BEAM BASED ALIGNMENT FOR BENDING MAGNETS WITH TRANSVERSE GRADIENT*

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Abstract

For storage rings, bending magnets with transverse gradient are commonly adopted to reduce the natural emittance. These magnets are typically offset quadrupoles, which generate combined dipole and quadrupole fields. Therefore, it is crucial to ensure that the beam travels at the designed off-axis position within the target magnets. Otherwise, particles would experience an additional dipole field due to the magnetic field feed-down effect, which could influence the beam dynamics. To determine the beam position in the bending magnets with transverse gradient, a beam-based alignment method is presented in this paper.

INTRODUCTION

Due to the superior performance of synchrotron radiation-based light sources, they play an important role in modern scientific research on quantum materials, catalytic science, bioscience, and other fields. As synchrotron radiation facilities, storage ring-based light sources are in operation, under construction, or in design around the world. The brightness of the light sources is the key parameter for end-users. Therefore, achieving low emittance is crucial.

To achieve low emittance, storage rings usually adopt the multi-bend achromat (MBA) lattice structure and some combined-function magnets. Bending magnets with transverse gradient are a common type of combined-function magnets, which can be realized using an off-axis quadrupole design [1, 2]. It is crucial to ensure that the beam position is corrected in these magnets in order to provide the designed bending angle and quadrupole field. Otherwise, the dynamic performance could be degraded due to the magnetic field feed-down effect. A beam-based alignment (BBA) method can be employed to determine the beam position in transverse gradient dipoles.

The remaining content is organized as follows. First, the BBA method for dipoles with transverse gradient is introduced. Subsequently, the simulation using the BBA method is presented. Finally, a concise summary is provided.

METHOD

The bending magnet with transverse gradient is an off-axis quadrupole. The beam position $\boldsymbol{X}(s_0)$ of the particles at the location of the quadrupole s_0 can be described by

$$\boldsymbol{X}(s_0) = x\hat{\boldsymbol{x}} + y\hat{\boldsymbol{y}}, \tag{1}$$

where x and y are the particle offsets relative to the magnetic center in the horizontal and vertical planes, respectively. The magnetic field strength can be expressed as

$$B_x = B_0\rho_0 K y, \tag{2}$$

$$B_y = B_0\rho_0 K x_0 + B_0\rho_0 K(x - x_0), \tag{3}$$

where x_0 is the designed offset of the beam in the combined-function magnets, $B_0\rho_0$ is the magnetic rigidity, and K is the normalized quadrupole strength.

Due to the magnetic field feed-down effect, the electron beam experiences an additional kick when it travels away from the design offset of the combined-function magnets, which has a significant influence on the ring dynamics. To suppress this effect, the beam should pass through the design offsets of the bending magnet with transverse gradient. The BBA technique is used to determine the current offset by using the dipole coils combined to the target magnets.

By changing the quadrupole strength by ΔK , the variation of the dipole field is given by

$$\Delta B_x = B_0\rho_0\Delta K y, \quad \Delta B_y = B_0\rho_0\Delta K x, \tag{4}$$

which causes a perturbation to the beam orbit.

To perform the beam-based alignment technique, the magnets are equipped with horizontal and vertical dipole corrector coils. During the measurement, the strengths of these corrector coils are adjusted, yielding

$$\Delta B_x = B_x^{\mathrm{VCM}} + B_0\rho_0\Delta K y, \tag{5}$$

$$\Delta B_y = B_y^{\mathrm{HCM}} + B_0\rho_0\Delta K x, \tag{6}$$

where B_y^{HCM} and B_x^{VCM} are the strengths of the horizontal and vertical dipole corrector coils, respectively. The variation of dipole field strength results in an orbit change at location s [3],

$$\Delta\boldsymbol{X}(s) = \frac{\Delta B}{B_0\rho_0}\frac{\sqrt{\beta(s)\beta(s_0)}}{2\sin(\pi\nu)}\cos\left(|\phi(s) - \phi(s_0)| - \pi\nu\right), \tag{7}$$

where $\beta(s_0)$ and $\beta(s)$ are the beta functions at the location of the quadrupole and the observation points respectively, $\phi(s_0)$ and $\phi(s)$ are the betatron phases, and ν is the betatron tune.

Assuming that the Courant-Snyder parameters are constant when the change of quadrupole field strength ΔK is small, the orbit change $\Delta\boldsymbol{X}(s)$ is proportional to ΔB. If the beam orbit is minimally affected by changing the quadrupole

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field strength of the target magnet, one can obtain $\Delta B = 0$. Then, the current offset can be obtained by

$$y = -\frac{B_x^{\mathrm{VCM}}}{B_0\rho_0\Delta K}, \quad x = -\frac{B_y^{\mathrm{HCM}}}{B_0\rho_0\Delta K}. \tag{8}$$

The offset obtained by this method represents the true beam position in the target magnet, as the dipole field is directly modified in this method.

SIMULATION

The Zhejiang Industrial Photon Source (ZIPS) is a dedicated storage ring for industrial applications, which adopts a 5BA lattice with 12 cells. Its emittance is 0.64 nm · rad. The lattice of the ZIPS storage ring is shown in Fig. 1. Main performance parameters are summarized in Table 1.

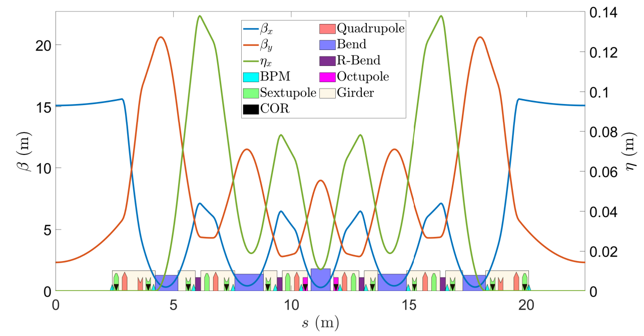

Figure 1: Optical functions of the ZIPS storage ring in one cell.

Table 1: Main Parameters of the ZIPS Storage Ring

Parameter	Unit	Value
Energy	GeV	2.70
Circumference	m	269.92
RF frequency	MHz	499.80
Harmonic number	–	450
Natural emittance	nm · rad	0.64
Transverse tunes	–	25.16/8.22
Natural Chroms	–	−49.64/−31.91
Corrected Chroms	–	2.0/2.0
Momentum compaction factor	–	3.11×10^{-4}
Damping time	ms	4.32/8.16/7.35
Bunch length	mm	3.49
Natural energy spread	–	1.04×10^{-3}
Energy loss per turn	keV	595.87

In this study, simulations are performed using the Accelerator Toolbox (AT) [4]. Bending magnets with transverse gradients are modeled directly as dipoles in AT, rather than utilizing off-axis quadrupoles. Consequently, within this simulation framework, the quadrupoles are treated as bending magnets with transverse gradients. To imitate conditions in a real machine, various errors have been introduced into the lattice.

The RMS values for the misalignment and field errors of the main components of the ZIPS storage ring are specified in Table 2. Here, dx, dy, and ds denote the shift errors in the horizontal, vertical, and longitudinal planes, respectively, while rx, ry, and rs represent the rotation errors around the corresponding axes. For BPMs, the shift and rotation errors are set as 100 µm and 100 µrad, respectively. The gain error is set to 5% in both planes, with a resolution of 1 µm. Random errors are generated following a 2σ-truncated Gaussian distribution. The errors are set the lattice as shown in Fig. 2 to Fig. 4. To perform the BBA technique, trajectory correction is required to establish a closed orbit.

Table 2: Misalignment and Field Errors

Element	dx/dy (µm)	ds (µm)	rx/ry (µrad)	rs (µrad)	Field
Bend	50	100	100	100	5e-4
Quad	50	100	100	100	5e-4
Sext	50	100	100	100	1e-3
Oct	50	100	100	100	1e-3
Girder	50	100	100	100	—

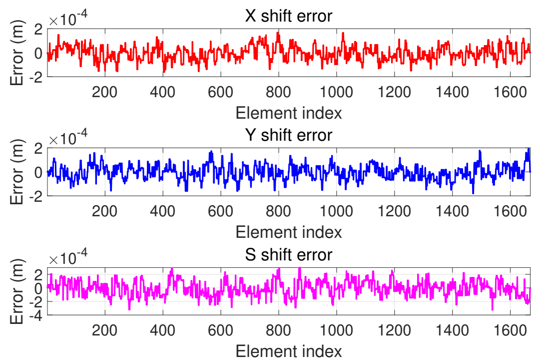

Figure 2: Shift errors of the storage ring.

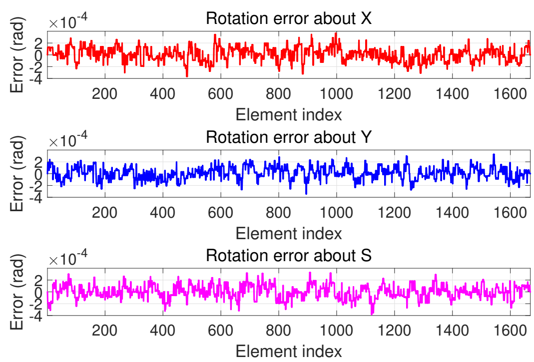

Figure 3: Rotation errors of storage ring.

For a target bending magnet with transverse gradient, the procedure to determine the beam offset is as follows:

- Adjust the quadrupole field strength of the target magnet.

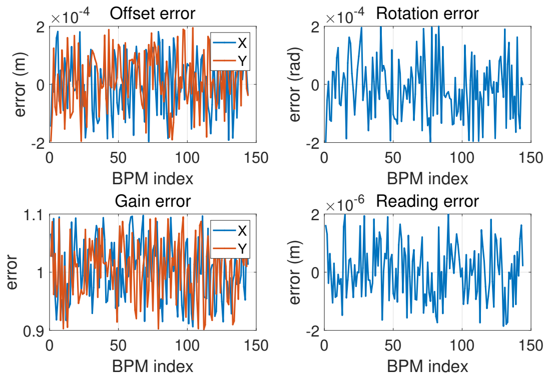

Figure 4: BPM errors of storage ring.

- Vary the excitation current of the dipole corrector coil associated with the target magnet, and record the resulting change in the closed orbit.
- Determine the zero-crossing point by applying a linear fit between the orbit variation and the dipole field strength.
- Calculate the current offset using Eq. (8).

As shown in the top panels of Fig. 5, a zero-crossing point can be derived from each BPM, from which the corresponding beam offset is obtained. The average of all individual beam offsets yields the final measured result, presented in the bottom panels of Fig. 5. The all results are shown in Fig. 6.

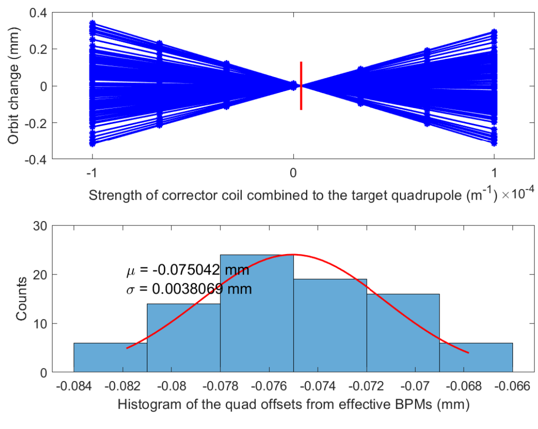

Figure 5: Horizontal beam offset from beam-based alignment: upper red line – BBA-derived beam offset; lower red line – Gaussian fit.

To validate the BBA method, a second error set excludes quadrupole and girder errors. Under full errors, calculating the true beam offset from the closed orbit is complicated, and the BBA-derived offset results from the interaction between the beam trajectory and the integrated field of a finite-length quadrupole. This causes the measured offset to deviate from the AT-computed value. Removing quadrupole and girder errors yields reliable geometric offsets, and as shown in Fig. 7, the measured offsets agree well with the true ones.

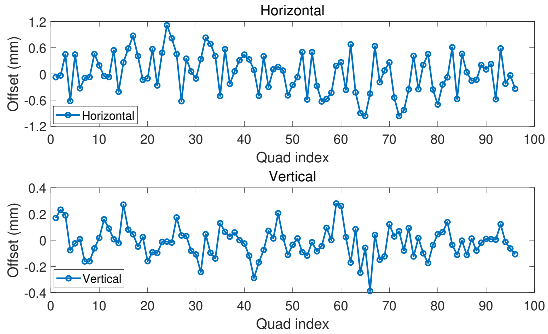

Figure 6: BBA measurement results.

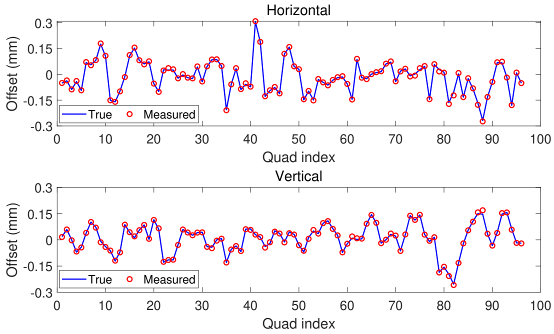

Figure 7: BBA measurement results compared with true offsets.

SUMMARY

In this paper, a beam-based alignment method is presented to determine the beam position in transverse-gradient bending magnets. By adjusting the strengths of the dipole corrector coils, the beam position can be obtained through linear fitting. Simulation results based on the ZIPS storage ring demonstrate that the measured beam positions are consistent with the actual positions, confirming the effectiveness of the BBA method. This technique provides a reliable approach for optimizing the dynamic performance of low-emittance storage rings.

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