IMPLEMENTATION OF FAST BEAM-BASED ALIGNMENT AT THE TAIWAN PHOTON SOURCE

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Abstract

A fast beam-based alignment (BBA) method has been implemented at the Taiwan Photon Source to significantly enhance the efficiency of aligning beam position monitors with quadrupole magnet centers. By utilizing sinusoidal excitation of correctors and employing synchronous detection algorithms, alignment offsets are efficiently extracted across the entire storage ring. Experimental results demonstrate that the total measurement time is reduced from 8 hours to under 40 minutes, while maintaining precision comparable to conventional BBA methods. The primary sources of measurement uncertainty are attributed to betatron tune and orbit variations induced by magnetic hysteresis and ocean-induced ground motion. This approach provides a robust and time-efficient solution for routine orbit characterization in modern synchrotron light sources.

INTRODUCTION

The Taiwan Photon Source (TPS) operates at an electron energy of 3 GeV with a 500 mA nominal beam current [1]. During startup after long shutdowns, beam-based alignment (BBA) is performed to calibrate offsets between the 173 beam position monitors (BPMs) and 240 quadrupole magnets. The standard BBA procedure [2] at the TPS utilizes slow correctors and slow-acquisition data, requiring approximately 8 hours for full-ring measurements.

To improve efficiency, a fast BBA (FBBA) method has been developed using fast correctors [3,4] to excite the beam at distinct frequencies. This system records 30 kHz fast-acquisition data for real-time signal processing. This paper describes the FBBA methodology, hardware configuration, and discusses measurement uncertainties along with optimization strategies.

MEASUREMENT PRINCIPLE AND SETUP

Each cell at the TPS is equipped with four horizontal and four vertical fast correctors to perform fast orbit feedback, with a corrector bandwidth exceeding 5 kHz. These eight fast correctors are managed by a corrector power supply controller (CPSC) in each cell. The CPSC is capable of delivering arbitrary waveforms to each individual power supply. To calibrate the l-th BPM, the nearest quadrupole magnet is selected and its current is increased by 1 A. The most effective i-th fast corrector is determined using the response matrix $\boldsymbol{R}$. A sinusoidal current $C_i(t)$ is applied to the corrector to excite the beam, and the resulting beam position at the k-th BPM (BPM$_k$) is denoted as X_{k1}, as illustrated in Fig. 1(a).

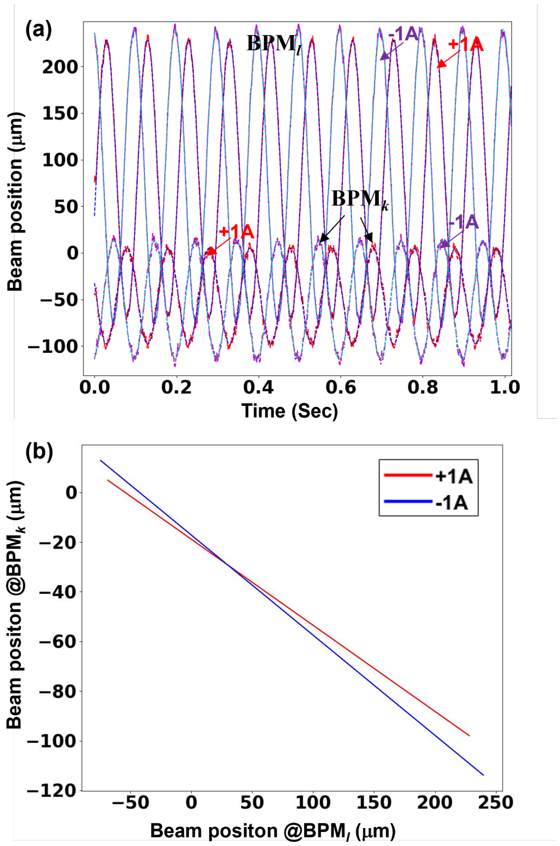

Figure 1: (a) Beam motion at BPM$_l$ and BPM$_k$ resulting from resulting from a ±1 A change in the current of the quadrupole magnet near BPM$_l$, and (b) the relationship between beam positions at these two BPMs under two different quadrupole current settings.

A dedicated computer is used to record the beam positions from all BPMs at a 30 kHz sampling rate. The data is transmitted from the BPM electronics, which aggregate the synchronized data from all monitors, to the computer via Gigabit Ethernet. The relationship between the corrector currents and the beam positions at the BPMs is given by [5]:

$$X_{l1}(t) - X_{l1}^0 = R_{li1}(C_i - C_0), \tag{1}$$

$$X_{k1}(t) - X_{k1}^0 = R_{ki1}(C_i - C_0), \tag{2}$$

where C_0 and X_{k1}^0 in Eqs. (1) and (2) represent the initial corrector current and the beam position at the k-th BPM, respectively, prior to the application of the excitation waveform. The indices l and k denote the target BPM undergoing FBBA and the other observation BPMs in the storage ring.

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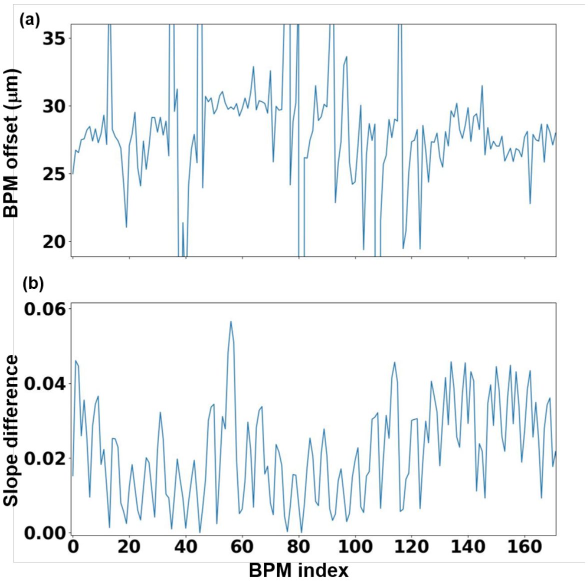

Figure 2: (a) BPM offsets derived from the intersection points across various BPMs and (b) the corresponding slope differences at two different quadrupole current settings.

Equations (1) and (2) can be combined and rewritten as:

$$X_{k1}(t) - X^0_{k1} = \frac{R_{ki1}}{R_{li1}}(X_{l1}(t) - X^0_{l1}). \tag{3}$$

Equation (3) represents a linear relationship between the beam positions at two different BPM locations, which can be expressed in a simplified form as:

$$z_k(t) = a_1 z_l(t) + b_1. \tag{4}$$

where

$$z_k = X_{k1}, z_l = X_{l1}, a_1 = \frac{R_{ki1}}{R_{li1}} \quad \text{and} \quad b_1 = X^0_{k1} + \frac{R_{ki1}}{R_{li1}} X^0_{l1}. \tag{5}$$

When the current of the nearest quadrupole magnet adjacent to the target BPM is decreased by 1 A, a distinct linear relationship is observed between the beam positions at the l-th and k-th BPMs, which can be expressed as:

$$z_k(t) = a_2 z_l(t) + b_2. \tag{6}$$

The intersection point, $z_l = (b_2 - b_1)/(a_1 - a_2)$, shown in Fig. 1(b) represents the alignment offset of the l-th BPM.

When a fast corrector excites the beam with a sinusoidal signal at frequency f, the beam positions measured at the l-th and k-th BPMs can be expressed as:

$$z_l(t) = c_l \sin(2\pi f t + \phi) + d_l, \tag{7}$$

$$z_k(t) = c_k \sin(2\pi f t + \phi) + d_k, \tag{8}$$

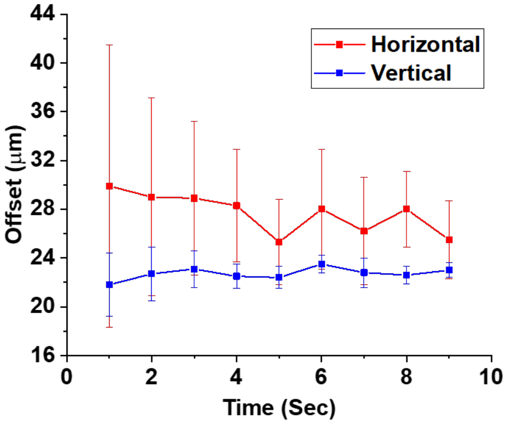

Figure 3: Average and standard deviation of the measured offsets from ten independent trials at various measurement durations.

where the parameters c, d, and ϕ represent the amplitude, offset, and phase, respectively, which are determined by fitting the beam motion data. From Eqs. (7) and (8), the linear relationship between $z_l(t)$ and $z_k(t)$ can be derived as:

$$z_k(t) = \frac{c_k}{c_l} z_l(t) + \left(d_k - \frac{c_k}{c_l} d_l\right). \tag{9}$$

By comparing this result with Eqs. (4) and (6), the slope a and intercept b are identified as:

$$a = \frac{c_k}{c_l} \quad \text{and} \quad b = d_k - \frac{c_k}{c_l} d_l. \tag{10}$$

For each BPM alignment, beam responses are recorded at two quadrupole current settings to yield linear fits (a_1, b_1) and (a_2, b_2). The intersection of these lines, representing the BPM offset, is then calculated as $(b_2 - b_1)/(a_1 - a_2)$.

In a storage ring with 173 BPMs, a total of 172 such intersection points can be calculated, as illustrated in Fig. 2. Due to measurement uncertainties, these calculated points are not perfectly identical. When the difference between the slopes a_1 and a_2 is small, the calculated intersection point becomes highly sensitive to noise, typically resulting in larger errors. In general, the intersection points derived from the largest slope differences are preferred for determining the final BPM offset.

RESULTS AND DISCUSSION

Situated on an island, the TPS is notably susceptible to ocean-induced ground motion (0.3 Hz) with micrometer-scale amplitudes [6]. This weather-dependent motion induces horizontal beam oscillations that impact FBBA accuracy. As shown in Fig. 3, increasing the measurement duration reduces the standard deviation; however, this reduction plateaus after 3 second. Consequently, a 3-second measurement window was adopted for all subsequent measurements to optimize both precision and efficiency.

Figure 4 compares conventional BBA and FBBA results alongside FBBA repeatability. Discrepancies between the two methods are typically within 50 μm, while the differences between successive FBBA runs are significantly

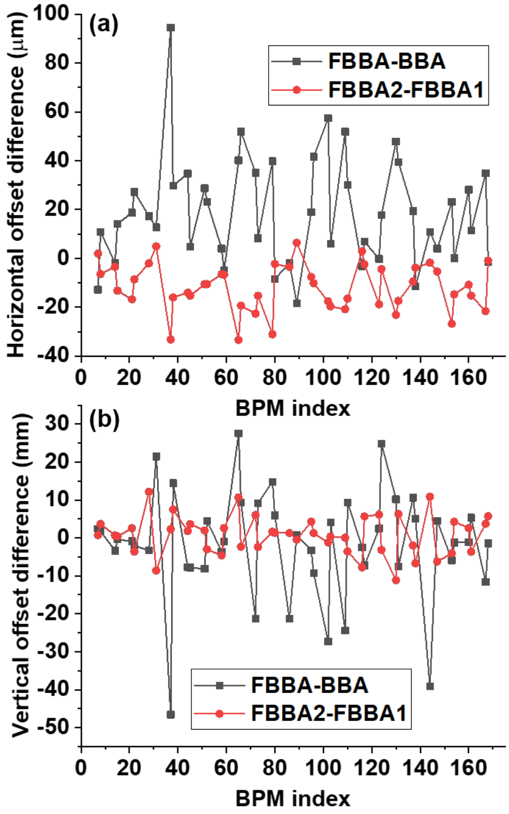

Figure 4: Comparison of BPM offsets between conventional BBA and FBBA, and the repeatability between successive FBBA runs in the (a) horizontal and (b) vertical planes.

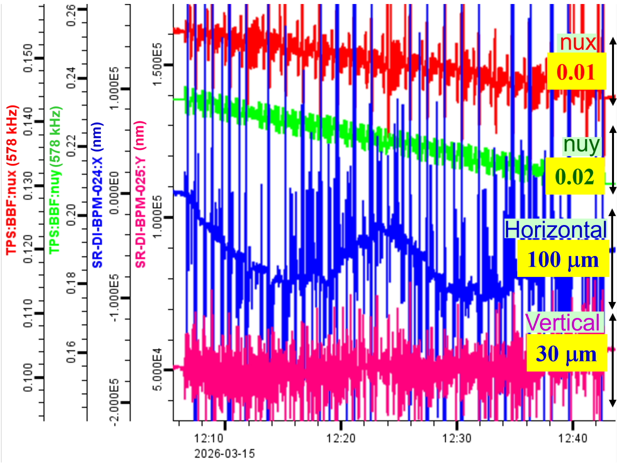

Figure 5: The variation of tune and orbit during the FBBA measurement. The BPMs with larger position variations are plotted.

smaller and comparable to those of successive conventional BBA trials. Because BBA references the nearest quadrupole magnet, the longitudinal distance between the magnet and the BPM introduces uncertainties when different correctors are employed, accounting for the larger BBA-FBBA discrepancies.

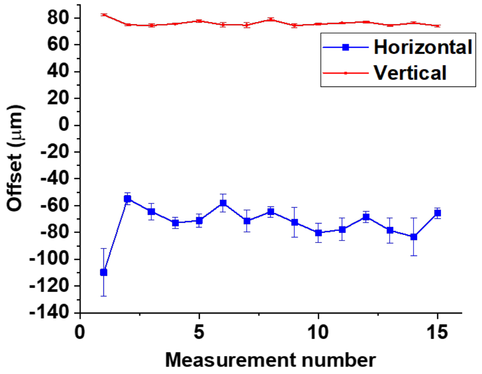

Figure 6: BPM offsets across multiple FBBA measurement runs.

Furthermore, magnetic hysteresis in the quadrupoles and correctors induces significant variations in the betatron tune and orbit as shown in Fig. 5, leading to non-reproducible responses and accumulated errors for BPMs measured later in the sequence. Similarly, when a single BPM is measured multiple times, shown in Fig. 6, a substantial offset discrepancy is often observed between the first and second trials, particularly for magnets with high hysteresis. After this initial cycle, the tune and orbit reach a steady state, and subsequent variations become much smaller. While betatron tune and orbit corrections following each BPM measurement could mitigate these systematic effects, the absence of such procedures in the standard routine makes these errors unavoidable.

CONCLUSION

Fast beam-based alignment (BBA) has been successfully implemented at the Taiwan Photon Source (TPS). By utilizing fast correctors for dual-frequency excitation (horizontal and vertical planes), beam position monitor (BPM) offsets are extracted from oscillation amplitudes and average positions under ±1 A quadrupole current modulations. To mitigate ground-motion induced perturbations, a measurement duration of at least 3 second per BPM is required, resulting in a total calibration time of approximately 40 minutes.

Analysis indicates that the longitudinal separation between BPMs and quadrupoles leads to corrector-dependent variations; consequently, the discrepancy between conventional BBA and fast BBA (FBBA) is larger than the repeatability observed between independent FBBA runs. Furthermore, magnetic hysteresis induces tune and orbit shifts that stabilize after the initial measurement cycle. While real-time compensation of these shifts could further reduce systematic errors, it would significantly increase the total measurement time.

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