

PEP-II Operations Report

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Abstract

PEP-II is a two-ring asymmetric B factory operating at the $\Upsilon(4S)$ resonance. It was constructed by a SLAC-LBNL-LLNL collaboration. The collider comprises two rings, a High-Energy Ring (HER) storing 9 GeV electrons, and a Low-Energy Ring (LER) storing 3.1 GeV positrons. Commissioning of the HER began in mid-1997 and commissioning of the LER began in mid-1998. First evidence for collisions was obtained on July 23, 1998. The BABAR detector was installed in early 1999, and commissioning with the detector commenced in May 1999. By September 1999, PEP-II had reached a peak luminosity of $1.35 \times 10^{33} \text{ cm}^{-2} \text{ s}^{-1}$. In the present run, which began in October 1999, the peak luminosity has reached $3.1 \times 10^{33} \text{ cm}^{-2} \text{ s}^{-1}$ and the integrated luminosity delivered is 25 fb^{-1} . At present, PEP-II is the world's highest luminosity collider. In this paper we describe the startup experience and summarize the operational experience during fiscal year 2000 (from October 1999 through September 2000). Plans for luminosity upgrades are briefly described.

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1 Introduction

PEP-II [1], an upgrade of the original PEP collider, was designed and constructed during the period from January 1994 through July 1998 by a team from SLAC, Lawrence Berkeley National Laboratory (LBNL) and Lawrence Livermore National Laboratory (LLNL). The facility has two storage rings, a 9 GeV electron ring (the High-Energy Ring, HER) and a 3.1 GeV positron ring (the Low-Energy Ring, LER). The LER is located above the HER (see Fig. 1) except in the collision straight section, IR-2, where the low-energy beam is brought down into the plane of the HER. The main design parameters for the two rings are given in Table 1. To reach the design luminosity of $3 \times 10^{33} \text{ cm}^{-2} \text{ s}^{-1}$, the nominal beam currents required for the LER and HER are 2.14 A and 0.75 A, respectively. The beam current in each ring is stored in 1656 bunches of roughly 12 mm rms length. The design value for the interaction point (IP) beta functions is 1.5 cm.

The PEP-II injection system is based on the world's most powerful positron source—the SLAC 50 GeV linac. Injection for each ring is on-energy, with transport lines running from the linac extraction point to the ring injection point. Typical intensities are about 1×10^{10} electrons or positrons per pulse at rates up to 30 Hz. Topping up the two beam currents takes about 2 minutes, and filling the rings from zero takes less than 10 minutes.

The design of the collider was done with parameter flexibility in mind. Provisions were made at the beginning of the design for emittance adjustment of the LER by means of wigglers, beta function adjustments in both rings, and easily adjustable bunch patterns. As will be discussed later, we have already made full use of this flexibility to reach high luminosity quickly. Thus, some of the parameters presently being used are different than those in Table 1. In particular, the beam current in the LER is typically 1.4 A and the number of colliding bunches is in the range of 600–700. Beta functions at the IP have been reduced to 1.25 cm.

Reliability was also a key design criterion, that is, we aimed from the outset for a “factory.” This is not to say that there are no component failures in the collider, but it does mean that we are already able to reach, and sometimes exceed, the daily luminosity goal of 135 pb^{-1} that corresponds to delivering 30 fb^{-1} per year at a peak luminosity of $3 \times 10^{33} \text{ cm}^{-2} \text{ s}^{-1}$.

The implementation concept for the facility was to carry out a phased commissioning. This was a natural choice, as the HER was mainly a rebuild

of the earlier PEP ring and could be completed and installed more quickly than could the newly constructed LER. The HER was ready for beam in mid-1997 and began commissioning at that time. The LER was ready for beam in mid-1998 and thus had less time available for commissioning. However, the shakedown of the various subsystems for the HER (RF, feedback, injection, diagnostics, and controls), all of which were identical to those used by the LER, helped immeasurably in rapidly commissioning the LER.

In what follows, we will focus on the early commissioning and operational performance of the collider. We also mention briefly the successes at the end of the recent run, in October 2000, and outline initial luminosity upgrade plans.

2 History

The idea for an asymmetric B factory originated with Pier Oddone in 1987 [2]. Development of the accelerator concept continued in 1988, led by Swapan Chattopadhyay, with help on the lattice by Al Garren [3]. Later, the effort was joined by a few others from LBNL, Caltech, and SLAC. In the early days, the design goal was a luminosity of $1 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$. As we got closer to a formal Conceptual Design Report (CDR), the stated goal was reduced to $3 \times 10^{33} \text{ cm}^{-2} \text{ s}^{-1}$ in an attempt to gain some credibility with a skeptical high-energy physics experimental community. In 1990, the SLAC and LBNL Directors launched a formal collaborative design study that culminated in the first of three CDRs for the facility [4]. This design was reviewed by a U.S. Department of Energy review team in 1991 and was deemed ready for construction. Unfortunately, no funding was forthcoming and we continued our design and R&D effort for several more years.

Funding for PEP-II was finally approved in 1993. The five-year construction project was led by Jonathan Dorfan (Project Director), Tom Elioff (Deputy Project Director), Lowell Klaisner (Chief Engineer), and John Seeman (Chief Accelerator Physicist). Funding for the BABAR detector [5] was approved separately, and an international collaboration of some 500 physicists, with David Hitlin from Caltech as its Spokesperson, was formed to build it.

3 Startup

3.1 HER Commissioning

Beam was first stored in the HER in July 1997. A modified lattice was employed that did not have a “microbeta” at the interaction point [6]. Due to a misunderstanding, initial beam storage was accomplished with all sextupole magnets having inverted polarity compared with their design value, thus doubling (rather than reducing to zero) the natural chromaticity of the ring. After successfully storing a beam (via on-axis injection) with a usable lifetime, a chromaticity measurement immediately diagnosed this error, which was quickly fixed. Thereafter, commissioning progress was rapid, and by January 1998 the HER had reached its full design current of 0.75 A.

During the initial HER-only commissioning period, most of the major subsystems were debugged and made operational. This included the injection system (kickers and timing), the RF system [7], the longitudinal [8] and transverse [9] bunch-by-bunch feedback systems, diagnostics (beam position monitors, beam loss monitors), the abort kicker, and the control system (e.g., orbit and dispersion correction).

Given the high beam currents and large numbers of bunches, it should come as no surprise that the RF and feedback systems are the critical technologies for PEP-II. Without feedback, the HER would be unstable longitudinally beyond 500 mA, and unstable transversely beyond about 20 mA (which is lower than expected and still not well understood). Similarly, the LER would become unstable longitudinally beyond 330 mA and unstable transversely beyond 100 mA in the absence of feedback. With the feedback systems, both beams are stable to the maximum currents obtained so far.

Figure 2 shows the 476-MHz RF cavities located in a straight section of the HER. The curved waveguides contain lossy ceramic loads to damp higher-order modes in the cavity; each cavity has three such loads. Dimensions of the damping waveguides are chosen such that the cavity fundamental does not propagate to the loads. In the HER, a set of four RF cavities (each providing 700 kV) is powered by one 1.2-MW klystron. In the LER, there are two cavities (each providing 800 kV) per klystron.

The longitudinal feedback system [8] operates bunch-by-bunch in the time domain. The phase offset of each bunch is detected and then corrected with

a series drift-tube kicker. Signal processing is done with Digital Signal Processor (DSP) technology. The transverse feedback system [9] also operates bunch-by-bunch in the time domain, but uses analog circuitry for processing (with a digital delay) and includes orbit-offset-rejection circuitry. The transverse system uses a stripline kicker.

3.2 LER Commissioning

The LER was completely installed and ready for beam on July 10, 1998. In this case, the initial ring configuration included the complete low-beta Interaction Region (IR), so the ring was commissioned with $\beta_y^* = 1.5$ cm. The IR geometry is illustrated in Fig. 3. First beam was stored on July 16, 1998 [10]. This was made difficult by the (undetected) presence of a folded-over copper RF seal that occluded much of the available beam aperture. Prior to locating and removing this obstruction, the maximum LER beam current was 53 mA and the maximum lifetime was 3 minutes. Despite this, first evidence for beam collisions was obtained on July 23, 1998. After 15 weeks of LER commissioning without the detector in place (in February 1999), the ring had reached a positron beam current of 1.16 A.

The BABAR detector came on-line on May 10, 1999, after which the focus shifted mainly to collider (as opposed to single-ring) commissioning. As anticipated, the addition of the strong (1.5-T) solenoidal field had a major impact on the LER beam. Both the IR orbit and horizontal-vertical coupling were difficult to correct. After tuning, first collisions were observed in the detector on May 26, 1999. Based on extrapolation from initial background studies without the detector in place, it had been predicted that we might be stalled at low currents for a long time. Fortunately, the scrubbing was rapid and by July 1999 we were colliding with 300 mA in the HER and 700 mA in the LER. By the end of FY99 (September 30, 1999), PEP-II had reached a peak luminosity of $1.35 \times 10^{33} \text{ cm}^{-2} \text{ s}^{-1}$ and had delivered 1.5 fb^{-1} to BABAR.

4 FY00 Operation

4.1 1999 Experience

The goal of the run that started in mid-October 1999 was to provide integrated luminosity for BABAR. The run started out well, and by November PEP-II had reached a peak luminosity of $1.43 \times 10^{33} \text{ cm}^{-2} \text{ s}^{-1}$ with 0.91 A of positrons and 0.64 A of electrons in 829 bunches. During this period the measured beam size at the IP was $\Sigma_x = 200 \text{ } \mu\text{m}$ and $\Sigma_y = 6.5 \text{ } \mu\text{m}$, where Σ_x (Σ_y) is the quadrature sum of the electron and positron horizontal (vertical) beam sizes at the IP. By carrying out two-dimensional luminosity scans, it was also determined that the beam spot at the IP was tilted by 1.1° from horizontal. The highest beam-beam tune shifts obtained during this period were estimated as $\nu_x = 0.035$, $\nu_y = 0.02$, compared with a design value of 0.03 in each plane. Waist scans showed the beams to be longitudinally well centered at the IP.

During normal operation, beam sizes at the IP are measured routinely via luminosity scans and occasionally via deflection scans. Results from the two methods are reasonably consistent and are in rough agreement with what is expected. To keep the beams from the two independent rings in collision, we employ dedicated feedback systems. An (unplanned) example of how the feedback works is shown in Fig. 4. In this case, a power supply for the LER injection septum tripped off, giving rise to a small orbit shift of the LER beam. As can be seen in Fig. 4, the luminosity feedback system (without operator intervention) was able to reoptimize the luminosity for the new conditions over the next several minutes.

The main problem we encountered during this period was that of numerous beam aborts, about 30 per day, necessitating frequent refilling of the rings from scratch (rather than the nominal top-up filling mode where the beam currents have decayed for about 40 minutes and the rings are then restored to their initial beam currents). There were two primary causes for the beam aborts: radiation bursts in the detector-protection diodes that are set up to prevent large doses of radiation to the sensitive portions of the detector, and RF system trips. Clearly, the net result of the beam aborts is to decrease the integrated luminosity per shift.

In mid-November a vacuum leak developed in one of the HER synchrotron radiation masks in the IR. The leak occurred just upstream of the IP—the worst possible spot. A temporary repair was made and the run resumed, but after a few days the initial leak reopened and a second leak developed at a similar mask nearby. The engineering staff concluded that we were cracking the welds due to stress fatigue. It was estimated that this had occurred after

about 3000 thermal cycles. Given the unfortunate location of the leaks, the BABAR backgrounds made the HER essentially unusable for collisions. To allow time to design and fabricate replacement chambers, we limped along with a LER-only development program until December, when we shut down for installation of the new vacuum chambers. During this portion of the run, the LER beam current reached 1.7 A in tests, though colliding beam operation was at lower LER currents.

4.2 2000 Experience

Operations resumed in mid-January after a yeoman effort of the shop and vacuum installation crews to get the IR rebuilt over the Christmas holiday. Unfortunately, due to the venting of the IR, the vacuum in this region was quite poor, and detector backgrounds (dominated by the HER) were high. It took about one month of scrubbing to restore the IR vacuum to its previous low level. During this startup period, the radiation bursts from the HER were markedly worse than before the shutdown. BABAR-requested aborts were happening several times per hour.

At this point, we launched a concerted effort to identify the source of the beam abort problem. No correlation was found with power supply glitches, orbit changes, or RF system behavior. Moreover, we saw no evidence for beam instabilities. This conclusion came from examining the orbit at various beam position monitors (BPMs) around the ring at the time of an abort. (The control system keeps a 1000-turn circular buffer of position information, for many BPMs, that stops when an abort occurs.) Sometimes the high background could be eliminated by topping off the HER beam; occasionally it was eliminated by taking the two beams out of collision; and, as a last resort, the HER beam was manually aborted and refilled. Though this last measure almost always eliminated the problem, even this was not a sure cure, and sometimes a second abort and refill were needed.

The radiation bursts are believed to be caused by “dust” particles trapped by the beam. Their appearance is random and they can last many seconds, or even longer. These high-background events often, but not always, correspond to a decrease in HER beam lifetime. The high backgrounds typically appear in several BABAR detector subsystems simultaneously. We have also found that such events can be induced by tapping on a section of HER beam pipe located upstream of the detector. We sometimes see events in

which the HER lifetime is temporarily reduced but the backgrounds do not increase markedly and there is no beam abort. These are interpreted as cases where the trapped dust particle is far from the IP. At this point we have not identified the source of the dust particles. The dust could be due to any or all of the following: debris from NEG pumps, dirt associated with venting, sputtered material from ion pumps, ablated metal from bellows fingers, etc. The encouraging news is that the events seem to process away over time. That is, their occurrence decreases as we continue to run. After three months of steady running, the dust events happen only a few times per day. On the other hand, at our present production rate, each such event costs the detector about 1 pb^{-1} in integrated luminosity.

In March 2000, the LER wiggler magnets (whose function is to increase the beam emittance from 22 nm-rad to 48 nm-rad) were turned off. This was not the first time this had been tried. In November 1999, a brief test with the wiggler off gave indications of higher luminosity. However, because of the ensuing vacuum difficulties we did not continue in this mode, nor did we return to it until we were back in “steady-state” running. The rationale for this change was evidence that the LER beam was too large vertically at the IP, either due to beam-beam effects or to beam blowup from “electron cloud” effects (to be discussed below). Thus, we expected that starting from an initially smaller beam might increase the luminosity.

This idea turned out to work admirably. By mid-March 2000 we had reached a peak luminosity of $1.72 \times 10^{33} \text{ cm}^{-2} \text{ s}^{-1}$ with 0.96 A of positrons and 0.75 A of electrons in 829 bunches. At this point, our best 8-hour shift produced 33 pb^{-1} and our best 24-hour day produced 84 pb^{-1} . By early April, the operators had tweaked the orbits and IR skew quadrupoles to reach a peak luminosity of $1.95 \times 10^{33} \text{ cm}^{-2} \text{ s}^{-1}$ with 0.975 A of positrons and 0.86 A of electrons in 829 bunches. Note that the LER was operating with roughly half of its design current and half the design number of bunches, whereas the HER was operating at a beam current somewhat above its design current. In terms of single-bunch parameters, the LER was operating at nominal value and the HER was operating at roughly twice its nominal value.

As can be inferred from the description above, most of the luminosity gain was associated with increasing the HER beam current. We continued on this path, reaching a beam current of 0.92 A in the HER, until a leak developed in the high-power synchrotron radiation dump 17 m downstream from the IP. This area is designed to handle some 50 kW of synchrotron radiation from

the B1 separation dipoles near the IP. After repairs, we resumed running, with the HER beam current limited administratively to ≤ 0.65 A. (This limit was relaxed progressively as we pushed up the luminosity toward the end of the run in October 2000.)

As mentioned earlier, we see evidence (Fig. 5) for an increase in the LER vertical beam size at high current. We also see corresponding evidence (Fig. 6) for strong vacuum activity—mainly in the straight sections but observed in the arcs as well. These observations are consistent with expectations from the so-called Electron Cloud Instability [11]. This instability is due to an interaction between positron beam bunches and the copious electron cloud that fills the beam duct. (The cloud is made up of secondary electrons produced at the beam duct wall, which is bombarded by high-energy electrons accelerated by the large potential of the beam bunches—essentially a multipactor phenomenon.) Recognition of this effect [12] came shortly after the conceptual design of PEP-II was completed but, fortunately, before actual construction began. To combat this effect, we have added solenoid windings around the LER straight section pipes. Energizing these coils to modest fields (10–20 G) improves the luminosity immediately. Because the instability has a rapid, but not instantaneous, risetime, we have also been able to mitigate the growth of the beam size by tailoring the bunch train with various “microgaps” and “minigaps,” as illustrated in Fig. 7.

The best measure of collider performance is the integrated luminosity. As of September 3, 2000, PEP-II had delivered 18.8 fb^{-1} to the detector and BABAR had logged 17.6 fb^{-1} , corresponding to a logging efficiency of 94%. The best 24-hour day delivered more than 160 pb^{-1} . While this is not typical, we have had this level of performance many days. A more typical performance corresponds to an average luminosity of $1.5 \times 10^{33} \text{ cm}^{-2} \text{ s}^{-1}$, that is, 130 pb^{-1} per day or 5.4 pb^{-1} per hour. From the initial design specifications, we consider a “design day” to correspond to 135 pb^{-1} , in the sense that our design goal of delivering 30 fb^{-1} in one operating year at the design peak luminosity of $3 \times 10^{33} \text{ cm}^{-2} \text{ s}^{-1}$ requires this daily average. Our results to date mean that we are doing somewhat better in terms of operating efficiency than we had estimated in 1993. The peak luminosity reached by early September was $2.4 \times 10^{33} \text{ cm}^{-2} \text{ s}^{-1}$ with 1.44 A of positrons and 0.65 A of electrons in 605 bunches.

4.3 End of Run Performance Records

The present PEP-II run did not end until October 31, 2000, extending slightly beyond the fiscal year boundary. In the last few days of the run, several important performance milestones were reached. For completeness, we include these here. At the end of the run, the collider parameters were successfully pushed in an attempt to reach the luminosity design goal. The best 24-hour luminosity during this period was 174 pb^{-1} . Our design goal was reached on October 29, 2000, when the best fill produced a peak luminosity of $3.1 \times 10^{33} \text{ cm}^{-2} \text{ s}^{-1}$ with 1.55 A of positrons and 0.79 A of electrons in 692 bunches; the detector was able to record data under these conditions. The following day, the LER stored beam current (in single-ring operation) was raised to its design value of 2.14 A, with a lifetime of better than two hours. Most importantly, by the end of the run the collider had delivered a total of 25 fb^{-1} to BABAR.

4.4 Performance Summary

A summary of the performance records at the end of the run is given in Table 2. After 17 months, PEP-II has reached its design goals for peak luminosity, daily average design luminosity, HER beam current, and LER beam current.

Though not really the subject of this paper, for completeness the first physics measurement result should be included. Based on the analysis of 9 fb^{-1} of data, the Babar collaboration reported at Osaka a value of $\sin(2\beta) = 0.12 \pm 0.37(\text{stat}) \pm 0.09(\text{syst})$.

5 Upgrade Plans

Though we have just now reached our luminosity design goal, planning for luminosity upgrades is already under way. The next performance goal set by SLAC Director Jonathan Dorfman is to reach a peak luminosity of $1 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$ during 2003. This will involve one or more of the following changes:

- Increasing the number of bunches (possibly changing to every RF bucket spacing); this would require a crossing angle and perhaps crab cavities

- Roughly doubling the beam current in each ring; this would require more RF power and perhaps augmented feedback and vacuum systems
- Reducing β_y^* to 0.75–1.0 cm
- Increasing the beam-beam tune shift to 0.06, adjusting the emittance as needed; this will likely involve relaxing the “energy transparency” conditions that are approximately maintained in the present design

An even more ambitious luminosity goal is to reach a peak luminosity of $3 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$ during 2006. A concept for an IR configuration to accomplish this is shown in Fig. 8.

6 Summary

It took PEP-II just 17 months after the detector was installed to reach its design luminosity of $3 \times 10^{33} \text{ cm}^{-2} \text{ s}^{-1}$, making it the world’s highest luminosity collider. The PEP-II LER has reached a maximum current of 2.14 A, making it the world’s highest current positron storage ring; it routinely operates at 1.4 A during collision runs. Clearly there is still work to be done to reach our extended luminosity goal of $1 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$, and even more work to reach our ultimate goal of $3 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$. The rapid and steady progress we have made thus far gives us optimism that we will reach these more ambitious goals as well.

Acknowledgments

The successes reported here belong to many people. The engineers, designers, and technicians provided robust and reliable hardware to work with, and the installation crew put it into the tunnel without any problems. The commissioning team, along with the superb SLAC operations group, were able to relatively quickly coax the collider into performing up to its design level. It has been a pleasure and a privilege to work with such dedicated and skilled people during the design, construction, and commissioning of PEP-II.

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Table 1: PEP-II collider design parameters.

| | LER | HER |
|---|--------------------|-------------------|
| Energy, E [GeV] | 3.1 | 9.0 |
| Circumference, C [m] | 2199.32 | 2199.32 |
| $\varepsilon_y \varepsilon_x$ [nm-rad] | 1.5 49 | 1.5 49 |
| $\beta_y^* \beta_x^*$ [cm] | 1.5 50 | 1.5 50 |
| $\xi_{0x,0y}$ | 0.03 | 0.03 |
| f_{RF} [MHz] | 476 | 476 |
| V_{RF} [MV] | 3.2 | 14.0 |
| Bunch length, σ_ℓ [mm] | 12 | 11.5 |
| No. of bunches, k_B | 1656 ^a | 1656 ^a |
| Bunch separation, s_B [m] | 1.26 | 1.26 |
| Damping time, $\tau_E \tau_x$ [ms] | 30.2 62.7 | 18.3 36.8 |
| Total current, I [A] | 2.14 | 0.75 |
| Energy loss, U_0 [MeV/turn] | 0.75 | 3.59 |
| Luminosity, L [cm ⁻² s ⁻¹] | 3×10^{33} | |

^aIncludes gap of 5% for ion clearing.

Table 2: PEP-II performance records to date.

| | Achieved | Design Value |
|--|-----------------|---------------------|
| HER beam current [A] | 0.92 | 0.75 |
| LER beam current [A] | 2.14 | 2.14 |
| Peak luminosity [10 ³³ cm ⁻² s ⁻¹] | 3.1 | 3.0 |
| 24-hour luminosity [pb ⁻¹] | 174 | 135 |



Figure 1: View of PEP-II tunnel showing HER (below) and LER (above).



Figure 2: View of HER RF straight section. The curved waveguides on each cavity lead to damping loads that eliminate unwanted higher-order modes.

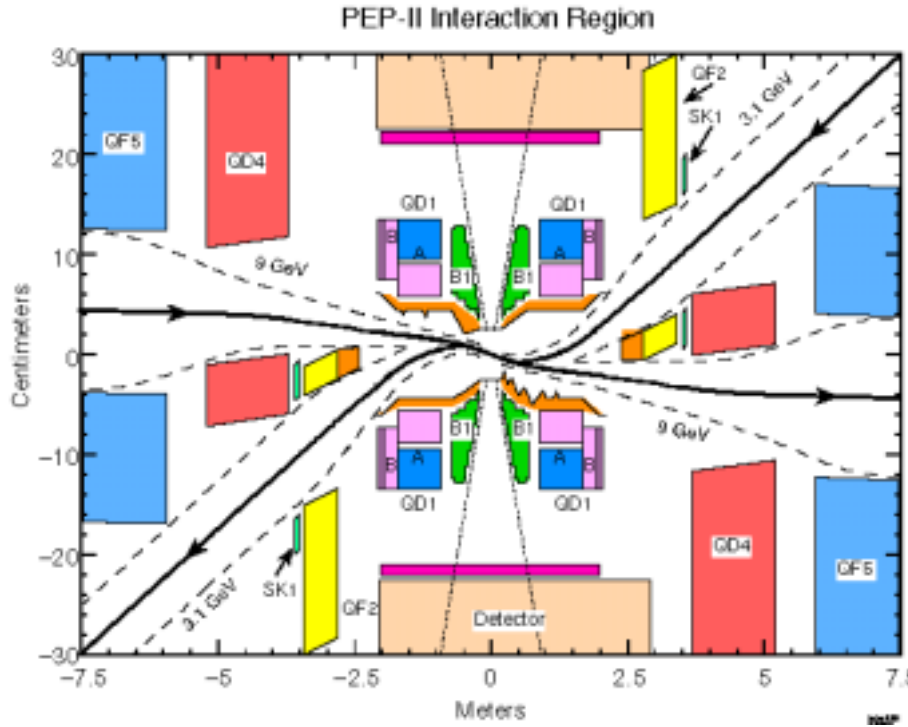


Figure 3: PEP-II IR geometry. Collisions are head-on at the IP. Because they are immersed in the detector solenoidal field, the inner separation dipoles (B1) and quadrupoles (QD1) are permanent magnets.

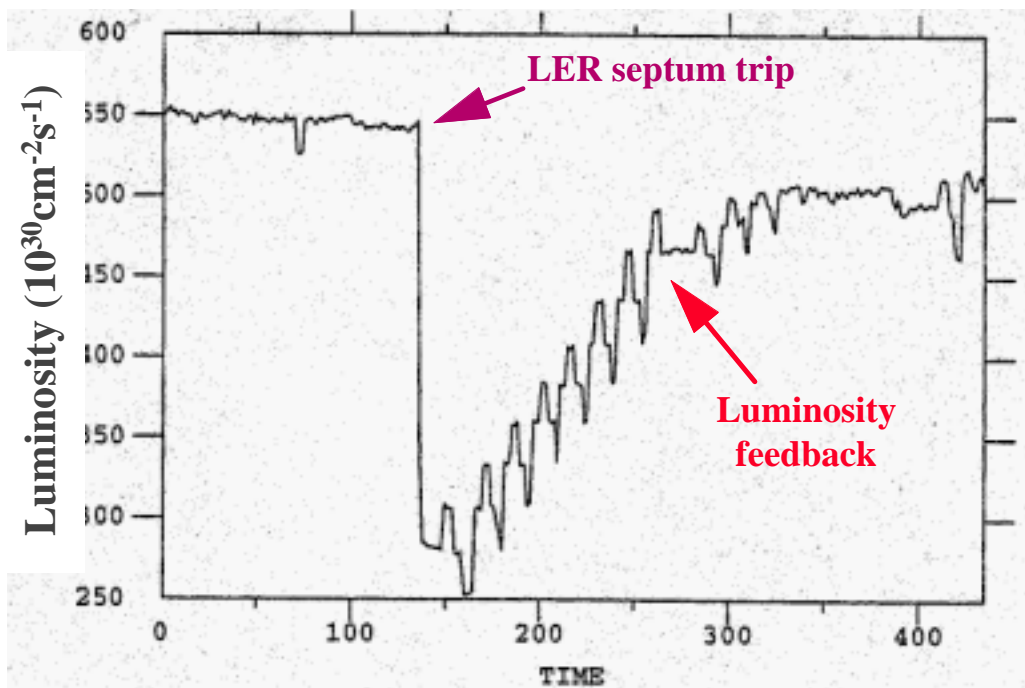


Figure 4: Illustration of automatic recovery of luminosity by collision feedback system after an unexpected trip of LER injection septum power supply.

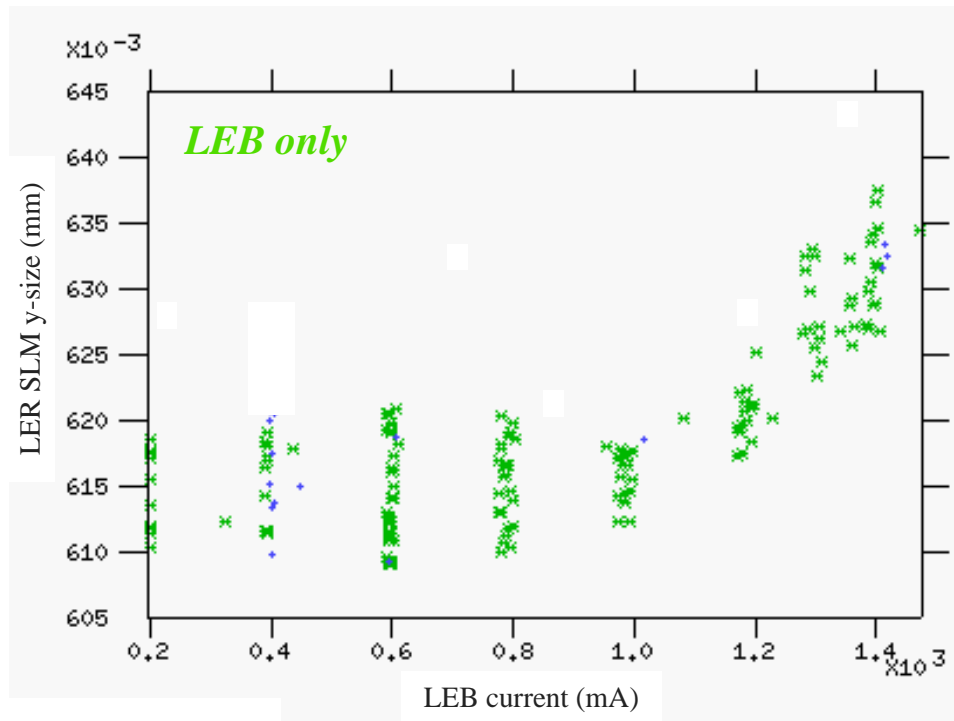


Figure 5: LER beam size as a function of beam current, as measured by digitizing the synchrotron light monitor output.

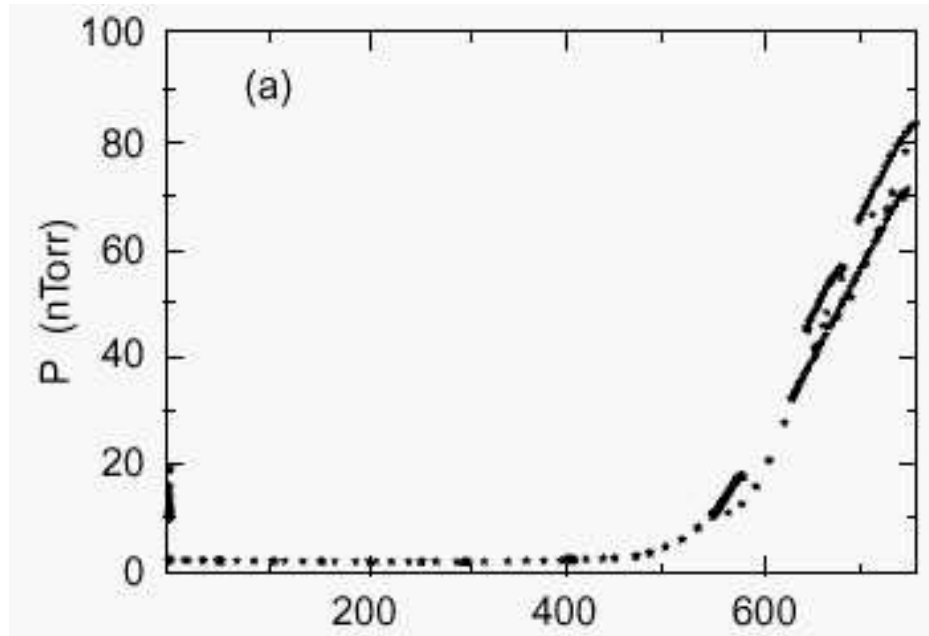


Figure 6: LER vacuum pressure at the downstream end of a 110-m straight section, showing rapid increase in pressure when beam current exceeds 500 mA. The small initial slope demonstrates that synchrotron radiation plays no role in the effect. There is evidence for cleaning, and the pressure rise has become much less visible as the ring conditions.

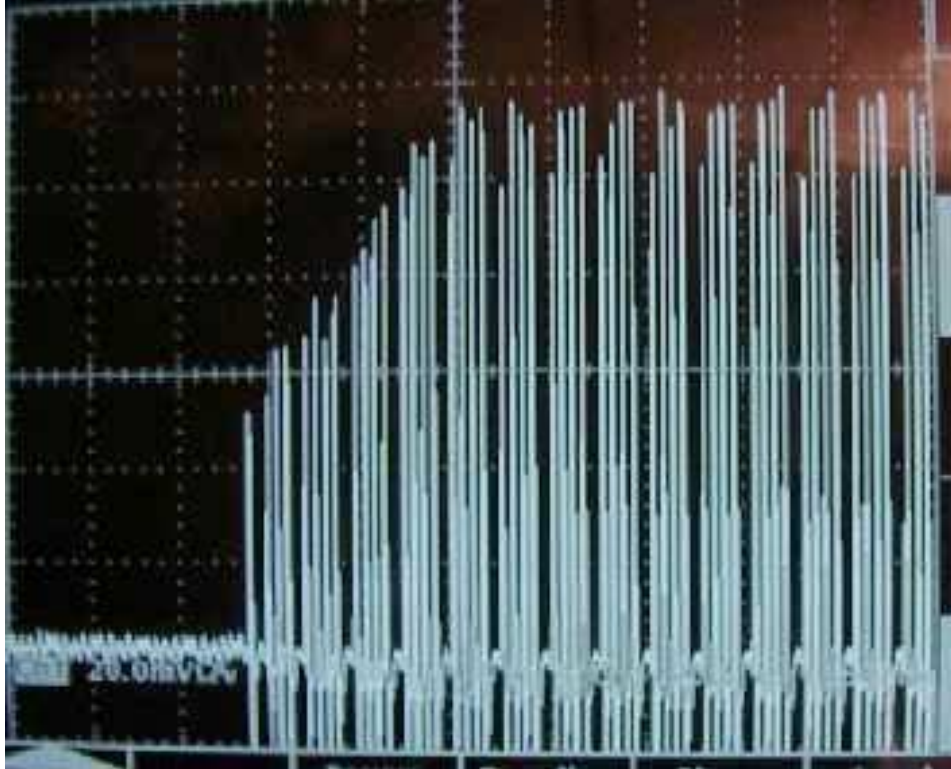


Figure 7: Representative bunch fill pattern during collisions, showing “mini-gaps.” The gaps mitigate the beam size increase indicated in Fig. 5 and roughly maintain the specific luminosity as the LER beam current is increased.

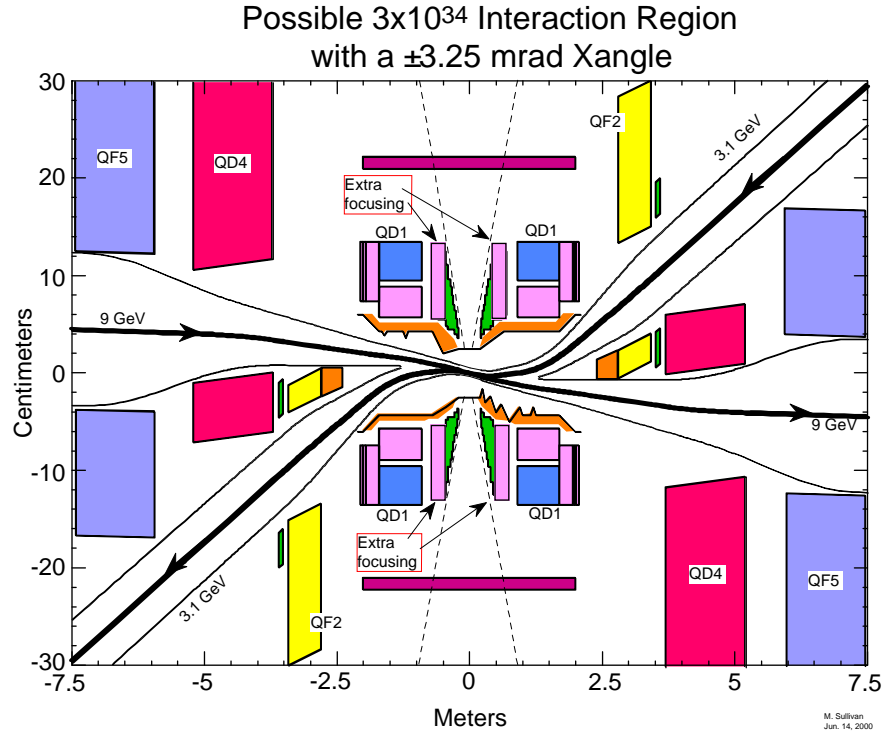


Figure 8: Possible IR configuration for reaching a luminosity of $3 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$. Compared with Fig. 3, the B1 dipoles are reduced in length to provide room for additional quadrupole focusing. Such a configuration results in a small crossing angle at the IP.