BEAM INSTRUMENTATION NEEDS FOR A FUTURE ELECTRON-POSITRON COLLIDER BASED ON PEP-II OBSERVATIONS*

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Abstract

Instrumentation for e+e- colliders is very important to monitor collider operations, detector data taking quality, accelerator physics, hardware status, and beam error analysis. The required instrumentation grows with the complexity of the collider and must be constantly advanced to higher functionality.

Future e+e- colliders will operate with many bunches, short bunch lengths, small emittances, high currents, and small interaction point betas. The stability of the colliding beams with these characteristics will depend on detailed, high precision, and continuous measurements. The various beam measurement requirements and techniques will be discussed with using PEP-II observations [1-13].

PEP-II BEAM MEASUREMENTS

The topics covered will be:

- Beam parameter overview
- Beam position (single pass and stored)
- Bunch transverse and longitudinal instabilities
- Beam tunes
- Beam size
- Bunch length
- Beam loss rates
- Beam lifetime
- IP luminous size
- HOM measurements
- Chamber vacuum pressure

Table 1: PEP II Parameters and Ultimate Potential

Parameter	Units	Design	April 2008 Best	2008 Potential
I+	mA	2140	3210	3700
I-	mA	750	2070	2200
Number bunches		1658	1722	1740
β_y*	mm	15-25	9-10	8.5
Bunch length	mm	15	11-12	9
ξ_y		0.03	0.05-0.06	0.07
Luminosity	x10^{33}	3	12	20
Int lumi / day	pb^{-1}	130	911	1300

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The parameters of PEP-II are shown in Table 1. PEP-II operated until April 2008. The general layout of the instrumentation in the HER ring is shown in Figure 1. The LER layout is similar but reversed relative to IR 2 where the BaBar detector was located. The instrumentation needs of PEP-II covered every possible beam and accelerator parameter and most were crucial to the ultimate operation of the accelerator and the detector. During the design of PEP-II, the instrumentation was integrated into the collider design. For construction, the desire was to be as inexpensive as possible but as broad as possible. For operations, the need was for low power costs, reliable running, and low maintenance costs with as many standard units as possible.

BEAM POSITION

The beam position monitors BPM for PEP-II were button type feedthroughs as shown in Figure 2. The diameter was 15 mm and resolution 20 microns. They worked well except at the highest currents (>3 A) as the button heads could fall off. The BPMs were used to make many measurements: initial turn observations (Figures 3 and 4), tune measurements in the longitudinal and transverse planes of stored beams (Figures 5 and 6), orbit corrections and feedback, and feedback of the tunes with beam current (Figure 7) which was done automatically by computer.

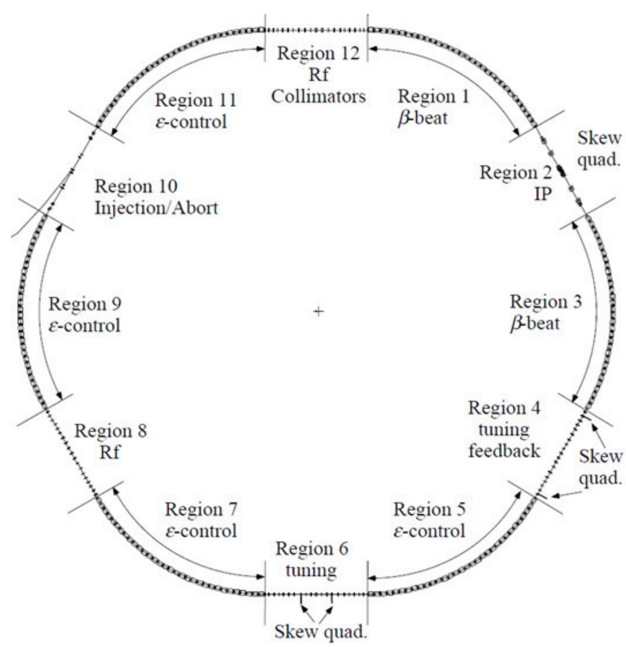

Figure 1: PEP-II layout with insturmentation.

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Figure 2: PEP-II BPM buttons and HER Cu chamber.

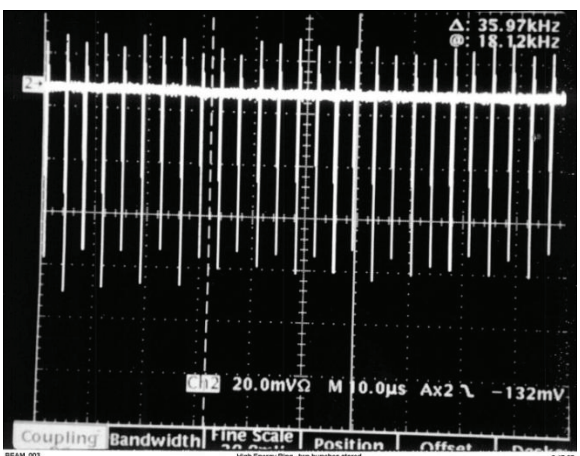

Figure 3:HER BPM signals showing the first few turns.

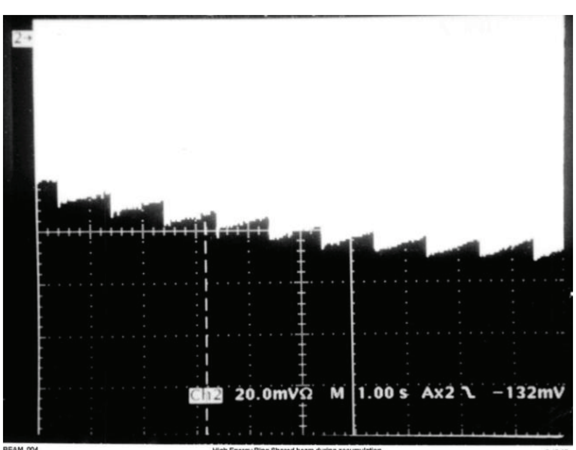

Figure 4: HER BPM signals indicating initial storage and stacking with beam current accumulation. A new injection was about every 10 seconds.

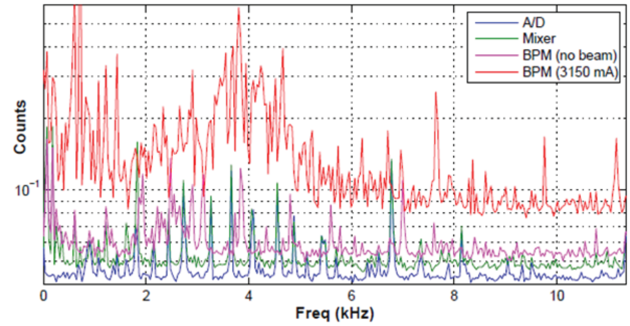

Figure 5:LER tune spectrum from a BPM showing the synchrotron frequency of about 4 kHz = 0.028.

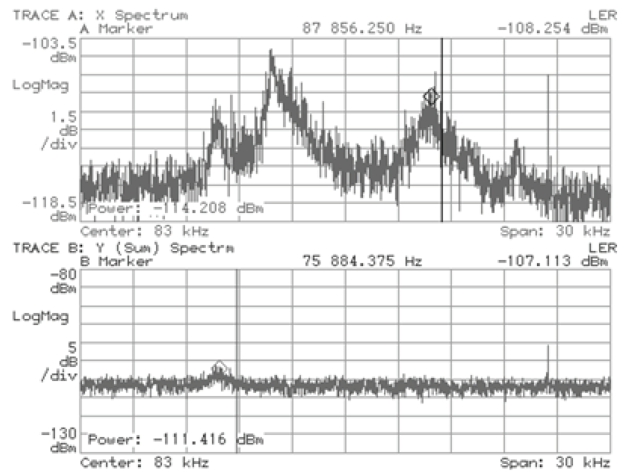

Figure 6: LER tune spectrum with colliding beams with 1550 mA (LER) on 850 mA (HER). The spectrum shows a lot of tune structure which makes it hard to use as a feedback to align the two beams.

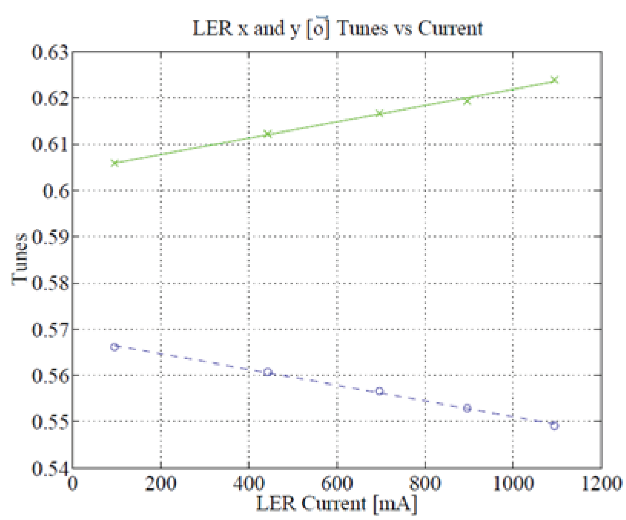

Figure 7: LER tune variation versus beam current with 700 bunches in a by-4 pattern. The measured x and y and following tune compensation adjustments have about the same values with opposite signs. Slope about 0.017 per A.

The BPMs were used in the bunch-by-bunch feedback systems to control instabilities at high currents. A schematic of the feedback is shown in Figure 8. The feedback

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could not only control the instabilities but used to determine the causes as well as, as shown in Figure 9 and 10. When the instabilities are large the beam tails could scrape, get lost on the vacuum chambers and then detected by the fast (~1 microsecond) loss monitors (Figure 11) which feeds into the abort system input triggers.

The loss monitors and lifetime calculation can be used to measurement transverse tails of the beams as shown in Figure 12. Here the effect of the beam-beam interaction on the transverse beam size can be quite significant and leads ultimately to a strong limit of the beam-beam parameter and luminosity. As the beam currents are raised the beam parameter increases and then saturates followed by beam size enlargement and finally beam loss. PEP-II had vertical beam-beam parameters on the order of 0.08 to 0.09 in HER and LER respectively.

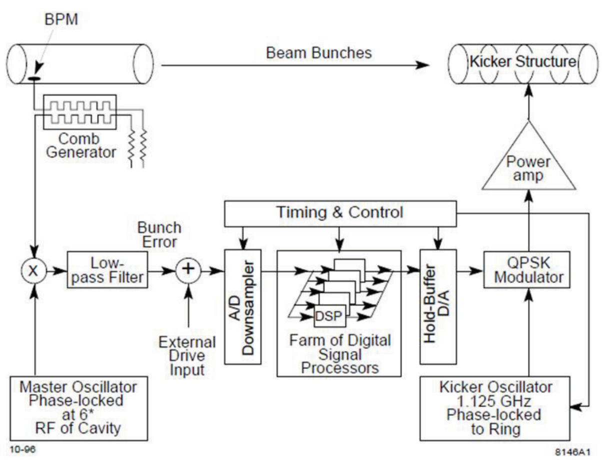

Figure 8: Longitudinal feedback system for 4 nsec spaced bunches showing BPM pickups, digital signal processing, high power amplifiers and kicker structures.

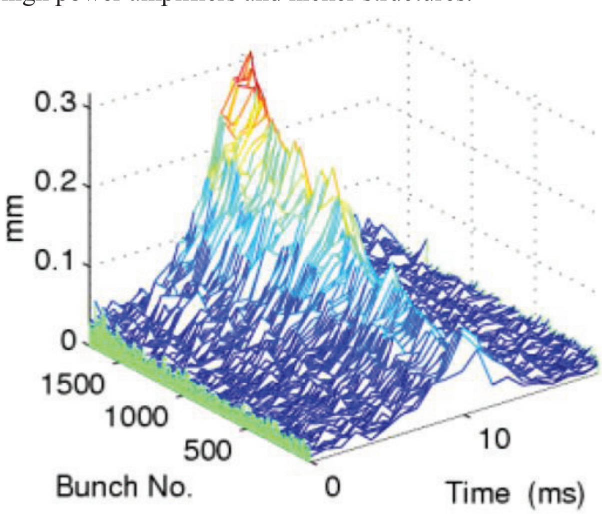

Figure 9:Time domain plot from the digital feedback system showing mode development with time in the HER after the feedback was turned off at t=0. Bunch 0 is just after the ion gap. Later bunches show larger growth. The HER beam had 1087 mA in 1740 bunches.

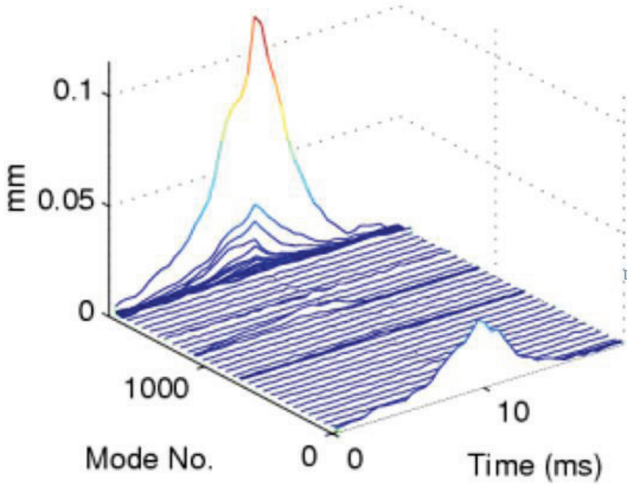

Figure 10: Evolution of modes in HER from the data from Figure 9 indicating low order and very high order modes.

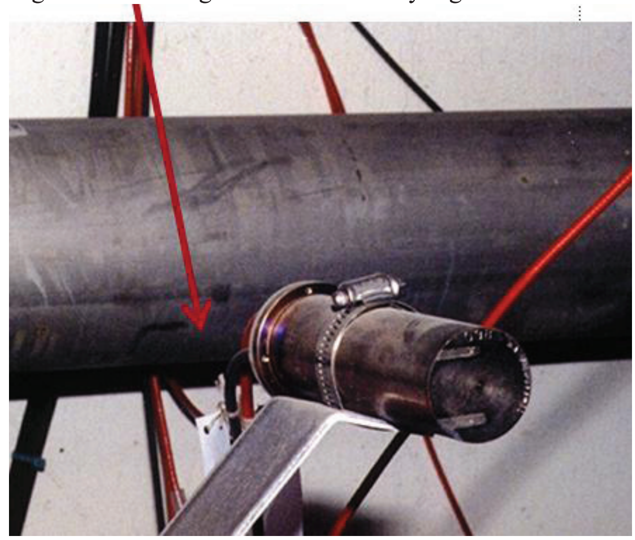

Figure 11: PEP-II beam loss monitor using PMT and SiO2.

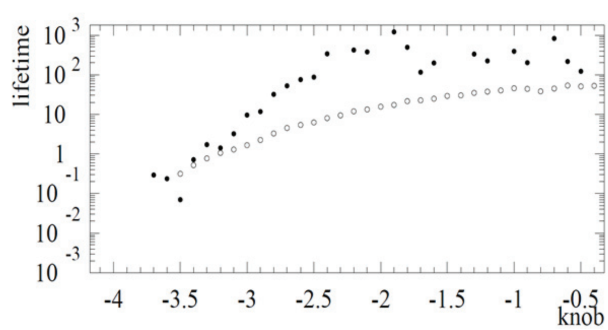

Figure 12: Results of scraping measurements in LER with colliding beams. Open circles are with high currents and bullets with low. The knob settings are in mm of the collimator position setting. Inward is negative. Lifetime measurements are in minutes. The HER data is similar.

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SYNCHROTRON LIGHT BEAM SIZE MONITORS

The synchrotron light monitor was used to measure the transverse and longitudinal beam sizes (at 600-200 nm). The main parameters are shown in Table 2 and the hardware in Figures 13 and 14. With multi-ampere beams the synchrotron light mirrors used to extract the light needed to handle high concentrated power. HER used a slotted water cooled polished mirror inside the vacuum. Both the HER and LER beam signals were put on to the same analysis table under the HER to reduce construction costs.

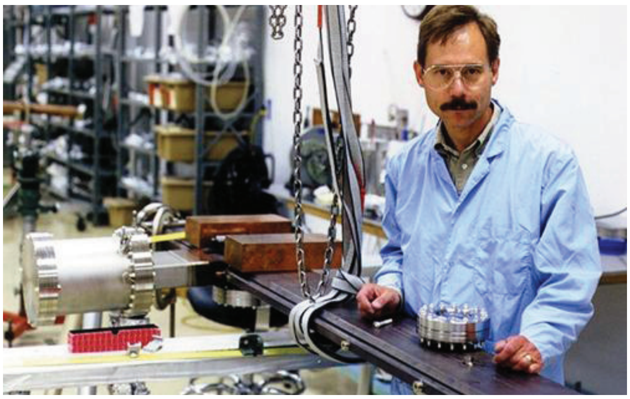

Figure 13: HER synchrotron light monitor in the lab.

Figure 14: HER synchrotron light mirror with main power slot down the center to reduce mirror distortions.

Table 2: PEP-II SLM Synchrotron Monitor Parameters

Parameter	HER	LER
Circumference [m]	2199.318	
Revolution time [µs]	7.336	
RF frequency [MHz]	476	
Harmonic number	3492	
Number of full buckets	1658	
Bunch separation [ns]	4.20	
Nominal current [A]	0.99	2.16
Maximum current [A]	3	3
Nominal energy [GeV]	9.01	3.10
Maximum energy [GeV]	12 (at 1 A)	3.5
Bend radius in arc dipoles [m]	165	13.75
Critical energy in dipoles [keV]	9.80	4.83

The light monitor signals were gated so we could observe the bunch sizes of individual bunches spaced 4 nsec apart. In Figure 15 are shown bunch sizes along the train showing the effects of the mini-gaps and the electron cloud effect (LER). As the size signals were weak, the size measurements had to be averaged over a few hundreds of turns to get these measurements.

A streak camera was used to measure the bunch lengths. The calibration of the bunch length measurements was done with an etalon as shown in Figure 17. In Figure 18 are shown measurements of the bunch length

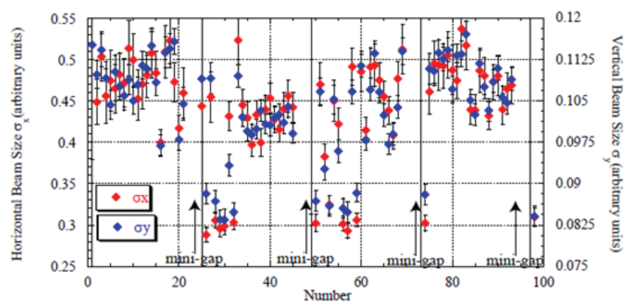

Figure 15: Vertical and horizontal bunch sizes versus bunches along the train. The bunch gaps reduce the electron cloud allowing bunches to have smaller sizes and higher luminosity, thus, indicating strong e- cloud effect in the LER.

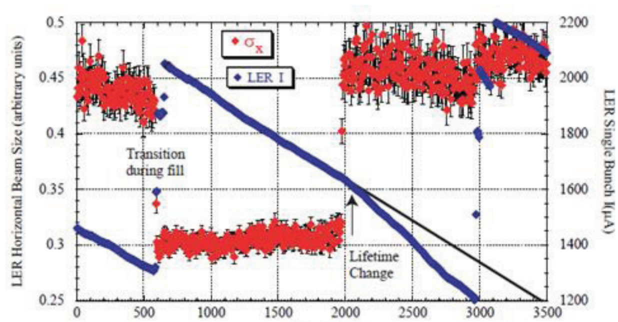

Figure 16: The LER beam current and horizontal beam size as a function of time for a single colliding bunch during transition between the flip-flopped states.

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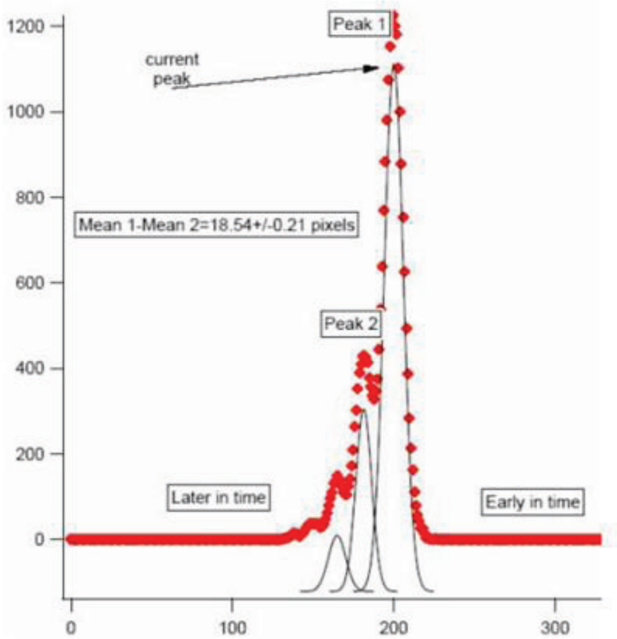

Figure 17: A streak-camera scan of a light pulse that was transmitted through an etalon and projected onto the camera's time axis with strength versus pixel number. The distance between reflections indicates the calibration.

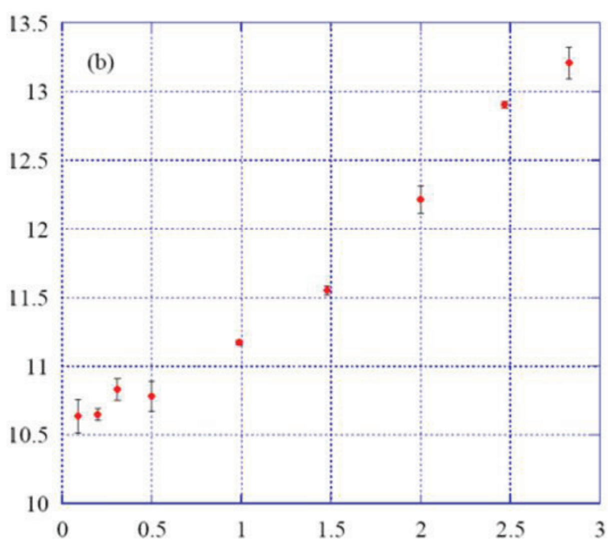

Figure 18: Streak camera measurements of the LER bunch length (mm) versus bunch current (mA) indicating growth in bunch length due to the ring longitudinal impedance.

with beam current showing an increase with current. The individual bunch lengths along the train could also be measured as shown in Figure 19.

LUMINOSITY MEASUREMENTS

The luminosity was measured using straight ahead gammas produced by beam-beam collisions from the LER beam measured in the upstream HER as shown in Figure 20. The gammas exited the HER chamber about 4 m from the IP and entered a hodoscope and PMT array as shown in Figure 21. Average luminosity and the luminosity from single bunches could be measured and then calibrated with the wide angle Bhabas in BaBar. The hodoscopes could give information on the angular divergence of the LER IP spot size and the centering of the beams in the IR. The luminosity for each bunch could be measured as shown in Figure 22. The overall luminosity could be measured to about 1% in about one second and was used extensively as a tuning aid for improving the luminosity.

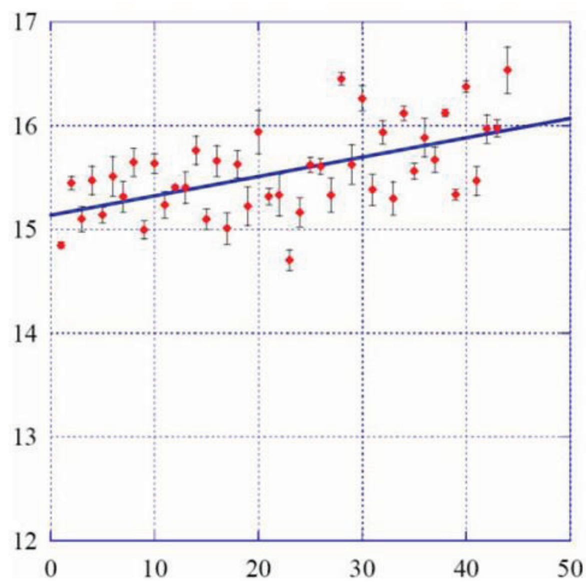

Figure 19: Streak camera measurements of the LER bunch length (mm) versus bunch number along the twentieth bunch train with 1.4 mA per bunch and 3.8 MW in the RF cavities.

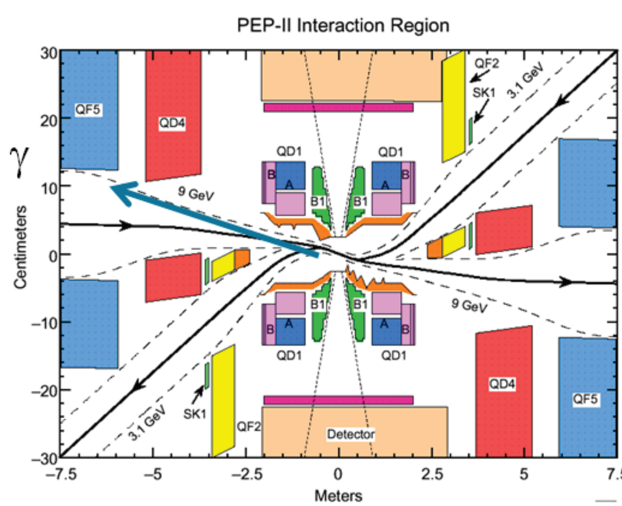

Figure 20: The PEP-II interaction region showing the beam-beam e-e+→e+e-γ emission to the upper left for luminosity measurements using the LER γs.

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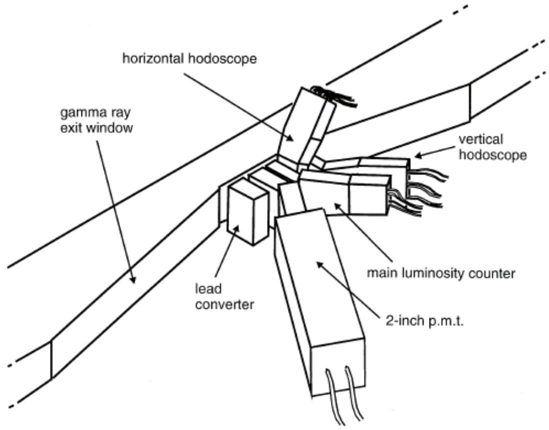

Figure 21: Luminosity monitor using γs with position hodoscopes in the horizontal and vertical and an integrating 2 inch photomultiplier tube.

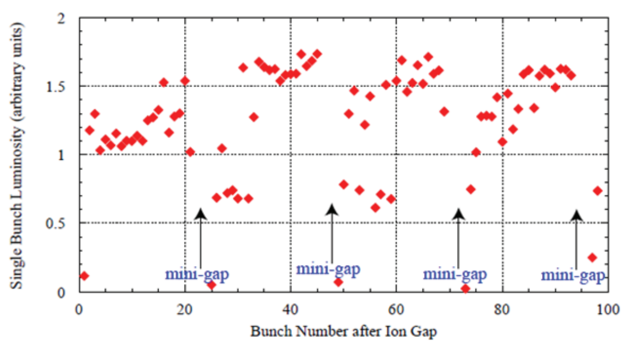

Figure 22: Bunch-by-bunch luminosity measurements of the first four mini-trains after the ion gap.

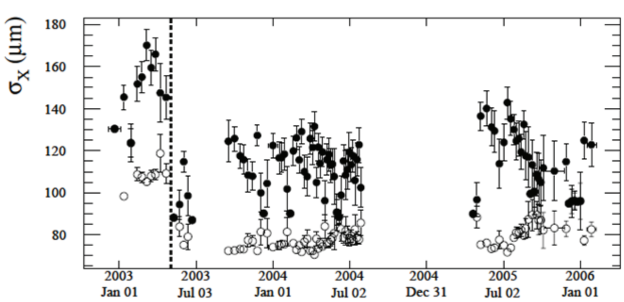

Figure 23: History of the horizontal combined IP beam size at the IR luminous region as measured by BaBar over several years. The dotted line indicates the time when both x tunes were moved close to the half integer resulting in a sizable luminosity improvement. HER indicated by black dots and LER open circles.

BABAR IP ACCELERATOR MEASUREMENTS

The BaBar detector used the recorded particle physics events to measure accelerator parameters at the IP taking several thousand events to make a measurement. Examples of the horizontal luminous beam size at the IP are

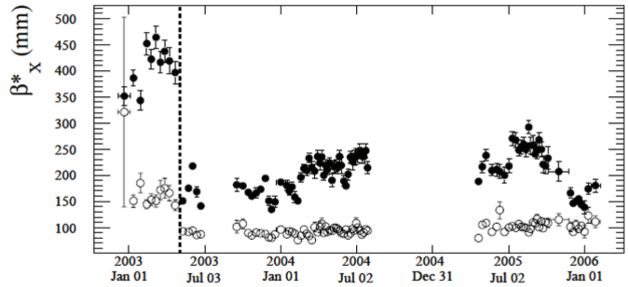

Figure 24: Horizontal beta function at the IR luminous region as measured by BaBar over several years. The dotted line indicates the time when both x tunes were moved close to the half integer resulting in a sizable luminosity improvement. HER indicated by black dots and LER open circles.

shown in Figure 23. Assuming an emittance from other beam measurements, the IP collective horizontal beta function can be calculated as displayed in Figure 24.

VACUUM MEASUREMENTS

The vacuum pressure was measured at several thousand locations in the rings and RF systems. Real time recorded signals allowed investigation of vacuum events that correlated with other beam related signals. An example is shown in Figure 25 with an RF arc and correlated pressure and IP background spikes.

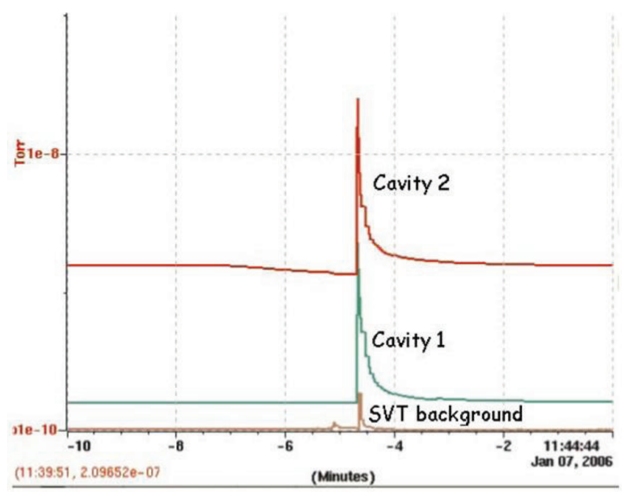

Figure 25: A cavity vacuum spike caused by an RF vacuum arc in the RF station 4-2 cavity in LER. The following vacuum pressure and associated background event in BaBar resulting in a beam abort.

RF SPECTRAL MEASUREMENTS

The RF spectrum of the beam could be measured in several devices, e.g. as shown in Figure 26. These measurements could be used to calculate the longitudinal length of the bunch producing these RF signals. The HER and LER bunch lengths were measured by their RF spectra are shown in Figure 27 which can be correlated with streak camera measurements such as in Figure 18.

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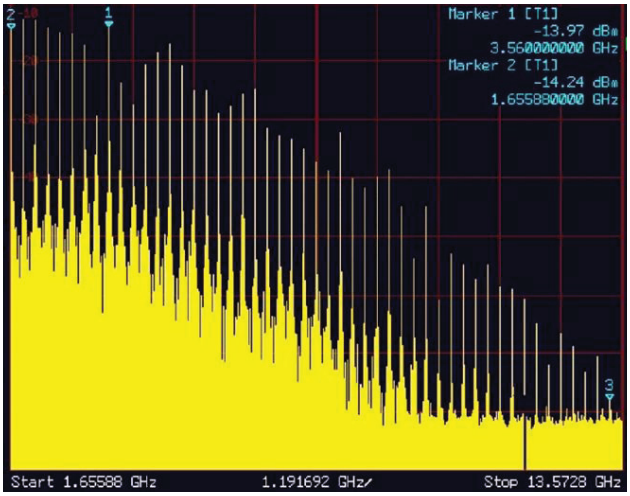

Figure 26: Measured RF spectrum of the LER positron beam for the bunch pattern of by-2 and 12 mm bunch length. The horizontal scale is 1.2 GHz per division. The spectrum fall off is reated to the bunch length.

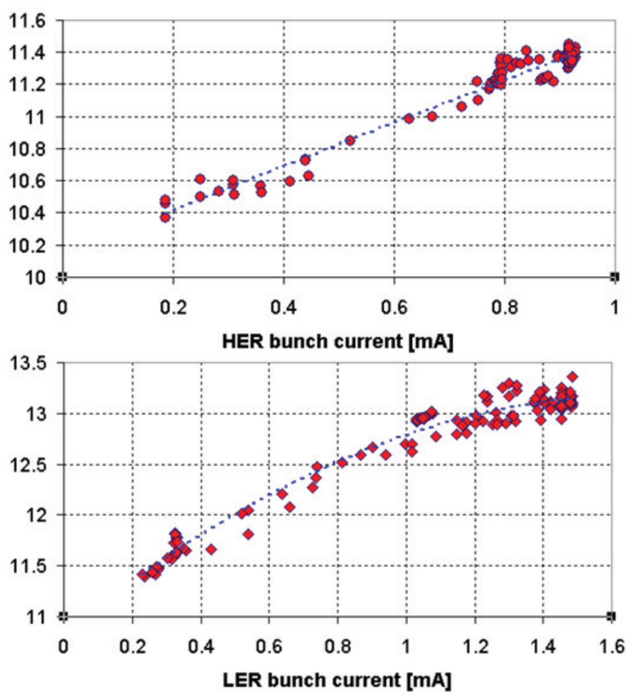

Figure 27: Bunch length (mm) meaurements using the RF spectra for HER (16.5 MV) (above) and LER (3.8 MV) (below) as a function of bunch current (mA) in a colliding multi-bunch pattern.

CONCLUSIONS

Many complicated measurements are needed in a high-power, high-current collider to make it function well. The accelerator control system must measure and record versus time as many parameters as possible to diagnose issues. The commissioning team must find new and innovative measurement techniques. Many of the measurements relate to potential hardware damage to the accelerator. As many as possible of the measurements need to automated and computer monitored to make the accelerator operation safe and allow pushing the luminosity limit.

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