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/√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.

<table>
<thead>
<tr>
<th>Description</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>First Turn, 1 mA</td>
<td>200 μm / 500 μm</td>
</tr>
<tr>
<td>Stored Beam, Single or Multiple Bunches @ 5 mA Total</td>
<td>25 μm / 200 μm</td>
</tr>
<tr>
<td>Resolution / Accuracy</td>
<td></td>
</tr>
<tr>
<td>Stability, Long Term</td>
<td>±30 μm</td>
</tr>
<tr>
<td>Dynamic Range, Intensity</td>
<td>≥ 40 dB</td>
</tr>
<tr>
<td>Dynamic Range, Position</td>
<td>±20 mm</td>
</tr>
</tbody>
</table>

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.
存储环在第 III 节。一个总结和讨论在第 IV 节。

II. BEAM-BASED BPM OFFSET
DETERMINATION

A. Theory

让我们考虑一个由一个四极和一个 BPM 组成的对。在图 1 中。图 1 的偏移位置与磁轴的关系可以变化，因为随着四极和 BPM 之间的距离变化，束流通过四极时可以写为

\[
\begin{pmatrix}
x_q \\
x_q'
\end{pmatrix}_{\text{out}} = M_q \cdot \begin{pmatrix}
x_q \\
x_q'
\end{pmatrix}_{\text{in}},
\]

(1)

其中 \( M_q \) 是四极的转移矩阵。

同样地，如果我们让 \( M_{iq} \) 是四极和第 \( i \)-个 BPM 之间的转移矩阵，则可以表达束的位于第 \( i \)-个 BPM 时束流为

\[
\begin{pmatrix}
x_i \\
x_i'
\end{pmatrix} = M_{iq} \cdot \begin{pmatrix}
x_q \\
x_q'
\end{pmatrix}_{\text{out}} = M_{iq} \cdot M_q \cdot \begin{pmatrix}
x_q \\
x_q'
\end{pmatrix}_{\text{in}}.
\]

(2)

转移矩阵 \( M_{iq} \) 可以从从计算机生成的函数或通过将转移矩阵的所有元素乘以束通过四极和 BPM 时的四极的转移矩阵元素中得到。在以下讨论中，我们将丢弃在在简化的记法中的下标 \( \text{in} \)。

在另一方面，BPM 读数 \( x_{bi} \) 是由

\[
x_{bi} = S_i x_i + x_{oi},
\]

(3)

其中 \( S_i \) 和 \( x_{oi} \) 是 BPM 的灵敏度和偏移的偏移，分别。我们假定该名义值的 \( S_i \) 是 1。在 order to obtain \( S_i \) and \( x_{oi} \) 基于 Eqs. (2) 和 (3)，我们首先需要知道 \( x_q \)。假设我们有一个 BPM 太接近四极以至于我们可以将 \( x_{bi} = x_{bi} \)，然后我们有 \( x_{oi} = x_{bi} - S_i x_q \)。一般地，\( x_{oi} \) 可以表示为两个相邻四极的 \( x_q \) 的线性组合。

现在，如果 \( M_q \) 被改变为 \( \Delta M_q \) 通过改变四极强度，Eq. (2) 给出第 \( i \)-个 BPM

\[
\begin{pmatrix}
\Delta x_{iq} \\
\Delta x'_{iq}
\end{pmatrix} = M_{iq} \cdot \Delta M_q \cdot \begin{pmatrix}
x_q \\
x_q'
\end{pmatrix}.
\]

(4)

由于 BPM 不测量束流角，我们只收集来自四极的 BPM 和写第 \( i \)-个 BPM 的表达式 \( \Delta x_{iq} \) 对于 \( M \) BPMs 下游的四极和写

\[
\Delta x_q = A_q \cdot \begin{pmatrix}
x_q \\
x_q'
\end{pmatrix},
\]

(5)

其中 \( A_q \) 是一个 \( M \times 2 \) 矩阵。每一行 \( A_q \) 包含了矩阵上部的行 \( M \) \( M_{iq} \cdot \Delta M_q \) 在 Eq. (4) 中的 \( M_{iq} \) 与第 \( i \)-个 BPM 为四极和第 \( i \)-个 BPM 的转移矩阵。对于 \( x_q \) 和 \( x_q' \) 的和可以来自 Eq. (5) 使用的单值分解 (SVD) 技术。

如果薄透镜近似是有效的，第二个列的矩阵 \( A_q \) 是零和 \( \Delta x_q \) 可以在包含在 \( x_q \) 的束流中。在 BPM 读数中变化的束流角会然后被表达为

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

(6)

其中 \( \Delta K \) 是四极强度变化并且

\[
m_{12,iq} = \sqrt{\beta \beta_q} \sin(\psi_q - \psi_q).
\]

(7)

束流角 \( x_q' \) 是行的不定。从 Eq. (6)，\( x_q \) 是给定的

\[
x_q = -\frac{1}{\Delta K L_q S_i m_{12,iq}} \Delta x_{biq}.
\]

(8)

B. Error Reduction

从 Eq. (8) 它是足以在单个 BPM 中得到 \( x_q \)。然而，如果实际的格子是显著不同的从模型，测量可以受到相位错误的影响和的结果的误差可以是相当大的。一种减少这种误差的方法是统计上平均由四方对的乘积中的周期性项后。我们，我们用

\[
x_q^2 = \frac{1}{(\Delta K L_q)^2} \sum_i \Delta x_{biq}^2,
\]

(9)

其中我们假设的平均值的 \( S_i \) 是等价于 1 而且误差可以计算在每个 BPM 中。束流分量的相位的误差是不显著的。从 Eq. (7) 和 (9) 和使用标识关系
\[ \sin^2 x = \frac{1}{2} (1 - \cos 2x) , \]  

(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

\[ S_i^2 = \frac{\sum \Delta \chi^2_{bq}}{\sum (A K L \chi^q \chi^q \chi^q \chi^q)^2} . \]  

(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 \(\Delta y\) 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 \(\Delta y\) (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.](image)

**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

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

(12)

where \(D_{x,y}\) and \(\Sigma\) 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.](image)

#### 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/Hz resolution and 2-\(\mu\)m/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


