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BEAM INSTRUMENTATION SYSTEM FOR SHANGHAI SOFT X-RAY FEL TEST FACILITY*

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Abstract

Shanghai Soft-Xray FEL (SXFEL) test facility was designed and built to demonstrate EEHG and HGHG schemes and verify key technologies for the future hard x-ray FEL facility (SHINE). After three years commissioning 8.8 nm FEL radiation with peak power of 1 MW had been achieved at the end of 2019. The design, fabrication, commissioning and operation of BI system including stripline-BPM, Cavity-BPM, screen monitor, bunch length monitor, beam arrival monitor, bunch energy monitor, will be introduced in this paper. Several lessons learned during design stage and beam commissioning stage, such as radiation damage of CCDs and step-motors, bad choice of CBPM working frequency, thermal drift of BAM and so on, will be addressed as well.

INTRODUCTION

SXFEL Test Facility (SXFEL-TF) was initiated in 2006 and founded in 2014. Its 0.84GeV linac and undulators were installed through 2016 to 2018, it is for testing the cascaded seeding schemes. The main parameters are listed in Table 1. The SXFEL-TF commissioning has completed this year, and the SXFEL user facility (SXFEL-UF) is under construction. The layout of SXFEL-TF and SXFEL-UF are shown in Figure 1.

Table 1: SXFEL-TF Parameters

Parameter	**Value**
Total length	293m
Electron energy	0.84 GeV
Bunch charge	0.5 nC
Repetition rate	10 Hz
FEL output	8.8 nm
FEL scheme	HGHG/EEHG
FEL pulse	100-200 fs
FEL power	>100 MW

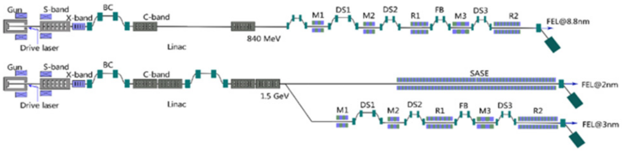

Figure 1: Layout of SXFEL-TF (top) and SXFEL-UF (bottom).

In order to maintain high FEL gain, high performance beam instrumentation system is required for the SXFEL-TF. Measured beam parameters including bunch charge, beam position (BPM), beam profile, beam arrival time (BAM) and bunch length (BLM). Table 2 lists the beam diagnostic devices included and the required resolution.

Table 2: Requirements of SXFEL-TF Diagnostic System

	Quantity	Resolution
Bunch charge	7	1%
Beam position (injector and linac)	28	10μm
Beam position (undulator)	17	1μm
Beam profile	56	20μm
Arrival time	4	100fs
Bunch length (CSR)	1	100fs
Bunch length(deflector)	1	100fs

The system control and data acquisition are based on the EPICS platform, which enables bunch-by-bunch measurement.[1]

BEAM INSTRUMENTATION SYSTEM DESIGN AND PERFORMANCE

Bunch Charge Measurement

Integrated current transformers (ICT) from Bergoz are adopted to monitor the bunch charge along the accelerator. Instead of using analog integrator BCM-IHR-E from Bergoz and a digitizer to sample the bunch charge result, we using an oscilloscope to sample the signal from ICT directly and perform the integral calculation in the digital zone. The ADC of the oscilloscope is 10 bits, bandwidth is 600 MHz, and maximum sampling rate is 5GSPS. An embedded EPICS soft-IOC has been developed on the oscilloscope to get the sampled data and calculate the charge.

One of the advantages of this solution is avoiding the interference of noise signal to the analog circuit. Another advantage is that digital signal processing algorithms can be

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applied in the oscilloscope to improve the measurement performance. For example, Fig. 2(top) is the output signal of ICT on linac coupling a high frequency noise signal. This is hard to find and hard to remove in the traditional solution. However, the noise signal is displayed on the oscilloscope directly and can be removed perfectly by applying PCA algorithm in the soft-IOC(Fig. 2 (bottom)).

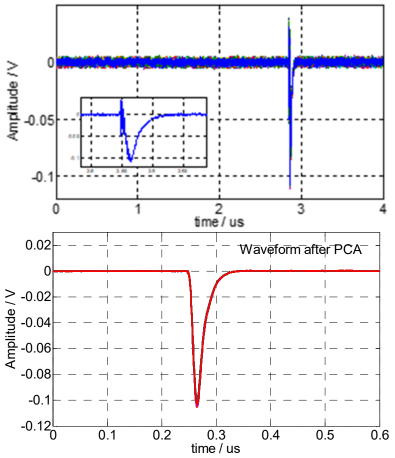

Figure 2: PCA algorithm applied on oscilloscope.

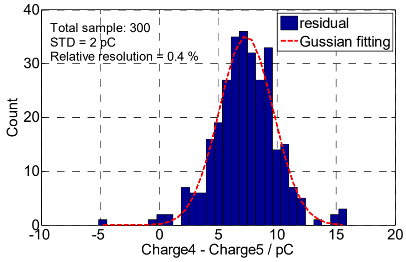

Figure 3: Bunch charge measurement resolution evaluation with PCA.

The system relative resolution is 0.7%, and improved to 0.4% after applying PCA algorithm (Fig. 3). This is better than the 1.0% requirement.

Beam Position Measurement

Accurate beam trajectory measurement and control are the foundation of XFEL success radiation. There have two different types of transverse BPM monitors on the XFEL. Stripline BPMs are applied in the injector and linac section. The electrode length is 150mm, and the stripline BPM total length is 250mm. The electrode K=5.24mm. Figure 4 is the design of the BPM.

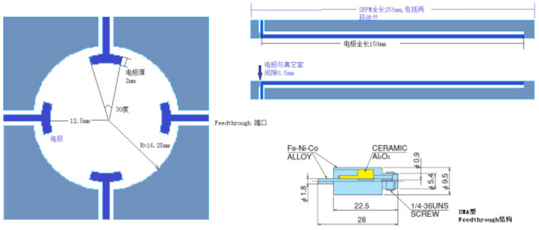

Figure 4: Stripline BPM design.

The strongest frequency of the stripline output RF signal is 500MHz. The RF signals are fed into an in-situ developed Digital BPM signal processor (DBPM) directly. RF signals firstly passing through a serial of conditioning components, including 500MHz IF, 20MHz BW Band Pass Filters (BPF), Low Pass Filters (LPF), amplifiers and 31dB configurable attenuator, then sampled by 16bits, 125MSPS ADCs on the DBPM[2]. The output signal amplitude of each pick-up is calculated by implementing $\sqrt{\sum_{i=1}^{N} {x_i}^2}$ calculation in the FPGA on the DBPM, x_i is the sampled N points BPM signal. Then Δ/Σ algorithm is applied to get beam position. An EPICS IOC is developed on the ARM, which communicate with FPGA through PCIE bus. Figure 5 shows the BPM pickup installed in tunnel (up left), the DBPM in cabinet (up right) and DBPM OPI control panel(bottom).

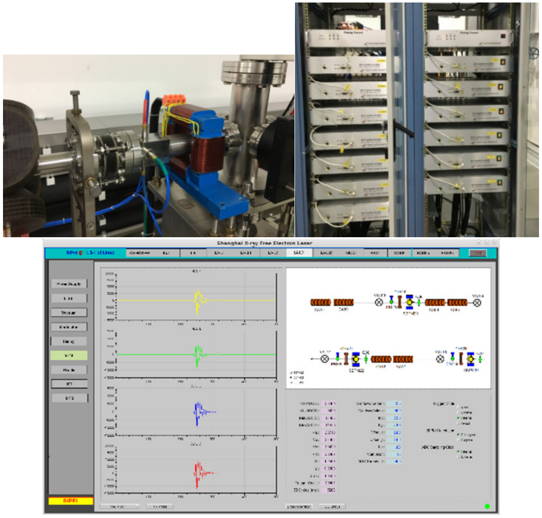

Figure 5: Stripline BPM and DBPM.

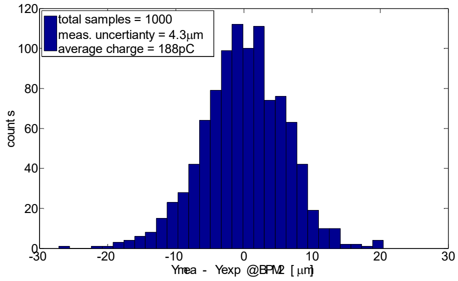

Figure 6: Stripline BPM system performance.

The stripline BPM system performance is evaluated by applying three adjacent BPM in a straight section. Figure 6 shows the resolution is 4.3μm@188pC, which is much better than the required 10μm @500pC.

Cavity BPMs are used in the undulator section to meet the 1μm high resolution requirement. The cavity BPM structure refers to the SCALA design. Table 3 shows the frequency and loaded Q value of each cavity.

Table 3: Cavity BPM Parameters

Cavity	Frequency	Loaded Q
Reference	4693 ± 3MHz	2250 +-10%
Horizontal	4681 ±3MHz	4500 +-10%
Vertical	4688 ± 3MHz	4500 +-10%

There is no tuner for the cavities, and the frequency of the three cavities are separated to avoid the possible cross-talk between cavities.

The same narrow band DBPM is applied for the cavity BPM signal DAQ because of time rush and lack of experience. The sampling clock is 119MHz synchronized with machine. Then a complex analog LO signal generator is designed to down convert the output RF signals of the three cavities to around 500MHz. Figure 7 shows the cavity BPM pickup and pre-amplifier installed in tunnel(left) and the LO, down-mixing front-end and the DBPM installed in cabinet (right).

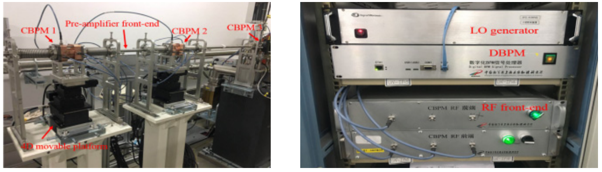

Figure 7: Cavity BPM and the electronics.

FFT algorithm is applied in the FPGA to get the amplitude and phase of each cavity signal. Phase difference calculation and direction judgement algorithm is developed in FPGA, and each BPM has been calibrated by beam experiment.

Figure 8 shows the three adjacent BPM evaluation test result. The resolution is 880nm@±800µm, which is better than the required 1µm@±500µm.

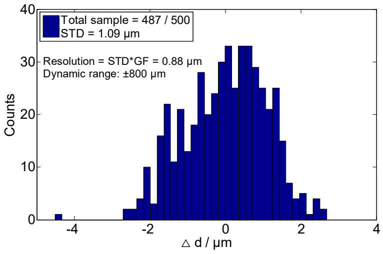

Figure 8: Cavity BPM system performance.

Beam Profile Measurement[3]

An Ce:YAG/OTR and CCD based beam profile system is designed for the measurement of beam size and emittance on SXFEL-TF. By using GigE Vision bus cameras (JAI and Basler) and network-based step-servo motors (MOONS SSM24Q-3RG), image data and motors can be accessed via TCP/IP protocol. IOCs deployed on servers (IBM System x3550 series) are responsible for the image processing and system control. Figure 9 is the system scheme. This DAQ scheme simplifies the system structure, also used on the measurement of beam energy and bunch length.

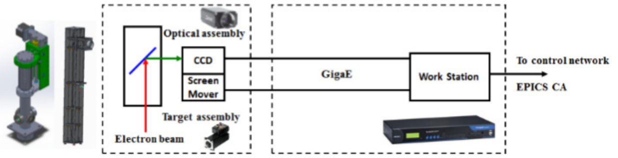

Figure 9: Beam profile measurement system.

The image horizontal and vertical RMS resolution is 13µm@41µm, 15µm@50µm respectively.

Beam Arrival Time Measurement[4]

There have four RF cavity based beam arrival time (BAM) measurement systems deployed on the SXFEL-TF. The BAM pickup consists of two monopole cavities. Table 4 lists the parameters.

Table 4: BAM Pickup Parameters

Parameters	Cavity #1	Cavity #2
Frequency/MHz	4685	4720
Bandwidth/MHz	1	1
Decay time/ns	318	318
Q_{load}	4671	4716

The BAM cavity #1 output signal is down converted to around 500MHz by mixing with synchronized 4184.5MHz LO signal. The down converted IF signal is sampled and processed by the narrow band DBPM as cavity BPM solution.

Figure 10 shows the best beam test uncertainty of the system is 45 fs over 20 minutes.

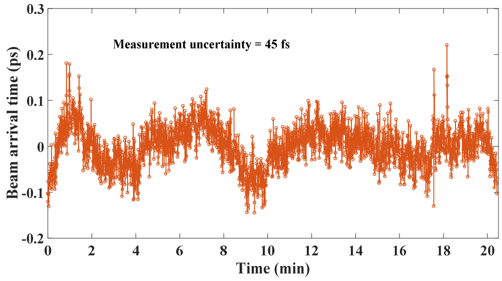

Figure 10: BAM system performance.

Time-of-Flight (ToF) Measurement

Two dual-cavity BAMs are installed at the upstream and downstream ends of chicane section respectively to measure the TOF in the chicane section. Figure 11 is the system diagram. The output signals from cavity#1 of BAM#1 and cavity#2 of BAM#2 are mixed together and down converted to about 35M, then sampled with a wide bandwidth DBPM to get the TOF. When the electron bunch passes through the chicane structure, the difference in beam energy will be converted into different beam paths, resulting in different beam flight times. This design can be used to measure the beam energy.

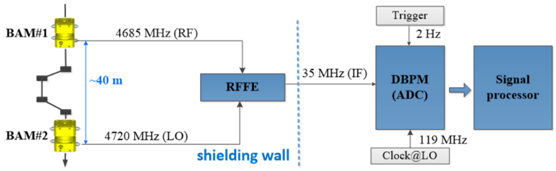

Figure 11: TOF system.

Figure 12 shows the best result of measurement uncertainty in is 38 fs and 53 fs in 20 minutes and 18 hours respectively.

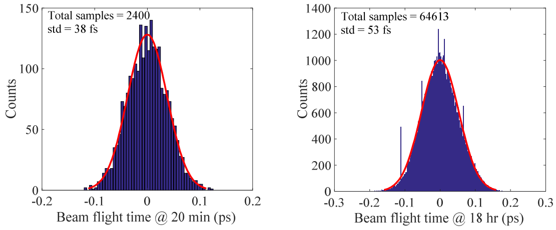

Figure 12: TOF performance.

Bunch Length Measurement

In order to measure the bunch length, a system based on X-band radio-frequency deflector system is established in the end of undulator. Table 5 lists the design parameters.

Table 5: Deflector Parameters

Parameters	Value
Frequency	11.424GHz
Phase advance	120Deg.
Maximum power	20MW
Transverse voltage	0~30MV
Total length	0.6m
Filling time	60ns
Repetition frequency	50Hz
Parameters	Value

The deflector makes the single FEL pulse reconstruction possible, including FEL profile, FEL pulse energy, relative timing jitter, correlation between two stages FEL pulse.

A non-destructive bunch length monitor using Coherent Synchrotron Radiation (CSR) is installed after linac chicane section to get relative bunch length. Figure 13 shows the system diagram.

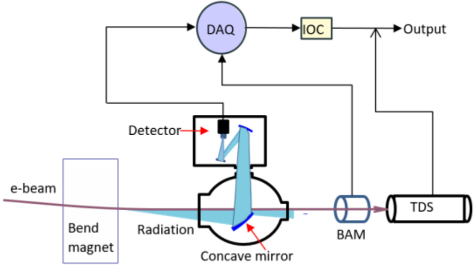

Figure 13: CSR bunch length measurement system.

Pyroelectric detector from QMC INSTRUMENTS is used as signal detector. BAM cavity output signal is used to monitor the bunch charge and normalize the pyroelectric output signal. The DAQ is NI PXI-5122, it consists of 2 channels, 14 bits, 100MSPS ADCs. The deflector is used to calibrate the system. Figure 14 is the calibration between CSR and deflector. The test results show the resolution is better than 30fs.

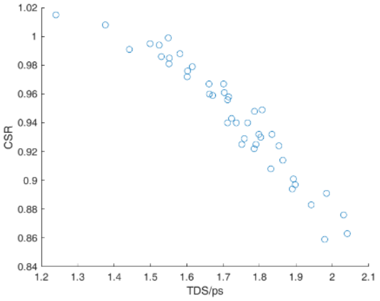

Figure 14: Bunch length calibration between CSR and deflector.

SUMMARY

The beam diagnostic system in SXFEL-TF has been introduced briefly in this paper. Each subsystem meets the performance requirement, thus assisting FEL commissioning to the designed radiation successfully. However, some lessons are learned on SXFEL-TF. For example, because of the frequency of the cavity BPM's three cavities is inconsistent and the DBPM is narrow band, the two restrictions make the RF front-end module complex. CCD lack of radiation protection and there have high dose radiation during commissioning, resulting in a lot of CCDs are damaged at that time. The lessons learned from SXFEL-TF will help to improve the BI system in SXFEL-UF.

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