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X-BAND LOW Q CAVITY BEAM POSITION MONITOR STUDY *

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Abstract

The high repetition-rate and high peak brilliance of X-ray free-electron laser (XFEL) allow studying many scientific experiments that have not been feasible. To realize such high performance, a sub-micron beam transverse position measurement is required. The cavity-type beam position monitor (CBPM), as a non-destructive diagnostics tool with high potential in resolution performance, has been applied in different free electron laser facilities (FELs). In this research, an X-band high bandwidth CBPM has been studied and used for pre-research on bunch-by-bunch diagnostic for the pulsed FEL with high repetition-rate. Its bandwidth reaches 300 MHz. Design considerations and simulation results of the CBPM have been discussed and presented in this paper.

INTRODUCTION

A number of FEL facilities have been constructed and are in operation currently, more are under construction or planning. This is because FELs feature ultrafast temporal resolution, ultra short light pulse duration, high intensity, and extreme-high brightness, etc. Thus FEL offers a unique powerful tool to understand, predict or even control the properties of matter, answer the fundamental scientific questions, and explore an undiscovered complex system. However, an important limitation currently is that these facilities can only accommodate a small number of users at a time. To break the limitation, a multi-user FEL scheme has been proposed based on sending accelerated electron bunches to a switchyard at a high bunch repetition rate [1]. A 1MHz bunch repetition rate has been proposed in a design concept of The Next Generation Light Source (NGLS) by LBNL [2]. European XFEL will integrate a high-repetition rate of about 4.5MHz laser to FEL experiments [3]. CXFEL is going to work at an ultra-high repetition rate of about 400 MHz [4]. Therefore, high repetition rate has led a trend of FEL development.

For a successful and proper operation of FEL, a beam based alignment is essential to ensure a stringent overlap between the electron and the photon beam. This requires a beam position monitors (BPM) with a resolution under the sub-micron meter. Moreover, given the high repetition rate, the signal coupled from BPM has to decay fast in multiple bunch modes so as to reduce the superposition of each single bunch signal. Cavity beam position monitor (CBPM) as a non-destructive diagnostics device, has sufficient precision and high resolution. In addition, it has been equipped and successfully used for beam position measurement by many facilities. Therefore, a research based on high bandwidth CBPM has to bring into action.

Cavity BPM normally consists of two cavities, a position cavity for position measurement and a reference cavity for bunch charge normalization. When an electron beam passes a cavity, radio-frequency (RF) oscillations will be generated and it can be represented by a sum of various modes [5]. In particular, a common mode TM_{010} and a dipole mode TM_{110} will be excited. Moreover, under a paraxial approximation, the amplitude of TM_{010} only depend on the charge q while the amplitude of TM_{110} is proportional to the charge q and electron beam displacement δx. Therefore, the reference cavity and position cavity measure TM_{010} and TM_{110} yielding signal, respectively.

In this research, we focus on the study of a broadband CBPM. Using the main parameters of CXFEL, the bunch pulse duration is only about 2.3 ns (see Fig. 1). Thus the signal induced by electron beam has to decay in a few nanoseconds. Table 1 shows the main parameters of CXFEL. Although this bunch charge of 200 pC is not very low, even lower electron bunch charge of few pC has to be considered for facility debugging or upgrade in the future. In addition, an X-band CBPM can acquire high amplitude signals for low bunch charge [6]. The remainder of this paper introduces the main design procedure and simulation results.

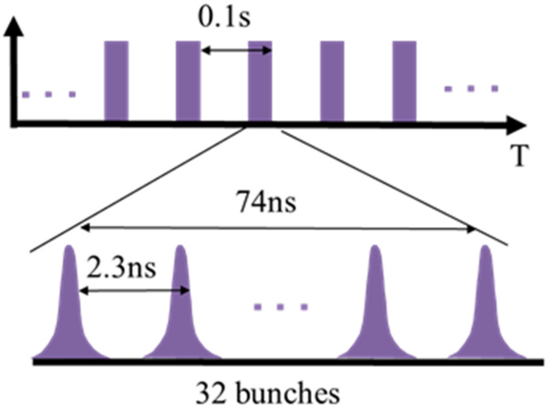

Figure 1: Electron beam characteristic.

Table 1: Main Parameters

Parameter	Value	Unit
Beam energy	15	GeV
Beam charge	200	pC
Bunch length	20	ps
Pulse separation	2.3	ns
Pulse repetition rate	10	Hz

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DESIGN OF THE CBPM

In this study, the working frequency of the CBPM is selected as 11.44 GHz. The electron bunch charge is 200 pC and the bunch length (FWHM) of a Gaussian beam is 6 mm. Since this CBPM will serve for a multi-bunch mode operation, the decay time constant is required to be shorter than bunch pulse duration. However, too short RF signal length will cause the data point deficiency after signal sampling. Thus it's a trade-off to choose an appropriate decay time constant. Table 2 presents the fundamental requirements.

Table 2: Fundamental Requirements of the CBPM

Parameter	**Position cavity**	**Reference Cavity**
Frequency/GHz	11.44	11.44
Bandwidth/MHz	>300	>300
Decay time constant/ns	<1.06	<1.06
Q_{load}	<38	<38

CST Studio Suite was applied to accomplish the design, including determining the final size of the CBPM and giving the simulation results. As discussed above, the CBPM has two cavities. The position cavity consists of a re-entrant cylindrical cavity, four rectangular waveguides, and four feed-throughs. The waveguide here is indispensable because it can enable TM_{110} to pass through while stop TM_{010} entering. To be mentioned, the TM_{010} will have a serious interference on beam position measurement if it is not suppressed. This is due to the TM_{010} yielding signal is much stronger than the TM_{110} yielding signal. Figure 2 shows the schematic of the CBPM. Four waveguides are not only connected to the cylindrical cavity but the beam pipe. In fact, the waveguide is independent of the beam pipe at first simulation, but it is difficult to acquire low Q or high bandwidth. Therefore, the final scheme adopts this structure. Moreover, the feed-through is then connected with the waveguide. The magnetic coupling is preferred to attain a higher bandwidth compared with electrical coupling.

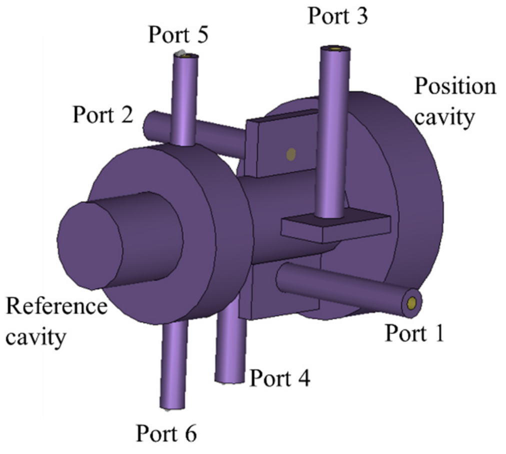

Figure 2: Schematic of the CBPM.

SIMULATION

Wakefield Solver Simulation

To simulate the RF characteristic and output signal response, the Wakefield solver and Time domain solver of CST STUDIO SUITE have been used to perform the simulation. Figure 3 shows the simulation results of the Wakefield solver. It gives the time-domain and frequency-domain output signal of reference cavity and position cavity in a 1mm beam offset. The amplitude of reference cavity signal is about fourfold greater than that of position cavity signal. This also illustrates the importance of waveguide. The frequency spectrum of position cavity signal shows the TM_{010} mode has been strictly rejected. Moreover, the bandwidths of reference cavity signal and position cavity signal are 405 MHz and 372 MHz, respectively. Using MATLAB to fit the time-domain signal, a 0.78 ns decay time constant of reference cavity signal is obtained. And the position cavity's decay time constant is about 0.84 ns. In addition, the bandwidth and decay time constant satisfy:

$$\tau = \frac{1}{BW \cdot \pi}. \tag{1}$$

Here τ is decay time constant and *BW* is bandwidth. In short, the simulation results meet the requirement of the CBPM.

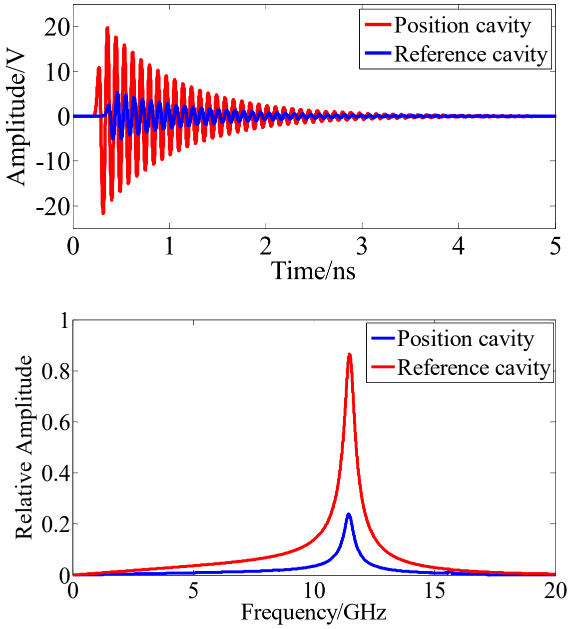

Figure 3: (Color online) Time-domain and frequency-domain RF signals of position cavity and reference cavity. Red and blue line show the signal of reference cavity and xy-position cavity respectively.

Moreover, since there are two same-frequency dipole modes in the position cavity, they can couple to both X- and Y-ports. If a dipole mode coupled to both ports, it is difficult to determine the beam offset direction. To improve the accuracy of direction determining and reduce the crosstalk, it is essential to evaluate the XY-coupling. When an

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electron beam passes through a beam pipe with a 1mm offset in Y-direction, the beam induced output signal from X-port and Y-port can be collected, as shown in Fig. 4.

Ideally, only X-port can output signal. However, in reality, the Y-port can couple out signal because of the crosstalk. The crosstalk level is about -50dB.

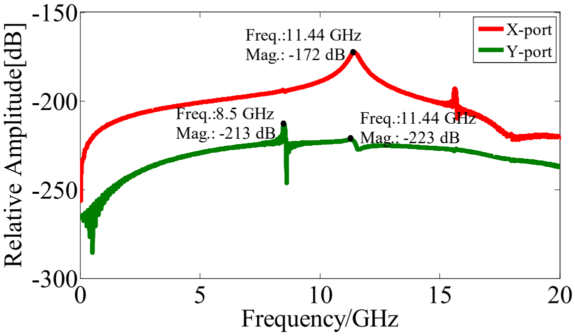

Figure 4: (Color online) Crosstalk evaluation between X- and Y-port.

Furthermore, in order to estimate the linear region of an output signal with regard to the beam offset, a simulation with different beam offset ranging from -1mm to 1mm has been conducted. Figure 5 shows the correlation between the beam offset in y-direction and the output voltage peak. It verifies the linearity between them. In addition, the sensitivity is about 5.32V/mm. Table 3 gives more detailed simulation parameters.

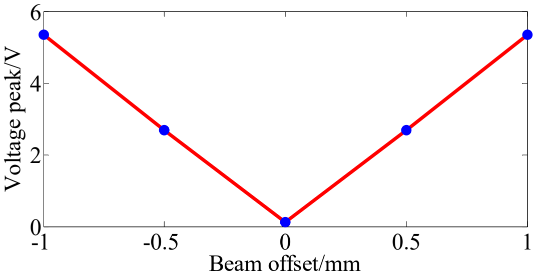

Figure 5: A Correlation between the beam offset and output voltage peak.

Table 3: Simulation Results of the CBPM

Parameter	Reference Cavity	Position Cavity
Frequency/GHz	11.44	11.44
Bandwidth/MHz	405	372
Decay time constant/ns	0.78	0.86
Q_{load}	28	31
V_{peak}	21.6	5.3
XY-Coupling/dB	~	-50
Sensitivity /(V/mm/200pC)	~	5.32

Time Domain Solver Simulation

To further investigate the crosstalk between position cavity and reference cavity and the reflection of each port, S-parameters are calculated using this Time domain solver.

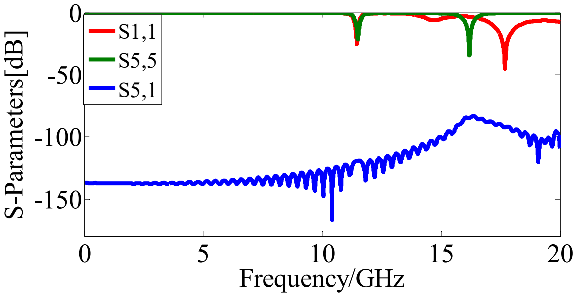

Figure 6: (Color online) S-parameters simulation results.

Figure 6 shows the simulation results of S-parameters. S1,1 and S5,5 access the reflection of port 1 of position cavity and port 5 of reference and they are both about -20 dB at a working frequency. In addition, the crosstalk between reference cavity and position cavity can be evaluated by S5,1. Thus the crosstalk level is about -120dB when the cavities separation is about 20mm. In conclusion, both results meet the demand while the reflection coefficients of the ports has to be reduced via more simulations.

CONCLUSION

In this paper, an X-band high-bandwidth CBPM has been designed so as to achieve a sub-micron beam position measurement. The CBPM consists of a reference cavity and a position cavity. Both cavities work at a frequency of 11.44 GHz and have a high-bandwidth. The simulation was finished using a Gaussian electron bunch equipped with a bunch charge of 200 pC and a 6 mm bunch length. In addition, the simulation results show that the reference cavity features with a 450 MHz bandwidth and a voltage peak of 21.6V. And the position cavity has a 372 MHz bandwidth and a 5.3 V voltage peak. Moreover, the crosstalk level between the two perpendicular ports of position cavity and between the two cavities are very low. In brief, the properties of the CBPM have reach the basic requirement. Further research on the CBPM is ongoing to improve its performance. Related signal acquisition system will also be developed in the near future.

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