THERMAL MODELING OF THE PROTOTYPE SUPERCONDUCTING UNDULATOR (SCU0)*

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Abstract

A cryocooler-cooled superconducting undulator (SCU0) has been built, and cryogenic and magnetic tests have been completed. The device is currently installed in the Advanced Photon Source (APS) beamline. The device consists of a dual-core 42-pole magnet structure that is cooled to 4.2K with a system of four cryocoolers operating in a zero-boil-off configuration. In this paper, a thermal model of the beam chamber and its cooling circuit are presented. A temperature profile of the cooling circuit and heat load to cryocoolers are calculated based on steady-state temperatures. Comparison with cryogenic test results and future improvements will be discussed.

BACKGROUND

The superconducting undulator (SCU0) consists of a dual-core 42-pole magnetic structure that is cooled to 4.2K with a system of four cryocoolers operating in a zero-boil-off configuration. The design of the cryostat is based on a concept developed at the Budker Institute, Novosibirsk [1]. Figure 1 shows the overall cooling scheme of the cryostat. The beam chamber is cooled by the two bottom cryocoolers (Sumitomo RDK-408S) together with the inner thermal radiation shield, which is called the 20K circuit. The main and correction magnet leads and the thermal transitions of the beam chamber are connected to the first stages of all four cryocoolers through the outer thermal radiation shield, which is called the 60K circuit. The 4K circuit consists of the helium vessel, the magnetic structure, and the superconducting part of magnet leads. These are cooled by the 2nd stage of the top cryocoolers (Sumitomo RDK-415D). The magnet is cooled by circulating LHe, and it is thermally isolated from the beam chamber [2-4].

FEA MODEL

Finite element analysis (FEA) was conducted using ANSYS 14.5. Initially, heat loads at individual parts of the cryostat were calculated with fixed end temperatures. Thermal radiation heat was calculated in a separate model. Joule heating of the resistive parts of the current leads was also calculated separately. Then using these results, the 20K and 60K circuits were modeled including a simulated heat load imposed by the circulating electron beam. Temperatures and heat load at each cryocooler were calculated and compared with measured data. Table 1 is the calculated heat load of the individual parts of the cryostat based on the original design before the installation [1]. The 60K circuit heat loads are dominated by the magnet current leads. Static heat load through the main current leads are 47 W and through the correction current leads are 8.0 W. Main current lead heat increases to 63.85 W when they are energized to 650 A. The correction current lead heat increases to 12.2 W when they are energized to 70 A. Other sources include beam tube conduction and radiation from 295K to the outer shield. The 20K circuit heat loads are primarily the beam-induced heat load in the beam chamber that goes to the second stages of the bottom cryocoolers (408S) through the copper busbar and thermal links. The beam heat load is predicted to be 10 W at the 20K circuit and 6 W at the 60K circuit. The 4K circuit heat loads consist of the high-temperature superconducting (HTS) section of the magnet current leads, a very small portion of the beam heat through the beam chamber supports, heat through the cold mass supports made of Kevlar strings, and radiation from the inner shield to the cold mass.

In order to calculate the 20K and 60K circuit temperatures and heat, the magnet leads, the beam chamber, and the outer shield are modeled at steady state conditions. Figure 2 shows the overall temperatures of the 20K and 60K circuits as well as boundary conditions of this model. The outer shield is included in the calculation but not shown. Temperatures of the end flanges of the beam chamber and the top of the magnet leads are fixed at 295K. The coldest ends of the magnet leads are fixed at 3.42K, which is the measured temperature of the 2nd stage of the top cryocooler (415D). The load maps of the 1st stage top and 1st and 2nd stages of the bottom cryocoolers are implemented as temperature-dependent heat flow at each cold head.

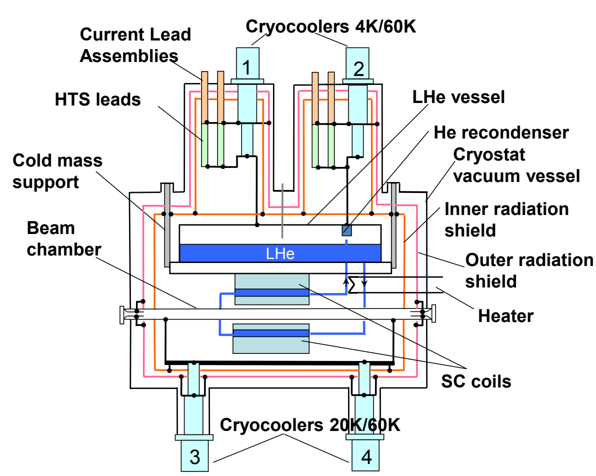

Figure 1: Cooling schematic.

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Table 1: Calculated Heat Loads of Individual Parts [W]

Heat Source	4K	20K	60K
Beam Induced Heat		10	6
Thermal Radiation	0.017	0.205	0.3
Beam Tube Bellows			4.8
Beam Tube Support@20K	0.08		
He Vent Bellows	0.0004	0.008	0.6
Cold Mass Supports	0.08		
Thermal Shield Supports		0.22	3.25
Correction Current leads (70 A)	0.064		8.02 (12.2)
Main Current Leads (650 A)	0.285		47 (63.85)
Total	0.526	10.43	69.97 (91)

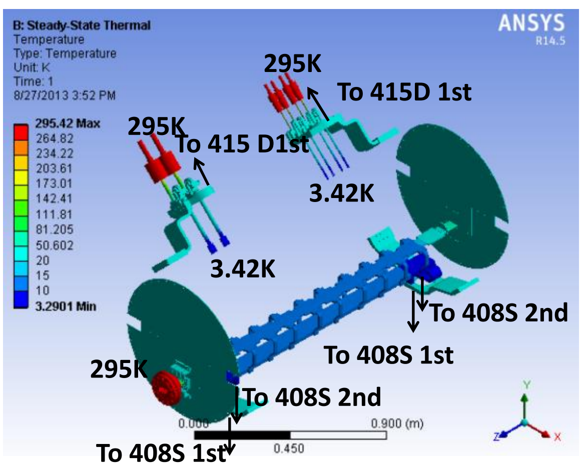

Figure 2: Calculated temperatures at the 20K and 60K circuits and their boundary conditions.

The cold head temperatures and heat loads at each cryocooler, except the top cryocooler 2nd stages, were calculated. The temperatures of the beam chamber were calculated based on the predicted beam-induced heat load [5,6]. The static heat load is calculated first, then the two dynamic heat loads. One is with beam on and the other is with both the beam and the magnet current on.

BEAM CHAMBER TEMPERATURES

Figure 3 shows the 20K circuit and the locations of temperature sensors. The sensors are numbered from the beam upstream to downstream. The main current leads are at the downstream side. Sensors 0 and 8 are on the stainless steel (SS) taper sections of the beam chamber while sensors 1 and 7 are on the stainless steel flat sections. These sections are linked to the outer shield and then to the 1st stages of the cryocoolers. The aluminum section is between the stainless-to-aluminum bi-metallic joints. Five sensors (2, 3, 4, 5, and 6) are on the aluminum section of the beam chamber and sensor 4 is near the center of the chamber. The aluminum section of the beam chamber is (thermally connected to the copper busbar through 20 copper links. The copper busbar is connected to the two bottom cryocooler 2nd stages (not shown).

Initially the beam heat was implemented in the model as a uniform heat flux in the beam chamber. However, the model calculated much lower temperatures at the stainless steel flat section than the measurement. So instead, the beam chamber inner surface is divided into three sections (aluminium, stainless steel flat, and stainless steel taper), and the heat load is applied based on S.H. Kim et al.'s beam-induced heat load calculation [5,6]. The SS taper heat load is 6.2 W, the SS flat heat load is 5.9 W, and the Al heat load is 4.7 W at 24-bunch mode and 100-mA beam current.

To reflect the circular beam shape, the beam chamber inner surfaces are divided into several strips and heat flux is distributed only on the center strips. The calculated temperatures are compared with the measurement by Harkay et al. in Fig. 4 [6]. For the static case, sensors 3 to 5 show ~7K. So the temperatures in the aluminum sections are uniform. Sensors 1 and 7 in the SS flat section are ~23K. When the beam current is on and the SCU magnet main current is at ~650 A, temperatures at sensors 2 and 6 rise above 20K since these are outside of the thermal links. Temperatures at 3, 4, and 5 rose to 13K. The SS flat sections 1 and 7 show as high as ~70K. Sensors 0 and 8 do not show the same temperatures in the measurement because the sensor positions are not known with sufficient accuracy. However, the average of these numbers agrees with the calculated values. So the calculated temperatures and measured temperatures have shown good agreement. Higher temperatures at sensors 1 and 7 suggest that more heat goes to the outer shield than originally designed [1]. An additional thermal link will be

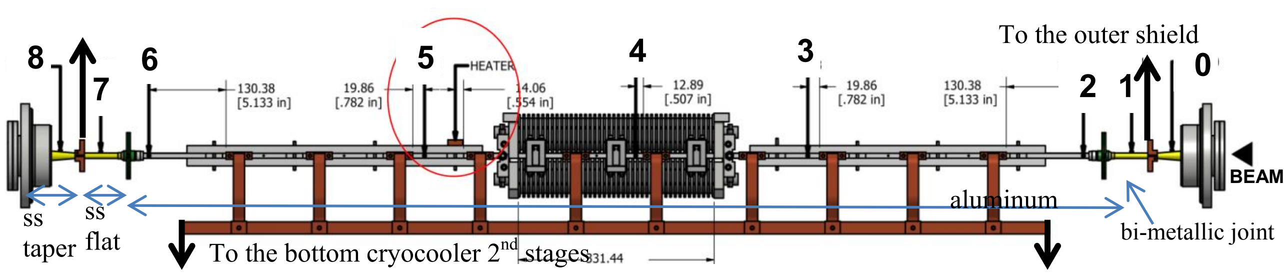

Figure 3: A schematic of the beam chamber, copper busbar, and locations of temperature sensors.

attached to the end of the aluminum section of the beam chamber to lower the temperatures at sensor locations 1, 2 and 6, 7.

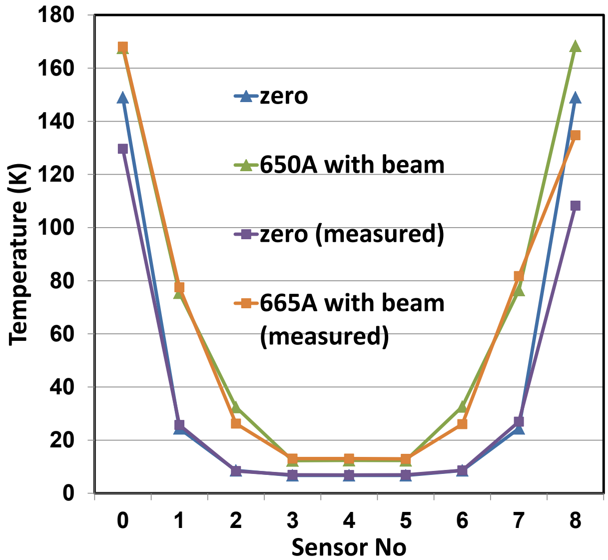

Figure 4: Calculated beam chamber temperatures are compared with measured temperatures.

COLD HEAD TEMPERATURES

Table 2 shows the calculated cold head temperatures based on the 20K and 60K circuit model and measured heat loads with 24-bunch mode beam and 665 A of SCU main current.

Table 2: Summary of Cold Head Temperatures [K]

	Static		Beam		Beam and current	
	Calc.	Meas.	Calc.	Meas.	Calc.	Meas.
TP1US	30.5	30.82	31.4	32.16	33.5	33.829
TP1DS	35.2	33.57	37.2	34.88	41.9	40.057
BT1US	30.0	30.18	30.9	32.16	32.7	33.736
BT1DS	31.1	30.83	32.3	34.88	34.7	35.116
BT2	6.75	6.715	10.38	10.09	10.40	10.335

In the actual system, the 20K circuit operates at ~10K and the 60K circuit at ~31K. The cold head temperatures show good agreement with measurement. Since measured heat is derived from the measured temperatures, the heat load at each cryocooler cold head agrees as well. A higher temperature at the top cryocooler downstream 1st stage (TP1DS) indicates the existence of a higher heat load from the main current leads. The bottom cryocooler downstream (BT1DS) also shows a slightly higher temperature than the upstream one (BT1US). However overall they are ~31K. So the magnet lead heat is well distributed to the 1st stage of all four cryocoolers as designed. A summary of heat loads is shown in Table 3. The 4K heat load is the sum of the heat loads of the individual parts from Table 1. The 20K and 60K heat loads are from the 20K and 60K circuit model. The calculated 60K static heat load was 63.66 W. The dynamic heat load with 650 A is 89.88 W. The measured static heat load is 63.01 W, and the dynamic heat load is 90.26 W. The calculated 20K heat load is 15.54 W due to the beam-induced heat. It agrees with the measured heat load of 15.09 W. Since the stainless steel flat sections show much higher temperature than expected, the beam heat going to the 60K circuit needs to be considered.

Table 3: Summary of Heat Loads [W]

	Static		Beam		Beam and current	
	Calc.	Meas.	Calc.	Meas.	Calc.	Meas.
4K	0.526	0.66	0.526	0.72	0.526	0.98
20K	0.188	-0.63	14.55	14.35	15.54	15.09
60K	63.66	63.01	68.13	68.0	89.88	90.26

DISCUSSION

The FEA calculated temperatures and heat loads show good agreement with the heat loads based on temperature measurements. The 4K heat load may include a larger error since the cryocooler load map does not have enough data points at this temperature range. The cryocooler cooling capacity is 3 W (1.5 W ea) at 4K, 40 W (20 W ea) at 20K, and 224 W (57 W ea for 415D and 55 W ea for 408S) at the 60K circuit. Thus, these heat loads are within the range. The 4K circuit model will be established in the next phase of this work. This FEA thermal model will be used for the future development of 1.1-m and 2-m devices (SCU1 and SCU2).

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