

BEAM BASED ALIGNMENT OF QUADRUPOLES AT HEPS

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Abstract

In modern storage ring light source, large offset of quadrupoles will degrade the beam quality in the ring. Beam based alignment (BBA) methods have been used widely in storage rings, to correct the orbit of the beam to the magnetic center of quadrupoles. The BBA algorithm and commissioning procedure at HEPS is described in this paper. Two measurement algorithms were implemented: a fast BBA method using AC excitation and turn-by-turn BPM data, and a traditional BBA method based on closed orbit distortion optimization. The commissioning campaign spanned 16 months from September 2024 to January 2026, during which several key technical challenges were identified and resolved, including 50 Hz power line interference, quadrupole corrector coil effects, and low-frequency beam orbit jitter. Through systematic optimization of slow corrector power supplies and iterative measurement procedures, all 578 BPMs in the HEPS storage ring were successfully calibrated with RMS precision better than 30 μm , meeting the design requirements for high-performance accelerator operation.

INTRODUCTION

In modern synchrotron light sources, even small offsets of the beam relative to the magnetic center of quadrupoles can significantly impact accelerator performance. Due to the high field gradient of quadrupole magnets, micrometer-level position deviations can cause beam position instability, emittance growth, and reduced dynamic aperture. Beam Based Alignment (BBA) is a precision calibration technique that actively steers particle beams through the exact magnetic center of quadrupole magnets, thereby determining the offset between the Beam Position Monitor (BPM) electrical center and the quadrupole magnetic center [1]. BBA technology has been adopted by leading synchrotron facilities worldwide as a critical commissioning procedure for achieving design specifications [2, 3].

The High Energy Photon Source (HEPS) is a fourth-generation synchrotron light source in Beijing, China. The storage ring features a 48-period hybrid multi-bend achromat (HMBA) lattice, with each period containing 12 BPMs strategically positioned for comprehensive orbit measurement. Including two additional BPMs in the injection and extraction regions, a total of 578 BPMs require precise offset calibration [4]. Pre-commissioning simulations established the requirement that BBA precision must achieve better than 30 μm RMS to meet orbit correction and optics analysis specifications. This paper summarizes the complete BBA commissioning

campaign at HEPS from September 2024 to January 2026, describing the measurement algorithms, key technical challenges encountered, and the solutions that enabled successful calibration of all BPMs.

METHODOLOGY

Fast BBA Algorithm

The Fast BBA (FBBA) method follows the approach described in reference [2]. A sinusoidal excitation at 10 Hz is applied to a fast corrector magnet, creating controlled beam oscillation. Turn-by-turn (TBT) BPM data is then acquired across the storage ring. Under this excitation, the readings of any two BPMs in the ring exhibit a linear relationship. Subsequently, the strength of the quadrupole near the target BPM is adjusted, and a new set of TBT data is acquired, yielding a modified linear relationship. Linear fitting is performed on both datasets, and the intersection point of the two fitted lines reveals the BPM offset relative to the quadrupole magnetic center.

The primary advantage of the FBBA method is its speed, with a typical measurement time of approximately 1–2 minutes per BPM. The small-amplitude AC excitation from the fast corrector has minimal impact on the stored beam. However, the method is susceptible to various noise sources in the ring, and the precision of TBT data is generally lower than that of SA BPM data. The HEPS team developed an automated FBBA measurement program using the Pyapas high-level application framework [5], which integrates control system APIs for magnet control, BPM readout, and real-time data analysis.

Traditional BBA Algorithm

The traditional BBA method, also referred to as Slow BBA (SBBA), is based on the principle that in an ideal linear optics system, when the beam passes exactly through the magnetic center of a quadrupole, a small perturbation of the quadrupole strength produces no change in the beam orbit. Conversely, the sensitivity of the orbit to quadrupole strength variations directly reflects the degree of beam offset from the magnetic center [3].

The measurement procedure consists of the following steps. First, a strength perturbation of $\pm\Delta k$ is applied to the target quadrupole. The orbit change function $f = \sum [x_i(+\Delta k) - x_i(-\Delta k)]^2$ is defined using readings from all BPMs in the ring, where x_i represents the orbit position at BPM i . Next, nearby correctors are adjusted to change the beam position through the quadrupole, and an optimization algorithm is employed to find the orbit state that minimizes f . When f reaches its minimum value, the beam is judged to pass through the quadrupole magnetic center. The BPM reading at this condition is recorded as the offset. This process is repeated for all BPMs in the ring. The SBBA method offers

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higher precision through statistical averaging, but requires multiple iterations and carries a higher risk of beam loss due to larger orbit adjustments. The HEPS team developed a Python-based automated SBBA program within the same Pyapas framework.

MEASUREMENT PROGRESS AND CHALLENGES

The HEPS BBA commissioning campaign began in September 2024 and concluded in January 2026, spanning approximately 16 months. The timeline of key milestones is summarized as follows:

September 2024: First round of FBBA measurements based on TBT BPM data. Initial offset calibration was completed for all 578 BPMs (horizontal and vertical planes).

November–December 2024: FBBA re-measurement revealed unexpectedly large deviations in some BPMs. Transition to SBBA method began.

Throughout 2025: Systematic troubleshooting, multiple repeated measurements, and beam stability improvements.

January 2026: Final verification completed. High-precision offset calibration achieved for all 578 BPMs.

During this extended commissioning period, the team encountered and resolved several significant technical challenges that are described in the following sections.

50 Hz Power Line Interference

During the December 2024 re-measurement of FBBA data, some BPMs showed unexpectedly large measurement errors. Analysis of 100,000-turn TBT data revealed significant scatter beyond the expected 10 Hz excitation component. Frequency analysis identified a strong 50 Hz component originating from power line interference. This uncontrolled oscillation distorted the linear relationship between BPM readings, substantially reducing the fitting precision. To mitigate this effect, the TBT acquisition would need to be extended to tens of thousands of turns, making the FBBA method impractical. As a result, subsequent measurements transitioned to the SBBA method, which provides better noise immunity and higher precision.

Quadrupole Corrector Coil Impact

Anomalous observations in 2024 showed significant deviations concentrated at BPM06 and BPM09 positions across multiple consecutive measurements. The pattern suggested a systematic effect related to specific magnet configurations. A controlled experiment was conducted: the corrector coil current on quadrupole R01QD1H was varied from 0 to 0.05A, resulting in a shift of approximately 300 μm in the BBA results of neighboring BPMs. Magnetic measurements further confirmed that quadrupole corrector coil current significantly shifts the magnetic center of the combined magnet, whereas varying only the main quadrupole current had a negligible effect. The solution implemented was to set all quadrupole corrector coil strengths to zero during subsequent BBA

measurements, thereby eliminating this systematic error source.

Orbit-Quadrupole Linear Relationship

To verify BBA measurement precision, a physics-based cross-validation method was developed. The principle is that the orbit change induced by a quadrupole kick should be proportional to the orbit at that location. For each quadrupole, its strength was changed, the global orbit change was measured, and this was compared to the local orbit (with offset subtracted). With correct offsets, the two quantities should exhibit a strong linear correlation.

Analysis revealed poor linearity at certain BPM locations, specifically those with small beta function values. At locations with small beta functions, the same measurement error has an amplified impact on the results, making precise calibration more difficult.

Beam Orbit Jitter

Beam stability was identified as the primary limiting factor for BBA measurement repeatability. Before August 2025, measurement comparisons showed that only 36–57% of BPMs met the $<30 \mu\text{m}$ precision target, indicating significant random errors. Investigation traced the issue to low-frequency orbit drift originating from slow corrector (SC) power supplies. Orbit jitter during the measurement process directly translates to offset calculation error, fundamentally limiting the achievable precision.

SOLUTIONS AND RESULTS

Slow Corrector Power Supply Optimization

The breakthrough came in August 2025 with systematic adjustment and optimization of the SC corrector PWM frequency. The PWM frequency adjustment shifted the power supply noise spectrum away from the sensitive low-frequency band, resulting in an order-of-magnitude reduction in orbit drift amplitude. Improved orbit stability directly translated to dramatically improved BBA repeatability. Post-optimization measurements showed significantly higher consistency, with over 80% of BPMs achieving precision better than 30 μm .

Final Calibration Results

By January 2026, all 578 BPMs in the HEPS storage ring were successfully calibrated. The majority of BPMs achieved the $<30 \mu\text{m}$ RMS precision target, meeting the facility performance requirements for orbit correction and optics correction. As the BBA iterations progressed and measurement precision improved, the orbit RMS values in the ring gradually converged to smaller values, establishing a solid foundation for high-performance operation of the HEPS accelerator.

CONCLUSIONS

The HEPS BBA commissioning campaign produced a comprehensive set of best practices and technical insights. The key lessons learned are summarized as follows:

Hardware stability is the prerequisite for high-precision BBA. Low-frequency orbit drift is the primary limiting factor. Power supply optimization, such as the SC corrector PWM frequency adjustment implemented at HEPS, is essential for achieving the required measurement precision.

Environmental and magnet parameters must be carefully controlled. Quadrupole corrector coils must be set to fixed values (preferably zero) during BBA measurements to avoid magnetic center drift. BPM hardware parameters such as attenuation factors need to be adjusted according to actual beam conditions.

Systematic validation methods are essential. Cross-checks such as the orbit-quadrupole linearity test are critical for identifying measurement anomalies and verifying calibration quality. The iterative interplay between BBA and orbit/optics correction is also important for achieving convergence.

Through sustained technical efforts, the HEPS team overcame various commissioning challenges and completed high-precision offset calibration for all 578 BPMs in the storage ring. Building on the HEPS BBA experience, development of BBA techniques for sextupole magnets has already been initiated, and future work will continue to advance BBA technology for improved accelerator performance.

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