ISBN: 978-3-95450-262-2 ISSN: 2673-5350 doi: 10.18429/JACoW-IBIC2025-WEPMO09

ONLINE POSITION CONVERSION FACTOR CALIBRATION STUDY FOR BPM SYSTEM*

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Abstract

Transverse beam position is one of the most critical parameters in accelerator commission and operation. As non-invasive diagnostic devices, beam position monitors (BPMs) are the main “workhorse” in accelerators, providing beam center of mass position information. The position conversion factor (K-factor) of BPM systems constitutes a fundamental determinate of measurement accuracy. While precision calibration traditionally relies on moveable calibrate platforms, the prohibitive cost of equipping each BPM with a dedicated two-dimensional calibration platform remains a widespread practical constraint. In this paper, an innovative online calibration method that synergizes machine learning with beam response matrix analysis to achieve per-BPM K-factor determination is introduced. The preliminary beam experiments have been carried out at Shanghai Soft X-ray Free-Electron Laser (SXFEL) facility. The proposed method offers a robust and resource-efficient calibration solution, particularly advantageous for cavity BPM systems where conventional approaches such as theoretical calculation and offline wire scanning, fail to provide reliable results.

INTRODUCTION

Beam Position Monitors (BPMs) are indispensable and critical diagnostic devices in particle accelerators, whose performance is directly related to the precise measurement of beam trajectory, the stability of feedback controls, and the optimization of accelerator performance. Transverse beam position is one of the most critical parameters during accelerator commissioning and operation. As non-invasive devices, BPM systems continuously provide beam center-of-mass position information, serving as the main "workhorse" for ensuring high-quality beam transmission and efficient experimentation.

For stripline or button-type BPMs, the position conversion factor (K-factor) is primarily determined by the vacuum chamber aperture and electrode geometry, and can often be approximated by a simplified theoretical formula:

$$K_x = \frac{a \cdot s}{4\sin{(\phi_s/2)}} \ , \tag{1}$$

where K_x is a conversion coefficient related to the electrode shape and size, a is the beam pipe radius and ϕ_s is the angle of the electrode. This model provides a reasonable estimation of the K-factor under ideal conditions. In practical engineering, besides theoretical calculation, electromagnetic simulation software such as CST Studio Suite or ANSYS HFSS can be used for precise modeling of BPM probes to obtain the K-factor for both stripline and button BPMs. Numerous studies have shown that simulation results are generally in good agreement with theoretical values [1]. Furthermore, establishing a high-precision wire-scanning test platform is a widely adopted offline calibration method. By simulating the beam with a moving wire in a laboratory environment and measuring the electrode response, integrated K-factor calibration for the probe, front-end electronics, and data acquisition system can be performed [2]. These methods are relatively mature and reliable for SBPMs.

However, for cavity BPMs (CBPMs) based on the resonant cavity principle, their working mechanism and calibration challenges are fundamentally different from those of SBPMs. CBPMs utilize the wake-field excited by the beam in the resonant cavity to couple out signals, aiming to accurately characterize the original information of the bunch (e.g., position, charge). The sensitivity of a CBPM probe (i.e., the system K-factor) is a more complex systemic issue: it depends not only on the electromagnetic design of the cavity (e.g., operating mode, R/Q value) but is also significantly influenced by a combination of factors including probe manufacturing precision (e.g., dimensional tolerances, surface finish), signal conditioning circuitry (e.g., bandwidth, gain flatness), and channel characteristics of the digital acquisition system (e.g., amplitude/phase consistency, impedance matching). This implies that even two perfectly identical CBPM probes may exhibit significantly different final system K-factors if connected to different electronics systems. More critically, the traditional offline wire-scanning calibration method has limited applicability for CBPMs. When a metal wire is inserted through the CBPM resonant cavity, it severely perturbs the cavity's electromagnetic field distribution, altering its resonant frequency and quality factor (Q-value). Furthermore, the excitation signal propagates along the wire, causing mode leakage and introducing systematic deviations between the measured signal response and the actual response under real beam excitation. Consequently, the K-factor obtained offline can hardly reflect the true system performance during online beam operation and fails to provide reliable results.

For large-scale accelerator projects like the Shanghai High repetition rate XFEL and Extreme light facility (SHINE), which deploy a vast number of CBPM probes, a comprehensive strategy is essential. To ensure the consistency of all BPM measurement data and obtain accurate K-factors, we must implement strict quality control at the source (probe manufacturing) to ensure the performance consistency of individual probes. On the other hand, there is a pressing need to develop a novel online calibration method that does not rely on offline platforms and can

*Work supported by The National Science Foundation of China (Grant No.12175239). Youth Innovation Promotion Association, CAS (Gant No.2019290). Outstanding member of the Youth Innovation Promotion Association, CAS(Gant No.Y2023079).
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14th International Beam Instrumentation Conference,Liverpool, UK JACoW Publishing
ISBN: 978-3-95450-262-2 ISSN: 2673-5350 doi: 10.18429/JACoW-IBIC2025-WEPMO09

characterize the entire BPM system under actual beam conditions. The innovative technique proposed in this paper, which synergizes machine learning with beam response matrix analysis, is born precisely to meet this urgent requirement.

PROBE MANUFACTURING CONTROL

The Shanghai High repetition rate XFEL and Extreme light facility (SHINE) imposes extremely high demands on beam position measurement accuracy. Over 200 Cavity BPM (CBPM) probes are distributed along its entire beam transport line, primarily concentrated in key areas such as the linac sections, distribution sections, and undulator segments for precise beam trajectory monitoring and feedback. Confronted with such a large-scale CBPM system requiring exceptionally high-performance uniformity, relying solely on online calibration methods is insufficient. It is imperative to implement stringent consistency control at the source-the manufacturing stage of the probes-to establish a solid foundation for subsequent online calibration, thereby ensuring the high reliability and accuracy of the final measurement system. The schematic layout of SHINE as shown in Fig. 1, and the number and types of CBPMs are listed in Table 1.

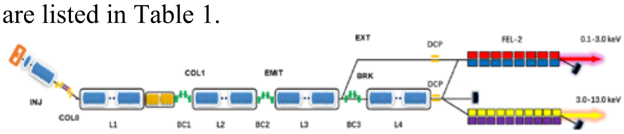

Figure 1: Schematic layout of SHINE.

Table 1: The Number and Types of CBPMs in SHINE

Parameters	CBPM-35	CBPM-8
Aperture	35 mm	8 mm
Length	250 mm	112 mm
Usage	LINAC, Distribution sections	Undulators
Resolution	≤1 µm@100 pC	≤ 200 nm@100 pC
Dynamic range	≥ ±1 mm	≥ ±100 µm
Bunch charge	10 ~300 pC	10~300 pC
Quantity	5, 80	140

Figure 2 shows the three-dimension model of the CBPM-35 probe specifically designed for SHINE. To increase the isolation between the X and Y dipole modes, a resonant frequency deviation of approximately 7 MHz was intentionally introduced between the X and Y dipole modes during the design (resonant frequency of X, Y and Reference is 3518 MHz, 3525 MHz and 3521 MHz). The cavity BPM probes have no tuners but were precision-machined to the resonant frequency, bandwidth and other RF parameters [3]. For example, during the mass production of the probes, the frequency deviation for the X, Y and reference cavities was controlled within ±2 MHz, the bandwidth (load Q value) was kept within ±10 %, and the difference in the reflection coefficient (S11 parameter) between opposite ports was controlled within 2 dB.

At processing, each completed probe undergoes rigorous RF performance testing. A Vector Network Analyzer was used to measure the S parameters for each probe around the

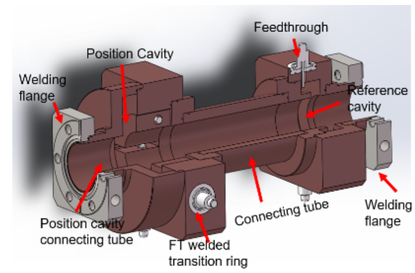

Figure 2: Three-dimension model of the CBPM-35 probe.

operational frequency. In first phase, the total of 80 probes is finished, Fig. 3 and Fig. 4 show that the batch-produced probes exhibit a center frequency deviation of less than ±1.5 MHz, a variation in the quality factor (Q-value) or bandwidth of less than ±10 %, and Fig. 5 illustrate the S11 parameters for the relative feedthrough ports of X, Y and REF are less than 2 dB, also demonstrate high consistency in coupling strength. These highly consistent S-parameters indicate that the intrinsic electromagnetic properties of the probes are effectively replicated during mass manufacturing, which is the primary prerequisite for achieving system-level K-factor uniformity. Any probes showing significant outliers in S-parameters were screened out for rework or rejection.

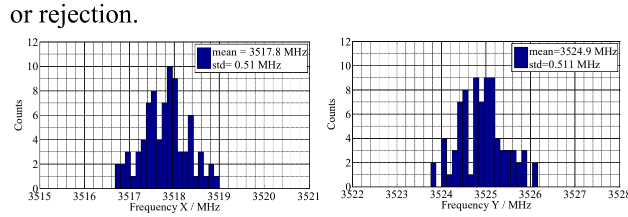

Figure 3: The statistical results of the resonant frequencies in X (left) and Y (right) direction dipole modes for 80 sets of probes.

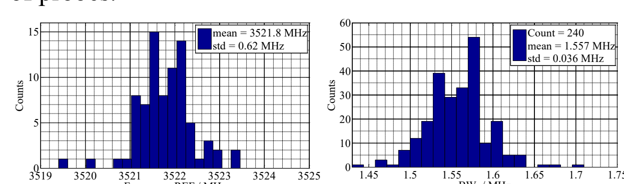

Figure 4: The statistical results of the resonant frequencies in reference cavity and the working bandwidth for 80 sets of probes.

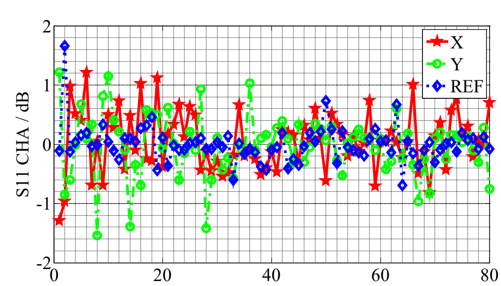

Figure 5: The statistical results of S11 parameters for the relative feedthrough ports of X, Y and REF of probes batch processed.

Despite being fully aware of the fundamental limitations of offline wire-scanning tests for CBPMs, a high-precision

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2D wire-scanning platform was established, and tests were conducted on a subset of probes (Fig. 6). The primary purposes of this exercise were not to obtain an absolutely accurate K-factor, but rather to verify the signals coupling from the relative feedthrough ports are consistent with the S11 test results.

Figure 6: Two-dimension wire_scanning test platform for CBPM_35 probes.

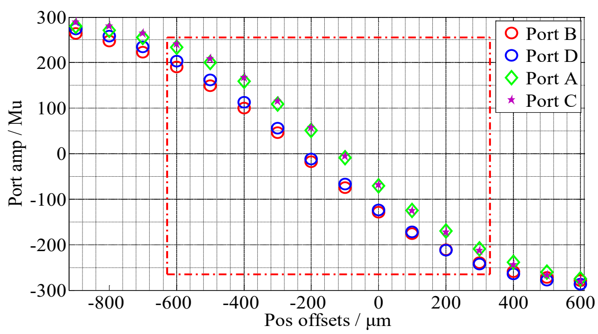

Figure 7: Test results of signal coupling from the relative feedthrough ports by wire-scanning test platform.

As shown in Fig. 7, the test results of using 2D wire-scanning are presented. In the experiment, the wire was moved in steps of 100 µm from -900 µm to +600 µm to simulate the beam offset. Although the wire scanning altered the cavity mode signal, it can be used to evaluate the consistency of the relative ports. A and C represent the two feedthrough ports in the Y direction, while B and D represent the two feedthrough ports in the X direction. The results can well verify the consistency of the signal output of the relative ports and also demonstrate the feasibility of using a network analyzer to test S11.

MACHINE LEARNING MODEL

To address the online calibration challenge for the CBPM system K-factor, we attempt to train a neural network model. The core insight of our approach is to treat the combined system of probes and electronics as a parameterized physical model and use machine learning to infer its intrinsic parameters from beam response data. The Model can represent by:

$$f_{\theta^*} : (D - D_{baseline}) * k -> C \ , \tag{2}$$

$$f_{\theta^*} = \arg\min_{\theta \in \Theta} ||C - C_0|| \ , \tag{3}$$

$$f_{\theta^*} -> D_{baseline}, k \ . \tag{4}$$

D is the position signal calculated by BPM, baseline represents the reference value of absolute position 0, C_0 is the coefficient, and *C* is the coefficient predicted by the neural network. After training, baseline and *k* can be output.

CONCLUSION

This paper addresses the critical challenge of accurately calibrating the position conversion factor (K-factor) for Cavity Beam Position Monitors (CBPMs) by proposing a online calibration methodology. We have explored an approach that integrates machine learning with the physical response model of the BPM system. Currently, we have completed the initial model construction and algorithm design, laying a foundation for further in-depth investigation. The next phase of this work will involve comprehensive training and validation of the model using experimental data from the SXFEL facility.

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