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Beam-Beam Performance Of The SLAC B-Factory*

W. Kozanecki[§]
Y. Cai[¶], F.-J. Decker[¶], R. Holtzapple[¶†], J. Seeman[¶], M. Sullivan[¶], U. Wienands[¶]

[§] *DSM-DAPNIA-SPP, CEA-Saclay, 91191 Gif-sur-Yvette (France)*
[¶] *Stanford Linear Accelerator Center, Stanford, CA 94309 (USA)*
[†] *now at Alfred University, Alfred, NY 14802 (USA)*

Abstract. The beam-beam performance of PEP-II has been monitored by parasitic measurements recorded during routine physics running, and by a few dedicated accelerator physics experiments. These measurements indicate that in some cases, the beam-beam interaction and the electron-cloud-induced blowup of the low-energy positron beam are somehow coupled and enhance each other. Tailoring the bunch pattern to carefully balance these effects has proven very effective in maximizing the integrated luminosity. The comparison of recent simulation results with experimental data is encouraging.

INTRODUCTION

The main parameters of the SLAC B-Factory [1] are listed in Table 1. In contrast to what is naturally enforced in single-ring colliders, the emittances and IP β-functions can be quite 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 1.5 to 2.0, where one would naively expect 2.9 from the simplified energy-transparency condition [2]:

$$I^+E^+ = I^-E^-$$

Steady luminosity and background improvements have relied on maintaining a delicate empirical balance between the currents, tunes, beam-beam parameters, and ECI-induced blowup as these quantities vary along each bunch train. 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.

TABLE 1. PEP-II Collision Parameters. The symbols "LER" and "HER" refer to the low-energy (e^+) and high-energy (e^-) ring, respectively.

IP Parameter	Design	Recent peak performance	Units
Beam energy E (LER/HER)	3.1 / 9.0	3.1 / 9.0	GeV
Crossing angle	0	< 1	mrad
Luminosity	3.00	6.57	10^{33} cm^{-2}s^{-1}
Number of bunches	1658	1034	
Beam current I (LER/HER)	2146 / 750	1550 / 1175	mA
β^*_y / β^*_x	1.5 / 50	1.2 / 40 (e^+), 1.2 / 28 (e^-)	cm
Emittances ε_y / ε_x (low I)	1.5 / 49	1.8 / 30 (e^+), 1.8 / 49 (e^-)	nm-rad
LER tunes ν_x / ν_y	38.64 / 36.57	38.52 / 36.57	
HER tunes ν_x / ν_y	24.62 / 23.64	24.52 / 23.62	
ξ_y (e^+ / e^-)	0.03 / 0.03	0.082 / 0.040	
ξ_x (e^+ / e^-)	0.03 / 0.03	0.109 / 0.040	

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INTERPLAY BETWEEN ELECTRON-CLOUD & BEAM-BEAM ISSUES

The build-up of the electron cloud along the positron bunch, and its impact on the luminosity, exhibit a strong dependence on the bunch pattern. An example from early PEP-II running is shown in Fig. 1. The first bunches of each mini-train have a high luminosity, which drops to 40 % of its initial value at the end of the longest train. The long gaps clear the electron cloud, which slowly builds up again along the next mini-train.

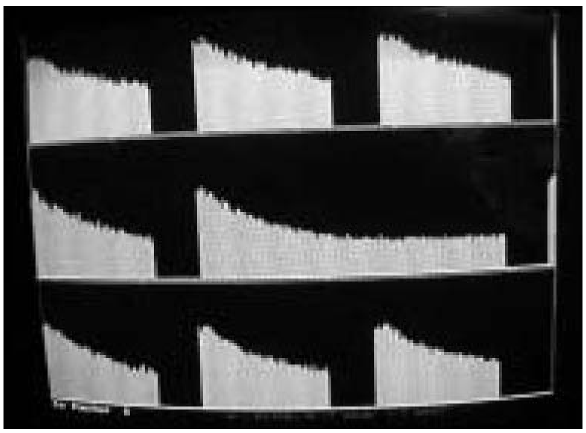

FIGURE 1. Luminosity vs. position along the bunch train. Pattern: 8.4 ns bunch spacing with 7 large gaps (July 2000). This data was acquired with the solenoids turned on in part of the straight sections only.

A related (and so far unexplained) observation is that of self-blowup of the e^+ beam during high-current collisions. This is illustrated in Fig. 2. With the e^- current kept constant at 625 mA while increasing the e^+ current from 100 to 1300 mA, the transverse e^+ beam size grew rapidly, both horizontally and vertically, once the LER current exceeded a 900 mA threshold. In contrast, the e^- horizontal and vertical beam sizes (not shown) remained constant. In the absence of an electron beam, the e^+ horizontal size was, at low current, 15% smaller than in collision, and remained constant with increasing LER current (Fig. 2). When a similar sequence of measurements was performed by varying the e^- current instead, the e^+ beam size was independent of HER current (above 150 mA), but its value depended on the LER current itself. These surprising observations were interpreted as the electron-cloud instability (ECI) and the beam-beam interaction mutually "enhancing" each other at high positron current.

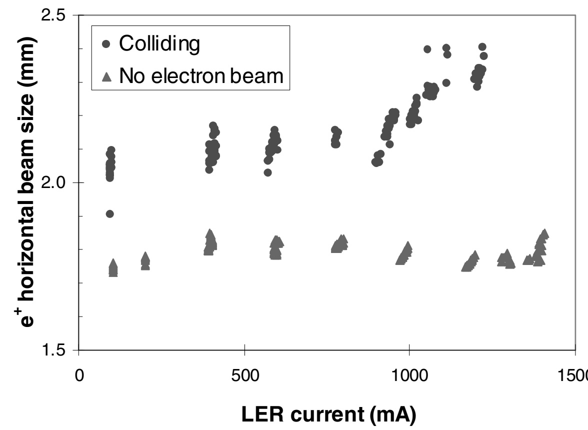

FIGURE 2. LER-current dependence of the e^+ horizontal beam-size averaged over the bunch train, in collision (circles) and with no e^- beam circulating (triangles). The beam size is measured by a synchrotron-light monitor (SLM). Pattern: 597 bunches, 10.5 ns spacing (July 2000).

More recently, direct measurements of the e^+ beam size along the bunch train, using a gated synchrotron-light camera, revealed both a short-range blowup (within each mini-train), and a long-range buildup of the cloud over the entire length of the train. Such e^+ beam-size variations directly impact the luminosity *via* the positron charge density at the IP. But they also induce variations of the e^- beam-beam tune shift along the train, resulting in an effective increase of the e^- tune footprint and/or in e^- spot-size variations. In addition, the PEP-II luminosity and beam lifetimes are quite sensitive to minor adjustments in the tunes of either beam. Because the tunes can only be optimized in an average sense (*i.e.* for the train as a whole), specific bunches (at the head or tail of the train, or at the front of individual mini-trains) occasionally exhibit significantly lower luminosity and/or poor lifetime.

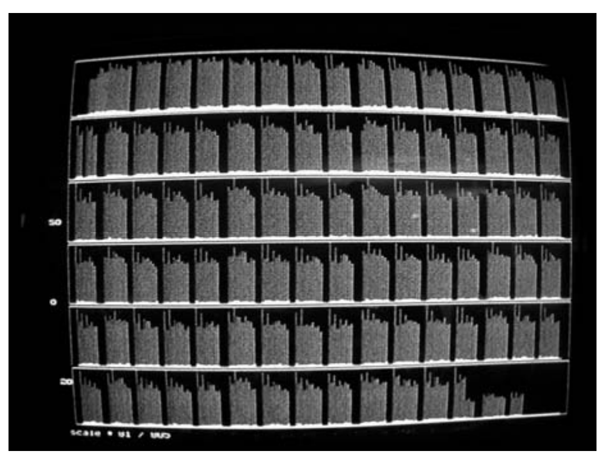

FIGURE 3. Standard luminosity pattern in 2003 (6.3 ns spacing), alternating mini-trains of 10 and 11 bunches. Each

mini-train has constant luminosity except for bunches 1 and 3. During this measurement, solenoids covered most of the LER vacuum chamber in all arcs and straight sections.

These observations lead to an empirical optimization [3] of the bunch pattern to maximize the luminosity, taking into account:

- the total-current budget (limited by RF power and by beam-induced heating);
- the spacing between mini-trains (the longer the gaps, the better the e^--cloud suppression);
- the mini-train length (the shorter the mini-train, the less the cloud builds up);
- the number of mini-trains (fewer mini-trains mean fewer "fragile" bunches).

The severity of the e^--cloud effects, for a fixed bunch pattern, has been steadily decreasing over the years. The winding of low-field solenoids (25-35 Gauss) around all accessible sections of the LER vacuum chamber, combined with synchrotron-radiation scrubbing of vacuum surfaces, has progressively allowed operating PEP-II with increased beam currents and a denser bunch pattern (Fig. 3). Several electron-cloud-related phenomena are no longer apparent, such as the single-beam e^+ blowup at high current or the mutual enhancement of the ECI- and beam-beam-induced blowup. During recent running, the effects of the cloud typically reach equilibrium after the first two or three bunches in each mini-train.

Exploratory measurements, aimed at improving the luminosity, suggest that in the design bunch pattern (4.8 ns spacing), the ECI may again turn into a significant limitation as currents are further increased. Recent simulations suggest that doubling the solenoid field strength may prove an effective countermeasure: this upgrade is in progress.

BEAM-BEAM FLIP-FLOP

The strong beam-beam forces between colliding bunches can result in a “flip-flop” of the transverse size of some bunches. The flip-flop occurs when the transverse size of the positron bunch shrinks and the corresponding e^- bunch size grows. This phenomenon accounts for several concomitant observations: increase in IP beam size (evidenced by a reduced luminosity), shorter e^+-beam lifetime, and higher background in the *BABAR* detector.

Flip-flop has been studied [4] in the LER using a 2-ns gated camera. Measurements have shown that when an e^+ bunch flips: (i) the horizontal and vertical e^+ bunch sizes decrease by ~30% (Fig. 4); (ii) the luminosity drops by ~50% (Fig. 5), presumably because the corresponding e^- bunch size(s) increase substantially; (iii) the LER lifetime drops when the bunch goes from its "flipped" (shrunk) state to the "flopped" state (Fig. 4); (iv) the transition is rather fast (~ 0.5 sec.) and usually occurs at the top of a store, where the LER x-tune is optimized for high luminosity; and (v) flip-flop primarily affects bunches in the front of a mini-train, which might be due to such bunches experiencing a different tune shift because the ECI has been suppressed there by the mini-gap.

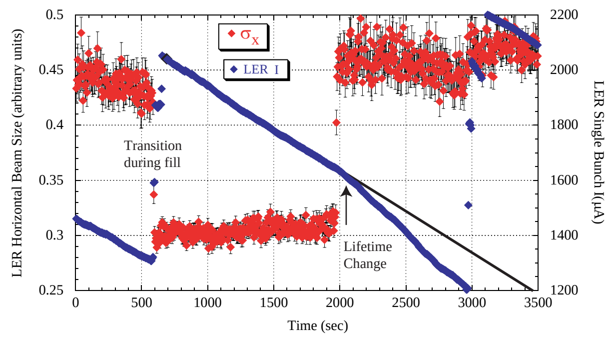

FIGURE 4. Single-bunch e^+ current and horizontal beam size vs. time, illustrating the flip-flop transition.

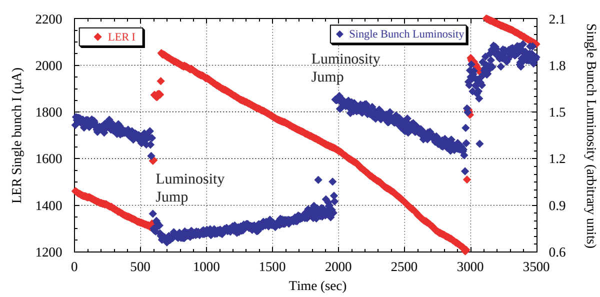

FIGURE 5. Single-bunch luminosity and e^+ current vs. time, illustrating the flip-flop transition.

A more detailed study is planned using two gated cameras, one per ring, to gain further insight into flip-flop dynamics.

BEAM-BEAM LIMITS NEAR ν_x=1/2

All of the above observations were carried out with the horizontal LER tune, and the vertical HER tune, near the 2/3 resonance (Table 2). Both rings were recently moved closer to the 1/2-integer to take advantage of the eventual luminosity enhancement associated with the dynamic-β effect.

TABLE 2. History of PEP-II working points.

Fractional tune	1999-2003	Since 5/2003
LER (ν_x / ν_y)	0.64 / 0.56	0.52 / 0.57
HER (ν_x / ν_y)	0.57 / 0.64	0.52 / 0.62

The new working point yields significantly improved luminosity performance, but also a qualitatively different beam-beam blowup pattern. The positron beam size now depends only on the e^- current (and vice-versa): "self-blowup" of the e^+ beam, in particular, is no longer observed. Over the current range of a typical store, the vertical e^- beam size shrinks by 30-40% as the LER current decays (Fig. 6). Similarly, the horizontal positron beam size is a linear function of the HER current, and is typically 50-60% larger at full e^- current than in single-beam mode. These mutual blowup effects are reflected in the beam-current dependence of the luminosity, which exhibits clear saturation at high intensity (Fig. 7).

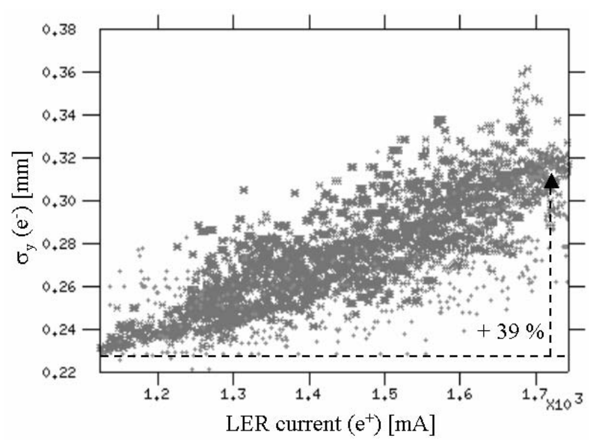

FIGURE 6. Dependence of the vertical e^- SLM beam size on the LER current, during a typical store ($\nu_x^{+,-} \sim 0.52$).

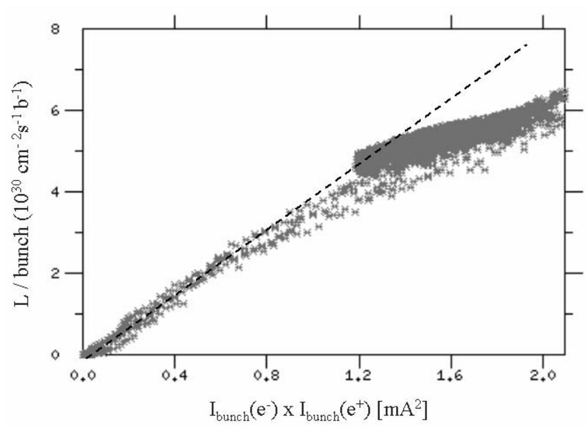

FIGURE 7. Beam-current dependence of the luminosity during a typical store.

Combining the measured beam-current dependence of the e^+ and e^- beam sizes and of the luminosity with (measured or assumed) emittances and IP β-functions, provides an estimate of the beam-beam parameters $\xi_{x,y}^{+,-}$ (Table 1). Although approximate, the results constitute a measure of the actual beam-beam performance of the machine, as well as a guide towards further luminosity improvements.

SIMULATIONS

As a result of dramatic increases in available computer speed, it has become feasible to use the particle-in-cell method for beam-beam simulations. Such an approach is self-consistent, because the electromagnetic field is computed by solving the Poisson equation with the charge distributions being updated as the beams collide. Recently, it was found that the extent of the x-y grid can be much reduced if an inhomogeneous potential is assigned on the boundary [5]. A smaller spatial extent allows for a denser mesh, thereby increasing the resolution of the Poisson solver.

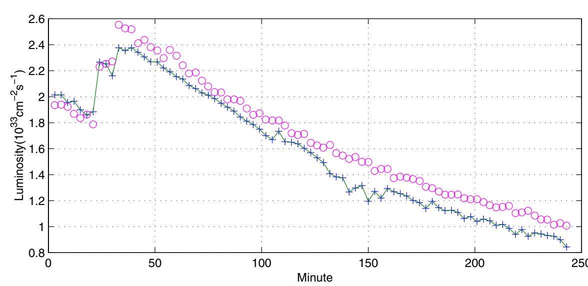

FIGURE 8. Time evolution of the measured luminosity on 10/1/2000 (crosses), and comparison with that predicted by a two-dimensional simulation (circles).

Fig. 8 compares the PEP-II luminosity measured during physics running, with that computed using a two-dimensional simulation [6] at the same beam currents. The prediction is absolute in that none of the simulation input parameters were fitted: all of them had been chosen close to their nominal value except for the vertical emittance, which is not so important because of the vertical beam-beam blowup at high intensity. The agreement between simulation and measurement is surprising, and is remarkable given the simplicity of such a 2-D model. This success is largely attributed to the fact that the operating tunes were well optimized and that many resonances (including synchro-betatron lines) had been carefully avoided.

In general however, three-dimensional effects such as hourglass effect and phase averaging must be included in beam-beam simulations. Achieving the necessary numerical convergence in three dimensions requires the use of parallel supercomputers.

One of the most important aspects of parallel computing is how to minimize the communication among processors. Each application may have a different optimal solution. For beam-beam simulations, we have developed an efficient strategy utilizing dual processors (Fig. 9). Macro-particles are evenly distributed across many processors. The processors are divided into two groups, one for the positron beam and the other for the electrons. Before the collision, the beam distribution on the grid is summed within each group, and the resulting distribution is distributed back to all processors in the group. Then the total distribution is exchanged between the groups. That allows us to solve the Poisson equation and compute the force on the macro-particles in every local processor.

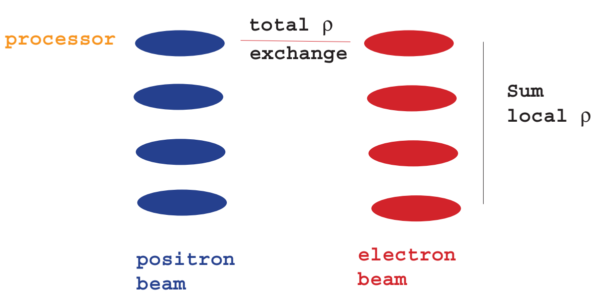

FIGURE 9. Illustration of how the processes in the parallel computer communicate with each other.

In this scheme, the macro-particles always remain confined to the same computing process. Only the beam distribution on the grid is exchanged among the processors. The division into two groups essentially allows to double the speed without much penalty. With a parallel supercomputer comprising 32 processors in all, we increased the speed of the simulation by a factor of 24. This enabled us to achieve numerical convergence in a three-dimensional simulation using 15 longitudinal slices, for a typical set of symmetric PEP-II parameters at high beam intensities.

SUMMARY

The impact of the electron-cloud instability on the PEP-II luminosity has been minimized by a combination of scrubbing, installation of solenoid windings around the LER, and bunch-pattern optimization. But electron-cloud effects still play an ubiquitous role in the beam-beam performance of the B-Factory. Even though they appear less important at the new working point, they may still constitute a significant limitation at high luminosity.

The PEP-II horizontal tunes were recently moved close to the 1/2 integer. At this working point, the machine achieved a peak luminosity of 6.57 10^{33}cm^{-2}s^{-1}, with estimated beam-beam parameters ξ_x/ξ_y of about 0.109/0.082 (0.040/0.040) in the LER and HER respectively.

Beam-beam simulations show encouraging agreement with experiment, but more extensive validation of 3-dimensional codes is urgently needed.

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