Development of a flight-worthy 10 to 4 K Continuous Adiabatic Demagnetization Refrigerator

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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

• The 4 to 10 K ADR is newly tested and characterized for use in the 10 K to 0.05 K CADR

• A CADR is much lighter compared to its single-shot counterpart
Performance Requirements

- 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

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

High Temperature CADR (4K – 10 K)  Low Temperature CADR (50mK – 4 K)

Magnetic shield (outside B<5 μT)

Thermal shield against 10 K components

Passive Gas Gap Heat Switch

Stage 4a: 1.2 K - 4K
Stage 3: 260 mK - 1.4K
Stage 2: 45 mK - 300 mK
Stage 1: Continuous and constant at 50mK

Salt pill

Passive Gas Gap Heat Switch

Nb/35Sn superconducting magnet

Active Gas Gap Heat Switch

Salt pill

Passive Gas Gap Heat Switch

Nb/35Sn superconducting magnet

Salt pill

Passive Gas Gap Heat Switch

Nb/35Sn superconducting magnet

Salt pill

Superconducting heat switch

50 mK to 10 K CADR system
CADR Component Packaging

- Magnetic shield
- 4 K to 0.05 K CADR
- 4 K interface
- 10 K to 4 K CADR
- 10 K interface
10 to 4 K CADR Subsystem

10 K platform

Stage 5a: 4 K – 10 K
Passive Gas Gap Heat Switch

Stage 5b: 4 K – 10 K
Passive Gas Gap Heat Switch

Active Gas Gap Heat Switch

4 K platform

Active Gas Gap Heat Switch

Nb3Sn superconducting magnet
10 to 4 K single-stage ADR

• A 10 K platform is simulated by temperature controlling the cold plate.

• The Passive Gas Gap Heat Switch (PGGHS) is tuned to turn “on” at 10 K.

• The salt pill, a single crystal of Gadolinium Gallium Garnet (GGG), slightly protrudes out of the magnet bore (optimized size).

• 4K platform is simulated by a small plate and instrumented with heater to enable temperature controlling.
10 to 4 K CADR Components

10 K Nb$_3$Sn Magnet

GGG Salt Pill Assembly

Kevlar Suspension Assembly

Passive Gas Gap Heat Switch

Active Gas Gap Heat Switch
Single-Stage 10 - 4 K ADR

- Passive Gas-Gap Heat Switch
- 10 K Test Plate
- Silicon-Iron Shield
- Copper Strap
- Salt Pill End Flange
- Nb$_3$Sn 10 K magnet
10 to 4 K ADR Test Results

- Optimized cycle for a 2-stage (parallel configuration) is one where the recycle time equals the hold time.

- The optimized cycle was experimentally found to have a 130 second hold time/recycle time.

- This corresponds to a cooling power of 13 mW at 4K. Timing affects demag start temperature.

- Earlier a model predicted 20 mW of cooling power however the underperformance is partly due to historical misinterpretation of GGG magnetization data, and partly due to the addenda mass.
10 to 4 K single stage ADR test results
10 to 4 K single stage ADR test results
Conclusion

• A designed-for-flight 2-stage 10K to 4 K CADR is being assembled
  - 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