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# Some Solved Problems with the SLAC PEP-II B-Factory Beam-Position Monitor System

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# Some Solved Problems with the SLAC PEP-II B-Factory Beam-Position Monitor System[1]

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**Abstract.** The Beam-Position Monitor (BPM) system for the SLAC PEP-II B-Factory has been in operation for over two years. Although the BPM system has met all of its specifications, several problems with the system have been identified and solved. The problems include errors and limitations in both the hardware and software. Solutions of such problems have led to improved performance and reliability. In this paper we will report on this experience. The process of identifying problems is not at an end and we expect continued improvement of the BPM system.

## INTRODUCTION

The PEP-II B Factory [1] at SLAC has been in operation for nearly two years. Built as an asymmetric collider for the production of heavy mesons, the PEP-II rings store up to 1.0 A of electrons at 9.0 GeV in the High Energy Ring (HER) and up to 2.1 A of positrons at 3.1 GeV in the Low Energy Ring (LER). The rf is 476 MHz and the rings can contain up to 1658 bunches (every other rf bucket). PEP-II has achieved about two-thirds of its design luminosity and with the BaBar detector is well into production operation.

There are about 300 Beam-Position Monitors in each of the rings; most of them configured for single-axis measurement. The BPM system has been described previously [2-4]. Signals from four 1.5-cm diameter buttons are filtered (952-MHz center frequency and 150-MHz bandwidth) in a Filter-Isolator Box (FIB) located near the buttons. The FIB also combines signals to create x-only or y-only BPMs, except in a few cases (25) where both x and y information is preserved.

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Signals from the FIB are processed in a CAMAC unit, the Ring I&Q (RInQ) module. The processing is based on baseband conversion using in-phase and quadrature (I&Q) demodulation. A RInQ module can process the signals from up to two BPMs for each of the HER and LER, through mutiplexing. A block diagram of the analog portion of a RInQ is shown in Figure 1.

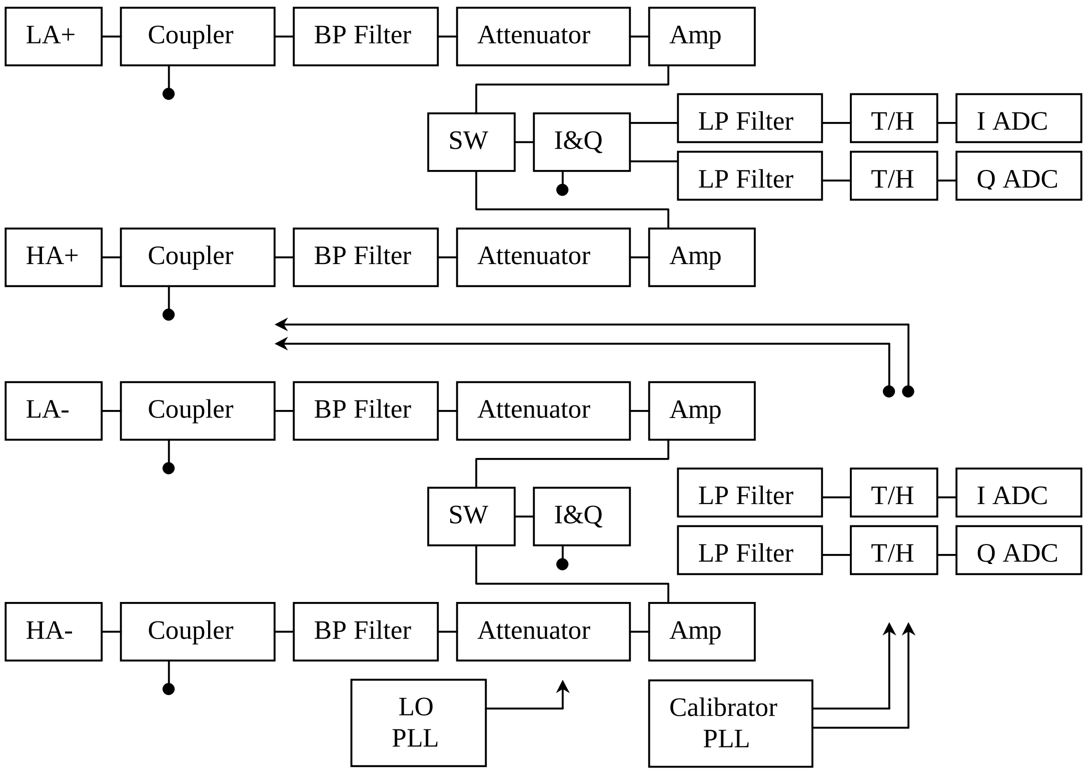


**FIGURE 1.** Ring I&Q (RInQ) Processor Block Diagram. Only the analog portion of the A-half of the module is shown. (LA - LER, A channel; BP - Bandpass; Amp – Amplifier; SW – Switch; I&Q – In-phase and quadrature demodulator; LP – Lowpass; T/H – Track and hold; ADC - Analog-to-digital converter; LO – Local oscillator; PLL – Phase-locked loop)

The front end of the RInQ contains a 10-dB coupler (to accept calibration signals through the coupling port) followed by a 952-MHz bandpass filter (50-MHz bandpass), a programmable attenuator, and an amplifier. Switches multiplex HER and LER signals into the I&Q demodulator where they are brought down to baseband. A lowpass filter sets the system bandwidth to 20 MHz. Track and holds and 14-bit, 308-kHz analog-to-digital converters convert the I and Q signals to digital at the ring frequency, 136 kHz. A digital signal processor (DSP) calculates the position.

Calibration and local-oscillator signals are provided on board through direct-digital synthesis (DDS) phase-locked loop synthesizers. The calibrator is adjustable in amplitude as well as frequency.

The BPM system has performed well from the start of PEP-II commissioning and has contributed to the excellent performance of both HER and LER. This is not to say that the BPM system has been problem free. Although the problems that have appeared have not prevented the system from meeting its requirements, they have hindered the system from meeting its design potential. The purpose of the present paper is to describe some of the problems, especially those we have been able to solve. We trust that our experience will be interesting and useful to the accelerator diagnostic community.

## CALIBRATION ERRORS

Early in the commissioning of the HER, the first and perhaps most annoying of our problems appeared. The beam position as reported by the BPMs oscillated at a rate of 21 Hz with an amplitude of about 50 μm. This so called 21-Hz problem was soon traced to errors in the calibration parameters. For each channel in the RInQ there are four parameters determined through a calibration, i.e., a least-squares fit to data obtained from signals produced by the calibrator oscillator. The parameters are the pedestals for I and Q and the ratio and phase error between I and Q. The calibration also determines the ratio of the positive and negative channels. Errors in these parameters lead to oscillations of a position measurement at harmonics of the baseband frequency (the difference between the measurement and local oscillator frequencies). Note: the size of the errors in these parameters is generally less than 0.5%.

A quick fix to the problem was to set the baseband frequency to a value in which the oscillations will be averaged out in a multiturn measurement. Typically the default measurements for the BPMs average 1024 turns, so the baseband frequency is set to 133 Hz. Although this fix is adequate operationally, it does not solve the fundamental problem and the resolution remains limited in single-turn measurements.

Eventually it was realized that in a position measurement the error vector for each RInQ channel contains the second order information necessary to correct the calibration parameters. In particular a fit to the error vectors using sine and cosine functions of the fundamental and first harmonic provide corrections to all the calibration parameters, i.e.,

$$\Delta V = a_0 + a_1 \sin x + a_2 \cos x + a_3 \sin 2x + a_4 \cos 2x, \tag{1}$$

where $x = \omega t + \phi$, $\omega$ is the angular frequency, t is time, and $\phi$ is the phase. For example, assume that the data has been properly corrected except that a phase error remains. Thus,

$$V' = \left[V_I^2 + V_Q^2\right]^{1/2}, \tag{2}$$

where $V_I = V\sin(x - \Delta\phi/2)$ and $V_Q = V\cos(x + \Delta\phi/2)$. $\Delta\phi$ is the uncorrected phase error. Expanding the expression and using the fact that $\Delta\phi$ is small the following is obtained:

$$V' = V(1 - \frac{\Delta\varphi}{2}\sin 2x) \tag{3}$$

$$\Delta V = V' - V = -V\frac{\Delta\phi}{2}\sin 2x \tag{4}$$

The coefficient of the sin2x term ($a_3$) is a correction to the I and Q phase error. Similarly the $a_1$ and $a_2$ terms are corrections to the pedestals and $a_4$ is the correction to the I and Q ratio.

An example of the improvement to the resolution by applying this procedure is shown in Figures 2 and 3 where error vectors for the positive and negative channels are shown along with the fits (Figure 3). The position as a function of turn number before and after this correction is shown in Figure 4. These data were obtained on our test bench and the baseband frequency was set at 4.0 kHz.

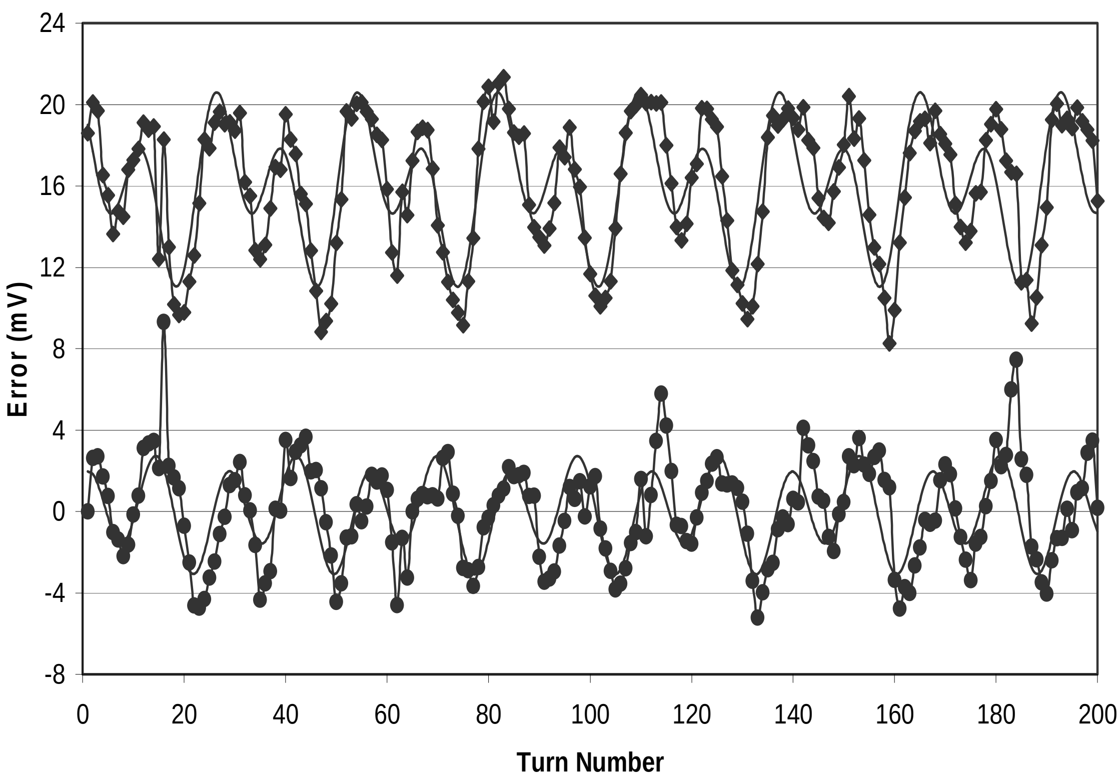


**FIGURE 2**. ΔV+ (top) and ΔV- (bottom) from a typical RInQ module. The smooth curves are the fits. Note: ΔV+ has been offset by 16 mV.

It is apparent in Figure 3 that there are higher harmonics in the data. This fact is even clearer when a Fourier transform is performed. We believe that the higher harmonics are due to non-linearities in the system. However, we have been unable to parameterize them such that they can be predicted and thus removed.

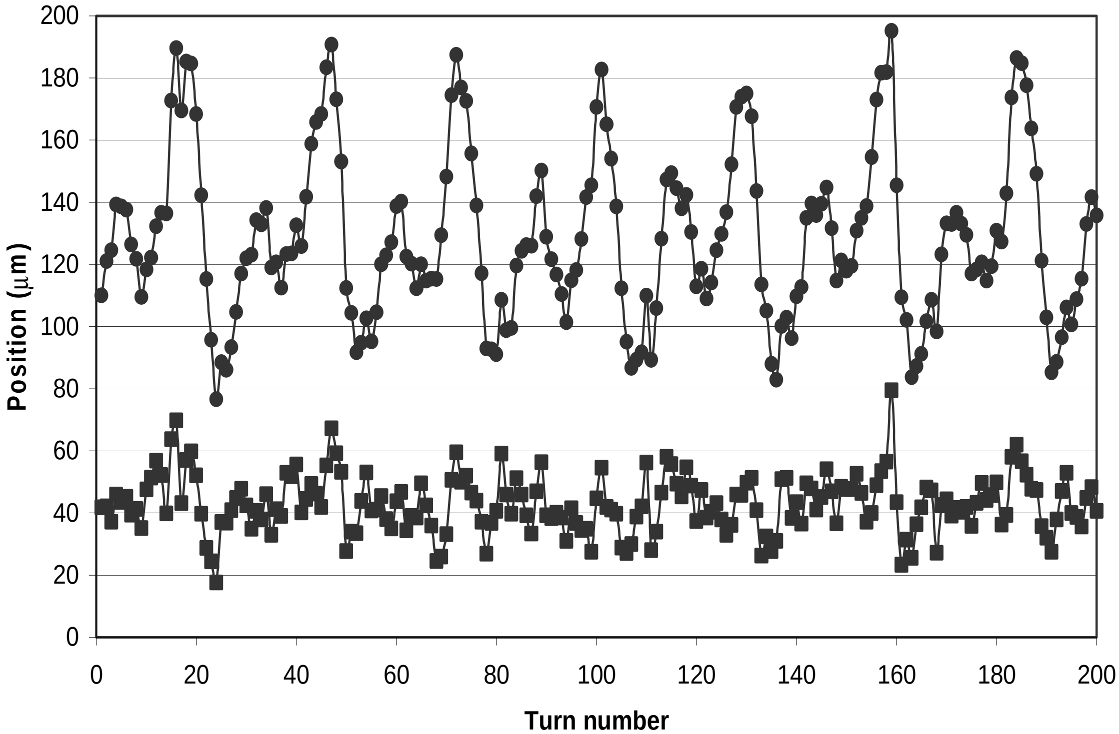


**FIGURE 3.** Position measurement from a typical RInQ module before and after calibration refinement. Note: the before refinement data has been offset by 80 μm for clarity.

In practice the beam itself becomes the source to refine the calibration for the RInQ modules. When running with stable beam, a request is issued to the modules to refine the calibration. Each module takes 1024-turn data and fits the position information with equation (1). The parameters of the fit are used to correct the calibration parameters. Typically this procedure improves the resolution by a factor of two to three.

## HARDWARE PROBLEMS

In this section we will discuss two hardware problems that affected a small but significant number of RInQ modules. The importance of these problems is mainly in the lesson to be learned on complete pre-installation testing and on-line diagnostics.

The first problem began with a report from the PEP-II operations staff that several BPMs showed a large change in position (50-150 μm) as a function of beam current. When we tested the modules on our test bench we found a significant difference in the phase error between calibration and position measurements. The problem was then traced to a strong dependence of the phase error on frequency ~ 5-8 degrees per MHz (ten times the usual). Finally, the problem was found to be incorrect components (usually capacitors of the wrong value) installed in the low-pass filters following the I&Q demodulators. Since calibrations are done at a few hundred kHz off the beam frequency to avoid interference, the calibrations were badly off for these modules.

Once the problem was identified a simple check was made of all modules by comparing calibrations at the usual frequency and then moving 5 MHz off that frequency and repeating the calibration. Fifteen (15) modules with this problem were found and repaired.

In our pre-installation check out of the RInQ modules we did not specifically do a test of the frequency response. In hindsight we should have. Alternatively, we could have caught the problem if our on-line software had the appropriate diagnostic. In calibrating for single beam pulse measurements a scan (in 5-MHz steps) over the bandpass of the system is made and the average is used. If the appropriate check had been incorporated, the problem would have been seen here.

The second problem also came to light with a complaint from the PEP-II operations staff that several BPMs were reporting large position changes (several hundred micrometers) when changing from one calibration to another (each optimized for a different beam current). The effect was easy to reproduce but the symptoms revealed two problems. First, for the problem BPMs, the attenuators that allow for different expected beam currents were not working correctly. One of the binary coded attenuations was not turning on for one channel. Secondly, the software that should correct for the ratio of positive and negative channels was also not working.

After examining the code, an error was found which had the effect of setting the plus to minus ratio to unity. In this case the software error allowed us to find and repair twelve (12) RInQ modules with inoperative attenuators.

Again this problem could have been found in pre-installation testing; but, we did not have the appropriate test routines to do so, nor the foresight to see the need. The on-line code does have a check on the counts received in each channel but the check is set very loosely and did not catch this problem.

## OFFSET AS A FUNCTION OF ATTENUATION

In testing for the second hardware problem discussed above another problem was discovered. Offsets due to mismatch of channels were measured on the test bench by injecting equal signals into the positive and negative channels and measuring position. The measured offsets (combined with offsets from other sources) are stored in the on-line database and positions are corrected accordingly. The RInQ offsets were measured at zero attenuation.

The tests for attenuator hardware problems revealed a slow change of offset as a function of attenuation. It was apparent that a small fraction of the calibrator signal was coupled to each channel after the attenuator. As the channel attenuation is increased the calibrator signal amplitude is increased to produce sufficient signal for the calibration. Depending on which coupling is larger the offset is driven in that direction. For all channels except LA the direction appears to be random. For LA the offset increases in the negative direction.

Under the theory that a fixed fraction of the calibrator signal is coupled to each channel following the attenuator, it can be shown that the offset should be given by

$$x_{Off} = x_0 + mf(A) \tag{5}$$

where

$$f(A) = 10^{-(A/20-1.5)} \tag{6}$$

and A is the channel attenuation in dB. Offsets for a typical RInQ module are shown in Figure 4. The smooth lines in this figure are fits using equation (6).

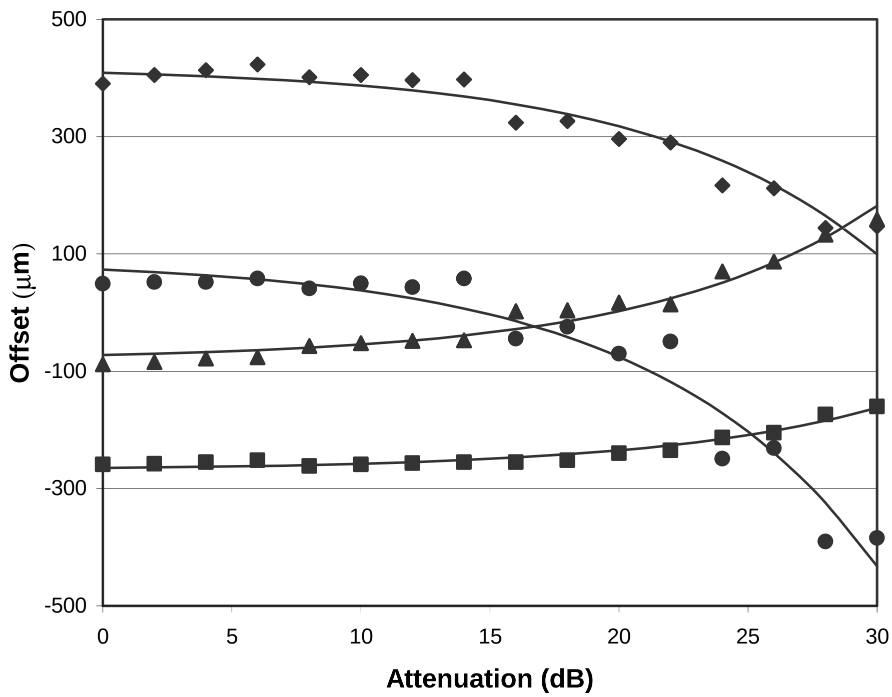


**FIGURE 4.** Offset vs attenuation for a typical RInQ module. LA – circles, HA – diamonds, LB – squares, and HB – triangles. The smooth curves are the fits to the data.

Since these fits work so well, no attempt was made to fix the problem in hardware, e.g., isolating the calibrator traces. Instead the on-line code and database were modified to calculate the offset at each channel attenuation using equation (6). All RInQ modules were tested to measure the slope and intercept of the offsets.

## CONCLUSIONS

Although the PEP-II BPM system has met all its requirements, several problems have appeared. The solutions to those problems have improved the performance and reliability of the system. In the future other problems are almost certain to be revealed.

We believe that the solutions to those problems will continue to improve the BPM system.

Calibration of the active electronics is certainly needed; but it is also clear that small error in those calibrations lead to larger effects. The positions determined from button or stripline sensors are the difference between large signals. Thus errors in calibrations are magnified. We have developed a method that allows for the correction of the calibration parameters and results in a factor of two to three improvement in resolution.

Hardware problems will occur in almost all electronics, especially new designs. The lessons learned by our experience are to carefully test all aspects of the electronics before installation. Hindsight is of course clear and in the pressure to begin operations predicting all the items that should be tested is not easy. In the two cases sighted, the problems would have been detected by simple tests.

The final problem presented (offset variation with attenuation) is a design problem. Again such problems are almost certain to occur in a new electronics design. In this case the problem was solved in software rather than the harder fix to the hardware.

## ACKNOWLEDGMENTS

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