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REPORT OF THE B-FACTORY GROUP: II. ACCELERATOR TECHNOLOGY*

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1. INTRODUCTION

The accelerator requirements for observing CP violation in the decay $B^0 \rightarrow \Psi K_s$ with roughly one year of running are summarized in Table 1. The experimental technique appropriate for each collider leads to the luminosity range and the other collider requirements. The latter are important considerations that affect the design approach and performance.

The B-factory luminosities are well above that of any operating machine, but there are ideas for accelerators capable of meeting the performance in Table 1. These fall into one of two categories:

i. Those with well-defined accelerator physics questions needing positive answers before detailed design work could begin. This class includes symmetric storage rings (Sec. 2.3), asymmetric storage rings (Sec. 2.4), and LEP (Sec. 4.1).
ii. Concepts with several major accelerator R&D questions that must be addressed successfully before a design could begin. The issues are interconnected, and the results of the R&D could affect the design and performance significantly. This class includes the linear colliders for the $\Upsilon(4S)$ and continuum (Sec. 3) and the Z-factory linear collider (Sec. 4.2). Some of these have potential that far exceeds that of the colliders in the class above, and for those the R&D is well worth pursuing.

This distinction is important, but it should not cloud the overall conclusion that through advances in accelerator physics the bottom end of the luminosity range in Table 1 is within reach.

2. STORAGE RINGS FOR THE $\Upsilon(4S)$ AND CONTINUUM

2.1 Introduction

The accelerator physics issues can be understood by writing the luminosity in terms of quantities that limit performance. For a storage ring these are the beam-beam interaction, single bunch currents, and the total beam current. For clarity of presentation the beams are assumed to have the same properties: equal energies, number of particles, etc. This assumption is not valid for one of the important cases, an asymmetric collider; more general formulae are presented in Sec. (2.4).

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Table 1: Comparison of B–Factories

Case	Description	W (GeV)	$\mathcal{L}^*$ (10^{33} cm^{-2} s^{-1})	Collider Requirements
1	Asymmetric collider at the $\Upsilon(4S)$	10.6	0.45–16.	Beam energy ratio 2 to 10 1–1.5 cm radius IR beam pipe σ_δ<0.001
2	Symmetric collider above BB* threshold	10.6	2.1–77.	σ_δ<0.001
3	Collider in the continuum	16.	18.–640.	No requirement on σ_δ
4	Collider at the Z, no polarization	93.	0.68–25.	
5	Collider at the Z, with polarization	93.	0.14–5.0	90% polarization

*The luminosity needed to observe a three standard deviation effect in the CP violating asymmetry for $B^0 \to \Psi K_s$ in 10^7 sec of running at peak luminosity.

Table 2: Symbols*

Beam energy (in units of mc^2)	γ
Center-of-mass energy	W, $\gamma_{\rm cm} = 2\sqrt{\gamma_1\gamma_2}$
Luminosity	$\mathcal{L}$
Beam sizes (horiz., vert., ratio)	$\sigma_h, \sigma_v, R_\sigma = \sigma_v/\sigma_h$
Collision and revolution frequencies	f_c, f_0
Particles per bunch	N
Amplitude (β) functions at IR	β_v, β_h
Dispersion at the IR (horiz.)	η
Natural emittance	ϵ
Bunch length & energy spread	σ_L, σ_δ
Momentum compaction	α
Effective longitud. impedance	$\langle Z_L/n\rangle$
Loss factor	k
Beam-beam tune shift	ξ
Disruption parameter	D
Enhancement parameter	H
Beamstrahlung parameters	δ_{cl}, Υ
Normalized emittance	ϵ_n
Classical electron radius	$r_e = 2.82 \times 10^{-15}$ m
Fine structure constant	$\alpha = 1/137$
Impedance of free space	$Z_o = 377\ \Omega$
Electronic charge	$e = 1.6 \times 10^{-19}$ C

*subscripts h and v refer to horizontal and vertical, + and − to e^+ and e^-, and 1 and 2 to the two beams. If the energies are unequal, $\gamma_1 \geq \gamma_2$.

The luminosity is given by

$$\mathcal{L} = \frac{N^2 f_c}{4\pi\sigma_h\sigma_v} \ . \tag{1}$$

Symbols are defined in Table 2.

Usually a phenomenological approach to the beam-beam interaction is used in storage ring design. The strength of the beam-beam interaction is parametrized by the beam-beam tune shifts

$$\xi_j = \frac{r_e}{2\pi}\ \frac{N\beta_j}{\gamma\sigma_j(\sigma_h+\sigma_v)};\ (j = v, h) \ . \tag{2}$$

A maximum tune shift, a "tune shift limit," is chosen based on experience,[1] and $\mathcal{L}$, written in terms of ξ, is maximized. The beam-beam limit is a dynamical effect where details matter, and the effective tune shift limit could depend on the the way $\mathcal{L}$ is maximized. The phenomenological approach assumes this is not the case.

If there are no intensity limits, the horizontal and vertical tune shift limits are equal, and making $\beta_v\ /\beta_h = R_\sigma$ so that the ring operates simultaneously at both limits

$$\mathcal{L} = \frac{\pi\gamma_{cm}^2 f_c}{4r_e^2}\ \xi^2(1+R_\sigma)^2\ \frac{\sigma_h^2}{\beta_h\beta_v} \ . \tag{3}$$

The vertical β function, β_v , should be minimized consistent with the limit[2,3]

$$\beta_v \gtrsim \sigma_L \ . \tag{4}$$

The horizontal beam size and β_h enter in the ratio

$$\frac{\sigma_h^2}{\beta_h} = \epsilon_h + \frac{\eta^2\sigma_\delta^2}{\beta_h} \ , \tag{5}$$

which should be as large as possible. Large emittance and/or dispersion is needed. Within the limits of this analysis these are equivalent, but the same mechanisms leading to Eq. (4), synchrotron modulation of the beam-beam kick, could play a role here.[4] If so, the dispersion should be zero and the emittance must be large. Either the machine aperture or a breakdown of the assumption of no intensity limits will determine the maximum.

It is more likely that there would be a limit from the beam-beam interaction and a limit on the single bunch intensity. The microwave instability is expected to be the dominant single bunch effect;[5] the threshold is

$$N\ <\ \frac{\sqrt{\pi}\alpha\gamma\sigma_\delta^2\sigma_L Z_o}{\sqrt{2}r_e\langle Z_L/n\rangle} \ . \tag{6}$$

$\langle Z_L/n \rangle$ is the effective impedance of the accelerator. Crudely, it measures the "smoothness" of the beam enclosure—the number and types of discontinuities. In detail $\langle Z_L/n \rangle$ is not a simple concept; the frequency content of the bunch, the cut-off frequency for electromagnetic wave propagation in the vacuum chamber, and unresolved physics such as coherent synchrotron radiation are incorporated in that one quantity. The value of Eq. (6) is that it gives the dependences on accelerator parameters and provides a rule-of-thumb based on experience. Modern storage rings have $\langle Z_L/n \rangle \sim 1\Omega$, and a value as small as 0.1 to 0.2 Ω might be possible with a combination of a large aperture, smooth vacuum chamber and an RF system designed to reduce impedance.

When there is a single bunch intensity limit,

$$\mathcal{L} = \frac{\gamma_{\rm cm} f_c}{4 r_e} \xi (1 + R_\sigma) \frac{N}{\beta_v} , \qquad (7)$$

and σ_h^2/β_h is not free; rather it is set by the requirement of reaching the tune shift limit when N is at its limit. Combining Eqs. (4), (6) and (7), the upper limit to the luminosity is

$$\mathcal{L} \ < \ \frac{\sqrt{\pi} Z_o}{8\sqrt{2} r_e^2} \left(\gamma_{\rm cm} \sigma_\delta\right)^2 \frac{\alpha f_c (1 + R_\sigma) \xi}{\langle Z_L/n \rangle} . \qquad (8)$$

The middle factor depends on particle physics. For Cases 1 and 2 in Table 1, $\gamma_{\rm cm}$ is fixed and there is an energy spread requirement for kinematic reconstruction to be useful. For continuum running, $\gamma_{\rm cm}$ is roughly determined, but there is no constraint on σ_δ. Therefore, this has a higher luminosity potential, but probably it is not the most cost effective way to study CP violation.

A large RF system would be part of any storage ring B-factory. This has consequences for instabilities (discussed above), "higher mode losses," and RF power; any of these could cause an intensity limit. An example of higher mode losses is the energy lost by the beam when it excites the resonant modes of an RF cavity. These losses are

$$P_{HOM} = k \ N^2 e^2 f_c \ , \qquad (9)$$

where k is the loss factor (with units V/C) that is related to the impedance. This energy loss depends on N^2 and can be comparable to the synchrotron radiation power. Coupled bunch instabilities are caused primarily by high-Q resonant modes of the RF cavities. All designs assume that multibunch feedback[6] and cavity mode damping are used and that these are sufficient to control the coupled bunch instabilities. Overall, the RF system must be designed to minimize $\langle Z_L/n \rangle$ and k, effectively damp high-Q modes, and have a reasonable power demand.

Table 3: Present and Upgraded CESR Parameters*

Revolution frequency		390 kHz	
RF frequency		500 MHz	
Beam energy range		4.5–6.0 GeV	
Fractional energy spread		6.2×10^{-4}	
Energy loss/turn		1.04 MeV	
Bending radius		89 m	
		Present	Upgraded
Number of interaction regions		2	1
Collision frequency (MHz)		2.7	5.5
Particles per bunch (10^{11})		1.8	3.3
Horizontal emittance (mm-mrad)		0.16	0.16
Crossing parameters (cm)	β_v	1.5	1.5
	β_h	100	100
	η	55	66
Tune shifts	ξ_v**	0.021	0.030
	ξ_h	0.026	0.036
Bunch length (cm)		1.7	1.7
Momentum compaction (10^{-2})		1.5	1.0
$\langle Z_L/n \rangle$ limit (Ω, Eq. 6)		0.89	0.32
Synch. radiation power (kW)		85	320
Higher order mode power (kW)		39	300
Peak luminosity (10^{32} cm^{-2}s^{-1})		1.0	5.0

*Energy dependent parameters are calculated at 5.3 GeV.
**ξ_v is determined for the effective β.

Specific storage rings are now discussed. They are separated into upgrades and near-term prospects (Sec. 2.2) and possibilities for the further future (Secs. 2.3 and 2.4).

2.2 Upgrades and Near Term Prospects

2.2.1 Cornell electron storage ring (CESR). CESR is the highest luminosity e^+e^- collider in the world. It operates with seven bunches per beam in a single ring; electrostatically produced orbit distortions separate the beams at parasitic crossings.[7] The luminosity records are a peak of 1×10^{32}cm^{-2}s^{-1} and integrated luminosities of 4.7 pb^{-1}/day and 27 pb^{-1}/week. CESR parameters and present performance are given in Table 3.

An upgrade is planned that could produce a factor of five increase in luminosity. The two major elements of the upgrade are eliminating one of the interaction regions (IR's) and doubling the number of bunches. The plan also includes other, less significant changes and injection and efficiency improvements; the latter will increase the ratio of integrated to maximum luminosity.

With the installation of the CLEO II detector, there is reduced interest in running the CUSB detector, and the CUSB IR will be eliminated.[8] This will increase the synchrotron radiation emitted between collisions at the remaining IR. Synchrotron radiation leads to damping and randomization of oscillation phases. In both simple models[9,10] and data based on storage ring performance[11,12] this increases the tune shift.

The models predict the tune shift limit is proportional to the square root of the fractional energy loss between collisions; the parametric dependence of the data is not conclusive. The effects of synchrotron radiation have been studied experimentally in CESR. With one (two) collision(s) per revolution the tune shift limit was 0.021 (0.017).

The planned increase of ξ from more synchrotron radiation between collisions is $\sqrt{2}$. Based on the experiment at least one-half of that should be realized. There are also possibilities of increasing σ_h^2/β_h by raising η, but because of the precautions following Eq. (5), this is not anticipated to be a large factor. With no single bunch intensity limit, $\mathcal{L} \propto \xi^2$, and the increase in the tune shift limit would give a factor of two in luminosity.

Doubling the number of bunches requires new electrostatic separators close to the IR for less distance between bunches and a higher horizontal tune for more parasitic crossing points. The separators are being designed, and a lattice for 14 bunches per beam has been developed. The chromatic and nonlinear aspects of the lattice are acceptable; this is another consequence of eliminating one of the IR's. The higher tune decreases the momentum compaction, which is approximately inversely proportional to the square of the horizontal tune, and the microwave instability threshold [Eq. (6)]. The consequences are considered below.

The uncertainties in doubling the number of bunches are the effects of additional parasitic crossings and intensity limits. There is a luminosity degradation of 10 to 20% in collisions of single bunches when the electrostatic orbit distortions are applied. This is attributed to magnet errors and nonlinear elements that affect the separated beams differently. At low currents there is no further degradation as more bunches are added to the beam; the effects of parasitic crossings appear near the beam-beam limit. There, increasing the number of bunches requires greater beam separation to preserve tune shift and beam lifetime. By doubling the number of parasitic crossings the horizontal aperture could limit bunch charge.

With an upgraded CESR operating at the beam-beam limit, the synchrotron radiation and higher mode powers would be 320 kW and 300 kW. The number of RF cavity cells would have to be raised from 28 to 48 to support this beam while remaining conservative with factors such as RF window design. Feedback and cavity resonant mode damping are proposed to control coupled bunch instabilities, and when this is done the dominant effect of the cavities should be an impedance increase.

The impedance limit is 0.32 Ω. This is a factor of three below the present limit due to the increased number of particles per bunch and reduced momentum compaction. It is unlikely that the impedance is this low but there are no relevant data,[13] and the needed impedance and stability calculations have not been performed. These calculations and/or experience may show that a new RF system with reduced impedance is needed. Reducing the impedance and solving the problems from the increased number of parasitic crossings are the major obstacles to reaching the upgrade luminosity goal of 5×10^{32} cm^{-2} s^{-1}.

Table 4: TRISTAN Accumulation Ring

General parameters	
Maximum beam energy	6.5 GeV
Revolution frequency (f_0)	795 kHz
Maximum number of bunches	10
Fractional energy spread (5.3 GeV)	9.3×10^{-4}
Energy loss per turn (5.3 GeV)	2.94 MeV
Achieved single beam performance (May & June 1988)	
Beam energy	5.0 GeV
Collision β functions (horiz., vert.)	0.40 m, 0.02 m
Horizontal emittance (ϵ_h)	1.7×10^{-7} m-rad
Particles per bunch (N)	2.4×10^{11}
Projected Luminosity Performance	
Peak luminosity	2×10^{32}cm^{-2}s^{-1}
Beam lifetime	3 hours
Experimental time per fill	1 hour
Filling time	15 min
Lost time due to Main Ring transfers	20 min
Running time/year	3600 hours
Integrated luminosity per day	8 pb^{-1}
Integrated luminosity per year	1200 pb^{-1}

2.2.2 TRISTAN accumulation ring at KEK. The primary function of the Accumulation Ring is positron collection for the TRISTAN Main Ring. However, the ring has the size and energy range of a B-factory, and this use has been studied.

The collider would be a single ring with (electrostatically) separated electron and positron orbits to avoid unwanted collisions. Up to ten bunches per beam are possible, but the ring has a high energy loss per turn and total RF power will limit the average current. Optics including low β interaction regions have been designed, and single beam performance was tested earlier this year. The results are summarized in Table 4; two such beams and a tune shift of $\xi = 0.04$ would have given $\mathcal{L} = 6.8 \times 10^{31}$ cm^{-2} s^{-1}. It is planned to test single bunch colliding beam performance in November 1988.

Projected performance is given in Table 4. With that running time and peak luminosity the TRISTAN Accumulation Ring would be competitive with the best CESR performance to date.

2.2.3 Paul Scherrer Institute. The Paul Scherrer Institute (PSI) has prepared a proposal for a B-factory that has been submitted to the Swiss government.[14] This machine would be optimized for symmetric collisions at the $\Upsilon(4S)$

Table 5: Parameters* of the PSI Collider Operating at the $\Upsilon(4S)$

Revolution frequency (f_0)	463 kHz
Maximum number of bunches	20
Collision β functions (horiz., vert.)	1.00 m, 0.03 m
Beam-beam tune shift limit (ξ)	0.03 to 0.04
Horizontal emittance (ϵ_h)	5.5×10^{-7} m-rad
Particles per bunch (N)	6.6×10^{11}
Bunch length (σ_L)	0.02 m
Fractional energy spread (σ_δ)	7.0×10^{-4}
Momentum compaction (α)	0.025
Energy loss per turn (U_0)	1.75 MeV
Synch. radia. power (10 bunches)	860 kW
RF frequency	500 MHz

*These parameters are for one of the two rings.

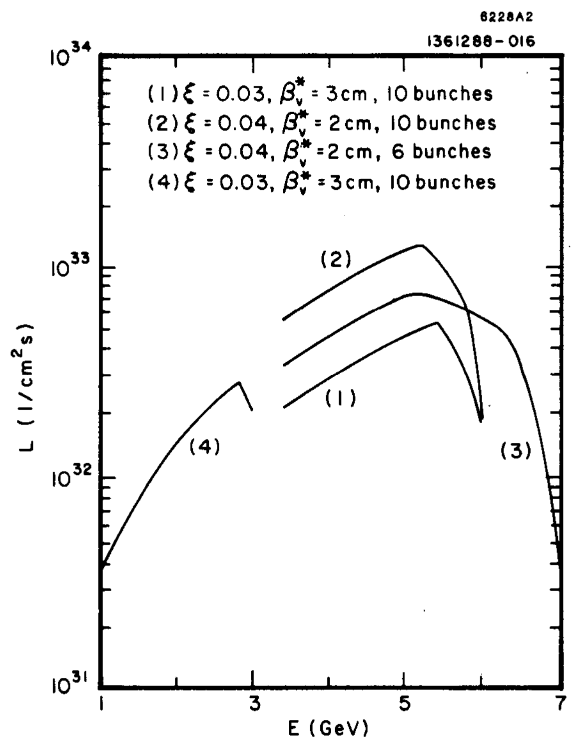

Fig. 1. Luminosity projected for the PSI B–factory. Parameters for the curves are given in the figure; (1) and (4) have different amounts of RF power.

energy, but an extended center-of-mass energy range, 2 to 14 GeV, and asymmetric collisions are part of the design. Principal parameters are given in Table 5, and Fig. 1 shows the performance estimates. The peak luminosity would be two to four times below the minimum for a symmetric collider in Table 1.

The design is that of a double storage ring with two interaction regions. The maximum number of bunches per beam is twenty; it is determined by the requirements of having head-on collisions and avoiding all parasitic collisions. The other parameters and performance result from assuming a beam-beam tune shift limit of 0.03 to 0.04, in the middle of the range for past colliders, and following Eqs. (3) and (4).

Little consideration has been given to factors that could limit the beam current. These could have substantial influence as the design develops, but they do not present fundamental problems. For the parameters in Table 5, the upper limit on $\langle Z_L/n\rangle$ to prevent bunch lengthening is 0.65 Ω, which should be achievable. The proposal calls for an RF cavity optimized for damping of higher modes and multibunch feedback to damp coupled bunch instabilities. Calculations showing the adequacy of this solution remain to be done. For a single RF cavity cell with the approximate geometry proposed, $k = 1.3 \times 10^{11}$ V/C for $\sigma_L = 2$ cm. This gives 330 kW higher mode loss in the RF system for 10 bunches, and more RF power than called for in the proposal would be needed.

The PSI B–factory should perform close to the design goals in Fig. 1. For the higher luminosities needed to study CP violation either the collision frequency, single bunch intensity and/or tune shift must be increased.

2.3 Future Symmetric Storage Rings

Two concepts have been proposed to reach these higher luminosities. Both require performance beyond present experience with storage rings, and, therefore, require accelerator physics R&D. The accelerator physics issues are highlighted by the contrast between the parameters in Table 6.

2.3.1 NOVOSIBIRSK. A. N. Dubrovin et al. have presented a conceptual design of a double storage ring collider with a luminosity of $10^{34}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$ at a beam energy of 5.3 GeV.[15] The features that lead to the high luminosity are the short bunch length and low β_v at the interaction point.

The bunch length, emittance and momentum compaction of a storage ring are not completely independent, and α is small as it must be for a short bunch. The short bunch and low α lead to a stringent impedance limit, $\langle Z_L/n\rangle < 0.06\ \Omega$. In addition, small α leads to a small ϵ_h, and dispersion must be used to produce horizontal beam size needed for high luminosity and moderate 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.

2.3.2 Round beams. Dynamical effects that lead to the beam-beam limit can be controlled by the profile of the beam at the collision point; Eq. (4) is a well-known example of this. A round beam, defined as a beam with $\epsilon_h = \epsilon_v$ and $\beta_v = \beta_h$, has a high tune shift limit,[16] and the

Table 6: Parameters of B–factory Storage Rings Designed to Operate Near the $\Upsilon(4S)$

		Dubrovin et al.*	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 (m-rad)	ϵ_v	0.3–[3] $\times 10^{-9}$	1×10^{-7}
	ϵ_h	0.1–[3] $\times 10^{-7}$	1×10^{-7}
Crossing parameters (m)	β_v	0.01	0.03
	β_h	0.56	0.03
	η	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} cm^{-2} s^{-1})		1.4	1.5

*Dubrovin et al. give the range of parameters in the first part of the table. The ones in square brackets were selected for the calculations in the second part.

"Round Beam" collider in Table 6 is based on this.[5)] The crucial question is whether high tune shifts can be reached for the more realistic situation of approximately round beams, beams that are nominally round but with some difference between horizontal and vertical.

Initial results from simulations are encouraging; Fig. 2 is an example. In this figure the betatron tunes differ by 0.01, but the tune shift is linear with current to $\xi \sim 0.1$. Simulations are continuing with the major thrust being to include synchrotron oscillations. Phenomena new to storage rings are expected. The disruption parameter which characterizes single pass effects and the tune shift are related as:

$$D = \frac{2r_e N \sigma_L}{\gamma \sigma_h^2 R_\sigma (1+R_\sigma)} = 4\pi \xi \frac{\sigma_L}{\beta_v} \quad . \qquad (10)$$

For $\xi \sim 0.1$ and $\beta_v \sim \sigma_L$, $D \sim 1.2$, and single pass collision effects become important, and the consequences are unclear. Luminosity enhancement (good!) and emittance dilution (bad!) are both possibilities. If simulation results remain encouraging, experimental studies are next, and the detailed design of a Round Beam collider could begin.

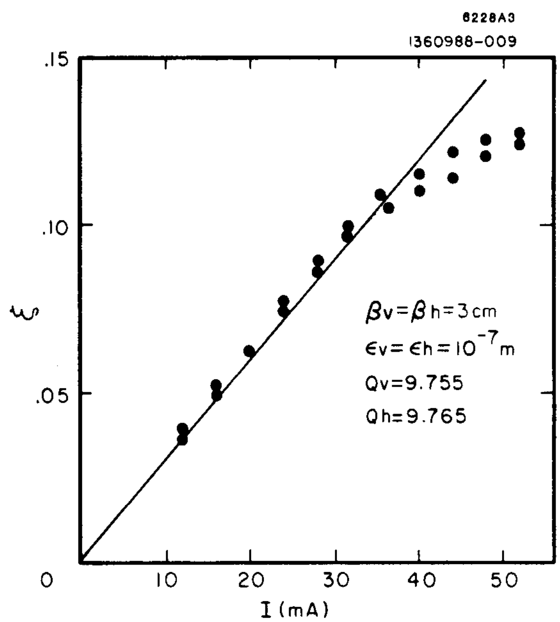

Fig. 2. Beam-beam tune shift vs. single bunch current for a machine with CESR-like parameters except for a round beam collision geometry.

2.4 Asymmetric Storage Rings

The interest in asymmetric colliders has been stimulated by the luminosity advantage in Table 1 and the possibility of low cost if an existing facility could be used as the high energy ring. The expressions in Sec. 2.1 can be generalized for beams with different properties; that generalization, keeping the restriction that the beams have equal sizes, is in Table 7.[17)] The comments in Sec. 2.1 regarding the beam-beam interaction, instabilities, higher

Table 7: Generalizations of Formulae in Sec. 2.1*

Eq. No.	Generalization	Revised Eq. No.
(1)	$\mathcal{L} = \frac{N_1 N_2 f_c}{4\pi\sigma_h\sigma_v}$	(1′)
	There are four tune shift equations; eg., Eq. (2′):	
(2)	$\xi_{v1} = \frac{r_e}{2\pi}\frac{N_2\beta_{v1}}{\gamma_1\sigma_v(\sigma_h+\sigma_v)}$	(2′)
(3)	$\mathcal{L} = \frac{\pi\gamma_{cm}^2}{4r_e^2} f_c\xi^2(1+R_\sigma)^2 \times \sigma_h^2\left(\frac{1}{\beta_{v1}\beta_{v2}\beta_{h1}\beta_{h2}}\right)^{1/2}$	(3′)
(4)	$\beta_{v1} \geq \sigma_{L2},\ \beta_{v2} \geq \sigma_{L1}$	(4′)
(5)	$\frac{\sigma_h}{\sqrt{\beta_{hi}}} = \left(\epsilon_{hi} + \frac{\eta_i^2\sigma_{\delta i}^2}{\beta_{hi}}\right)^{1/2} \quad (i\ =\ 1,\ 2)$	(5′)
(7)	$\mathcal{L} = \frac{\gamma_{cm}}{4r_e}\,\xi f_c\,(1+R_\sigma)\left(\frac{N_1}{\beta_{v1}}\frac{N_2}{\beta_{v2}}\right)^{1/2}$	(7′)

*Equal horizontal and equal vertical sizes are assumed: $\sigma_{h1} = \sigma_{h2}$, $\sigma_{v1} = \sigma_{v2}$.

mode losses, and RF system design are applicable to an asymmetric ring also. The interaction region design is unique because of the different beam energies and particle physics requirements.

There are two conceptual designs, one based on PEP[18] and the other on PETRA;[19] both are constrained to some degree by the existing machine. The parameters are in Table 8.

The beam-beam tune shifts are assumed equal for the two beams, $\xi_1 = \xi_2$; the values chosen are 0.05 and 0.03 for the PEP and PETRA based B-factories, respectively. There is no experience with collisions of unequal energy beams, and data on the energy dependence of the beam-beam interaction has large uncertainties. Different parametrizations of the dependence of ξ on synchrotron radiation energy loss[12] 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; computer simulations are likely to be a major component of that study.

Beam current limits in the high energy ring have been discussed for the PETRA design. The single bunch intensity limit is known from experiment to be above the values in Table 8,[20,21] and the single bunch currents are determined by the PETRA aperture. Coupled bunch instabilities are more serious. Eighty-eight 4-cell superconducting cavities make up the synchrotron radiation loss. Reduction of the Q's of higher modes and a newly developed feedback technique[6] are required for stability.

There are enough details for the PEP based collider to look at intensity limit for the low energy ring. The upper limit on $\langle Z_L/n\rangle$ for the low energy ring is 1 Ω; this is a reasonable design goal.

At the interaction region (IR) of an asymmetric collider two very different energy beams must be focused and separated in a short distance. The solution adopted in the PEP design is shown in Fig. 3; the PETRA one is similar. Quadrupoles close to the IR focus the low energy beam. They are followed by dipole magnets acting as beam separators and focusing quadrupoles for the high energy beam.

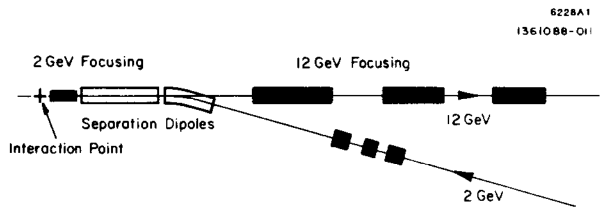

Fig. 3. IR geometry for the PEP B-factory.

This particular design has a 0.16 T dipole beginning 1 m from the collision point. The critical energy of the synchrotron radiation from the 12 GeV beam is 15 keV, and, without masking, the fan of synchrotron radiation is 16 mm wide at the interaction point. Vertex detection is an essential feature of an asymmetric collider, and a beam pipe with 10 to 15 mm radius is required for this. Synchrotron radiation masking must be a central feature of the interaction region. The masks can act as sources for secondary high energy particles,[22] and the mask design must include this as a consideration. The combination of focusing different energies, beam separation, a small beam pipe, and synchrotron radiation masking make the IR a major accelerator physics problem of asymmetric colliders.

2.5 Conclusions

There are plans at Cornell, KEK and PSI for upgrades, conversions, or new storage rings that will advance knowledge of B physics but would not have enough luminosity to observe Standard Model CP violation. There are some uncertainties in these ideas, but they should perform near proposed levels.

There are concepts for symmetric storage rings with $\mathcal{L} \sim 10^{34}\,\mathrm{cm^{-2}\,s^{-1}}$ and asymmetric storage rings with $\mathcal{L} \sim 10^{33}\mathrm{cm^{-2}s^{-1}}$. They all require performance beyond our experience, but the accelerator physics issues are clearly defined and could be addressed on the time scale of a year. If resolved successfully, a detailed design of a collider with luminosity in the range needed to see CP violation could begin.

3. LINEAR COLLIDERS FOR THE Υ(4S) AND CONTINUUM

3.1 Introduction

Compared to a storage ring, a linear collider has a small number of particles per bunch and a low collision

Table 8: Parameters of Asymmetric B–Factories

		Based on PEP	
Collision frequency		11.6 MHz	
Luminosity		0.5×10^{33} cm^{-2} s^{-1}	
		Large Ring	Small Ring
Beam energy (GeV)		12	2
Revolution frequency		136 kHz	1.9 MHz
Particles per bunch (10^{11})		1.4	2.9
Emittances (mm-mrad)	ϵ_v	0.01	0.03
	ϵ_h	0.1	0.3
Crossing parameters (cm)	β_v	7.6	2.5
	β_h	76	25
Tune shifts ($\xi_v = \xi_h$)		0.05	0.05
Energy spread (10^{-3})		0.80	0.56
Bunch length (cm)		1.9	2.4
Momentum compaction $\times$ (10^{-3})		3.0	63
$\langle Z_L/n \rangle$ limit (Ω, Eq. 6)		1.0	1.1
Fractional energy loss/turn (10^{-4})		9.3	0.63
Bending radius (m)		166	10.8
Synchrotron radiation power (MW)		2.9	0.067
		Based on PETRA	
Collision frequency		2.6 – 31.2 MHz	
Luminosity		0.09–2.2 $\times 10^{33}$ 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 (mm-mrad)	ϵ_v	0.03	0.07
	ϵ_h	0.2	0.47
	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})		0.85	1.1
Fractional energy loss/turn (10^{-4})		12.7	1.5
Bending radius (m)		192	4.65
Synchrotron radiation power (MW)		1.1–13.	0.05–0.6

frequency; the luminosity comes from focusing the beam to a small spot. The beam-beam interaction is stronger, and this gives additional focusing that leads to a luminosity enhancement. The luminosity is given by Eq. (1) with an additional enhancement factor H that is a function of the disruption parameter D [Eq. (10)] and σ_L/β_v[23]

$$\mathcal{L} = \frac{N^2 f_c}{4\pi\sigma_h\sigma_v} H . \qquad (11)$$

The principal accelerator physics issues are the beam-beam interaction (disruption and beamstrahlung), positron production and damping, and the appropriate RF system for acceleration. The issues are the same for TeV energy colliders, but B–factory parameters are so different that each is a unique problem. The discussion at Snowmass was (and this paper is) restricted to symmetric linear colliders, but the linear collider idea could be applied equally well to an asymmetric machine.

At small values of D the beam-beam interaction acts like a lens with focal length σ_L/D. At larger values particles oscillate with approximately $(D/10)^{1/2}$ oscillations during the beam passage. The luminosity enhancement from focusing during the collision has been calculated using simulations.[23,24] Recent results for H are shown in Fig. 4. This particular calculation assumes a head-on collision and beams with equal properties (number of particles, transverse dimensions, ...) and has a strong restriction on the electromagnetic fields.[25] As a result it gives the largest possible enhancement and no information on the effects

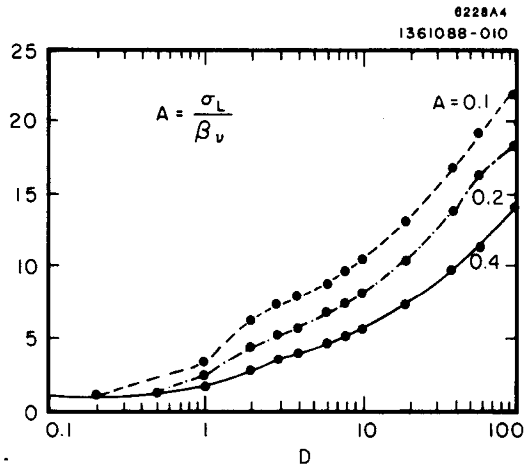

Fig. 4. Luminosity enhancement calculated by Chen and Yokoya.

of errors. This work is being generalized and information about errors should be available in the future.[26)]

The maximum value of disruption is likely to be determined by tolerance to errors, and knowing that value is central to any linear collider design. The maximum value of D is analogous to the tune shift limit of storage rings. Assume that N is limited, e.g., by wakefields, then

$$\mathcal{L} = \frac{\gamma_{cm}}{16\pi r_e} H \; f_c(1+R_\sigma)\; \frac{ND}{\sigma_L} \; . \tag{12}$$

This equation is to be interpreted in the same way as Eq. (7); the transverse dimensions of the bunch are chosen to reach the disruption limit at the intensity limit. For a fixed $\mathcal{L}$, the collision frequency, positron production rate (Nf_c), bunch length, etc., depend on the intensity and disruption limits. Changing D would affect all of these. Linear collider B–factory parameter lists have values of D ranging from 9 to 28. Without the appropriate calculations it is difficult to know whether these values are practical.

Beamstrahlung contributes to the center-of-mass energy spread. This gives a strong constraint on the luminosity for colliders that have an energy spread specification. The beamstrahlung parameter is

$$\Upsilon \;=\; \frac{5r_e^2}{6\alpha}\; \frac{N\gamma}{(1+R_\sigma)\sigma_h\sigma_L} \; . \tag{13}$$

(α is the fine structure constant in this equation.) With its low energy a B–factory would be in the classical beamstrahlung regime, $\Upsilon \ll 1$. The center-of-mass energy spread is[27)]

$$\frac{\sigma_W}{W} = \left[\frac{\sigma_\delta^2}{2} \;+\; 0.10\; \delta_{cl}^2 \left(1 + 3.9 \frac{\gamma r_e}{\sigma_L \Upsilon}\right)\right]^{1/2} \; . \tag{14}$$

The first term comes from the energy spread of the beams and the second from beamstrahlung; it includes contributions from variation of the deflecting fields within the bunch and fluctuations in the number of photons emitted. The quantity δ_{cl} is the mean fractional energy loss from beamstrahlung

$$\delta_{cl} = \frac{5N^2 r_e^3\; \gamma}{6(1+R_\sigma)^2 \sigma_h^2 \sigma_L} \quad ; \tag{15}$$

roughly, δ_{cl} is proportional to $\mathcal{L}/f_c\sigma_L$. The ideal would be a high collision frequency and a beam with a low energy spread and a long bunch. This has implications for the accelerator choice and the positron source. When their performances are considered, requiring a low energy spread limits the luminosity to about $10^{33}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$. A specific example is given for ARES in Sec. (3.2).

It is likely that an electron beam with appropriate longitudinal and transverse emittances could be generated with a photocathode gun. Positrons have to be produced by an electron beam striking a converter followed by a damping ring to reduce emittances. Positron production and damping have been major R&D areas for the Stanford Linear Collider (SLC), and a B–factory has still harder demands. A comparison of typical B–factory parameters with the SLC shows that: (i) the number of particles per bunch and (ii) the instantaneous power incident on the converter are comparable; (iii) the collision frequency and (iv) the average converter power are two orders of magnitude higher; and (v) the normalized emittance, ϵ_n, is a factor of ten smaller.

The average and instantaneous powers are about 1 MW and 1–10 TW, respectively. There is a conceptual design of a converter for these power levels that has identified the major problems.[28)] These are thermal shock, removal of heat, high radiation doses, and high levels of residual radioactivity. This design could serve as the starting point for the R&D program needed in positron production.

The damping ring must produce e^+ bunches with an invariant emittance of about 10^{-6} m at a rate of roughly 10 kHz. Because of this combination, the appropriate ring would have a large circumference, many closely spaced bunches, and high field wigglers. One such ring has been studied at the Courmayeur Workshop;[29)] it has a 670 m circumference (1.7 T wigglers make up 2/3's of this) and bunches spaced at 7 m. Wideband multibunch feedback and ultrafast extraction kickers are central features of the ring.

The study also considered the suitability of the ring for colliders with a low energy spread requirement. The energy spread and bunch length at the collision point are related to their values in the damping ring by

$$\gamma\sigma_L\sigma_\delta|_{\text{collision point}} \;\geq\; \gamma\sigma_L\sigma_\delta|_{\text{damping ring}} \; . \tag{16}$$

The right-hand-side determines an upper limit on the damping ring impedance through Eq. (6). At typical linear collider intensities that limit is $\langle Z_L/n\rangle \leq 1\ \Omega$, which is reasonable.

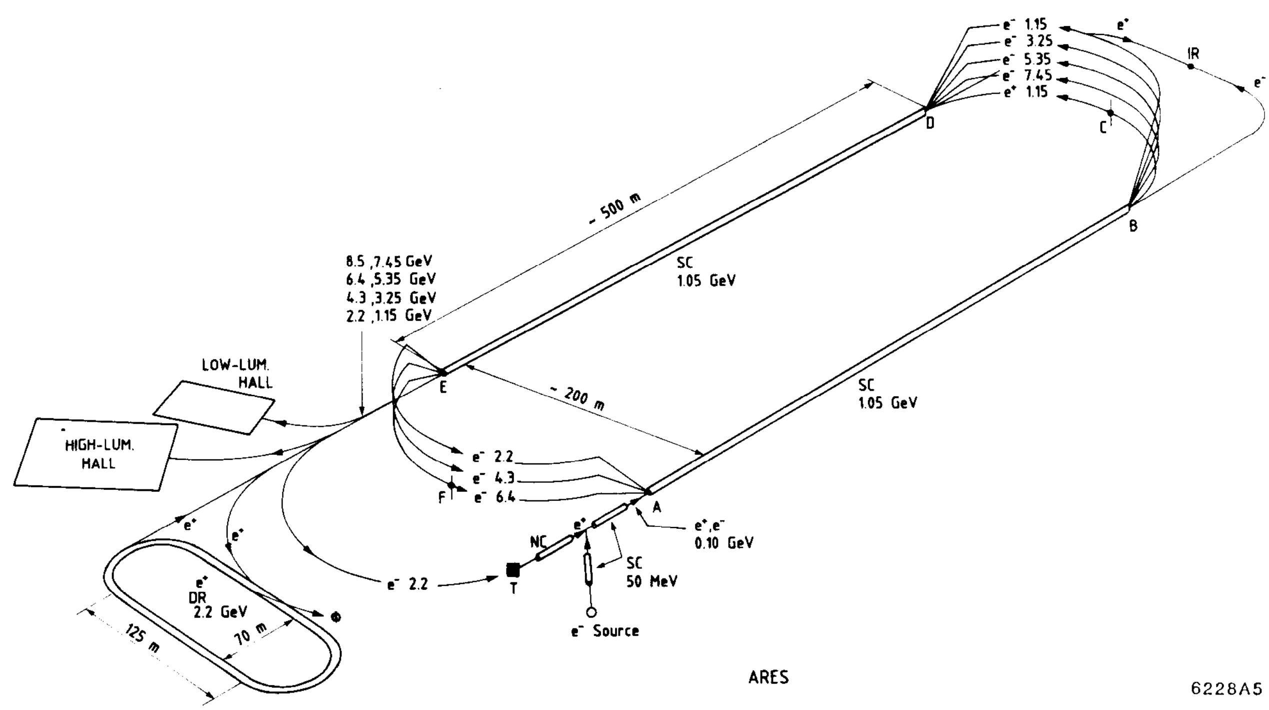

Fig. 5. Schematic of the ARES collider.

The accelerator choice is between a low frequency, superconducting RF linac and a high frequency, room temperature one. From almost all points-of-view superconducting RF seems preferable:

1. A room temperature structure could have a higher acceleration gradient, but the present day gradients and Q's of superconducting RF are adequate.

2. A power source would have to be developed for a high frequency linac but not for a superconducting one.

3. The wall-plug power of a superconducting accelerator would be substantially lower.

4. Transverse emittance increase from wakefields is less serious for low RF frequencies.[30]

5. A low frequency would permit a longer bunch without introducing energy spread. This could be significant for colliders with an energy spread requirement (Cases 1 and 2 in Table 1).

However, a high frequency linac might serve as a prototype for a TeV energy collider. This is discussed in Sec. 3.3. With this introduction specific colliders are now considered.

3.2 ARES

The concept of a linear collider B-factory based on superconducting RF which originated with the work of Amaldi and Coignet[31] has evolved into part of the ARES (Acceleratore Ricircolato per Elettroni, Superconduttore) R&D project at LNF, the Frascati National Laboratory. In December 1987 a workshop was held at Courmayeur, and the proceedings has details about the collider and the associated physics program.[32]

The facility is illustrated in Fig. 5. It is a recirculating superconducting linac with 500 m long accelerating sections with a 5 MeV/m gradient. The accelerator design is based on present day technology; superconducting cavities with 5 MeV/m are available commercially, and the power source is a CW klystron such as the ones used at DESY, KEK, and Cornell. The positron source is a converter, labeled T in the figure, and a 2.2 GeV damping ring. There is no electron damping ring; it is assumed that after some R&D a photocathode gun with appropriate intensity and emittances would be developed. Features that are not part of the B-factory are the experimental halls for nuclear physics and the 0.13 GeV linac for collisions with positrons in the damping ring for producing ϕ's.

Three modes of operation with different values of center-of-mass energy spread, σ_W/W, have been anticipated: high resolution for the $\Upsilon(4S)$, medium resolution for a wide resonance such as the $\Upsilon(5S)$, and low resolution for the continuum. Parameters for the first and third of these are in Table 9.

These parameters reflect the discussion in Sec. 3.1. The narrow energy spread of the high resolution mode is achieved by reducing the luminosity by about an order of magnitude. The design has fewer positrons than electrons

Table 9: ARES Parameters[33]

Parameter:		High Resolution $\Upsilon(4S)$	Low Resolution Continuum
Beam energy (GeV)		5.29	7.5
$\mathcal{L}$ (10^{34}cm^{-2}s^{-1})		0.13	1.1
$\sigma_W/W(10^{-3})$		0.9	5.8
Particles/bunch (10^{10})	e^-	8.0	8.0
	e^+	2.5	5.0
RF frequncy (MHz)		500	
Gradient (MV/m)		5	
Collision frequency (kHz)		10	
Invariant emittance (10^{-6} m)		2.0	
Spot aspect ratio (R_σ)		1.0	
Beta function ($\beta_v = \beta_h$, mm)		5.0	2.0
Spot radius (μm)		1.0	0.5
Bunch length (mm)	e^-	1.0	0.5
	e^+	3.0	0.7
Disrupt. parameter, D	e^-	22	28
	e^+	21	25
Luminosity enhance., H		7.7	9.5
σ_W/W from beamstrahlung		0.0004	0.005
σ_W/W from σ_δ		0.0009	0.003
Average e^+ converter power (MW)		0.9	1.8
AC power (MW)		18	20

per bunch; this was done to reduce the converter power. The disruptions of the beams are made equal by having a longer positron bunch. The disruption parameter is in the range $D \sim$ 20–30. These large values remain to be justified; both the effects of errors and the intentional differences between the beams need study.

Raising the luminosity would require increasing the disruption and/or the collision frequency. The collision frequency is already high, and increasing it would require a multi-megawatt converter and a damping ring with more bunches or a shorter damping time. Substantial R&D would be needed to show this was feasible. The conclusion is that the luminosities in Table 9 are close to the maximum that could be expected.

Superconducting RF development for use in free electron lasers (FEL), nuclear physics accelerators, and future linear colliders (including a B–factory and a TeV energy machine) is the focus of a 70 GLit proposal that the National Institute for Nuclear Physics (INFN) has submitted to the Italian Government. Present plans are that there will be emphasis on the FEL and nuclear physics applications because of the difficulty of the collider.[34]

Table 10: Parameters for a B–factory Linear Collider

Parameter:	
Beam energy	10.0 GeV
Luminosity	1.0×10^{34}cm^{-2}s^{-1}
σ_W/W	0.005
Particles per bunch	2.2×10^{10}
RF frequency	10 GHz
Gradient	100 MV/m
RF repetition rate	11.1 kHz
Collision frequency	44.4 kHz
Beam bunches/RF pulse	4
Invariant emittance	3.0×10^{-6}m
Spot aspect ratio (R_σ)	1.0
Beta function ($\beta_v = \beta_h$)	0.7 mm
Spot radius	0.32 μm
Bunch length	0.3 mm
Disruption parameter, D	9.0
Luminosity enhancement, H	6.0
σ_W/W from beamstrahlung	4.8×10^{-3}
σ_W/W from σ_δ	1.4×10^{-3}
Average e^+ converter power	1.9 MW
AC power	100 MW

3.3 Linear Colliders with High Frequency RF

Scaling laws for a high frequency, room temperature linear collider B–factory have been developed by P. Wilson;[35] these account approximately for beamstrahlung and disruption, energy efficiency, wakefields, and final focus design. Starting with values for the acceleration gradient, RF frequency, and AC mains power that are typical of the TeV collider work at SLAC these scaling laws lead to the parameters in Table 10. There are four beam pulses per RF pulse for adequate efficiency, and the RF repetition rate must be about 10 kHz for $\mathcal{L} \sim 10^{34}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$.

Could a B–factory serve as a prototype of a TeV energy collider? Yes, if the principal R&D issues are the same; no, if they are not.[36] Both colliders must accelerate multiple bunches per RF pulse. This has implications for the accelerator structure, and many aspects of the structure development are the same. The RF power sources and positron sources are significantly different because the B-factory RF repetition rate and collision frequency are over an order of magnitude higher. The beam-beam interaction limits are different; a B–factory would have large disruption and low beamstrahlung compared to the TLC.

R. Palmer has written a computer program that estimates linear collider performance based on the properties and performance of accelerator subsystems. As part of the Snowmass study he used this to estimate the performance of "pure TLC prototypes," linear colliders using TLC technology. For the TLC gradient (186 MeV/m), RF frequency

Table 11: Linac-Storage Ring B–factory

Luminosity	$1.6\times10^{34}\,\mathrm{cm^{-2}\,s^{-1}}$	
Collision frequency	5 MHz	
Spot radius ($R_\sigma = 1$) (μm)	2.0	

Parameter	Electron Beam	Positron Beam
Beam energy (GeV)	2.5	10.0
Circumference (km)	–	2.0
Particles per bunch (10^{10})	0.2	50
Average current (mA)	1.6	400
Bunch length (μm)	–	5.0
Invariant emittance (μm)	1.0	7.8
Emittance (nm)	0.20	0.40
$\beta_h = \beta_v$ (cm)	2.0	1.0
Beam-beam effects	$D = 360$	$\xi = 0.057$

(18 GHz), and RF repetition rate (400 Hz) the luminosity depends on center-of-mass energy as[37)]

$$\mathcal{L} \sim 10^{34}\,\mathrm{cm^{-2}\,s^{-1}} \left(\frac{W}{1\ \mathrm{TeV}}\right)^{1.6} . \tag{17}$$

A TLC prototype with W $\sim$ 10–20 GeV would have a luminosity of about $10^{31}\,\mathrm{cm^{-2}\,s^{-1}}$. The repetition rate would have to be raised significantly to get a more interesting luminosity.

The conclusion is that a B–factory is not a prototype for a TeV energy machine. It would require its own R&D program with comparable time scale and cost.

3.4 Linac-Storage Ring Collider

Positron production and damping is one of the major limiting factors of a linear collider B–factory. Therefore, it is natural to consider concepts with positron recovery. There are a number of approaches: (i) recovery, deceleration, and damping at a low energy,[38)] (ii) recovery and damping without changing energy,[39,40)] and (iii) collisions between a linac beam and a beam stored in a storage ring.[41,42)] The latter idea has recently been revived by P. Grosse-Wiesmann as the basis of a B–factory[41)] that was discussed at Snowmass.

The paper by Grosse-Wiesmann has parameters for colliders with luminosities of 0.3, 1.6 and 7.0 $\times$ 10^{34} $\mathrm{cm^{-2}\ s^{-1}}$; the intermediate one is in Table 11. The electron beam is accelerated in a superconducting linac with a high average current, and the positron beam is stored in a low emittance ring. The accelerator physics issues are the beam-beam interaction, instabilities in the storage ring, and the properties of the linac.

The beam-beam interaction is in a regime where there is no experimental or computer simulation information at the present time. The electron beam is highly disrupted, and the electrons will perform many oscillations during the collision. This could lead to a channeling effect with luminosity enhancement, or emittance blow-up due to nonlinearities. The implications for the positron beam are unknown also.

The storage ring emittance is about a factor of ten below the record minimum of 6.4 nm,[43)] and a combination of a high betatron tune and damping wigglers would be needed to reach it. A high tune alone leads to a small momentum compaction and an unacceptably low impedance limit, $\langle Z_L/n\rangle \sim 0.02\ \Omega$. Damping wigglers increase the energy spread and RF power demand by a few MW but can raise the impedance limit to $\langle Z_L/n\rangle \sim 0.2\ \Omega$ by allowing a lower tune.[44)]

The average linac current is about a factor of ten higher than the CEBAF design. Implications of this have been looked at in a recent paper with the conclusion that, from the point-of-view of wakefields, 10^9 electrons/bunch, an invariant emittance of 10^{-6}m, and a fractional energy spread of 10^{-3} is reasonable.[45)]

The linac-storage ring collider is in an early stage of development. The potential is high, but there are several serious issues that need study before it will be clear whether that potential could be realized.

3.5 Conclusions

Linear colliders and linac-storage ring colliders operating at the $\Upsilon(4S)$ and in the continuum could reach the luminosities needed to study CP violation. These concepts are at an early stage of development with interlocking accelerator physics issues, and developing these ideas will require substantial R&D programs. The results of that R&D could affect the design and performance potential significantly.

The principal issues for a linear collider are the same as for a TeV energy machine: disruption and beamstrahlung, positron production and damping, the accelerator structure, and the RF power source. However, the B–factory parameters are sufficiently different that it cannot serve as a prototype for a higher energy machine. It would need its own R&D program with time and cost scales comparable to those for a higher energy machine.

4. STORAGE RINGS AND LINEAR COLLIDERS FOR THE Z

There are two approaches for studying B physics at the Z. In one of them the beam is unpolarized, and the experimental techniques are similar to those used in the continuum. The advantage of working at the Z is the large cross section for $B\bar{B}$ production. The required luminosity range is 0.68 to 25. $\times$ $10^{33}\,\mathrm{cm^{-2}\,s^{-1}}$. It is natural to compare the projected performance of LEP to this goal; this is done in Sec. 4.1.

A collider operating at $W = m_z$ with a longitudinally polarized electron beam would need significantly less luminosity; the factor depends on the degree of polarization. Polarization in a storage ring is uncertain,[46] and this approach is most likely in the domain of linear colliders. This is discussed in Sec. 4.2.

4.1 LEP Performance

Construction of the LEP storage ring at CERN is nearing completion. Commissioning is scheduled to begin in July, 1989, and it is anticipated that Z's will be observed before the end of that year. This first phase of LEP, LEP I, is designed for running in an energy range near the Z; the beam energy at maximum luminosity is 55 GeV.

The best estimates are that LEP I will be limited to a single bunch current of 0.75 mA (4.16×10^{11} particles) by instabilities at the injection energy of 20 GeV. Using this, an assumed tune shift of $\xi = 0.03$, and four bunches per beam the luminosity at 55 GeV would be $1.6 \times 10^{31} \mathrm{cm}^{-2}\mathrm{s}^{-1}$.[47] The installed RF power in LEP I is 16 MW, and above 55 GeV the luminosity falls because of RF power limits. If the instability threshold could be raised with feedback[48] such that the luminosity at $W = m_z$ was limited only by the beam-beam interaction and the available RF power, that luminosity[49] would be 3.2×10^{31} cm^{-2} s^{-1}. This would require doubling the number of particles per bunch.

For the second phase of LEP, LEP II, superconducting RF will replace the room temperature RF of LEP I, and the energy will reach up to perhaps 100 GeV per beam. That upper energy will be determined by the configuration and gradient of the RF system that is installed.

In addition to raising the energy, superconducting RF would allow a significantly larger current at $W = m_z$. In LEP I most of the RF power goes to producing the accelerating voltage; roughly 10% is radiated by the beam as synchrotron radiation. The LEP II superconducting RF reduces the power needed to produce the voltage, and the stored current can be increased. Some of that increase could be in single bunch current since changing the RF reduces the impedance, but to fully utilize the RF power the number of bunches would have to be raised.

Electrostatic orbit distortions would have to be used to separate the beams at unwanted collision points. It has been suggested that up to 60 mA/beam is possible;[50] the number of bunches would depend on the single bunch current. The luminosity would be approximately $3 \times 10^{32}\,\mathrm{cm}^{-2}\,s^{-1}$ if a factor equal to the increased number of bunches were realized. Based on experience with CESR (Sec. 2.2.1) this is an optimistic assumption. This suggestion is under study at CERN. Separation schemes and their implications for LEP are being considered. If a successful detailed plan emerged from that study, LEP would have substantial potential as a B-factory.

Table 12. Z–Factory Parameters

Parameter:		
Beam energy		50 GeV
Luminosity		$5.7 \times 10^{33}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$
Particles per bunch		1.2×10^{11}
RF frequency		5.9 GHz
Gradient		93 MeV/m
Peak power		270 MW/m
RF repetition rate		872 Hz
Collision frequency		4.36 kHz
Beam bunches/RF pulse		5
Invariant emittance	horiz.	2.69×10^{-5} m
	vert.	2.75×10^{-7} m
Spot aspect ratio (R_σ)		5.7×10^{-3}
Beta function	β_h	7.34 cm
	β_v	0.233 mm
Spot dimensions		4.49 μm × 25.7 nm
Bunch length		0.20 mm
Disruption parameter	D_h	0.05
	D_v	11.7
Luminosity enhance., H		1.7
σ_W/W		0.6%
Average e^+ converter power		1.4 MW
AC power		200 MW

4.2 Z–Factory Linear Collider

The degree of polarization in a linear collider, P, is determined by the electron source. With the presently achievable $P = 0.45$ the luminosity to observe CP violation would be in the range 0.37 to 13. $\times\ 10^{33}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$. There are R&D programs to raise the polarization to $P = 0.90$;[51] if successful, the luminosity requirements would be reduced to 0.14 to $5.0 \times 10^{33}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$. This is well above the SLC design, and a new linear collider designed without constraints from an existing accelerator would be called for.

The parameters for a Z-factory, a linear collider optimized for running at $W = m_z$ are in Table 12.[37] The design approach is the same as that developed for TeV energy machines. The total AC power is fixed at 200 MW, and the luminosity is maximized while remaining consistent with the performance limitations of collider subsystems. The resulting Z-factory would see CP violation in a year or less of running with a 90% polarized beam! The accelerator physics issues are the same as those discussed in Sec. 3.1.

Constraints and uncertainties from the beam-beam interaction are reduced compared to a linear collider at the Υ(4S). A narrow energy spread is not needed, so there is no limitation from beamstrahlung or the energy spread of the beam. The beam profile at the collision point is flat, $R_\sigma = 0.0057$. Beam steering errors have been simulated for flat beams, and for the Z-factory disruptions in Table 12 the beams tend to self-align and correct these errors.[52]

Positron production and damping need substantial R&D. The converter power and damping rate are comparable to those for ARES, and the discussion in

Sec. 3.2 applies. The design luminosity and the constraint from positron damping rate leads to a high single bunch intensity, 1.2×10^{11} particles per bunch, and an optimum RF frequency of 5.9 GHz. Emittance blow-up would be severe at a higher frequency. An RF power source at that frequency with a peak power capability of 270 MW/m would need to be developed.

A Z–factory R&D program would be a substantial one. Some of the issues are the same as for a TeV energy collider, but the machine could not serve as a "pure TLC prototype" without a substantial reduction of luminosity. A restriction to use TLC technology would reduce the luminosity to 2.5×10^{32} cm^{-2} s^{-1} [Eq. (17)].

4.3 Conclusions

There are opportunities to measure CP violation with machines running at the Z. LEP, upgraded to operate with a large number of bunches, would have a luminosity at the bottom end of the required range and substantial potential as a B–factory. A successful R&D program aimed at a linear collider Z–factory would lead to a machine that exceeds the upper limit given in Table 1. Building such a machine would be a major national commitment.

5. CONCLUSIONS

The conclusions from the three major sections are:

Section 2:

> There are plans at Cornell, KEK and PSI for upgrades, conversions, or new storage rings that will advance knowledge of B physics but would not have enough luminosity to observe Standard Model CP violation. There are some uncertainties in these ideas, but they should perform near proposed levels.
>
> There are concepts for symmetric storage rings with $\mathcal{L} \sim 10^{34}$ cm^{-2} s^{-1} and asymmetric storage rings with $\mathcal{L} \sim 10^{33}$ cm^{-2} s^{-1}. They all require performance beyond our experience, but the accelerator physics issues are clearly defined and could be addressed on the time scale of a year. If resolved successfully, a detailed design of a collider with luminosity in the range needed to see CP violation could begin.

Section 3:

> Linear colliders and linac-storage ring colliders operating at the $\Upsilon(4S)$ and in the continuum could reach the luminosities needed to study CP violation. These concepts are at an early stage of development with interlocking accelerator physics issues, and developing these ideas will require substantial R&D programs. The results of that R&D could affect the design and performance potential significantly.
>
> The principal issues for a linear collider are the same as for a TeV energy machine: disruption and beamstrahlung, positron production and damping, the accelerator structure, and the RF power source. However, the B–factory parameters are sufficiently different that it cannot serve as a prototype for a higher energy machine. It would need its own R&D program with time and cost scales comparable to those for a higher energy machine.

Section 4:

> There are opportunities to measure CP violation with machines running at the Z. LEP, upgraded to operate with a large number of bunches, would have a luminosity at the bottom end of the required range and substantial potential as a B–factory. A successful R&D program aimed at a linear collider Z–factory would lead to a machine that exceeds the upper limit given in Table 1. Building such a machine would be a major national commitment.

Taken as a whole, the accelerator performance needed to see CP violation in B–decay is within reach.

FOOTNOTES AND REFERENCES

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