Thermal analysis of superconducting undulator cryomodules

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Abstract. A cryocooler-cooled superconducting undulator (SCU0) has been operating in the Advanced Photon Source (APS) storage ring since January of 2013. Based on lessons learned from the construction and operation of SCU0, a second superconducting undulator (SCU1) has been built and cold tested stand-alone. An excess cooling capacity measurement and static heat load analysis show a large improvement of cryogenic performance of SCU1 compared with SCU0. ANSYS-based thermal analysis of these cryomodules incorporating all the cooling circuits was completed. Comparisons between measured and calculated temperatures at the three operating conditions of the cryomodule (static, beam heat only, beam heat and magnet current) will be presented.

1. Introduction
In a previous paper, a subset of the cooling circuits of the first superconducting undulator (SCU0) operating at APS was modeled based on the cryocooler manufacturer’s published load maps and compared with the data of the operating SCU0 [1]. However, this model did not include the magnet cooling circuit (4 K circuit). In this paper, the 4 K circuit was included and the model has been completed. In the course of the 4 K circuit modeling, more detailed cryocooler load maps became necessary. The load maps were measured precisely for two Sumitomo RDK-415D and two RDK-408S cryocoolers in order to provide accurate cooling power data to the ANSYS numerical simulation. The second superconducting undulator SCU1 has been built and installed in the storage ring. The calculated thermal performance was compared to the measured operating data for both SCU0 and SCU1, which was installed in the APS in May 2015.

2. Cooling Schematic
Figure 1 shows the schematical layout of the SCU0 and SCU1 cryomodules. The cryogenic system was designed in conjunction with the Budker Institute of Nuclear Physics, Novosibirsk, Russia, based upon design concepts used on their superconducting wigglers [2], [3]. The system is designed so that the beam chamber and magnets are cooled independently. The beam chamber and inner thermal radiation shield are cooled by the second stages of cryocoolers in figure 1 (Sumitomo RDK-408S). The magnetic structure was cooled separately by liquid helium (LHe). The magnet and associated helium circuit are cooled by the second stages of cryocoolers (Sumitomo RDK-415D) shown in Figure 2. The outer thermal shield is cooled by the first stages of all four cryocoolers. The main and correction magnet current leads and thermal transitions of the beam chamber are connected to the outer thermal radiation shield. In Figure 2, two thermal shields, cold mass supported by Kevlar, the beam chamber and one of the bottom cryocoolers, are shown. The beam chamber support consist of low thermal conductivity
ceramic balls and stainless steel position adjustment rods. The Figure 3 is a material property used for the ceramic balls.

Figure 1. SCU schematic layout. 4K circuit consist of LHe vessel, magnets and stainless steel frame and the beam chamber support which are cooled by 2\textsuperscript{nd} stage of 415D. 20K circuit (inner shield circuit) consist of the beam chamber, 20K busbar and the inner shield which are cooled by 2\textsuperscript{nd} stage of 408S. The outer shield circuit (60K circuit) consist of the current lead assembly and outer shield and the warm part of the beam chamber which is cooled by 1\textsuperscript{st} stage of all four cryocoolers.

Figure 2. A side view of SCU1 cryostat showing thermal shields, cold mass and beam chamber.

Figure 3. A thermal conductivity of Ultem and Alumina which is used for the beam chamber supports.
3. Numerical Simulation

A finite element thermal analysis of the system was conducted. Constraints consist of known fixed temperatures and available cooling power as defined by the cryocooler load maps. Loads consist of known heat leaks and applied external heat loads. A room temperature constraint is applied to the top of all magnet leads, the ends of the beam chamber, and the top of the dewar neck. Available cooling power is applied to the first and second stages of the cryocoolers. Conduction heat leaks are simulated from the geometry while radiation heat leaks are input directly. Heat leaks from the magnet current leads consist of both a conduction term and a Joule heating term when the magnets are powered. Additional heat input to the inner shield circuit comes from power dissipated to the beam chamber during device operation in the APS storage ring. This power is modeled as an applied heat load based on the electron beam-induced heat load calculation for SCU0 [4], [5]. This power depends on electron beam current and bunch filled pattern. Additional applied loads include the cold mass supports and instrumentation.

The simulation was run for three different operating modes: Mode 1 (static heat load only), Mode 2 (static plus electron beam) 16 W heat load for 24 bunch mode was applied as beam heat on the beam chamber inner surfaces, and Mode 3 (static plus electron beam plus magnet current lead Joule heating). Operating current was 690A. Joule heating at non-superconducting section were calculated in a separate model and added to outer shield cooling circuit. Joule heating due to the joint resistance 0.25W (estimated from the measurement) was added to the copper pad on the LHe tank.

4. SCU0 Analysis and Measurement

Table 1 shows the simulated and measured SCU0 magnet cooling circuit (4 K circuit) heat loads for Mode 1. Although simulation was conducted for all thermal circuits, particularly the input and output of FEA model for the magnet cooling circuit (4K circuit) are shown in Figure 4. Simulated loads are represented by an original (“as designed”) model and a revised (“as-built”) model of the cryostat geometry. A revised model was necessary when it was discovered that certain components in the actual cryostat did not meet the heat leak requirements of the design. Measured thermal performance is derived from actual cryocooler second stage temperatures via the load map. Figure 5 shows the cooling power of the RDK-415D second stage as function of second stage temperatures for a variety of first stage loads. Cooling power is shown to be a weak function of first stage load. Figure 6 shows the cooling power vs. second stage temperature for two different RDK-415D cryocoolers. The spread in cooling power between the two individual cryocoolers at 3.5 K is ~100mW. For Mode 1, a measured trim heater power of 0.166 W was needed to maintain LHe pressure at 760 Torr (4.2 K). The derived cooling power for this Mode based on measured temperatures is 1.05 W, which yields a static load of 0.88 W.
Table 1. Sources of magnet circuit heat load for SCU0 (Mode 1)

| Heat Source          | Original Model [W] | Revised Model [W] | Measured [W] |
|----------------------|--------------------|-------------------|--------------|
| HTS Main             | 0.285              | 0.285             |              |
| HTS Correction       | 0.064              | 0.064             |              |
| radiation            | 0.04               | 0.04              |              |
| Kevlar supports      | 0.08               | 0.18              |              |
| Beam chamber supports| 0.02               | 0.28              |              |
| Instrumentation      | 0.04               | 0.04              |              |
| LHe level Gauge      | 0.004              | 0.004             |              |
| Dewar Neck           | 0.002              | 0.002             |              |
| **Total static heat load** | **0.54** | **0.89** | **0.88±0.1** |

*measured trim heater power is subtracted from applied cooling power to yield total static heat load.

Figure 5. The 2nd stage cooling power of RDK-415D is plotted as a function of the 2nd stage temperature at the 1st stage heat load of 0, 10, 20, 30, 40, and 50W.

Figure 6. The figure shows the individual cryocooler difference for RDK-415D. For example, there is 100mW of error bar at 3.5K.

Figure 7. Temperature distribution of the cold mass for the revised model for Mode 1. The stainless steel support temperature is ~10 K. 22mW each at Kevlar support is added instead of 10mW of the original model.

Kevlar heat leak were calculated separately using Kevlar 49 thermal conductivity and diameter and length.
Figure 8. Temperature distribution of the end of the cold mass for the revised model for Mode 1. The stainless frame and the beam chamber support are shown. The beam chamber support makes point contacts with beam chamber by 6 ceramics balls. In the original model, thermal conductivity of ultem were used for the ceramic balls and in the revised model, it was replaced with alumina thermal conductivity. The stainless steel support temperature of the revised model became ~10 K as shown.

Figures 7 show the temperature of the revised model for Mode 1. Figure 8 shows the detail of the same model which includes one of the beam chamber support system. For the original model, the calculated temperature of the stainless steel support is ~ 4 K. In reality, there was a larger heat leak through Kevlar support system. So the heat leak is added accordingly. As shown in Figure 8, Kevlar strings are wound around the support at 1, 2, 3, and 4. There are total eight surfaces for both ends to apply Kevlar heat leaks. In the original model 10 mW of Kevlar heat leak were applied to these surfaces. 22mW were applied to the same surfaces for the revised model. Kevlar heat leaks were calculated based on the length, area and number of the strings. As shown in the Figure 8, the beam chamber support system consist of low thermal conductivity ceramic balls and stainless steel rods for position adjustment. The chamber is contacted to “4K circuit” by point contacts at ceramic balls to minimize heat leak to 4K circuit. However, in the actual construction, alumina (high thermal conductivity) was mistakenly delivered and used. So in the revised model alumina thermal conductivity was used for the ceramic balls (see Figure 3), static heat leak at the support increases from 0.04W to 0.28W and thus stainless steel frame temperature became t~10 K which corresponds to the measured temperatures.

Table 2. Summary of heat load of SCU0

| Operating Mode | Cooling circuit | Original Model [W] | Revised Model [W] | Measured [W] |
|----------------|-----------------|--------------------|------------------|--------------|
| Mode 1         | Outer shield    | 69                 | 69               | 44.46±0.1    |
|                | Inner shield    | 0.9                | 0.9              | 2.68±0.1     |
|                | Magnet (trim heater off) | 0.51             | 0.89             | 0.88±0.1     |
| Mode 2         | Outer shield    | 71                 | 71               | 63.43±0.1    |
|                | Inner shield    | 15.97              | 15.9             | 15.02±0.1    |
|                | Magnet (trim heater off) | 0.58             | 1.06             | 0.97±0.1     |
| Mode 3         | Outer shield    | 91                 | 91               | 93.59±0.1    |
|                | Inner shield    | 16.1               | 15.9             | 15.67±0.1    |
|                | Magnet (trim heater off) | 0.58             | 1.31             | 1.22±0.1     |
Heat loads for all cooling circuits are summarized in Table 2. For Mode 3, the heat load to the magnet circuit is large enough to keep the LHe pressure above 760 Torr without using the trim heater.

5. SCU1 Analysis and Measurement

The SCU1 cryomodule contains a 1.1 m long magnetic structure. The magnetic performance of this device has recently been published [6]. The overall cryogenic design is based on SCU0 and includes lessons learned. Table 3 lists the simulated and measured heat loads for the magnetic circuit for Mode 1. SCU1 fabrication did not deviate from the design so the numerical model did not require revision to the as-built. Measured data were collected both during off-line commissioning and during operation after installation in the APS storage ring. Differences between off-line and installed measurement data can be attributed to additional heat load associated with the magnetic measurement system used for off-line device characterization.

| Heat Source                  | Model [W] | Measured (off-line) [W] | Measured (installed) [W] |
|-----------------------------|-----------|-------------------------|--------------------------|
| HTS Main                    | 0.212     |                         |                          |
| HTS Correction              | 0.064     |                         |                          |
| radiation                   | 0.04      |                         |                          |
| Kevlar                      | 0.032     |                         |                          |
| Beam chamber support        | 0.02      |                         |                          |
| Instrumentation             | 0.07      |                         |                          |
| Level Gauge                 | 0.004     |                         |                          |
| Dewar Neck                  | 0.002     |                         |                          |
| **Total static heat load**  | **0.44**  | **0.55**                | **0.49**                |

*measured trim heater power is subtracted from applied cooling power to yield total static heat load.

Figure 9. Temperature distribution of the magnet cooling circuit for the SCU1 model for Mode 1 (no beam no current). The second stage temperatures 2.9 K and 3.1 K yield 0.44 W total heat load.

For Mode 1, measured trim heater powers of 0.38 W (off-line) and 0.44 W (installed) were needed to maintain LHe pressure at 760 Torr (4.2 K). The derived cooling powers for this Mode based on measured temperatures are 0.93 W for both operating locations, which yield static loads of 0.55 W (off-line) and 0.49 W (installed). Several changes were implemented in SCU1 based on the SCU0 experience, including optimized current leads and enhanced thermal links. For example, the SCU1 stainless steel cold mass support operates at ~ 6 K. Figure 9 shows the calculated temperatures at the cold mass of SCU1 for Mode 1 without trim heater heat. The second stage temperatures 2.9 K and 3.1 K yield 0.44 W total heat load. The static heat load of SCU1 was also measured off-line using an alternative technique.
that does not use a trim heater to maintain positive helium tank pressure. After reaching equilibrium at a pressure of 278 Torr under controlled conditions, the cooling capacity was derived from the cryocooler second stage temperatures. A cooling capacity of 0.53 W was recorded, which is in good agreement with other measurements. SCU1 heat loads are summarized in Table 4. For each mode, the measured heat load for the magnetic circuit is the difference between the derived cooling power and the average trim heater power. SCU1 demonstrates improved cryogenic performance compared to SCU0.

Table 4. Summary of heat load of SCU1

| Operating Mode | Cooling circuit | Model [W] | Measured [W] |
|----------------|-----------------|-----------|--------------|
| Mode 1         | Outer           | 41        | 39±0.1       |
|                | Inner           | 2.9       | 1.8±0.1      |
|                | Magnet (trim heater off) | 0.44       | 0.50±0.1     |
| Mode 2         | Outer           | 57        | 59±0.1       |
|                | Inner           | 15        | 15±0.1       |
|                | Magnet (trim heater off) | 0.47       | 0.60±0.1     |
| Mode 3         | Outer           | 70        | 74±0.1       |
|                | Inner           | 15        | 15±0.1       |
|                | Magnet (trim heater off) | 0.60       | 0.67±0.1     |

6. Future Optimized Cryomodule Designs
The existing SCU cryomodule design has room for optimization. The numerical simulation is a useful tool for exploring alternative concepts including re-configuration of cooling stages and simplification of the thermal shielding design. One revised concept eliminates the use of RDK-408S cryocoolers as well as the inner thermal shield in favor of four RDK-415D cryocoolers and a single thermal shield. In this model, the electron beam chamber is thermally intercepted by the first stages of the cryocoolers along with the single thermal shield.

Simulation results for the optimized design are shown in Figure 10. The end result of such an optimization is a smaller, simpler cryostat with a factor of four increase in the cooling margin at 4.2 K.
The total heat load of 0.9 W leads to 3.1 K at LHe tank. By adding trim heater heat of 1.9 W, LHe tank is maintained at 4.2 K, 760 Torr. Table 5 compares simulation results for this optimized design with the SCU1 simulation.

| Table 5. Comparison of model results for an optimized design with SCU1 design |
|---------------------------------|-----------------|-----------------|-----------------|
| Number of 415D cryocoolers | Number of 408S cryocoolers | Total 4 K cooling power [W] | Static Heat Load [W] | Excess cooling power [W] |
| Optimized model | 4 | 0 | 2.8 | 0.9 | 1.9 |
| SCU1 model | 2 | 2 | 0.9 | 0.45 | 0.45 |

7. Conclusion

The thermal model of the SCU cryomodule has been completed, including all the thermal circuits. It has also been revised with improved cryocooler load map measurements in the temperature range of interest. The calculated heat loads and temperatures were compared with measured data of SCU0 and SCU1 in the storage ring. The discrepancy between the original SCU0 model and measurement was due to higher than expected heat leaks in certain SCU0 components. These analysis results were directly reflected to SCU1 design and construction. As a result, the SCU1 heat leak calculated by this model matches the measurements and no model revisions were required. SCU1 therefore has sufficient excess capacity to be operated at 760 Torr with beam and magnet current. The model can be used for different cryocooler configurations for further cryomodule optimization.

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