THERMAL ANALYSIS OF A FEL SCU CRYOSTAT

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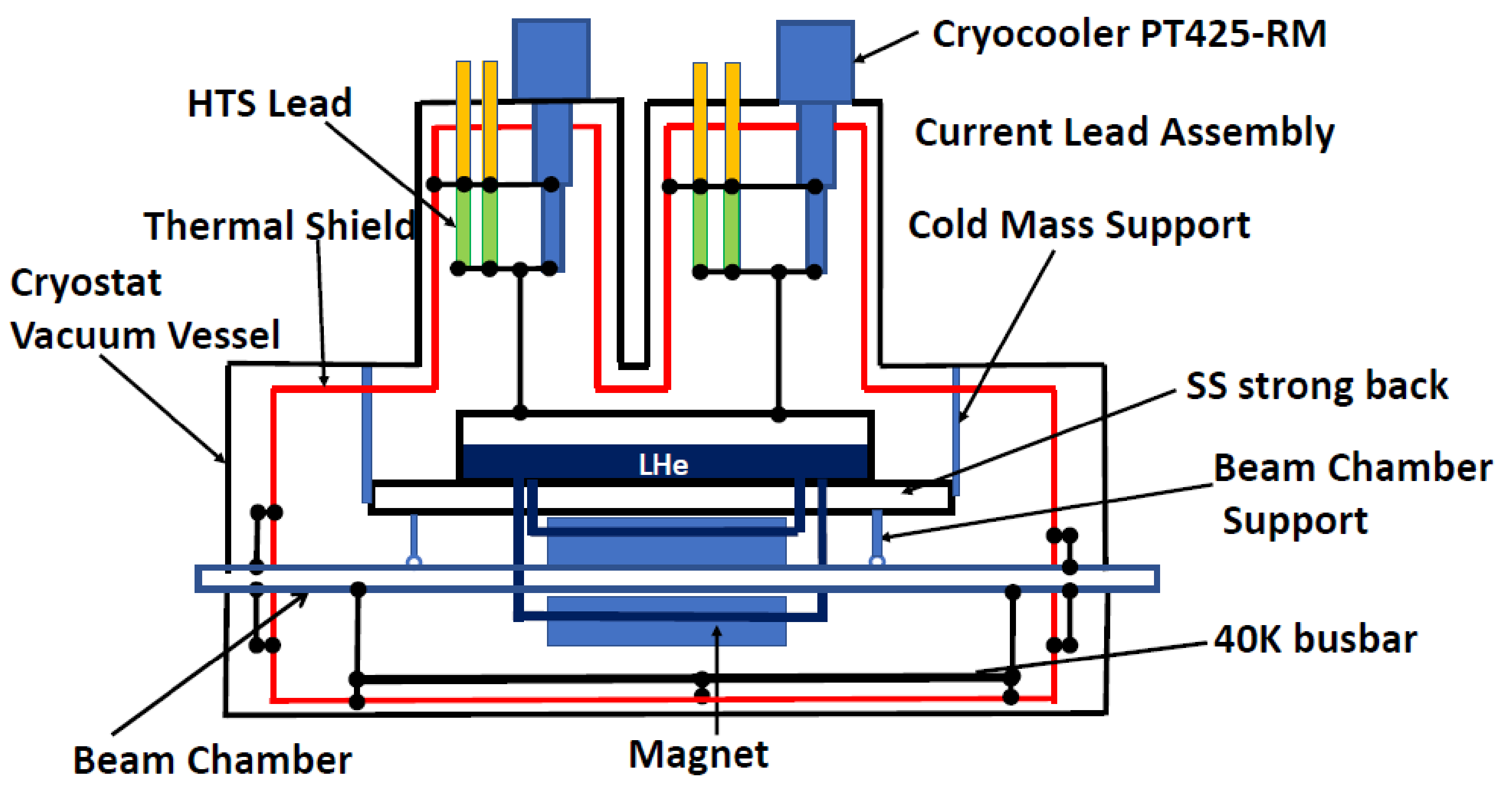
ABSTRACT

An ANL-SLAC collaboration is working on the design of a planar superconducting undulator (SCU) demonstrator to be tested at the SLAC Free Electron Laser (FEL) [1, 2]. The demonstrator cryostat is multi-segmented, and each segment includes an ~1.5-m-long superconducting undulator as well as other magnetic components like a phase shifter and a beam position monitor (BPM). This LHe-based cryostat is cooled by two stage pulse tube cryocoolers (Cryomech PT425-RM). A detailed load map of the cryocooler was measured and benchmarked with the manufacturer's load map. A thermal model of one segment of the cryostat, which includes all cooling circuits, has been created in ANSYS and analyzed using the measured cryocooler load map. This paper presents the calculated cooling power requirement and the temperatures in the cryostat.

1. INTRODUCTION

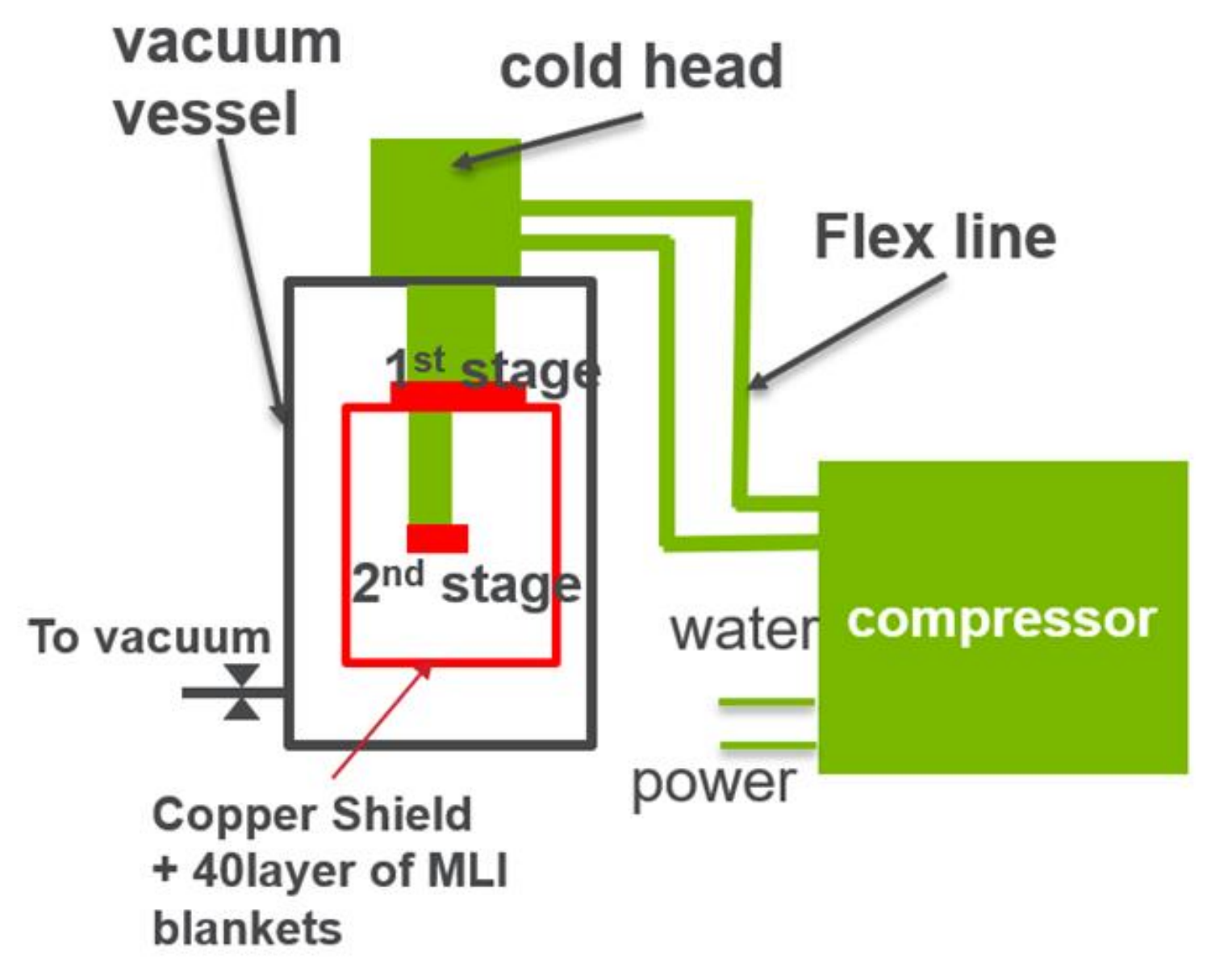
The thermal design of this cryostat is based on the operational experience of three planar superconducting undulators (SCUs) and one helical SCU (HSCU) at the Advanced Photon Source (APS) storage ring [3, 4]. It is also based on the cryogenic design of the APSU-SCU cryostat [5, 6]. In these systems, 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. This FEL-SCU cryostat has two thermal circuits. The thermal shield cooling circuit (40 K) consists of the warm part of the magnet current leads, one thermal shield, and the beam chamber, which are linked through the copper busbars and cooled by the 1st stages of the cryocoolers. The magnet cooling circuit (4 K) consists of a LHe tank, SCU magnets, and the HTS part of the magnet leads, which are cooled by the cryocooler 2nd stages. The beam chamber operates at a higher temperature and is thermally isolated from the magnets. Since pulse tube cryocoolers cannot be installed from the bottom, both horizontal and vertical copper busbars are used to avoid temperature difference across the stainless-steel frame. The length of one segment of the cryostat is ~2.3 m, which is like the existing planar SCUs. It contains NbTi magnets as long as ~1.5 m.

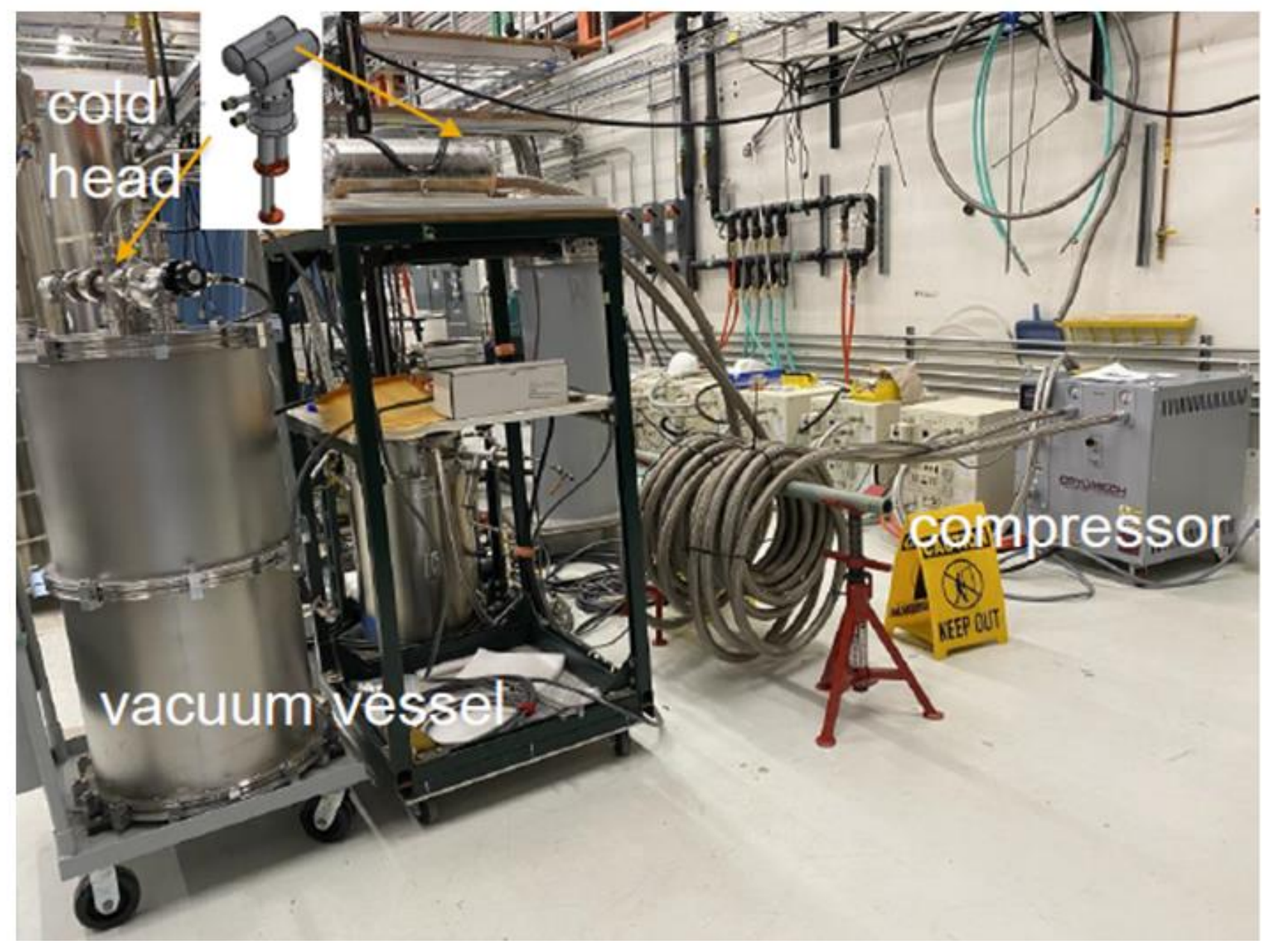
Schematic of one segment of the FEL-SCU cryostat.



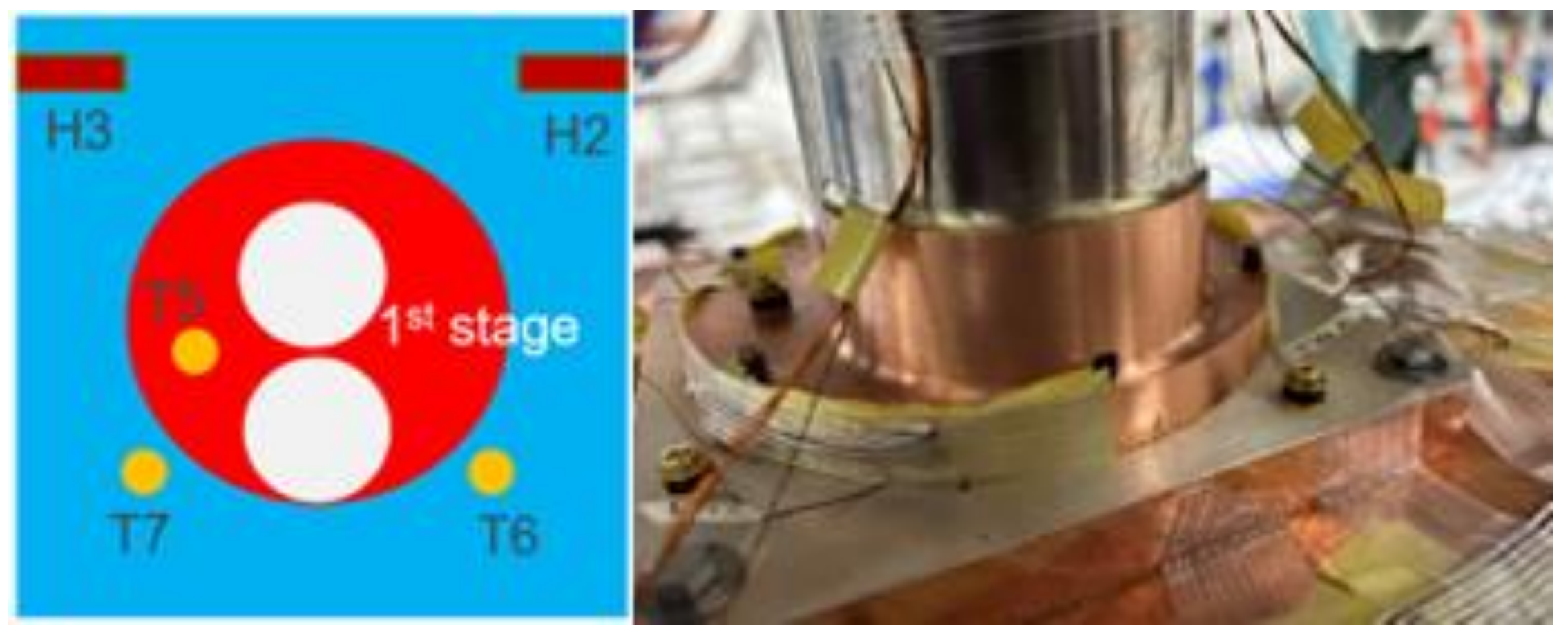
2. LOAD MAP OF PULSE TUBE CRYOCOOLERS (CRYOMECH PT425-RM)

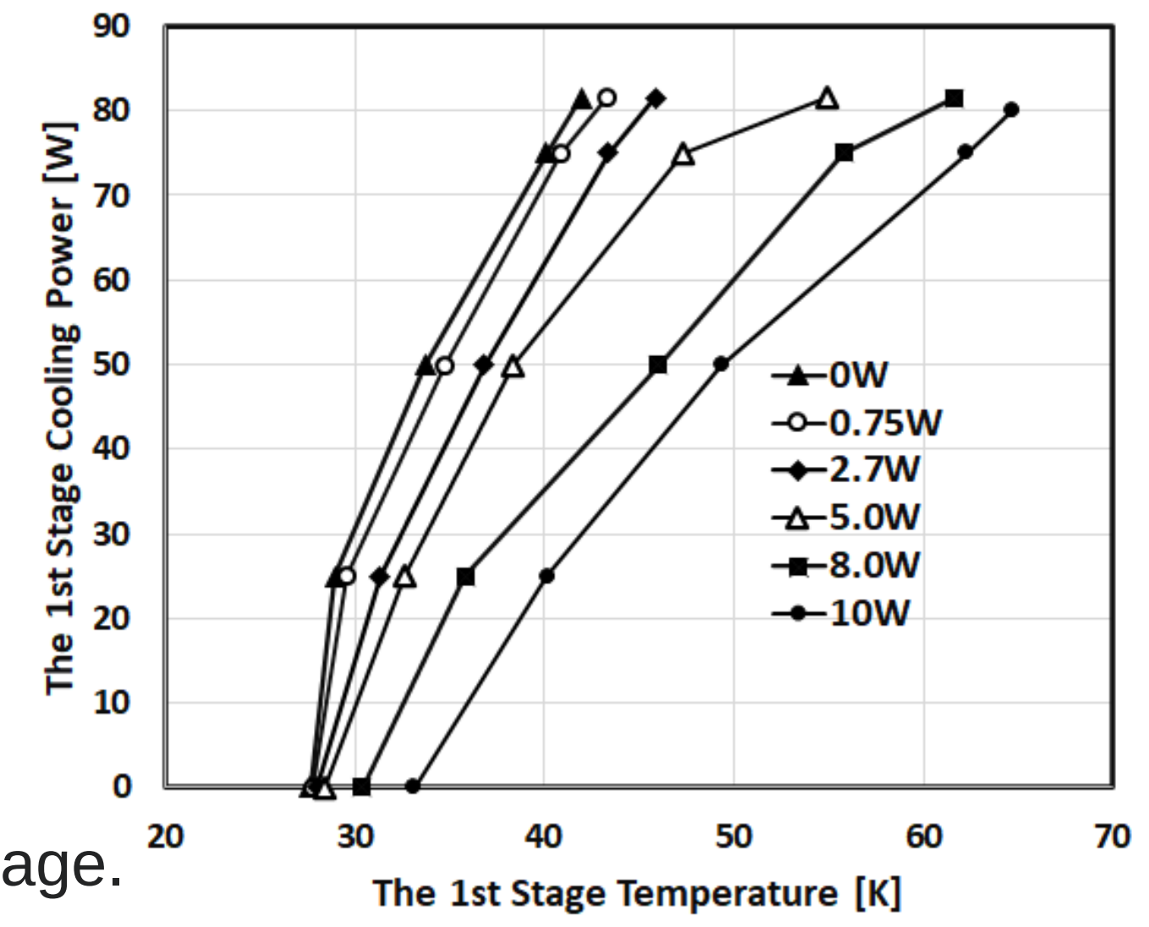
The load maps from the manufacturer do not include detailed performance at 4.2 K and lower. Usually only a few performance points (4.2 K and 50 K) are guaranteed by the manufacturer [7]. So, we measured the performance of the cryocoolers to benchmark the manufacturer's load map and to provide input for our thermal analysis.



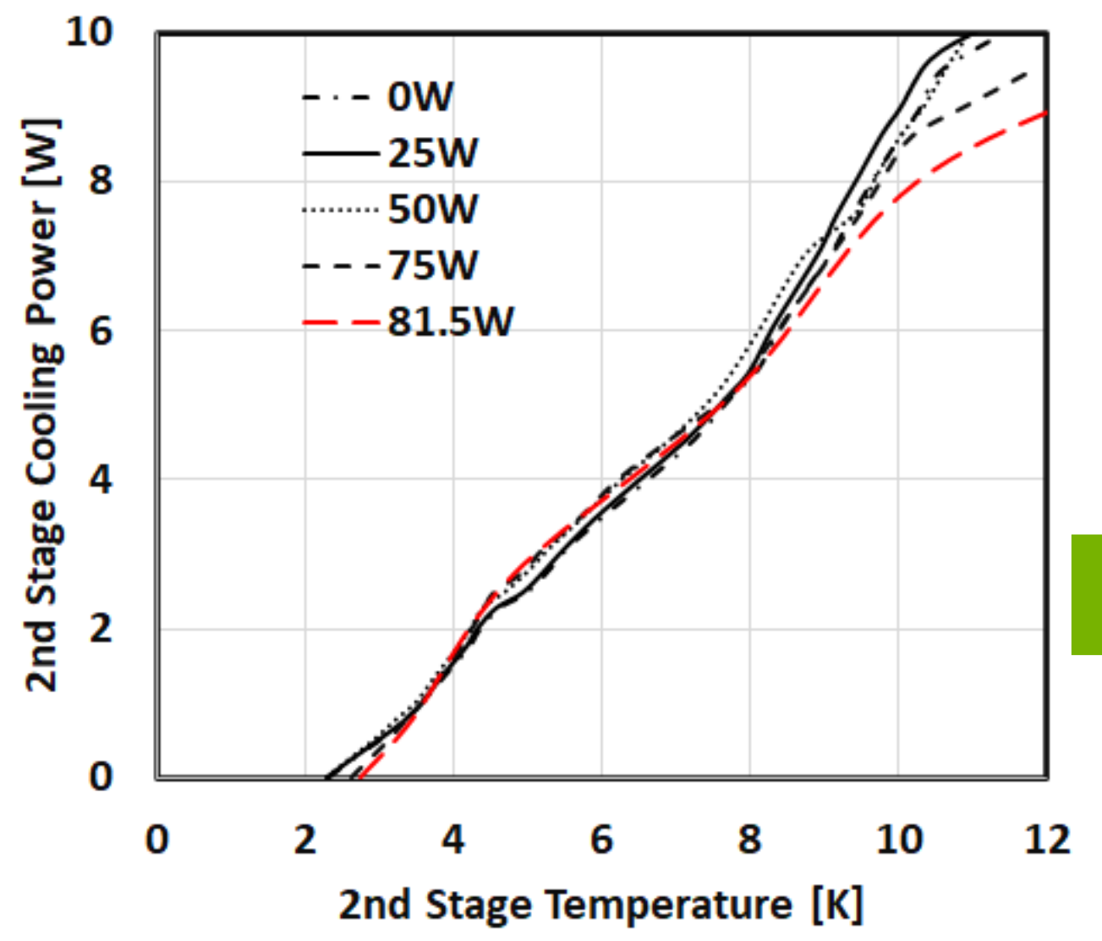


The 2nd stage temperature was measured by heating the 2nd stage from 0 W to 3 W in 0.25 W increments and from 3 W to 10 W in 0.5 W increments while heat was added on the 1st stage at 0 W, 25 W, 50 W, 75 W, and 81.5 W.





Location of three temperature sensors and two heaters at the 1st stage.

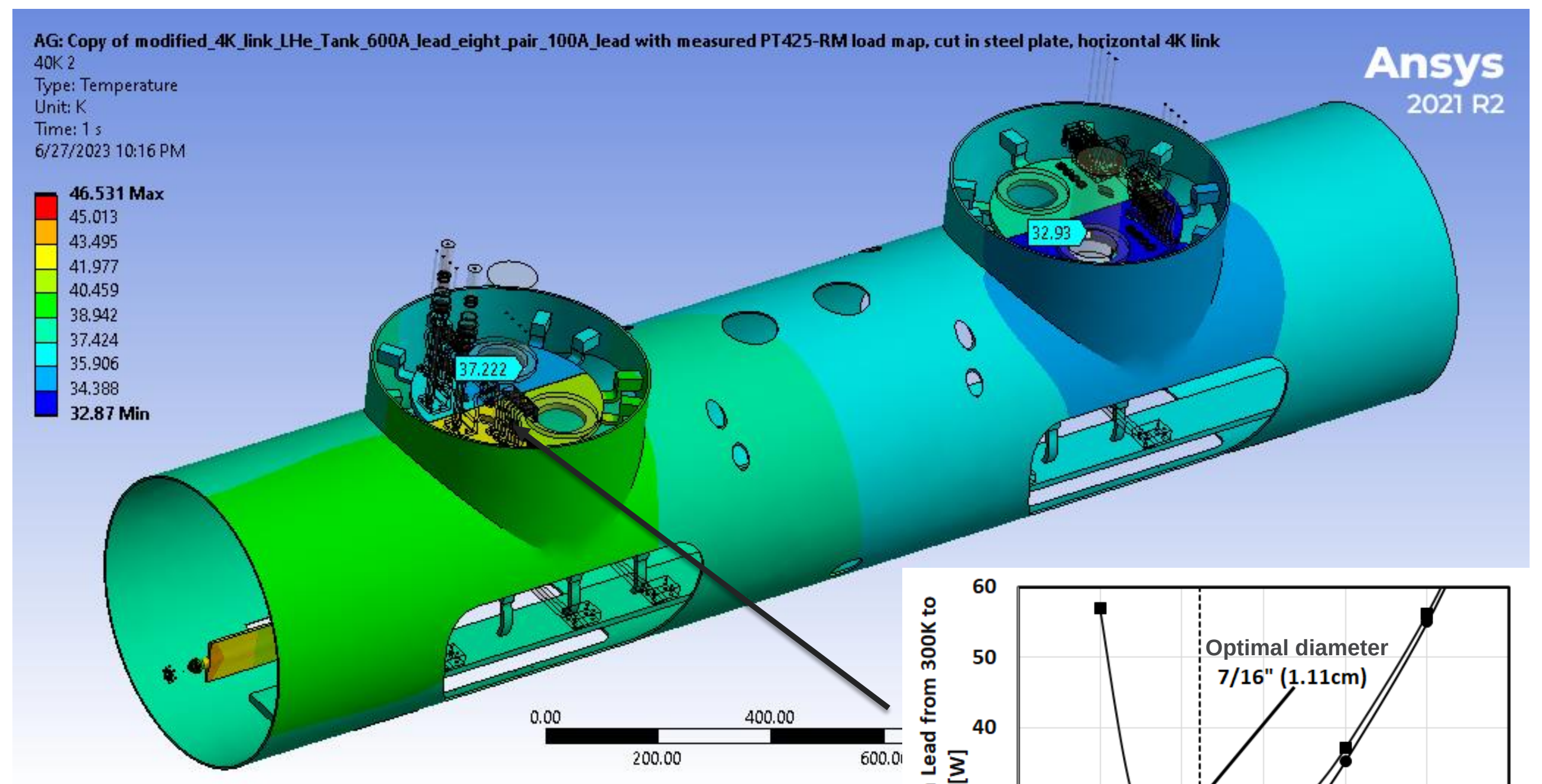


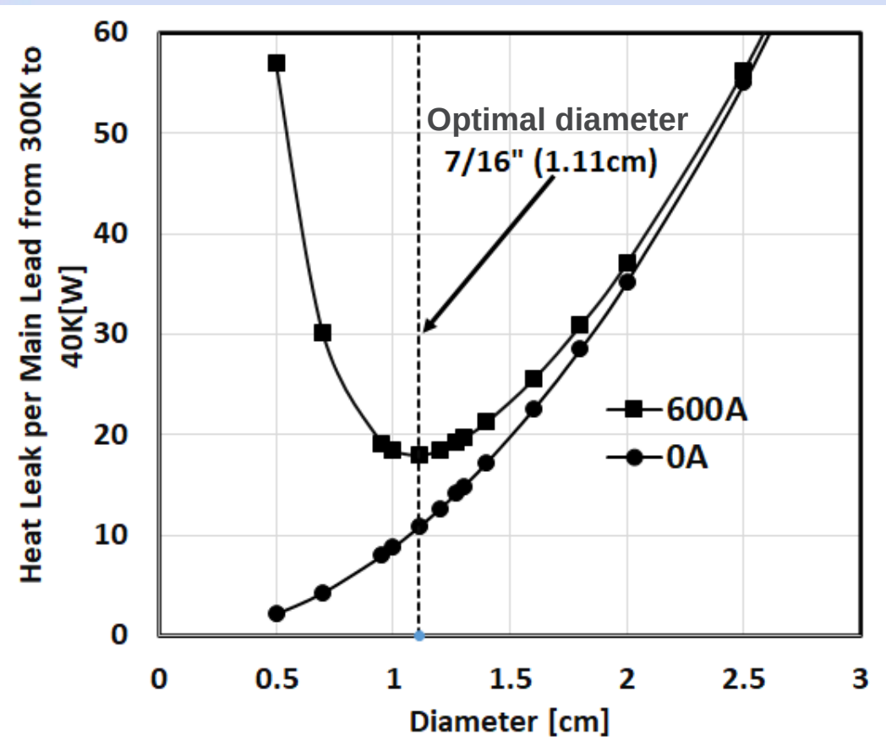
Location of four temperature sensors and two heaters at the 2nd stage.

3. THERMAL ANALYSIS OF THE ONE SEGMENT CRYOSTAT

3.1 40K COOLING CIRCUIT

Location	Static (W)	With beam and magnet current (W)
Beam chamber transitions	12.59	
Conduction heat through main current leads (300K to 40K)	21.30	
Conduction heat through correction current leads	32.61	
Joule heat through main current leads	0	
Joule heat through correction current leads	0	
Coldmass supports	2.24	
Thermal radiation from RT to shield (40 layers of MLI)	5.74	
LHe and relief piping	2.34	
Instrumentation	0.25	
Beam heat	0	9.315
Joule heat of main current leads	0	14.24
Joule heat of correction current leads	0	12.47
Total 1st stage heat load	77.1	113.1





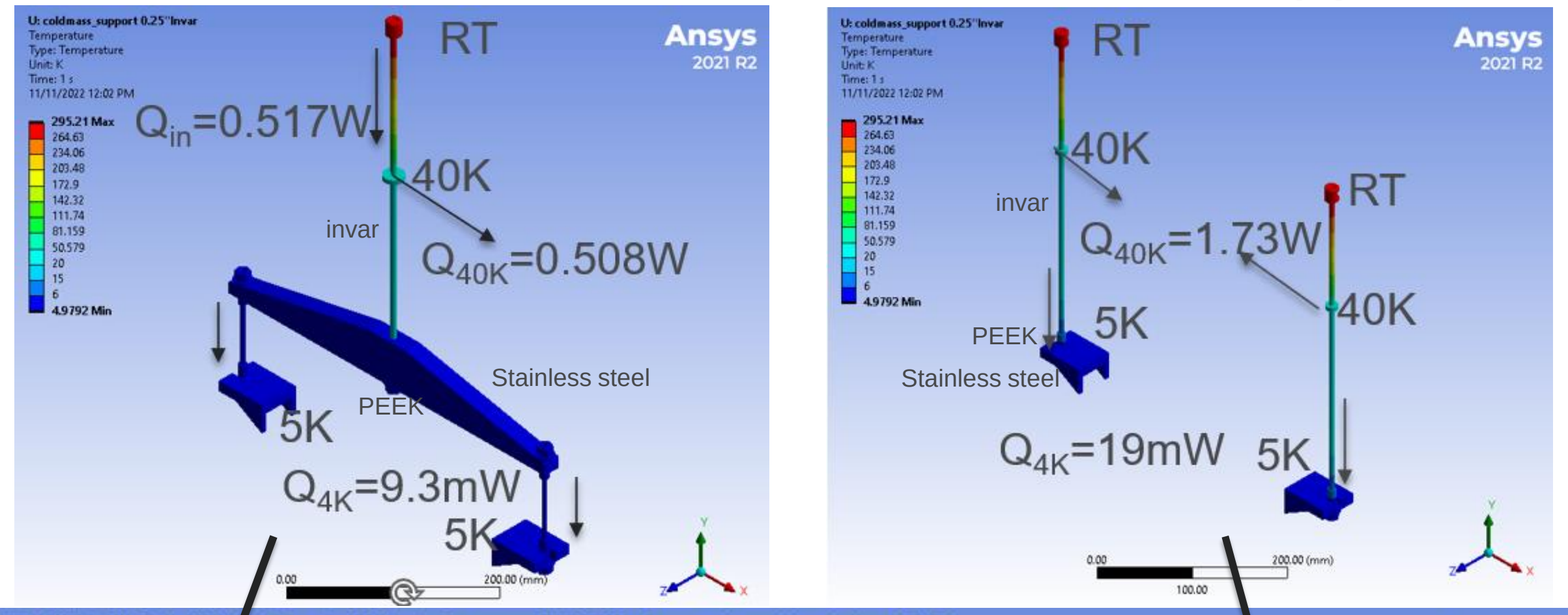
3.2 4K COOLING CIRCUIT

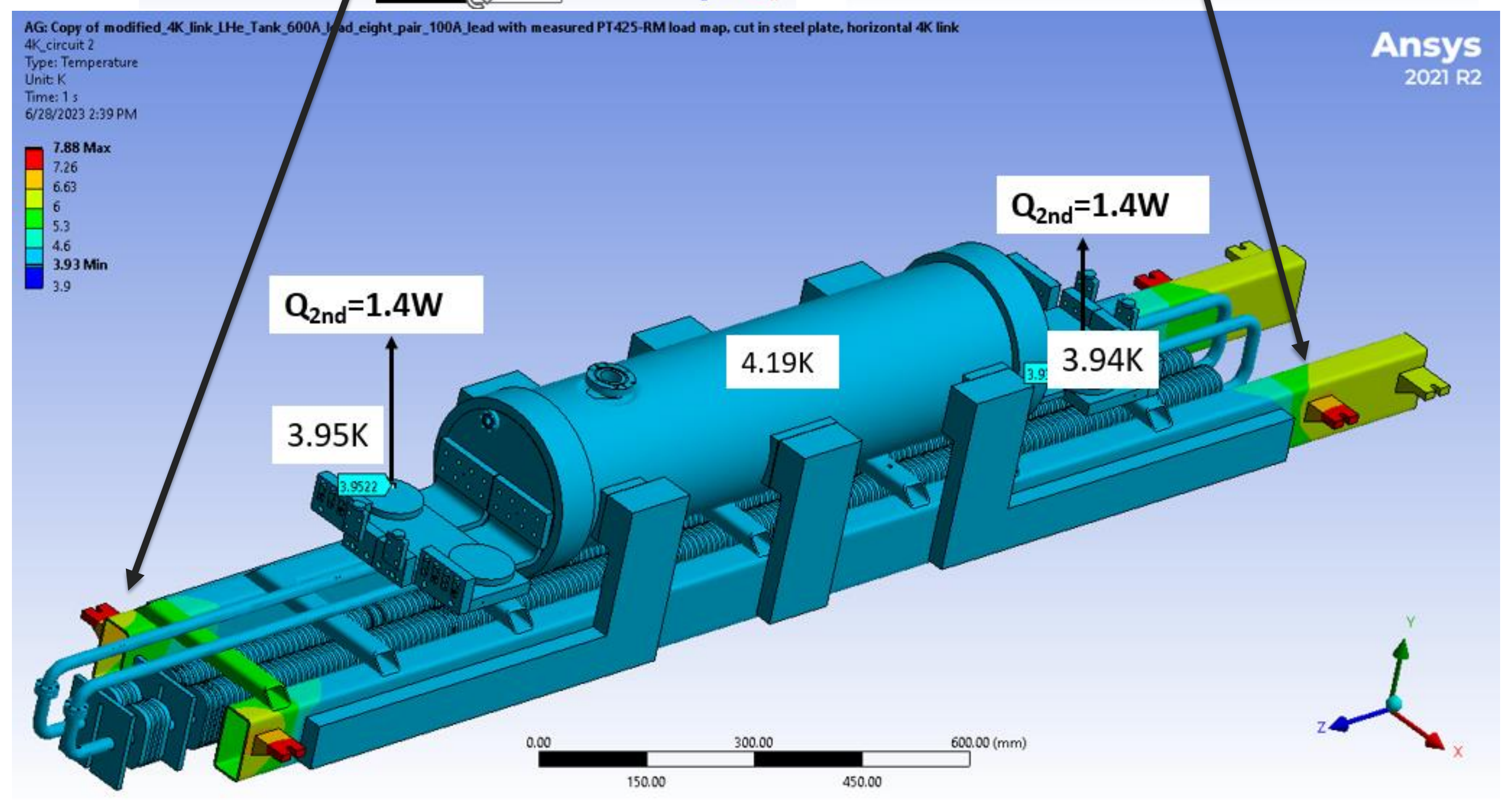
Location	Heat Load (W)
Conduction heat through HTS section of main lead to 4K circuit	0.285*
Conduction heat through HTS section of correction lead to 4K circuit	0.28*
Coldmass support vertical: 0.25", L = 0.416m (L = 0.265m from 40K to 4K)	0.0283
Thermal radiation from beam chamber (40K) to magnet	0.006
Thermal radiation from shield (40K) to magnet	0.078
Beam chamber support (Torlon) (no beam)	0.003
LHe and relief piping (40 K to 4K)	0.04
Instrumentation (320 phosphor bronze 32 AWG, 1m)	0.02
Total 2nd stage heat load	0.74

*One pair of 1kA HTS110 leads is used for main and 8 pairs of 150A HTS 110 leads are used for correction [8]

The 1st stage cooling power increases as the 1st stage temperature increases. However, its gradient depends on the 2nd stage heat load. The 2nd stage cooling power also increases as the 2nd stage temperature increases and is independent from the 1st stage heat load.

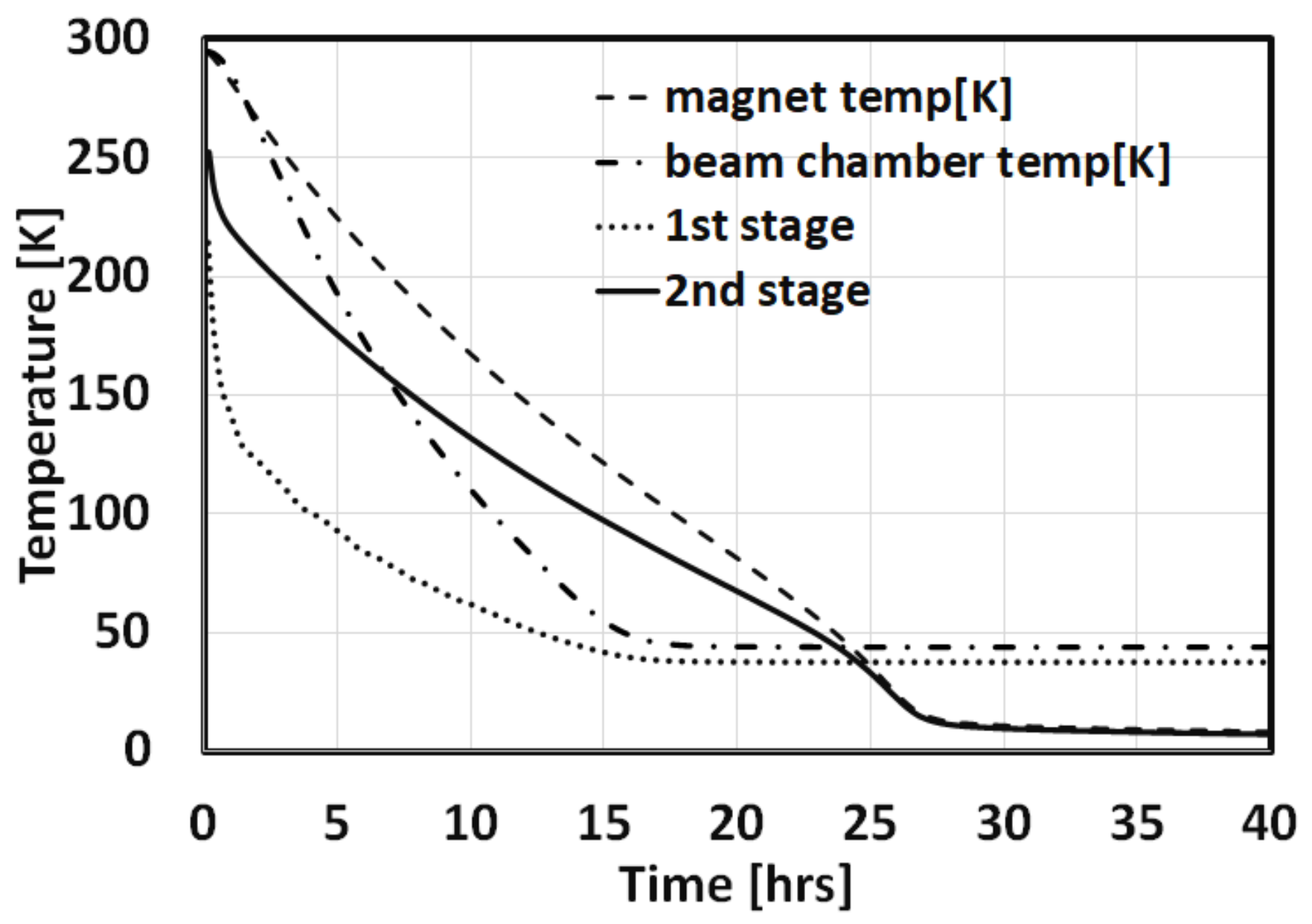
Conduction heat leak through the coldmass supports





CALCULATED COOLDOWN CURVE

Based on the same cold mass and thermal shield geometry, PT425-RM load maps, temperature dependent thermal conductivity, and heat capacity, cooldown curves are calculated using transient thermal model. An estimated cooldown time of 10^5 sec = 27.8 hrs is reasonably fast.



CALCULATED EXCESS COOLING POWER

The calculated total 2nd stage cooling is 2.8 W, and the calculated excess cooling power is 2.0 W for the static case. When beam and current are on, the excess cooling power is 1.8 W.

Total 2nd stage cooling power
= 2nd stage heat load +excess cooling power.

Cooling Power (W)	Static (W)	Beam and magnet current (W)
Total 2nd stage heat load	0.74	0.94
Total 2nd stage cooling power	2.8	2.8
Excess cooling power	2.0	1.8

4. CONCLUSION

The pulse tube cryocooler PT425-RM load map was measured for benchmarking. Thermal model of one-segment cryostat is modelled for each load case using measured load maps. Additionally, cooldown curves were calculated. Cooldown time of 27.8 hrs and calculated excess cooling power of 2 W with two pulse tube cryocoolers is reasonable as a preliminary design.

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