Development of high-resolution Cavity BPM systems for SHINE

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Abstract

The Shanghai High Repetition Rate XFEL and Extreme Light Facility (SHINE), currently under construction, is poised to become one of the most advanced free-electron laser (FEL) facilities globally. Designed to generate coherent X-rays with wavelengths ranging from 0.05 to 3 nm, and a maximum repetition rate of 1MHz. SHINE requires precise beam trajectory monitoring and stable alignment of electron and photon beams within the undulator, to meet these demands, cavity beam position monitors (CBPMs) with beam pipe diameters of 35 mm for the linear accelerator (LINAC) and bunch distribution sections, and 8 mm for undulators were developed. These systems requires transverse position resolution better than 1 m and 200 nm, respectively, for a single bunch of 100 pC. This paper details the design, fabrication, and performance evaluation of the CBPM system. The beam test bench has been established at the Shanghai Soft X-ray FEL facility (SXFEL), and preliminary beam experiments have shown that, with a bunch charge about 100 pC, the position resolution of the CBPM-35mm and CBPM-8mm are better than 312 nm and 41 nm, respectively, within the dynamic range of $±$1 mm and $±$300 m. These results not only align with theoretical predictions but also surpass SHINE's operational requirements, marking the highest resolution achieved by a cavity BPM system in an FEL facility under typical operational conditions.

Full Text

Development of High-Resolution Cavity BPM Systems for SHINE

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The Shanghai High Repetition Rate XFEL and Extreme Light Facility (SHINE), currently under construction, is poised to become one of the most advanced free-electron laser (FEL) facilities globally. Designed to generate coherent X-rays with wavelengths ranging from 0.05 to 3 nm at a maximum repetition rate of 1 MHz, SHINE requires precise beam trajectory monitoring and stable alignment of electron and photon beams within the undulator. To meet these demands, cavity beam position monitors (CBPMs) with beam pipe diameters of 35 mm for the linear accelerator (LINAC) and bunch distribution sections, and 8 mm for undulators were developed.

These systems require transverse position resolution better than 1 µm and 200 nm, respectively, for a single bunch of 100 pC. This paper details the design, fabrication, and performance evaluation of the CBPM system. A beam test bench has been established at the Shanghai Soft X-ray FEL facility (SXFEL), and preliminary beam experiments have shown that, with a bunch charge of about 100 pC, the position resolution of the CBPM-35mm and CBPM-8mm are better than 312 nm and 41 nm, respectively, within dynamic ranges of $±$1 mm and $±$300 µm. These results not only align with theoretical predictions but also surpass SHINE's operational requirements, marking the highest resolution achieved by a cavity BPM system in an FEL facility under typical operational conditions.

Keywords: Cavity Beam Position Monitor, High-resolution, SXFEL, SHINE

INTRODUCTION

Free-electron lasers (FELs) are transformative tools for generating high-intensity, ultra-short, and tunable coherent radiation pulses [1, 2], enabling breakthroughs in ultrafast and ultra-small science at atomic length scales [3, 4]. High-gain FELs have been successfully operating for users at several facilities worldwide, including the Linac Coherent Light Source (LCLS) [5], European XFEL [6], SPring-8 Angstrom Compact Free-Electron Laser (SACLA) [7], Pohang Accelerator Laboratory X-ray Free Electron Laser (PAL-XFEL) [8], Swiss-FEL [9], Free electron LASer in Hamburg (FLASH) [10], Free Electron laser Radiation for Multidisciplinary Investigations (FERMI) [11], and SXFEL [12]. The Shanghai High Repetition Rate XFEL and Extreme Light Facility

(SHINE), under construction since April 2018, is designed to deliver femtosecond X-ray pulses at rates of up to one million pulses per second using an 8 GeV continuous-wave superconducting RF LINAC, coupled with two undulator beamlines, two X-ray beamlines, and ten experimental stations in its initial phase [13].

A critical challenge for FELs lies in maintaining precise alignment between the electron beam and the radiation. Since X-rays travel in a straight line, the electron beam position must be accurately aligned with this straight line using high-resolution BPMs. This requirement has driven the development of diverse cavity BPM systems across major FEL facilities, each adapted to specific beam parameter requirements. LCLS and PAL-XFEL developed a high-quality factor (Q) X-band CBPM, achieving a position resolution of 200 nm at a bunch charge of 200 pC [14–16]. SACLA's C-band low-Q cavity with a resonant frequency of 4.76 GHz demonstrated comparable 200 nm resolution at 300 pC bunch charge within a $±$300 µm dynamic range [17]. Swiss-FEL employs a hybrid approach: low-Q cavities in the LINAC section resolve 28 ns spaced bunches, while undulator-embedded high-Q cavities provide higher resolution, achieving position resolution better than 1 µm for bunch charges from 10 pC to 200 pC [18, 19].

In the European X-ray FEL, a low-Q CBPM for multi-bunch operation with a resonant frequency of 3.3 GHz was developed and combined with relevant electronics to achieve position resolutions of 183 nm at a bunch charge of 200 pC [20, 21], representing the best beam experimental result reported so far under normal operational conditions. In China, several institutes have made significant progress in cavity-based multi-parameter beam diagnostics [22–25]. The high-Q C-band cavity BPM developed for SXFEL achieved a position resolution of 176 nm at a bunch charge of 500 pC, representing current domestic capabilities [26].

In SHINE's undulator section, beam-based alignment (BBA) requires position resolution better than 200 nm to maintain the electron beam trajectory within 1 µm, while the LINAC and beam distribution sections demand sub-micrometer position resolution to ensure beam stability. Traditional button or stripline beam position monitors (BPMs) face limitations in resolution. In contrast, cavity BPMs leverage resonant electromagnetic modes to achieve high sensitivity and noise immunity, making them indispensable for SHINE's stringent operational requirements.

This paper presents the development and evaluation of two CBPM systems tailored for SHINE: a 35 mm aperture system with S-band for LINAC and beam distribution sections, and an 8 mm aperture system with C-band for undulators (the number and types of CBPMs are listed in Table 1). The design integrates precision cavity fabrication, advanced RF signal conditioning, and robust digital processing to address the facility's unique challenges.

II. CAVITY BPM SYSTEMS AT SHINE

This section provides an overview of the detection principle of cavity BPMs. Based on the operational mode and beam conditions of SHINE, a systematic design process was undertaken to determine key parameters. Additionally, the basic performance of each component is discussed.

A. Detection Principle

A short, relativistic electron bunch passing near the center of the cavity pickup excites electromagnetic fields with certain resonances. For a typical cylindrical pill-box cavity BPM, the electrical fields induced by a beam passing close to the center of a cavity can be derived from the D'Alembert equation [27]. Its solutions lead to Bessel functions J_m of order $m = 0$ and 1 as the first two eigenmodes, TM010 and TM110 modes, which are used for beam position measurements. The axial electric field component of the TM110 mode in cylindrical coordinates can be expressed by [28–30]:

$$E_D(\rho, \varphi, z) = E_{0D} J_1 \left(\frac{\chi_{11} \rho}{r} \right) \cos(\varphi) e^{-i\omega_{110} t}.$$

And the TM010 mode can be expressed by:

$$E_M(\rho, z) = E_{0M} J_0 \left(\frac{\chi_{01} \rho}{r} \right) e^{-i\omega_{010} t}.$$

where E_{0D} and E_{0M} are the amplitudes of the electric field of the dipole mode and monopole mode, respectively. J_m is the Bessel function of the first kind of order m, χ_{11} is 3.832, χ_{01} is 2.405, r is the cavity radius, φ is the angle between the field of TM010 mode and axial direction, and ρ is the radial coordinate. ω_{110} and ω_{010} are the resonant angular frequencies of TM110 and TM010 modes, respectively.

Near the cavity center, the Bessel function is approximated linearly to $J_1(x) \propto x$ and $J_0(x) \approx 1$, as expressed by $J_m(\rho) \sim \rho^m$. Thus, the excited voltage of the TM110 mode is zero when the beam is at the cavity center and is proportional to the beam offset and beam charge. The excited voltage of the TM010 mode is independent of the beam position but proportional to the beam charge only. As a result, even a small variation can be easily detected using a high-gain amplifier if the beam position is close to the center. This feature is a significant advantage over button or stripline BPMs [31], where measurement of small beam displacement requires the small difference between relatively large amplitude signals from opposite electrodes. Furthermore, the resonant characteristics of the pickup enhance signal processing gain, making cavity BPMs particularly attractive for high-resolution position measurements, especially in cases where the beam does not experience large orbit deviations, such as along the undulator sections of an FEL.

B. System Composition and Analysis of Key Parameters

A typical CBPM system consists of a position cavity and a reference cavity for charge and phase normalization, an RF signal conditioning front end, and data acquisition and processing electronics. Performance is mainly limited by the effective number of bits (ENOB), sampling rate, and analog bandwidth of the Analog-to-Digital Converter (ADC), as well as signal loss during high-frequency transmission from the pickup. Directly sampling raw high-frequency signal output from the cavity pickup while preserving signal integrity presents significant challenges, especially for operating frequencies in C-band and X-band.

Based on the optimized amplitude extraction method for cavity BPM described in Reference [32], for an ADC with sampling rate F_s, N points of waveform (window size T) are used for digital signal processing. An optimal signal processing window $T = 1.257\tau$ exists that minimizes amplitude extraction uncertainty. The relationship between amplitude extraction uncertainty (R_s) and the relative noise-to-signal ratio (σ), the sampling rate of the data acquisition and processing system (F_s), and the decay time of the cavity pickup (τ) can be expressed by:

$$R = 1.567\frac{\sigma}{\sqrt{F_s\tau}}.$$

Considering the typical structure of the cavity BPM system, σ of the whole system can be expanded:

$$R_s = 1.567 \cdot \frac{\sqrt{(G_{RFFE} \cdot N_F \cdot N_{RF})^2 + N_{adc}^2}}{G_{RFFE} \cdot A_{RF}\tau \cdot F_s}.$$

where G_{RFFE} and N_F are the gain and noise figure of the RF front-end, respectively. N_{adc} represents the noise amplitude of the ADC, A_{RF} is the amplitude of the RF signal output by the cavity pickup, and N_{RF} is the thermal noise amplitude at the output of the cavity pickup. Thus, the parameter design and allocation of the whole system are based on this principle to achieve system optimization.

Considering the beam pipe diameter of the LINAC and bunch distribution section is 35 mm, with the cut-off frequency of the TE11 mode of the circular waveguide being 5.02 GHz, the resonant frequency of the cavity pickup is set in the S-band. Given that the machine reference clock of SHINE is based on 1300/6 MHz, the local oscillator is designed to operate at 3466.67 MHz. Consequently, the resonant frequency of the cavity pickup is chosen to be approximately 3521 MHz, which also avoids interference from the dark current of the 1.3 GHz superconducting acceleration module. The corresponding intermediate frequency (IF) signal is around 54 MHz. For cavity pickups in undulators with a beam pipe diameter of 8 mm, located farther from the superconducting acceleration module, the dark current from the acceleration modules becomes negligible in the undulator section. Thus, the resonant frequency is set at approximately 5254 MHz.

Regarding cavity type selection, since the estimated beam jitter in SHINE is on the order of tens of micrometers, it is crucial to minimize the impact of beam jitter on beam position measurement accuracy and resolution. Therefore, the isolation between the X and Y direction dipole modes needs to be better than 46 dB [33]. A cylindrical pillbox cavity type was selected to balance manufacturing feasibility with electromagnetic performance.

For the physical design of the cavity pickup, beam parameters are set with a bunch charge of 100 pC and bunch length of 1 ps. Oxygen-free copper is selected for the cavity material to achieve a high loaded Q value. Numerical simulations are then performed based on Eq. (5). For the CBPM-35mm, with a dynamic range of $±500*m, therelationshipbetweenmeasurementuncertaintyandthepositioncavityandreferencecavityp* are obtained, as shown in Fig. 1 [Figure 1: see original paper] and Fig. 2 [Figure 2: see original paper]. Similarly, for the CBPM-8mm, with a dynamic range of $±$100 μm, the relationship is shown in Fig. 3 [Figure 3: see original paper] and Fig. 4 [Figure 4: see original paper].

Considering that the maximum repetition rate of SHINE will reach 1 MHz, the decay time of the cavity is selected at 200 ns to minimize crosstalk between bunches. Simulation results indicate that while increasing cavity length enhances energy storage, the benefits diminish as cavity length grows. Additionally, longer cavity length increases single-bunch instability, such as increased energy spread and emittance. Therefore, a cavity length of 9 mm is determined. For the reference cavity, the TM010 is the main mode, and the coupled signal amplitude is large, which is not the main factor limiting system performance, as shown in Fig. 2 and Fig. 4. To simplify system structure, the frequency and decay time of the reference cavity are matched with those of the position cavity. Furthermore, to minimize the impact of cavity length on bunches, the reference cavity length is designed to be approximately 5 mm. The theoretically designed parameters for the CBPM-35mm and CBPM-8mm are summarized in Table 2 .

Due to limitations imposed by the effective bits of high-bandwidth ADCs, a single-channel down-conversion to low intermediate frequency scheme is adopted to condition the RF cavity pickup signals. To adjust signal amplitude to match the optimal range of the ADC, a switchable gain amplifier is included to handle the dynamic range of the electronics. The noise figure (N_F) is primarily determined by structural design and manufacturing process, with lower values being better, so this RF front-end is located in the tunnel close to the cavity BPM pickups. Based on structural design and manufacturing, the NF of the RF front-end can be kept below 3 dB. Additionally, to accommodate operation under different bunch parameters, the adjustable dynamic range of the RF front-end needs to be greater than 50 dB. The IF signal is then sampled by the data acquisition system and quantized into a digital signal. Using appropriate algorithms such as Fourier transform, the beam position and phase information are extracted. In the data acquisition system, key parameters affecting performance include the sampling rate and effective bits of the ADCs. Based on Eq. (5) and considering specifications of commercial mainstream ADCs [34], the relationship between ADC parameters and signal amplitude extraction uncertainty was simulated by incorporating parameters of the designed cavity pickup and RF front-end, with results shown in Fig. 5 [Figure 5: see original paper].

C. Cavity Pickups

To ensure structural consistency, both types of pickups were designed using pillbox cavities. In accordance with the pickup requirements and design boundary conditions outlined in Table 2, SHINE's cavity BPM pickups were designed as shown in Fig. 6 [Figure 6: see original paper] and Fig. 7 [Figure 7: see original paper]. To increase isolation between orthogonal dipole modes, a resonant frequency deviation of approximately 7 MHz was intentionally introduced between the X and Y dipole modes during design (resonant frequencies of X, Y, and reference are 3518 MHz, 3525 MHz, and 3521 MHz for CBPM-35mm; and 5251 MHz, 5258 MHz, and 5254 MHz for CBPM-8mm). The cavity BPM pickups have no tuners but were precision-machined to the resonant frequency, bandwidth, and other RF parameters. For example, during mass production of the pickups, the frequency deviation for the X, Y, and reference cavities was controlled within $±$2 MHz, the bandwidth (loaded Q value) was kept within $±10S_{11}$ parameter) between opposite ports was controlled within 2 dB.

To minimize impedance to the beam, the sections of the cavity that "see" the beam are constructed from oxygen-free copper. Furthermore, to facilitate assembly, tuning, and welding during fabrication, the entire cavity BPM is subdivided into eight components. These include the left welding flange, position cavity connection pipe, position cavity, reference cavity connection pipe, reference cavity, right welding flange, feedthrough welded transition ring, and coaxial feedthrough. The position and reference cavities are independently cold-tested and welded before being brazed together as a whole, thereby improving manufacturing yield. Pictures of the first three sets of cavity pickups are shown in Fig. 8 [Figure 8: see original paper], with corresponding cold test results based on the network analyzer summarized in Table 3 .

The cold test results demonstrate that the frequency and bandwidth consistency of the first three sets exceed requirements. By strictly controlling the orthogonal symmetry of the dipole mode coupling waveguide and the concentricity of assembly between components, isolation between X and Y dipole modes can be controlled better than -50 dB. To ensure consistency of signal amplitude at the output ports, a clamping fixture was used to control the insertion depth of the feedthrough, thereby achieving a reflection coefficient difference of less than 1 dB between opposite ports. This further guarantees consistency of the position conversion factor for the whole system.

D. RF Front-end

To process high-frequency signals from cavity pickups and standardize the architecture of the two CBPM system specifications as much as possible, the RF front-end adopts the same structure, with the only difference being the operating frequency. A three-channel heterodyne receiver is designed to mix the RF signals to an intermediate frequency of about 54 MHz, based on the resonant frequency of the cavity pickups and the machine reference clock. Combined with the 866.7 MHz sampling rate of the data acquisition processor, this configuration enables nearly 16x oversampling, thereby enhancing system processing gain. The block diagram of the RF front-end is shown in Fig. 9 [Figure 9: see original paper].

Each receiver input is limited to about 100 MHz bandwidth around the center frequency (3521 MHz and 5256 MHz for CBPM-35mm and CBPM-8mm, respectively), providing greater than 60 dB out-of-band rejection to suppress higher-order modes. A two-stage cascade switchable amplifier is used to reduce the increase in system noise figure under large dynamic range. The local oscillator (LO) of 3466.67 MHz and 5200 MHz with low phase noise is multiplied by the reference clock of 1300 MHz to down-convert the RF signal to IF at about 54 MHz, combined with a digital step attenuator, amplifier, and filter to achieve signal filtering and amplitude adjustment to match the ADC input range. Additionally, an external reference clock of 216.67 MHz is generated for the data acquisition system, which is then quadrupled to 866.67 MHz using a phase-locked loop (PLL) to serve as the phase-locked sampling clock. In terms of structural design, physical isolation is applied to each receiver channel and LO module to reduce crosstalk between channels, and a separate metal cover is used to shield electromagnetic interference and reduce signal crosstalk and spatial coupling. A picture of the RF front-end is shown in Fig. 10 [Figure 10: see original paper].

To evaluate RF front-end performance, the noise figure (NF) at different dynamic ranges was measured using a Noise Figure Analyzer (Agilent N8973A), with results shown in Fig. 11 [Figure 11: see original paper]. Additionally, amplitude and phase stability during long-term operation are crucial considerations. To address this, a vector signal generator (R&S SMW200A) was used to simulate the sin-exponential decay signal typically output by the cavity pickup. The signal was fed into the RF front-end, where a phase-locked sampling test bench was set up in combination with the digital BPM signal processor, and amplitude and phase variations were measured over 20 hours. The block diagram of the test bench is shown in Fig. 12 [Figure 12: see original paper]. The sin-exponential signal from the vector signal generator at the same frequency and decay time as the cavity pickup was split using a power divider and fed into the position and reference channels of the RF front-end. A 20 dB attenuator was added to the position channel to simulate the power difference between the position and reference cavities.

Fig. 13 [Figure 13: see original paper] illustrates the amplitude variation (the ratio of recent amplitude over mean amplitude) observed in the position and reference channels over 20 hours. This variation reflects both amplitude fluctuations of the vector signal generator and variations in environmental temperature, with a peak-to-peak value of approximately 0.1 dB. Notably, the variation exhibits a clear periodicity of around 47 minutes. Analysis reveals that this period closely corresponds to the Proportional Integral Derivative (PID) period of the air conditioning system in the laboratory.

Additionally, relative amplitude and phase variations were assessed by normalizing signals from the position and reference channels, with results shown in Fig. 14 [Figure 14: see original paper]. The peak-to-peak amplitude variation of channel X relative to the REF channel is 0.03 dB, with no significant slow drift in amplitude. The slow phase drift of X to REF is about 0.0024 rad over 20 hours, corresponding to the resonant frequency of 5.254 GHz, which translates to a slow drift of only 73 fs. The results also include periodic variations due to environmental temperature changes, with a peak-to-peak value of only 0.003 rad, or 91 fs peak-to-peak. The test results for the CBPM-35mm front-end are comparable, confirming the amplitude and phase stability of both the front-end and electronic system.

E. Digital BPM Processor

A digital signal acquisition processor capable of handling 1 MHz repetition rate for BPM signal processing has been developed [35, 36]. The core component is a Xilinx SoC Zynq Ultra-Scale Field Programmable Gate Array (FPGA) paired with an ADC daughter board connected via the FPGA Mezzanine Card (FMC) interface. The ADC features 14-bit resolution, maximum sampling rate of 1 Gsps, and analog bandwidth of 2 GHz. The processor utilizes the JESD204B high-speed serial interface for efficient, high-bandwidth data transmission with the FPGA. External logic interfaces include 8 GB DDR4 on the Programmable Logic (PL) side and 4 GB DDR4 on the Processing System (PS) side to store raw ADC waveforms and processed data, two RJ45 connectors for Ethernet communication, 10 Gbps SFP+ port, JTAG, SD slot, and so on. The processor specifications are listed in Table 4 .

The effective number of bits of the signal processor was tested to be better than 10.8 bits when processing a constant waveform signal of 50 MHz. Additionally, a phase-locked sampling test bench, as shown in Fig. 12, was used to simulate the cavity pickup signal and evaluate digital BPM processor performance. Following the RF front-end, the IF signal was divided and fed into two channels of the processor for data correlation analysis. The amplitude extraction uncertainty was found to be approximately 0.011%, as shown in Fig. 15 [Figure 15: see original paper], which is well within the required specification of 0.1%.

III. BEAM EXPERIMENTAL RESULTS

Based on theoretical analysis and development of key components, a beam test bench was built at the undulator section of the SXFEL user facility. Due to space constraints, only one cavity pickup of each type was installed, each equipped with a two-dimensional mover for precise calibration of the position conversion factor, as shown in Fig. 16 [Figure 16: see original paper].

To validate the performance of the fabricated cavity pickups with electron beam, the feedthrough ports were connected via coaxial cable to the RF front-end outside the tunnel for testing. The insertion loss of the cable was measured in advance. With bunch charge of about 100 pC, the cavity pickup was aligned using the two-dimensional mover to ensure the beam passed close to the center of the pickup. The pickup was then offset by 500 µm to measure the amplitude of the excited signal. By accounting for the gain settings of the RF front-end, the sensitivity of the cavity pickups was determined. Test results showed that the position cavity sensitivity of the CBPM-35mm pickup was 0.5 V/nC/mm, while the reference cavity exhibited 7.95 V/nC. For the CBPM-8mm pickup, the position cavity sensitivity was around 1.17 V/nC/mm, with the reference cavity showing a sensitivity of 9.95 V/nC. These results closely match the theoretical design values presented in Table 2, confirming the accuracy of the design and fabrication of the cavity pickups.

Owing to spatial constraints, only one cavity pickup of each type was installed. To evaluate the performance of the cavity BPM system, a correlation analysis method was implemented using signals from the two opposite feedthroughs of the same pickup, as illustrated in Fig. 17 [Figure 17: see original paper]. This evaluation method encompasses not only the RF front-end and electronics but also incorporates the signal coupling structure of the pickup, which comprises two independent subsystems. The only non-independent component is the intra-cavity signal, whose inherently high signal-to-noise ratio ensures it is not the bottleneck of the entire measurement system.

When the electron beam passes through the cavity, the IF signals from opposite feedthroughs of the position cavity are denoted as U_1 and U_2, respectively, while the signal from the reference cavity is U_3. The signals U_1, U_2, and U_3 are characteristic of the cavity pickup, RF front-end, and digital BPM processor. Therefore, the difference between the complex normalized amplitudes (to normalize bunch charge jitter), along with the position conversion factor (K), can be used to represent the position resolution of the whole system. These can be expressed by Eq. (6):

$$\delta_{CBPM} = \mathrm{std}\left(\frac{U_1 - U_2}{U_1 + U_2} \cdot \frac{1}{U_3}\right) \cdot K.$$

In the experiment, the bunch charge was adjusted close to 100 pC, and the system dynamic range was determined by the two-dimensional mover and configured through RF front-end parameters. For the CBPM-35mm system, the dynamic range was set to $±$1 mm, and the mover imitated beam offset ranging from -1 mm to 1 mm in steps of 400 µm. The position conversion factor was then obtained, as shown in Fig. 18 [Figure 18: see original paper]. Through data correlation analysis, the position resolution was measured to be 312 nm. Moreover, with the system dynamic range controlled within $±$600 µm and the above process repeated, the measured position resolution is 137 nm, with residual distributions shown in Fig. 19 [Figure 19: see original paper].

Similarly, for the CBPM-8mm system, with dynamic range set to $±$300 µm, the position conversion factor was calibrated as shown in Fig. 20 [Figure 20: see original paper]. Based on data correlation analysis, the position resolution was found to be 41 nm at a bunch charge of about 92 pC. Considering the large jitter of the beam during initial commissioning of SHINE, system performance at an expanded dynamic range of $±$500 µm was also evaluated, with position resolution reaching 127 nm, and residual distribution shown in Fig. 21 [Figure 21: see original paper].

The beam experimental results closely match the theoretical simulations presented in Fig. 1 and Fig. 3, validating both the accuracy of the system design and the effectiveness of the fabrication. Improvements in system design, fabrication, and signal acquisition have significantly enhanced performance compared to the SXFEL facility.

IV. CONCLUSION

Through systematic design, development, and performance evaluation, the CBPM system for SHINE has achieved its technical objectives with exceptional results. The system, featuring apertures of 35 mm and 8 mm, demonstrated position resolutions of 312 nm and 41 nm, respectively, surpassing the required specifications. Close agreement between experimental results and theoretical simulations confirms both the accuracy of the system design and the fabrication tolerances. Advancements in system design, fabrication, and signal acquisition have significantly improved performance. These achievements lay a solid foundation for SHINE to fully realize its potential in delivering high-quality photon beams for cutting-edge scientific research.

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Note: Figure translations are in progress. See original paper for figures.