A Four-Stage Continuous ADR for Space Missions

Jim Tuttle, Amir Jahromi, Mark Kimball, Rich Ottens, Evan Sheehan, Ed Canavan, Michael DiPirro, Peter Shirron

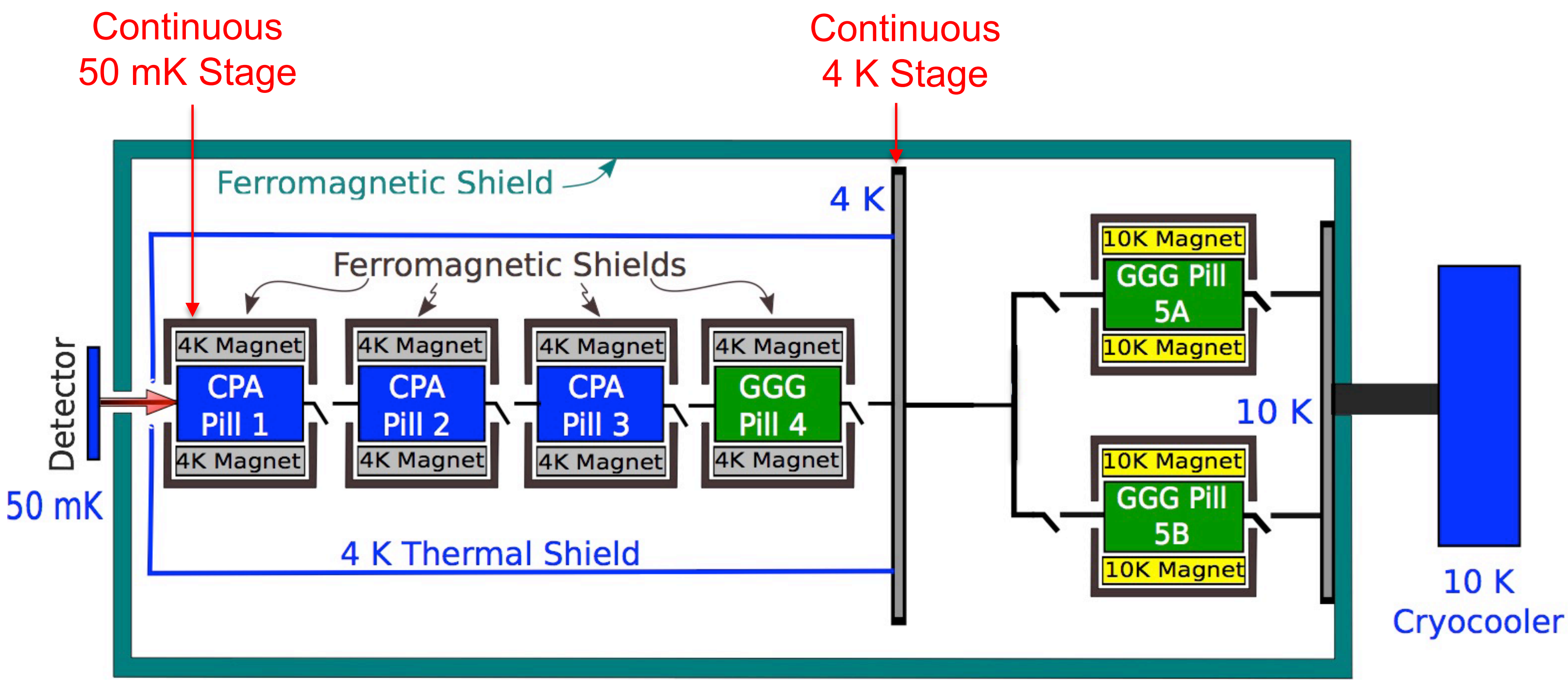
NASA Goddard Space Flight Center, Greenbelt, MD 20771 USA

Introduction

- Future space-flight missions will need:
  - sub-Kelvin detector cooling (at 50 mK or below) with higher heat loads than past missions
  - significant cooling at ~ 0.5 K – 4 K for optics/instrument
- In 2016 NASA/GSFC proposed to develop a flight-ready 10 K to 0.05 K continuous adiabatic demagnetization refrigerator (CADR) to meet these needs
- Original funding from NASA HQ for years 2017 – 2019
- Additional intermittent funding through September, 2022
- We report the progress on this effort

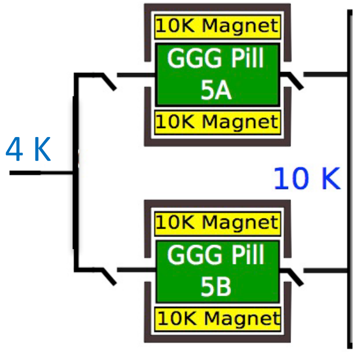
Originally Proposed CADR

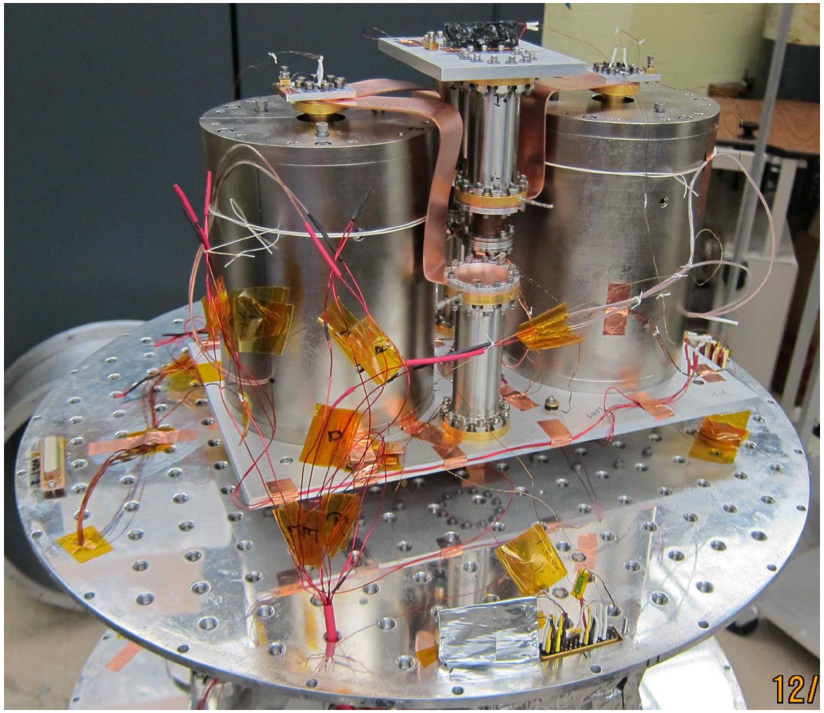
- 4 K to 50 mK subsystem to be flight-worthy version of a lab CADR
- Heat switch between stages 1, 2 is superconducting; all others are gas-gap
- Salt pills: gadolinium-gallium-garnet (GGG) and chrome potassium alum (CPA)
- Design included 10 K overall magnetic shield



10 - 4 K CADR Subsystem

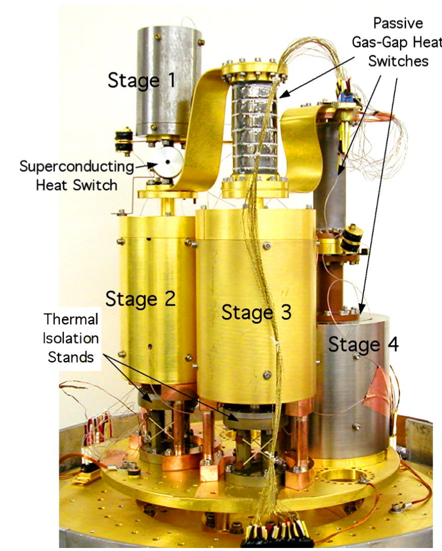
- Two parallel GGG salt pills alternating cooling/recycling
- Includes two 10 K, shielded Nb_3Sn magnets from Superconducting Systems
- Includes four gas-gap heat switches (2 passive, 2 active)
- Original target was 20 mW of continuous 4 K cooling
- Early test with single stage suggested that 10 mW cooling more realistic
- As 2-stage system began testing, one of the magnets failed.
- Due to limited resources, this subsystem was shelved before arrival of replacement magnet



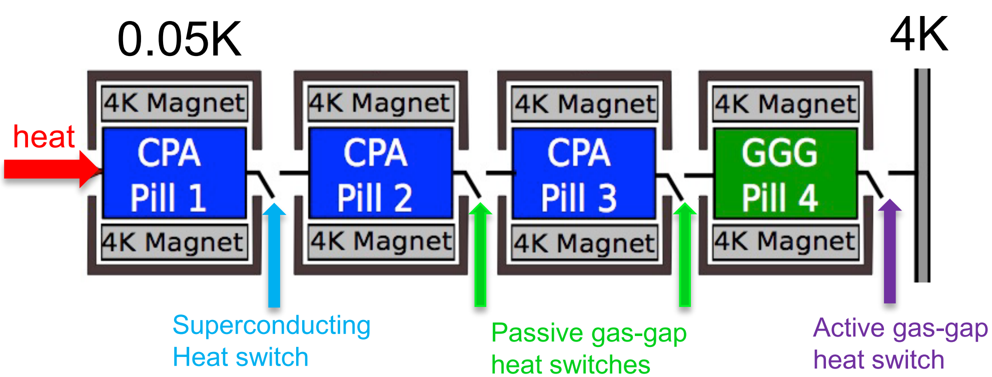


4 K – 0.05 K CADR Background

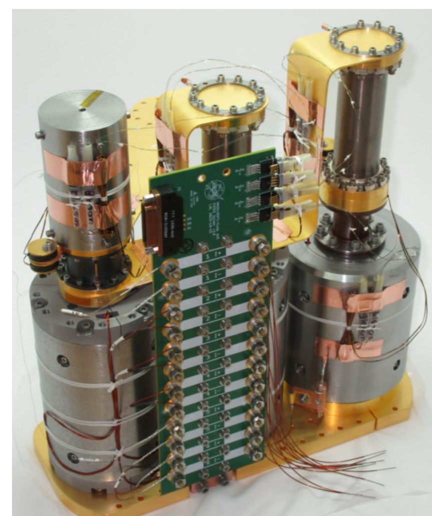
- Four-stage lab CADR: 6 μW of cooling at 50 mK in 2004
- New iterations for lab use (2017) and a balloon flight (2018)
- Our primary task: analyze/re-design salt pill suspensions to survive launch loads
- Secondary goal: identify/implement minor design/process improvements
- **Useful-cooling target: 6 μW at 0.05 K, rejecting to 4.0K**



2004 Lab CADR



Current CADR Schematic



2017 Balloon CADR

2017 Lab CADR

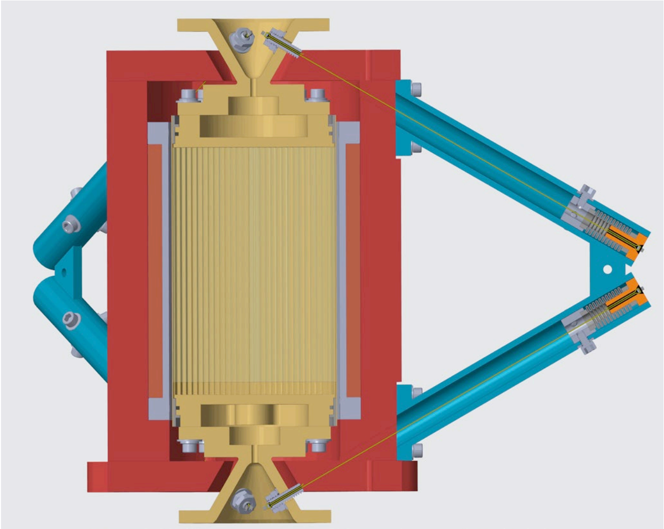
CADR Modelling

- NASTRAN model used to guide design and plan vibe test
- Amperes, FEMM and Comsol magnetic field models for magnet, salt pill and shield designs
- LabView system simulator to guide operating parameter optimization

Stage 2, 3 Salt Pill Suspensions

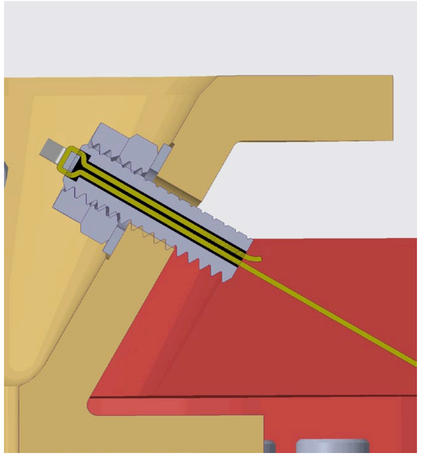
Cryogenics and Fluids Branch

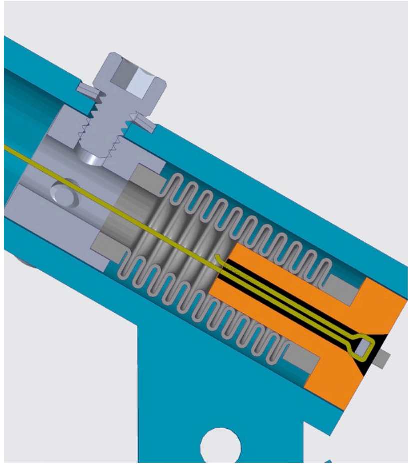
- Kevlar suspension was modified from lab design (after analysis) to survive launch loads
- Each of 6 Kevlar legs needed 3 times the tension of the lab system
  - Tripled each leg's cross section area and length
  - Each leg consists of 9 x 195 denier Kevlar yarns
- Kevlar tensioning scheme was improved
  - Compression bellows' act as springs
  - Fixturing allows precise deflection measurement



Stages 2, 3 final design

Stages 2, 3 are identical

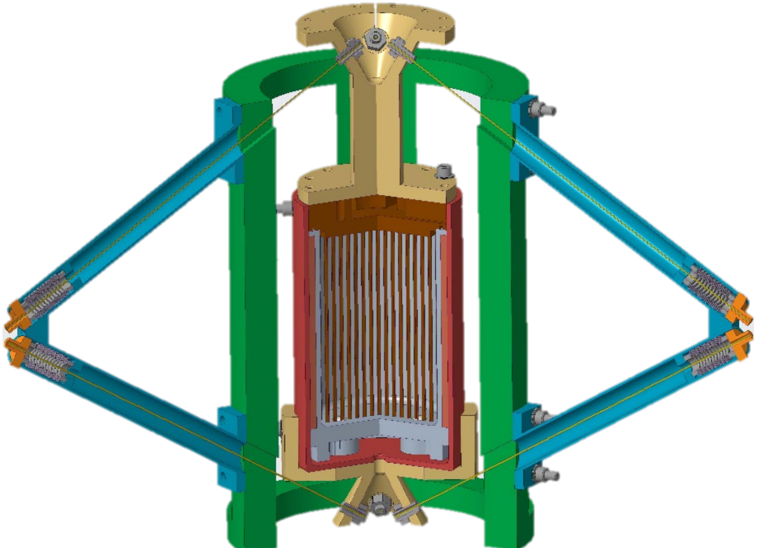




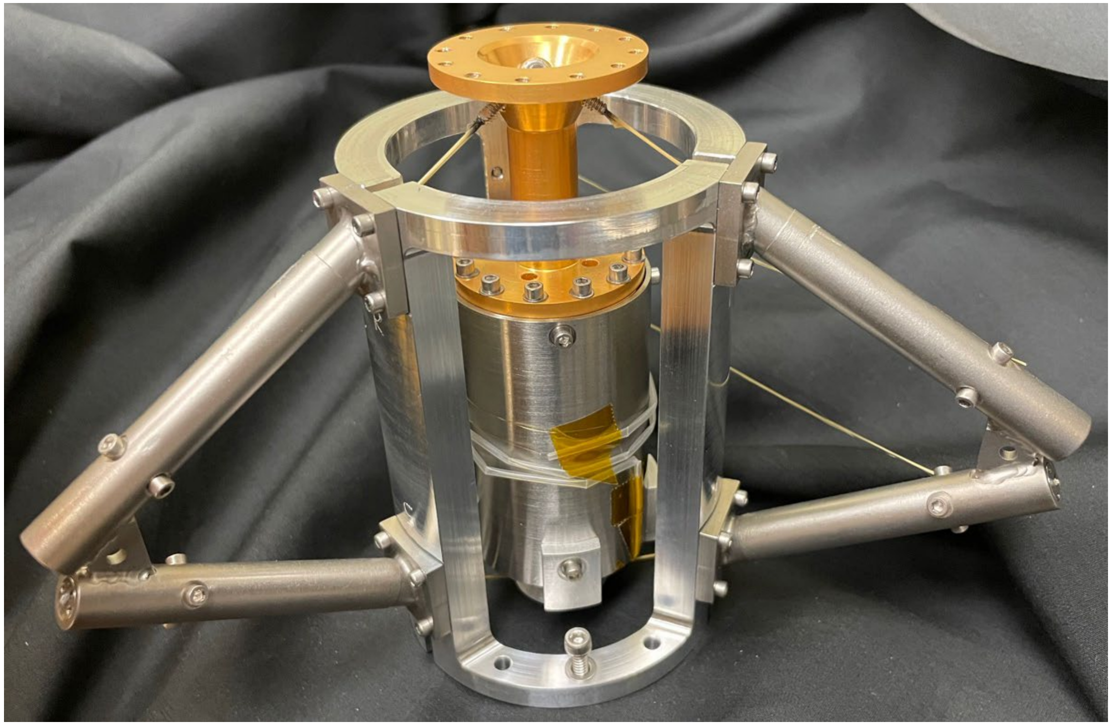
Details of Bonded Kevlar Ends

Stage 1 Salt Pill Suspension

- Stage 1 suspension differs slightly from those of Stages 2 and 3:
  - Magnet & shield are parts of suspended mass
  - Suspension tubes are mounted on a frame



Stage 1 final design

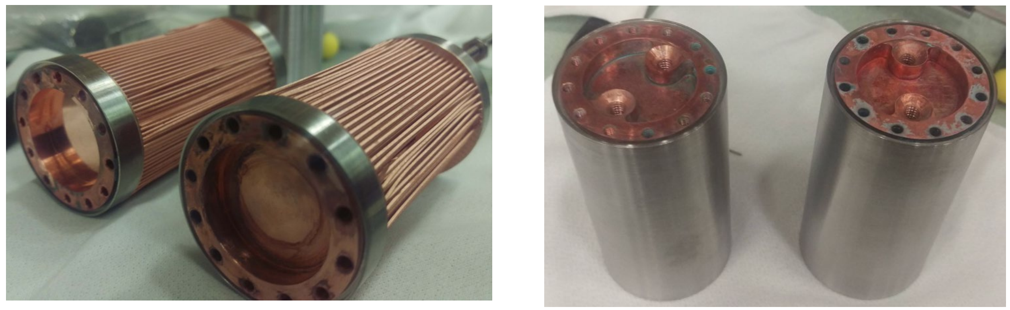


Stage 1 Fully Assembled

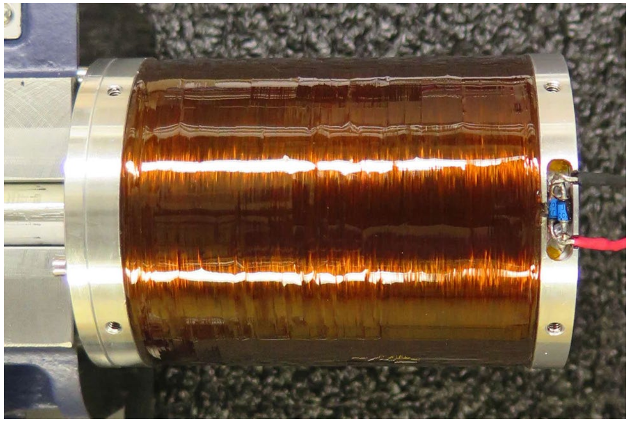
Other Components

- Stage 4, as well as the salt pills, magnets, shields, passive gas-gap switches, and superconducting heat switch were very similar to those of the lab systems

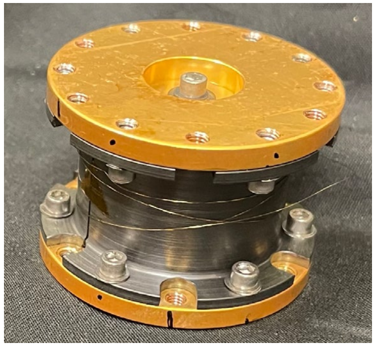
Stage 4



Stage 2/3 Salt Pills



Stage 2/3 Magnet

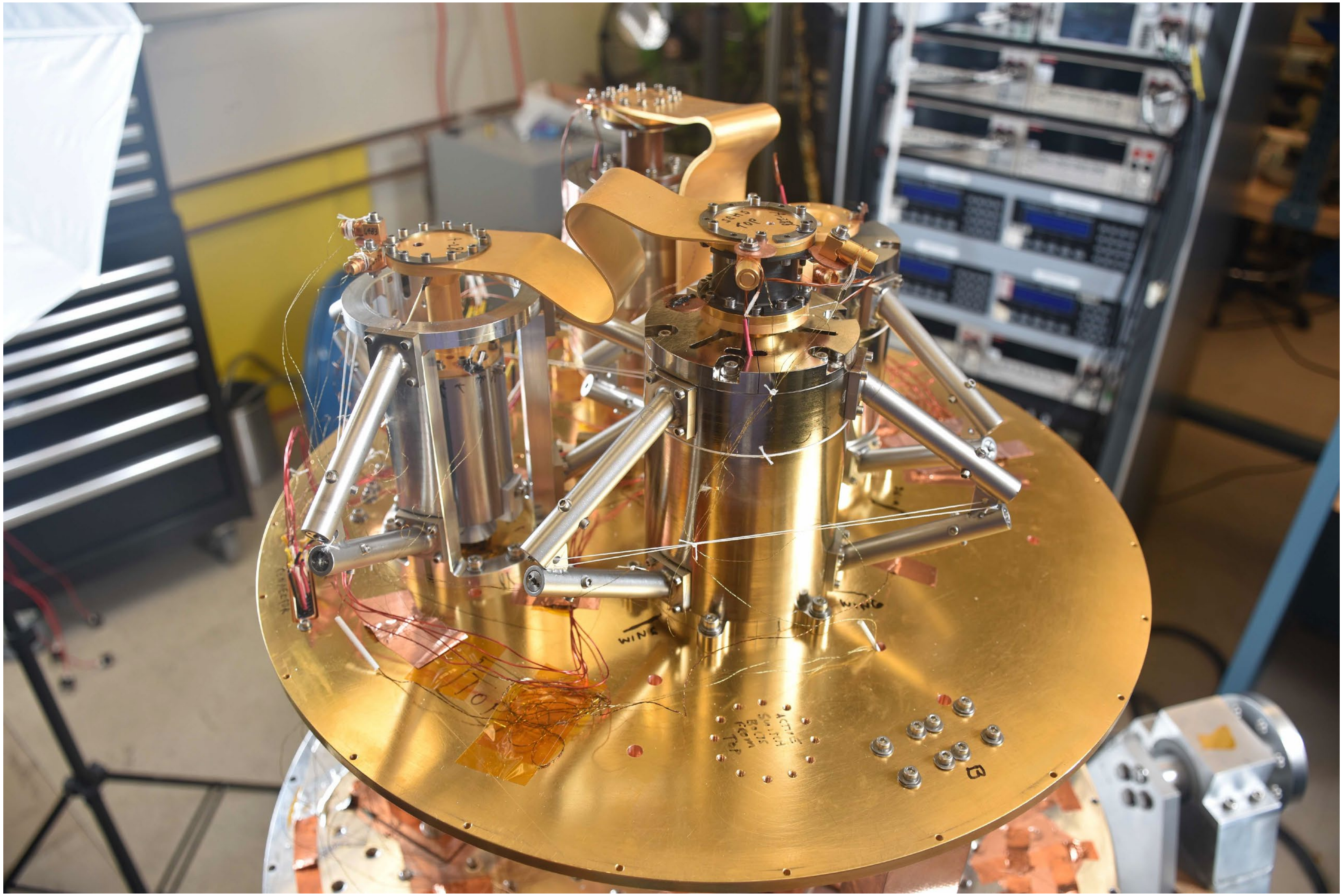


Superconducting Heat Switch

Passive Gas-Gap Heat Switch

The 4-Stage CADR

Cryogenics and Fluids Branch



4 K – 50 mK CADR Optimization

Many cooldowns, system modifications over 16 months of testing.

- Magnets trained to appropriate operating currents after each cooldown from room temp.
- Passive gas-gap heat switch fill levels tuned for appropriate on/of temperatures
- CADR operating parameters tuned and varied to maximize heat lift
- Two suspension legs (with earlier design) failed after 8, 12 cold cycles
  - Epoxy joints sheared away from metal parts due to cycling
  - We re-designed epoxy joints to include failsafe pins; replaced all legs
- Sub-standard copper was used to fabricate the salt-pill-bus end pieces
  - We assumed RRR = 50 – 100; actual values were 3.5 and 7; (Pot Metal!)
  - We re-made and replaced these parts; RRR = 65
- Our cryostat had a poor conductive path from cooler head to stage 4
  - We bolted on flexible copper straps to enhance conduction
- In June, 2023 we finally achieved nearly our target performance parameters

Test Results Summary

- Useful cooling measured at different temperatures (rejecting to 4.0 K)
  - 5.4 μW at 0.05K (target was 6.0 μW)

- "Closed" conductance of superconducting heat switch (SCHS) at 0.05K: 6 mW/K
  - Will be compared with post-vibe value

- "Open" SCHS conducts 4.6 μW from 0.3K to 0.08K
  - Matches calculated value

- Heat conducted into stage 1 @ 0.08K from 3.1K: 0.8 μW
  - Calculated 0.33 μW; difference might be due to vibration heating?

Options to Improve Performance

- Use Gadolinium Lithium Fluoride (GLF) in Stage 4 salt pill
- Use Yttrium Barium Gallium Garnet (YBGG) in Stage 3 salt pill
- Use titanium 15-3-3-3 in all gas gap heat switch shells (in place of stainless steel)
- Use ultra-pure annealed copper in SCHS
- Increase effective Area/Length in Stage 1 copper linkage
- Increase conductive link between Stage 4 and cryocooler in test cryostat

Path Forward

- Vibration test will occur in late July, 2023
  - A mass/moment-simulator of suspended Stage 2/3 salt pill/switch
  - Our actual SCHS
- SCHS will be re-installed in CADR for post-vibration re-test
- CADR will be kept as a test bed; perhaps implementing some upgrades
- The overall magnetic shield will be tested this summer
- Development continues on an updated CADR (Amir Jahromi is the PI)