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CRYOGENTIC PERMANENT MAGNET UNDULATOR OF SSRF*

Y. He, M. Qian, H. Wang, W. Zhang, Q. Zhou, Shanghai Institute of Applied Physics, CAS, 201204, Shanghai, China

Abstract

Two Cryogenic Permanent Magnet Undulators (CPMU18 with PrFeB magnets P46H and CPMU20 with NdFeB magnets N48H) were designed and developed in SSRF in the past few years (2014-2017).This paper introduces the magnetic performance of the permanent magnets, design parameters of the two CPMUs, cryogenic cooling and magnetic field of the two CPMUs and so on. When the gap of the two CPMUs is about 6.0 mm, the measurement results showed that the effective magnetic field peak of CPMU18 at 300 K and 77 K was 0.82 T, 0.92T, respectively, and the magnetic field phase error is about 3 degrees and 5 degrees respectively. The effective magnetic field peak of CPMU20 at 300 K and 140 K was 0.94T and 1.03T, respectively, and the magnetic field phase error was 3 degrees and 3.5 degrees respectively.

INTRODUCTION

The remanence Br and intrinsic coercivity Hcj of NdFeB and PrFeB at low temperature can increase at the same time [1]. By this characteristic, the developed Cryogenic Permanent Magnet Undulator (CPMU) can obtain a high magnetic field along with the shortened period length [2, 3, 4]. Compared with Superconducting Undulator [5, 6], CPMU has a low cost and stable operation. Compared with In-vacuum undulator (IVU) [7], CPMU has a high magnetic field and a good vacuum, and CPMU can be improved on the design of IVU. Several CPMUs will be installed and run in an engineering project of the Shanghai Synchrotron Radiation Facility (SSRF) in the future. In the past few years, the project group of SSRF used NdFeB and PrFeB to develop two CPMUs prototypes in order to master the key technology. This paper introduced the design and development of the new type undulator of China.

MAGNETIC PROPERTIES OF MAGNETS

Before development of the CPMU prototype of SSRF, the project group joined the Zhejiang Innuovo Magnetic Industry Co., Ltd of China have developed the two kinds of permanent magnets: NdFeB (N50M, N48H) and PrFeB (P42H, P46H), and have studied the change mechanism of magnetic properties at low temperature, see Fig. 1. It can be seen that, with decrease of temperature: (1) The Br of N50M and N48H shows a near linear increase before 150K and 140K, and then decreases gradually for the spin reorientation effect (SRT) [8]; the Br of P42H and P46H shown near linear increase. (2) The Hcj of all permanent magnets has been enhanced, but the increase amplitude of PrFeB is larger than that of NdFeB. At 150 K and 140 K for N50M and N48H, compared with room temperature, the Br increased by 15.4% and 14.1%, respectively, the Hcj increased by 220% and 150%, respectively. Nearly 77 K compared with room temperature, the Br of P42H and P46H increased by 14.8% and 15.0%, and Hcj increased by 366% and 200%, respectively [9].

The CPMU20 use N48H and the CPMU18 use P46H as magnetic source, respectively. The two magnets are placed under a higher the Br at room and low temperature. This making undulator obtained the higher peak magnetic field. At the same time, the Hcj of the two magnets is about 1600 kA/m at 300 K, which is also conducive to magnetic stability when they be located in room temperature. Although the Br of N50M is greater at low temperature, but the Hcj at room temperature is only about 1200 kA/m, which is not conducive to the stability of the magnetic field at room temperature. The low temperature Br and room temperature Hcj of the P42H are not very ideal.

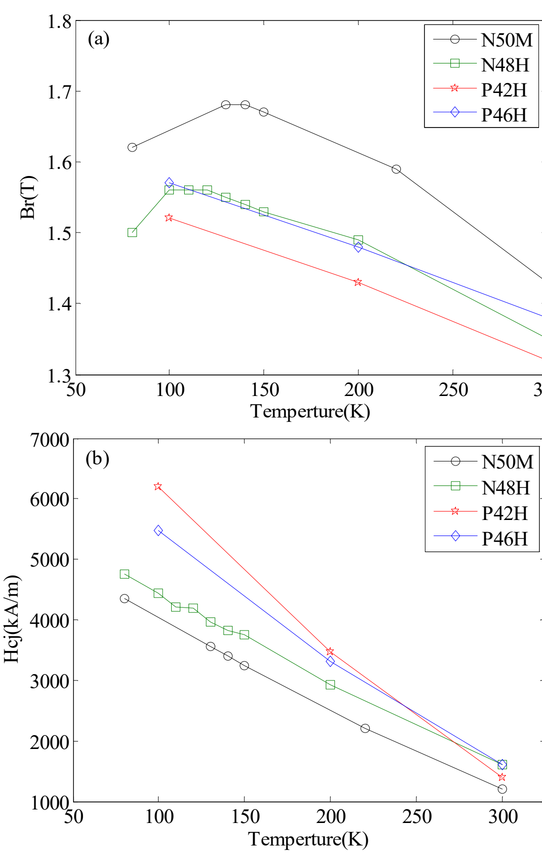

Figure 1: Magnetic properties of magnet for CPMU (a) Remittance, (b) Intrinsic coercively.

MAGNETIC FIELD DESIGN OF CPMU

The two CPMUs prototype of SSRF use the anti-symmetric hybrid magnetic structure design programme,

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using OPERA to calculate the magnetic field distribution of the periodic region of CPMU, including the effective magnetic field of the neutral plane and the magnetic field of the permanent magnet, and optimize the size of the permanent magnet and the soft iron. Table 1 is the design parameter of the magnetic field. The thickness of the permanent magnets and the pole is smaller 0.1mm than the half cycle length, this mainly considering the cold shrinkage of magnetic structure under low temperature. The one or two integral of the CPMU is equal to zero at the same time by the optimization of the end magnetic structure, this is the same as IVU, and the small permanent magnets column "Magic Fingers" arrangement is designed on the outside of the end of the magnetic structure component, which is used to correct the one or two integral and multipolar components of CPMU. Fixed components of the permanent magnet compose of two types, the adjustable height pole for phase shimming.

Table 1: Magnetic Field Design Parameters of CPMU

Project /undulator	CPMU20		CPMU18	
Period length(mm)	20		18	
Periodic quantity	80		144	
Minimum gap(mm)	6		6	
Phase error(°)	<6°@120-150 K		<6°@80K	
Permanent magnet	NdFeB(N48H)		PrFeB(P46H)	
Soft pole	Pure iron(DT4C)		Pure iron(DT4C)	
Magnet size(mm)	65W×25H×6.2D		65W×25H×5.9D	
Pole size(mm)	43W×20H×3.7D		43W×20H×3.0D	
Temperature(K)	300	120	300	77
Br of magnet(T)	1.35	1.53	1.36	1.57
Hcj of magnet(kA/m)	1600	>4000	1580	>6000
Peak field(T)	---	1.07	0.86	0.99
Effective peak field(T)	---	1.04	0.84	0.96
Demag(kA/m)	1050	1160	1200	1400
Magnetic force(kN)	20	23	16	21

CRYOGENIC COOLING SYSTEM

The work temperature of CPMU20 and CPMU18 is about 140 K and 80 K, respectively. The cold source of the magnets is circulation subcooled liquid nitrogen system. The liquid nitrogen supercooling system of CPMU is evaporated by liquid nitrogen (77 K/1atm), it mainly includes vacuum vessel, liquid nitrogen container, liquid nitrogen circulation pump, control valve, vacuum jacket nozzle, heat exchanger, vacuum pump unit system, safety valve, low temperature transmission pipeline, vacuum interlayer hose and measurement and control system.The CPMU20 adopts an indirect nitrogen forced flow cooling methods, the subcooled liquid nitrogen with certain pressure, temperature and flow passes through the cooling line connected to the inner beam,the inner beam and the permanent magnet are cooled by the cooling zone, as showed in Fig. 2(a). The CPMU18 adopts direct forced flow cooling method inside the girder, as showed in Fig. 2(b), the upper and lower beams are cooled by one way conduit.

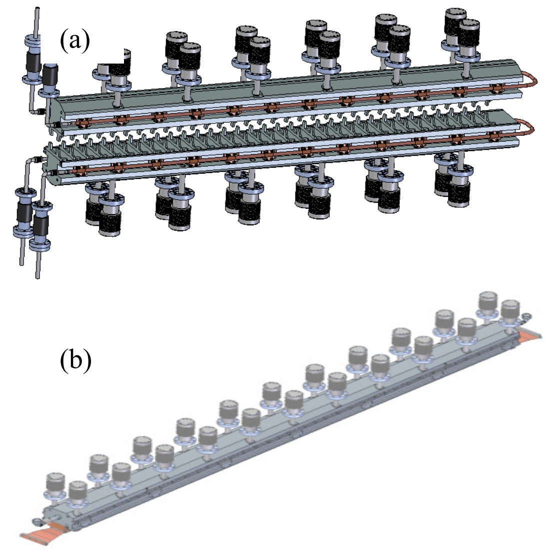

Figure 2: The cooling of the magnet for CPMU (a) CPMU20, (b) CPMU18.

The estimated values of the static thermal load of CPMU20 and CPMU18 are about 200 W and 300 W, respectively. ANSYS internal girder temperature uniformity distribution of the CPMU, the results showed that the temperature difference between the two ends of the inner beam was 1.2 K and 3.8 K, respectively, and the temperature difference both occurred in ends of the CPMU. The reduction of temperature also leads to the cold contraction deformation of the inner beam. The ANSYS simulation results demonstrate that the maximum cold contraction deformation also appears at both ends of the CPMU. The large temperature difference at the end and the cold contraction deformation will cause the distortion of the magnetic field at the two ends of the CPMU, thus increasing the phase error, so the distance between the supporting poles of the two ends is optimized in order to reduce the distortion of the end magnetic field.

MEASUREMENT AND SHIMMING

The measurement and shimming of magnetic field for the two CPMUs prototype are the same as IVU at room temperature, and then repeated measurement and adjust at low temperature. The adjustable connecting rod between the inner and outer beams can change the local air gap of the undulator and compensate for the magnetic error caused by the uneven temperature of the magnets. Fig. 3(a) is the curve of the peak magnetic field and the effective peak magnetic field measured with the temperature at gap@6 mm for CPMU20, the effective peak magnetic field reaches the maximum near the temperature 130 K, is about 1.03 T. Fig. 3(b) is the variation curve of the effective peak magnetic field with gap measured at room temperature and low temperature for CPMU18, the effective peak magnetic field is about 0.82 T and 0.92 T when gap is 6 mm at room temperature and low temperature, respectively.

Figure 4(a) is the phase error distribution of CPMU20 at gap 6 mm @140 K, and its the root mean square value is about 3 degree at 140 K. Fig. 4(b) is the phase error

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distribution of CPMU18 at gap 6 mm@80 K, and its the root mean square value is about 5 degree at 80 K.

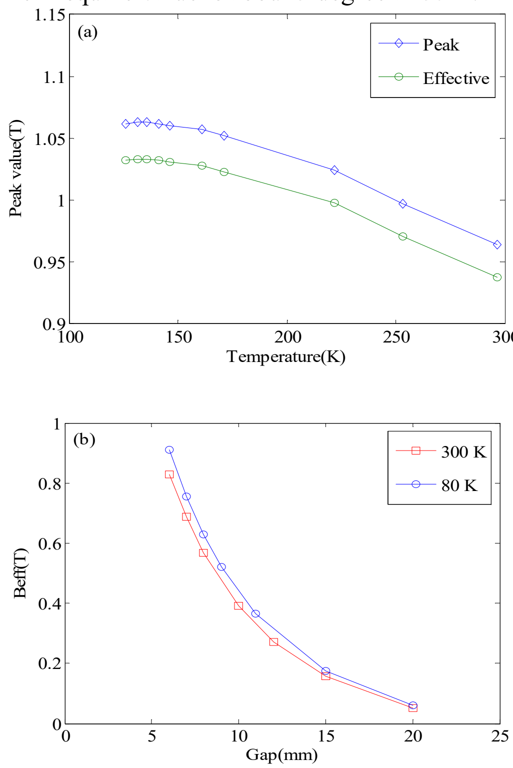

Figure 3: The magnetic field variation of CPMU (a) CPMU20, (b) CPMU18.

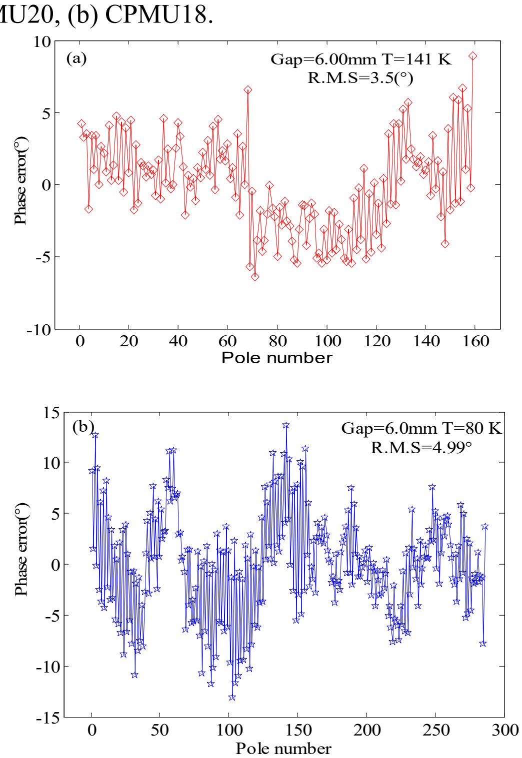

Figure 4: Magnetic field phase error of CPMU (a) CPMU20, (b) CPMU18.

BAND BEAM TEST RESULTS

The CPMU20 was installed in the storage ring of SSRF in January 2017, see Fig. 5(a). When it operating in the 3.5 GeV/240 mA state and the minimum gap 6 mm, the 17U beam line was used to measure the spectrum, the clear 9 harmonic radiation was obtained, and the corresponding magnetic phase error was 3.5 degrees. The CPMU20 measured in the photon energy 12.66 keV commonly used than the high photon flux of 40% 17U at room temperature for IVU25. The CPMU18 was installed in the storage ring of SSRF in September 2017, see Fig. 5(b), the experiment used 13W beam line to measure the spectrum of the CPMU18, and got a clear 9 harmonic emission, the corresponding magnetic field phase error is 5 degree, when energy is about 26.6 keV, the 9 harmonic radiation has a luminous flux of 8×10^{-12} phs/s/0.1% btw.

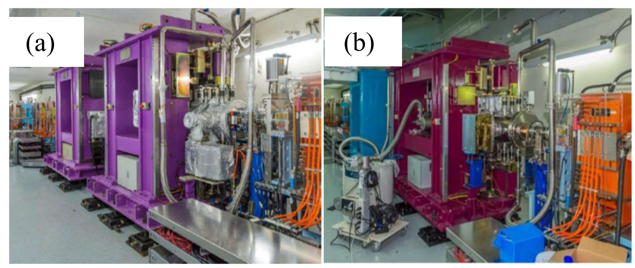

Figure 5: CPMU mounted on storage ring of SSRF (a) CPMU20, (b) CPMU18.

SUMMARY AND PROSECT

After more than two years of efforts, the insert device project team of SSRF have solved the key technical problems of the CPMU, for example, the preparation of higher performance NdFeB and PrFeB, the cooling of internal beam, the temperature uniformity control, and the measurement and shimming of the magnetic field of the CPMU in the low temperature and vacuum environment, the Cryogenic Permanent Magnet Undulator prototype of China have were firstly developed successfully. This work set the stage for the foundation for design and development of the higher performance of CPMU. The main problems to be resolved are: (1) For CPMU made of NdFeB magnets. It is necessary in the problem of high temperature baking of permanent magnets, which are beneficial for the acquisition of ultra-high vacuum at low temperature. (2) For CPMU made of PrFeB magnets. It is necessary for solve the problem of magnetic stability of PrFeB under the constant high temperature baking and installation at room temperature, which is beneficial to the realization of the design index of the magnetic field for CPMU, (3) At present, the magnetic field phase error at the low temperature of the two CPMU prototype is not very ideal, the follow-up needs to study and improve the permanent magnet, the internal beam cooling, the magnetic structure design and so on.

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