TFAWS Cryothermal Paper Session

Development of a 50 mK – 10 K flight-worthy vibration-free Continuous Adiabatic Demagnetization Refrigerator

NASA (Goddard Space Flight Center)

Presented By

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Thermal & Fluids Analysis Workshop
TFAWS 2018
August 20-24, 2018
NASA Johnson Space Center
Houston, TX

Introduction

Our team[*] proposed the development of a flight-worthy vibration-free Continuous Adiabatic Demagnetization Refrigerator (CADR) in 2016 that lifts heat at 50 mK and rejects its heat to a platform at 10 K.

The proposal was awarded by NASA-HQ and work began in January of 2017 (to be completed by 2020).

The work entails development of two CADRs that are modular:

- A Low temperature CADR (50 mK to ~4 K)
- A high temperature CADR (~4 K to 10 K)

The two systems work hand to hand to operate vibration-free and continuously by removing > 6 μW at 50 mK and rejecting its heat to a thermal sink at 10 K with an intermediate platform held constantly at 4 K.

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Necessity

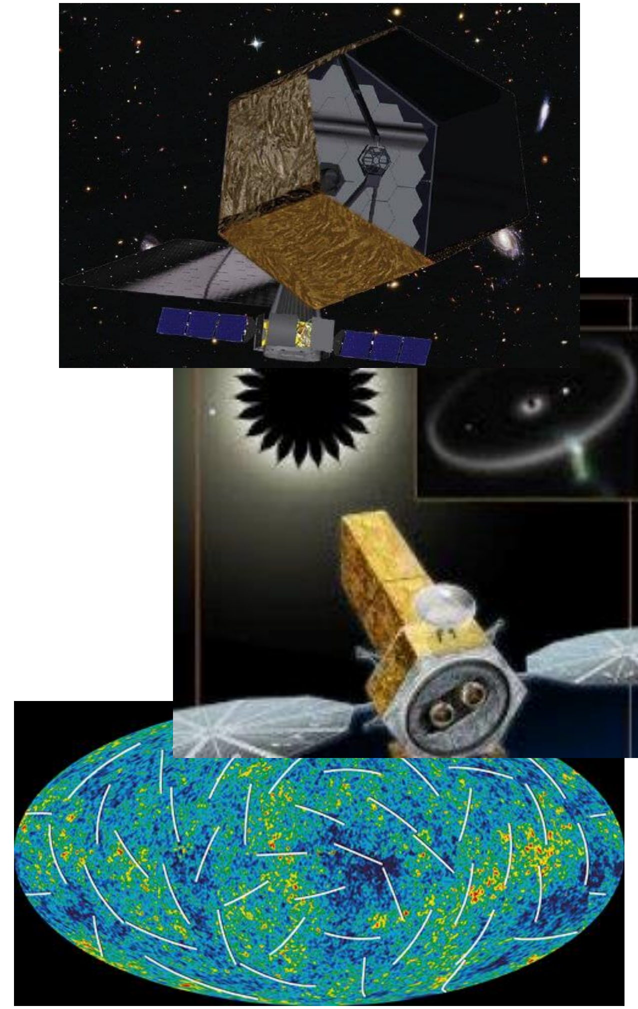
Origins Space Telescope (OST) and Lynx (X-ray) presently under consideration in the 2020 decadal survey process, require cooling of large focal plane arrays to sub-Kelvin temperatures. → TES and MKIDs. Other components also require a low temperature background (T < 1-2 K optics).

Sub-Kelvin, energy resolving detectors would enhance the two other flagship missions, HabEx and Large UV Optical and near InfraRed (LUVOIR). Inflation Probe, Explorer, as well as international CMB polarization and absolute spectrum experiments also require cooling of very low temperature detectors.

High cooling power, high efficiency, high duty cycle sub-Kelvin coolers are required for the next generation of sensitive instruments. Both Cosmic Origins and Physics of the Cosmos Program Annual Technology Reports listed sub-Kelvin cooling as technology gaps.

Current sub-Kelvin technologies are inadequate to meet the requirements of future missions, as summarized in requirements table.

This work will raise the TRL of a CADR with high efficiency, 100% duty cycle, and high heat lift at sub-Kelvin temperatures relative to the requirements for future sub-Kelvin coolers listed in requirements table.



Requirements

Performance metrics	Future 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)	2	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	20@4 K-45@6 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

*For this CADR a more modest cooling power at 4 K will be achieved. For future telescope cooling the 10K to 4K stage can potentially expand to reach the 100 mW at 4 K requirement.

Vibration-free CADR

ADRs have no moving parts therefore they contribute zero vibrations.

Mechanical cryocooler vibrations end up being an issue on flight missions.

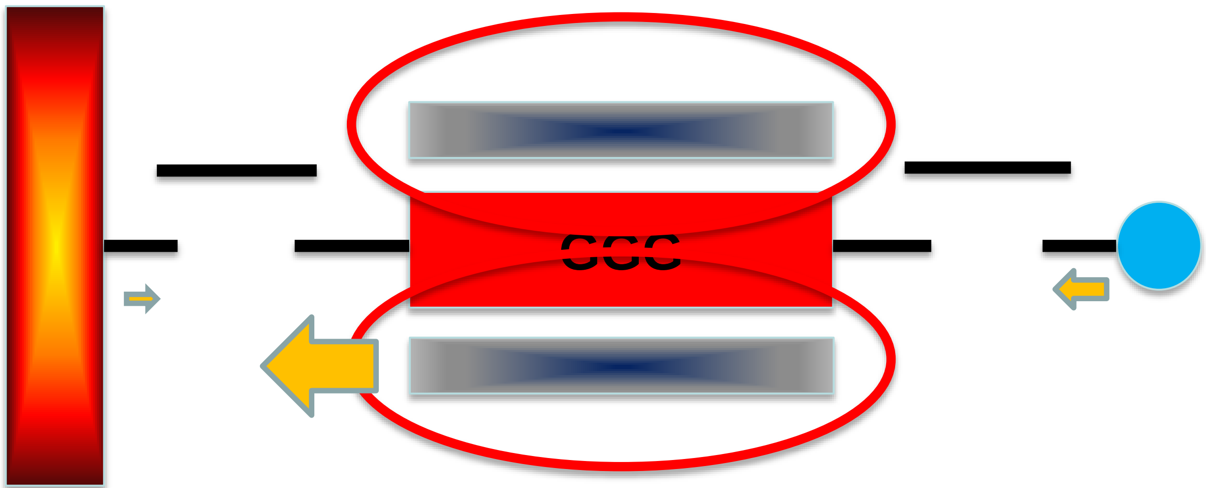
Recently Creare demonstrated sub-10 Kelvin operation of their Turbo-Brayton cooler

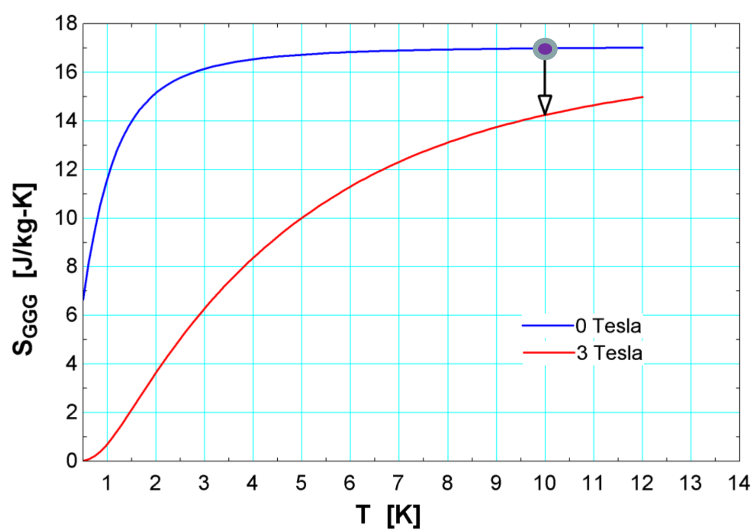
- Very high-frequency vibrations – heavily damped by spacecraft structure

A 10 K Nb_3Sn superconducting flight-compatible magnet was developed during a phase I and II SBIR that was funded between 2002 and 2010

- A proof of concept 4 – 10 K ADR was designed, fabricated and tested that enabled this work.

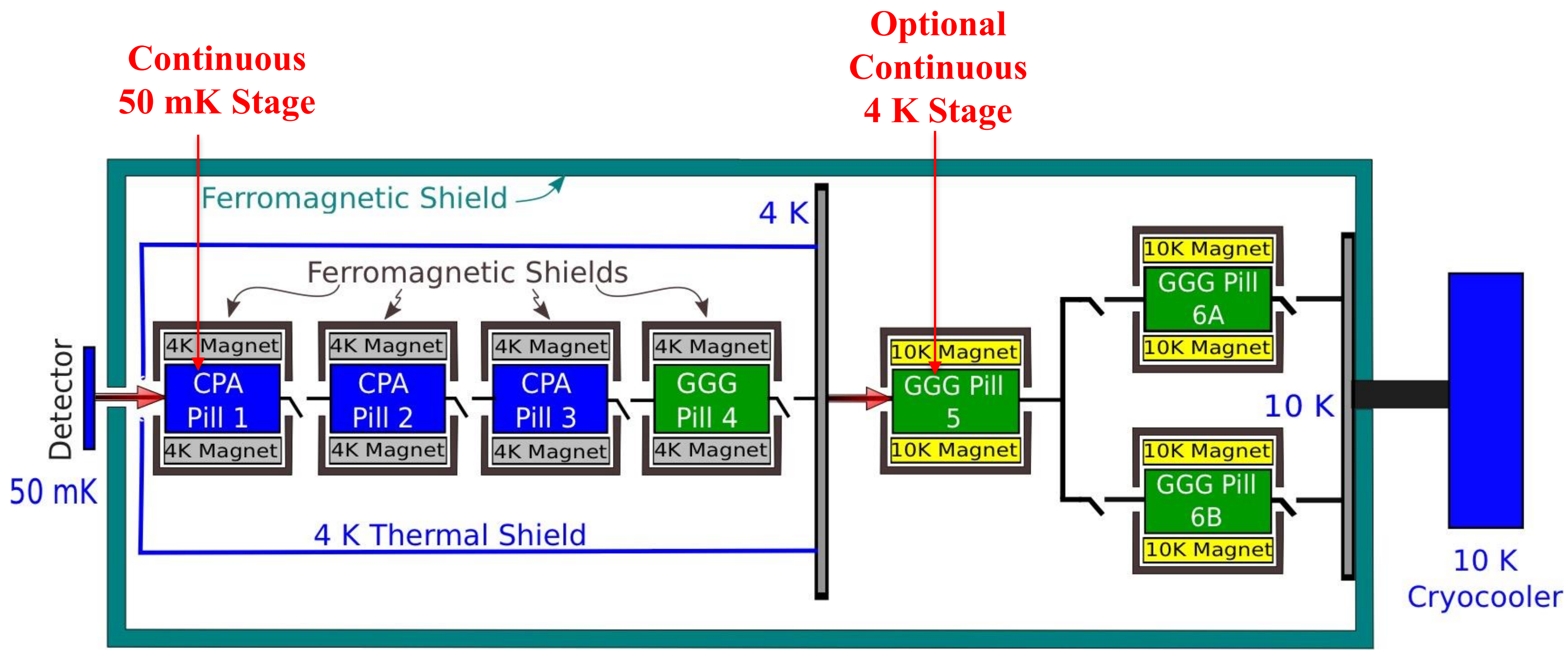
Therefore these two new technologies (The Creare cooler and the GSFC CADR) enable 50 mK to 300 K "vibration-free" cooling with high heat lifts in the future.


GGG


18
16
14
12
10
8
6
4
2
0
1 2 3 4 5 6 7 8 9 10 11 12 13 14
T [K]
S_{GGG} [J/kg-K]
0 Tesla
3 Tesla

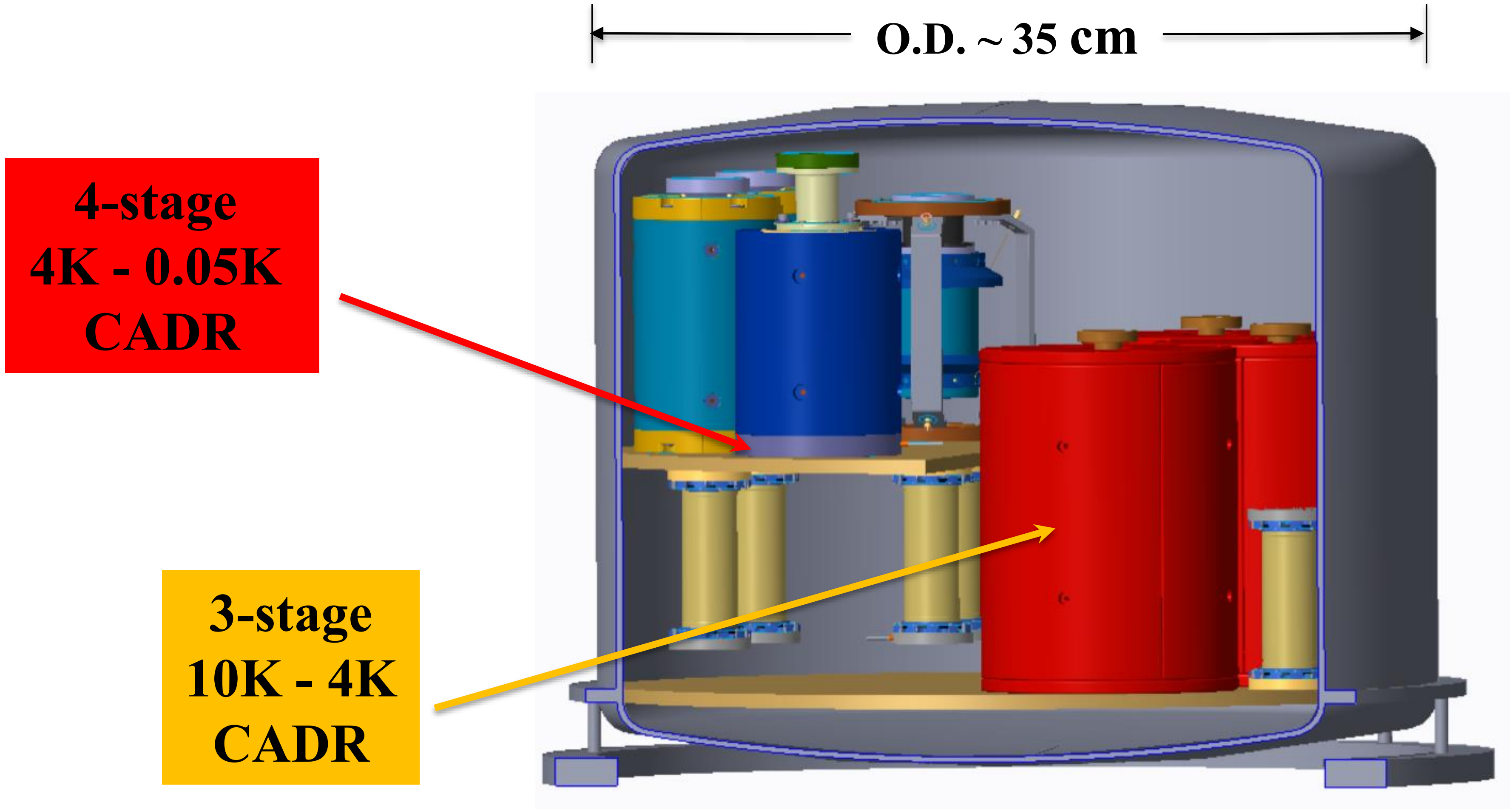
CADR schematic

- Switch between stages 1,2 is superconducting; all others passive gas-gap
- Includes 10 K overall magnetic shield
- Optional stage 5 provides better control, extra cooling at 4 K
- 4 K to 50 mK subsystem will be flight-worthy version of lab CADR



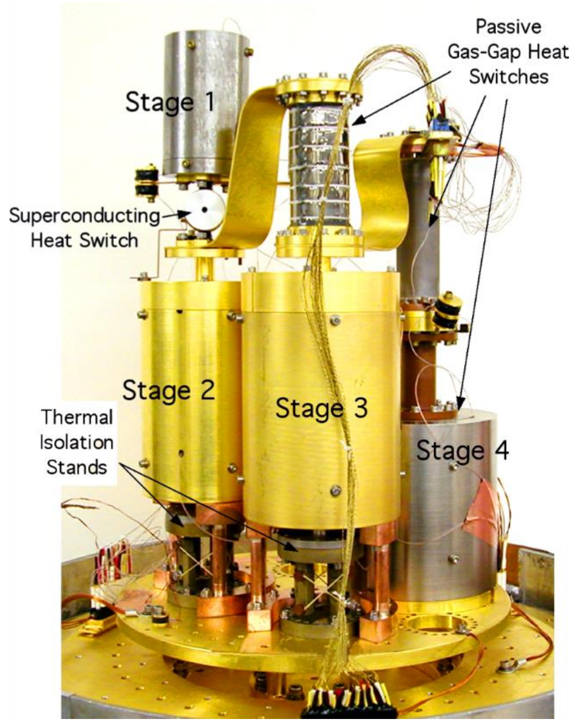
CADR component packaging

(4 K thermal shield and some straps not shown)

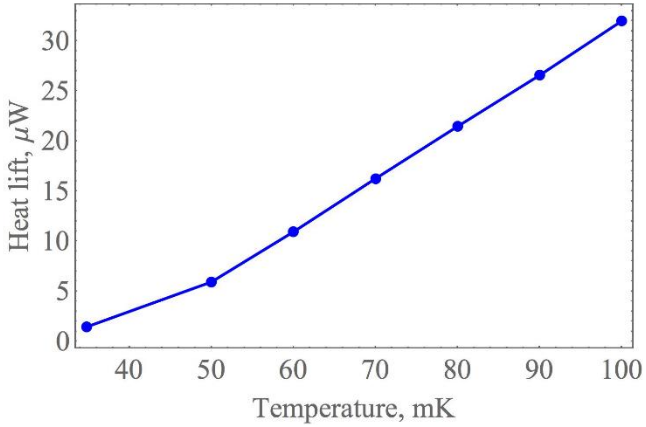


50 mK – 4 K lab CADR

2004 Version



2004 performance test results



2017 Version (~35 cm tall)

4 K – 10 K stage

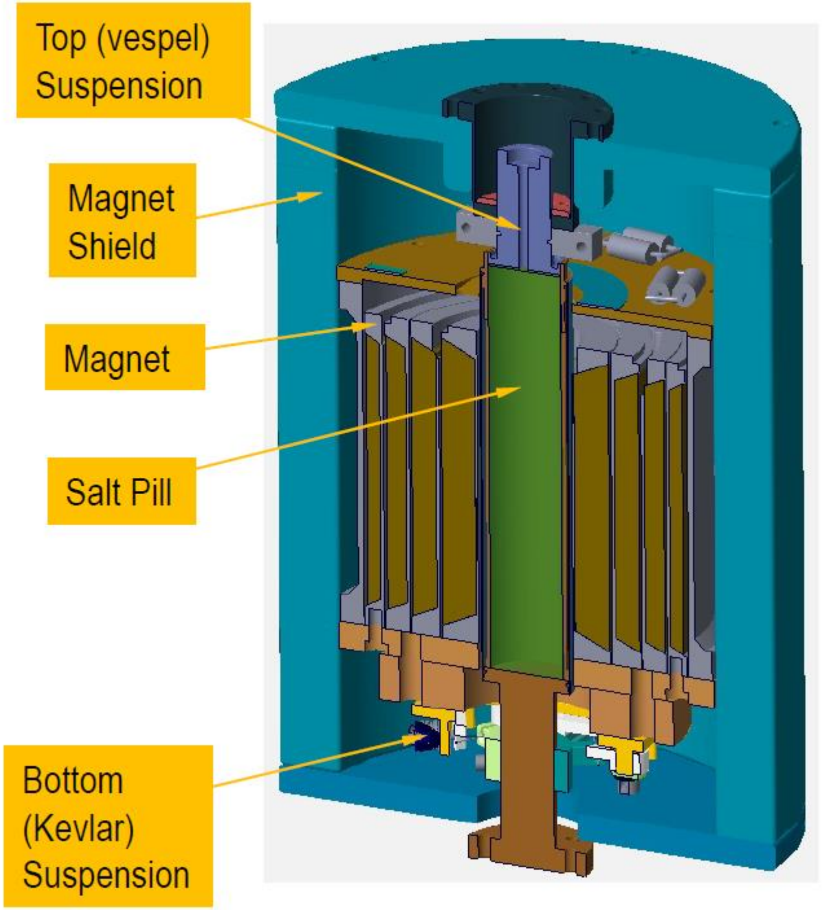
Magnet shield:
- Made out of SiFe Core "A" – lower Si content
- Annealed to enhance saturation condition
- Features to enhance field

Suspension system:
- One end Vespel → provides full constraint
- One end LSD suspension (Kevlar) → provides lateral constraint

Magnet:
- 10 K Nb_3Sn superconducting magnet
- 4 concentric coils
- 4 Tesla maximum field at central bore @ 6.5 Amp

GGG crystal:
- Extends beyond magnet bore → shield design

Heat transfer from crystal to interface via Helium gas in hermetically sealed capsule.



4 K – 10 K stage - magnet

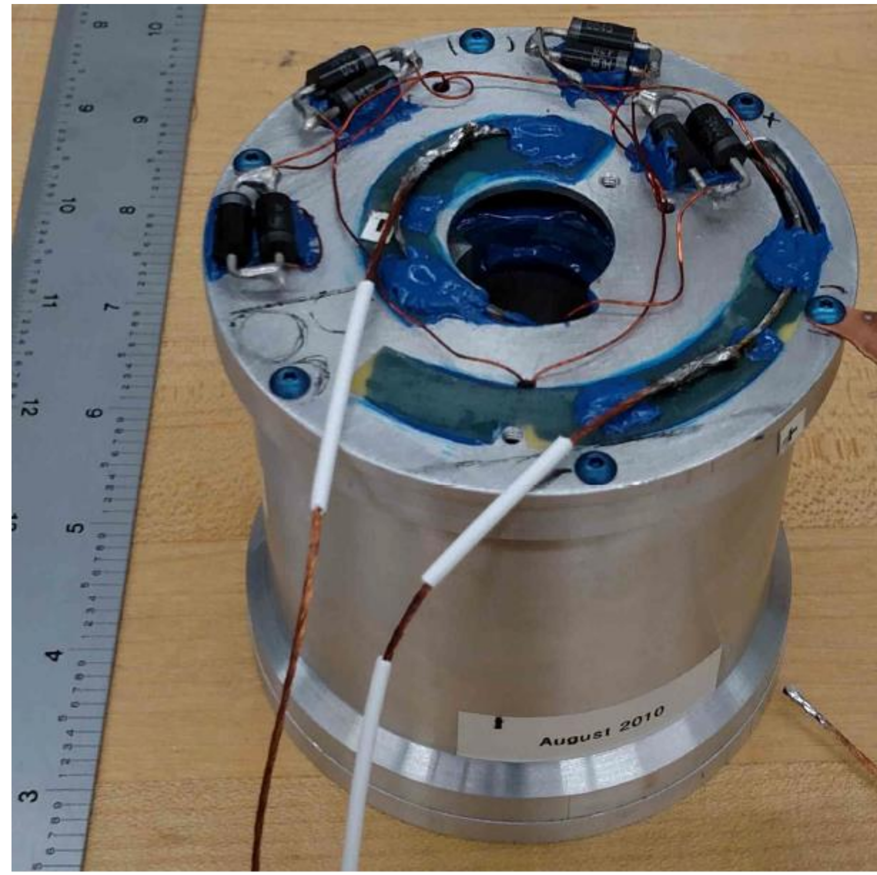
Developed in collaboration between GSFC code 552 and Superconducting Systems Inc. via phase I and II SBIR from 2002 until 2010.

Central field at dead center of bore 4 Tesla at 6.5 Amp operating current

Mass is 1.85 Kg

We measured AC heating for one cycle from zero – 4 Tesla – zero field:

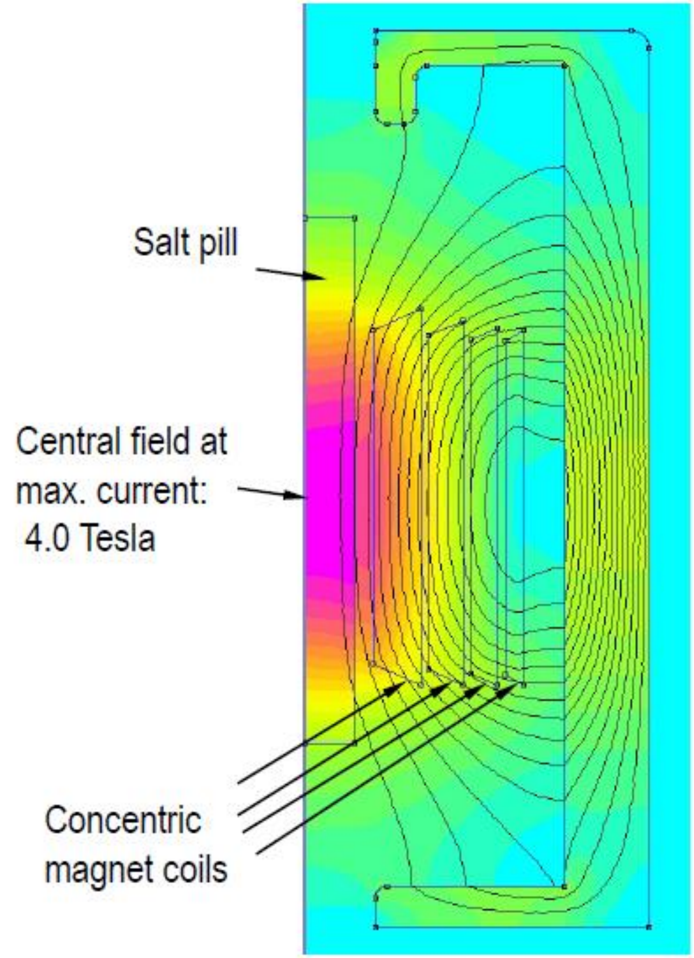
- 0.9 J/cycle
- Nearly independent of ramp rate → hysteresis heat dominates over eddy current heating
- During CADR operation we expect AC heating ~4 mW at 10 K from all 3 magnets



4 K – 10 K stage - shield

Structural model

- No resonance modes below 600 Hz
- No high stress concentrations
- Helicoil inserts will be placed in future magnets to make them flight compatible



Magnet/Thermal model results:

- Shield's shape and wall thickness chosen to keep its internal field below 2.1 Tesla saturation limit
- Shield enhanced central field (or reduces operating current)
- Field as low as 1.5 Tesla produces useful cooling in GGG
- Optimum salt length extends beyond magnet coil ends
- Corners have been rounded to exclude saturation condition

<u>***ALL models include the crystal in field to accurately capture saturation conditions</u>

4 K – 10 K stage – heat switch

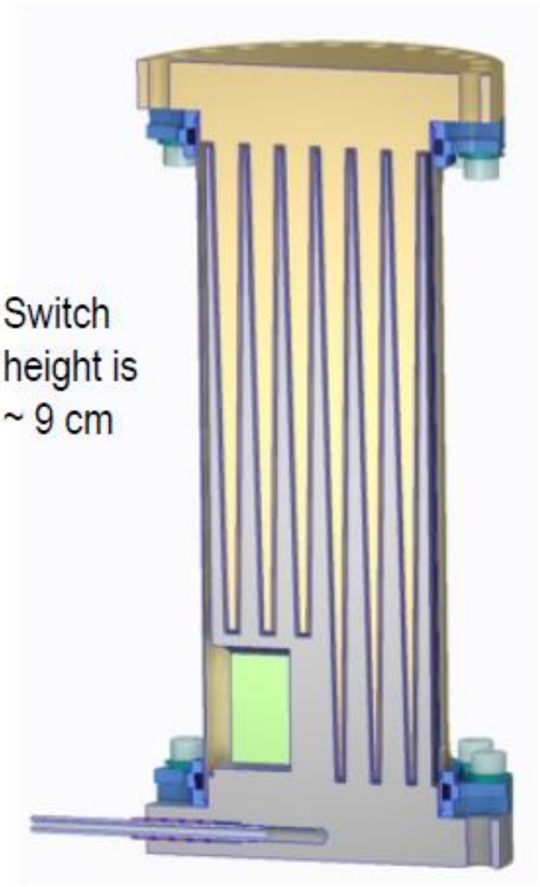
Two copper stages separated by a stainless steel hermetic shell

He gas is sealed inside shell volume

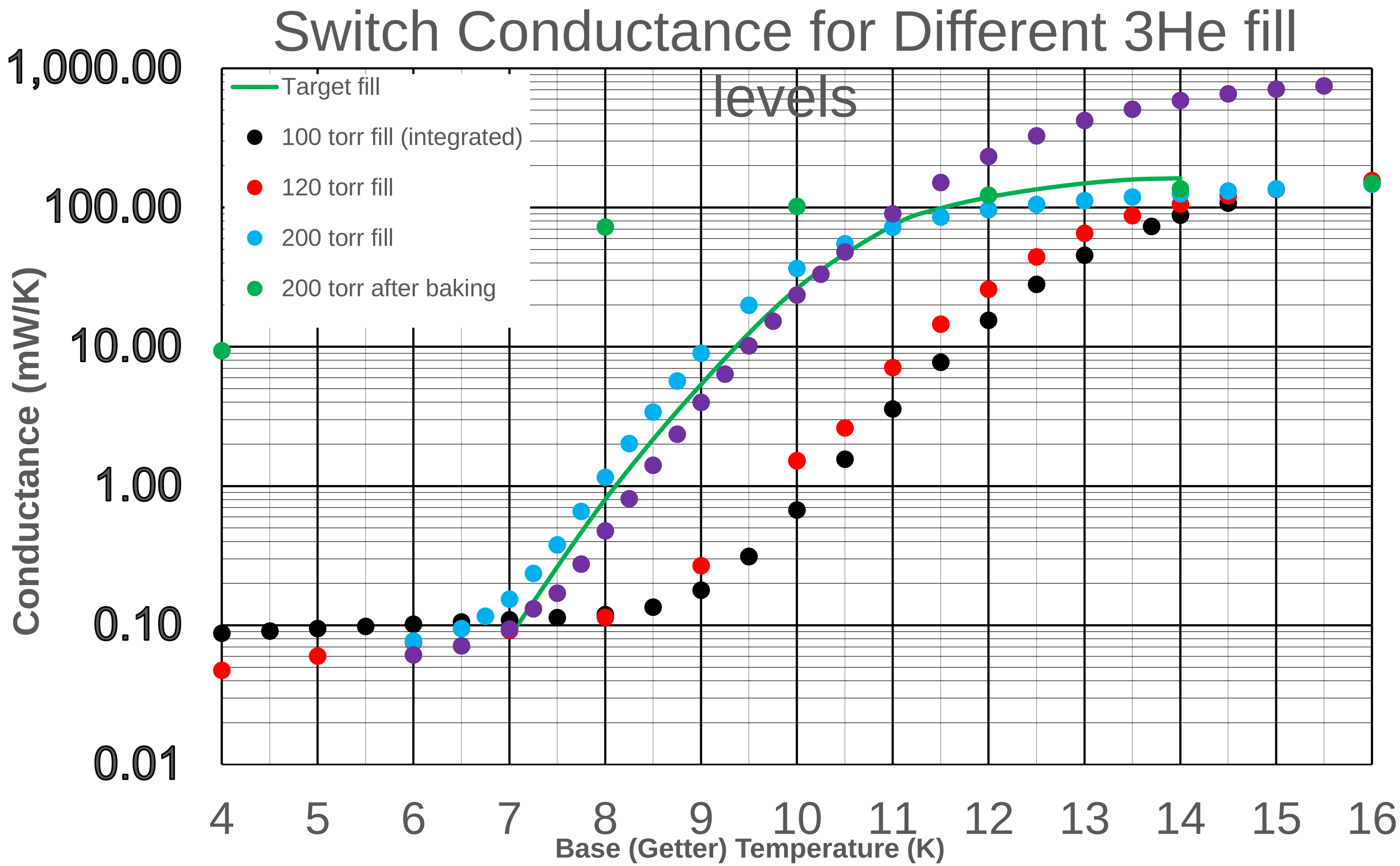
High gas thermal conduction between interleaved fins when switch is closed

Contains a charcoal getter on cold side

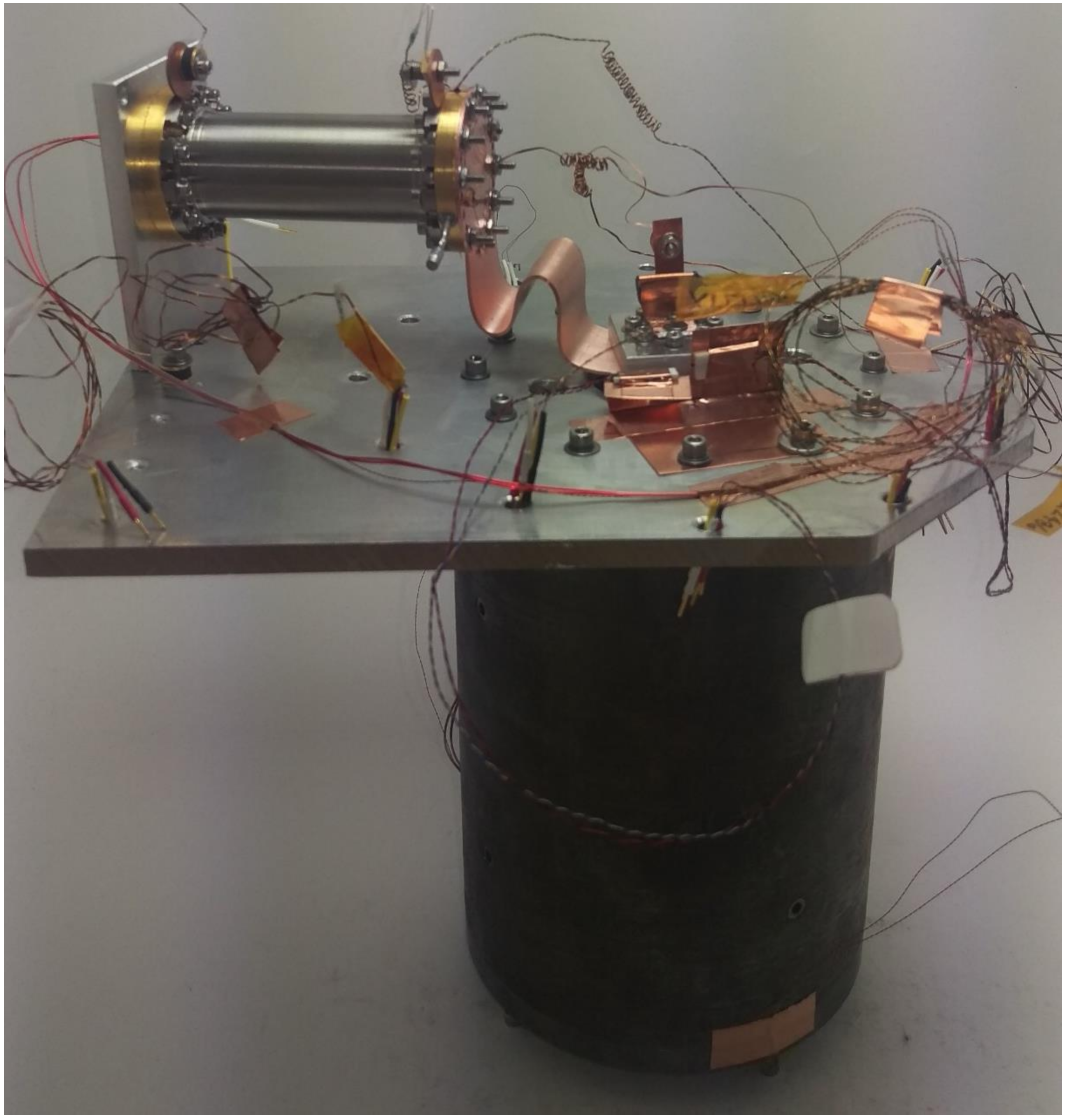
Gas pressure optimized so switch opens at just below 10 K



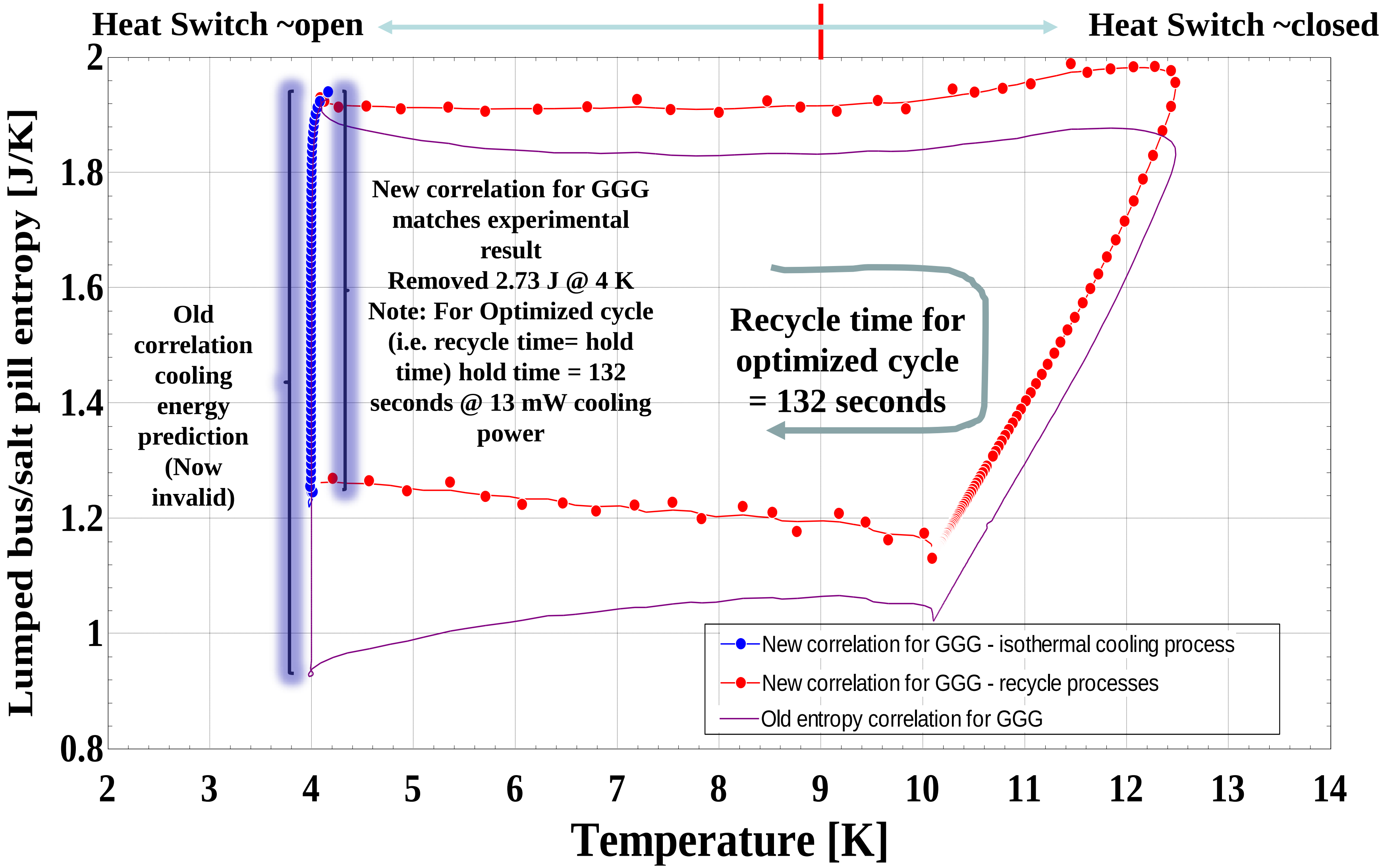
4 K – 10 K stage – PGGHS performance



4 K – 10 K single stage test



4 K – 10 K single stage results



Past work & Plan forward

2017:

Demonstrated a one-stage 10 to 4 K ADR

2018:

Assemble/test a flight-worthy 3-stage (or 2-stage) 10 to 4 K CADR

2019:

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