

DEVELOPMENT OF A PrFeB CRYOGENIC PERMANENT MAGNET UNDULATOR (CPMU) PROTOTYPE AT IHEP*

H. H. Lu †, W. Chen, Y. F. Yang, S. C. Sun, S. T. Zhao, X. Z. Zhang, L. Zhang, X. Y. Li, Z. Q. Li, L. L. Gong, Y. J. Sun, Institute of High Energy Physics, Chinese Academies of Sciences, Beijing, China

Abstract

A PrFeB cryogenic permanent magnet undulator (CPMU) prototype is under construction for High Energy Photon Source Test Facility (HEPS-TF) at IHEP. The device is a full scale in-vacuum undulator with a magnetic length of 2 meters and a period of 13.5 mm, and it will work at less than 85K. The whole design scheme of prototype is presented and the specifications are given, where the consideration of in-vacuum magnetic measurement bench is also included. The development progress is introduced.

INTRODUCTION

High Energy Photon Source (HEPS) will be a storage-ring-based light source with a beam energy of 6 GeV and emittance less than 60 pm-rad, which can provide high brilliance hard X-rays to several tens of experimental stations [1]. The HEPS Test Facility (HEPS-TF) was built to bridge the technology gap between the design and the construction. Cryogenic Permanent Magnet Undulator (CPMU) is a main type of insertion devices for HEPS, its R&D is in progress.

The concept of CPMU is proposed by SPring-8 [2]. It's a kind of insertion devices in which permanent magnets (PMs) are cooled to a cryogenic temperature to improve magnetic performance in terms of remanence and coercivity. Neodymium Iron Boron (NdFeB) and Praseodymium Iron Boron (PrFeB) are main magnetic materials for CPMU. Using PrFeB instead of NdFeB generally employed for CPMUs can avoid the magnetic remanence loss due to Spin Reorientation Transition phenomenon [2]. PrFeB CPMUs have already been built and a few of them have been installed in 3rd generation light sources [3]. After a few years' evolution and based on machine operation experience, CPMU is considered as a possible future substitute of in-vacuum undulators.

A PrFeB CPMU prototype with a magnetic length of 2 meters and period length 13.5mm is to be built for the HEPS-TF. Its specifications are derived from Time-Resolved Beam line (TRB) requirements. The main parameters and specifications are listed in Table 1. The design scheme and development progress are presented in the paper.

DESIGN CONSIDERATION

Magnetic Design

According to the user's requirements, the main

* Work supported by Project of High Energy Photon Source Test Facility
† Email address: luhh@ihep.ac.cn

parameters of CPMU, such as period length, K value, peak field, are optimized using the SPECTRA code [4] and analytic formula. Hybrid structure is selected to reach higher peak field. Anti-symmetric field pattern is benefit for depressing the gap dependence of field integral error. The classic 1/4-3/4-1 terminal structure is adopted. The geometric dimensions are optimized by RADIA code [5].

Table 1: Specifications and Parameters of CPMU13.5

Period Length	13.5 mm
Period Number	140
Working Temperature	<85K
Temperature Gradient	<1.5K/m
Working Gap	5-9mm
K value	1.26@Gap=5mm
Peak field	1T@Gap=5mm
RMS of Phase errors	<3°
1 st field integral	<100Gscm

A special feature of CPMU is that the performance of magnetic field at room temperature (RT) is different from that at cryogenic temperature (CT) due to property change of magnetic materials and cold contraction of mechanical structure. The temperature influence is simulated in magnetic design [6]. Second field integrals and phase errors at 80K and 293K are carefully investigated. According to the calculation result, the temperature gradient along each girder needs to be less than 1.5K/m.

The strategy of magnetic field error correction is considered. The field error correction will proceed in two phases: at room temperature and at cryogenic temperature. At RT stage, magnets sorting with simulated annealing algorithm will be carried out after single block characterization. The single girder will be assembled period by period to control the accumulated error. Approaches including magnets swapping, pole height tuning, magic finger and so on, will be used for error compensation. After tuning at RT, the magnetic field performance will nearly reach the final specification except the cold effect influence. At CT, end segments and in-vacuum girder deformation will be adjusted further to improve the field quality. The expected magnetic field performance is seen in Table 1.

Mechanical Design

Mechanical structure is the core component of CPMU [7]. It mainly includes following parts: magnetic material holding mechanism to keep the magnets and poles, vacuum chamber to provide vacuum environment, driving mechanism, and supporting frame.

One of the challenges for CPMU13.5 mechanical design is its quite small period length. The keepers should resist strong magnetic force and be adjustable for height and tilt tuning to compensate the field errors as well. The design is verified with the short prototype test, where the holder for one period is divided into a M1 unit for one pole and a M3 unit to keep two magnets and one pole.

Other considerations for the design are as follows: I-shape of cross section is designed for in-vacuum girder, two holes are drilled for cryogenic cooling. The driving force will be transferred from motor-gearbox unit to spindle, then to the out-vacuum girders with the guide rail. The in-vacuum girders are connected with the out-vacuum girders by rods passing through the vacuum chamber and move synchronously. The vacuum chamber includes main chamber and two kinds of end parts, one kind to fulfill the in-vacuum field measurement, the other to accommodate RF finger for operation. The taper mode of girder motion can be done through special design of the supports for out-vacuum girder. The spring is used to decrease the load. The whole structure is shown in Fig. 1, and the details of mechanical design are presented in Ref. 7.

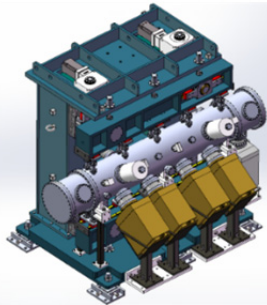


Figure 1: Sketch of the CPMU13.5.

Other Subsystems' Scheme

Motion control system will use 4-motors-driven architecture, it can change gap very flexibly and can correct magnetic field centre at any time to ensure its consistency with the beam centre. Sheathed thermocouple and thermal resistance will be mounted along the in-vacuum girder to detect the temperature gradient. A thermal contraction diagnose system [8] is used to measure the gap variation in cryogenic environment. The operation of cooling system and vacuum system will be monitored at the same time.

A cryogenic system is used to cool the CPMU magnetic arrays to liquid nitrogen temperature [9]. In addition, it is designed to reduce temperature gradient along the magnet assembly. The heat load including static and dynamic contributions is estimated at the beginning of the design. A closed-loop liquid nitrogen circulation cooling system is adopted, which mainly includes liquid nitrogen pump, heat exchanger and refrigerant channels. The simulation results show that the temperature of refrigerant channels is about 79K and the temperature gradient along the magnet assembly is about 1K/m which corresponds to the simulation of temperature influence and meets the CPMU technical requirements in Table 1.

Vacuum system provides an ultra-high vacuum environment for CPMU operation. The total gas load of CPMU is estimated. It mainly consists of outgassing of each material in CPMU chamber, gas load of beam and the leak of CPMU chamber. Then the effective pumping speed is calculated. Finally a series of vacuum pumps are selected. The static vacuum degree of CPMU is expected to be less than 5×10^{-10} Torr.

To reduce the resistive-wall impedance and the relevant parasitic loss of electron beam, a conductive foil and RF finger are needed [10]. Based on the calculation and engineering experience, the thickness of copper layer is chosen as $40 \mu\text{m}$ while the thickness of nickel layer is $60 \mu\text{m}$. Preliminary engineering design is finished.

Magnetic Measurement Bench

In-vacuum Hall Probe system and Stretched Wire (SW) system [11] dedicated for CPMU magnetic measurement are developed. The specifications are listed in Table 2.

Table 2: Specifications of CPMU13.5 Magnetic Measurement Bench

Peak field (RMS)	$\leq 2 \times 10^{-4}$ T
Phase error (RMS)	$\leq 0.3^\circ$
I1 (RMS)	≤ 4.5 Gs-cm
I2 (RMS)	≤ 500 Gs-cm ²

In-vacuum Hall probe system consists of Hall probe and data acquisition devices, motion actuator for Hall probe, moving position detector and measurement program. The difficulties of this system are development and calibration of 3D Hall probe for quite narrow gap and accurate positioning of Hall probe in the chamber with very restricted space. The accuracy required in the positioning of the Hall probes will be $\pm 3 \mu\text{m}$. An optical scenario will be used to detect and compensate the motion position and error of Hall probe, the components mainly include position sensitive detectors (PSDs), interferometer and laser encoder.

The layout of in-vacuum SW system is same as normal SW system except the wire with fixed assembly works in the vacuum chamber. The system consists of single wire, two-dimensional moving stages and Keithley 2182A nanovoltmeter with preamplifier as data acquisition devices.

DEVELOPMENT PROGRESS

PrFeB Mass Production

PrFeB is not widely used as NdFeB in CPMU and not commercially available yet. So lots of researches are carried out to investigate cryogenic properties [9] and key processing technics of PrFeB. Large scale production is implemented, the main magnetic performances, including remanence, coercivity, magnetic moment and North-South pole asymmetry, all reach the specifications through GBD technique [12], and TiN coating is realized successfully. Single block characterization is seen in Fig. 2.

Other Progress

The manufacturing of mechanical structure is ongoing. The main components including C-Frame, out-vacuum girder, vacuum chamber, in-vacuum girder are ready now,

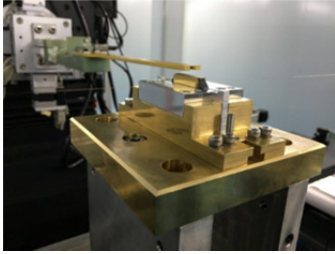


Figure 2: Characterization of PrFeB single block.

shown in Fig. 3. The next step will be cleaning procedure for ultimate vacuum, then the mechanical assembly and acceptance test will start, such as motion precision test, cold shock test for liquid nitrogen pipes with in-vacuum girder, ultimate vacuum test for vacuum chamber.



Figure 3: Progress of mechanical structure production.

After the review of engineering design, phase achievement is obtained for other subsystems of prototype. The motion components of control system are purchased. The integration of control cabinet is finished, and off-line debugging of hardware and software is in progress. Sub-cooler cold box, the main component of cooling system, is in manufacturing. Other key components, including liquid nitrogen pump, cryogenic valves, compact air compressor, refrigerant channels, and so on, are procured. Key equipment is ready for vacuum system. All pumps such as sputter ion pump, NEG pump, Titanium sublimation pump, Turbomolecular pump, Dry Pump, passed the acceptance test.

As for the in-vacuum magnetic measurement bench, Hall probes for small gap and high vacuum environment are investigated carefully. Prototypes with different materials are made and their performance is compared. Printed Circuit Board (PCB) is the final solution. The calibration experiment of the relative angle between three dimensional hall sensors was carried out [13]. Motion mechanism of Hall probe system is in processing. The light path of Hall probe position detection and compensation was set up, and the accuracy and stability are tested. The challenge for in-vacuum stretched wire system is to keep constant tensioning force and to improve the repeatability precision. The spring and wire made of titanium-aluminium alloy may be a good solution. The test with 3-meter-long wire out of vacuum was finished and reached the expectation.

SUMMARY

The mass production of magnetic material was finished. Main components for all subsystems are available. Next step will be very crucial for assembly, commissioning and acceptance test. The development is expected to be finished at the beginning of 2018.

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