
# Design and performance testing of the 3-stage ADR

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# Outline



1. Background

2. System design

3. Performance testing

4. Summary

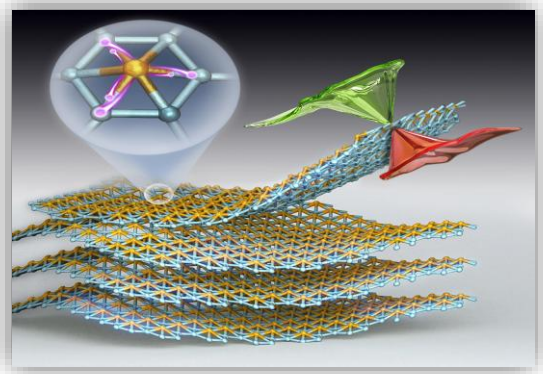
# Sub-Kelvin refrigeration



- **Sub-Kelvin refrigeration** (< 1 K) is a critical technology for space exploration, fundamental physics and quantum technologies

- **Adiabatic demagnetization refrigeration (ADR)** based on the magnetocaloric effect, is one of the dominant technologies, because of its wide temperature coverage, high efficiency and gravity-independence

Space detectors



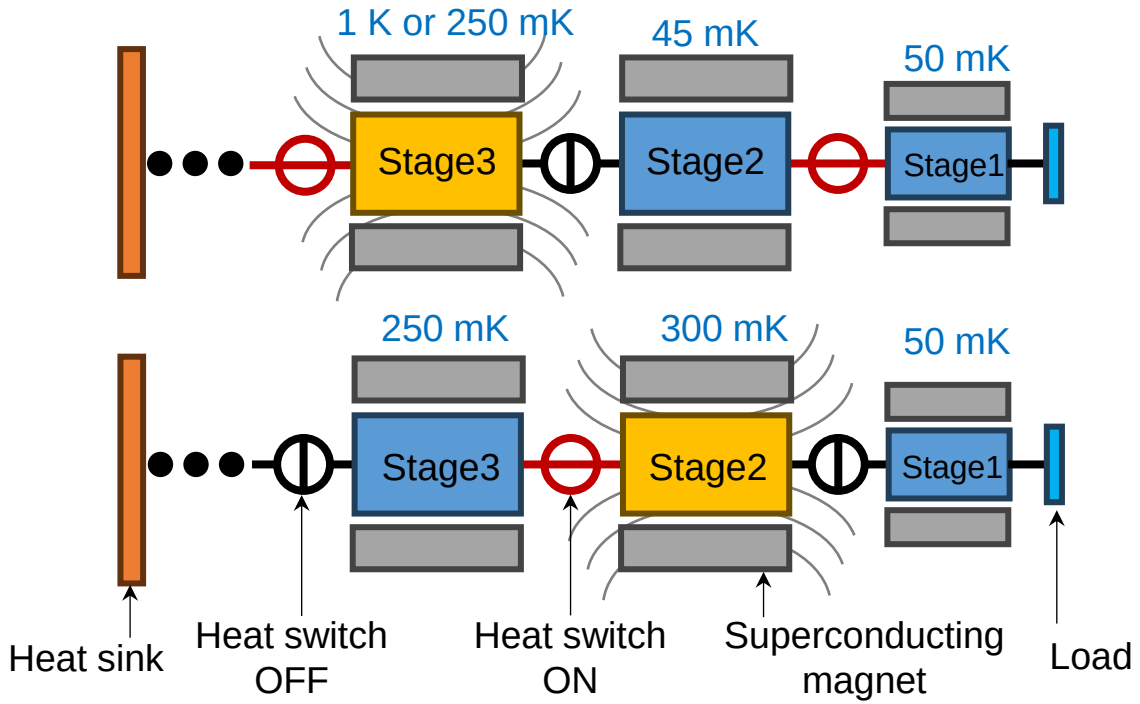
Fundamental physics

Quantum Computing

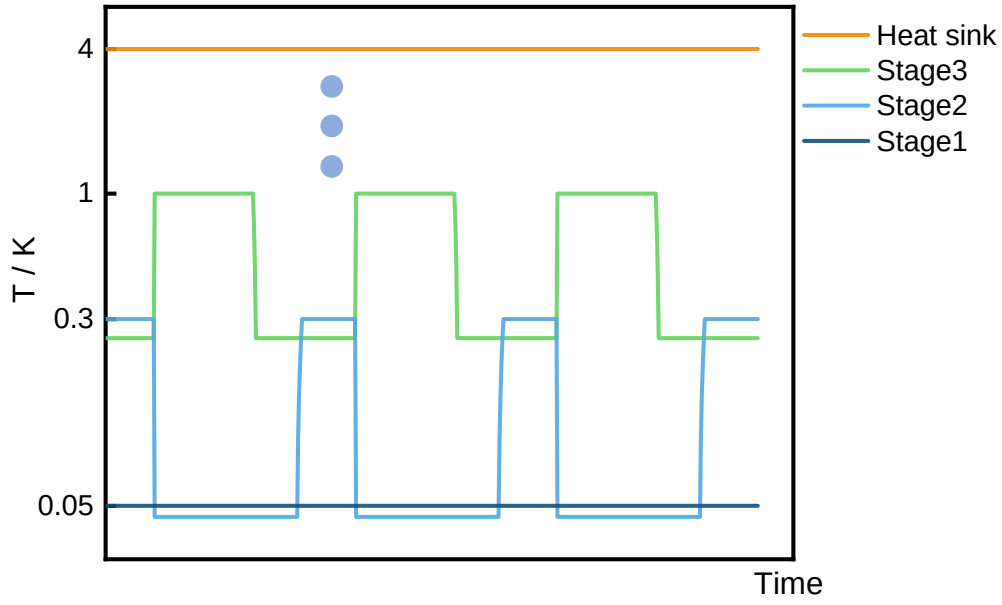
# Muti-stage ADR



- For space exploration mission and many ground-based experiments, it will need **muti-stage ADR**:
  - milli-kelvin cooling (50 mK or even lower) with higher heat loads
  - continuous sub-Kelvin refrigeration




**Muti-stage ADR schematic**



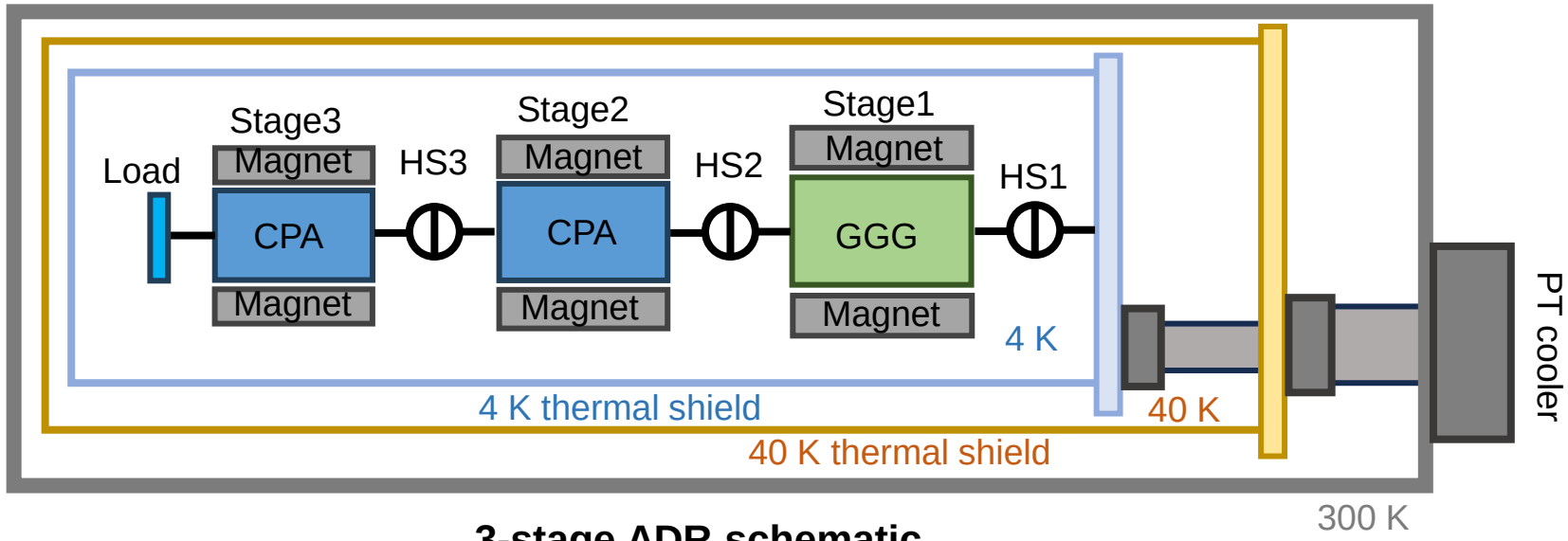

**Typical temperature curve of CADR at 50 mK**

# 3-stage ADR at 4 K to ~ 50 mK



## 3-stage ADR at 4 K to ~ 50 mK:

- ADR is pro-cooled by a GM-type pulse tube cooler
- Salt pills: stage 1-Gadolinium Gallium Garnet (GGG), stage 2 and 3-chromium potassium alum (CPA)
- Design includes the novel 3D-printed PEEK suspension
- All heat switches are gas-gap: HS1-active, HS2 and 3-passive
- All magnets and magnetic shields are installed on the 4 K cold plate




**3-stage ADR schematic**

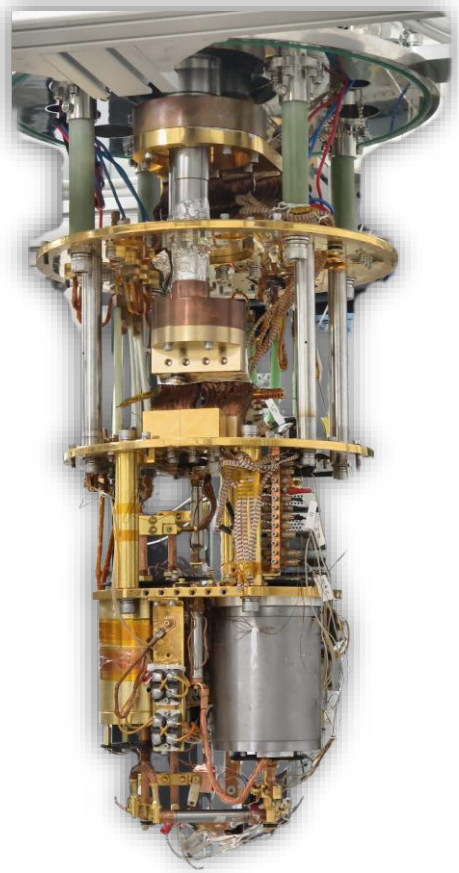
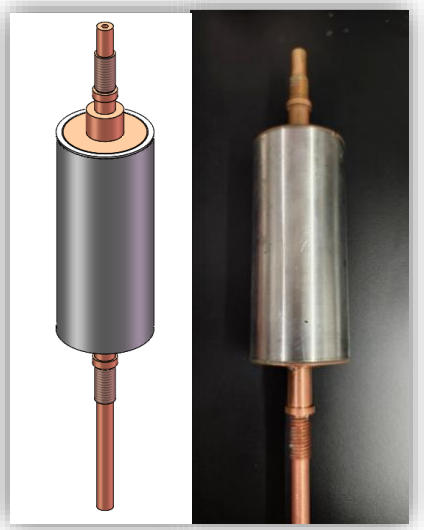


**Photo 3-stage ADR**

# Components

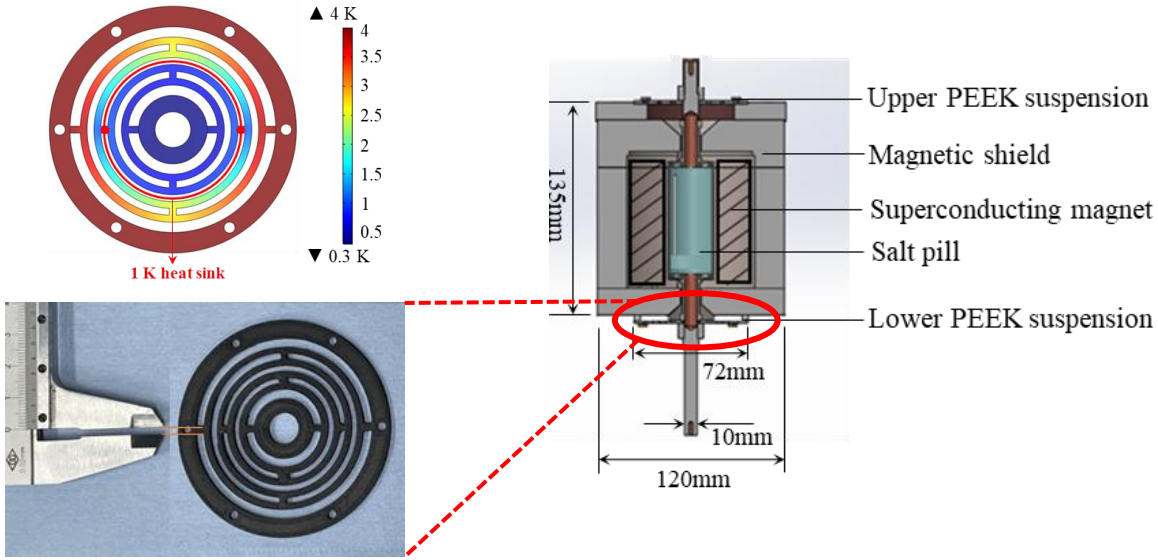


- **Salt pill**: GGG (1078 g) with heat transfer via $^3$He, CPA (54 g and 45 g) with the wire thermal bus
- **PEEK suspension**:
  - The Kevlar suspension is replaced with the 3D-printed PEEK suspension
  - With a 1 K heat sink, PEEK suspension has 0.18 μW thermal leak between 4 K and 300 mK



Stage 1 GGG salt pill

Stage 2 and 3 CPA salt pill



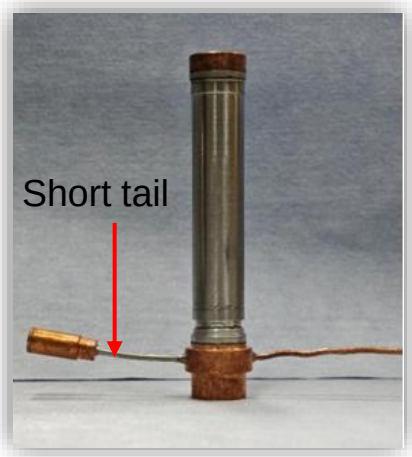

PEEK suspension for 3-stage ADR

# Components

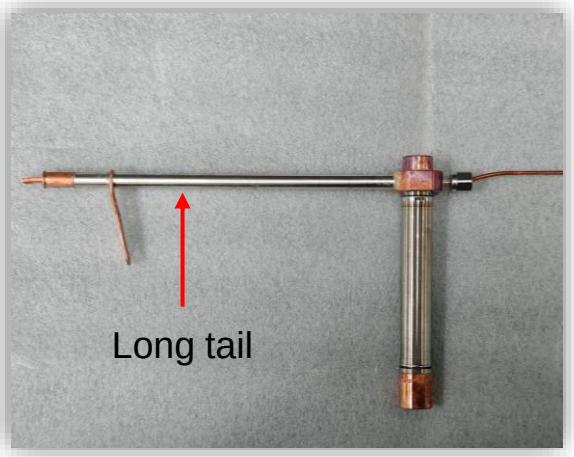


- **Other components**: heat switch, superconducting magnet and magnetic shield
  - **Superconducting magnets** are designed with 4T for stage 1, 2T for stage 2 and 3
  - **Active gas-gap heat switches** are used at stage 1 (4 K→1 K) and stage 2 (1 K→200 mK)
  - **Passive gas-gap heat switch** is used at stage 3 (200 mK→50 mK) with a switch temperature of ~150 mK to avoid extra heat for low temperature stage


**Magnet and magnetic shield**




**Active gas-gap HS1**




**Active gas-gap HS2**


**Passive gas-gap HS1**

# System design



| System design details | | | |
|---|---|---|---|
| | Satge 1 | Stage 2 | Stage 3 |
| Refrigerant type | GGG | CPA | CPA |
| Refrigerant mass / g | 1078 | 54 | 45 |
| Maximum magnetic field / T | 4 | 2 | 2 |
| Maximum magnetic current / A | 14.1 | 17.7 | 11 |

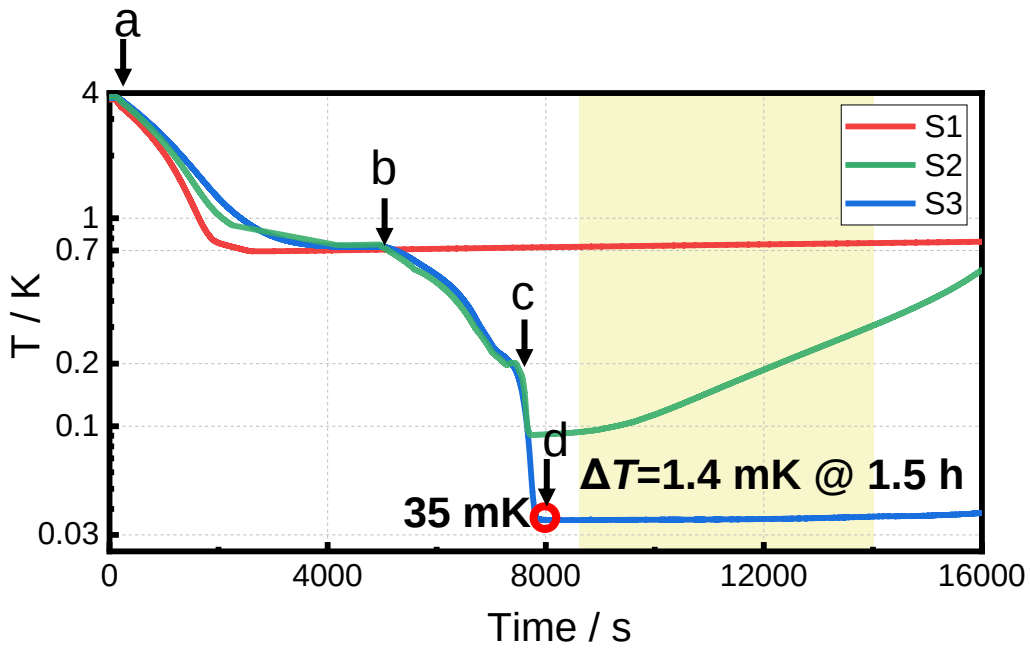
**A large-mass GGG extends 1 K cooling duration, focusing on stage 2 and 3 testing**

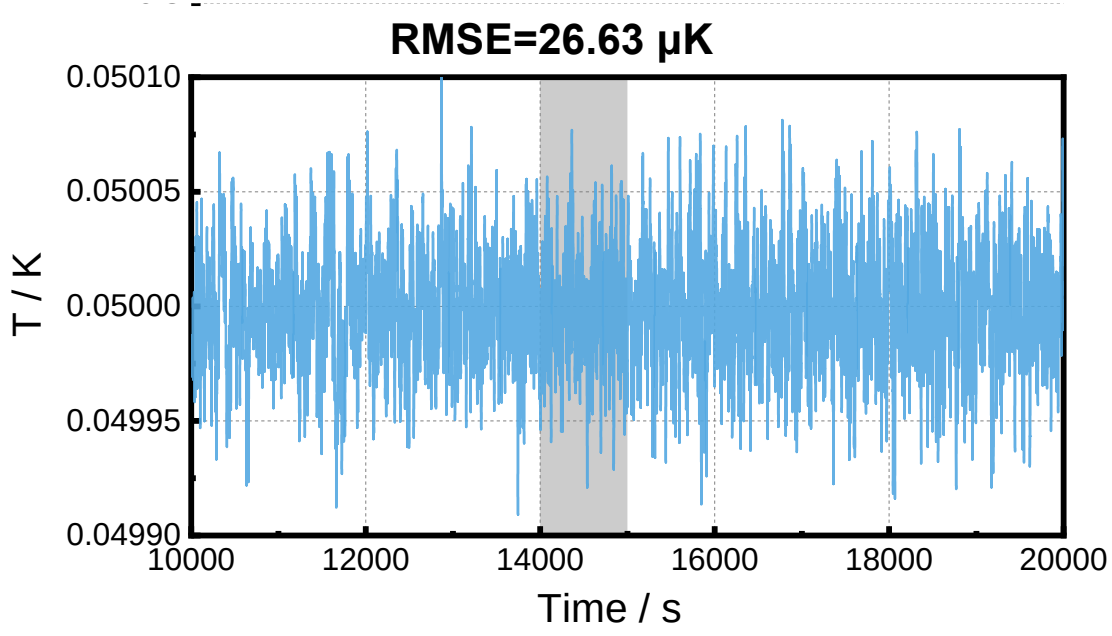
# Single-shot mode



## ☐ Lowest temperature and cooling capacity

- In the single-shot mode, the system achieves a lowest temperature of 35 mK
- With the total heat loss ~ 0.31μW, Δ*T*=1.4 mK @ 1.5 h
- Guess: Salt pills have a large internal thermal resistance, and CPA crystals may reach a much lower temperature  with a large heat capacity
- Cooling at 50 mK @ 0 μW about 2.7 h, total capacity of 31.28 mJ by the theoretical calculation



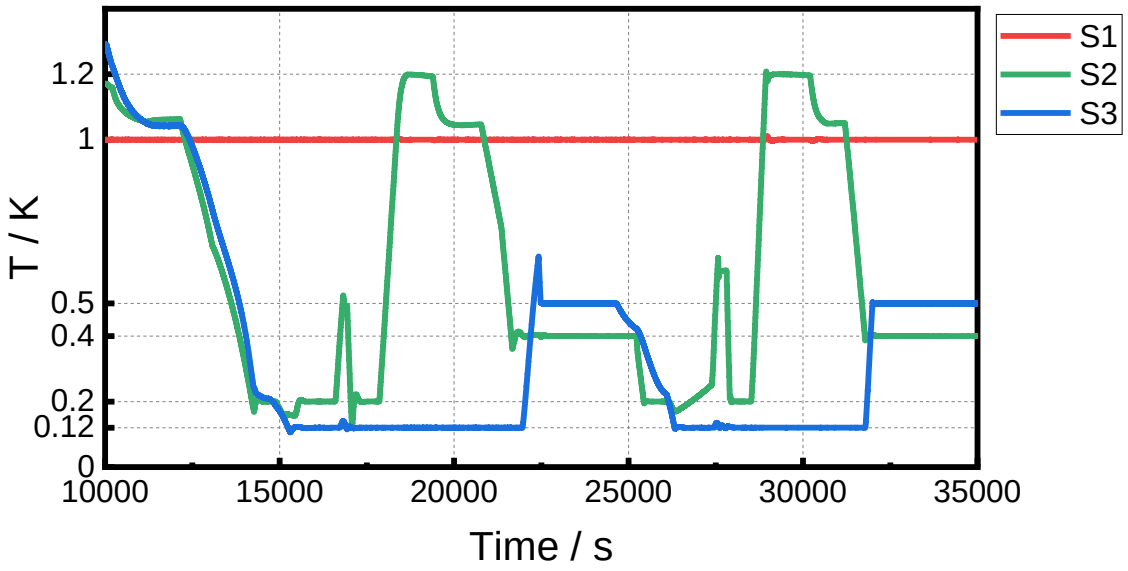



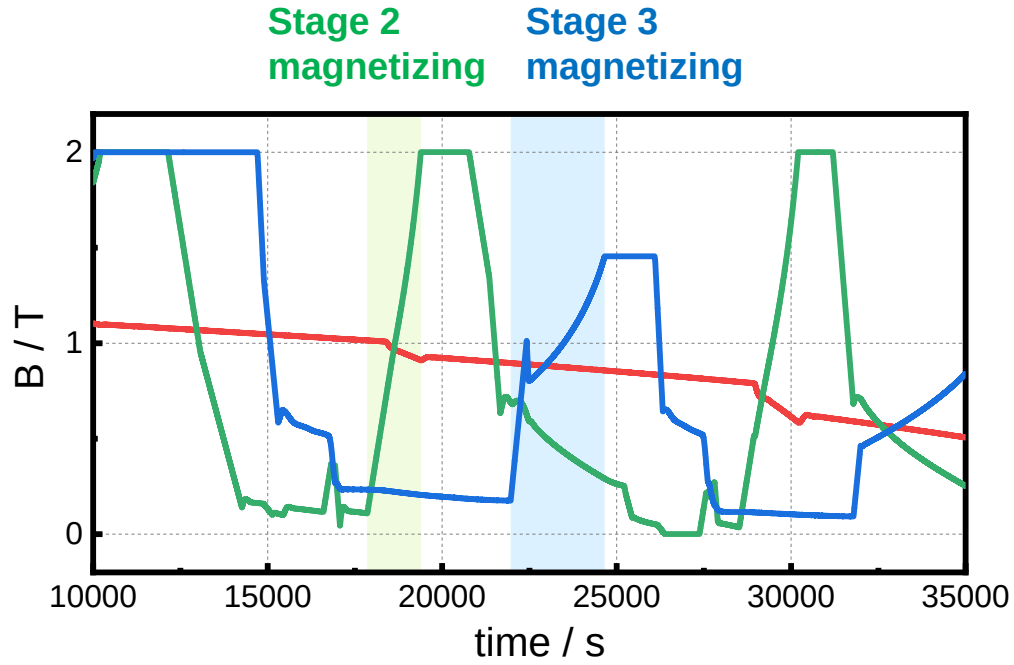
# Intermittent cooling



## ☐ 100 mK intermittent cooling

- In the intermittent cooling, stage 1 stabilizes at 1 K
- Stage 2 works at ~200 mK – 1.2 K, with an intermediate cooling temperature of 400 mK
- Stage 3 works at ~120 mK – 500 mK, with a hold time of ~ 1.5 h @ 0 μW
- Passive gas-gap HS3 is used to transfer the heat generated by stage 3 during magnetizing with the thermal conductance of 0.52 mW/K at 400 mK



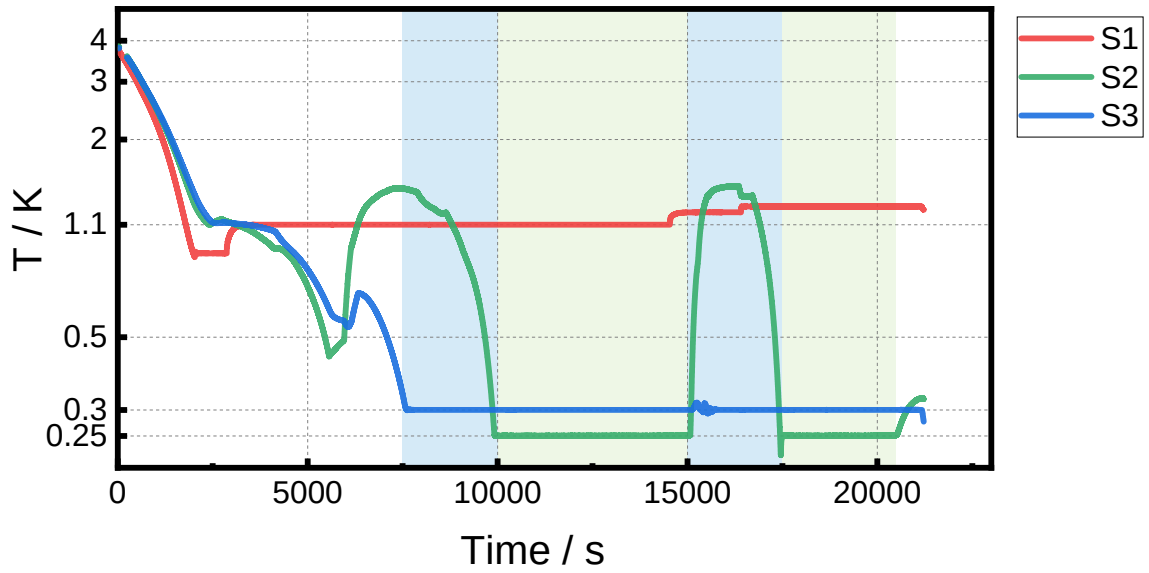



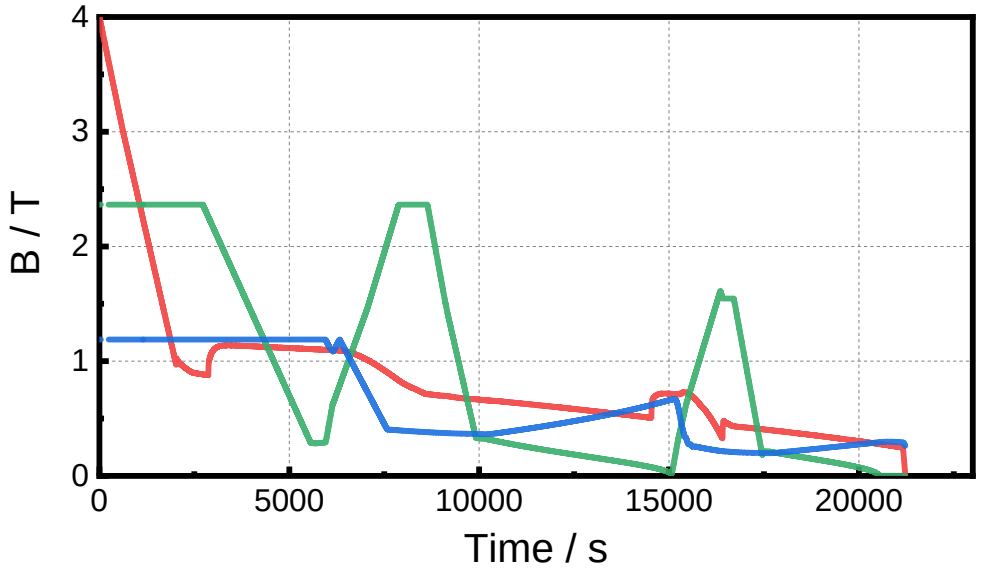
# Alternate cooling



## ☐ 300 mK alternate cooling based on new configuration

- 250 g GGG salt pill for stage 1, CPA (54 g and 45 g) salt pills for stage 2 and 3
- Active gas-gap heat switches for each stage
- Cooling at 300 mK @ 0 μW for 3.75 h and achieving 2 cooling cycles



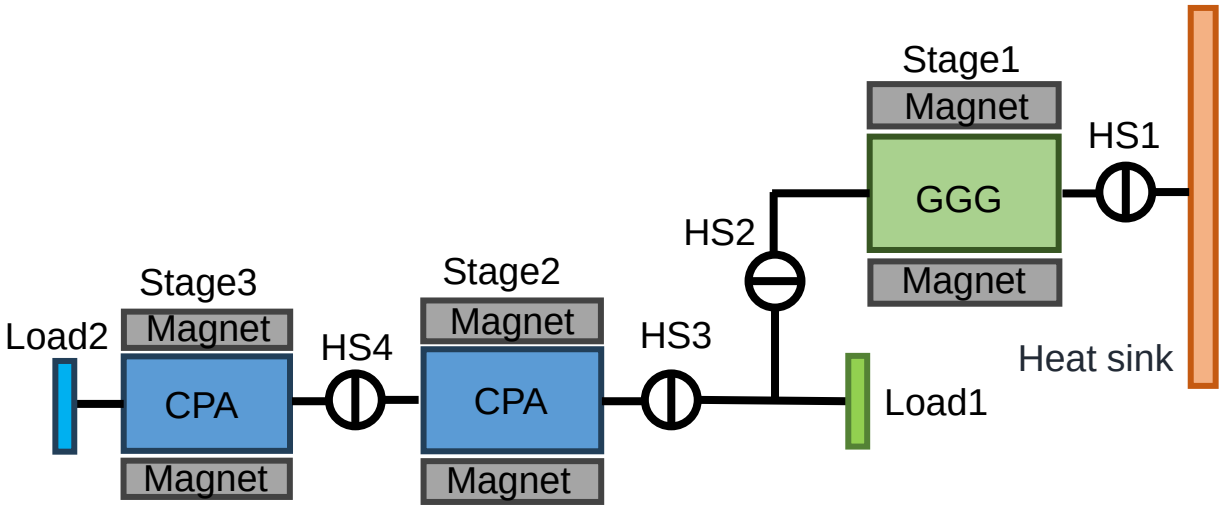



# Path forward

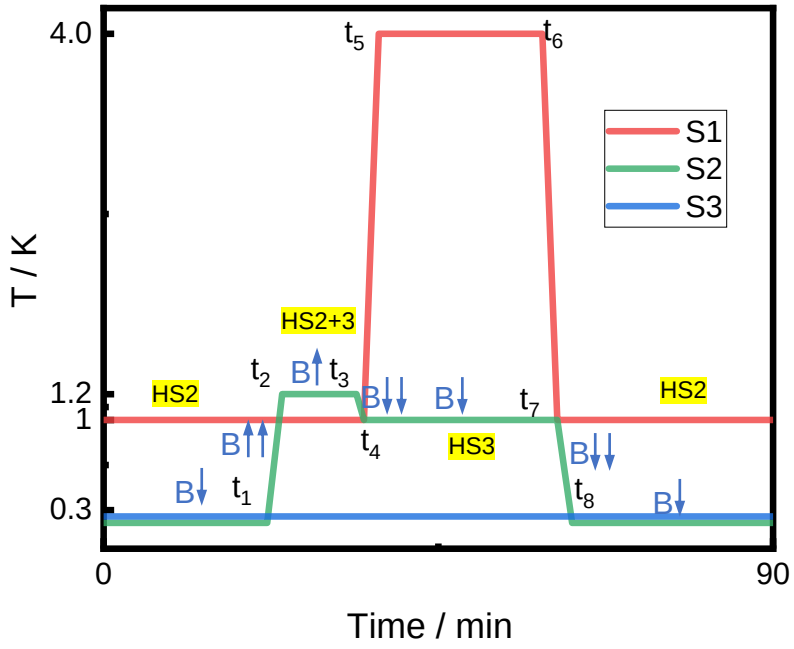


## ☐ Multiple continuous cooling stages ADR

- Based on the above 3-stage ADR, we designed an interesting configuration for realizing 1 K and 300 mK continuous cooling




**2 continuous cooling stages ADR schematic**




**Typical temperature curve**

Wei Dai. An adiabatic demagnetization refrigeration with multiple continuous cooling stages: CN202311336781.7[P]. 2023.12.05

# Summary



- A 3-stage ADR operating from 4 K to 50 mK is designed with GGG for high temperature stage and CPA for low temperature stages
- The system has achieved a lowest temperature of 35 mK in a single-shot mode as well as 100 mK intermittent cooling
- At the cooling temperature of 50 mK, the system could holds ~ 2.7 h with no load and the temperature fluctuation is 26.63 μK (RMSE)
- A new ADR configuration is designed for multiple continuous cooling stages


# THANKS

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