BEAM DIAGNOSTICS SYSTEM FOR HALF STORAGE RING

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Abstract

The Hefei Advanced Light Facility (HALF) is a fourth-generation, low-energy diffraction-limited synchrotron light source currently under construction. Its storage ring has an energy of 2.2 GeV, a circumference of 480 meters, and an emittance of 86 pm·rad. To ensure the smooth commissioning of HALF to meet its design specifications and to fully exploit the operational potential of this facility, it is necessary to develop a comprehensive beam diagnostic system with high temporal and spatial resolution. This paper will introduce the overall structure and design of the HALF storage ring beam diagnostics system, focusing on the latest development progress of the high-resolution, high-stability beam orbit measurement and feedback system, and the bunch-by-bunch multi-parameter diagnostic system.

SYSTEM OVERVIEW

The Beam Instrumentation system is one of the critical subsystems of the Hefei Advanced Light Facility (HALF) storage ring. It will play a pivotal role during the key stages of the facility, including commissioning, acceptance testing, and user operation. The system is required to provide precise and comprehensive beam parameter information for evaluating machine operational performance, while also offering real-time data and diagnostic tools for accelerator physicists, thereby comprehensively ensuring the stable and efficient operation of the accelerator. To meet these requirements, the BI system must be capable of real-time measurement of key parameters, including beam position, beam current, lifetime, filling pattern, tune, beam profile/emittance, bunch length, and beam loss. Furthermore, to effectively guarantee the stability of the orbit and the beam, the system must incorporate bunch-by-bunch feedback and fast orbit feedback subsystems, laying a solid foundation for the high-quality operation of the HALF storage ring.

Table 1: Specification for HALF Ring BI system

Measurement	Specification	Quantity
Beam position	50 nm @ 10Hz 200 nm @ 20 kHz 1 μm @ TBT	240
Average current	2 μA @ 1 Hz	2
Bunch charge	0.05 % @ 1 kHz	1
Beam profile	2 μm / 10 μm	3
Bunch length	2 ps	1
Tune monitor	0.0001	1
FOFB	BW 500 Hz	1
MBFB	BW 250 MHz	1

Table 1 shows the primary specification of the all subsystems. Figure 1 shows the layout of all diagnostics sensors around the entire ring.

The layout of beam instrumentation probes around the entire ring is shown in the figure below:

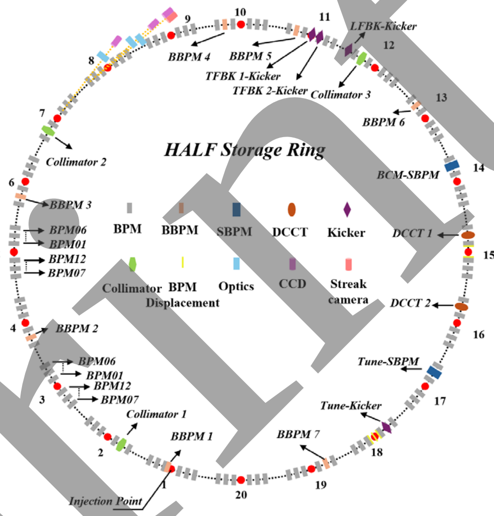

Figure 1: The layout of beam instrumentation probes around the entire ring.

BEAM POSITION MONITOR

Beam orbit measurement will be done at a total of 240 monitoring points across 20 units around the ring. It uses small-diameter (6 mm) button electrodes as beam probes and is equipped with a digital beam signal processor. Under the condition of a beam current higher than 100 mA, the resolution of the closed-orbit data (with a sampling frequency of 10 Hz) must be better than 50 nm; the resolution of the fast feedback data (with a sampling frequency of 20 kHz) must be better than 200 nm; and the resolution of the turn-by-turn data must be better than 1 μm [1].

To meet the above requirements, a custom designed DBPM processor using dual pilot tones and high oversampling ratio technologies have been developed tested in the SSRF ring. Figure 2 shows the photo of prototype.

Figure 2: Prototype of DBPM processor for HALF storage ring.

The beam experimental results demonstrate that the resolution of this prototype is better than 10 nm for SA, better than 80 nm for FA, and better than 400 nm for TBT. Figure 3 shows the TBT data (left) and coresponding FFT

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(right) acquired during the beam injection process, proving that the measurement results of this prototype can accurately reflect the actual physical processes and fully meet the requirements for beam tuning and operation at HALF.

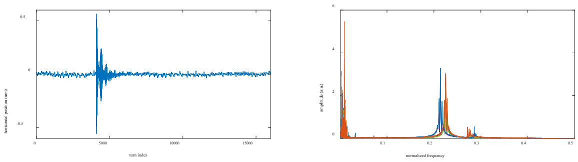

Figure 3: TBT data (left) and corresponding FFT (right) acquired during the beam injection.

Two additional sets of button electrodes are installed in the injection straight section, paired with a dedicated bunch-by-bunch processor. This configuration enables the measurement of the real-time 3D position, bunch length, and charge of each bunch. It provides more powerful diagnostic tools for the monitoring and analysis of the injection transient process and beam instabilities, and offers more diagnostic information for optimizing injection accumulation during the first day of storage ring tuning and the early stages.

BEAM CURRENT MONITOR

Average current monitor adopts Bergoz's in-flange DC Current Transformer (DCCT) probes, equipped with a customized high-speed (with a maximum sampling rate of 2 MHz) and high-precision (24-bits) ADC. It can simultaneously achieve ultra-high-precision (0.6 µA RMS) slow measurement (1 Hz sampling rate) of the average beam current, as well as high-precision (2 µA RMS) high-speed measurement (300 Hz sampling rate). Thanks to the high beam current sampling rate, the accurate calculation of beam lifetime can be completed within 1 second.

Bunch charge monitor uses short-strip electrodes combined with a fast digitizer card (1 GHz sampling rate, two times RF freqeuncy). The system employs a two-point phase-separated sampling compensation technology to achieve precise extraction of signal amplitude, completing the measurement of the charge per bunch and the bunch-by-bunch lifetime. The relative resolution of the bunch-by-bunch charge is required to be better than 0.05% [2].

Figure 4: Customized beam current signal processor equipped with a high-speed (1 GHz sampling rate) ADC and a high-precision (24-bits) ADC.

Both the high-precision ADC card and the high-speed ADC card adopt the FMC format. Once integrated into the FPGA motherboard (XCZU19EG-2FFVC1760), they form a dedicated beam current signal processor. The online calibration and lifetime calculation of the bunch-by-bunch charge measurement subsystem can be completed in real time within the FPGA. A physical photograph of the processor is shown in Figure 4.

TUNE MONITOR

Two methods for tune measurement are selected, including the frequency sweep method and the harmonic analysis method based on BPM turn-by-turn position data. It publishes tune measurement results in real time to meet measurement requirements under different scenarios. During the beam injection cycle, turn-by-turn position data from the BPMs is collected for harmonic analysis. Real-time tune measurement is achieved by locating the resonance peak frequency of the residual betatron oscillation. This scheme relies on the position measurement data of the existing BPM probes and can quickly obtain tune values during injection without additional complex hardware configuration. For tune measurement during non-injection cycles, dedicated strip electrodes and a differential RF front-end are used to monitor the residual oscillation signal of the beam position, achieving high-sensitivity, non-intrusive real-time tune measurement. This scheme avoids interference with the beam. The resolution of both measurement schemes must be less than 0.0001.

BEAM DIAGNOSTIC BEAMLINES

X-ray and visible synchrotron light signals are extracted from two different source points and combined with various high-precision imaging and measurement devices to achieve detailed diagnosis of beam parameters.

The first diagnostic beamline is the X-ray focusing imaging diagnostic subsystem. It uses an X-ray focusing imaging system based on Fresnel zone plates, with a resolution better than 2 µm. It enables high-precision X-ray imaging of the beam profile and accurate measurement of the profile size, and is mainly used during the machine acceptance test phase and the machine study phase. Figure 5 shows the side view of Xray imaging beamline.

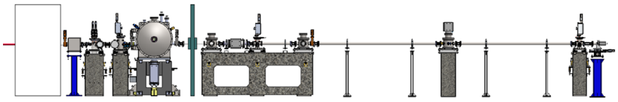

Figure 5: Side view of Xray focusing imaging system based on Fresnel zone plates.

The second diagnostic beamline includes three subsystems: an X-ray pinhole camera, a visible light spatial interferometer, and a visible light streak camera. The X-ray pinhole camera is used to quickly obtain online real-time dynamic changes in the beam profile distribution, and is mainly used as a tool for beam tuning and facility operational status monitoring. The visible light imaging system and the visible light spatial interferometer feature a simple structure and are easy to debug. They are mainly used in the early stage of facility beam tuning as convenient tools for quick monitoring and diagnosis of the beam's transverse distribution, ensuring that there are sufficient observation means during beam tuning. The streak camera is mainly used for the precise measurement of bunch length and the observation and analysis of longitudinal beam instabilities. It is required to have a time resolution better than 2 ps, enabling it to accurately capture the longitudinal distribution characteristics of the bunches. Figure 6 shows the configuration of visible light diagnostics beamline.

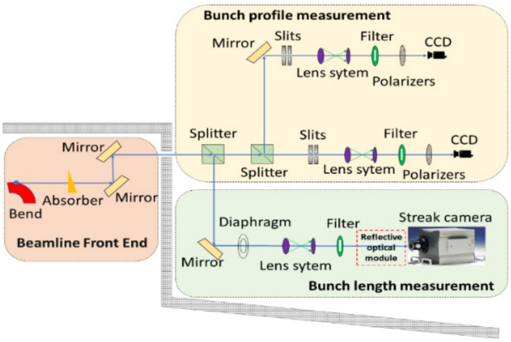

Figure 6: Layout of visible light diagnostics beamline.

BUNCH-BY-BUNCH FEEDBACK

This subsystem uses button electrodes to pick up beam signals. A customized home-made feedback controller is used to achieve precise extraction of the bunch-by-bunch transverse and longitudinal oscillation amplitudes and calculate the feedback control values. A broadband amplifier amplifies the feedback signals. Two stripline kickers serve as the transverse feedback actuator, and a cavity kicker serves as the longitudinal feedback actuator, forming a complete feedback link to accurately address transverse and longitudinal beam instabilities. The customized bunch-by-bunch feedback controller must meet the following core specifications: a feedback bandwidth of larger than 250 MHz to ensure a fast feedback response; a transverse damping time of better than 0.1 ms, and a longitudinal damping time of better than 1 ms, to effectively suppress beam instabilities and guarantee stable beam operation. Figure 7 shows the architecture of MBFB system [3].

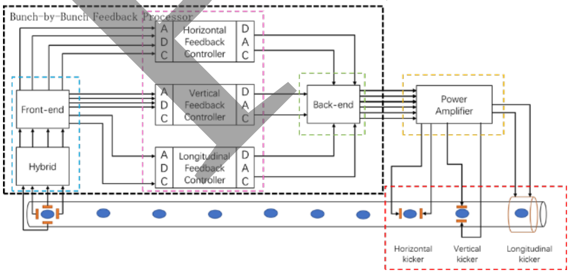

Figure 7: Architecture of MBFB system.

FAST ORBIT FEEDBACK

Among the 240 BPMs used for closed-orbit measurement around the ring, 80 high-stability ID BPM probes located at both ends of the straight sections are selected exclusively for fast orbit feedback to ensure real-time orbit stability. A distributed fast orbit feedback system is constructed with 10 customized self-developed feedback controllers based on FPGA and SFP communication interfaces as the core nodes. Each feedback controller connects 8 BPM signal processors from two standard units and 16 fast correction power supplies (8 for horizontal and 8 for vertical) in a star topology. The feedback controllers are interconnected via a redundant dual-ring topology to form a dedicated network for data exchange around the ring. All orbit correction values are independently calculated within the feedback controllers. The total delay of the entire system is less than 160 μs, and the feedback data refresh rate is 20 kHz, ensuring an effective feedback bandwidth of no less than 500 Hz. Figure 8 shows the archtecture of fast orbit feedback system [4].

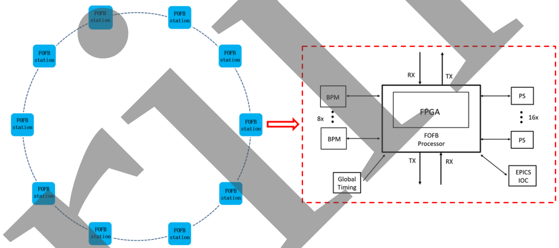

Figure 8: Architecture of fast orbit feedback system.

BEAM LOSS MONITOR

Eight sets of optical fiber probes are deployed to achieve rapid detection of beam loss. Optical fiber probes have advantages such as fast response speed and strong anti-interference capability. They can timely capture beam loss signals, providing strong support for the early warning and troubleshooting of beam loss, and ensuring the safe operation of the storage ring.

CONCLUSION

All engineering designs for the HALF storage ring beam diagnostics system have been completed, and batch manufacturing of the equipment has commenced. The installation and commissioning are scheduled to be finished by the end of 2026, paving the way for the HALF facility to begin beam tuning as soon as possible.

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