B-FACTORIES: A Perspective of B-Physics and Possible Accelerator Design Approaches

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Introduction

Experiments studying B-meson decays have produced results that were unexpected five years ago:[1] the B lifetime is long, and mixing of neutral B's has been observed. In addition, there is some evidence of the decay of the b-quark to the u-quark, but this result is in doubt. These measurements determine parameters of the Kobayashi-Maskawa (KM) matrix, the weak decay matrix in the Standard Model, and using those parameters, estimates can be made of CP violation asymmetries in B-meson decay. Based on these estimates, there is a prospect of observing CP violation in B-meson decay!

B-mesons are produced prolifically in high energy hadron-hadron collisions; the rate at the SSC will be astronomical. However, at such machines identifying events with B's is a substantial experimental problem. In this case the challenge is one for the experimenters. The production rate is lower at e^+e^- colliders, but the experimental problems are easier. Here the challenge is to the accelerator physicists to design a high luminosity collider suitable for study of CP violation.

Particle Physics[2]

CP violation could be seen in a variety of channels of neutral and charged B-meson decays. The most straight forward result to interpret would be a measurement of the CP violation asymmetry arising from mixing of neutral B's with decay to a CP eigenstate. One such decay, $B^0 \to \psi K_s$, was studied in detail at the recent DPF workshop (Snowmass, 1988). The goal of the study was a clarification of the particle physics, experimental requirements, and accelerator physics needed for such a measurement. Although the study was focused on a specific decay, others would result in similar accelerator parameters.

The results are summarized in Table I where five techniques are compared. For any one technique the factor of 36 range in luminosity arises from uncertainty in the CP violating phase in the KM matrix. Comments about the techniques follow.

#0 Symmetric collider operating at the Υ(4S): This natural choice, a collider with equal beam energies operating on a resonance with an enhanced cross section, doesn't appear in the table because CP violation via mixing cannot be measured for the reason that follows. In the reaction

$$e^+e^- \to \Upsilon(4S) \to B^0\bar{B}^0$$

the $B^0\bar{B}^0$ are produced in a CP=-1 state and approximately at rest in the Υ rest frame. As a consequence of the former, the first B decay determines the CP of the second B and mixing begins at the time of the first decay. To observe CP violation the time difference between the B decays must be measured. However, with equal beam energies the Υ, and the B's, are approximately at rest in the laboratory, and the time difference measurement is well beyond the capability of present vertex detectors. A symmetric collider operating at the Υ(4S) could observe CP violation via mechanisms other than mixing. As mentioned above such a result would not be straight forward to interpret.

#1 Asymmetric collider operating at the Υ(4S): In an asymmetric collider the beam energies are unequal, and the Υ is produced moving in the laboratory. Because of time dilation the (laboratory) lifetimes of the B's increase. With a beam energy ratio of 5 to 10 the time difference between decays can be measured using state-of-the-art silicon vertex detectors and a small radius, 1 to 1.5 cm, beam pipe at the interaction point. The center-of-mass energy spread must be small to take advantage of the resonance cross section and for background rejection through kinematic reconstruction.

#2 Symmetric collider operating above BB^* threshold: A different way to address the difficulties of case #0 is to produce the $B^0\bar{B}^0$ in a state with CP=+1 through the reaction

$$e^+e^- \to B^*\bar{B}^0 \to \gamma B^0\bar{B}^0$$

The threshold is at an energy above the Υ(4S), and the resonance cross section enhancement is lost. Most of the integrated luminosity difference between cases #1 and #2 is due to this. The beam energy spread must be small to avoid contamination from $B^*\bar{B}^*$ production and for kinematic reconstruction for background rejection.

#3 Collider operating in the continuum: B's are produced inclusively in the reaction

$$e^+e^- \to B\bar{B}X\ .$$

Either B may be charged or neutral. The decay of one of the B's into a mode with a clear CP signature and a large branching ratio tags the CP of the other B at the moment of production. The time evolution of the decay of the tagged B into ψK_s is measured. The center-of-mass energy (W) must be at least 15-16 GeV for the B to have a long enough laboratory lifetime to make the measurement feasible. The continuum cross section falls as W^{-2}, so W be near the minimum needed for the measurement. There is no energy spread requirement because the B's are produced inclusively and kinematic reconstruction cannot be used.

#4 Collider at the Z without polarization: The experimental techniques would be the same as for #3. The advantage is the large cross section of the Z resonance.

#5 Collider at the Z with polarization: With a longitudinally polarized electron beam on the Z resonance there is a large forward-backward asymmetry in B

Table I: Comparison of B-Factories[2]

#	Description	W (GeV)	∫Ldt (10^{40} cm^{-2})	Collider requirements
1	Asymmetric collider at the Υ(4S)	10.6	0.3 - 12.	Beam energy ratio 5-10, 1-1.5 cm radius beam pipe at IP, σ_δ<0.001
2	Symmetric collider above BB^* threshold	10.6	2.2 - 78.	σ_δ<0.001
3	Collider in the continuum	16.	14. - 490.	no requirement on σ_δ
4	Collider at the Z, no polarization	93.	0.5 - 19.	
5	Collider at the Z with polarization	93.	0.1 - 3.6	90% polarization

The integrated luminosity needed to observe a 3 standard deviation effect in the CP violating asymmetry for $B^0 \to \psi K_s$. Cross sections, decay fractions, tagging efficiencies, detection efficiencies and misidentification probabilities are included in arriving at the luminosity estimate.

production. Depending on the electron helicity either B's or $\bar{B}$'s are produced preferentially along the electron direction, and the direction of the decaying B is an efficient tag of its CP. This leads to a reduction in the integrated luminosity if a high degree of polarization can be achieved. A linear collider with polarized electron source would be needed.

Table I gives the integrated luminosities expected to be needed for measuring a three standard deviation effect. The table can also be interpreted as the peak luminosity, in units of $10^{33}cm^{-2}sec^{-1}$, to perform such a measurement in about a year. A peak luminosity over $10^{32}cm^{-2}sec^{-1}$ would be needed at the Z. A collider capable of this is distinct in overall scale from the lower energy facilities. Construction would require a major national or international effort, and the decision to undertake that effort would be based on a broad physics program with CP violation as one element.

This paper concentrates on the smaller scale machines. The luminosity requirements are well above the record of $1x10^{32}cm^{-2}sec^{-1}$ achieved at CESR. New accelerator design approaches are needed.

Storage Rings

The accelerator physics issues can be understood by writing the luminosity in terms of quantities that limit performance. For a storage ring B-Factory these are the beam-beam interaction, single bunch currents, and the total beam current.

Luminosity and the beam-beam interaction: The two beams are assumed to have equal horizontal sizes and equal vertical sizes. The luminosity is given by

$$L = \frac{N_1 N_2 f_c}{4\pi\sigma_h\sigma_v} . \qquad (1)$$

Symbols are defined in Appendix A.

The strength of the beam-beam interaction is parametrized by the beam-beam tune shifts. For example the vertical beam-beam tune shift of beam #1 is given by

$$\xi_{v1} = \frac{r_e}{2\pi} \frac{N_2\beta_{v1}}{\gamma_1\sigma_v(\sigma_h+\sigma_v)} \qquad (2)$$

To proceed, assume $\xi_{v1} = \xi_{h1} = \xi_1$ and $\xi_{v2} = \xi_{h2} = \xi_2$; this is satisfied if $\beta_{v1}/\beta_{h1} = \beta_{v2}/\beta_{h2} = R_\sigma$. The luminosity written in terms of N and ξ is

$$L = \frac{\gamma_{cm}}{4r_e} f_c \ (1+R_\sigma) \left[\frac{N_1\xi_1}{\beta_{v1}} \frac{N_2\xi_2}{\beta_{v2}} \right]^{1/2} \qquad (3)$$

In writing and interpreting this equation it is assumed that the number of particles is at a maximum value determined by instabilities and/or RF power and σ_h and R_σ are adjusted to reach the maximum tune shift.

Usually the maximum tune shifts, the "tune shift limits", are treated as basic design parameters, but this is oversimplified. The beam-beam limit results from the non-linearity of the beam-beam force while the tune shift parametrizes the linear part of the force. An example is the limit

$$\beta_v \geq \sigma_L \qquad (4)$$

that has been observed in simulations[3] and experiments.[4] It is a dynamical effect arising from the modulation of the beam-beam force by synchrotron oscillations. This makes the point: dynamics determine the "tune shift limit".

Can other dynamics besides this well-known example lead to a tune shift limit, and can that dynamics be modified and the limit raised? Answering these questions has been the subject of recent work[5] motivated substantially by the parametric amplifier model of the beam-beam interaction in flat beams.[6] In this model the vertical emittance growth that is one of the manifestations of the beam-beam limit is due to modulation of the vertical beam-beam kick by horizontal oscillations. These could be betatron oscillations or synchrotron oscillations if the crossing point dispersion is not zero.

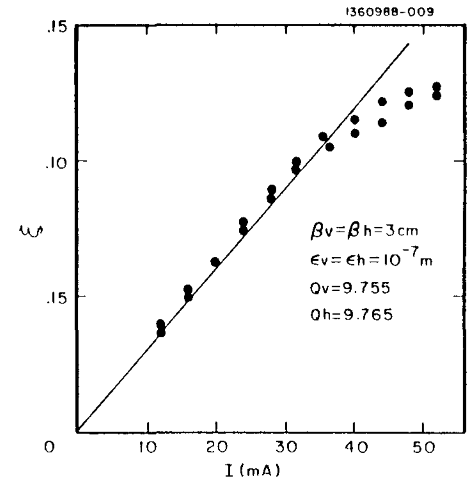

Figure 1: Beam-beam tune shift vs single bunch current for a machine with CESR-like parameters (ref. 8) except for a round beam collision geometry.[5] Feedback is used in the simulation to suppress coherent beam-beam effects.

For a round beam, defined as a beam with $\varepsilon_h=\varepsilon_v$ and $\beta_v = \beta_h$, modulation is not important. The distinction between horizontal and vertical is gone, and the problem becomes that of the one-dimensional beam-beam interaction. This can be analyzed analytically and is known to have a high tune shift limit.[7] Computer simulations are being used to study approximately round beams, beams that are nominally round but with some difference between horizontal and vertical. Initial results are encouraging; figure 1 is an example. In this figure the betatron tunes differ by 0.01, but the tune shift is linear in current to $\xi \sim 0.1$. Above that there is an emittance growth; at 50 mA the emittance increase is about 25%.

Plans are to continue this work with the major thrust being to incorporate synchrotron oscillations in the simulation. For $\xi \sim 0.1$ phenomena new to storage rings are expected. The disruption parameter which characterizes single pass effects and the tune shift are related as

$$D = \frac{2r_e N\sigma_L}{\gamma\sigma_h^2 R_\sigma(1+R_\sigma)} = 4\pi\xi \frac{\sigma_L}{\beta_v} . \qquad (5)$$

For $\xi \sim 0.1$ and $\beta_v \sim \sigma_L$, $D \sim 1.2$, and single pass collision effects start to become important. The consequences are not clear; luminosity enhancement (good!) and emittance dilution (bad!) are both possibilities. If simulation results remain encouraging, experimental studies are the next step.

Beam current limits: Single bunch instabilities, higher mode losses, coupled bunch instabilities, and total RF power are all important. PSI has proposed a storage ring with a design luminosity in the range $0.5\text{-}1x10^{33}cm^{-2}sec^{-1}$.[9] Although low compared to that needed for CP violation measurements, the parameters, summarized in Table II, are used in this discussion to estimate typical numbers.

Consider single bunch instabilities first. The microwave instability threshold is substantially lower than the fast head-tail threshold. It is

$$N_\mu < \frac{\sqrt{\pi}\alpha\gamma\sigma_\delta^2\sigma_L Z_o}{\sqrt{2}r_e\langle Z_L/n\rangle} \qquad (Z_o = 377\Omega) \quad . \qquad (6)$$

When the natural bunch length is substituted for σ_L, eq. (6) gives the bunch lengthening threshold. Above the threshold the bunch lengthens to satisfy eq. (6), and the luminosity is affected through the β_v limit, eq. (4). For the PSI collider $\langle Z_L/n\rangle \lesssim 0.6\Omega$ to avoid bunch

Table II: Beam Current Related Parameters for the PSI Collider Operating at the $\Upsilon(4S)$ [9]

Particles per bunch (N)	6.6×10^{11}
Bunches per beam	10
Collision frequency (f_c)	4.63 MHz
Revolution frequency (f_o)	463. kHz
Bunch length (σ_L)	0.02 m
Fractional energy spread (σ_δ)	6.6×10^{-4}
RF Frequency	500 MHz
Number of five-cell RF cavities	10
Synchrotron radiation power	530 kW

These parameters are for one of the two rings.

lengthening at the design current. This is about a factor of two better than achieved in operating rings.

$\langle Z_L/n\rangle$ in eq. (6) is determined by the imaginary part of Z_L. The real part leads to higher order mode losses that are given by

$$P_{HOM} = G\,\frac{N^2e^2f_c}{4\pi\varepsilon_o} \tag{7}$$

where G is the loss factor. For a single RF cavity cell with the approximate geometry proposed by PSI, $G=14.4\text{m}^{-1}$ for σ_L=2cm. The higher order mode losses in the RF system are about 330 kW. Losses in the rest of the ring could be roughly equal. Higher mode losses are comparable to the synchrotron radiation power.

Coupled bunch instabilities are associated primarily with high Q resonant modes of the RF cavity. Effective mode damping must be part of the RF system design, but this could be insufficient and multibunch feedback would also be needed.

From these numbers it is clear that B-Factories will be heavily beam-loaded and that minimizing impedance is of central importance. The RF design should trade-off fundamental mode shunt impedance and high frequency impedance while keeping the overall RF power (and operating cost) within reason. Such a trade-off has been studied using the PEP RF system as a model. This system was designed with cavities of approximately the same geometry but with beam pipe radii ranging from 3.8 cm to 6.4 cm. The fundamental mode shunt impedance depends on the beam pipe radius, b, as $b^{-0.4}$.[10] The high frequency longi-tudinal and transverse impedances have been calcu-lated.[11] They vary with b as $Z_L\sim b^{-1.4}$ and $Z_T\sim b^{-3.0}$, and the G depends on b as $G\sim b^{-1.3}$. Compared to the fundamental, these decrease more rapidly with b. Although a limited study with only one parameter varied, it illustrates that an optimization of the RF system is possible.

Equal beam energies: Consider CESR performance for some typical numbers. At present CESR is limited by total beam current and the beam-beam interaction. Parameters are: $\Upsilon_{cm}=2.1\times10^4$, $R_\sigma<<1$ (a flat beam), ξ=0.02, σ_L=1.7 cm, β_v=1.5 cm, and $Nf_c=4.4\times10^{17}$ (70 mA/beam). Eq. (3) gives $L=1.1\times10^{32}\text{cm}^{-2}\text{sec}^{-1}$; this is within 10% of the luminosity achieved.

CESR performance shaped the discussion earlier in this paper. The CESR current limit has many components that include: reliability, higher order mode heating of the vacuum system, RF power, and effects of beam induced fields in the RF system. These must be central design issues for a future B-Factory. The cause of the CESR beam-beam limit is not as clear, but most evidence points to beam-beam resonances.[12]

The strategy for higher luminosity is clear; f_c, β_v, N, and ξ must be optimized. A double ring is needed for a high collision frequency. The collisions must be head-on to avoid a tune shift limit arising from a crossing angle,[13] and the beams must be separated close to the interaction point to avoid extraneous collisions. These will limit $f_c\lesssim$10 MHz.

Equations (4) and (6) can be combined to give an upper limit on L

Table III: Parameters of B-Factory Storage Rings Designed to Operate Near the $\Upsilon(4S)$

		Dubrovin et al[14]	Round Beam
Collision frequency (MHz)		4.0 - [11.3]	10
Particles per bunch (10^{11})		4 - [10]	6
Energy spread (10^{-3})		[1] - 1.5	1
Bunch length (cm)		0.8	1.5
Momentum compaction (10^{-2})		0.1 - [0.4]	1.
Synchrotron tune		0.009 - 0.013	0.07
Emittances	ε_v	.3 - [3]$\times10^{-9}$	1×10^{-7}
(m-rad)	ε_h	.1 - [3]$\times10^{-7}$	1×10^{-7}
Crossing parameters	β_v	0.01	0.03
(m)	β_h	0.56	0.03
	η_h	1.28	0.00
Tune shifts	ξ_v	0.05	0.10
	ξ_h	0.0025 - 0.01	0.10
CALCULATED QUANTITIES			
Beam sizes	σ_v	5.5 µm	55. µm
	σ_h	1.3 mm	55. µm
	R_σ	0.004	1.
$\langle Z_L/n\rangle$ limit (Ω, eq. 6)		0.06	0.44
Luminosity limit (eq. 8) ($10^{34}\text{cm}^{-2}\text{sec}^{-1}$)		1.4	1.5

The last entries in the table were calculated. The parameters in [ ] were used for Dubrovin et al.

$$L < \frac{\sqrt{\pi}Z_o}{8\sqrt{2}r_e^2}\,[\,\Upsilon_{cm}\sigma_\delta\,]^{-2}\,\frac{\alpha f_c(1+R_\sigma)\xi}{\langle Z_L/n\rangle}\,. \tag{8}$$

The middle factor depends on particle physics and is different for cases #2 and #3. The latter case has higher luminosity potential but probably is not the most cost effective way to study CP violation.

The last fraction of eq. (8) relates to the design of the collider. Table III contains two parameter lists for B-Factories operating near the $\Upsilon(4S)$. The contrast between them highlights the accelerator physics issues. The "Round Beam" collider is based on the ideas discussed above, and the crucial question is whether $\xi\sim0.1$ can be reached. The conceptual design of Dubrovin et al[14] has a flat beam crossing geometry. The bunch length is short, and β_v is small. The momentum compaction is small, as it must be for a short bunch; a short bunch and low α leads to a stringent impedance limit, $\langle Z_L/n\rangle$ <0.06Ω. In addition, small α leads to a small ε_h, and dispersion must used be to produce horizontal beam size and limit the tune shift. The resultant synchrotron modulation of the vertical beam-beam kick raises the question of the feasibility of ξ_v=.05. This together with the impedance limit are the crucial issues for this design.

Unequal beam energies: The recent interest in asymmetric colliders has been stimulated by their particle physics advantage and the possibility of low cost if a present facility could be used as the high energy ring. There are two conceptual designs based on PEP[15] and PETRA;[16] both are constrained to some degree by the existing machine. The parameters of the PETRA machine are in Table IV.

Equal beam sizes, $\sigma_{h1}=\sigma_{h2}$ and $\sigma_{v1}=\sigma_{v2}$, are used because of lower tune shift limits for unequal size beams at the SPS[17] and the absence of a strong argument for unequal sizes.[18] The tune shift limits are also taken as equal, $\xi_1=\xi_2$, but there is little justification for this and doing so introduces uncertainty. For example, different parametrizations of the dependence of ξ on synchrotron radiation energy loss[19] lead to conclusions ranging from $\xi_2\sim\xi_1$ to $\xi_2\sim\xi_1/3$. An investigation of the beam-beam interaction with unequal beam energies is needed.

The upper limits on $\langle Z_L/n\rangle$ are in range of 1-2 Ω's, and the single bunch currents are determined by the aperture of the existing ring and the assumed tune shifts. Multi-bunch instabilities are the more serious issue. The PETRA design has 88 4-cell superconducting

Table IV: Parameters of Asymmetric B-Factory Based on PETRA[16]

Collision frequency	2.6 - 31.2 MHz	
Luminosity	0.09 - 2.2 x $10^{33} cm^{-2} s^{-1}$	
	LARGE RING	SMALL RING
Beam Energy (GeV)	14.	2.
Revolution frequency	130. kHz	2.6 MHz
Particles per bunch (10^{11})	1.4	4.3
Emittances ϵ_v	0.03	0.07
(mm-mrad) ϵ_h	0.2	0.47
Crossing parameters β_v	7.0-3.5	3.0-1.5
(cm) β_h	47.-24.	20.-10.
Tune Shifts ($\xi_v=\xi_h$)	0.03	0.03
Energy spread (10^{-3})	1.2	1.1
Fract. energy loss/turn (10^{-4})	12.7	1.5
Bending radius (m)	192.	4.65
Synch. rad. power (MW)	1.1-13.	0.05-0.6

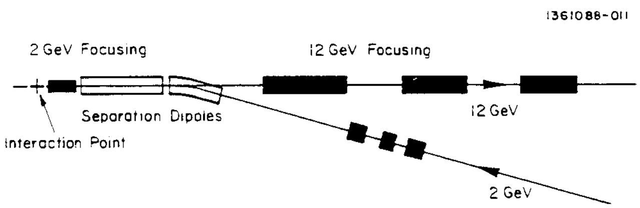

Figure 2: IR geometry for the PEP B-Factory.[15]

cavities to make up the synchrotron radiation loss; it relies on reduction of the Q's of higher modes and a newly developed feedback technique[20] for stability.

The interaction region (IR) of an asymmetric collider is unique. Two very different energy beams must be focused and separated in a short distance. The solution adopted is shown in figure 2. Quadrupoles close to the IR focus the low energy beam. They are followed by dipole beam separators and the focusing quadrupoles for the high energy beam. This particular design illustrated has a 1.6 T dipole beginning 1 m from the interaction point. Dealing with synchrotron radiation produced inside a detector with a 1-1.5 cm diameter beam pipe is required. This combination of the interaction region design and its implication on the high energy physics detector is the major accelerator physics problem of the asymmetric colliders.

Linear Colliders[21,22]

Compared to a storage ring, a linear collider has a small number of particles/bunch and a low collision frequency; the luminosity comes from focusing the beam to a small spot. The beam-beam interaction is stronger, and there is focusing and luminosity enhancement during the collision. L is given by eq. (1) with an additional enhancement factor, H.

The principal design issues are disruption and beamstrahlung, acceleration mechanisms, and positron production and damping. These are the same issues as for TeV energy colliders, but the parameters are so different that a B-Factory is a unique problem. Parameter lists have been developed for two approaches with different acceleration mechanisms. ARES[23] is based on superconducting RF. High frequency, room temperature RF is used by Wilson[24] and Cline.[25] The parameters of three B-Factories in Table V are referred to in the discussion that follows. The discussion is restricted to symmetric, round beam colliders (#2, #3, Table I), but it could be extended to an asymmetric collider (#1).

Disruption and beamstrahlung: At small values of D the beam-beam interaction acts like a thin lens with focal length σ_L/D. At larger values the beam undergoes plasma

Table V: Linear Collider Parameters[23,24]

Parameter	ARES-I	ARES-II	Wilson
$\gamma(10^4)$	1.04	1.47	1.96
$L(10^{34} cm^{-2} sec^{-1})$	0.13	2.0	1.0
$N(10^{10})$	$2.5(e^+), 8.0(e^-)$	$5.0(e^+), 8.0(e^-)$	2.2
RF freq. (GHz)	0.50	0.50	10.
Gradient (MV/m)	5.	5.	100.
$\epsilon_n (10^{-6} m)$	2.0	2.0	3.0
σ_L(mm)	$3.0(e^+), 1.0(e^-)$	$0.7(e^+), 0.5(e^-)$	0.3
σ_h(μm)	1.0	0.5	.32
R^σ	1.0	1.0	1.0
$\beta_v = \beta_h$(mm)	5.0	5.0	0.7
f_c (kHz)	10.	10.	44.4
bunches/RF pulse	-	-	4.
D	$21.(e^+), 22.(e^-)$	$25.(e^+), 28.(e^-)$	9.0
H	10.	10.	6.
$\sigma_W/W(10^{-3})$	0.9	5.8	5.
AC power (MW)	18.	20.	100.

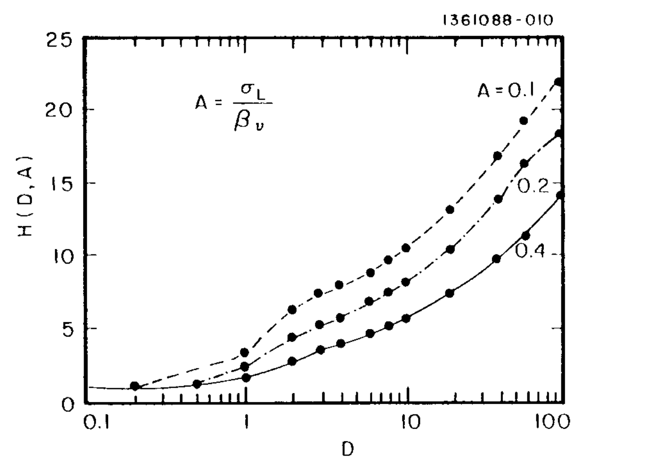

Figure 3: Luminosity enhancement calculated by Chen and Yokoya.[27]

oscillations with approximately $(D/10)^{1/2}$ oscillations during the beam passage.[26] Recent results for the luminosity enhancement from disruption are shown in figure 3.[27]

What is the maximum value of D? The answer is central to any design for the reason that follows. Assume D has a maximum value and N is limited, e.g. by wakefields, then

$$L = \frac{\gamma_{cm}}{16\pi r_e} H f_c (1+R_\sigma) \left[\frac{N_1 D_1}{\sigma_{L1}} \frac{N_2 D_2}{\sigma_{L2}}\right]^{1/2} . \qquad (9)$$

This equation is to be interpreted in the same way as eq. (3). The maximum value of D is analogous to the tune shift limit of a storage ring and has implications for impedances, e^+ production rates,....

This maximum is likely to be determined by tolerance to errors such as position offsets. An investigation of tolerances introduces substantial complications into the simulations such as the one leading to figure 3, and it remains to be done. Until it is, it is difficult to know whether the values of D in the table are conservative. If they are, parameters (eg. f_c) could be changed in the ARES-II and Wilson parameter lists. For ARES-I energy spread is also a strong constraint.

That constraint comes from beamstrahlung. With its low energy, a B-Factory is in the classical beamstrahlung regime. Beamstrahlung introduces a center-of-mass energy spread[28]

$$\frac{\sigma_W}{W} = 0.32\, \delta_{cl} \left[1 + \frac{4.6T}{\delta_{cl}}\right]^{-1/2} \qquad (10)$$

where T and δ_{cl} are the beamstrahlung scaling parameter and mean fractional energy loss, respectively[29]

$$T = \frac{1.45 r_e \lambda_c \gamma}{\sigma_L} \left[\frac{L}{f_c}\right]^{1/2} ; \quad \delta_{cl} = \frac{.88 \pi r_e \gamma L}{\sigma_L f_c} . \qquad (11)$$

When there is an energy spread requirement from particle physics (#1, #2 in Table I), beamstrahlung places an upper limit on $L/\sigma_L f_c$. For ARES-I a narrow energy spread is a design goal, and it is the reason for the different luminosities of ARES-I and ARES-II.

Acceleration mechanisms: Scaling laws for a high frequency, room temperature collider have been developed by Wilson.[24] Beginning with parameters typical of the high gradient work at SLAC (gradient, RF frequency, and wall plug power) and working with the constraints from beamstrahlung and disruption, structure efficiency, wakefields, and final focus design he arrives at the parameters in Table V. RF related results are a) there must be more than one beam bunch per RF pulse (four is the minimum), and b) the RF rep rate must ~ 10kHz. Multiple bunches per RF pulse are also a feature of TeV energy colliders, and B-Factory structure development could take advantage of this work.[30] The high rep rate makes the RF power source for a B-Factory unique, and it will need its own R&D program.

Superconducting RF seems the more natural choice. Present day gradients and Q's are adequate, power source development is not needed, and the wall plug power is substantially lower. Another advantage is that limits arising from wakefields are less severe because of the low RF frequency and large structure size.

Positron production and damping: A comparison of the numbers in Table V with the SLC shows that f_c is two orders of magnitude higher, ϵ_n is a factor of ten smaller, and N is comparable. Positron production and damping have been major R&D areas for the SLC, and a B-Factory has still harder demands. (Designs have the e^- beam generated with a photocathode gun.)

The instantaneous power incident on the e^+ converter is comparable to the SLC because N is comparable, but the average power is several orders of magnitude higher. An energy of about 1.9×10^{-9} J incident on a converter produces one positron;[31] therefore, an average power of about 1 MW incident on a converter is needed to produce the e^+ beam. There is a conceptual design of a converter for this power level that has identified the major problems. These are thermal shock, removal of heat, high radiation doses, and high levels of residual radioactivity.[32] This design could serve as the starting point for an R&D program in e^+ production.

The damping ring must produce e^+ bunches at a rate of about 10 kHz. The ring that has been studied is a large ring, f_o~450kHz, with bunches spaced at 7 m.[33] Wideband multibunch feedback and ultrafast extraction kickers are central features of the ring. Wigglers with a 1.7 T field make up 2/3 of the circumference giving a 1.5 ms betatron damping time. The study shows also that the ring is suitable for a low energy spread collider. Here there is a restriction on the longitudinal emittance of the beam because beam energy spread adds (in quadrature) with energy spread from beamstrahlung. The longitudinal emittance is limited by the microwave instability, eq. (6), but at the ARES-I design intensity the impedance limit is $\langle Z_L/n \rangle \lesssim 1\Omega$. While a question remains about the synchrotron radiation impedance, this seems like a reasonable limit.

Overall, the positron production and damping problems are serious; work to date has identified possible solutions. These need to be developed.

Conclusions

The prospect of observing CP violation in B decays has stimulated research into the accelerator physics of storage rings and linear colliders. Both offer the prospect of luminosity high enough to study this new manifestation of CP violation. Both also have unresolved accelerator physics questions that are central to realizing this prospect.

Further increases in the luminosity of symmetric storage rings depends on reducing impedances and increasing the beam-beam limit. An asymmetric storage rings would be less demanding in those respects, but it would require solving the problem of a complex, highly constrained interaction region.

The crucial questions for linear colliders are the limits from disruption and the production of a suitable positron beam. The work is less advanced than that on storage rings, and, as a result, the possibility of an innovative breakthrough is larger. This could change the comparison dramatically.

Whatever the ultimate solution, the problems of designing, building, and using a B-Factory are exciting and challenging. I am sure they will lead to new discoveries in particle and accelerator physics.

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Appendix A: Symbols

Beam energy (in units of mc^2)*	γ
Center-of-mass energy	W, $\gamma_{cm} = 2\sqrt{\gamma_1 \gamma_2}$
Luminosity	L
Beam Sizes (horiz, vert, ratio)	σ_h, σ_v, $R_\sigma = \sigma_v/\sigma_h$
Collision & revolution freq.	f_c, f_o
Particles per bunch*	N
β and η functions at IR*	β_v, β_h, η
Natural emittances	ϵ_v, ϵ_h
Bunch length and energy spread	σ_L, σ_δ
Momentum compaction	α
Long. impedance & loss factor*	$\langle Z_L/n \rangle$, G
Beam-beam tune shift	ξ
Disruption & enhancement parameters	D, H
Beamstrahlung parameters	δ_{cl}, T
Normalized emittance	ϵ_n

* The subscripts 1 and 2 refer to the two beams if the energies are unequal; $\gamma_1 \geq \gamma_2$ and + and − to e^+ and e^-.