COMPENSATION STRATEGY FOR OPTICAL DISTORTIONS ARISING FROM THE BEAM-BEAM INTERACTION AT CESR*

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Abstract

Following more than two decades of operation at 5 GeV beam energy for studies of bottom quark bound states, the Cornell Electron Storage Ring (CESR) converted to 2 GeV operation in 2001 for the purpose of investigating bound states of charm quarks. This reduction of beam energy increased the relative contributions of the beam-beam force. The beam-beam interaction has been found to have considerable consequences for the optics and for the injection aperture. We describe recent developments in our modeling of the beam-beam interaction, experimental validation techniques, and investigations into compensation strategies.

INTRODUCTION

In 1994 CESR began operations with counter-rotating trains of electron and positron bunches traveling in the same vacuum chamber using four horizontal and two vertical electrostatic separators; the orbits of the two beams place the bunches in collision only at the single interaction point (IP.) These orbits, called Pretzels, have permitted collisions with as many as 9 trains (with the lead bunches spaced by either 84 or 88.2 m) of 5 bunches (having a 4.2 m spacing.) Presently at beam energies of approximately 2 GeV[1], CESR operates with 3 bunches of 2.7 mA in 8 trains, giving a total current of 130 mA in the two beams. (The ninth train has been omitted for purposes of ion clearing.) This current, limited by lifetimes due to the beam-beam interaction (BBI), is well below the maximum single bunch electron current of 8 mA which can be injected against a full load of positrons. The operating bunch current is also below the maximum current of 4 mA that can be collided with single bunches in each beam. Observations of the importance of the pattern of bunches for the lifetimes have motivated the investigation of distortions of the lattice functions caused by the parasitic crossings of the counter-rotating bunches. Each bunch encounters bunches from the other beam in 47 different locations. As an example, the parasitic crossings for an electron of the first bunch in the first train are shown as tick marks and displayed along with the Pretzel orbits of the two beams in Fig. 1. The horizontal separation typically ranges from 20 to 35 mm with the separation of the beams at the diametrically opposite location from the IP being provided by an electrostatic orbit bump using vertical separators. To study the magnitude of these effects, we have modeled the BBI for both the parasitic crossings and the main IP in the weak-strong approximation and observed significant tune shifts and beta-function errors varying from bunch to bunch. For core particles the effect of each of the horizontally separated parasitic crossings causes a vertically focusing and horizontally defocusing gradient error, while the IP causes a focusing error in both planes. Because the operating point for CESR has the horizontal tune very close to the ½ integer resonance, gradient errors from the BBI can produce very significant optical distortions and tune shifts vs. beam current. We present an overview of the modeling, our attempts to design a scheme for partial compensation of the optical errors, our observations during operations and future plans.

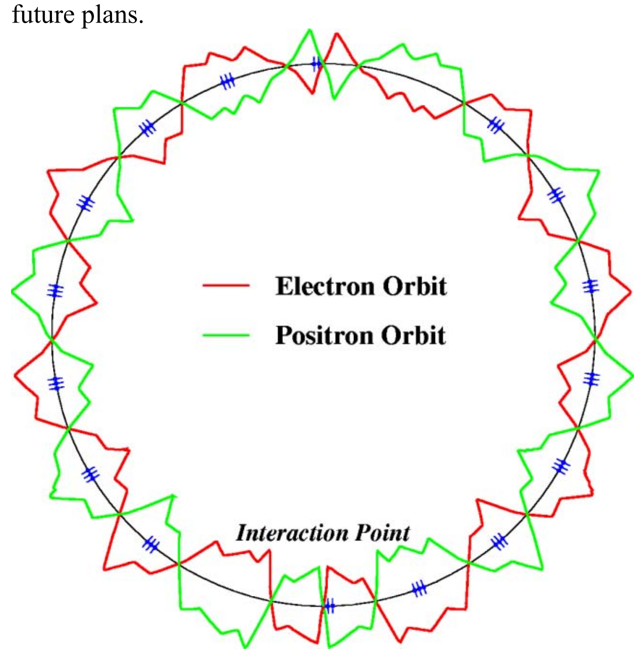

Figure 1: Closed orbits for electrons and positrons.

MODEL FOR THE BEAM-BEAM INTERACTION

The optical effects of the BBI for the electron beam from the parasitic crossings and IP have been modeled using the Bassetti-Erskine complex error function formula [2] assuming a Gaussian shape for the positron (strong beam) in a weak-strong approximation. The symmetry of the Pretzel causes the focusing and tune errors for positron bunches to be almost the same as those for the electron bunches, while orbit errors are nearly opposite for the two beams. The horizontal angular deflections at the parasitic crossings predicted by the model typically are in the range of 1 to 3 μrad. As a quantitative test of the model, the deviation of the electron orbit caused by the parasitic BBI in the presence of 5 trains of 5 bunches of 1.6 mA of positrons was

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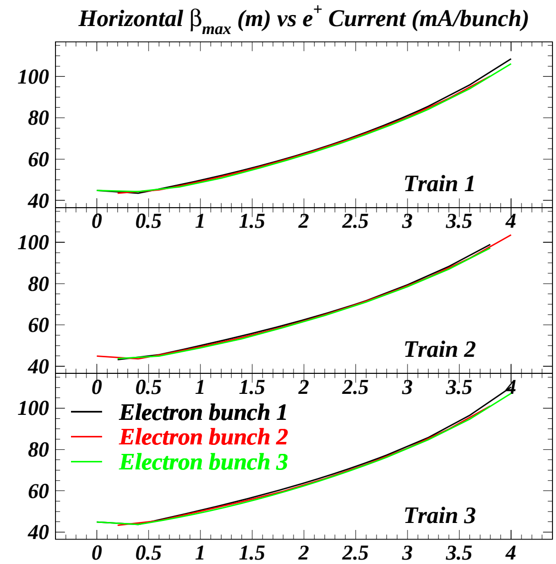

Figure 2: Maximum horizontal β-functions for 3 trains.

measured and found to be in good agreement with the model calculation [3].

In December 2005, the lattice design algorithm was modified to include parasitic crossings in the weak-strong approximation. This change was included since the separation of the beams at the parasitic crossings is much larger than the beam sizes, so the leading effects of the BBI will produce opposite deflections and common focusing errors for the two beams. One effect of the design change for the optics was to decrease the strength of the horizontal ½ integer resonance in the presence of the BBI. The model's result for such a set of optics designed using this algorithm has been displayed in Figs. 2 through 4. The maximum horizontal beta-function in the ring for the 3 electron bunches in trains 1-3 vs. current in the 8 trains of 3 positron bunches is presented in Fig. 2, which indicates an enlargement of about a factor of two for the beta-functions for a bunch current of 4 mA. Plots of the corresponding horizontal tune shifts for the first three trains of electron bunches vs. positron bunch currents are shown in Fig. 3, illustrating the non-linear behavior of the tune distortion and the fact that there are some variations from bunch-to-bunch within a train; there are likewise variations from train-to-train. These occur because the set of beta-function values and pretzel displacements at the parasitic crossings are in general different for different electron bunches. Since the current limit for luminosity production in operations is determined by the reduced lifetime of the beams at high currents, the model also tracked particles in the weak beam for 500 turns to determine the dynamic aperture limit in the presence of the BBI. Fig. 4 gives the limiting horizontal and vertical initial displacements for on-momentum electrons at 0 mA and 4 mA currents per bunch in the positron beam for the same optics as in Fig. 2 and 3, but the global tunes are held constant to match operating conditions. Prior to modifying the lattice design algorithm, the dynamic aperture at higher bunch currents (e.g. 4 mA) was significantly reduced, especially for particles with small vertical amplitudes.

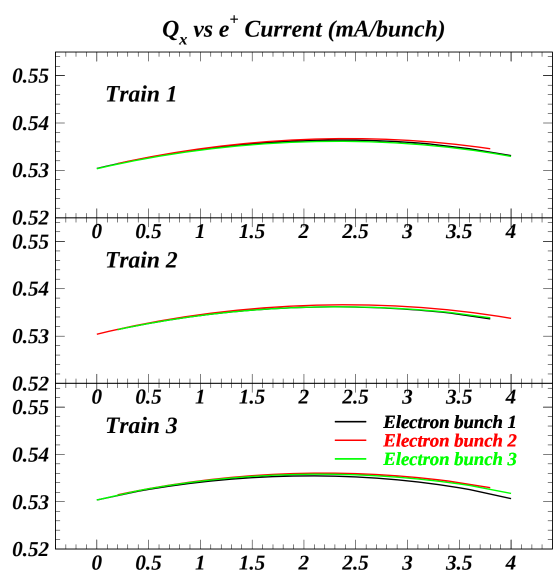

Figure 3: Horizontal tunes for different trains.

PARTIAL COMPENSATION OF THE BEAM-BEAM INTERACTION

Since the modeling predicts significant distortions of the optical functions from the parasitic crossings with the opposite beam and since the difference of these effects for particles in core or tails of the beam is not expected to be very different in magnitude, we decided to explore the possibility of providing partial compensation for the gradient errors. The strategy makes use of the fact that

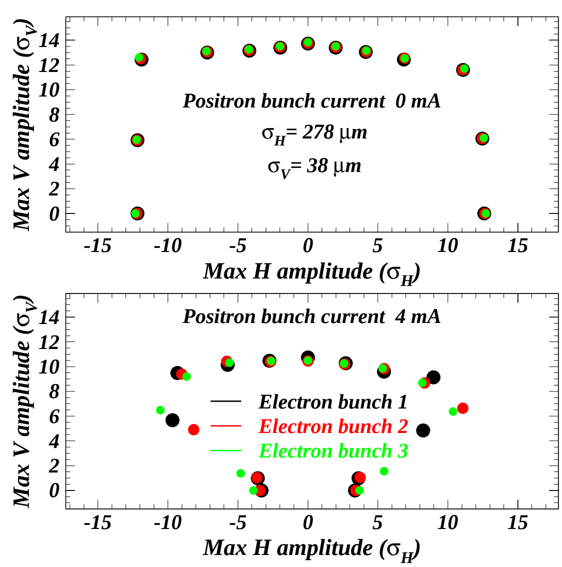

Figure 4: Modeled dynamic aperture for the design optics. Units are horizontal σ and fully coupled vertical σ at the IP.

the parasitic crossings are clustered within lobes of the Pretzel orbits. In CESR a group of eight quadrupoles, covers each lobe of the Pretzel and the region between the parasitic crossings of adjacent lobes. This gives 8 elements for the local correction of the average tune and sine- and cosine-like beta-function errors in both planes, which are generated by the BBI in this lobe. Since the effects from the BBI for only one lobe of the Pretzel are fairly small, the corrections for all of the lobes are linearly superposed. This partial compensation should reduce the size of the optical distortions on the average and will allow the colliding bunch currents in trains (presently 2.7 mA) to approach the single bunch colliding current limit (4 mA) with possibly more bunches in each train. This combination should produce higher colliding beam currents and ultimately higher luminosities.

Using the fact that the quadrupoles in CESR are independently powered, software controls have been designed to correct six optical errors in each lobe of the Pretzel. As described elsewhere, the corrections have been accomplished in a fairly general manner to make it easy to change corrections if the Pretzel or the pattern of bunches or trains is altered[3]. For the IP, separate corrections are determined by first estimating these for small amplitude particles (an over-estimate for the errors) and then varying the strength of the corrections while looking for the best improvement in lifetime during single bunch collisions. Operationally these corrections are applied to the CESR quadrupole commands in proportion to the total current in the two beams producing an average correction of the optical errors experienced by both beams. The software also allows for manual adjustment of the scale for each control.

SIMULATIONS AND OBSERVATIONS

During the spring of 2006, partial compensation for the operating conditions for 1.88 GeV were simulated and observations were undertaken. As a test of this method, the compensation for the parasitic crossings was calculated as described above. Rather than tracking to produce the IP corrections, the commands for these controls were adjusted for the highest beam lifetimes in the presence of 3-turn pulsed horizontal bumps with single bunches in collision in CESR. At this time the operating conditions gave a peak luminosity of 6.4×10^{31} cm^{-2} s^{-1} with a total current for the two beams of 8 trains of 3 bunches of 120 mA. The proximity of the horizontal ½ integer resonance made operations very sensitive to the horizontal tune. After establishing conditions with partial compensation applied for 8 trains of 4 bunches and making some slight tuning adjustments, the control software automatically adjusted the horizontal tunes while tracking the beam currents. In these conditions we achieved a total two-beam current of 144 mA and a peak luminosity of 6.7×10^{31} cm^{-2} s^{-1}. Simulating this resulting compensation shows the average distortion of the beta-functions and the average tune shift vs. current were both reduced, and the horizontal dynamic aperture at small vertical amplitudes increased (see Fig. 5.)

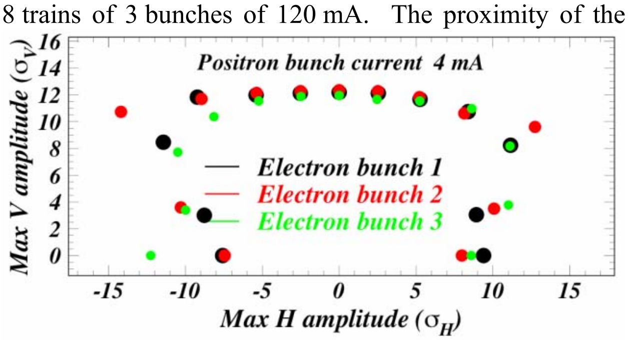

Figure 5: Dynamic aperture with BBI compensation.

FUTURE DEVELOPMENTS

This correction has not yet been applied to routine operations for a couple of reasons. The switch to a different energy and optics occurred shortly after the initial tests. Optics had been designed to include the BBI effects from parasitic crossings for this new energy, but they have very poor injection characteristics. This was traced to a location where the horizontal aperture was significantly reduced due to a displaced vacuum chamber. However the conditions, in which CESR operated for the next several months, was an earlier set that had large beta-function errors compared to its design. Until a “reversed” design set of optics was fit to the beta-function and Pretzel measurements no compensation design could begin. Presently we are studying the compensation controls for these “reversed” optics. The modeled dynamic aperture appears to be improved, inspiring the hope of trying these corrections during the next low energy run. In addition, new optics are being designed to reduce the BBI effects from parasitic crossings and also to account for the horizontal aperture restriction. When these are completed, we will design the partial compensation controls and simulate their effects. If these are successful, we will try the controls in operations. Since the partial compensation controls are more effective for the parasitic crossings, we would also like to increase the number of bunches in each train from 3 to 4 or 5.

REFERENCES

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