THERMAL MODELING AND CRYOGENIC DESIGN OF A HELICAL SUPERCONDUCTING UNDULATOR CRYOSTAT*

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Abstract

A conceptual design for a helical superconducting undulator (HSCU) for the Advanced Photon Source (APS) at Argonne National Laboratory (ANL) has been completed. The device differs sufficiently from the existing APS planar superconducting undulator (SCU) design to warrant development of a new cryostat based on value engineering and lessons learned from the existing planar SCU. Changes include optimization of the existing cryocooler-based refrigeration system and thermal shield, as well as cost reduction through the use of standard vacuum hardware. The end result is a design that provides a significantly larger 4.2 K refrigeration margin in a smaller package for greater installation flexibility in the APS storage ring. This paper presents ANSYS-based thermal analysis of the cryostat, including estimated static and dynamic (beam-induced) heating, and compares the new design with the existing planar SCU cryostat.

BACKGROUND

Two planar superconducting undulators (SCU) are currently in operation at APS. The cryogenic system was designed in conjunction with the Budker Institute of Nuclear Physics in Novosibirsk, Russia, based upon design concepts used on their superconducting wigglers [1, 2]. In the past, ANSYS thermal analysis for a planar undulator was conducted based on the cryocooler load lines and estimated heat loads. Calculated excess cooling capacity was matched to the measurement for the operating planar SCU (SCU1) [3]. Based on the same principle, the thermal model of HSCU cryostat was built.

COOLING SCHEMATIC

The overall cooling schematic for the current planar SCU and HSCU cryostat are shown in Fig. 1 and Fig. 2, respectively. For both the planar SCU and HSCU cryostat, the magnet assembly is thermally isolated from the beam chamber. Magnets are indirectly cooled by LHe flowing through the channels inside the magnet assembly. The cryostat is operated in zero-boiloff mode.

The current planar SCU has three thermal circuits. All four cryocooler 1st stages (RDK-408S and RDK-415D) are connected to the outer thermal shield, the warm section of the current leads, and the beam chamber stainless steel transition. Arrows 1, 2, 3, and 4 of Fig. 1 represent the heat flow of this circuit. The 2nd stages of the two RDK-408S cryocoolers are connected to the inner thermal shield and the Al beam chamber section passing through the magnets. Arrows 5 and 6 represent heat flow within this cooling circuit. The third circuit is the connection of the 2nd stage of the two RDK-415D to the LHe tank and HTS current leads. Arrows 7 and 8 represent the heat flow within this circuit.

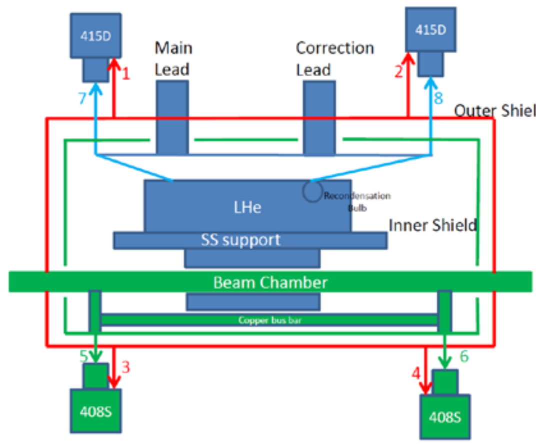

Figure 1: Cooling schematic of the planar SCU Cryostat.

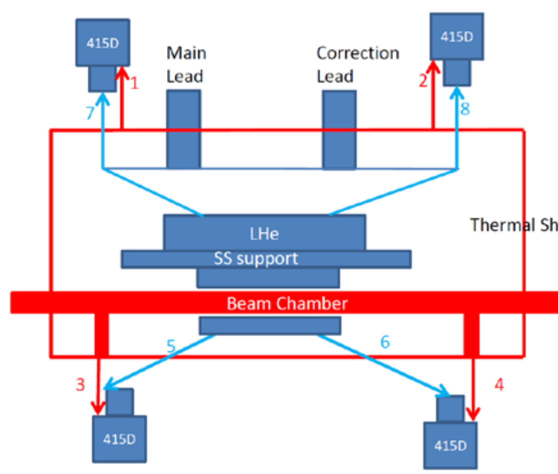

Figure 2: Cooling schematic of HSCU cryostat.

The HSCU has only two thermal circuits: the thermal shield cooling circuit and the magnet cooling circuit. The first stages of all four RDK-415D cryocoolers are connected to the warm magnet current leads, the thermal shield, and the beam chamber stainless steel transition sections. Arrows 1, 2, 3, and 4 of Fig. 2 represent the heat flow within this circuit (thermal shield circuit). The 2nd circuit is the connection of all four cryocooler 2nd stages to the HTS section of the current leads and the magnet / LHe tank assembly. Arrows 5, 6, 7, and 8 of Fig. 2 represent the heat

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flow within this circuit (magnet cooling circuit). The dedicated intermediate thermal shield and beam chamber cooling circuit has been eliminated. This cooling configuration allows the use of four versus two RDK-415D cryocoolers, doubling the cooling power to the magnet cooling circuit.

DESIGN

The required dimension of the beam chamber and magnets are more compact than the planar SCU magnets. In order to strengthen the structure of the long and thin magnet (1.2 m long 0.0486 m OD, 0.029 m ID), the epoxy impregnation mold remains installed as a strong back. Fig. 3 shows the cold mass assembly and the four cryocoolers. The LHe channels reside in the mold not the magnet itself. The thermal contact between the mold and the magnet is given by the thin layer of epoxy.

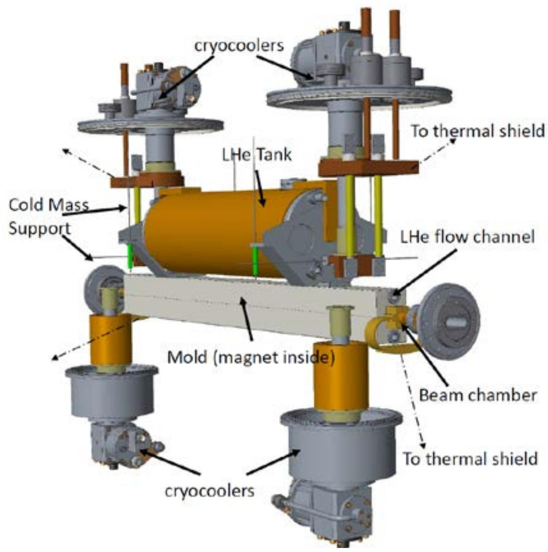

Figure 3: Coldmass assembly and cryocoolers.

The beam chamber is cooled by the cryocooler 1st stages through the thermal shield as shown in Fig. 3. With elimination of the intermediate thermal shield and copper thermal bus, the diameter of the cryostat decreases about a half from that of the planar SCU. This is beneficial, as it allows the upper cryocoolers to be installed in a fully vertical orientation, easing both cryostat assembly and installation into an accelerator storage ring.

Beam Chamber Support Design

Since the beam chamber is cooled only at the ends by the 1st stage of four of the cryocoolers, the Al chamber segment passing through the magnet bore is expected to have a higher temperature than experienced on the planar SCU. With the magnet cooled to 4 K via LHe flowing through the strongback, this temperature difference could result in a substantial conductive heat leak through the required beam chamber locating support. To limit this heat leak, the beam chamber supports are carefully designed and incorporated into FEA calculation of the temperature distribution along the aluminium length of the beam chamber (Model 1). A constant heat 40 W is applied to the inner surface of the beam chamber to simulate heating of beam chamber by electron beam, which is cooled by the 1st stage of 415D cryocoolers at the ends. Fig. 4 shows the temperature of the beam chamber and positions of the beam chamber support for CASE 1 (no heat is applied) and CASE 2 (40W is applied). The Torlon pins are located at four locations, at ~ 0.4 m apart. Using known thermal conductivity of Torlon [4], total conduction heat from beam chamber to the magnet through the Torlon pins is 33mW for CASE 1 and 140mW for CASE 2.

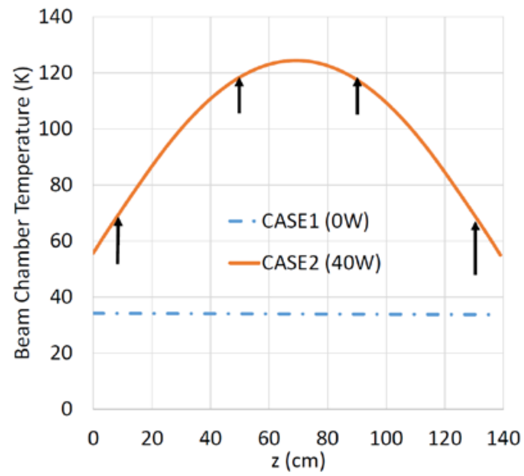

Figure 4: Beam chamber temperature and the position of the supports.

FEA MODEL OF HSCU

The HSCU model is made with the fixed end temperatures (300 K) and separately calculated heat sources (e.g. Model 1) as an input and sink temperature based on cryocooler load line. HSCU analysis includes following three cases. CASE 1 is a static case when zero beam heat and zero magnet current are applied. CASE 2 is a case with beam heat only (40 W) and zero magnet current are applied. CASE 3 is a case when a beam heat (40 W) and magnet current (500 A) are applied.

Table 1 shows the heat source for the warm part of HSCU (thermal shield circuit). Heat loads specific for CASE 2 and CASE 3 are shown in separate rows below the total static heat load. For CASE 1, a primary heat source is a current lead conduction heat. The total static heat leak becomes 43.5 W. For CASE 2, 40 W is added uniformly into the beam chamber inner surface. Non-superconducting main current leads (CrCu) are optimized for 500 A. Correction current leads (4 pairs) are optimized for 40 A. Joule heat of resistive part of leads were calculated separately.

Table 1: Thermal Shield Circuit Heat Load

CASE	Heat Source	Model [W]
CASE 1	Beam chamber transition	7.67
	Main Lead	20.74
	Correction lead	10.73
	Thermal radiation from shield	0.63
	Cold mass support	2.54
	LHe & relief piping	1.17
	Total static heat load	**43.5**
CASE 2	Beam Heat	40
CASE 3	Joule heat (Main)	12.5
	Joule heat (Correction Lead)	10

Table 2 shows the heat source to the magnet cooling circuit of the HSCU cryostat. A primary heat source is a conduction heat through HTS lead for both cases. Instrumentation heat leak is calculated as a direct heat from room temperature to 4 K to estimate maximum heat leak. These wires are to be heat sunk to the shield. The total static heat leak is 0.50 W. Heat loads specific to CASE 2 and CASE 3 are shown in separate rows. The beam chamber support conduction heat is 0.033 W for CASE 1 and is 0.14 W for CASE 2 as calculated in Model 1.

Table 2: Magnet Cooling Circuit Heat Load (HSCU)

CASE	Heat Source	Model [W]
CASE 1	HTS Main (one pair)	0.212
	HTS Correction (4 pairs)	0.128
	Thermal radiation from shield	0.025
	Cold mass support (Invar rods)	0.055
	Beam chamber support	0.033
	Instrumentation (300 K to 4 K)	0.034
	LHe & relief piping	0.02
	Total static heat load	**0.50**
CASE 2	Beam chamber support conduction	0.14
	Thermal radiation from beam chamber	0.042
CASE 3	Total Joule heat due to joints	0.13

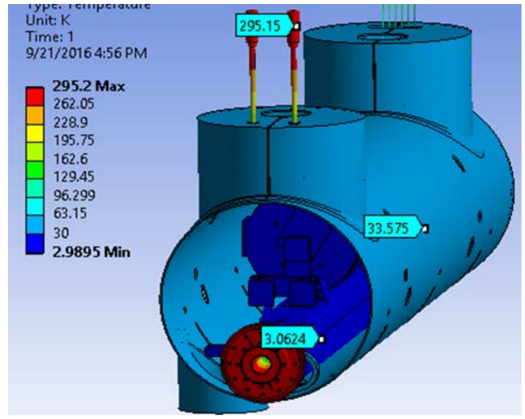

Figure 5: Overall temperature of the shield, magnet, and the beam chamber for CASE 1 (static).

Fig. 5 shows temperature of the cryostat, which includes the thermal shield, the beam chamber, LHe tank, and magnet assembly for CASE 1. Calculated 2nd stage temperatures are at 2.9 K and LHe and magnet are ~ at 3.1 K (208 Torr of LHe vapour pressure). In the real operation, the trim heater heat is used to maintain LHe at 4.2 K (760 Torr). Temperature at the shield and the 1st stages are at ~34 K for CASE 1, 37 K for CASE 2 and 40 K for CASE 3. Although both beam chamber heat and Joule heat of the non-superconducting part of magnet leads (CrCu) are added, the thermal shield temperature is low enough to operate the HTS part of the leads safely.

DISCUSSION

Table 3: Summary of Heat Loads for HSCU and SCU1

	CASE	Total Heat Load [W]	Excess Cooling Capacity [W]
HSCU calculated	CASE 1	0.5	1.3
	CASE 2	0.65	1.15
	CASE 3	0.79	1.0
SCU1 observed	CASE 1	0.5	0.44
	CASE 2	0.6	0.36
	CASE 3	0.67	0.34

Table 3 shows the summary of the calculated heat load of HSCU and the observed heat load of the planar SCU at a magnet cooling circuit. Excess cooling capacity is a total available cooling power of cryocoolers (at 760 Torr in LHe tank) minus total heat load. When the contact resistance between the cold head and a thermal link are similar to the current planar SCU, the 2nd stage cold head temperature is at ~3.3 K, which corresponds to 0.45 W of cooling power for each. Therefore, an excess becomes 0.45 W × 4 - 0.5 W = 1.3 W. In the FEA model, a trim heat is added until LHe tank temperature matches to 4.2 K to estimate this excess. Since total heat load of the HSCU and the planar SCU are quite similar, and cooling capacity of HSCU is doubled, calculated excess cooling capacity is higher in all operational cases.

CONCLUSION

Based on the current planar SCU design and operation experiences, a more compact cryostat for HSCU has been designed and FEA analysis was conducted. The analysis indicates that HSCU has larger excess cooling capacity compared with the planar SCU in all operational cases.

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