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FIRST RESULTS OF THE IVU16 PROTOTYPE UNDULATOR MEASUREMENTS

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Abstract

The Shanghai Synchrotron Radiation Facility (SSRF) has developed a 16 mm period length, 4 mm gap, in-vacuum undulator (IVU) that is planned to be installed and tested in the 1.5 GeV SXFEL-SBP beam line. This paper will describe the main parameters of the undulator and the key design choices that have been made. The first undulator prototype was assembled and magnetically tested. First measurements with vacuum chamber will be presented.

INTRODUCTION

The Shanghai soft X-ray Free-Electron Laser Facility (SXFEL), located in SSRF, as a phased project, is composed of the SXFEL test facility (SXFEL-TF), and the SXFEL user facility (SXFEL-UF). The SXFEL-TF will be upgraded to the SXFEL-UF, with the radiation wavelength extended to cover the water window region by boosting the electron beam energy to 1.5 GeV with more C-band accelerating structures [1]. Currently, the SXFEL-TF is under commissioning and the key equipment of SXFEL-UF such as undulators is under manufacturing.

The layout comparison between the SXFEL-TF and SXFEL-UF is shown in Figure 1. Two undulator lines, a seeded FEL line and a SASE FEL line will be built. The latter will consist of 10 in-vacuum undulator sections to realize 2 nm soft X-ray saturation. Up to now only SACLA and SwissFEL have developed long IVUs with short period and variable gap in FEL devices that has been built.

Now the IVU16 prototype undulator of the SXFEL-UF has been assembled, measured and shimmed in March 2019. Table 1 shows some IVU16 Technical specifications and measured values of the prototype, and they will be described in detail below. The problems found during the development of the prototype will have been improved in subsequent mass manufacturing. Specific design and measurement data of the prototype will be described in this paper.

Table 1: Design Parameters of IVU16 Prototype

Parameters	Required	Achieved
Period Length (mm)	16	
Electron Energy (GeV)	1.5	
Scope of Gap (mm)	4~12	
Effective Length (m)	4	
Effective Field (T)	1.05	1.07
K Value	1.52	1.61
Phase Error (Deg)	< 5	4.8@Gap= 4.2mm
RMS Trajectory (μm)	< 5	1.3@Gap= 4.2mm

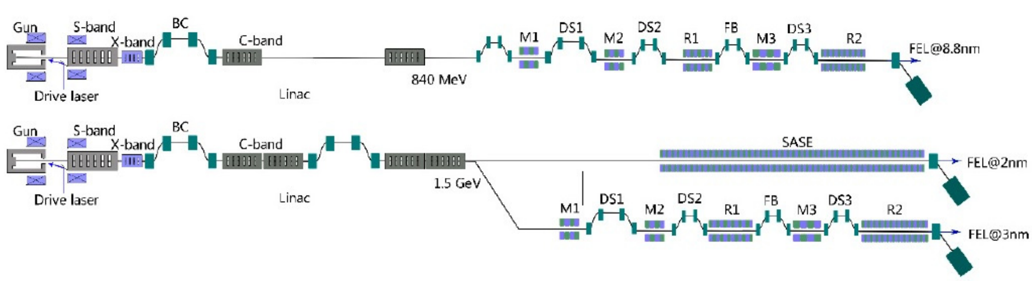

Figure 1: Schematic layouts: SXFEL-TF (upper) and SXFEL-UF (lower)[1].

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MAGNETIC DESIGN

The IVU16 adopts a standard hybrid magnet structure, consists of nearly 250 periods, and the upper and lower magnetic arrangements are periodically arranged by Sm2Co17 permanent magnets and cobalt vanadium ferromagnetic poles. SSRF Magnet Group has developed a novel magnetic camera for fast characterizing the field distribution of each magnet block by means of a sensor array of 16 Hall samples which were calibrated by comparing their measurements of the same magnet block[2], see Figure 2. At a temperature of 20 °C, the permanent magnet has an average remanence of 1.13 T and an intrinsic coercive force of 22 kOe. Most of the nearly 1,000 permanent magnets have a deviation angle of less than 1 degree, the absolute value of the center point N/S symmetry is controlled within 2%, and the consistency of the total magnetic moment is also within 2%. The magnetic block sorting method based on the magnetic camera is effective in reducing the shimming distances and maintaining gap space and all magnets installed on the IVU prototype had been sorted.

There is a small gap between the poles and the keepers, so the position of the poles can be adjusted in Y axis, the max shimming distance is less than 0.1 mm, see Figure 2.

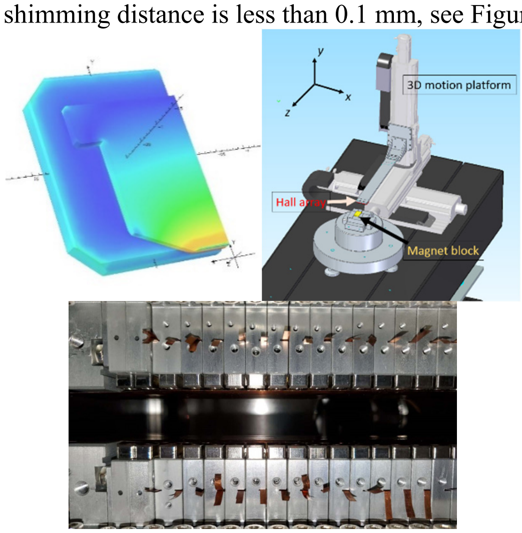

Figure 2: On the top left, the size of the magnet and the pole were optimized in Opera-3D. On the top right, the 3D model of the magnetic camera [2]. On the bottom, thin copper sheets are inserted to adjust the height of the poles.

MAGNETIC MEASUREMENT

The whole measurement process can be divided into three stages, measuring when the vacuum chamber was not installed (2018.09), re-measuring after installing vacuum chamber (2018.11) and re-measuring after baking at 100 °C (2019.03).

Because of the side flanges of the vacuum chamber, see Figure 3, the prototype can be measured whether the vacuum chamber is installed with a Magnetic Measurement Bench (MMB) that has been integrated from SSRF Magnet Group. The high-precision 3D Hall probe of SENIS company is used, and the measurement resolution can reach 1 µT, which can meet the requirements of undulator repeatability for trajectory measurement.

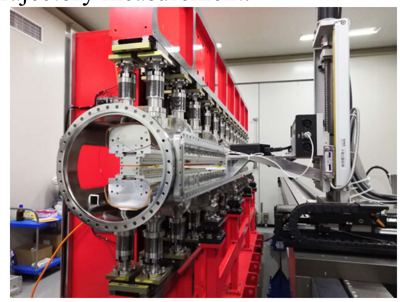

Figure 3: The IVU16 prototype undulator was under measuring with the Hall probe head through the flange driven by a granite bench.

When all the magnets and poles are installed in place and all columns were adjusted to parallel two girders, we measured and shimmed the magnetic field when the gap was 4.6 mm. First, we eliminated the half-period integral error of By, then the trajectory and the phase error are satisfied by adjusting the height of part of the poles and adding the necessary analog quantity- Bx and By uniform fields to the original field. Because we didn't place the magnetic shields at the beginning and end of measurement at that time, we thought both the Bx and By uniform fields were caused by the environmental field. There are grooves around the two girders, By long coils can be placed and generate the By uniform field. The Bx first integral was too large to shim by rotating some poles around the center or moving the poles horizontally. So, we also decided that we could use Bx long coils placed around the side flanges on the vacuum chamber.

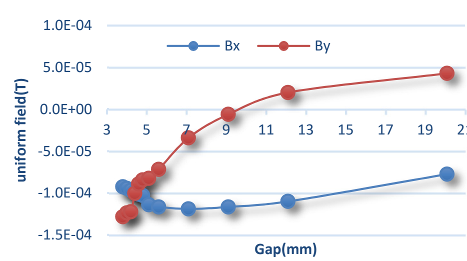

Figure 4: The By uniform field (red circle) the Bx uniform field (blue circle).

Figure 4 shows the two uniform fields for trajectory correction after the magnetic shields were placed. The Bx uniform field did not change significantly with the gap. The installed By long coil had been tested in March 2019, see Figure 5. While the By long coil was properly energized, the By uniform field was less than 0.05 Gs, and the trajectory change was well in line with our expectations, see Figure 6. In Figure 7, the trajectory for all relevant gaps is reported

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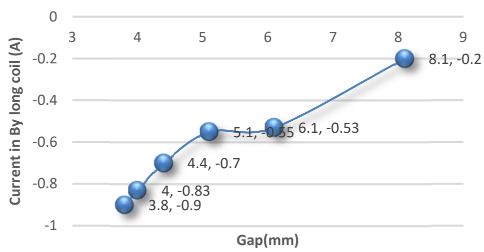

Figure 5: By long coil current test. In the data label, the left value is the gap value and the right value is the current value.

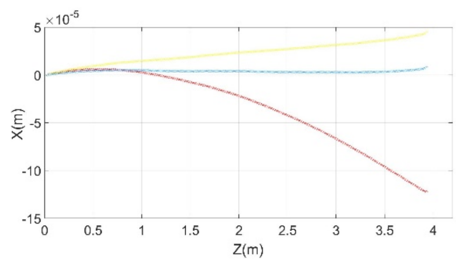

Figure 6: Trajectory change from coil energizing. No current (red), energizing (yellow) and energizing with entrance kick (blue) while gap is 4.4 mm.

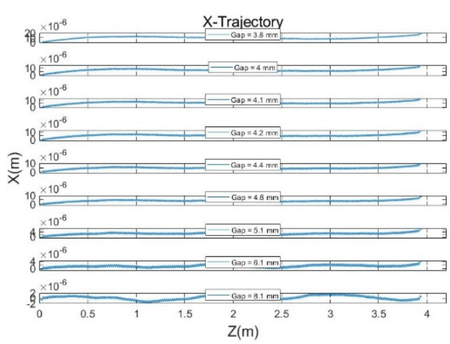

Figure 7: The trajectory straightness for different gaps. Residual entrance and exit kicks are not represented in this picture.

Figure 8: On the left, the side flange was being installed. On the right, final inspection before baking.

When the vacuum chamber was installed, we remeasured the field immediately to verify installation repeatability of the columns. The data shows that the mechanical design and assembly of the prototype is reliable, the peak value of By at each measurement point barely changed. Two months later, the vacuum chamber had been baked at 100 °C for a week, see Figure 8.

The results of the two re-measurements are in good agreement. After high temperature baking, the magnetic field performance, such as By peak, electron trajectory, especially the RMS phase error, has not changed. The RMS phase error is about 6.7 degree when the gap is 4 mm, this is slightly unsatisfactory. The phase error deteriorates rapidly as the gap becomes smaller, see Figure 9, the phase distribution versus the pole number at different gaps reflects this phenomenon more intuitively. The ends of the girders are not supported by the columns, this make the girders become deformed more seriously when the gap gets smaller. For this IVU16 prototype, the 4.6 mm shimming gap is not small enough and the minimum gap that satisfies the phase error requirement is 4.2 mm, we will try shimming at this gap in the future.

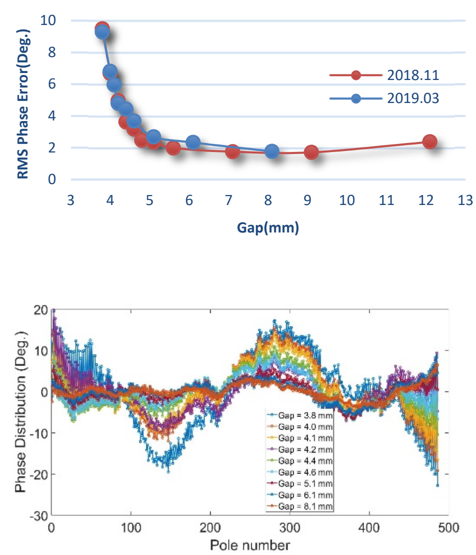

Figure 9: On the top, the RMS phase error as a function of the gap. On the bottom, the phase distribution versus the pole number at different gaps.

CONCLUSION

The test of the IVU16 prototype was an important milestone for the SXFEL-UF. The original design was assessed and some residual problems were discovered. The use of long side flange of the vacuum chamber provides a new convenient and intuitive way to measure the magnetic field of long IVUs. In the future work, we will continue to optimize the shimming and measurement methods to accumulate the technical foundation for the mass production of IVUs.

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