LAST YEAR OF PEP-II B-FACTORY OPERATION*

J. T. Seeman, SLAC, Menlo Park, CA 94025 USA

Abstract

The PEP-II B-Factory [1] at SLAC (3.1 GeV e^+ x 9.0 GeV e^-) operated from 1999 to 2008, delivering luminosity to the BaBar experiment. The design luminosity was reached after one and a half years of operation. In the end PEP-II surpassed by four times its design luminosity reaching 1.21 x 10^{34} cm^{-2} s^{-1}. It also set stored beam current records of 2.1 A e^- and 3.2 A e^+. Continuous injection was implemented with BaBar taking data. The total delivered luminosity to the BaBar detector was 557.4 fb^{-1} spanning five upsilon resonances. PEP-II was constructed by SLAC, LBNL, and LLNL with help from BINP, IHEP, the BaBar collaboration, and the US DOE OHEP.

PEP-II TIMELINE

1987: Particle physicists determine that asymmetrical beam energies are preferred.
1991: First PEP-II CDR.
1993: Second PEP-II CDR.
1994: Construction started
1997: First HER stored beam 6:30 am June 5.
1998: First LER stored beam 2:49 am July 16.
1998: First collisions 12:05 pm July 23.
1999: BaBar placed on beam line in May.
1999-2008: Collisions for BaBar.
2000: Design luminosity achieved ($3x10^{33}$) Oct. 29.
2006: Luminosity $1.2x10^{34}$ achieved 8 pm Aug. 17.
2008: PEP-II turned off 23:22 pm April 7.

Table 1 : PEP-II Collision Parameters

Parameter	Units	Design	April 2008 Best	Gain Factor over Design
I+	mA	2140	3213	x 1.50
I-	mA	750	2069	x 2.76
Number bunches		1658	1732	x 1.04
β_y*	mm	15-25	9-10	x 2.0
Bunch length	mm	15	10-12	x 1.4
ξ_y		0.03	0.05 to 0.065	x 2.0
Luminosity	10^{34} /cm^2/s	0.3	1.2	x 4.0
Int lumin per day	pb^{-1}	130	911	x 7.0

*Supported by US DOE contract DE-AC02-76SF00515.
[†]seeman@slac.stanford.edu

PEP-II PARAMETERS

In PEP-II the Low Energy Ring (LER) is mounted 0.89 m above the High Energy Ring (HER) in the 2.2 km tunnel as shown in Figure 1. The interaction region is shown in Figure 2 where the beams are collided head on. Figure 3 shows the Be vacuum chamber inside the detector with the permanent magnet dipoles on either side. The interface cone angle at the IR between BaBar and PEP-II was 300 mrad. To bring the beams into collision, LER is brought down 0.89 m to the HER level and then with horizontal deviations for both rings the beams are made to collide as shown in Figure 2. Since both rings have the same circumference, each bunch in one ring collides with only one bunch in the other ring. There are small parasitic collision effects as the bunches separate near the interaction point but at full currents these only reduce the luminosity a few percent.

The luminosity in a flat beam collider is given by

$$L = 2.17x10^{34} \frac{n\xi_y E I_b}{\beta_y^*}$$

where n is the number of bunches, ξ_y is the vertical beam-beam parameter limit, E is the beam energy (GeV), I_b is the bunch current (A), and β_y* is the vertical beta function value at the collision point (cm). This equation holds for each beam separately. These parameters for PEP-II are shown in Table 1 with the design and best values. PEP-II exceeded all design parameters, in particular the luminosity by a factor of 4 and the integrated luminosity per day by a factor of 7.

Figure 1 : PEP-II tunnel with LER above the HER.

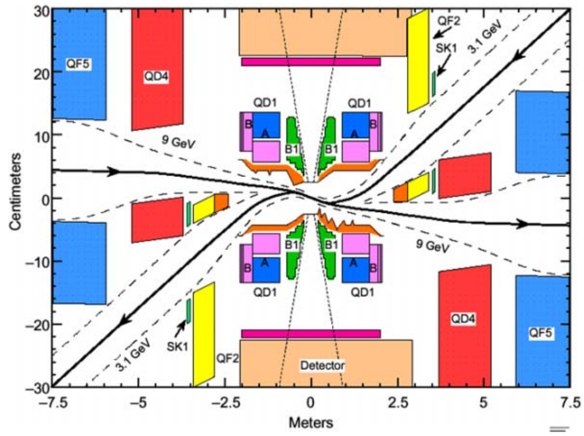

Figure 2 : PEP-II Interaction Region (IR) with head-on collisions. There are four permanent magnets within the BaBar 1.5 T solenoidal field covering +/- 2.5 m.

Figure 3 : IR double-walled Be collision chamber with nearby water cooling and permanent magnet dipoles.

The high beam currents are supported by large RF systems consisting of 1.2 MW klystrons at 476 MHz and high power cavities with HOM absorbing loads. Each cavity has three loads each with the capability of 10 kW. A cavity is shown in Figure 4. At peak currents a HER cavity receives on average 285 kW and the LER cavities 372 kW. The average klystron power was 1.01 MW. An overhead of about 20% in power was needed to allow the RF feedback systems to be stable. At high currents there were about 3 RF trips each day. The longitudinal bunch-by-bunch (4 nsec) feedback system is shown in Figure 5. The bunch-by-bunch (4 nsec) transverse feedback system is shown in Figure 6. Once tuned, these systems were quite robust. These systems were used to measure and feedback on beam instabilities (Figure 7). The coupled bunch instabilities were damped up to the highest current with some head room but the HER growth rates were somewhat anomalous being stronger than predicted.

The vacuum systems were extruded copper in the HER arcs and extruded aluminium with antechambers and photon-stops in the LER arcs. Both rings had stainless steel double walled chambers in the straight sections. The chambers were water cooled continuously over their 2.2 km lengths due to beam heating. From beam-off to beam-on the vacuum chambers expanded and high power expansion bellows were needed (Figure 8).

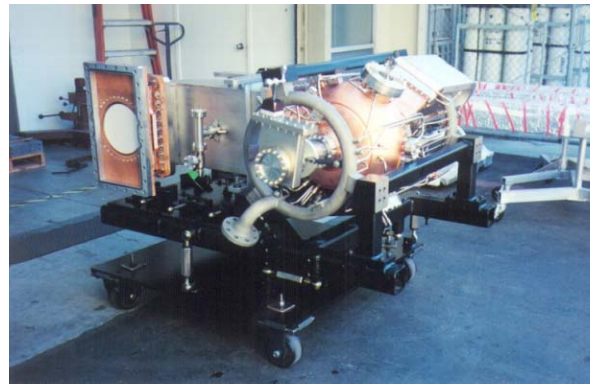

Figure 4 : PEP-II high power copper RF cavity, water cooled with a 500 kW ceramic window and 3 HOM loads.

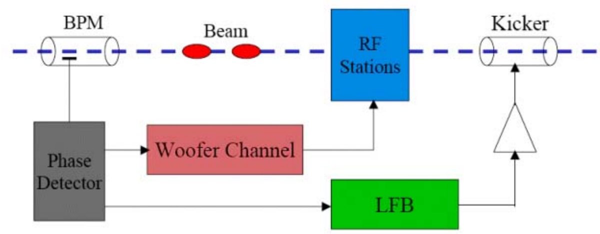

Figure 5 : Bunch-by-bunch longitudinal feedback system with an added low level (woofer) channel.

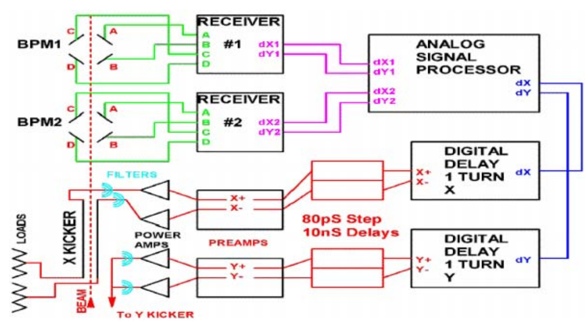

Figure 6 : Bunch-by-bunch transverse feedback system.

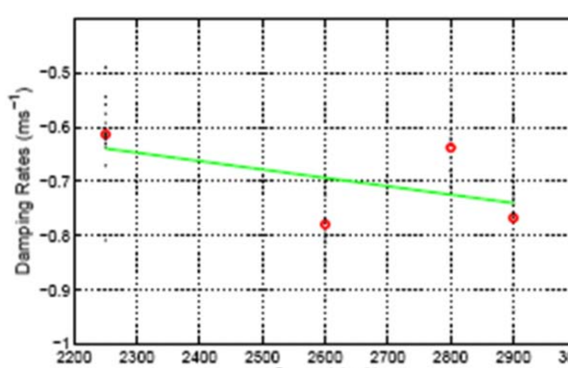

Figure 7 : LER longitudinal feedback damping rates with total positron current.

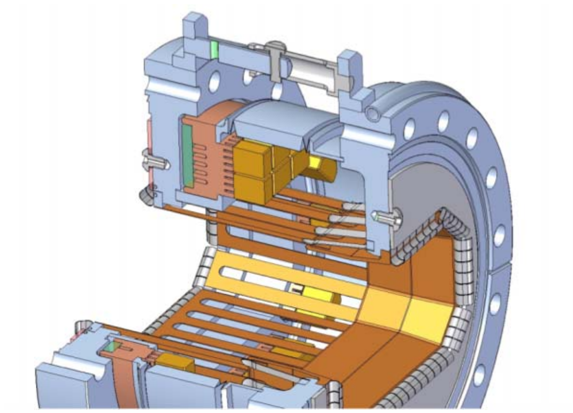

Figure 8 : Ultimate design of the PEP-II high power expansion bellows module with sliding fingers, compression (hold down) fingers, beam RF seals at the ends, and water cooled HOM absorbing tiles.

BEAM-BEAM AND LUMINOSITY

The best location in the tune plane was chosen by the best beam-beam performance. The best location was obtained with the horizontal tune just above the half integer ~0.508 and the vertical tune around 0.574. In Figure 9 are shown simulation luminosity contours on the x-y tune plane indicating optimal performance near the observed best location. Considerable but successful work was needed to correct horizontal beta beat errors at these horizontal tunes.

The measured luminosity versus the product of the bunch currents is shown in Figure 10 and the specific luminosity in Figure 11. The resulting maximum vertical beam-beam parameters in the two rings were 0.05 to 0.065. At the highest currents with collisions, the HER current was limited by the LER lifetime and the LER current by HER generated IR backgrounds in the detector. In collision an increase in the LER current also increased its own horizontal beam size, which is not understood.

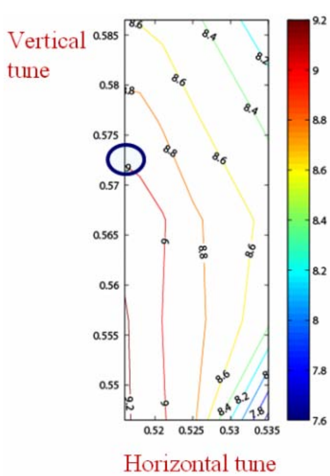

Figure 9 : Contours of simulated luminosity in the tune plan. The best fractional tunes were 0.508 horizontally and 0.574 vertically, generally agreeing with experiment.

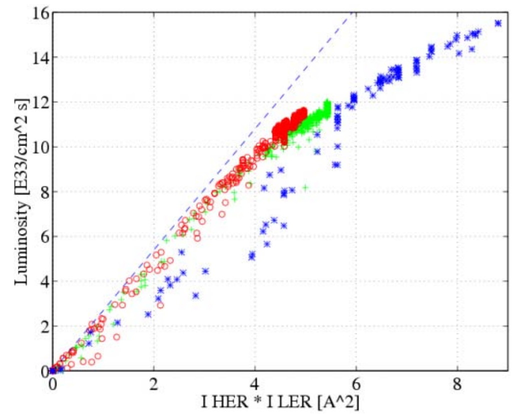

Figure 10 : Luminosity versus the product of the bunch currents. The red and green curves show luminosity in the By-2 pattern (4 nsec) bunch spacing during routine operation achieving a luminosity of 1.2 x 10^{34}. The blue curve shows the By-4 bunch pattern (8 nsec) scaled to a By-2 bunch pattern, indicating an increased luminosity may have been possible in PEP-II with the By-2 pattern.

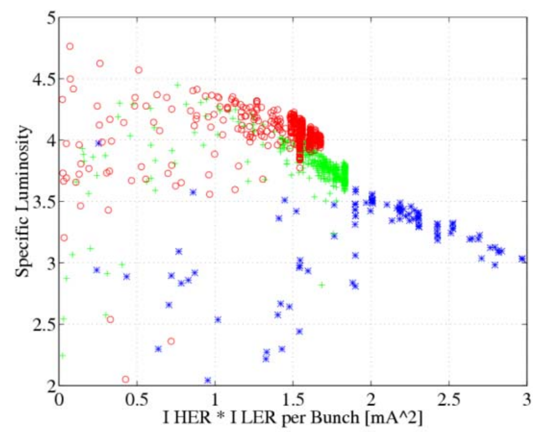

Figure 11 : Specific luminosity versus the product of the bunch currents. The specific initially rises because of dynamic beta effects and then falls due to beam-beam interaction from both primary and parasitic collisions. The parasitic beam-beam effect was only a few percent. The blue points are By-4 pattern scaled to the By-2 pattern.

Continuous (trickle charge) injection was planned for from the initial design phase of PEP-II. The LER was accomplished first in November 2003 with BaBar taking data. The HER continuous injection occured six months later. See Figure 12 before and Figure 13 after. A 40% increase in average integrated luminosity was achieved.

OVERALL BEAM PERFORMANCE

PEP-II was operated on five upsilon resonances with the majority of data on the Y4S as shown in Table 2. Figure 14 shows the total integrated luminosity of PEP-II achieving 557.4 fb^{-1}. The flat regions are maintenance and installation periods. Figure 15 shows the monthly integrated luminosity delivered to BaBar by PEP-II. The period of the last few months was for running on the Y2S, Y3S, and the energy scan above the Y4S. In Figure 16 is shown the highest luminosity in each month over the life of PEP-II. The design luminosity was achieved just over a year into operations. The luminosity record of PEP-II of 1.2 x 10^{34}/cm^2/s was achieved in August 2006.

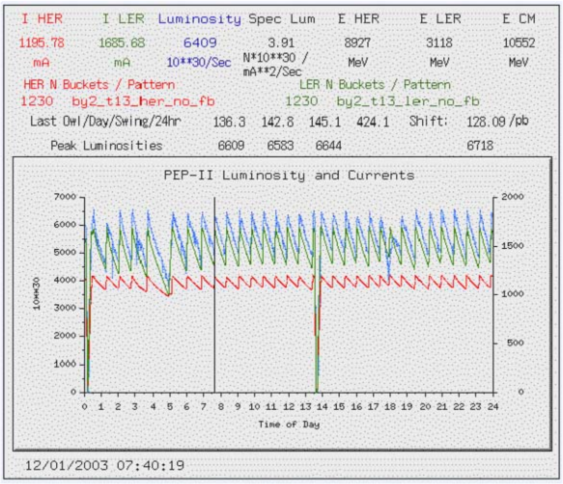

Figure 12 : Luminosity and beam currents for 24 hours showing the fill-coast mode of PEP-II in early years.

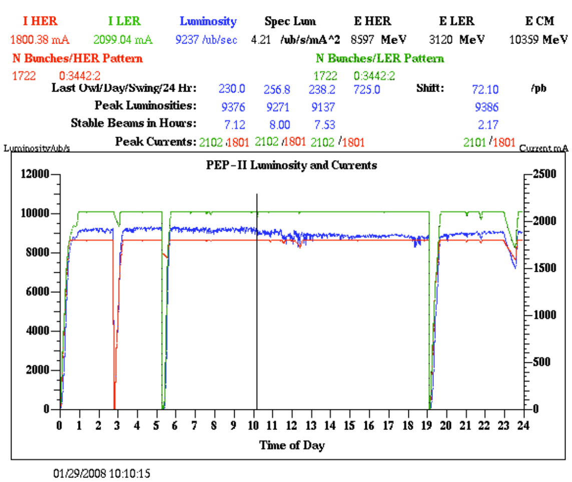

Figure 13 : Continuous injection of both PEP-II beams.

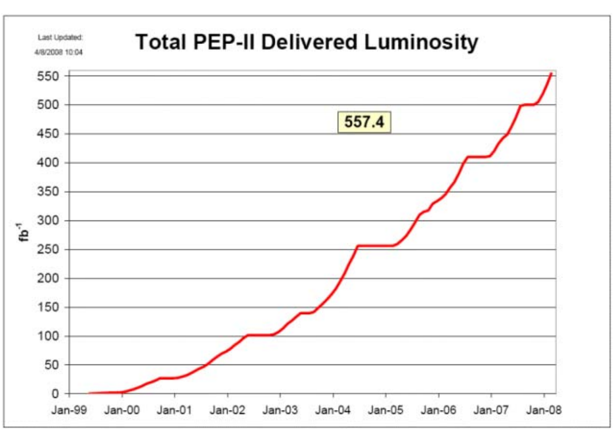

Figure 14 : Total integrated luminosity from 1999 to 2008.

Table 2 : Operation of PEP-II on different upsilon resonances. The remainder of the total integrated luminosity not listed of the 557.4 fb^{-1} was taken as "off resonance" data near the resonances, together totalling about 78 fb^{-1}. Due to the permanent magnet IR quadrupoles, the LER energy was not changed.

Resonance	Data	HER Energy
Y2S	14.5 fb^{-1}	8.1 GeV
Y3S	30 fb^{-1}	8.4 GeV
Y4S	433 fb^{-1}	8.97 GeV
Y5S	0.9 fb^{-1}	9.47 GeV
Y6S	0.8 fb^{-1}	9.73 GeV

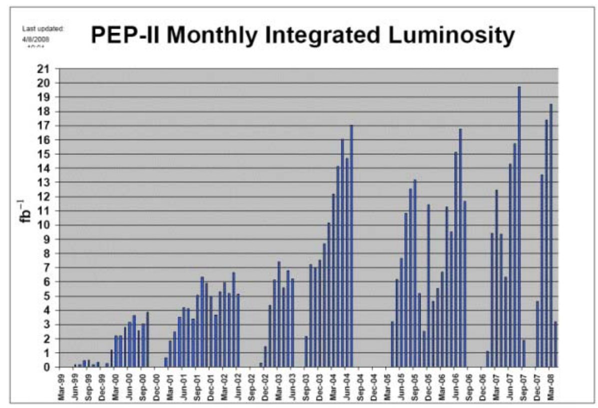

Figure 15 : Monthly integrated luminosity from 1999 to 2008. The best month was August 2007 with 19.7 fb^{-1}.

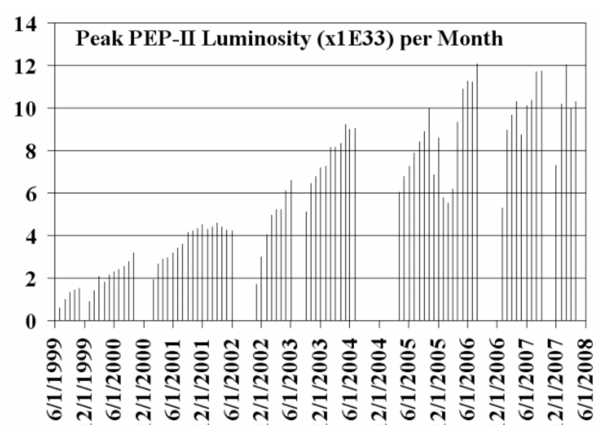

Figure 16 : Peak luminosity in a given month from 1999 to 2008. A peak luminosity of 1.21x10^{34}/cm^2/s was achieved.

PEP-II PERFORMANCE IMPROVEMENTS

All PEP-II components as designed worked to get above the design luminosity parameters (magnets, RF system, vacuum system, interaction region, background mitigation, beam instabilities, bunch-by-bunch feedbacks, injection, and controls).

However, to get far above the design up to x 4 design luminosity and x 7 integrated luminosity per day, several major upgrades were done [2-13].

A) The electron cloud instability (ECI) in the LER for e^+ needed ~30 gauss solenoids on the straight section stainless steel vacuum chambers. About 1.8 km of solenoid was wound. This proved very successful. The LER Arc chambers with ante-chambers, photon stops and TiN coatings worked well against ECI as designed. In the end, ECI did not degrade the peak luminosity.

B) The small (10 cm O.D.) expansion bellows on each end of the IP Be chamber had to have extra air and water cooling installed to survive the higher combined beam currents of over 5 A.

C) The synchrotron and lost particle masking near the detector was improved as the currents were raised.

D) Seven RF stations were added for a total of 15 stations to handle the highest beam currents in the two rings (3.2 A x 2.1 A).

E) The feedback kickers were upgraded for both the longitudinal and transverse systems. The new cavity style (Frascati) longitudinal kickers worked very well.

F) As the beam currents were increased, the RF controls were refined with modest upgrades.

G) Higher power vacuum expansion bellows went through several designs being able to handle ever increasing HOM powers. See Figure 8 for the best design.

H) Continuous injection needed a lot of careful work to make it acceptable to BaBar data taking. Both the accelerator and detector people worked together on masking, injection control, and diagnostics.

I) The abort gap was reduced from 5% of the circumference to about 1.6% with an improved abort kicker pulser.

J) Nearly continuous improvements to the quadrupole lattices were made. Tuning of the interaction region made for better beta and dispersion control, detector solenoid coupling correction, and minimizing vertical emittance.

K) Improved x-y coupling control was needed in the LER to maximize the luminosity. Permanent magnet skew quadrupoles were built and installed in very tight locations.

L) Vertical and horizontal beta-beats in the arcs near the IR were carefully worked to maximize the luminosity.

M) Simulation codes in 3-D were developed to understand all the aspects of the beam-beam interaction and tune shift limits. Good agreement with experiments was reached in most cases.

N) Every beam abort was studied, categorized, and analyzed offline. There were on average about 8 beam aborts per day with about 3 from RF, 3 from unstable beams, and 2 from detector backgrounds.

ACKNOWLEDGMENTS

The author and the PEP-II team wish to thank the operations staff, the maintenance crews, the safety teams, and all other supporting staff at SLAC for their hard work and efforts. Many thanks go to the US DOE Office of High Energy Physics for support. The two PEP-II Machine Advisory Committees helped the project in many ways. Our colleagues at LBNL, LLNL and Frascati made many contributions. M. Sullivan, U. Wienands, and T. Himel were PEP-II Run Coordinators. Y. Cai, Y. Yan, S. Heifets, and J. Irwin led beam dynamics and lattice calculations. R. Akre, J. Fox, D. Teytelman, C. Rivetta, D. Van Winkle, and W. Barry led the feedback efforts. H. Schwarz, P. McIntosh, and C. Pearson led the high power RF efforts. R. Humphrey, R. Larsen, and P. Bellomo led controls and power conversion. F.-J. Decker, G. Yocky, W. Wittmer, and the operators mastered luminosity tuning. A. Fisher excelled in beam size measurements. S. Ecklund led the IR effort. A. Kulikov and R. Iverson made injection work. W. Kozanecki and M. Weaver studied backgrounds. S. DeBarger, N. Kurita, S. Metcalfe, D. Kharakh, and L. Klaisner carried out mechanical engineering. J. Dorfan was PEP-II project manager and senior advisor. Many others made strong contributions.

REFERENCES

[1] "PEP-II an Asymmetric B Factory", Conceptual Design Report, CALT-68-1869, LBL-PUB-5379, SLAC-418, UCRL-ID-114055, UC-IIRPA-93-01, June 1993.

[2] J. Seeman, et. al., "PEP-II at $1.2\text{x}10^{34}/\text{cm}^2/\text{s}$ Luminosity", PAC 2007, pg. 37.

[3] M. Sullivan, et. al., "Results from a Prototype Permanent Magnet Dipole-Quadrupole Hybrid for the PEP-II B-Factory", PAC 1997, pg. 3330.

[4] J. L. Turner, et. al., "Trickle-charge: a New Operational Mode for PEP-II", EPAC 2004, pg. 881.

[5] U. Wienands, et. al., "High-temperature Kicker Electrodes for High-beam-current Operation of PEP-II", EPAC 2004, pg. 2843.

[6] J. D. Fox, et. al., "Development and Testing of a Low Group-delay Woofer Channel for PEP-II", Proceedings of EPAC 2004, pg. 2822.

[7] P. A. McIntosh, et. al., "An Over-damped Cavity Longitudinal Kicker for the PEP-II LER", PAC 2003, pg. 1341.

[8] P. A. McIntosh, et. al., "PEP-II RF System Operation and Performance", EPAC 2004, pg. 1087.

[9] U. Wienands, "Vacuum Performance and Beam Lifetime in the PEP-II Storage Rings", PAC 2001, pg. 597.

[10] U. Wienands, et. al., "Tracking Down a Fast Instability in the PEP-II LER", EPAC 2006, pg. 658.

[11] M. Sullivan, et. al., "Anomalous High Radiation Beam Aborts in the PEP-II B-factory", EPAC 2006, pg. 652.

[12] A. Novokhatski, et. al., "Modeling of the Sparks in Q2-bellows of the PEP-II SLAC B-factory", PAC07, 2007, pg. 658.

[13] A. Novokhatski, et. al., "Damping the High Order Modes in the Pumping Chamber of the PEP-II Low Energy Ring", EPAC 2004, pg. 854.