Performance of the Beam Position Monitor System for the SLAC PEP-II *B* Factory[1]

Ronald G. Johnson, Stephen R. Smith, and G. Roberto Aiello[2]

Stanford Linear Accelerator Center
P.O. Box 4349, Stanford, CA 94309

Abstract. the beam position monitor (BPM) system for the SLAC PEP-II *B* Factory was designed to measure the positions of single-bunch single-turn to multibunch multi-turn beams in both rings of the facility. Each BPM is based on four button-style pickups. At most locations the buttons are connected to provide single-axis information (x only or y only). Operating at a harmonic (952 MHz) of the bunch spacing, the BPM system combines broadband and narrowband capabilities and provides data at a high rate. The active electronics system is multiplexed for signals from the high-energy ring (HER) and low-energy ring (LER). The system will be briefly described; however, the main purpose of the present paper is to present operational results. The BPM system operated successfully during commissioning of the HER (primarily) and the LER over the past year. Results to be presented include on-line calibration, single-bunch single-turn resolution (<100 µm), and multibunch multi-turn resolution (<3 µm), multiplexing, and absolute calibration. Thus far, the system has met or exceeded all the requirements that have been tested. The remaining requirements will be tested when both rings are completed and commissioned this summer. In addition, typical results of beam physics studies relying on the BPM system will be presented.

INTRODUCTION

The PEP-II *B* Factory (1) at SLAC is nearing the end of the construction phase. At present the high-energy ring (HER) is complete and is being commissioned. The low-energy ring (LER) will be complete this summer and the commissioning phase will continue. The beam position monitor (BPM) system (2) for both rings is also nearly complete. All of the cables and active electronics are in place. As the last of the ring components are installed, it only remains to connect the BPMs. Since the active electronics are multiplexed between the HER and LER, much of the system for both rings has been commissioned along with the HER.

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[2] Present Address: Interval Research Corp., 1801 Page Mill Road, Bldg. C, Palo Alto, CA 94304

The PEP-II storage rings are 2200 m in circumference and are located in a common tunnel. Both rings use rf of 476 MHz and fill 1658 buckets (every other bucket). The HER stores up to 1.0 A of electrons at 9.0 GeV and the LER stores up to 2.1 A of positrons at 3.1 GeV.

The BPM system is required to measure the positions of multibunch beam on a turn-by-turn basis (136 kHz) and single-bunch beam injected in a 200 ns ion-clearing gap. The electronics work in both a narrowband mode, for multibunch, and in a wideband mode, for single bunch. A simple difference over sum algorithm is used for position calculation. A 952 MHz bandpass filter selects the processing frequency in multibunch and generates an rf burst in single bunch. The system bandwidth is set at 10 MHz. Requirements for high accuracy and wide dynamic range led to development of an on-line calibration system which can operate in the presence of beam.

In the next two sections, the BPM system will be described, with particular attention to the active electronics. However, the main purpose of this paper is to present some of the operational results obtained in the commissioning. Finally, the status of requirements not fully tested will be presented.

BPM SYSTEM DESCRIPTION

Button-style pickups (3) were chosen as the basis of the BPM system. There are three basic types of vacuum chamber used in the rings, which necessitated somewhat different mechanical designs for the buttons. However, all buttons are 1.5 cm in diameter and have nearly identical electrical characteristics, 50 Ω impedance and 2.6 pF capacitance. The shapes of the vacuum chambers in the arcs of both HER and LER and the necessity to avoid the synchrotron radiation fan led to placing the buttons on the diagonal rather than the vertical and horizontal axes.

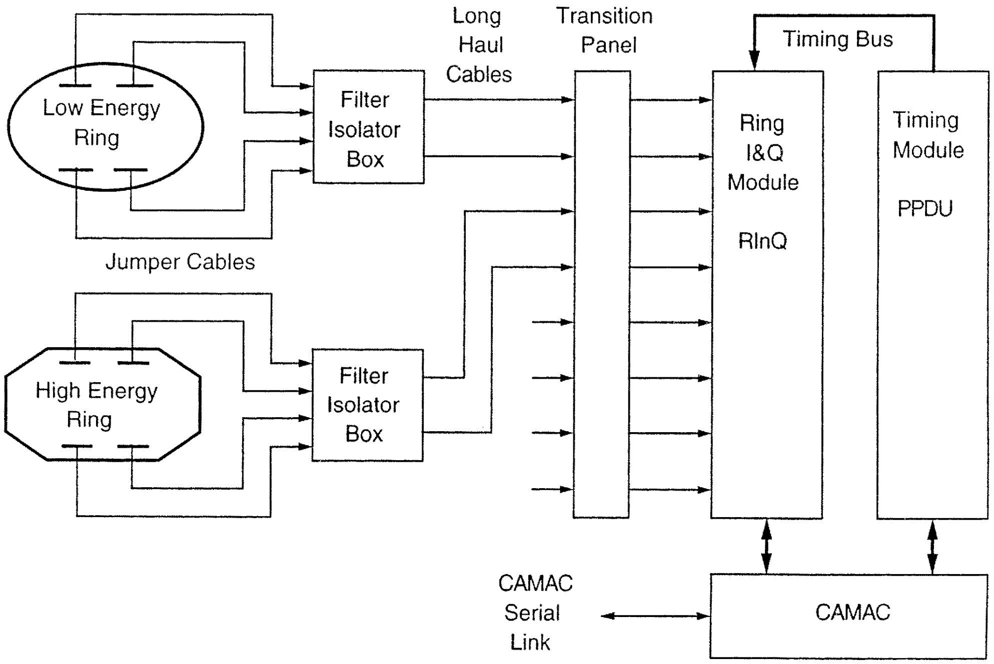


FIGURE 1. BPM system block diagram (4 of 8 channels fully shown).

In Figure 1, a block diagram of the BPM system is shown. Signals from the four electrodes are filtered (center frequency, 952 MHz and bandwidth 150 MHz) and in most cases combined by the Filter-Isolator Box (FIB) located close to the buttons. The signals from the buttons are combined to create *x*-only or *y*-only BPMs. In a few cases (25) the signals are not combined in the FIB, preserving both *x* and *y* information from the same set of buttons. The FIB absorbs out-of-band power and has provision to allow biasing the buttons (to 350 V). The signals from the FIB are processed in the Ring I&Q (RInQ) module and delivered to the control system through the CAMAC interface.

Timing for each BPM is supplied by the PEP-II Programmable Delay Unit (PPDU) which provides 16 independent channels of signals delayed relative to one of the two fiducials received from the PEP-II timing distribution system. The PPDU has a resolution of 2.1 ns. The RInQ module contains timing verniers with 40 ps resolution.

Measurement accuracy for single bunches is limited by reflection of the multibunch signal through the cable. The RInQ was designed to have a VSWR better than 1.2. An isolator was included in the FIB to reduce reflections.

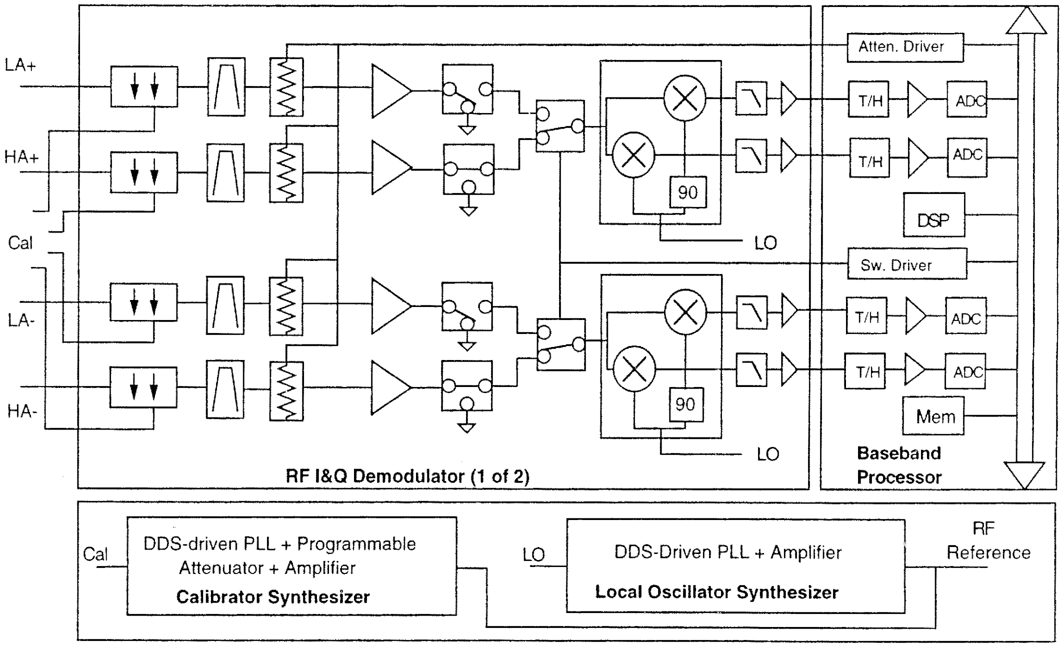


FIGURE 2. Ring I&Q (RInQ) processor block diagram.

ACTIVE ELECTRONICS

Processing of BPM signals by the RInQ module is based on baseband conversion using in-phase and quadrature (I&Q) demodulators. The RInQ module accepts two or four signals for HER and similarly for LER, where the processing is multiplexed between the two rings. A calibrator is also included on each RInQ. A diagram of the RInQ module is shown in Figure 2.

The 10 dB directional coupler receives signals from the FIB and the calibrator (through the coupling port). A 952 MHz bandpass filter selects the processing frequency. The programmable attenuator extends the dynamic range and an amplifier optimizes the signal to the I&Q demodulator. Switches multiplex HER and LER and provide the required 86 dB isolation. A low-pass filter sets the system bandwidth to 10 MHz. Track-and-hold and 14-bit analog-to-digital converters acquire the signals. A digital signal processor calculates the position and signal strength.

The RInQ module also contains a direct-digital synthesis (DDS) phase-locked loop (PLL) synthesizer, adjustable in amplitude and frequency, to provide calibration signals to each channel. Using the calibration signals, each channel can be calibrated for offset and gain mismatch. By operating the calibrator at a few kHz off the local oscillator frequency and using a fixed-frequency curve-fitting algorithm (4), the amplitude and quadrature phase unbalance can be added to the calibration parameters.

CALIBRATION RESULTS

The RInQ modules can be calibrated on-line in either narrowband or wideband mode. The wideband mode is calibrated by taking a series of measurements over the working bandwidth and taking a weighted average of the calibration parameters. Calibration parameters consist of offsets (4), gains (4), and phase errors (2) for both I and Q of the positive and negative channels, i.e., ten parameters. These calibration parameters have been shown to be stable over several hours; but they do depend on channel attenuation. Recalibration is performed whenever the beam current changes by 25% which would require a change in channel attenuation to achieve the optimum measurement.

Typically when a calibration of all BPMs is requested through the control system over 95% of the BPMs report a successful calibration for either HER or LER. Multiplexing works for calibration and for separate operation of HER or LER; but, both rings have not been run at the same time as yet.

Absolute calibration of the BPM system has been made. This calibration is described in Reference (5) and the on-line data base contains the offsets for calculating absolute positions. There have been no beam-based tests of the calibration to this time.

MEASUREMENT RESULTS

The BPM system was operational for each stage of PEP-II commissioning. Most of this commissioning has been with HER. After being timed, the BPMs produced position information which aided the tuning of the ring. There were of course some problems such as incorrect conversion constants for calculating position and a few incorrectly connected modules.

Each part of the system was tested and repaired if necessary before installation. Many of the FIBs and RInQ modules did require repair. However, after the system was installed problems have been minimal. About 15% of the RInQs installed have developed problems. All of these modules have been repaired.

The calculated minimum resolution of the BPM system is 0.2 μm which is dominated by the ADC quantization error. For measurements from the operating BPM system, the random error for multibunch multi-turn data closely approaches this limit. However, systematic errors have limited the resolution obtained thus far.

Noise which appears at the frequency difference between the measurement frequency (952 MHz) and the local oscillator, or twice that frequency, actually dominates the system resolution. Errors at these frequencies indicate that the calibration parameter set is not correct for the measurement. The source of this problem appears to be either the CAMAC power supply or the PPDU; but, the problem has not been isolated as yet.

In any case, single-turn measured resolutions for individual RInQ modules do not exceed 100 μm and the average resolution is about 50 μm. For multibunch multi-turn measurements the resolutions are 3 μm or better.

In addition to an aid in tuning, the BPM system was used as a fundamental measurement tool in a number of ring studies. In the paragraphs below two of those studies will be described.

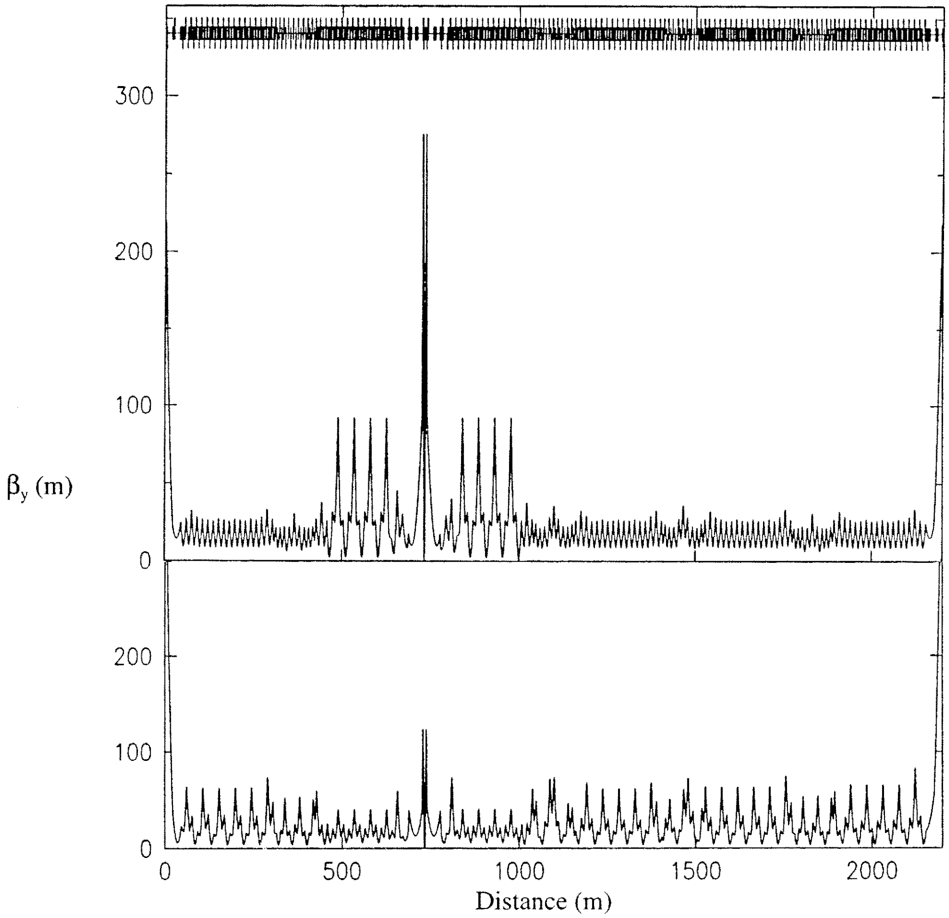


FIGURE 3. Model β_y: Upper, design and lower, fit. The representation at the top of the plots is the ring lattice.

Ring Study 1

The first study uses a very powerful method for determining the linear optics in a storage ring by comparing a model response matrix to a measured response matrix

(6). A computer code called LOCO (Linear Optics from Closed Orbit) varies the parameters in the model response matrix to minimize the χ^2 deviation between the model and the measured orbit response matrices. The measured response matrix is obtained by measuring the change in orbit at the BPMs with changes in steering magnet excitation. The method is quite powerful and can be used to determine quadrupole magnet gradients; the calibration of steering magnets and BPMs; the roll of quadrupoles, steering magnets, and BPMs; etc. The example cited here is the determination of quadrupole gradient errors. In Figure 3, β_y from the design model and the fit model are shown. In Figure 4, the quadrupole gradient error derived from the β-distortion evident in Figure 3 is shown.

The strong errors shown in Figure 4 are due to the four quadrupole magnets near the interaction point. The gradient error is only about 0.5%. Apart from the quadrupoles near the interaction point, the remaining gradient errors represent the resolution of the method. Subsequent adjustment of the interaction quadrupole magnets brought β_y around the ring close to the design value.

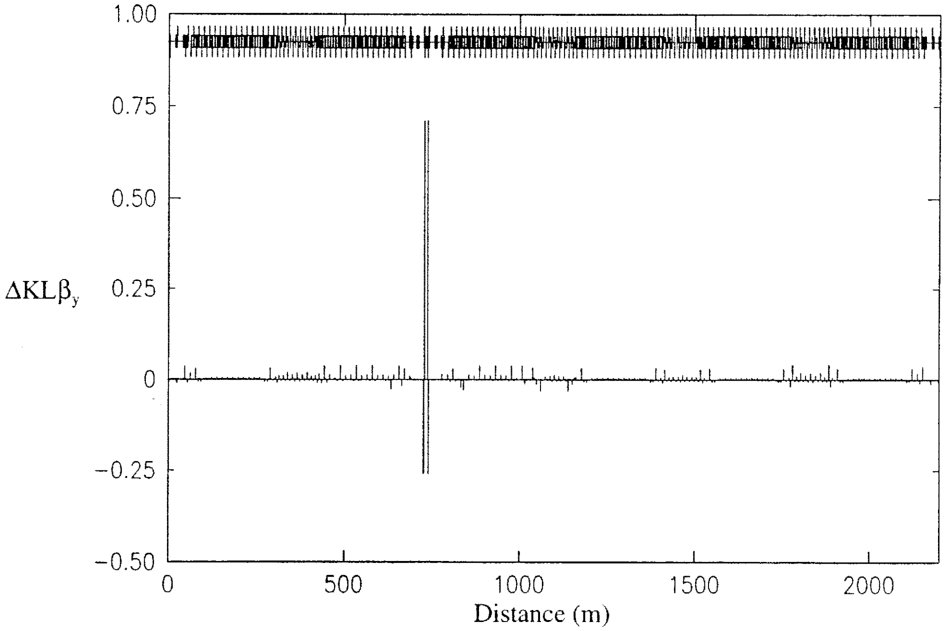
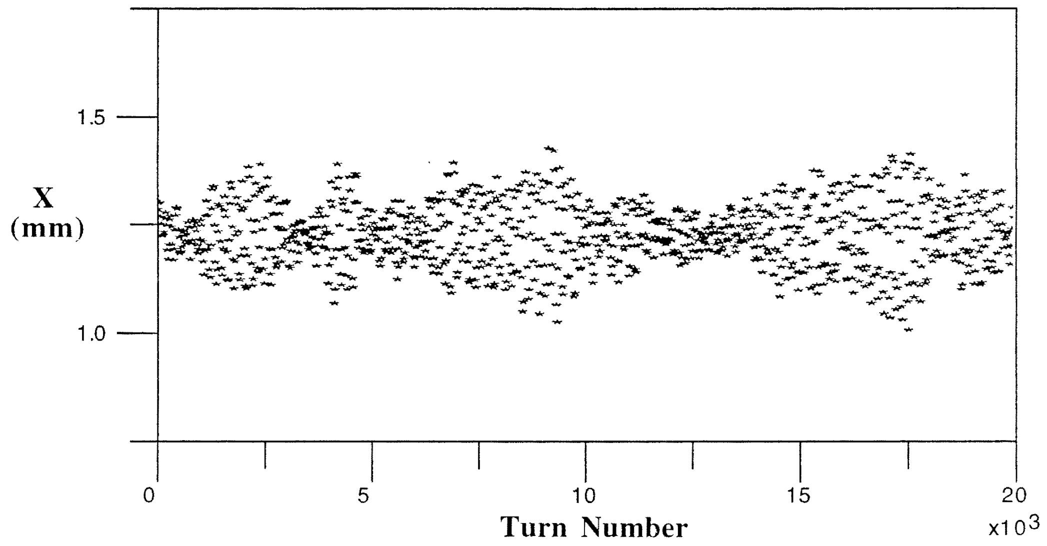


FIGURE 4. β- distortion due to quadrupole gradient errors.

Ring Study 2

In the second study, the BPM system was used to identify coherent bunch to bunch instabilities through the bunch train. The PEP-II rings have 3492 rf buckets of which every other one is filled. The ion-clearing gap comprises 5% of the ring circumference. This leaves 1658 filled buckets in a train, preceded by a gap. With feedback off a coherent bunch to bunch oscillation is seen to develop through the bunch train. This effect can be seen in the BPMs by measuring a particular bunch turn-by-turn at a point with some dispersion, and by observing the size of the transverse oscillation at the synchrotron frequency grow as a function of bunch number through the bunch train. The data in Figure 5 was taken in rather unstable conditions.


(a) BPMS PR04 6022 Bucket 10

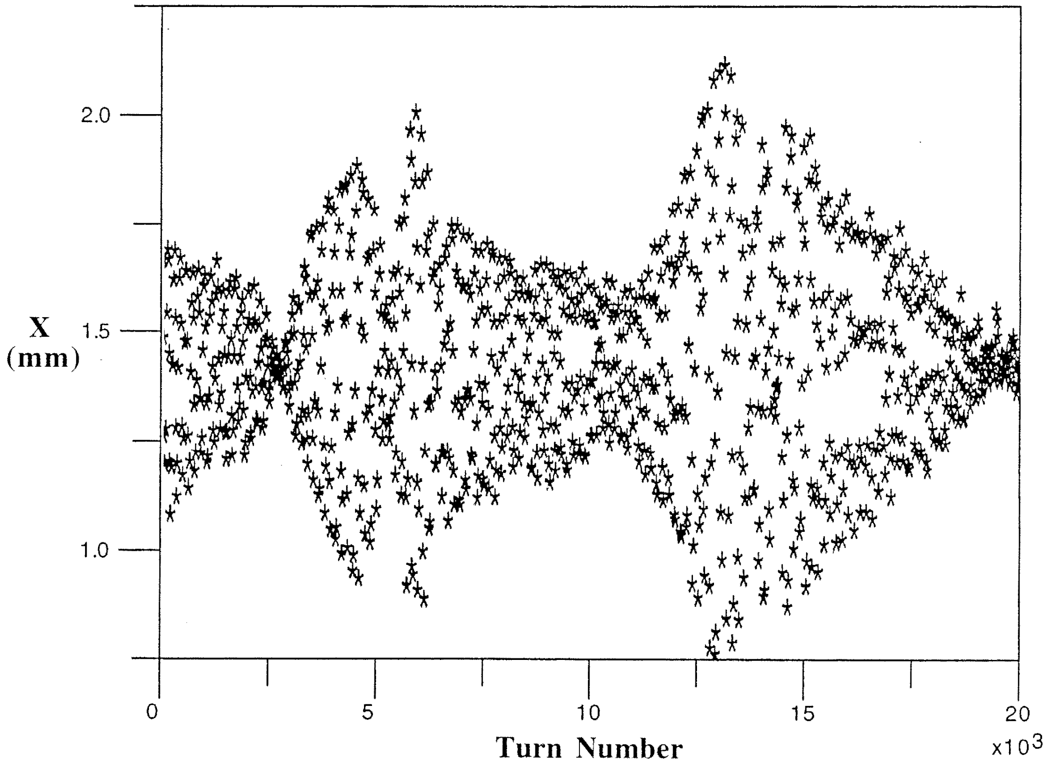

(b) BPMS PR04 6022 Bucket 3000

FIGURE 5. Coherent bunch to bunch instability: (a) *x*-position vs turn number for bucket 10; (b) *x*-position vs turn number for bucket 3000.

In Figure 5(a), 1000 measurements of the horizontal beam position of the 10th filled bucket, sampled every 20 ring turns, at a particular BPM are shown. In Figure

5(b), the oscillations of the 3000th bunch, at the same BPM, sampled at the same rate is shown. The amplitude in the second case is a factor of five larger. The amplitude is small following the gap and then builds up rapidly. The Fourier transform of these position sequences shows all of the signal is at the synchrotron frequency.

Even with the feedback on some coherent bunch-to-bunch instabilities were seen. However, it is expected that these instabilities can be controlled as the feedback systems are fine-tuned.

CONCLUSIONS

The PEP-II BPM system has performed very well thus far. It was operational from the start of commissioning of both HER and LER. The system has been an aid to the commissioning team in meeting all the goals set for PEP-II through this stage of the commissioning process. The BPMs have provided results which exceed all the requirements set for them. However, this is not to say that they have reached the limit of their performance. In addition, there are parts of the system which have not been tested completely or at all.

Isolating and fixing the problem which affects the position resolution is the most pressing issue. However there are a few individual BPMs that need to be repaired. About 15% of the RInQ modules have suffered infant mortality (of various components). All of these modules have been repaired. Problems with other parts of the BPM system (buttons, FIBs, and cables) have been negligible.

Further testing of the BPM system include: 1) full tests of multiplexing, 2) isolation between HER and LER channels, 3) measurement of a single low-intensity bunch in the ion clearing gap, and 4) absolute calibrations. Most of these tests require running both the HER and LER together.

The continued good performance of the PEP-II BPM system will be expected to contribute to the successful commissioning and operation of the PEP-II *B* Factory.

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