MECHANICAL DESIGN OF A CRYOGENIC PERMANENT MAGNET UNDULATOR AT IHEP*

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Abstract

High Energy Photon Source (HEPS) built at Institute of High energy Physics (IHEP) is a new 6 GeV synchrotron radiation light source. Insertion devices play a significant role in achieving the high performance of the photons. A 13.5mm period-length Cryogenic Permanent Magnet Undulator (CPMU) prototype is designed and under construction. The mechanical design scheme will be presented.

INTRODUCTION

A 2m-long CPMU prototype is designed and now under construction for the HEPS-TF [1]. Working temperature of the prototype is around 80K to improve the remanence and intrinsic coercivity of the magnets at the same time, the magnetic material is PrFeB, which supplies a better performance than NdFeB in cryogenic environment [2]. To guarantee the field performance, physical design based on cryogenic environment is made at first [3], main parameters are listed in Table 1.

Table 1: Parameters of CPMU13.5

Period length	13.5mm
Period number	140
Working temperature	<85K
Working gap	5-9mm
K value	1.26@Gap=5mm
Peak field	1T@Gap=5mm
RMS of Phase errors	<3°
1st field integral	<100Gcm

There are various sources which will cause field errors, including differences of individual magnets, mechanical assembly errors, machining errors and so on. In principle, minimizing the errors always helps to obtain better magnetic field. However, parts of these errors are inevitable. To facilitate such situations, sufficient adjusting methods must be reserved to eliminate the errors [4].

Mechanical structure design plays a significant role in CPMU prototype. It not only provides basic functions in a most stable way to reduce field errors, but also offers series of field error tuning methods. The structure is divided into 4 components according to their function: 1) Supporting frame is the main load-carrying structure. 2) Vacuum chamber is a vacuum container used to provide vacuum environment; 3) Drive mechanism is used to convey driving torque from motor and compensate the shrink deformation caused by low temperature; 4) Magnetic material holding mechanism is designed to fix and adjust the height and tilt of magnetic materials. The 3-D model of CPMU is presented in Fig.1.

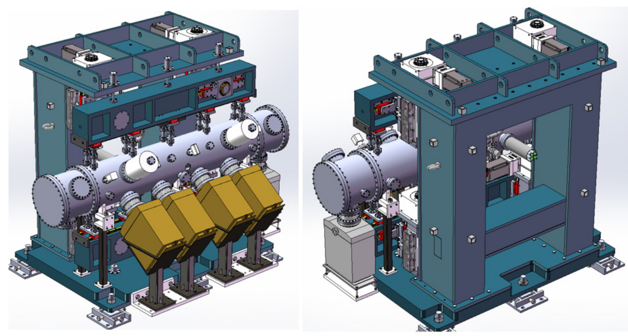

Figure 1: 3-D model of CPMU.

In this article, design of supporting frame on how to reduce the deformation; and the design of magnetic holding mechanism on how to realize the installation and adjustment of magnet array are introduced.

DESIGN AND OPTIMIZATION OF SUPPORTING STRUCTURE

Supporting structure is mainly used for withstanding the magnetic force and the self-weight of undulator. Design schemes and optimization procedure of gap offset should be concerned.

Design of the Frame

In order to give the reasonable design, there are two principles to follow: 1) Frame structure should be simple to leave sufficient space for assembly and magnetic measurement. 2) The frame should be as stable as possible to acquire small deformation.

According to the feasibility study, "C" shape and "H" shape structure are both available [5]. The advantage of C-shape frame is the sufficient space in front of the undulator, which provides plenty of convenience for housing regular hall measurement bench and moving wire measurement system. Compared with the C-shape frame, the advantage of H-shape frame is the symmetrical stable structure with small deformation.

The total force comes from the gravity and magnetic force (1ton@gap=5mm for upper girder), for upper girder the gravity and magnetic force is in same direction, but

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for lower girder the two forces are in opposite direction. Finite element analysis was made by ANSYS [6], the results are shown in Table 2. After finite element analysis, the C-shape frame is chosen finally due to its operational advantage since its deformation is also acceptable.

Table 2: Deformation of C-frame and H-frame

Largest deformation	C-frame	H-frame
Upper girder	0.036mm	0.018mm
Lower girder	0.017mm	0.006mm

Optimization of the Gap Offset Caused by Magnetic force

As mentioned previously, total load is made up of self-weight and magnetic force. For CPMU prototype, the magnetic attraction force is changing with gap (Fig. 2a black curve). Result shows the deformation changes drastically at small gap, which will lead to gap offset. Although gap offset can be reduced by linear encoder and compensated by control program, it is still recommended to minimize the offset through the mechanical design. Belleville springs mounted between C-frame and out girder are used to compensate the force. When only working gap (5mm~9mm) is taken into account, the attraction force can be treated as linear. Red curve in Fig. 2a is the magnetic force after spring is adopted. It is more flat compare to the black curve with no spring.

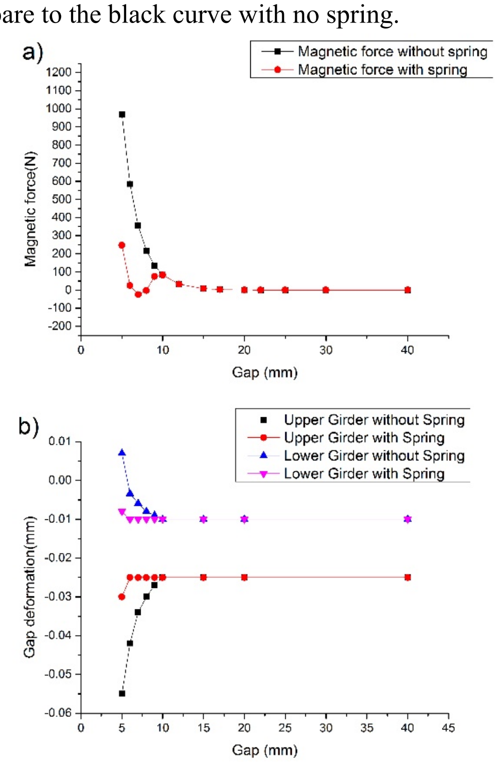

Figure 2: a) Magnetic force at different gaps and b) Deformation at different gaps.

Deformations of girder at different gap are calculated by ANSYS when self-weight and magnetic forces are imposed. The results are shown in Fig. 2b. As a result, the deformation is tending to be smooth and flat. Gap offset is significantly reduced.

IN-VACUUM GIRDER AND MAGNETIC MATERIAL HOLDING MECHANISM

Magnetic holding mechanism is mounted to the in-vacuum girder. Three main functions of in-vacuum girder are: 1) It connects to the out-vacuum girder by rods, and follows the movement of out-vacuum girder. 2) It supplies the mounting surface of magnetic materials. 3) It supplies cryogenic environment for the magnetic materials. Therefore, small deformation, good thermal conductivity and diversity of adjusting methods are goals of the design.

Section Configuration of Girder

The in-vacuum girder is designed into a typical I-beam. Beam theory shows that the I beam section is a very efficient form for carrying both bending and shear loads in the plane of the web, which can guarantee the accuracy of mounting surface. The working temperature of CPMU is about 80K. Two 2 meters long through-holes are drilled for cryogenic cooling. Thermal resistance between magnets and liquid nitrogen should be small and coincident to avoid big temperature gradient. 3 kinds of section shape were compared in Fig. 3.

a) b) c)

Figure 3: 3 kinds of section of in-vacuum girder.

Deformations are calculated by ANSYS. Results show that deformations are very close which verify the characteristics of the I-beam. In other words, the thermal conductivity is the key issues for section choosing. The magnet materials are mounted to the surface nearby the cooling channel. The ideal situation is the magnet in transverse direction be cooled down evenly, which requires equivalent thermal resistance gradient. Based on the above considerations, section A is excluded. Section B and section C own similar thermal conductivity. By considering the convenience of installation, section C was chosen at last.

Magnet Holding Mechanism

Magnet holding mechanism is an important structure which supplies tuning methods in different ways. For regular out-vacuum undulators, it is convenient to build an integrated holding mechanism that can provide easy installation and pole adjusting methods at same time.

However, the thickness of magnet and pole in CPMU13.5 is too thin. (Magnet thickness=4.5mm, pole thickness=2.25mm) Due to the limitation of machining technology, it is hardly to build an integrated holding structure for magnet clamping. The alternative way is dividing the whole structure into individual cells. Those cells can realize tuning methods with the simplest structure.

At first, M2 cell is designed (Fig. 4a and 4b), in M2 design, each magnet and pole are clamped by their own base. The pole is pushed upward by magnetic force all the time, in that case, two jackscrews at the each side of pole holders can restrain and adjust the freedom of height. Longitudinal position is ensured by a pin in the middle of holders, which also enables the angle adjusting ability. It looks like M2 cell is a good choice, which provides abundant adjusting methods and easy structure. The biggest drawback of M2, however, is the low structural strength.

Magnetic force between adjacent cells is estimated to be 20kg. Deformation is calculated by ANSYS, maximum deformation of M2 cell is too large and cannot be accepted (about 0.23mm). To improve the structure strength, M3 cell scheme is given (Fig. 4c and 4d). In a M3 design, one base called M3 clamps 2 magnets and one pole at the same time, the strength is enhanced greatly, deformation is calculated to be 0.01mm.

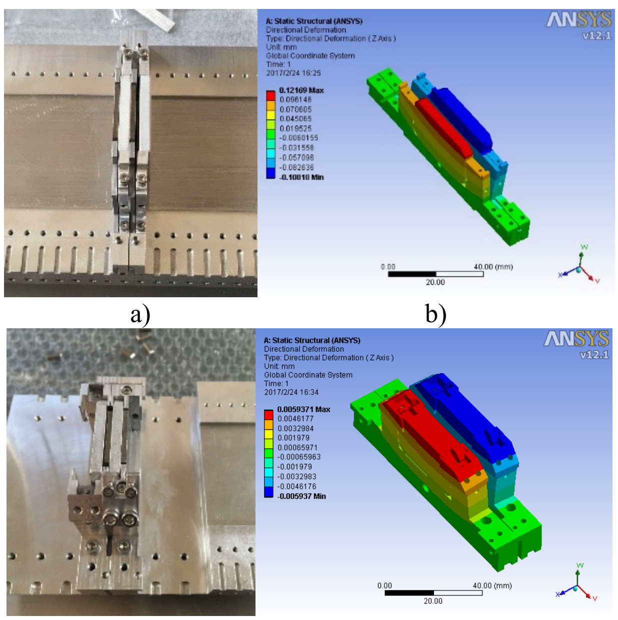

Figure 4: Short period samples of M2 cells (top) and M3 cells (bottom) were built to test the feasibility. Repulsive force between adjacent cells for M2 leads to an unacceptable clearance.

The M3 cell is more robust, although part of the pole adjusting ability is missing. The adjusting methods are sufficient for magnetic field error correction. So M3 scheme is adopted at last.

Installation of M3 Cells

There are more than 280 M3 cells, it is necessary to make a specified jig to increase the efficiency and reduce the risks in magnet installation procedure. Special jig is designed to mount the M3 cell. The installation sequence is “magnet-pole-magnet”.

It is also important to consider the contraction of girder during the installation, because the in-vacuum girder is working at cryogenic temperature. The girder is made of aluminium alloy, and the contraction can be calculated by its coefficient of thermal expansion, the contraction of a two meters long girder is up to 10mm. To avoid squeezing of adjacent cells, a 0.1mm clearance between each cell is designed, and this clearance is ensured by flat keys as shown in Fig. 5.

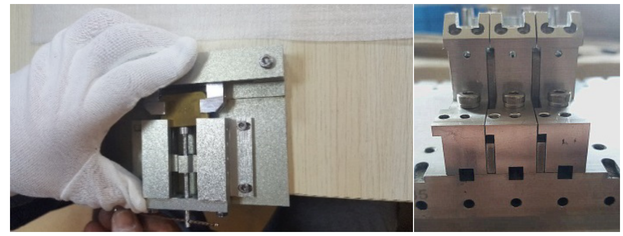

Figure 5: a) Jig for magnet installation b) 0.1mm clearance between adjacent cells

CONCLUSION

A CPMU13.5 prototype was under construction successfully. The core parts like C-frame, in-vacuum girder and M3 units were designed and optimized to realize the basic function of CPMU and supply abundant magnetic field adjusting methods. According to the current schedule, most parts were finished. In the near future, mechanical components will be assembled and motion precision will be tested. After that, cryogenic system, vacuum system [7], control system and magnetic measurement system [8] will be integrated together for the joint commissioning.

ACKNOWLEDGEMENT

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