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EXPERIMENTAL CHARACTERIZATION OF PEP-II LUMINOSITY AND BEAM-BEAM PERFORMANCE*

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Abstract

The beam-beam performance of the PEP-II B-Factory has been studied by simultaneously measuring the instantaneous luminosity, the horizontal and vertical e^+ and e^- beam sizes in the two rings, and the spatial extent of the luminous region as extracted from BaBar dilepton data. These quantities, as well as ring tunes, beam lifetimes and other collider parameters are recorded regularly as a function of the two beam currents, both parasitically during routine physics running and in a few dedicated accelerator physics experiments. They are used to quantify and improve the PEP-II beam-beam performance.

INTRODUCTION

The main parameters of the SLAC e^+-e^- B-Factory [1] are listed in Table 1. In contrast to what is naturally enforced in single-ring colliders, the emittances and interaction-point (IP) β- functions can be different in the two rings. The best performance has so far been achieved with rather different e^+ and e^- beam-beam parameters. High luminosity also reproducibly favours an e^+/e^- current ratio of about 1.6, where one would naively expect 2.9 from the simplified energy-transparency condition [2].

Steady luminosity and background improvements have relied on maintaining a delicate empirical balance between the currents, tunes, and beam-beam parameters. Spot-size, beam-current and luminosity diagnostics (both bunch-by-bunch and averaging over the entire train) have proven essential to unravel these coupled phenomena. These tools have been used successfully [3] to control the interplay between electron-cloud and beam-beam issues, observe flip-flop effects, explore beam-beam limits during routine physics running, as well as optimize the bunch pattern [4] to maximize the luminosity.

In this paper, we report on accelerator experiments aimed at characterizing the dependence of the specific luminosity on the beam currents. The degradation of specific luminosity at high current is analyzed in terms of the measured beam blow-up pattern in the two rings, and has been confronted with the predictions of recent three-dimensional, strong-strong beam-beam simulations [5].

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Table 1: Typical PEP-II operating parameters. “LER” and “HER” refer to the low- and high-energy rings respectively.

Parameter	LER (e^+)	HER (e^-)
c.m. energy	10.58 GeV	
Luminosity	$8.9 \times 10^{33} cm^{-2} s^{-1}$	
Beam energy (GeV)	3.1	9.0
Beam current (mA)	2370	1500
Number of bunches	1563	1563
Bunch current (mA)	1.52	0.96
β_x^* / β_y^* (cm)	32 / 1.05	32 / 1.05
ϵ_x / ϵ_y (nm-rad)	31 / 1.5	60 / 1.4
Bunch length (cm)	1.3	1.3
ν_x / ν_y	0.512 / 0.564	0.520 / 0.622
ν_s	0.027	0.040
ξ_x/ξ_y	0.053 / 0.064	0.055 / 0.046

BEAM-CURRENT SCANS

An essential PEP-II optimisation tool is the fast luminosity monitor that counts photons emitted in the radiative-Bhabha process $e^+e^- \rightarrow e^+e^-\gamma$ [6]. Horizontal and vertical $e^\pm$ beam sizes are measured by, respectively, a synchrotron-light monitor (SLM) [7] and an interferometer [8] located downstream of an arc dipole in each of the PEP-II rings.

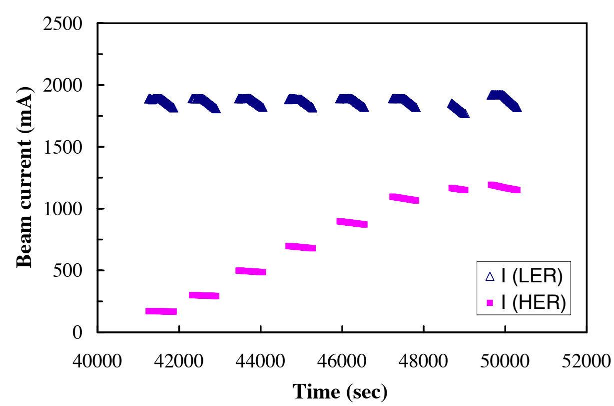

Figure 1: Beam-current history in the LER (triangles) and the HER (squares), during the HER current scan.

The bunch-current dependence of the luminosity and beam sizes was measured in dedicated experiments where the current of one beam was varied over the largest possible range, while maintaining the other beam at a constant bunch current typical of routine physics running (Fig. 1).

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Single-beam scans were also recorded to characterize the evolution of transverse beam sizes in the absence of any beam-beam interaction.

In single-beam mode, both the e^+ and e^- spot sizes remain constant over the accessible current range, suggesting that the e^+ beam is not significantly affected – if at all – by electron-cloud effects. In contrast, when the HER current progressively increases, the low-energy beam (LEB) experiences up to 65% horizontal blowup.[1] The vertical e^- spot size first decreases (presumably because the e^+ charge density drops), then remains approximately constant as the HEB current increases further (Fig. 2). At e^- currents above 0.8 mA/bunch, one also observes a rapid increase in horizontal HEB spot size (5–8%). This is accompanied by a sharp rise in the beam-loss rate at vertical betatron collimators in both the HER and the LER, and suggests the onset of a more violent beam-beam regime near the upper edge of the current operating range. The combination of these blowup patterns is reflected in the evolution of the specific luminosity (Fig. 3), which reaches a broad maximum around an e^- bunch current of 0.5 mA/bunch.

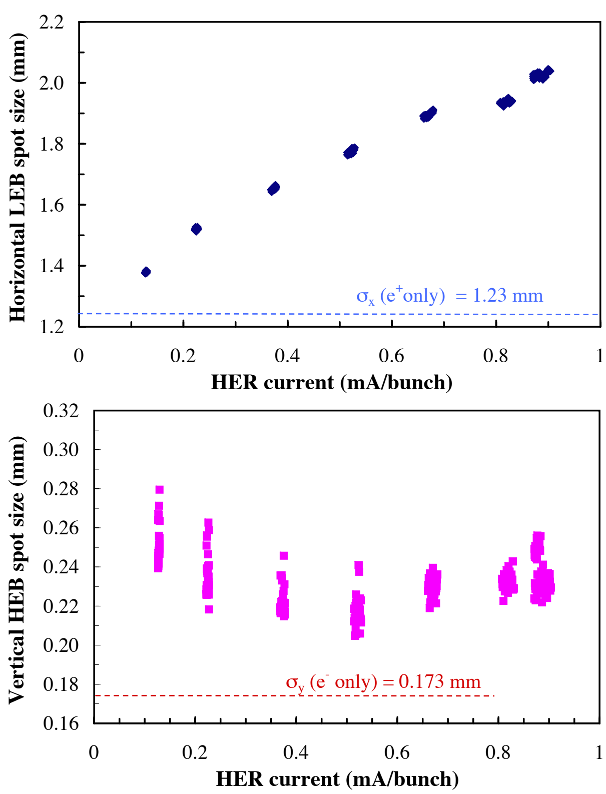

Figure 2: Dependence of the horizontal e^+ (top) and vertical e^- (bottom) spot sizes on the e^- current. The e^+ current varies by $\pm 2\%$ around an average value of 1.4 mA/bunch. The dashed lines indicate the corresponding single-beam spot sizes.

[1] One also observes a 20–25% increase in vertical e^+ spot size, but this should be interpreted with caution, because the LER interferometer is located in a strongly coupled section of the ring.

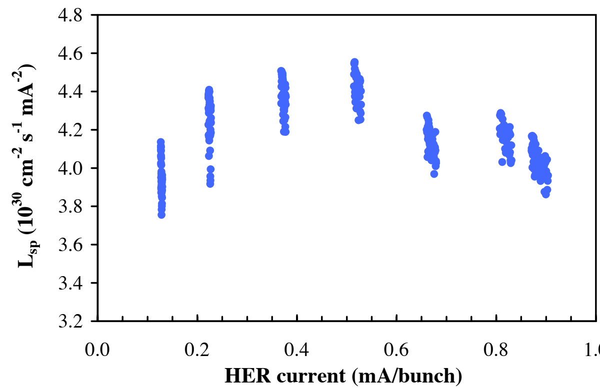

Figure 3: Dependence of the specific luminosity on the e^- current. The e^+ current varies by $\pm 2\%$ around an average value of 1.4 mA/bunch.

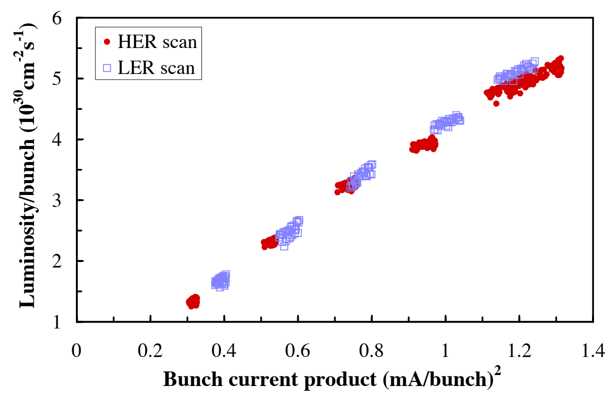

Figure 4: Evolution of the luminosity per bunch during the HER and LER current scans.

In a complementary experiment, the LER current was scanned over a wide range, with the HEB fixed at 0.9 mA/bunch. The horizontal LEB spot size remains constant; the most striking feature is the 40% blow-up of the vertical e^- spot size (Fig. 5), accompanied by moderate horizontal HEB blow-up (4–8%), and, at the two highest LER currents, by a very rapid increase in beam losses at both the horizontal and vertical betatron collimators in the HER. The specific luminosity degrades by at most 5% at high current. The luminosity proper exhibits only moderate saturation at the highest bunch currents (Fig. 4), where it is limited instead by rapidly degrading lifetime and beam-beam backgrounds.

Similar measurements, performed parasitically using luminosity and spot-size data recorded during routine physics running, reveal an evolution of the blow-up patterns as luminosity tuning progresses. Combining low-current IP overlap beam sizes ($\Sigma_{x,y}$) with archived measurements of luminosity and e^+e^- spot sizes, assumed emittances and measured IP β-functions, eventually provides an estimate of the beam-beam parameters $\xi^{+-}_{x,y}$ (Table 1). These results constitute a rough measure of the actual beam-beam performance of the machine, and provide guidance towards

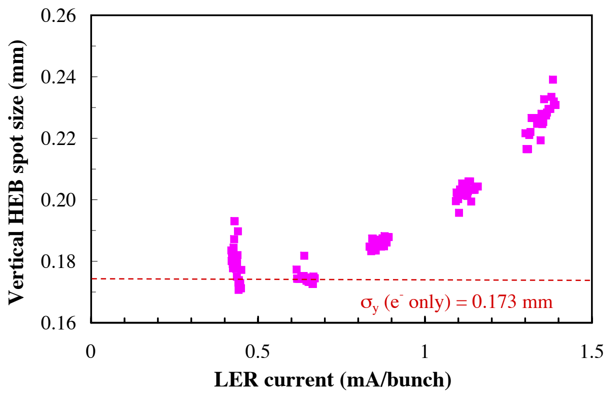

Figure 5: Dependence of the vertical e^- spot size on the e^+ current. The e^- current is fixed at 0.9 mA/bunch.

further luminosity improvements.

LUMINOUS-REGION MEASUREMENTS

The vertexing capabilities of the BaBar detector allow to measure directly the size of the luminous region. This observable, labeled σ^L, is related to the transverse sizes of the e^+ and e^- beams at the IP by $(\sigma^L_{x,y})^{-2} = (\sigma^+_{x,y})^{-2} + (\sigma^-_{x,y})^{-2}$. The BaBar IP-finding algorithm uses $e^+e^- \rightarrow \mu^+\mu^-$ and $e^+e^- \rightarrow e^+e^-$ events. The two charged tracks are reconstructed using the silicon tracker and central drift chamber [9], and the spatial distribution of the reconstructed vertices are accumulated over 10-minute periods, yielding a continuous measurement of the centroid and R.M.S. width of the luminous region. The spatial resolution (~ 35 μm) remains moderate compared to the expected horizontal luminous size (60-100 μm). Such measurements have provided direct evidence for the shrinkage of the horizontal beam sizes at the IP associated with the dynamic-β effect (Fig. 6), and have been also been used to validate recent beam-beam simulations [5].

The vertexing resolution is too coarse for vertical-size measurements ($\sigma^L_y \sim 5\ \mu m$); but the corresponding information can be extracted from the product of σ^L_x and of the specific luminosity (with mild additional assumptions). The same analysis also returns the history of the longitudinal and transverse centroids of the luminous region, with the potential to monitor drifts in the position of the collision point, in the RF phase difference between the two rings, in the settings of magnetic elements close to the IP, etc.

SUMMARY

We have studied, in dedicated accelerator experiments, the beam-current dependence of the PEP-II luminosity and of the $e^\pm$ beam sizes measured using visible synchrotron light. The high-current evolution of the specific luminosity is dominated by a combination of vertical e^- beam blow-up, accompanied by an as yet unexplained large horizontal blow-up of the e^+ beam. At the highest bunch currents, the

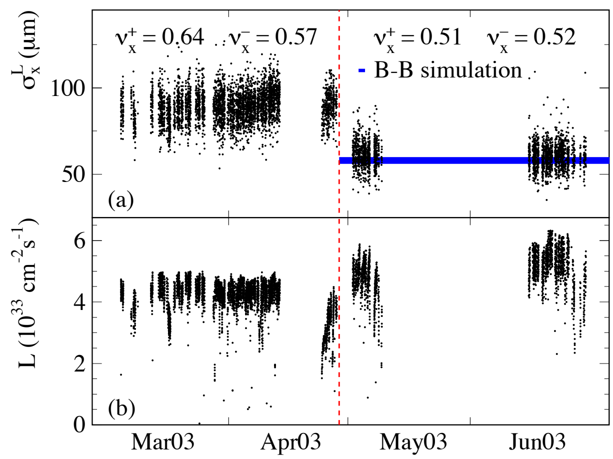

Figure 6: Time history of (a) the horizontal size of the luminous region (corrected for resolution), and (b) the total luminosity, during routine physics running. The vertical dashed line indicates the time when the horizontal ring tunes were moved close to the half-integer. The drop in σ^L_x and the luminosity improvement are clearly visible. The band illustrates the predictions of the beam-beam simulation.

total luminosity exhibits little saturation, and is in practice dominated by degrading beam lifetime and rapidly rising beam-beam backgrounds. Direct measurements of the horizontal luminous size at the IP, using the BaBar detector, are in agreement with beam-beam simulations, and confirm the onset of dynamic-β luminosity enhancement as both horizontal tunes approach the half-integer.

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