CESR Status and Plans *

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Introduction

The CESR electron positron collider has been configured to operate with trains of closely spaced bunches that collide with a small horizontal crossing angle. The crossing angle scenario provides for an increase from seven to as many as 45 bunches per beam. Two pairs of electrostatic separators yield differential horizontal closed orbits for the electron and positron beams. The separators are powered antisymmetrically with respect to the two-fold symmetry of the storage ring. The bunches collide with a small horizontal angle of $\pm 2.1 mrad$, that serves to separate the counter-rotating bunches at the parasitic crossing points adjacent to the IP. Nine trains, with temporal length of up to 56ns can be accomodated. The storage ring has operated for high energy physics with trains of two bunches spaced 28ns apart and reached peak luminosity of $3.3 \times 10^{32} cm^{-2} s^{-1}$. The Phase II upgrade of the interaction region, now underway, will permit an increase in current to 300mA per beam, and luminosity to $6 \times 10^{32} cm^{-2} s^{-1}$. In Phase III of the CESR upgrade, scheduled for completion in 1995, the room temperature RF system will be replaced with single cell superconducting cavities. The single beam limit will increase to 500mA, and the luminosity to $10^{33} cm^{-2} s^{-1}$.

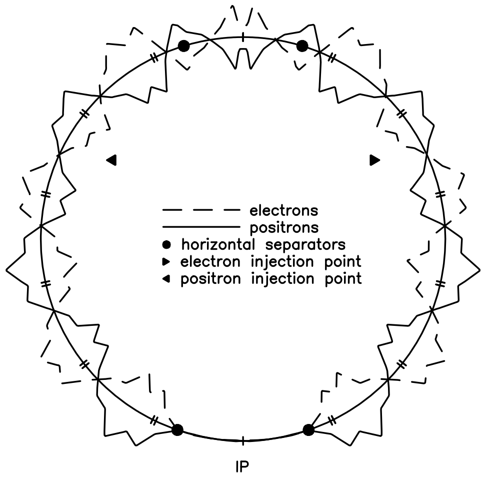

Figure 1: Electron and positron closed orbits for head on collisions. Tic marks along the circumference indicate parasitic crossings with 7 almost evenly spaced bunches per beam. Electrons travel counterclockwise.

Seven Bunch Operation

Prior to the switch to crossing angle operation in March of 1994, beams of seven nearly equally spaced bunches were directed into head-on collisions at a single interaction point. The then symmetrically powered electrostatic deflectors separated the beams at the thirteen parasitic crossing points. The "pretzeled" orbits characteristic of the head-on scheme are shown in figure 1. At the interaction point, $\beta_v^* = 18mm$, $\beta_h^* = 1m$, and $\eta^* = 0$. The integer part of the horizontal tune was chosen to yield differential orbits consistent with seven bunches per beam. The horizontal emittance with permanent magnet wigglers closed was $3.3 \times 10^{-7} m-rad$. Peak luminosity was $2.9 \times 10^{32} cm^{-2} s^{-1}$ at 5.3GeV beam energy, with 112mA/beam, corresponding to a beam-beam tune shift parameter of $\xi_v = 0.04$. The long range interaction of the beams at the parasitic crossings in the arcs precluded a further increase in bunch current, and the proximity of the electrostatic separators to the interaction point, along with the constraint that the beams collide head-on, limited the number of bunches per beam to seven.

Crossing Angle Optics

The notion that a small horizontal crossing angle might permit a significant increase in the number of bunches in each beam is due to R. Meller [1]. He proposed that we store trains of closely spaced bunches in each beam, and that we take advantage of a horizontal crossing angle to separate the bunches at the parasitic crossings adjacent to the interaction point.

Criteria for the requisite separation of the bunches at the parasitic crossings is based on our experience with multiple bunch beams. It was established in seven bunch operation that the bunch current was limited by long range interactions when:

1. The largest long range horizontal tune shift of any of the parasitic crossings was $\Delta\nu_h = 0.00072$
2. The largest long range vertical tune shift of any of the parasitic crossings was $\Delta\nu_v = 0.0011$,

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3. and that

$$\frac{1}{I_{bunch}(mA)} > \sqrt{\Sigma_i^N \left(\frac{\epsilon_h(mm-mrad)\beta_i^h(m)\beta_i^v(m)}{s_i^2(mm)}\right)^2}$$

The last is a phenomonological attempt at including the collective effect of multiple crossings and horizontal tails[2]. The sum is over all of the N parasitic crossings and β_i^h, β_i^v, and s_i are β-functions and separation at each crossing.

Linear Optics

The linear optics are designed to maximize the bunch current consistent with the separation criteria. The differential closed orbits that result are shown in figure 2. Nine 56ns long trains can be accomodated in each beam. If the bunches are spaced 28ns apart, then the long range tune shift at each of the parasitic crossings, including the one nearest the IP, are comparable. We expect the long range beam-beam limit at bunch currents over 11mA. For more closely space bunches (14ns), the vertical β at the parasitic crossing nearest the IP (at 2.1m) is large, and may limit bunch current below 11mA prior to the Phase III IR upgrade (see below).

A half wave vertical displacement bump (not shown in the figure) separates the beams at the crossing point diametrically opposed to the interaction region. The integer part of the horizontal betatron tune is increased to ten, (as compared to 8 for the head-on pretzel), while the integer part of the vertical tune remains at nine. Fractional tunes are just above the half integer. Note that the orbits are displaced toward the injection septa. A consequence of the increased horizontal tune is a significantly reduced emittance; $\epsilon_h = 2.1 \times 10^{-7} m - rad$ with wigglers closed. The interaction point focusing functions are unchanged ($\beta_v^* = 18mm$,$\eta^* = 0$,$\beta_h^* = 1m$.)

The horizontal phase advance the separator just west of the interaction point to the separator just east of the IP is $\frac{11}{2}$ wavelengths. During injection a symmetric voltage is superimposed on these two separators so that the beams are horizontally separated at the interaction point.

Inspection of figures 1 and 2 reveals a complication of the crossing angle versus head-on configuration. In the crossing angle scheme there is no place in the machine where electrons and positrons share a common orbit. In particular, the beams are horizontally displaced in essentially all of the skew quads. Adjustment of the transverse coupling, a critical aspect of luminosity tuning, effects a differential vertical kick to the beams, altering the closed orbits and the vertical overlap at the IP. Luminosity tuning is inevitably more difficult.

Sextupole Optics

The distribution of sextupole strengths is designed to:

1. Correct chromaticity

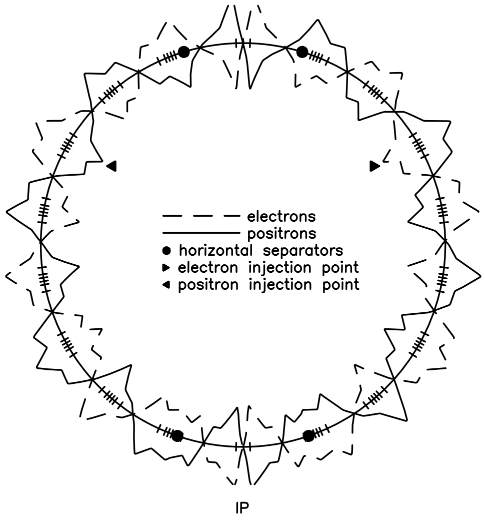

Figure 2: Electron and positron closed orbits in crossing angle operation. The crossing angle is $\pm 2.3 mrad$. Tic marks along the circumerence indicate parasitic crossings with 9 trains with the 2 bunches/train spaced 28ns apart.

2. Minimize the chromatic function, (the energy dependence of the β-function through the arcs as well as at the interaction point)

3. Maximize dynamic aperture for on and off energy particles

4. Minimize the "pretzel" dependence of the β-function.

5. Yield flexibility to differentially adjust betatron tune.

Except for a two-fold symmetry about the IP, all sextupoles are varied independently in the optimization of the distribution[3]. We break the symmetry to generate different tunes for electron and positron beams.

Crossing Angle Operation

Initial operation of CESR with beams crossing at an angle (beginning in March 1994) was characterized by poor injection efficiency and poor beam-beam performance. The horizontal displacement of the stored beams in the interaction region forced the injected bunch to large amplitudes. The lost particles found there way into the CLEO detector and through the shielding walls into the experimental area of the synchrotron light facility, effectively limiting injection rate. We observed a significant degradation of luminosity with crossing angle and displacement of the beams in the permanent magnet wigglers. In tests with a single bunch in each beam, the crossing angle was set to zero and a tune shift parameter of $\xi_v \sim 0.04$ was measured. The tune shift parameter fell to 0.03 with a crossing angle of $\theta^* \sim \pm 2.1 mrad$, and with nine bunches in each beam it deteriorated further to $\xi_v \sim 0.023$. Solutions to the various complications peculiar to crossing angle operation were evolved during the Spring and Summer of 1994. There follows a brief description of that work.

Injection

As noted above, a symmetric eletrostatic displacement bump is superimposd on the crossing angle to separate the beams during injection. Its sign is chosen so that the asymmetric displacement that results in the interaction region quads is greater in the east and smaller in the west. Electrons, which are injected into the horizontal plane with positrons already stored, approach the interaction region from the west (from the left in figure 2). Large amplitude particles in the injected electron bunch are therefore more likely to be scraped leaving the IR than while entering. With attention to the orbit correctors east of the IR, it is possible to reduce electron losses into the synchrotron light experimental area to tolerable levels.

As the electron beam current increases during injection, the long range beam-beam interaction tends to blow up the stored positrons. The tails of the positron beam are typically lost into the CLEO detector as they approach from the east. We discovered that the beam-beam coupling that is responsible for the blow-up can be reduced by introducing a difference in the betatron tunes of the two beams, via an asymmetry in the sextupole distribution. A horizontal tonality ($\Delta Q_h \sim 0.05$) is typical of electron injection conditions. The large tonality is essential to control losses of positrons during injection of electrons. The tonality is restored to nearly zero with beams in collision.

Wigglers

CESR operates with two $2.5m$, $1.2T$, permanent magnet wigglers for generating intense x-ray beams. In the crossing angle separation scheme beams are displaced $\pm 11mm$ in the wigglers. (The beams are on axis in the wigglers in head-on operation.) At least part of the degradation of the beam-beam performance with crossing angle pretzel was observed to be due to that large displacement. In experiments with single bunches in head-on collision we learned that a closed orbit displacement in the wigglers, generated by magnetic steering elements, yields the same degradation as the crossing angle pretzel. Elimination of the sextupole component of the wiggler and implementation of a skew sextupole correction magnet were somewhat effective in compensating the impact of the wigglers. Theoretical investigation of the effects of the wiggler fields on the colliding beam dynamics continue.

Operating Point

Exploration of the tune plane by CESR operators[4] with single and multiple bunch colliding beams, lead to the discovery of a new operating point more tolerant of the crossing angle dynamics. The change in the fractional tunes ($\Delta Q_h \sim -0.05$ and $\Delta Q_v \sim -0.04$) brought the operating point very near to the half integer as shown in figure 3.

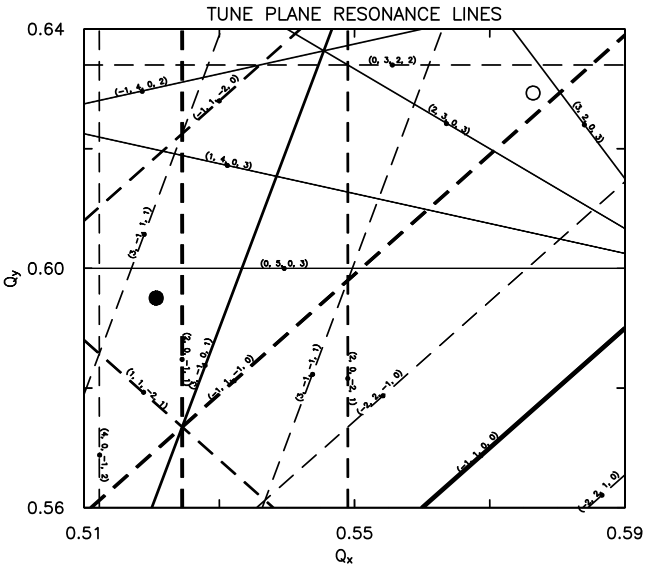

Figure 3: The region of the tune plane in the vicinity of the CESR operating point. The solid circle is the operating point that yields good performance for beams colliding at an angle. The operating point that proved effective in head-on operation is indicated by the open circle. (2,0,-1,1) corresponds to $2Q_h + 0Q_y - 1Q_s = 1$

With careful attention to injection orbits and suitable tonality, repair and compensation of the permanent magnet wiggler, and subsequent tuning at the low operating point, we eventually recovered performance typical of earlier head-on operation. We measured luminosity $L = 2.4 \times 10^{32} cm^{-2} s^{-1}$ with $11mA/bunch$ as shown in figure 4, with nine bunches per beam colliding at an angle of $\pm 2.1mrad$. The beam-beam tune shift parameter was 0.038.

Bunch Trains

In late October of 1994, 2-bunch trains with 28ns interbunch spacing were introduced into the crossing angle pretzel. Total current in the 18 bunch beams was limited by synchrotron radiation heating of various components of the CESR vacuum system, and by electron injection. Transverse stability of the trains of bunches was ensured by a wideband bunch by bunch feedback system[5]. During a three week down period in November and December, cooling was added to overheating flanges and sliding joints, and rebuilds of offending vacuum transitions installed. Following runs with nine bunches per beam at $\Upsilon(1s)$ and $\Upsilon(2s)$ energies, we returned to $\Upsilon(4s)$ (5.3 GeV/beam) and bunch train operation. Total current was gradually increased over a period of several weeks as the CESR operators learned how to tune so as to minimize the effects of parasitic inter-

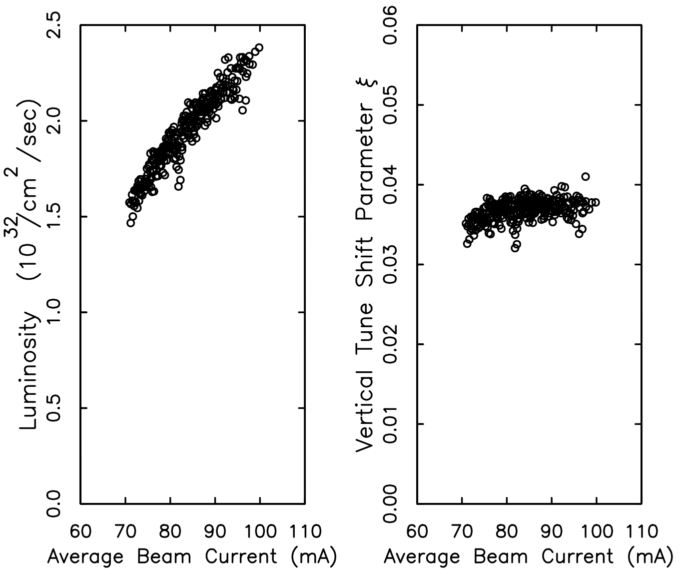

Figure 4: Luminosity versus beam current with nine bunches per beam and crossing angle of $\pm 2.1 mrad$.

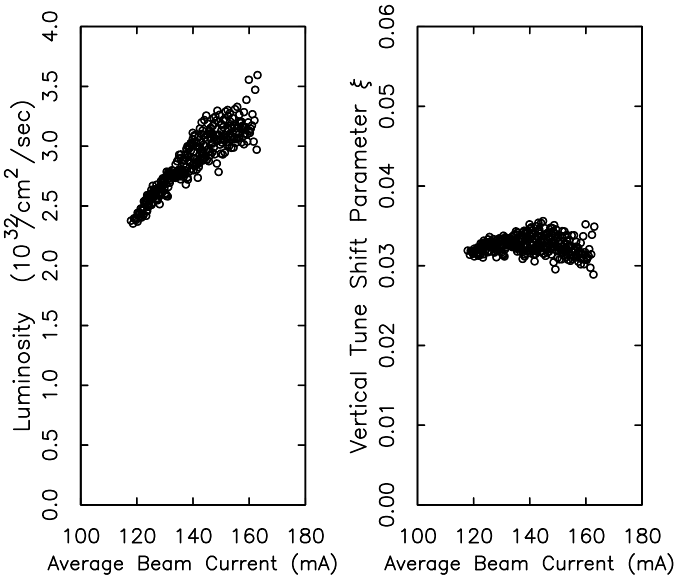

Figure 5: Luminosity versus beam current with 18 bunches per beam and a horizontal crossing angle of $\pm 2.1 mrad$.

actions during injection. Tonality and pretzel amplitude were the critical tuning parameters. By mid March of this year we measured a luminosity of $L = 3.3 \times 10^{32} cm^{-2} s^{-1}$ with $160 mA/beam$ and an integrated luminosity of nearly $18 pb^{-1}$ in a single day. The current dependence of luminosity and tune shift parameter are shown in figure 5.

Trains with 14ns spacing and more bunches

During periods of machine studies we have experimented with three bunch trains with 28ns interbunch spacing, and two, three and four bunch trains with 14ns spacing. At currents of at least 7mA/bunch, with two bunches/train, and nine trains, the beam-beam performance is essentially identical for 14ns and 28ns spacing. Injection may indeed be easier with the shorter train, presumably because the ends of the train are not so far from the pretzel maxima in the arcs. Single train experiments with three and four bunches per beam are consistent with the expectation that the luminosity will scale with the number of bunches.

Phase II

Beginning in April of 1995 the interaction region has been taken apart for the installation of a silcon vertex detector for the CLEO experiment and a rearrangement of final focus quadrupoles.

Increased Aperture

As noted above, the horizontal aperture in the interaction region severely impacts injection into the crossing angle pretzel due to the large horizontal displacement of the beams in the horizontally focusing lens. In the Phase I IR (pre-April 1995), the vertically focusing permanent magnet quadrupole is followed by a vertically focusing electromagnet. By eliminating the vertical trim in favor of a lengthened permanent magnet, it is possible to bring the horizontally focusing lens closer to the interaction point. The peak horizontal β and displacement of the beam in the horizontal lens is reduced from nearly 100m to just over 60m as shown figure 6.

In addition to reducing the required horizontal aperture in the IR, the bores of the IR quads, (Q1 and Q2), are being enlarged, increasing the physical aperture. The available aperture will be increased by nearly 2cm at the peak of the orbit displacement in the interaction region. Finally, the rebuild of the shielding walls will reduce radiation rates in the synchrotron light experimental area by factors of 30 to 100.

During the 4-5 month shutdown we will complete the replacement of horizontal separators. The modern separators operate at somewhat reduced electrode voltage and half the broadband impedance of the original equipment. Rebuilt vertical separators will also be installed. The four, 5-cell RF cavities will be retuned for optimal coupling at 600mA total current. (We have stored 220mA in single beams and 350mA in two beams and anticipate with beam processing, to reach 300mA/beam.)

The vacuum chamber through the interaction region is being replaced to accomodate the new vertex detector, the increased aperture IR quads, and to provide better pumping. In addition, beam position monitors are being installed at the IP end of the REC quadrupoles. The beam detectors will provide a direct measure of the overlap of the beams at the collision point.

At the conclusion of the installation of Phase II hard-

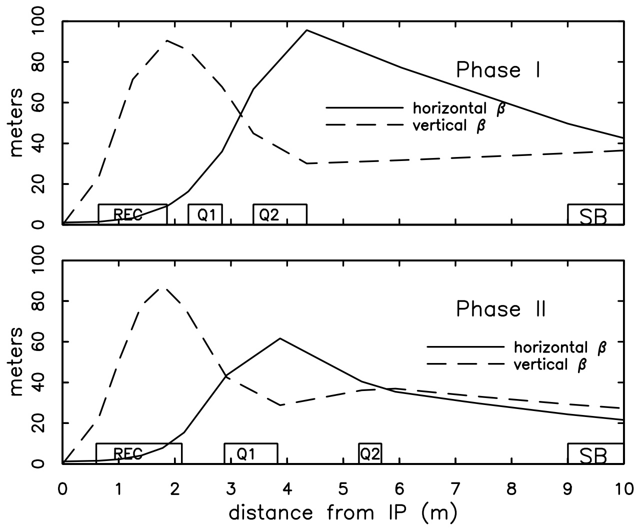

Figure 6: Optical functions in the Phase I and Phase II interaction regions. In Phase I, Q1 and Q2 are vertically and horizontally focusing respectively. In Phase II, Q1 is horizontally focusing and Q2 vertical.

ware (September 1995) CESR will operate with two to five bunches in each of nine trains. The number of bunches in each train and the bunch spacing (14ns or 28ns) will be chosen on the basis of operating experience to optimize performance. At currents of 300 mA per beam we expect a luminosity of $6 \times 10^{32} cm^{-2} s^{-1}$.

Phase III

Installation of Phase III hardware will begin in late 1997. The interaction region quadrupoles will be replaced with a high gradient, 30cm long permanent magnet at 30cm from the IP, followed by a pair of superconducting lenses. The scheme permits reduction of β_v^* to $7mm$ while limiting the value of the β functions at the first parasitic crossing point that occurs 2.1m from the IP. The optical functions for the phase III IR with $\beta_v^* = 1cm$ are shown in figure 7.

At the same time the 20-cell copper RF system will be replaced with 4 single cell superconducting cavities. Each cell is designed to deliver $325kW$. The beam test of the prototype cavity completed in August of 1995, is described elsewhere in these proceedings[6]. The broadband impedance of the superconducting system is approximately %6 of the room temperature system. The superconducting RF system will increase the current limit to 500mA/beam and the luminosity to $10^{33} cm^{-2} s^{-1}$ with $\beta_v^* = 18mm$. Substantial upgrade of the vacuum system will be required to accomodate the higher current.

With the increase of voltage of the superconducting cavities to the design goal of $10MV/m$, ($3MV$/cell), it will be possible to reduce the bunch length and exploit the capability of the superconducting IR to shrink β_v^* and further

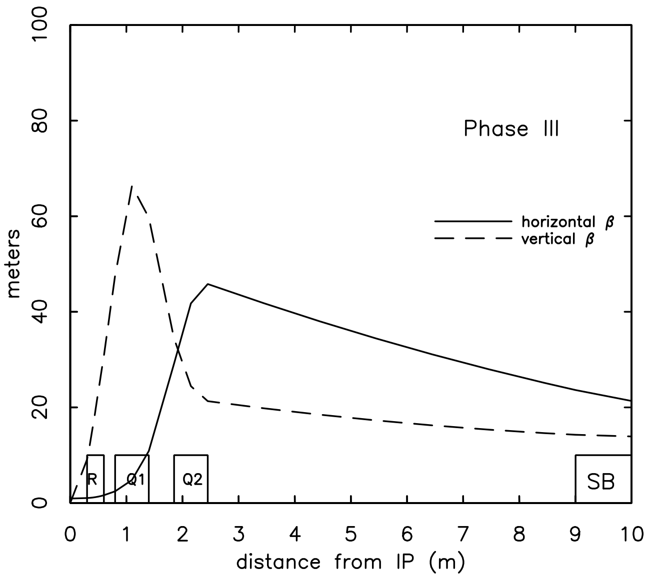

Figure 7: Optical functions in the superconducting IR.

increase the luminosity.

Summary

Peak luminosity $L = 3.3 \times 10^{32} cm^{-2} s^{-1}$ has been achieved with trains of bunches colliding at a horizontal crossing angle of $\theta^* = \pm 2.1 mrad$. The 2-bunches in each train are spaced 28ns apart and there are nine trains in each beam. The beam current is 160mA. Tests indicate that the extension to at least four bunches per train, spaced 14ns apart is straightforward. During Phase II operation (Fall 1995-Fall 1997) we expect to deliver peak luminosity of $6 \times 10^{32} cm^{-2} s^{-1}$ and with the completion of the Phase III upgrade in 1998 to reach luminosity in excess of $10^{33} cm^{-2} s^{-1}$.

References

[1] Meller,R.E., CON 90-17, July 1990.

[2] A.Temnykh and J.Welch, *Coherency of the Long Range Beam-Beam Interaction in CESR*, these proceedings

[3] T. Pelaia, PhD thesis, Cornell University, January, 1994, p. 31-45.

[4] Exploration of the tune plane and discovery of the low tune operating point is due to J. Hylas.

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[6] H. Padamsee et. al.,S. Belomestnykh et. al., and J. Kirchgessner, these proceedings.