STATUS OF CRYOGENIC PERMANENT MAGNET UNDULATOR DEVELOPMENT

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Abstract

The cryogenic permanent magnet undulator (CPMU), a modified form of the in-vacuum undulator, is an insertion device in which permanent magnets are cooled down to a cryogenic temperature to improve the magnetic properties in terms of the remanence and coercivity. The former relates to the achievable magnetic field, while the latter to the resistance to radiation damage. A variety of R&D activities carried out toward realization, such as the cold magnetic measurement and investigation on radiation damage, are presented together with other important issues.

INTRODUCTION

In development of insertion devices (IDs) as synchrotron radiation (SR) sources, shortening the magnetic period is important not only to reduce the electron energy for generation of hard x rays but also to increase the number of periods and thus the available flux. The in-vacuum undulator (IVU) is an ID in which magnetic arrays are installed inside the vacuum chamber to decrease the minimum gap and increase the peak magnetic field. Technologies for the IVU have been established in 90's, and the IVU has become a mature ID toward shorter magnetic period.

In 2004, a novel concept toward shorter period was proposed at SPring-8 as a modified form of the IVU [1],in which permanent magnets (PMs) are cooled down to a cryogenic temperature (CT) around liquid nitrogen temperature. Because the remanence and coercivity of NdFeB magnets have negative temperature coefficients, they are enhanced significantly at a CT and thus the peak field and resistance to radiation damage are improved. The undulator based on this concept is called the cryogenic permanent magnet undulator (CPMU), and has an advantage over superconducting undulators operated at liquid helium temperature that the heat load problem during accelerator operation is no more serious because the cooling capacity of state-of-the-art cryo coolers operated at liquid nitrogen temperature is large enough to remove the expected heat load.

Proof-of-principle experiments were carried out at SPring-8 by measuring the dependence of remanence and coercivity of several kinds of PM material that are commercially available. The typical temperature coefficients of remanence and coercivity at room temperature (RT) were found to be -0.1% and -0.6%, respectively. While the coercivity increased monotonously as the temperature decreased, the remanence reached its maximum value at a CT around 140 K and decreased below it. This means that there exists an optimum temperature to operate a CPMU. Because of the large temperature coefficient, the coercivity increases at least by a factor of 3 at the optimum temperature. Thanks to such a large enhancement of coercivity, PM material with high remanence that cannot be applied to IVUs at room temperature (RT) due to low coercivity, are now available to CPMUs. As a result, the typical peak field available in CPMUs can be larger than that of conventional IVUs by 40%.

After the proof-of-principle experiments, various R&D activities have been carried out toward realization of the CPMU concept and several SR facilities have already constructed CPMU prototypes to be installed in their storage rings. In this paper, the activities for CPMU development are reviewed.

HISTORY OF DEVELOPMENT

The first CPMU prototype was built in 2005 at SPring-8 [2] by modification of an existing IVU. The magnetic array was replaced with a new one having a length of 0.6 m and a magnetic period of 15 mm. NEOMAX50BH (Hitachi Metals), which has the largest remanence among the NdFeB magnets commercially available, was adopted for the PM material. The so-called Halbach configuration was adopted for the magnetic circuit. It was found that demagnetization due to demagnetizing field during assembly was negligible. In order to cool down the magnetic arrays, one cryocooler was installed and connected to the magnetic arrays by means of a flexible Cu sheet with a thickness of 0.1 mm as a thermal conductor together with sheath heaters for temperature control.

A cooling test was carried out to verify the cooling capacity of the cryocooler, stability of the temperature control system, and gap variation during cooling. In addition, the field distribution over the whole magnetic array was measured by actuating the Hall sensor installed inside the vacuum chamber by means of double bellows to compensate the force due to the atmospheric pressure. The minimum temperature of the magnetic array reached 70 K without turning on the sheath heater, and the gap variation was around 1 mm at 73 K. By controlling the current in the

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heater, the temperature was successfully stabilized at 130 K, at which the peak field was found to have its maximum value by the field measurement. It should be noted, however, that the field measurement with the double-bellows system was not so accurate owing to the stress by the bellows as to deduce the phase error variation due to cooling. A more precise measurement system was developed at SPring-8 in 2007, which will be discussed later in detail.

In 2006, a “cryo-ready” IVU was constructed in BNL for NSLS beamline X25 [3]. It has a magnetic array with a length of 1 m and a magnetic period of 18 mm and is equipped with a cooling system based on cold nitrogen gas from a boil-off of liquid nitrogen. The magnetic circuit is of a hybrid type and the PM material has coercivity large enough to be baked at 100 ^oC. Thus, the device can be operated both as a simple IVU at RT and as a CPMU at CT.

In 2008, a CPMU prototype was constructed in ESRF and installed in the storage ring [4]. They also chose a PM material with a high coercivity for UHV bakeout in case of failure in cryogenics. The magnetic array is of a hybrid type and has a length of 2 m and a magnetic period of 18 mm. They built a specialized vacuum chamber to measure the magnetic field at a CT to check the magnetic performance and found that the phase error increased as the temperature decreased, due to a temperature gradient induced during the cooling process. The device is now under routine operation at a CT and characterization is being carried out [5].

In 2009, PSI started to build a CPMU for the SLS storage ring in collaboration with SPring-8. The magnetic array is of a hybrid type and has a length of 1.7 m and a magnetic period of 14 mm. Unlike the other two CPMUs for NSLS and ESRF, the PMs are not to be baked. Details of this device and results of various tests including the magnetic measurement and vacuum test will be presented elsewhere.

KEY ISSUES TOWARD REALIZATION

Even though the CPMU concept is quite simple and looks feasible, there exists several challenges to be overcome. A variety of R&D activities have been carried out toward realization of the CPMU concept, part of which is presented in this section.

Radiation Damage on Magnets

In order to check the improvement of resistance to radiation damage by cooling down, experiments were carried out with the 2-GeV electron beam at Pohang Accelerator Laboratory [7]. NEOMAX50BH, the PM material used in the SPring-8 CPMU prototype, was taken as an example. The coercivity of this material is around 1.1MA/m at 300 K, which is not high enough to be adopted in IVUs and is easily demagnetized by electron irradiation. In fact, it was found that irradiating 10^{15} electrons led to 15% demagnetization, being much higher than that for NEOMAX27VH, the typical PM material for IVUs. On the other hand, demagnetization of NEOMAX50BH under the same condition except that the temperature was set at 145 K was found to be less than 1% and similar to that of NEOMAX27VH. This means that NEOMAX50BH used at 145 K has resistance to radiation damage high enough to be applicable to undulators.

In addition to the demagnetization at CT mentioned above, i.e., demagnetization under the nominal condition of CPMUs, there is another concern on demagnetization: the so-called memory effect. Even if the demagnetization is avoided by cooling the PMs during the accelerator operation, the radiation damage can be accumulated inside the PMs, and demagnetization can take place once they are heated up to RT. If this is true, it is not allowed to heat up the magnetic arrays to RT and thus the maintenance is impossible.

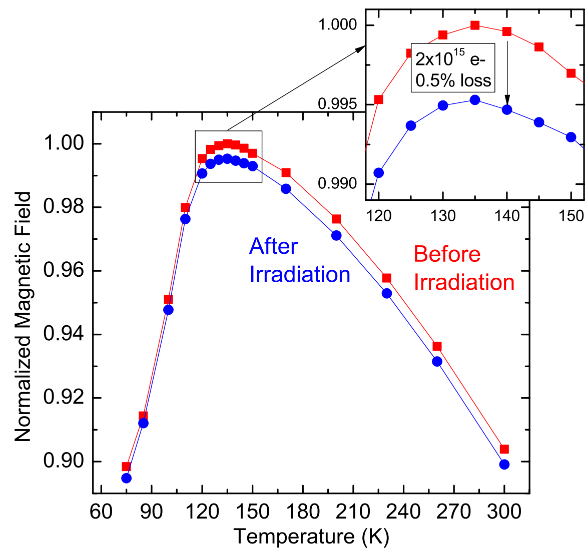

Figure 1: Temperature dependence of remanence of NEOMAX50BH before and after electron irradiation.

In order to investigate the memory effect, temperature dependence of remanence of NEOMAX50BH was measured before and after electron irradiation. Figure 1 shows the result of measurement. After the temperature dependence measurement (red curve), 2×10^{15} electrons were irradiated at 140 K that led to 0.5 % demagnetization. Then, the temperature dependence was measured again (blue curve). We find similar temperature dependence between the two except offset induced by the the demagnetization due to electron irradiation. This means that the memory effect is negligible.

Choice of PM Material

As in the case of normal IVUs, the choice of PM material should be made with compromise between the remanence and coercivity.

Figure 2 shows the temperature dependence of remanence and coercivity for various kinds of PM material measured with superconductive magnetometer (Quantum

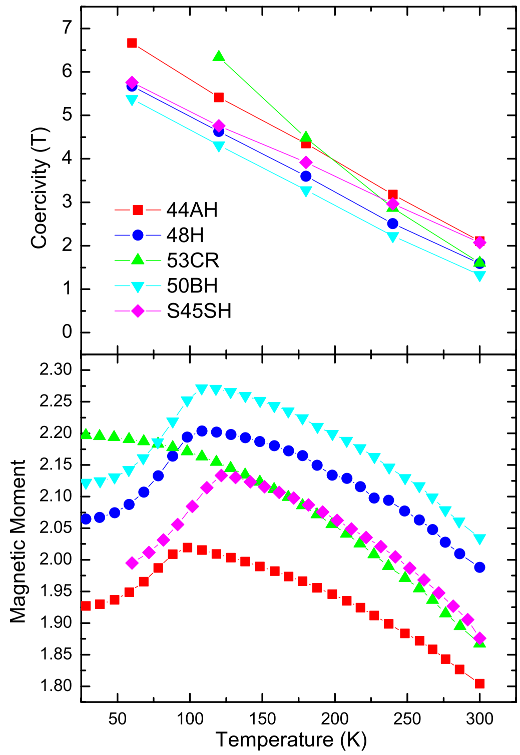

Figure 2: Temperature dependence of remanence for various kinds of PM material. All of the PM material have been supplied by Hitachi Metals. The prefix "NEOMAX" have been omitted from the material names for simplicity. Note that remanence is indicated by the magnetic moment of the PM sample.

Design MPMS XL7). From the point of view of available magnetic field, NEOMAX50BH is the best choice. It should be noted, however, that its coercivity at RT is relatively low. If the PMs experience a large magnetizing field during assembly as in the hybrid configuration, we have to choose PM material with coercivity at RT large enough to avoid demagnetization during assembly. In the case of the CPMU for SLS, NEOMAXS45SH has been chosen as a compromise between the coercivity at RT and the maximum remanence at a CT. In addition, larger coercivity will be required if the device should be baked at a high temperature so that it can work also as a simple IVU as in the case of CPMUs for NSLS and ESRF. Note that this choice necessarily limits the available PM material and achievable magnetic field.

Cold Magnetic Measurement

Because the CPMU is an undulator but not a wiggler, the magnetic error, especially the phase error, should be as low as possible to avoid flux loss in the higher harmonics region. This means that a precise field measurement should be made in order to verify the magnetic performance at a CT. Because the conventional field measurement apparatus, such as the Hall sensor driven by a rigid linear stage made of massive granite, cannot be used under vacuum environment, we have to develop an alternative system that is not only vacuum compatible and but also reliable enough to measure the phase error.

In 2007, a new measurement system for CPMUs has been developed in SPring-8 [6]. In this system, the Hall sensor is dynamically aligned by means of detecting variation of its transverse position with optical laser beams introduced into the vacuum chamber. Using the developed system, magnetic measurements of the CPMU prototype built at SPring-8 have been carried out at RT and 130 K, where the peak field becomes maximum. It was found that the differences both in the phase and trajectory errors between the two temperatures were negligible. This means that apart from the field enhancement, the deviation of magnetization vector in each magnet unit from the nominal value does not change significantly after cooling down, and the field correction at RT is still effective at a CT. This is an encouraging result toward realization of the CPMU concept, because we can do the field correction based on the magnetic measurement at RT. If this is not the case and the measurement at a CT is significantly different from that at RT, we have to repeat the cooling-heating cycle to complete the field correction process, which takes too long time.

Temperature Gradient

The temperature gradient can be induced over the whole magnetic array as a result of the cooling process from RT to a CT. In conventional undulators, the temperature gradient causes a field variation and gives rise to a large phase error. On the other hand, the field variation along the undulator due to the temperature gradient is expected to be negligibly small for CPMUs, because the temperature dependence of remanence is negligibly small at the operation point. Nevertheless, the temperature gradient can cause a large phase error due to gap variation as is schematically shown in Fig. 3.

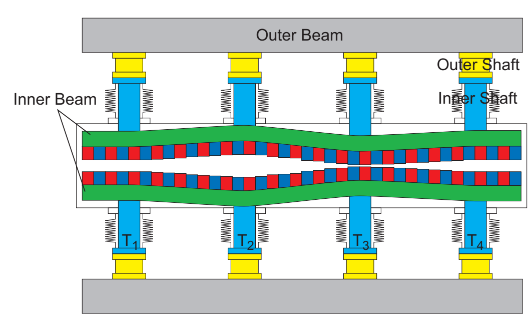

Figure 3: Gap variation induced by the temperature gradient.

In this example, the temperatures $T_1 \sim T_4$ at 4 different positions of the supporting shaft have the relation

$$T_3 > T_1 \sim T_4 > T_2,$$

and thus the gap variation is given by

$$g_3 < g_1 \sim g_4 < g_2,$$

where g_n is the gap value at the n-th shaft position.

In order to avoid the phase error due to the temperature gradient as mentioned above, the most straightforward way is to reduce the temperature gradient as much as possible. Although this can be done by carefully designing the cryogenics and cooling system based on numerical analysis of the undulator model, the real situation is not known until the device is built and the cooling test is carried out.

An alternative method has recently been proposed at SPring-8, in which the length of the (outer) supporting shaft is adjusted to compensate the gap variation induced by the temperature gradient. For this purpose, a new outer shaft based on a "differential adjuster" concept has been developed. The schematic illustration and the photograph of the new outer shaft is shown in Fig. 4.

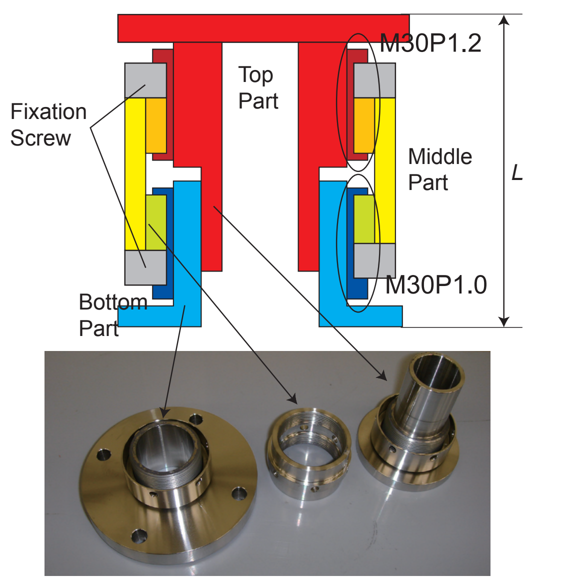

Figure 4: Differential adjuster for the adjustable outer shaft.

The function of the new shaft is similar to that of a turnbuckle: a device to adjust the tension or length of ropes and cables. The typical turnbuckle consists of a metal loop with two tapped holes having opposite direction of the threads, and two hooks screwed into the holes. The distance between the two hooks can be controlled by revolving the loop and thus the tension can be adjusted.

The new shaft has a similar structure to that of the turnbuckle. The difference is that the pitch distances of the two threads are slightly different (1.2 mm and 1.0 mm), but the directions of the threads are identical. By revolving the middle part that corresponds to the metal loop in the case of the turnbuckle, the distance L can be controlled with a resolution of 0.2 mm per revolution. The fixation screws are used to rigidly fix the position of each component after adjustment.

The new shaft based on the above concept has been adopted for the outer shaft of the CPMU for SLS and the performance has been checked in the normal undulator field correction process at RT. The example of correction by the differential adjuster is shown in Fig. 5 in terms of the phase error as a function of the pole number. There exists 6 positions per inner beam for the supporting shaft. In this example, outer shafts at 4 positions have been adjusted by a few microns to reduce the r.m.s. phase error from 4.7 degree to 3.3 degree. In correction, the optimum value for adjustment at each shaft has been determined by analyzing the field data measured by actuating the Hall sensor and calculate the expected phase error. Then actual adjustment has been made by monitoring the field change with the Hall sensor located at the position of the shaft to be adjusted. The procedure at RT mentioned above can also be applied at a CT, which is to be made soon.

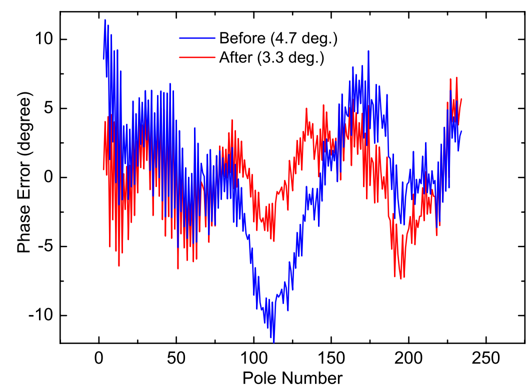

Figure 5: Example of the field correction by the differential adjuster applied to the CPMU for SLS at RT. Note that this is not the final status of the phase error.

Other Topics

Besides the topics mentioned in the former sections, we have other important issues to be concerned.

Firstly, we have to consider the cooling system. Three different systems have been tried so far: cryocooler at SPring-8, gas coolant at NSLS, and liquid nitrogen circulation at ESRF. In each case, the temperature was successfully reduced below the optimum operation point and thus it is feasible to use any of these options. The choice should be made according to the infrastructure available, initial and maintenance cost, and manpower.

Secondly, the gap variation brought by the thermal shrink of the supporting shaft should be monitored and compensated. This is important to determine the optimum temperature by measuring the averaged peak field as a function of the magnet temperature. In SPring-8 and BNL, an optical micrometer (KEYENCE, LS-7000) has been used for this purpose.

Thirdly, the vacuum system should be carefully considered if PMs have been chosen that are not allowed to be baked at a high temperature due to low coercivity. It is worth noting that IVUs without bakeout are operated at RT in the linac of the SCSS test facility, the prototype for SPring-8 X-ray FEL. Although the total pumping speed is half of that of the standard IVUs at SPring-8, the nominal vacuum of the SCSS IVU is better than 10^{-7} Pa. Because the PM pieces that account for most of the surface area in the vacuum chamber are cooled down to a CT, the outgas is significantly reduced in the CPMU. The achievable vacuum is thus expected to be much better than 10^{-7} Pa and probably meet the requirements for installation in the storage ring.

Finally, it should be emphasized that a new PM material with Pr instead of Nd for the rare earth element has been developed (Hitachi Metals) and found to have a remanence as large as 1.64 T at 77 K [8]. Although further research will be required for application to a CPMU, it is expected to be another PM material to broaden the possibility of the CPMU concept.

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