Effect Analyses of Thermal Deformation on Magnetic Performance of the CPMU Prototype in SSRF

Jian Wang1, Li Wang2, Yiyong Liu3, Wei Zhang3
1Huazhong University of Science and Technology (HUST) Wuhan, Hubei, 430074, China
2Lawrence Berkeley National Laboratory (LBNL), Berkeley, California, 94720, USA
3Shanghai Advanced Research Institute, Chinese Academy of Science (SARI-CAS) Shanghai, 201204, China

Abstract. A cryogenic permanent magnet undulator (CPMU) prototype cooled by sub-cooled liquid nitrogen was developed in Shanghai Synchrotron Radiation Facility (SSRF) in 2016. The CPMU prototype mainly consists of NdFeB based hybrid magnet arrays with a period of 20 mm and a magnetic length of 1.6 m, a pair of girders to support the magnetic arrays, parallel SLN2 cooling loops attached to the girders, thermal spacers connecting the girders and the copper LN2 tubes, electric heaters to heat the girders and regulate the magnet working temperature at around 120 K, and stems made of stainless steel to support the girders. During the first magnetic field measurement, the RMS phase error of the CPMU prototype changed from 3.2 degree at room temperature to 4.5 degree at 135 K. By shimming the magnetic field, its RMS phase error is reduced to 3.5 at low temperature finally. This paper presents detailed analyses of temperature distribution and thermal deformation along the CPMU girder during cool down process. By comparison with test results, the deterioration of the RMS phase error is well explained. The analyses can provide guidance for magnetic field shimming and avoid or reduce the deterioration of the RMS phase error at low temperature.

1. Introduction

In 2016, SSRF installed an NdFeB based CPMU in the storage ring and achieved its first synchrotron radiation spectrum under high beam current of 240 mA. The magnetic phase error was 3.5°.

The magnetic structure of the CPMU was designed with a period of 20 mm in hybrid type, which consisted of pure iron poles and NdFeB blocks. [1] The poles and magnet blocks were mounted on a pair of girders made of aluminum alloy through clappers. Along the side grooves of the girders, cooling loops with 78 K SLN2 flowing inside were attached to the girders. With the thermal spacers connecting the girders and the copper SLN2 tubes and the electric heaters attached to the girders, the CPMU could be regulated to work at the temperature range from 119 K to 145 K. [2]

During the first cooling process and the magnetic measurement of the CPMU prototype, the max effective peak field of 1.038 T at gap 6 mm appeared around 135 K. At the same time, the RMS phase
The RMS phase error is one of the key parameters indicating the magnetic performance of the undulators including the CPMU. The cooling process affects the CPMU’s RMS phase error under low temperature through two ways. One of them is through the remanence of the magnet material, namely NdFeB in this CPMU prototype. There is intrinsic difference in the remanence change curves with temperature among the magnet blocks. [3] This difference can deteriorate the RMS phase error randomly when the magnetic blocks are cooled to low temperature. Another way is through the magnetic gap. The magnetic gap changes with temperature decreasing of the magnetic structure globally and locally. Because the non-uniformity of temperature brings non-uniform cold shrink deformation to the magnetic structure, the RMS phase error can be enlarged with CPMU’s temperature decreasing.

To reduce its magnetic phase error and temperature difference along the magnetic structure, the effect analysis including the magnetic field, temperature distribution and deformation has been conducted with FEA tools. The detailed effect analyses of thermal deformation on magnetic performance of the CPMU will be described and argued in this paper.

2. Measurement result
During the first test before shimming the magnetic field based on cold test result, the CPMU was assembled with magnetic measurement bench and tested under different working temperature. The peak field of the CPMU with the gap of 6 mm increased from 0.96 T at room temperature to 1.06 T at around 130 K. Meanwhile, the phase error increased from 3.2 ° to 4.5 ° due to the deformation caused by cooling process.

![Figure 1. (a) CPMU prototype under magnetic test. (b) CPMU installed in the storage ring.](image)

![Figure 2. Peak and effective field curves with temperature[1]](image)

![Figure 3. RMS phase error curves with temperature[1]](image)
Comparing the peak field before cooling process and afterwards, the peak field variation, namely, increments of the different periods were not uniform. The variation distribution curves of the peak field along the magnetic structure between room temperature condition and cryogenic condition of 130 K are shown in figure 4. The peak field at ends increased more than it at the middle part.

![Variation distribution curves of the peak field along the magnetic structure between room temperature condition and cryogenic condition of 130 K](image)

**Figure 4.** (a) peak field distribution of the periodic magnetic field under 297 K and 135 K  
(b) Peak field increment of CPMU between 297 K and 135 K

At the same time, during the working temperature regulated from 119 K to 145 K through the electric heaters, the max temperature difference of each girder were lower than 2 K. As shown in figure 5, the platinum temperature sensors were mounted on the two girders to measure the temperature distribution of the magnetic structure. The temperature uniformity of the bottom girder is as good as 0.5 K.

![Layout of heaters and temperature sensors on CPMU girders](image)

**Figure 5.** Layout of heaters and temperature sensors on CPMU girders
Figure 6. Max temperature differences of CPMU girders with temperature (measured)[1]

3. Numerical analyses

Whether the temperature difference can explain the deterioration of the magnetic phase error completely? How does the temperature uniformity influence the gap deformation and the magnetic field? To answer these questions and to find methods to improve the CPMU’s performance, numerical analyses about the magnetic structure of CPMU has been conducted based on FEA tools.

The magnetic attraction force between the poles mounted on the two girders is about 21 kN when the undulator works at room temperature. The vertical deformation, namely, gap deformation of one girder distributed as figure 7(a) showed. The vertical deformation is between -0.01167 mm—0.1958 mm. While the deformation at the ends is larger than it at the girder’s middle area. The deformation curve along the girder is like flat parabola. The deformation caused by magnetic attraction force is compensated through initial magnetic shimming before cooling down. This deformation is original mechanical deformation and compensated during the magnetic measurement without vacuum chamber.

As shown in figure 7(b), when the magnetic structure down was cooled to the low temperature conditions, three cases including 115 K, 130 K and 145 K have been simulated. The temperature distribution result of case 130 K are shown in figure 8. In this case, the max temperature difference of the girder is below 0.4 K. The temperature distribution curve along the girder is nearly parabolic with the highest temperature point locating at the middle area in all cases.

In addition, the vertical deformation of the three cases are shown in figure 7(b). The average vertical deformation variation rate with temperature is evaluated about 0.0073 mm/K. The curves are also nearly flat parabola. With the temperature decreasing, the deformation difference between the ending part and the middle part is enlarged.

Normally speaking, the mid part with higher temperature should have had a smaller cold shrinkage. The peak field of the mid part should have been bigger than the end part. However, as shown in figure 4, comparing the magnetic measurement results and the simulating ones, the magnetic field at the ends became higher than the mid part due to the non-uniform deformation of magnetic structure, which is totally different from the ‘common sense’. This non-uniform deformation is mainly determined by the original mechanical deformation which can be enlarged by cooling process as shown in figure 7(b).

As a conclusion, the temperature difference of the girders is not the main factor causing the deterioration of the phase error in this CPMU prototype. The original mechanical deformation influenced by stems and the girders’ rigidity is responsible to the magnetic performance and should be modified.
It was observed that the magnetic gap of the magnetic arrays’ ending would become smaller than the middle part during the cooling process which deteriorated the performance of the CPMU especially the RMS phase error. By regulating the supporting ending stems of the CPMU, the difference of the magnetic gap along the girders was compensated. As a result, the phase error of the CPMU under low temperature is nearly the same as the room temperature condition. In 2016, SSRF installed the CPMU prototype in the storage ring and achieved its first synchrotron radiation spectrum successfully with the RMS phase error of 3.5°.

5. Conclusion
The SSRF developed an NdFeB based CPMU prototype in 2016. The CPMU’s RMS phase error deteriorates with the working temperature decreasing from room temperature to 135 K, at which the max peak field appeared. The temperature uniformity of the magnetic structure was good enough, while the deterioration of the phase error was caused by the original mechanical deformation that can be enlarged by temperature decreasing. Through pre-compensating the gap difference of the magnetic arrays by regulating the supporting stems, the CPMU was modified and then installed in the storage ring of SSRF.
6. References

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