TUP04

Development and performance evaluation of the CBPM system for the SHINE

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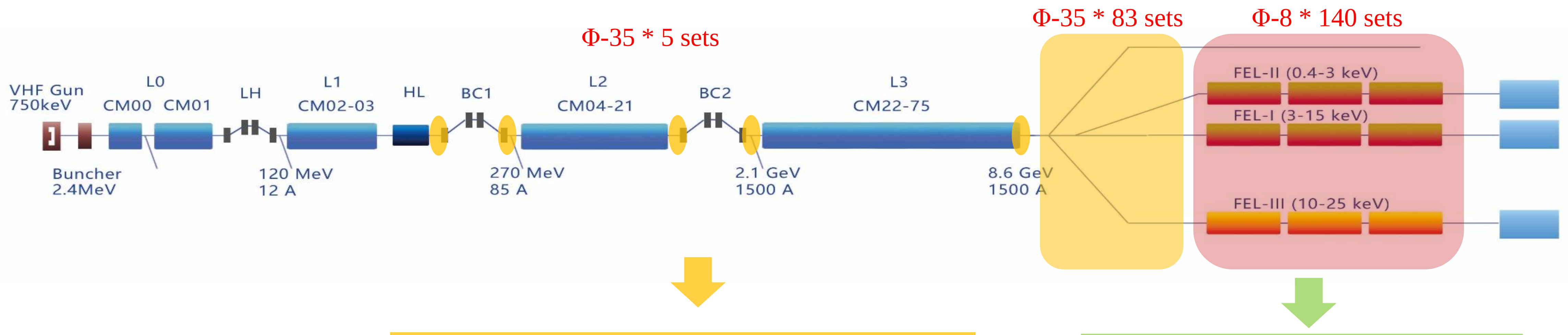
Abstract

The Shanghai high repetition rate XFEL and extreme light facility (SHINE) under construction is designed as one of the most advanced FEL facilities in the world, which will produce coherent x-rays with wavelengths from 0.05 to 3 nm and maximum repetition rate of 1MHz. To achieve precise beam trajectory measurement and stable alignment of the electron and photo beams in the undulator, the cavity beam position monitors (CBPM) including beam diameters of 35mm in LINAC and Bunch distribution section and 8mm in undulator have been designed and developed for the SHINE. The requirement of the transverse position resolution is better than 1μm and 200 nm for a single bunch of 100 pC, respectively. In this paper, we present the design of the cavity BPM system and the processing of the key equipment. The beam test bench has been established at the Shanghai Soft X-ray FEL facility (SXFEL), and preliminary beam experiments indicate that, with the bunch charge about 100pC, the position resolution of CBPM-35mm and CBPM-8mm is better than 312 nm and 41 nm, respectively.

Introduction



LINAC & Bunch Distribution / CBPM-35mm
Resolution: 1μm@100 pC
Dynamic range: ±1mm

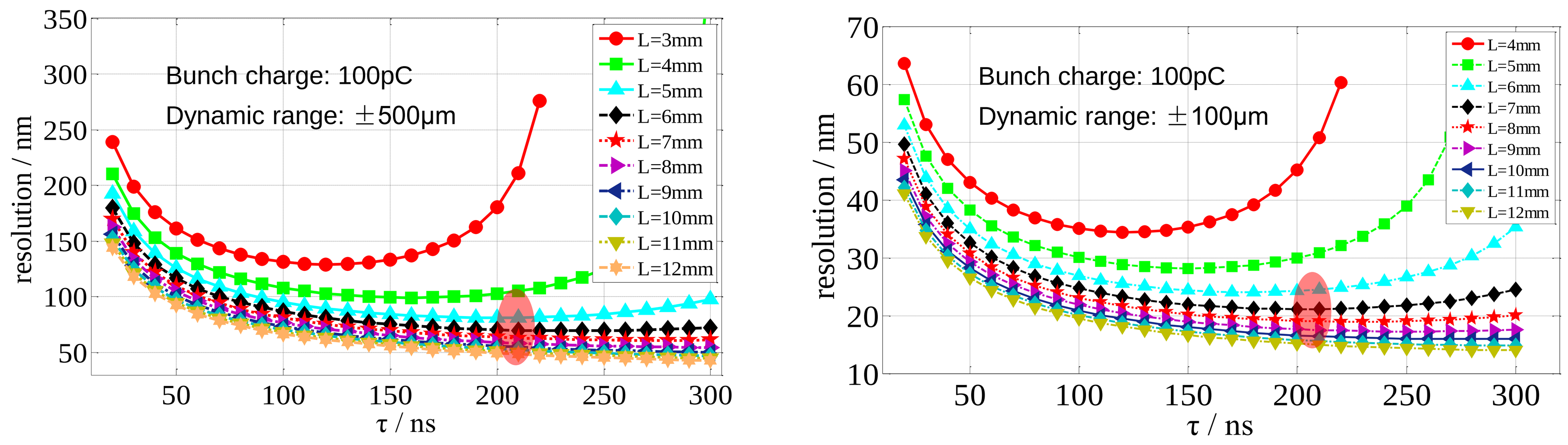
Undulator / CBPM-8mm
Resolution: 200 nm@100 pC
Dynamic range: ±100 μm

- Accurate beam position monitoring is essential for maintaining the stability and quality of the FEL radiation
- SHINE calls for a significant enhancement in the performance of the Cavity Beam Position Monitor (CBPM) systems compared to the existing Shanghai Soft X-ray FEL (SXFEL) facility.
- The transverse position resolution must be improved about 5 to 25 times, necessitating a comprehensive evaluation of the technical solutions, from the design and manufacturing of key components to the implementation of advanced signal acquisition and processing algorithms

System Analysis

- By following the analysis as given in the [Nuclear Inst. and Methods in Physics Research, A 1012 (2021) 165627], the relationship between the amplitude extraction uncertainty and the relative noise-to-signal ratio (σ), sampling rate of the processing system (Fs), and the decay time (τ) under the optimization algorithm can be obtained:

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



Types	CBPM-D35		CBPM-D8	
Parameters	Position cavity	Reference cavity	Position cavity	Reference cavity
Resonant frequency / MHz	3520.87	3520.87	5254.2	5254.2
Cavity radius / mm	51.9	32.6	34.8	21.8
Cavity length / mm	9	4.5	9	5
Decay time / ns	200	200	200	200
Bandwidth / MHz	1.59	1.59	1.59	1.59
Loaded Q	2212	2212	3301	3301
Normalized shunt impedance	0.175@1mm	50.65	0.56@1mm	82.6
Sensitivity /V/nC	0.575 @1mm	7.26	1.15@1mm	9.4
Total length	250 mm		112 mm	
Quantity	88		140	

Fig.1: Simulation results between measurement uncertainty and the parameters of the CBPM-D35 & CBPM-D8.

Cavity pickups

- Two types Cavity pickups with beam apertures of 35mm and 8mm are designed and fabricated.
- Cold test results is in good agreement with the design and simulation results.

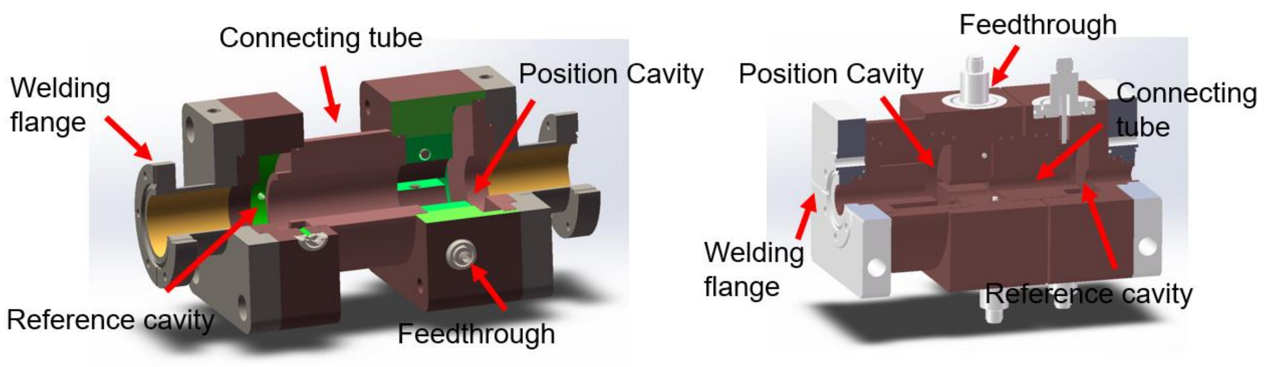


Table 2: Cold test results of the Cavity BPM pickups.

Types	CBPM-D35		CBPM-D8	
Parameters	Position cavity	Reference cavity	Position cavity	Reference cavity
Resonant frequency / MHz	3518.8 / 3524	3520.9	5253.5/5259	5257.8
Decay time / ns	200	200	200	200
Bandwidth / MHz	1.52 / 1.43	1.58	1.60/1.44	1.63
Crosstalk between X/Y	-50.8 dB	----	-50 dB	----
Crosstalk between POS and REF cavity	-95 dB		-87 dB	

RF Front-end & Digital Signal Processor

- SHINE 1MHz repetition rate, and the high-Q cavity pickups selected, the RF front-end with down-conversion in a single channel, and high-repetition-rate digital signal processing electronics has been applied.

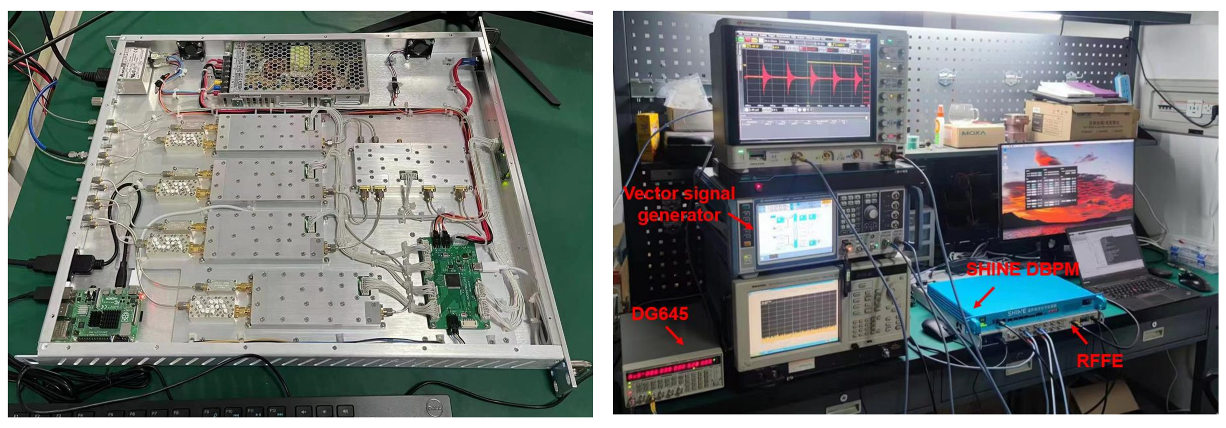


Fig.2: Phase-locked test bench in the laboratory (25±3℃).

Parameters	Value
Channels	4
Analog Bandwidth	1.2 GHz
ADC bits	16 bits
SNR@170MHz input	70 dBFS
ENOB	10.8 bits
Sampling rate	1000 MSPS max
Sampling clock	External / Internal
Trigger	External / Internal

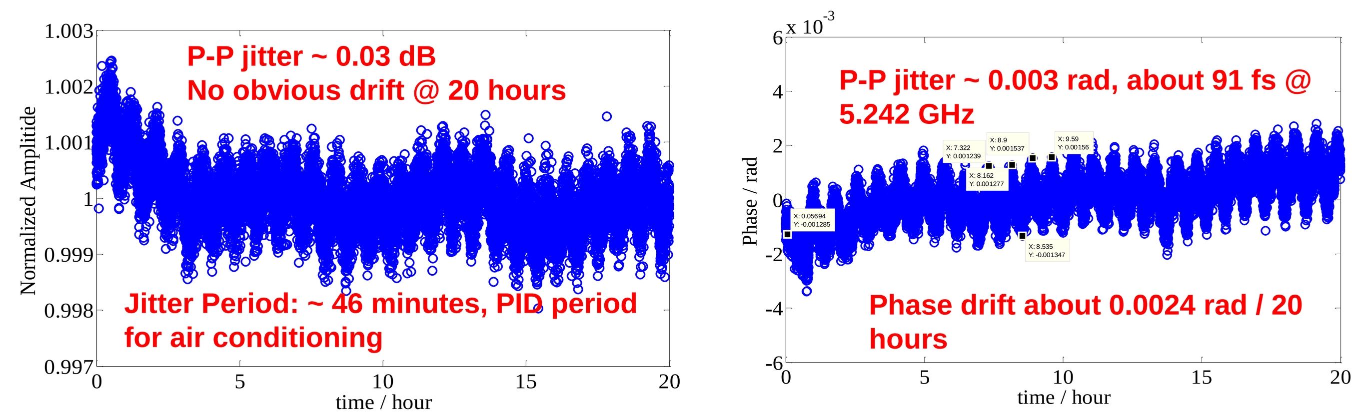
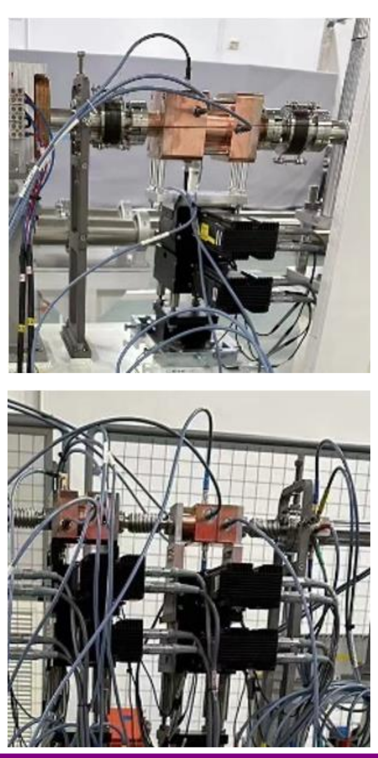


Fig.3: Relative amplitude and phase drift and jitter of the position cavity channel compared to the REF channel

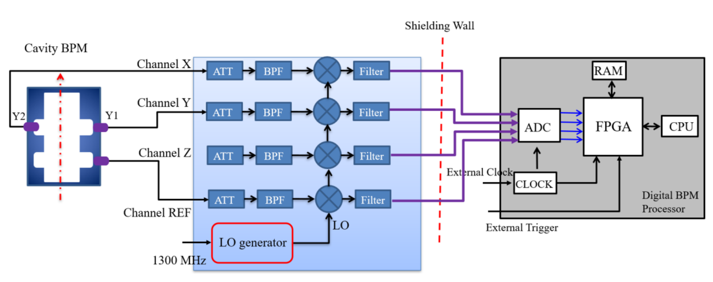
- ✓ The **Noise Figure** of the RF front-end was controlled **better than 2.3dB**
- ✓ Independent module design enhances the amplitude and phase stability of the RFFE links and improves its anti-interference performance
- ✓ Relative amplitude extraction uncertainty is better than **0.13‰ @ -26 dBm input**.

Performance evaluation @ SXFEL

- The beam test bench was built at the undulator section of the SXFEL user facility.
- Signals from the two opposite feedthroughs of the same pickup are used for correlation analysis to evaluate the performance of the CBPM system.

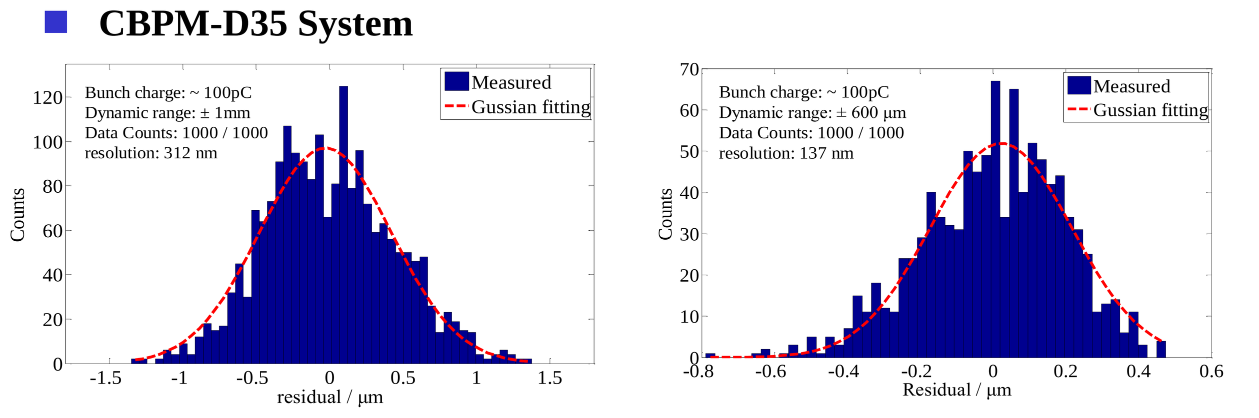


- The bunch charge was adjusted to about 100pC at the beam experiment.



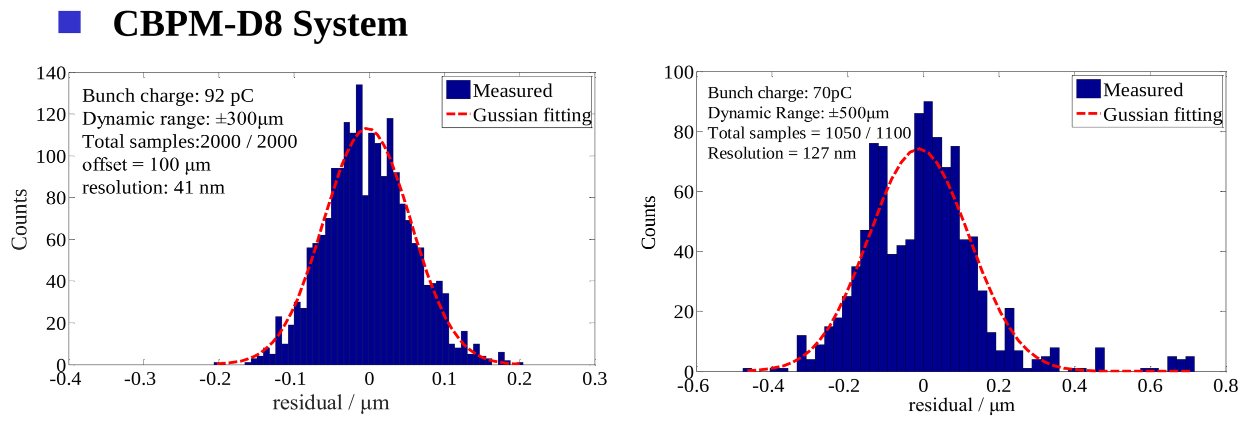
$$\delta_{CBPM} = std\left(\frac{U_1}{U_3} - \frac{U_2}{U_3}\right) \cdot K.$$

CBPM-D35 System



The position resolution can reach 312 nm@±1mm &137nm@±600μm dynamic range

CBPM-D8 System



The position resolution can reach 41 nm@±300μm &127nm@±500μm dynamic range

Conclusion

- The CBPM system, with apertures of 35mm and 8mm, has been designed and developed, the beam test was performed in SXFEL
- Beam experiment demonstrated position resolutions of 312 nm and 41 nm, respectively, surpassing the required specifications.
- The experimental results closely matched the theoretical simulations, validating the accuracy of the system design and the effectiveness of the equipment processing.
- According to the FEL commissioning schedule of 2025, the batch processing and installation of the Cavity BPM are underway.