Thermal Analysis of a Superconducting Undulator Cryostat for the APS Upgrade

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Abstract. The Advanced Photon Source Upgrade includes four 4.8-m-long superconducting undulator (SCU) cryostats, each containing two planar undulator NbTi magnets up to 1.9 m long. The cooling is provided by six cryocoolers arranged in three thermal circuits. The magnets are indirectly cooled with LHe penetrating through channels in the magnet cores. This 4 K circuit, which also includes a LHe tank, is cooled by five 4 K cryocooler 2nd stages. A beam vacuum, which is thermally isolated from the magnets, is cooled by one 10 K cryocooler 2nd stage. A thermal shield and warm parts of current leads are cooled by the 1st stages of all six cryocoolers. This paper presents an ANSYS-based thermal analysis of the new SCU cryostat including all thermal circuits. The benchmarked thermal conductance between the cryocooler cold heads and the LHe tank are used in the calculations as well as the measured cryocooler load lines. The model predicts temperatures in the system, total 4 K heat loads, and excess cooling power for various operational modes of the undulator.

1. Background
Currently two planar superconducting undulators (SCUs) and one helical SCU (HSCU) are installed and in operation at the Advanced Photon Source (APS) storage ring. In these systems, the magnets are indirectly cooled with LHe penetrating through channels in the magnet. The system operates in “zero-boil-off” mode using a regulating trim heater that matches the operational heat load to the installed cooling power. The cooling of the LHe circuit is provided by cryocoolers. The beam chamber operates at a higher temperature level and is thermally isolated from the magnets. The 1st-generation cryostat has two thermal shields and three thermal circuits. This design was originally developed by the Budker Institute of Nuclear Physics (BINP) and implemented for planar SCUs. An ANSYS-based thermal model of the planar SCUs was developed and validated based on the planar SCU first. All the thermal circuits are included in one FEA model [1, 2]. The same method is applied for the 2nd-generation cryostat, which has one thermal shield and two thermal circuits with the beam chamber connected to the shield [3, 4]. The APS Upgrade (APSU)-SCU cryostat is a one-shield cryostat (similar to the 2nd-generation cryostat) but with three thermal circuits. This cryostat design is based on the operational experiences of existing SCUs. The overall length of the cryostat is twice as long as the existing SCU cryostats, and it contains two up to 1.9-m-long planar undulator NbTi magnets.

2. Cooling schematics of the APSU-SCU cryostat
The cooling schematic of the APSU-SCU cryostat is shown in Figure 1. The cooling is provided by six cryocoolers arranged in three thermal circuits. The thermal shield and warm parts of current leads are cooled by the 1st stages of all six cryocoolers. The 4 K circuit, which includes a LHe tank and magnets,
is cooled by five 4 K cryocooler (Sumitomo RDK-415D or RDE-418D4) 2nd stages. The beam chamber is cooled by one 10 K cryocooler (Sumitomo RDK-408S) 2nd stage.

Figure 1. Cooling schematic of the APSU-SCU cryostat.

The cold mass and the magnet lead turret assembly of this cryostat are shown in Figure 2. The image on the right shows the side view of this cryostat. Two pairs of 4 K cryocoolers together with the magnet current leads comprise the right and left turret assemblies. These are connected through copper flexible links to the ends of the LHe tank. The fifth 4 K cryocooler is at the top center and cools the LHe tank via a copper flexible link to the tank center. The two pairs of magnets are supported from the underside of the LHe tank. The 10 K cryocooler cools the beam chamber and is located at the bottom center. It connects to a copper busbar which in turn cools the beam chamber through an array of thermal links.

Figure 2. The cold mass of the cryostat includes the LHe tank, the beam chamber assembly, magnet lead assembly, four magnets, and six cryocoolers. Each turret assembly includes two cryocoolers, as shown on the right.

3. Method to calculate excess cooling power

When the SCU is in operation, a trim heater is energized to regulate the LHe reservoir at 760 Torr, maintaining saturated conditions at 4.2 K. The SCU tank pressure will equilibrate below 760 Torr without this power since the cooling power at 4.2 K exceeds the system heat load. This additional trim heat represents the excess cryocooler cooling power. In our ANSYS numerical simulation, this excess
is calculated by constraining the temperature at the LHe tank inner surface to a value of 4.2 K. A reaction probe in ANSYS automatically calculates the additional heat to keep the LHe at 4.2 K, which corresponds to the excess cooling power. The validity of this method has been confirmed with thermal models of existing planar undulators that have been benchmarked against actual performance data [1].

3.1. Measured load map of cryocoolers

Load maps for all the cryocooler models were measured at low temperature in detail and used as inputs of the model. Figure 3 shows the 2nd stage cooling power as a function of the 2nd stage temperature when the 1st stage heat load is at 0 W for a Sumitomo RDE-418D4 and 415D [5]. Although the minimum temperature slightly increases as the 1st stage power increases, the cooling power of the RDE-418D4 is 2 W at 4.2 K for 30 W at the 1st stage. Table 1 summarises the 2nd stage cooling power of the RDE-418D4 at 4.2 K for various 1st stage heat loads. These data are incorporated into the ANSYS thermal model to correlate available cooling power with cryocooler cold head temperature.

| The 1st stage heat (W) | The 2nd stage cooling power (W) |
|-----------------------|---------------------------------|
| 0                     | 2.25                            |
| 10                    | 2.25                            |
| 20                    | 2.0                             |
| 30                    | 2.0                             |
| 40                    | 1.75                            |
| 50                    | 1.49                            |

Figure 3. The load line of the 418D4 2nd stage is shown as square dots and a solid line. For comparison, the load line of the 415D is also shown as a dotted line.

3.2. Thermal links

The thermal conductance of thermal links that were used in current SCUs was directly measured using the 415D cold head as a sink and by directly applying heat from 0 W to 2.5 W incrementally. Table 2 shows the summary of the measured thermal conductance at 4.2 K. The 4 K link conductance of a planar SCU (SCU1) and a helical SCU (HSCU) was ~ 1–2 W/K, which resulted in a loss of available 4.2 K cooling power relative to higher-conductance links. The SCU1 copper foil 10 K links show a better thermal conductance of ~4 W/K at 4.2 K; however, these links were used only for a 10 K circuit. The measured conductance values are consistent with the temperature gradient observed at current SCUs in operation and, therefore, improvement was made. Consequently, copper foil links will be used for the 4 K links of APSU-SCU cryostat. The conductance value is designed to be ~5 W/K at 4.2 K. Figure 4 is
the calculated conductance of the copper link based on the designed geometry and heat flow using RRR=100 copper. This link will be used between the cryocooler 2nd stage and the LHe tank.

Table 2. Measured thermal link conductance @ 4.2 K

| Name and Position of the Link       | Thermal Conductance (W / K) |
|-------------------------------------|----------------------------|
| SCU1 Cu foil 10 K link set 1        | 3.9–4.4                    |
| SCU1 Cu foil 10 K link set 2        | 3.43                       |
| SCU1 top Aluminium foil 4 K link   | 1.1                        |
| HSCU top Cu braided 4 K link       | 1.4                        |

Figure 4. The thermal link between the LHe tank and the 2nd stage cold head of the APSU-SCU cryostat. RRR = 100 gives a thermal conductance of 5.5 W/K at 4.2 K.

4. FEA model

Thermal analysis of three thermal circuits is shown in the following sections. The temperature-dependent cooling power as a heat sink and heat loads are used as input heat sources. Calculated temperature and heat loads are shown for each cooling circuit: the thermal shield circuit, the beam chamber cooling circuit, and the magnet cooling (4 K) circuit. The original cryostat design used Sumitomo RDK-415D cryocoolers. However, recently a new cryocooler RDE-418D4 with higher capacity became available, prompting a comparison.

4.1. The thermal shield circuit

Table 3 summarizes the thermal shield circuit heat load and the 408S 2nd stage heat load for static, beam only, and beam and magnet current (450A) cases. These include the conduction heat through the warm part of the magnet current leads, conduction heat through the transition section, and radiation from room temperature to the shield (which is wrapped by 40 layers of Multilayer Insulation (MLI) blankets. Direct line-of-sight heat leaks from room temperature through shield gaps are minimized.

Table 3. The thermal shield circuit heat load and 408S 2nd stage heat load

| Location of Heat Load                      | Static (W) | Beam only (W) | Beam and Current (W) |
|--------------------------------------------|------------|---------------|----------------------|
| Beam Chamber Transition                    | 7.8        |               |                      |
| Conduction Heat through Main Current Lead  | 39.7       |               |                      |
| Conduction Heat through Correction Current Lead | 31.7     |               |                      |
| Cold Mass Support (vertical and horizontal)| 5.3        |               |                      |
| Thermal Radiation from RT to 40 K          | 9.4        |               |                      |
| LHe Relief Piping (RT to 40 K)             | 2.3        |               |                      |
| Instrumentation (RT to 40 K)               | 0.245      |               |                      |
Joule Heat through Main Current Lead 18.7
Joule Heat through Correction Lead 16.6
Total 1st stage Heat Load 96 96 131
Beam Heat 0 7 7
Conduction Heat from the Shield to 408S 2nd stage 1.06 1 1
Total 408S 2nd stage Heat Load 1.06 8.0 8.0

The largest 1st stage heat load is from the warm part of the magnet leads. The total static heat load is 96 W. In that case, a calculated shield temperature is 28.9–32.9 K, as shown in Figure 5. When the beam heat of 7 W is applied in the beam chamber, the heat is directly coupled to the 408S 2nd stage. So the total 408S 2nd stage heat load becomes 8 W, and the 1st stage heat load is not affected much. However, when the magnet is in operation (450 A), the shield heat load increases by 35 W due to the Joule heat at the non-superconducting section of the leads, resulting in a temperature increase to 29.6–34.9 K. The total heat load on the 1st stage becomes 131 W. The maximum temperature is always at the end sections where the magnet current leads are located.

**Figure 5.** The shield temperature stays at 28.9–32.9 K at static and beam heat only. The shield temperature increases to 33.1–36.0 K when both beam and magnet current are on.

4.2. **The beam chamber cooling circuit**

As shown in Figure 6, one 10 K cryocooler RDK-408S is used to maintain the beam chamber temperature below 20 K with the designed heat load [6]. The shield temperature (~35K), the end flange temperature (~room temperature) and the load line of the 408S 2nd stage are used as the boundary condition of the model.

**Figure 6.** The Al 6063-T5 beam chamber and copper busbar with one 10 K cryocooler. There are 18 copper thermal links between the busbar and the beam chamber.

Calculated temperatures of the beam chamber and the busbar are shown as a function of the positions in Figure 7. When no heat is applied, the minimum temperature of both the busbar and the beam chamber is ~7 K at the center where the cryocooler is located, and the highest temperature is 7.8 K at the end, which is close to the thermal intercept at the shield. Since no heat is applied, temperature across the link is zero and the beam chamber and busbar are at the same temperature except the very ends. When 7 W of heat is applied uniformly along the length of the chamber, the minimum temperature of the beam
chamber and the busbar increases to 12.1 K and 13 K, respectively which is shown in the top two plots in Figure 7. The beam chamber temperature is slightly lower at the positions where the thermal links are attached. The temperature difference between the beam chamber temperature and the busbar is ~0.2 K, due to impedance through the links. Since a few thermal links at the center are missing due to position interference with the corrector magnet assembly, the temperature difference at the center is ~1.7 K. The thermal isolation between the beam chamber and the magnets is achieved using low thermal conductivity Torlon standoffs, as shown in Figure 8. Conduction heat leak through the beam chamber support is calculated as a function of the beam heat load. The conduction heat through the beam chamber support is 3 mW when no heat is applied in the beam chamber, as shown in Figure 9. Conduction heat through the beam chamber support increases monotonically as the beam heat load increases. The heat leak to the 4 K circuit is 15 mW when the beam heat load is at 7 W. Since the beam chamber temperature is below 20 K, radiation from the beam chamber is negligible (less than 1 mW).

### Figure 7. Temperature of the beam chamber (solid lines) and the copper busbar (dotted lines) as a function of the position from the end. The beam heat load is 0 W for the bottom two lines. The beam heat load is 7 W for the top two lines.

![Figure 7](image7.jpg)

### Figure 8. Beam chamber support, busbar, and thermal links are shown. 7 W of beam heat is applied in a 16-mm-wide section of the beam chamber.

![Figure 8](image8.jpg)

### Figure 9. Conduction heat through the beam chamber support monotonically increases as beam heat load increases. When the beam heat load is at 7 W, it is 15 mW.

![Figure 9](image9.jpg)

4.3. The 4 K circuit
The 4 K circuit consists of the LHe tank and magnets with the LHe channel and the 2nd stages of 418D4s (see Figure 2). The LHe tank is a copper cladded stainless steel tank. The top part is 4.75-mm-thick stainless steel and 4.75-mm-thick copper. The bottom of the tank is a 19.05-mm-thick stainless steel plate that is used as a magnet strongback. Five cryocooler cold heads are connected through the copper thermal links [7]. The 2nd stage load lines (see Figure 3) are used as an input. Table 4 shows the static heat load of the 2nd stage. The largest 4 K heat load is conduction heat through the high-temperature superconducting (HTS) section of the leads. The next largest heat loads are the thermal radiation from the shield and the conduction heat through the cold mass support. Thermal radiation heat is estimated by

\[ Q = \epsilon\sigma A(T_{\text{hot}}^4 - T_{\text{cold}}^4), \]

where \( \epsilon \) is emissivity; \( \sigma = 5.670374419 \times 10^{-8} \text{ W} \cdot \text{m}^{-2} \cdot \text{K}^{-4} \); \( A \) is surface area of the shield; \( T_{\text{hot}} \) is shield temperature; and \( T_{\text{cold}} = 4.2 \text{ K} \). For the static case, the shield temperature is 28.9–32.9 K, as shown in Figure 5. On average, \( T_{\text{hot}} = 30.5 \text{ K} \), shield area \( A = 7.24 \text{ m}^2 \), and emissivity \( \epsilon = 0.1 \), which yields 36 mW.

| Location of Heat Load                                      | Heat Load (W) |
|-----------------------------------------------------------|---------------|
| Conduction Heat through HTS section of Main Lead to 4 K circuit (2 pairs) | 0.424         |
| Conduction Heat through HTS section of Correction Lead to 4 K circuit (8 pairs) | 0.256         |
| Cold Mass Support (vertical and horizontal, 40 K to 4 K)  | 0.045         |
| Thermal Radiation from shield (emissivity = 0.1)         | 0.036         |
| LHe Relief Piping (40 K to 4 K)                           | 0.04          |
| Instrumentation (40 K to 4 K)                             | 0.02          |
| Beam Chamber Support                                      | 0.003         |
| Total 4 K Heat Load                                       | 0.824         |

Figure 10 shows the temperature of the LHe tank and thermal links (RRR=100 copper) with five 1.5W coolers (415Ds) as originally designed. The calculated total cooling power is 4 W, and the excess cooling power is 3.16 W for the static heat load case. Temperatures at the cold head are higher; however, the total cooling power is lower than using 418D4s. Figure 11 shows the temperature of the LHe tank and thermal links with five 2 W coolers. The excess cooling power significantly increases with the 2 W cryocoolers. The calculated total cooling power is 5.61 W, and the excess cooling power is 4.78 W for the static heat load case. Although four cryocoolers may be sufficient for the total cooling capacity, it is necessary to have a fifth cryocooler to help condensation of the LHe. The additional cooling capacity decreases the total quench recovery time. The detailed quench recovery analysis is given in [7].
5. Discussion

This ANSYS-based thermal model of the new SCU cryostat including all thermal circuits has been completed. The benchmarked thermal conductance between the cryocooler cold heads and the LHe tank are used in the calculations. The measured 2 W cryocooler load lines were also used in the model. In Table 5, the total heat load and excess cooling power are summarized for three cases: static, beam only, and beam and current. The heat load increase due to the beam only is mainly from the conduction heat from the beam chamber support, which is ~0.02 W. The observed 4 K load increase on the HSCU is 0.07 W due to the operating magnet current. Thus the two sets of magnet leads of this new cryostat yield 0.07 W×2 resistive heat increase. Additionally, radiation heat from the thermal shield increases from 0.036 W to 0.043 W when the magnet current is on. The original design with 415D has 3.16 W of excess cooling power. Using a 2 W cryocooler increases the excess cooling power by as much as 4.8 W. The high cooling capacity of the entire system suggests the feasibility of a conduction-cooled system in the near future. The thermal model predicts temperatures in the system, total 4 K heat loads, and an excess cooling power for various operational modes of the superconducting undulator.

Table 5. 4 K heat load and the excess cooling capacity

| Total                      | Static (W) | Beam Only (W) | Beam and Current (W) |
|----------------------------|------------|---------------|----------------------|
| 2nd stage Heat Load        | 0.82       | 0.84          | 0.99                 |
| 2nd stage Cooling Power (415D) | 3.99       | 3.99          | 4.0                  |
| Excess Cooling Power       | 3.16       | 3.14          | 3.0                  |
| 2nd stage Cooling Power (418D4) | 5.61       | 5.61          | 5.62                 |
| Excess Cooling Power       | 4.78       | 4.77          | 4.63                 |

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