A PRELIMINARY CRYOGENIC PERFORMANCE TEST OF THE 4.8-M-LONG CRYOSTAT FOR SUPERCONDUCTING UNDULATORS

Y. Shiroyanagi, E. Anliker, H. Hu, I. Kesgin, M. Kasa, Q. Hasse and Y. Ivanyushenkov

***Abstract*— A 4.8-m-long cryostat has been developed to cool a pair of 1.9-m-long planar superconducting undulator magnets (SCUs). The final design and the thermal model of this cryocooler-cooled LHe-based cryostat have been completed. The cryostat is fabricated, and a preliminary cooldown test has been performed. This paper presents a comparison between measured and calculated thermal performance of the 4.8-m-long cryostat for the SCU.**

***Index Terms*—cooldown performance, cooling power, superconducting undulator, beam chamber, cryocooler**

I. INTRODUCTION

THE 4.8-m-long cryostat has been developed to cool a pair of 1.9-m-long planar superconducting undulator magnets (SCUs). The final design and the thermal analysis of this cryocooler-cooled LHe-based cryostat have been completed. The cryostat has been fabricated, including two 1.9-m-long SCUs, and a preliminary cooldown test has been performed. In this cooldown, only one SCU was powered and other SCU was used as a thermal mass. The purpose of this test was to make sure the system reached the designed temperatures and to determine whether magnets can be operated in zero-boiloff mode. This paper presents a comparison between calculated and measured thermal performance of the 4.8-m-long cryostat for the SCU.

II. THE CRYOSTAT AND THE THERMAL MODEL SUMMARY

The cryogenic system of the long SCU follows the proven design of planar SCUs that are in operation at the Advanced Photon Source (APS). The basic design concept of this cryostat is the arrangement of the thermal stages in such a way that the beam vacuum chamber and SCU magnets are cooled independently [1]. The cooling schematic of the APSU-SCU cryostat is shown in Fig. 1. The cooling of three thermal circuits is provided by six GM cryocoolers. 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 the 2nd stages of five 4 K cryocoolers (Sumitomo RDE-418D4). The 10 K cryocooler (Sumitomo RDK-408S), located at the center bottom, cools the beam chamber through the copper busbar and an array of thermal links. The cryostat thermal model in ANSYS has been completed and used for thermal analysis [2], [3].

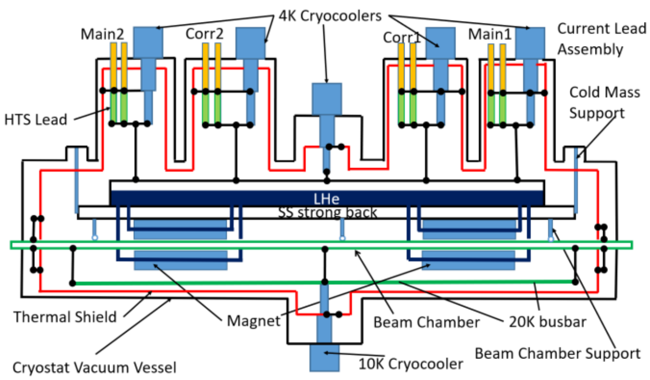

Fig. 1. Cooling schematic of the 4.8-m-long cryostat.

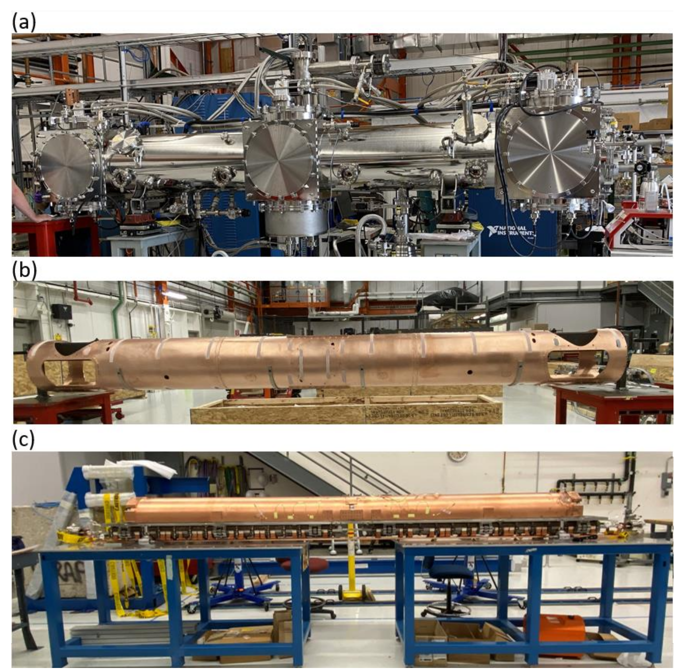

Fig. 2 (a) Photograph of the overall cryostat assembly. (b) Photograph of the thermal shield. (c) Photograph of the cold mass, which consists of a LHe tank, magnets, and the beam chamber.

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The cryostat has been fabricated and photographs are shown in Fig. 2 and Fig. 3. Fig. 2(a) shows the overall cryostat assembly. The left and right end turrets with 4 K cryocoolers are shown, as well as the center turret with the top (4 K) and bottom (10 K) cryocoolers. Fig. 2(b) shows a thermal shield before installation. Fig. 2(c) shows the cold mass assembly. The cold mass consists of a LHe tank, two pairs of magnet cores, and the beam vacuum chamber located between the magnet cores. The SCUs (four magnets) are located at the underside flat section of the LHe tank so that the bottom 19.05 mm thick stainless-steel plate of the LHe tank provides structural supports (strong-back) for two long SCUs. Two pairs of 4 K cryocoolers (Sumitomo

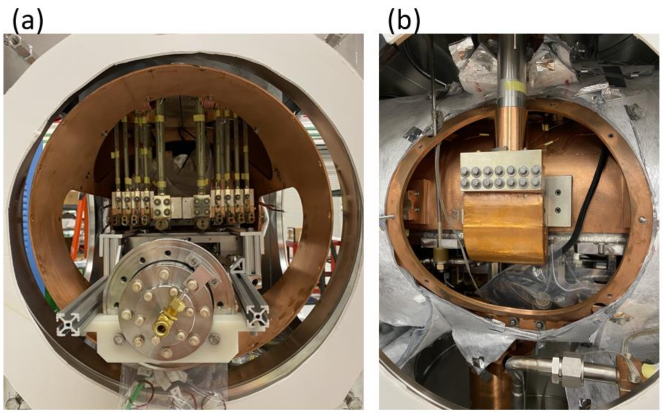

Fig. 3. (a) Detailed view of the end turret assembly. (b) Detailed view of the center turret assembly.

RDE-418D4) together with the magnet current leads comprise the right and left turret assemblies. Fig. 3(a) shows the detailed view of the end turret assembly. The main leads at the center and eight correction leads are shown above the beam chamber. These are connected through flexible copper foil links (not shown) to the ends of the LHe tank. Fig. 3(b) shows the center turret assembly. The fifth 4 K cryocooler is at the top center and cools the LHe tank via a flexible copper foil link attached to the tank center.

III. Preliminary Cooldown Test

A. *Cooldown Temperature Curves*

Fig. 4 shows the cooldown temperature curves of this cryostat. The cooldown took ~4 days. Three thermal circuits are clearly observed. The cryocooler 1^{st} stages were cooled down first and reached ~40 K at 25 hrs. The beam chamber reached ~15 K at 55 hrs. The 4 K cryocooler 2^{nd} stages and magnets reached ~6 K at 80 hrs. About 50 L of LHe were successfully transferred on the fifth day. After the LHe was transferred, the system was operated for 14 days with zero boiloff mode. During operation, a constant heat of ~7 W was applied to the beam chamber through the magnetic measurement system [4], [5]. Therefore, the measured heat load corresponds to an expected dynamic beam heat load.

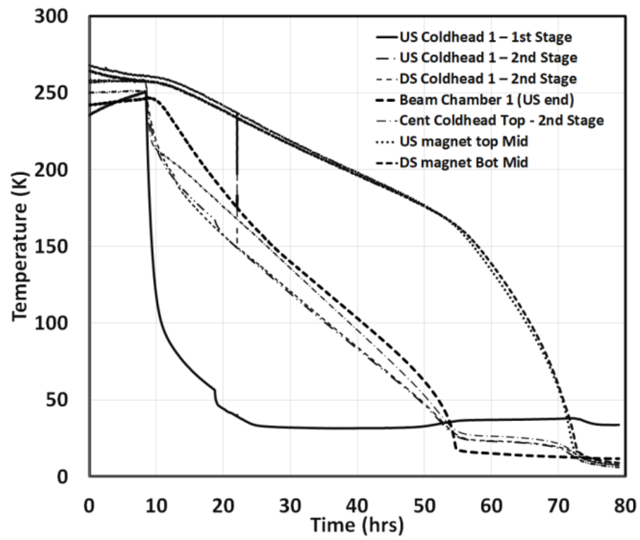

Fig. 4. Cooldown of the long SCU cryostat. US denotes upstream. DS denotes downstream. The overall cooldown took ~4 days. The 1^{st} stage reached ~40 K at 25 hrs. The 2^{nd} stages reached ~6 K at 80 hrs. The beam chamber reached ~15 K at 55 hrs.

B. *The Cryocooler 1^{st} Stage Temperatures*

The calculated and observed 1^{st} stage temperatures are given in Table I when the magnet current is zero. The four end cryocooler 1^{st} stages are at ~32 K and the two center cryocooler 1^{st} stages are at ~29 K. Due to the heat load from the main and corrector current leads, the 1^{st} stage temperatures at the ends are ~3 K higher than the center cryocooler 1^{st} stages. The total six 1^{st} stage heat load is calculated to be 87.5 W from the observed temperatures and cryocooler load line. This is in good agreement with the model calculated heat load of 90.1 W. Temperatures in parentheses are when only the upstream magnets are energized at 400 A. The upstream 1^{st} stage temperatures increase by 1.0 K when only the upstream magnets are energized at 400 A. The downstream cryocooler 1^{st} stage temperature does not change since the leads are disconnected.

TABLE I
Calculated and Measured 1^{st} Stage Temperatures of Six Cryocoolers

Location	Calculated (K)	Measured * (K)
Upstream 1 (418D1st)	32.52	32.74 (33.76)
Upstream 2 (418D1st)	32.51	32.3 (33.21)
Downstream 1 (418D1st)	32.58	33.15 (33.06)
Downstream 2 (418D1st)	32.59	31.98 (31.88)
Center Top (418D1st)	29.73	28.61 (28.41)
Center Bottom (408S 1st)	28.96	28.95 (28.86)

*Temperatures in parentheses are when only the upstream magnets are energized at 400A.

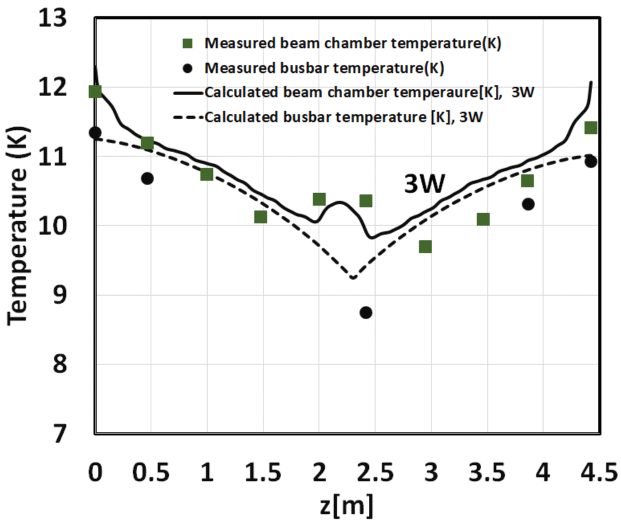

Fig. 5. Comparison with measured and calculated beam chamber temperatures is shown. The measurement does not match with 7 W case; however, it matches with the 3 W in the beam chamber. So ~3 - 4 W of the heat leaks to the other thermal circuit.

TABLE II
CALCULATED AND MEASURED 10 K STAGE TEMPERATURES

The beam chamber heat load(W)	MEASURED (K)	Calculated (K)
7		10.96
3	8.9	8.76

C. Beam Chamber Temperature

Fig. 5 shows the beam chamber temperatures as a function of location in the longitudinal direction. An about 7 W heat load was added through the magnetic measurement system, which is close to the estimated beam heat load [4], [5]. The measured temperatures were much lower than the case with 7 W in the beam chamber. If the temperature is calculated with 3 W in the beam chamber, the calculated temperatures match with measurements. The temperature difference between the beam chamber and the copper busbar is ~0.5 K except for the center section where the distance between thermal links is large. This lower beam chamber temperature suggests that there is an incidental contact between the beam chamber and the magnet. The calculated 10 K stage temperatures with the beam chamber heat load of 3 W and 7 W are shown in Table II for comparison. 3 W case matches to the measurement.

TABLE III
CALCULATED AND MEASURED 4K STAGE TEMPERATURES

Location	Calculated (K)	Measured (K)
Upstream 1 (418D 2nd)	3.44	3.48
Upstream 2 (418D 2nd)	3.44	3.48
Downstream 1 (418D 2nd)	3.44	3.51
Downstream 2 (418D 2nd)	3.44	3.51
Center Top (418D 2nd)	3.78	3.75

D. The Magnet Cooling (4K) Circuit

Table III shows the comparison between observed and calculated temperatures at the 2nd stage cryocoolers. For 4 K cryocoolers, the measured temperatures match with calculated temperatures. The heat loads can be calculated from the temperatures and the 4 K cryocooler load line. Since the temperatures match, the heat load at each of the 4 K stages matches.

The thermal conductance of the 4 K links shown in Table IV was calculated using the heat load at each 4 K 2nd stage and the temperature difference across the thermal link. An average temperature drop across the 4 K links is 0.14 K. The upstream and downstream 2nd stage thermal links are geometrically identical. However, temperature difference is larger for the upstream links. The magnets at downstream are not connected to the magnet current leads. This may explain the temperature difference. The observed total cooling power is 6 W based on the five measured 2nd stage temperatures and cryocooler load lines. The average thermal conductance across the copper foil links is 6 W /0.14 K/ 5 =~8 W/K. Therefore, the thermal conductance does not limit the performance of the cryocoolers. This total cooling power includes additional trim heater power of ~1.8 W to maintain the LHe tank at 760 Torr. This is excess cooling power. Therefore, the net 2nd stage heat load is 6.0 – 1.8 =

TABLE IV
4K STAGE HEAT LOAD AND LINK CONDUCTANCE

Location	Heat Load (W)	Temperature Difference (K)	Link Conductance (W/K)
Upstream 1 (418D 2nd)	1.12	0.144	7.8
Upstream 2 (418D 2nd)	1.12	0.144	7.8
Downstream 1 (418D 2nd)	1.15	0.107	10.7
Downstream 2 (418D 2nd)	1.15	0.11	10.5
Center Top (418D 2nd)	1.45	0.21	6.9
Total 2nd stage cooling power	6.0		

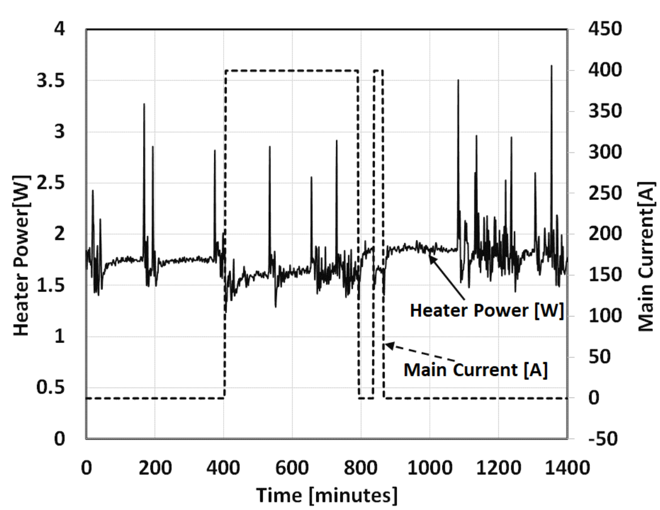

Fig. 6. Trim heater power at the LHe tank and main current are shown as a function of time during the stable operation (no quench). The excess cooling power is reduced by ~0.1 W when the magnet is in operation at 400A. Therefore, the heat load increases by ~0.1 W when the magnet current is at 400A.

4.2 W. The excess cooling power of 1.8 W is large enough to operate the magnets in a stable condition.

The magnets were maintained at ~4 - 5 K and were operational up to ~450 A; the thermal isolation between the beam chamber and magnets was "successful". The trim heater power at the LHe tank and the main current are shown as functions of time in Fig. 6. The excess cooling power is reduced by ~0.1 W when the magnet is in operation at 400 A. Therefore, the 4 K heat load increases by ~0.1 W when the magnet current is at 400 A. The estimated resistance from one set of main lead pairs and correction lead pairs is ~0.1 W/(400A)^2 = 0.625 μΩ. In this operation, only one 1.9 m SCU is energized. The other SCU

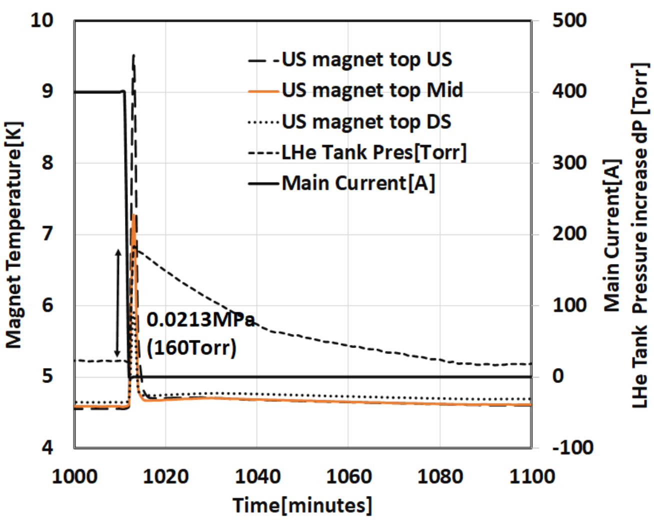

Fig. 7. LHe Tank pressure increase dP, main current and the upstream magnet temperatures at three locations are plotted as a function of time during the 400A quench. US denotes up-stream; DS denotes down-stream. The peak LHe tank pressure increased by 0.0213 MPa above atmospheric pressure. The recovery took 70 - 80 minutes.

was used as a thermal mass and was not energized. Therefore, the heat increases by two SCUs at operation current would be 0.2 W. Fig. 7 shows quench behaviors with the main current 400 A. The magnet temperature rose from 4.6 K to 9.5 K then recovered within a minute. The LHe tank pressure increased by 0.0213 MPa (160 Torr) from 0.1013 MPa (760 Torr). The pressure came back to equilibrium state after 70 minutes.

IV. Discussion and the Next Step

The first 4.8-m-long cryostat including two 1.9-m SCUs has been fabricated, and its standalone thermal performance was tested. The cooldown time was ~4 days, and it operated with zero-boiloff mode for more than two weeks. Comparison of calculated and measured 4 K cooling power is shown in Table V. Excess cooling power with "simulated beam heat" was 1.8 W and the measured total cooling power is 6 W. Thus, the net 2nd stage heat load is 6 W-1.8 W = 4.2 W, which is 3.3 W higher than calculated 0.84 W [3]. The possible explanation for an extra 3.3 W heat leak at the 4 K circuit is radiation from room temperature through gaps in the shield. This happened in the installation of a helical superconducting undulator; when those gaps were closed, the final installations were successful [6], [7]. The other likely candidate is from incidental contacts between the beam chamber and the magnets because thermal deformation of the LHe tank was observed. The vacuum gap above and below the beam chamber was 0.2 mm, and any shift in the alignment could cause incidental contact between the chamber and the magnets. The position of the beam chamber appeared to be lower than expected when it was cold. If the contact area is 0.1 m^2 and a poor contact conductance per area, i.e., ~1 W/m^{2}K, is applied between the magnet and the beam chamber, the estimated heat leak would be 0.1 m^2 × (10 K – 4.5 K) × 1 W/m^{2}K = 0.55 W. Since the magnets are long enough, this can also add up when the contact area becomes larger.

For the final cooldown, the cores used as an only thermal mass will be replaced with new cores and all four cores will be energized. The observed thermal deformation was small enough so that it could be mitigated by magnet alignment method.

TABLE V
Calculated and Measured Cooling Power

Cooling Power (W)	Calculated (W)	Measured (W)
Total 2nd stage Cooling power	5.61	6.0
Excess Cooling Power	4.77	1.8
The 2nd stage Heat Load	0.84	4.2

Acknowledgment

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