

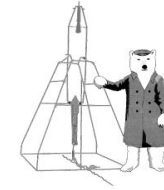
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Sub-Kelvin Coolers for Space Missions: ADR Development at NASA/GSFC

Dr. Peter Shirron
Cryogenics and Fluids Group, Code 552



Topics



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- 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

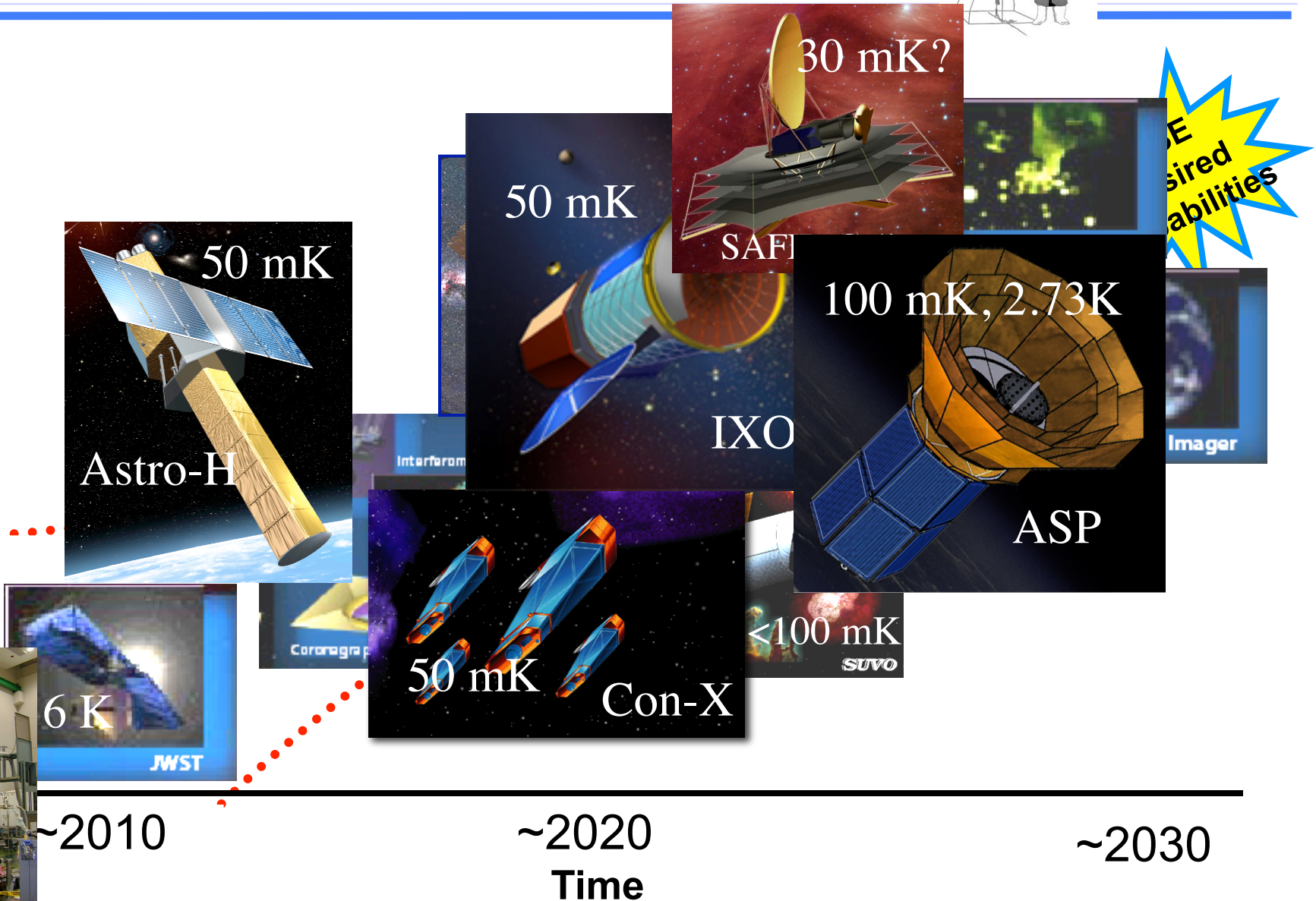
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Technological Capability

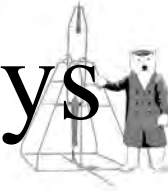


2005, 60 mK





Microcalorimeter Arrays

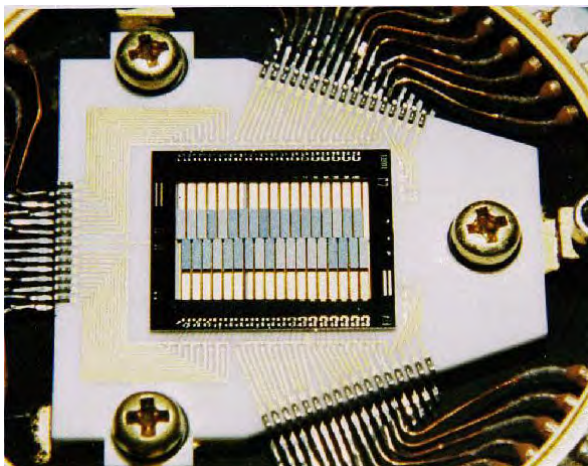
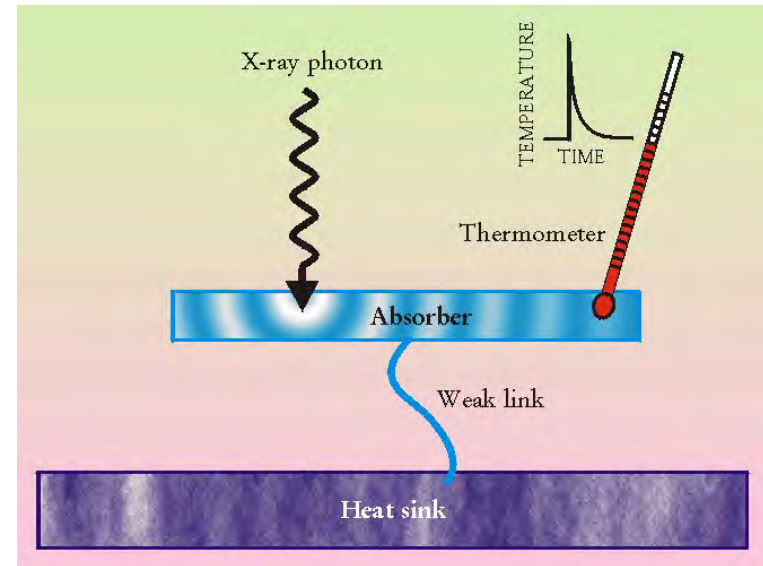


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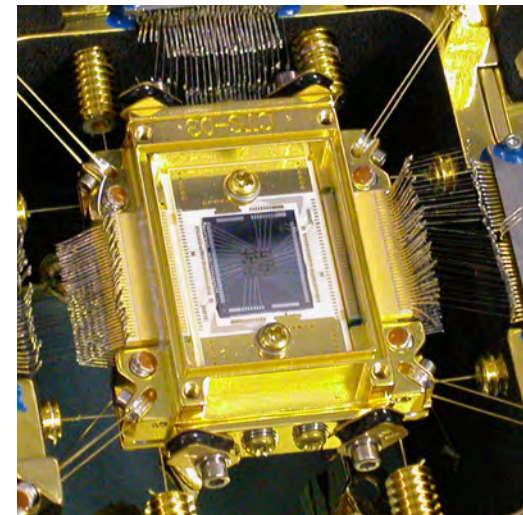
X-ray microcalorimeter: Thermal detection of individual x-ray photons.

- 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



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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

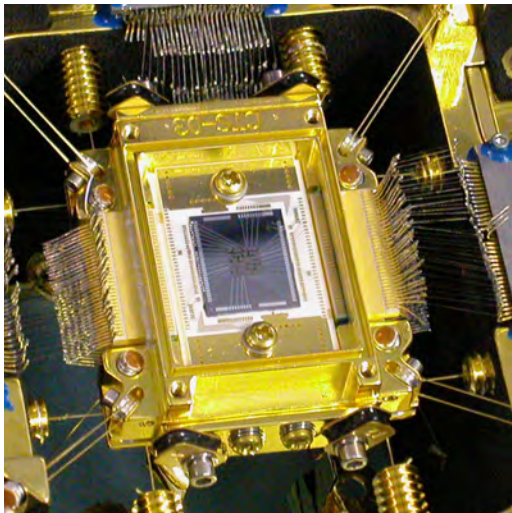
$0.3 \mu\text{W}$ load

32-pixel array at 50 mK

$0.3 \mu\text{W}$ load

~1000-pixel array at 50 mK

$2\text{--}5 \mu\text{W}$ load



Increasing need for more
capable cooling systems

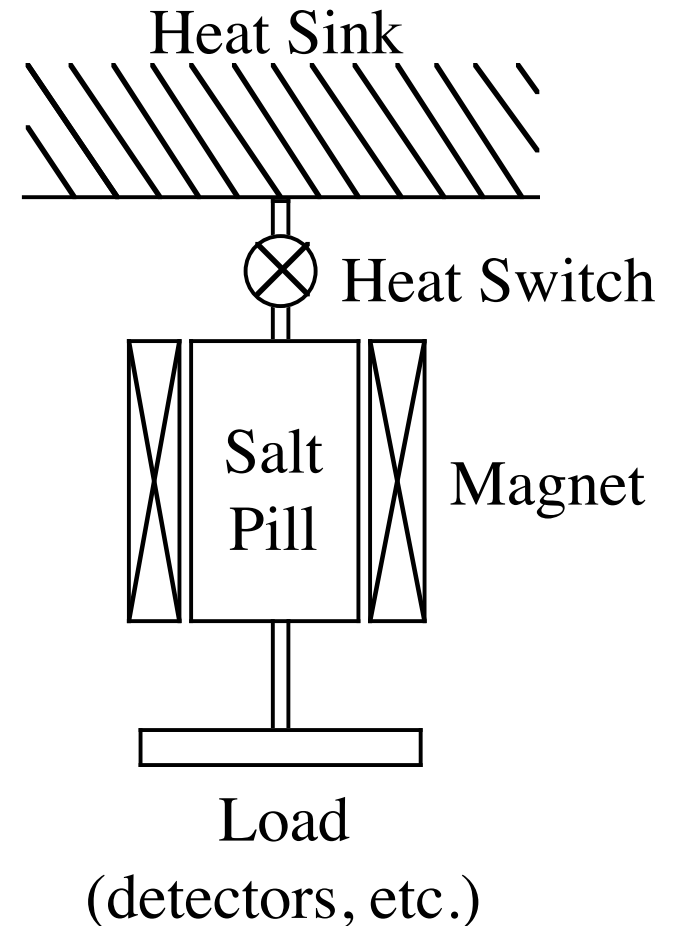


ADR Essentials



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- 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

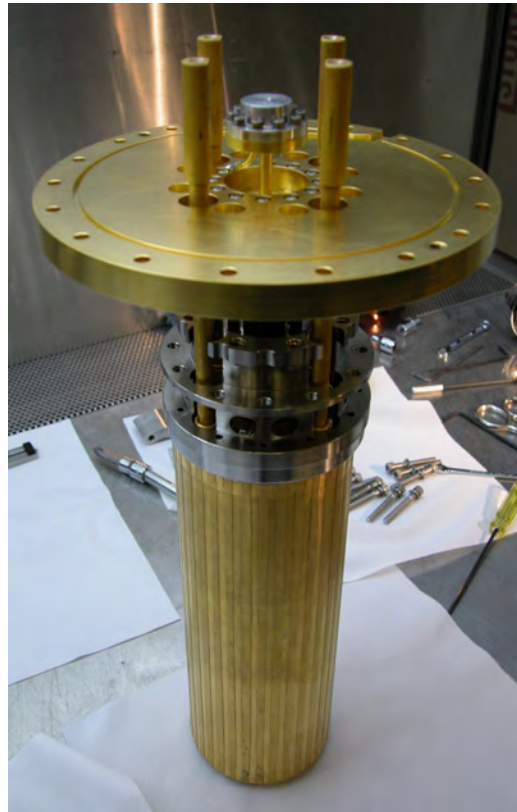




Basic (XRS) ADR



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Salt pill, heat switch,
Suspension, baseplate



Magnet (immersed
In liquid helium)

Total mass: 15 kg



Practical Limits



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- Single-stage ADR must cool from heat sink to low T
- Typical values
 - Net cooling power: $\sim 0.5 \mu\text{W}$
 - Heat sink: 1.3 K 20:1
 - Magnetic field: 2 T (2 amps)
 - Refrigerant mass: 1-2 moles
 - 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: $\gg 2 \text{ T}$ is unpractical
- Bottom line: improved performance ➡ multi-stage ADRs

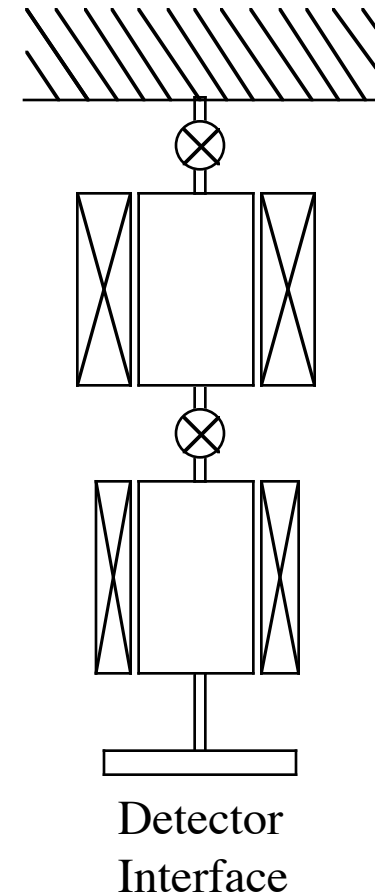
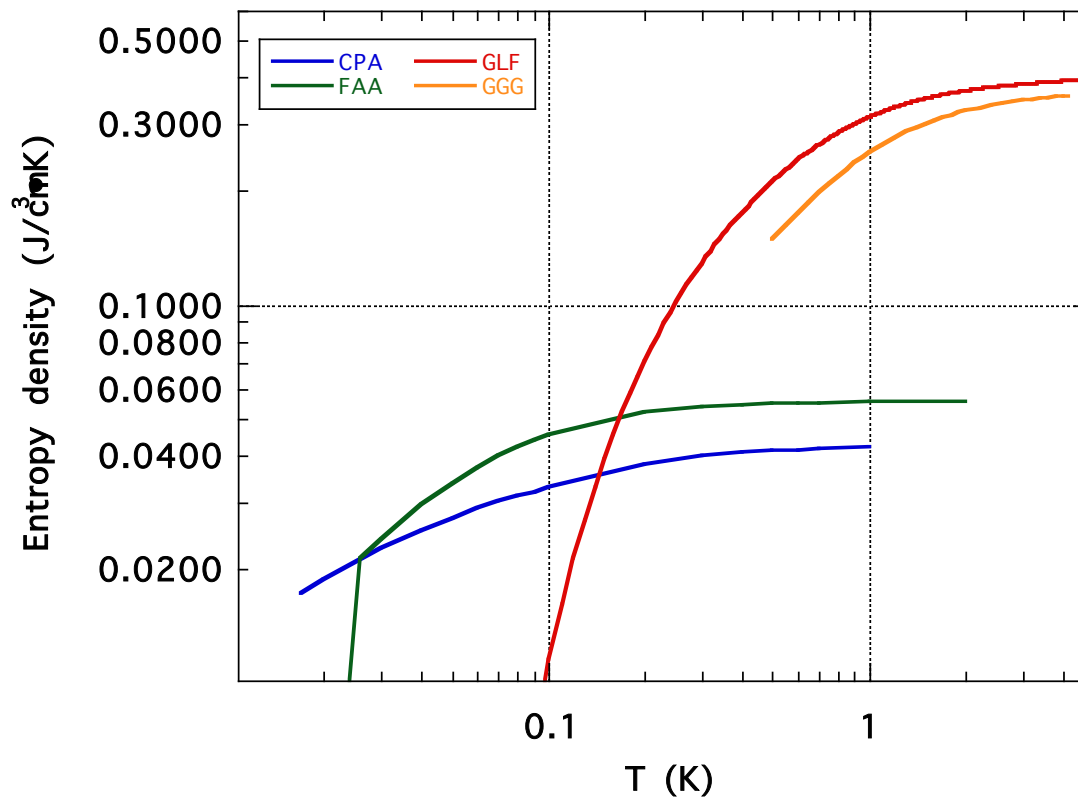


Two-Stage ADR



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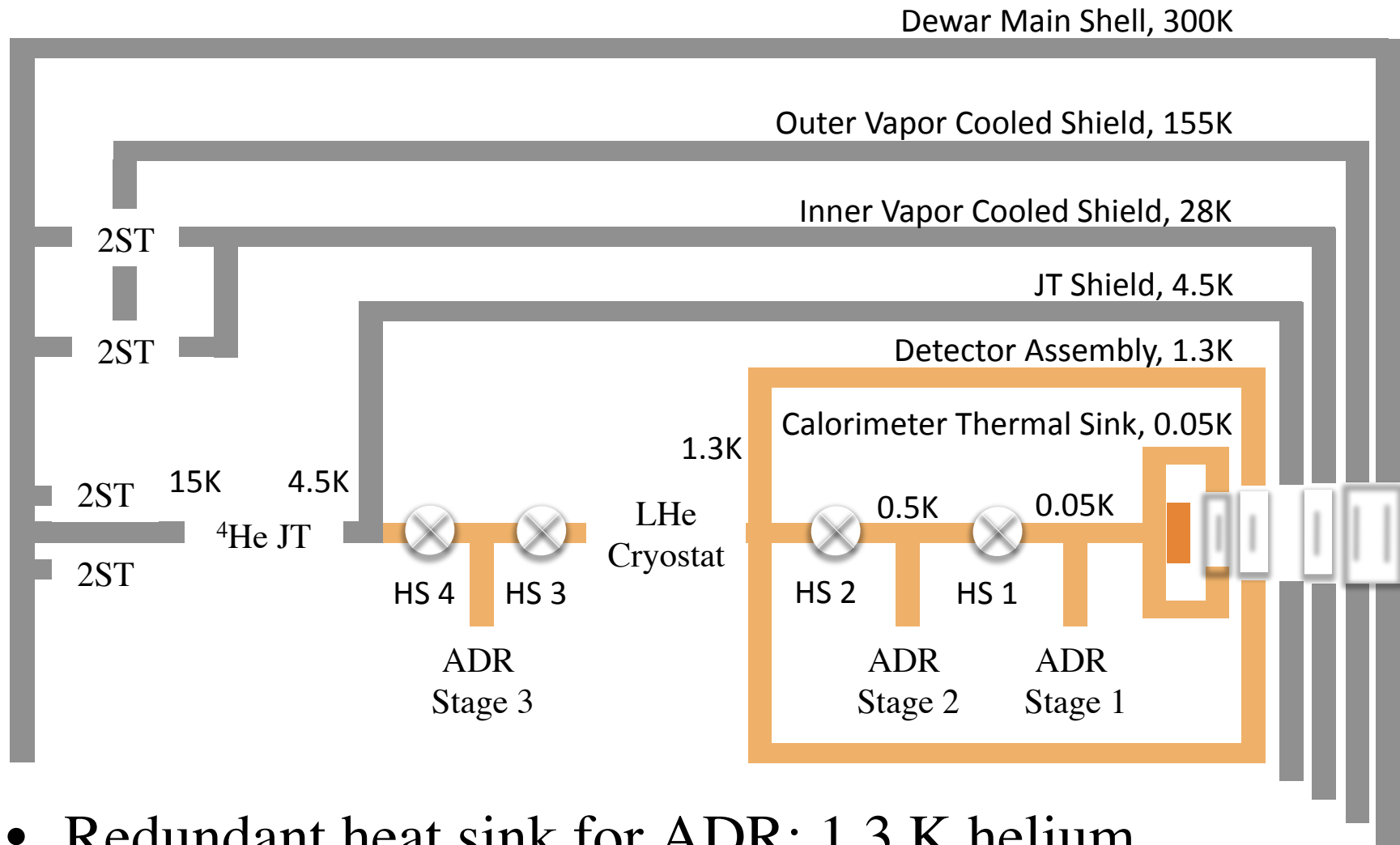
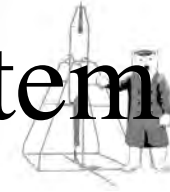
- Series configuration
 - Upper stage pre-cools lower stage and reduces heat load
- Upper stage can cool from much higher temperature and have much higher cooling power





Astro-H Cryogenic System

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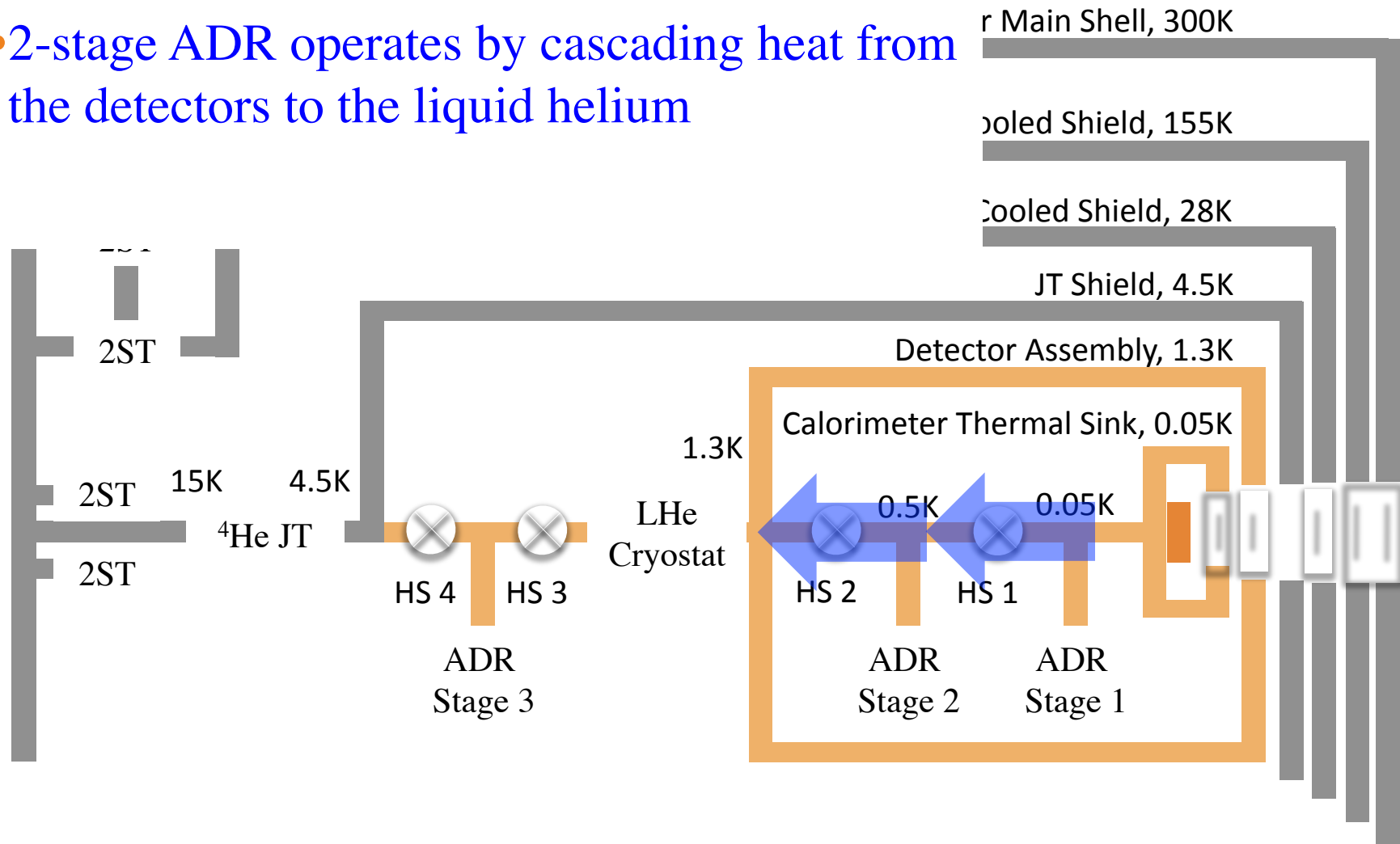
- Redundant heat sink for ADR: 1.3 K helium, 4.5 K cryocooler



Astro-H Cryogenic System

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

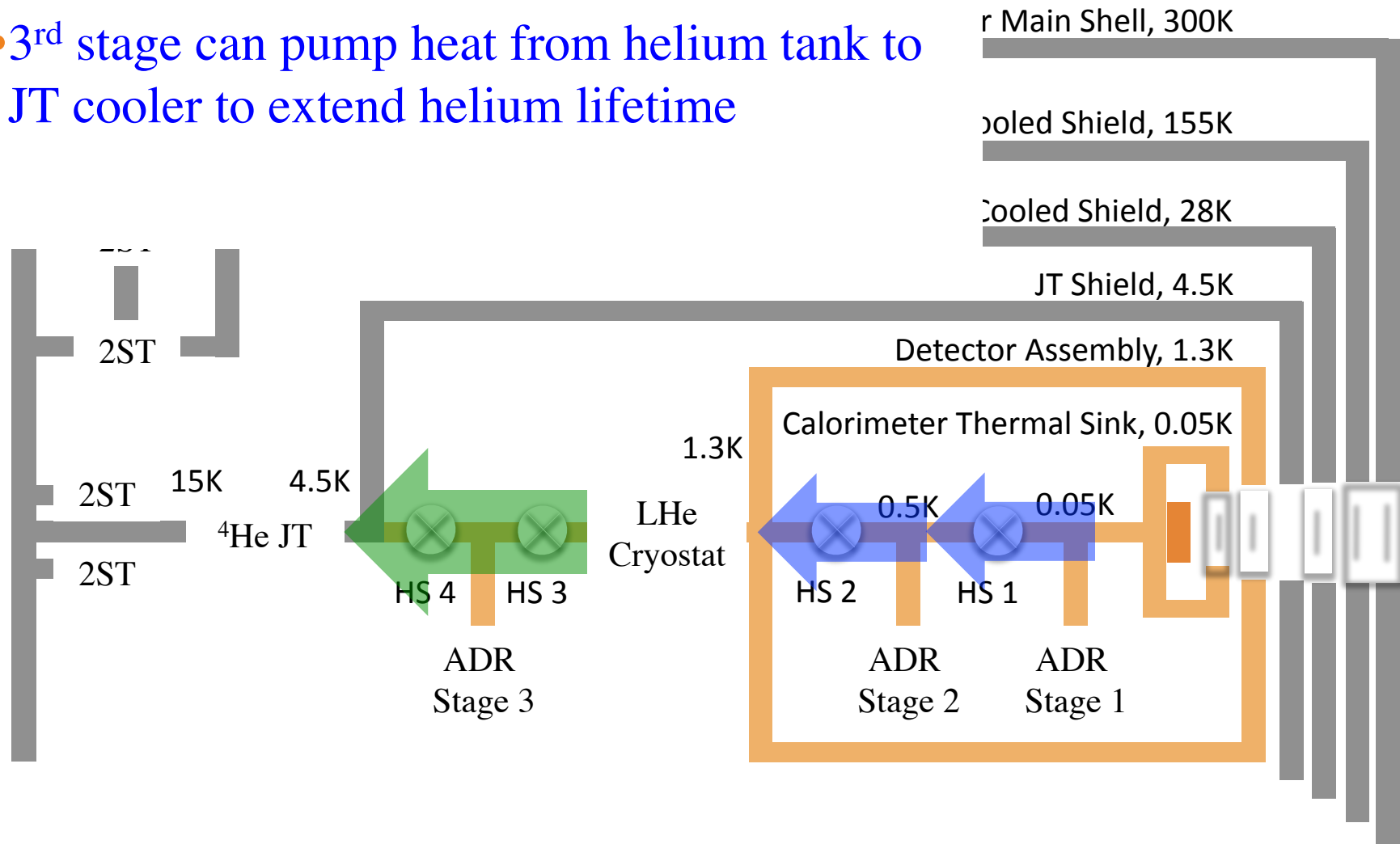




Astro-H Cryogenic System

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

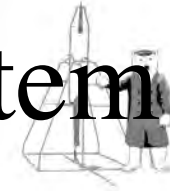


Critical Design Review, November
14-16, 2011

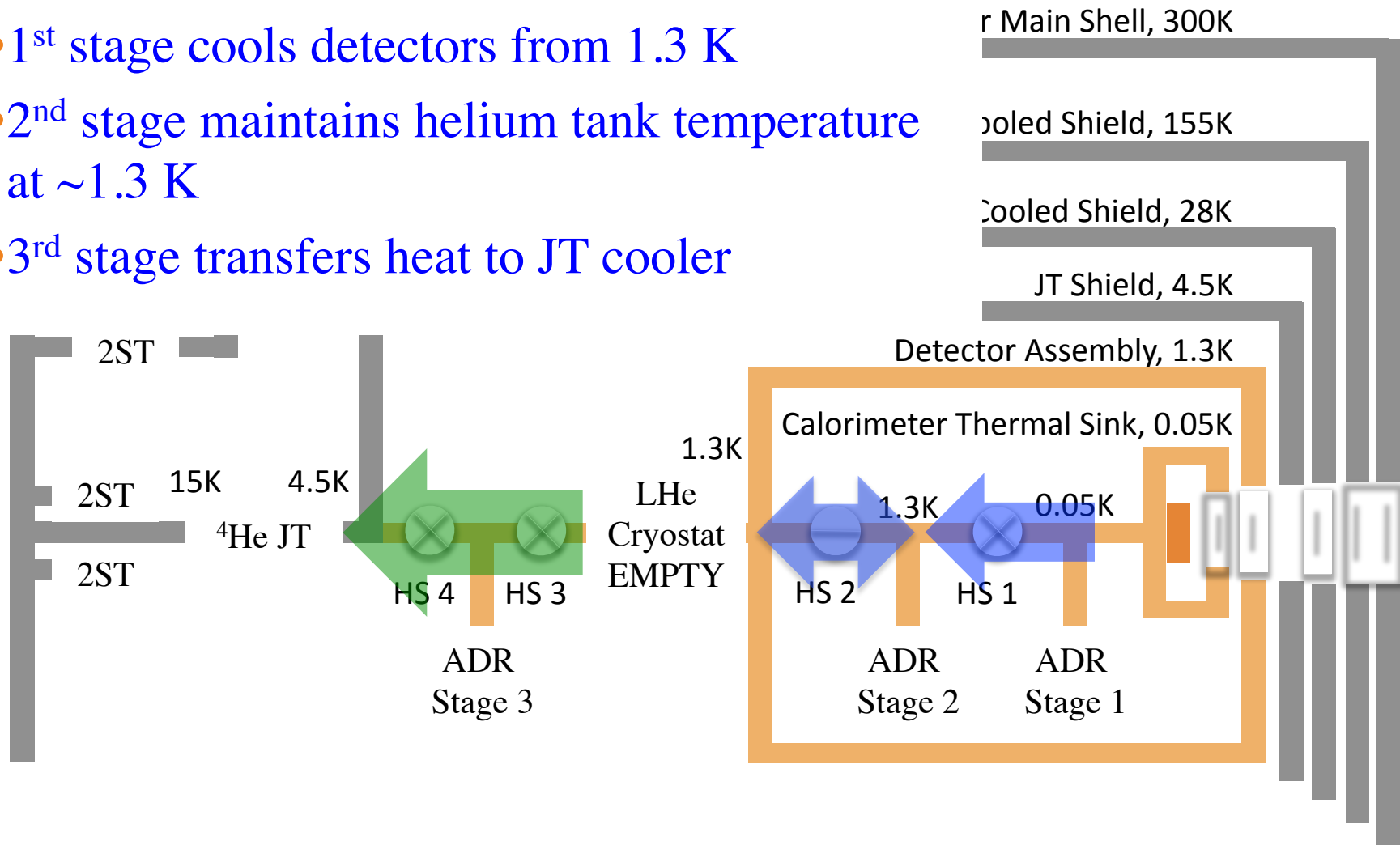


Astro-H Cryogenic System

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- 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

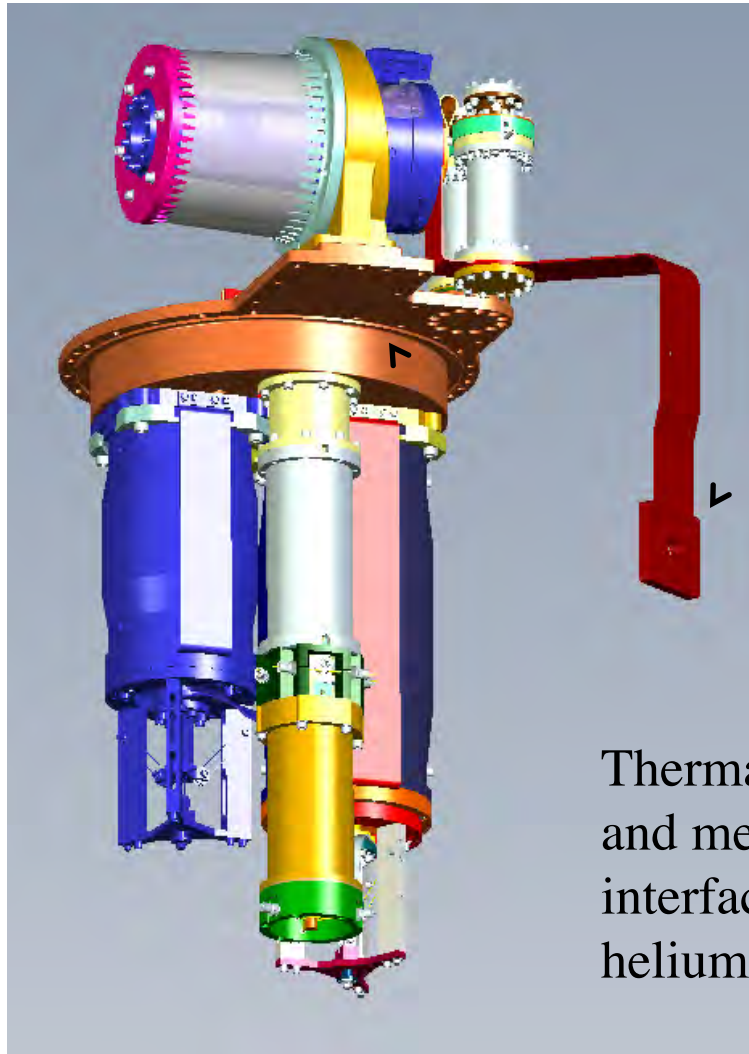




ADR Interfaces - Thermal

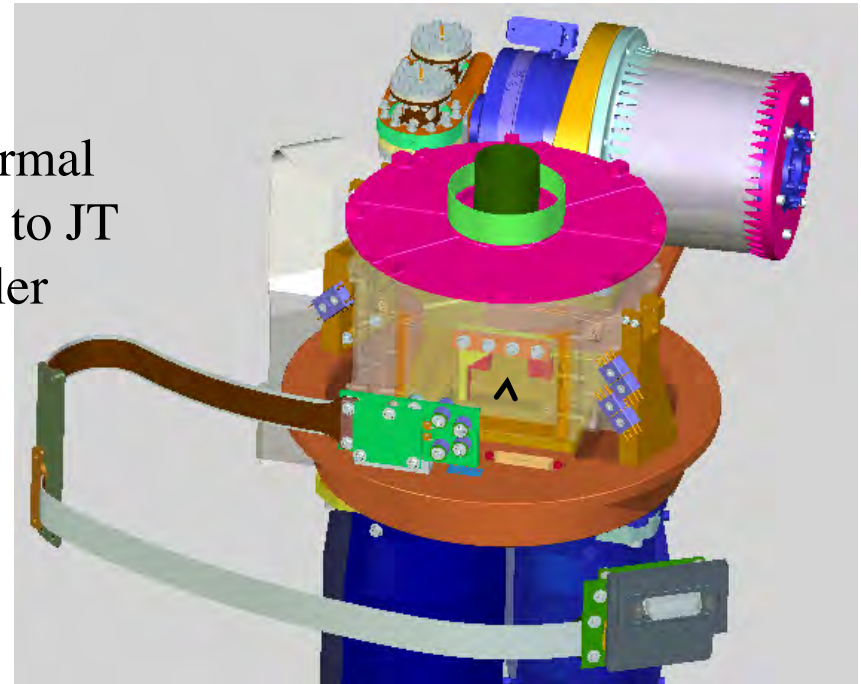


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Thermal
and mechanical
interface to
helium tank

Thermal
link to JT
cooler



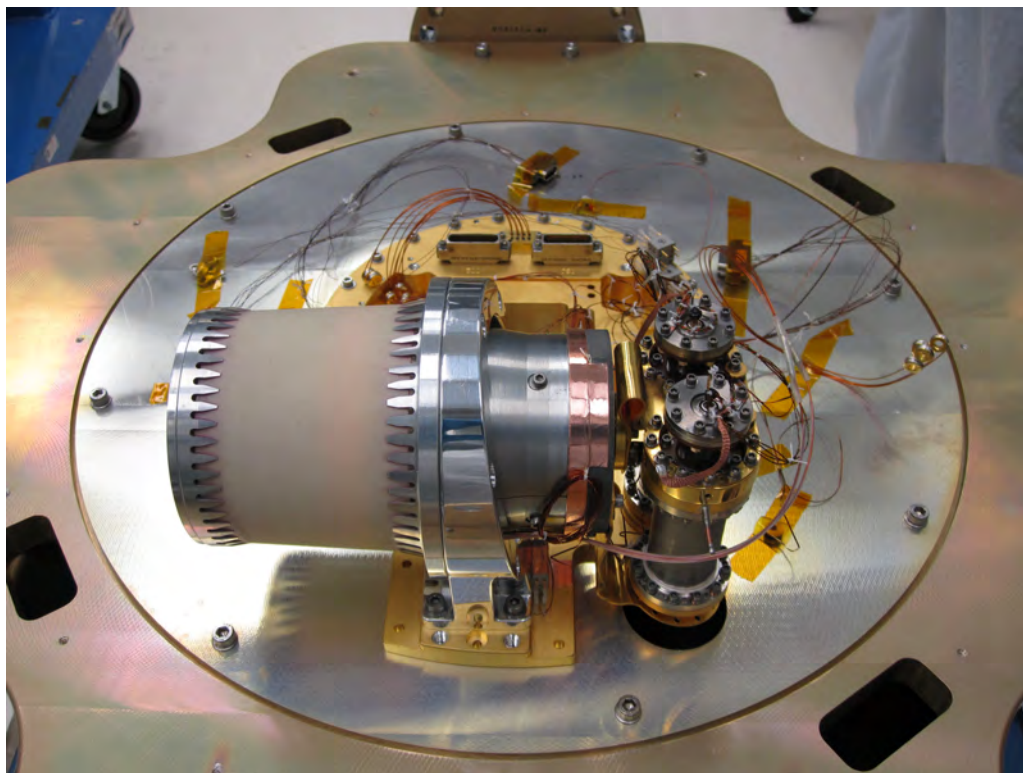
Thermal
link to
detectors



EM ADR



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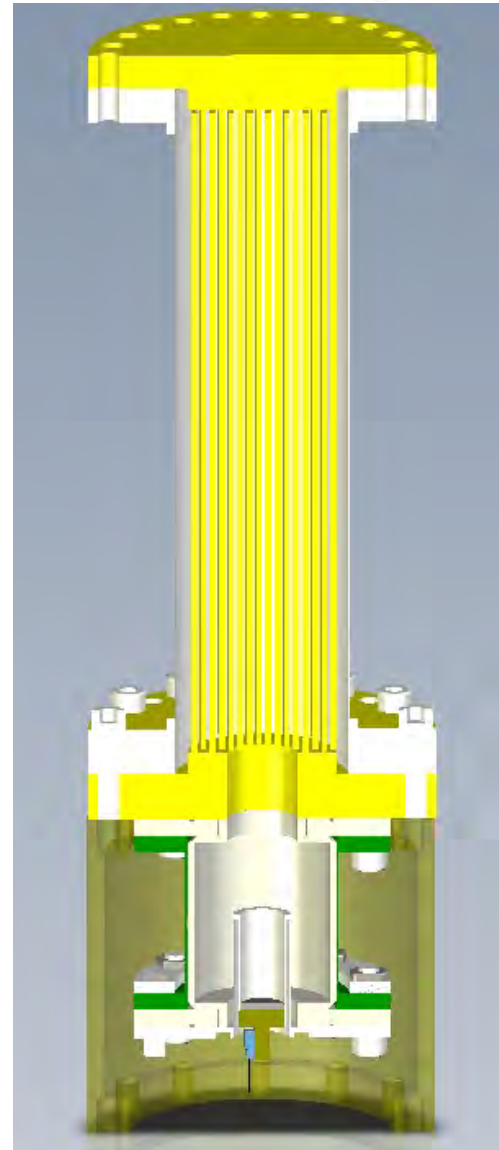


AGGHS Design



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- Design goals
 - <0.25 mW activation power
 - >100 mW/K on-state conductance
 - Off-state conduction
 - $0.1 \mu\text{W}$ from 0.5 K to 50 mK
 - $1 \mu\text{W}$ 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



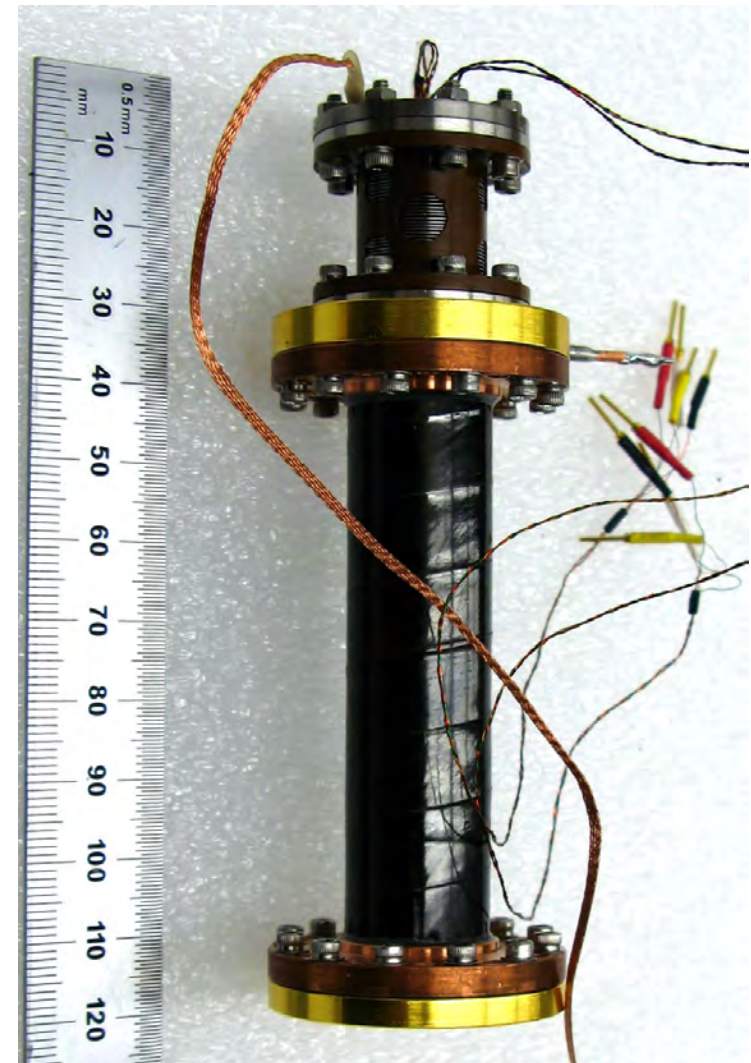


Heat Switches



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



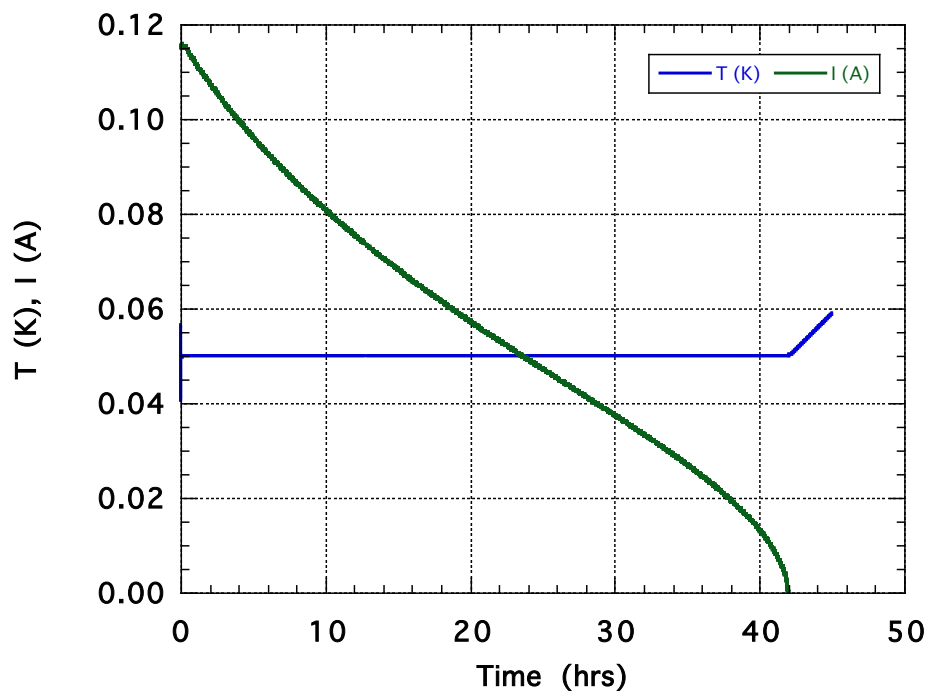


Hold Time (Cryogen)

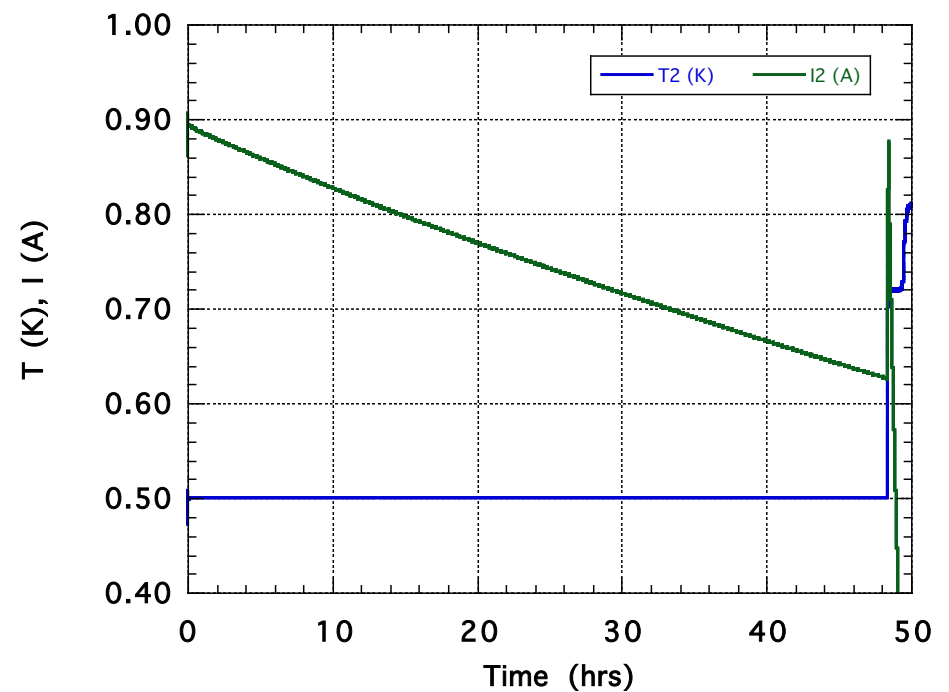


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- Detector heat load is $0.27 \mu\text{W}$
 - Total heat load is $0.86 \mu\text{W}$



Stage 1



Stage 2

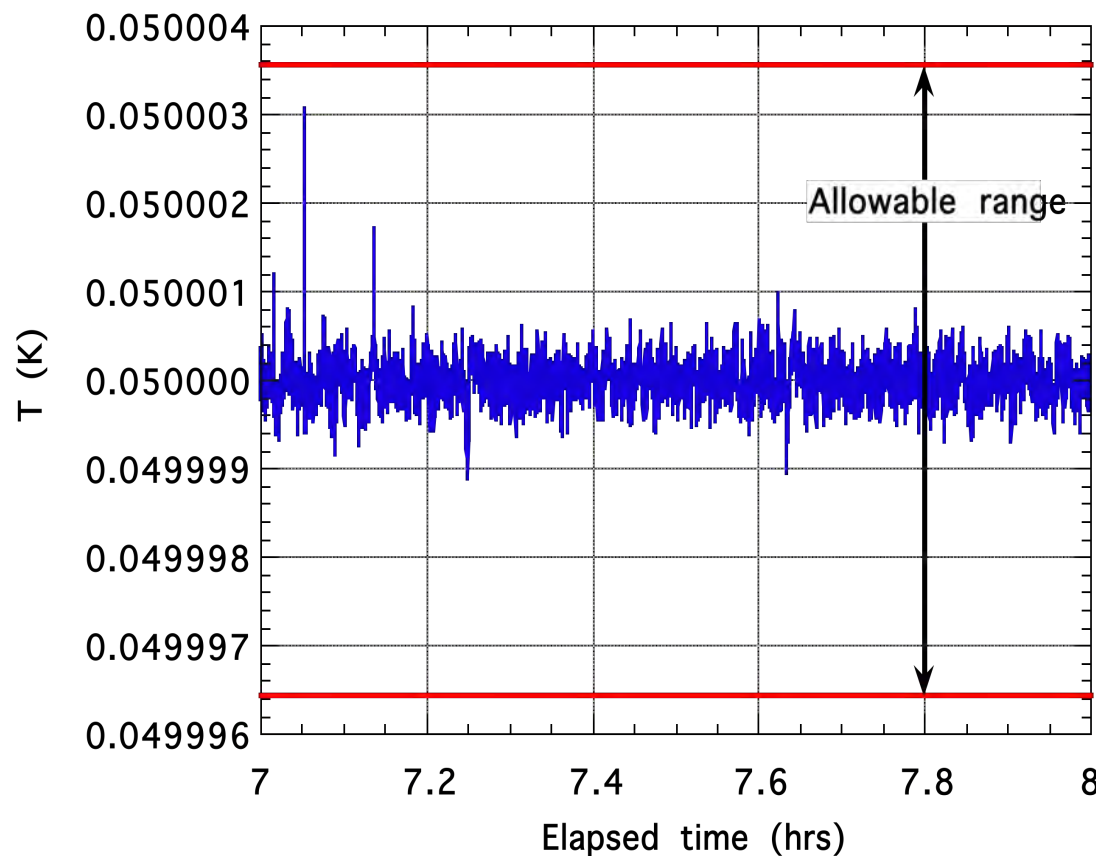


Temperature Stability



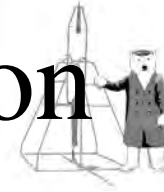
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- Temperature stability requirement is $2.5 \mu\text{K rms}$
 - Achieving $<0.4 \mu\text{K rms}$



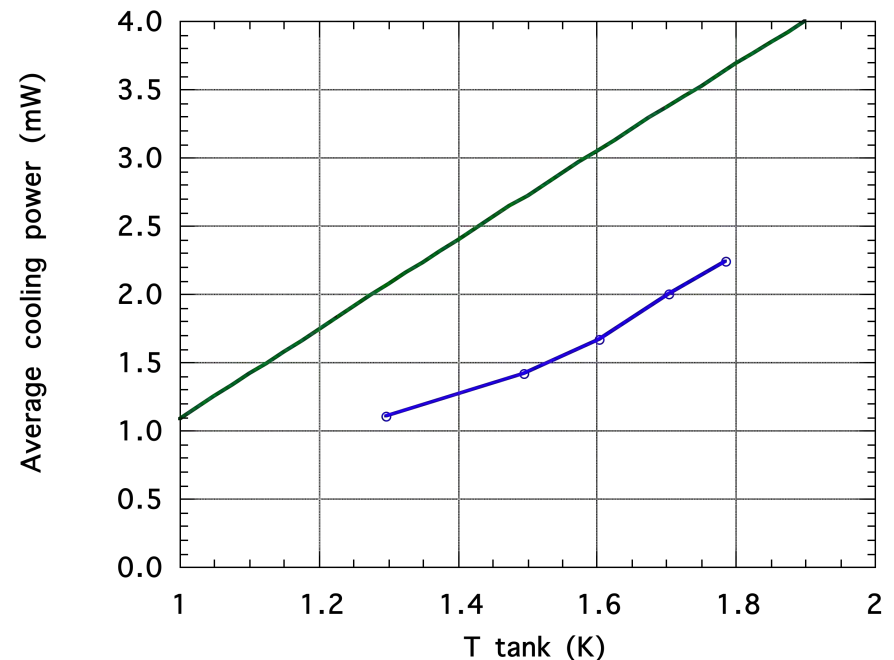
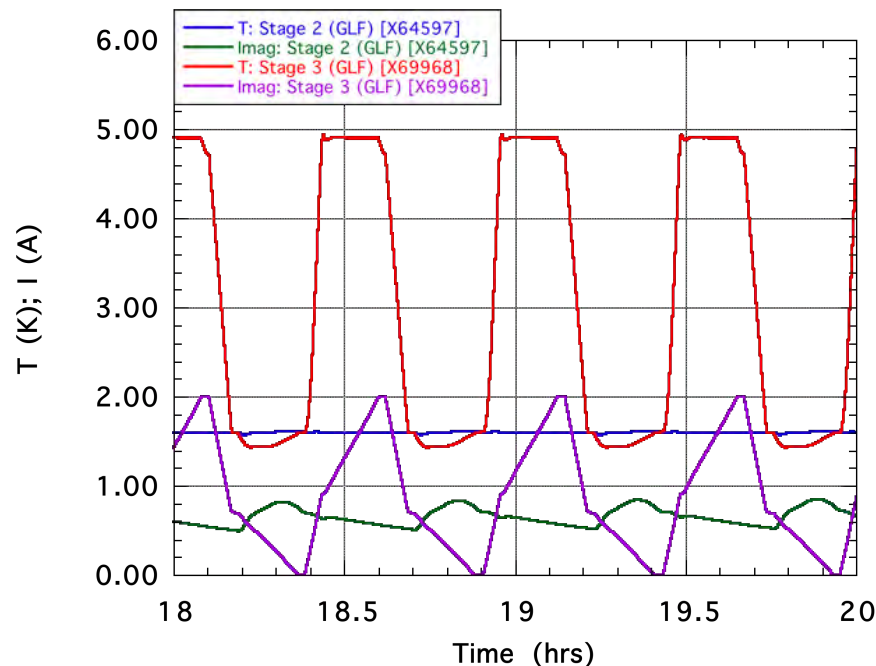


Cryogen-Free Operation



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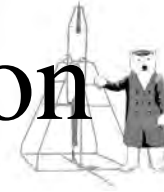
- 3rd stage is continually cycled to transfer heat from helium tank to JT cooler



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

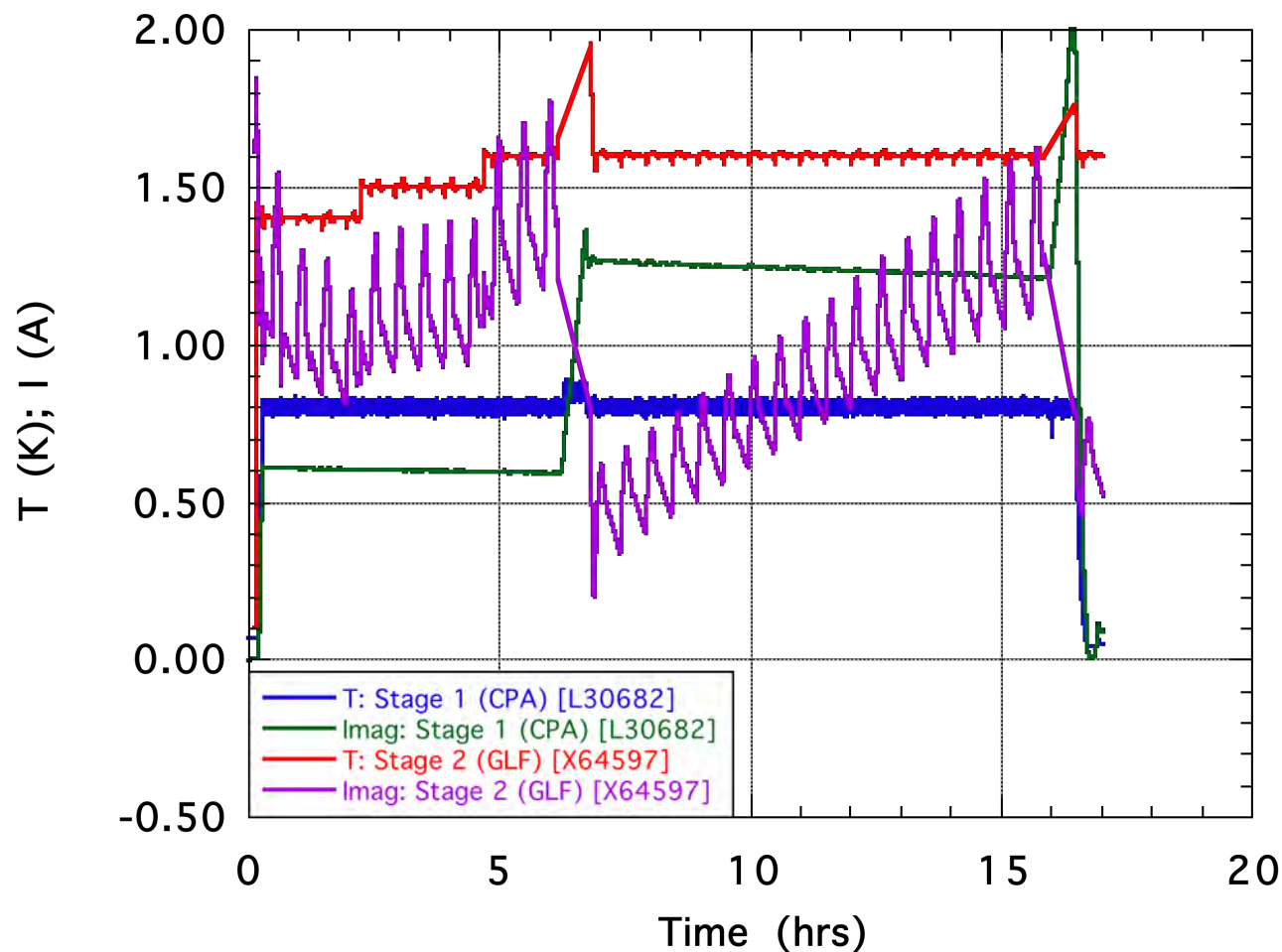


Cryogen-Free Operation



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



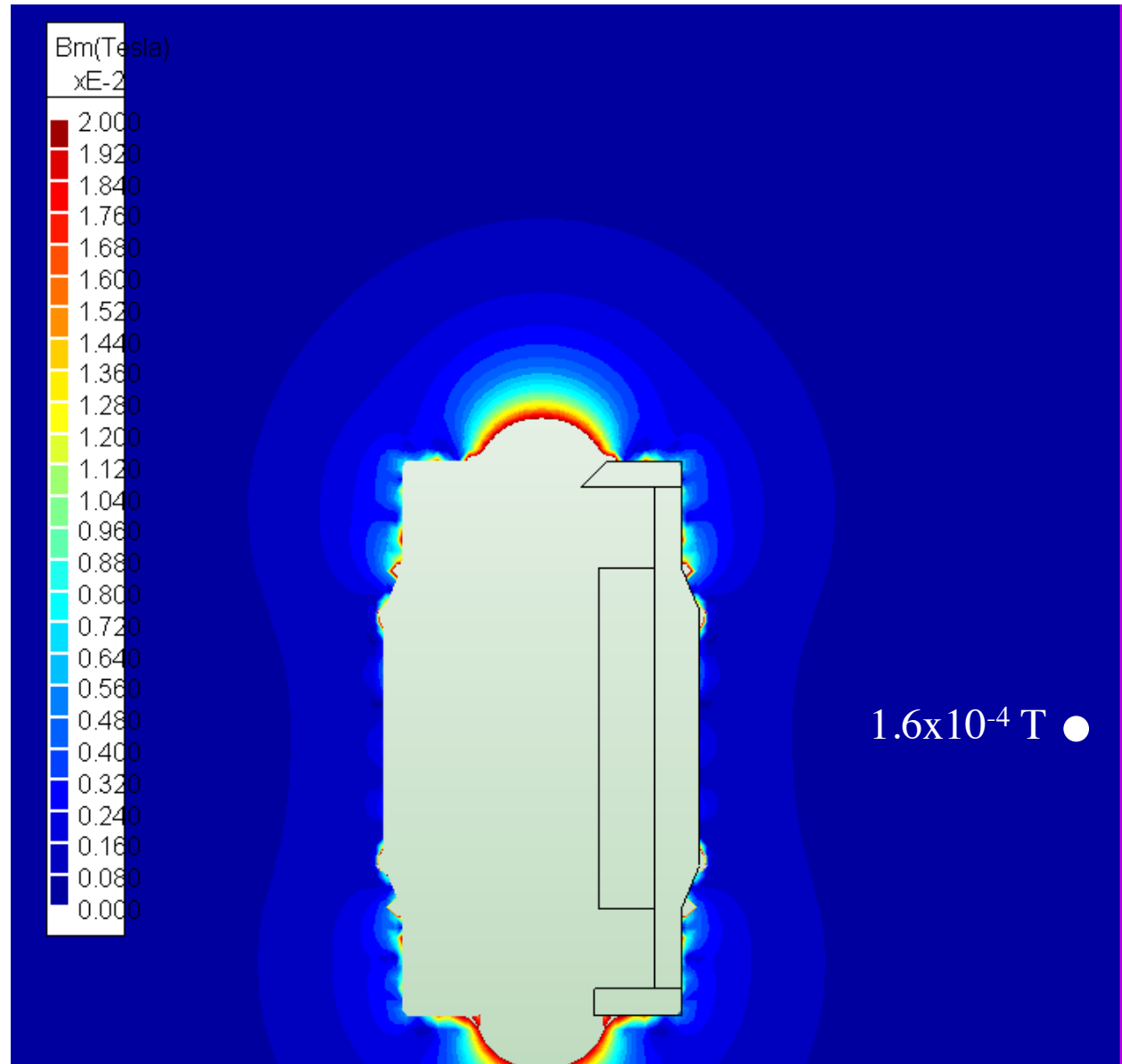


Magnetic Fields



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- 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 $\sim 10^{-4}$ T

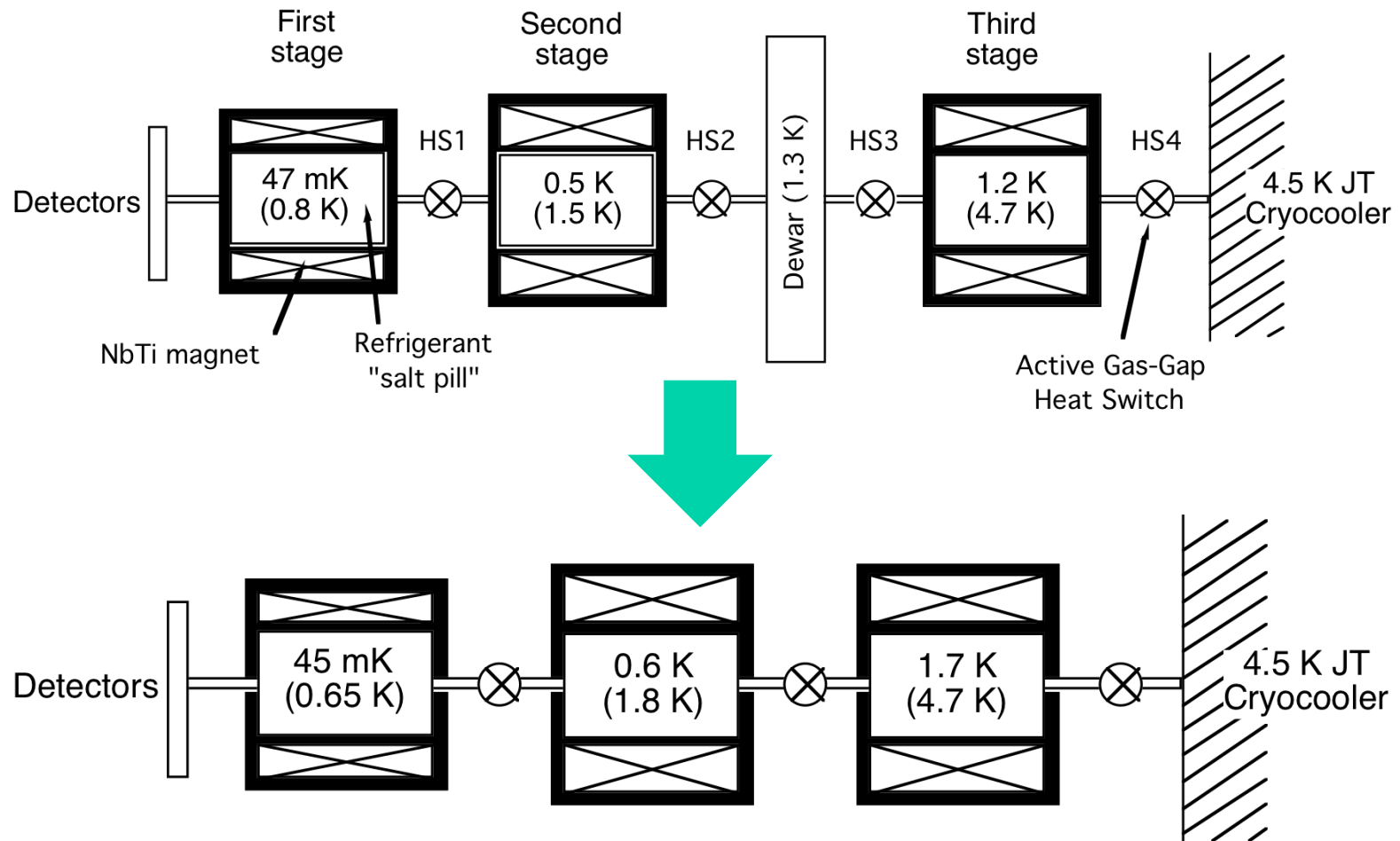




3-Stage ADR for Athena

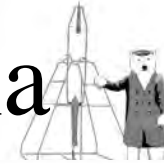


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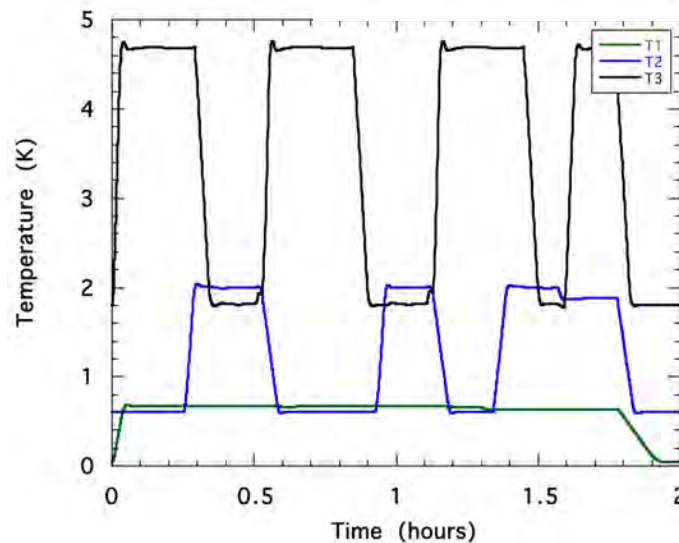
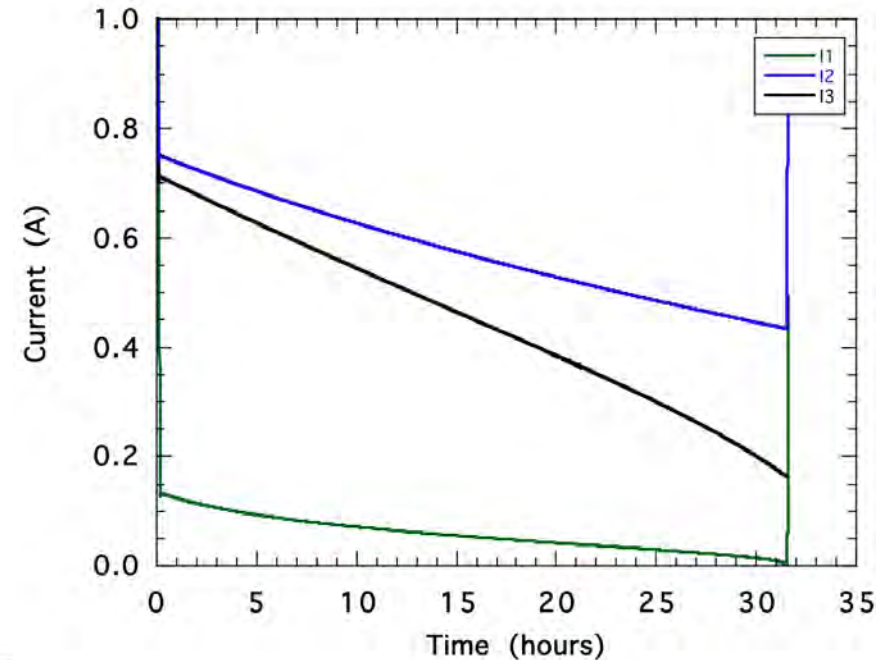
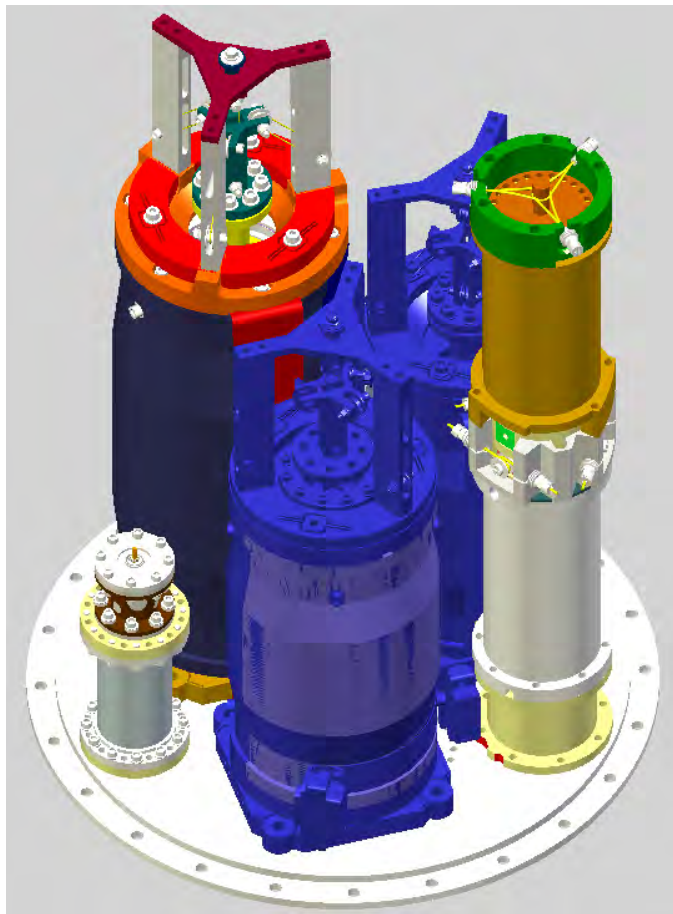


3-Stage ADR for Athena



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- Designed for $1 \mu\text{W}$ detector load at 50 mK
- Peak heat rejection rate of 20 mW at 4.5 K
- 15 kg total mass



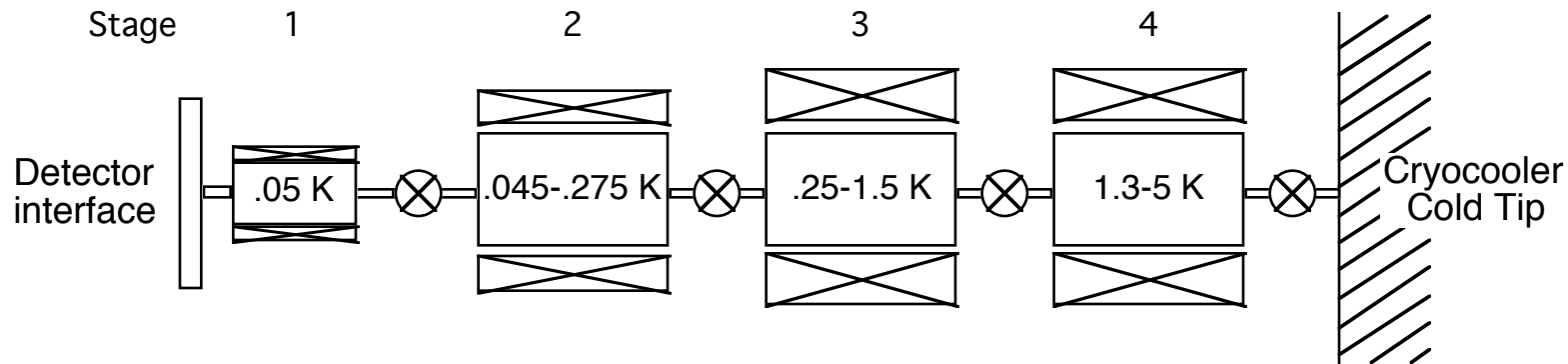
- Recycle time of <2 hours
- Hold time of >30 hours
- Duty cycle of >94%



Continuous ADR

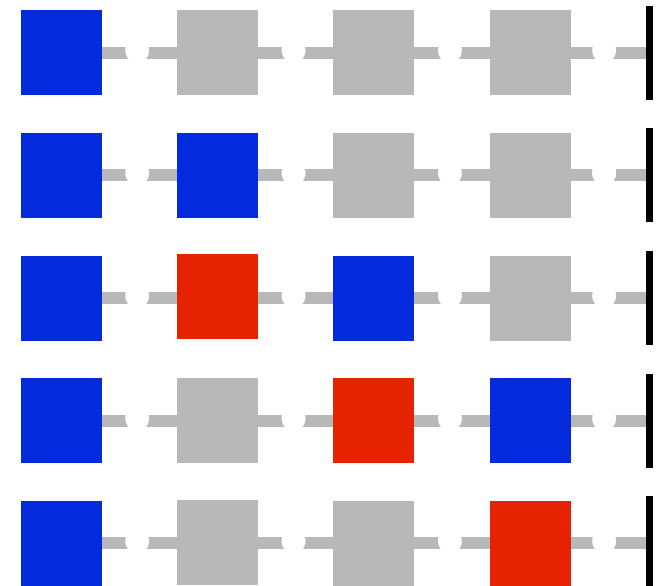


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- Load is cooled by a “continuous” stage
- Other stages work to cascade heat up to the heat sink
 - Number of stages depends on temperature range and heat switch properties
- Cycle time can be short, 20-30 minutes
 - Much shorter heat storage time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

Recycling Sequence

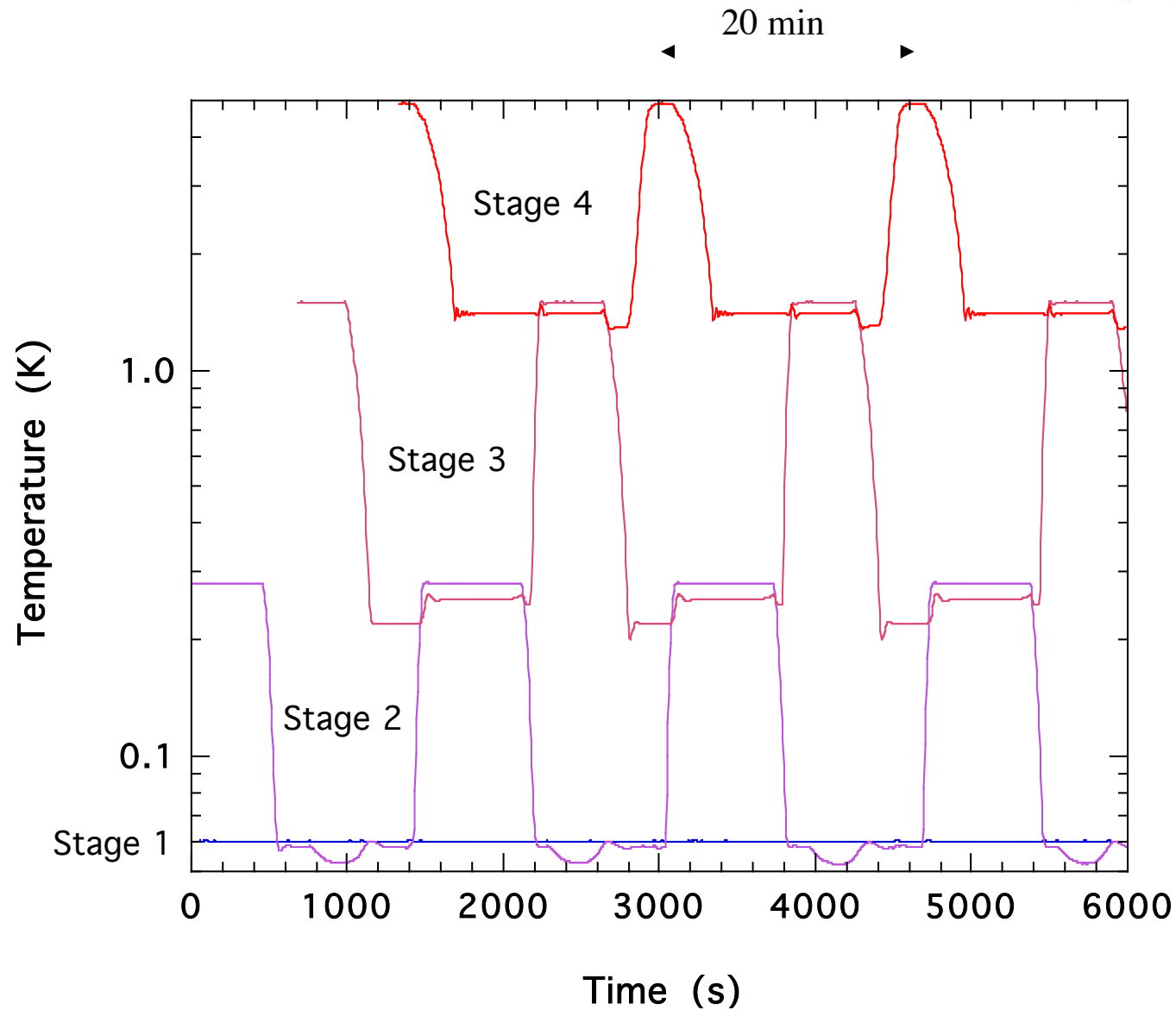




4-Stage Cycling



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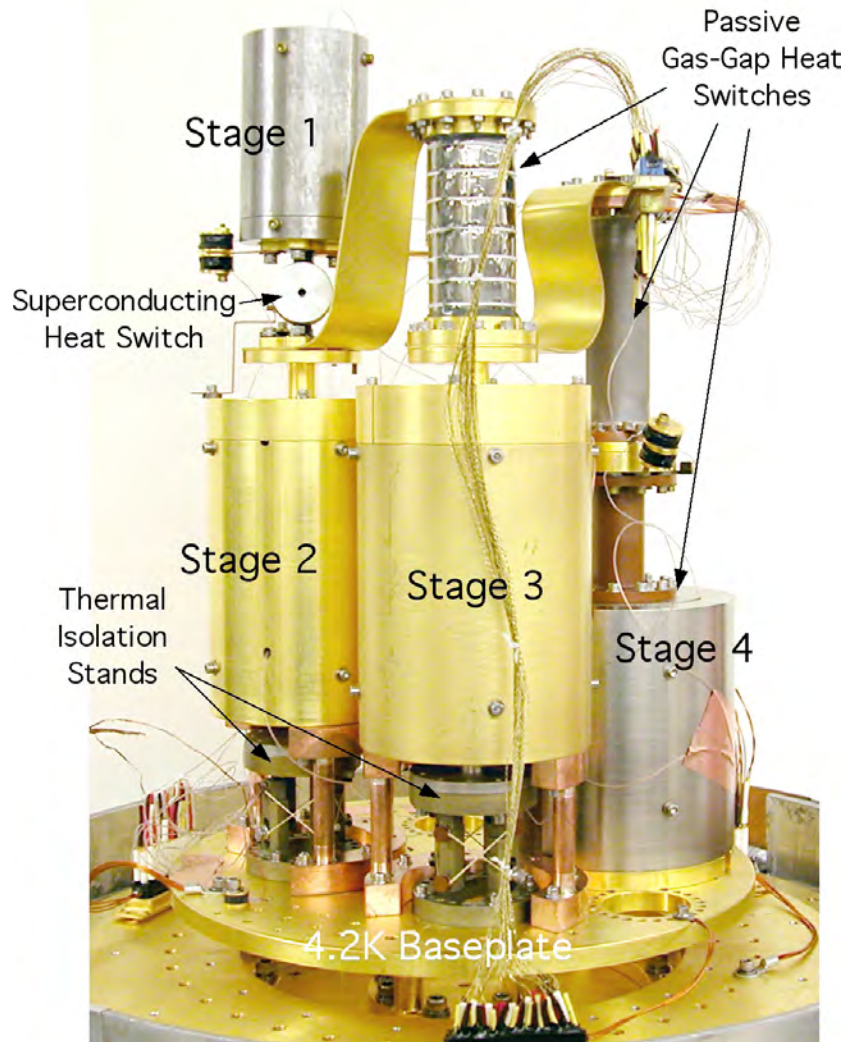




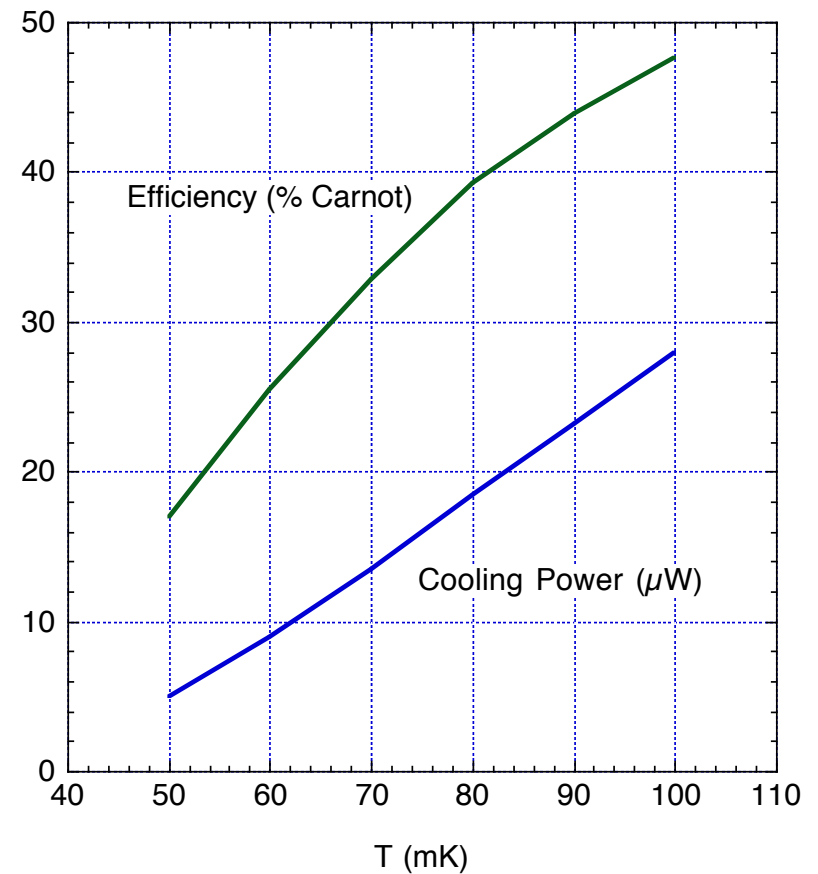
4-Stage CADR



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



Complete in-house GSFC build

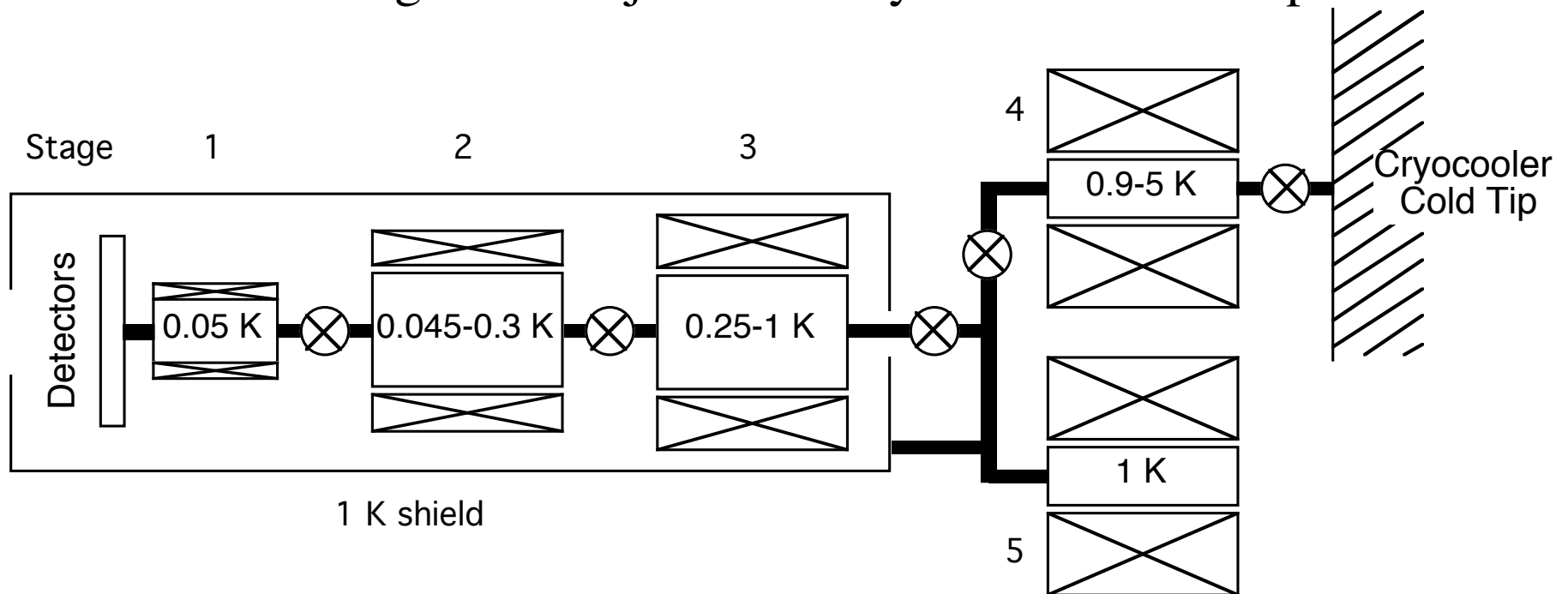


5-Stage CADR



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- 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”



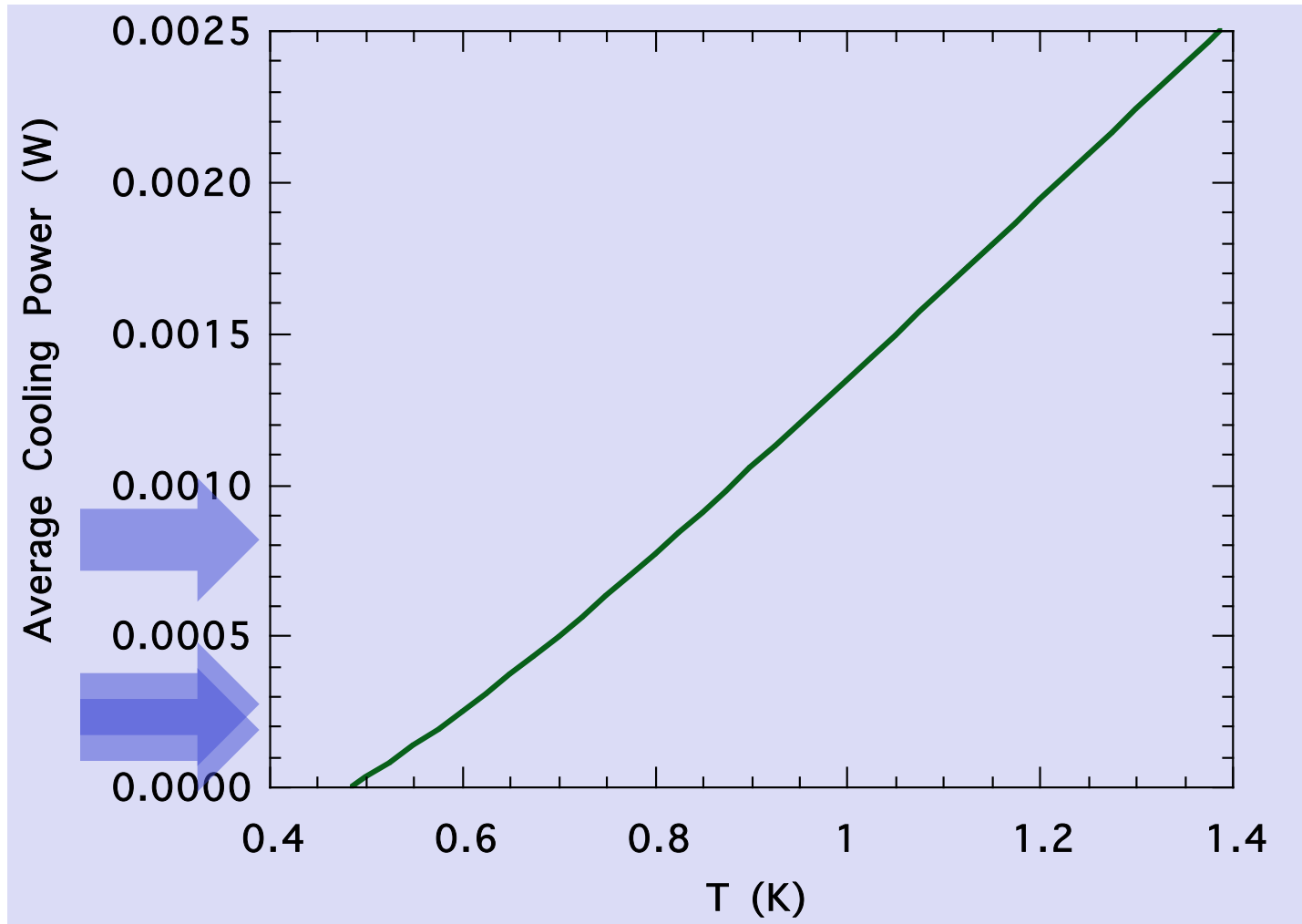
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- Cycle time is approximately 15 minutes

3-stage load:

5 μ W @ 50 mK

+ load from 4 K
1 μ W @ 50 mK



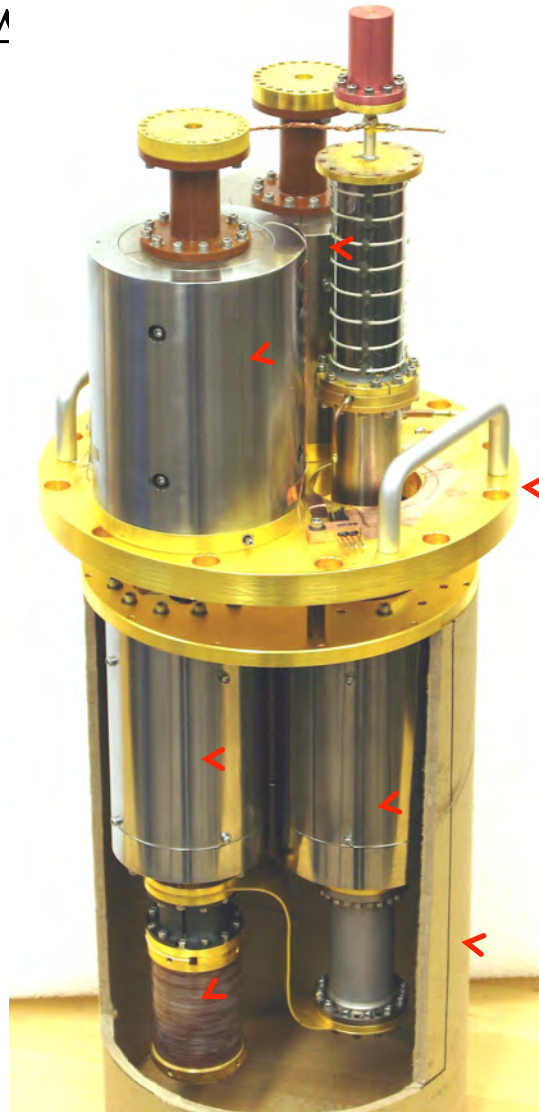


5-stage CADR



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- 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



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- Highest fields
away from
detectors

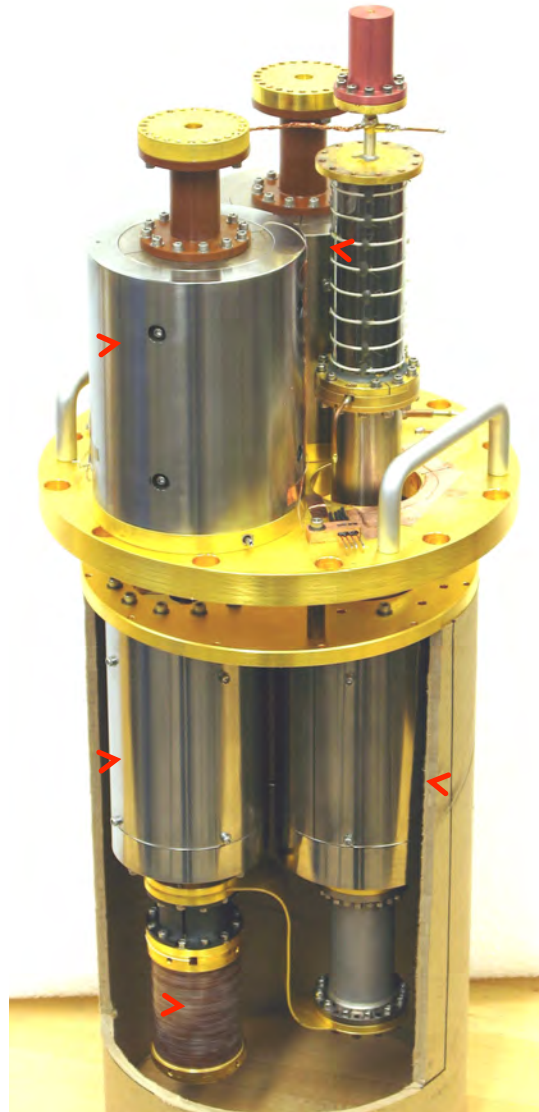
2 T @ 1.5 A

1 T @ 2 A

0.1 T @ 0.5 A

4 T @ 3 A

0.5 T @ 1 A





5-Stage CADR



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- Cooling requirements for future x-ray missions are typically:
 - Detector dissipation/wiring: $0.5\text{-}2\ \mu\text{W}$
 - “1 K” load
 - Wire conduction: $<0.1\ \text{mW}$
 - Amplifiers: $<0.1\ \text{mW}$
- Can reduce mass from current estimate of $\sim 11\ \text{kg}$
- Low peak heat rejection rate ($1\text{-}2\ \text{mW}$) also allows reduction in cryocooler requirements