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Study of Beam-Beam Effects at PEP-II*

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Abstract

Using a self-consistent three-dimensional simulation running on parallel supercomputers, we have modeled the beam-beam interaction at the PEP-II asymmetric e^+e^- collider. To provide guidance for luminosity improvement, we scanned the tunes and currents in both rings and computed their impact on the luminosity and transverse beam sizes. We also studied the effects of colliding the beams with a small crossing angle. Where possible, the code was benchmarked against experimental measurements of luminosity and beam sizes, yielding an acceptable agreement.

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Abstract

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INTRODUCTION

The beam-beam interaction is an important factor that limits the luminosity of e^+e^- colliders. Due to the complexity of the interaction, a simple analytical model does not lend itself to detailed quantitative predictions. Effects of the beam-beam interaction have been studied extensively, both experimentally [1]–[4] and using computer simulations [5]–[10].

In this paper, we present results of a computer simulation study of the beam-beam interaction at the PEP-II e^+e^- collider. PEP-II is an asymmetric machine with a low-energy ring (LER) for positron storage at 3.1 GeV and a high-energy ring (HER) for electron storage at 9.0 GeV. It currently operates with $\sim$1550 bunches in each beam, at peak e^+ and e^- currents of 1.5 and 0.9 mA/bunch. Head-on collisions typically achieve an instantaneous luminosity of $\sim 8.8 \times 10^{33}$ cm^{-2}s^{-1}. We first compute the luminosity and beam sizes by solving the Poisson equation numerically on a reduced mesh [8]. We then study the dependence of the specific luminosity on tunes, bunch currents, horizontal IP crossing angle and transverse beam separation, and compare the predicted values with those experimentally measured.

SIMULATION

Historically, many approximations, such as strong-weak [6], have been introduced to simulate the beam-beam interaction within a reasonable computing time. Increased CPU power now allows full strong-strong simulations [5, 7, 8, 9, 10], where each bunch is modeled as a set of macroparticles. Each macroparticle is propagated through one turn of a storage ring using a linear matrix with damping and quantum excitations to the machine lattice. At the interaction point (IP), the beam-beam effect is modeled by projecting the macroparticle distribution onto a transverse mesh, solving the Poisson equation on the mesh and evaluating the force that acts on the opposite beam. The method deployed here [8] uses a reduced fine mesh that covers only the central part of the beam pipe, large enough to contain the whole beam. The uniqueness of the Poisson solution is enforced by an appropriate choice of conditions at the mesh boundaries.

For ultra-relativistic particles, the beam-beam force is purely transverse. Therefore, each bunch can be split into several longitudinal slices and the beam-beam interaction can be computed for each pair of colliding slices sequentially. In this simulation, we split each bunch into 5 longitudinal slices of approximately equal charge with interpolation of the force between the slices.

Typical values of simulation input parameters are shown in Table 1. The beams are tracked up to several damping times to ensure that the output parameters have converged to equilibrium values. From the simulation, we obtain the transverse bunch size and the luminosity integrated over the macroparticle distribution, as well as full distributions of macroparticle positions and momenta in the bunch. Parasitic-crossing effects are not included in the simulation.

Table 1: Nominal values of PEP-II simulation input parameters. All parameters are quoted for single beams.

Parameter	LER	HER
ν_x / ν_y	0.512 / 0.564	0.520 / 0.622
ν_s	0.027	0.040
β_x^* / β_y^* (cm)	51 / 1.21	25 / 1.25
ϵ_x / ϵ_y (nm)	22 / 1.40	49 / 2.33
E (GeV)	3.1	9.0
σ_E/E (%)	0.065	0.061
Bunch length (cm)	1.05	1.25
τ_x / τ_y (turns)	9995 / 9733	5012 / 5056
τ_s (turns)	4800	2573
Number of mesh cells	128x128	
Mesh cell size (μm^2)	15x2	
Longitudinal slices	5	5
Macroparticles	160,000	160,000

The algorithm described above is implemented in C++ code. Simulation jobs are typically run at the NERSC com-

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puting facility with each beam processed by 16 parallel CPU's. Data are exchanged between the parallel processors through the Message Parsing Interface (MPI) protocol. It takes about eight hours of wall-clock time to track the simulated beams through 16,000 turns with 10,000 macroparticles per CPU.

TUNE SCANS

The predicted dependence of the specific luminosity $L_{\rm sp}$ on horizontal tunes is shown in Fig. 1. As the LER tune approaches the half-integer, the e^+ IP spot size experiences growing horizontal blow-up, leading to a rapid luminosity loss. The luminosity drop-off at larger e^+ x-tune is due to vertical low-energy beam (LEB) blow-up; the e^- IP spot sizes remain unaffected. In contrast, the luminosity degradation close to $\nu_x = 1/2$ in the HER is associated with horizontal high-energy beam (HEB) blow-up at the IP, partially compensated by a shrinking vertical e^+ spot size. Finally, simulations predict very little sensitivity to either vertical tune.

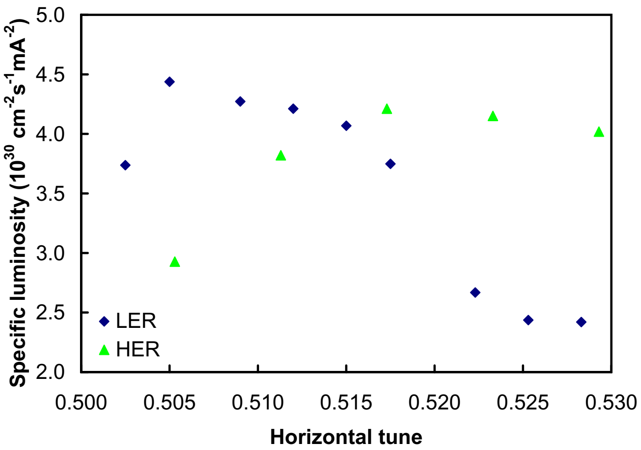

Figure 1: Simulated specific luminosity *vs.* horizontal tune in the LER (diamonds) and the HER (triangles). The HER tune is fixed at 0.520 for the LER scan; similarly, the LER tune is fixed at 0.512 for the HER scan.

BEAM-CURRENT DEPENDENCE

An essential PEP-II optimization tool is a fast luminosity monitor that counts photons emitted in the radiative-Bhabha process $e^+e^- \to e^+e^-\gamma$. This gas-Cherenkov detector, located 10 m downstream of the IP in the outgoing-positron direction, provides an instantaneous luminosity measurement at a rate of a few Hz. Its calibration is verified periodically, by comparing its integrated-luminosity measurement with that extracted from large-angle Bhabha events reconstructed in the BaBar detector.

A beam-current scan is shown in Fig. 2. The predicted peak luminosity agrees with the measured value within 10–20%. Increasing the assumed e^+ and e^- bunch lengths by 10% improves the agreement to 5–15%, suggesting that bunch lengthening might be partially responsible for the discrepancy. The simulation correctly predicts some of the qualitative features of the current-dependence, such as the initial luminosity increase caused by the dynamic-β effect, followed by a continuous degradation associated with vertical beam blow-up at the IP. But it fails to reproduce quantitatively the steep drop in measured specific luminosity at high bunch currents, or the 70% horizontal blow-up of the e^+ beam observed on the synchrotron-light monitor (SLM).[1]

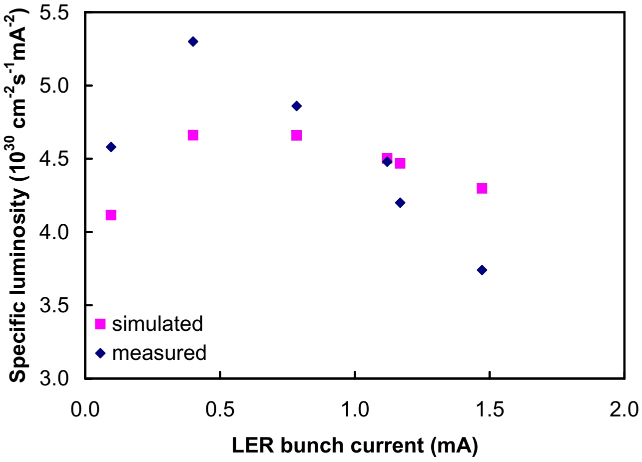

Figure 2: Bunch-current dependence of the specific luminosity, for data (diamonds) and simulation (squares). The ratio of the beam currents is fixed at $I_{\rm LER}/I_{\rm HER} = 1.6$.

HORIZONTAL CROSSING ANGLE

The predicted sensitivity of the luminosity to small horizontal crossing angles is shown in Fig. 3. At low bunch currents, the luminosity degradation is expected to be dominated by geometric overlap effects, which remain negligible. The degradation becomes noticeable at about 50% of the nominal bunch currents, and reaches 10% at the highest bunch charges simulated so far, for a half-crossing angle of 0.5 mrad. The luminosity degradation is primarily associated with vertical HEB blow-up at the IP .

An effect of comparable magnitude has been measured in a dedicated experiment, performed at e^+/e^-currents of 1.35/0.85 mA/bunch in a bunch pattern devoid of parasitic crossings. Inducing a half crossing angle of 0.35 mrad originally results in a 15% luminosity degradation, associated with a 25% vertical blow-up in the HER. Reoptimizing the tunes and coupling corrections brings the luminosity and SLM spot sizes to within less than 5% of their zero crossing-angle values. A more sensitive experiment is required to fully validate this aspect of the simulations.

For typical bunch lengths of 1 cm and half-crossing angles of 1 mrad, positrons and electrons located 1 bunch

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[1] This may reflect more an increase in dynamic emittance than in IP spot size, because the phase advance between the IP and the SLM is not a multiple of π.

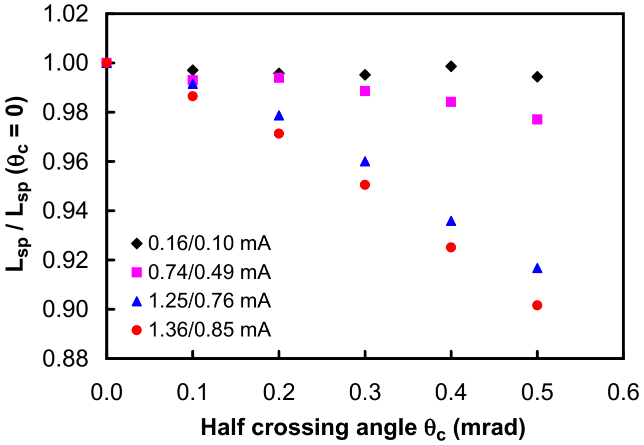

Figure 3: Simulated horizontal crossing-angle dependence of the specific luminosity, for various e^+/e^- bunch currents, assuming no parasitic crossings. At each current, the luminosity is normalized to its value at zero crossing angle.

length from the longitudinal center will be separated horizontally by about 20 μm. This suggests a related measurement: a closed IP-position bump is used to offset the two colliding beams horizontally from each other, while maintaining a zero crossing-angle as well as vertically aligned collisions. Data and simulation agree very well at low current. At higher currents, the simulation correctly predicts (Fig. 4) the large vertical HEB blow-up and the corresponding luminosity fall-off out to x-separations of about 20 μm (20% of the nominal beam size); the agreement degrades at larger distances.

SUMMARY

Using a three-dimensional beam-beam simulation program, we scanned the luminosity and beam spot sizes *vs.* tunes, beam currents, horizontal crossing angle, and horizontal separation of the beam centroids. The simulated performance is in acceptable qualitative agreement with the experimental measurements, but the quantitative description of the current- and crossing–angle-dependence of the luminosity and IP spot sizes requires further study. Several effects need to be better controlled experimentally, and/or taken into account in the simulation. These include, for instance, actual optical imperfections (uncorrected vertical dispersion, residual IP coupling, and lattice non-linearities), as well as potentially mismatched longitudinal positions of the e^+ waist, the e^- waist and/or the collision point.

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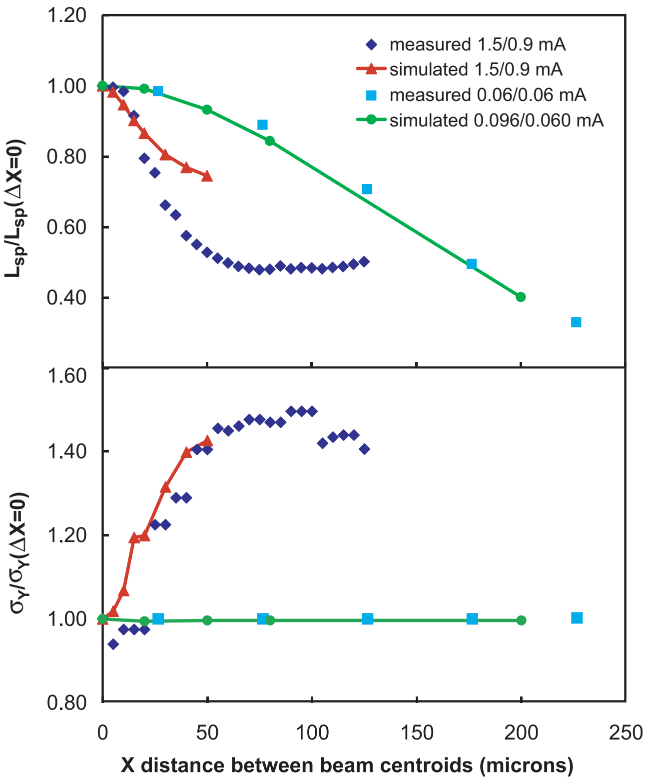

Figure 4: Specific luminosity and vertical HEB size *vs.* horizontal beam separation, for various e^+/e^- bunch currents, for data (squares and diamonds) and simulation (triangles and circles). At each current, the luminosity and spot size are normalized to their value at zero separation. The data are from a bunch pattern without parasitic crossings. No tune or other optical adjustments are carried out during the scan.

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