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HIGH-LUMINOSITY, ELECTRON-POSITRON COLLIDERS AS STRANGENESS, CHARM, AND BEAUTY FACTORIES

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High Luminosity, Electron-Positron Colliders as Strangeness, Charm, and Beauty Factories+

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Abstract

High luminosity electron-positron colliders operating at the mass of the ϕ meson (1.02 GeV) can produce copious $K\overline{K}^{o}$ pairs from a single quantum state. Temporal correlations in the decays of the K's provide a measure of the direct CP violating amplitude and also allow a high precision test of CPT invariance. A low energy collider with high luminosity can serve as a beam physics testbed to evaluate novel approaches to collider design that may be necessary for B factories to attain luminosities $\gtrsim 10^{34}\ cm^{-2}s^{-1}$.

I. Introduction

Colliding beam accelerators have become the mainstay in advancing the high energy frontier of elementary particle physics. Beyond the upgrade of LEP to 100 GeV per beam, the extension of e^+-e^- colliders to still higher energies will take the form of linear accelerators producing sub-micron beams. In contrast, the study of rare processes such as CP violation in the B meson system, or the high precision measurement of CP violation parameters in the K system, or high precision tests of CPT invariance are likely to be performed with a new generation of e^+-e^- storage ring colliders operating at extremely high luminosity (flavor factories). The high collision rates and high beam currents implied by the combination of high luminosity and low-to-moderate beam energy introduce a complex of accelerator design difficulties.

The lowest energy flavor factory operates at the formation energy of the ϕ meson (1.02 GeV). Several groups throughout the world are actively considering the design of a ϕ factory with a luminsoty $>10^{32}\ cm^{-2}s^{-1}$. One group (UCLA) is aiming at a configuration sufficiently flexible to permit the exploration of novel approaches to realizing very high luminosity.

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I.A. Physics motivation

The $K\overline{K}^{o}$ system has been the most sensitive "laboratory" for tests of discrete symmetries, having provided conclusive evidence[1] of CP violation in the two π decay modes of the K_L. Twenty five years later, the physical origin of the violation is still not understood. Present experimental evidence for CP violation can be described in terms of a single, complex mixing parameter, ε, that expresses the mass eigenstates, K_L and K_S, in terms of the CP eigenstates, K_1 and K_2. Direct (not mass-matrix) sources of CP violation imply a second complex mixing parameter, $\varepsilon' \leq O(\varepsilon^2)$, that leads to differences in the amplitudes for K_L decay into $\pi^+\pi^-$ and $\pi^o\pi^o$. Recent measurements at CERN[2] find that $\varepsilon'/\varepsilon \approx 3 \times 10^{-3}$; in contrast, the E731 group at Fermilab reports that ε'/ε is consistent with zero to within an accuracy of 10^{-3}. This conflict suggests the usefulness of making a direct measurement of CP violation and of CPT invariance in a system with different systematics and one in which assumptions about the relative magnitude of the phase of the mixing parameters are unneccessary.

An especially sensitive probe[3] of CP physics is provided by measuring the decays of the neutral kaons produced in the process

$$e^+ e^- \rightarrow \phi\ (1020) \rightarrow K_L\ K_S. \qquad (1)$$

The quantum numbers of the $\phi(1020)$ meson ($J^{PC} = 1^{--}$) ensure that only $K_L K_S$ are produced in the final state even when CP (or CPT) is violated in the kaon system. By measuring asymmetries in the distribution of times of the decays $K_L \rightarrow \pi^+\pi^-$ (at time t_1) and $K_S \rightarrow \pi^o\pi^o$ (at time t_2) near $(t_2 - t_1) \approx 0$ and by measuring the branching ratio of the decay into all charged versus all neutral pions, one can make a direct measurements of both $Im(\varepsilon'/\varepsilon)$ and $Re(\varepsilon'/\varepsilon)$ respectively.

Knowing the cross section for ϕ production ($\approx 2.4\ \mu b$) and the branching ratio for the decay of the ϕ into $K_L K_S$ (34%), one estimates the range of luminosity of an $e^+\text{–}e^-$ collider neccessary to obtain 10^{10} - 10^{11} clean ϕ events per year to be 2×10^{32} to 2×10^{33} $cm^{-2}s^{-1}$. This range can yield an effective measurement of ε'/ε of order 10^{-4}. By measuring the ratio of decay into two pion channels versus that into semi-leptonic channels, one can determine the relative mass difference between the K and $\overline{K}^{o}$ to better than 10^{-20}. The sensitivity of the experiment is limited by the background channel, $\phi \rightarrow K\overline{K}^{o}\gamma$, which may have a branching ratio[4] as large as 10^{-6}.

Other possible physics accessible in this luminosity range include study of CP violation in decays of the K^+ and K^-, search for CP violation in K^o_L and $K^o_S \rightarrow \gamma\gamma$ (to 10^{-6}

in branching ratio) and in K_L^o and $K_S^o \rightarrow 3\pi^o$ (to 10^{-8} in branching ratio). Measurements of the branching ratio at low energy of $e^+e^- \rightarrow \omega / \rho$ are also important for calculations of $(g\text{-}2)_\mu$.

I.B. Detector considerations

The design of flavor factories is likely to be tightly constrained by detector requirements. In a ϕ factory one need not record each of the ϕ formation events; with proper triggering of the detector only 10^4 to 10^5 per 10^{10} ϕ events need actually be recorded for kinematic reconstruction. For these events one must measure the ϕ formation and decay at a rate of 10 to 100 Hz with good particle identification, efficiency, vertex measurement, and background rejection over a range of ≈ 10 K_S lifetimes (10cm). Thus the detector will need a uniform B field, tracking with high spatial resolution, minimal material in the tracking volume to minimize multiple Coulomb scattering of the pions, precise energy determination plus some directional information for the γ's. Indentification of the μ, π, e is essential. Fortunately, the decay of the ϕ into K^+ and K^- allows for a self-calibration of detector efficiencies and resolutions. This question is presently under study by the UCLA group.

Avoiding K_S regeneration requires that the beam pipe must be large (>6 cm) in the interaction region (IP), permitting injection of undamped positron beams. In contrast, detectors for B factories demand a small beam pipe $\approx$ 2 cm for adequate vertex resolution implying that positron bunches must be damped to their equilibrium emittance in a separate storage ring prior to injection into the collider.

As the c.m. energy of the collider is raised from 1 GeV to 10.6 GeV (B-factory), the difficulties of masking the detector from the synchrotron radiation from the beams will increase considerably. Indeed it may preclude some design options.

II. Luminosity challenge for flavor factories

Several approaches are available for the design of the flavor factory; these are a) a true linear collider, b) a linac-on-ring collider, c) single or multiple storage rings, d) a beam from a normal or superconducting linac colliding with a bunch in a storage ring by-pass (quasi-linear collider). In all the cases except that of a single storage ring one can choose either equal or unequal beam energies.

The luminosity of a collider is given by the well known relation

$$L = \frac{N_- N_+ f_c H(D)}{4\pi \sigma_x \sigma_y}, \qquad (2)$$

where f_c is the collision frequency, N_- and N_+ are the charges in the electron and positron bunches, H(D) is the disruption enhancement due to the pinch effect, and σ_x and σ_y are the horizontal and vertical beam sizes respectively. The disruption parameter, D, is related to the bunch length, σ_z, and transverse size by

$$D = \frac{r_e N \sigma_z}{\gamma \sigma_t^2}, \qquad (3)$$

where r_e is the classical electron radius. For linear collider, the interaction area $\pi\sigma_x\sigma_y$ should be $<10^{-8}$ cm (optimistic for beam energies < 1GeV). The maximum practical N_- is $\approx 10^{11}$. If H(D) is 4 (an optimistic assumption), a luminosity of 10^{33} cm^{-2}s^{-1} implies that positrons must be supplied to the collision point at a rate, $f_c N_+ \approx 10^{14}$ s^{-1} $\approx 2\times10^4$ nA. Based on the typical performance of positron targets at many laboratories, one can expect to generate, capture, cool and transport $\approx 5\times10^{-3}$ e^+/e^-/GeV or $\approx$ 20 nA of positrons per kW of electrons incident on the positron production target. A luminosity of 10^{33} cm^{-2}s^{-1}, therefore, requires ≥ 1MW on the target and fast damping rings. For comparison the present SLC target is a 30 kW design. One concludes that true linear colliders are impractical for beam energies < 10 GeV. This consideration drives one to a storage ring based scenario in which the positrons can be recovered and reused after each collision.

An immediate modification of the linear collider scheme is to pass an electron beam from a linac through the positron bunches contained in the ring. In this scheme the disruption (i.e., equivalent tune shift) of the positron beam must be kept sufficiently small, although the electrons could be strongly disrupted. Collision frequencies are limited to the kilohertz range with room temperature linacs making high luminosity extremely difficult. In contrast, use of a superconducting linac allows megahertz collision rates. As the electron bunch is always newly formed, disruption compensation techniques may permit higher tune shifts ($\approx$0.1) in linac-ring colliders than in storage ring colliders, especially if the damping time of the ring is reduced to $\approx$ 1ms by the use of superconducting dipoles or high field wigglers. A superconducting linac-on-ring ϕ factory with $L = 3\times10^{32}$ cm^{-2}s^{-1} has been proposed[5] by Amaldi and Coignet. However, the consistency of a practical lattice with the high collision rates, small normalized emittance and short bunch length in their design is unclear. Moreover, the use of a superconducting linac raises the cost of such a ϕ

factory to well over 100 M$. A B-factory using this approach has also been suggested by Amaldi and Coignet and is under study at CEBAF.

The megahertz collision rates achievable with superconducting linacs can also be realized with both beams contained in storage rings. If the beams have equal energies the electrons and positrons can share a common ring. The linear beam-beam tune shift, ξ, in a storage ring collider is typically limited to ≈0.5 where

$$\xi_\iota = \frac{r_e}{2\pi} \frac{N \beta_\iota^*}{\gamma \sigma_\iota (\sigma_x + \sigma_y)}, \quad (\iota = x, y) \tag{4}$$

where the transverse beam size is related to the geometrical emittance, ε, and the β^* at the interaction point by

$$\sigma_\iota = \sqrt{\varepsilon_\iota \beta_\iota^*} . \tag{5}$$

A commonly used, simplifying assumption is that of "optimal coupling"; i.e.,

$$\xi_x = \xi_y \Rightarrow \frac{\beta_x^*}{\sigma_x} = \frac{\beta_y^*}{\sigma_y} . \tag{6}$$

In this case, for round beams the tune shift and disruption are related by

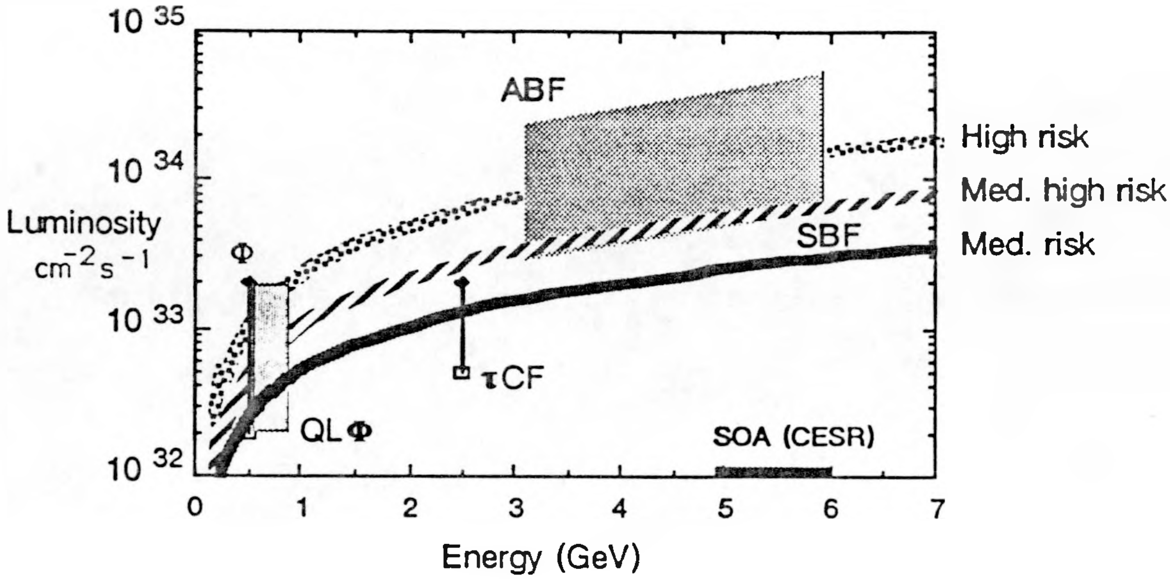
$$D_{ring} = 4\pi \xi \left(\frac{\sigma_z}{\beta^*} \right) . \tag{7}$$

Generally, one assumes that the beam-beam tune shift will limit the allowable value of N; in that case, one has the scaling law

$$L = 2.17 \times 10^{34}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}\ \xi\ (1 + r) \left[\frac{E(\mathrm{GeV})\ I(\mathrm{A})}{\beta_y^*(\mathrm{cm})} \right], \tag{8}$$

where $r = \sigma_y / \sigma_x$. For an asymmetric double ring collider in which the beams may have unequal energy, the proposed condition of energy transparency[6] (equal beam sizes, equal tune shifts, equal damping decrements for both beams) implies the equality of the quantity in brackets for both low and high energy beams.

The figure plots the luminosity scaling vs physics requirements for a symmetric (Φ) and quasi-linear (QLΦ) ϕ factory, a τ-charm factory (τCF), and for symmetric (SBF) and asymmetric B factories (ABF). The curve labelled medium risk corresponds to a collider with round beams (r=1), a tune shift of 0.05, a current of 1 Amp, and a β^*_y of 4 cm. Even this combination represents a difficult design, especially in the case of a B factory where difficulties of masking the detector from synchrotron radiation are severe and may preclude round beams colliding head-on.



Synchrotron radiation effects aside, at the lower end of the desirable luminosity range both the ϕ and B factories represent comparable technical risk for a storage ring collider. With respect to beam dynamics increasing the luminosity of an energy symmetric ϕ factory to $>10^{33}$ $cm^{-2}s^{-1}$ is similar in difficulty to designing an asymmetric B factory of 10^{34} $cm^{-2}s^{-1}$; the risk will be high unless an innovative design approach is adopted.

III. UCLA ϕ factory design

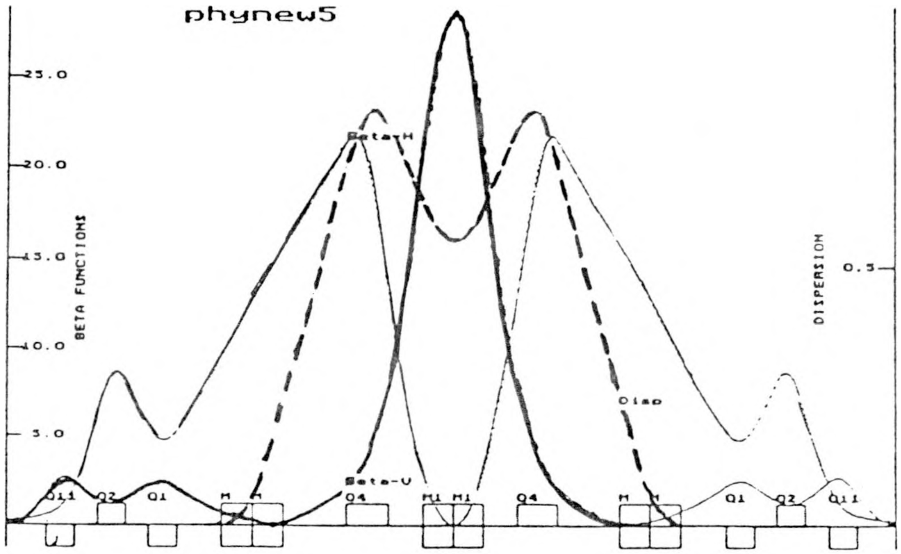
The UCLA group has been studying the design of a ϕ factory in two phases, with the following goals : 1) Start operation at a minimum luminosity ($> 10^{32}$ $cm^{-2}s^{-1}$) in the shortest possible time and at the minimum cost; 2) Subsequently increase the luminosity to $\approx 10^{33}$ $cm^{-2}s^{-1}$, with the option of unequal e^- and e^+ energies. In phase 1 the collider would consist of a single, compact storage ring holding one bunch of electrons and one bunch of positrons. The characteristics of the storage ring are given in the table.

Circumference	12.9 m	Z/n	0.7 Ω	Emittance	4.5 mm-mrad
Beam Energy	510 MeV	Mom. compaction	0.12	Coupling	0.2
Beam Current	≈ 2 A per species	Charge/bunch	100 nC	Loss.turn	14.1 kV
Bending Field	4 T	$\xi_x = \xi_y$	0.05	RF freq.	348 MHz
Luminosity	2.9×10^{32} $cm^{-2}s^{-1}$	ν_s	0.007	σ_z	2.7 cm

The choice of a compact ring with superconducting dipoles yields a very high collision rate, ≈23 MHz, producing a large luminosity with a small number of positrons. In such a ring the synchrotron radiation damping time becomes very short (≈2 ms), which increases the beam stability, lifetime and the allowable beam-beam tune shift. The luminosity limit for this configuration comes from the beam-beam bremsstrahlung and Touschek lifetimes, from the maximum current that can be stored without excessive bunch lengthening, and from the beam-beam interaction. This technical approach is similar to that adopted by INP, Novosibirsk, albeit with a different topology.

The design of the cold ring is a modification of the SXLS ring being developed at Brookhaven National Laboratory. The SXLS design has been modified in four significant ways. a) The 4 T dipole configuration is divided into six 40 cm segments with a field index n ≈1 as compared with two long (≈ 3 m) segments planned for SXLS. b) As injection is at full energy, the superconducting dipoles can operate at constant field. These two differences should reduce both the technical risk and the cost of the magnets. c) The straight sections are lengthened to allow easier injection and extraction. d) The number of quadrupoles is increased to allow operation in both high and low equilibrium emittance conditions and to allow variation of the momentum compaction from (10^{-5} to >0.1)

A promising lattice[7] for the ring employs a triple bend achromat configuration.



High Emittance Ring Configuration

The vertical chromaticity and the maximum vertical β are reduced by placing a quadrupole doublet approximately 50 cm from the interaction point. To correct the relatively large residual chromaticity of this design (-12 and -5) while maintaining adequate dynamic aperture, one may use strong, modified sextupoles of the type proposed by Cornacchia and Halbach[8]. Whether this design approach is actually consistent with the high precision detectors needed for the ϕ factory must still be studied.

The injector[9] uses a full energy, travelling wave S-band linac with a low power (300 W) positron source to fill the ring in ≈ 60 s.. For the ϕ factory (unlike a B factory) the beam pipe must be large (several K^0_S path lengths) near the interaction point to avoid regeneration. Even at injection the aperture will be 5 times the size of an undamped positron pulse. The quantum lifetime is related to the damping time τ_x by

$$\tau_q = \tau_x \frac{\exp\left(\wp^2/2\right)}{\wp^2} . \qquad (9)$$

As the quantum lifetime of the bunch for $\wp = 5$ would be much longer than the damping time, most of the originally injected pulse is should survive the damping process. In contrast, the small beam pipe at the interaction region of a B-factory plus the lower equilibrium emittance associated with higher energy operation imply the a B-factory will require a damping ring for the positrons.

IV. Increasing the luminosity of future B and ϕ factories

To increase the luminosity and reduce the cost of future colliders one must increase the beam density in 6-D phase space. One can adopt a number of design strategies[10]:

a) Increase the beam current by increasing the number of bunches or the bunch current. In the latter case one must lower the longitudinal impedance of the ring to avoid bunch lengthening instabilities. Unfortunately increasing current also increases the difficulty of handling synchrotron radiation and increases the cost of rf-power.

b) Reduce the degree of asymmetry of the collisions. This choice may restrict the possible particle physics experiments and/or can make detector design more difficult.

c) Try to raise the ξ above 0.05. This choice risks instabilities. The systematics of the beam-beam tune shift limit need careful experimental study with existing rings.

d) Reduce the β^* by decreasing the bunch length ($L \propto \sigma_z$). To avoid synchro-betatron resonances β^* should be greater than the bunch length. One can decrease the bunch length by raising the rf-frequency or voltage or by reducing the momentum compaction, α, of the ring to a value near zero. At UCLA an on-going study[11] of nearly isochronous rings is exploring the latter option. For stable motion in longitudinal (Ψ, $\Delta p/p$) phase space

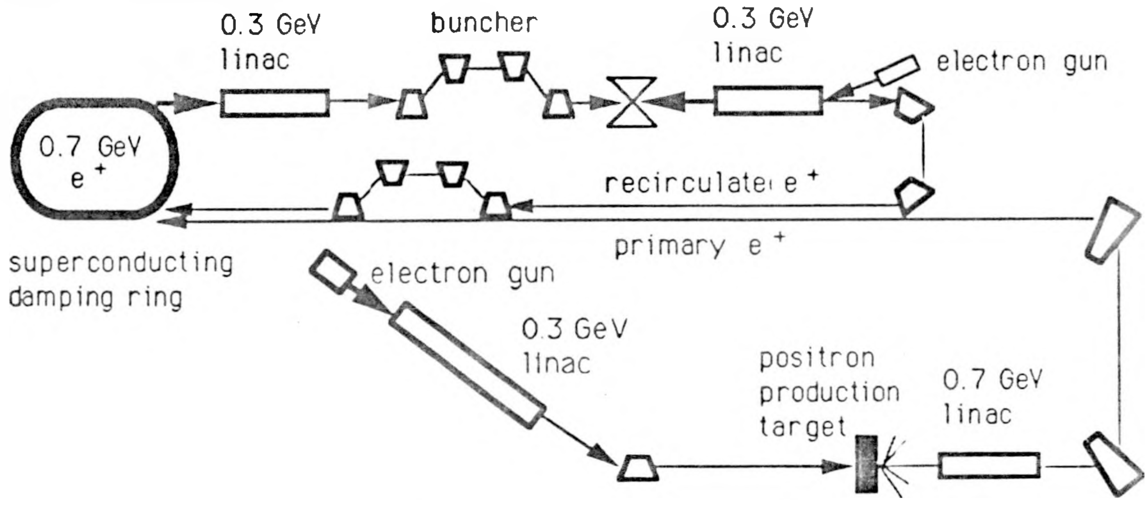
$$\alpha_1 \approx \alpha_2 \left(\frac{\Delta p}{p}\right), \tag{10}$$

where the momentum compaction is defined as

$$\alpha \equiv \frac{\left(\frac{\Delta \Psi}{2\pi}\right)}{\left(\frac{\Delta p}{p}\right)} \approx \alpha_1 + \alpha_2 \left(\frac{\Delta p}{p}\right). \tag{11}$$

For large damping decrements ($10^{-3} - 10^{-2}$), the minimum value of α_1 required for stability is reduced even further. With $\Delta p/p \approx 10^{-3}$ (common in many rings), one should be able to reduce α to $<10^{-4}$, two orders of magnitude lower than is typical. Because $\sigma_z \propto \alpha^{0.5}$, σ_z and β^* in a nearly isochronous ring could be reduced ten-fold to $\approx$ 1mm. The consequence is that the current (and operating cost) of a very high luminosity B factory could be reduced by an order of magnitude. The proposed UCLA ring would allow one to test this approach.

e) Strongly disrupt and discard the electrons ($D_- >> 1$). As $L \propto \sigma_t^{-2}$, by allowing the electron bunch length to be much shorter than the positron bunch length, the elctrons could be focussed to a very small spot. If $D_+ < 1$, the electrons should form a stable pinch channeled by the positrons.



Schematic of asymmetric quasi-linear Φ factory with by-pass

In the quasi-linear collider, the storage ring serves as a positron accumulator/recovery ring that can be continually "topped-off". The collisions take place in a by-pass with the electrons being supplied by a bright, high repetition rate, high gradient linac. By moving the interaction point to a by-pass outside the storage ring, one may reduce the coupling of the ring dynamics and the beam-beam effects. In the by-pass the positron bunch must be compressed to permit a small value of β^* at the interaction point and then stretched before re-insertion in the ring. A B-factory using this approach has been proposed by Cline and Pellegrini.[12] If the damping ring can operate isochronously, the buncher and debuncher could be eliminated from the by-pass. The technical difficulties of quasi-linear collider include frequent beam manipulation without degradation of emittance, the development of high frequency extraction and injection systems, and the development of very bright, high repetition rate electron beam sources. These issues could also be tested in the second phase of the proposed UCLA ϕ factory.

V. Conclusions

Pushing the luminosity of future flavor factories to the limits that full exploration of CP violation in the K and B systems may demand will require electron-positron colliders of novel design. Several approaches, outlined in Table 2, could be evaluated experimentally with a compact storage ring collider that is proposed for building on the UCLA campus. This collider will also serve as a next generation ϕ factory with sufficient luminosity to explore CP violation and test CPT invariance to a sensitivity beyond that of previous experiments.

Table 2. Comparison of collider schemes

	Linear	Linac-Ring	Storage ring
IP	outside	inside	inside
β^* (-)	< 1 mm	< 5 mm	<5 cm
β^* (+)	< 1 mm	<5 cm	<5 cm
N^-	≈10 nC	≈1 nC	≈ 100 nC
N^+	≈10 nC	≈ 100 nC	≈ 100 nC
ε^-_n	very low	very low	medium
ε^+_n	low	medium	medium
σ_t	(< 1 μm)	(≈ 10 μm)	(≈100 μm)
f_c	≈1 - 10 kHz	≈ 10 MHz	≈10 MHz
D^+D^-	>> 100	≈ 10	< 1
H(D)	5 – 10	1 – 2	1
Source issues	Low emittance e^-, e^+ Low emittance e^-	lifetime, refill refill	lifetime
Dynamics issues	ε^+_n preservation large D effects	ξ limits beam-beam effects	ξ limits beam-beam
Structure issues	S.C. cavities high gradients	Z/n, I	Z/n, I

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