Sensitivity and Offset Calibration for the Beam Position Monitors at the Advanced Photon Source*

Y. Chung, D. Barr, G. Decker, K. Evans, Jr. and E. Kahana
Argonne National Laboratory, Argonne, IL 60439

Abstract

The beam position monitors (BPMs) play a critically important role in commissioning and operation of accelerators. Accurate determination of the offsets relative to the magnetic axis and sensitivities of individual BPMs is thus needed. We will describe in this paper the schemes for calibrating all of the 360 BPMs for sensitivity and offset in the 7-GeV Advanced Photon Source (APS) storage ring and the results. For the sensitivity calibration, a 2-dimensional map of the BPM response in the aluminum vacuum chamber is obtained theoretically, which is combined with the measured nonlinear response of the BPM electronics. A set of 2-dimensional polynomial coefficients is then obtained to approximate the result analytically. The offset calibration of the BPMs is done relative to the magnetic axis of the quadrupoles using the beam. This avoids the problem arising from various mechanical sources as well as the offset in the processing electronics. The measurement results for the resolution and long-term drift of the BPM electronics shows 0.06-μm/$\sqrt{\text{Hz}}$ resolution and 2-μm/hr drift over a period of 1.5 hrs.

I. INTRODUCTION

For beam position monitoring of the charged particle beam, button-type pickups will be used in the storage ring, injector synchrotron, and insertion devices (IDs) of the Advanced Photon Source (APS). In order to meet the requirements on the accuracy of the measured beam position as shown in Table 1, it is necessary that the beam position monitors (BPMs) are accurately calibrated for the offset and sensitivity.

Table 1: APS Storage Ring BPM Specifications.

First Turn, 1 mA Resolution / Accuracy	200 μm / 500 μm
Stored Beam, Single or Multiple Bunches @ 5 mA Total Resolution / Accuracy	25 μm / 200 μm
Stability, Long Term	±30 μm
Dynamic Range, Intensity	≥ 40 dB
Dynamic Range, Position	±20 mm

In the past few years, significant effort has gone into implementation of the offset calibration using the external method developed by G. Lambertson [1,2]. This method requires separate measurements in air and vacuum, since the APS storage ring vacuum chamber is subject to significant deformation under vacuum due to the photon exit channel. For the sensitivity calibration, a different method is needed, such as a wire, antenna, or charged particle beam whose transverse position can be controlled with precision. This approach has met with certain implementation difficulties due to scheduling conflicts with installation and bakeout of the vacuum chambers and relatively high sensitivity of measurement error to the mechanical environment surrounding the BPMs.

An alternative method, which takes advantage of independent powering of the quadrupoles, has been developed for use during the commissioning phase with charged particle beams. From the change in the particle trajectory in the downstream of a quadrupole due to quadrupole strength change, the particle beam offset at the quadrupole relative to the magnetic center can be deduced. The offset of the neighboring BPM can then be determined by comparing the BPM reading and the measured beam offset at the quadrupole. This method has a few advantages over other methods based on laboratory bench measurements or external measurements. First, since this is an end-to-end measurement, all the BPM components between the button electrodes and the digitizers are calibrated as an integrated system. Second, the offsets are calibrated with respect to the magnetic axis adjoining the quadrupoles, and therefore, the calibration includes survey and alignment error of the BPMs and quadrupoles. A possible down side is that this method uses up valuable beam time and the stability of the beam property may not be good during commissioning. As a requirement for this method, the transfer matrices between each quadrupole and each BPM needs to be known. These matrices can be obtained from the lattice model or the lattice functions calculated from it.

Separate from the above procedure for offset determination, measurements need to be made for individual BPMs for mapping between the beam position and the BPM output in the 2-dimensional space [2]. This takes into account the geometric effect of the vacuum chamber and the nonlinear characteristics of BPM electronics. Comparison of the measurement and analytical results on the geometric effect of the vacuum chamber showed good agreement. Therefore, measurements were made only on electronics, whose results were combined with a theoretical model of the vacuum chamber to obtain 2-D polynomial coefficients.

The remainder of this paper will be a theoretical discussion of the beam-based BPM offset determination and error analysis in Section II and a result of measurement in the APS

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storage ring in Section III. A summary and discussion are in Section IV.

II. BEAM-BASED BPM OFFSET DETERMINATION

A. Theory

Let us consider a pair consisting of a quadrupole and a BPM in the ring as shown in Fig. 1. The beam offset x_q and angle x'_q with respect to the magnetic axis can change as the beam goes through the quadrupole as written by

$$\begin{pmatrix} x_q \\ x'_q \end{pmatrix}_{out} = \mathbf{M}_q \cdot \begin{pmatrix} x_q \\ x'_q \end{pmatrix}_{in}, \qquad (1)$$

where $\mathbf{M}_q$ is the transfer matrix for the quadrupole.

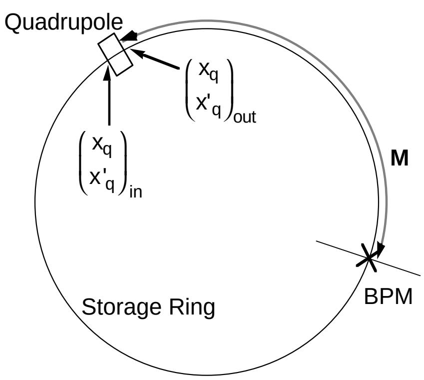

Fig. 1: The transfer matrix $\mathbf{M}_{iq}$ between a quadrupole and a BPM.

Similarly, if we let $\mathbf{M}_{iq}$ be the transfer matrix between the quadrupole and the i-th BPM, we can express the beam position x_i and x_i' at the BPM as

$$\begin{pmatrix} x_i \\ x'_i \end{pmatrix} = \mathbf{M}_{iq} \cdot \begin{pmatrix} x_q \\ x'_q \end{pmatrix}_{out} = \mathbf{M}_{iq} \cdot \mathbf{M}_q \cdot \begin{pmatrix} x_q \\ x'_q \end{pmatrix}_{in}. \qquad (2)$$

The transfer matrix $\mathbf{M}_{iq}$ can be obtained from the lattice functions or by multiplying the transfer matrices of all elements between the quadrupole and the BPM. In the following discussion, we will drop the subscript *in* from the notation for simplicity.

On the other hand, the BPM reading x_{bi} is given by

$$x_{bi} = S_i x_i + x_{oi}, \qquad (3)$$

where S_i and x_{oi} are the sensitivity and offset of the BPM, respectively. We assume that the nominal value of S_i is 1. In order to obtain S_i and x_{oi} based on Eqs. (2) and (3), we first need to know x_q. Suppose we have a BPM close enough to the quadrupole so that we can write $x_{bi} \approx x_q$, then we have $x_{oi} = x_{bi} - S_i x_q$. In general, x_{oi} can be expressed in terms of the linear combination of x_q's for two adjacent quadrupoles.

Now, if $\mathbf{M}_q$ is changed by $\Delta\mathbf{M}_q$ through the change in quadrupole strength, Eq. (2) gives for the i-th BPM

$$\begin{pmatrix} \Delta x_{iq} \\ \Delta x'_{iq} \end{pmatrix} = \mathbf{M}_{iq} \cdot \Delta\mathbf{M}_q \cdot \begin{pmatrix} x_q \\ x'_q \end{pmatrix}. \qquad (4)$$

Since the BPM does not measure beam angle, we collect only the expressions from Δx_{iq} for M BPMs downstream of the quadrupole and write

$$\Delta\mathbf{x}_q = \mathbf{A}_q \cdot \begin{pmatrix} x_q \\ x'_q \end{pmatrix}, \qquad (5)$$

where $\mathbf{A}_q$ is an M×2 matrix. Each row of $\mathbf{A}_q$ consists of the upper row of the matrices $\mathbf{M}_{iq} \cdot \Delta\mathbf{M}_q$ in Eq. (4) with $\mathbf{M}_{iq}$ evaluated for the quadrupole and the i-th BPM. The solution for x_q and x'_q can be obtained from Eq. (5) using the technique of singular value decomposition (SVD).

If the thin lens approximation is valid, the second column of the matrix $\mathbf{A}_q$ is zero and $\Delta\mathbf{x}_q$ can be expressed in terms of x_q alone. The change in the BPM reading would then be expressed as

$$\Delta x_{biq} = S_i \Delta x_{iq} = -S_i m_{12,iq} \Delta K L_q x_q \quad (i = 1,\ 2,\ \ldots,\ \mathrm{M}), \qquad (6)$$

where ΔK is the quadrupole strength change and

$$m_{12,iq} = \sqrt{\beta_i \beta_q}\,\sin(\psi_i - \psi_q). \qquad (7)$$

The beam angle x'_q is indeterminate in this case. From Eq. (6), x_q is then given by

$$x_q = -\frac{1}{\Delta K L_q} \frac{\Delta x_{biq}}{S_i m_{12,iq}}. \qquad (8)$$

B. Error Reduction

From Eq. (8) it is sufficient to measure the beam position change at a single BPM to obtain x_q. However, if the actual lattice is significantly different from the model, the measurement can be sensitive to the phase error and the resulting error in x_q can be quite large. One way to reduce this error is to statistically average out the oscillatory term after squaring the numerators and denominators. That is, we put

$$x_q^2 \approx \frac{1}{\left(\Delta K L_q\right)^2} \frac{\sum_i \Delta x_{biq}^2}{\sum_i m_{12,iq}^2}, \qquad (9)$$

where we assumed the average of S_i is equal to 1 and the error cancels out after summation over i. The sign of x_q is determined separately by applying Eq. (8) to a few selected BPMs adjacent to the quadrupole for which the betatron phase error is not significant. From Eqs. (7) and (9) and using the identity relation

$$\sin^2 x = \frac{1}{2}(1 - \cos 2x), \tag{10}$$

the effect of the phase error is reduced roughly as 1/M, where M is the number of BPMs included in the summation.

Once x_q is determined, the BPM sensitivity S_i can be obtained in a similar manner from Eq. (6) as

$$S_i^2 \approx \frac{\sum_q \Delta x_{biq}^2}{\sum_q \left(\Delta KL_q x_q m_{12,iq}\right)^2}. \tag{11}$$

The summation is done over the quadrupoles.

III. MEASUREMENTS

A. Beam-based Offset Measurement

An electron bunch of typically 1-nC charge with 7-GeV energy is injected from the booster into the storage ring at 1-Hz rate. The beam makes one turn around the ring and is stopped by a scraper at the end of sector 40. Figure 2 shows the vertical orbit change Δy due to the quadrupole strength change in S1B:Q2. The beam offset y_q at the quadrupole was determined to be 0.7 mm, which gave the BPM offset y_o for the nearby S1B:P1 as -0.96 mm. The solid line is the fit to the lattice model.

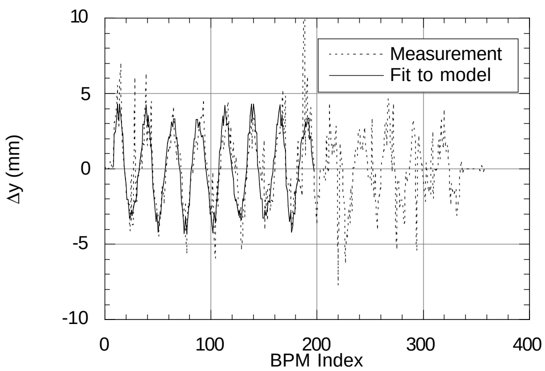

Fig. 2: The vertical orbit change Δy (dotted line) due to the quadrupole strength change in S1B:Q2 in the APS storage ring. The solid line is the fit to model using y_q = 0.7 mm. The BPM offset y_o for the nearby S1B:P1 is -0.96 mm.

B. BPM Electronics

The BPM system consists of four button-type electrodes, filter-comparator, monopulse receiver, signal conditioning and digitizing unit (SCDU), memory scanner, beam history module, and timing module [3]. For calibration of the electronics for offset and sensitivity, the SiO_2 cables connecting the buttons and the filter-comparator are replaced with a CW rf source (352 MHz) and four switched attenuators. The beam motion is simulated by changing the gain on the attenuators with 0.125-dB resolution. During the measurements, the attenuators are changed in steps of 0.5 dB in the low-gain mode and 0.125 dB in the high-gain mode. These correspond to approximately 1 mm and 0.25 mm of beam motion near the center. The response of the monopulse receiver is theoretically given by

$$V_{x,y} = \frac{4}{\pi} \tan^{-1}\left(\frac{D_{x,y}}{\Sigma}\right), \tag{12}$$

where $D_{x,y}$ and Σ are the output of the filter-comparator.

Figure 3 shows examples of BPM electronics in the low- and high-gain modes. The measurement data from each BPM is combined with the theoretical model of the vacuum chamber geometry to derive 2-D polynomial coefficients [2].

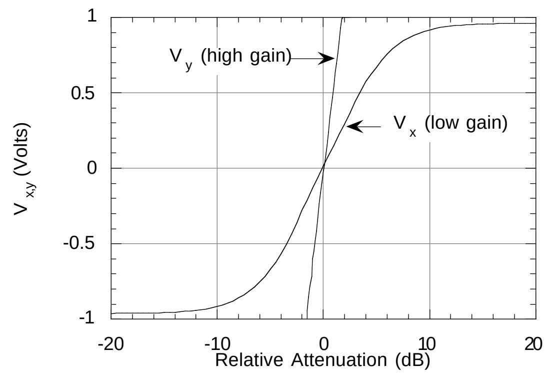

Fig. 3: Measurement on the BPM electronics response using switched attenuators. V_x with low gain and V_y with high gain are shown.

IV. DISCUSSION

In this work, we have discussed methods for calibrating the offset and sensitivity of beam position monitors in the APS storage ring. As operational diagnostic tools and for orbit feedback, BPMs are required to have high resolution and low drift. Results of measurements made at ESRF indicate 0.06-$\mu m/\sqrt{Hz}$ resolution and 2-μm/hr drift over a period of 1.5 hrs with 5 mA of stored beam for the APS [4], which is confirmed through preliminary measurements made on selected BPMs.

V. REFERENCES

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