ISBN: 978-3-95450-231-8 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2023-THPL183

OPTIMIZATION AND DEVELOPMENT OF THE CBPM SYSTEM FOR THE SHINE *

J. Chen†, Y.B. Leng#, S.S. Cao, L.W. Lai, R.X. Yuan, R.T. Jiang, X. Yang
Shanghai Advanced Research Institute, CAS, Shanghai, China

Abstract

Beam-based alignment and feedback systems are essential for the operation of the Free Electron Lasers (FELs). Cavity BPMs having the advantage of high position resolution are widely used in the field of accelerators. Systematically analyze the impact of the key parameters of each subsystem on the performance of the whole system, so that the key technical indicators of each subsystem can achieve the optimal and balanced allocation, is the primary issue to be considered when designing a CBPM system. In this paper, the relationship between the relative amplitude extraction uncertainty of the CBPM system and the key parameters of each subsystem is proposed based on theoretical analysis. And this method has also been applied in the development of the CBPM system for the Shanghai High repetition rate X-ray Free Electron Laser and Extreme Light facility (SHINE). Based on the beam test bench in the Shanghai Soft X-ray FEL facility (SXFEL), the position measurement uncertainty of the CBPM system can reach 40 nm at the bunch charge of 100 pC, which is consistent with the theoretical analysis results and better than the requirements of the SHINE.

INTRODUCTION

Cavity BPM (CBPM) adopting a resonant cavity structure and using the characteristic modes excited by the electron beam to measure the beam parameters, has the advantage of high resolution and is widely used in FEL facilities and Linear Colliders. A typical CBPM system is composed of a cavity pickup, a radio frequency (RF) signal conditioning front end, and a data acquisition and processing electronic. This is mainly limited by the Effective number of bits (ENOB), sampling rate, analog bandwidth of the Analog-to-Digital Converter (ADC), it is difficult to directly sample the high-frequency signal output by the cavity pickup. And the factors that affect system performance mainly include the signal-to-noise ratio (SNR) of the cavity pickup, crosstalk between different modes, beam trajectory with a finite angle, noise figure of RF front-end, performance of ADC and digital signal processing algorithms. Various institutes have completed the research and development of the CBPM systems after years of research and experience accumulation, and got good results. But there is no clear guiding formula so far for the design or optimization of the system, how to systematically analyze the impact of the key parameters of each subsystem on the performance of the whole system, and how to achieve the optimal and balanced allocation of the key technical indicators of each subsystem.

In response to these issues, in this paper, based on theoretical analysis, the guidance formula about the impacts of key parameters of each subsystem on relative amplitude extraction uncertainty of the CBPM system is discussed. And this method applied in the research and development of the CBPM prototype of the SHINE is also introduced[1].

THEORETICAL ANALYSIS

By following the analysis as given in the Reference [2], the relationship between the amplitude extraction uncertainty (***R****s*) and the relative noise-to-signal ratio (σ), sampling rate of data acquisition and processing system (***F****s*), and the decay time of the cavity pickup (***τ***) can be obtained, expressed by:

$$R_s = 1.567 \cdot \frac{\sigma}{\sqrt{\tau \cdot F_s}} . \quad (1)$$

Taking into account the typical structure of the CBPM system, the σ of the whole system can be expanded, the Eq. (1) can be expressed in detail by:

$$R_s = 1.56 \cdot \frac{\sqrt{(G_{RFFE} \cdot NF \cdot N_{RF})^2 + (N_{ADC})^2}}{G_{RFFE} \cdot A_{RF}} \cdot \sqrt{\frac{T_s}{\tau}} . \quad (2)$$

Among them, parameters related to the cavity pickup are the decay time (τ), the amplitude of RF signal output by the cavity pickup (A_{RF}) and the thermal noise amplitude at the output of the cavity pickup (N_{RF}). The gain factor (G_{RFFE}) and the noise figure (NF) represent the characteristic parameters of the RF front-end. Correspondingly, the sampling period ($T_s = 1/F_s$) and equivalent noise amplitude (N_{ADC}) of ADC express the characteristic parameters of the data acquisition system.

Although each subsystem in Eq. (2) contains two parameters, they are related to each other in theory, so independent variables can be reduced. For a certain cavity pickup, if the resonant frequency (***w***) of the cavity pickup and the bunch parameters such as bunch charge (***q***), bunch length (σ_z) and beam offset (ρ), the A_{RF} of TM_{110} mode and TM_{010} mode only related to the cavity length (***L***) and the decay time (***τ***). Therefore, once the cavity length is further determined, the relationship between A_{RF} and τ is fixed and the number of independent variables can be reduced.

For the ADC parameters, N_{ADC} and F_s, there is no clear theoretical quantitative formula between them. Therefore, by investigating the parameters of the commercial mainstream ADCs, it is found that there is a relatively close relationship between the ENOB and F_s of the ADC (10 ~ 100MHz input), as shown in Fig. 1.

*Work supported by National Natural Science Foundation of China (2016YFA0401903) and Ten Thousand Talent Program and Chinese Academy of Sciences Key Technology Talent Program
† chenjian@zjlab.org.cn
# lengyb@ustc.edu.cn

ISBN: 978-3-95450-231-8 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2023-THPL183

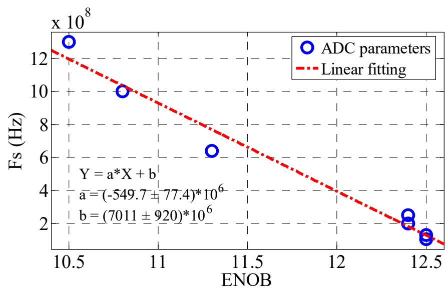


Figure 1: The relationship between the sampling rate and ENOB of commercial mainstream ADCs.

Therefore, the relationship between F_s and $ENOB$ can be approximately expressed as

$$F_S = -k_1 \cdot ENOB + b_1 . \quad (3)$$

And the relationship between $ENOB$ and the signal to noise ratio (SNR) of ADC is expressed as

$$ENOB = \frac{SNR - 1.76}{6.02} . \quad (4)$$

The SNR of the ADC is simply defined as the rms value of the full scale (V_{full}) and the noise floor of the ADC. Substituting Eq. (4) into Eq. (3), then the Eq. (5) can be expressed as

$$F_s = -3.322k_1 \cdot lg(\frac{V_{full}}{N_{ADC}}) + 0.2924k_1 + b_1 . \quad (5)$$

Then the relationship between N_{ADC} and T_s can be simplified to Eq. (6).

$$N_{ADC} = V_{full} \cdot 10^{\frac{\frac{1}{T_s} - 0.2924k_1 - b_1}{3.322k_1}} . \quad (6)$$

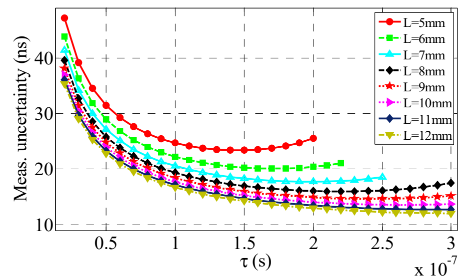
The unit of $\boldsymbol{T_s}$ is second, and the $\boldsymbol{N_{ADC}}$ is Volt, $\boldsymbol{k_1}$ and $\boldsymbol{b_1}$ can be obtained by linear fitting in Fig. 1.

Therefore, the multiple variables in Eq. (2) can be simplified into three independent variables related to cavity pickup, RF front-end, and ADC. In next chapter, the quantitative relationship between the relative amplitude extraction uncertainty and the key parameters of each subsystem based on the guidance formula will be introduced in the design of the CBPM system for SHINE.

APPLICATION IN THE DESIGN OF THE CBPM PROTOTYPE FOR SHINE

The Shanghai high repetition rate XFEL and extreme light facility (SHINE) is the first hard X-ray FEL facility under construction in China, which is a quasi-continuous wave hard X-ray free electron laser facility. It will utilize a photocathode electron gun combined with the superconducting Linac to accelerate electron beams to 8 GeV with maximum repetition rates of 1 MHz. In order to ensure that the degradation of the FEL radiation power is less than 5%, the requirement for the transverse position resolution of the BPMs in the undulator section has to be better than 200 nm for a single bunch of 100 pC at the dynamic range of ± 100 μm.

The CBPM prototype for SHINE is to be installed in the SXFEL facility for test, considering the beam pipe diameter of 16mm and the limitation of the installation space, the resonant frequency of the cavity pickup is set at the C-band. On the other hand, the machine reference clock of SXFEL is 2856MHz, the resonant frequency of the cavity is selected at about 5771.5 MHz, so the IF is determined to be about 59.5 MHz. The numerical simulation is carried out according to Eq. (2), the relationship between the measurement uncertainty and the position cavity parameters of decay time ($\boldsymbol{\tau}$) and cavity length ($\boldsymbol{L}$) is obtained, as shown in Fig. 2.



Figures 2: Simulation results between measurement uncertainty and the parameters of the position cavity.

As for the reference cavity, TM_{010} is the main mode, and the coupled signal amplitude is very large, which is not the main factor limiting the system performance (if the amplitude is too large, additional attenuators will be added), as shown in Fig.3.

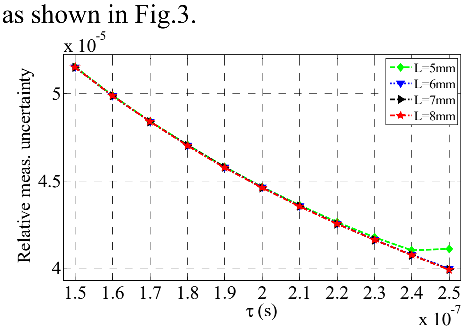


Figure 3: Simulation results between relative measurement uncertainty and the parameters of the reference cavity.

The theoretically designed parameters of the cavity BPM are summarized in Table 1.

Table 1: Theoretically designed parameters of CBPM

Parameters	POS cavity	REF cavity
Resonant frequency / MHz	5771.5	5771.5
Cavity radius / mm	31.7	19.9
Cavity length / mm	8.5	5
Decay time / ns	200	200
Bandwidth / MHz	1.59	1.59
Loaded Q	3626	3626
Normalized shunt impedance	0.7@1mm	90
Sensitivity /V/nC	1.29 @1mm	9.27

The three-dimensional structure of the cavity BPM pickup as shown in Fig. 3, and the cold test result is listed in Table 2.

ISBN: 978-3-95450-231-8 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2023-THPL183

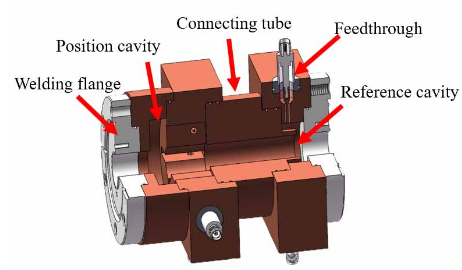


Figure 3: Three-dimensional structure of the cavity BPM pickup.

Table 2: Cold test results of the cavity BPM.

Parameters	POS cavity	REF cavity
Frequency / MHz	5775 / 5770	5769
Bandwidth / MHz	1.67 / 1.52	1.54
Crosstalk between POS and REF cavity	-95 dB	

And the layout of the main functional modules and the picture of the RF front-end are shown in Fig. 4.

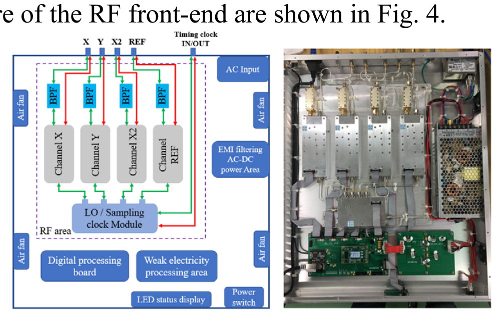


Figure 4: The layout of the main functional modules and the picture of the RF front-end.

PERFORMANCE EVALUATION AT SXFEL

Derived from the theoretical analysis and development of the key equipment, the beam test bench was built at the end of the main accelerator of the SXFEL user facility. Since the peak-to-peak beam jitter of the SXFEL is about 100μm (the designed peak-to-peak beam jitter is better than 10μm for SHINE), the X-Y crosstalk will have a great impact on the evaluation of the system performance. Therefore, in order to verify the correctness of the optimized design method and evaluate the performance of the cavity BPM prototype, an evaluation method of dividing the power of the X-direction dipole mode signal to construct two equivalent RF signals is adopted. The diagram of the beam test bench is shown in Fig. 5.

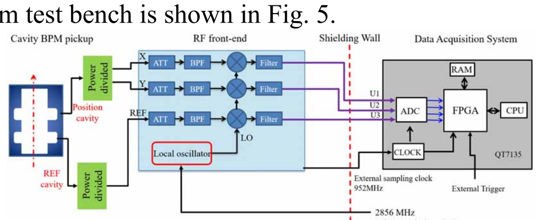


Figure 5: The diagram of the beam test bench.

The drive laser of SXFEL was adjusted to make the bunch charge close to 100 pC, and adjust the system dynamic range of ±100μm, the position conversion factor was shown in Fig. 6. After position convert factor is calibrated, move the cavity to make the beam pass through close to the cavity center and then fix the motors, based on the evaluation method of divided power for correlation analysis, the beam experiment results show that the position measurement uncertainty can reach 40 nm at the bunch charge of 100pC, which is better than the 200nm required for SHINE, the residual distribution as shown in Fig. 7.

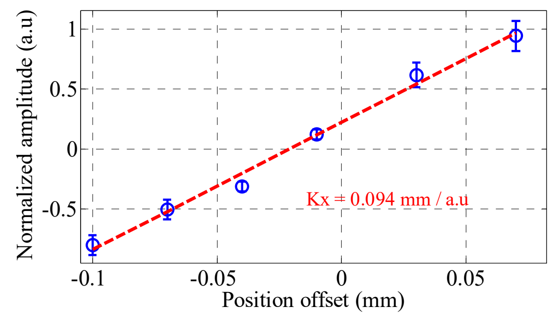


Figure 6: The position conversion factor of the CBPM system.

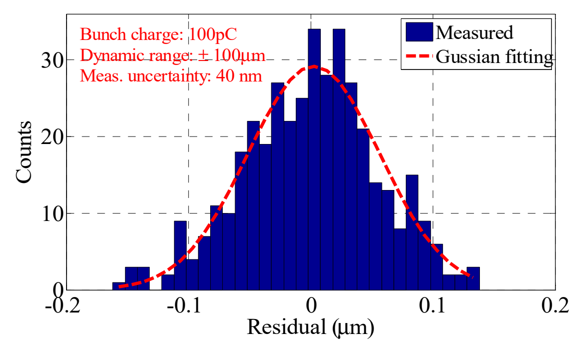


Figure 7: Residual distribution of the system based on the evaluation method of divided power.

CONCLUSION

This research proposes an optimized design method for cavity BPM system based on the relationship between the relative amplitude extraction uncertainty of the system and the key parameters of each subsystem. The cavity BPM prototype for SHINE was developed by this method, and the beam test was performed in SXFEL. The experimental results are consistent with the theoretical analysis results, which verify the superiority and practicability of the design method and is expected to be used in the engineering application of the CBPM system for SHINE.

REFERENCES

[1] J. Chen et al., "Study of the optimal amplitude extraction algorithm for cavity BPM", *Nucl. Instrum. Methods Phys. Res., Sect. A*, vol. 1012, p. 165627, 2021. doi:10.1016/j.nima.2021.165627

[2] J. Chen et al., "Optimized design method study for Cavity BPM System", *Nucl. Instrum. Methods Phys. Res., Sect. A*, vol. 1044, p. 167509, 2022. doi:10.1016/j.nima.2022.167509