STATUS REPORT ON PEP-II PERFORMANCE*

J. Seeman#, Y. Cai, J. Clendenin, F.-J. Decker, M. Donald, S. Ecklund,
R. Erickson, A. Fisher, R. Iverson, P. Krejcik, A. Kulikov, M. Minty, J. Nelson, I. Reichel,
M. Stanek, M. Sullivan, J. Turner, U. Wienands, SLAC, Stanford, CA 94309, USA
C. Steier, M. Zisman, LBL, Berkeley, CA, USA
W. Kozanecki, Saclay, France
M. Biagini, INFN, Frascati, Italy
M. Placidi, CERN, Geneva, Switzerland

Abstract

PEP-II [1-9] is an e+e- collider with asymmetric energies (3.1 and 9 GeV, respectively) in a 2200 m tunnel at the Stanford Linear Accelerator Center. The collider produces B mesons to study a particle physics effect called CP violation as well as other physics topics. PEP-II was completed in 1998 with the first luminosity generated in July of that year. The installation of the BaBar Detector was finished in May 1999.

The overall layout of PEP-II is shown in Figure 1 and the interaction region of PEP-II in Figure 2. The accelerator parameters and achievements of the High Energy Ring (HER) are listed in Table 1 and those for the Low Energy Ring (LER) in Table 2. The two beams collide at a single point in the IR2 hall where the BaBar detector is located. Beam parameters at the best luminosity are shown in Table 3 and PEP-II milestones in Table 4.

In August 1999 PEP-II passed the world's record for luminosity which was $8.1 \times 10^{32}/cm^2/s$. The present luminosity in PEP-II is 2.15×10^{33} $/cm^2/s$ which is 72% of the design. In June 2000 PEP-II delivered an integrated luminosity of 150 pb^{-1} in one day, which is above the design integrated luminosity per day of 135 pb^{-1}. Over the past year PEP-II has delivered over 12 fb^{-1} to BaBar. BaBar has logged over 11 pb^{-1}. The present plan is collide until the end of October 2000 followed by a three month installation period.

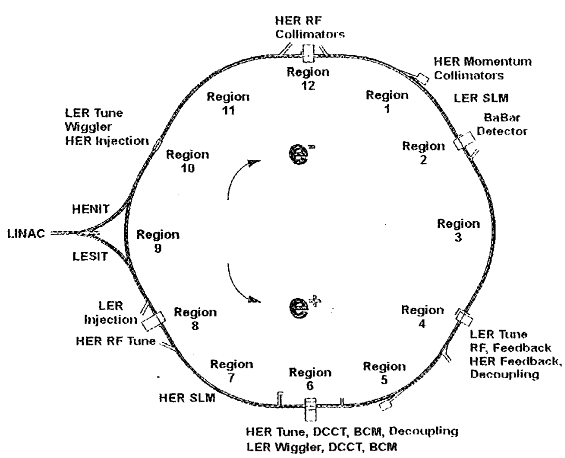

Figure 1: PEP-II B-Factory Overview

Table 1: HER e- PARAMETERS

HER Parameter	Design	Achieved
Beam energy (GeV)	9.0	9.1
Number of bunches	1658	1658
Particles per bunch	2.1×10^{10}	5.6×10^{11}
Total current (mA)	750	950
Current per bunch (mA)	0.45	>12.
Bunch spacing (m)	1.26	0.63
Bunch length (mm)	11.0	11.0
ΔE/turn (MeV)	3.6	3.6
RF frequency (MHz)	476.	476.
Ion clearing gap (%)	5	5
RF voltage (MV)	14.0	14.0
Rel. energy spread (10^{-3})	0.61	0.61
Synchrotron tune	0.045	0.045
Betatron tune (ν_x/ν_y)	24.62/23.64	24.57/23.64

Table 2: LER e+ PARAMETERS

LER Parameter	Design	Achieved
Beam energy (GeV)	3.1	3.1
Number of bunches	1658	1658
Particles per bunch	5.9×10^{10}	3.2×10^{11}
Total current (mA)	2140	1720
Current per bunch (mA)	1.29	>7.
Bunch spacing (m)	1.26	0.63
Bunch length (mm)	10.0	12.2
ΔE/turn (MeV)	0.75	0.68
RF frequency (MHz)	476.	476.
Ion clearing gap (%)	5	5
RF voltage (MV)	5.1	3.4
Rel. energy spread (10^{-3})	0.77	0.79
Synchrotron tune	0.033	0.027
Betatron tune ($\nu_x/\nu y$)	38.57/36.64	38.65/36.58

*Work supported in Department of Energy contract number DE-AC03-76SF00515.
Email: SEEMAN@slac.stanford.edu

Table 3: PEP-II COLLISION PARAMETERS

IR Parameter	Design	Present Operating
C-M energy (GeV)	10.28	10.28
Crossing angle (mrad)	0.0	<0.1
Luminosity (x1E33)	3.00	2.15
Number of bunches	1658	598
HER current (mA)	750	700
LER current (mA)	2146	1100
Beam-beam parameter (y+/-)	0.03	0.025/0.015
Beam-beam parameter (x+/-)	0.03	0.06/0.05
$\beta y^*/\beta x^*$ (cm/cm)	1.5/50.	1.25/50.
Optimum coupling (%)	3.0	3 to 10
Emittance (nm-rad) (y/x)	1.5/49.	3/30-,50+
IP rms beam σ_y/σ_x (mm)	4.7/157.	5.0/147
Σx,y (microns)	6.7/222	7.0/207
Injection top-off time (min)	3	2
Injection full fill time (min)	10	8
Detector solenoid field (T)	1.5	1.5
Peak integrated luminosity in 8 hours		53 pb^{-1}
Peak integrated luminosity in 24 hours		150 pb^{-1}
Peak integrated luminosity per week		782 pb^{-1}
Peak integrated luminosity per month		2.7 fb^{-1}
Total integrated luminosity thru 6/21/00		12 fb^{-1}

Table 4: PEP-II MILESTONES

Date	Milestone or Commissioning
1994 January	Start of PEP-II construction
1997 June	HER installation complete
1997 June 16	HER beam first stored
1998 July 10	LER construction complete
1998 July 16	LER beam first stored
1998 July 23	First collisions
1998 Dec. 8	8 x10^{31} luminosity
1998 Feb. 8	5.2 x 10^{32} luminosity
1999 May 10	BaBar detector installed
1999 May 26	First hadronic events recorded
1999 June 15	Scan of the Upsilon 4S
1999 Aug 12	Luminosity peak of 8.3x10^{32}
1999 Sept 14	Luminosity peak of 1.35x10^{33}
2000 Mar 5	Luminosity peak of 1.56x10^{33}
2000 June 11	Integrated 150 pb^{-1} in one day
2000 June 20	Integrated luminosity of 12 fb^{-1}
2000 June 22	Luminosity peak of 2.15x10^{33}

1 FY1999 PEP-II PROGRESS

The PEP-II e+e- collider was completed with the finishing of the Low Energy Ring (LER) in July 1998. Initial collisions were seen shortly thereafter. Fall and winter PEP-II runs were concentrated on raising the beam currents and increasing the luminosity. A peak luminosity in February 1999 reached 5.2 x $10^{32}/cm^2/s$. In a two month spring down time the BaBar detector was installed. PEP-II turned on May 10 and BaBar saw its first events on May 26, 1999.

During summer 1999 accelerator physics work was concentrated on reducing the collision spot sizes, raising the beam currents, and reducing the beam backgrounds in BaBar. The spot sizes were reduced by working on compensation of the BaBar solenoid using local skew quadrupoles in both rings near the detector. Twenty four skew quadrupoles are used. Subtle cross plane beam measurements, off-line analysis, and empirical tuning have been successful in reducing the spot sizes to the design sizes. Cap-sigma values of 6.5 microns vertically and 200 microns horizontally have been achieved. The beam currents were slowly raised watching for heating of vacuum chambers, effects in the high power RF systems, and stability of the bunch by bunch feedback systems. A current of 650 mA in the High Energy Ring (HER) was achieved which was stable for collisions. A current of 1550 mA in the LER was achieved which was also stable for collisions. This positron current was a new world's record for a stored anti-particle beam. Finally, the BaBar backgrounds were reduced with the use of collimators in both rings, careful trajectory control in the interaction region, and care with the injection beam quality and beam orbits.

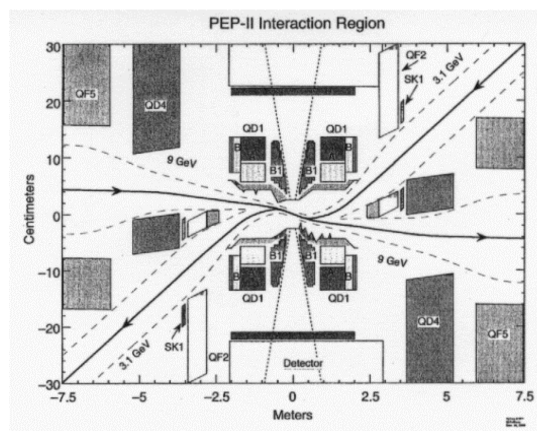

Figure 2: PEP-II interaction region using permanent magnet quadrupoles and dipoles inside the detector.

On August 18, 1999, a luminosity of 8.3 x $10^{32}/cm^2/s$ was achieved which tied the world's record set by Cornell earlier in 1999. On September 14, 1999, a new world's record luminosity was achieved of 1.35 x$10^{33}/cm^2/s$ with BaBar taking data. The beam currents at this peak luminosity were 900 mA in the LER and 600 mA in the HER in 830 bunches. In fall 1999 PEP-II delivered data to BaBar about 5 days per week with machine development about 2 days per week. By October PEP-II had so far delivered about 1300 pb^{-1} of data to BaBar on the Upsilon 4S resonance and about 200 pb^{-1} off the resonance. BaBar has logged and recorded on tape about 92% of this data. A two week fall down time was taken in October to install the BaBar DIRC bars and PEP-II vacuum equipment.

2 FY2000 PEP-II PROGRESS

After the October downtime, PEP-II recovered beams by about October 18 and e+e- collisions were restored in the following week. The primary purpose of the fall run was to integrate luminosity for BaBar. The run was going well until November 13 when a vacuum leak opened on a synchrotron radiation mask in the interaction region in the HER. This leak was fixed but opened again a few days later, and was fixed again. A few days after that, a second vacuum leak developed in another IR mask with a similar design. The problem was stress fatigue in stainless welds after 1000 heating cycles. Therefore, it was determined that the construction of these masks (three total in PEP-II) was not adequate. A decision was made to remove the chambers containing the masks and to rebuild them, starting in December, 1999. These chambers were reinstalled by January 12, 2000, when PEP-II returned to collisions.

October and November 1999 accelerator physics produced several results. A new record luminosity of $1.43\text{x}10^{33}/\text{cm}^2/\text{s}$ achieved on November 10 where 830 bunches were collided with 908 mA of positrons, 642 mA of electrons and a specific luminosity of 2.0. The cap-sigma spot sizes were about 6.5 and 200 microns vertically and horizontally, respectively. Note the current ratio is 1.4 e+ to e- whereas the design is 3.0. The beam-beam tune shifts were about 0.035 horizontally and 0.02 vertically. The beams at the IP were measured to be tilted by about 1.5 degrees. The LER current was raised to 1.72 A. Parasitic beam-beam crossing studies were done by filling adjacent bunches in both rings. The main effect was to shift the vertical tune by about 0.01. When these tune shifts were corrected, the parasitic crossings did not change the peak luminosity achievable per bunch. Tests were made to center the minima of the IR beta functions at the collision point by moving the waists with the IR quadrupoles while measuring the luminosity using the rf relative phase. The waists were found to be very nearly centered.

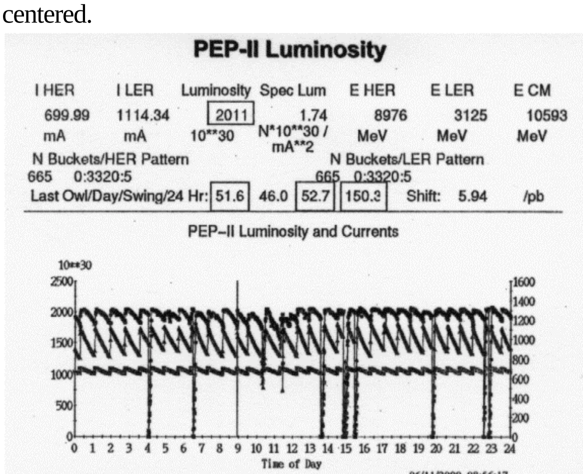

Figure 3: PEP-II luminosity and beam currents recorded over 24 hours on June 11, 2000, with a peak luminosity of $2.01\text{x}10^{33}\ /\text{cm}^2/\text{s}$ and a daily integrated luminosity of 150 pb^{-1}.

During the brief fall run PEP-II delivered about 0.5 fb^{-1} to BaBar bringing the total to about 2.0 fb^{-1}, with 1.8 fb^{-1} on the peak of the Upsilon 4S and 0.2 fb^{-1} off the resonance. Radiation bursts which last for a short time (1 sec) started to dominate the causes of the beam aborts during the colliding coasts. RF system trips were the second largest cause of aborts. There were about thirty beam aborts per day

The LER synchrotron radiation wiggler was turned off and the beams collided. The LER emittance decreased by a factor of two. The specific luminosity of PEP-II increased from 2.0 to about 2.7.

After turn-on January 12, 2000, the overall beam lifetimes were satisfactory as the vented fraction of each ring was quite small. As expected, the vacuum levels in the interaction region were high for a while during the first few weeks, causing detector backgrounds dominated by the HER beam. After a month of operation the average backgrounds were down to the Fall 1999 levels if not slightly better.

However, increased radiation bursting in BaBar occurred in January 2000. PEP-II has always had short (a second or two in duration) bursts of high radiation in BaBar. After turn-on, the bursting rate was three to four times higher. At first BaBar would abort the beams every ten minutes or so leading to about 40 trips per day. With practice, injection has become very efficient with a full injection from zero current taking about 10 minutes and a top-off only 2 minutes. The cause of the bursts is known to be small dust particles most likely from the NEG pumps stirred and spread by vacuum venting gasses. A small mechanical solenoid was made to tap on the chamber and could produce the radiation bursts. Tune jumps, rf glitches, and orbit moves have been looked at carefully and ruled out. Fortunately, the aborts from bursts have decreased from beam processing after three months of operation to a few per day.

In early March 2000, the LER wiggler was turned off to reduce the LER spot sizes at the interaction point. Immediately, a new luminosity record of $1.56\text{x}\ 10^{33}/\text{cm}^2/\text{s}$ was achieved with 670 mA in the HER and 810 mA in the LER in 829 bunches. By mid-March 2000 the luminosity had reached $1.72 \text{ x } 10^{33}/\text{cm}^2/\text{s}$ with 829 bunches and 750 mA on 960 mA. The best integrated luminosity was 33 pb^{-1} in an eight hour shift and 84 pb^{-1} in 24 hours.

During March 2000 the PEP-II operators made steady adjustments to skew quadrupoles, orbits, and bunch charges during collisions for BaBar. The luminosity in PEP-II by early April 2000 reached 1.95 x 10**33/cm**2/s with 829 bunches, 860 mA of electrons, and 975 mA of positrons.

On April 6 with a HER current of 900 mA a vacuum leak developed in the high power dump downstream of the interaction region where 50 kW radiation fans from the permanent magnet B1 dipoles strike. An external guard vacuum was successfully mounted over the leaky chamber and machine operation resumed. To avoid a potentially larger problem and to allow BaBar to collect data, the HER current has been administratively limited to 600 mA (and later 700 mA). A plan is being prepared to fix or replace the leaky chamber during the November-January down this fall. With the limited current the peak luminosity was about 1.6E33.

Using the synchrotron light monitor, we have observed for several months that the positron beam size increases with beam current above about 800 mA. This enlargement is consistent with the Electron Cloud Instability. The likely source of electrons in the PEP-II LER is multipacting electrons in the LER straight sections. See Figure 4. During our repair days, we have been winding a single layer solenoid on the beam pipes in the straight sections. About 340 m of solenoid is now in place. After energizing these solenoids from 5 to 10 gauss, the positron beam size enlargement with current is now smaller and the specific luminosity is higher. The solenoids were empirically adjusted to maximize the luminosity. The optimum luminosity depends somewhat at the polarity and amplitude of the solenoids. Most of the solenoids are not operating at their maximum excitation. More studies are planned and we will be winding more solenoids over the remaining 150 m of straight section.

After turning on the solenoids the luminosity jumped from 1.6 to about $1.9x10^{33}$ in a few hours. A clear correlation. See Figure 5. The present peak PEP-II

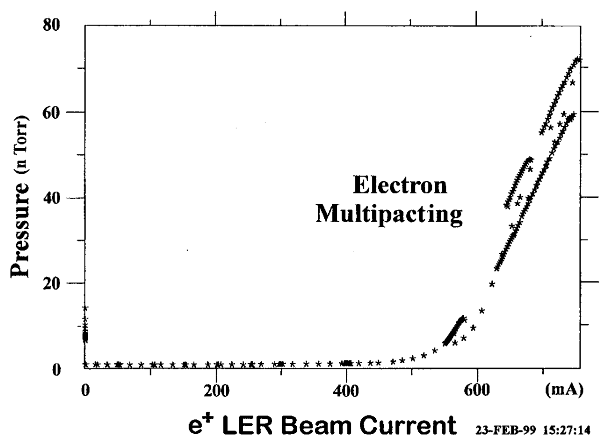

Figure 4: Electron multipacting in the PEP-II LER straight section vacuum chambers increases the vacuum pressure.

operating parameters are: The maximum luminosity is 2.15x10**33/cm**2/s with 598 bunches, 700 mA of e-, and 1100 mA of e+. The peak luminosity per bunch is now twice the design. The integrated luminosity per day is shown in Figure 6 and the integrated per month is shown in Figure 7.

3 FEEDBACK SYSTEMS

All beams are stable with bunch-by-bunch feedbacks in all planes: x, y, and z. Without feedbacks the LER is stable longitudinally to about 330 mA and the HER to about 500 mA, agreeing with predictions. Transversely, the LER instability threshold is at least 100 mA, again near the prediction. However, the HER transverse threshold is about 10 to 20 mA which is much lower that predicted. The data do not point to ions. However, there is likely a resonance in the interaction region vacuum chamber which excites the HER multibunch beam. This resonance depends strongly on the HER horizontal angle. Without transverse feedback very short trains in either ring are unstable at low currents with the tail of the train oscillating.

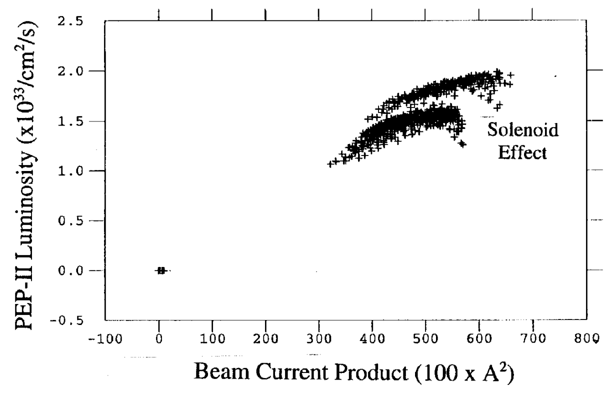

Figure 5: Luminosity versus the product of the beam currents. The luminosity increased sharply after the straight section beam pipe solenoids were energized.

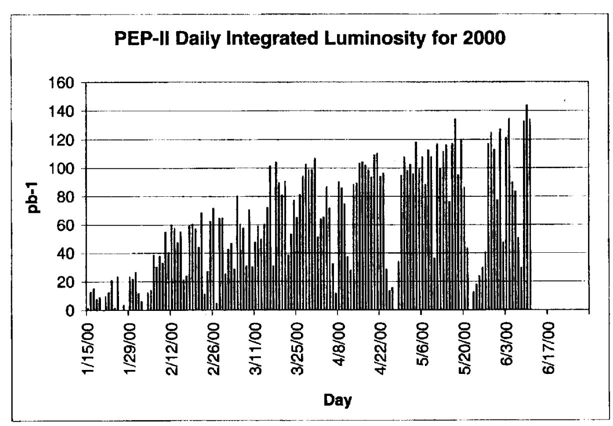

Figure 6: Daily integrated luminosity in PEP-II since January 2000. The peak is 150 pb^{-1} per day.

4 SUMMARY

PEP-II has had a good start, integrating about 12 fb^{-1} by mid-June 2000. Issues for the future include understanding the empirical skew quadrupole adjustments to make smaller spot sizes, raising the LER and HER currents, reducing beam aborts from short radiation bursts in BaBar and from the RF system, lowering beta y* from 1.25 cm to 1.0 cm, reducing the electron cloud instability, and raising the number of bunches.

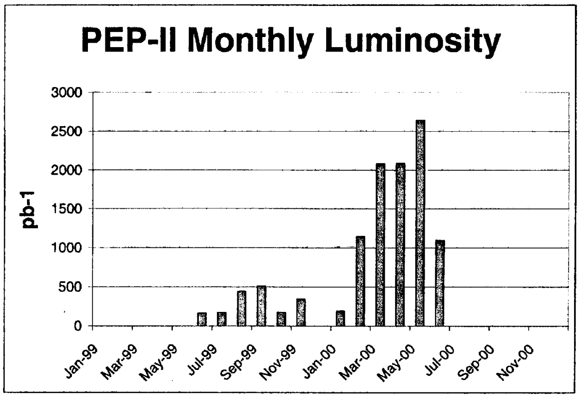

Figure 7: Monthly integrated luminosity delivered by PEP-II. A total of 12 fb^{-1} has been delivered, over 11 fb^{-1} has been logged by BaBar.

REFERENCES

[1] "PEP-II Conceptual Design Report", SLAC Report 418, LBL-PUB-5379, June (1993).

[2] M. Sullivan, "Beam-Beam Collisions at PEP-II," PAC99 proceedings, March 1999.

[3] P. Corredoura et al., "Low-level RF System for the PEP-II B-Factory", PAC95, p. 2672 (1995) and PAC99 proceedings, March 1999.

[4] M. Zisman, "Commissioning Results of the PEP-II LER," PAC99 proceedings, March 1999.

[5] J. Seeman, "KEKB and PEP-II B Factories," Proceedings of Flavor Physics Conference, Nuc. Phys. B 59 (1997), p. 51.

[6] J. Fox, "Multi-Bunch Instability Diagnostics via Digital Feedback Systems," PAC99 proceedings, March 1999.

[7] J. Seeman, "PEP-II Status', Proceedings of the e+e- Factories Workshop, p. 7, KEK, September, 1999.

[8] F.J. Decker, et, al, "Multibunch Operation of PEP-II", EPAC 2000, Vienna, Astria.

[9] Y. Nosochkov, et al, "Recent PEP-II Lattice Developments', EPAC 2000, Vienna, Austria.