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PROTOTYPE DESIGN OF BUNCH ARRIVAL TIME MEASUREMENT SYSTEM BASED ON CAVITY MONITOR FOR SHINE*

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Abstract

The Shanghai high repetition rate XFEL and extreme light facility (SHINE) is planned to be built into one of the most efficient and advanced free-electron laser user facilities over the world to provide a unique tool for kinds of cutting-edge scientific research. The measurement of bunch arrival time is one of the key issues to optimize system performance. This is because the FEL facility relies on the synchronization of electron bunch and seeded lasers. Currently, there are mainly two methods to measure the bunch arrival time: the electro-optical sampling method and the RF cavity-based method. Considering the latter one has a simpler system and lower cost, the method has been adopted by SXFEL. The previous results show that the measurement uncertainty of bunch arrival time has achieved to be 45 fs, which can be further optimized. For SHINE, the bunch arrival time resolution is required to be better than 25 fs@100pC, and 200 fs@10 pC. The RF cavity-based method will also be applied. This paper will present the system prototype design and related simulation results.

INTRODUCTION

To achieve high-intensity and ultra-fast short wavelength radiation, several X-ray FEL facilities have been completed or under construction around the world[1-3]. Shanghai HIgh repetition rate XFEL aNd Extreme light facility (SHINE) is the first hard X-ray FEL light source in China, which constructed began in April of 2018. The total length of the entire device reached 3.1 km. It will build an 8GeV superconducting linear accelerator, 3 undulator lines, 3 beamlines, and 10 experiment stations in phase-I. It can provide the XFEL radiation in the photon energy range of 0.4-25keV. The main parameters are presented in Table 1[4]. The SHINE has many excellent characteristics such as ultra-high brightness (up to 109 times that of the third-generation synchrotron radiation), high repetition frequency (1MHz), femtosecond ultra-fast pulse (pulse width < 100fs), and strong spatial and temporal coherence. Moreover, it also possesses nano-level ultra-high spatial resolution capabilities and femtosecond-level ultrafast time resolution. Therefore, the establishment of the SHINE will provide cutting-edge research methods such as high-resolution imaging, ultra-fast process exploration, and advanced structural analysis for physics, chemistry, life sciences, materials science, energy science, and other disciplines, forming a unique and multidisciplinary interdisciplinary advanced scientific research platform.

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High precision bunch arrival time is one of the key technologies because it is the foundation for the synchronization of electron bunches and seeded lasers. At present, two main detection methods, the electro-optical sampling method and the RF cavity-based method, are widely used. Since the system of the latter method is very simple and economical, it has been successfully applied to SXFEL. The measurement uncertainty of bunch arrival time has reached 45fs[5, 6]. However, DESY conducted a theoretical analysis on this and found that the theoretical limit of this method is 1-3fs[7], and the best result obtained by the LCLS experiment is 13fs[8]. Therefore, we consider further optimizing the system to improve the measurement accuracy. It is hoped that the RF cavity-based method can be applied to the SHINE and achieve 25fs@100pC, 200fs@10pC measurement uncertainty of bunch arrival time.

This paper will focus on the prototype design of the bunch arrival time measurement system (BAM) based on the cavity monitor in the SHINE. The system mainly includes four modules: cavity probe, RF front-end, local oscillator, and signal acquisition system. A detailed introduction and experimental simulation results have been presented.

Table 1: Main Parameters of the SHINE

Parameter	Value
Beam energy	8GeV
Energy spread	0.01%
Photon energy	0.4-25keV
Repetition rate	1MHz
Wavelength	0.05-3.0mm
Pulse length	20-50fs
Bunch Charge	10-300pC

SYSTEM FRAMEWORK

A typical framework of the bunch arrival time system is shown in Figure 1. The main method is to perform digital acquisition after down-converting the signal to an intermediate frequency (IF) signal. A cavity probe used to measure the bunch arrival time is installed at a specific position in the accelerator, and the signal of the probe is led out via a long/short cable as the RF input of the RF front-end. The

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local oscillation (LO) signal obtained by the main oscillator after multiplier/divider is used as the LO input of the RF front-end. Then, the two signals complete signal shaping, filtering, down-conversion, and amplification in the RF front-end. At last, the IF signal will change from an analog signal to a digital signal in the data acquisition system, and complete offline/online processing at the terminal. Therefore, the entire system consists of four major modules: cavity probe, RF front-end, local oscillator, and signal acquisition system.

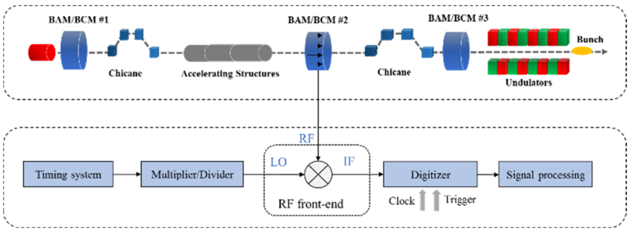

Figure 1: Typical diagram of bunch arrival time system.

Currently, the parameter settings of the BAM prototype refer to the SXFEL. Future beam experiments will also be carried out on this facility. Next, the design and construction of each module will be introduced one by one.

Cavity Probe

When the beam passes through the center of the cavity, the common-mode field is most excited. Therefore, the TM010 mode signal is used as the main mode to extract phase information (bunch arrival time). The electric field center of this mode is symmetrical, and the intensity is almost independent of the transverse position at the paraxial position.

Many parameters need to be considered when designing a phase cavity, such as frequency, damping time, bandwidth, signal amplitude, and load quality factor, etc. For the prototype design, the working frequency of the cavity is temporarily selected at 5771.5MHz. Besides, other parameters of electronic devices need to be considered comprehensively. In short, it is necessary to increase the signal-to-noise ratio of the output signal and reduce the crosstalk of the cavity to the bunch.

The main design of the cavity is done using CST/MAFIA simulation tools, and the structure refers to Spring-8. Considering the high repetition frequency of SHINE, we designed three BAM prototype probes with damping times of 100ns, 200ns, and 300ns, and only one of them will be selected as the final BAM probe after testing. The main technical parameters are shown in Table 2. For detailed design content and test results, please refer to the paper WEPP13 in this conference[9].

Table 2: Main Technical Parameters of Phase Cavity

Parameter	**Cavity 1**	**Cavity 2**	**Cavity 3**
Frequency (MHz)	5771.5	5771.5	5771.5
Damping time (ns)	100	200	300
Bandwidth (MHz)	3.18	1.59	1.06
Q load	1813	3626	5440
Vpeak (V/nC)	11.4	3.9	6.7
Radius (mm)	19.9	19.9	19.9
Length (mm)	3	4	7.5

RF Front-end

The goal of the RF front-end is to achieve signal filtering, amplification, and down-conversion. To reduce the loss of effective signals, it needs to be close to the cavity probe in the tunnel. The design block diagram is shown in Figure 2. Three prototypes with different design techniques have also been delivered to different companies for production. A narrow-band BPF with 5771MHz center frequency and 100MHz bandwidth is used to remove the interference signal and noise of non-primary mode. The system uses cascaded adjustable attenuation and fixed gain amplifiers. The purpose of that is to broaden the dynamic range and reduce the noise figure so that the system can obtain the best performance. Besides, a limiter is added after the attenuator to prevent damage to the amplifier, mixer, and other components in the subsequent circuit. The last-stage analog voltage variable attenuator (VVA) is used to control the attenuation accuracy.

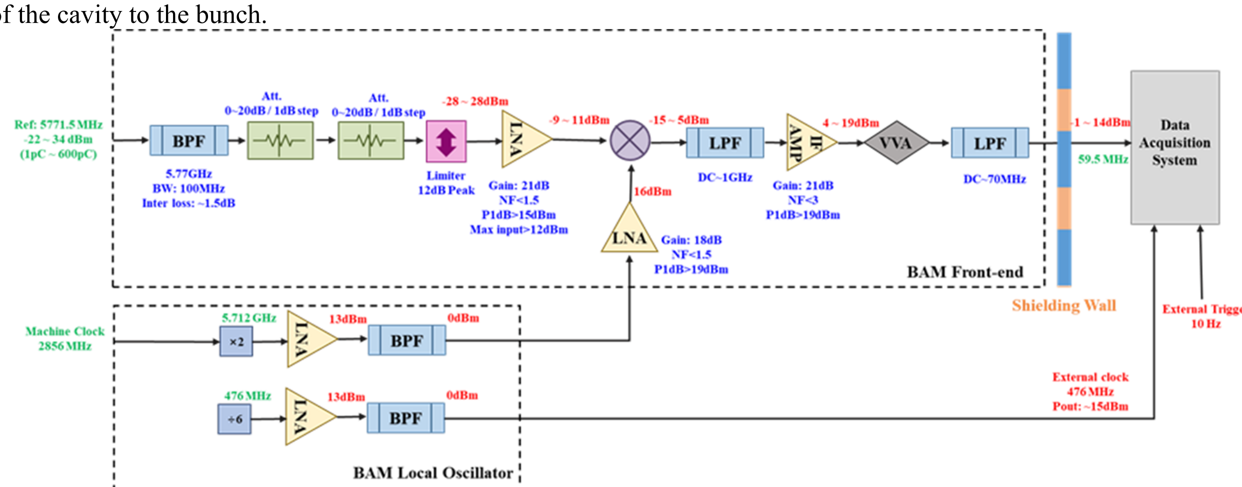

Figure 2: Design block diagram of BAM front-end for SHINE.

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Local Oscillator

The clock frequency of the local oscillator unit mainly refers to 2856MHz of SXFEL. After the multiplier, the LO signal frequency is 5712MHz. Therefore, the IF signal obtained after down-conversion is 59.5MHz. To achieve system integration, the local oscillator module will be combined with the front-end module in the same chassis. The phase jitter of the output local oscillator signal is about 60fs rms @ 10Hz~10MHz when the phase jitter of the 2856MHz input signal is 50fs rms.

The whole system can work in the input power range of -22~34dBm, and the corresponding bunch charge is about 1pC~600pC, which meets the design requirements.

Signal Acquisition System

For signal processing, a dedicated DBPM based on commercial data acquisition boards is under development for SHINE, which is convenient for debugging and application.

At present, the formulation of the plan has been completed, and the modular design of the daughter-mother board structure with the FMC interface will be adopted. FPGA will use the ZYNQ MPSoC system to improve system compactness and stability. The DBPM used for IF signal sampling will select an ADC with 12 bits and 500MHz sampling rate.

SIMULATION RESULTS

To evaluate the influence of different parameters on time resolution, simulations based on CST and MATLAB were carried out.

Assuming that the signal sampling is stable and the initial phase is zero, the main factors that affect the arrival time resolution are signal amplitude, damping time, signal length, and front-end noise. Figure 3 shows the CST simulation results of the cavity probe with a damping time of 100ns. The condition is completed under 100pC bunch charge. After 100MHz BPF filtering, the signal becomes as shown in Figure 4. Some spurious noise and interference signals have been removed. The signal amplitude is about 1.14V (14dBm). Then, the signal is mixed with an ideal LO signal (16dBm) and sampled by a sampling rate of 500MHz. The IF signal result is shown in Figure 5.

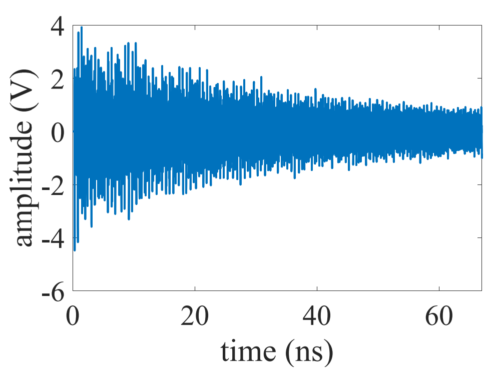

Figure 3: Signal of 100ns damping time by CST.

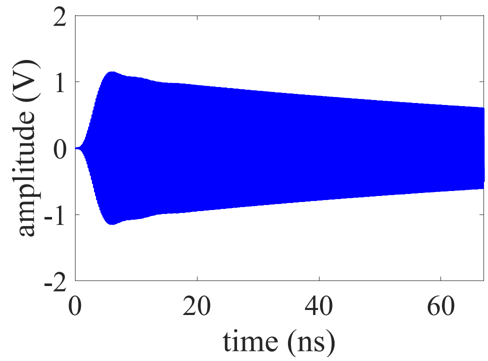

Figure 4: Signal filtered by a 100MHz BPF.

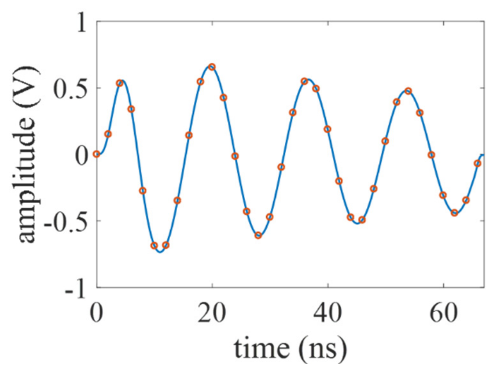

Figure 5: IF signal sampled by 500MHz.

After evaluation, the larger the signal amplitude, the better the phase resolution, as shown in Figure 6. When the signal is not amplified (0.66V), the phase resolution can reach 12fs under 0.1% noise. However, due to the limitation of the ADC acquisition board, when the signal amplitude is close to the ADC full scale (1.1V), the signal needs to be amplified by 1.6 times (4dB). The best phase resolution that this system can achieve is 8fs. This result is only based on an ideal theoretical model.

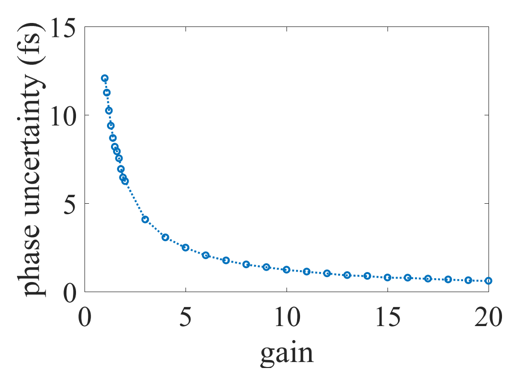

Figure 6: Phase uncertainty of different gain.

CONCLUSIONS

The prototype design of a bunch arrival time measurement system (BAM) based on the cavity monitor was completed. The entire system design and framework were described in detail, including four main modules: cavity probe, RF front-end, local oscillator, and signal acquisition system. The ideal simulation results have been presented.

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When the signal is sampled at full scale, the best phase resolution can reach 8fs, which meets the design requirements.

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