MEASUREMENT OF SPRING-8 XFEL UNDULATOR PROTOTYPE WITH THE SAFALI SYSTEM

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Abstract

The in-vacuum undulator (IVU) is one of the key technologies of the SPring-8 XFEL. This makes it possible to select a shorter magnetic period, and thus a lower electron energy. One concern on the use of IVUs is that the magnetic performance cannot be checked easily after assembling of the vacuum components, because the magnetic array is placed inside the vacuum chamber and thus the conventional field-measurement system is not available. To solve this problem, we have recently developed a new measurement system called "SAFALI", based on laser instrumentation and dynamic feedback of the magnetic sensor position. With the SAFALI system, we measured the magnetic field of the prototype IVU for the SPring-8 XFEL and checked the reproducibility of the magnetic performance before and after vacuum chamber assembly. The magnetic performance was found to degrade due to gap errors in the 3 units of the magnetic arrays, which has been corrected by finely adjusting the ball screws that drive the magnetic arrays.

INTRODUCTION

In the X-ray free electron laser (XFEL) facility under construction at the SPring-8 site, 18 segments of in-vacuum undulators (IVUs) are to be installed. The magnetic length and magnetic period of each segment are 5 m and 18 mm, respectively, and the magnet circuit is of the hybrid type with pole pieces made of permendur (Fe-Co alloy). Because the maximum K value of 2.2 is obtained at the gap of 3.5 mm, it is possible to tune the photon energy over the wide range as in the case of the storage-ring based synchrotron radiation facility. As a matter of course, it is also possible to change the electron energy if it is necessary to tune the wavelength more widely than is available by the gap movement alone.

Between two undulator segments, a drift section with a length of 1.2 m is inserted, where quadrupole magnets for the betatron matching, steering magnets for orbit correction, cavity-type beam position monitors, and phase shifters to adjust the optical phase between the two adjacent undulators, are to be installed.

At the SPring-8, an undulator prototype (UP18) for the XFEL has been constructed, prior to mass production of the 18 undulator segments. A number of tests with UP18 have been carried out for the final decision of the specifications. Among them, the most important is to establish a new field measurement technique that is indispensable to the undulators for the XFEL, which is the main subject of this paper.

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IN-SITU FIELD MEASUREMENT FOR IVUS

Because the permanent magnet blocks that form the undulator magnetic array have always some magnetic errors in terms of the direction and the strength of magnetization, it is necessary to measure the magnetic field distribution along the undulator axis. If the optical performances evaluated from the measured field distribution is not satisfactory, the magnetic errors should be corrected.

In order to measure the magnetic field distribution, a rigid and accurate linear stage usually made of granite is used to actuate the Hall-effect sensor along the undulator axis. The typical accuracy of the transverse position during the actuation is less than 30 μm, which is good enough to do magnetic measurement of an undulator with a magnetic period longer than, e.g., 10 mm. It should be noted, however, that this method cannot be applied to IVUs because the magnetic arrays are installed inside the vacuum chamber. Therefore, the magnetic field measurement is carried out without the vacuum chamber in construction of IVUs. In order to install the vacuum chamber, the magnetic arrays are deassembled from the mechanical frame, and then reassembled after the vacuum chamber installation. Although such an assembling process can cause degradation of the magnetic performances, no serious problems have been reported so far for the IVUs installed at the SPring-8. However, we have recently realized that a new measurement technique would be necessary for IVUs installed in the XFEL, which enables the magnetic measurement under the condition that the magnetic arrays are installed inside the vacuum chamber. By means of this technique, we can confirm the final state of the magnetic distribution of IVUs after assembling the vacuum components and also check the magnetic performance even after installation inside the accelerator tunnel. Let us call the new measurement technique the "in-situ" field measurement.

SAFALI FOR IN-SITU MEASUREMENT

The most straightforward way to realize the in-situ field measurement is to install a simple and small linear guide or equivalent inside the vacuum chamber and actuate the Hall sensor along the undulator axis. It should be noted, however, that the straightness of the linear guide, which is so small as to be inserted into the chamber, cannot be good enough to measure the magnetic distribution of an undulator, especially the IVU with a short magnetic period. The long linear guide can be deflected due to the weight itself or other load. We have recently developed a new field measurement system that enables the in-situ field measurement [1], which is schematically shown in Fig. 1. In this system, the transverse position of the Hall sensor is monitored by means of optical laser beams in conjunction with position sensitive detectors (PSDs) to measure the laser spot created by intercepting the beam by two irises attached to the Hall sensor module. The linear guide to actuate the Hall sensor is supported by 2-axis linear stages. Therefore, the positional variations can be corrected easily, once they are detected by the above scheme. This system is called "SAFALI" for Self-Aligned Field Analyzer with Laser Instrumentation.

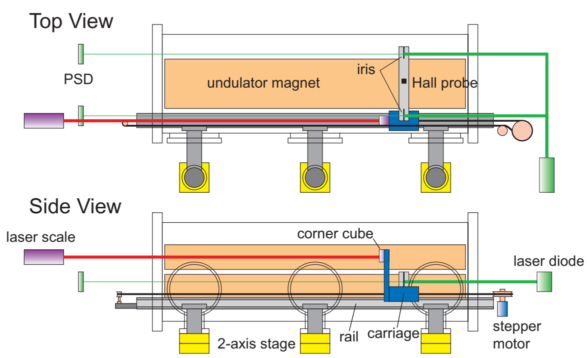

Figure 1: Schematic illustration of the SAFALI system.

We measured the magnetic field of an IVU with a magnetic length and period of 1.5 m and 24 mm, by means of the SAFALI method to demonstrate the performance and reliability of the SAFALI concept and found a good agreement with the conventional measurement method [1].

FIELD MEASUREMENT OF THE UNDULATOR PROTOTYPE

Having verified the concept, we measured the magnetic field of UP18 with the SAFALI system in order to check the reproducibility of the magnetic performance after the assembling process.

Before installation of the vacuum chamber, we measured the magnetic field at the gap of 4 mm for a final check of the magnetic performance. The result is shown in Fig. 2 (a) in terms of the phase error as a function of the magnet pole number. Note that the r.m.s. phase error of 3.3 degree is good enough for the FEL driver.

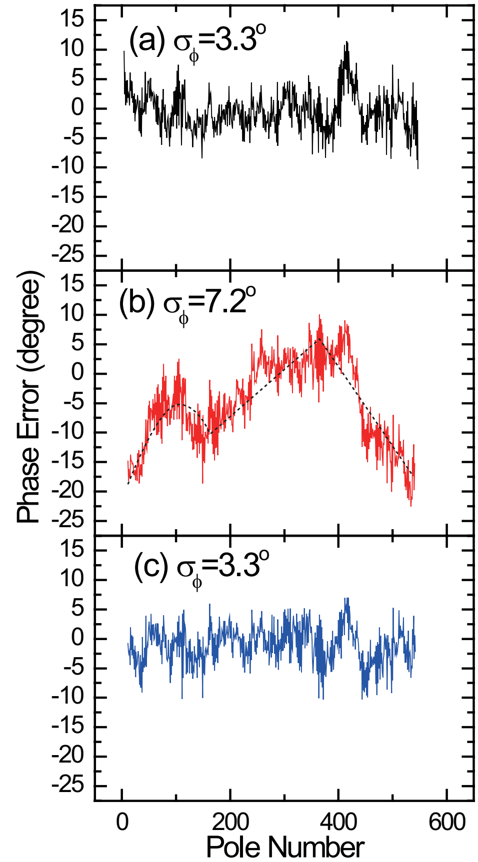

Figure 2: Phase error as a function of the magnet pole number calculated with the magnetic field distribution (a) before the vacuum chamber installation (b) just after the installation (c) after gap fine tuning.

Next the magnetic arrays were deassembled and the vacuum chamber was installed. Then the magnetic arrays were reassembled inside the vacuum chamber. After that, the components for the SAFALI system, such as the liner guide, 2-axis stages, optical elements and PSDs were installed and aligned. What is the most important is that the optical axes of the laser beams should be parallel to the undulator axis. Otherwise, the positional feedback of the Hall sensor does not work well.

After alignment of all the components, we measured the magnetic field at the gap of 4 mm. Figure 2 (b) shows the results of measurements. Compared with the results before the vacuum chamber installation (a), it was found that the phase error increased by about a factor of 2. This means that the magnetic distribution changed to some extent during the process of deassembly and reassembly of the magnetic arrays. It is worth noting that we found little difference between the two measurements in terms of the electron trajectory, i.e., the 2nd field integral.

GAP ERROR AND CORRECTION

By carefully looking to the phase error distribution, we can find a systematic error composed of 3 parts. To be specific, the dotted line indicated in Fig. 2 (b) shows the global trend of the phase error, while no such a trend curve can be found in Fig. 2 (a). Clearly this systematic error is attributable to the process of deassembly and reassembly of the magnetic arrays. In order to look for the reason, let us recall the structure of UP18, which is schematically shown in Fig. 3

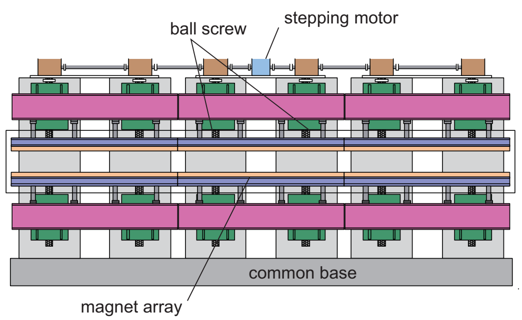

Figure 3: Schematic illustration of the structure of UP18, the undulator prototype for the SPring-8 XFEL.

Because the magnetic length of 5 m is too long to be built in a single piece, the magnetic array is divided into 3 units. Each magnetic unit is supported by an iron beam which is connected to a couple of linear guide tables. Each table is connected to a ball screw to give a linear motion. Thus the magnetic array is composed of 3 units, each of which is supported by 2 points. In such a structure, we have two error sources that spoils the gap uniformity, which is crucially important in the undulator magnetic performance. One is the gap offset, i.e., the displacement of a specific magnet unit with respect to the other units. The other is the gap taper, i.e., the slope of the magnet unit. The former brings a slope error in the phase error distribution, while the latter brings a deflection error [2]. Because the magnetic array is composed of 3 units, these error sources give rise to a systematic error composed of 3 independent profiles, as has been found in Figure 2 (b). It is possible to deduce the gap offset and taper in each unit from the phase error distribution. The result is schematically shown in Fig. 4.

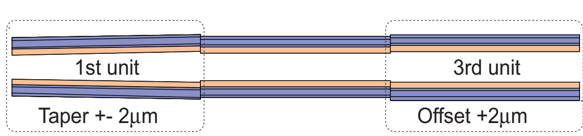

Figure 4: Gap taper and offset deduced from the phase error distribution.

As a result of the phase error analysis, we have found the gap taper of $\pm 2\mu$m in the 1st unit and the gap offset of $+2\mu$m in the 3rd unit. This is a consequence of the fact that the phase error has a deflection error in the 1st unit and the slope in the 3rd unit is significantly different from the other 2 units. In practice, we determined the gap taper and offset by fitting the phase error distribution in each unit by a 2nd order polynomial, with the dependence of the phase error on the magnetic strength taken into account.

After the above analysis, we corrected the gap error of each unit by adjusting the angle of the ball screws and measure the magnetic field distribution. The result is shown in Fig. 2 (c), where we can find that the magnetic performance was recovered and the r.m.s. phase error has been close to that before the vacuum chamber installation.

DISCUSSION

The results of measurement and investigation described in the previous section, that the gap error of 2μm can affect the magnetic performance of an undulator, is amazing. It should be noted, however, that this does not necessarily mean that all IVUs have the same criterion on the tolerance of the gap error. As is well known, the magnetic strength B of the undulator composed of magnetic arrays with the Halbach configuration is roughly given by [3]

$$B = B_0 \exp(-\pi g/\lambda_u), \tag{1}$$

where λ_u is the undulator period and B_0 is a parameter dependent on the type and dimension of the magnetic circuit and remanence of the permanent magnet. Using this formula, the magnetic field error ΔB due to the gap error Δg is given by

$$\left|\frac{\Delta B}{B}\right| = \frac{\pi \Delta g}{\lambda_u}.$$

Thus, the magnetic error is proportional to the ratio $\Delta g/\lambda_u$. This means that the magnetic error is more sensitive to the gap error for undulators with a shorter magnetic period. In addition, the exponent in eq. 1 is somewhat different for the hybrid magnetic circuit and contains the second order polynomial $(g/\lambda_u)^2$. Since the magnetic array of UP18 is of the hybrid type with a magnetic period of 18 mm, the criterion on the gap error is much more stringent than that of the SPring-8 standard IVU, which has the Halbach array with a magnetic period of 32 mm.

REFERENCES

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