Development of an ultra-low-temperature 5-stage continuous adiabatic demagnetization refrigerator that provides cooling at two unique temperatures

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Motivation

Future space-flight missions will need:

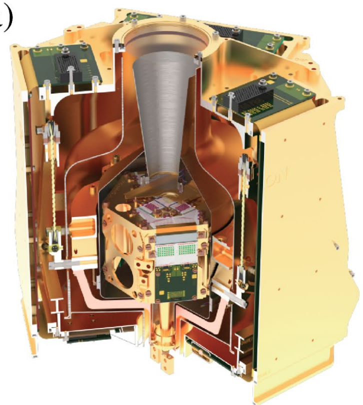
- sub-Kelvin detector cooling (at 40 mK and below) with higher heat loads than past missions
- significant cooling at Intermediate temperatures 0.04 K < T < 4 K (for Series Array SQUIDs, Filter & Termination banks, Cryogenic Mu Metal shield, other heat sinking…)

- NASA/GSFC is developing a flight-ready **4 K to 1 K to 0.03 K** Continuous ADR (CADR) to meet these needs

- In addition to its continuous operation, the major advantage of a CADR lies in its much higher cooling power per unit mass compared to its single-shot counterpart.

- Various future missions are eyeing this technology, including probe missions such as the Line Emission Mapper X-ray probe (LEM), the PRobe Far Infrared Mission for Astrophysics (PRIMA), and the Far-IR Spectroscopy Space Telescope (FIRSST). Additionally, there are under study flagship missions like the Habitable Worlds Observatory (HWO).

(a)



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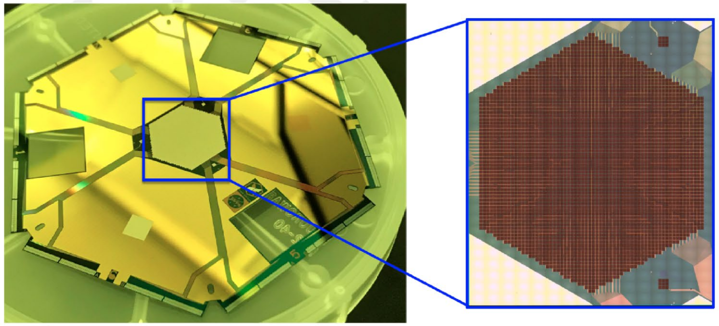
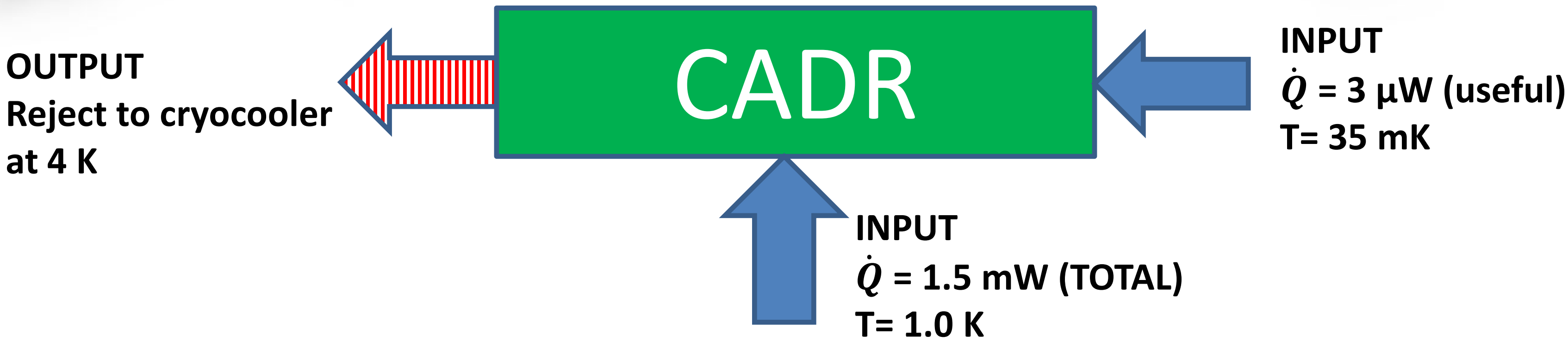


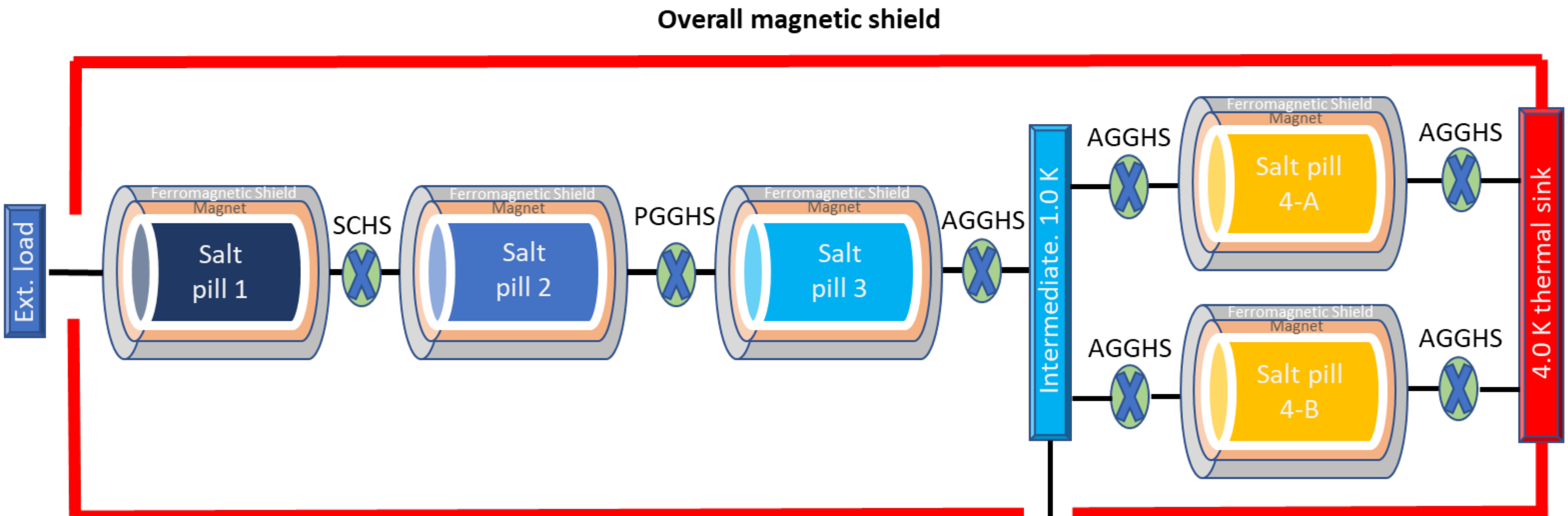
X-IFU prototype array with more than 3,000 pixels on a pitch of 260 µm. Courtesy of the X-IFU FPA team at SRON and NASA-GSFC

Performance Requirements



Performance Metric	Requirements	Current SOA of TRL 6+ Coolers	2017 SAT CADR*	Proposed New CADR
Cold Stage Operating Temp. (mK)	≤ 50	50	50	35
Cold Stage Temp. stability (µK) rms	2	1	1	1
Cold Stage Cooling power @ 50 mK (µW) (@ 35mK)	6	0.5	6	10 (3)
Heat Sink Temperature (K)	4	4.5	4	4
Intermediate Stage Stability at Operating Temperature (mK@K)	1 @ 1	1@1.4	N/A	0.5 @ 1
Mag. Field outside ADR shield assembly (µT)	5	250	1	< 2
Lifetime (years)	>10	>10	>10	>10
Mass (kg)	<25	15	18	20

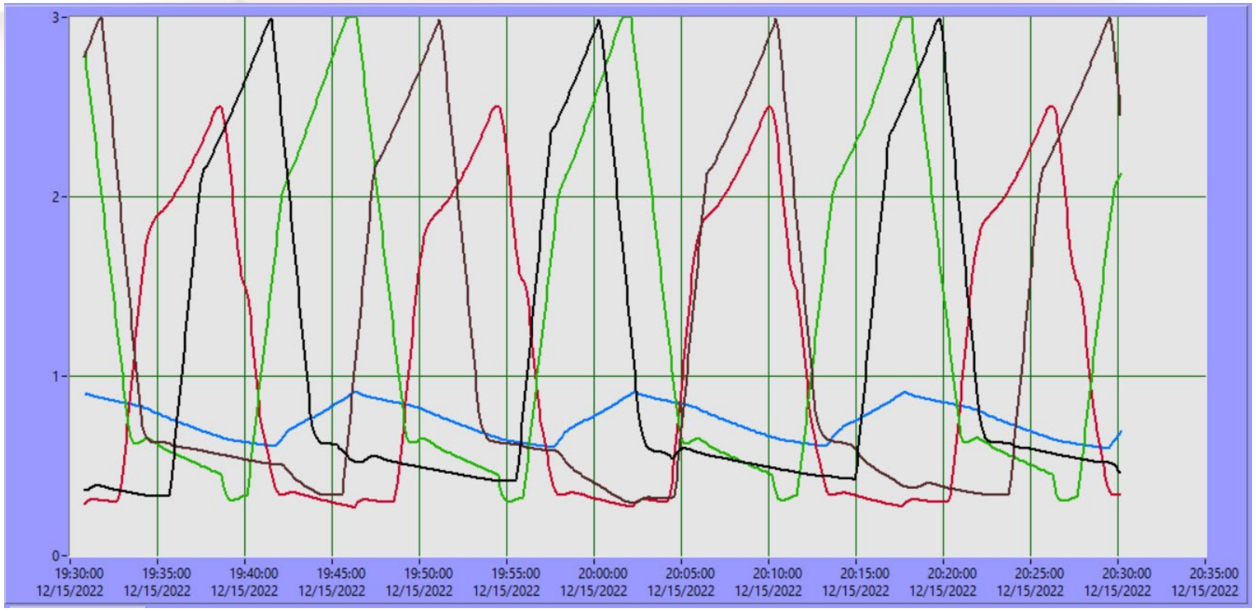
System introduction - Approach



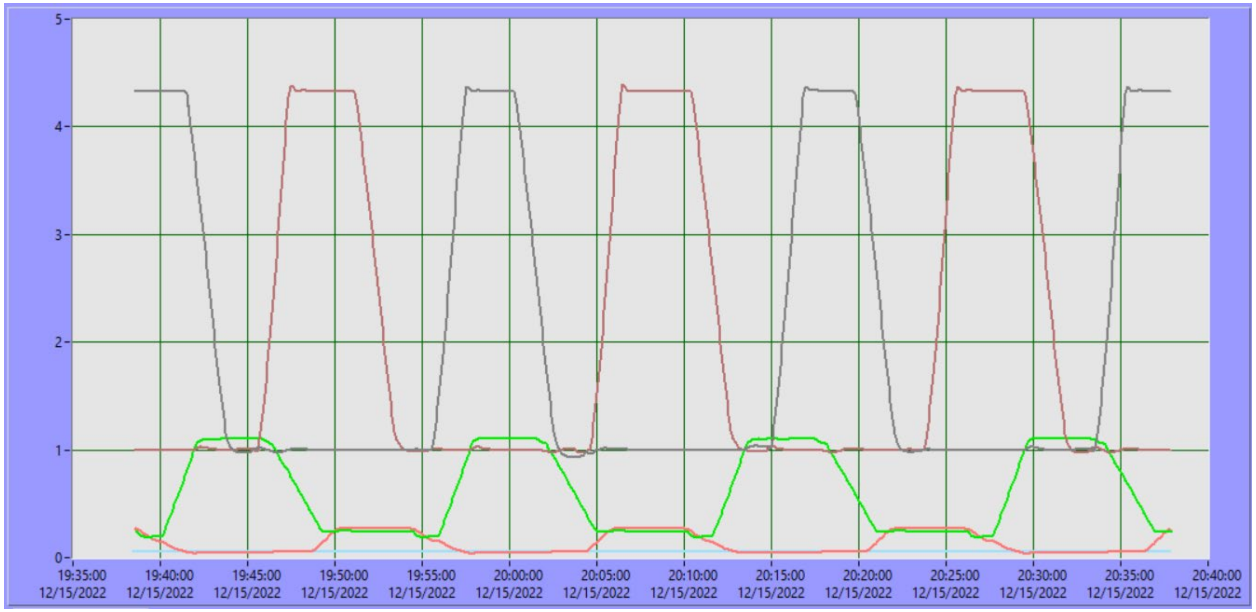
PGGHS: Passive Gas Gap Heat Switch
AGGHS: Active Gas Gap Heat Switch
SCHS: Superconducting Heat Switch

Thermodynamic model

Current profiles produced by the simulator for the 5-stage CADR (S1: Blue, S2: Red, S3: Green, S4A: Black, S4B: Brown)



Temp profiles produced by the simulator for the 5-stage CADR (S1: Blue, S2: Red, S3: Green, S4A: Black, S4B: Brown)



Model results and design drivers

Stage	4A/4B	3	2	1
Salt material & form	GLF -single crystal	CPA - polycrystal (or YbGG -single crystal	CPA-polycrystal	CPA-polycrystal
Salt mass	150 g	150 g	150 g	100 g
B/I ratio	1.33 T/A	0.38 T/A	0.38 T/A	0.1 T/A
Max mag current	3 A	3 A	2 A	1 A
T span	4.35 K to <0.7K	1.1 K to 250 mK	300 mK to 25 mK	35 mK

Min conductance of Heat Switches	**90 mW/K**	**80 mW/K**	**35 mW/K**	**18 mW/K**	**7 mW/K**
	AGGHS Sink-4A/4B	AGGHS 4A/4B-Int.	AGGHS Int.-3	PGGHS 3-2	PGGHS 2-1

Design of the high T CADR

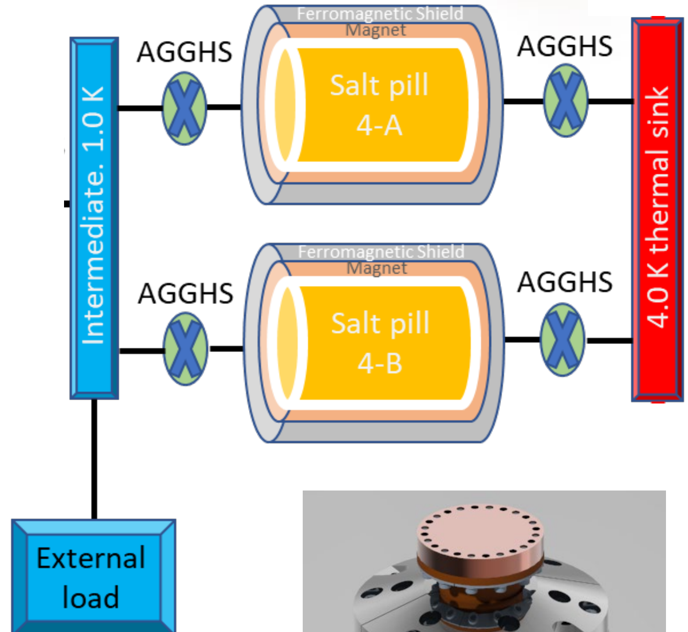
Stage 4A/4B:

X2 AGGHS to thermally link to sink
X2 AGGHS to thermally link to intermediate T platform

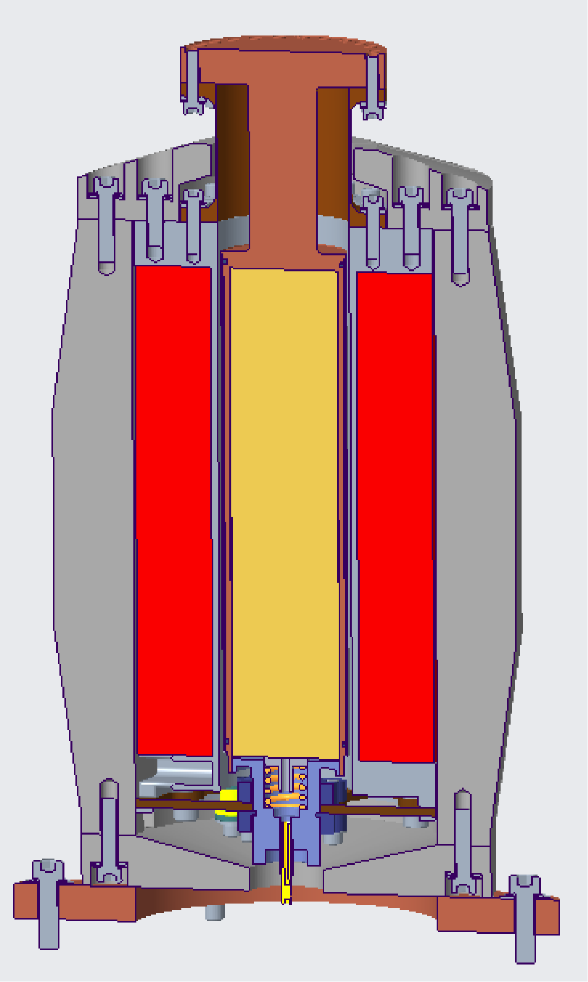
Operation in tandem to provide continuous cooling in a temperature range between 700 mK and 1.1 K

Design of this stage is baselined from Hitomo/XRISM’s stage 3 with the following modifications:

- Adapted to higher current 3A (Vs. 2A)
- Longer salt pill to accommodate required mass of GLF
- Kevlar suspension replaced with Vespel
- SC magnet constrained flat against shield cap (Vs. radially)



High T CADR salt pill

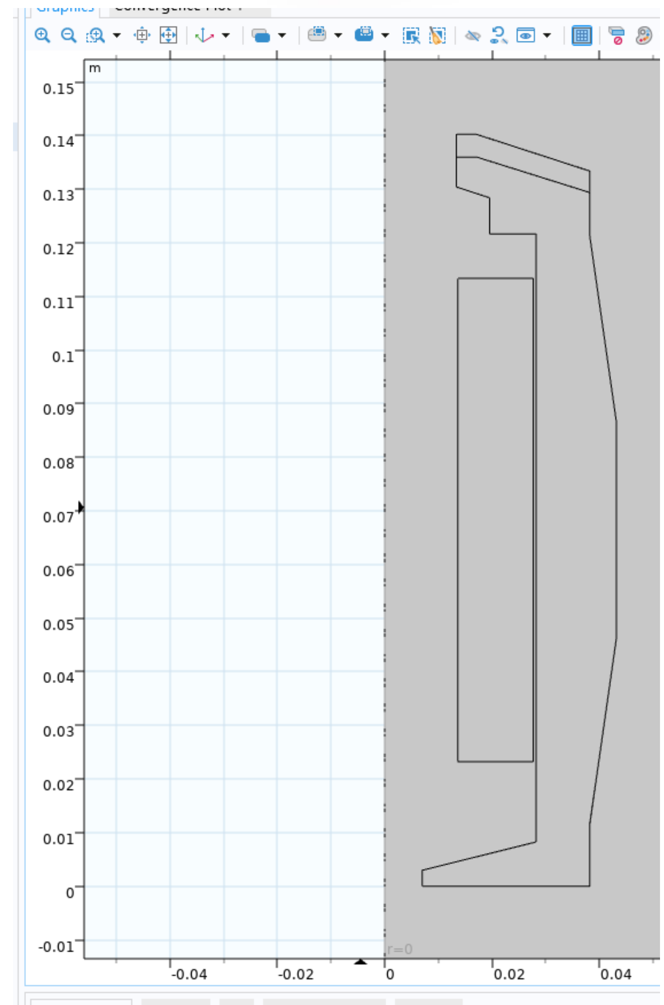


High T CADR shield design

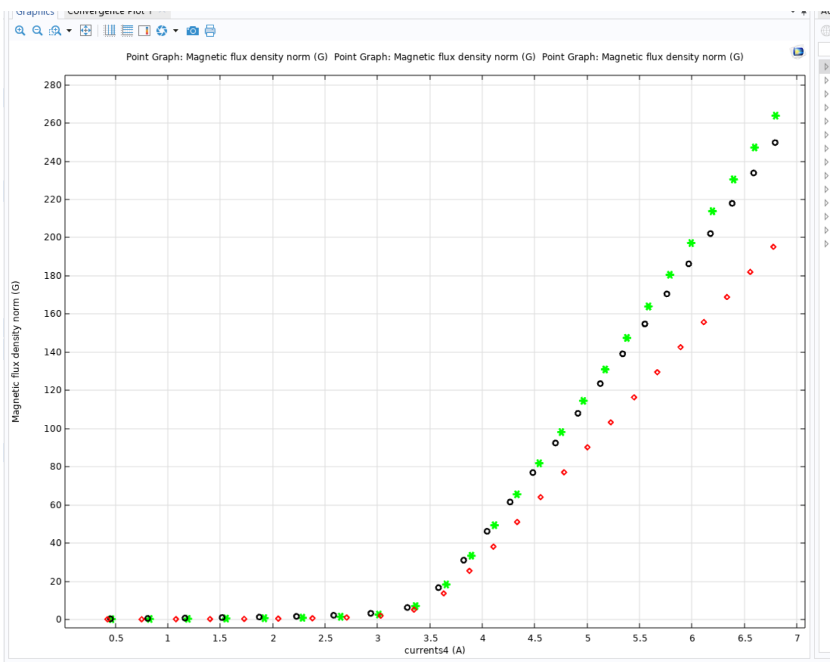
Using 2V-Permendur (tradename Hiperco-50) as the shield

Modeled the magnetic shield via Ampere and COMSOL to determine proper geometry

Shield must not saturate at currents up to 3A in SC magnet



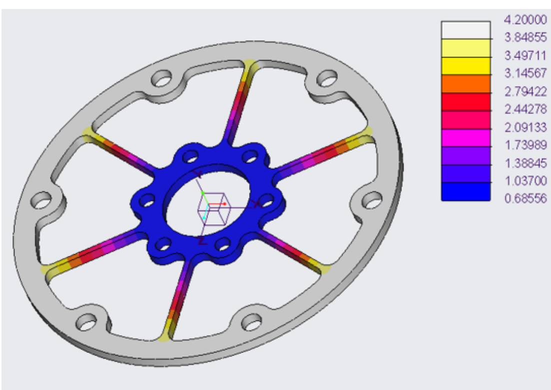
Probe points 10 cm away from top, bottom and outer mid-section

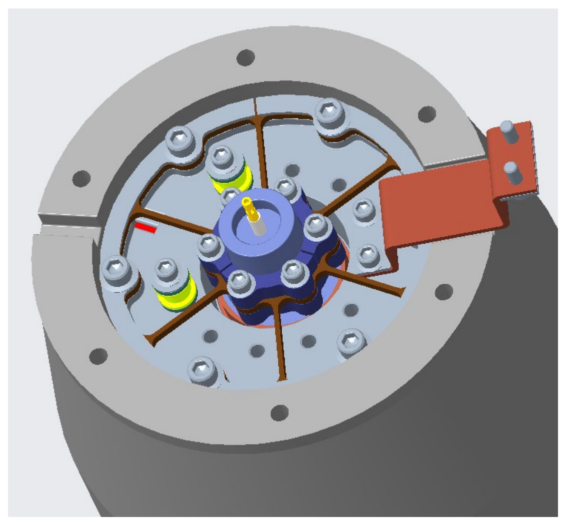


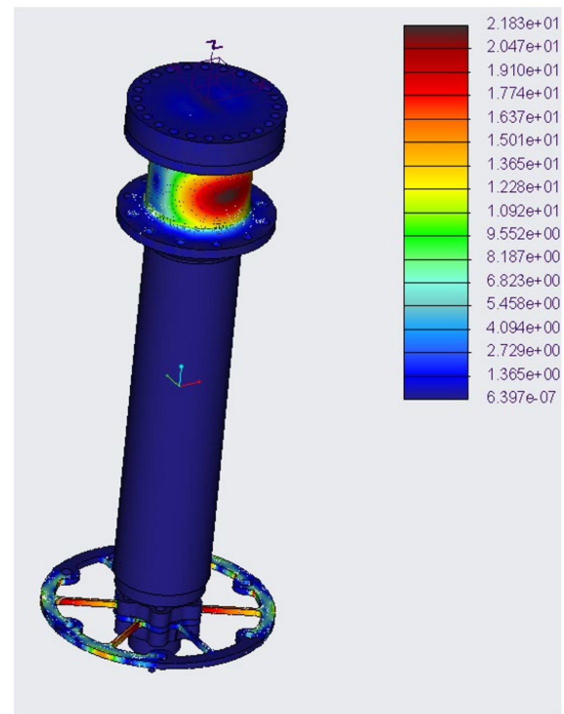
High T CADR Suspension

Previously Kevlar was used to laterally (LSD: Lateral Suspension Device) constrain the salt pill in the bore of the SC magnet on one side of the pill and Vespel SP-1 for the other side.

The Kevlar LSD is replaced with a Vespel SP-1 wheel and spokes design and rigorous mechanical and thermal analysis was carried to ensure the design meets requirements for vibration loading as well as thermal performance.





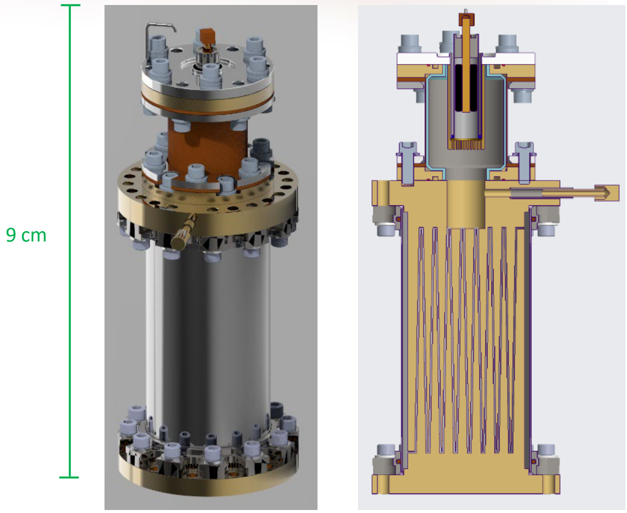


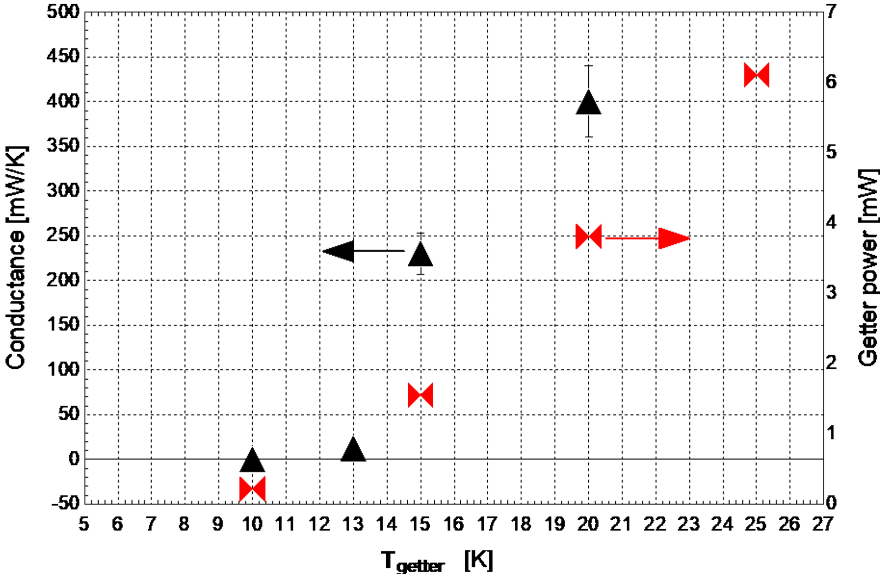
AGGHS testing and design

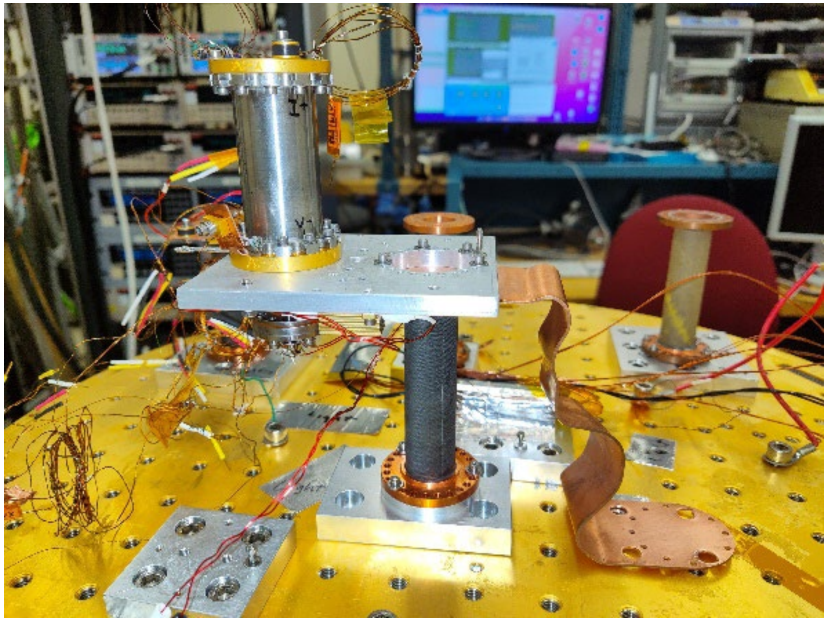
In order to verify that our existing flight AGGHS meets the minimum conductance required for the high T CADR, testing of an AGGHS was necessary.

Troubles in test setup resulted in large errors, however within the errors conductance values were verified to fall within requirement.

Need to refill switch to allow activation of getter at lower temp → lower conducted heat into gas and reentrant structure. (switch was previously tuned for 10 K operation)





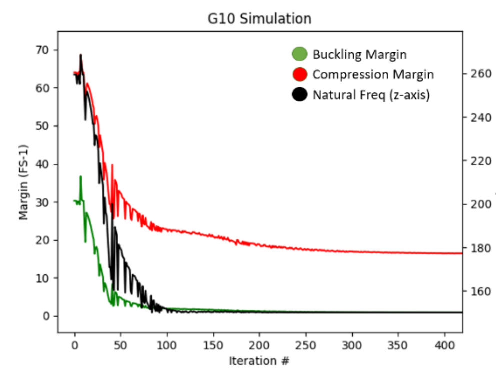


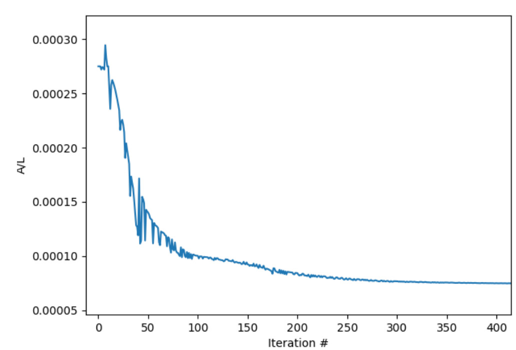
Hexapod structure

The 3 lower T CADR stages will need to mounted on a plate that is thermally isolated from the base 4 K plate.

This requires careful design of the hexapod structure holding up the intermediate T plate to meet structural requirements for vibration loading and in the meantime minimize thermal loads to the intermediate T plate due to conduction.

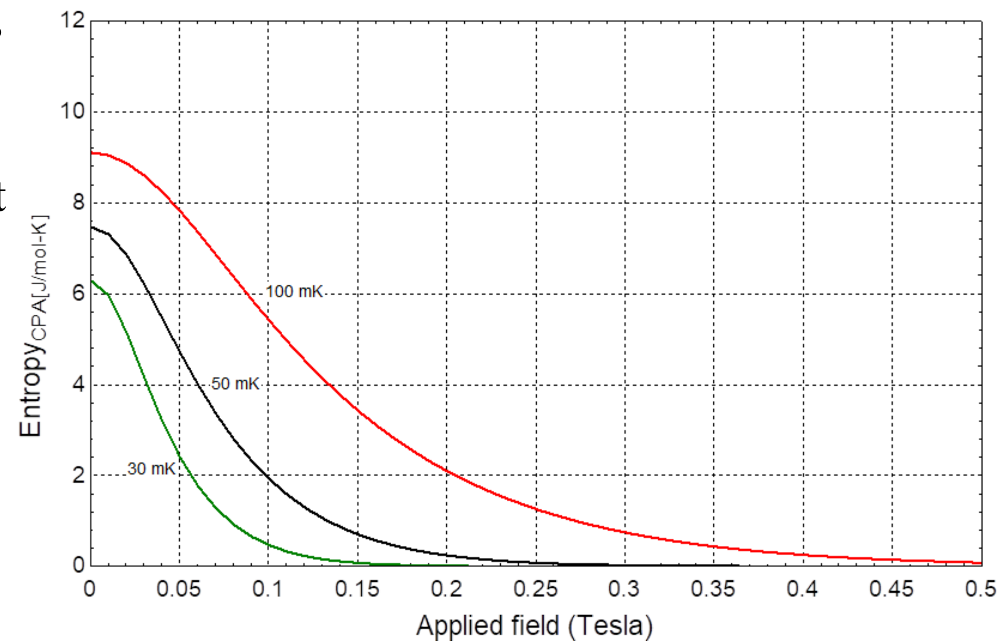
Iterative process was modeled via Python and Creo to find the optimum geometry, material, and positioning of the hexapod legs.





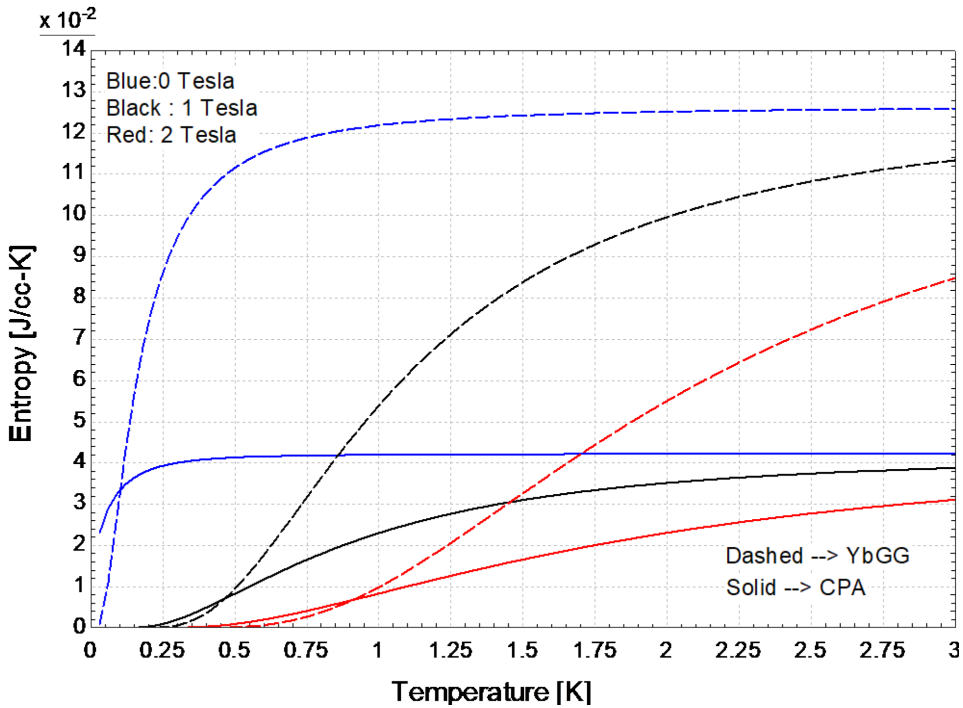
Low T CADR stages

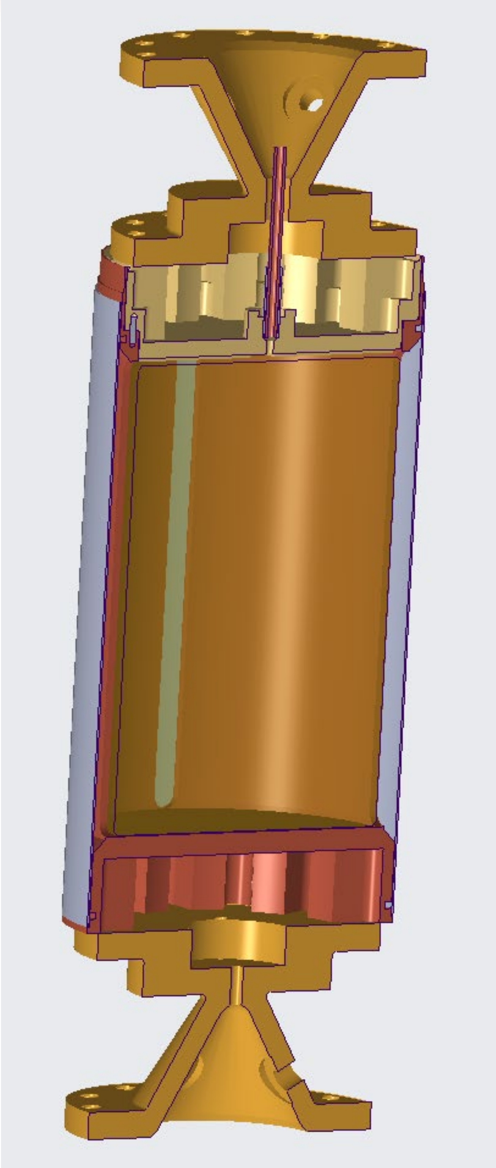
- Hysteresis loss of all low T CADR stages are dumped at the intermediate T platform
- These stages will use reentrant tubular suspensions as opposed to Kevlar. This allows for simpler assembly and integration.
- Parasitic heat load into each stage must be minimized (less than 1 uW)
- Unlike previous iterations, the lowest temperature stage salt pill will be suspended identically to other stages (SC magnet not integrated with salt pill)
- Higher conductance heat switches will be used to fasten the cycle time
- YbGG can be used instead of CPA for stage 3



Stage 3 - YbGG

- Ytterbium Gallium Garnet (YbGG) has cooling capacity several times higher than Chromium Potassium Alum (CPA) per unit volume
- Single crystal YbGG is procured and will be used in stage 3 of this CADR effort (pending test).
- We will use He-3 to fill the voids in the salt pill bus to increase the conductance between the salt and the bus.





Overall magnetic shield

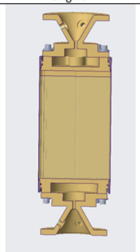
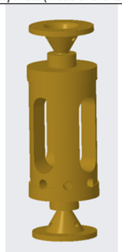
- Our shield concept will be similar to the one we designed and procured for the last SAT effort.
- Use of high permeability material (A4K) to construct the shield wall and lids. Closeout shields designed for thermal straps exiting and leads entering the shield.

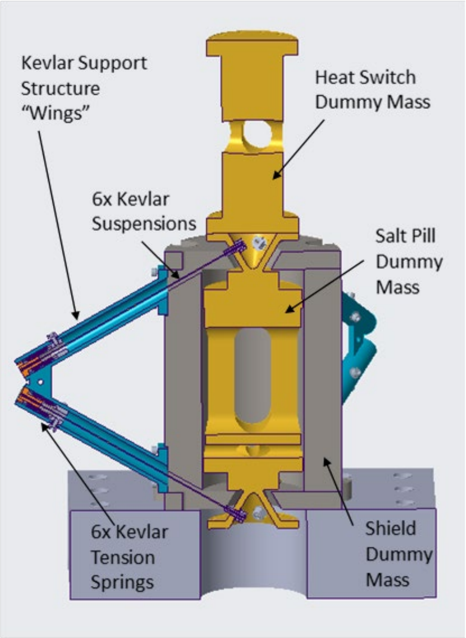
Old business…Dummy mass and SCHS vibe plan

Stages 3 thru 1 internal mechanical support:

- For missions that don't require an intermediate T platform, a viable pat would be to use the suspension system from the previous SAT effort (parasitic heat load from 4 K sink).

- The mechanical support for the salt pill on these stages has not been vibration tested and qualified yet. → A plan to vibration test a Dummy Mass suspended identically to the actual stages is scheduled for late July 2023.

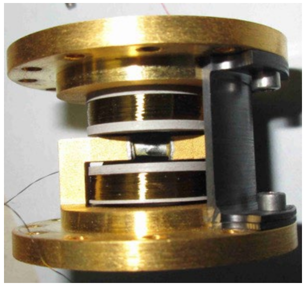
Original	Dummy Mass (made of CU110)	Dummy Mass (made of Brass 360)	Dummy Mass (made of Bronze 510)
			
MASS = 1.2575021e+00 POUND	MASS = 1.2528115e+00 POUND	MASS = 1.2521703e+00 POUND	MASS = 1.2544913e+00 POUND
CENTER OF GRAVITY (from Geometric Center) = X Y Z 0.0000000e+00 0.0000000e+00 6.2521579e-02 INCH	CENTER OF GRAVITY (from Geometric Center) = X Y Z 0.0000000e+00 0.0000000e+00 6.1977925e-02 INCH	CENTER OF GRAVITY (from Geometric Center) = X Y Z 0.0000000e+00 0.0000000e+00 6.2498663e-02 INCH	CENTER OF GRAVITY (from Geometric Center) = X Y Z 0.0000000e+00 0.0000000e+00 6.2557586e-02 INCH
INERTIA TENSOR at CoG (POUND * INCH^2): Ixx Ixy Ixz 2.4856000e+00 0.0000000e+00 0.0000000e+00 Iyx Iyy Iyz 0.0000000e+00 2.4864855e+00 0.0000000e+00 Izx Izy Izz 0.0000000e+00 0.0000000e+00 4.0569380e-01	INERTIA TENSOR at CoG (POUND * INCH^2): Ixx Ixy Ixz 2.4701380e+00 0.0000000e+00 0.0000000e+00 Iyx Iyy Iyz 0.0000000e+00 2.4701370e+00 0.0000000e+00 Izx Izy Izz 0.0000000e+00 0.0000000e+00 4.0719314e-01	INERTIA TENSOR at CoG (POUND * INCH^2): Ixx Ixy Ixz 2.4775328e+00 0.0000000e+00 0.0000000e+00 Iyx Iyy Iyz 0.0000000e+00 2.4775316e+00 0.0000000e+00 Izx Izy Izz 0.0000000e+00 0.0000000e+00 4.0542087e-01	INERTIA TENSOR at CoG (POUND * INCH^2): Ixx Ixy Ixz 2.4807964e+00 0.0000000e+00 0.0000000e+00 Iyx Iyy Iyz 0.0000000e+00 2.4807953e+00 0.0000000e+00 Izx Izy Izz 0.0000000e+00 0.0000000e+00 4.0507729e-01



SCHS:

- A plan to subject the SCHS to a vibration test is scheduled for late July 2023.

- The SCHS will undergo post-vibe thermal tests once it survives vibration testing.



Conclusion

We are on a path to build the high T CADR stages, the AGGHSs, thermal straps, and the base plate to meet our first milestone.

We then plan to move onto the detailed design of the low T CADR stages, including suspension, SC magnets, shield, etc. then proceed to building the stages, heat switches, thermal straps, etc.

We will design our hexapod structure and have it analyzed by a structural analyst, after which we will begin fabrication and assembly of parts.

We will conduct a thermal performance of the system, subject it to vibration loads commensurate with flight, and conduct post-vibe thermal test.