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PEP-II at 1.2×10^{34} /cm^2/s Luminosity*

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Abstract

PEP-II is an asymmetric e$^+$-e$^-$ collider operating at the $\Upsilon(4S)$ energy and has recently set several performance records. The luminosity has reached a peak of 1.2×10^{34}/cm^2/s. Operating in continuous injection mode for both beams PEP-II has delivered up to 0.91/fb/day. Peak currents have reached 3.0 A of positrons and 1.9 A of electrons in 1732 bunches. Total delivered luminosity since turn-on in 1999 has exceeded 450/fb. This paper reviews the present performance issues of PEP-II and also the planned increase of luminosity in the near future to 2×10^{34}/cm^2/s.

INTRODUCTION

The PEP-II *B*-Factory has had spectacular running, exceeding its design luminosity by a factor of 4 and its daily integrated luminosity by up to a factor of 6. Total delivery to the BaBar experiment is approaching 0.5 /ab, see Fig. 1. Figure 2 shows the evolution of the peak luminosity by month, Fig. 3 the daily delivered luminosity average for each month from the beginning of running until now. Table 1 summarizes the important machine parameters of PEP-II.

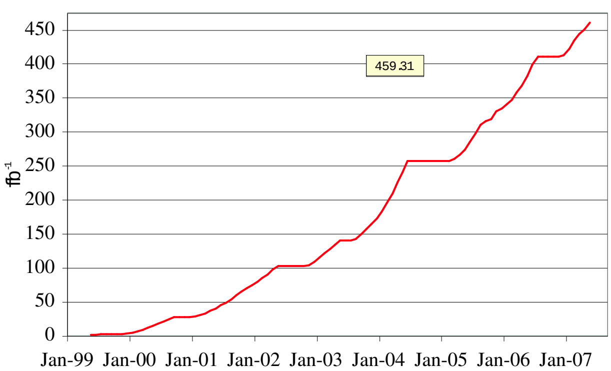

Figure 1: PEP-II & BaBar total delivered luminosity.

The improvements evident in the run statistics are due to a number of parameter improvements made over the years: Beam currents in both rings have increased steadily, made possible by adding rf power as needed and by upgrading vacuum components where necessary. Beam sizes at the interaction point (IP) have been reduced by lowering β_y^* in both rings and also improving the vertical beam emittance, which is driven by coupling and vertical dispersion. The latter has raised the beam-beam tune-shift parameter ξ_y.

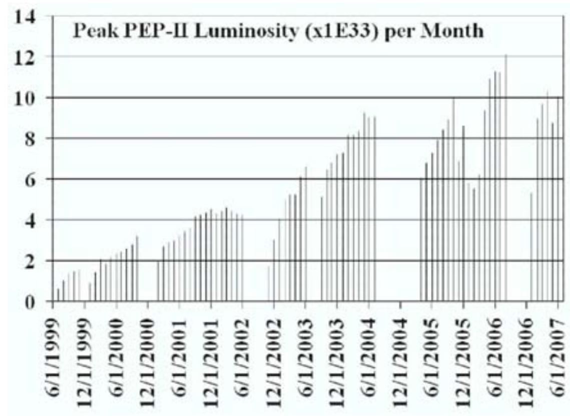

Figure 2: PEP-II & BaBar peak luminosity by month.

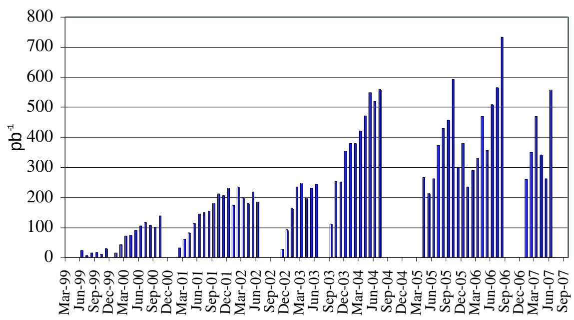

Figure 3: PEP-II & BaBar delivered luminosity by month.

PERFORMANCE IMPROVEMENTS

Raising Beam Currents

In order to accommodate the increased beam currents the number of bunches was increased up to its maximum of about 1730 bunches, leaving only a very small gap to allow the beam abort kickers to fire when required. Conversely the bunch currents have actually gone down.

In raising the number of bunches eventually every other rf bucket was filled (4.2 ns or 1.26 m bunch spacing). In this fill pattern, parasitic crossings can become an issue as at 0.63 m from the IP, where the first parasitic crossing occurs, the beams are only separated by about 3.2 mm. Operationally this was tested by running the same number of bunches first in a "by-3" fill (1.85 m bunch spacing) and then in a 1.26 m spacing. Immediate loss in luminosity

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Parameter	Unit	HER	LER
Energy	GeV	8.9918	3.1
Beam current	A	1.9	3.0
# bunches		1730	
Rf Voltage	MV	16	4.05
Mom. compact. α_p		0.00241	0.00124
Bunch length	mm	12.5	13.5
horiz. emittance	nmr	73	36
vert. emittance	nmr	1	1
β^*_y	mm	11	10
β^*_x	cm	74	21
ξ_y		0.074	0.058
Luminosity	/cm^2/s	1.2×10^{34}	

Table 1: PEP-II Parameters at end of Run 5.

was about 10%, recovering over the next two weeks of tuning to about 98% of the original specific luminosity, see Fig. 4. The lowest-order effect of the parasitic crossings is a shift of the average tune, which is compensated for by changing the phase trombones in the rings. Due to the rich spectrum of the beam-beam force there are higher harmonics present, the leading term of which which causes a tune shift in y depending on the x position thus introducing tune spread in y which cannot be tuned out. Since in PEP-II the beams are vertically offset at the parasitic crossings a coupling component is also present, and it is this effect which takes time to compensate by tuning measures. At present beam currents, parasitic crossings do not appear to cause major reduction in luminosity.

Raising the beam currents causes increased heat load on the vacuum system; this has been dealt with by applying extra cooling where needed, but the high beam currents also brought a number of new challenges

LER BPM buttons In order to be able to decrease β^*_y below 10 mm, the bunch length should be kept as short as possible. To this end the rf voltage in the LER was raised

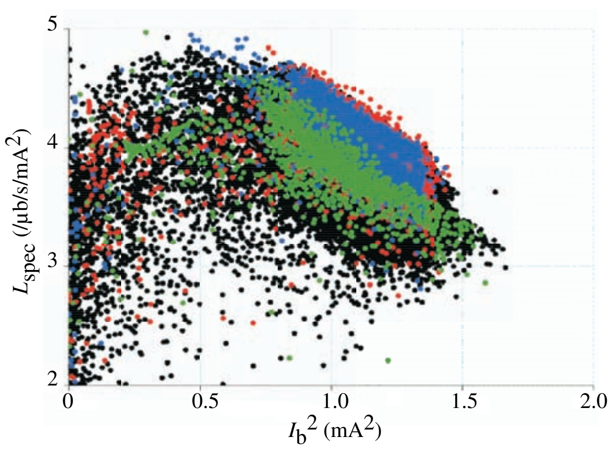

Figure 4: PEP-II specific luminosity in 6.3 ns and 4.2 ns bunch spacing.

from 4 MV to 5.4 MV. Soon after this a catastrophic vacuum leak—found to be a destroyed BPM feedthrough—opened up in the ring. Inspection revealed that a BPM button had come lose and fallen down, lodging on its below companion button in such a way as to strongly absorb energy from the beam and cause melting of the glassy-ceramics seal of the lower feedthrough (Figure 5). The

Figure 5: LER BPM feedthrough after overheating.

short bunches lead to overheating of the buttons in particular in a region of the ring already affected by strong HOM absorption. Since the buttons absorb HOM energy from the beam at a 7 GHz resonance, their sensitivity to bunch length is several times stronger than a mere $\hat{I} \times \bar{I}$-dependence would suggest. More detailed analysis gives a relative power dissipation as shown in Figure 6. Following this event the buttons were pulled off the welded-in feedthroughs in the IR. The BPMs in the LER arcs were replaced with smaller units extracting less power from the beam, and the design was changed from a press-fit stainless-steel button to a molybdenum button integral to the feedthrough pin. Deployment of these buttons is complete except for one arc and one straight section.

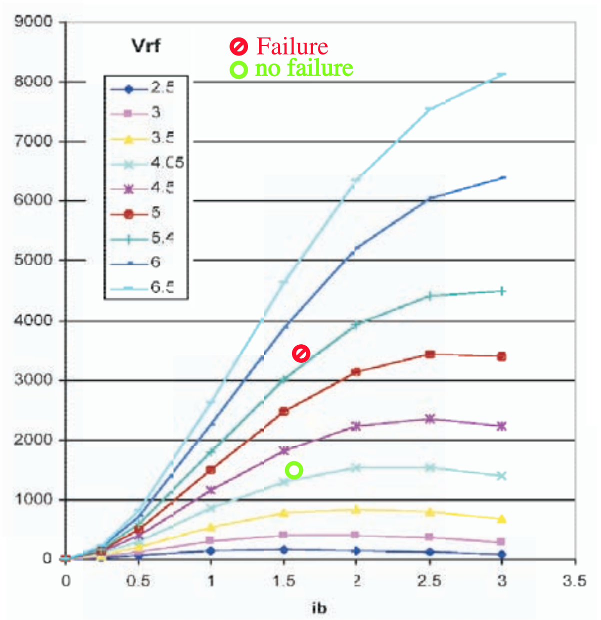

Figure 6: Relative power to BPM buttons *vs* bunch current. Parameter: rf voltage. Symbols: Operational experience.

Feedback kickers The LER feedback kickers were expected from the beginning to need upgrading beyond 2 A of beam current. In fact, both longitudinal drift-tube kicker and the transverse strip-line kicker operated successfully at 2.5 A beam current.

Longitudinal feedback kickers The original lfb kicker is an ALS-style aluminum drift-tube design which has the advantage of directionality, thus avoiding the need for (costly) circulators.[1] For higher beam current the overdamped rf cavity kicker is a structure easier to cool since cooling can be applied easily to the walls of the cavity. At PEP-II a 4-port copper cavity was designed and built, with 7/8 DIN rf connections for maximum robustness and power handling capability.[2] Low-pass filters and circulators are used to prevent power (in-band and HOM) from coming back to the amplifiers. Aside from issues with the low-pass filters due to bad connectors the structure has performed well up to the highest beam current achieved in the LER (3 A as of this writing). For the HER at 2.2 A, the drift tube design can handle the heat load.

Transverse feedback kickers The tfb kickers use 0.63-m long aluminum strip line electrodes. Because the electrodes are supported only by the feedthroughs at either end and are externally terminated, cooling is not easily applied and radiative cooling facilitated by sputtered-on CuO coating with high emissivity is used. Thermal monitoring with optical pyrometers has indicated temperatures of several hundred °C at the electrodes when beam current reached 2.5 A, suggesting the kicker would likely not survive beam currents in excess of 3 A.

The kicker has been upgraded with electrodes made of molybdenum. Molybdenum can withstand very high temperatures, moreover, it expands very little at high temperatures thus avoiding stress on the feedthroughs that serve as supports. The high emissivity required to effectively cool the electrodes is achieved in a straightforward way by oxidizing the electrodes in air at about 600°C[3]. This process is much simpler than the CuO sputtering needed for the aluminum electrodes, and the emissivity achieved (0.6 on an actual electrode in the IR, 8…13 μm wavelength) is equal or better than that of the CuO coating. A drawback of molybdenum is its higher density requiring care in supporting the electrodes.

HOM Absorbers

Higher beam current and shorter bunches brought with them a number of areas, where the heat load increased rather dramatically, in particular near aperture irregularities like beam collimators and the interaction region (IR). Origin of the heat load was found to be the generation of HOMs at these irregularities, in case of certain beam collimators this was experimentally verified by moving the beam towards and away from the collimator jaw and being able to affect the heating in this way.

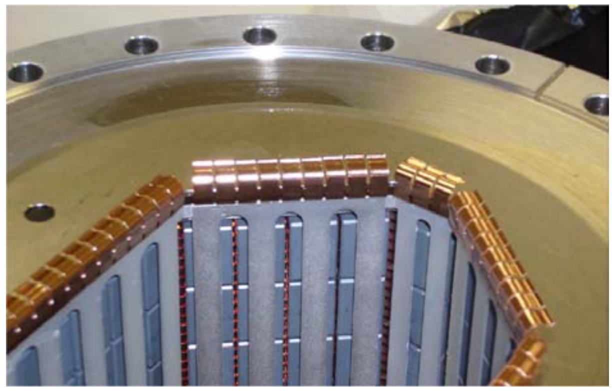

Figure 7: HOM absorber with bellows module.

To absorb the heat, dedicated HOM absorbers were built with absorbing ferrite tiles in a cavity strongly coupled to the beam by relatively wide slots.[4] Figure 7 shows a close-up of such an absorber. They are combined with bellows to replace extant bellows in the ring. The effect of these absorbers was estimated for regions where the source of the HOMs was known and found to agree well with the prediction.

Vacuum Chambers

NEG pumps Increase of the beam-currents eventually led to a nonlinear increase in the vacuum pressure in the interaction straight, originating from the NEG pumps used liberally in both rings upstream of the detector. The NEGs are shielded from the beam by screens, the design of which is a compromise between good rf shielding and good vacuum conductance. A screen 0.125” deep with slots 0.125” wide, backed by a 0.020” thin Cu sheet with 0.118” slots across, was particularly leaky to HOMs, while a 0.125” deep screen with ⊘0.125” holes on 0.167” center provided a much better HOM barrier (and much less conductance!).

The resultant heating of the NEG lead to outgassing once the temperature exceeded 150…175°C, as determined in laboratory experiments. The highest temperature we measured on installed NEGs was above 400°C, exceeding the regeneration temperature. This problem was addressed in part by installing chambers with improved screens, in part by removing the NEG pump, sometimes replacing it with an rf absorber to dissipate the rf energy. Removal of the NEG is possible because the vacuum system is now in a well conditioned state and the pumping speed required is not as high as in the earlier days of PEP running.

IR chambers A number of vacuum chambers in the interaction region (IR) were approaching their thermal limit due to the absorption of considerable s.r. power emanating from the strong bending magnets in the detector. Some of these also had “bad” NEG screens. This upgrade also allowed us to add bellows at strategic locations thus mechanically decoupling the vacuum system in the insertion quadrupoles. Strong thermal forces on the original

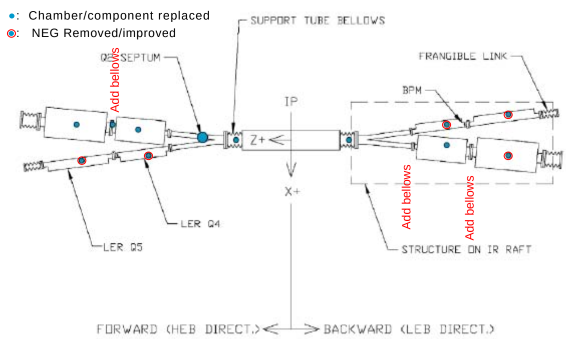

Figure 8: IR diagram with chamber upgrades.

rigid system were known to cause intensity-dependent orbit drifts, including non-negligible cross terms between the rings. Figure 8 indicates the improvements made. The upgraded chambers are made of aluminum for ease of manufacturing, allowing us to shape the chambers along the available space on the outside and along the aspect ratio of the beam ellipse on the inside, maximizing the aperture for the beam. Fig. 9 shows the Q5 chamber during installation.

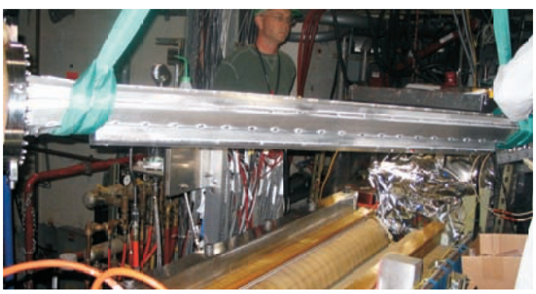

Figure 9: New HER Q5 chamber during installation.

Trickle-Charge Operation

Operational efficiency of PEP-II was enhanced greatly by operating in continuous-injection mode, thus avoiding the ramp-down and -up of the detector during injection periods. This resulted in an effective gain in luminosity of about 40%. Commissioning this operational mode required strong cooperation between the detector and machine groups as diagnostics had to be developed that allowed tuning of the machine for minimal injection losses without reduction in injection rate. On the detector side, 2-d gating had to be implemented to blank out the unavoidable injection losses. Details of these developments have been published elsewhere.[5]

Optics changes

Specific luminosity is directly affected by the vertical focusing, $1/\beta_y^*$. β_y^* was lowered in steps from the original 1.5 cm to about 1 cm. In the LER this change was effected by designing new optics using MIA-derived lattice models of the actual machine optics.[6] For the HER, a particularly successful way to lower β_y^* was to change the matching at the beginnings of the adjacent arcs, thus avoiding the need to change the local chromaticity correction in the arcs. The resultant β beat has just the correct phase and amplitude to change β_y^* to the desired value.

PEP-II PLANS

High Bunch-current Experiment

In order to assess the potential to reach higher luminosity by increasing the bunch current, an experiment was performed running at bunch-current corresponding to the ultimate bunch currents expected (2.2 mA on 1.6 mA) but at reduced bunch number as at that time the machine could not have stored such high total beam current. Fig. 10 shows the luminosity per bunch during that experiment, with the then-present operational bunch current at the left side. The bunch luminosity of 9×10^{30} corresponds to a total of 1.6×10^{34} for 1730 bunches. The vertical beam-beam parameters reached $(\xi_{y,H}, \xi_{y,L}) \approx (0.097, 0.055)$. The experiment is not fully conclusive since the pattern used had no parasitic crossings, however, the operational result shown in Fig. 4 suggests that similar bunch currents can be reached with all available buckets filled and good luminosity.

Shortening Bunches and Lowering β_y^*

Further reduction of β_y^* requires shorter bunches. This can be achieved by either increasing the rf voltage, or by reducing the momentum compaction α_p. In the LER, sufficient rf voltage for 8 mm bunches ($\approx$ 6 MV) is installed. In the HER, the voltage necessary to achieve 8 mm bunches would be prohibitive, requiring more rf stations than necessary to support the expected beam current of 2.2 A. We therefore designed a lattice modification to raise the phase advance/cell in four of the 6 arcs to 90°, which lowers α_p from 0.00241 to 0.00169 with a corresponding reduction

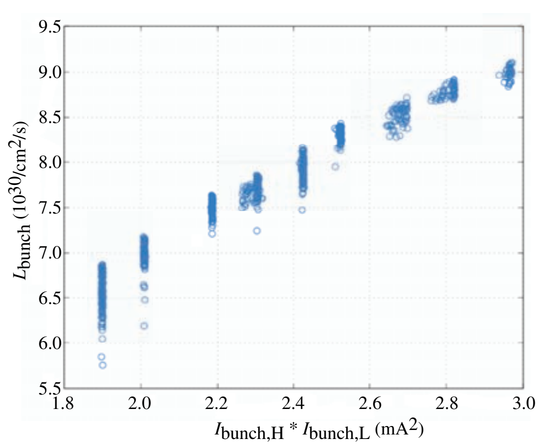

Figure 10: Luminosity/bunch vs bunch current, 870 bunches.

in bunch length to 84% at the same rf voltage.[7] Additionally, the synchrotron tune will remain close to its original value; this is likely to have a positive effect on the luminosity. Implementation required changing some of the magnet strings to allow higher excitation current through the 90° quadrupoles, in addition several strings had to be broken up to allow for the necessary matching. This lattice will be commissioned for Run 7, in the meantime we are raising the rf voltage to 18 MV. In parallel to raising the rf voltage we will further reduce β_y^* in both rings as the shorter bunches allow us to do.

Low-Emittance Lattice for the LER

Beam-beam simulations have indicated that with a significantly reduced vertical beam emittance much higher vertical beam-beam parameters may be achieved.[8] While straightforward for the HER which has a minimum emittance of about 0.1 nmr, the LER lattice needed a modification to reduce its minimum emittance from about 0.5 nmr by theoretically about a factor of 10. This required shortening the section of the lattice within which the coupling introduced by the BaBar solenoid is compensated and was achieved by adding a number of small permanent-magnet skew quadrupoles to the interaction straight section of the LER. In this way, H is reduced to near 0 before entering the adjacent arcs, thus reducing the vertical emittance.[9] The magnets have been installed and the lattice commissioned to the point that performance of the machine with the installed skew quads is now equal or better than before installation. Further improvement is expected with reduced orbit excursions and better decoupling of the machine.

Rf Improvements

While the HER beam current will eventually be limited by the available rf power, in the LER, the beam-current limit will actually be determined by the maximum beam loading achievable in the rf system. The PEP-II rf system is stabilized by a series of rf feedback loops, which effectively reduce the impedance of the cavities seen by the beam. Recent work has determined that the loop gain achievable is limited by imperfections in the driver amplifiers.[10] New and improved amplifiers have been acquired and in part installed. Together with improved tuning of the rf loops these amplifiers are expected to help raise the beam current limit in the LER towards 4 A. Other improvements to this end are new SLAC-built klystrons which can sustain higher output than the Philips/Marconi klystrons we have used in the LER.

Ultimate Parameters

Assuming cumulative benefit realized from all of the improvements, the ultimate parameters of PEP-II are shown in Table 2. Operationally, we do not expect all the above possible luminosity increases to work perfectly, thus leading to a likely peak luminosity of 2×10^{34}/cm^2/s.

Parameter	Unit	HER	LER
Energy	GeV	8.9918	3.1
Beam current	A	2.2	4.0
# bunches		1730	
Rf Voltage	MV	18	6
Mom. compaction α_p		0.00169	0.00241
Bunch length	mm	9	9
horiz. emittance	nmr	50	29
vert. emittance	nmr	0.3	0.3
β_y^*	mm	8	8
β_x^*	cm	25	50
ξ_y		0.13	0.085
Luminosity†	/cm^2/s	2×10^{34}	

Table 2: Ultimate PEP-II Parameters. † Note: Not all parameters at their ultimate values.

ACKNOWLEDGMENTS

PEP-II operation and improvements is a team-effort with many contributors. The authors would like to acknowledge in particular the many contributions by members of the BaBar collaboration as well as by the Beam Physics Dept. at SLAC. Finally, operation of PEP-II would be impossible without the dedicated operations staff in the control room.

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