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Development of magnetic field measurement system for SHINE superconducting undulator

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Abstract. The Shanghai High Repetition Rate XFEL and Extreme Light Facility (SHINE), under construction, will use 40 vacuums superconducting undulators (SCU) to generate linearly polarized free-electron lasers. Its magnetic field measurement system relies on the Hall probe method, featuring components like a Hall probe sledge, laser positioning, vacuum chambers, motion control, and data acquisition. At 4K, as the sledge moves, the system performs precise magnetic measurements. The paper discusses the magnetic field measurement system, the low-temperature calibration of the Hall probe and recent experimental data.

1. Introduction

The Shanghai High Repetition Rate XFEL and Extreme Light Facility represents a significant advancement in the generation of linearly polarized free-electron lasers, which are crucial for various scientific applications. SHINE is under construction and aims at generating X-rays between 0.4 and 25 keV with three FEL beamlines at repetition rates of up to 1 MHz [1]. The FEL-III is designed to cover the photon energy range of 10–25 keV, in which the SCU with a 16 mm undulator period, 1.583 T maximum magnetic peak field, and a 4 m segment length.

A critical aspect of SCU's development is the precise measurement of magnetic field to ensure optimal performance of the undulators.

2. Magnetic field measurement system

Various magnetic field measurement techniques have been developed and applied to different scales of SCUs. Hall probe scanning is the most mature technique for the local field characterization of both PMUs and SCUs [2]. In response to the inability of existing magnetic field measurement systems, such as those at APS and ANKA, to accommodate SCU with a length of up to 4 meters and a gap of 4 mm, we have developed a state-of-the-art magnetic field measurement system specifically for the SCU at SHINE.

The magnetic field measurement system of the SHINE SCU, as shown in Figure 1, consists of a Hall probe sledge, a traction mechanism, a laser positioning system [3], and a data acquisition system. The sledge, equipped with Hall probes, is connected to actuators on both sides of the

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cryostat via a titanium wire. Under the traction control of these actuators, the sledge conducts measurements of the magnetic field along the gap. Additionally, the laser positioning system is installed on one side of the undulator to measure the trajectory of the sledge during its movement and to provide a trigger signal for the data acquisition system, enabling on-the-fly measurements.

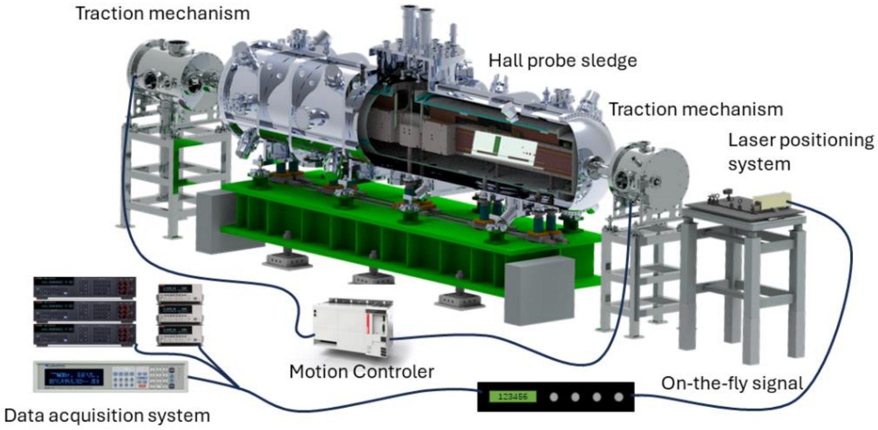

Figure 1. The magnetic field measurement system of the SHINE SCU.

2.1 Hall probes sledge

We laid a cylindrical aluminium wire as a rail with a diameter of 3.5 mm on the base of the gap to form a continuous surface. The circular cross-section of the rail minimizes the heat generated by the sliding friction between the sledge and the rail, thereby reducing the heat transferred to the magnet during the measurement. As the sledge is in direct contact with the surface of the aluminium wire and moves by sliding, we selected G10 as the material for the sledge.

As shown in figure 2, the sledge has a length of 120 mm, a width of 46 mm, and a thickness of 3.6 mm. On the back of the sledge there is a retroreflector with the diameter of 3 mm which are used to position the sledge [3]. Near the position of the retroreflector, three Hall probes and a temperature probe are installed. Two of the Hall probes are used to measure the horizontal magnetic field, while the other measures the vertical magnetic field. The temperature probe is used to monitor the temperature profile of the sledge during the measurement process.

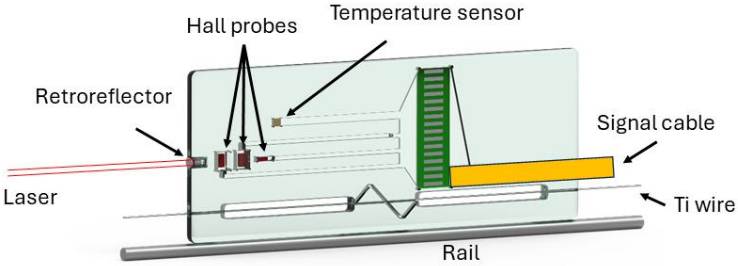

Figure 2. The layout of the Hall probe sledge.

2.2 Traction mechanism

In conventional magnetic field measurements of undulators, Hall probes are often installed on the mechanical arm of a measurement platform that can move along a highly linear marble platform to scan the magnetic field. For long SCUs with narrow gaps, the traction mechanism for the Hall probes need to operate in a vacuum and cryogenic environment. However, deformation of the precision rail at low temperatures and the significantly increased machining cost of longer rail make this system difficult to apply to long-range measurements. To ensure the smooth movement of the sledge in long-range narrow-gap magnetic field measurements, it is necessary to develop an entirely new traction mechanism.

The traction mechanism of the sledge is shown in Figure 3. The sledge with a thickness of 3.6 mm is placed in the gap, where an aluminium wire with a diameter of 3.5 mm is laid on the base of the gap. The sledge is connected via titanium wires to actuators located within vacuum chambers at both ends.

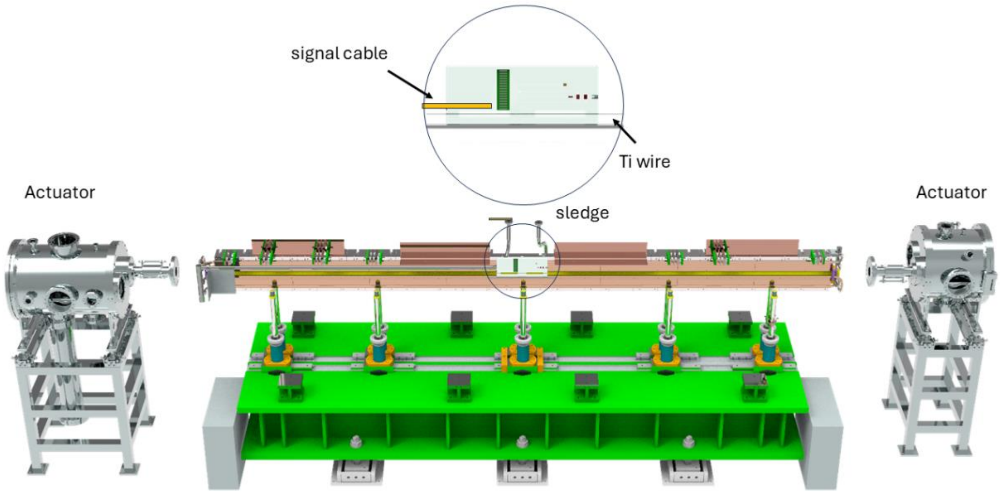

Figure 3. The layout of the traction mechanism.

As the sledge moves during the measurement process, one end of the cable needs to move along with it. The cable inside the vacuum chamber must be 6 meters long. To ensure the stable operation of the measurements, a cable pulling-pushing mechanism has been designed. This mechanism facilitates smooth and reliable cable movement, preventing entanglements or disruptions during measurements. As shown in Figure 4, the cable is wound sequentially around a set of pulleys. When the sledge moves from left to right, the movable pulleys rise, allowing the cable to extend within the gap. Conversely, when the sledge moves to the left, the movable pulleys descend, neatly collecting the cable within the vertical vacuum chamber.

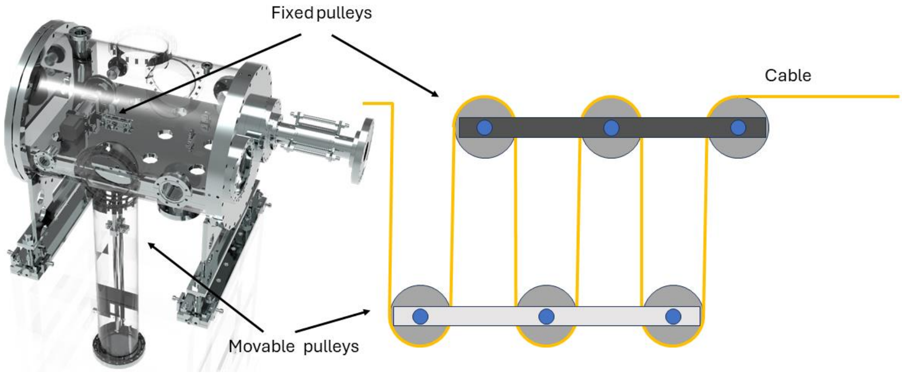

Figure 4. The cable pulling-pushing mechanism.

3. Low-Temperature Calibration of hall probes

These Hall probes will experience temperatures ranging from 4.2 K to 50 K as they traverse the undulator gap, making it crucial to address the temperature-dependent variations in their sensitivity and linearity. As shown in Figure 5, a cryogenic calibration system has been designed for low-temperature calibration of hall probes, which enables accurate calibration within a temperature range of 2.8 K to 300 K and a magnetic field range of ±1.9 T. The standard magnet with a large gap ensures a sufficiently wide magnetic good field region for calibration, while the adjustment mechanism of the magnet and Hall probe guarantees the orthogonality of the magnetic field and the Hall probe. The correction process of the calibration data effectively mitigates the influence of temperature instability and unrepeatability of the magnetic field on calibration results.

The calibration results highlight several trends [4]:

1. The sensitivity of the Hall probe increases with decreasing temperature above 80 K, with the rate of increase gradually decreasing from 3.0×10^{-4} /K to 0 as the temperature decreases from 300 K to 80 K. This trend persists, with only a minimal change in sensitivity below 80 K.

2. The nonlinearity becomes apparent when the magnetic field exceeds 0.5 T, reaching approximately 5% at 1.8 T. As the temperature decreases, the nonlinearity initially increases until the temperature reaches 150 K, after which it begins to decrease. The nonlinearity also exhibits a notable difference between positive and negative magnetic fields.

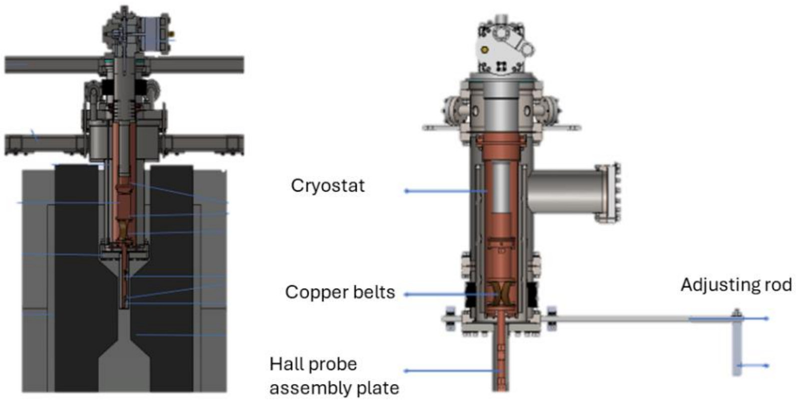

Figure 5. The cryogenic system; The angle adjustment platform of the Hall probe.

This calibration system provides crucial information to correct for temperature-dependent variations in the Hall probe readings. This correction ensures the accuracy of magnetic field measurements, contributing significantly to the successful development and operation of the superconducting undulator for the SHINE project.

4. EXPERIMENT

Under normal temperature conditions, the optical system was adjusted, and the trajectory of the sledge within a 4-meter-long gap was measured, as shown in Figure 6 [3].

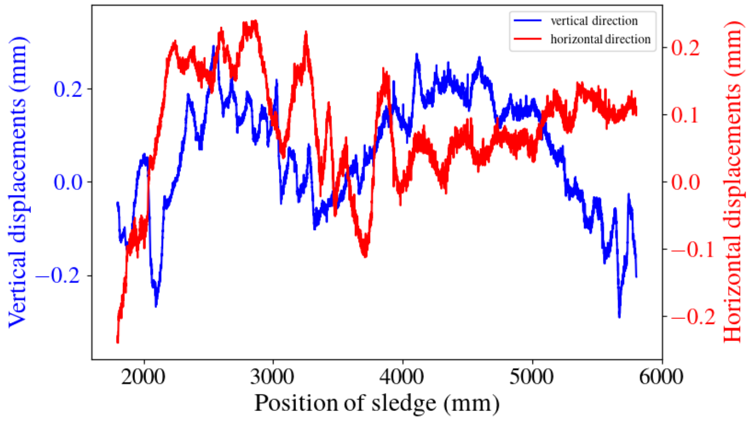

Figure 6. The trajectory of the sledge

As shown in figure 7, the magnetic field measurement for a 2-m undulator segment was conducted at a temperature of 4K with the coil current of 100A, obtaining the trajectory of the sledge, temperature variation curves, and magnetic field from the dual Hall probes. Additionally, the mid-plane field By_0 was calculated.

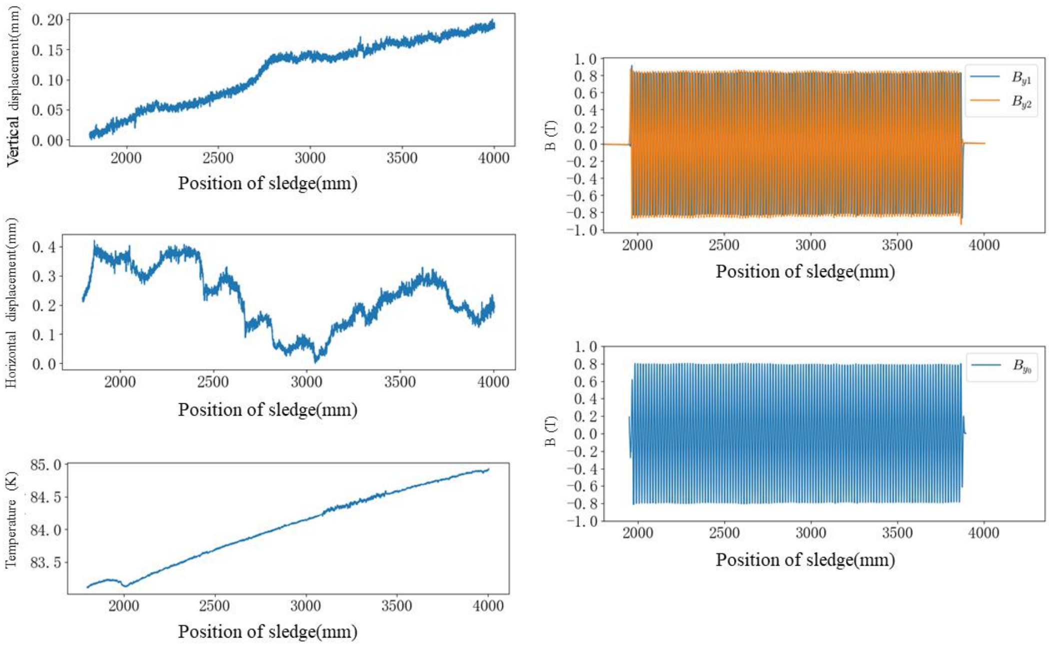

Figure 7. The test results of the 2-m segment.

The results indicate that the measured peak magnetic field is approximately 0.8 T, which is in close agreement with the theoretically simulated peak magnetic field of 0.81 T.

5. Conclusion

Currently, the commissioning of the laser positioning system has been successfully completed under normal temperature conditions. The trajectory of the sledge has also been measured. Additionally, the calibration of the Hall probes for the temperature magnetic field voltage coefficient has been completed. During the testing of the undulator, the magnetic field measurement system was tested and corresponding data were obtained. Further research and validation are still required. Future research will concentrate on extracting the undulator axis to fulfil the installation requirements for FEL-Ⅲ.

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