Development of a Space-Flight ADR Providing Continuous Cooling at 50 mK With Heat Rejection at 10 K

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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

- NASA/GSFC is developing a flight-ready 10 K to 0.05 K continuous ADR (CADR) to meet these needs

Performance Requirements

Cryogenics and Fluids Branch

- Anticipated future missions with sub-Kelvin detector arrays:
  - Origins Space Telescope (OST) (two instruments)
  - Lynx
  - Probe of Inflation in Cosmic Origins (PICO)
  - Galaxy Evolutioin Probe (GEP)

- Proposed CADR can exceed most expected performance requirements

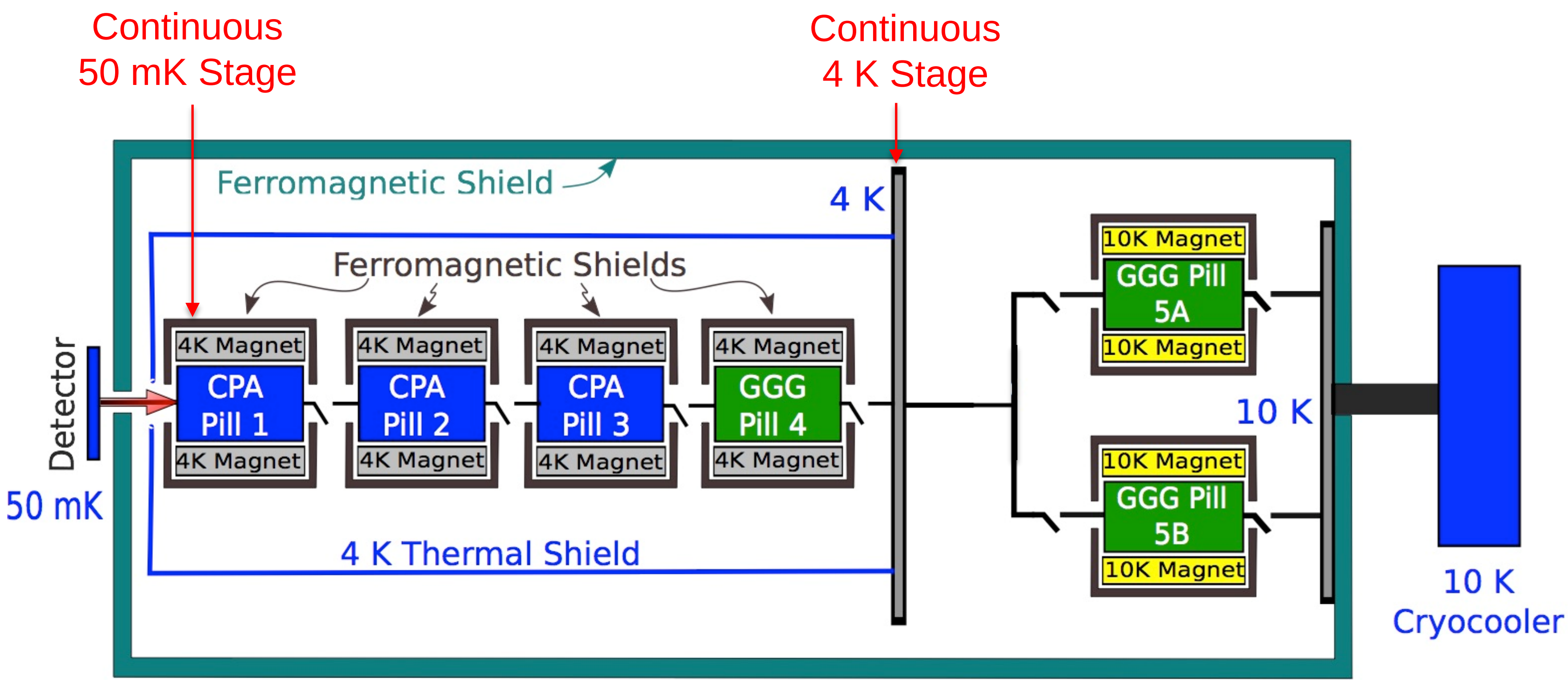
Performance metrics	Requirements	Current SOA	Proposed CADR
Cold Stage Operating temp. (mK)	≤ 50	50	≤ 50
Cold Stage temp. stability (μK)	1	1	≤ 1
Cold Stage Cooling power (μW)	3	0.5	> 6
Warmer Stage Stability at Operating Temp. (mK@K)	1@4-6	1@4.5	1@4
Telescope Cooling (power@temp., mW@K)	100@4-6	20@4.5	~10@4 K
Mag. Field at detector assembly (μT)	5	7500	< 5
Allowable vibration levels (milli Newtons, mN)	0.001	5	~ 0
Lifetime (years)	> 5	> 5	> 5

Vibration Reduction

- ADRs have no moving parts; contribute zero vibrations
- Mechanical cryocooler vibrations are an issue on many flight missions
- Creare demonstrated sub-10 K operation of their Turbo-Brayton cooler
  - Very high-frequency vibrations - heavily damped by spacecraft structure
- A 10 K superconducting flight-compatible magnet was developed with NASA funding between 2002 and 2010
  - It’s now possible for a flight CADR to reject heat at 10 K
- These two technologies enable 300 K to 50 mK “vibration-free” cooling

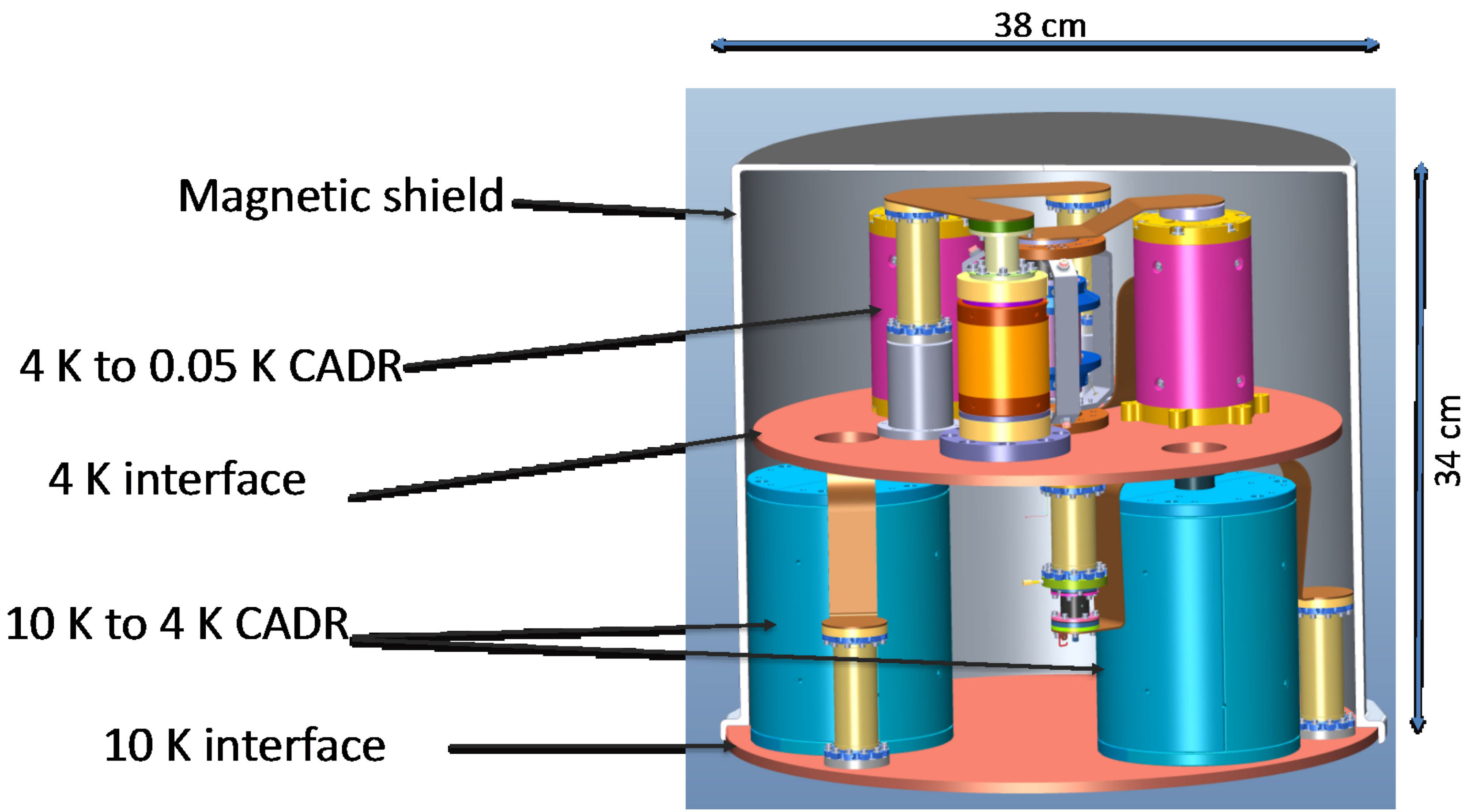
New CADR Schematic

- 4 K to 50 mK subsystem will 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 includes 10 K overall magnetic shield



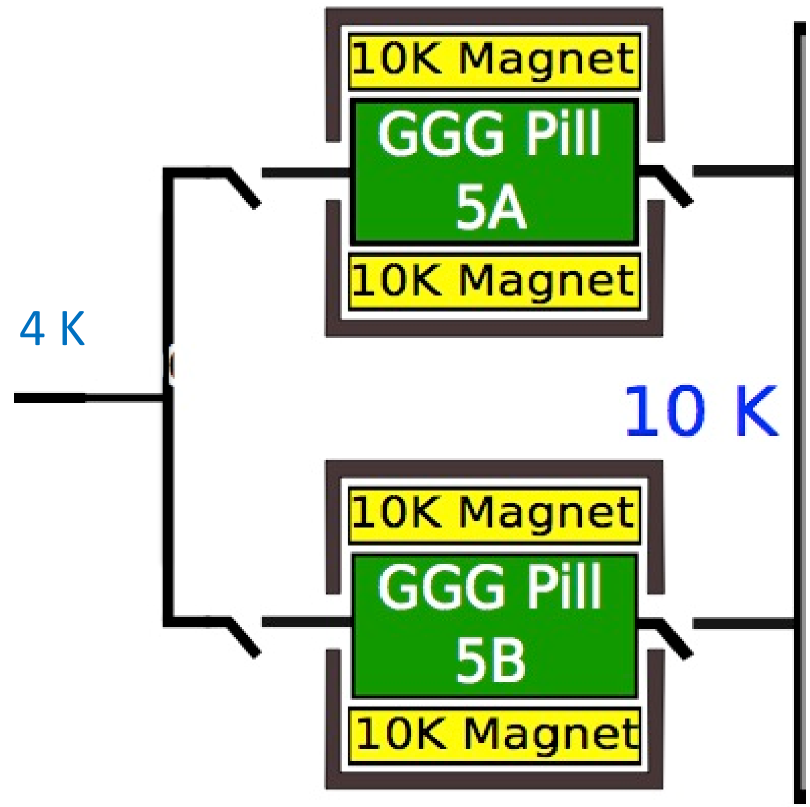
CADR Component Packaging

- 4 K thermal shield not shown
- Shields' strap feedthrough details are TBD



10 - 4 K CADR Subsystem

- Two parallel GGG salt pills alternating cooling/recycling
- Kevlar yarn and Vespel tubes used to suspend salt pills
- Includes two 10 K, 4 Tesla 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



10 - 4 K CADR Components

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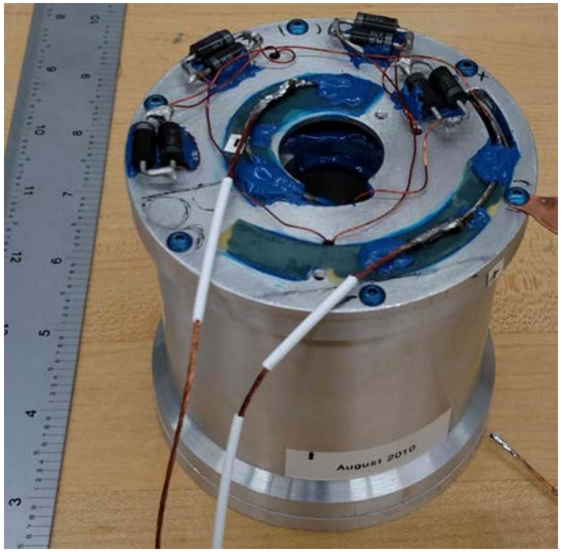
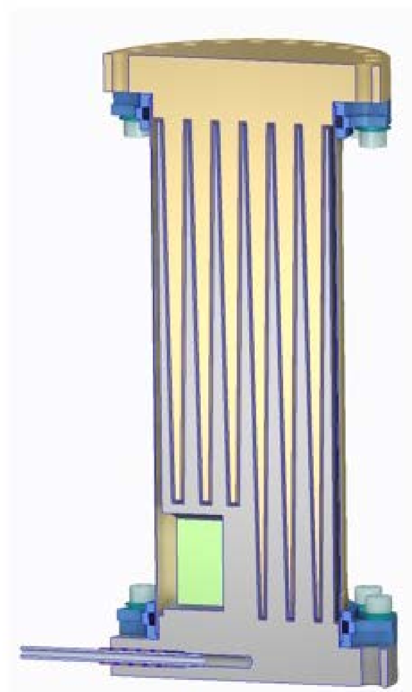


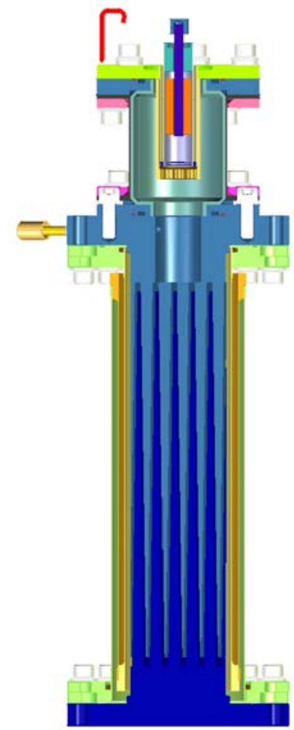
10 K Nb_3Sn Magnet

GGG Salt Pill Assembly

Kevlar Suspension Assembly



Passive Switch



Active Switch

Single-Stage 10 - 4 K ADR

Passive Gas-Gap Heat Switch

Copper Strap

10 K Test Plate

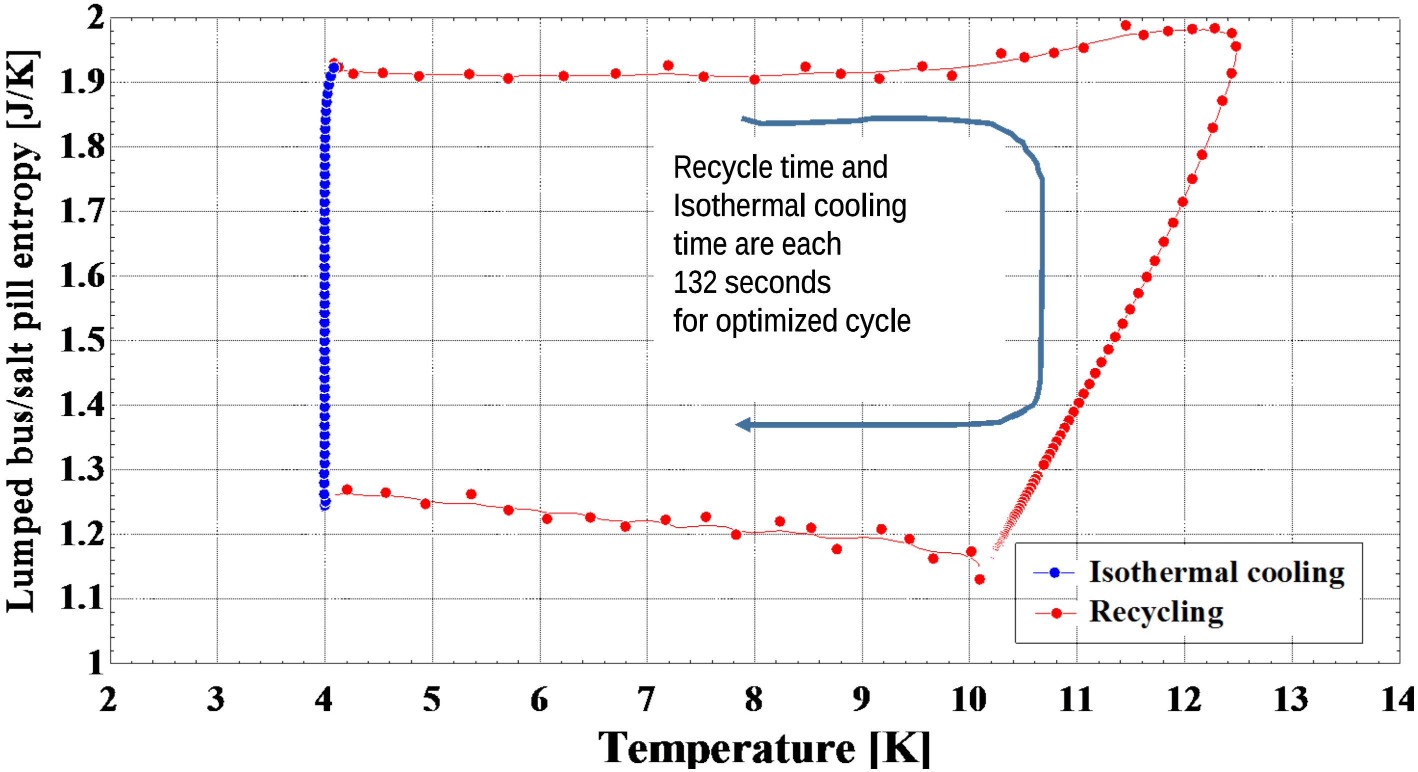
Silicon-Iron Shield

Salt Pill End Flange

Nb_3Sn 10 K magnet

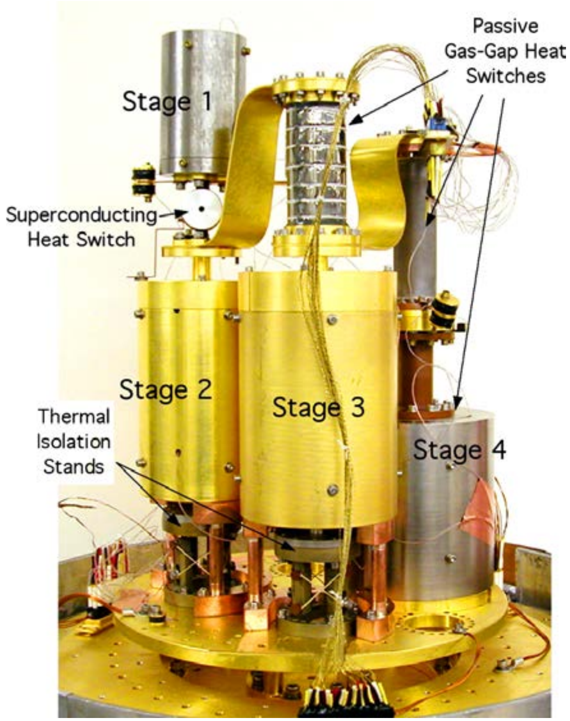
10 - 4 K ADR Test Results

- For 13 mW load, cycle time equals 4 K hold time (prediction was 20 mW)
  - Under-performance partly due to historical misinterpretation of GGG magnetization data
  - Amir Jahromi's paper at CEC will discuss in more detail



4 K – 0.05 K CADR Subsystem

- Four-stage lab CADR produced 6 μW of cooling at 50 mK in 2004
- New iterations have been built for lab use (2017) and a balloon flight (2018)
- Primary task: analyze/re-design salt pill suspensions to survive launch loads
- Secondary goal: identify/implement minor design/process improvements

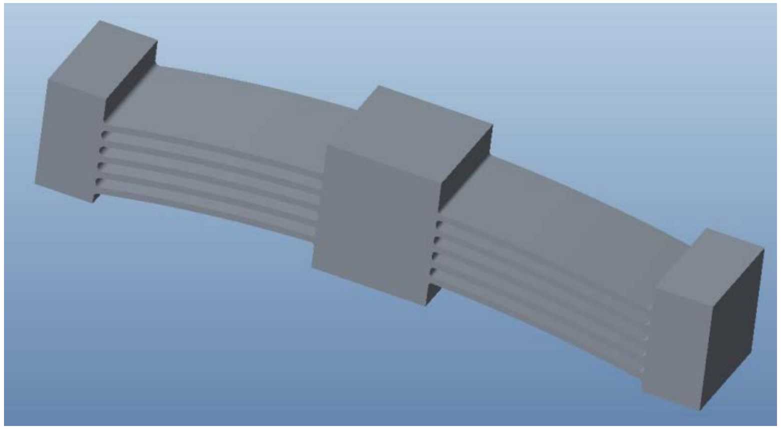


2004 CADR

2017 CADR

Suspension System Re-design

- Lab Kevlar Suspension must be made to survive TBD launch loads
- Preliminary analysis of lab suspension:
  - Resonance frequencies are sufficiently high
  - May require larger Kevlar cross section in some locations
- We are studying strength of Kevlar/epoxy configurations
- Replacing Belleville washer stacks with flexures and stiff springs



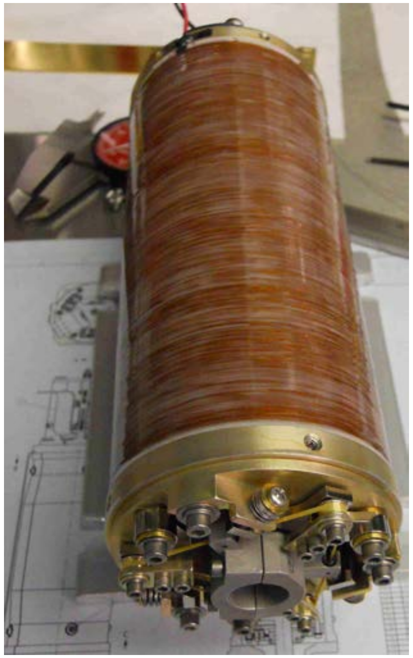
Preliminary flexure design

Testing of Kevlar/epoxy joints

4 K Magnets

Cryogenics and Fluids Branch

- Our group has had great success fabricating NbTi magnets in-house
- New CNC winding system will improve the winding process
- We are beginning fabrication of four magnets for the 4 K to 0.05 K CADR



NbTi magnet wound on our old machine

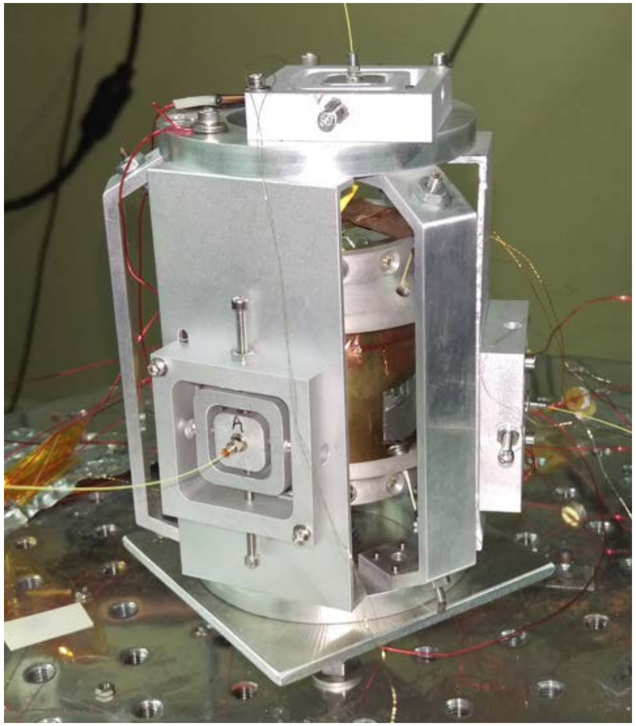
Our new CNC coil winding system

Magnetic Shielding

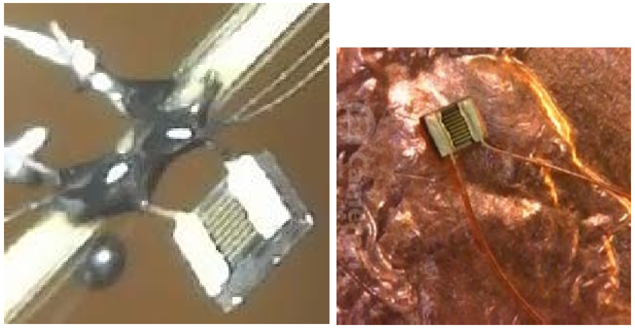
- Each magnet in the system has a ferromagnetic shield
- Overall 10 K ferromagnetic shield will bring nearby stray field < 5 μT
- Analysis shows that overall shield thickness is driven by structural concerns
- Baffled feed-thrus for 50 mK and 4 K straps have yet to be designed
- We will performance test prototype shield
  - Small coil on inside to produce field fluctuations
  - Flux-gate magnetometer on outside (20 nT resolution)

Vibration-Heating in Kevlar

- Lab CADR stages showed occasional 10+ μW heat loads correlated with excessive cryocooler vibrations
- Our theory: heating is due to stretching/rubbing in Kevlar suspension legs
- We developed a test rig to produce measureable vibrations in a 6 K simulated suspended CADR stage
- Simultaneously measure heat load into suspended mass and temperature at midpoint of one Kevlar leg
- Results consistent with uniform heating along Kevlar legs
- Tuttle presentation at CEC will describe this work in detail



Test rig on cryostat cold plate



LakeShore Cernox chip sensor

Conclusion

- We are assembling a designed-for-flight 2-stage 10K to 4 K CADR
  - Testing to begin soon

- Steps to follow:
  - Assemble a flight-worthy 4 to 0.05 K CADR
  - Integrate 10 to 4 K CADR with 4 to 0.05 K CADR
  - Performance test full 10 to 0.05 K CADR
  - Vibrate CADR to flight levels
  - Post-vibe performance test

- This work is very valuable for Goddard's ADR program
  - Developing a product to meet the known needs of future missions
  - Expanding the flight ADR expertise of the Cryogenics group