Performance of the Beam Position Monitor for the Advanced Photon Source

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Performance measurement and analysis of the Advanced Photon Source (APS) beam position monitor (BPM) electronics are reported. The results indicate a BPM resolution of $0.16 \mu\text{m} \cdot \text{mA}/\sqrt{\text{Hz}}$ in terms of the single-bunch current and BPM bandwidth. For the miniature insertion device (ID) BPM, the result was $0.1 \mu\text{m} \cdot \text{mA}/\sqrt{\text{Hz}}$. The improvement is due to the 3.6 times higher position sensitivity (in the vertical plane), which is partially canceled by the lower button signal by a factor of 2.3. The minimum single-bunch current required was roughly 0.03 mA. The long-term drift of the BPM electronics independent of the actual beam motion was measured at $2 \mu\text{m}/\text{hr}$, which settled after approximately 1.5 hours. This drift can be attributed mainly to the temperature effect. Implications of the BPM resolution limit on the global and local orbit feedback systems for the APS storage ring will also be discussed.

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I. INTRODUCTION

Measurement of the particle beam position in accelerators is an essential part of the beam diagnostics system, and the beam position monitors (BPMs) provide the basic diagnostics tool for commissioning and operation of accelerators. One of the primary applications of the BPMs is the stabilization of the particle and X-ray beam positions through feedback.^{1,2} The specification of the required BPM resolution for beam position feedback in the Advanced Photon Source (APS) storage ring is listed in Table I.

TABLE I: Specification of the orbit feedback systems.

Orbit measurement device	Global DC All of the rf BPMs	Global AC rf BPMs (1/sector)	Local rf BPMs X-ray BPMs
Correctors	All correctors	Subset of correctors	Local bump
Specified orbit measurement resolution	25 μm	25 μm	1 μm
Achievable resolution	5 μm	5 μm	1 μm
Required range of correction	$\pm 20 \text{ mm}$	$\pm 500 \mu\text{m}$	$\pm 100 \mu\text{m}$

The BPMs in the storage ring (SR) and injector synchrotron (IS) of the APS have four button-type pickups mounted directly on an elliptically shaped vacuum chamber.³ The button size and the sensitivity of these BPMs are listed in Table II. The theoretical calculation was done analytically with an elliptic vacuum chamber with no photon exit channel,⁴ which shows significant difference from the measured value in the case of the insertion device (ID) BPM due to the asymmetry in geometry.

In this paper, we will describe measurements of resolution and long-term drift of the APS BPM electronics using the charged particle beam. Design, development, and

preliminary tests of the BPM electronics are described in Refs. 5, 6, and 7.

TABLE II: Parameters for the APS BPMs in the storage ring (SR), injector synchrotron (IS), and insertion devices with 12-mm and 8-mm gap.

	SR	IS	ID 12 mm	ID 8 mm
Button radius (cm)	0.5	0.5	0.2	0.2
S_x (cm^{-1})	0.57	0.70	2.08	3.44
S_x^* (cm^{-1})	0.58	0.70	1.63	—
S_y (cm^{-1})	0.53	0.58	1.51	1.47
S_y^* (cm^{-1})	0.55	0.57	1.54	—

(*: measured sensitivity)

II. BPM OPERATION AND ERROR ANALYSIS

The BPM samples the beam position N consecutive times with the time interval Δt with 12-bit resolution. Due to the time delay in the processing electronics, the minimum Δt is roughly 1.2 μs . With the 3.68- μs revolution time, there can be at most three samples per revolution. If we let $x(t)$ be the actual beam position at time t and if we let t_n be the starting time of sampling, the averaged beam position x_n is then given by

$$x_n = \frac{1}{N} \sum_{k=0}^{N-1} (x(t_n + k\Delta t) + \delta x_{n,k}), \quad (1)$$

where $\delta x_{n,k}$ is the BPM error assumed to be randomly independent of n and k .

The BPMs can be put in one of three modes: x -only, y -only, and xy -toggling. In the x -only mode, the BPM processing electronics sample only the x coordinate of the beam position, and only the y coordinate is sampled in the y -only mode. In the xy -toggling mode, both the x and y coordinates are sampled but only at half the rate of the x -only or y -only modes for each plane. Therefore, in the xy -toggling mode, Δt is twice as large as the x -only or y -only modes.

Suppose the beam motion has the harmonic time dependence as given by

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$$x(t) = ae^{-i\Omega t}, \quad (2)$$

where Ω is the frequency of oscillation and a is a complex number representing the amplitude and phase. Inserting Eq. (2) into Eq. (1), we obtain

$$x_n = \frac{2a}{N\Omega\Delta t} \exp(-i\Omega t_n) \sin\left(\frac{1}{2}N\Omega\Delta t\right) + \frac{1}{N} \sum_{k=0}^{N-1} \delta x_{n,k}, \quad (3)$$

where a constant complex factor was absorbed into a and it is assumed that $\Omega\Delta t \ll 1$. The rms beam position measurement error would then be given by

$$\Delta x^2 \leq \Delta x_b^2 + \frac{(\delta x_e(I_b))^2}{N}, \quad (4)$$

where $\Delta x_b = |a|/\sqrt{2}$ is the rms beam motion and $\delta x_e(I_b)$ is a measure of the BPM resolution as a function of the beam current I_b .

In this work, we want to measure the second term in Eq. (4) apart from the actual beam motion. Since the two terms are added in quadrature, measurements would be more accurate if the second term dominates, e.g., by using small N and by reducing the beam current as much as possible. If this condition is satisfied, the BPM electronics resolution Δx_e would be given by

$$\Delta x_e = \frac{\delta x_e(I_b)}{\sqrt{N}}. \quad (5)$$

The unwanted contribution Δx_b can be further reduced by cross-connecting the cables attached to the BPM buttons and putting the processing electronics in x -only or y -only mode. For example, if the top or bottom two cables are crossed, the first-order BPM response would be negligible in the x -only mode. Another method of canceling the BPM response is to use a pair of power divider/combiners. The former method was used in this work.

III. MEASUREMENTS

The APS storage ring has 40 sectors. For this work, the BPMs in sectors 1, 2, 3, 6, 7, and 9 were used as shown in Table III. Some BPMs that had crossed connections were picked from different sectors to minimize the impact on operation. For sector 7, all of the BPMs were used under normal configuration. The measurement setup and data collection were done through the APS control system.

TABLE III: BPM configuration

BPMs	Configuration
S1B:P1, S2A:P1	ID BPMs. Normal connection
S3A:P1, S6B:P1	Top buttons crossed
S7(A,B):Pn	Normal
S9A:P1, S9B:P1	Inboard buttons crossed

Figure 1 shows the results of measurements on the BPM measurement error as a function of N for the single-bunch current $I_b = 0.22$ mA. The error decreases as $1/\sqrt{N}$ as shown in Eq. (5). As the beam current increases, this relation

becomes less apparent, and at $I_b \sim 7$ mA, the error on S7:x was virtually independent of N .

FIG. 1. Results of beam position measurement errors Δx and Δy as a function of N for the single-bunch beam current $I_b = 0.22$ mA.

The dependence of the beam position measurement error on the beam current I_b is shown in Fig. 2. For the BPMs with crossed connections, the error decreases as $1/I_b$. For the normal BPMs (S7:x and S7:y), the error decreases initially but approaches asymptotically about $30 \mu\text{m}$ for x and $15 \mu\text{m}$ for y due to the contribution from the actual beam motion. For miniature ID BPMs, the intensity is decreased by roughly 2.3, but the sensitivity is increased by 2.7 (S_x) and 3.6 (S_y), respectively. Therefore, we obtain from the results shown in Figs. 2 and 3

$$\Delta x_e [\mu\text{m}] \approx \frac{\delta x_e(I_b)}{\sqrt{N}} \approx \frac{1}{\sqrt{N} I_b [\text{mA}]} \times \begin{cases} 40 & \text{Regular} \\ 25 & \text{ID} \end{cases}. \quad (6)$$

FIG. 2. The beam position measurement error as a function of the single bunch current I_b for $N = 2$.

Let us now convert Eq. (6) using the $\mu\text{m} \cdot \text{mA}/\sqrt{\text{Hz}}$ unit. The frequency response of the simple averager on the BPM can be written as

$$|H(f)| = \frac{1}{N} \frac{\sin(N\pi f / F_s)}{\sin(\pi f / F_s)}, \quad (7)$$

where F_s is the sampling frequency. In the xy -toggling mode with a single bunch, it is equal to 136 kHz for the APS storage ring. Then, the bandwidth (-3 dB) corresponds to approximately $Nf = 1.39F_s/\pi \approx 60$ kHz. From Eq. (6), the BPM resolution is

$$\Delta x_e [\mu\text{m}] = \frac{\sqrt{f_{\text{BPM}} [\text{Hz}]}}{I_b [\text{mA}]} \times \begin{cases} 0.16 & \text{Regular} \\ 0.1 & \text{ID} \end{cases}. \quad (8)$$

where f_{BPM} is the BPM bandwidth.

Since the BPM resolution is inversely proportional to $\sqrt{F_s}$, it can be improved by increasing the sampling frequency F_s . The minimum sampling time by the processing electronics is 1.2 μs , and therefore, with the 3.68- μs revolution time in the APS storage ring, there can be as many as three triggers per turn if the bunches are grouped into three equally spaced clusters.

FIG. 3. The BPM button signal sensitivity Σ as a function of the single-bunch beam current I_b .

Measurement of the BPM button signal sensitivity Σ as a function of the single bunch current is shown in Fig. 3. The logarithmic fit to the data gives

$$\Sigma [\text{Counts}] \approx \begin{cases} 700 + 500 \log(I_b [\text{mA}]), & \text{Regular} \\ 520 + 490 \log(I_b [\text{mA}]), & \text{ID} \end{cases} \quad (9)$$

As a comparison, we made separate measurements in the laboratory using a CW rf source (-10 dBm with 40 dB amplifier) feeding a 1-to-4 divider connected to a filter-comparator. The result indicated 12 μm of resolution with $N = 2$. Average Σ was 930 counts, which is equivalent to 2.9 mA according to Eq. (9). This is in good agreement with Eq. (6), which gives 10 μm .

The long-term drift of the BPM electronics was measured on the ESRF storage ring using the 1-to-4 divider to balance the signal and thus cancel the beam position sensitivity.⁸ The stored beam current was $I_b = 102.5$ mA with 1/3-fill. In order to reduce the short-term fluctuation, the highest number of averages $N = 2048$ was used. The result indicates a long-term drift of about 2 $\mu\text{m/hr}$.

IV. SUMMARY AND DISCUSSION

In this work, we described measurements of resolution and long-term drift of the Advanced Photon Source beam position monitor electronics using the charged particle beam.

BPM resolution measurements were done using a single bunch on the regular storage ring BPMs and the miniature insertion device BPMs. Different beam currents and BPM bandwidths were used to estimate the BPM resolution and contribution from the actual beam motion. The results indicate that the resolution is proportional to $\sqrt{f_{\text{BPM}}} / I_b$,

where f_{BPM} is the BPM bandwidth and I_b is the single-bunch beam current. The constant of proportionality is 0.16 for the regular storage ring BPM and 0.1 for the miniature ID BPM in units of $\mu\text{m} \cdot \text{mA} / \sqrt{\text{Hz}}$. These results are in good agreement with separate laboratory measurements conducted with a CW rf source.

The long-term drift measurement on the ESRF storage ring with the stored beam current of 102.5 mA with 1/3-fill indicates 2 $\mu\text{m/hr}$. This drift can be attributed mainly to the temperature effect.

In the APS storage ring, the rf BPMs will be used for global and local beam position feedback to stabilize the particle and x-ray beams. The correction bandwidth is expected to be approximately 100 Hz with projected sampling frequency of 4 kHz. Within this bandwidth and with the single-bunch current of 1 mA, the resolution would be better than $0.16 \times \sqrt{100} = 1.6$ μm for regular BPMs and 1 μm for miniature ID BPMs. Beam position perturbation larger than this resolution will be corrected by feedback.

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