IN-SITU MAGNETIC CORRECTION FOR CRYOGENIC UNDULATORS

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Abstract

The cryogenic permanent magnet undulator (CPMU) is an insertion device in which permanent magnets are cooled down to cryogenic temperature (CT) to improve the magnetic performances. Toward realizataion of CPMUs, it is important to establish a technique to measure the magnetic field at CT and to correct it if necessary. A new method of the undulator magnetic correction has been developed at SPring-8 based on a mechanical adjustment of the in-vacuum beam. This method is available at CT without breaking the vacuum and thus enables the "in-situ" field correction. The feasibility of this method has been tested with the CPMU for the SLS storage ring, the results of which are reported in this paper.

INTRODUCTION

The cryogenic permanent magnet undulator (CPMU) is an insertion device (ID) first proposed at SPring-8 [1] to improve the performance of permanent magnets (PMs) in terms of the remanent field and coercivity. In particular, the improvement of coercivity is pronounced, and thus PM materials with a high remanent field but a low coercivity at room temperature (RT), which cannot be used in in-vacuum undulators (IVUs), are available in CPMUs. This is a great advantage over the conventional IVUs toward shortening the magnetic period and thus several facilities have already constructed prototype CPMUs [2]-[4].

CPMUs are easily realized by a slight modification of IVUs. What we need to do is to install an additional cryogenics and to cool down the PM arrays to an optimum temperature (T_o) at which the undulator field becomes maximum. It should be noted, however, that we have several technical challenges to be overcome. Among them, the most important is how to check the magnetic field error at T_o, and how to correct it if it is beyond the acceptable level.

The magnetic measurements at CT for CPMUs have been carried out at several institutes [4],[5]. It has been found in these measurements that the magnetization vectors of individual PM pieces did not significantly change both in magnitude relative to average and in angle. In other words, the deviation of the temperature coefficient of PM material is nearly negligible. This means that the conventional undulator field correction, which is to be done at RT, is still effective even at CT and is applicable to CPMUs as well as the other normal IDs. Nevertheless, it was found in [4] that the phase error increased by about 1 degree at T_o compared to that at RT. This performance degradation was found to be attributable to a variation in the magnet gap along the undulator axis (gap variation) induced by temperature gradient, and can be an obstacle to the realization of longer CPMUs with less phase errors for the utilization of higher harmonics.

In order to compensate the temperature gradient and to correct the resultant phase error increase, a new method has been proposed at SPring-8 [6], in which the gap variation is corrected by the mechanical adjustment of the out-vacuum shafts supporting the in-vacuum beam. What is important in this method is that the correction can be done at CT without breaking the vacuum, i.e., an "in-situ" field correction is possible. In this paper, the principle and results of the in-situ correction are presented.

PRINCIPLE OF CORRECTION

The temperature gradient along the PM arrays of conventional IDs gives rises to a variation in the remanent field of PMs, resulting in a large phase error. In CPMUs, however, this problem can be avoided by operation at T_o at which the remanent field reaches maximum and becomes less sensitive to temperature change. Nevertheless, the temperature gradient in CPMUs can cause a large phase error as explained in Fig. 1. After cooling down, the out-vacuum beam is kept at RT, while the in-vacuum beam is cooled down to CT. If the temperature gradient along the PM array is large, a nonnegligible gap variation is induced by difference in thermal shrink between the in-vacuum shafts.

In order to correct the phase error as described above, we have to solve two problems: one is how to retrieve the information on the gap variation and the other is how to correct these variations, which are explained in the following sections.

How to Retrieve the Information?

The most straightforward way to get the information on the gap variation is to directly measure the gap values along the undulator axis. It is easy to understand, however, that a better solution is available, i.e., to measure the magnetic ditribution and deduce the gap variation from the measurement results. In order to do so, we have developed a

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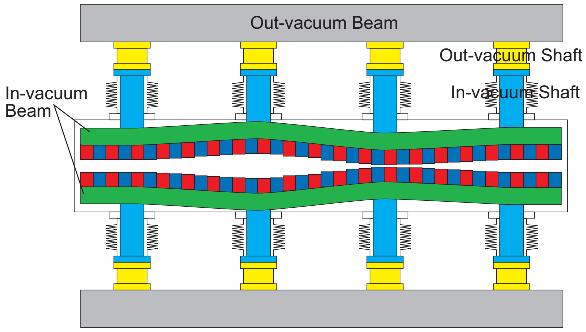

Figure 1: Deformation of the in-vacuum beam and resultant gap variation along the undulator axis.

new magnetic measurement system to be available in an ultra high vacuum (UHV) environment, and an analytical method to retrieve the gap variation.

The new measurement system is based on the SAFALI (self aligned field analyzer with laser instrumentation) system [7]-[8] developed for the measurement of IVUs for SPring-8 XFEL. The original SAFALI system was not applicable to the measurement under the UHV environment. In the new system, all the components have been modified to be compatible to UHV and thus it is called the in-vacuum SAFALI system. It is worth noting that the in-vacuum SAFALI system does not require any special vacuum chamber dedicated to measurement.

Once the magnetic distribution is measured, it is possible to deduce the gap variation according to the relation [6]

$$\eta(z) = \frac{\lambda_u(1+K^2/2)}{2\pi K^2}\frac{d\phi(z)}{dz}, \quad (1)$$

where $\eta(z)$ denotes the peak field deviation and z the longitudinal position. In the derivation of the above formula, it has been assumed that the field error is well corrected at RT and that $\eta(z)$ is a slowly varying function of z. This means that the magnetic field distribution $B_y(z)$ at CT is given by

$$B_y(z) = B_0[1+\eta(z)]\cos(2\pi z/\lambda_u), \quad (2)$$

where B_0 is the nominal peak field and λ_u is the undulator period. If these conditions are satisfied, the field deviation function $\eta(z)$ is given by differentiating the phase error $\phi(z)$. Then it is easy to get the gap variation by calculating or measuring the dependence of the magnetic peak field on the magnet gap.

How to Adjust the Gap Values?

In order to correct the gap variation, a new out-vacuum shaft whose total length can be adjusted by a differential screw mechanism, has been developed.

As shown in Fig. 2, the developed out-vacuum shaft has a similar structure to that of a turnbuckle and is called the "differential adjuster". The difference from the turnbuckle 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 corresponding to the metal loop of the turnbuckle, the distance L can be adjusted with a resolution of 0.2 mm per revolution. The sensitivity of the gap correction is found to be better than 5 μm. The fixation screws on the top and bottom sides are used to rigidly fix the position of the individual components after adjustment.

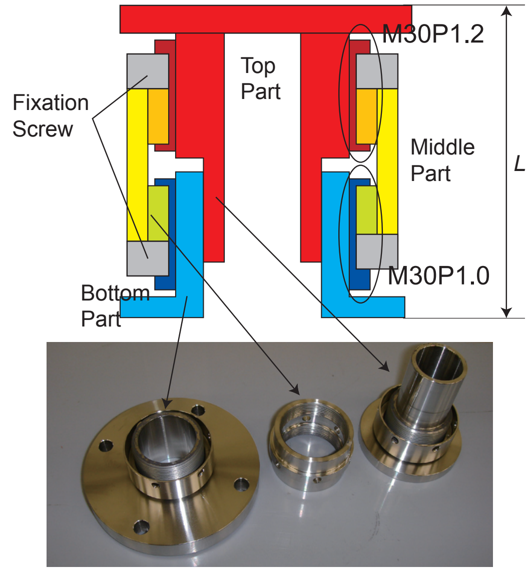

Figure 2: Structure and picture of the differential adjuster as an out-vacuum shaft.

RESULTS OF FIELD MEASUREMENT AND IN-SITU CORRECTION

The in-situ correction method described above has been applied to a new CPMU constructed for installation in the SLS storage, the details of which are out of scope of this paper and to be presented elsewhere.

After installing all the components of the in-vacuum SAFALI system, we measured the field distribution at the gap of 8 mm to check the magnetic performance at RT. The results are shown in red lines in Figs. 3 (a) and (b) in terms of the 2nd field integral (beam trajectory) and phase error, respectively. The r.m.s. phase error was found to be 1.0 degree, which was good enough to observe the performance degradation due to cooling.

We then started to cool down the PM arrays with the liquid nitrogen (LN_2) cooling system, which is originally dedicated to the monochromator cooling. The lowest temperature of the PM arrays was 117 K, at which the field measurement was carried out to compare with the measurement at RT. It should be noted that the optimum temperature T_o was found to be around 140 K and thus 117 K was well below T_o. The reason why we have done the magnetic measurement at 117 K is to enhance the effect of the temperature gradient.

The results of the field measurement are shown in blue lines in Figs. 3 (a) and (b), where we find that the r.m.s. phase error increased largely to 3.8 degree as opposed to the small change of the beam trajectory. Obviously, this is attributable to the gap variation induced by the temperature gradient.

In order to correct the phase error, we applied the in-situ correction method. After smoothing the phase error data $\phi(z)$ by fitting with the 6th order polynomial function to eliminate the rapidly oscillating term due to the trajectory error, it was differentiated to obtain the field deviation function $\eta(z)$ according to Eq. (1). The order of polynomial was chosen to be equal to the number of in-vacuum shafts, i.e., the fixation points of the in-vacuum beam. For reference, the locations of the fixation points are indicated in dotted lines in Fig. 3(b). The approximate gap variations at these locations were found to be -10 μm, 0, $+30$ μm, 0, -30 μm, -30 μm, respectively from left to right, which were corrected easily by the differential adjuster with the sensitivity better than 5 μm.

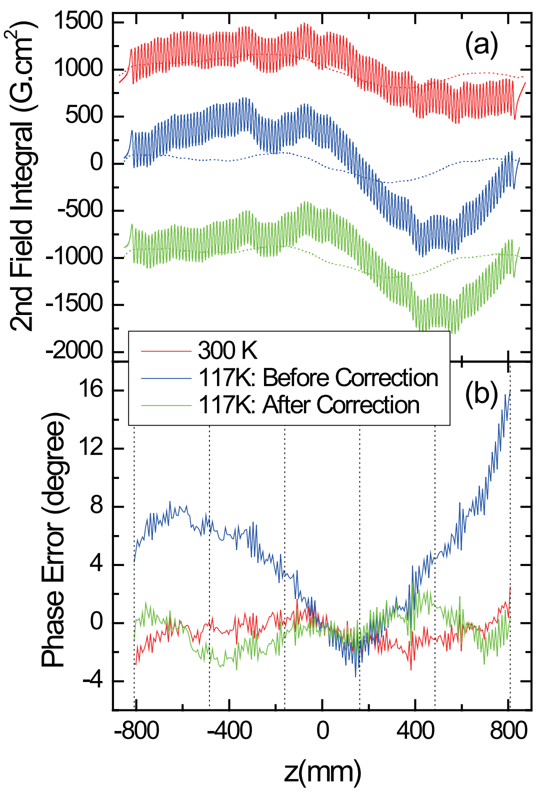

Figure 3: Reults of magnetic measurement at different conditions in terms of (a) the electron trajectory and (b) the phase error. The solid and dotted lines in (a) show the horizontal and vertical trajectory, respectively.

The result of correction is shown in green lines in Figs. 3 (a) and (b). The r.m.s. phase error was reduced to 1.1 degree, comparable to that at RT. Note that the trajectory did not change before and after the correction, meaning that the trajectory error is not the main reason for the phase error increase due to cooling.

SUMMARY

We have shown that the proposed in-situ field correction method worked well in the CPMU to reduce the phase error induced by the temperature gradient. It should be stressed that this method is also applicable to normal IVUs to correct the phase error that is attributable to the slowly varying field deviation but not to the localized field errors. For example, let us consider two possible error sources to increase the phase error.

One is the reassembling of the PM arrays. In the manufacturing process of IVUs, the PM arrays should be usually detached from the mechnical frame to be installed inside the vacuum chamber. This reassembling process can give rise to the gap variation as in the case of the cooling process in CPMUs. The other is the demagnetization of PMs due to the irradiation of the electron beam during a long-term accelerator operation. In both cases, it is obvious that the field deviation function will probably be a slowly varying function, and thus the resultant phase error can be corrected by the in-situ correction technique described in this paper.

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