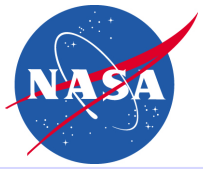
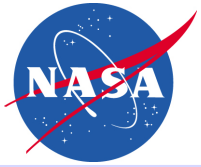


Cryogenics and Fluids Branch

Sub-Kelvin Coolers for Space Missions: ADR Development at NASA/GSFC

Dr. Peter Shirron

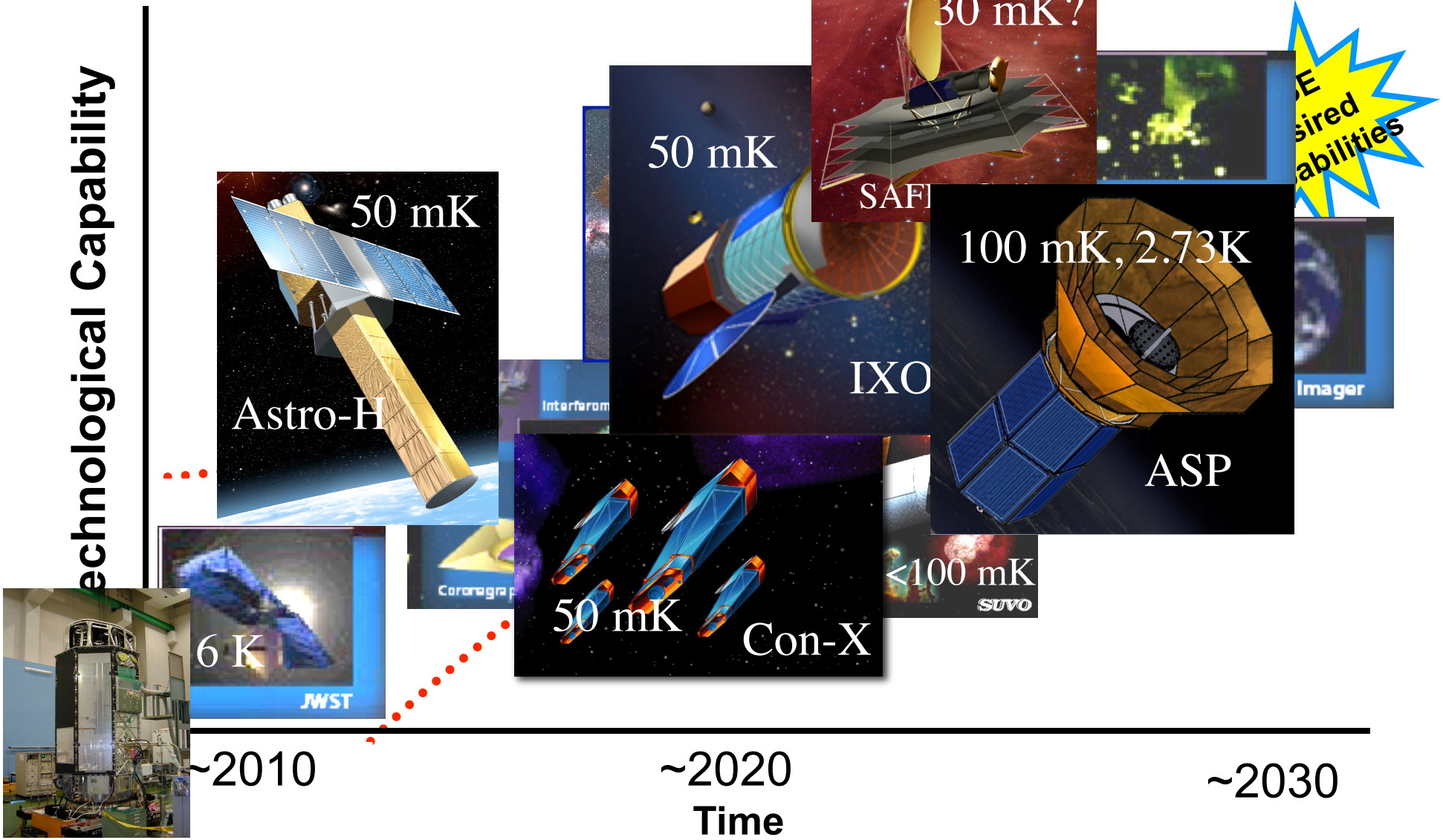
Cryogenics and Fluids Group, Code 552



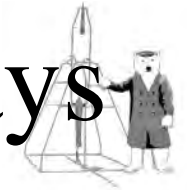
Topics

- Science drivers for low temperature cooling
- ADR architectures and cooling capabilities
  - Single-stage ADR
  - Two-stage ADR
  - Astro-H 3-stage
  - Continuous ADR: 5-stage

Science Mission Vision



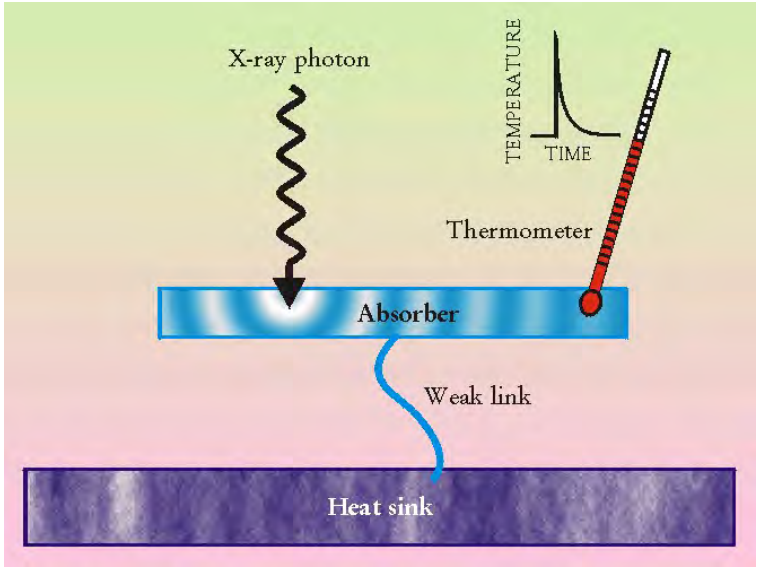
Microcalorimeter Arrays



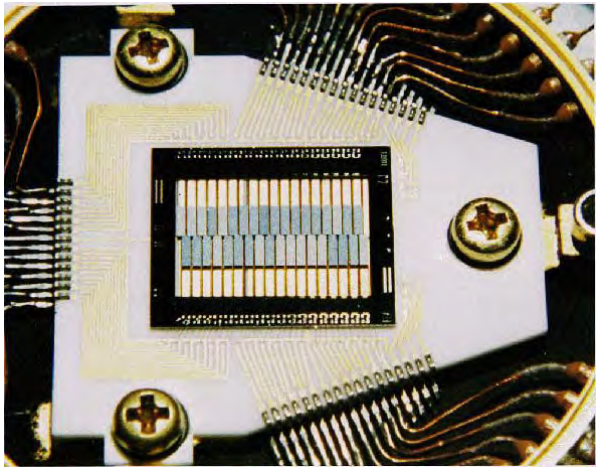
Cryogenics and Fluids Branch

X-ray microcalorimeter: Thermal detection of individual x-ray photons.

- High Spectral Resolution
- High Intrinsic quantum efficiency
- Non-dispersive - spectral resolution non affected by source angular size

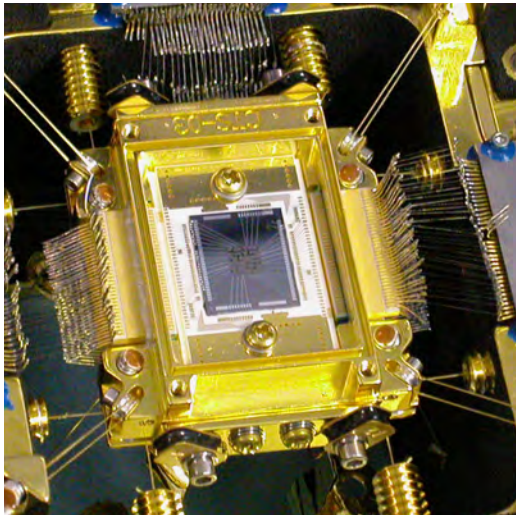


Arrays have been developed for sounding rocket payload and orbiting observatory:

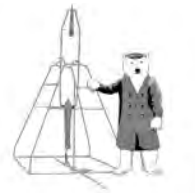


XQC

Astro-E2/XRS



Instrument Trends



Cryogenics and Fluids Branch

XRS2 on Astro-E2

Launched July 2005

SXS on Astro-H

Launch in 2013

Con-X➔IXO➔Athena, AXIO

32-pixel array at 60 mK

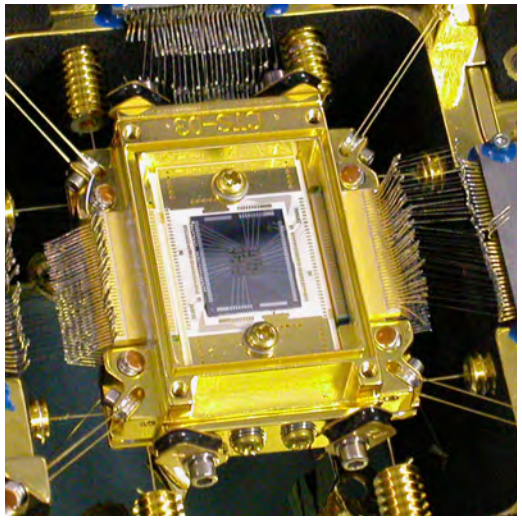
0.3 μW load

32-pixel array at 50 mK

0.3 μW load

~1000-pixel array at 50 mK

2-5 μW load

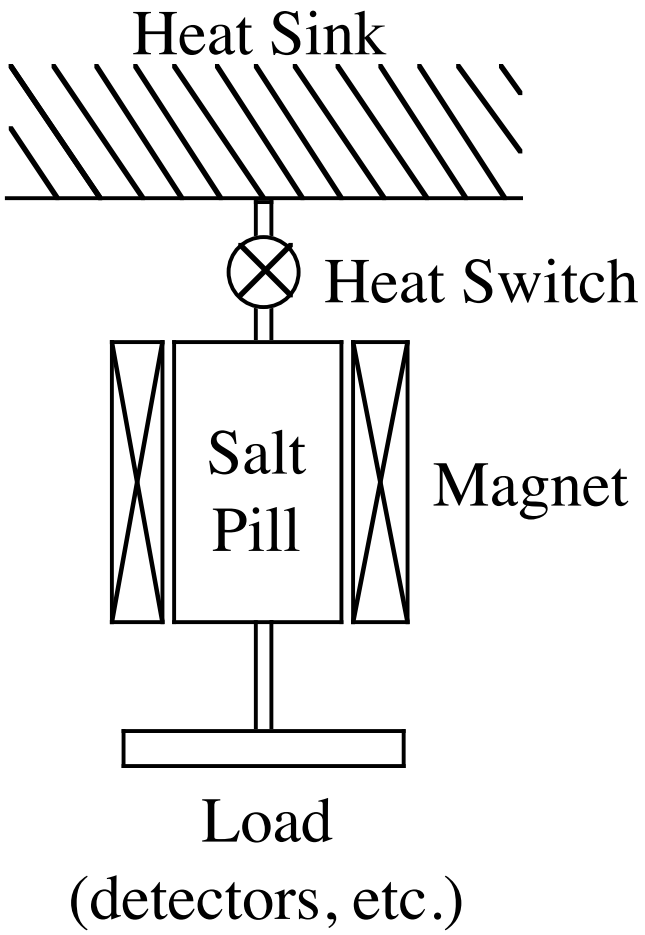


Increasing need for more capable cooling systems

ADR Essentials

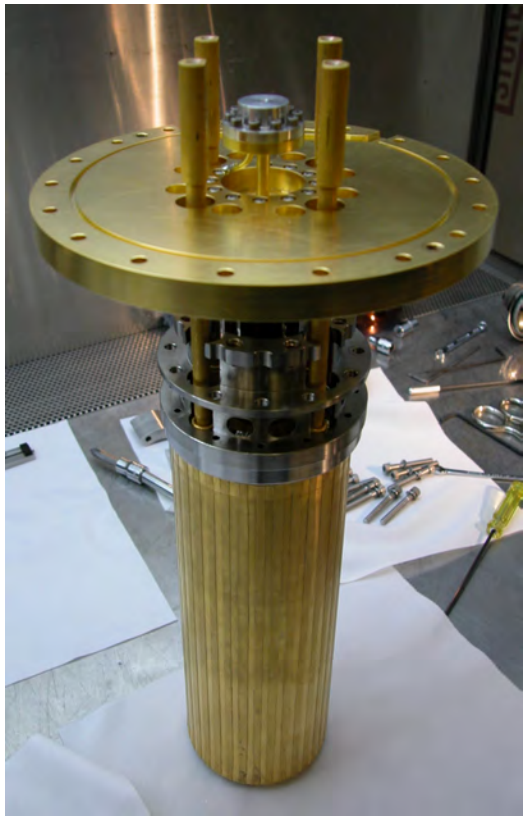
Cryogenics and Fluids Branch

- Solid-state cooler
  - Paramagnetic material
    - "Salt pill"
  - Magnet
  - Heat switch
  - Suspension
- Based on the "magnetocaloric effect"
  - Increasing magnetic field generates heat
  - Decreasing magnetic field generates cooling



Basic (XRS) ADR

Cryogenics and Fluids Branch



Salt pill, heat switch, Suspension, baseplate

Magnet (immersed In liquid helium)

Total mass: 15 kg

Practical Limits

Cryogenics and Fluids Branch

- Single-stage ADR must cool from heat sink to low T
- Typical values
  - Net cooling power: ~0.5 μW
  - Heat sink: 1.3 K
  - Magnetic field: 2 T (2 amps)
  - Refrigerant mass: 1-2 moles

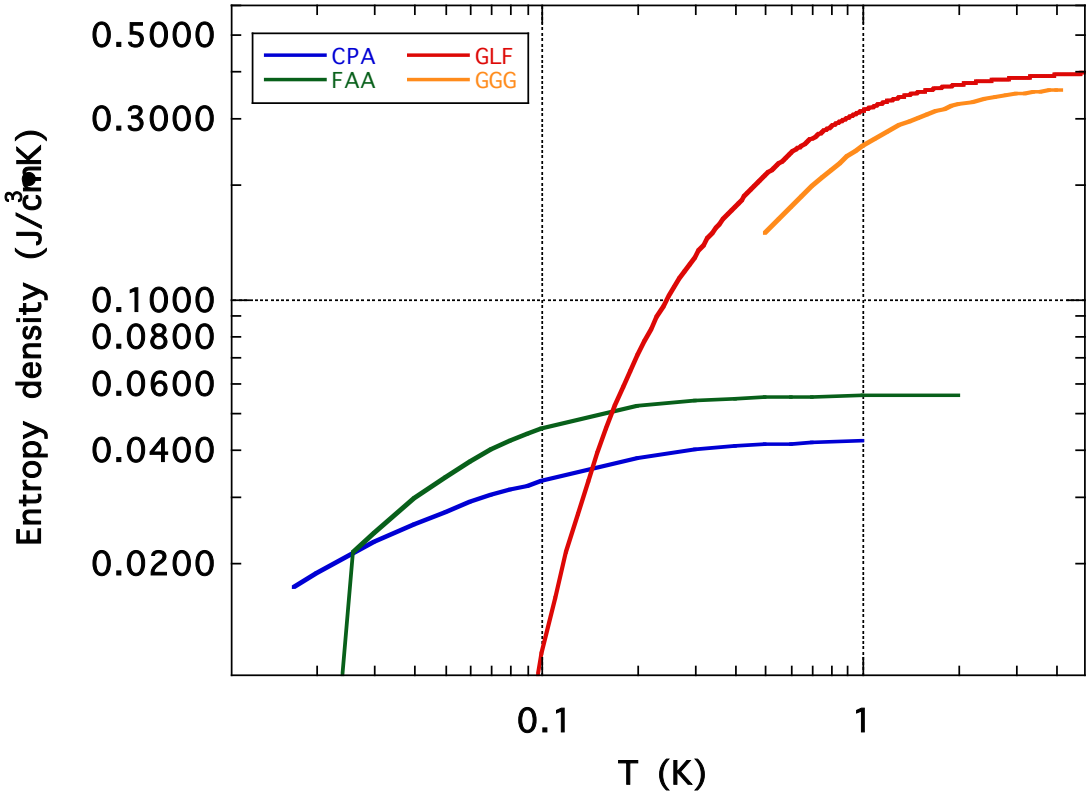
  20:1

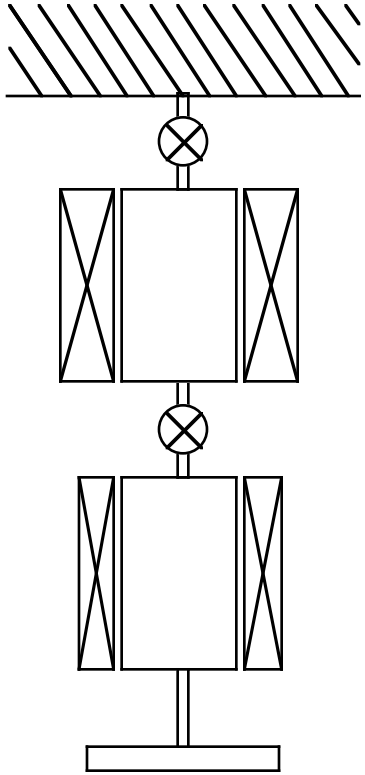
  - Operating T: 50-60 mK
  - Hold time: 24 hours
  - Recycle time: 1 hour
- Trends
  - Higher heat sink T: higher magnetic field
  - Lower operating T: higher magnetic field
  - Higher cooling power/longer hold time: higher magnetic field, more refrigerant, lower parasitics
- Magnet mass grows very rapidly with increased bore volume and increased magnetic field: >>2 T is unpractical
- Bottom line: improved performance ➡ multi-stage ADRs

Two-Stage ADR

Cryogenics and Fluids Branch

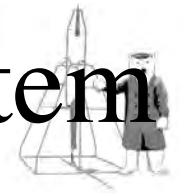
- Series configuration
  - Upper stage pre-cools lower stage and reduces heat load
- Upper stage can cool from much higher temperature and have much higher cooling power



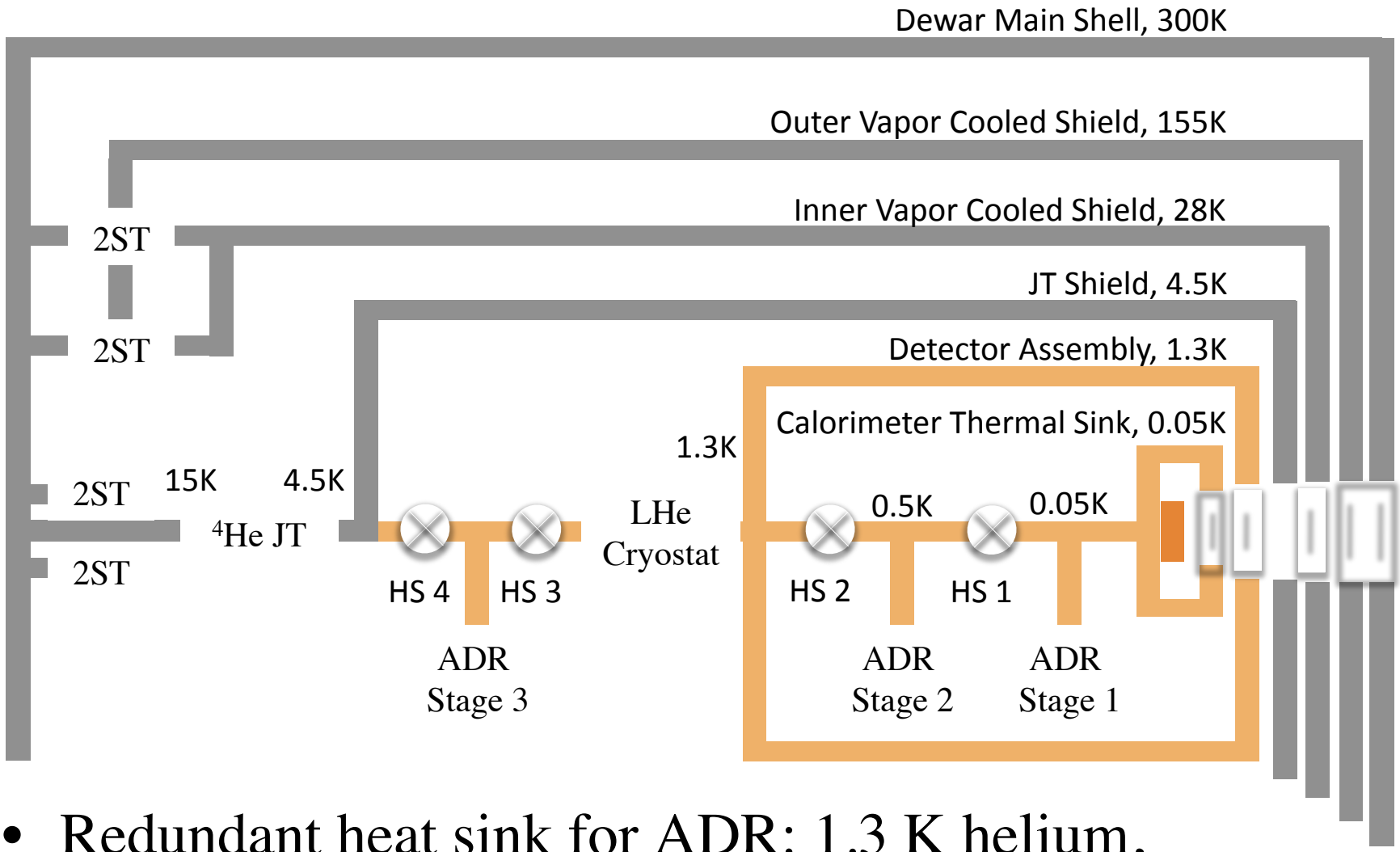


Detector Interface

Astro-H Cryogenic System

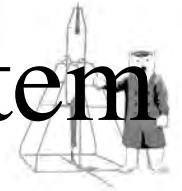


Cryogenics and Fluids Branch



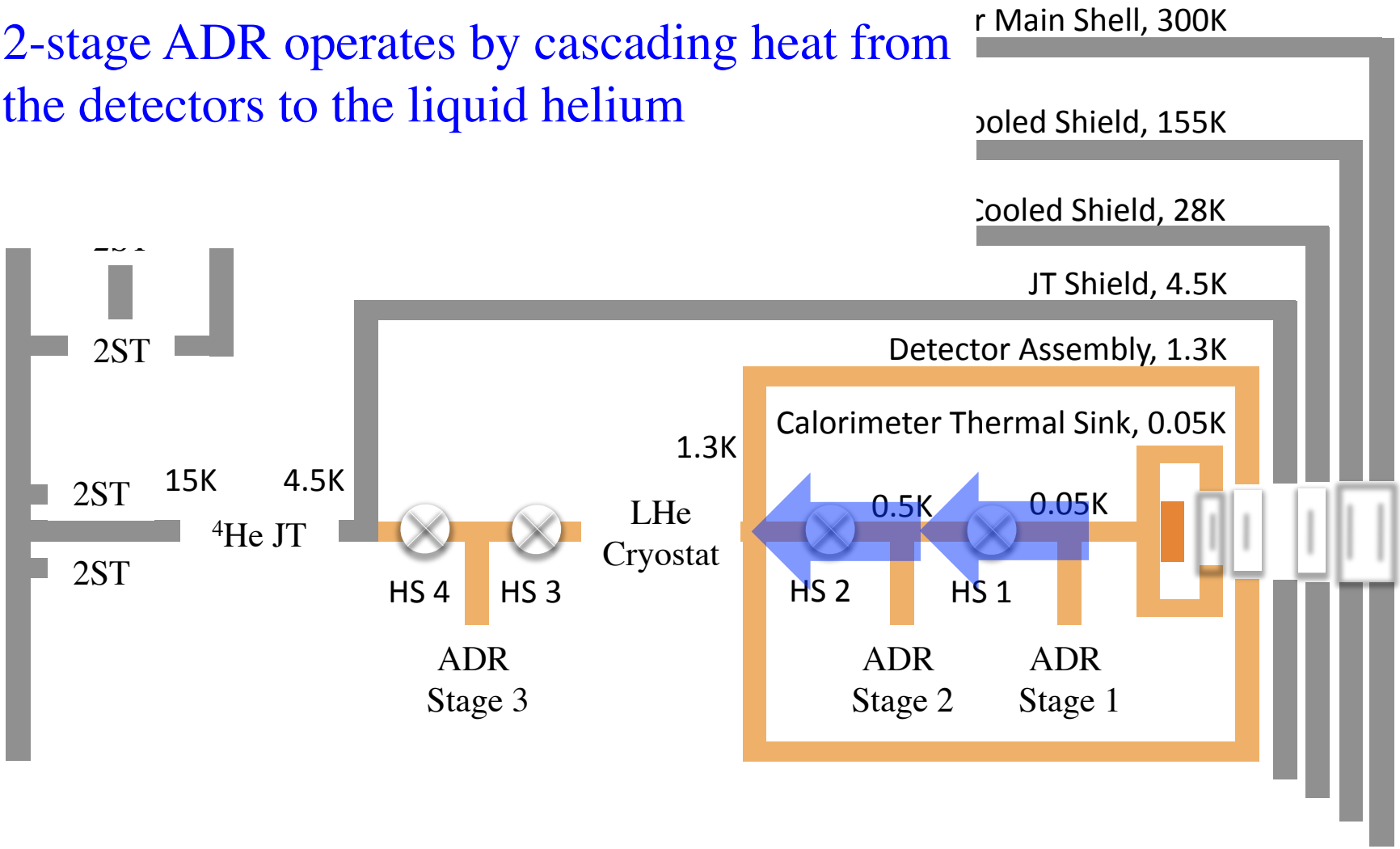
- Redundant heat sink for ADR: 1.3 K helium, 4.5 K cryocooler

Astro-H Cryogenic System



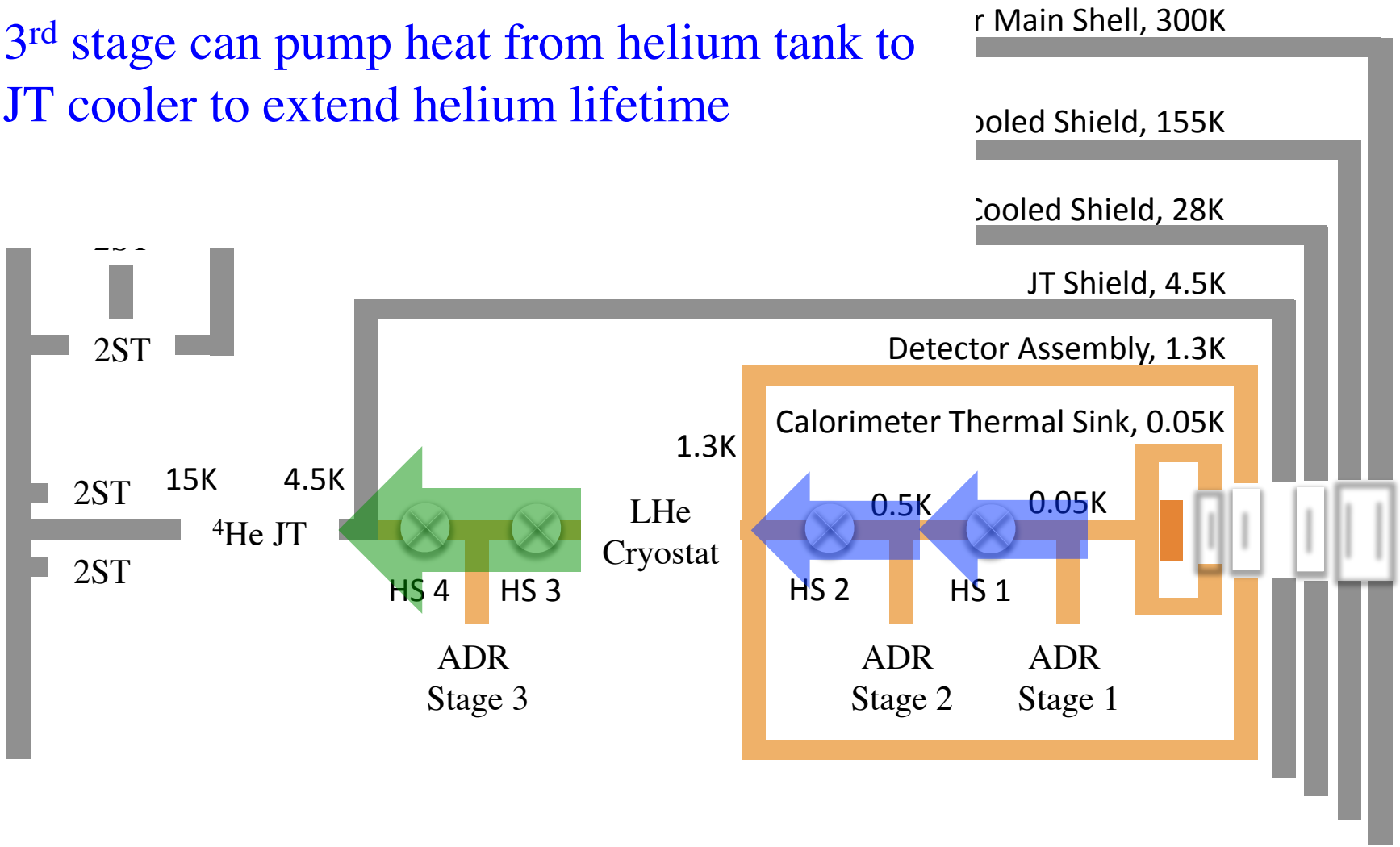
Cryogenics and Fluids Branch

- 2-stage ADR operates by cascading heat from the detectors to the liquid helium

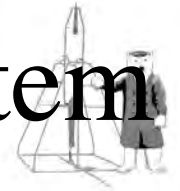


Astro-H Cryogenic System

- 3rd stage can pump heat from helium tank to JT cooler to extend helium lifetime

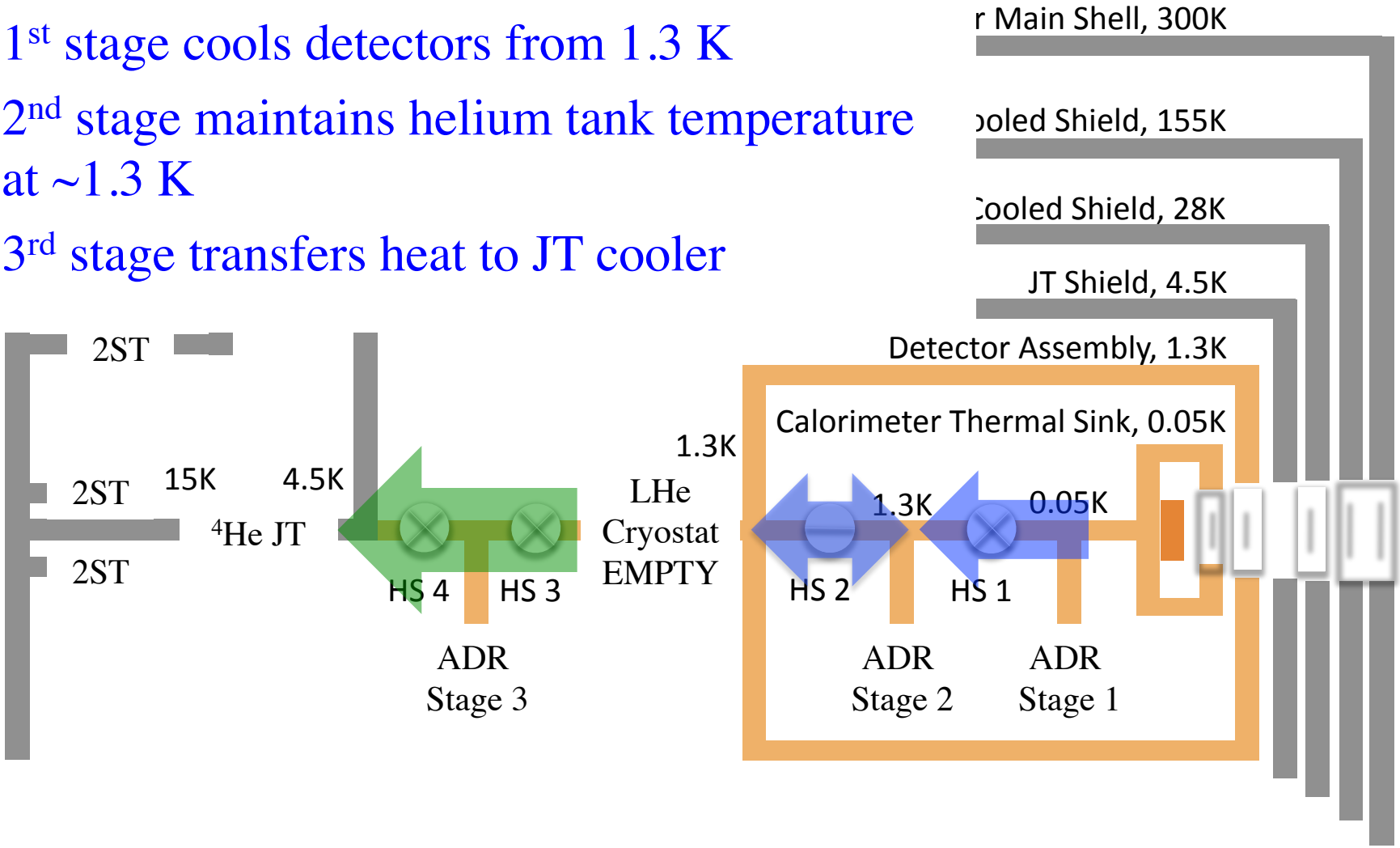


Astro-H Cryogenic System

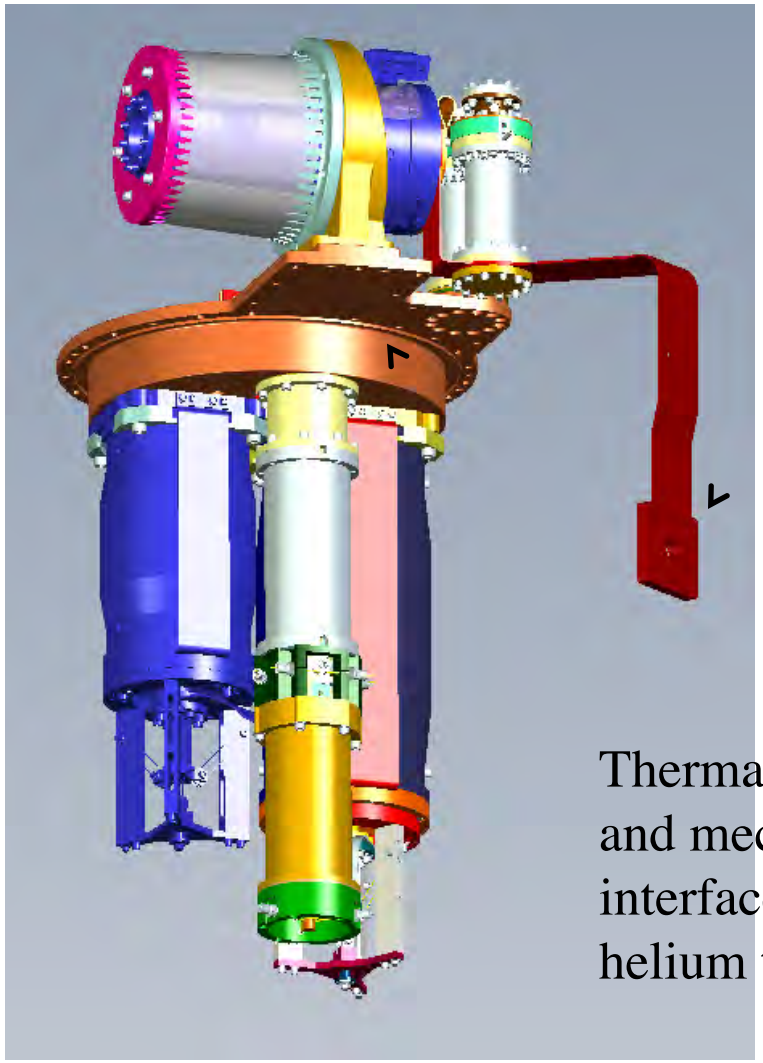


Cryogenics and Fluids Branch

- 1st stage cools detectors from 1.3 K
- 2nd stage maintains helium tank temperature at ~1.3 K
- 3rd stage transfers heat to JT cooler

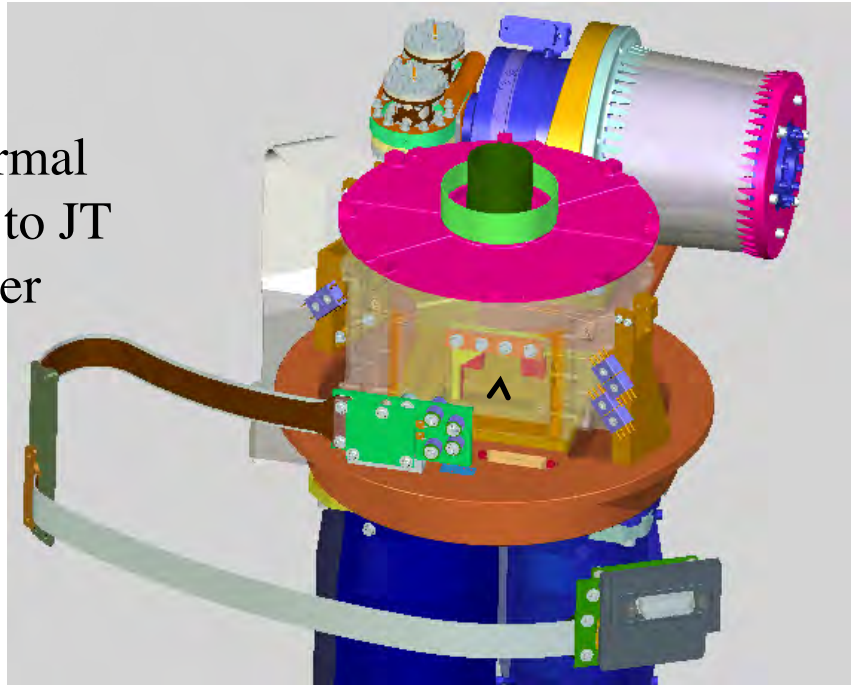


ADR Interfaces - Thermal



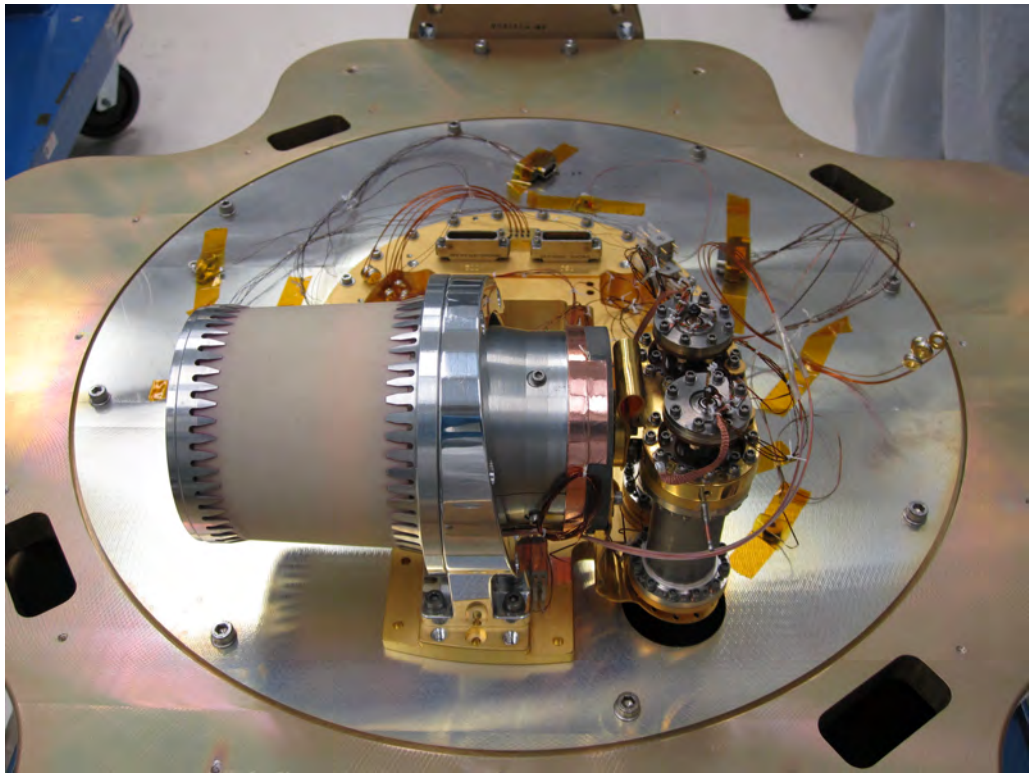
Thermal and mechanical interface to helium tank

Thermal link to JT cooler



Thermal link to detectors

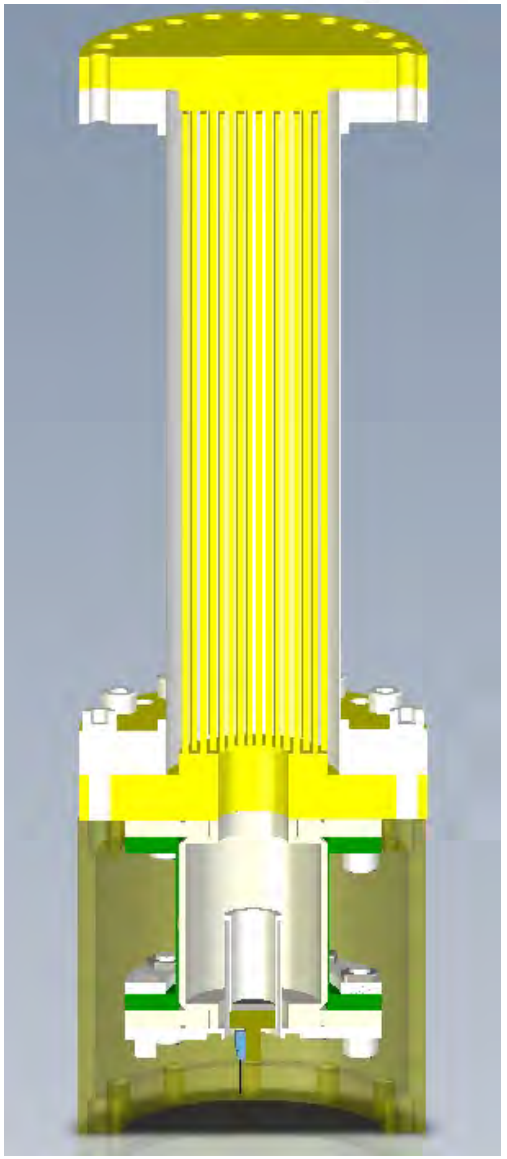
EM ADR



AGGHS Design

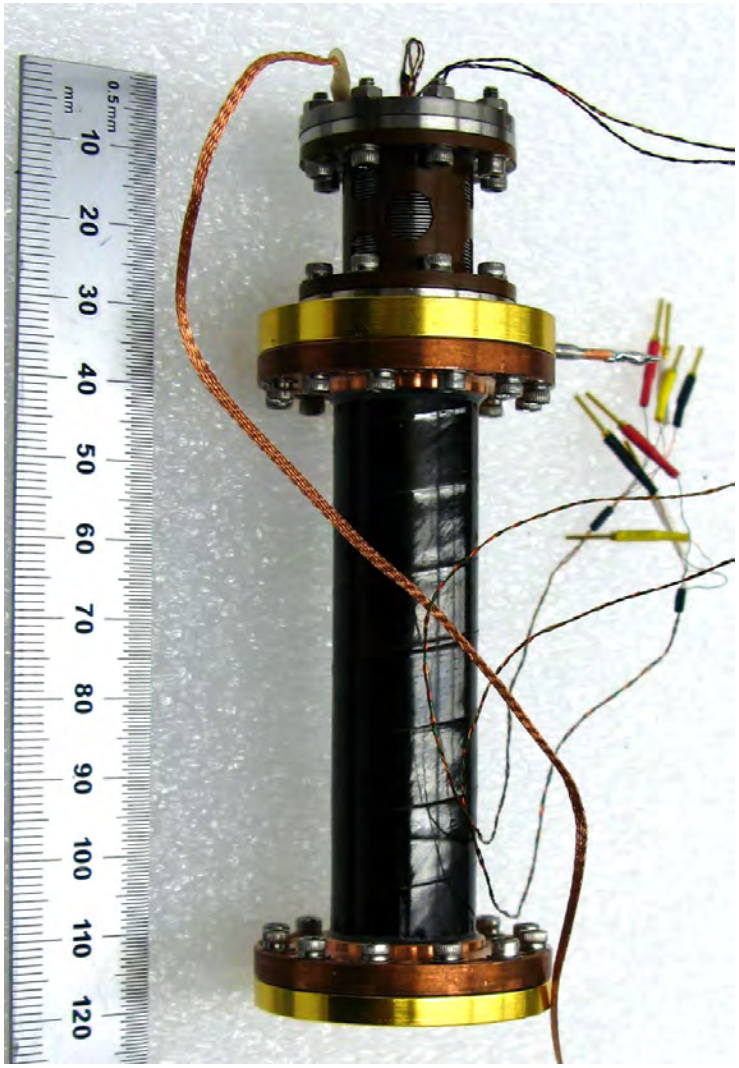
Cryogenics and Fluids Branch

- Design goals
  - <0.25 mW activation power
  - >100 mW/K on-state conductance
  - Off-state conduction
    - 0.1 μW from 0.5 K to 50 mK
    - 1 μW from 1.3 to 0.5 K
- Key features
  - Getter is located in re-entrant tube assembly
  - Bellows/Vespel support has very low conductance from intermediate heat sink
  - Charcoal getter has direct view of HS interior
  - Mass which must be warmed is kept very low

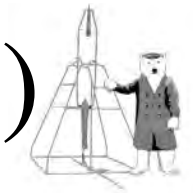


Heat Switches

- Containment shell made from T300 composite (Composites Group) with 0.5 mil Ti15333 foil lineer
  - End flanges epoxied with Scotchweld 2219
- Getter assembly uses indium, e-beam, and braze seals

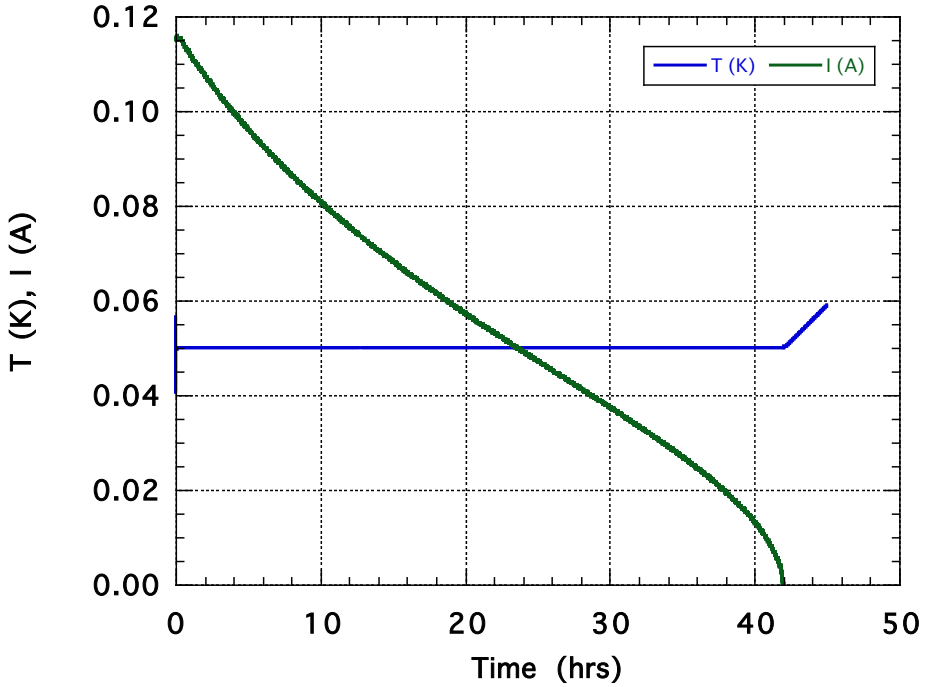


Hold Time (Cryogen)

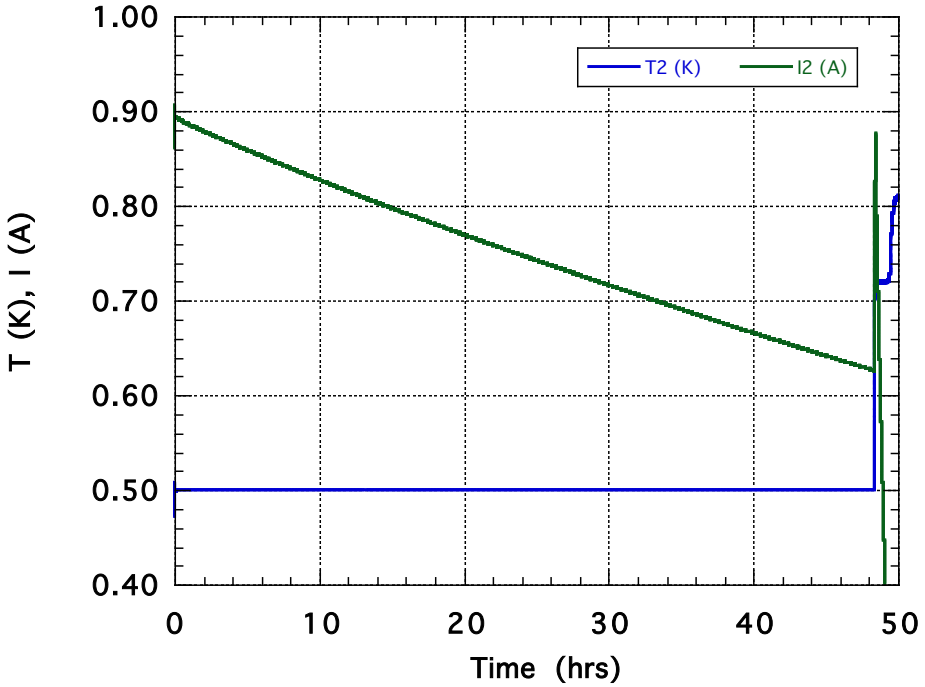


Cryogenics and Fluids Branch

- Detector heat load is 0.27 μW
  - Total heat load is 0.86 μW

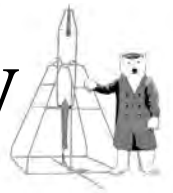


Stage 1

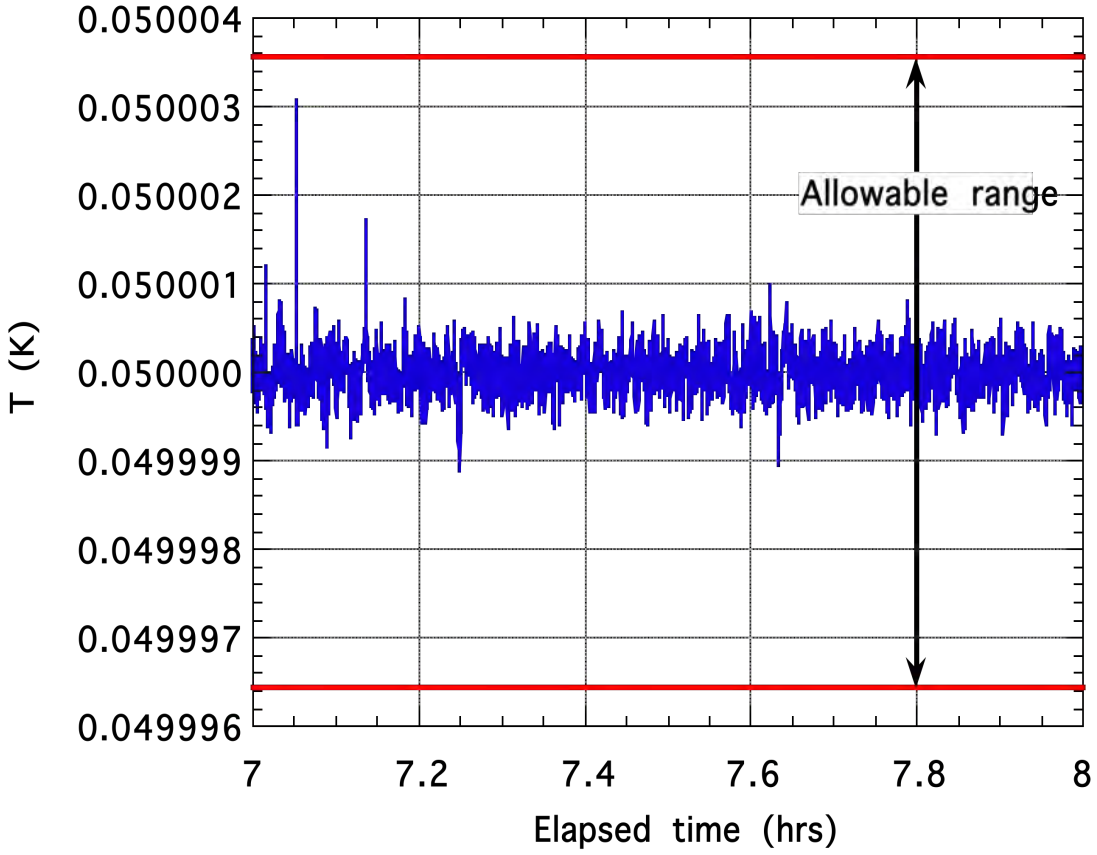


Stage 2

Temperature Stability

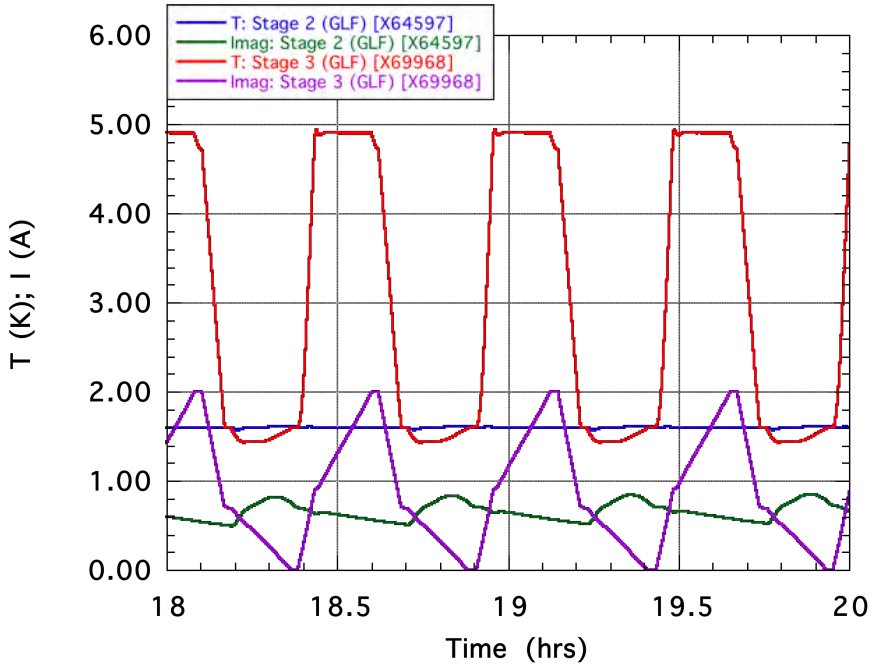


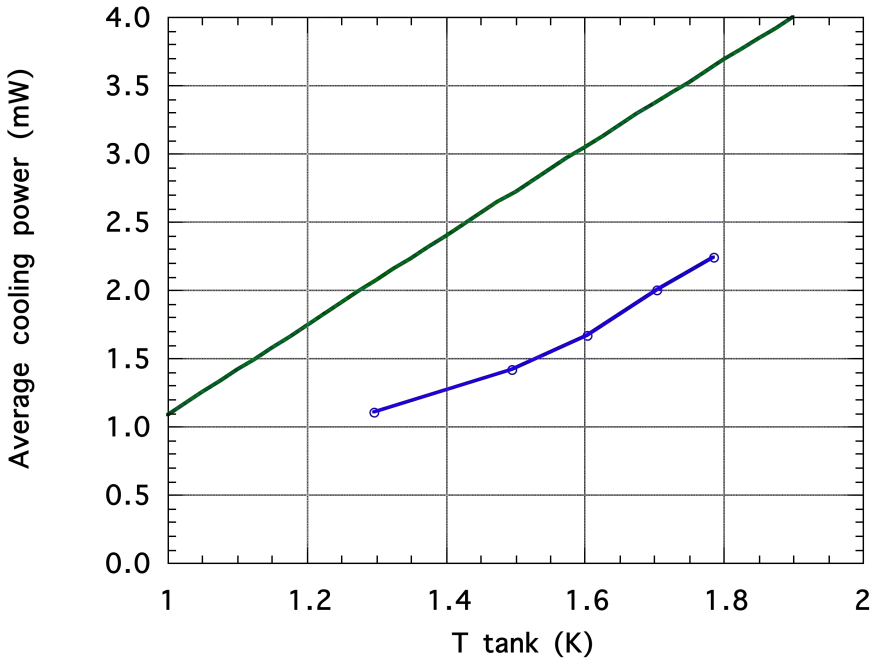
- Temperature stability requirement is 2.5 μK rms
  - Achieving <0.4 μK rms



Cryogen-Free Operation

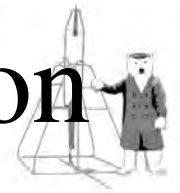
- 3rd stage is continually cycled to transfer heat from helium tank to JT cooler



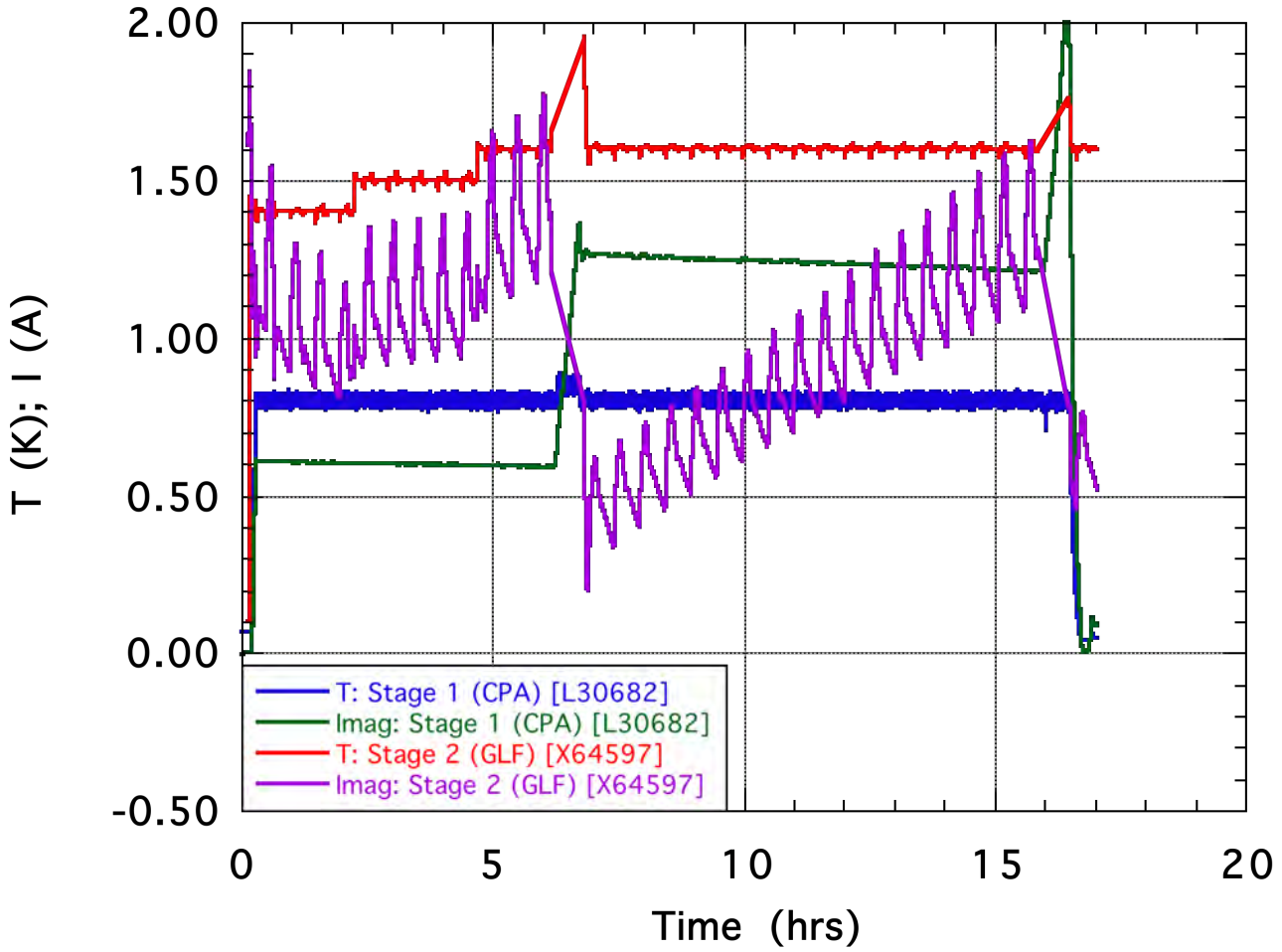


- Cooling power is limited by low thermal conductance of thermal path between stage 2 and helium tank

Cryogen-Free Operation

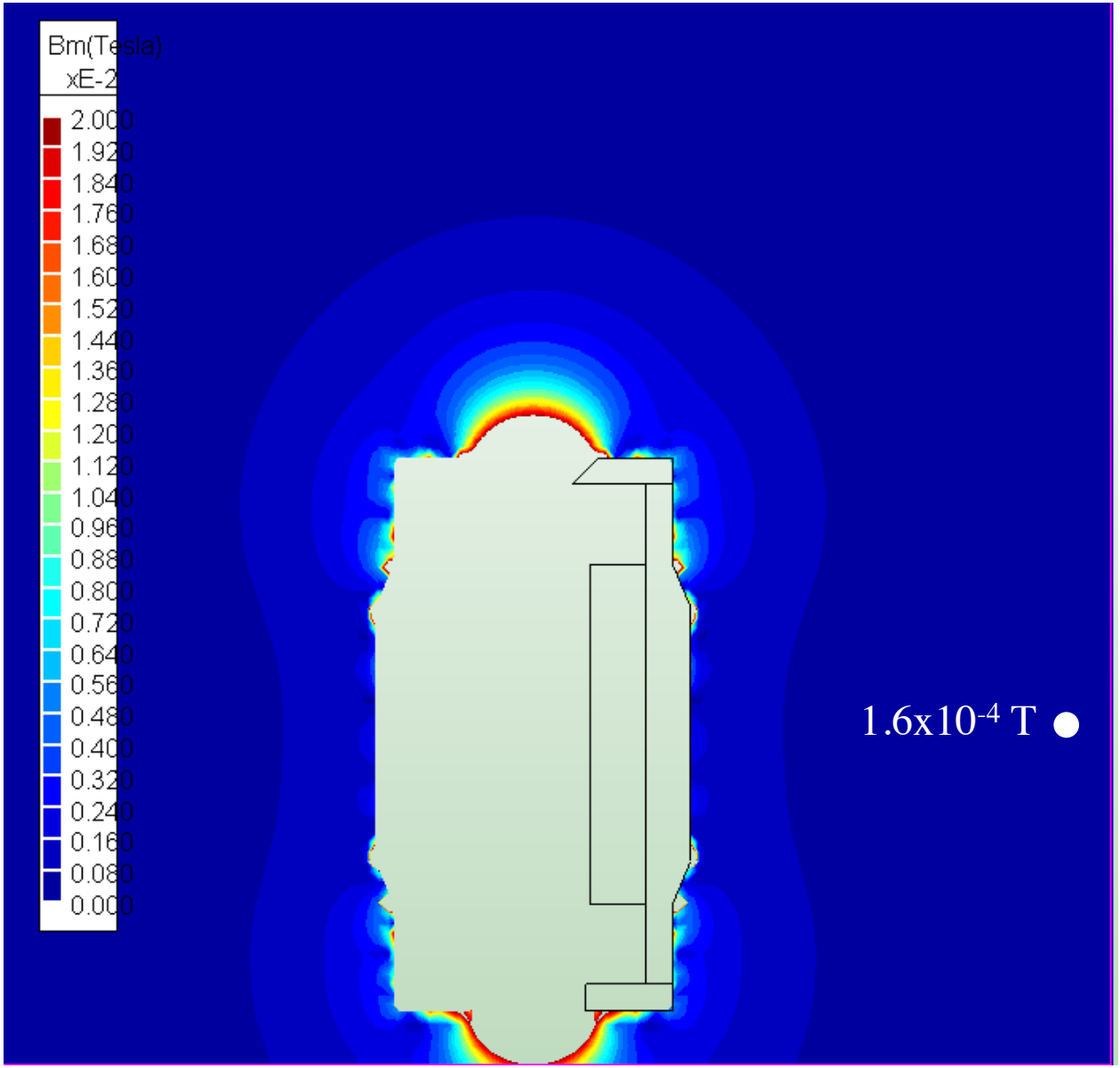


- Stage 2 builds up cooling capacity
- Periodically recycles Stage 1

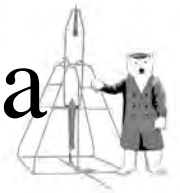


Magnetic Fields

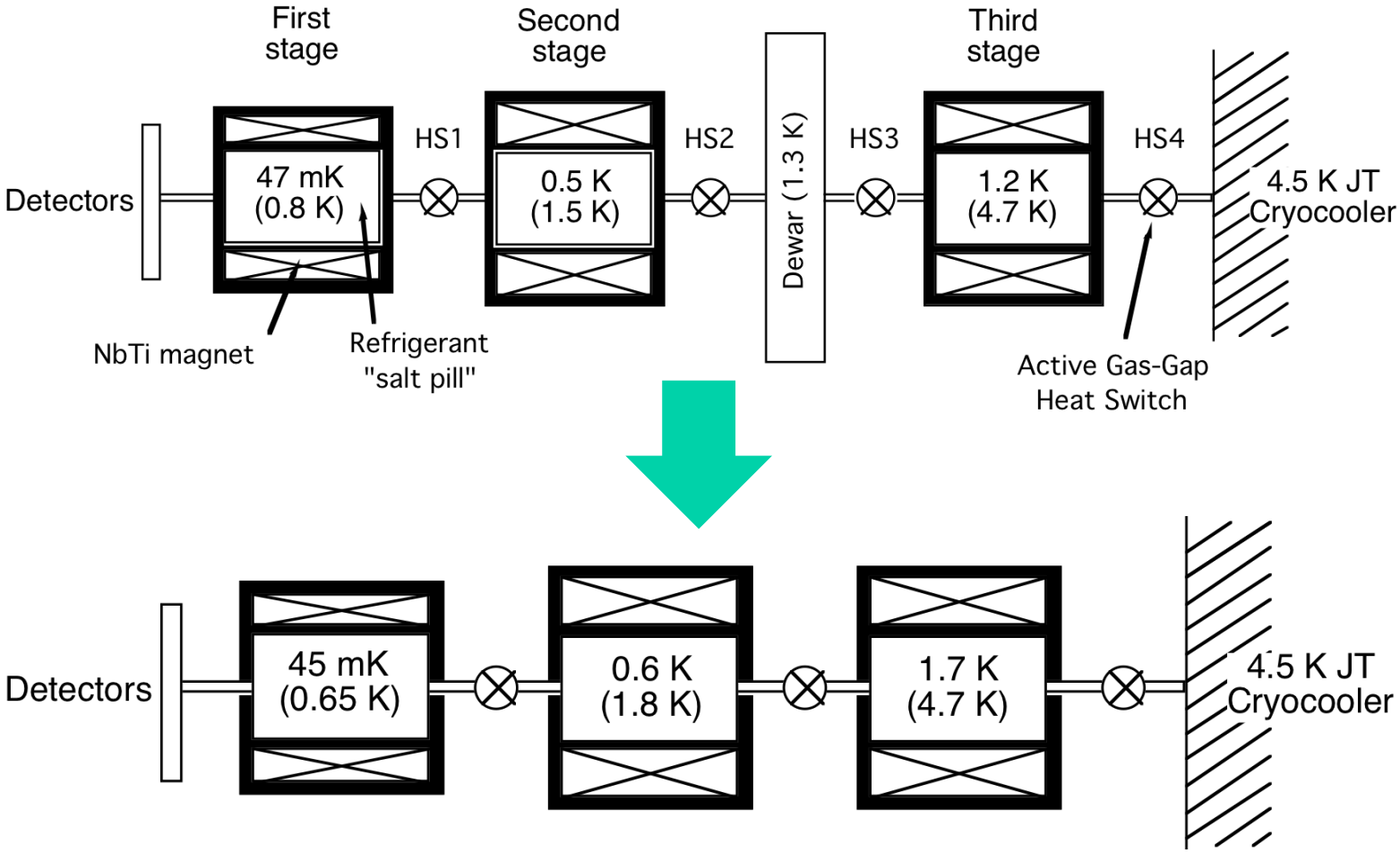
- Optimization of Astro-H shield
  - Redistribute mass to minimize dipole moment
    - Reduced shield mass from 2.5 kg to 2.0 kg
- Fields at detector location ~10^{-4} T



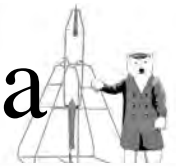
3-Stage ADR for Athena



Cryogenics and Fluids Branch

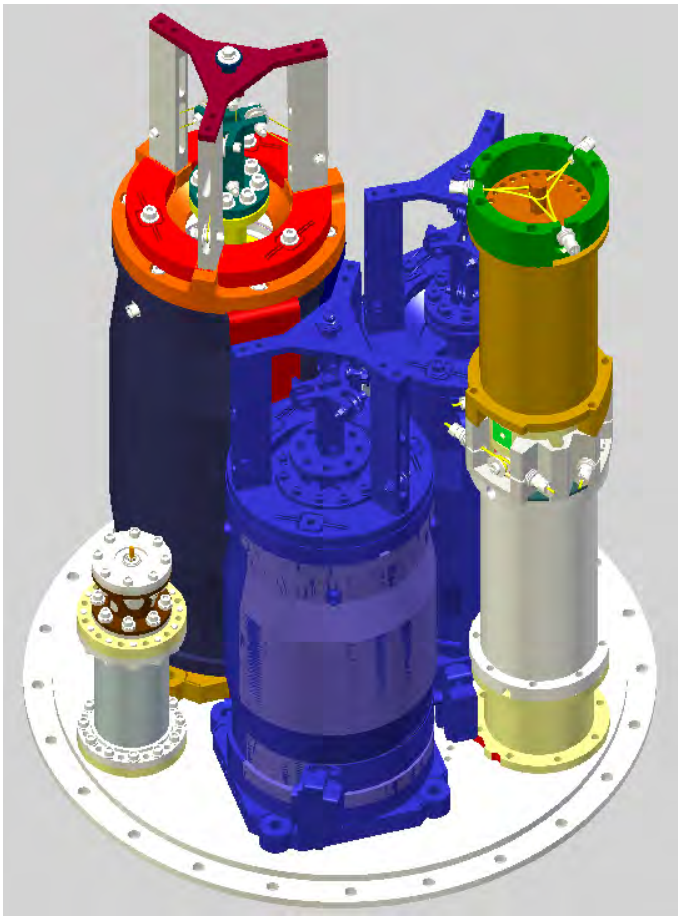


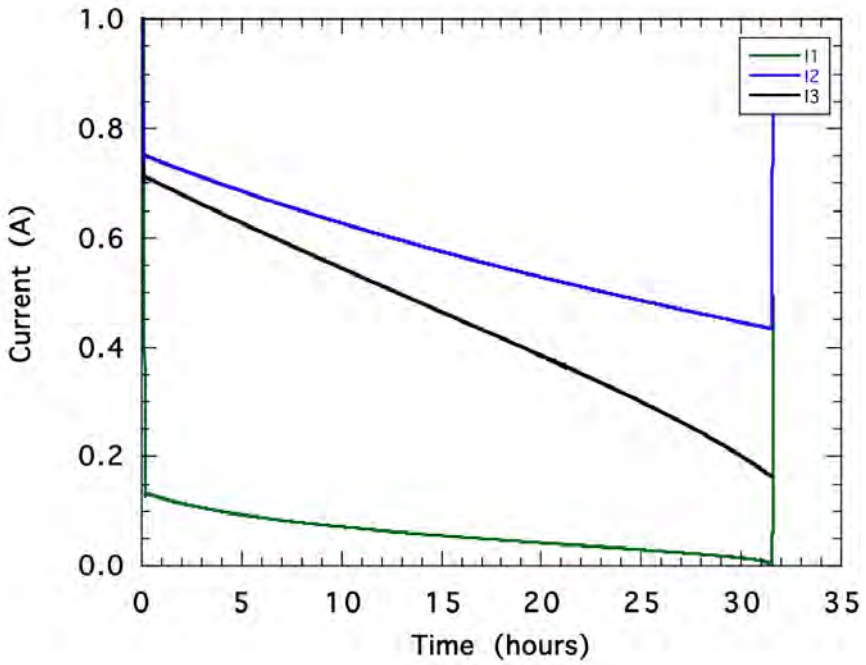
3-Stage ADR for Athena

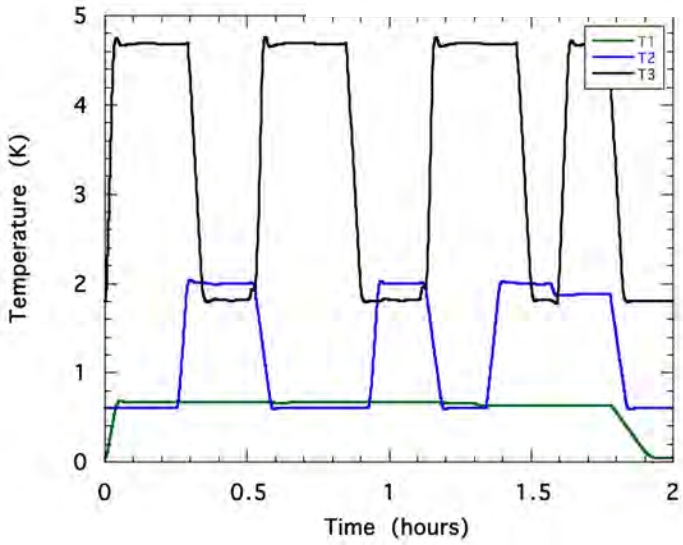


Cryogenics and Fluids Branch

- Designed for 1 μW detector load at 50 mK
- Peak heat rejection rate of 20 mW at 4.5 K
- 15 kg total mass



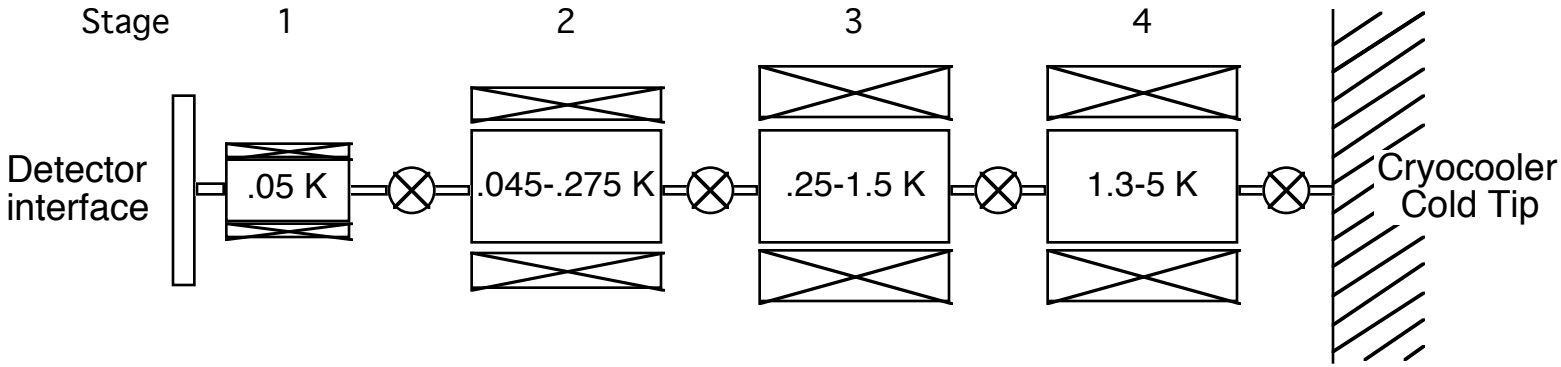




- Recycle time of <2 hours
- Hold time of >30 hours
- Duty cycle of >94%

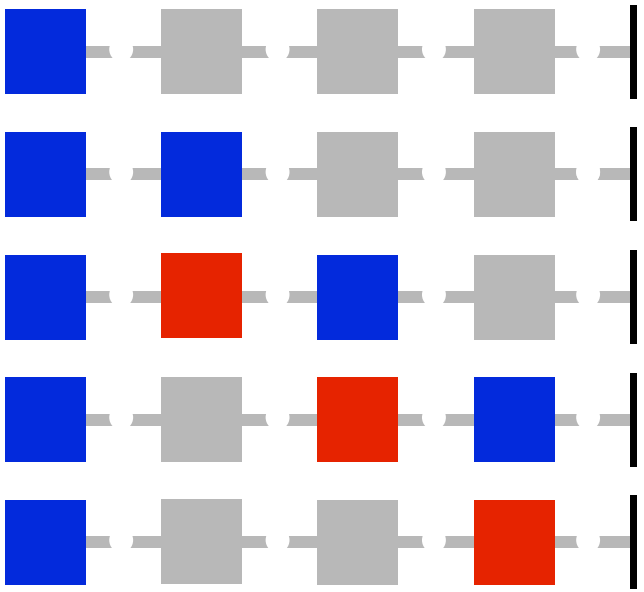
Continuous ADR

Cryogenics and Fluids Branch



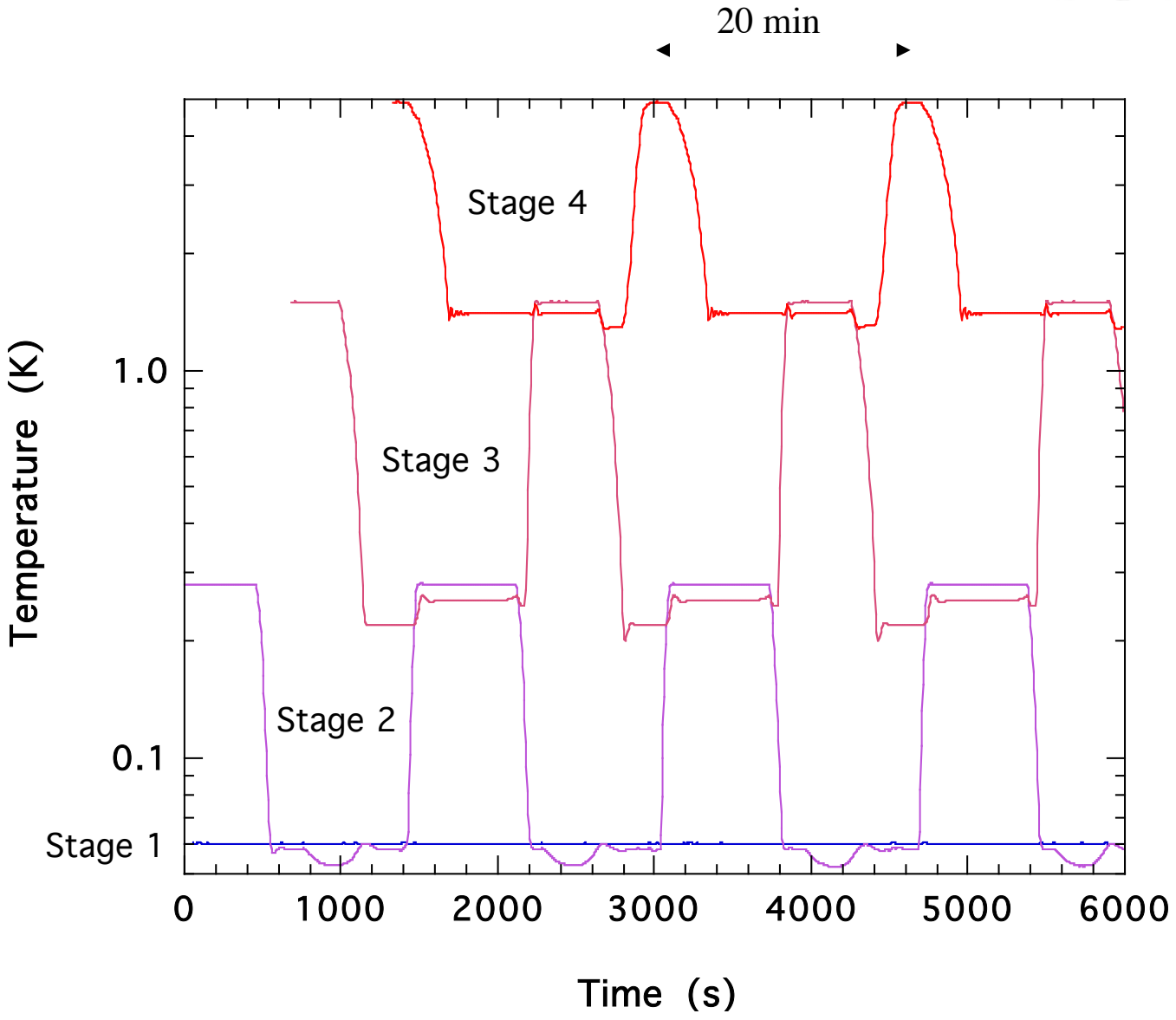
- Load is cooled by a "continuous" stage
- Other stages work to cascade heat up to the heat sink
  - Number of stages depends on temperature range and heat switch properties
- Cycle time can be short, 20-30 minutes
  - Much shorter heat storage time
  - Order of magnitude less refrigerant needed
- Can add stages to achieve lower T_{det} or higher T_{sink}

Recycling Sequence



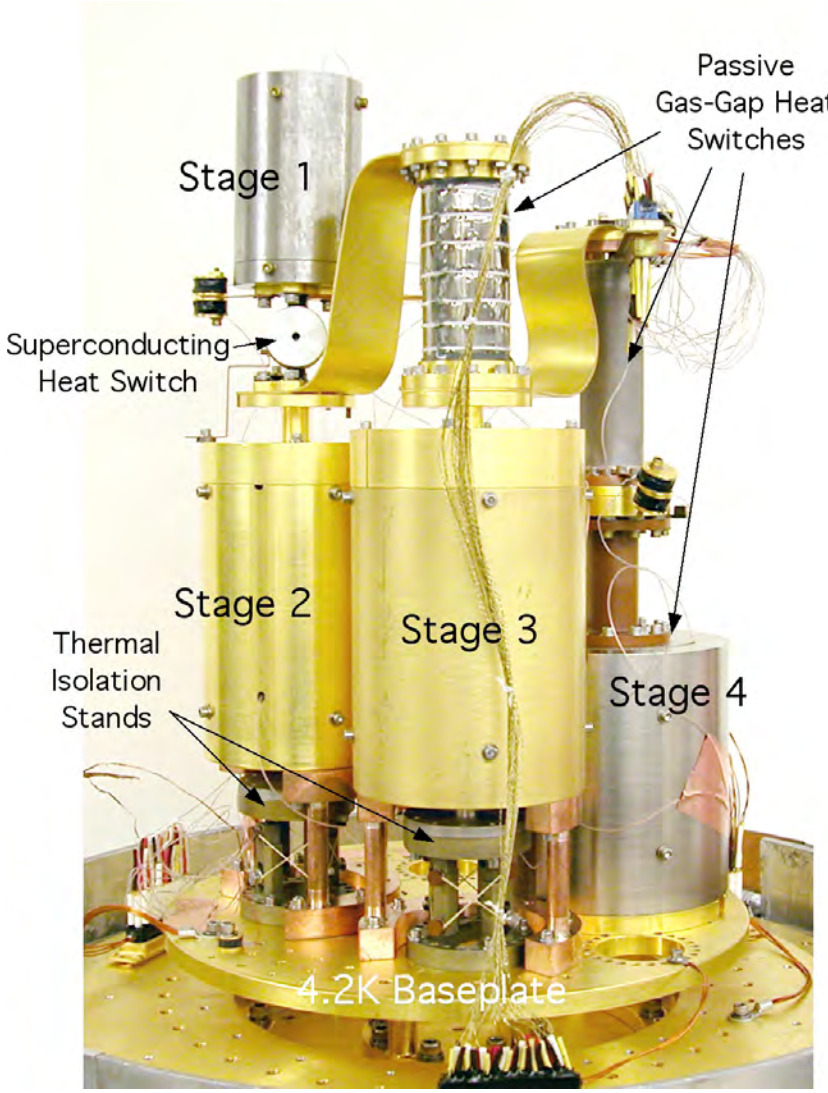
4-Stage Cycling

Cryogenics and Fluids Branch



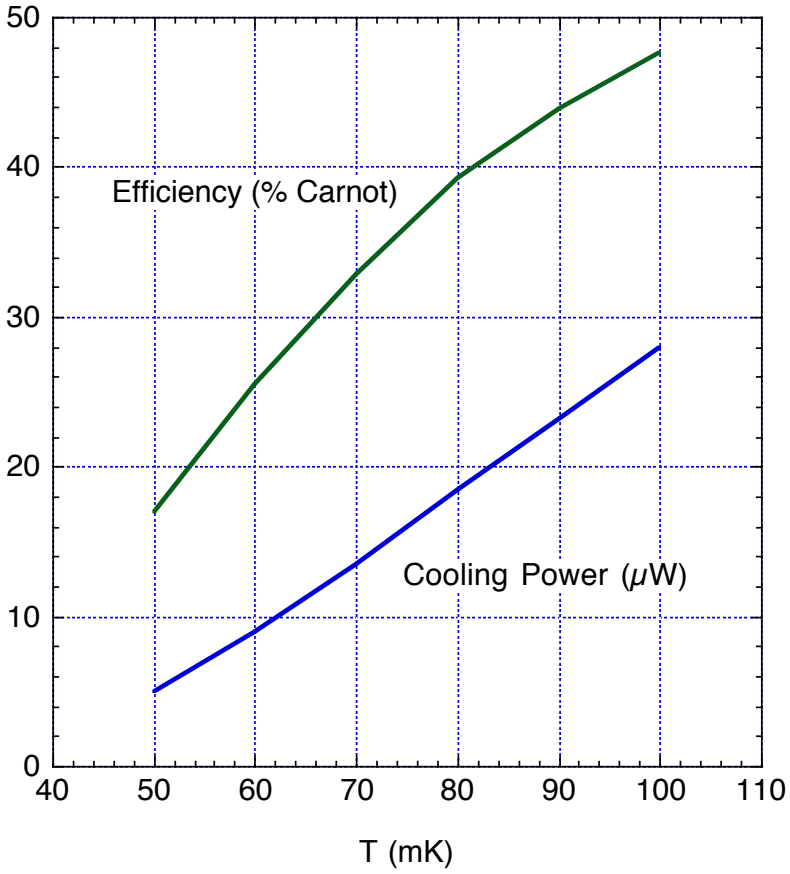
4-Stage CADR

Cryogenics and Fluids Branch



Complete in-house GSFC build

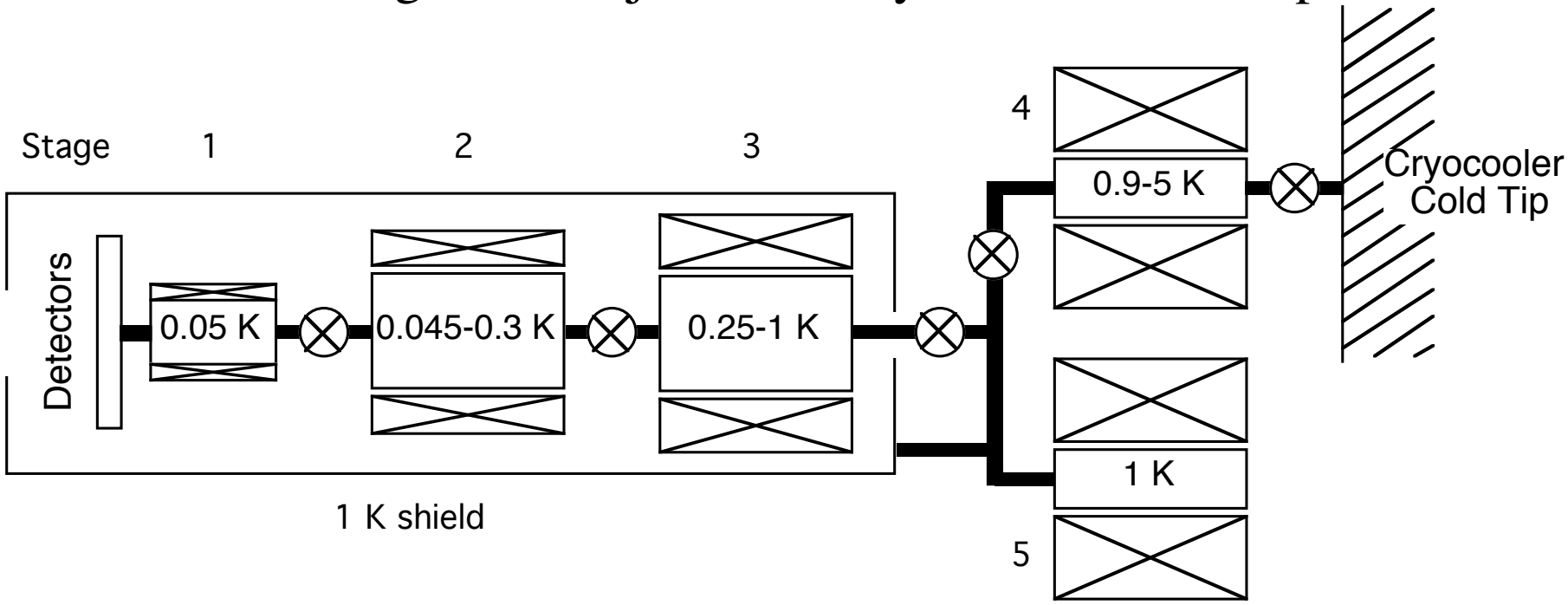
- Uses 4.2 K helium bath
- Total mass of 7.7 kg
- Magnets are fully shielded
- Fully automated operation



5-Stage CADR

Cryogenics and Fluids Branch

- Provides 2 fixed temperatures: 50 mK and 1 K
  - Allows longer heat rejection to cryocooler at lower peak rate



- Improved performance at 50 mK over 4-stage
  - 1 K base temperature reduces radiated and conducted (suspension components, heat switch) loads on cold stages

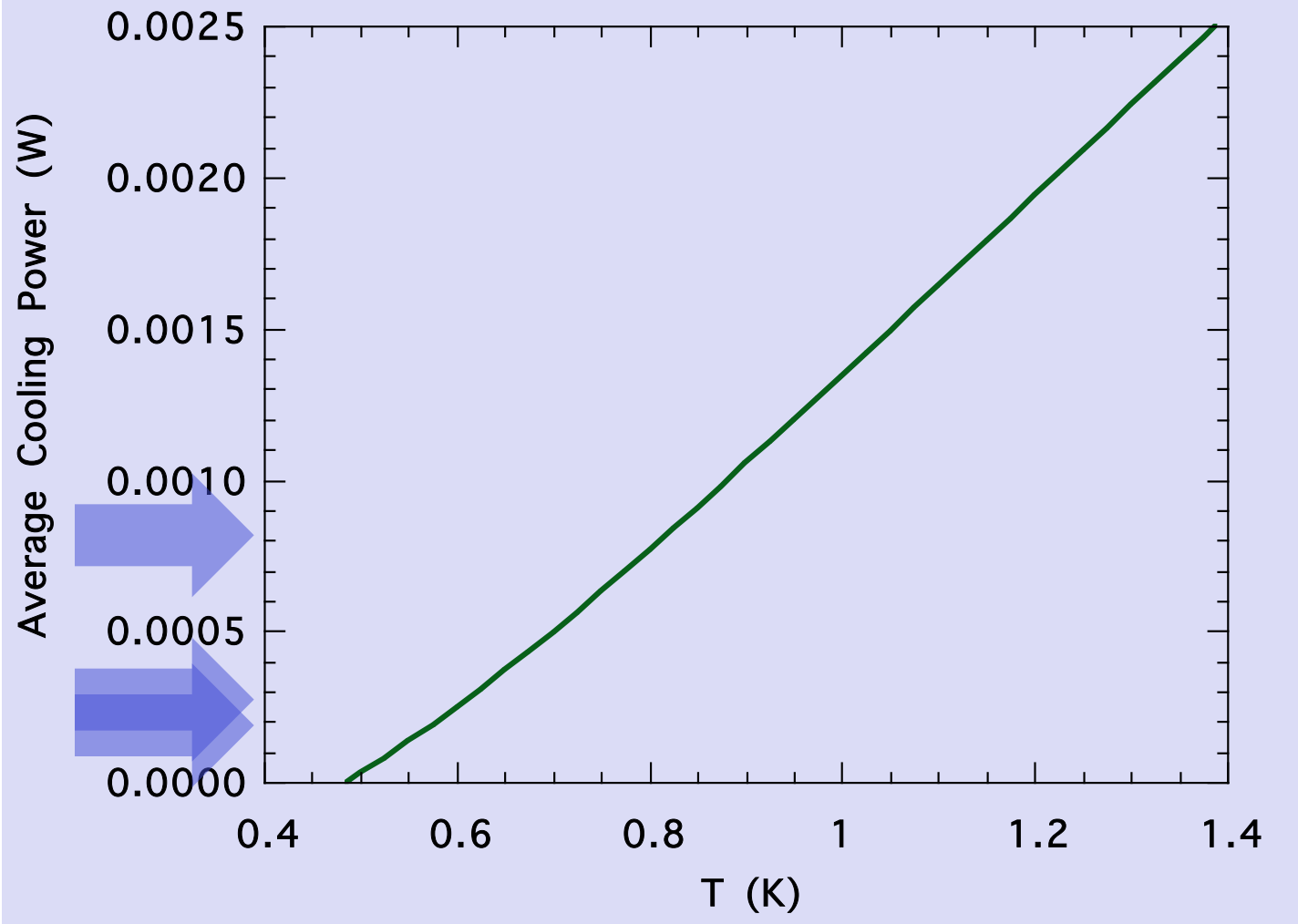
Cooling Power at “1 K”

- Cycle time is approximately 15 minutes

3-stage load:

5 μW @ 50 mK

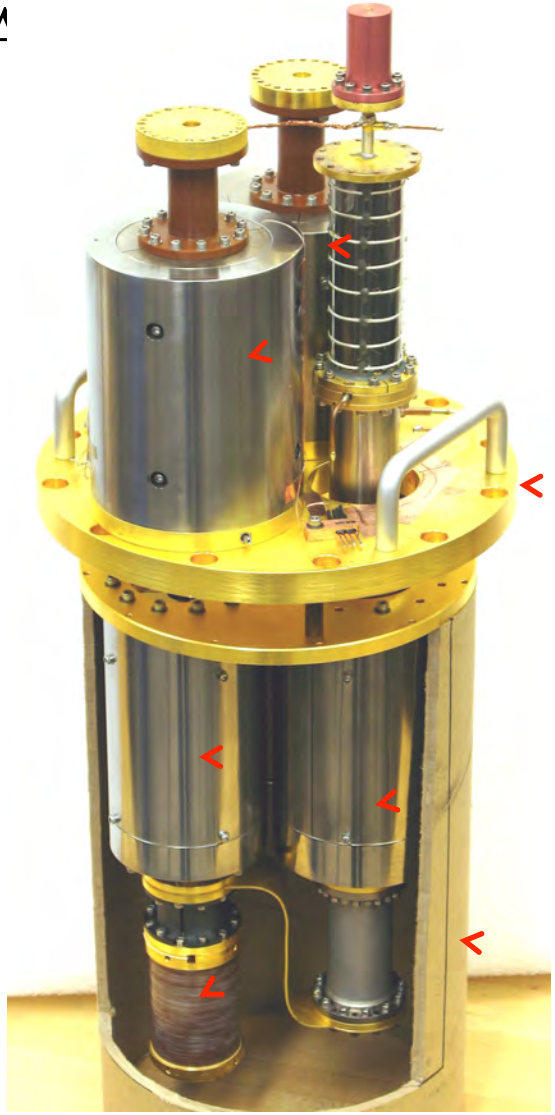
+ load from 4 K
1 μW @ 50 mK



5-stage CADR

Cryogenics and Fluids Branch

- Funded by GSFC IRA



Thermal straps not shown

2 stages cool continuously to ~1 K (~15 minute cycle)

Cryocooled heat sink at 4-5 K

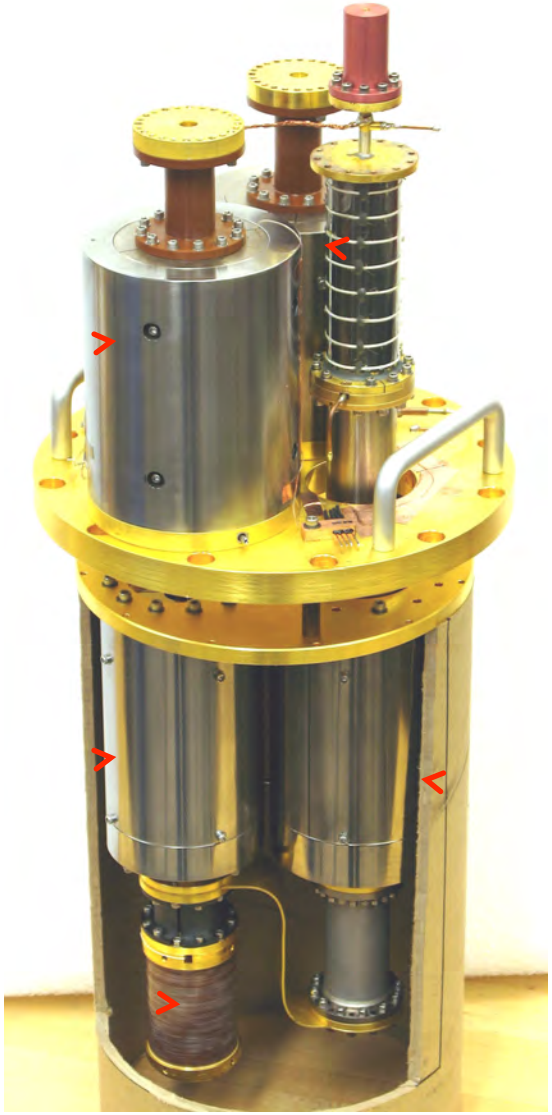
3 stages cool continuously to 50 mK (~15 min cycle)

1 K shield not shown

5-stage CADR

- Highest fields away from detecors

2 T @ 1.5 A



4 T @ 3 A

1 T @ 2 A

0.5 T @ 1 A

0.1 T @ 0.5 A

5-Stage CADR

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- Cooling requirements for future x-ray missions are typically:
  - Detector dissipation/wiring: 0.5-2 μW
  - "1 K" load
    - Wire conduction: <0.1 mW
    - Amplifiers: <0.1 mW
- Can reduce mass from current estimate of ~11 kg
- Low peak heat rejection rate (1-2 mW) also allows reduction in cryocooler requirements