A Survey of Beam-Beam Effects at CESR *

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Abstract

The Cornell Electron Storage Ring is a single-ring e^+e^- collider operating in a train-bunch configuration. Electrostatic separators are employed to prevent collisions at all crossing points around the ring except for the primary interaction point. Nevertheless, the long range beam-beam interaction at the parasitic crossings introduces several complications to machine performance. This document summarizes these effects and their impact.

1 INTRODUCTION

The Cornell Electron Storage Ring (CESR) is a symmetric energy collider in which both beams share a common beam pipe. When running for high energy physics (HEP), CESR typically operates in a mode where 9 trains of bunches are brought into collision at a single interaction point (IP) [1, 2]. The machine's RF structure has 1281 buckets (not a multiple of 9) so a three-fold pattern is imposed on the spacing between trains giving train-to-train intervals of 280 ns–280 ns–294 ns. The bunches within trains have 14 ns spacing and two operating configurations, one with 4 and a second with 5 bunches/train, have been explored during the 2000–2001 HEP run. When referring to bunches in trains, we will use the term "car 1" to denote the leading bunch, "car 2" for the second bunch, etc. To prevent collisions between bunches at locations other than the IP, electrostatic separators impose "pretzel" orbits on the two beams. At parasitic crossing points in the arcs, this results in approximately $8\sigma_{beam}$ horizontal separation between the beams. At the point diametrically opposite the IP, vertical separators displace the beams to prevent collisions. We have found that the long range beam-beam interaction (LRBBI) at these parasitic crossings places significant constraints on machine performance.

2 EFFECTS OF THE PRETZEL ORBIT

In the CESR arcs the pretzel displacement of the closed orbits can be written as

$$x(s) \sim \pm a\sqrt{\beta_h(s)}\,\sin(\phi_h(s) - \phi_0) \qquad (1)$$

where the sign of the displacement is species-dependent. The pretzel displacements for one species are shown in Figure 1. The corresponding horizontal tune shift due to the LRBBI is

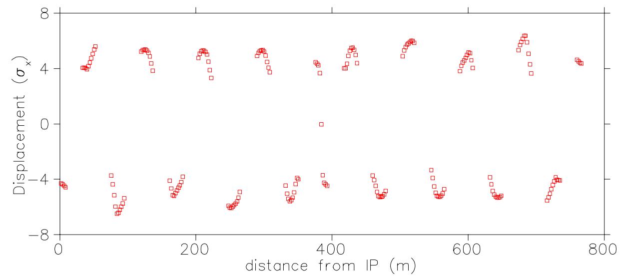

Figure 1: Horizontal displacement of the beam, in units of beamsize, as a function of longitudinal coordinate in CESR. The displacement changes sign for the other species. At the center point in the plot, which is the crossing diametrically opposite the IP, the beams are separated vertically.

$$\Delta Q_h \sim \frac{I_b \beta_h}{x^2} = \frac{I_b}{a^2 \sin^2(\phi_h(s) - \phi_0)} \qquad (2)$$

The resulting tune shift is minimized for parasitic crossings near the peak of the pretzel displacement at $\phi_h(s) - \phi_0 \sim \pi/2$. Since the parasitic crossings differ from bunch to bunch, a spread in tunes is induced. We have calculated both the horizontal and vertical tune shift for each of the bunches in three consecutive trains using a detailed strong-strong simulation[3]. Bunch-to-bunch variations of approximately 1.5 and 1 kHz are found for the horizontal and vertical tunes, respectively. These results are plotted in Figure 2 and have been verified by direct measurement. In order to understand the impact of this spread, it can be compared with the width of our working point in the tune plane which is approximately 100 Hz in the horizontal and 1 kHz in the vertical. The size of this spread limits the overall length of the trains and the maximum bunch current during HEP operation. The possibility of correcting the bunch-to-bunch spread in tunes by means of a radiofrequency quadrupole is currently under investigation.

Another effect is that particles in the horizontal tail of one beam that approach the core of the opposing beam experience strong vertical kicks that degrade the beam lifetime [4]. The lifetime can be improved, at the expense of luminosity, by adjusting the transverse coupling to decrease the horizontal beam size.

Figure 3 shows the vertical beam-beam tune shift parameter and luminosity obtained in 4-bunch and 5-bunch running. In the 4-bunch case the average beam-beam tune shift parameter saturates at a value of nearly 0.07 with approximately $7.5\mathrm{mA/bunch}$. Although luminosity performance

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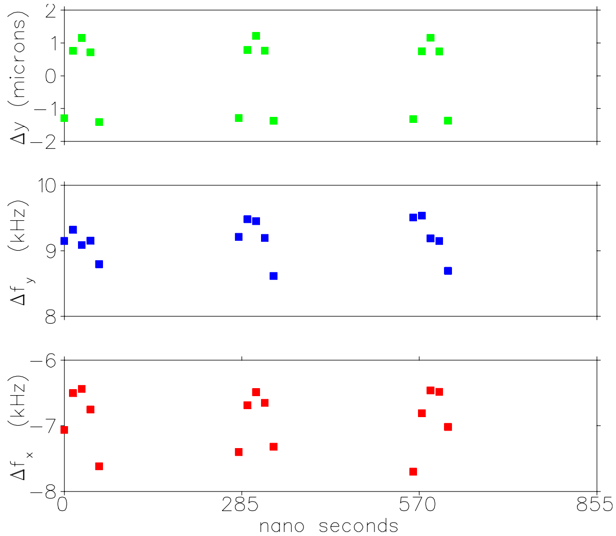

Figure 2: Calculated tune shifts in one beam due to the LRBBI with the opposing beam are shown in the bottom two plots. There are 9, 5-bunch trains with 7.5 mA/bunch in each beam and 14ns bunch spacing. The revolution frequency is f_{rev} = 390.1kHz. The difference in the vertical orbits at the IP for the two beams is shown in the top plot.

improves by ∼10% with 5 bunches, the beam-beam tune shift is consistently 10% smaller than in the 4-bunch case. This clearly demonstrates the performance limiting impact of the parasitic long range interactions. In fact, we measure nearly 25% higher specific luminosity for the cars in the middle of a train relative to those at either end (See Section 3 and Figure 7).

Large beta functions near the IP make us particularly sensitive to the parasitic crossings nearby. A superconducting focusing system has recently been installed [5] which significantly lowers the beta functions at these locations. This should lessen the impact of these parasitic crossings and may allow operation with smaller bunch spacings. Figure 4 shows the beta functions near the IP for the old and new optics.

3 DIFFERENTIAL ORBIT EFFECTS

Vertical displacements of the beams at parasitic crossings also affect performance. Such displacements occur for the parasitic crossings nearest the IP and those diametrically opposite the IP. In the latter case, the vertical electrostatic separation scheme gives rise to the displacements. At the IP, the beams are brought into collision with a horizontal crossing angle of approximately 2.5 mrad. In the field of the CLEO solenoid, this results in vertical displacements at the parasitic crossings just outside the IP. The vertical kicks between beams at these parasitic crossings distort the vertical closed orbits and result in differential vertical displacements, $\delta y \equiv y_{e+} - y_{e-}$, at the IP. This effect has a strong car dependence. At the IP, the first(last) car in a train experiences parasitic interactions only as it exits(enters) the IP

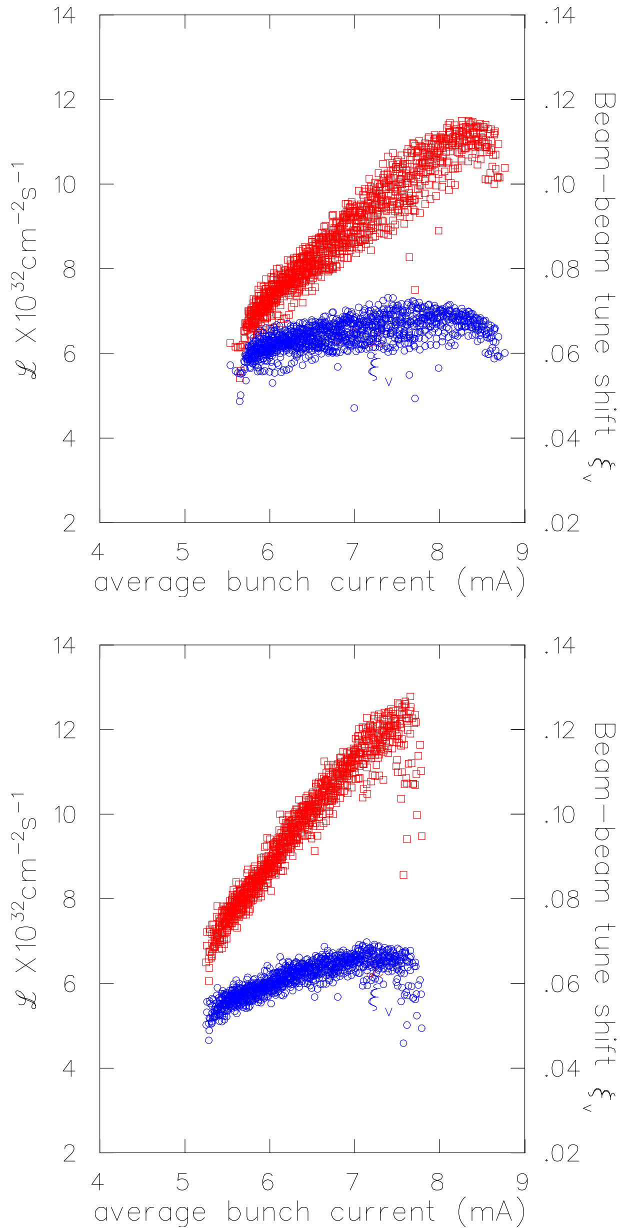

Figure 3: Beam-beam tune shift, ξ_v (blue circles), and luminosity (red squares)versus bunch current with nine 4-bunch trains/beam (top) and nine 5-bunch trains/beam (bottom).

while cars in the middle experience them on both entrance and exit. Similarly, in the region of the vertical electrostatic bump, each car experiences its own set of parasitic interactions. The variation in kicks experienced from car to car means that not all cars can simultaneously collide head-on. Expected displacements, based on our strong-strong simulation, are shown in the upper plot of Figure 2. Such differences have been previously observed [6]. Additional orbit distortions may also arise from wakefields, field asymmetries in the RF cavities, and vertical separator voltage fluctuations.

We employ three methods to monitor car-to-car orbit

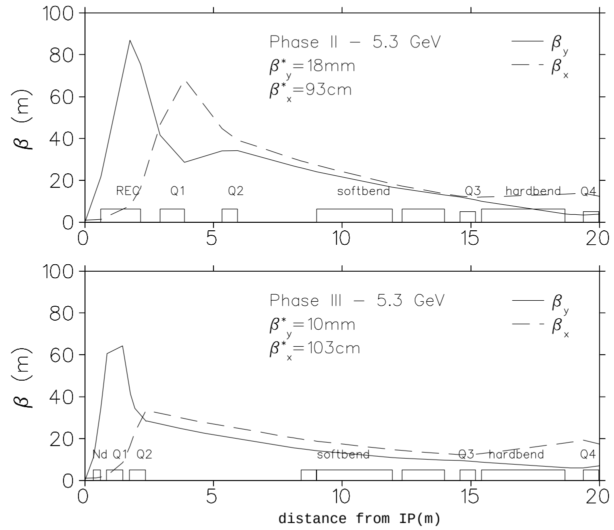

Figure 4: Betatron functions near the IP for CESR without (PHASE II) and with (PHASE III) the superconducting focusing magnets in the interaction region. For reference, the parasitic crossing nearest the IP occurs at 2.1 m.

variations [7]. The first uses the Beam-Beam Interaction Luminosity Monitor (BBILM)[6] where a bunch in one beam is shaken at a fixed frequency and the BBI-induced oscillation in the opposing bunch is measured. The amplitude of the induced oscillation is maximized when the opposing bunches collide head-on. A second method utilizes the DC pedestal of the beam feedback system which monitors the bunch positions at a point 1.16 wavelengths from the IP. Assuming no differential kicks between the monitor and the IP, a pure displacement at the IP corresponds to the measured displacement at the feedback monitor(FM) scaled by $1.87\sqrt{\beta_{ip}/\beta_{fm}}$. An added feature of the feedback system is its ability to apply fraction of a micron corrections at the IP using a vertical kicker [8]. Our third monitoring method does not measure offsets directly. Instead we use the CLEO barrel bhabha luminosity [9], which can be assigned to specific bunches by means of CLEO tracking system information, to monitor the impact of orbit offsets.

Figure 5 shows the differential displacement obtained with the BBILM as a function of time, or equivalently current, over the course of an HEP run. Each point resulted from varying the differential vertical displacements at the IP until the BBILM signal was maximized for the car of interest. Differential displacements at the IP were generated by adjusting the phase advance in the vertical electrostatic bump which separates the beams at the point diametrically opposite the IP. The theoretical calibration for these adjustments was used to calculate the resulting differential displacement at the IP. Over the course of the measurements the current in each beam decreased nearly linearly. This decrease was from approximately 330 mA to 285 mA for electrons and from 315 mA to 265 mA for positrons. A current dependence in the differential positions of cars during a run is clearly evident. The roughly 2 μm variation be-

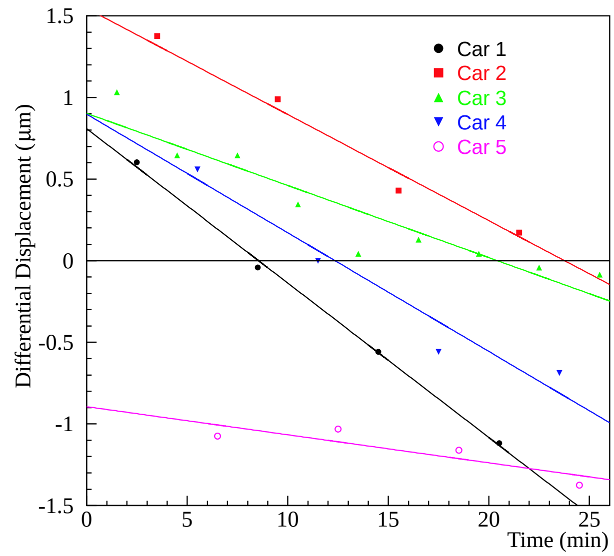

Figure 5: The vertical differential displacement for head-on collisions as a function of time as determined by maximizing the BBILM signal. The value for each car is averaged over all trains. The lines are linear fits to the data. The zero of the vertical axis is arbitrary.

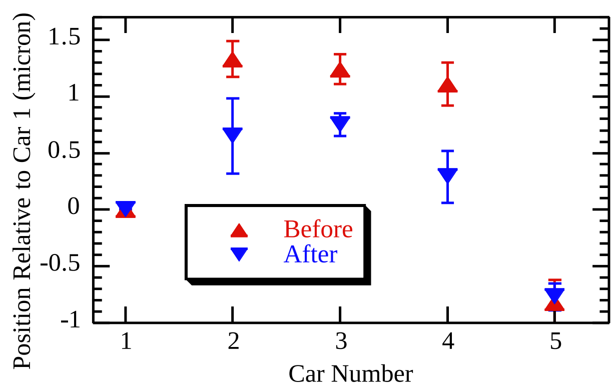

Figure 6: Positron - electron differential positions obtained with the CESR feedback system. The positions are averaged over all trains and are plotted relative to the average differential position obtained for car 1. The two sets of data were taken before and after adjusting the vertical positioning of all bunches using the feedback system's kicker.

tween the extreme bunches is in good agreement with our LRBBI simulation and corresponds to about $0.5\,\sigma_y$, where σ_y is the vertical beam size at the IP.

Figure 6 shows two measurements of average differential positions by car as measured by the feedback system during HEP operation. The measurements occur before and after applying correction kicks to bring cars 2, 3 and 4 closer to cars 1 and 5. All differential positions are displayed relative to those of car 1. The size of the spread agrees well with our the BBILM measurement. After correction, cars 2–4 have moved 0.5 to 0.6 microns closer to car 1 as expected. It is clear, however, that a significant increase in

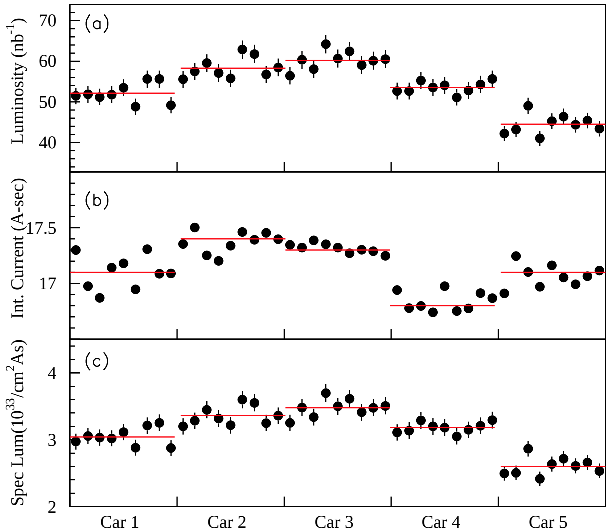

Figure 7: The (a) integrated luminosity, (b) integrated current, and (c) run-averaged specific luminosity of an HEP run with 9 trains of 5 bunches. The points represent the performance for individual cars while the lines indicate the average over all trains for each car.

vertical kicker strength is required for effective differential orbit correction.

Figure 7 shows the CLEO integrated luminosity, current, and run-averaged specific luminosity for a recent run. We observe a substantial variation in the luminosity performance between cars. Roughly speaking, this relative performance can be divided into a lifetime component, the integrated current in each car is not equal, and a specific luminosity component. We find that the typical variation between the specific luminosity of the best and worst car is 15-25%. If this were strictly due to the cars failing to collide head-on, the necessary displacements, using the bunch overlap formula $\mathcal{L} = \mathcal{L}_0 \exp[-(\delta y)^2/4\sigma_y^2]$, would be in the range 0.8–1.1 σ_y. In the context of our other measurements, this suggests that the poor specific luminosity of the worst bunch is likely due to a combination of effects such as beam blowup in addition to the offset.

4 CONCLUSION

During the 2000-2001 HEP run, CESR has achieved a beam-beam tune shift of nearly 0.07 while running with 9 trains of 4 bunches. Although a switch to operating with 9 trains of 5 bunches has provided greater total luminosity, it has also led to a decrease in the beam-beam tune shift parameter. This observation is consistent with the poor luminosity performance of the leading and trailing bunches which we expect from our LRBBI simulation and which is confirmed by our recent measurements. Work continues to refine our bunch-by-bunch diagnostics and we are actively pursuing several methods to improve the luminosity performance: a superconducting focusing system has been installed at the IP which should lessen the impact of the nearby parasitic crossings; we are exploring the use of a radiofrequency quadrupole for bunch-by-bunch tune correction; and, we are considering modifications to the feedback system to allow full correction of bunch-to-bunch vertical orbit differences at the IP.

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