STUDIES OF THE BEAM-BEAM INTERACTION AT CESR *

J. A. Crittenden, † and M. G. Billing
LEPP, Cornell University, Ithaca, NY 14853-8001

Abstract

The Cornell Electron Storage ring facility CESR operates with 2 GeV multi-bunch electron and positron beams in a single beam-pipe. Electrostatic separators are used to separate the two counter-rotating beams at the parasitic crossings. When the beam energy was lowered from 5 GeV in 2003, the strength of the beam-beam interaction became a more important factor in beam-current limitations, resulting in extensive experimental and modeling studies of their characteristics. The CESR lattice design procedure has been modified recently to account explicitly for their dynamic consequences. We describe our modeling of the beam-beam interaction, experimental validation techniques, and investigations into compensation strategies.

INTRODUCTION

CESR-c [1] is presently operating at a beam energy of 2.085 GeV with 3 bunches 4.2 m apart in each of 8 trains separated by 75.6 m or 79.8 m. A ninth possible train is omitted for purposes of ion-clearing. During luminosity operation, the current is limited to about 2.7 mA/bunch, i.e. 130 mA total current in both beams. Appreciably higher currents can be injected when the beams are not in collision. Single-bunch currents as high as 8 mA have been reached for a single electron bunch injected into a full load of positrons. Good luminosity lifetime has also been obtained with single-bunch collisions at bunch currents about twice as high as during multi-bunch operation. The apparent importance of the bunch pattern for beam lifetimes, luminosity lifetimes and injection limits have motivated extensive investigation into the distortions of the lattice functions caused by the parasitic crossings. Each electron bunch suffers such a beam-beam interaction (BBI) at 47 points around the ring (Fig. 1) as well as at the primary interaction point (IP). The beam separation at each crossing point is determined by the pretzel orbit induced by vertical and horizontal electrostatic separators, and ranges between 20 and 35 mm. The separation is vertical at the crossing point diametrically opposed to the collision point and horizontal at the remaining parasitic crossing points. The optical effects of the parasitic crossings have been modeled in a weak-strong approximation, where the beam functions of one of the beams are held fixed. The model for the beam-beam interaction uses the Bassetti-Erskine complex error function formula [2], in which a Gaussian transverse shape

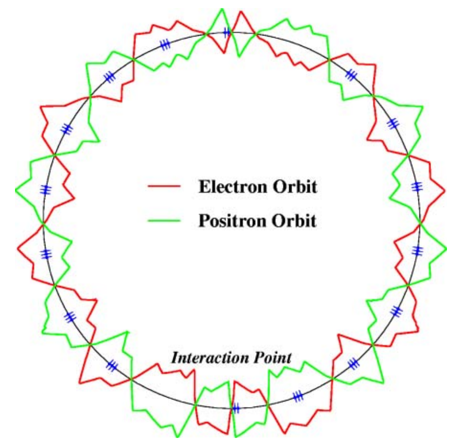

Figure 1: Electrostatic separators establish closed-orbit waves separating the electron and positron beams at the positions of the parasitic crossings (blue lines), shown here for the particular case of the first bunch of the first electron train against the counter-rotating positron configuration of three bunches in each of eight trains. This is the present operational configuration for CESR-c.

in the strong (positron) beam is assumed. The angular deflections induced at the parasitic crossings range between 1 μrad and 4 μrad, as shown in Fig. 2, whereby the operating current level of 2.5 mA/bunch has been assumed. The horizontally-separated parasitic crossings induce a vertically focusing and horizontally defocusing effect, while the interaction at the collision point focuses in both transverse planes. These beam-beam interactions have been found to have considerable consequences for optical distortions [3] and for injection aperture [4]. Here we report on measurements of the closed orbit distortions induced by the parasitic crossings, on operational strategies used to mitigate their effects, and on near-term plans for local phase compensation.

MEASUREMENTS OF ORBIT DISTORTIONS

We performed measurements of orbit distortions induced by the parasitic crossings in order to obtain quantitative tests of our modeling of the beam-beam kicks in a weak-strong approximation. A positron beam consisting of five trains of five bunches each was used in order to avoid creating parasitic crossings in the region of the beam-position monitors (BPM) which could be gated to measure exclu-

* Work supported by the National Science Foundation
† critten@lepp.cornell.edu

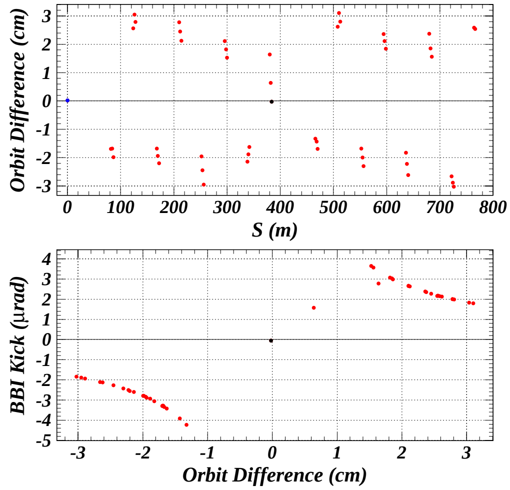

Figure 2: Horizontal positron-electron orbit difference at the crossing points in the CESR-c model of the operational 8x3 configuration as a function of their position around the ring (upper plot) and the horizontal kicks resulting in the Bassetti-Erskine approximation as a function of this orbit difference (lower plot). The black point indicates the crossing diametrically opposed from the main interaction point, where the separation is vertical.

sively the electron beam orbit. Figure 3 shows the modeled orbit separations and kicks for the first bunch of the first electron train which was used in the measurement. The positron bunch current was 1.6 mA. A comparison of the

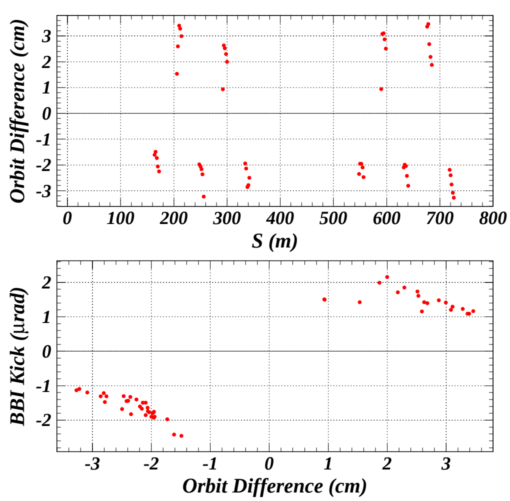

Figure 3: Modeled orbit separation and resulting BBI kicks in the 5x5 configuration employed to measure the orbit distortions shown in Fig. 4.

eleven BPM measurements available in this region to the modeled orbit distortion is shown in Fig. 4. The horizontal electron orbit in the presence of the positron beam with the undistorted orbit subtracted is shown. Orbit deviations up to 0.4 mm are observed and reproduced in the model to an accuracy of about 0.05 mm.

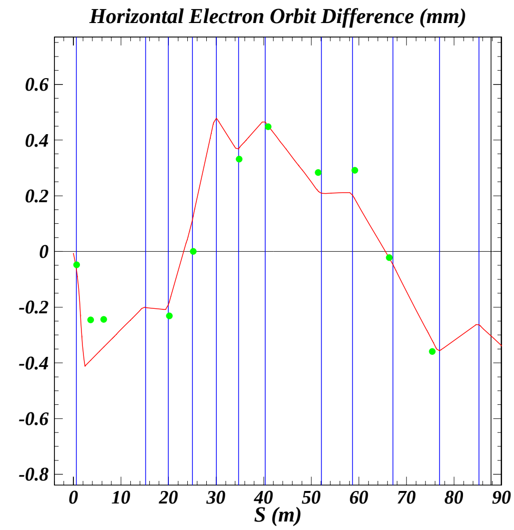

Figure 4: Comparison of the measured difference between the horizontal electron orbits at the eleven BPM positions (green dots) with and without the positron beam to the modeling result (red line). The blue lines show the positions of the quadrupole magnets and nearby superconducting wiggler magnets are shown as well (black line).

We performed several systematic checks of this measurement: 1) the current in the single electron test bunch was reduced from 2 mA to 1 mA, validating the weak/strong approximation, 2) the positron bunch current was raised to 1.9 mA and lowered to 0.9 mA, testing the scaling properties of the model, and 3) the orbit separation was reduced by 15%, increasing the orbit distortion similarly in both measurement and model. The orbit distortion was found to be qualitatively similar for a wide variety of positron bunch configurations, as the effects of the parasitic crossings tend to add coherently, but was found to be quite different when only train 9 was filled. This qualitative difference was also found to be modeled correctly. All observed comparisons showed accuracy comparable to that shown in Fig. 4.

We also attempted to measure the betatron phase distortion induced by these long-range beam-beam interactions. We did not obtain satisfactory results, however, owing to 1) the small size of the distortion (about a degree), and 2) the fact that at the time of the measurements (August, 2005), the injection optics differed substantially from the colliding optics. Now that CESR-c operates in a mode where the injection and collision optics are similar [5], we hope to be able to measure the phase distortion later this summer.

CONSEQUENCES OF THE BEAM-BEAM INTERACTION FOR CESR-C OPTICS

Our model of the CESR-c optics has shown that the consequences of the beam-beam interactions are severe. Figure 5 shows the maximum value in the ring of the horizontal beta function for electrons as a function of positron bunch current. At a bunch current of 4 mA, this value increases to 110 m from its design value of 45 m. Operationally we find an empirical current limit of 2.5 mA, where the maximum beta value has increased by about 70%. The optical distortion differs for each electron bunch due to the different parasitic crossing pattern, but the primary effect results from the BBI at the interaction point and is common to all bunches. In December, 2005, the lattice design

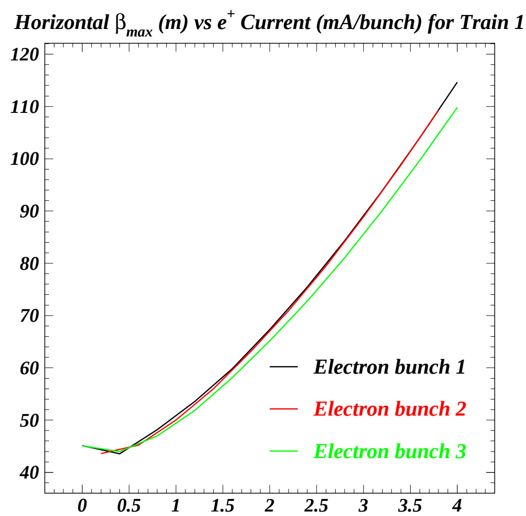

Figure 5: Maximum value of the electron horizontal beta function the CESR-c optics as a function of the positron bunch current.

algorithm was modified to take the parasitic crossings into account. This meant that the optimal lattice was designed for a specific bunch (train 1 bunch 3) and a specific operating current (2.5 mA/bunch). A design procedure was developed which handled the electron and positron optics symmetrically, each in the weak/strong approximation. Figure 6 shows calculations of the dynamic aperture at the interaction point based on tracking electrons through the modeled optics, demonstrating that this design procedure indeed succeeded in improving the aperture at the design current.

FUTURE PLANS FOR BBI COMPENSATION

The primary operational tool for compensating the beam-beam interaction at CESR has been global tune adjustment employing all quads to compensate the beam-beam interaction. The tune shift at the interaction point is typically five time greater than that from all the parasitic crossings combined, so the primary operational adjustment is to reduce the horizontal and vertical tunes globally as the colliding current increases.

Such a global adjustment necessarily results in local distortions of the phase function. We are presently developing a compensation method based on local phase distortion

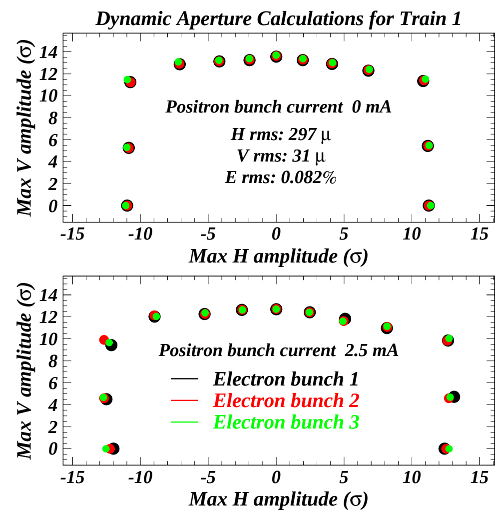

Figure 6: Comparison of the electron dynamic aperture in the distortion-free optics (upper plot) to that in the optics distorted by 2.5 mA/bunch in the positron beam (lower plot). The aperture is calculated at the interaction point in units of RMS beam size. The vertical beam size is the value assuming full coupling. The lattice design procedure developed to account for the effects of the parasitic crossings yields an improved aperture at the operating current.

correction using the eight quadrupole magnets surrounding each of the sets of three parasitic crossings. Six quantities are compensated: the phase advance, and the sine and cosine components of the beta function in each of the transverse planes. We have demonstrated during machine studies experiments that empirically tuned values for the correction coefficients originally designed for the near-IP crossings are effective in compensating the distortions arising from the IP itself. Modeling results of the reduction in beta function distortion and improvement in dynamic aperture for this compensation algorithm are encouraging. Near-term plans include further machine studies and operational implementation.

REFERENCES

[1] D. Rice *et al.*, *Parameters for Low-Energy Operation of CESR*, proceedings of PAC2001.

[2] M. Bassetti and G. A. Erskine, *Closed Expression For The Electrical Field Of A Two-Dimensional Gaussian Charge*, CERN-ISR-TH/80-06 (1980).
R. Talman, *Multiparticle Phenomena and Landau Damping*, AIP Conf. Proc. **153**, pp. 789-834, American Institute of Physics, New York (1987).

[3] M.G. Billing *et al.*, *A Study of the Effects of Beam-Beam Interactions on CESR Optics*, proceedings of PAC2005.

[4] M.G. Billing *et al.*, *Investigations of Injection Orbits at CESR Based on Turn-by-turn BPM Measurements*, proceedings of PAC2005.

[5] J.A. Crittenden, *Operational Status of CESR-c*, these proceedings.