ISBN: 978-3-95450-214-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2021-FRXC06

DEVELOPMENT OF THE PROTOTYPE OF THE CAVITY BPM SYSTEM FOR 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 1 MHz. In order to achieve precise, stable alignment of the electron and photo beams in the undulator, the prototype of the cavity beam position monitors (CBPM) including C-band and X-band have been designed and fabricated for the SHINE. And the requirement of the transverse position resolution is better than 200 nm for a single bunch of 100 pC at the dynamic range of ±100 μm. In this paper, we present the design of the cavity with high loaded Q and the RF front-end with low noise-figure, adjustable gain, single-stage down-conversion and phase-locked with reference clock, and also described the structure and specifications of the home-made data acquisition (DAQ) system. The construction of the experiment platform and preliminary measurement result with beam at Shanghai Soft X-ray FEL facility (SXFEL) will be addressed as well.

INTRODUCTION

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 [1]. It will utilize a photocathode electron gun combined with the superconducting Linac to produce 8 GeV FEL quality electron beams with 1 MHz repetition rates. The total length of the SHINE is about 3.1 km, mainly contains 3 undulator lines, 3 light speed lines, and the first batch of 10 experimental stations. Together with Shanghai Synchrotron Radiation Facility (SSRF) and (Shanghai Soft X-ray Free-Electron Lasers) SXFEL to build a photonic science center in China.

For FEL facilities, the requirement of the transverse position resolution is better than sub-micrometer or even nanometer scale, so that it can be used for the beam alignment in the undulator section where the electron beam and the radiation should be overlapped precisely. And for SHINE, it has an extreme high-resolution requirement for cavity BPM system in undulator section, the target is to achieve the beam position measurement resolution better than 200 nm at the bunch charge of 100 pC and the dynamic range within 100 μm, and fight for 100 nm.

In China, some universities and research institutes start CBPM research about 10 years ago but have not beam test at now. In 2016, the first operational CBPM system was developed by SSRF and widely used in SXFEL and Dalian Coherent Light Source (DCLS) [2, 3], and got the resolution about 300 nm at the bunch charge of 500 pC and the dynamic range of ± 300 μm, the performance is good enough for SXFEL and DCLS but not for SHINE. Therefore, on the basis of the original work, it is necessary to develop a new CBPM prototype with the resolution that can meet the target requirements for SHINE. The global goals are optimized system design which resolution fully meet the requirement of SHINE facility and cultivate few more qualified manufactures for batch production. Of course, there also has several technical issues needs to be investigated:

1. CBPM cavity
   - Evaluate position and arrival time resolution with different Q value.
   - Trying to minimize or compensate X/Y crosstalk. This issue is important in the early stage of the commission when the beam jitter is quite severe.
   - Finalize fabrication procedure to guarantee the uniformity of different cavities and different ports.
2. RF Front-end
   - Evaluate the performance with different architectures.
   - Programable cascade amplifiers or switching amplifiers, Digital gain control or voltage gain control, Coaxial RF components or printed circuit board based.
3. Digital signal processor
   - Basic: Develop a processor with sampling rate and ENOB can meet the demands.
   - Explore new architectures and technologies for digital signal processor.
   - Compare and evaluate the performance of the new DBPMs (higher sampling rate but lower ENOB) and old one (lower sampling rate but higher ENOB) under the condition of large and small bunch charge. Determine which architecture will be used for SHINE (high sampling or low sampling).

SYSTEM DESIGN

Based on the exploration of the above technical issues, the systematic design was carried out. The overall system architecture is shown in Fig. 1, which mainly includes a cavity probe, an RF front end and a digital signal processor.

Due to the whole requirement is the beam position resolution better than 200 nm, fight for 100 nm, based on this, the indicator was divided into three parts.

1. CBPM cavity
   - Max bunch repetition rate of 1 MHz，so the decay time ≤ 300 ns.

*Work supported by National Natural Science Foundation of China (2016YFA0401903) and Ten Thousand Talent Program and Chinese Academy of Sciences Key Technology Talent Program
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ISBN: 978-3-95450-214-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2021-FRXC06

- Reference frequency of 2856 MHz, the resonant frequency of cavity was designed at 5712 + 60 MHz.
- The requirement for pos sensitivity is large than 1.15 V/nC·mm, and for the reference cavity is large than 1 V/nC.

2. RF Front-end
- The Noise Figure of position channel < 6 dB @ 100 pC·100 µm.
- The SNR of output signal need to better than 65 dB, and the absolute noise floor less than 0.2 mV (better than digitizer noise floor).

3. Digital signal processor
- The sampling rate > 500 MSPS and the ENOB better than 9 bits.
- SNR ~ 60 dB for single sample points.
- Signal processing gain > 6 dB and total SNR better than 66 dB.

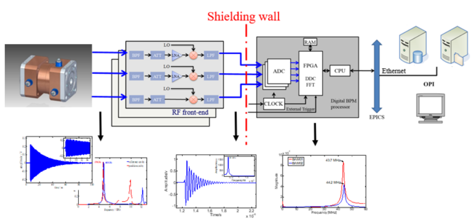

Figure 1: System architecture of the CBPM system.

R&D OF THE KEY COMPONENTS

For the cavity BPM pickup, we designed and fabricate three prototypes with different decay time, 100 ns, 200 ns and 300 ns to evaluate beam position and arrival time resolution with different Q values. The specifications of these three cavity pickups are list in Table 1.

Table 1: Specifications of Three Type Prototypes

SN	Fre/ MHz	BW/ MHz	XY cross-talk	SNR/ dB
CBPM100	5771.5	3.18	< -40 dB	> 80
CBPM200	5771.5	1.59	< -40 dB	> 80
CBPM300	5771.5	1.06	< -40 dB	> 80

Figure 2 shows the picture of these three type cavities, and in the cold test, the network analyzer was used to record all S parameters to measure the cavity parameters, such as cavity frequency, bandwidth, and the crosstalk factor, etc. The clod test results shown that the frequency deviation between three small batch productions of one type less than 1 MHz, and the bandwidth deviation less than 0.03 MHz, crosstalk between X and Y better than -35 dB. The processing consistency of the pickups is better, but the crosstalk between X/Y needs to be further improved.

On the other hand, in physical design, in order to reduce the influence of the crosstalk between X and Y, the crosstalk control and compensation methods was introduced in CBPM-200 ns for evaluated.

The X/Y frequency are shifted about 8 MHz by tuning the width of waveguide, so the spectrum of X and Y are separated, based on this method, the crosstalk can be reduced to a certain extent and the crosstalk compensation also can be done with calibrated crosstalk factor.


Figure 2: The picture of these three type cavities. Top-left: CBPM-100 ns; Top-right: CBPM-200 ns; Bottom: CBPM-300 ns.

For the RF front-end, the method of single-stage to down-converted the RF signal to intermediate frequency about 60 MHz was used. The schematic diagram of the RF front-end was shown in Fig. 3. A bandpass filter with a bandwidth of 100 MHz is used to remove interference from other mode signals coupled by the pickup. Based on this architecture, in order to get a small noise figure, three prototypes with different architectures were designed. Figure 4 is the picture of the three prototypes.

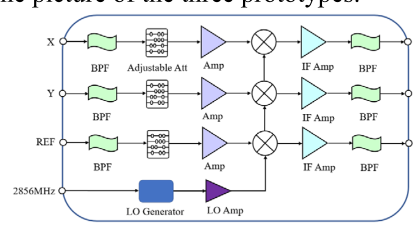

Figure 3: Schematic diagram of the RF front-end.

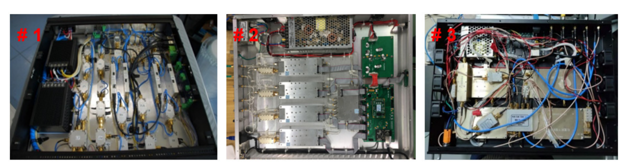

Figure 4: Picture of the three types of RF front-end.

Table 2 shows the difference in the architectural between these three prototypes, mainly compared the coaxial or PCB based for RF units, and for the dynamic range control, the cascaded and switching methods, digital and voltage gain control methods were also compared.

Table 2: The Difference in the Architecture Between These Three Prototypes

Architecture	Prototype #1	Prototype #2	Prototype #3
RF unit: coaxial/ PCB	both	PCB	PCB
Amplifier: cascaded/ switching	cascaded	cascaded	switching
Gain control: digital/ voltage	digital	both	digital

Under the beam experimental, the noise floor of these three protypes was evaluated, the results shown that the noise floor of prototypes #3 is the best and much smaller than digitizer, the performance is better than the design requirements. And the architecture of PCB based combined

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with switching gain and digital gain control method will be our best choice in the RF front-end for SHINE.

FIRST BEAM EXPERIMENT

After the development of the key components, we set up a beam test platform in SXFEL and completed the first beam experiment. As shown in the left of Fig. 5, three adjacent CBPMs of same type were installed to evaluate the position resolution, bunch charge and BAM resolution, and the 4-dimension mover was equipped as the cavity support. Due to the bunch charge of SXFEL is 500 pC, in order to simulate the bunch charge about 100 pC on SHINE, additional 14 dB attenuator was added in the front of the RF front-end.

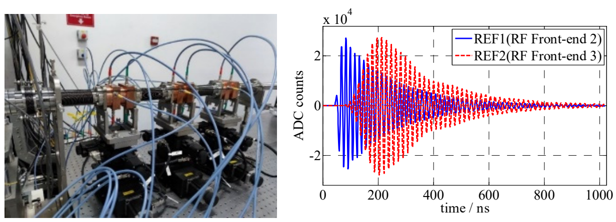

Figure 5: (left) The BPM test array installed at the SXFEL; (right) Waveform of the two adjacent reference cavities.

Based on the two adjacent reference cavities, the waveform is shown in the right of Fig. 5, the amplitude and phase extraction resolution of the system was evaluated. As shown in Fig. 6, the relative bunch charge resolution can reach 0.025% and the beam arrival time resolution can reach 6.9 fs rms at the bunch charge of 500 pC, which all better than SXFEL old system. The results verified that the protype we developed has an excellent performance in amplitude and phase extraction.

In addition, three adjacent cavity BPMs was used to evaluate the beam position resolution, as shown in Fig. 7, the beam position resolution about 300 nm at the dynamic range of 100 μm was obtained. This results almost the same as the SXFEL old system, have not meet our expectations.

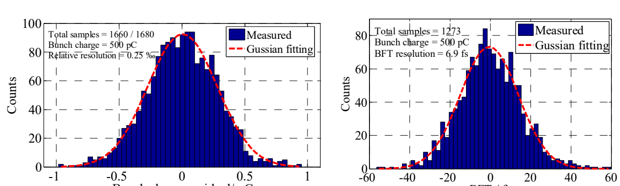

Figure 6: (left) Bunch charge resolution and (right) beam arrival time resolution based on the two adjacent reference cavities.

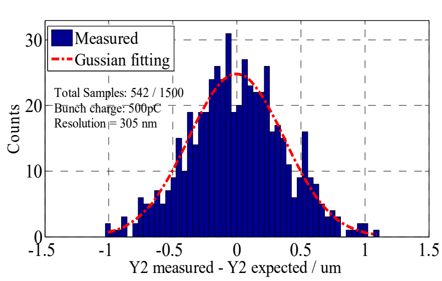

Figure 7: Histogram of the differential of the Y measured and the Y expected.

So, compare the results of bunch charge and position resolution, the difference in amplitude extraction performance is a bit obvious. After analysis and discussion, the factors affecting the performance of the position channels may mainly come from two aspects, first is the crosstalk between X and Y. Equation (1) illustrates the influence of measured position of Y direction when there has beam jitter in the X direction [4]

$$Position\_Y_{measure} = \frac{A_y}{A_{ref}} * k_y + \frac{A_x}{A_{ref}} * k_x * C_{x-y} + \frac{\Delta A_x}{A_{ref}} * k_x * C_{x-y}. \quad (1)$$

The first term is the position measured by the vertical position cavity without crosstalk, and the latter two terms represent the contribution of the crosstalk from the beam position jitter of the X-direction. The second term contributed an offset related to the beam position of the X-direction, and this term affects the precision of the position measurement and has no effect on the resolution. The third term has an effect on the resolution of the Y-direction when the beam position of the X-direction is jittered. Considering that the beam jitter of SXFEL is about 150 um peak to peak and the crosstalk from X to Y about -43 dB, then the influence of crosstalk on the beam position resolution is about 230 nm, which is close to the beam position resolution of 300 nm we got at now. Second is the beam trajectory with a finite angle. In this experiment, the dynamic range was controlled within ±100 μm, when the beam pass through the cavity with an angle especially very closed to the electric center, it will also have a big influence on the beam position measurement. These two aspects will be the optimization direction of the second beam experiment, and we expect to get an ideal result by adjust the beam trajectory and compensate the crosstalk.

CONCLUSION

In response to SHINE's demand for high-resolution beam position measurement, three sets of CBPM prototype with different Q values (100 ns, 200 ns, 300 ns) were developed (one under beam test and two more to go). The RF front-end electronics with low noise figure and data acquisition and processing electronics have also been developed. The beam experimental platform has been built at the end of SXFEL LINAC section, and the first test of CBPM 200 ns shows the bunch charge resolution can reach 0.025% and BAM resolution can reach 6.9 fs rms, which are better than old system in SXFEL. But the position resolution about 300 nm at the dynamic range of 100 μm, which not meet the requirements yet. The major bottleneck could be beam trajectory variation and XY crosstalk induced uncertainty. In the upcoming second beam experiment, the beam trajectory will be adjusted and the crosstalk will be compensated in the DSP module, and we expect it will get an ideal result.

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