FIELD ERROR CORRECTION CONSIDERATIONS OF CRYOGENIC PERMANENT MAGNET UNDULATOR (CPMU) FOR HIGH ENERGY PHOTON SOURCE TEST FACILITY (HEPS-TF)*

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Abstract

Considerations are made for field error corrections of a 2m-long CPMU in built for HEPS-TF. Field changes in cooling to liquid nitrogen temperature are simulated. 1st field integral of terminal changes by tens of Gauss cm and RMS of phase errors induced by cold contraction is less than 1° when temperature gradient along girder is below 1.5K/m. Field signature of magic finger is unchanged with temperature. Strategy of the field error correction is discussed.

INTRODUCTION

A 2m-long CPMU with period length 13.5mm is to be built for the HEPS-TF. The undulator is to be cooled down to liquid nitrogen temperature (80K) to improve its magnetic performance. Both magnetic strength and radiation hardness will be enhanced in cold environment [1]. PrFeB other than NdFeB material is employed to build the magnet blocks since it has a lot of superiorities in low temperature [1]. The undulator adopts the classic 1/4-3/4-1 terminal structure [2] and the two terminals are anti-symmetric, which makes zero 1st field integrals in nature. However 1st integral of each terminal may exist in practical, due to the design and manufacturing errors. The parameters and specifications of the CPMU at 80K are listed in Table 1.

To guarantee the field performance in cryogenic environment, considerations are made for field error correction. Field simulation is made and field correction strategy is discussed.

PRIMARY CONSIDERATIONS

Current devices showed that magnetic performance of cryogenic undulator changes with cooling [3-4]. Two aspects are observable: First, susceptibility of magnet materials varies and affects the 1st field integral of the terminal and electron trajectory. Second, inhomogeneous cold contraction makes the mechanical structure deformed and field errors appear.

To improve the field quality, the CPMU will be manipulated in both room and cryogenic conditions to eliminate field errors after manufacturing and assembly. It may take several times of cooling-warming-cooling cycle to reach the specifications. The process in combined with vacuum pumping will spend weeks of time.

According to the mechanical design of CPMU13.5, the field error correction tools include the adjustment of poles, the exchange of magnets, machining and tuning of terminal magnets and poles, differential shafts [5] and magic finger (small magnet sticks).. Shim (thin iron piece) is not applying since glue is forbidden in vacuum. Smoothness of the assembly surface requires pole tuning amount not more than tens of microns, with only weak field signature. Current studies favour that magnet swapping is a more effective tool and the in-situ method has been developed [6].The cryogenic effect of magic finger need be investigated. Finally, field error correction is a searching problem of operation for specific errors, and stochastic algorithm is applying [7].

Table 1: Parameters of CPMU13.5

Period length	13.5 mm
Period number	140
Working temperature	80K
Working gap	5-9mm
K value	1.26@Gap=5mm
Peak field	1T@Gap=5mm
RMS of Phase errors	<6°
1st field integral	<100Gscm

Field Simulations in Room and Cryogenic Conditions

A 3D model was built with RADIA [7] to simulate the magnetic fields of CPMU13.5 (Fig. 1). Both room and cryogenic conditions are simulated. The simulation bases on the measured PrFeB properties and the simulation of mechanical performance.

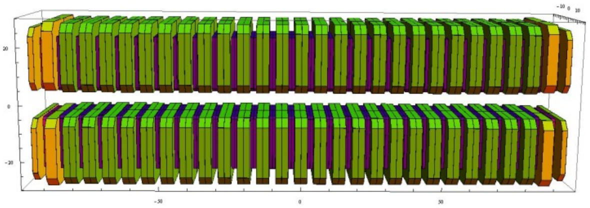

Figure 1: A 12-period model of CPMU13.5 with RADIA.

Figures 2-3 gives the simulated fields and their second integrals at 80K and 293K using the model in Fig.1, without regard for any mechanical deformations. The peak field at gap 5mm is 1T at 80K, 25% stronger than that at 293K. The 2nd field integral (proportional to the electron trajectory) is parallel to the beam axis at 80K while has a deviation angle with the axis at 293K. The slope of the second integral equals to the 1st integral of the entrance terminal, where the magnetic design makes these values approaching zeros at all gaps in cryogenic condition (Fig. 2).

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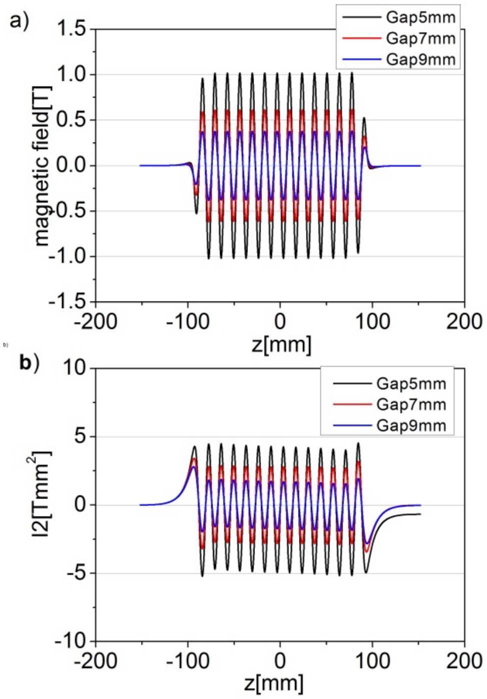

Figure 2: a) Magnetic fields, b) the 2nd integrals at 80K

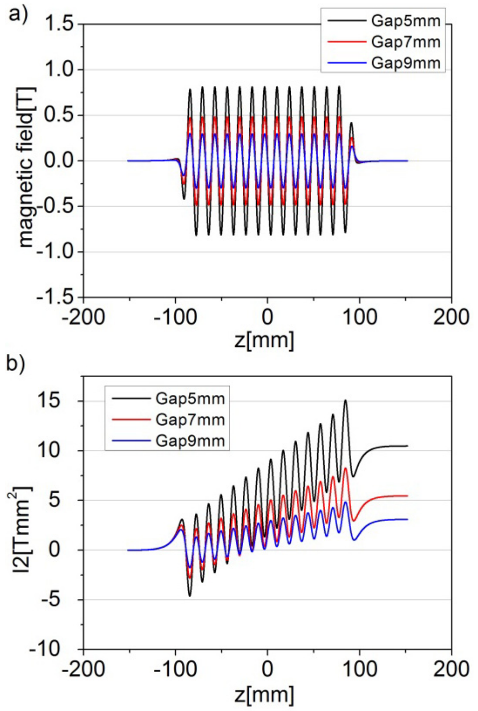

Figure3: a) Magnetic fields, b) the 2nd integrals at 293K

Table 2: 1st Field Integrals of Entrance Terminal

Gap	80K	293K
5mm	-0.4	67.2
7mm	-2.3	35.8
9mm	-1.1	20.9

As is seen in Table 2, change of terminal 1st field integral with cooling is 67.6Gscm at gap=5mm, comparable with the measured device of ESRF with period length 18mm and that value about 60Gscm at Gap=6mm when cooled from 300K to 120K [4]. The value change is gap-dependent and gives the signature for room manipulation.

A longer RADIA model with full 140 periods is built to investigate the field performance in the existence of cold contraction. In low temperature, structure contracts and deformation generates. The deformation makes the gap between the assemblies change. If the gap change is universal along the beam axis (z direction), it will be compensated by movement of motors. However, if the gap change along z is various, field errors occur. The gap variance is to be corrected by differential shafts [3-5] in cold. Many factors affect the style and amount of mechanical deformation, e.g., design of the structure and cooling system. With ANSYS [8], structure deformation can be simulated in different conditions. ANSYS shows that girder deformation in force is much more significant than magnets and poles. By combining the contraction of top and below girders, the gap variance along z is obtained and used as the input of RADIA. By comparing the field performance for different design, structure and cooling scheme can be optimized. Figure 4 shows the gap variance along the girder with 3 support rods and liquid nitrogen pipelines connected in parallel in three conditions: the temperature gradients along each girder is 1K/m, 1.5K/m and 3K/m respectively at 80K. The gap variance has excluded the averaged 0.6mm contraction of each girder, with 1.2mm enlargement of the gap. The gap variance along z is in ±0.01mm at 1K/m and ±0.02mm at 3K/m, and the maximal deformation occurs at both terminals.

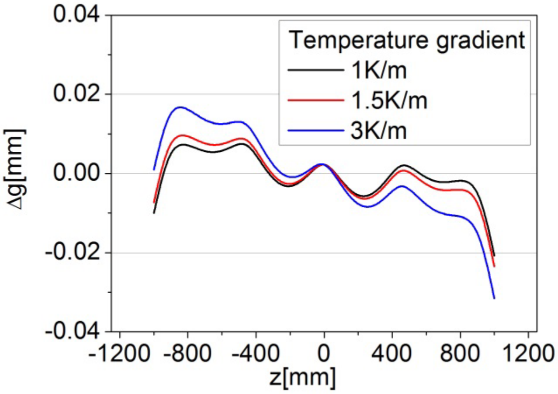

Figure 4: Gap variance along the beam axis at 80K.

Figure 5 shows the field errors in the same conditions with Fig. 4. Field errors are proportional to the gap variance, ranging 20-40Gauss. The phase errors rise rapidly with temperature gradient, as Fig. 6 shows. When temperature gradient increases from 1K/m to 3K/m, the phase errors grow from 0.4° to 1.8°. The non-linear growth of phase errors is due to the accumulation effect of field errors:

$$\varphi(z) = \frac{2\pi}{\lambda_r\left(1+\frac{K^2}{2}\right)}\left(\frac{z}{2\gamma^2}+\frac{1}{2}\int_{-\infty}^{z} x'(z')^2 dz'\right) \qquad (1)$$

where

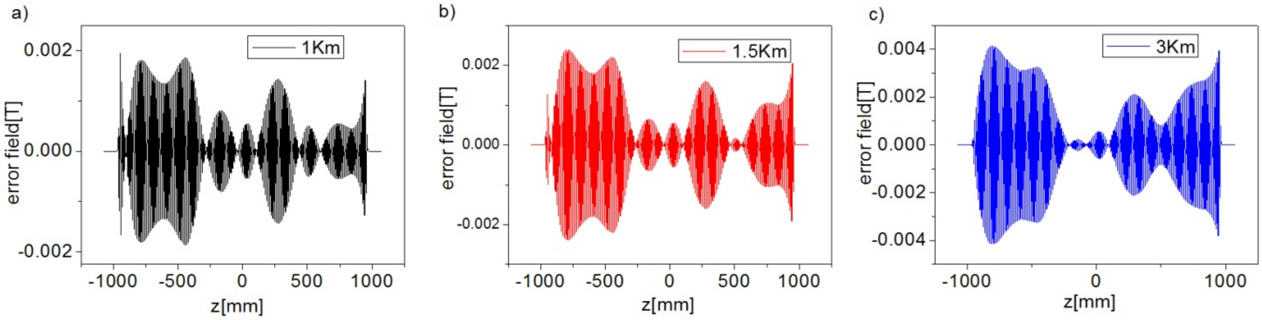

Figure 5: Magnetic field errors in the same conditions with Fig.4.

$$\lambda_r = \frac{\lambda_u}{2\gamma^2}\left(1 + \frac{K^2}{2}\right) \quad (2)$$

$$x'(z') = -\frac{e}{\gamma m_e c}\int_{-\infty}^{z} B(z')dz' \quad (3)$$

λ_u is the period length and γ is the relative electron energy.

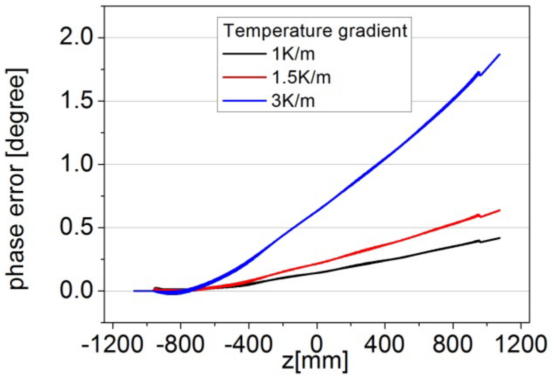

Figure 6: Phase errors in the same conditions with Fig.4.

Simulations have been made in more conditions to optimize the mechanical and cooling system. The results show that temperature gradient is much more important than other factors, such as stress strength and layout styles of cooling pipelines. When temperature gradient of each girder is less than 1.5K/m, RMS of phase errors keeps below 1° in those simulations.

Magic finger is also simulated with RADIA. Field signature doesn't change with temperature, implying that the non-linear interaction between finger and undulator is insignificant.

Field Error Correction Strategy

Field error correction is a searching problem in essence. Objective function is the performance of magnetic fields and answer is the operations. All the magnetic performance is related with the 1st field integral of each half period (including the terminal sections). 1st and 2nd field integrals along the beam direction (corresponding to electron deflection angel and trajectory), and phase errors (Eq.1-3) can be derived from it. In this sense, 1st field integral of each half period is a basic signal, and a signal library with all operations can be built with calibration or simulation. A routine applying generic algorithm is in fabrication to resolve the problem.

It is divided into two steps to correct field errors: First, field uniformity of standard periods is sufficient. Second, Terminal fields can properly compensate the accumulated errors of the middle section.

SUMMARY

The cold effect on field errors has been simulated. 20 microns of girder deformation increases phase errors about 2°. The temperature gradient along the girder is suggested to not more than 1.5K/m to depress the field errors in cold. Magic finger shows good temperature characteristics and make itself suitable for cryogenic use. Strategy and steps of field error correction is discussed.

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REFERENCES

[1] J. Chavanne , G. Le Bec, and C. Penel, “Cryogenic Permanent Magnet Undulators, Synchrotron Radiation Synchrotron Radiation News, 24: 3, pp.10- 13,2011.

[2] D. Humphries, et al., “Design of End Magnetic Structures for the Advanced Light Source Wigglers”, in *Proc. PAC95*, pp1447-1449, 1995.

[3] Takashi Tanaka, et al., “In situ correction of field errors induced by temperature gradient in cryogenic undulators”, Phys. Rev. Spec. TOP-AC, 12, 120702, 2009

[4] Charles, Kitegi, “Development of a Cryogenic Permanent Magnet Undulator at the ESRF”, Doctoral Dissertation, 2008.

[5] T. Tanakaa,T. Seikeb, and H. Kitamuraa, “Undulator field correction by in-situ sorting”，Nucl. Instrum. Methods Phys. Res., Sect. A 465, p600–605, 2001.

[6] O.Chubar, O.Rudenko, C.Benabderrahmane, O.Marcouille, J.M.Filhol, and M.E.Couprie, “Application of Genetic Algorithms to Sorting, Swapping and Shimming of the SOLEIL Undulator Magnets”, in *AIP Conf. Proc.* 879, pp359-362, 2007

[7] P. Elleaume, O.Chubar, and J.Chavanne, “Computing 3D Magnetic Field from Insertion Devices”, in *Proc. PAC97*, pp3509-3511,1997.

[8] ANSYS, `http://www.ansys.com`