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PRELIMINARY DESIGN OF COOLING SYSTEM FOR A PRFEB-BASED CRYOGENIC PERMANENT MAGNET UNDULATOR PROTOTYPE AT IHEP

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Abstract

A circulation cooling system is under progress for a 2-m-long PrFeB-based cryogenic permanent magnet undulator (CPMU) prototype at IHEP. Sub-cooled liquid nitrogen flows through each in-vacuum girder back and forth once. Refrigerant channels for both girders are parallel connected in vacuum chamber. Numerical simulation shows that the cooling system is able to cool down magnet array from 300 K to 83 K. Meanwhile, phase error increases about 0.1 degree.

INTRODUCTION

The cryogenic permanent magnet undulator is an effective method to produce high-brilliant hard X-ray. The original concept of CPMU was proposed by SPing-8 in 2004 as a modified form of in-vacuum undulator. [1] In order to exploit the negative temperature coefficient of the remanence and the coercivity of NdFeB or PrFeB magnets, CPMUs lower the magnet temperature to liquid nitrogen temperature or higher, thus obtain higher peak field and stronger resistance to radiation-deduced demagnetization than at room temperature. So far, several CPMUs have been constructed and put into practice.

In general, liquid nitrogen circulation system applied to CPMUs is identical to that developed for cryogenic cooling monochromators. [2] However, the refrigerant channel in vacuum chamber is the characteristic of CPMU cooling system because it influences both magnetic field intensity and phase error. It is necessary to analyse refrigerant channel design as a key component of preliminary design.

In this paper, the preliminary design of liquid nitrogen cooling system for the PrFeB-based CPMU prototype at IHEP was present. Numerical simulation method is used to analyse the influence of refrigerant channels on magnet temperature and phase error.

TECHNICAL REQUIREMENT

Schematic diagram of the CPMU prototype mechanical structure is shown in Fig. 1. In-vacuum girders are connected to out-vacuum girders by stems. Magnet array is mounted on the in-vacuum girders. The gap between both magnet array get adjusted by changing the position of out-vacuum girders. Heat load of the prototype is estimated under 700 W at 80 K, including 200 W dynamic heat loads caused by electron beam at most.

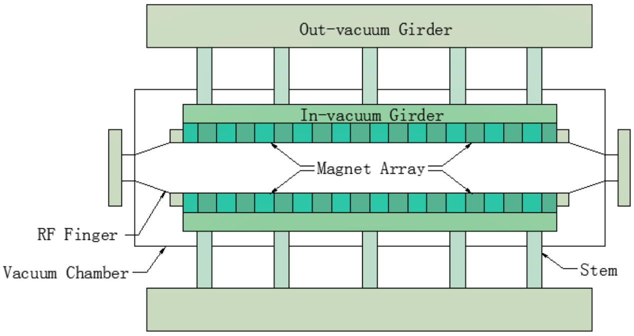

Figure 1: Schematic diagram of the CPMU prototype mechanical structure.

Remanence and intrinsic coercivity of PrFeB have been tested by Physical Properties Measurement System (PPMS). As shown in Fig. 2, both remanence and intrinsic coercivity keep increasing monotonously when temperature decreases from 300 K to 50 K. Br of PrFeB is about 1.58 T and Hcj is 6200 kA/m at 85 K. Considering both peak field requirement and construction cost, it is reasonable to lower the temperature of magnets under 85K.

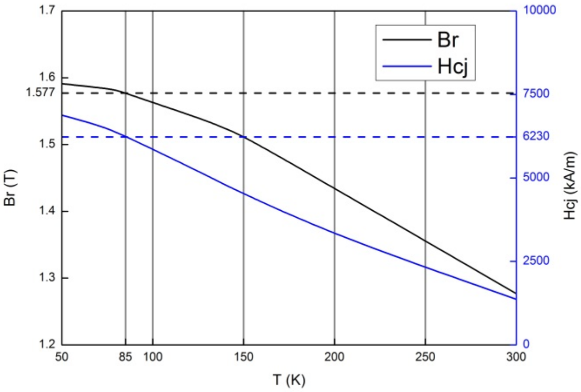

Figure 2: Variation of remanence and intrinsic coercivity of PrFeB versus temperature.

When cooling system starts working, mechanical structure in vacuum chamber tends to shrink and magnet gap become no uniform along Z direction. Consequently, field phase error increases, which reduces the flux of synchrotron radiation. However, only rod-shimming method helps to correct the field when cooling system and vacuum system are working. [3] Therefore, the phase error increment caused by cooling-down procedure is expected to be reduced as much as possible.

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LIQUID NITROGEN CIRCULATION

Schematic diagram of the cooling system is shown in Fig. 3. Liquid nitrogen is cooled down in heat exchanger at sub-cooler cold box and forced flowing into CPMU refrigerant channels by a circulation pump. After absorbing heat load and cooling the girders and magnets, liquid nitrogen re-enters the sub-cooler cold box. It is a closed-loop circulation system so that the pressure head of liquid nitrogen pump only needs to cover the pressure loss along the path without consideration of height changes.

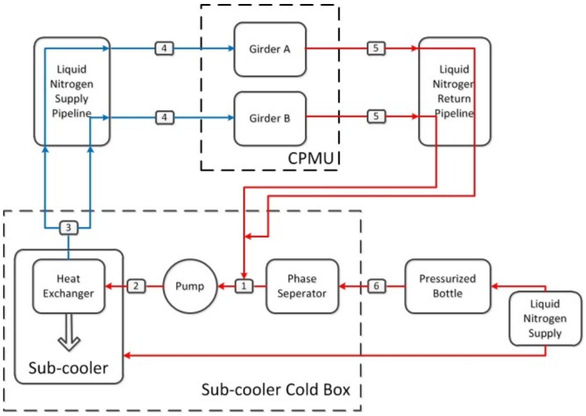

Figure 3: Flow diagram of cooling system.

The cooling system for the CPMU prototype is design with a heat removal capacity of 700 W at 80 K. The liquid nitrogen inlet and outlet temperature of CPMU are set at 79 K and 81 K respectively. Thus, the total design flow rate of circulating liquid nitrogen is about 12 L/min.

Considering space limit in CPMU vacuum chamber, liquid nitrogen flow is divided into two pipelines to cool down the girders separately instead of flowing through two girders in succession. To ensure the temperature difference between two in-vacuum girders is ignorable, flow rate of two pipelines need to be the same by cryogenic valves.

The phase separator incorporates a heater to control pressure throughout the system to ensure that the liquid nitrogen remains sub-cooled and there is no gas bubbles in the flow. The pressure at the inlet of pump is the minimum of the whole circulation. In order to protect liquid nitrogen pump, it is necessary to keep the pressure of phase separator higher than the saturated pressure of circulating liquid nitrogen at the inlet of pump with a certain value which must be larger than the net positive suction head required (NPSHR). The phase separator also acts as an expansion vessel to compensate for density fluctuation.

REFRIGERANT CHANNELS

One of the most critical components in the cooling system is the refrigerant channels. In order to remove heat from the CPMU in time, it is necessary to provide enough heat transfer area. Fig. 4 shows the one-channel design from SOLEIL PrFeB-based CPMU. [4] A hole is machined in each in-vacuum girder as the refrigerant channel to increase heat transfer area and reduce thermal resistance between liquid nitrogen and magnet array.

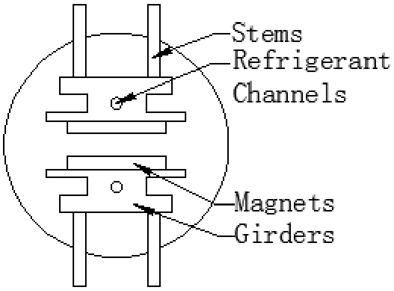

Figure 4: Layout of SOLEIL CPMU refrigerant channels.

In the design of IHEP CPMU prototype, shown in Fig. 5, two holes are drilled on both in-vacuum girders as refrigerant channels. Sub-cooled liquid nitrogen flows through each in-vacuum girder back and forth once. Refrigerant channels for both girders are parallel connected in vacuum chamber.

Temperature field of the mechanical structure in vacuum chamber was modelled by ANSYS. When liquid nitrogen temperature is 80 K and heat load is 700 W, the average temperature of magnets cooled by two-channel design is lowered to 83 K. However, the temperature difference between refrigerant channels and magnet array with one-channel design is about 5 K. Heat transfer area of two-channel design is enough to keep the temperature of magnets under 85 K when the max temperature of liquid nitrogen is 81 K.

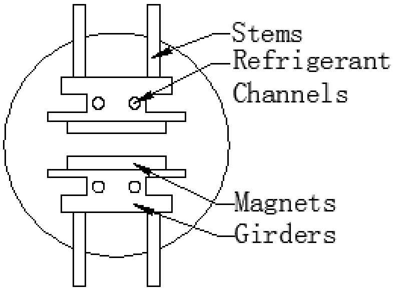

Figure 5: Layout of IHEP CPMU refrigerant channels.

The phase error caused by cooling process is estimated by numerical modelling as well. The shrink deformation is simulated by ANSYS in order to acquire the gap variation along Z direction. According to the gap variation, RADIA program is used to calculate the phase error (see Eq. 1).

$$\delta\phi_{\mathrm{i}} = \frac{2\pi K^2}{\lambda_0\left(1+\frac{K^2}{2}\right)} \int_0^{i\frac{\lambda_0}{2}} \left(\left(\delta_x(s)\right)^2 - \frac{\delta B_Z(s)}{\pi B_{Z0}} \sin\left(\frac{2\pi}{\lambda_0} s\right) \right) ds \qquad (1)$$

As shown in Fig. 6, four kinds of design with one or two refrigerant channels in each girder are compared. Flow direction is taken into consideration as well. Figure

7 shows the simulation result of gap variation between Girder A and B.

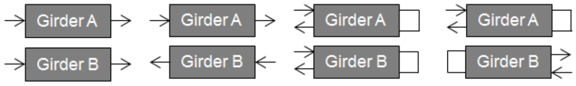

Figure 6: Layout of different refrigerant channels.

It is obvious that the gap variation caused by two channels is smaller than that caused by one-channel design. In terms of two-channel design, flow direction influences the phase error little. The modelling result is shown in Table. 1. The phase error caused by two-channel design is 0.1 degree, which is about 50% of that caused by one-channel design flowing in the same direction.

However, it is very important to choose opposite flowing direction for one-channel design because the opposite direction of temperature gradient makes girders taping in different direction, compensating the gap variation. For the same reason, it is also a better choice to make liquid nitrogen flow in opposite direction when refrigerant channels are series connected (see Fig. 7).

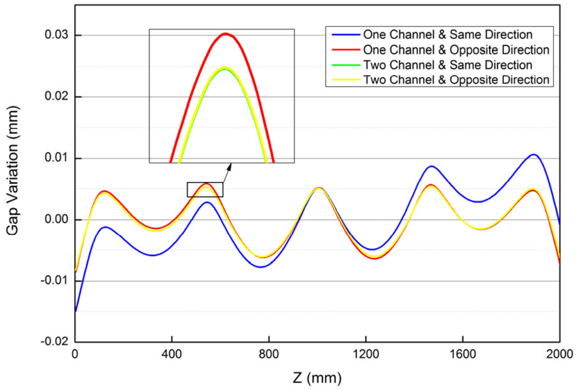

Figure 7: Gap Variation of different refrigerant channel design.

Table 1: The RMS of Phase Error Increment

Number of Channels	Flow Direction	Phase Error
1	same	0.2
1	opposite	0.1
2	same	0.1
2	opposite	0.1

CONCLUSION

A liquid nitrogen circulation cooling system for PrFeB-based CPMU is introduced. The average temperature of magnets and the phase error caused by cooling process is studied by numerical simulation. To meet technical requirements, it is an ideal method to use two refrigerant channels for each in-vacuum girder because the design helps lower magnet temperature under 85 K. Besides, liquid nitrogen flows through each in-vacuum girder back and forth once, resulting in an increase of 0.1 degree phase error.

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