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DESIGN AND TEST OF CBPM PROTOTYPES FOR SHINE*

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Abstract

SHINE (Shanghai High repetition rate XFEL aNd Extreme light facility) is designed to be an extremely high performance hard X-ray free electron laser facility located at Zhangjiang, Shanghai. As one of the key parameters of the facility, the resolution of the beam position measurement in the undulator section is required to be under 200 nm at a low bunch charge of 100 pC and better than 10 µm at 10 pC. To achieve this, a pre-study based on cavity beam position monitors is under development. Four sets of cavity monitors with different frequencies or load quality factors have been designed and are now manufactured by four different companies. It aims to select the cavity with the best performance and select the most capable company. This paper will briefly introduce the motivation, cavity design considerations, and cold test results.

INTRODUCTION

SHINE is a newly proposed high-repetition-rate X-ray FEL facility, which is designed to become one of the most efficient and advanced free electron laser user facilities in the world, providing a tool for cutting-edge research subjects. The facility includes a superconducting linear accelerator with an energy of 8 GeV, 3 underlines, 3 optical beam lines, and the first 10 experimental stations [1,2]. The fundamental parameters of SHINE are presented in Table 1.

Table 1: The Fundamental Parameters of SHINE

Parameters	Values	Units
Beam energy	8	GeV
Bunch charge	100	pC
Max rep-rate	1	MHz
Pulse length	20-50	fs
Peak brightness	5×10^{32}	~

The construction of such a high-level FEL facility has strict requirements for each subsystem. Beam position as one of the key parameters can be used to monitor the electron beam orbital changes. For SHINE, the position resolution requirement at the undulator is better than 200 nm. To achieve that, the high-resolution and high-sensitivity cavity beam position monitor (CBPM) is utilized to extract the beam position [3,4]. The principle is that the intensity of the TM110 mode excited by the beam is proportional to the beam position. By extracting the signal of TM110 mode, the beam position can be obtained. Moreover, the signal of TM_{110} mode is also related to the bunch charge, thus it is essential to use a reference cavity to normalize the bunch charge.

Four different types of CBPM are currently under development. The reason for developing four types of CBPM is based on the following considerations. Firstly, the higher the cavity frequency, the more compact the cavity, and the higher sensitivity and higher the ratio of signal-to-noise (SNR) of the output signal is expected. Thus the C-band and X-band CBPM are proposed. Secondly, the higher the Q_{load}, the longer the signal length, the higher the signal processing gain and the greater the crosstalk between the bunches. Thus the cavities with different Q_{load} are also proposed. Thirdly, it is also necessary to cooperate with several manufacturers and evaluate the processing capabilities so as to select the most capable one. At present, some CBPMs have been fabricated and are awaiting acceptance checks, while others are still under development.

The following subsections will introduce this in detail.

DEVELOPMENT OF FEEDTHROUGH

As an indispensable part of all beam position monitors (BPMs), feedthrough is used to couple the energy stored inside the cavity to the outside to the cavity and convert it to an electrical signal for subsequent electronic processing. Previously, the feedthroughs are purchased from companies. However, the bandwidth of purchased feedthrough is only about 8 GHz, which cannot meet the requirements of X-band CBPM, while the customized feedthroughs are too expensive. Therefore, we decided to independently develop high-bandwidth feedthroughs. Since Dr. Yuan has successfully completed the design of the high-bandwidth N-type feedthrough, we decided complete the design of the SMA-type feedthrough based on the N-type feedthrough.

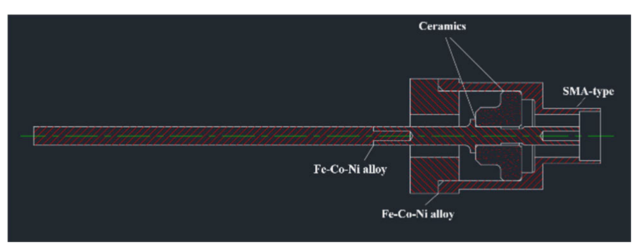

Figure 1: Structure of the SMA-type feedthrough.

The structure of the SMA-type feedthrough is shown in Fig. 1. The first batch of 20 prototypes have been developed, as shown in Fig. 2, including 8 dual-port SMA prototypes and 12 SMA-type feedthroughs. The dual-port SMA prototypes are used to evaluate the bandwidth of the feedthrough and the processing consistency. To improve the connection stability of the SMA interface, a gold-

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plated test was performed. The test results show that gold plating can significantly improve the connection stability of the interface, and none of the feedthrough prototypes shows the poor connection.

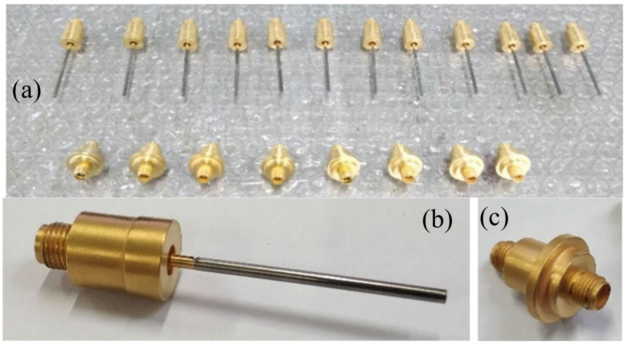

Figure 2: Prototypes of the SMA-type feedthrough:(a) 20 feedthrough prototypes; (b) SMA-feedthrough; (c) dual-port SMA-feedthrough.

Moreover, the S21 parameters of dual-port SMA-feedthroughs and S11 parameters of single-port SMA-feedthrough with a high-bandwidth network analyzer have been tested, as presented in Fig. 3. Among them, the bandwidth results of the 8 prototypes can be obtained through the S21 parameters. The test results show that all 8 prototypes can satisfy the design requirement and can be used in X-band CBPM. Except for the first prototype, the bandwidths of the other 7 prototypes are better than 15.5 GHz. The S11 parameters of the other 12 prototypes produced in the same batch are generally the same, and no prototypes with an obvious deviation of S11 are found.

In general, the high-bandwidth feedthroughs have been successfully developed this time, and they also have a good consistency.

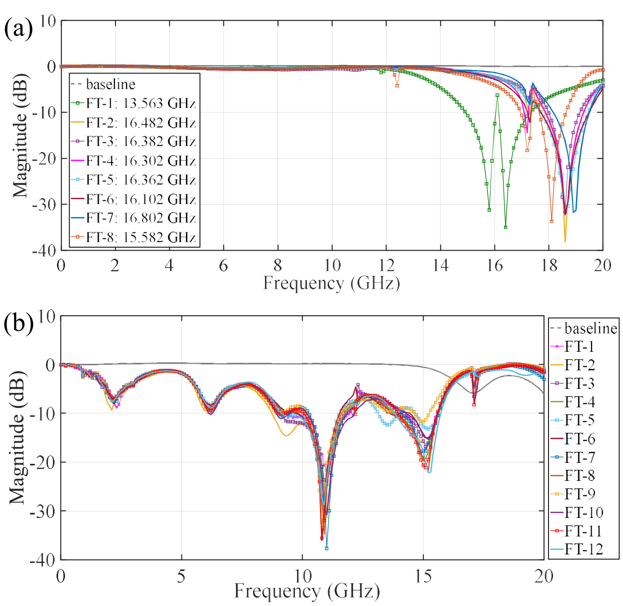

Figure 3: The S parameter tests: (a) S21 test of dual-SMA-feedthroughs; (b) S11 test of single-SMA-feedthroughs.

DEVELOPMENT OF CBPM

As described above, the development of four types of CBPMs with different frequencies and Q_{load} are the key task of this research. To evaluate the impact of frequency on system performance, the frequencies of the C-band and X-band CBPM are specific to be 5771.5 MHz and 11483.5 MHz. And to evaluate the impact of decay time constant (τ) on system performance, CBPM-100, CBPM-200, and CBPM-300 with a decay time (τ) of 100 ns, 200 ns, and 300 ns are going to be developed. The design parameters of the CBPMs are listed in Table 2.

Table 2: Design Parameters of the CBPMs

Parameters	CBPM-100	CBPM-200	CBPM-300	X-CBPM
Freq./MHz	5771.5	5771.5	5771.5	11483
τ/ns	100	200	300	100~200
Qload	1813	3626	5440	3611~7222
BW/MHz	3.18	1.59	1.06	1.59~3.18

With respect to cavity radius of TM_{mnp} mode, it is related to the cavity frequency f_{mnp} and it can be expressed as:

$$r_{mnp} = \frac{cj_{mn}}{2\pi f_{mnp}}$$

where c is the light speed, j_{mn} is the root of Bessel function, especially $j_{01} = 2.405$, $j_{11} = 3.832$. Normally, the tolerance of lathes machining is about 20 µm, which will cause a large frequency difference. The following Table (see Table 3) summarizes the cavity radius and the frequency sensitivity to radius of the C- and X-band CBPMs. The results in the table show that X-band CBPM has higher processing requirements, so we have to pay more attention on it.

Table 3: Radius and Frequency Sensitivity of CBPMs

Cavities	Radius /mm	$\Delta f/\Delta r$ (MHz/µm)	Δf @20 µm
C-CBPM Ref.	19.9	-0.3	6 MHz
C-CBPM Pos.	31.7	-0.2	4 MHz
X-CBPM Ref.	10	-1.1	22 MHz
X-CBPM Ref.	15.9	-0.7	14 MHz

Design of CBPMs

Basically, the design of the reference cavity is relatively simple compared to the position cavity. The C-band reference cavity adopts a re-entrant structure to facilitate frequency tuning and be convenient for cable connection, as shown in Fig. 4 (a). However, for the X-band cavity, due to the limitation of the cavity size and the size of the beam pipe, two rectangular waveguides are added on both sides of the cavity to extend the distance between the

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feedthrough and the beam pipe to facilitate the installation of feedthroughs, as shown in Fig. 4 (b).

The structure of the pillbox-position cavity is relatively complicated, and it can be divided into the following two types, as shown in Fig. 5. To compare the pros and cons of the two structures in design and fabrication, CBPM-100 and CBPM-200 adopt the first structure, as shown in Fig. 5 (a), and CBPM-300 and X-CBPM adopt the second structure, as shown in Fig. 5 (b).

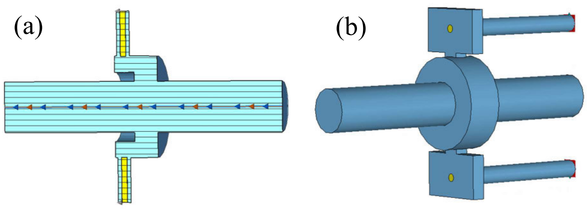

Figure 4: The 3D simulation model: (a) The C-band reference cavity; (b) The X-band reference cavity.

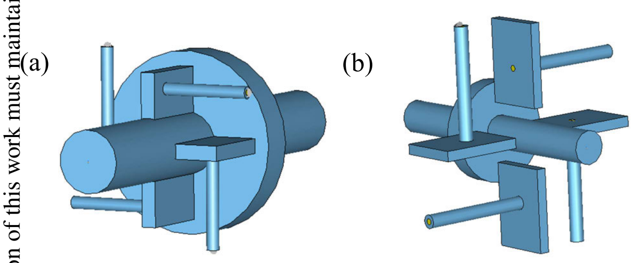

Figure 5: Two types of CBPM position structure.

Based on the above structures, an electromagnetic field simulation software is applied to attain the final cavity size as well as the simulation results. The simulation results can be found in Table 4. Generally, the simulation result of frequency is consistent with the design goal, the simulation result of τ is slightly different from the design goal, but it does not affect our evaluation purpose.

Table 4: Simulation Results of CBPM Reference Cavities

Cavities	Freq. /GHz	τ/ns	Q_{load}	BW /MHz	Vp/ (V/nC)
CBPM100Ref	5.771	101	1831	3.15	12
CBPM100Pos	5.771	109	1976	2.92	2
CBPM200Ref	5.771	211	3825	1.51	4
CBPM200Pos	5.772	203	3681	1.57	0.8
CBPM300Ref	5.772	262	4751	1.21	6
CBPM300Pos	5.773	245	443	1.30	1.1
XCBPM_Ref	11.483	164	5916	1.94	14
XCBPM_Pos	11.483	176	6349	1.81	2

Cold Test

Currently, three sets of CBPM-200 have been fabricated and welded, as shown in Fig. 6. The cold tests with a network analyzer have been performed. The results have also been presented in Table 5. The frequency results of three sets of CBPM with 6 cavities show that the maximum frequency difference between two cavities is 9 MHz, and the maximum frequency difference from the design frequency is 6 MHz. And the maximum bandwidth difference between two cavities is 0.26 MHz, and the maximum frequency difference from the design frequency is less than 0.2 MHz. The preliminary results show that the three sets of cavities have good consistency, but they can be further improved in the future.

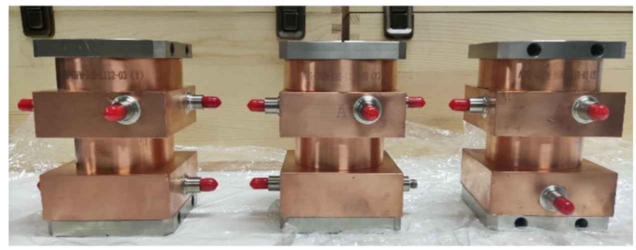

Figure 6: Photo of CBPM-200.

Table 5: Cold Test Results of CBPM-200

Cavities	Freq /GHz	BW /MHz	XY Crosstalk
CBPM#1 Ref.	5.769	1.54	~
CBPM#1 X	5.775	1.67	-60 dB
CBPM#1 Y	5.77	1.52	
CBPM#2 Ref.	5.773	1.49	~
CBPM#2 X	5.774	1.55	-53 dB
CBPM#2 Y	5.768	1.46	
CBPM#3 Ref.	5.776	1.56	~
CBPM#3 X	5.77	1.46	-54 dB
CBPM#3 Y	5.777	1.41	

CONCLUSION

The first version of the four sets of CBPM has been designed. In addition, the pre-research cavity of CBPM-200 has been processed, welded and tested. The test results are in good agreement with the simulation results, but it can be further improved.

Reviewing the entire development process, we still need to pay attention to the mode interference problem during the design process, either remove other interference modes, or move them to a frequency far away from the tested mode; on the other hand, we also need to pay special attention to the XY crosstalk problem. The cavity structure and manufacturing method can be optimized.

In the future, we will further optimize the unreasonable parts of the cavity design and monitor each process of manufacturing to lay the foundation for subsequent mass production.

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