CAA0050–UCLA–12/89

HIGH LUMINOSITY $\bar{B}B$ FACTORIES USING NOVEL TECHNIQUES

W. A. BARLETTA[1,2], D. B. CLINE[1], C. PELLEGRINI[1]
[1]Center for Advance Accelerators, University of California, Los Angeles, CA 90024-1547
[2]Lawrence Livermore National Laboratory, Livermore, CA 94550

ABSTRACT

To increase the luminosity and reduce the cost of future colliders one must increase the beam density in 6-D phase space. We describe two design strategies to realize a high luminosity, asymmetric e^+e^- colliders suitable for a $10^{34}\,cm^{-2}sec^{-1}$ $\bar{B}B$ factory. The colliders are an isochronous storage ring collider with short bunches and very low β^* and a quasi-linear collider that uses e^+ recirculation and small spot size at the interaction point (IP). The R & D effort associated with the proposed UCLA ϕ Factory can establish the principles and resolve the attendant physics issues of these options.

1. INTRODUCTION

Numerous examinations of the potential to study CP violation in the B meson system have established the requirements for a $\bar{B}B$ factory working at the $\Upsilon(4S)$: i) asymmetric beam energies, ii) a luminosity of $\geq 10^{34}$ $cm^{-2}sec^{-1}$, and iii) an integrated number of 10^8 or greater reconstructed $\bar{B}B$ events of per year. Three concepts have survived for establishing a high luminosity $\bar{B}B$ factory: 1) high current storage rings colliders with a few Amps, 2) low current, isochronous storage rings, 3) quasi-linear (or linac-ring) colliders with e^+ positron recirculation. Although raising the current in storage rings to a few amps may the most straight forward approach to increasing luminosity, such a collider would require very large power due to the synchrotron radiation. In the second scheme, operating the circular collider in an isochronous mode allows short bunches. Short bunches in turn allow for a lower β^* at the IP and a corresponding small spot size. The quasi-linear collider aims at even smaller spot size at the IP. Its potential difficulty of positron production is overcome by e^+ recirculation. In this scheme large disruption is allowed for the electron beam. A major limitation of high luminosity colliders is the reduced lifetime due to beam-beam interactions. The Quasi linear collider option removes this obstable since it is a continuously filled system.

2. AN ISOCHRONOUS COLLIDER $\bar{B}B$ FACTORY

High luminosity may be obtained in storage rings with beam currents at 100 mA level, by using an "isochronous" lattice and by reducing the bunch length and the beta function at the IP[2.1]. The luminosity can be written as

$$\mathcal{L} = \frac{\mathcal{P}_1\mathcal{D}_1}{4\pi r_e mc^2\sigma_{L2}} \qquad \text{(or with } 2 \leftrightarrow 1) \quad (2.1)$$

where $(\mathcal{P}_1)$ and $(\mathcal{D}_1)$ are the power and the disruption parameter of beam 1, and σ_{L2} is the bunch length of beam 2. To increase $\mathcal{L}$ without increasing the power, one must either increase $\mathcal{D}$ and/or decrease σ_L.

In an isochronous storage ring, the revolution frequency is independent of energy. Previous studies [2.2,2.3] of isochronous rings as damping rings for linear colliders and as beam sources for free electron lasers have examined some of their properties. Potential advantages of an isochronous ring as a collider are: reduction of the bunch length from the centimeter range to the millimeter range; the elimination of synchro-betatron resonances that limit the beam density at the IP and constrain the geometry of the IP. By reducing σ_L by 10 and increasing $\mathcal{D}$ by a factor of 2, we can reduce the current to ≈ 100 mA for a luminosity of $10^{34}cm^{-2}s^{-1}$. The reduced current considerably ameliorates the formidable masking problem associated with the design of the interaction region in conventional high current colliders.

Analysis of the equations of motion for the longitudinal degree of freedom of a storage ring reveals the major differences in longitudinal beam dynamics between conventional rings and isochronous storage rings. Using as variables the relative energy deviation, $\delta = (E - E_s)/E_s$, and the angular distance $\psi = \phi - \phi_s$, from a reference particle of energy E_s and angle ϕ_s, we can write the equations of motion as[2.4]

$$\psi' = \alpha(\delta)\delta \qquad (2.2)$$

$$\delta' = -\kappa(\psi - \phi_s) - \frac{U_0}{E_s}(1 + J_\epsilon\delta) + \text{fluctuations} \qquad (2.3)$$

where U_0 is the energy radiated per turn by the reference particle, J_ϵ is the radiation damping partition number, and fluctuations indicate the influence of fluctuations in the emission of synchrotron radiation. The superscript $'$ implies a derivative with respect to $\omega_0 t$, where t is time and ω_0 is the revolution frequency.

The momentum compaction term α is defined as

$$\alpha = \frac{(\frac{\Delta\psi}{2\pi})}{(\frac{\Delta E}{E})} \qquad (2.4)$$

where $\Delta\psi$ is the change in ψ per turn for given ΔE. In the simplest approximation

$$\alpha \approx <\frac{\eta}{\rho}> - \frac{1}{\gamma^2} = \alpha_1 \qquad (2.5)$$

where γ is the ratio of the particles total energy to that of its rest energy[2.4].

For highly relativistic particles, the first term dominates; it is usually positive but it can be made nearly zero or negative

$$\alpha = \frac{1}{\delta} - \frac{1}{L\delta}\oint ds\sqrt{(1+\frac{x}{\rho_s})^2 + (x')^2 + (z')^2} - \frac{1}{\gamma^2} \quad (2.6)$$

Expanding α to first order in δ and neglecting the contributions from the betatron oscillations, we have

$$\alpha = \alpha_1 + \alpha_2\delta \quad (2.7)$$

with α_1 given by Eq. (2.5). The α_2 term is given by

$$\alpha_2 = \frac{1}{L\delta}\oint ds\left[\frac{(\eta')^2}{2\rho} + \frac{(\eta')^2}{2}\right]\delta^2 \quad (2.8)$$

The value of α_1 can be adjusted to be zero or negative but, as α_2 is always positive, its effect can never becompletely eliminated. For $\alpha_1 = 0$ and negligible damping the Eq. (2.2) becomes

$$\delta'' + 2\pi\omega_0\kappa\alpha_2\delta^2 = 0 \quad (2.10)$$

This equation leads to unstable phase trajectories, described by, $(\delta')^2 + (\frac{4\pi}{3})\omega_0\kappa\alpha_2\delta^3$ = constant.

There are two ways to stabilize the longitudinal motion. The first makes $\alpha_1 \neq 0$ and dominant over α_2 to introduce an elastic-like focusing force and thus to provide a stable oscillation region near the origin ($\delta = \psi = 0$). The area of the stable region can be usually made large enough for convenient accelerator operation as in all existing proton and electron synchrotrons and storage rings. The second method, when α_1 is small, is to increase the rate of synchrotron damping of the system to slow the rate of the instability growth.

Next we address the question: given α_2, what is the smallest value of α_1 necessary to make the equations of motion stable?

Initially we chose $\psi_0 = 0.0001$, $\delta_0 = 0.001$ and $\kappa T_0 = -0.01$, where T_0 is the period of oscillation. The ψ_0 corresponds to an initial displacement of about 1 cm for a ring with a circumference of 760 m. With no damping, for each α_2 there exists an α_1 which just stabilizes the motion. The graph of δ verses ψ is a closed separatrix. All choices of ψ_0 and δ_0 lying inside the separatrix result in stable states. Conversely, all choices lying outside are unstable. Choosing α_1 greater than the limiting value also produces a closed curve that lies inside the limiting separatrix and that is smoother than the limiting separatrix. In contrast, for smaller values of α_1, the curve will be open and the trajectory will be unstable.

With finite damping again every α_2 has a corresponding α_1 such that all larger values are stable and all smaller values are unstable. The graph of of δ verses ψ for this limiting case no longer yields a closed separatrix, but rather a spiral which is sharp at the bottom and slowly converges to origin. As α_1 increases, moving the system farther into the stability region, the phase trajectory becomes smoother and rotates more quickly.

For stable operation of a storage ring, α_1 must be chosen to lie above the curves. If we increase ψ and δ, by a factor of three, we find similar stability boundaries, except that the corresponding values of α_1 are almost three times larger. Hence, the "tighter" the initial conditions for the bunch, the smaller one can make α_1.

Applying the concept of the isochronous ring to a collider we exploit the fact that the bunch length scales roughly as the square root of the momentum compaction. Reducing α_1 by a factor of 100 allows to reduce β at the IP by a factor of 10. This freedom allows us to reduce the average current in the ring to practical values

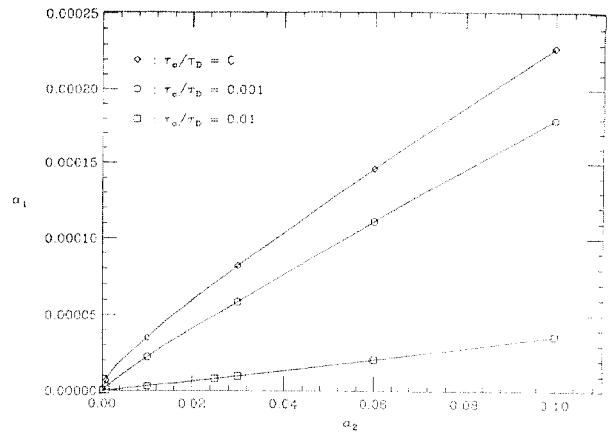

Figure 2.1: Three curves which define the stability limits for α_1 shown for three different values of damping with $\delta_0 = 0.001$ and $\phi_0 = 0.0001$.

3. A QUASI LINEAR COLLIDER $\bar{B}B$ FACTORY[3.1]

The design of a quasi-linear collider is based on the following features:[3.2] 1) unequal beam energies, 2) positron recovery and cooling; 3) possibility of positioning the vertex detectors very near to the interaction point (IP); 4) possibility of changing the center of mass energy in the 10 to 15 GeV range, maintaining a high luminosity, to be able to operate effectively at the $\Upsilon(4S)$ resonance or above; 5) a small beam energy spread, less than 0.1%, to utilize effectively the $\Upsilon(4S)$ resonance.

To satisfy these conditions we propose a scheme utilizing: 1) a 3 to 6 GeV, high gradient electron linac, with a 5 kHz repetition rate, 2) one positron cooling and recovery ring (CRR) provided with a bypass where the IP is located; 3) a positron converter, low energy positron accumulator, and booster synchrotron to provide the positrons. This scheme is illustrated in Figure 3.1a. Other proposals[3.3,3.4] utilizing a linac and a storage ring to obtain electron-positron collisions in the same

In contrast, we assume the collisions to occur in a bypass to decouple the cooling and recovery function of the ring from the IP, thus allowing an independent optimization of these different parts. For example the vacuum beam pipe near the interaction point can have very small diameter without limiting the beam lifetime in the storage ring or increasing the background in the detector.

As each bunch passes through the IP only every few damping times, one may increase the beam-beam tune shift ξ (or equivalently the disruption, D) to a value larger than that achievable in a storage ring collider, in which a collision occurs at each revolution, and thus increase the luminosity per interaction. As the electron beam is not stored, its disruption can be much larger than that of the positrons; hence, the electron beam power can be reduced for a given luminosity. To minimize the positron disruption the positrons should have an energy larger than that of the electrons. Thus, the characteristics of the two beams at the IP are completely asymmetric, with one beam having a large disruption, 1000 or more, and the other having a small or negligible disruption. This case has not yet been studied in the literature on beam-beam interactions[3.5], although it can make the collider design much more effective.

The collision frequency is set by the linac. For a room temperature linac rates will be in the 0.1 to 5 kHz range. Hence to compensate for the low rate, one must accelerate a train of ten bunches to collide with a similar train extracted from the storage ring. Thus one obtains an effective collision frequency between 1 and 50 kHz with a room temperature linac. To allow a small spot at the IP the electron gun should produce a bunch with a normalized transverse emittance $\epsilon_N = 10^{-6}$ m rad, a longitudinal emittance $\epsilon_L = 0.02$ m, and a charge per bunch of up to 10^{11} particles.

The heart of the quasi-linear collider is the CRR which provides low emittance bunches of positrons to the IP at a high repetition rate. The bunches are extracted from the ring and sent to the bypass where they collide with the electrons at the IP. After the collision the positrons are sent back into the CRR where radiation damping restores their initial condition after a few damping times. The disruption and beamstrahlung losses of the positrons during collisions should be such that only a small fraction, (less than 1%), are lost during the cycle. The CRR must provide fast damping, short bunches to reduce the electron beam disruption, high peak current for large luminosity, and small emittance.

To provide a positron beam with appropriate characteristics at the IP, we must manipulate the beam in the bypass to increase the bunch length and reduce its energy spread. For a 9 GeV CRR we can increase the bunch length to 0.5 cm, reducing the energy spread to a value smaller than the beamstrahlung parameter. If the damping ring can operate isochronously, the buncher and debuncher could be eliminated from the by-pass. The dispersion should zero at the entrance and exit points of the CRR and at the IP, where the beam should collide at a shallow crossing angle in the horizontal plane to avoid unwanted multiple collisions between bunches. Hence the bypass may need transverse deflection cavities to allow for crab crossing.

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.

New types of colliders discussed in this report could lead to higher luminosity ($10^{34} - 10^{35}\mathrm{cm}^{-2}\mathrm{sec}^{-1}$) and less expensive charm / τ, or $\bar{B}$B factories compared to the conventional approach. They would also advance the state of the art in accelerator physics. Consequently we advocate a major R & D program to study these possibilities. Our initial studies indicate the feasibility of constructing a test collider and ϕ factory that will reach a luminosity of $10^{33}\mathrm{cm}^{-2}\mathrm{sec}^{-1}$. The electron and positron beam densities in the ϕ factory will be variable over several orders of magnitude. Therefore, the disruption parameters can be varied over a wide range. Thus, this collider will allow a study of beam-beam interaction dynamics in totally new regimes.

REFERENCES

[2.1] Adapted from the original work of C. Pellegrini and D. Robin, "Isochronous Storage Rings and High Luminosity Electron-Positron Colliders", to be published by The New York Academy of Sciences in the proceedings of the Workshop on $\bar{B}$B Factories and Related Physics Issues, Blois, France June 1989.

[2.2] S. Chattopadhyay et al., Proceedings of the ICFA Workshop on Low Emittance $e^- - e^+$ Beams, Brookhaven National Laboratory, March 20 - 25, 1987

[2.3] D. A. G. Deacon, "Basic Theory of the Isochronous Storage Ring Laser", Physics Reports Vol. 76 No. 5, pp. 349-391 (Oct. 1981)

[2.4] M. Sands, SLAC-121 (1979)

[3.1] This section of the report is adapted from a paper to be published in NIM

[3.2] See for instance the Proceedings of the UCLA $\bar{B}$B Factory Workshop, D.H. Stork ed., World Scientific, Singapore 1987, or the paper by F.J. Gilman, Rare B decays and CP Violation, in the Proceedings of the Int. Symp. On Production and Decay of Heavy Flavors, Ann. New York Academy of Sciences, New York 1988, vol. 535.

[3.3] P. Grosse-Weismann, Colliding a Linear Electron Beam with a Storage Ring Beam, SLAC Report, SLAC-PUB-4548, 1988

[3.4] J.J. Bisognano, et.al., A Beauty Factory Using an SRF Linac and a Storage Ring, in Proc. of the LINAC 88 Conf., Williamsburg, Virginia 1988

[3.5] For a review of this literature see for instance P. Chen, Review of Linear Collider Beam-Beam Interaction, in Physics of Particle Accelerators, M. Month and N. Dienes eds., AIP Conf. Proc. Vol. 184, p.633, New York 1989; or R. Hollebeek, The Linear Collider Beam-Beam Problem, ibidem p. 680.

[3.6] C. Pellegrini and F. Ruggiero, Radiation Reaction Effects in High Energy Electron -Positron Colliders, CERN LEP-Th/86-03.

[3.7] M. Bassetti, S. Guiducci and L. Palumbo, Status of the Study on Damping Rings for a 5 to 10 GeV Linear Collider, Laboratori Nationali di Frascati Rep. LNF-88/20, 1988.

[3.8] For a review of coherent instabilities and coupling impedance see for instance C. Pellegrini, Single Beam Coherent Instabilities in Circular Accelerators and Storage Rings, in Physics of High Energy Particle Accelerators, AIP Conf. Proc. Vol. 87, New York 1982.