

EXPERIMENTAL STUDY OF CROSSING-ANGLE AND PARASITIC-CROSSING EFFECTS AT THE PEP-II e^+e^- COLLIDER*

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Abstract

In a series of dedicated accelerator experiments, we measure the dependence of the PEP-II luminosity performance on small horizontal crossing angles and on the horizontal separation at the first parasitic crossing. The experiment is carried out by varying the IP angle of one of the beams in two different bunch patterns, one with and one without parasitic crossings. The measurements show satisfactory agreement with three-dimensional beam-beam simulations.

INTRODUCTION

In the present design [1, 2] of the PEP-II interaction region (IR), two strong horizontal dipole magnets bring the beams into head-on collision and then separate them before they exit the BaBar detector (Fig. 1). In the nominal ('by-2') bunch pattern, where every second RF bucket is populated with charge, the first parasitic crossing (PC) occurs 63 cm on either side of the interaction point (IP). Future improvements to PEP-II performance include lowering the vertical IP β -functions in the two rings and increasing the e^\pm bunch currents. Both of these exacerbate the impact of the long-range interaction at the parasitic crossings, thereby reducing the maximum achievable beam-beam tune shift associated with the primary collision.

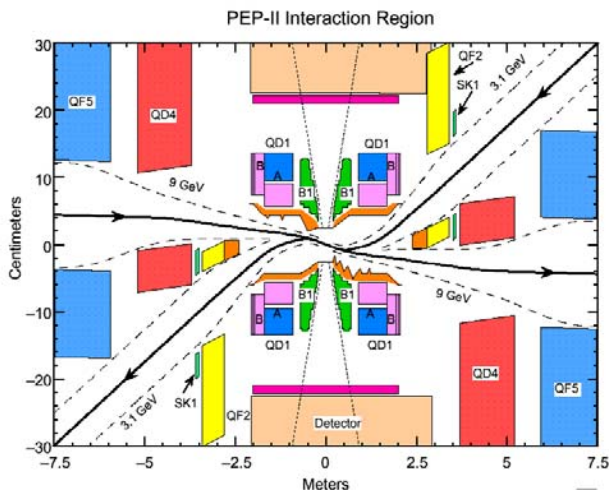


Figure 1: Layout of the PEP-II IR (top view). The beam separation dipoles (B1) are the magnets closest to the IP. The 1st parasitic crossings in the 'by-2' pattern are located at their outbound ends. A more positive e^- horizontal angle

($dx/dz > 0$) decreases the e^+e^- PC separation.

Because the parasitic beam-beam parameter depends quadratically on the beam separation, significant gains can potentially be achieved by increasing d_{PC} , the horizontal beam separation at the parasitic crossings [3]. In the actual machine however, this can only be done at the cost of introducing a horizontal crossing angle at the IP, which according to recent studies [4, 5] may result in a noticeable luminosity degradation.

This paper reports on a systematic experimental investigation of the impact of a small horizontal crossing angle and of parasitic crossings on the PEP-II beam-beam performance. The two contributions are disentangled by measuring, under carefully controlled conditions, the dependence of the specific luminosity on the horizontal angle of the e^- beam at the IP, using bunch patterns with and without parasitic crossings.

EXPERIMENTAL PROCEDURE

The specific luminosity is measured as a function of the horizontal e^- IP angle, in two different bunch patterns, keeping the other parameters unchanged (Table 1).

- In the 'by-4' pattern (one populated bunch every fourth RF bucket), PC's actually occur 1.26 m from the IP, but their effect is expected to be totally negligible ($d_{PC} \sim 30\sigma_x$). This bunch pattern, hereafter labeled 'no parasitic crossings', consists of one continuous train of 851 bunches (plus a 2% abort gap), with stored currents of 1.43 and 0.89 mA/bunch in, respectively, the low-energy (LER) and the high-energy (HER) ring. In this case the luminosity should be sensitive to crossing-angle effects only.
- A 'sparsified by-2' pattern, consisting of an appropriate number of mini-trains separated by empty gaps, is used to measure simultaneously the effect of varying the horizontal crossing angle and the separation at the first PC. The number of minitrains and their spacing are chosen so that both the total beam currents and the bunch currents remain essentially identical to those used in the 'by-4' pattern. The constancy of the total currents minimizes thermally-induced orbit differences between the two patterns. Keeping in addition the bunch currents the same, helps ensure that the collision parameters remain the same, at each crossing angle, as in the 'by-4' pattern – except for parasitic-crossing effects.

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Table 1: PEP-II single-beam parameters during crossing-angle experiments. The bunch currents and optical parameters are typical of stable physics running. The numbers in parentheses are specific to the ‘by-2’ pattern.

Parameter	LER (e^+)	HER (e^-)
Beam energy (GeV)	3.1	9.0
Total beam current (mA)	1221 (1201)	758 (751)
Number of bunches	851 (836)	851 (836)
Bunch charge (10^{10})	6.57 (6.56)	4.06 (4.11)
β_x^* / β_y^* (cm)	32/1.05	32/1.05
$\varepsilon_x^* / \varepsilon_y^*$ (nm-rad)	22/1.4	59/1.3
Bunch length (mm)	13	13
$\nu_x / \nu_y / \nu_s$.512/.564/.027	.520/.622/.040

In addition to the luminosity and bunch-current patterns, the tunes of both beams, as well as their horizontal and vertical spot sizes on synchrotron-light monitors (SLM’s), are continuously recorded during the experiment. A closed-orbit bump (calibrated using a symmetric pair of BPM’s separated from the IP by a drift only) is used to vary the horizontal e^- IP angle while keeping the vertical IP angle of the electron beam, as well as its horizontal and vertical IP positions, fixed throughout the scan. Although a crossing angle could be induced using either beam, an appropriate closed-orbit bump in the LER would induce horizontal-orbit displacements in sextupoles close to the IP. The IR straight in the HER, by contrast, contains only dipole and quadrupole magnets, and is therefore preferred in order to keep the beam optics as constant as possible as a function of the crossing angle. The accessible range of horizontal e^- angles is limited mainly by synchrotron-radiation heating, and extends at most to ± 1 mrad (corresponding to half-crossing angles θ_c of ± 0.5 mrad). The corresponding PC separation, nominally 3.22 mm ($10 \sigma_x$), varies from approximately 3.6 to 2.7 mm.

Throughout the crossing-angle scans, great care is taken to keep all other collision parameters constant. The beams are kept transversely aligned in collision by a luminosity-based feedback; the horizontal and vertical IP angles of both beams are monitored by nearby BPM’s (and if necessary reset to their original value); and the relative RF phase in the two rings is reoptimized at each e^- angle setting to ensure that the longitudinal position of the collision point remains optimum. The ring orbits and the total beam currents [6] are also kept constant. In first approximation therefore, the dominant sources of luminosity variation should be the relative horizontal angle of the two beams plus, in the ‘by-2’ pattern, the ensuing change in horizontal PC-separation.

RESULTS

In a first round of experiments [5] without parasitic crossings, crossing-angle effects were characterized by

slowly scanning the horizontal electron angle and recording the specific luminosity L_{sp} as a function of θ_c . No tune or other optical adjustments were carried out, except for those leading to the initial, carefully optimized configuration corresponding to $\theta_c = 0$. This procedure resulted in a sizeable L_{sp} degradation at moderate crossing angles (20% for $\theta_c = \pm 0.4$ mrad at the highest currents), a loss about three times as large as that predicted by simulations. At any given crossing angle however, a substantial fraction of the luminosity loss could be recovered by re-optimizing the HER optics (tunes, x-y coupling and vertical dispersion).

Even though the optimal tune settings are expected to vary with crossing angle [4], the large degradation observed above is primarily attributed to higher-multipole components in the final-doublet quadrupoles (Fig. 1): as the horizontal IP angle of the electron beam varies, so does its position when it crosses the quadrupoles. This in turn leads to systematic shifts in the electron tunes and horizontal spot size, that were finally evidenced in a separate, single-beam experiment. Re-optimizing the HER optics then compensates for these multipole errors. In subsequent experiments therefore, the tunes and optical corrections in both rings were thoroughly optimized at each crossing-angle setting, so as to eliminate sources of luminosity degradation associated with spurious variations in beam optics.

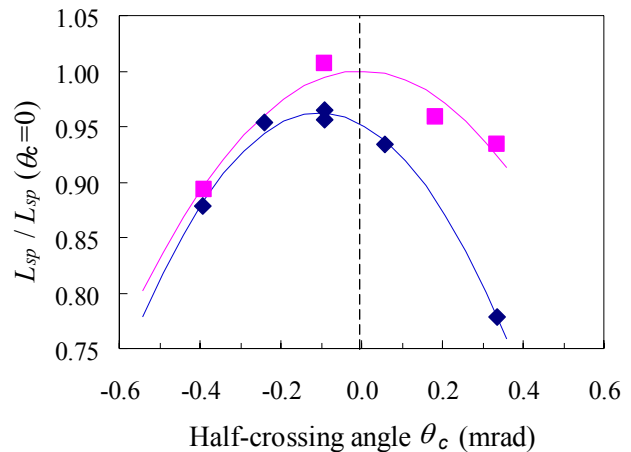


Figure 2: Crossing-angle dependence of the normalized specific luminosity without (purple squares) and with (blue diamonds) parasitic crossings. The lines are parabolic fits to the measurements. The data are normalized to the peak specific luminosity with no parasitic crossings.

These measurements are summarized in Fig. 2. The specific luminosity exhibits a parabolic dependence on the crossing angle. Because of unknown offsets in the BPM system, the e^\pm absolute IP angles are not known: the zero crossing angle ($\theta_c = 0$) is defined by the horizontal e^- angle that, after optical optimization, maximizes the luminosity in the ‘by-4’ pattern. With parasitic crossings (‘by-2’ pattern), the peak specific luminosity is about 4% lower than in the ‘by-4’ pattern: the more positive the

crossing angle, the steeper the degradation, because the smaller the PC separation. In addition, the optimum electron angle is significantly more negative (0.18 mrad) when parasitic crossings are present, suggesting that the best luminosity results from a compromise between crossing—angle- and PC-induced degradation. A detailed study of the θ_c -dependence of the luminosity pattern along the bunch train established that the luminosity degradation in the ‘by-2’ pattern is not caused by “pacman” effects at the edges of the minitrains.

The reproducibility of the measurements is illustrated by the two data points (lozenges) at $\theta_c = -0.1$ mrad: these were recorded several hours apart, after scanning the angle in different directions and performing multiple re-optimizations. That the crossing-angle dependence is intrinsic, rather than the result of an incomplete optical optimization, is confirmed by the detailed analysis of data recorded at several intermediate crossing-angle settings. For instance, when starting from a configuration carefully optimized at a large positive (negative) θ_c , and scanning the e^- angle back towards 0 from above (below), the specific luminosity always increases at first: the data reproducibly ‘favor’ head-on collisions.

COMPARISON WITH SIMULATIONS

The experimental measurements summarized above can be confronted with the predictions of the strong-strong beam-beam simulations described in Refs. [5, 6].

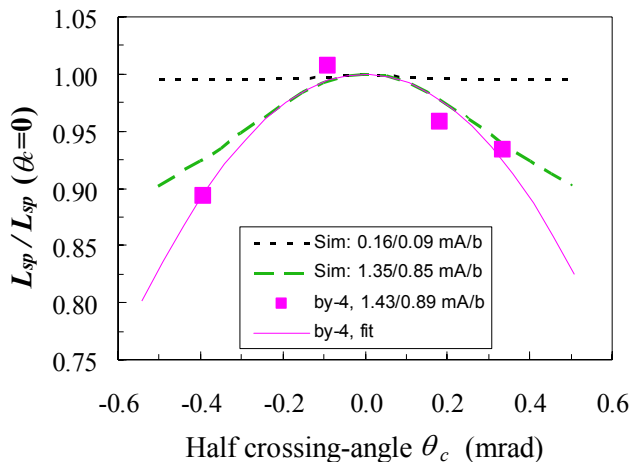


Figure 3: θ_c -dependence of L_{sp} (normalized to its value at $\theta_c = 0$), with no parasitic crossings, for data (purple) and simulation (dotted & dashed curves).

For collisions without parasitic crossings (Fig. 3), the geometric degradation, estimated from the low-current simulation, does not exceed 0.5%. At high current, the luminosity degradation associated with a half-crossing angle of $\theta_c = 0.4$ mrad is predicted to be about 7%; the measured effect is slightly larger (10-11%). At least within the experimentally accessible range, the agreement between data and simulation is satisfactory.

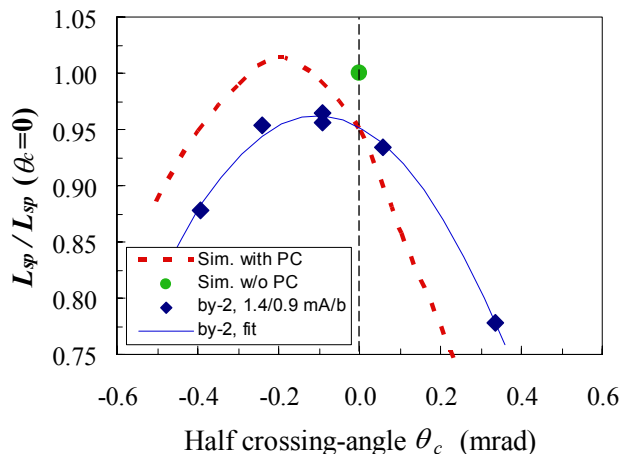


Figure 4: Crossing-angle dependence of the normalized specific luminosity with parasitic crossings, for data (blue) and simulation (red, dotted). The data (simulations) are normalized to the measured (predicted) value of L_{sp} at $\theta_c = 0$ without parasitic crossings (green dot).

The simulation confirms that in the presence of parasitic crossings, introducing a small negative crossing angle improves the luminosity (Fig. 4). The specific luminosity falls rapidly as θ_c grows more positive, *i.e.* as the PC separation decreases. In contrast to the data, parasitic crossings in the simulation do not degrade the peak achievable specific luminosity: they mainly shift the optimum e^- angle to a slightly negative value. However, at this stage the simulation ignores machine imperfections (spurious x-y coupling, non-linearities,...). In addition, the input tunes are the same for all simulated points, while in the actual experiment all four tunes are reoptimized for each bunch pattern and crossing-angle setting.

SUMMARY

The θ_c -dependence of the luminosity, and the impact of parasitic crossings, have been measured for half crossing angles up to ± 0.4 mrad, with full optical reoptimization at each setting. Simulations predict a crossing-angle dependence similar to that measured. The measurements indicate that parasitic crossings carry a 4% luminosity penalty under the present PEP-II typical conditions, with an approximately quadratic dependence on d_{PC} .

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