controlled by radiation damping. The result is a bunch as short as one millimeter with a higher current than could be obtained in a conventional ring. This scheme leaves open the limitation on peak current due to the fast head-tail instability. This instability can, in principle, be controlled with Landau damping using octupole magnets. However, these octupoles are likely to reduce the ring dynamic aperture to an unacceptably small value. This problem can possibly be solved using the "modified nonlinear lenses" proposed recently by Cornacchia and Halbach[24]. Such proposed lenses produce fields that are nonlinear near the beam axis but almost linear at large amplitudes. Modified sextupoles have been shown by means of calculations to be very effective in improving the dynamic aperture in the UCLA ϕ-factory design, and their use could be effective in other situations as well.

The quasi-isochronous ring and the modified nonlinear lenses might lead to improved storage ring design and (with a reduction of β^* by one order of magnitude), to higher luminosities. The concept should be further studied. A luminosity increase by a factor of 10 is conceivable as a result. In addition to the gain obtainable from a reduced bunch length and β^*, the small synchrotron tune in a quasi-isochronous ring will reduce the effect of synchrobetatron resonances in the beam-beam interaction, and might lead to a larger tune shift limit.

Another idea that we want to mention as an example of alternative collider concepts is that of a quasi-linear collider[22], using a ring to store and recover positrons, a high brightness linac to produce the electrons, and having the collisions in a bypass of the ring. This approach has some potential advantages: easing the positron refill requirements to compensate for beam losses due to beam-beam Bremsstrahlung; allowing a small beam pipe at the IP, thus facilitating vertex detection; and allowing a larger energy asymmetry. A luminosity in the $10^{33} - 10^{34}$ cm^{-2}s^{-1} range may be possible.

Each one of the effects discussed above has the potential to provide a luminosity increase by one order of magnitude. Although further analysis may show that such a large luminosity increase may not be obtainable from any one technique, it seems likely that by adopting a combination of new techniques, a total luminosity gain of a factor of ten or more, say 5×10^{34} $cm^{-2}s^{-1}$ for a B-factory, might be possible.

5. R&D Issues

The development of very high luminosity colliders pushes some aspects of the technology of accelerator design considerably beyond the present state-of-the-art. The high demands placed on the circulating beam current, on the optics design, and on the operational reliability require a plan for carrying out an R&D program. In this section, we briefly review what we perceive as the major R&D issues. The emphasis here is on the highest energy collider issues (B-factory), although, on a qualitative basis, the challenges are common also to lower energy colliders (ϕ-factories and τ-charm-factories).

The single most important technological challenge is represented by the high circulating beam current. For a B-factory, this is one to three amps, depending on the particular design. This current is up to a factor of 20 higher than in any collider ring in operation today (CESR has achieved a 170 mA current in one beam). The technological challenges involved in the extrapolation to the B-factory parameter regime concern the large amount of RF power that has to be provided to the beam to compensate for beam loading and synchrotron radiation losses, as well as the difficulty of getting rid of the radiation in a way that does not compromise the pressure.

We envisage an R&D program aimed at optimizing the location and characteristics of RF windows from the point of view of breakdown. Plans include investigating wave-guide coupling versus standard loop coupling, examining the feasibility of putting an RF window in an evacuated waveguide far from the cavity entrance, and studying the limits on the maximum power transmission through a window. The implications of beam loading on the fundamental accelerating mode of the RF cavities in the presence of amperes of beam current is also an important R&D issue.

Effort should be directed towards the development of RF cavities able to offer a low impedance for the potentially dangerous coupled-bunch modes of beam oscillation, while allowing a high impedance at the main accelerating frequency. Laboratory studies and bench measurements will examine cavity structures with transverse and longitudinal slots. Active cavity-to-cavity feedback should be pursued in an operating ring such as CESR or PEP. We also point out the need for studies aimed at understanding the HOM losses in the RF cavities under the heavy loading situation typical of a B-factory.

The synchrotron radiation power density astr long the curved sections of the ring is, again in the case of a B-factory collider, on the order of 10–20 kW/m. This value is several times that of existing accelerators but is expected to be manageable with a copper vacuum chamber. In addition, third-generation synchrotron radiation sources have made progress in the design and construction of vacuum systems that can get rid of the radiation in a controlled way. These systems involve the use of a beam duct with an antechamber. Further R&D is needed in order to improve our understanding of gas desorption from a chamber wall subjected to synchrotron radiation bombardment. These studies may make use of the intense radiation available from light sources and colliders (PEP, SPEAR, CESR, etc.).

As discussed earlier in this report, the road to high luminosity requires the use of many bunches. Longitudinal and transverse feedback systems able to observe and correct the motion of individual bunches will be necessary. The technological challenges here are represented by the demands of high power (to cope with fast-growing instabilities) and high bandwidth (to control each bunch individually). The estimated power levels and bandwidth are greater than anything in operation today. Several accelerator physics issues have emerged from the studies carried out so far. Many of these issues can be investigated, and hopefully resolved, by accelerator physics experiments at existing facilities (CESR, PEP, TRISTAN, etc.). A prototype feedback system of, say, 100 MHz bandwidth with kickers having high frequency shunt impedances on the order of 2.5–5 kΩ (and with fast processing circuits to handle the information) should be designed, fabricated and tested. Very high sensitivity beam position monitors should be developed, either in the form of stripline quarter-wavelength series loops, or as other traveling-wave structures.

New experiments may shed some light on the still-elusive beam-beam interaction. Such experiments may involve studies of tails in the bunch transverse charge distribution (relevant to experimental background), of the long range beam-beam interaction (relevant to the design of the experimental insertion and to the determination of the number of bunches), and of the sensitivity of the beam-beam interaction to small beam misalignments and beta function errors at the interaction point. Also, of great interest is the dependence of the beam-beam tune shift limit on energy and damping times. This study could be carried out at existing collider facilities where wigglers are installed (like CESR and PEP).

The crab-crossing scheme should be tested. The round-beam option is also an interesting R&D item if it could be tried in one of the operating facilities; here the background must be carefully evaluated as well. We also strongly recommend an experimental study at an existing machine of the impedance seen by a short bunch.

Trapping of ions in the potential well of the electron beam always represents a threat to the stability of electron-only accelerators. Although this is a very elusive phenomenon, difficult to interpret, a study should be made of ways to avoid ion trapping, such as a gap in the train of bunches. Clearing electrodes may also be effective in suppressing the ions: one should verify experimentally the benefits of a combination of a static electric field and a superposed electric field oscillating at the frequencies of the trapped ions. Calculations have shown[14] that this combination holds the promise of suppressing the ions while keeping the clearing electrode voltage at reasonable levels, and experiments[25] at the CERN Antiproton Accumulator ring have demonstrated the efficacy of the technique.

The R&D program suggested so far involves issues related to the present B-factory, ϕ-factory, and τ-charm-factory proposals. In spite of the challenging problems these machines offer to accelerator designers and builders, they are basically extrapolations of established accelerator concepts and technologies. We recommend that the study of "new ideas" should proceed in parallel with the R&D of more conventional technology. We have identified some ideas worth pursuing. The quasi-isochronous lattice concept carries the promise of providing very short bunches, one to a few mm, with associated luminosity benefits (described earlier in this report). It would be useful to explore the possibility of modifying the lattice of an existing facility in order to verify the method experimentally. The recently proposed[24] "modified multipoles" may allow high luminosities (sextupoles) and provide Landau damping against single-bunch transverse collective instabilities (octupoles) while preserving a large dynamic aperture. Prototypes of such magnets should be built and tested at existing facilities.

6. Summary and Conclusions

In this report we have examined the potential of e^+e^-colliders to achieve very high luminosity. Existing design studies of B-factories and ϕ-factories provided representative parameters that formed the starting point for our discussions. After examining these parameters, we considered what their limitations were and assessed what luminosity enhancement was possible by pushing the limits further than was deemed suitable for an initial machine proposal. Several alternative approaches to high luminosity were also discussed.

Given that we are attempting to enhance the collider luminosity by several orders of magnitude over today's machines, there are some issues that will require R&D to confirm parameter choices and optimize designs. We have identified several areas where R&D activities are deemed appropriate and outlined the requisite tasks. Besides the technology R&D, we wish to emphasize that new approaches to high-luminosity colliders will require a more generalized R&D effort in accelerator physics. To ensure a viable future for high-energy physics accelerators, it is essential that such R&D be properly supported.

Based on our discussions, we conclude that:

- Technical solutions for a B-factory at $\mathcal{L} = 3 \times 10^{33}$ cm^{-2}s^{-1} and a ϕ-factory at $\mathcal{L} = 3 \times 10^{32}$ cm^{-2}s^{-1} are in hand.
- A luminosity upgrade to $\mathcal{L} = 2\times 10^{34}$ cm^{-2}s^{-1} (B-factory) or to $\mathcal{L} = 3 \times 10^{33}$ cm^{-2}s^{-1} (ϕ-factory) is possible by extending the existing designs. Achieving these goals will require R&D activities in the key technical areas; this implies a commitment by the high-energy physics community for money, time, and people.
- New approaches offer the possibility of tenfold improvements in luminosity. Accelerator physics R&D programs to validate these projections are also crucial and should be supported.

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