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Beam Position Monitor Calibration for the Advanced Photon Source*

Y. Chung, G. Decker, E. Kahana, F. Lenkszus, A. Lumpkin, and W. Sellyey
Argonne National Laboratory, Argonne, IL 60439

Abstract

This paper describes the sensitivity and offset calibration for the beam position monitors (BPMs) using button-type pickups in the injector synchrotron, storage ring, and insertion devices of the Advanced Photon Source (APS). In order to reduce the overall offset and to isolate the error ($\lesssim$ 100 μm) due to the low fabrication tolerance in the extruded storage ring vacuum chamber, the electrical offset is minimized by carefully sorting and matching the buttons and cables according to the button capacitance and the characteristic impedances of the cable and the button feedthrough. The wire method is used for the sensitivity calibration, position-to-signal mapping, and measurement of resolution and long-term drift ($\lesssim$ 1 mV) of the processing electronics. The processing electronics was also tested at Stanford Synchrotron Radiation Laboratory (SSRL) using a real beam, with results indicating better than 25 μm resolution for the APS storage ring. Conversion between the BPM signal and the actual beam position is done by using polynomial expansions fit to the mapping data with absolute accuracy better than 25 μm within ±5 mm square. Measurement of the effect of button mispositioning and mechanical inaccuracy of the extruded storage ring vacuum chamber, including deformation under vacuum, will be also discussed.

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 of the 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 BPMs are accurately calibrated for the offset and sensitivity.

The offset calibration of the BPMs will be done using the external method developed by G. Lambertson. [1–4] Since the APS storage ring vacuum chamber is subject to significant deformation under vacuum due to the photon exit channel, separate measurements of the offset are needed in air and vacuum. The measurement, however, can be affected by the button position error and the resulting calibration error needs to be estimated for proper application. In order to isolate the mechanical error and to minimize the overall offset error, the buttons and cables will be matched electrically.

The sensitivity calibration, on the other hand, requires the use of a wire, antenna, or charged particle beam whose transverse position can be controlled. We will present results obtained using the wire in the lab and electron beam in SPEAR at Stanford Synchrotron Radiation Laboratory (SSRL). Comparison with the theory will be also discussed.

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

II. BUTTON CHARACTERISTICS

Let C_p be the capacitance of a button and let Z_T be the terminating impedance at the instrument end for measurement of the button signal. Then gain coefficient g_c for the button and connecting cable at frequency ω can be written as [5]

$$g_c = \frac{S_{21}}{1 - S_{11} - i\omega C_p Z_T(1 + S_{11})}, \quad (1)$$

where S_{11} and S_{21} (= S_{12}) are the reflection and transmission coefficients between the button and the terminating resistor Z_T, including the button feedthrough.

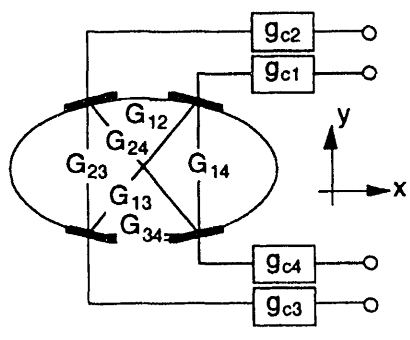

Fig. 1: The schematic of a BPM.

In terms of the capacitive coupling coefficient G between two buttons, the ratio V_{ij} of the voltage V_i detected on button i and the voltage V_j applied on button j can be written [1]

$$V_{ij} = \frac{V_i}{V_j} = 2\, Z_T\, g_{ci}\, g_{cj} G_{ij} \, . \quad (2)$$

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G_{ij} contains the geometric factors including the chamber deformation under vacuum.

Figure 1 shows the geometry of the positron beam chamber, the buttons, and associated g_c- and G-coefficients. The measured beam position (x, y) using linear approximation can be obtained from the button signals V_i ($1 \le i \le 4$) using

$$\frac{\Delta_x}{\Sigma} = \frac{V_1 - V_2 - V_3 + V_4}{V_1 + V_2 + V_3 + V_4} \approx S_x\,(x + \Delta x_w), \quad (3)$$

and similarly for Δ_y/Σ. Δx_w is the x offset, and S_x is the sensitivity coefficient. The coordinate origin (x = 0, y = 0) may be conveniently identified with a position that can be referenced from an external fiducial mark.

The overall gain g_i for the i-th button is the product of g_{ci} and the electrical gain coefficient g_{bi} for beam-to-button coupling for the beam centered at origin. That is,

$$g_i = g_{bi} \cdot g_{ci}\,. \quad (4)$$

Then, the BPM offsets Δx_w and Δy_w can be expressed in terms of the g-coefficients in dB unit as

$$\Delta x_w \approx \frac{0.0288}{S_x}\,(g_1 - g_2 - g_3 + g_4),\ (g_i \text{ in dB}) \quad (5)$$

$$\Delta y_w \approx \frac{0.0288}{S_y}\,(g_1 + g_2 - g_3 - g_4).\ (g_i \text{ in dB}) \quad (6)$$

Approximation was made assuming that the gain differences are small. In the following discussions, we will use dB units for g- and G-coefficients and V_{ij} unless noted otherwise.

III. BPM SENSITIVITY AND 2-D MAPPING

A. BPM Sensitivity

The coefficients S_x and S_y determine the sensitivity of the BPM in detecting beam motion. We used a thin wire of 12-mil diameter suspended along the vacuum chamber for calibration of injector synchrotron and storage ring BPMs. Figure 2 shows the result for the storage ring BPM and Table 2 lists theoretical and measurement results obtained for various BPMs in the APS.

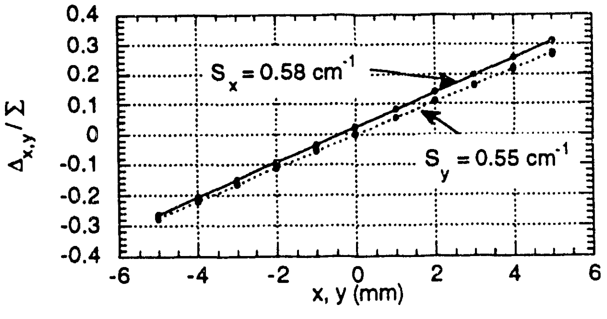

Fig. 2: Determination of the sensitivity coefficients S_x and S_y for the APS storage ring.

Table 2: Theoretical and measured sensitivities for the APS storage ring, injector synchrotron, and insertion device BPMs.

	Storage Ring	Injector Synch.	ID 12 mm gap	ID 8 mm gap
S_x	0.57 cm^{-1}	0.70 cm^{-1}	2.08 cm^{-1}	3.44 cm^{-1}
S_x*	0.58 cm^{-1}	0.70 cm^{-1}	–	–
S_y	0.53 cm^{-1}	0.58 cm^{-1}	1.51 cm^{-1}	1.47 cm^{-1}
S_y*	0.55 cm^{-1}	0.57 cm^{-1}	–	–

(*: measured)

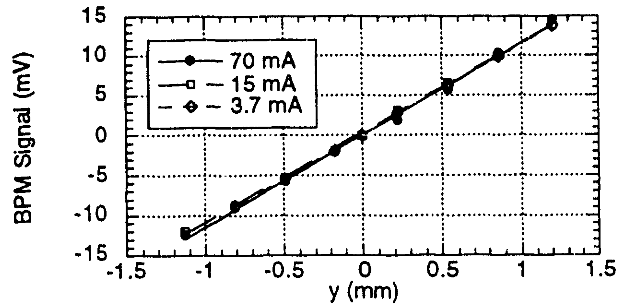

Fig. 3: BPM signal from the processing electronics measured on SPEAR, SSRL, for beam currents of 70, 15, and 3.7 mA.

In Fig. 3 is shown the BPM signal from the prototype processing electronics measured on the electron beam in SPEAR at Stanford Synchrotron Radiation Laboratory (SSRL). The average sensitivity is 11.4 mV/mm. With additional gain of 6 for the final design, this translates to approximately 20 μm resolution assuming 1 mV r.m.s. error.

B. 2-D Mapping

Figure 4 shows the 2-dimensional mapping (contour lines of $\Delta_{x,y}/\Sigma$) of the APS storage ring BPM response in the region $|x| \le 20$ mm and $|y| \le 10$ mm. This data is used to obtain the polynomial coefficients for conversion between the BPM signal (V_x, V_y) and the beam position (x, y),

$$P : (V_x, V_y) \rightarrow (x, y). \quad (7)$$

With 8th order both in x and y, absolute accuracy better than 25 μm within ±5 mm square was obtained. This calculation is done by local processors in the VME crates for the BPMs in real-time.

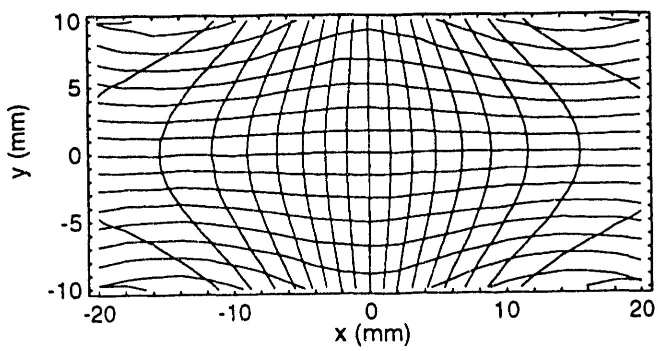

Fig. 4: 2-dimensional mapping of the APS storage ring BPM response. Grid spacing = 0.1.

The inverse of Eq. (7), which converts the beam positi·· to BPM signal for the fast beam position feedback systems acting on the raw BPM signal to enhance speed, cannot be in general represented as polynomials. Instead, the polynomial functions

$$Q : (x, y) \rightarrow (V_x, V_y) \quad (8)$$

are used as the initial guess for the iterative search following the direction of the steepest change.

IV. OFFSET CALIBRATION

In this section, we will discuss calibration of the BPM offset using the external method applied on the APS storage ring. From Eq. (2) and putting $a = 20 \log (2 Z_T)$, we have

$$a + g_{ci} + g_{cj} + G_{ij} = V_{ij} = V_{ji}. \quad (9)$$

The offsets are determined in terms of V_{ij} as

$$\Delta x_e = \frac{0.0288}{S_x}(V_{14} - V_{23}),$$

$$\Delta y_e = \frac{0.0288}{S_y}(V_{12} - V_{34}). \quad (10)$$

Other combinations are also possible and they may be used for error-checking. In this work, we will use the expressions in Eq. (10) only. Equation (9) can in principle be used to determine the g_c- and/or G-coefficients. This, however, requires shuffling of the buttons and cables to get a large enough number of independent measurements.

A. Analysis of Calibration Error

The tooling ball located on top of the vacuum chamber is used as the fiducial mark for survey and alignment of the BPM relative to an adjacent quadrupole or sextupole. The offset calibration error can be defined as the BPM signal after calibration with the beam at the position referenced by the tooling ball. Let us consider the button position error (h_i and v_i, $1 \le i \le 4$) and the tooling ball position error (x_t and y_t) as the dominant error sources. h_i is the button position error along the mounting surface in the direction outward from the center and v_i is the error in the outward direction normal to the surface. The surface is sloped at 15.11° about the horizontal plane.

Using Eqs. (10) and (11) and the partial derivatives listed in Table 3, the offset calibration errors Δx_{err} and Δy_{err} for the APS storage ring are given by

$$\Delta x_{err} \approx 0.14\, x_t - 0.22\left(h_1' - h_2' - h_3' + h_4'\right) + \Delta x'_w - \Delta x'_e, \quad (11)$$

and

$$\Delta y_{err} \approx 0.75\, y_t + 0.20\left(h_1' + h_2' - h_3' - h_4'\right) + \Delta y'_w - \Delta y'_e, \quad (12)$$

where the prime (') denotes random error. It is to be noted that the vertical position error v_i does not contribute to the calibration error. Equations (11) and (12) show that overall mechanical tolerance of a few mils is acceptable to achieve 100 μm (≈ 4 mils) of r.m.s. offset calibration error.

Table 3: Listing of the partial derivatives of the g- and G-coefficients in units of dB/mm. Analytical and numerical calculations were done in 2-D.

	$\frac{\partial G_{12}}{\partial h_1}$	$\frac{\partial G_{14}}{\partial h_1}$	$\frac{\partial g_{b1}}{\partial h_1}$	$\frac{\partial G_{12}}{\partial v_1}$	$\frac{\partial G_{14}}{\partial v_1}$	$\frac{\partial g_{b1}}{\partial v_1}$
Analytical	-0.83	-0.01	-0.45	–	–	–
Numerical	-0.74	0.07	-0.37	-2.9	-2.8	-2.8
Measurement	–	–	–	-3.4	-3.4	-3.4

B. Chamber Deformation under Vacuum

For the APS storage ring, BPMs are an integral part of the vacuum chamber with the buttons directly mounted on the machined surface of the chamber. When the chamber is put under vacuum, significant deformation of the chamber was observed. This effect led to approximately 400 μm shift in the x offset measured using the external method.

Assuming linearity, we found the relation

$$\Delta x_e = \Delta x_{ea} + k_v (\Delta x_{ev} - \Delta x_{ea}), \quad k_v \approx 0.65, \quad (13)$$

where Δx_{ea} and Δx_{ev} are the offsets measured in air and vacuum, respectively. The proportionality constant k_v was obtained with separate measurements using wire and simulation of vacuum pumpout by mechanical means.

Acknowledgment

R. Hettel at SSRL is to be thanked for his collaboration on measurements of the BPM response on SPEAR.

V. REFERENCES

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