Journal of
Synchrotron
Radiation

ISSN 0909-0495

Received 30 March 2007
Accepted 31 May 2007

Magnetic characterization for cryogenic permanent-magnet undulators: a first result

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The cryogenic permanent-magnet undulator (CPMU) is a novel insertion device recently proposed at SPring-8, in which permanent magnets (PMs) are cooled to cryogenic temperatures to improve the magnetic performances, such as remanence and coercivity. A new measurement system for carrying out high-precision magnetic field mapping using a Hall probe has been developed in order to characterize the magnetic field generated by PM arrays at cryogenic temperatures. In this system, alignment of the Hall probe was dynamically performed by means of detecting the variation in its transverse position using optical laser beams introduced into the vacuum chamber. Magnetic measurements of a CPMU prototype were made at different temperatures in order to investigate variations of the magnetic performances owing to temperature. The maximum remanence deduced from the average peak value of the field profile was found to be close to that obtained from a former measurement with a single piece of the same PM material. In addition, the error components in the field profile were found to be insensitive to temperature in terms of the electron trajectory and phase error. This result suggests that the field correction of CPMUs can be performed based on the field profile measured at room temperature, which considerably reduces the task and time necessary for construction of CPMUs.

Keywords: cryogenic undulators; field measurement; phase error.

1. Introduction

The growing demand for highly brilliant angstrom X-rays in various research fields, such as protein crystallography and material science, has required technological innovation in the development of synchrotron radiation sources, especially undulators. The recent trend in undulator development is thus towards shortening the magnetic period, which not only shifts the available photon range towards higher energies but also increases the number of magnetic periods resulting in higher brilliance (Kitamura, 2000).

To date, many efforts have been made to shorten the undulator period. The in-vacuum undulator (IVU), in which permanent-magnet (PM) arrays are installed inside the vacuum chamber to reduce the minimum gap, is one of the most successful concepts for a shorter magnetic period and is now widely adopted in many synchrotron radiation facilities (Kitamura, 1998, and references therein). Although the technology of IVUs is mature, it is restricted to selected PM materials, *i.e.* the possibility of irreversible demagnetization during operation should be avoided as much as possible. This is the reason why a PM material with high coercivity is usually selected for IVUs at the expense of remanence and thus the undulator peak field.

The cryogenic permanent-magnet undulator (CPMU) is a novel synchrotron radiation source proposed at SPring-8 (Hara *et al.*, 2004) based on a new idea to expand the possibility of IVUs, in which PMs are cooled down to a cryogenic temperature to improve the magnetic performances of the PM material in terms of the coercivity and remanence. It should be emphasized that, in this concept, the operating temperature can be much higher than that of liquid helium, unlike superconducting undulators that consist of superconducting coils made of low-temperature superconducting material such as NbTi (Chouhan *et al.*, 2003). This significantly reduces the thermal budget problems and makes the operation more feasible. Because the PM arrays of IVUs are placed in vacuum and thus thermally insulated, it is straightforward to modify the ordinary IVUs to CPMUs. In 2005, a CPMU prototype was constructed at SPring-8 in order to examine their technological issues. Other prototypes have also been constructed at Brookhaven National Laboratory (Tanabe *et al.*, 2005) and the European Synchrotron Radiation Facility (Kitegi *et al.*, 2006).

The CPMU prototype constructed at SPring-8 has a magnetic period of 15 mm and a total length of 600 mm. NEOMAX50BH (NEOMAX Ltd), the PM material with the highest remanence among those that are commercially available, has been selected as the PM material. Various kinds of experiments have been carried out to investigate the feasi-

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bility of CPMUs, such as cooling capability, variation of the magnetic gap and tapering during the cooling process. In addition, magnetic performances have been roughly estimated in terms of the temperature dependence of the peak field. The results of these experiments were found to be promising for the realisation of CPMUs. It should be noted, however, that there is still a technical challenge to overcome for the realisation of CPMUs, which is supposed to be crucial from an engineering point of view: how to measure accurately the magnetic field and how to correct it if necessary?

Preliminary measurements for the CPMU prototype were carried out by means of actuating the Hall probe cantilever placed inside the vacuum chamber using long bellows (Tanaka *et al.*, 2006). While this method was effective for estimating the peak field variation owing to temperature, it was found that the phase error distribution along the undulator axis evaluated from the measured field was less reproducible owing to the poor positioning accuracy of the Hall probe. Moreover, it is unsuitable for longer undulators owing to the limited stroke of the bellows. For realisation of CPMUs, it is therefore necessary to develop a vacuum-compatible magnetic measurement system that enables high-precision magnetic field mapping using a Hall probe for longer devices. The purpose of this paper is to describe details of a measurement system recently developed at SPring-8 to meet the above requirements. In addition, results of measurements for the CPMU prototype are presented together with discussions on undulator field correction schemes for CPMUs.

2. Magnetic measurement system for the CPMU prototype

In order to estimate the undulator performance correctly, it is necessary to measure the magnetic field distribution along the undulator axis and calculate the phase error or, more directly, the photon flux at every harmonic concerned. The field distribution is usually measured by moving magnetic sensors such as Hall probes driven by an actuation stage with a high mechanical precision, supported by a granite bench. It is obvious that application of this method to CPMUs is almost impossible. We have recently proposed an alternative method and constructed accordingly a measurement system for the CPMU prototype. Details of the system are described in the following.

2.1. System overview

The most straightforward way to move a Hall probe under vacuum is to install a cantilever with a Hall probe attached to its end, and bellows to enable actuation of the cantilever inside the vacuum chamber. If the actuation is driven by the granite bench with a high accuracy, the measurement results will be as reliable as those made using the conventional method. It should be noted, however, that the cantilever length and bellows stroke should be longer than the undulator length, which makes this method less feasible for longer undulators. In addition, the transverse position of the Hall probe can jitter significantly because the supporting point of the cantilever is necessarily far from the Hall probe location. In the former measurement using this method (Tanaka *et al.*, 2006) the cantilever was tilted by mechanical stress owing to contraction and expansion of the bellows during actuation, resulting in a large positional jitter of the Hall probe. Such a tilt error was corrected by measuring the tilt angle, but uncertainty of the Hall probe position still remained.

From the above experience we have recognized that, no matter what method is used for the Hall probe actuation, it would be necessary to detect dynamically the positional jitter and perform an adaptive feedback for a reliable measurement. In order to measure the Hall probe position, we need to place fiducial points along the undulator axis. The simplest way is to introduce a guiding laser beam with an optical axis coincident with the undulator axis. In addition, a laser interferometer scale can be used to measure the longitudinal Hall probe positions. Once the Hall probe alignment technique is established as described above, we can use any method for the Hall probe actuation as long as it is vacuum compatible.

2.2. Description of components

Fig. 1 shows a schematic illustration of the magnetic measurement system built for the CPMU prototype. As a Hall probe cantilever, a stainless-steel tube of diameter 16 mm was inserted into the vacuum chamber through two dynamic reciprocating Teflon seals. The translation table of an existing field measurement bench was connected to one end of the tube: the measurement bench in this system was used just to actuate the tube by pushing or pulling the end of the tube. Between the translation table and the tube, a two-axis linear guide was inserted to allow relative displacement in the transverse plane.

On the opposite end of the tube, a Hall probe was attached together with two irises, which were irradiated by two laser beams with a wavelength of 640 nm introduced from upstream through view ports. Two laser spots were created by the irises, the positions of which were measured using position-sensitive detectors (PSDs) located at the downstream end. The optical axes of the laser beams were aligned to coincide with the undulator axis prior to the magnetic measurement. The beam of the laser scale for the longitudinal position measurement was introduced from the downstream end and reflected by the cubic mirror attached to the Hall probe module.

O-ring seals were installed on the flanges of a T-shaped vacuum duct, which was evacuated for differential pumping. The typical vacuum inside the vacuum chamber was of the order of 10^{-4} Pa in the steady state, while it reached 10^{-3} Pa during the magnetic measurement. The T-shaped duct was supported by a four-axis actuator composed of two linear stages in the x and y directions and two swivel stages around the x and y axes. For the adaptive feedback of the Hall probe position, the x (linear) and θ_x (swivel) stages were used for the x and y directions, respectively.

During the cooling (and heating) process, the magnet gap was expected to vary owing to thermal contraction of the

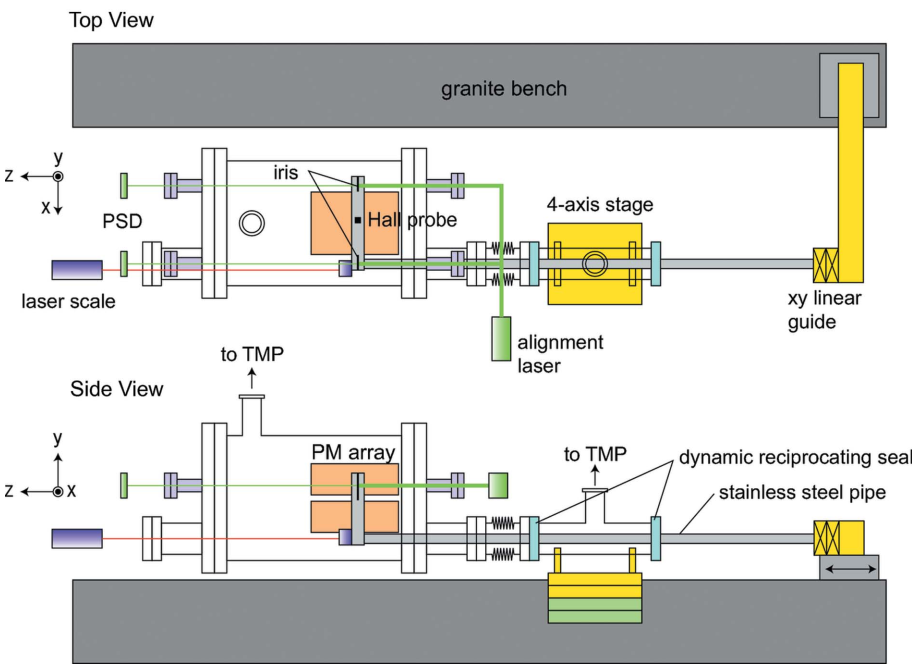

Figure 1
Schematic illustration of the field measurement system developed for the CPMU prototype. PSD: position-sensitive detector. TMP: turbo-molecular pump.

supporting rods of the magnet arrays. In the former measurements, capacitive displacement sensors (PS-I, Nanotex) were used to monitor the gap variation. In the current system, a laser scan micrometer (LS 5120, Keyence) has been adopted for wider measuring range and easier implementation.

2.3. Accuracy of positional feedback

After assembling all the components, we tested the feedback procedure. First, we actuated the cantilever tube without feedback over 600 mm, the length of the CPMU prototype, and found that the variations of the Hall probe position were around 2 mm and 0.1 mm in the y and x directions, respectively. Next, we performed feedback at various values of the actuation speed. It is, in principle, possible to create feedback with an accuracy similar to the repeatability of the PSD position measurement (~5 μm r.m.s.) by slowing down the actuation of the cantilever, which in turn gives rise to an increase in the measurement time. Thus we need to make a compromise between the accuracy of the position feedback and the time for the magnetic measurement. After several trials, we decided to actuate the cantilever tube at a speed of 0.6 mm s^{-1}, leading to ~1000 s for a single measurement. Fig. 2 shows an example of a measurement of the positional variation when the feedback is on.

2.4. Measurement reproducibility

Besides the positional accuracy of the Hall probe, the measurement reproducibility is also important. We measured the magnetic field distribution of the CPMU prototype under the same conditions to examine the reproducibility. The results are shown in Fig. 3 in terms of the phase error as a function of the pole number. The phase error variation was found to be less than 0.1° r.m.s. It is worth noting that the general goal of undulator field correction is to reduce the r.m.s. phase error to around 2°. Thus we can conclude that the field measurement system performs well, sufficient for magnetic characterization of the CPMU prototype.

3. Results for the CPMU prototype

In order to investigate the temperature dependence of the magnetic performance, and once the development of the measurement system had been completed, we measured the magnetic field distribution of the CMPU prototype over

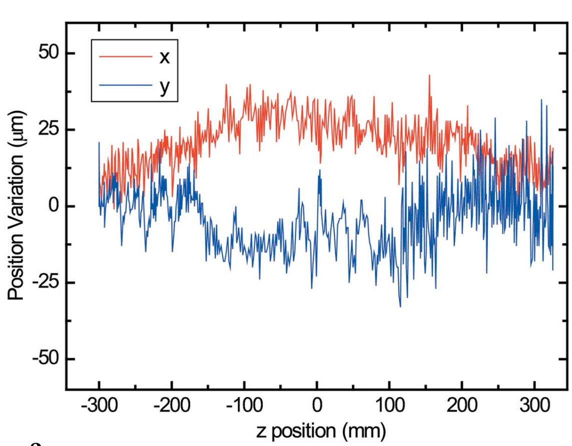

Figure 2
Variation in the transverse position of the Hall probe during the field measurement with the feedback. The r.m.s. positional deviations in the x and y directions were 7.9 μm and 10.5 μm, respectively.

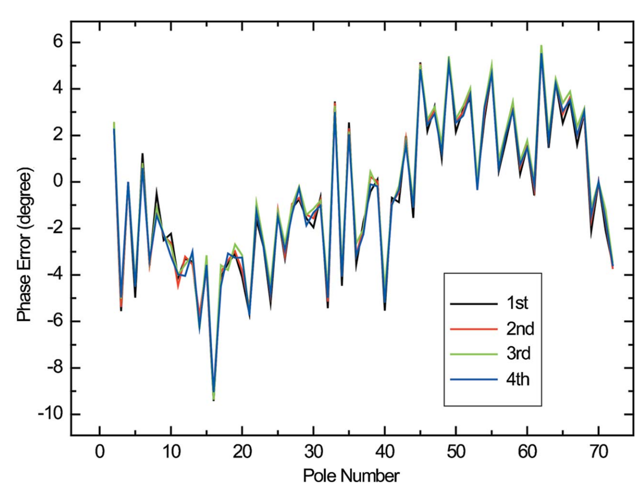

Figure 3
Reproducibility of the magnetic measurement between four measurements under the same conditions in terms of the phase error.

the total length of the magnet array at different temperatures. At each measurement we measured the gap variation owing to the thermal contraction of the supporting rods and other components using the laser scan micrometer, and compensated it to set the actual magnet gap to 5 mm. In the following sections the temperature dependence of the magnetic performance will be discussed from two different points of view: the peak field and the field profile.

3.1. Peak field enhancement

Fig. 4 shows the peak field averaged over the central 70 poles as a function of the magnet temperature. The remanence of the PM material deduced from the average peak field is indicated on the right-hand ordinate. The solid line shows the temperature dependence of the remanence measured for a single block of NEOMAX50BH. The peak remanence obtained for the CPMU prototype (1.56 T) was found to be close to that of a single piece (1.58 T). It should be noted, however, that the profile of the temperature-dependence curve was slightly different, which can be accounted for by the difference in the permeance coefficient, *i.e.* the operating point of PMs. As a result, the optimum temperature, or the nominal operating temperature, for the CPMU prototype was found to be around 130 K, but not 140 K that is expected from the single-piece measurement.

3.2. Variation of the field profile

The magnetic field profile of an ideal undulator is purely periodic. In fact, the undulator field always contains error components owing to imperfections in the PMs, which should be corrected as much as possible to improve the undulator performance. It is therefore crucial to establish a technique for the field correction towards the realisation of CPMUs. At SPring-8, the *in situ* sorting technique based on swapping and flipping the magnet units has been used for the field correction of PM undulators (Tanaka *et al.*, 2001). In principle, it is possible to apply such a conventional method to CPMUs but the procedure will be time-consuming and complicated: after measurement at a cryogenic temperature, the magnet array should be heated to room temperature to allow for the field correction. Here we ask the following question: do the error components in the field profile change when the temperature is changed? If they remain the same after cooling, warming and cooling cycles may not be needed to carry out the field correction.

In order to answer this question, we calculated two undulator properties that are quite sensitive to the error components in the field profile, *i.e.* the second field integral (electron trajectory) and the phase error, using the magnetic field distributions measured at 130 K and 300 K. The results are shown in Figs. 5(*a*) and 5(*b*). It was found that differences in both the trajectory and phase error between 130 K and 300 K were negligible, implying that cooling the PMs did not induce a large change in the error components that could affect the undulator performance. This is a very encouraging result towards the realisation of CPMUs. We do not have to repeat the temperature operation many times to carry out the field correction. Most likely, we must just verify the magnetic performance at a cryogenic temperature after completion of the normal field correction at room temperature.

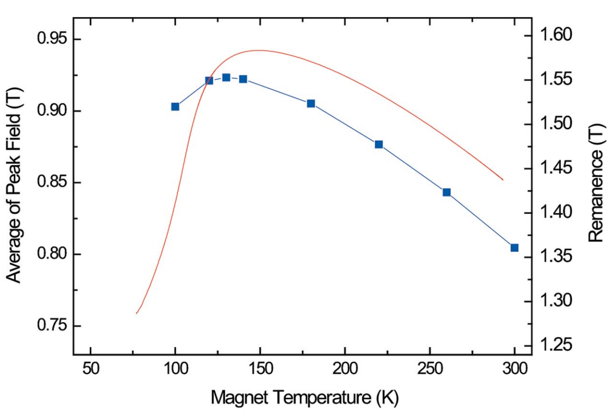

Figure 4
The averaged peak field measured at different magnet temperatures (squares). The right-hand ordinate indicates the remanence of PM material deduced from the peak field. The temperature dependence of the remanence measured for a single piece of NEOMAX50BH is also indicated (solid line).

4. Summary

An overview of the field measurement system developed for the CPMU prototype has been described. By means of

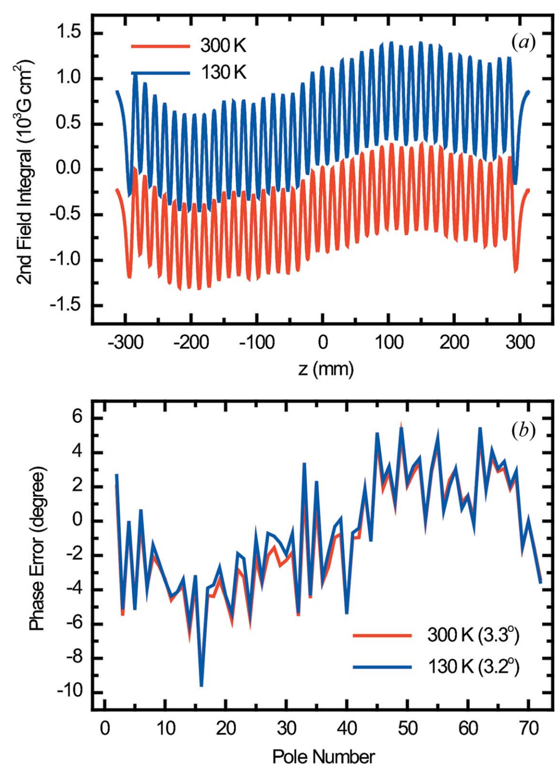

Figure 5
Comparison of the field profile between 130 K and 300 K in terms of (*a*) the electron trajectory and (*b*) the phase error. The electron trajectory is slightly offset from the original position for clarity. The r.m.s. phase errors at 300 K and 130 K were found to be 3.3° and 3.2°, respectively.

dynamic alignment using laser beams, it has become possible to actuate the Hall probe under vacuum with a high position stability. It is worth noting that this concept is easily extended to other applications. In particular, application to IVUs for the final examination of magnetic performances after assembling all the components, which has been impossible using a conventional field measurement method, is of importance. We are now modifying the system to measure the magnetic field of an IVU with a periodic length of 24 mm and total length of 1.5 m, the results of which will be presented elsewhere.

Only the electron trajectory and phase error have been taken into account so far as the magnetic properties to be optimized during the construction of undulators. There is, in fact, another important quantity, namely the integrated multipoles leading to electron beam instability especially in the storage ring, which is usually measured using a flipping coil or stretched wire system. Thus it is necessary to modify these systems to be available under vacuum (Kitegi *et al.*, 2006) for construction of CPMUs, which is supposed to be much easier than the vacuum-compatible Hall probe actuation system described in this paper.

The authors thank Mr Seike of SPring-8 for supporting the experimental set-up.

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