PEP-II STATUS*

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Abstract

PEP-II and BaBar have just finished run 7, the last run of the SLAC B-factory. PEP-II was one of the few high-current e+e- colliding accelerators and holds the present world record for stored electrons and stored positrons. It has stored 2.07 A of electrons, nearly 3 times the design current of 0.75 A and it has stored 3.21 A of positrons, 1.5 times more than the design current of 2.14 A. High-current beams require careful design of several systems. The feedback systems that control instabilities, the RF system stability loops, and especially the vacuum systems have to handle the higher power demands. We present here some of the accomplishments of the PEP-II accelerator and some of the problems we encountered while running high-current beams.

PEP-II DESIGN

The PEP-II is an asymmetric-energy double storage ring e+e- accelerator [1]. The rings are housed in a 2.2 km long tunnel with the low-energy ring (LER) above the high-energy ring (HER). The LER has eight RF cavities driven by 4 klystrons and the HER has 11 klystrons driving 28 RF cavities. Each ring contains two transverse bunch-by-bunch feedback systems (X and Y) and one longitudinal bunch-by-bunch feedback system. The beams collided head-on in the middle of the BaBar detector. The head-on collision is achieved through the use of powerful horizontal bending magnets made of permanent magnet (PM) material. The 0.5 m long magnets are positioned 0.21 m from the Interaction Point (IP). Both beams travel through a shared quadrupole, the next magnetic element outboard of the IP. This magnet is also built from PM material [2]. These two magnets the dipole and the quadrupole are inside the 1.5T solenoidal field of the BaBar detector. Table 1 lists some of the design parameters of PEP-II and figure 1 shows the tunnel layout. Figure 2 is an anamorphic layout of the IP showing the beam trajectories as they enter and exit the detector.

RUN 7

Throughout the history of PEP-II the beam energies have been constant and set to deliver luminosity at the peak of the upsilon 4S resonance (10.580 GeV E_{cm}). The

Table 1: Design and actual values of PEP-II parameters

	Design	Actual
Parameter	HER/LER	HER/LER
Beam Energy (GeV)	8.97/3.12	8.0-10.1/3.12
Beam Current (A)	0.75/2.14	2.07/3.21
β_x* (cm)	50	30-105
β_y* (mm)	15-25	9-10
Number of bunches	1658	1722
Ion gap (%)	5	1.6
Crossing angle(mrad)	0	<0.05
Horizontal ξ_x	0.03/0.03	0.113/0.027
Vertical ξ_y	0.03/0.03	0.062/0.047

Figure 1. Tunnel layout of the two beam lines. The LER is above the HER.

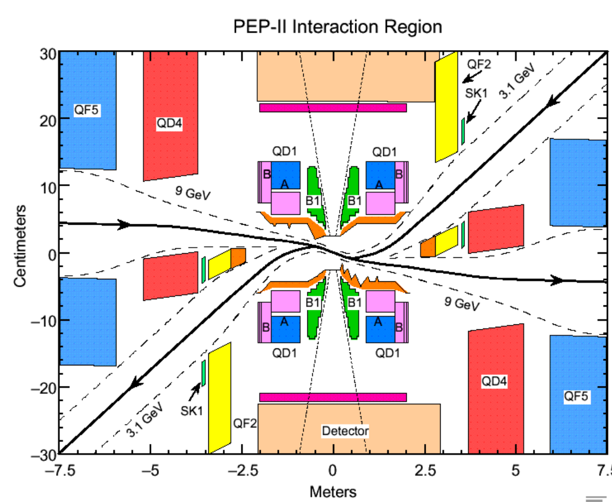

Figure 2. Layout of the beam trajectories at the IP. Note the change in vertical scale. The magnets labeled B1 and QD1 are permanent magnets.

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only change to any beam energy was to lower the HER by 68 MeV in order to collect off resonance data for the detector. This occurred about 10% of the time.

Run 7 was initially planned to be a similar run to the previous 6 runs. However, near the very beginning of the run we discovered that this run was going to be shortened and decided to move the accelerator E_{cm} to the upsilon 3S resonance (10.355 GeV). We did this by lowering the HER beam energy down by 377 MeV. After a little over two months of running at the 3S the E_{cm} was lowered again down to the 2S resonance (10.023 GeV) for the month of March. The very end of March and the first week of April were used to scan the E_{cm} from the 4S resonance to 11.200 GeV. All of the E_{cm} changes were done by adjusting the HER beam energy. It is very difficult to adjust the LER beam energy due to the fact that the final focus quadrupole for the LER is a permanent magnet and can not be changed.

ACHIEVEMENTS

Table 2 lists some of the luminosity accomplishments of PEP-II and the BaBar detector. As already mentioned, PEP-II has stored multiple ampere currents in both storage rings. In addition, luminosity achievements have all far exceeded the design goals.

Table 2: Some luminosity records of PEP-II

	Design	Record
Peak Luminosity ($cm^{-2}s^{-1}$)	3×10^{33}	12×10^{33}
Average daily lum./month (pb^{-1})	135	649
Luminosity/month (fb^{-1})	4	19.7
Best 24 hrs (pb^{-1})	135	911
Best 12 months (fb^{-1})	30	115

Figures 3-5 show plots of luminosity performance for PEP-II.

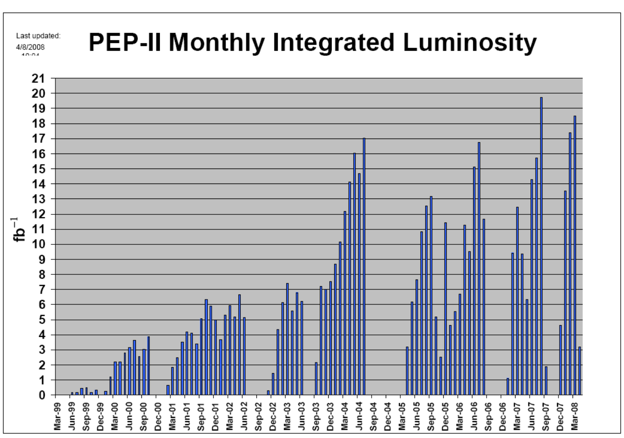

Figure 3. Plot of the monthly integrated luminosity delivered by PEP-II. There is a large increase in performance during the run 4 in 2004. This was the result of employing a continuous top up mode called "trickle-charge". The improved stability of the machine with fixed beam currents greatly improved efficiency. In addition, luminosity tuning could now be optimized for a single beam current thereby improving peak performance [3].

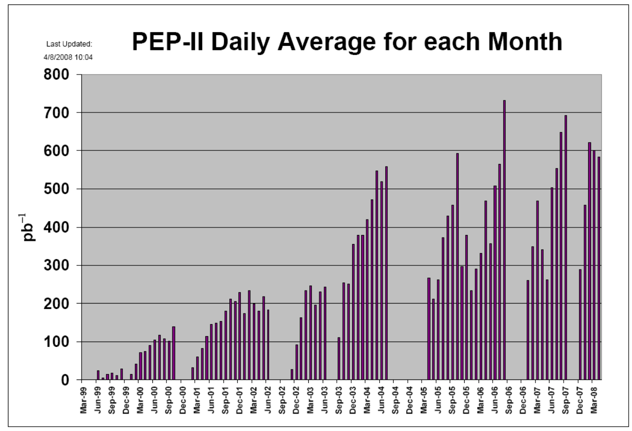

Figure 4. Plot of the average luminosity delivered each day for each month. Note that Aug. 2006, Sep. 2007 and Apr. 2008 were partial months. Aug. 2006 had 18 days of running, Sep. 2007 had 4 days and Apr 2008 had 7 days so the average is over fewer days. 135 pb^{-1}/day is the design performance level. Discounting the partial months, Feb. and Mar. of 2008 are the second and third best months after the month of Aug. 2007.

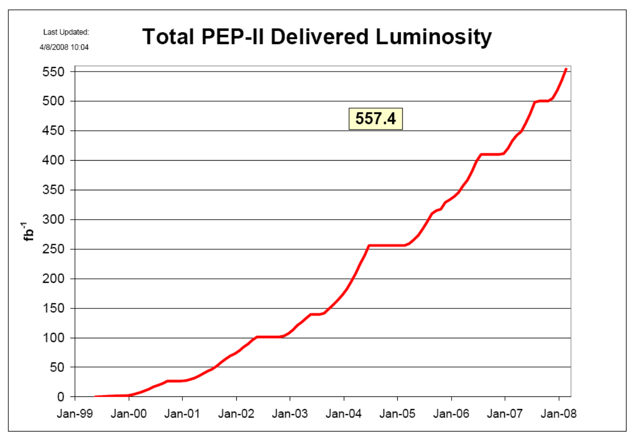

Figure 5. Plot of the total delivered integrated luminosity.

HIGH BEAM CURRENTS

As the beam currents of the two rings gradually increased over the years of running, we have found and fixed several weaknesses in the various subsystems of PEP-II. We will address several of these issues here but this will by no means be an exhaustive list.

Feedback systems

The single ring transverse stability threshold for the HER is about 100 mA. The transverse stability threshold for the LER is about 250 mA. Added stability is attained in the transverse planes through the beam-beam damping from the collision. This improved the margin for the bunch-by-bunch transverse feedback systems and in general the transverse systems worked quite well. Improved digital delay lines for these systems improved feedback loop stability. We also exchanged the initial Al transverse kicker electrodes for ones made from molybdenum [4].

The bunch-by-bunch longitudinal feedback systems had a few more high current related issues and they also had system upgrades [5]. The cable size and vacuum feed throughs from the beam kicker structure was increased in order to improve reliability and power transmitting capacity. For the LER, we installed a Frascati-style cavity kicker to handle the power loads from the higher LER beam current. This LER installation also included absorptive filters and RF circulators [6].

RF systems

The klystrons producing the RF to maintain the energy of the beams were controlled by a series of feedback loops. This entire low-level RF system (LLRF) was upgraded several times as power levels rose due to increases in the beam currents [7]. The last run of PEP-II had very little RF system troubles, mainly due to the reduced beam energy of the HER which greatly decreased the load on the RF system. Although we raised the HER energy to values never seen before at the end of the run, the system behaved very well.

Vacuum

Overall the vacuum systems of both rings performed very well [8]. PEP-II has accumulated over 60,000 A-hrs in the LER and over 40,000 A-hrs in the HER. These are undoubtedly the highest integrated beam currents achieved by any storage ring to date. The base pressure of the HER is 0.1 nTorr and the dynamic pressure is 1 nTorr/A. The base pressure of the LER is 0.1 nTorr and the dynamic pressure is 0.5 nTorr/A.

During the latter half of run 6 (spring-summer 2007) and near the end of run 7 (April 2008) we developed a problem with some of our HER distributed ion pumps (DIPs). These pumps are located in the large dipole magnets of the HER and use the dipole magnetic field as the pumping field. A subset of these pumps started to spontaneously outgas either with a slow rise in pressure or with a sudden increase in pressure and then a sudden drop in pressure. Some of these events would generate enough gas to make the HER beam go unstable. These events are not completely understood and the only cure was to turn off the pumps that were outgassing. One interesting note is that these pumps did not cause much trouble during run 7 until we raised the HER beam energy well above the value used for the 4S resonance. This increased the dipole magnetic field that these pumps use.

SR heating

In general, except for one issue which we discuss below, synchrotron radiation (SR) heating from the high-current beams was well controlled. There were a few initial issues in each ring that had to be fixed: a compound bending angle in the LER was not adequately shielded, some masking for SR in the HER was inadequately cooled, and the HER chamber for the high-power radiation fans from the interaction point (IP) dipoles had to be redesigned. As beam currents increased, a few vacuum components had to be replaced for units able to intercept higher levels of SR power.

We did have one problem that was the result of heated vacuum chambers from SR. The 5.5 m long HER dipole chambers were designed to intercept SR power from a beam with 3A of current at 9 GeV. Although well cooled, the dipole chambers still expand (or flex) when SR power strikes the chamber wall. This flexure was taken up by a bellows section on one end of the chamber and by a zero length bellows or flex flange at the other end of the chamber. The zero length bellows had a RF seal to maintain chamber wall continuity across the gap. However, we found that the chamber flexure was large enough to cause the RF fingers in this seal to become over-crushed allowing a gap to form. This gap allowed higher order mode (HOM) power to penetrate behind the RF seal and heat up vacuum components. In addition, the gap permitted arcing at the seal boundary. This problem was uncovered during the summer shutdown in 2006. Initially we thought there were perhaps a handful of RF seals that had failed. We replaced the ones we had found. During run 6 we found out that at least 50% of these shields had failed and we made plans during the shutdown to replace as many as we could. We ended up replacing all of the seals after finding that more than 95% had failed [9]. Figure 6 is a picture of one of the failed RF seals.

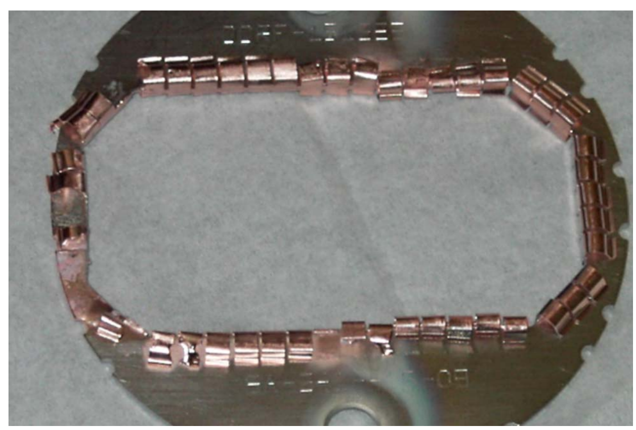

Figure 6. Picture of a damaged HER flex flange RF seal. HOM power getting behind the GlidCop (dispersion strengthened Cu) fingers heated up the stainless steel frame to the melting point of Cu (left side of picture). In addition, one can see signs of arcing where there is Cu deposition on the stainless steel frame top and bottom. The right hand side of the picture shows undamaged fingers.

High order mode (HOM) heating

HOM heating of various vacuum components probably had the largest impact on machine performance. Most of these issues were in the LER storage ring which had the higher beam current. We had to remove (and ended up not replacing) two out of four elliptically shaped vacuum valves located around the IP that persistently overheated due to HOM power getting past the RF screen. The other two valves of identical design and similar locations never caused any problems.

Upstream of the interaction region (IR), we have massive pumping from non-evaporative getter pumps (NEGs). The NEG wafers are stacked for capacity and the RF screens between the NEG pumps and the beam turned out to be too thin. As the LER beam current increased, some of the HOM power started to leak through these weak screens and be absorbed by the NEG material. The NEG would then heat up and start to outgas causing intolerable backgrounds for the detector. Roughly 10-15% of the total pumping in this area was affected. The NEG material was removed from those chambers with the thinnest screens during the summer downtime in 2004.

In the beginning of run 5 (Dec. 2005), we had two problems with arcing vacuum components. These events had a signature that showed up as a sudden beam instability followed, in most cases, by vacuum activity. This would cause a beam loss. One of the problems was found to be an RF flange gasket that was sticking into the vacuum chamber near the LER RF cavities [9]. The other was near the detector and was difficult to track down but eventually ended up being a problem with a flange RF seal not working properly [10,11].

In May 2006 we tried to shorten the LER bunch by increasing the LER RF total gap voltage and discovered that the beam position monitor (BPM) buttons would absorb too much HOM power and get hot enough for the top buttons to fall off. If the button fell onto the bottom button that button would all of a sudden receive an enormous amount of power and end up melting the ceramic in the feed through causing a vacuum leak. We ended up replacing or removing the BPM buttons in the entire LER. The replacements had smaller sized buttons and, in addition, the button and feed through were one piece of metal; a technology not readily available when PEP-II was built.

Another HOM heating issue was a particular feed through for a titanium sublimation pump (TSP) in the LER. We found a burned connector to the pump filaments and ended up not being able to use this pump. In the same area, we also had a single bellows section that was getting very hot. No other place in the LER had these problems (there are at least 190 other similar places). This was finally tracked down to the presence of a fixed collimator about 10 m upstream of the pump and bellows. The collimator was able to convert longitudinal modes into transverse HOMs and this transverse RF was getting into the bellows and into the pump connector. Installing a HOM absorber in the antechamber of the beam pipe greatly reduced the HOM power in this area [12].

SUMMARY

The PEP-II accelerator has surpassed all of its design goals. PEP-II can be called one of the most successful accelerators in the history of this field. Many doubted PEP-II would ever reach the design goals (3×10^{33} $cm^{-2}s^{-1}$ and 135 pb^{-1}/day). The BaBar detector has amassed one of the largest data samples in the history of e+e- colliding accelerators.

The high-current beams of both storage rings have pushed accelerator technology into new territory and have brought an increased awareness of the importance of HOM heating effects. Future high-current accelerators will have to pay close attention to the effects of HOM heating in all subsystems sensitive to this process.

ACCNOWLEDGEMENTS

We would like to acknowledge all of the people who, working together, designed, built and ran the PEP-II accelerator. The outstanding performance of PEP-II is a testament to the dedication of all of the support groups who maintained, repaired and upgraded the accelerator.

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