Design of Cold Mass Supports for a Superconducting Undulator Prototype at SINAP

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***Abstract*—A superconducting undulator (SCU) prototype with a period of 16 mm and a magnetic gap of 8 mm has been under design and fabrication at the Shanghai Institute of Applied Physics in China since late 2013. The SCU prototype is aimed at obtaining the magnetic field of 0.88 T at the beam axis. A set of support systems was designed to support the cold masses, including superconducting coils, a beam chamber, and thermal shields. A set of self-centering cold mass supports are adopted for the superconducting magnet for the purpose of self-alignment at low temperature. The beam chamber is supported by G-10 spacers against the magnet. The nonmetallic tension rods and spacers are used to support the 60- and 20-K thermal shields, respectively. The heat loads conducted to the cold masses through the supports need to be minimized. This paper presents the design details of the support system.**

***Index Terms*—Self-centering cold mass support, superconducting undulator (SCU), support system.**

I. 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, magnet structure, cooling, magnetic field measurement, cryomodule integration and alignment for the future Free Electron Laser (FEL) projects and Shanghai Synchrotron Radiation Facility (SSRF) upgrade project in China in last October. The SCU prototypes mainly consists of magnet, beam chamber and magnet cryostat. The magnet includes one set of main coils, two sets of end coils, their support frames and quench protection diodes. The engineering design for the SCU cryostat will be completed by the end of this October. The SCU prototype is expected to be installed at the SSRF for on-line test at the early of 2016.

TABLE I
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) (fixed)	8.0
Minimal beam gap (mm)	5.0
Central peak field (T)	≥0.88
Phase error (degree)	≤4
Operating current (A)	Main coil: 398A； 2 End coils: 28 A, 34 A
Magnetic storage energy (kJ)	41.2
Magnet length (mm)	800+32=832
Length of Cryostat along the beam line (m)	≤1.8
Magnet operating temperature (K)	4.2-5.0K
Beam chamber work temp. (K)	20 K or above (up to dynamic load)

The SCU cryostat is mainly composed of cooling system for the magnets and the beam chamber, thermal shields, power leads for the magnets, cold mass supports, vacuum chamber, instruments and so on. The cold mass supports include magnet supports, beam chamber supports and thermal shields supports. The design of cold mass supports is presented in this paper in detail.

II. Superconducting Undulator Prototype

The SCU magnet 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 I.

The SCU coils to work at 4.2 K and the beam chamber to work at around 20 K are thermally isolated and cooled respectively by cryocoolers. The coils are cooled by liquid helium flowing through cooling tubing brazed into the coil mandrel. The evaporated helium gas absorbed the heat is recondensed by two cryocoolers with each cooling capacity of 1.5 W at 4.2 K. The thermal-syphon cooling loops are used to transfer the liquid helium between the condenser and the coils. The beam chamber is conduction-cooled by another two cryocoolers with each cooling capacity of 22 W at 20 K. In order to reduce the radiation heat from room temperature to the 4.2 K cold mass, the conduction-cooled thermal shields made

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Manuscript received August 10, 2014; accepted December 21, 2014. Date of publication December 30, 2014; date of current version February 5, 2015. This work was supported in part by the Shanghai Institute of Applied Physics, Chinese Academy of Science, and by the Shanghai Key Laboratory of Cryogenics and Superconducting RF Technology.

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Digital Object Identifier 10.1109/TASC.2014.2386695

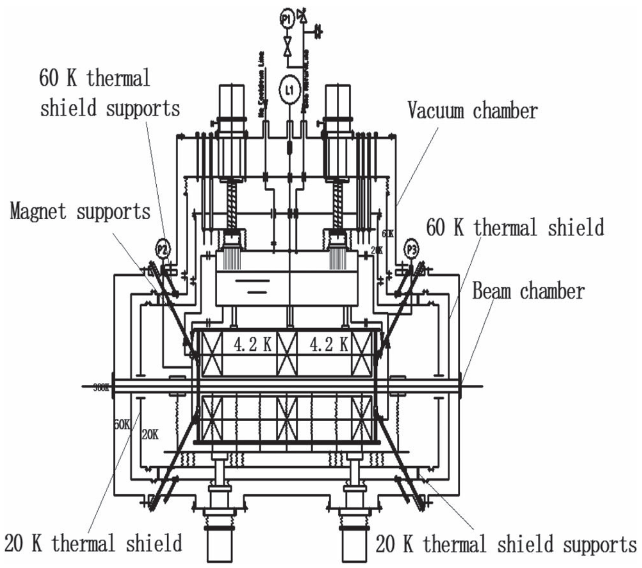

Fig. 1. Design scheme of the SCU prototype.

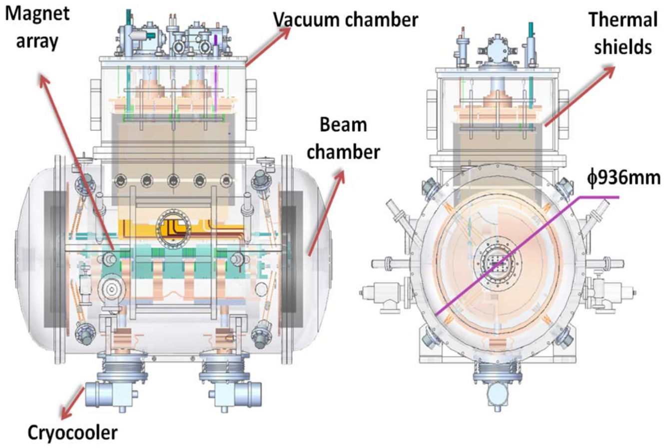

Fig. 2. Three-dimensional structure of the SCU prototype at SINAP.

of copper or aluminum are used between the 4.2 K magnet and the vacuum chamber. The shields separately work at 60 K and 20 K. A pair of binary current leads, composed of copper leads and high temperature superconducting (HTS) leads, have to be applied in order to reduce the heat leakage at 4.2 K. The vacuum of the cryostat is independent from that of the beam duct. The cryostat vacuum chamber and the beam chamber are respectively made of 304 stainless steel and Al alloy. The cold mass support system is designed to support the 4.2 K magnet, thermal shields and the beam chamber. The design scheme and 3D structure of the SCU prototype are shown in Figs. 1 and 2 respectively [2].

III. MAGNET SUPPORTS

The supports for the cold masses should meet the following requirements: 1) It should withstand the weight of the cold mass. 2) It should withstand the thermal stress during cool down. 3) The heat leak through the supports to the low temperature region should be minimized due to the limited cooling capacity of cryo-coolers. The magnet supports are required to be capable to align the magnet both at room temperature and low temperature with the beam line.

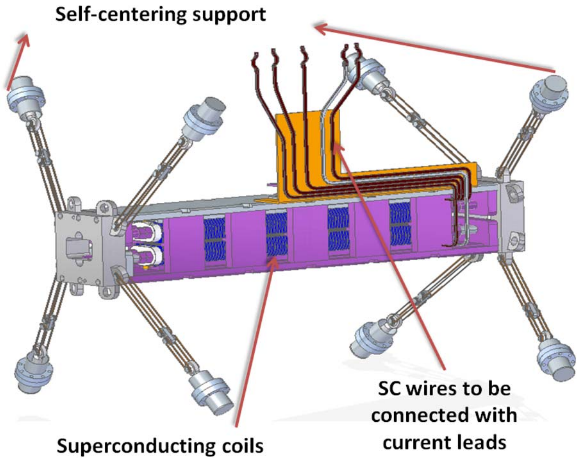

Fig. 3. Self-centering supports for the SCU magnet.

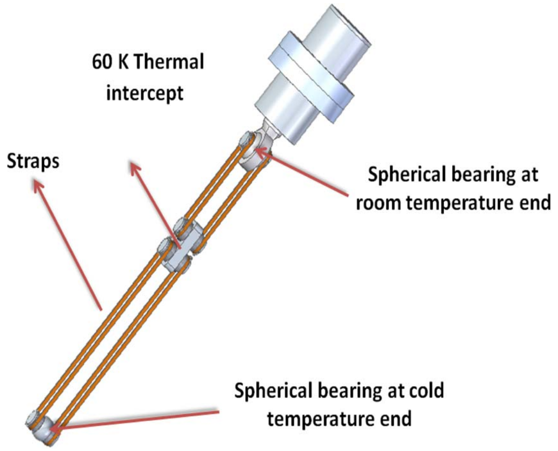

Fig. 4. Structure of one self-centering support assembly.

The self-centering support structure is applied for supporting the 4.2 K magnet assembly [3], [4], as shown in Fig. 3. It is well designed with the advantage of maintaining the magnet axis stable after cool down [5], [6].

The self-centering double-band cold mass support system consists of eight support strap assemblies, four at each end of the magnet. Each support assembly consists of two racetrack straps with attachment hardware at each end and an intermediate temperature intercept between the two straps [7]. The straps are made from non-metallic material of a unidirectional fiber with epoxy which has low heat conduction coefficient and high tensile strength [8]. The spherical bearings are applied at both room temperature end and cold end to allow the support rotating a little bit during cooling down in order to prevent the support from bending. The thermal intercepts are conduction-cooled by the first-stage cold heads of the coolers. The support structure is shown in Fig. 4.

The cross section of the straps is designed to stand the weight of the magnet assembly of about 140 kg and the thermal stress. Their length is designed to help reducing both the thermal

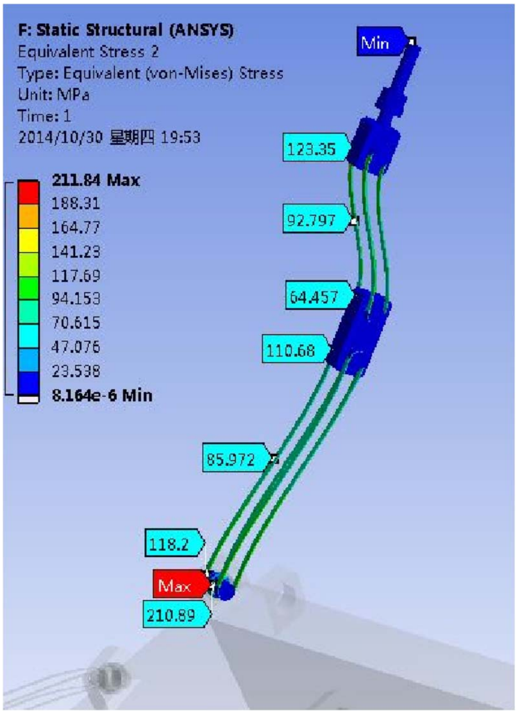

Fig. 5. Simulation for the stress on straps.

stress and the heat leakage. The optimized size of one strap is 3.25 mm wide and 2 mm thick. Its length between room temperature end and thermal intercept is 100 mm, and that between the intercept and cold end is 200 mm. The estimated heat load through the support system is 0.312 W at 60 K, and 0.014 W at 4.2 K. The maximal tensile stress on the straps is about 211 MPa after cooling down (Fig. 5), which is much lower than the tensile strength of the unidirectional fiber with epoxy.

For the finite elements analysis on the stress and deformation of the straps, since the spherical bearings is not easy to be simulated, they are not included in the simulation model. Therefore, the stress analysis shows that the straps are bent under the force loading. According to the analysis results, we adopted the spherical bearings for the engineering design of the supports to avoid the bending.

IV. BEAM CHAMBER SUPPORTS

The cross section of the beam chamber and its supports are shown in Fig. 6. The inner maximum height and width is 5 mm and 68 mm. When the SCU is under online operation, the beam chamber will subject to the dynamic heat loads resulting from image currents, electron cloud, beam loss and wakefield effects [9]. According to experimental results of the SSRF beam dynamic heat load, the dynamic heat load to be deposited on the beam chamber is around 20 W per meter [10]. The dynamic heat load of the 1.8 m SCU prototype is estimated to be 36 W.

The beam chamber is to be cooled by two cryocoolers with cooling capacity of about 22 W at 20 K each. The connection flexible straps between the cold heads and the beam chamber are made of oxygen-free copper (OFHC). The beam chamber is made of extruded 6063 Al. For keeping the coincidence of the beam chamber axis and the magnet center, for decreasing the deformation due to gravity of the beam chamber, and for reducing the heat conduction between the beam chamber and the magnet, the beam chamber is supported by 12 G10 spacers. The holes to hold the spacers are distributed symmetrically at the two sides of the beam chamber along the beam direction.

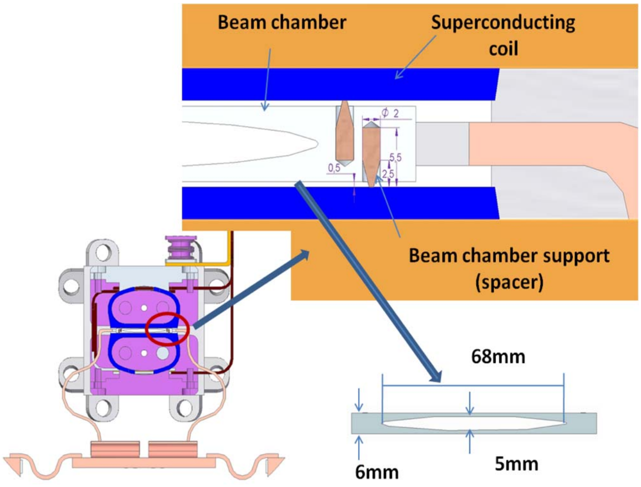

Fig. 6. Cross section of the beam chamber and its supports.

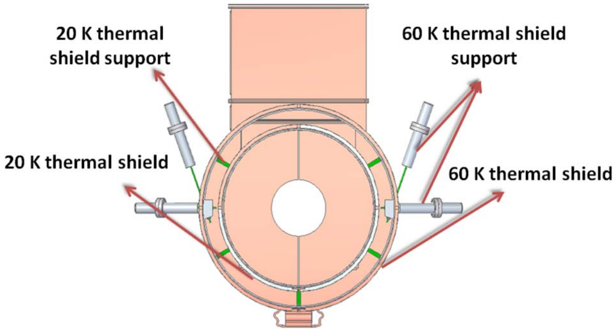

Fig. 7. Thermal shields with supports at 60 and 20 K.

As shown in Fig. 6, the columnar part of the spacer is installed in the hole, the rest part is designed with cone shape to minimize the heat conduction. The heat conducted from the 30 K beam chamber to the 4.2 K magnet through the spacers is no more than 0.016 W. The radiation heat between the outer surface of the beam chamber and the inner surface of the magnet is estimated to be 0.02 W.

V. THERMAL SHIELDS SUPPORTS

In order to reduce the radiation heat from room temperature to the 4.2 K cold mass, the conduction-cooled thermal shields made of copper or aluminum are used between the 4.2 K magnet structure and the vacuum chamber. The designed temperature of the two shields is set at 60 K and 20 K separately.

As shown in Fig. 7, each shield is composed of two parts, top part and bottom part. The top part is rectangular and the bottom part is cylindrical. The two parts are mechanically connected. If each part is made of 3 mm thick copper sheet, the 60 K shield is about 165 kg and the 20 K shield is about 105 kg.

TABLE II
HEAT LOAD THROUGH COLD MASS SUPPORT (UNIT: WATTS)

Heat Source	Heat Load at 4 K	Heat Load at 20 K	Heat Load at 60 K
Conduction heat through magnet support	0.014		0.3
Conduction heat through beam chamber support	0.016		
Conduction heat through 60 K thermal shield support			0.1
Conduction heat through 20 K thermal shield support		0.2	
Total	0.030	0.2	0.4

TABLE III
TOTAL HEAT LOADS AT 4.2 AND 60 K (UNIT: WATTS)

Heat Source	Heat Load at 4.2 K	Heat Load at 60 K
Radiation heat(SCU magnet)	0.55	8.097
Conduction heat through pipes	0.111	5.042
Conduction heat through supports	0.030	0.4
500A HTS leads	0.130	46.008
100A HTS leads	0.096	13.803
Instrument wires	0.05	0
Total	0.967	73.350
Cooling power	3	140

The support system for the 60 K thermal shield is composed of eight G-10 rods. Four of them are vertical supports and the rest four are horizontal supports. The diameter of the rod is 5 mm. The vertical rod is 350 mm in length and the horizontal one is 250 mm in length. The estimated heat load from room temperature to 60 K through all the supports is 0.1 W.

The 20 K thermal shield is inside the 60 K thermal shield and supported by 10 G-10 rods, which are in the space between the two shields. The 20 K thermal shield is supported by the 60 K thermal shield, There is no direct link between room temperature and 20 K thermal shield. The heat load to the 20 K thermal shield through all the spacers is only 0.2 W.

VI. ESTIMATION OF HEAT LOADS

The heat loads at different temperatures induced by the three kinds of cold mass supports are summarized in Table II. The heat loads through the supports at 4.2 K, 20 K, and 60 K are only 1%, 0.47%, and 0.2% of the cooling capacity of the cryocoolers respectively.Table III lists the estimation of all the heat loads at 4.2 K and 60 K. As shown in Table III, the heat load at 4.2 K excludes the beam dynamic load. The heat load at 60 K is far lower than the cooling power provided by coolers, which means the working temperature of the shields will be lower than 60 K.

VII. CONCLUSION

The engineering design for the SCU prototype at SINAP is nearly completed. The cold mass supports are designed to support the magnet, thermal shields and the beam chamber. A set of self-centering cold mass supports are adopted for the superconducting magnet for the purpose of self-alignment at low temperature. The beam chamber is supported by 12 G-10 spacers against the magnet. The non-metallic tension rods and the spacers are respectively used to support the 60 K and the 20 K thermal shields. The heat loads through the supports at 4.2 K, 20 K, and 60 K are minimized to be 0.03 W, 0.2 W, 0.4 W respectively, which is small compared to the total expected heat into the coolers.

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