CESR: STEPS TOWARD A B FACTORY*

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Abstract

CESR has provided colliding beams for the study of the B meson since 1979. The luminosity has increased by a factor of 300 since the first year of operation through a series of innovative upgrades in the storage ring configuration. The present layout, utilizing trains of bunches and a horizontal crossing angle at the interaction point, with the addition of super-conducting RF cavities to be installed in the storage ring, will reach luminosities well above 10^{33} cm^{-2}-sec^{-1}. Studies of single beam stability, parasitic beam-beam interactions, vacuum system characteristics, and the performance of a superconducting RF cavity in the storage ring are in progress.

1 OVERVIEW

The Cornell Electron Storage Ring [1,2,3] has been operating at Wilson Laboratory on the Cornell University campus since 1979. The present operating energy range is 4.7 to 5.8 GeV per beam to study the B meson family (Ψ(1S) - (5S) states). A single interaction region accommodates the CLEO[4] detector. A schematic layout is shown in Figure 1 and Table 1 lists several basic parameters.

Several design features have been essential in the implementation of performance upgrades:

1. A full energy injector (linac plus synchrotron) which is capable of filling multiple bunches in CESR each injection cycle.
2. A design peak energy of 8 GeV giving considerable margin for increasing beam currents at 5.3 GeV well beyond original design values.
3. Individually settable quadruples and sextupoles, providing flexibility in optics design.

Operating Energy	4.7 – 5.6 GeV / Beam
Circumference	768.43 m, T_{rev} = 2.56 µsec.
Bending Radius	88 m normal, 33 - 140 m range
Cell Length	No standard cell, each quadrupole individually optimized.
Tunes (now)	Q_X = 10.53, Q_Y = 9.61 Q_S = 0.052
ε_H (Beam emit.)	0.2-0.3 µm-rad @ 5.3 GeV
Energy Width (σ_E/E_0)	0.71 x 10^{-3} @ 5.3 GeV (with wigglers)
Beta funct. at I.P.	β_V = 1.8 cm, β_H = 1.2 m
Injector	150/300 MeV linac, 4-8 GeV synchrotron, (2.3 µs pulse width)
P_{SR} LOSS	1.2 MeV/turn @ 5.3 GeV (with wigglers)
RF Frequency	499.76 MHz
RF Complement	2 RF regions, each with 2 each 5-cell cavities

Table 1 - Basic CESR Parameters

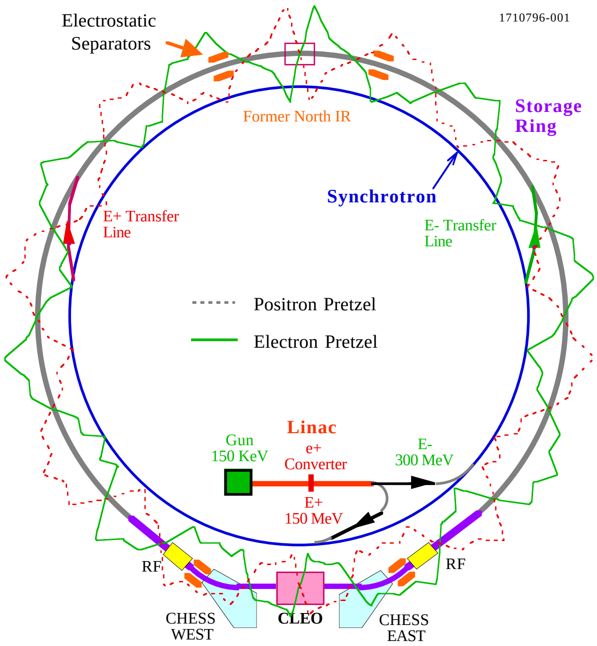

Figure 1 - CESR Layout with 9 Bunch Pretzels

2 STEPS TO THE PRESENT

2.1 Strategies for Luminosity Improvement

The performance of CESR today is the result of a series of upgrades to the storage ring and injector since initial commissioning in 1979.

Strategies for increasing luminosity are elucidated by the expression for luminosity in terms of directly controllable or measurable parameters:

$$L = 2.17\,(1 + r\,)\; E_{beam}\; \frac{I_{beam}\;\xi_V}{\beta_V^*} \qquad (1)$$

where L is in units of $10^{32}$$cm^{-2}$-$sec^{-1}$, r is the ratio of vertical to horizontal beam size at the interaction point, E_{beam} is in GeV, I_{beam} is the current per beam in amperes, ξ_V is the vertical beam-beam space charge parameter, and β_V^* is the vertical focusing function (m) at the interaction point.

In reviewing Equation (1), we observe that r has been close to zero in most electron-positron colliders and

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E_{beam} is determined by the physics goals. ξ_V is not so much a design parameter as it is a result of minimizing coupling effects and lattice errors. High values of ξ_V might be thought of as Nature's reward for clean living. Typically ξ_V has been in the range 0.03-0.05 for electron-positron colliders.

We are left with the current per beam and vertical beta function at the interaction point as the only free parameters with which to work.

2.2 Reducing β_V^*

Special optics are required to reduce β_V^* without creating excessive chromaticity or aperture requirements. The use of permanent magnet quadrupoles in CESR allows β_V^* as low as 1.5 cm without objectionable optics effects.

A more restrictive limit is imposed by the "hourglass" effect. The beam envelope cross section increases with a slope of $(\beta_V^*)^{-1/2}$ as the longitudinal coordinate, s, increases. If the bunch lengths are long compared to this scale, the beam cross section is larger in the outer parts of the interaction volume. This geometry factor reduces luminosity. In addition, the beam-beam interaction is aggravated because of the increase in β for $s>0$.

Since 1979, β_V^* in CESR has been reduced from 10 to 3 (1981) to 1.5 (1986) cm by changing quadrupole configurations in the interaction region. The last change pushed β_V^* below the bunch length (σ_l). A series of machine studies experiments [5,6] indicated that the best luminosity performance is attained when $\beta_V^* \approx \sigma_l$. This has been adopted as the normal operating condition for CESR.

The Phase III (see below) configuration of interaction region quads can easily achieve $\beta_V^* = 1.0$ cm. Practical values (for "flat" beams) will be limited by bunch length for the foreseeable future.

Decreasing the bunch length requires increasing the time derivative of the voltage in the RF cavities (Higher voltage or frequency) and modifying the accelerator optics (lower momentum compaction factor, α_p). A more persistent limit is found in the increasing parasitic mode losses (HOM losses) as the bunch length is decreased. Each machine has it own restrictions to bunch length depending on RF, optics, and vacuum component design. CESR's limit is probably around 1 cm with existing hardware. Concepts for local reduction of bunch length [7] have been proposed, but require a lot of space between the arcs and the interaction region.

2.3 Increasing I_{beam}

With the limit of around 2x gain in luminosity by reducing β_V^*, we must turn to I_{beam} for further improvement.

The current per bunch is limited by beam-beam effects [8] so adding bunches is the method of choice to increase current. CESR has a single vacuum chamber, shared by the counter-rotating beams. Additional collisions between bunches are prevented by establishing separate closed orbits in the horizontal plane by means of 4 electrostatic separators. These "pretzel" orbits are controlled by tailoring the betatron phase advance to maximize the separation between the two beams. Pretzel orbits are shown in the layout diagram in Figure 1.

The large closed orbit distortions are potentially detrimental to good beam-beam performance. The sextupole magnets used to correct chromaticity introduce gradient errors proportional to the horizontal displacement of the beam times the sextupole strength. Since all quadrupoles and sextupoles are individually controllable, the optics can be optimized to minimize the most serious effects of these errors. (Changes with pretzel amplitude of tunes, chromaticity, and interaction region optics parameters.)

A more difficult problem results from the long-range beam-beam interactions. A horizontal kick proportional to Q_b/d and a gradient error proportional to Q_b/d^2, where Q_b is the charge per bunch and d is the separation between electron and positron bunches, are generated at each parasitic crossing point. Because the horizontal phase advance must necessarily be close to π radians between each parasitic crossing point in order to provide maximum separation, the effects from all the parasitic interactions add coherently in the horizontal plane.

The beam-beam effects introduce an intensity dependent error which must be corrected by tuning. Each of the bunches in a beam has a somewhat different pattern of long range beam-beam encounters giving rise to differences in optics parameters between bunches. These differences can be minimized by appropriate manipulation of optics.[9]

2.4 Bunch Trains and Crossing Angles

CESR operation from 1983 until 1994 utilized almost evenly spaced bunches (3 and 7 /beam)with one parasitic interaction at each pretzel anti-node. In response to the need to further increase the number of bunches, a proposal [10] was made to utilize the extended separation regions to separate multiple crossing points and replace each single bunch with several in a "train." The added collision points in the interaction region would have no separation, however, so the pretzel orbits were extended through the interaction region, creating a horizontal crossing angle at the interaction point, to remedy this situation. These changes in separation method are illustrated in Figure 2.

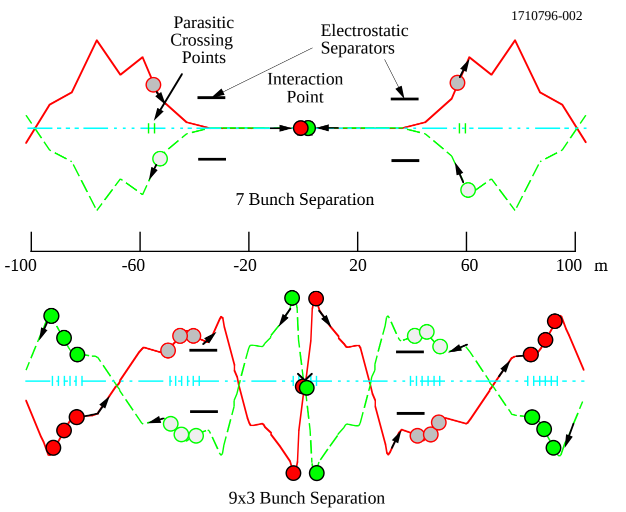

Figure 2 - Comparison of separation schemes for 7 bunch, head-on collisions with 9x3 bunch, crossing angle collisions.

In addition to the increased number of parasitic beam-beam interactions, the effects of a crossing angle on the primary beam-beam interaction must be assessed. The direct effect [11,12] of a crossing angle is to couple longitudinal and transverse motion, creating additional resonance lines in tune space. The crossing angle in CESR is small, ±2.5 mrad, and the scaling parameter for coupling, $b = \alpha_{1/2}\, \sigma_l / \sigma_x$, or the half angle times the ratio of longitudinal to transverse beam size at the interaction point, is about 0.1 and not expected to have a serious impact on operation. Extensive machine studies of both luminosity and lifetime effects [13] were carried out at CESR to confirm this prediction. The relatively weak resonances created by the small crossing angle are easily avoided by adjusting the operating point.

2.5 Interaction Point Parameters

Until 1990 CESR operated with 2 interaction points and was forced by the layout of bending magnets to have a large (1 m) horizontal dispersion at the interaction points. After the North interaction region detector was removed it was possible to operate with zero dispersion in the remaining South interaction region. After a year of single interaction point operation ξ_V rose from 0.02 to 0.03 and is now as high as 0.04. The relative roles of 1 vs. 2 interaction points and the dispersion have not been established.

3 PERFORMANCE ANALYSIS

3.1 Present Operating Status

CESR has been operating with 9 trains of 2 bunches in each beam since November, 1994. Best performance during physics operation (beam energy = 5.3 GeV) is summarized in Table 2 below.

Accurate alignment of accelerator magnets and faithful realization of design optics are important in any storage ring. The demands of the pretzel orbit and parasitic crossings reduce the tolerance for errors. Good alignment (0.2 mm for IR quads) is needed. Measurements of local coupling have been used to optimize the compensation of the experiment solenoid. Accurate measurement and correction of optics functions is critical. A phase based measurement is being used to check optics functions with pretzeled orbits. [14]

Peak luminosity	3.5 x 10^{32} cm^{-2}-sec^{-1}
Integrated lumin./Month	330 pb^{-1}
Current per beam	160 mA
Beam-beam parameter, ξ_V	0.04

Table 2 - Highest colliding parameters achieved during CESR HEP performance as of June, 1996

3.2 Experiment Background

The storage ring is intimately linked to the experiment detector and accelerator designers must consider detector background as much a machine problem as an experiment problem. High background increases trigger rate and deadtime and can cause premature failure of detector components. Since increased beam currents are the primary luminosity upgrade path for CESR, reducing background is a critical part of the upgrade plan.

Detector background comes from two principle sources: synchrotron radiation and particles lost through beam-gas collisions. The former is controlled by careful magnet layout and masking, though the pretzel orbits turn the IR quads into strong synchrotron radiation sources, making masking a non-trivial problem. The particle background can be reduced about ten fold by thick shielding. However, primary control must be by reduction of residual gas in the sensitive parts of the accelerator.

While studying background is a continuing project in any colliding beam machine, it has been particularly intense during the past 2 years at CESR. Extensive computer simulations predict background rates and the results are compared with experiment. [15] Scattering sources can be categorized by location or distance from the interaction point. The largest discrepancies are in the synchrotron radiation (x4) and hard bend (14-40 m from i.p.) (x6) areas. The synchrotron radiation is critically dependent on local orbits and geometry and a factor of 4 error without more exact input data to the simulation is not surprising. The disagreement between simulated and measured background from the hard bend region is being studied.

3.3 Discussion of Performance Limits

The beam-beam performance of CESR is as good as can be expected. Values of ξ_V above 0.04 have been measured. While there is some hope for further improvement, experience at other colliders suggests that exceeding 0.05 is unlikely, at least with flat beams. Maintaining the present level of beam-beam performance requires frequent attention to survey, alignment, and optics fidelity. As train currents increase, long range beam-beam effects could begin to affect beam-beam performance, although extrapolation of experience to date suggests that these effects will be manageable.

Beam current limits are from several effects. We have stored up to 340 mA total in both beams. Beam induced fields are significant in RF cavities and electrostatic separators and they must be conditioned to support large beam currents without breakdown.

Transverse instabilities are damped with a wide band feedback system [16]. The largest transverse impedance, coming from electrons trapped in the leakage fields of the distributed sputter ion pumps [17,18], are also being reduced by lowering the voltage on the pumps. The 0.5 millisecond damping rate of the transverse feedback system should be adequate to damp the beam at currents to at least 500 mA/beam.

The bunch currents in multibunch operation are a factor of 3 or 4 below single bunch currents stored in CESR; thus the wide band impedance of CESR will not be a limitation.

Longitudinal coupled bunch instabilities have been observed after recent increases in current. The amplitude of these oscillations is self-limiting but potentially affects luminosity and reduces the dynamic range of the transverse feedback system. Experiments suggest that the RF cavities harbor the high Q resonances driving this instability since changing cavity temperature and local orbits affect the instability threshold. However, the impedances of sliding joints, separators, and feedback kickers are also being reviewed. Superconducting RF cavities planned for installation in 1998 will dramatically reduce the impedance of cavity modes. A longitudinal feedback system is also under consideration.

4 FUTURE STEPS

4.1 Phase III

Phase III of the CESR luminosity upgrade will be implemented in 1998. The replacement of copper RF cavities with superconducting RF will reduce the impedance of the machine, allowing the current per beam to be raised to at least 500 mA. Stronger focusing from superconducting quadrupoles in the interaction region will allow the bunch spacing to be reduced to 14 ns so each train can carry 5 bunches (45 bunches per beam). The vacuum system of the hard bend region will be upgraded to keep the pressure, and thus beam-gas background, low.

4.2 Superconducting RF

A storage ring RF system using superconducting cavities has a lower impedance than its copper counterpart because of a two-fold advantage. The cell modes can be very well damped (Q's less than 100) and the higher gradient achievable decreases the number of cells needed. The CESR Phase III RF system [19] utilizes 4 single cell cavities operating at 6 MeV/m gradient.

There are several technical challenges to be met by a superconducting RF system, including HOM and synchrotron radiation power handling, a complex cryogenic system, and transfer of over 300 kW per cell to the beam. These issues are being managed by careful design, taking advantage of world experience with s.c. cavities in storage rings, and through beam tests in CESR.

A week-long test [20] of a superconducting cavity in CESR was carried out in August, 1994. 220 mA beam current was stored and 155 kW was transferred to the beam. Neither limit was due to the s.c. RF cavity. HOM power handling, synchrotron radiation effects, and cryogenic system operation were also checked to be o.k.

The weakest cavity component was the RF window. This is being replace with a new design. A new cryostat (to fit in the tunnel) and new dual 600 W refrigerator installation are also being implemented. A single superconducting cavity will be installed in CESR later this year and will be used during physics operation for several months.

4.3 Superconducting IR Quads

The length of each bunch train is limited by the wavelength of the pretzel orbit and the spacing between bunches is limited by the parasitic beam-beam interaction nearest the interaction point. Stronger quadrupoles in the Phase III IR will enable control of the beta function at a parasitic crossing point 2.1 m from the interaction point, (bunch spacing of 14 ns). A short permanent magnet quad starting 35 cm from the interaction point not only provides additional focusing, but particle background shielding as well.

Several other features of the Phase III IR design are: 1) β^*_V can be reduced to 1 cm or less without objectionable aperture requirements or chromaticity; 2) integral skew quads and dipole steering magnets allow better control of solenoid compensation elements; and 3) the restoration of a pair of the present iron IR quads provides the option for round beam optics with 3 cm β^* in each plane.

4.4 Phase III Vacuum System

The CESR vacuum system was designed for 100 mA, 8 GeV beams. The linear power density of 500 mA, 6 GeV beams is comparable. The primary motivation to upgrade a major part of the system (hard bend region) comes from particle background concerns. As mentioned, a large part of the particle background comes from beam-gas collisions in the hard bend region. The pressure normalized to beam current should be reduced by at least a factor of 5 for conservative operation at 500 mA/beam.

The hard bend vacuum chambers will be replaced with copper chambers (for radiation shielding) with extensive titanium sublimation pumping along the entire beam line.

The I.R. vacuum system is complex because of the severe space constraints. The assembly of the detector, magnets, and vacuum system would be greatly simplified if a remotely fastened flange could be used inside the detector. To meet this need, a remotely actuated flange employing double, differentially pumped, elastomer o-rings has been designed and tested.

4.5 Beyond Phase III

The pretzel separation scheme will eventually limit luminosity because of the large number of parasitic collision points and limited capability to add more bunches. Some additional gains may be made by reducing β^*_V and otherwise optimizing the lattice, but the ultimate luminosity limit will be around $2\text{x}10^{33}$ cm^{-2}-sec^{-1}. We are investigating options for further luminosity increases. Two are described here.

For more than a decade, analytic calculations and computer simulations have suggested that a round beam cross-section at the interaction point may be capable of achieving a larger ξ than flat beams. This is primarily due to elimination of one dimension in the geometry ($x,y \rightarrow r$). Simulations suggest that $\xi > 0.1$ may be possible [21]. In addition, a factor of 2 comes "for free" from the $(1+r)$ factor in Equation 1. A deficit is the difficulty of constructing optics which can produce a low β^* in both planes simultaneously. As mentioned above, the Phase III I.R. optics can optionally achieve β^*=0.03 m in both planes. We are presently carrying out round beam machine studies experiments with β^* =0.24 m in both planes to determine whether the impressive predictions are likely to be realizable.

Because of the small beam size in both transverse dimensions, round beam collisions are incompatible with uncompensated crossing angles. Head-on collisions and the concomitant larger minimum bunch spacing suggest the need for a second arc transport system to achieve the number of bunches required for high luminosity. Low cost, compact options for separating the beams around the arc are being investigated for either flat or round beam collisions. Small 2-in-1 superconducting quadrupoles have been modeled [22] which could be used with the present bending magnets for flat or round beam operation. A modification of the pole profile would accommodate two separate vacuum chambers for the counter-rotating beams.

CONCLUSION

The performance of CESR today is the product of many individuals' contributions and the unflagging support of the National Science Foundation and the physics community. We must specifically mention the dedicated work and innovations of the accelerator operators and technical support staff.

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