THERMAL ANALYSIS OF A SUPERCONDUCTING UNDULATOR CRYOSTAT FOR THE APS UPGRADE

Y Shiroyanagi[1], E Anliker[1] Q Hasse[1], Y Ivanyushenkov[1], M Kasa[1] and J. Fuerst[2] [1]Argonne National Laboratory, Argonne, IL 60439 USA
[2]SLAC National Accelerator Laboratory, 2575 Sand Hill Road, Menlo Park, CA 94025

ABSTRACT

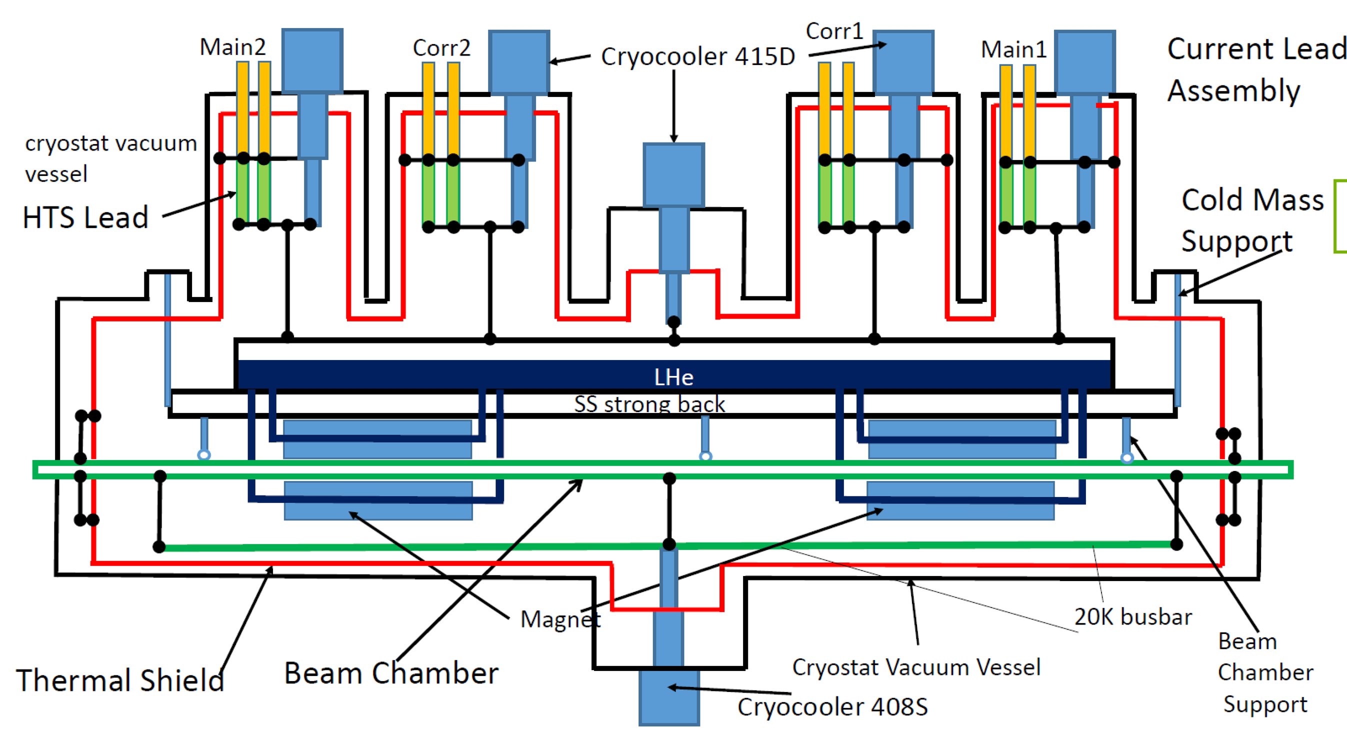
The Advanced Photon Source Upgrade includes four 4.8-m long superconducting undulator (SCU) cryostats, each containing two up to 1.9-m long planar undulator NbTi magnets. The cooling is provided by six cryocoolers arranged in three thermal circuits. The magnets are indirectly cooled with LHe penetrating 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 that 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 bench marked 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 an excess cooling power for various operational modes of the undulator.

1. INTRODUCTION

Currently two planar superconducting undulators (SCU) 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 systems operate in "zero-boil-off" mode using a regulating trim heater which 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.

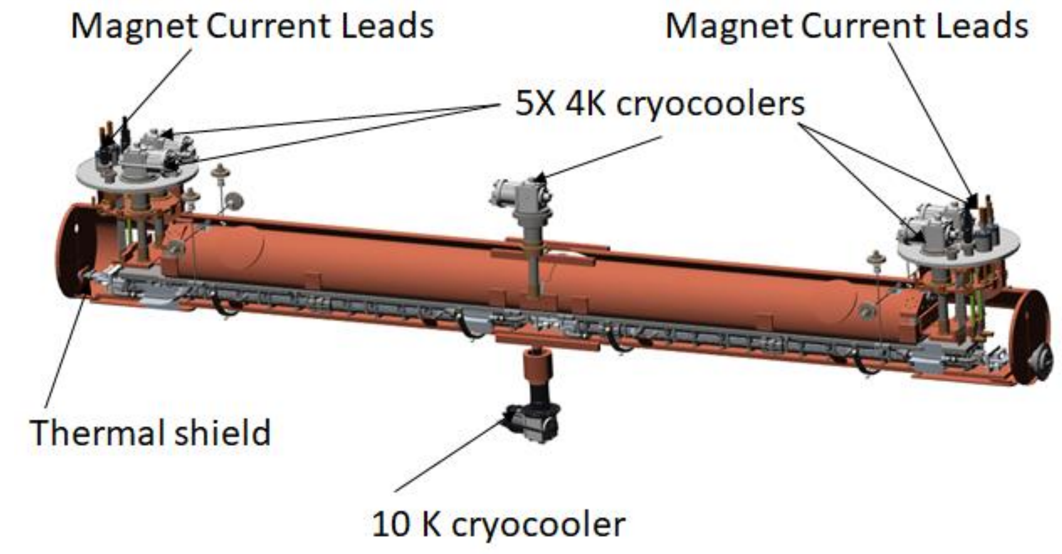
The 1st generation cryostat has two thermal shields and three thermal circuits. This design was originally developed by the Budker Institute of Nuclear Physics (BINP) and implemented for planar SCU's. ANSYS based thermal model of planar SCU's were developed and validated based on the planar SCU first. 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 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 SCU's. The overall length of the cryostat is twice as much long as the existing SCU cryostats and it contains two up to 1.9-m long planar undulator NbTi magnets.

2. COOLING SCHEMATICS



The APSU-SCU cryostat is a one shield cryostat (similar to the 2nd generation cryostat) but with three thermal circuits.

- 6 cryocooler 1st stages are connected to the shiled and magnet current leads.
- 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.
- Five 4K cryocooler 2nd stages are connected to the Lhe Tank . Magnets are cooled by the circulating LHe in the channel

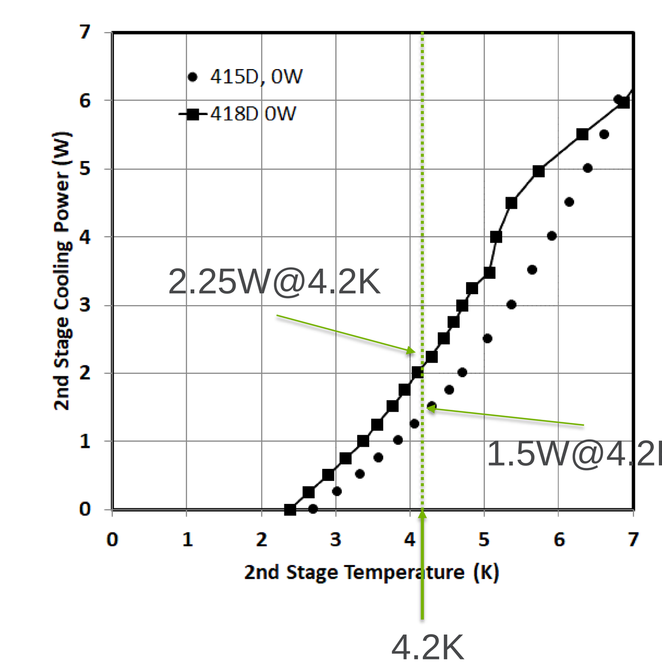


3.METHOD TO CALCULATE EXCESS COOLING POWER

- 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 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].
- The load line of all the cryocoolers (Sumitomo 415D, 418D4, 408S) of 1 st and 2nd stages are measured in detail at low temperatures and used for the FEA model as inputs.

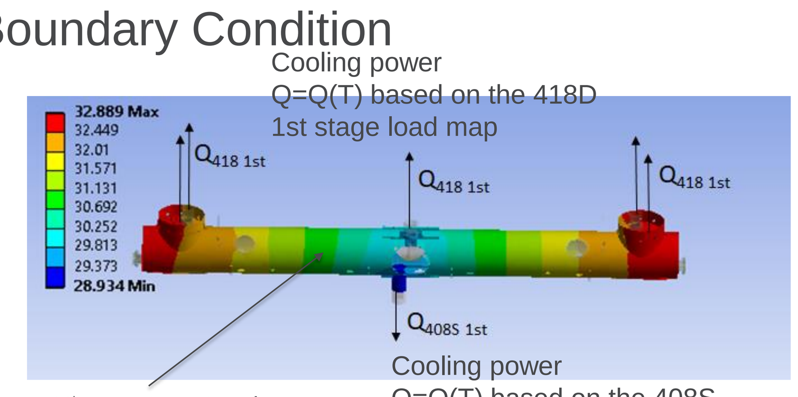
Over all load line has been published by the manufacturer. [5]

Our measured load lines of 415D 2nd stage (1.5 W cryocooler) and 418D4 2nd stage (2 W cryocooler) are compared and used as an input for the model.



4.1. FEA MODEL: THERMAL SHIELD CIRCUIT

Boundary Condition



$$Q_{418D\ 1st} + Q_{408S1st} = Q_{1st\ stage\ load}$$

The largest 1st stage heat load is from the warm part of the magnet leads. The next largest is the conduction from the room temperature to the shield through the transition section of the beam chamber. So the maximum temperature is always at the end sections since the magnet current leads are located at the ends.

1) The total static heat load is 96 W. In that case, a calculated shield temperature is 28.9 – 32.9 K.

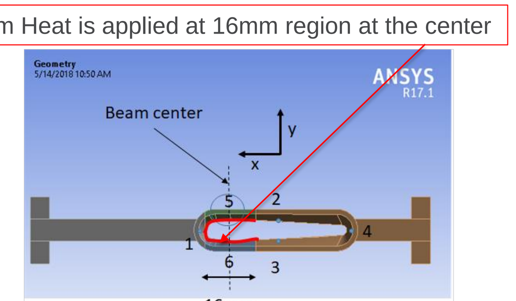
2) When the beam heat of 7 W is applied in the beam chamber, the heat is directly coupled to the 408S 2nd stage. So the total 408S 2nd stage heat load becomes 8W and the 1st stage heat load does not affected much.

3) When the magnet is in operation (450 A), 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.

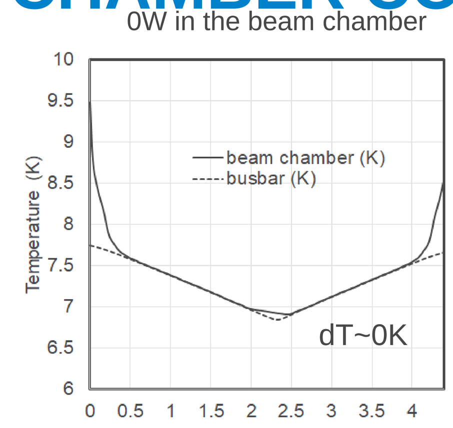
Location of Heat Load	Static (W)	Beam only (W)	Beam and Current (W)
Beam Chamber Transition	7.8		
Conduction Heat through Main Current Lead (2 pairs)	39.7		
Conduction Heat through Correction Current Lead (8 pairs)	31.7		
Cold Mass Support (vertical and horizontal)	5.3		
Thermal Radiation from RT to 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

4.2. FEA MODEL: THE BEAM CHAMBER COOLING CIRCUIT (10 K CIRCUIT)

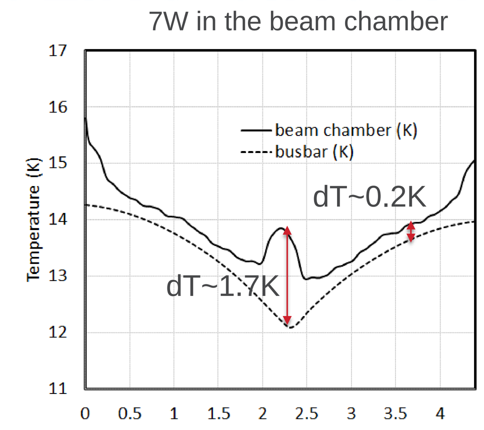
Beam Heat is applied at 16mm region at the center

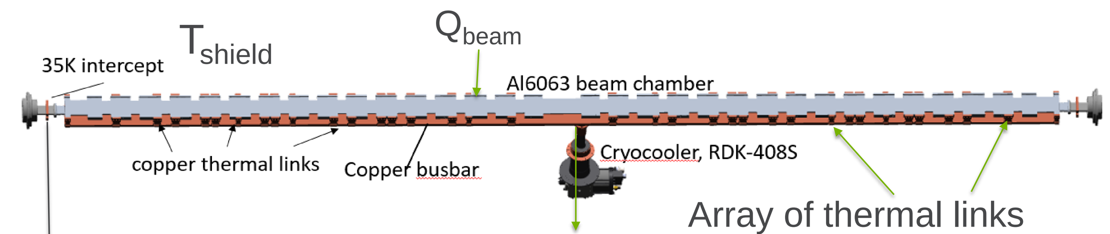


0W in the beam chamber



7W in the beam chamber





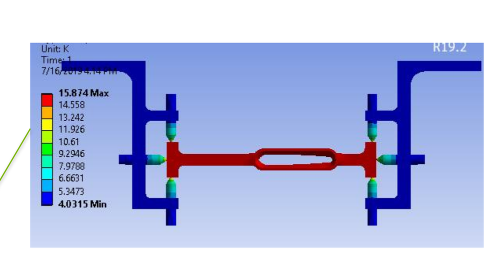
$$Q_{408S2nd} = Q_{10K\ load} = Q_{beam} + Q_{cond\ from\ the\ shield}$$

When no heat is applied, the minimum temperature of both the busbar and the beam chamber is at ~7 K at the center where the cryocooler is located and the highest temperature is at 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.

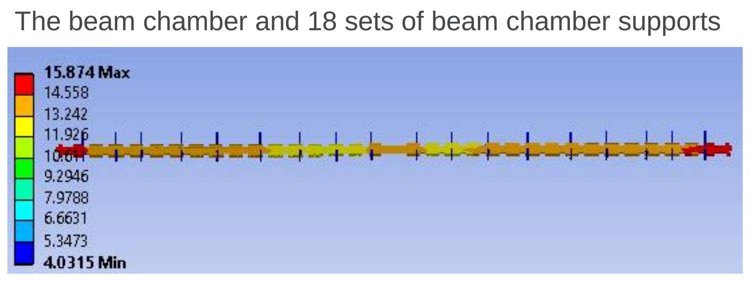
When 7 W of heat is applied uniformly along the length of the chamber, the minimum temperature of the beam chamber and the busbar increases to 12.1 K and 13 K respectively. The beam chamber temperature is slightly lower at the positions where the thermal links are attached. The temperature difference 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 the position interference with the corrector magnet assembly, the temperature difference at the center is ~1.7 K

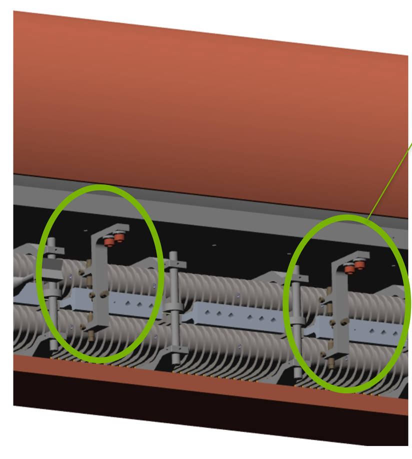
CONDUCTION HEAT LOAD THROUGH THE BEAM CHAMBER SUPPORTS

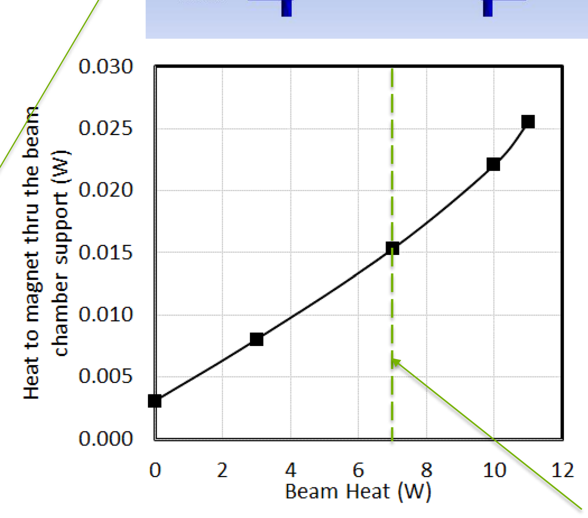
The thermal isolation between the beam chamber and the magnets are achieved using low thermal conductivity Torlon standoffs.



The beam chamber and 18 sets of beam chamber supports







- Conduction heat leak through the beam chamber support is calculated as a function of the beam heat load. The heat through beam chamber support increases monotonically as beam heat load increases.
- The total conduction heat through the beam chamber support is 3 mW when no heat is applied in the beam chamber and 15 mW when the beam heat load is at 7 W.
- Since the beam chamber temperature is below 20 K, radiation from beam chamber is negligible (less than 1 mW).

4.3. FEA MODEL: MAGNET COOLING CIRCUIT (4K CIRCUIT)

The 2nd stage load line as an input

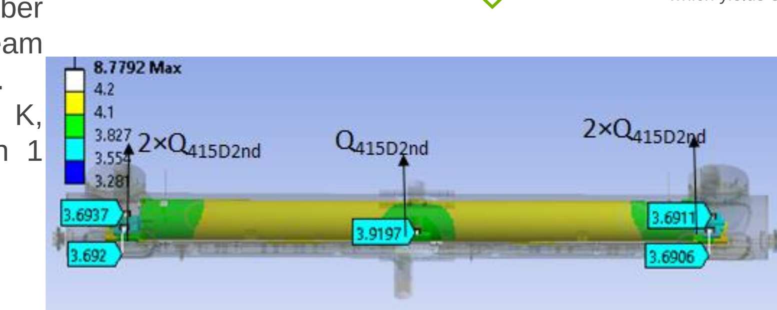
Conduction heat through the HTS section of the magnet lead, radiation heat from the shield etc (See table)

$$Q_{4K\ cooler\ 2nd\ stage} = Q_{excess} + Q_{4Kload}$$

The reaction probe in ANSYS automatically calculates the additional heat to keep LHe at 4.2 K which corresponds to the excess cooling power.

Location of Heat Load	Heat Load (W)
Conduction Heat through Main Current Lead (2 pairs)	0.424
Conduction Heat through Correction Current Lead (8 pairs)	0.256
Cold Mass Support (vertical and horizontal)	0.045
Thermal Radiation from the shield (emissivity = 0.1)	0.036
LHe Relief Piping (40K to 4.0 K)	0.04
Instrumentation (40K to 4.0 K)	0.02
Beam Chamber Support	0.003
Total 4 K Heat Load	0.824

Thermal radiation heat is estimated by $Q = \epsilon\sigma A({T_{hot}}^4 - {T_{cold}}^4)$: ϵ: emissivity, σ= 5.670374419 ×10^{-8} W·m^{-2}·K^{-4}, A: surface area of the shield, T_{hot}: shield temperature, T_{cold} = 4.2 K. For the static case, the shield temperature is 28.9 – 32.9 K as shown in Figure 5, on average T_{hot}= 30.5 K, shield area A = 7.24 m^2 and emissivity ϵ = 0.1 which yields 36 mW.



Five 415D is connected to LHe tank via thermal links. The cold head temperature 3.69 K and 3.92 K yields 4W of the total cooling power. Temperatures at the cold head are higher, however, the total cooling powers are lower than using 418D4's

By using Five 418D4s, the cold head temperature 3.4K and 3.8K yields total 5.61 W of the total cooling power. LHe tank is maintained at 4.2K. The additional cooling capacity decreases the total quench recovery time. The detailed quench recovery analysis is given in [6].

5. SUMMARY

Total	Static	Beam only	Beam and Current
2nd stage Heat Load	0.82	0.84	0.99
2nd stage Cooling power (415 D)	3.99	3.99	4.0
Excess Cooling power	3.16	3.14	3.0
2nd stage Cooling power (418 D)	5.61	5.61	5.62
Excess Cooling power	4.78	4.77	4.63

The additional cooling capacity decreases the total quench recovery time. The detailed quench recovery analysis is given in [6]. The joule heat at joint resistance yield 70mW ×2= 140mW

6. CONCLUSION

The original design with 415D has excess cooling power of 3.18 W. Using 2 W cryocooler increases the excess cooling power as much as 4.8 W. The high cooling capacity of the entire system suggests the feasibility of 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.

REFERENCE

[1] Y.SHIROYANAGI, C. DOOSE, J. FUERST, K. HARKEY, Q.HASSE, Y. IVANYUSHENKOV AND M. KASA, *THERMAL ANALYSIS OF SUPERCONDUCTING UNDULATOR CRYOMODULES*, ADVANCE IN CRYOGENIC ENGINEERING, PP 1097 – 1104
[2] Y.IVANYUSHENKOV ET.AL, *DEVELOPMENT AND OPERATING EXPERIENCE OF A SHORT-PERIOD SUPERCONDUCTING UNDULATOR AT THE ADVANCED PHOTON SOURCE*, PHYSICAL REVIEW SPECIAL TOPICS - ACCELERATORS AND BEAMS 18, 040703 (2015).
[3] J FUERST, Q HASSE, Y IVANYUSHENKOV, M KASA AND Y SHIROYANAGI, *A SECOND-GENERATION SUPERCONDUCTING UNDULATOR CRYOSTAT FOR THE APS*, 2017 IOP CONF. SER.: MATER. SCI. ENG. 278 012176
[4] J.D. FUERST, E. GLUSKIN, Q.B. HASSE, Y. IVANYUSHENKOV, M. KASA, I. KESGIN, Y. SHIROYANAGI, *CRYOGENIC TESTING AND INITIAL PERFORMANCE OF A HELICAL SUPERCONDUCTING UNDULATOR AT THE APS*, IPAC2018 PROCEEDINGS, PP1260
[5] HTTP://WWW.SHICRYOGENICS.COM/PRODUCTS/4K-CRYOCOOLERS/RDE-418D4-4K-CRYOCOOLER-SERIES/
[6] E. ANLIKER, ET AL, *A NEW SUPERCONDUCTING UNDULATOR CRYOSTAT FOR THE APS UPGRADE*, C1PO1F-02, THIS CONFERENCE.

U.S. DEPARTMENT OF ENERGY
Office of Science

Argonne National Laboratory is a U.S. Department of Energy laboratory managed by UChicago Argonne, LLC.
The Advanced Photon Source is a U.S. Department of Energy Office of Science User Facility operated for the U.S. Department of Energy Office of Science by Argonne National Laboratory under Contract No. DE-AC02-06CH11357.

Argonne NATIONAL LABORATORY