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STUDY ON COOLING TECHNOLOGY OF THE SUPERCONDUCTING UNDULATOR AT SSRF *

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Abstract

A superconducting undulator (SCU) prototype with the period of 16 mm and the magnetic gap of 9.5 mm has been designed and fabricated at the Shanghai Synchrotron Radiation Facility (SSRF) since late 2013. A set of cooling system is designed to cool down cold masses, this paper presents the details of their design, calculation and test: 4 small cryogenic refrigerators are used as cold sources, and the superconducting coil and beam pipe are independently cooled down; The 4.2 K superconducting coil is mainly cooled by the liquid helium tube of thermal siphon loop; The 10~20 K ultra-high vacuum beam tube is cooled by Cu strips conduction. The main sources and mechanism of thermal loads for the SCU were analyzed. And experimental test of cooling technology for SCU prototype had been performed, the feasibility of cooling scheme and the rationality of the cooling structure for the SCU prototype were verified. The cryogenic test and operation of the SCU doesn't require the input of liquid helium from the outside, and is not limited by the liquid helium source. This is the characteristic of SSRF's SCU cooling technology.

INTRODUCTION

The superconducting undulator (SCU) with the advantage of producing high peak magnetic field at smaller period length can bring higher photon brilliance, as a result, technologies of SCU attract more and more attention for the synchrotron facilities in the world [1].

The Shanghai Institute of Applied Physics (SINAP) has started the research and development of SCU technology such as the winding skill of the coils since 2009. SINAP decided to develop one SCU prototype in order to study all the key technologies including coil winding, cooling technology, magnetic field measurement, cryomodule integration and alignment for the future FEL (Free Electron Laser) projects and SSRF (Shanghai Synchrotron Radiation Facility) upgrade project in China in 2013. The SCU prototype mainly consists of superconducting coil, beam chamber and cryostat. The coils include one set of main coils, two sets of end coils, their support frames and quench protection diodes. The SCU prototype is expected to be installed at the SSRF for online test in the winter of 2018.

The SCU superconducting coils are made from commercial copper matrix niobium titanium conductors. Both the pole and the mandrel are made of the soft iron.

The parameters of the SCU prototype are summarized in Table 1.

Table 1: Parameters of Superconducting Undulator Prototype

SC conductors	NbTi/Cu=0.93(+/-0.05):1
Material of pole and mandrel	Soft iron (DT4C)
Period length (mm)	16
Period number	50
Magnetic gap (mm)	9.5
Minimal beam gap (mm)	7.5
Central peak field (T)	≥0.67
Phase error (degree)	≤4
Operating current (A)	Main coil: 400A; 2 End coils: 34 A
Magnetic storage energy (kJ)	7
Coil length (mm)	800+32=832
Length of Cryostat along the beam line (m)	1.8

COOLING SCHEME

High efficient and stable cryogenic cooling system is a necessary condition to ensure the operation of the SCU. In order to realize and maintain the cryogenic environment for superconducting coils, the cooling technology needs to be studied in consideration of the complicated structure of the coil arrays, UHV beam chamber, current leads, and thermal loads and so on.

The coils length of the SCU prototype is only 0.9 m, using low temperature superconducting material NbTi / Cu wound, the running temperature margin for the coils is only about 0.8 K, the operating current of the main coils is 400 A. The magnetic clearance and beam clear area of the prototype is 9.5 mm and 7.5 mm respectively, and the thickness of beam chamber is 0.5 mm, that means 0.5 mm space between the coils and the beam chamber. Considering that the measured dynamic heat load of the SSRF beam is about 30 W, in order to avoid the direct influence of beam dynamic thermal load on the stable operation of the coils, the overall cooling scheme of the SCU is as follow:

1. Using 4 cryogenic refrigerators as cold sources, which is more easier for operation and maintenance, and the equipment cost and operating cost is lower compared with large helium refrigerator system.

2. The coils and the beam chamber are independently cooled: The two upper refrigerators cooled the coils, the two down refrigerators cooled the beam chamber. The 4.2 K superconducting coil is mainly cooled by the liquid

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helium tube of thermal siphon loop, also it is zero evaporating; The 10~20 K vacuum beam chamber is cooled by Cu strips conduction.

3. Current leads and their cooling: Binary current leads made of conventional copper leads and high temperature superconducting leads (HTS) are used to reduce the heat load.

4. Cold mass cooling and liquid He accumulation: Two upper refrigerators are used not only as cold source for the normal operation of the SCU, but also cold source for helium liquefier. SCU system The cooling down procedure and normal operation do not require the input of liquid helium from the outside, only high-purity helium gas is required.

The overall cooling scheme of the SCU prototype is shown in Figure 1.

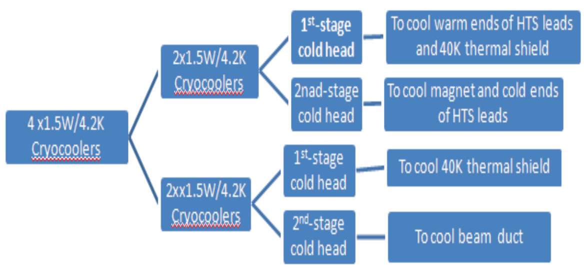

Figure 1: The overall cooling scheme of the SCU prototype.

As shown in Figure 2, the coils are cooled by the two refrigerators in the upper part of the thermostat. It is necessary to take into account the possibility to accelerate the re-cooling and cooling rate after quenching the coils. For more cooling capacity, a 30 L liquid helium tank is set to store liquid helium and provide a source of liquid helium for the thermal siphon circulation circuit.

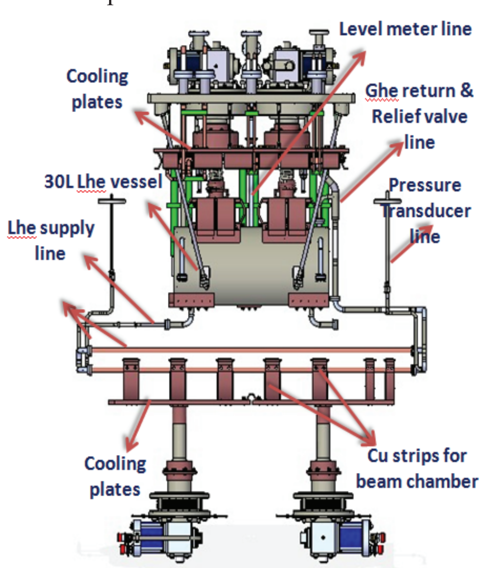

Figure 2: Cooling structures for SCU coils and beam chamber.

OPTIMIZATION OF COOLING STRUCTURES

The re-condenser is used to liquefy helium, it is directly connected to the secondary cold head and is located in the upper part of the liquid helium tank. Its structure is shown in Figure 3.

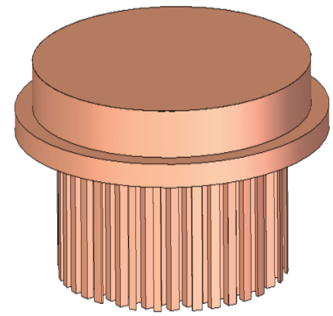

Figure 3: Re-condenser structure.

The optimal design of the re-condenser can minimize the temperature difference between the He gas and the condensing surface. According to Nusselt's pure saturated vapor laminar film condensation theory, the average temperature difference ΔTc of the condensing surface can be obtained as [2,3]:

$$\Delta T_c = \left[\left(\frac{Q}{A} \right) \left(\frac{4\mu_l H}{\rho_l^2 g h_{fg} \lambda_l^3} \right)^{1/4} \right]^{4/3} \tag{1}$$

In equation (1), (Q/A) is the heat flux density at the condenser surface; μ_l is the dynamic viscosity of the liquid helium; H is the height of the condenser fins; ρ_l is the liquid helium density; g is the gravitational acceleration; h_{fg} is the latent heat of vaporization of liquid helium; λ_l is the thermal conductivity of liquid helium.

The results are as follows: The cross-sectional dimension of a single fin is 3 mm × 3 mm, the number of complete fins is 121, the total heat exchange area is at least 0.06 m2, and the calculated heat transfer temperature difference is 0.021 K, which satisfies the design requirements. Taking into account the complexity of the actual heat transfer, the actual design, the total heat transfer area gives 2.5 times the margin, that is 0.15 m2, fin length is 42 mm, round copper diameter is 100 mm, thickness is 5 mm.

The beam chamber is independently cooled by the secondary cold heads of the two refrigerators at the lower part of the thermostat. The secondary cold head is connected with the copper plate firstly, the soft copper strips is connected between the copper plate and the beam chamber. In order to ensure the temperature uniformity of the beam chamber, 7 soft copper strips are arranged along the beam direction, and are distributed on both sides of the beam chamber. According to the performance of small refrigerators, the operating temperature of the beam chamber with dynamic thermal load can be ~20 K, which is shown in Figure 4.

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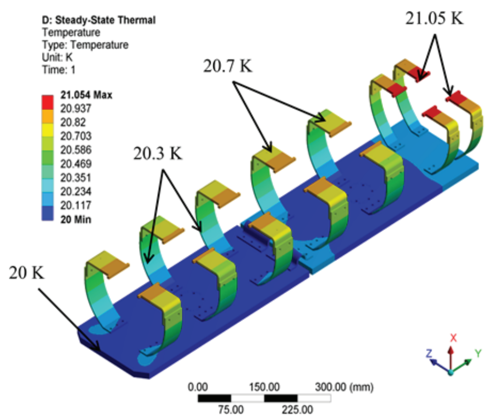

Figure 4: Temperature distribution of the beam chamber cooling structure.

EXPERIMENTAL TEST OF COOLING TECHNOLOGY

Experiments were conducted to monitor the temperature change of the cold masses to obtain the cooling down rate of each part. Figures 5 shows the cooling down curves of the secondary cold heads of the 1 and 2 coolers, the upper and lower ends of the liquid helium tanks, the HTS cold ends. In the 4 K temperature zone, about 160 kg of cold mass, from the beginning of cooling to a stable temperature, lasted about 51.5 hours, the minimum temperature of the liquid helium tank reached approximately 4.2 K, and the liquid helium pressure range in the liquid helium tank was 1~ 5 kPa.

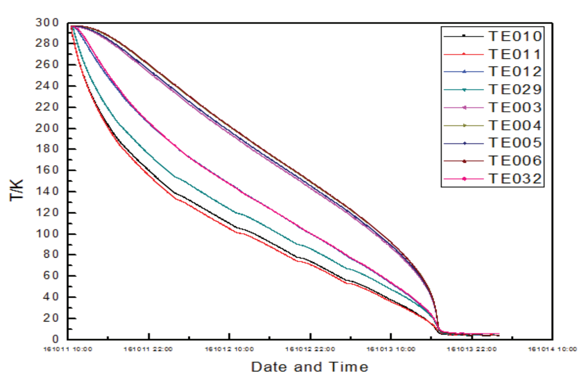

Figure 5: Cooling down curves at Liquid He temperature range of the SCU prototype.

After cooling down to 4.2 K, the cryogenic line in the cryostat was continuously filled with helium, and the liquid helium tank began to accumulate fluid. Figure 6 shows the time curve for accumulation. The whole process takes 53 hours when the L He level is up to 90% of the total volume.

The above experimental results verified: 1) The feasibility of the cooling design scheme of the SINAP SCU, that is, 4 small refrigerators used as cold sources, no need for liquid nitrogen pre-cooling or liquid helium input, only room temperature high purity helium needed to achieve cooling down cold mass and accumulating liquid helium; 2) The optimization of the cooling structure design of each cold mass successfully enables the superconducting coils to reach the operating temperature .

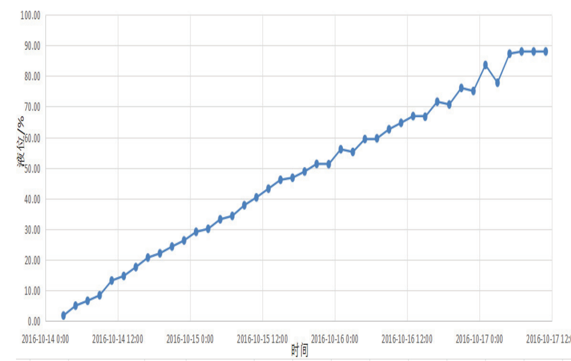

Figure 6: Liquid He accumulation curve of the SCU prototype.

ESTIMATION OF HEAT LOADS

Table 2 shows the thermal load calculation results for each temperature zone of the SCU prototype. The thermal shield is set to 40 K, the beam chamber is set to 20 K, and the superconducting coils is set to 4.2 K.

Table 2: Total Heat Loads at 4.2 K and 40 K (Unit: Watts)

Heat Source	Heat Load at 4.2 K	Heat Load at 40 K
Radiation heat	0.404	8.7
Conduction heat through pipes	0.076	3.2
Conduction heat through supports	0.025	4.1
500+100A HTS leads	0.258	64.4
Instrument wires	0.002	0.1
Total	0.765	80.5
Cooling power	3	88

As can be seen from Table 2, the current lead is the main load source in the 40-60 K temperature zone, accounting for about 80%, followed by radiation heat. The main sources of heat load in the liquid helium temperature zone are current leads and radiation heat, which account for 60% and 30%, respectively.

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