Thermal Analysis of Superconducting Undulator Cryomodules

C3PoD-08

Advanced Photon Source, Argonne National Laboratory

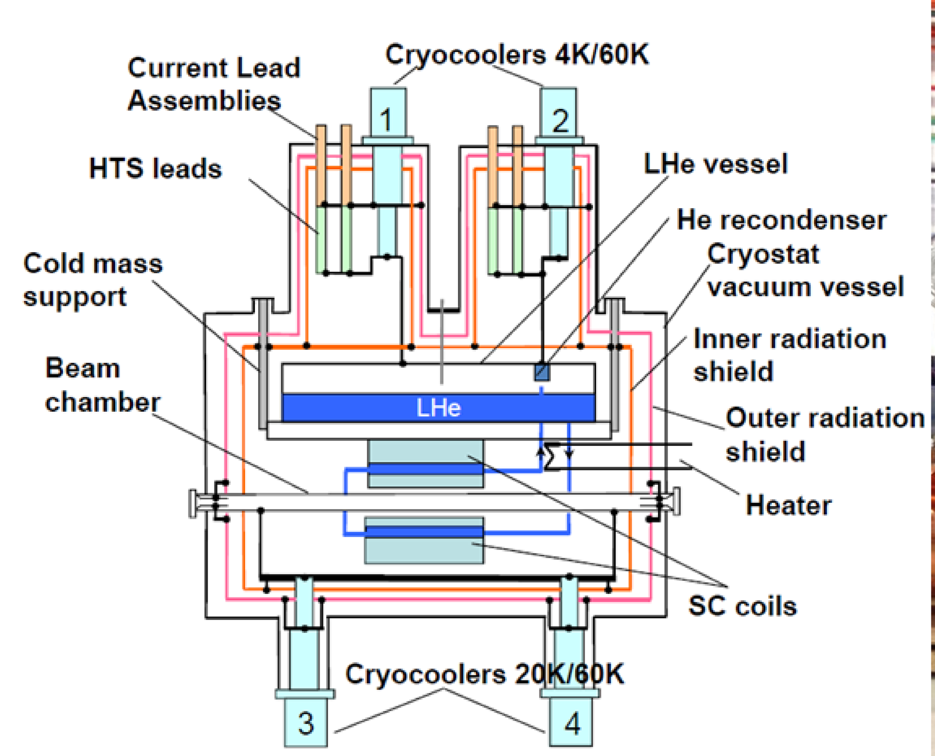
Y. Shiroyanagi, C. Doose, J. Fuerst, K. Harkay, Q. Hasse, Y. Ivanyushenkov and M. Kasa

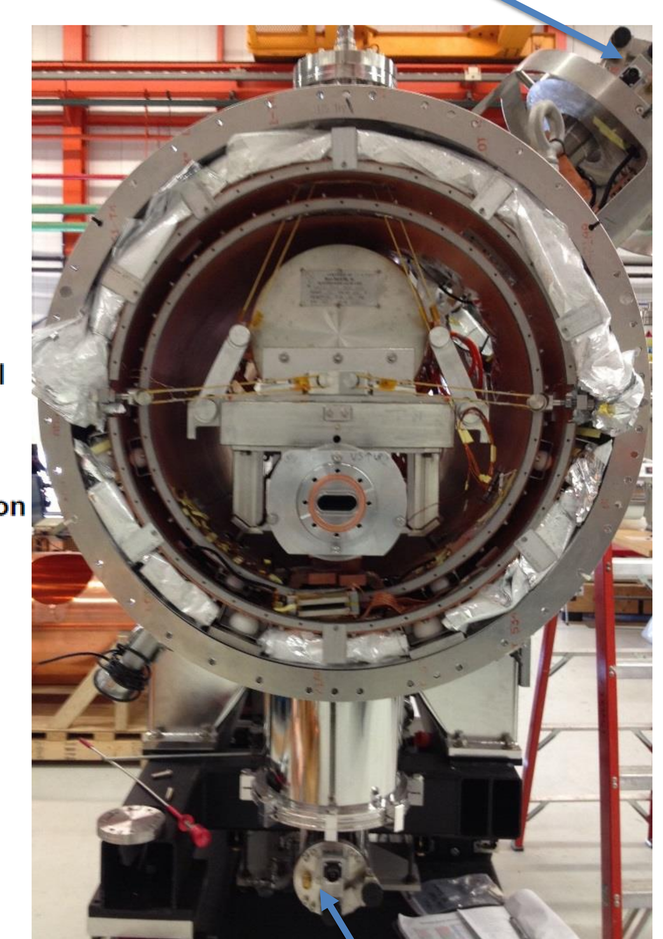
Advanced Photon Source, Argonne National Laboratory

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. Background

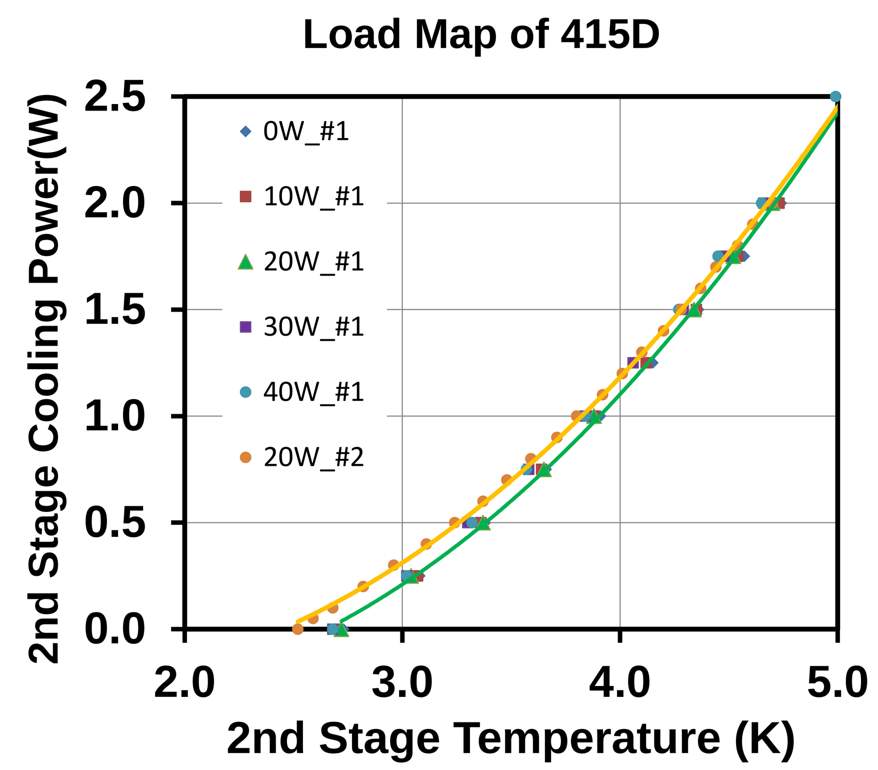




The magnetic structure and the beam chamber are cooled "independently"

- Outer Shield: the warm end of magnet leads, the beam chamber and the outer shield are cooled by the 1st stage of four cryocoolers
- Inner Shield: the beam chamber and the inner shield is cooled by two bottom cryocoolers (RDK-408S)
- Magnet Circuit: the magnet and LHe tank is cooled by two top cryocoolers (RDK-415D)

2. Numerical Analysis



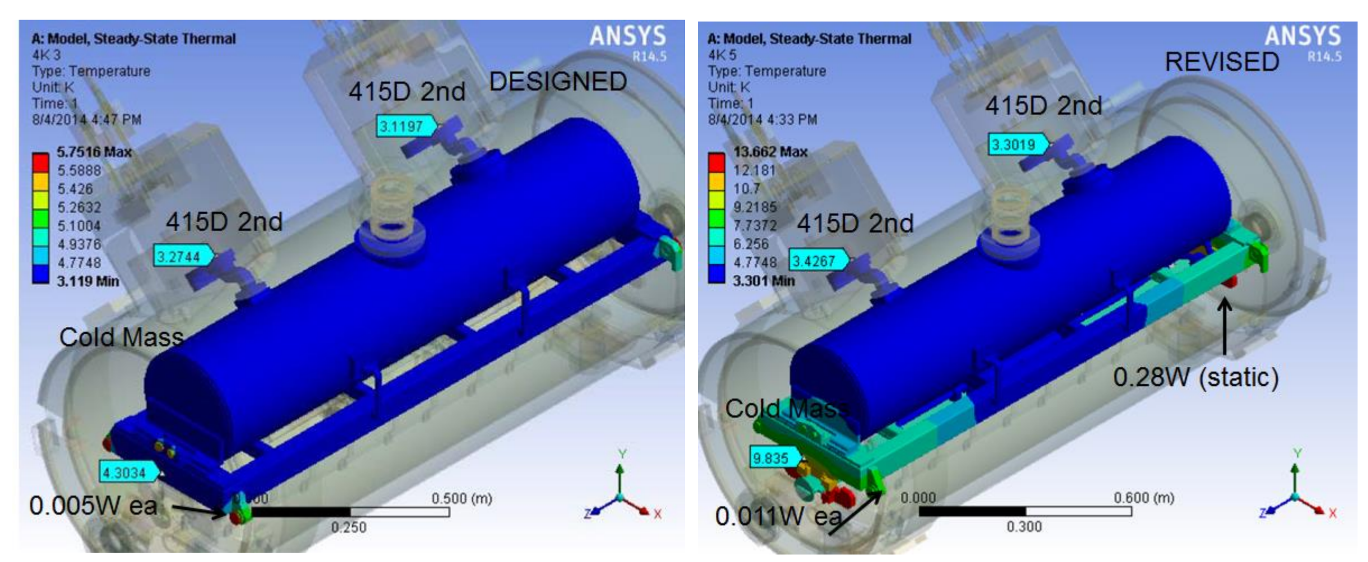
The 2nd stage Cooling power of RDK-415D is plotted as a function of the 2nd stage temperature at 0W to 40W at 1st stage. It can be approximated as a function of only the 2nd stage temperature.

#1 and #2 are different lots. Both of them are specified ~1.5W 4.2K, however #1 and #2 differs 100 mW @3.5K.

These load maps were used as the temperature dependent cooling power in the model. Thus the model has uncertainty of ±~50mW

- Top of the magnet lead and the end of the beam chamber is @300K
- The temperature dependent cooling power based on the load maps were applied on the eight cold head surfaces
- Additional Heat inputs (Kevlar, Instrumentations etc)

3. SCU0 Analysis and Measurement



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.

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	0.176	
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***

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

For Mode 1(static) , 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.

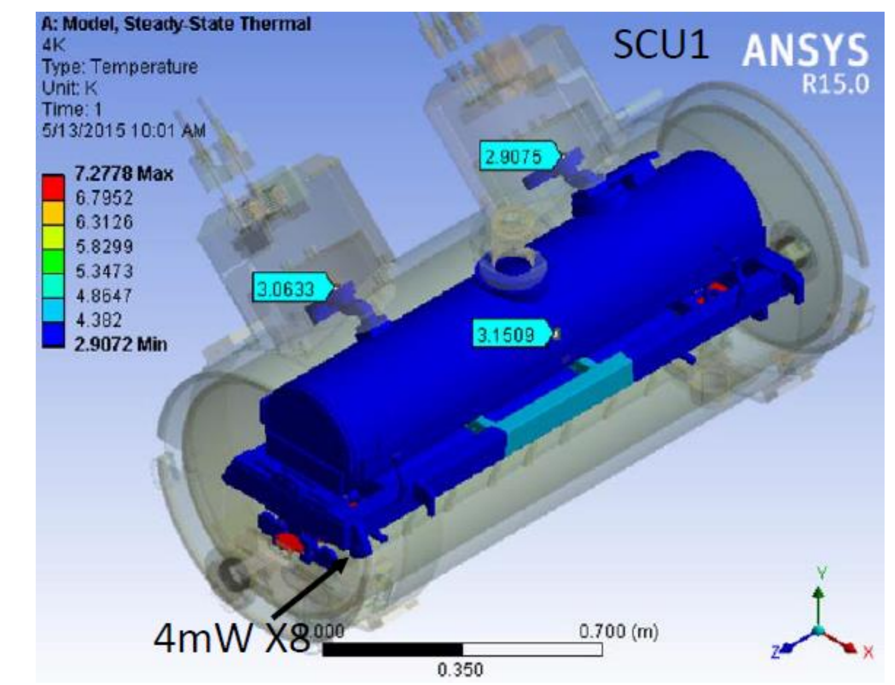
Summary of Heat Load of SCU0

Operating Mode	Cooling circuit	Original Model [W]	Revised Model [W]	Measured [W]
Mode 1	Outer shield	69	69	44.46
	Inner shield	0.9	0.9	2.68
	Magnet (trim heater off)	0.51	0.89	0.88
Mode 2	Outer shield	71	71	63.43
	Inner shield	15.97	15.9	15.02
	Magnet (trim heater off)	0.58	1.06	0.97
Mode 3	Outer shield	91	91	93.59
	Inner shield	16.1	15.9	15.67
	Magnet (trim heater off)	0.58	1.31	1.22

Mode 1: no beam, no magnet current
Mode 2: beam and no magnet current
Mode 3: beam and magnet current

Pres > 760 Torr

4. SCU1 Analysis and Measurement



Source of Magnetic Circuit heat load for SCU1 (Mode 1)

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.

The original calculation matched with the measurement. No revision of the model was necessary.

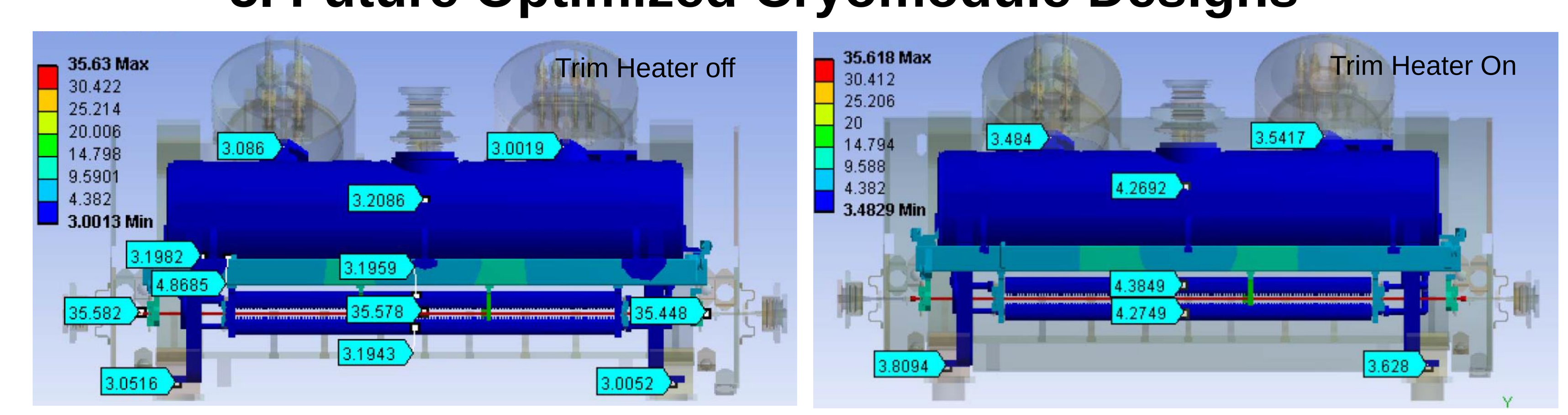
- Kevlar is thermally intercepted at the outer shield.
- Additional thermal links were attached to make the beam chamber temperature uniform.
- The right material was used for the beam chamber support

Summary of Heat Load of SCU1

Operating Mode	Cooling circuit	Model [W]	Measured [W]
Mode 1	Outer	41	39
	Inner	2.9	1.8
	Magnet (trim heater off)	0.44	0.49
Mode 2	Outer	57	59
	Inner	15	15
	Magnet (trim heater off)	0.47	0.60
Mode 3	Outer	70	74
	Inner	15	15
	Magnet (trim heater off)	0.60	0.67

For Mode 1(static), a measured trim heater power of 0.44 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 0.93 W, which yields a static load of 0.49 W. SCU1 has sufficient excess capacity to be operated at 760 Torr with beam and magnet current.

5. Future Optimized Cryomodule Designs



- Use four 415D's and eliminate the inner 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.
- higher beam chamber temperature (about 35 K compared to 12 K) and larger conduction heat leak between the chamber and the magnet circuit.
- However, the 4K cooling power is doubled, which more than offsets the added load.

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

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