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BUNCH ARRIVAL TIME MEASUREMENT SYSTEM TEST FOR SHINE*

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Abstract

To achieve high-precision synchronization between electron bunches and seeded lasers, a femtosecond resolution bunch arrival time measurement system (BAM) is required at SHINE (Shanghai High repetition rate XFEL aNd Extreme light facility). The bunch signal from a GHz-bandwidth cavity monitor is mixed with a reference signal from the device synchronization clock in the RF front-end. Then, the generated IF signal is collected by the digital acquisition system. In the pre-research stage, four sets of cavity monitors with different frequencies and load quality factors and three sets of analog front-ends with different schemes were performed, but now only one monitor with the attenuation time constant of 200 ns was installed for beam experiment testing. The system can measure the bunch charge, bunch arrival time, and bunch flight time. The first results will be presented in this paper.

INTRODUCTION

Shanghai High repetition rate XFEL aNd Extreme light facility (SHINE) is the first hard X-ray FEL facility in China, which started construction in April 2018 [1]. It will be used to generate brilliant X-rays between 0.4 and 25 keV at pulse repetition rates of up to 1MHz. Some important parameters are shown in Table 1.

Table 1: Main Parameters of the SHINE

Parameter	Value
Beam energy/ GeV	8.0
Bunch charge/ pC	100
Max repetition rate/ MHz	1
Pulse length/ fs	20-50
Photon energy/ keV	0.4-25
Total facility length/ km	3.1

The high-precision synchronization between the electron beam and the seed laser is of great significance to the debugging and operation of the accelerator. The SHINE project has very high requirements for the bunch arrival time measurement. The cavity probe has the characteristics of high resolution and high sensitivity. Therefore, the bunch arrival time monitor (BAM) system based on the radio frequency (RF) resonant cavity method can be used as an auxiliary measurement tool for the beam distribution area and the FEL section. It is hoped to accurately measure each bunch with a resolution better than 25 fs @100 pC.

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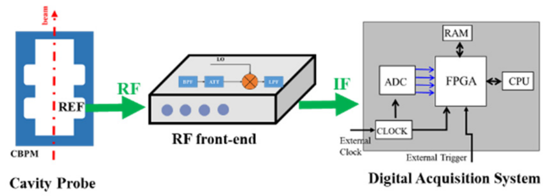

Figure 1: System block diagram.

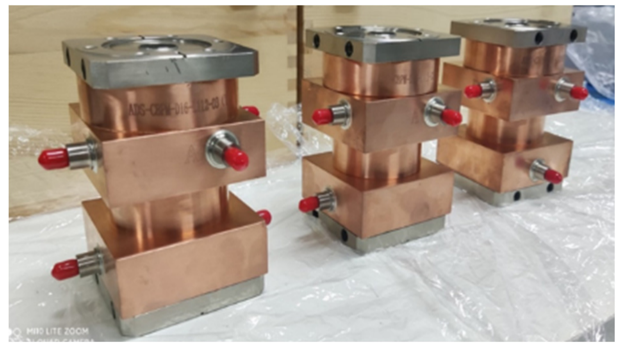

Figure 2: Photos of CBPM 200.

SYSTEM STRUCTURE

The BAM system is mainly composed of three modules, as shown in Fig 1. The cavity probe is used to couple beam electromagnetic fields, including beam charge, beam arrival time, and position information. The function of the RF front-end is to filter, amplify, and down-convert the high-frequency signal into an intermediate frequency (IF) signal. A real-time online digital IQ demodulation algorithm is implemented in FPGA to extract beam position and phase information. All signal processing will be completed in the tunnel.

Cavity Probe

In general, the design of the reference cavity is relatively simple compared to the position cavity. Therefore, the two will be designed jointly, but the reference cavity is mainly used for bunch arrival time measurement. We have designed four sets of cavity probes with different frequencies and load quality factors. The detailed design parameters and test results can be found in Ref [2]. So far, the manufacturing and laboratory testing of three CBPM200 probes have been completed, as shown in Fig.2. The cold tests with a network analyzer have been performed, the results are presented in Table 2. The S-parameter spectrum of the reference cavity is relatively close to the simulation result. The frequency of the three sets of cavities is within ±6 MHz of the design value, and the bandwidth is within ±0.2 MHz of the design value, which meets the design requirements. The three CBPM200 probes have been installed on the beam test platform of the SHINE. The experimental beam mainly comes from the Shanghai soft X-ray FEL (SXFEL) facility.

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Table 2: Cold Test Results of CBPM 200 Reference Cavity

Parameter	Cavity 1	Cavity 2	Cavity 3
Frequency/ GHz	5.769	5.773	5.776
BW/ MHz	1.54	1.49	1.56
Qload	3755	3877	3720
Amplitude/ dB	-37	-47	-32

RF Front-end

The BAM system shares a set of RF front-end with the beam position monitor (BPM) system during the testing process [3, 4]. The basic schematic diagram is shown in Fig. 3, which is made up of filters, adjustable attenuators, amplifiers, and mixers. To get a small noise figure (NF), three prototypes with different architectures were designed. The pictures are shown in Fig. 4. The main differences between them are RF units (coaxial or PCB), dynamic range control (cascade or switching), and gain control (numerical or voltage). The noise floor of the three prototypes has been evaluated, and the results show that prototype #3 is the best.

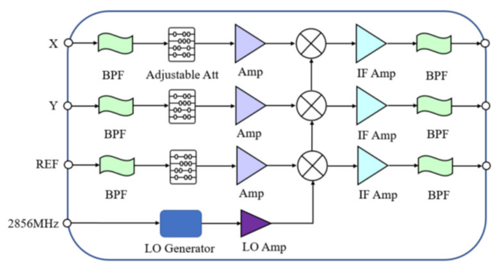

Figure 3: Schematic diagram of the RF front-end.

Figure 4: Photos of RF front-end.

Signal Acquisition System

We are developing a dedicated digital BPM signal processor that can meet the high repetition frequency of 1 MHz, which can realize real-time processing of beam position and phase information extraction in the SHINE. The technical requirements include:

a) The number of channels >3;
b) The analog input bandwidth >60 MHz;
c) The sampling rate >500 MSPS;
d) The ENOB > 9 bits;
e) The SNR >60 dB.

Figure 5 shows the main data acquisition board used for testing at this stage. It includes the zcu102 evaluation board based on Zynq UltraScale and MPSoC from Xilinx and the ADC daughterboard (QT7135) developed by Queentest. The ADC sampling rate is 1GSPS, the analog bandwidth is 1.2 GHz, and the ENOB is better than 10bits, which fully meets the design requirements.

Figure 5: Photo of data acquisition board.

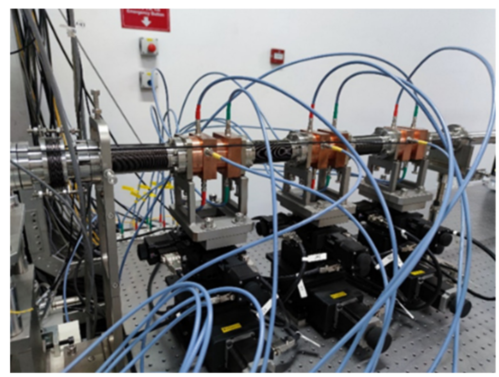

Figure 6: Photo of CBPM200 layout in the tunnel.

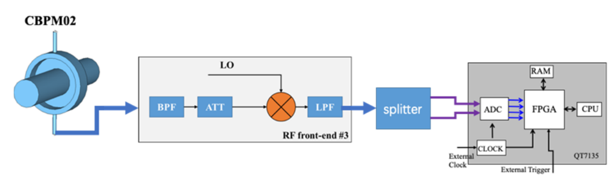

Figure 7: The scheme of evaluating the digitizer (QT7135).

EXPERIMENTS AND RESULTS

Figure 6 shows the layout of three CBPM 200 installed in the tunnel. They were placed on a three-dimensional movable platform. So far, we have conducted three experiments: 1) evaluating the digitizer (QT7135); 2) evaluating the RF front-end; 3) measuring the bunch arrival time and bunch flight time. The following will introduce the experimental design scheme and test results.

Evaluating the Digitizer (QT7135)

What we mainly used in this experiment is CBPM02 and RF front-end #3, the design scheme is shown as in Fig. 7. Only the digitizer was evaluated, so the front end and the probe need to be configured the same. The probe signal was filtered and mixed by the RF front-end to output an IF signal. Then, the IF signal was divided into two parts by a power divider. The data were obtained by four existing digitizers (SP ADQ14AC-4C, DAQ by USTC, QT7135, QT7126). We compared the performance of digitizers by evaluating the signal amplitude extraction uncertainty. The test results are shown in Table 3, indicating the QT7135 is currently the best (see Fig. 8).

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Table 3: Performance Comparison of Different Digitizers

DAQ	SP ADQ14A C-4C	DAQ by USTC	QT7135	QT7126
Resolution/ bits	14	16	16	12
Sampling rate/ MHz	1004.8	833	952	2380
Range/ V	±0.95	±1	±1	±0.6
Uncertainty/ ‰	0.116	0.15	0.071	0.33

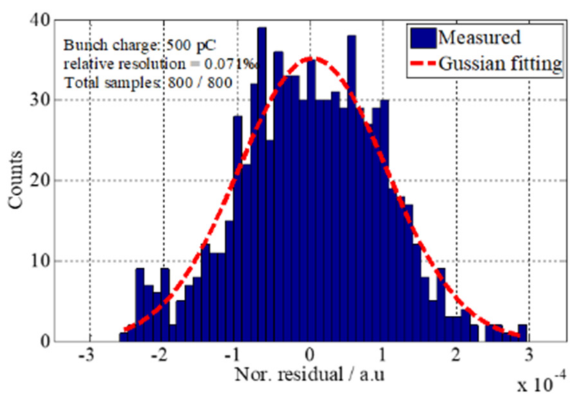

Figure 8: Signal amplitude extraction uncertainty of QT7135.

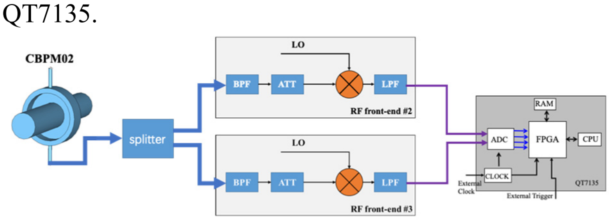

Figure 9: The scheme of evaluating the RF front-end.

Evaluating the RF Front-end

The purpose of this experiment is to evaluate the consistency of different front-ends. The laboratory test results of the noise floor of each front-ends are shown in Table 4. In the beam experiment, the amplitude extraction uncertainty of prototype #2 and prototype #3 is 0.032% (Fig. 10), which is consistent with the lab test results. The design scheme is shown in Fig. 9. The probe signal was directly divided into two parts by a power divider in the tunnel, and the two signals were respectively connected to prototype #2 and prototype #3. The data was sampled by the QT7135.

Table 4: Noise Test Results of RF Front-ends REF Channel

Parameter	Prototype #1	Prototype #2	Prototype #3
Adjustable gain dB/step	1	1	0.25
Crosstalk/ dB	<-61	<-62	<-66
Noise Figure/ %	0.059	0.056	0.037
Local oscillator phase noise / fs	36	20	7

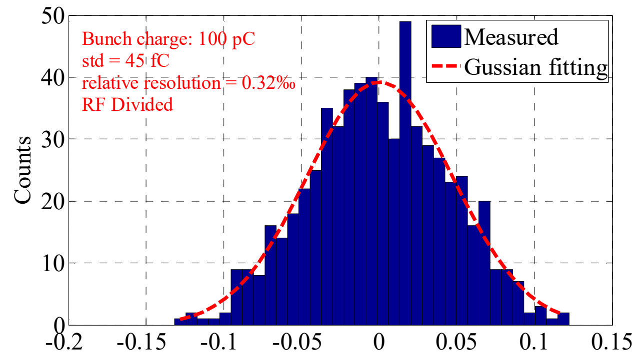

Figure 10: Signal amplitude extraction uncertainty between prototype #2 and prototype #3.

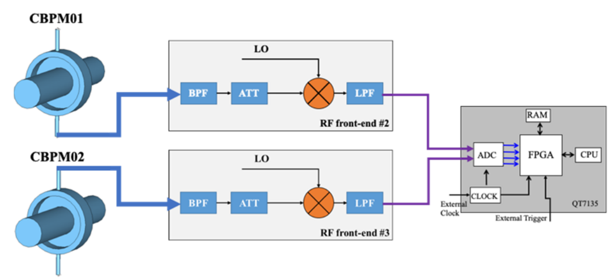

Figure 11: The scheme of measuring the bunch arrival time and bunch flight time.

Measuring the Bunch Arrival Time and Bunch Flight Time

Two adjacent probes can measure the bunch arrival time and bunch flight time. The probes used in this experiment are CBPM01 and CBPM02, the RF front-ends are prototype #2 and prototype #3. The data acquisition system is QT7135. The design scheme is shown in Fig. 11. The output waveforms of the IF signals from the two BAM systems are shown in Fig. 12, which indicates that the main error comes from the inconsistency of the two probes. The phase difference between them represents the bunch flight time, as shown in Fig. 13. After multiple acquisitions, the best resolution can reach 6.9 fs (shown in Fig. 14), which meets the design specifications.

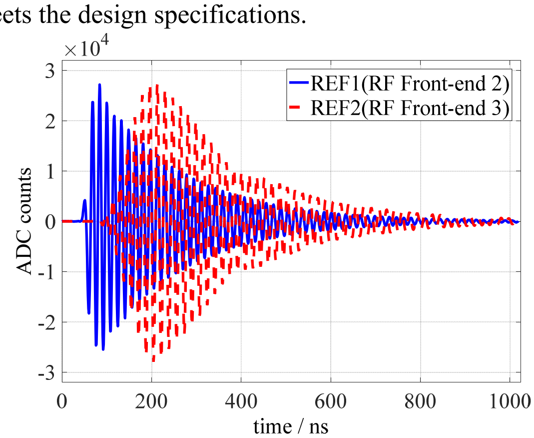

Figure 12: The output waveforms of the IF signals from the two BAM systems.

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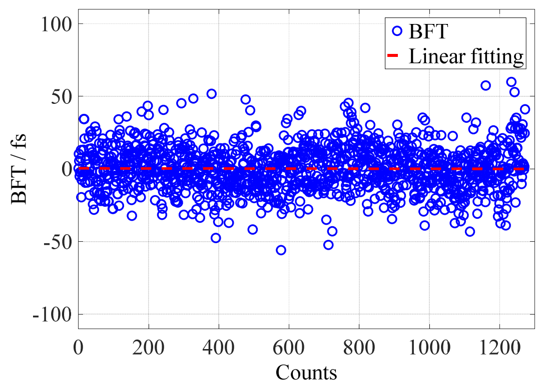

Figure 13: Bunch flight time measurement in scheme #3.

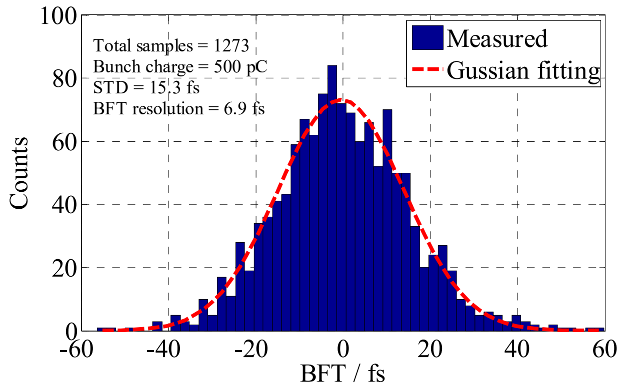

Figure 14: Bunch flight time resolution in scheme #3.

CONCLUSIONS

As an important beam diagnostic tool for FEL facilities, the BAM system is of great significance to beam adjustment and operation. The BAM prototypes for the SHINE have been designed and installed on the test platform. In this article, each sub-module was tested and evaluated, and bunch arrival time and flight time were measured. The best resolution of BFT reaches 6.9 fs, which meets the BAM system design specification of the SHINE.

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