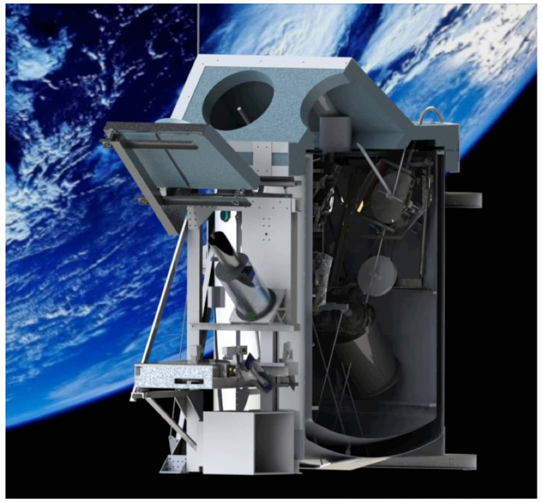
PIPER's Continuous Adiabatic Demagnetization Refrigerator

Eric Switzer (NASA GSFC)

Dec. 15 2015



PIPER

balloon-borne CMB polarization telescope

al: map most of the sky and constrain the inflationary
avitational wave signal and dust foregrounds.

A. Kogut (PI)
D. Benford
D. Chuss
B. Dotson (Ames)
D. Fixsen
C. Jhabvala
P. Mirel
S. Moseley
J. Staguhn
E. Wollack

P. Ade (Cardiff)
C. Bennett (JHU)
J. Eimer (JHU)
M. Halpern (UBC)
G. Hinshaw (UBC)
G. Hilton (NIST)
K. Irwin (Stanford)
J. Lazear (JHU)
J. McMahon (Umich)
C. Tucker (Cardiff)

PIPER CADR:

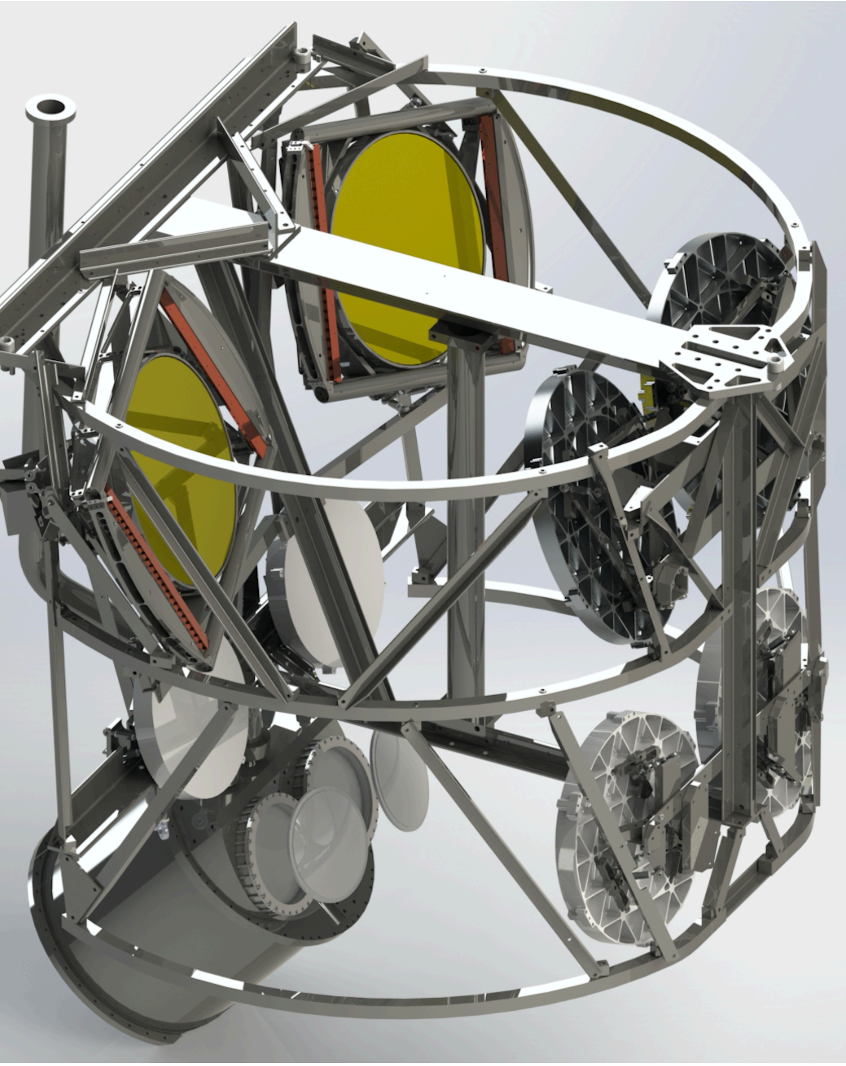
J. Hinderks
M. Kimball
J. Lazear
L. Lowe
P. Shirron
D. Sullivan
E. Switzer

PIPER's strategy

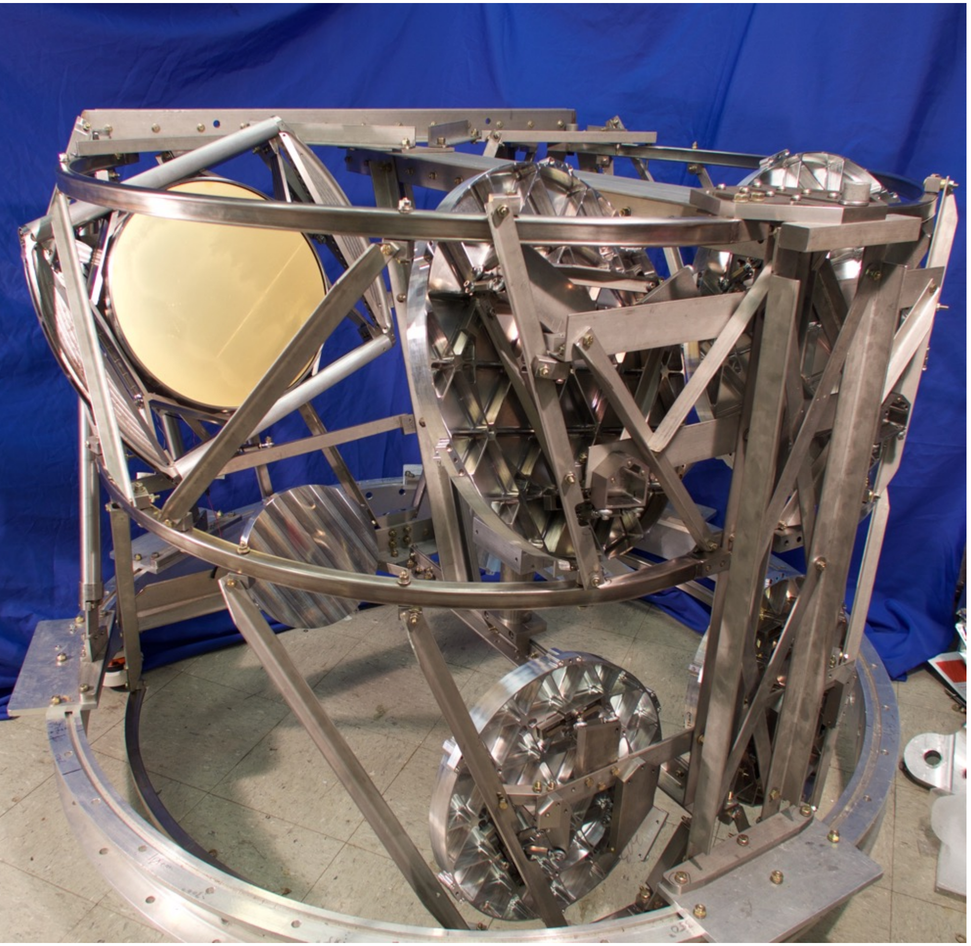
- **High frequency coverage for dust foregrounds. (200, 270, 350, 600 GHz)**
- **Cryogenic VPM modulator and scan support measurement of 85% of the sky; goal: reionization signature.**
- **Continuous ADR provides cooling to 100 mK**, colder than ~300 mK in adsorption coolers.
- No windows, cold optics → high sensitivity.
- One-day flights from Ft. Sumner and Alice Springs (simpler logistics). One flight per band.
- Single detector array for all bands.
- r < 0.007 for 8 flights, r < 0.03 for single flight.

Instrument in a bucket dewar of LHe:
4.3 K on the ground
1.6 K at float

PIPER Optics frame

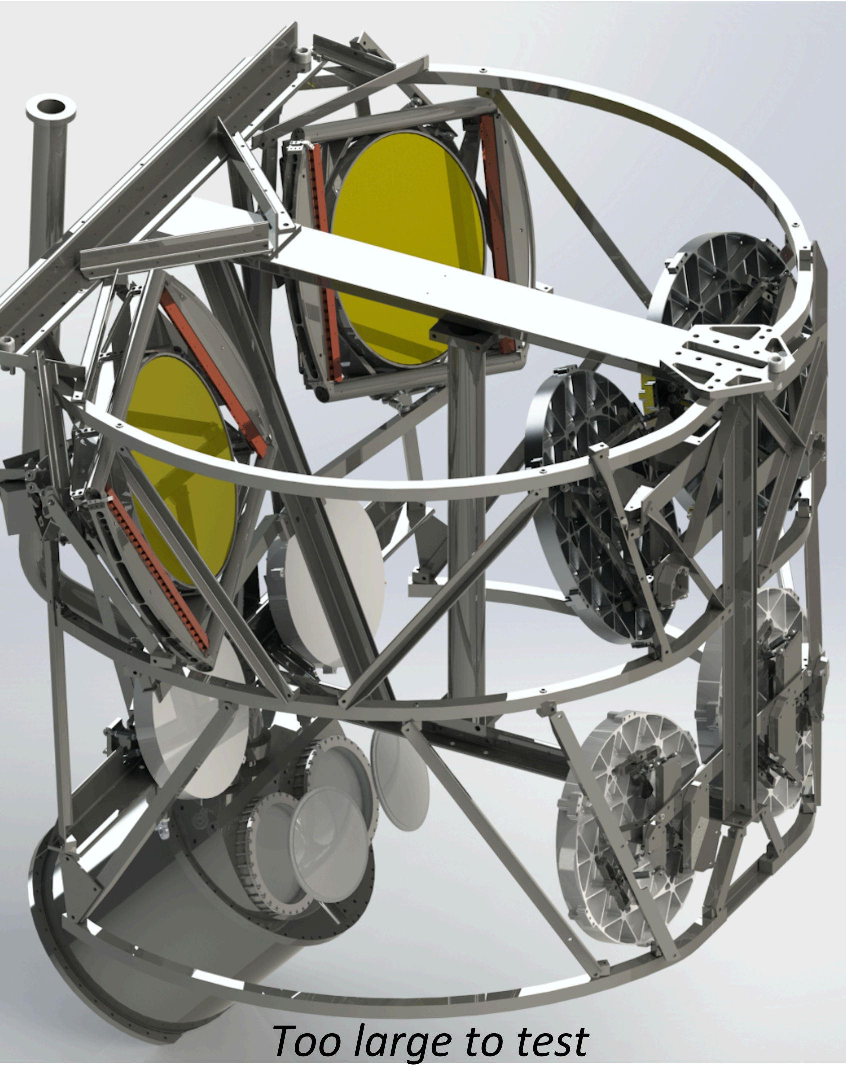


PIPER Optics frame



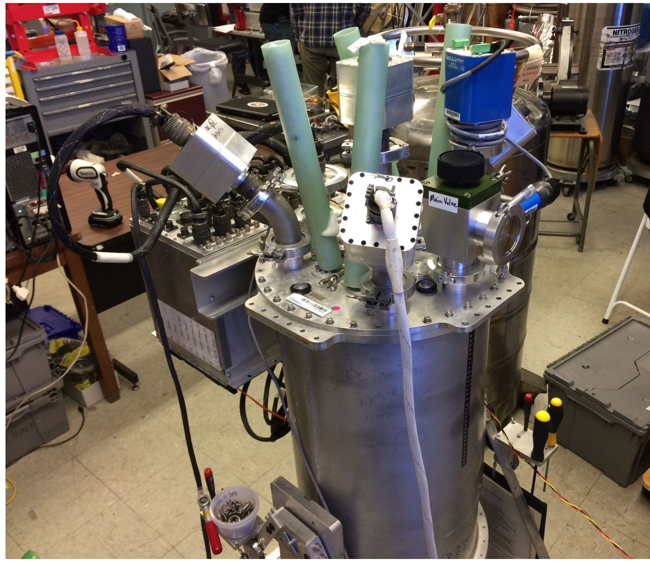
Silicon lenses, U. Michigan AR metamaterial

Test systems



Too large to test

Flight camera testing in an intermediate dewar.

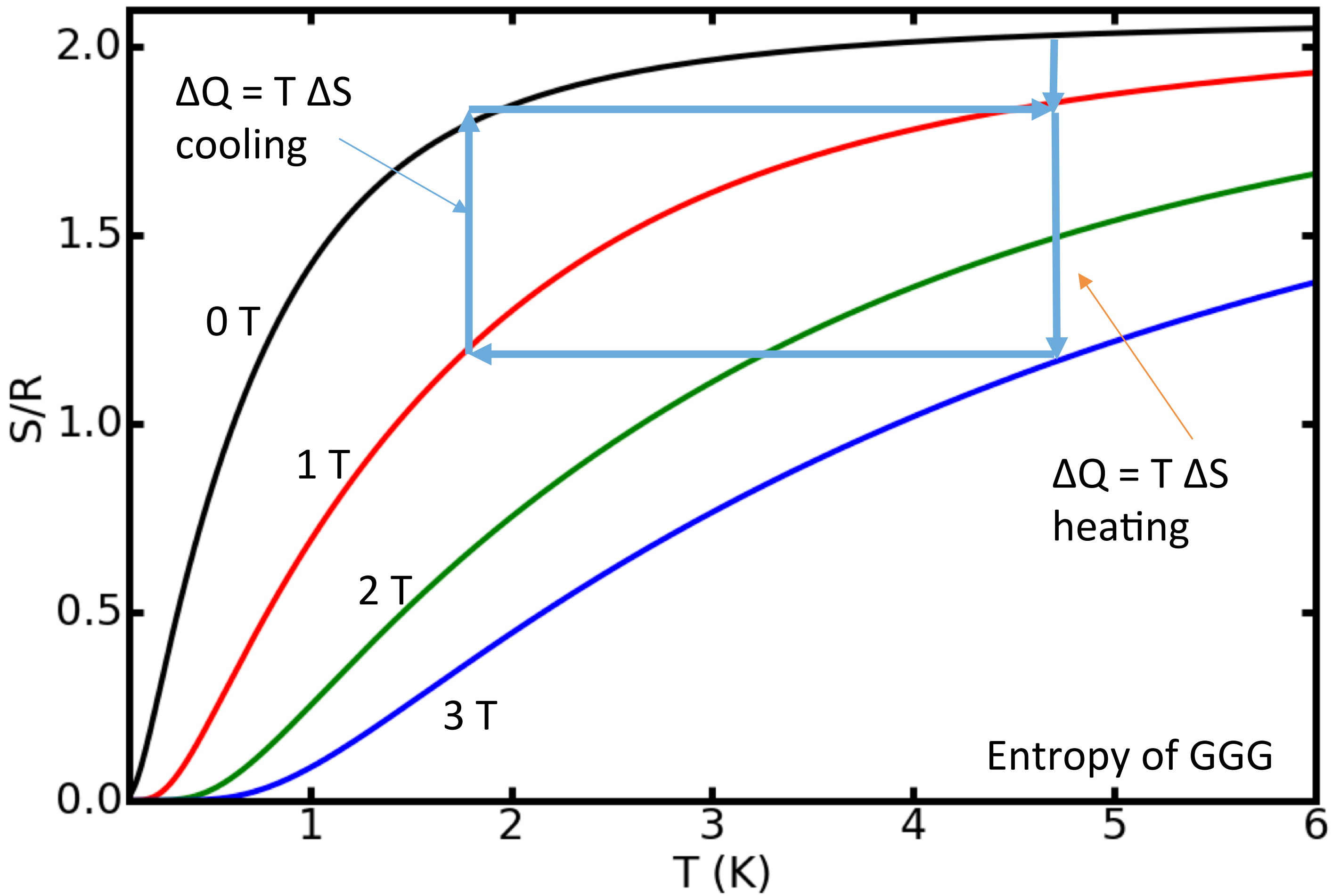


Rapid turnaround detector and CADR system.

LHe with LN_2 backing.

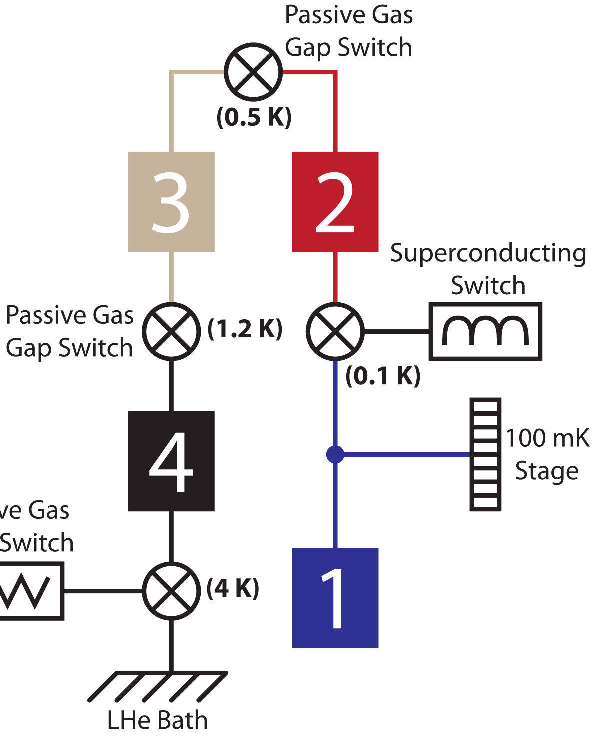
Can be pumped.

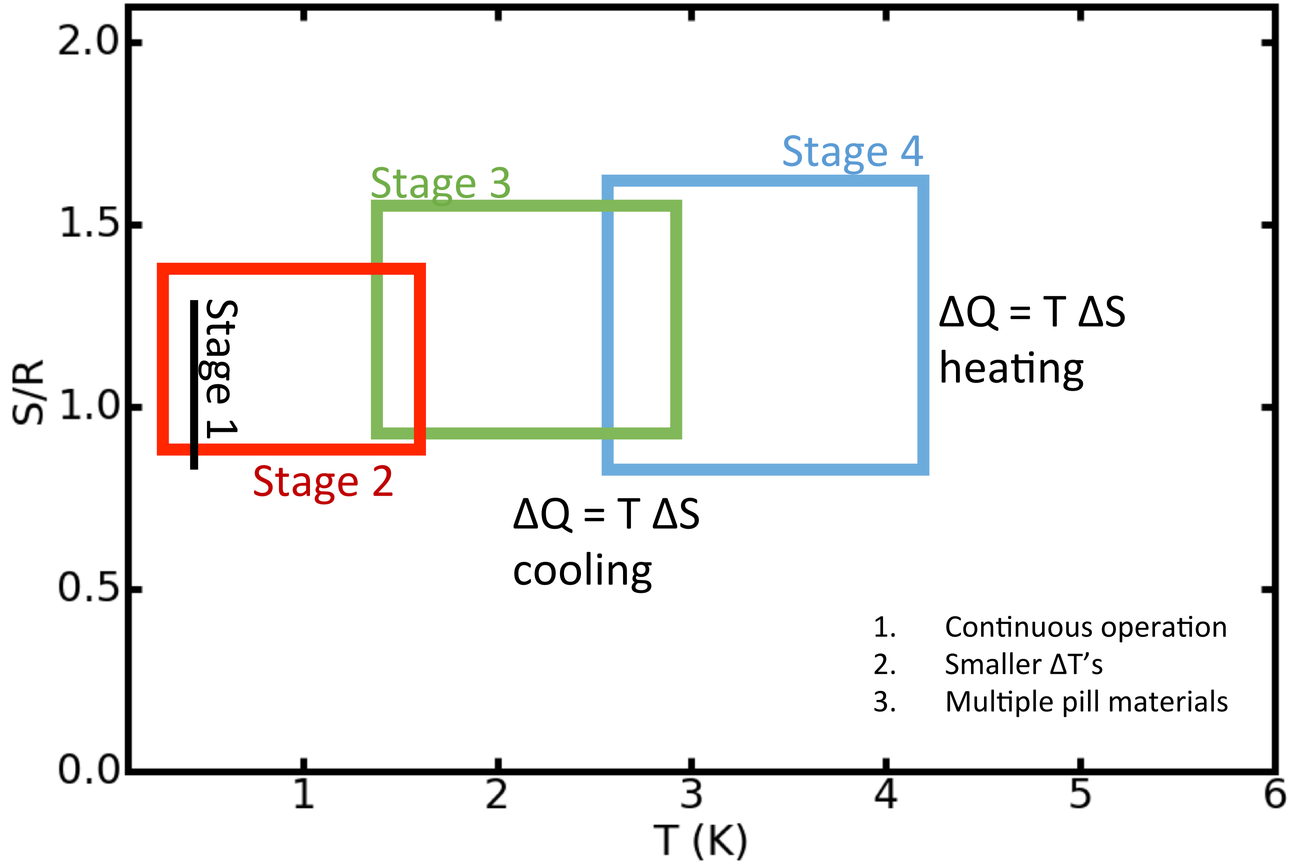
ADR thermodynamic cycle



Accept ΔS isothermally at operating point
Reject ΔS isothermally to the bath, or upper stage

Multi-stage operation



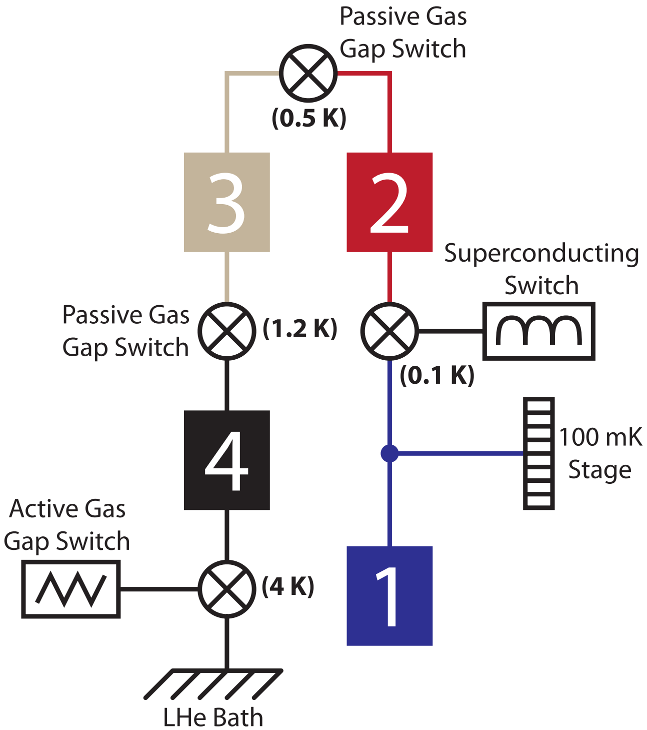


Power = Energy per cycle / time per cycle.

Want: fast cycle turn-around, high heat transfer rates, low gradients

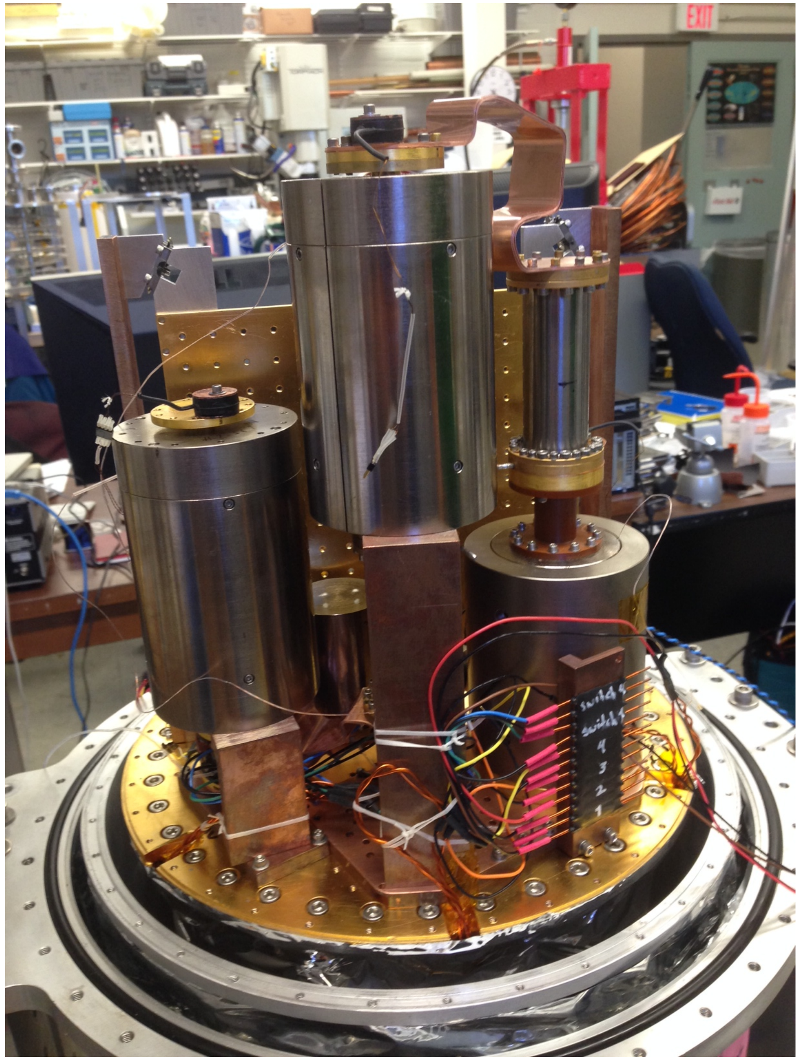
(Even at the expense of switch-off conductances, and larger thermal bus in salt volume.)

4-stage Continuous ADR (CADR)

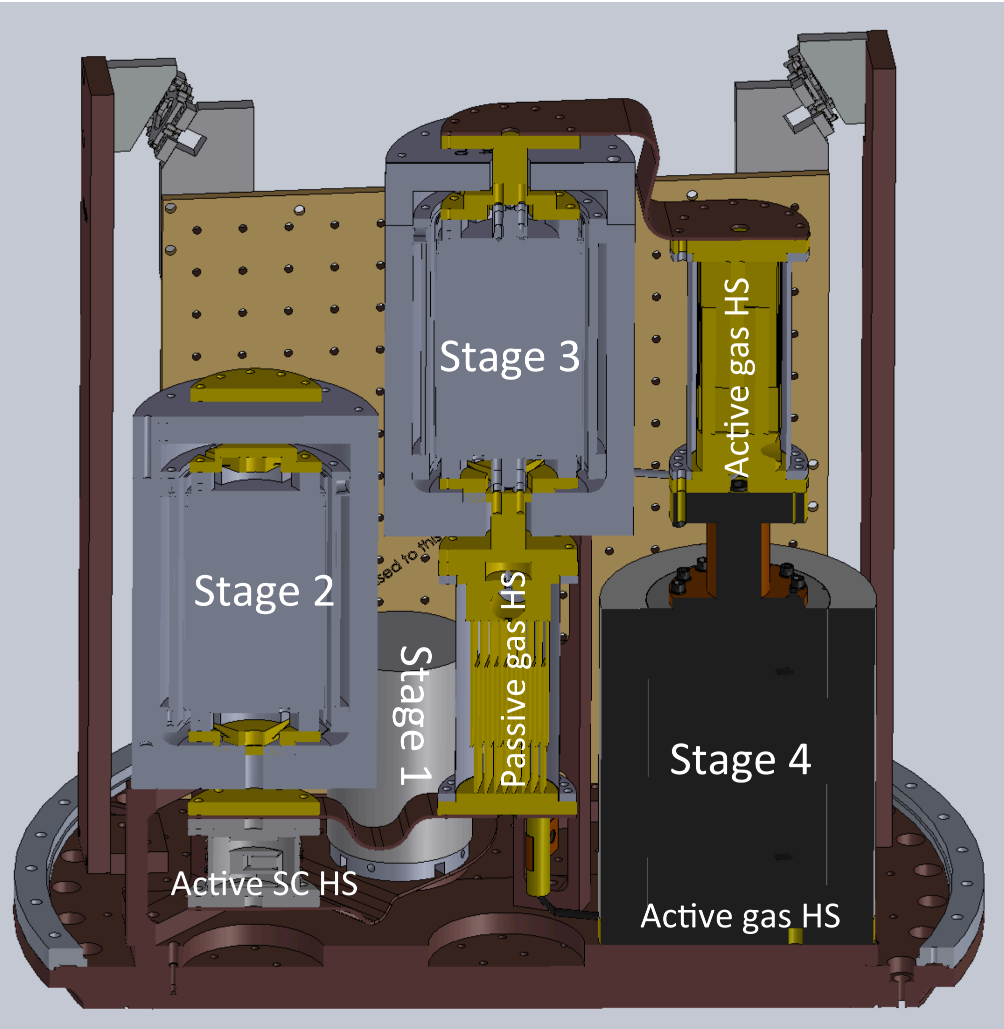


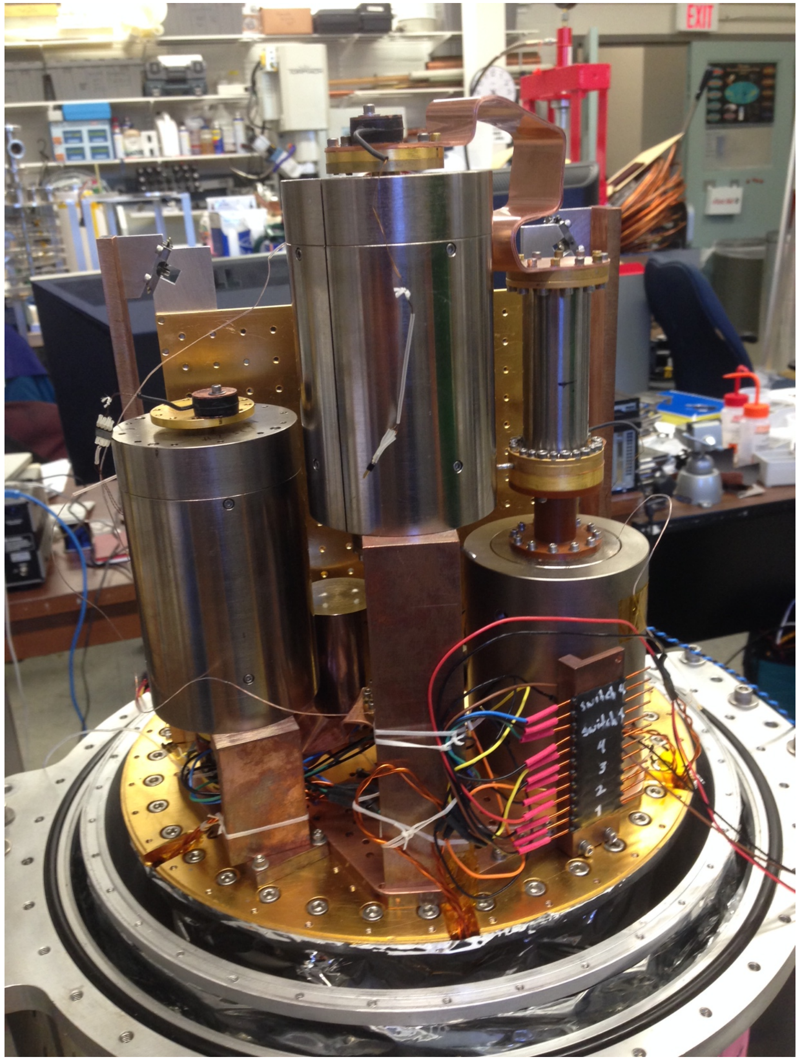
GROUND: **4 K**
FLOAT: **1.5 K**

Continuous operation is not just about stability!:
Single-shot: want ~24 hr hold times
Continuous: hold only needed as long as upper stages recycle (~20 min)

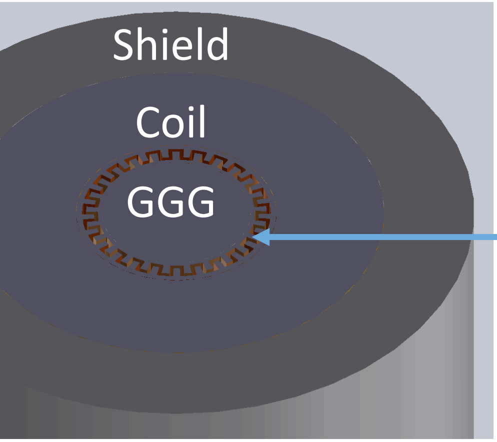


4-stage Continuous ADR (CADR)





Stage 4 (S4)



Stage 4 in cross-section

G(cond) ~ 50 mW/K

Connection to stage 3 through active gas-gap heat switch

Stainless bellows compliantly connect cold finger to the axis of the coil w/ low conductivity, and seal the gas in the heat switch.

Integrated active/passive HS, getter inside/outside
Serpentine fins to maximize conductivity

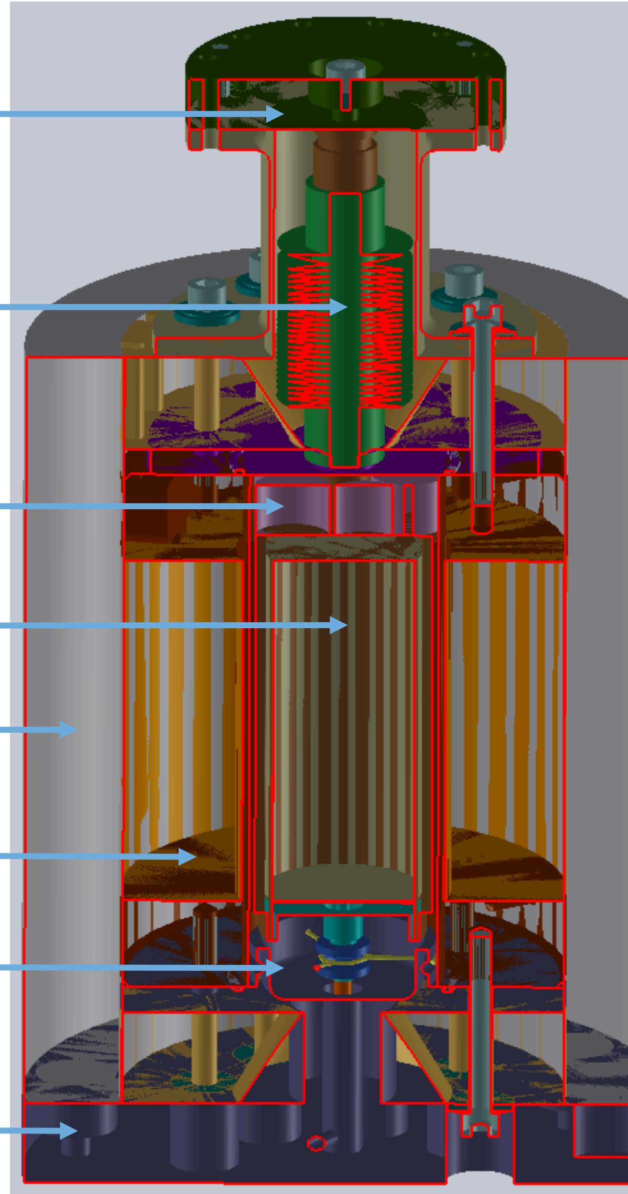
85g Gadolinium Gallium Garnet (> 0.5 K operation)

4% Si-Fe shield, 0.45" thick

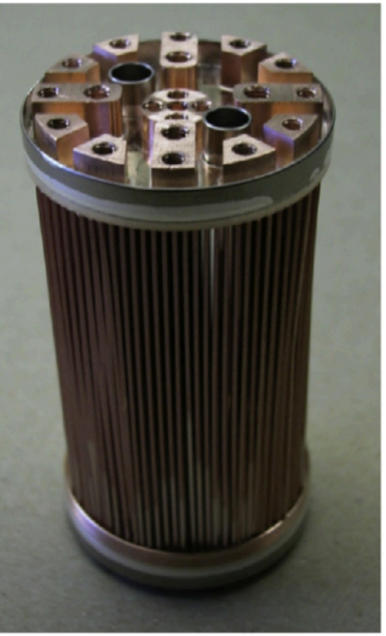
NbTi windings (1.3 T/A), 3 A maximum current
60 H inductance, 6 K maximum temperature

Kevlar suspension
Cavity and port to fill/external getter

Connection to LHe bath (4.3 K – 1.6 K)



Stage 3 (S3)



~30% of pill volume is high-purity copper thermal bus to achieve high heat transfer rates at low temperature.

CPA is not corrosive to copper (vs. FAA)

Connection to stage 4 through active gas-gap heat switch

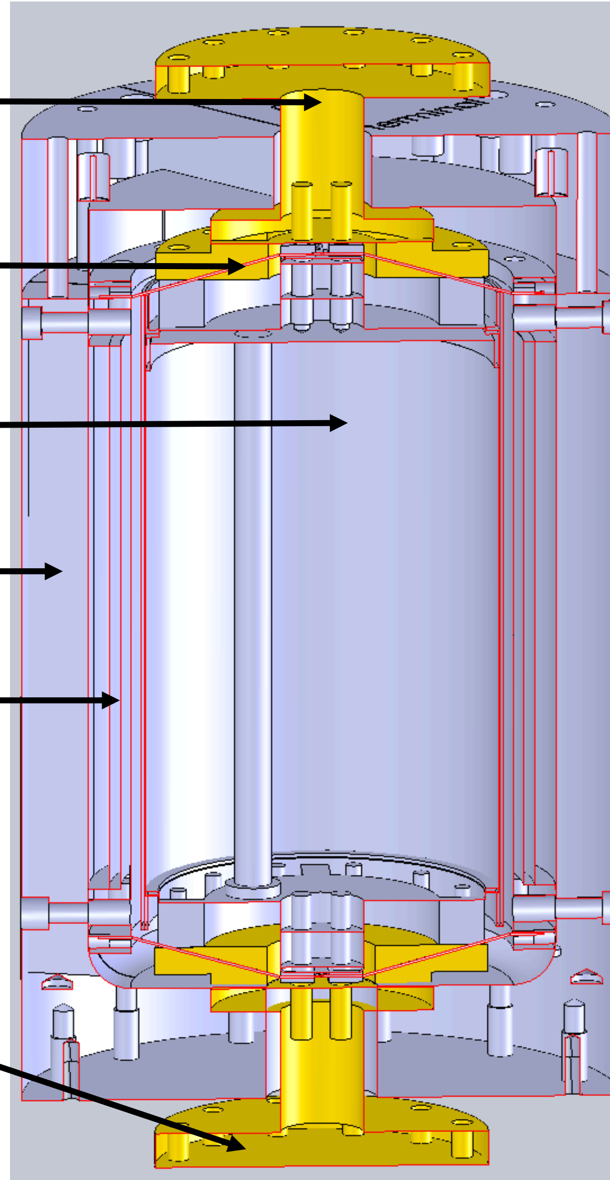
Kevlar suspension

100g Chromium Potassium Alum (CPA). Operation > 10 mK. Encapsulated.

4% Si-Fe shield, 0.3" thick

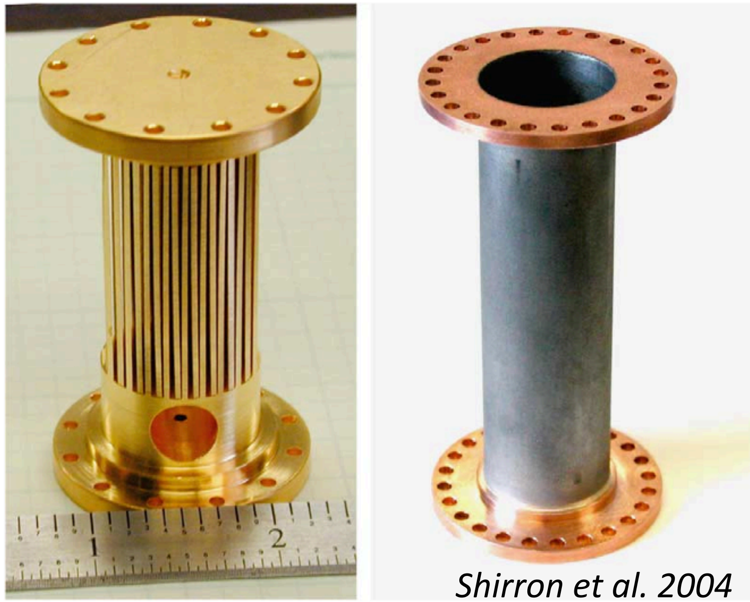
NbTi windings (0.4 T/A), 4 A maximum current.
14 H inductance, 6 K maximum temperature.

Connection between stages 2 and 3 (passive gas-gap switch)



Stage 2 is nearly identical to stage 3

Heat Switches

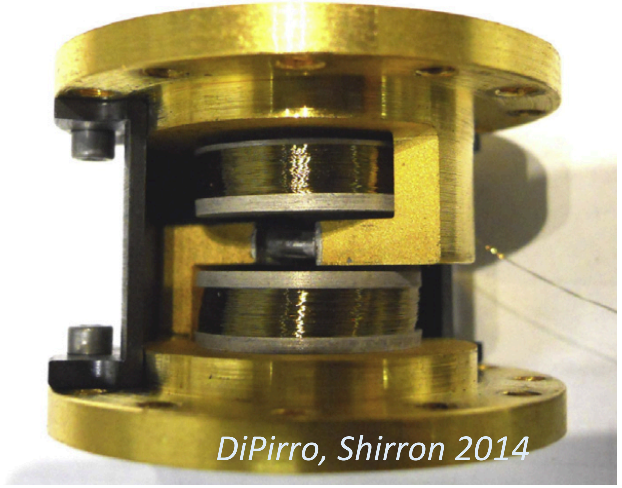


Shirron et al. 2004

Passive gas-gap heat switch. ^{3}He: high conductance below 10 K. Ti 15-3-3-3 for shell body: becomes superconducting at 3.8 K. Wall ~0.1 mm, EDM.

P ~ exp($-T_o/T$), T_o is ^{3}He binding energy ~2.6 K. PIPER switch is 145 mK, with abrupt transition.

G(nc) ~ 17 uW/K
G(cond) ~ 2 mw/K (~10 mW/K expected)



DiPirro, Shirron 2014

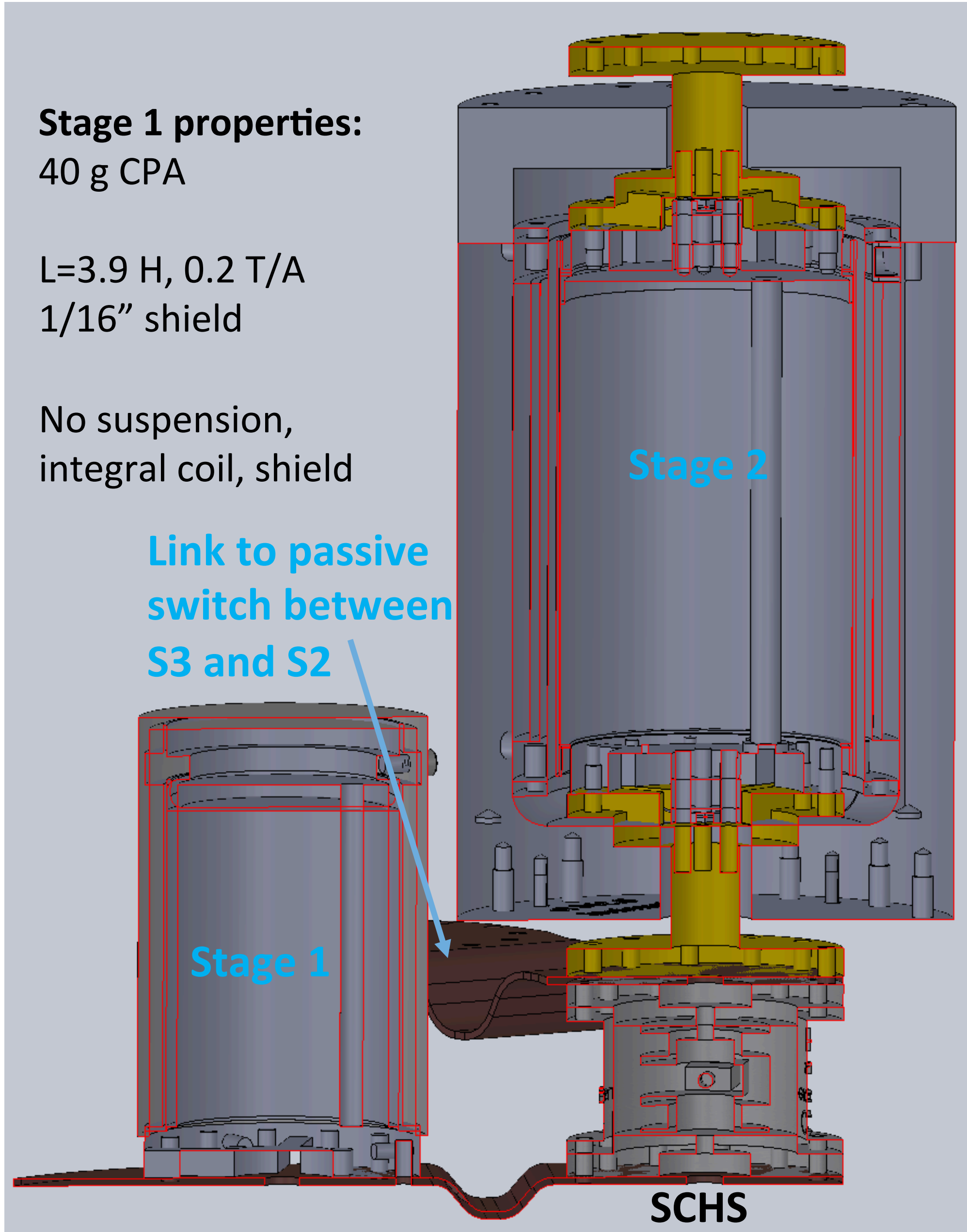
Gas gaps cannot be used below 0.2 K (saturated vapor pressure of ^{3}He is too low to provide conduction).

Lead Tc 7.2 K, H_c = 80.3 mT.
T_{max} < 0.5 K (above which ratio of off/on conductance > 1%)
Vespel-22 body, currently no shield.

G(nc) ~ 20 uW/K
measured G(cond) ~ 1 mW/K (~10 mW/K expected)

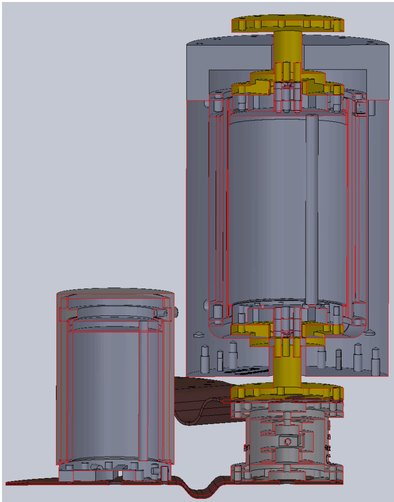
Continuous stage

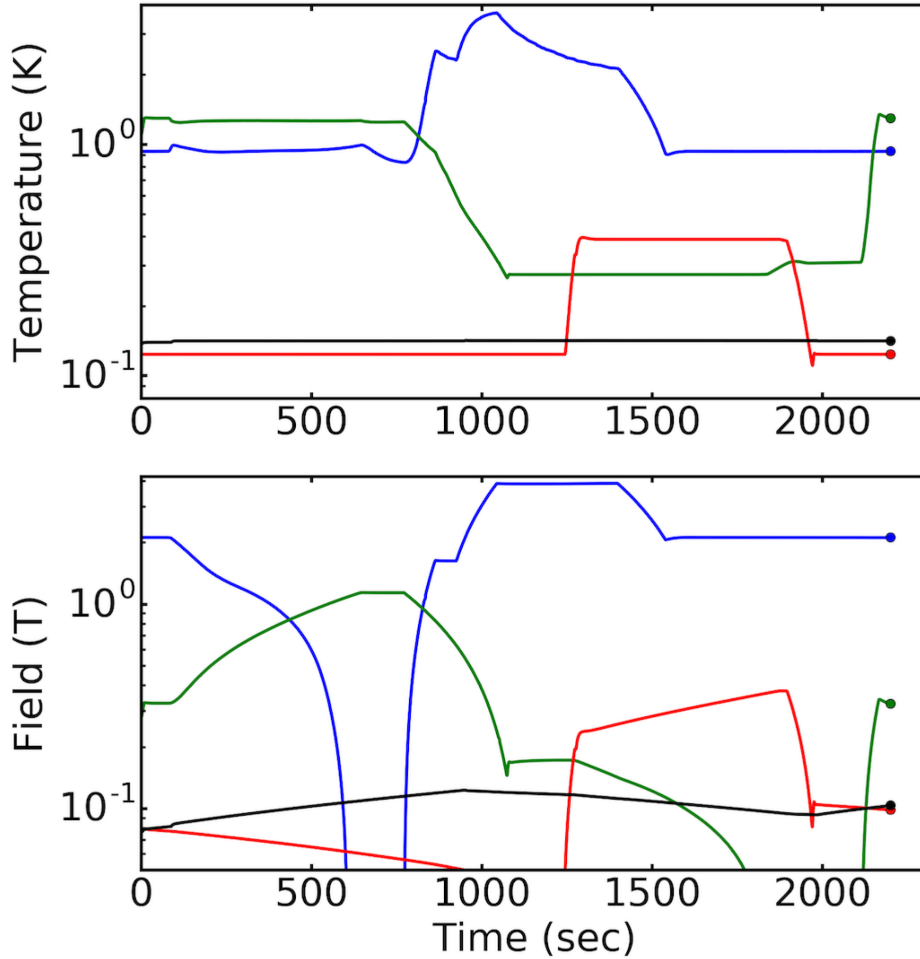
1. Stage 2 demagnetizes from its exchange (~370mK) and servos at 90 mK.
2. SCHS becomes conducting.
3. Stage 1 servos at 100 mK, magnetizes (now cooling) until Stage 2 is out of current.
4. SCHS becomes non-conducting.
5. Stage 1 servos at 100 mK, demagnetizes (now heating).
6. Stage 2 magnetizes and returns to exchange at 370 mK.



Continuous stage

1. Stage 2 demagnetizes from its exchange (~370mK) and servos at 90 mK.
2. SCHS becomes conducting.
3. Stage 1 servos at 100 mK, magnetizes (now cooling) until Stage 2 is out of current.
4. SCHS becomes non-conducting.
5. Stage 1 servos at 100 mK, demagnetizes (now heating).
6. Stage 2 magnetizes and returns to exchange at 370 mK.





Control electronics

SPID: One card per ADR stage (and SC HS). Read
:age thermometer and PID control coil voltage.
ead the coil voltage tap sense and currents.

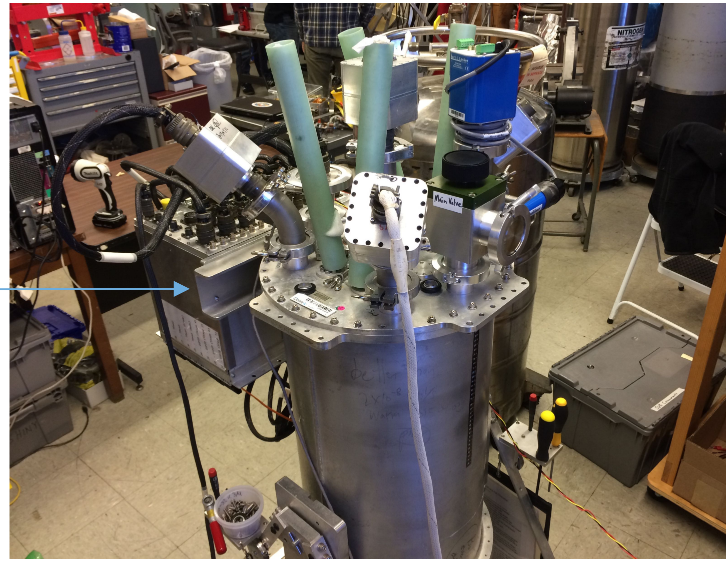
oost: take voltage signal and provide high-current,
onstant voltage to coil. Constant voltage ~ L dI/dt,
r a current ramp at constant rate.

READ: 12 diode or RuOx per card
nalog In/Out: 32 voltages

MASTER: synchronous with detector readout
hrough the UBC “sync box”, fiber optics transmit
o USB. Each board reports to, accepts commands
rom master at 1 Hz.

ompact and robust for balloon flight.

PIPER readout electronics: CADR control mini-rack



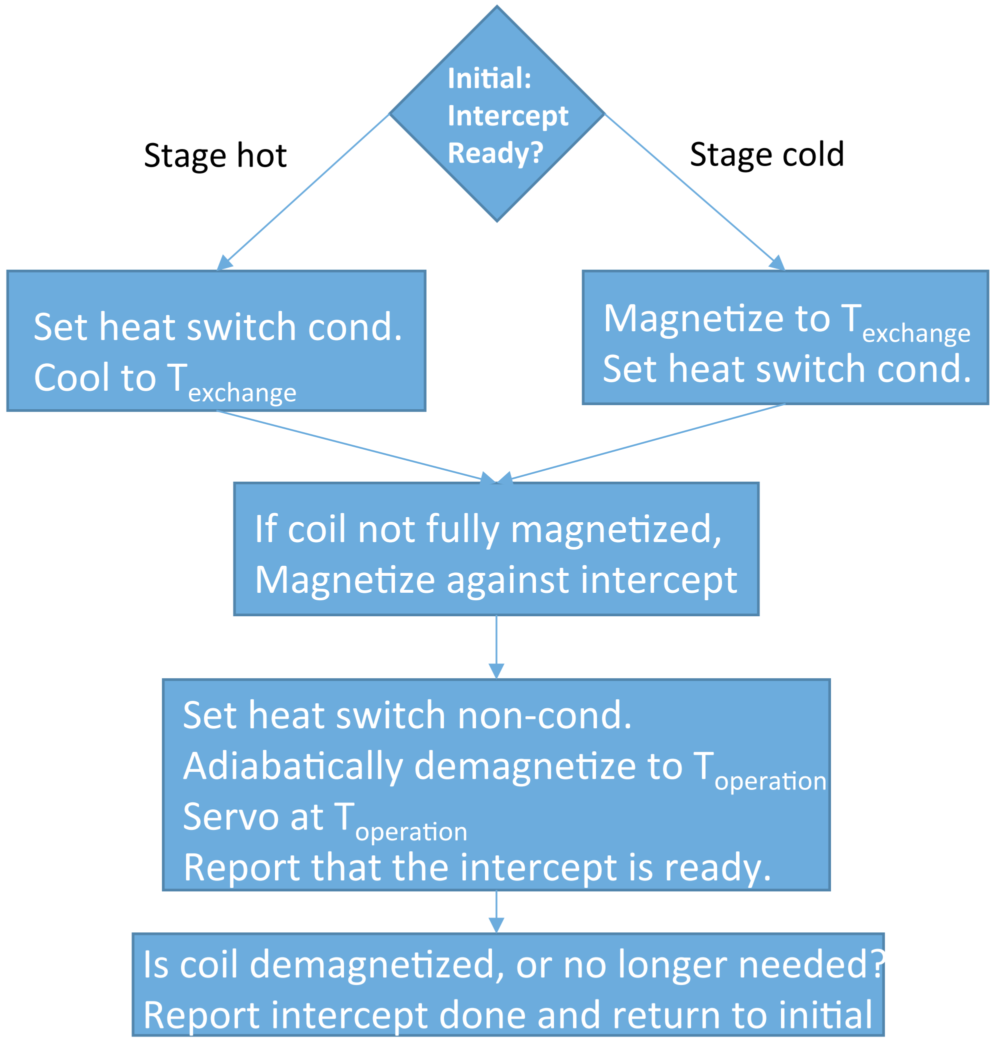
Control software

A single-process procedure for running all 4 stages would require a large number of conditionals on the status of each stage.

Strategy: use **one python process per stage**. Each process robustly recycles and cools to the operating temperature.

Communication between processes and the backplane through a *redis* database (publish/subscribe model).

Software started automatically using the Linux *upstart* system.



$T_{operation}$ = max(cold exchange temp, $T_{next} - \Delta T$)

Ratchet operation

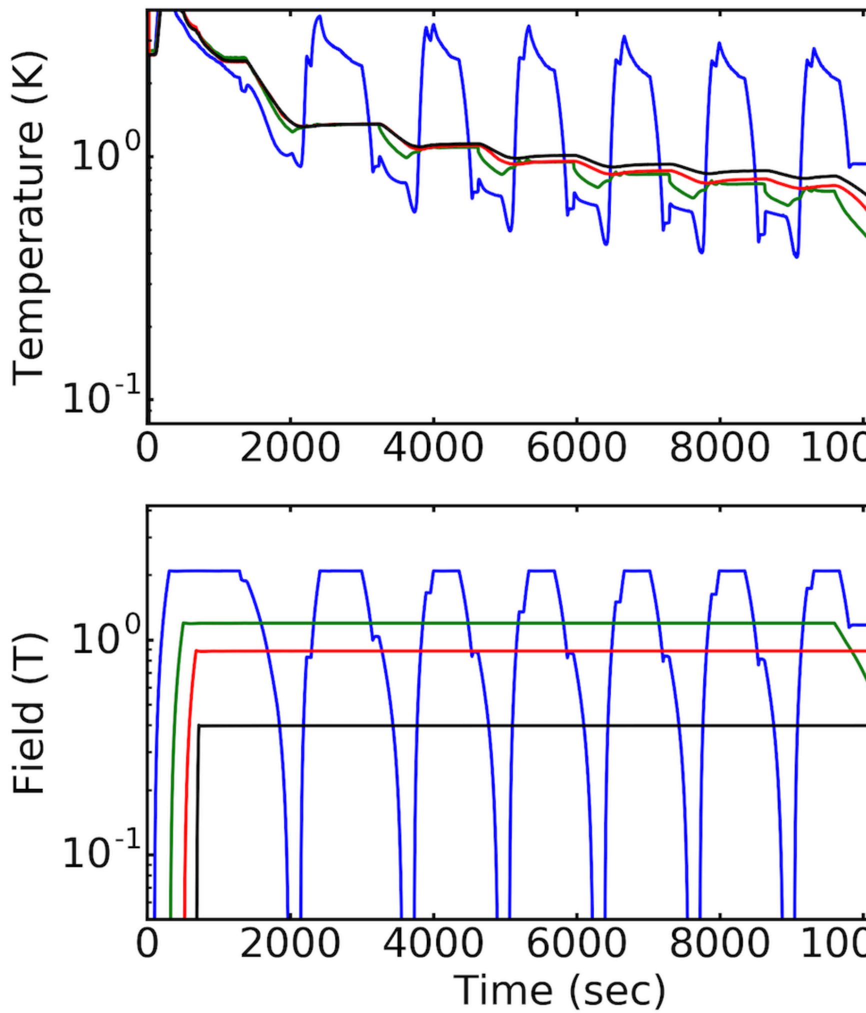
All components start at the bath temperature.

Ratchet operation to use stage 4 to cool lower stages.
Starting state: magnetize all stages, cool against bath

1. Disconnect S4-bath and demagnetize S4.
2. Connect S4 to S3 through active switch.
3. Set T_{S4} to ~90% of T_{S3} so that heat flows out of S3, S2 and S1.
4. Disconnect S4 and S3, recycle S4 against the bath.

Once ratchet reaches S3, S2 ~ 1K, demagetize to put S2, S1 below the emperature of the passive switch (145 mK). Then begin cyclic operation.

Consideration: when using passive switches, the heat capacities must e low enough that the stages can be cooled below the switch ctivation temperature.



Entropy models

Entropy from the Brillouin function for free spins:

$$S/R = n\left(x\coth(x) - (2J+1)x\coth((2J+1)x) + \ln\left(\frac{\sinh((2J+1)x)}{\sinh(x)}\right)\right)$$

$$x \equiv \mu_B g B_{eff}/2k_s T = (0.336K/T) g B_{eff}/T$$

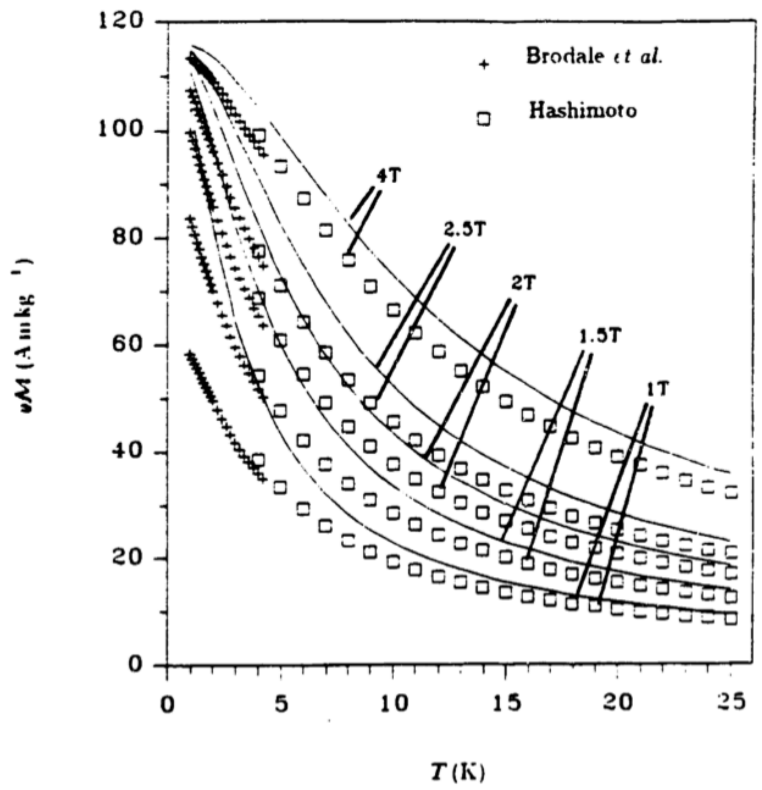
Effective field includes lattice field:

$$B_{eff} = \sqrt{B^2 + b^2} \qquad b(T) = b_0\left(1 - e^{-(T/T_0)^{\alpha}}\right)$$

Offset and values for common salts: *Shirron 2014*

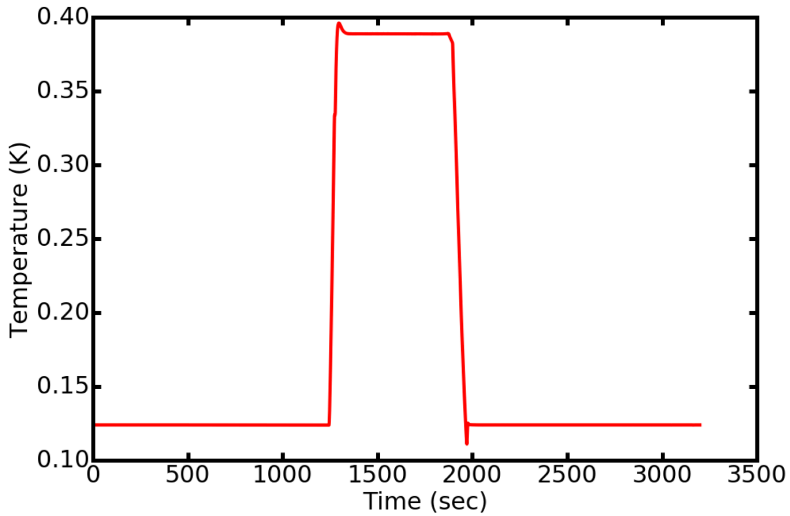
Gadolinium compounds have a poorer fit (see right).
GGG model: empirical fit to magnetization and heat capacity from *Gallagher 1986*.

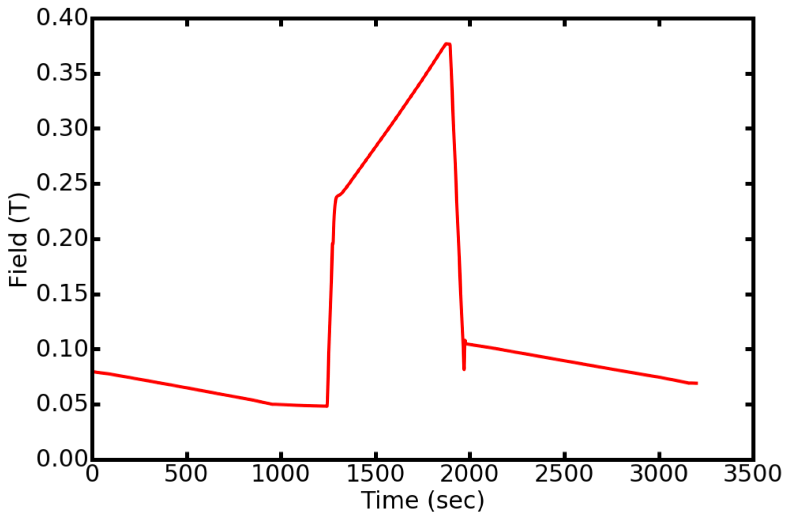
Unknown parameter: number of moles of spins.
Apply known power at controlled temperature, measure entropy rate → effective crystal mass.
Effective crystal mass typ. 85% of physical mass.



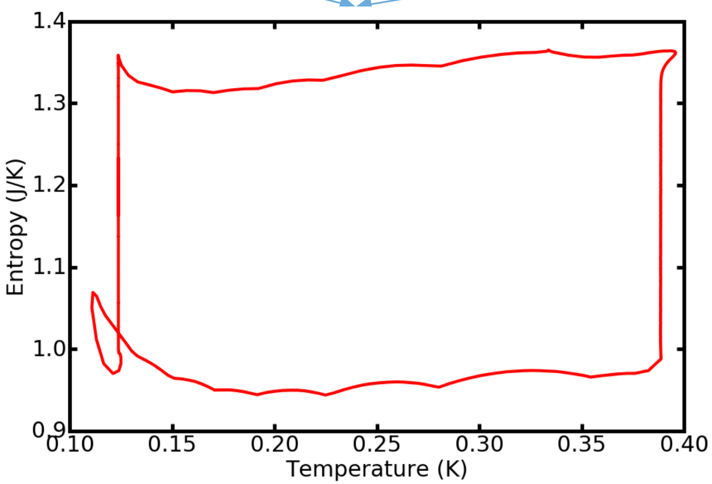
Gallagher (MIT thesis 1986)
Brillouin function vs. GGG magnetization
Reports fitting function from detailed measuremen

Entropy model applied to Stage 2





Plug in to S(B,T)



ΔQ = T ΔS

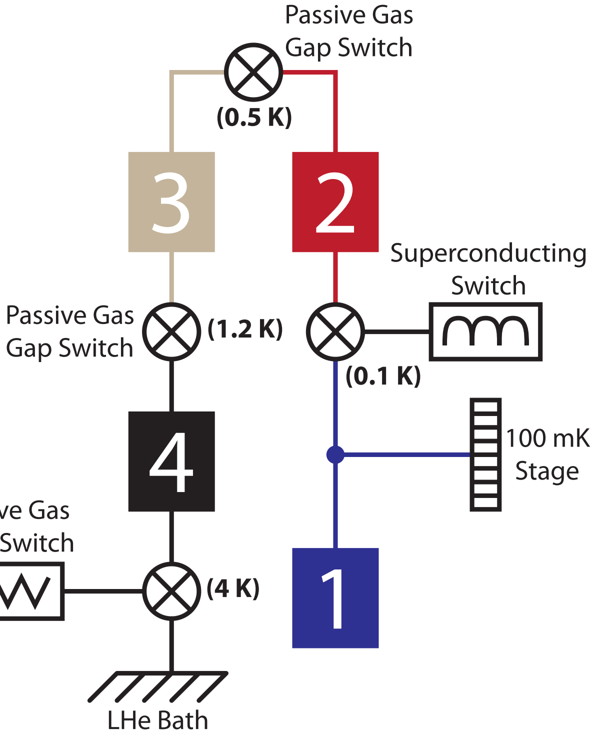
Hot side: ~0.4 K * 0.4 J/K= 0.16 J released

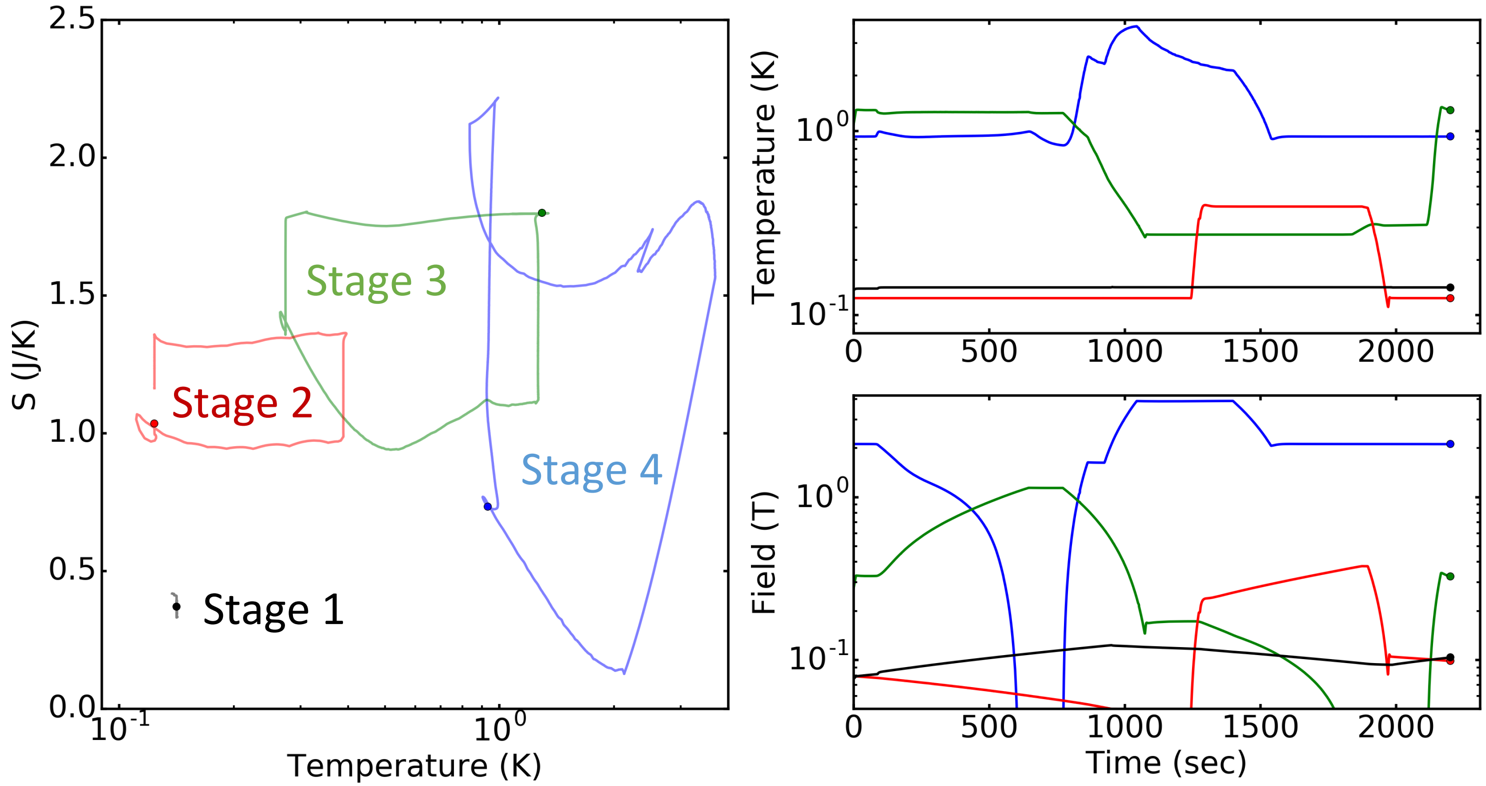
Cold side: ~0.12 K * 0.4 J/K = 0.05 J accepte

Or ~15 μW when spread over interval

P = T dS/dt

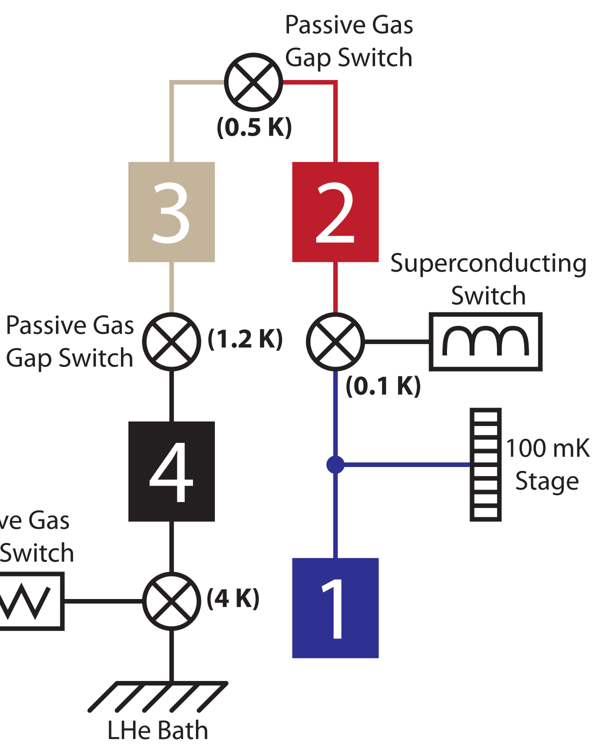
Multi-stage operation

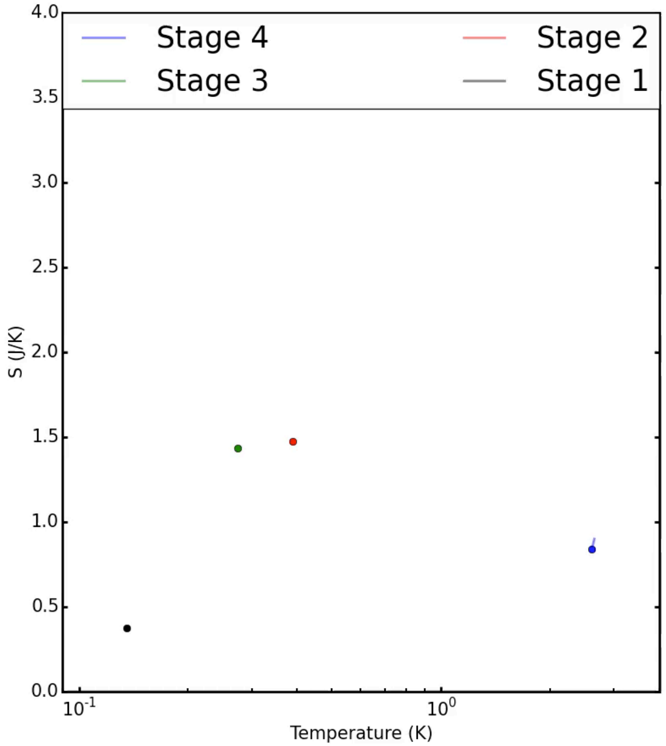


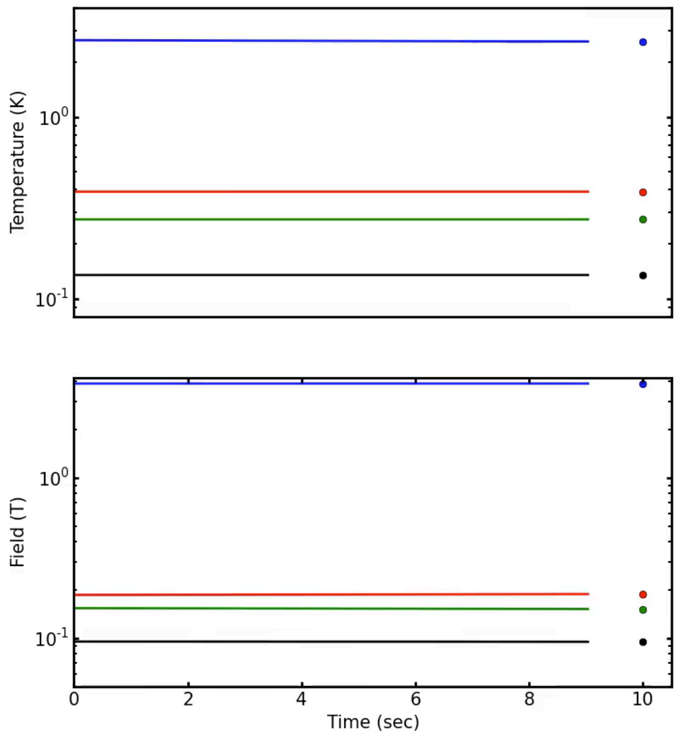


~15 µW cooling at 100 mK

Multi-stage operation



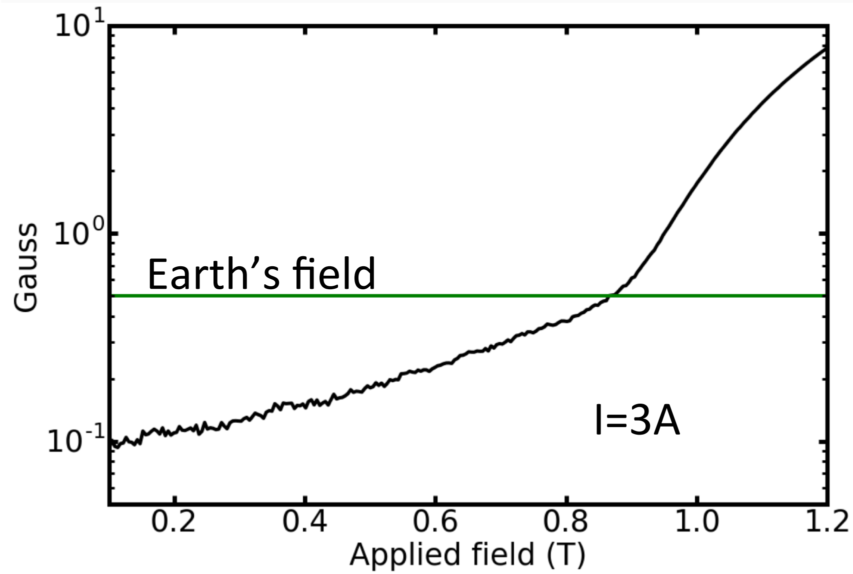


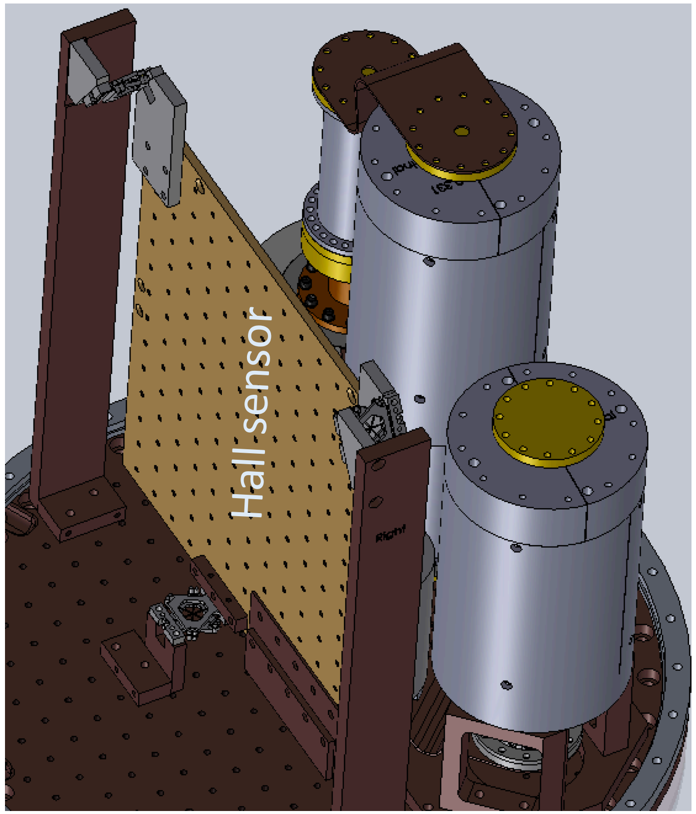


~15 μW cooling at 100 mK

Magnetic Shielding

Separation from probe and pill: 2.5” radial, 0” vertical
0.3" thick, 2.7" OD, 4% Si-Fe
After saturation: shield degrades by 80x





To-date: TES testing in single-shot mode (low field excursion), fully shielded box
CADR demonstrated Nov. 12 2015, next test in this system: 8x2 TES array with CADR.

Stability in the CADR

Current firmware PID can achieve 5 x 10^{-5} fractional stability in stable demagnetization conditions.

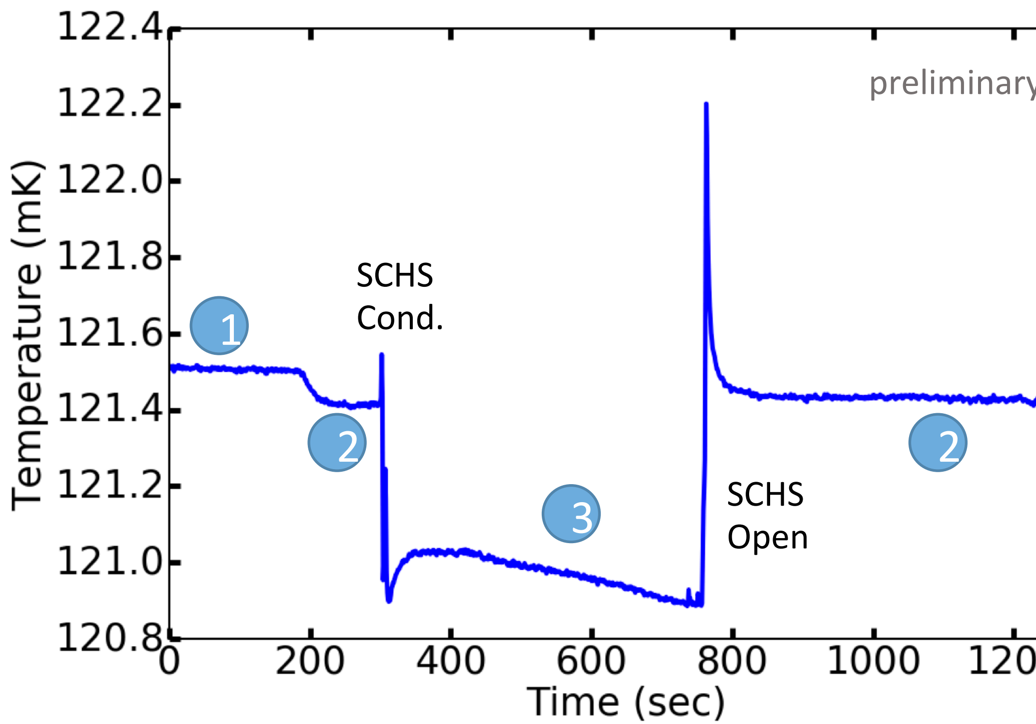
Essential problem: Slew from rapid magnetization against S2 to free demagnetization to cool the detectors.

Approach:
Power → dI/dt → voltage = L dI/dt.

Apply a feed-forward fixed voltage, calculated from the known temperatures, parasitics and switch conductance.

Let the PID stabilize additional fluctuations, e.g. release of heat in going from normal to superconducting.

Continuous stage 1 through Stage 2 cycle



Three states:

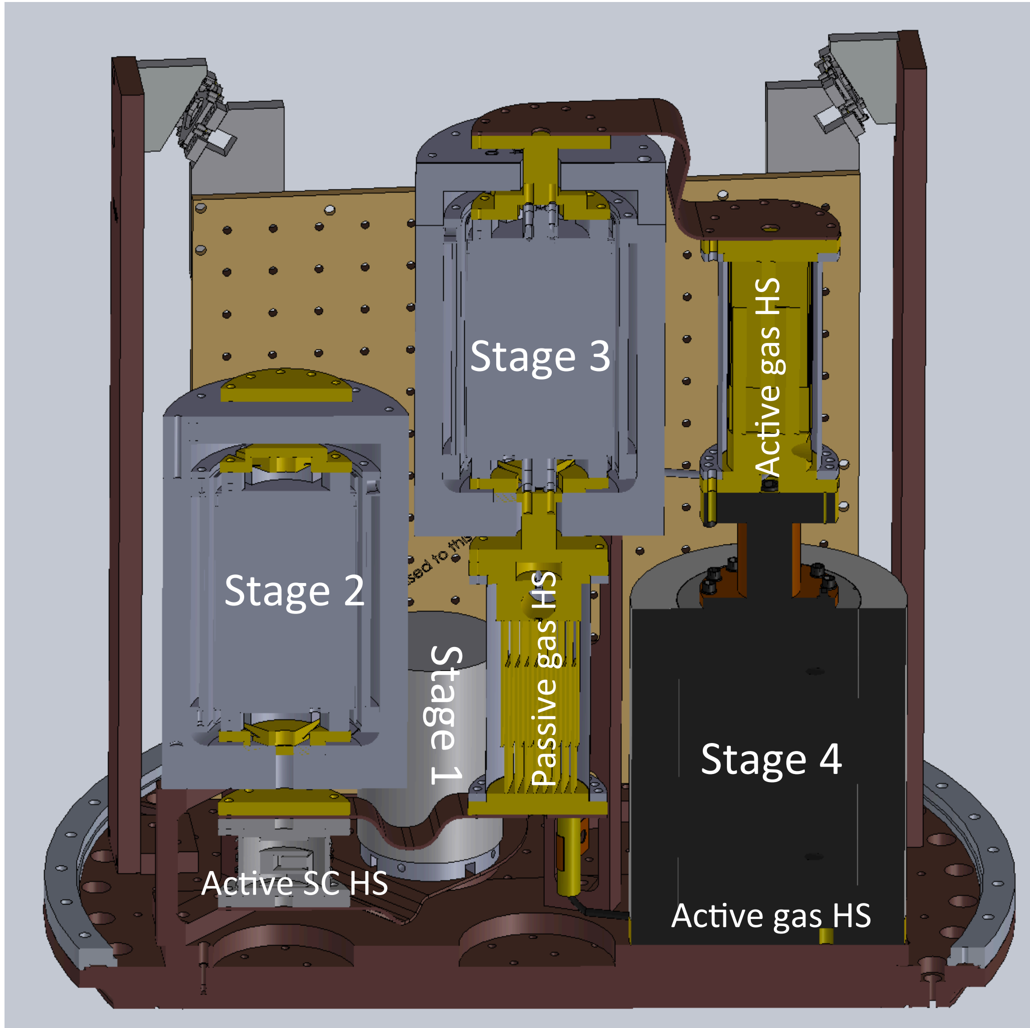
1. Stage 2 ~370 mK, charging against Stage 3
2. Stage 2 ~110 mK to start charging Stage 1
3. Stage 1 connected to Stage 2

Summary

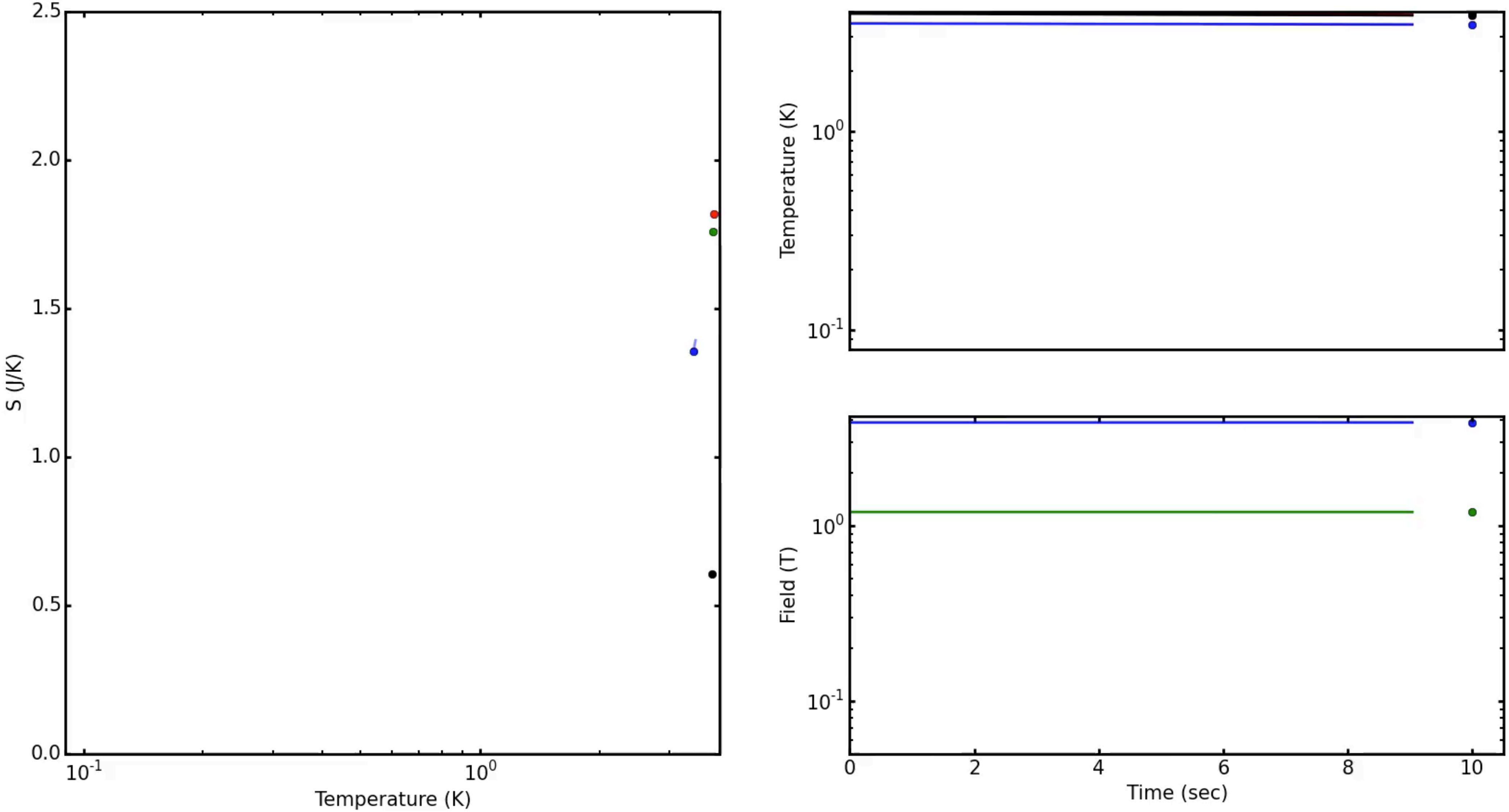
- GGG, CPA and a combination of heat switch types.
- Relative to single-shot: high heat transfer rates are the premium. Higher on and off switch conductance, coupling to salt.
- Compact control electronics and modular python software for robust control.

Future work:

- Optimize
- Cycle envelopes defined by shielding. Open detector box in flight geometry, CADR operation.
- Feed-forward model to stabilize continuous operation.
- Target spring engineering flight, fall science.

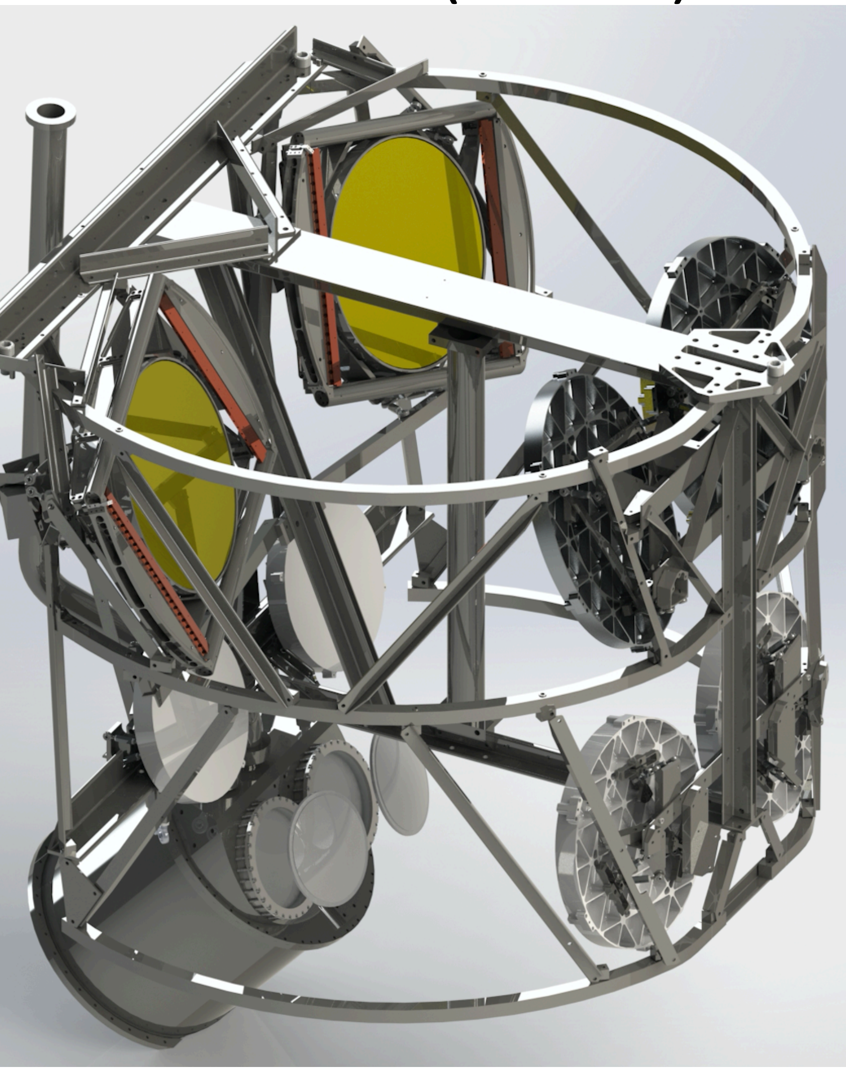


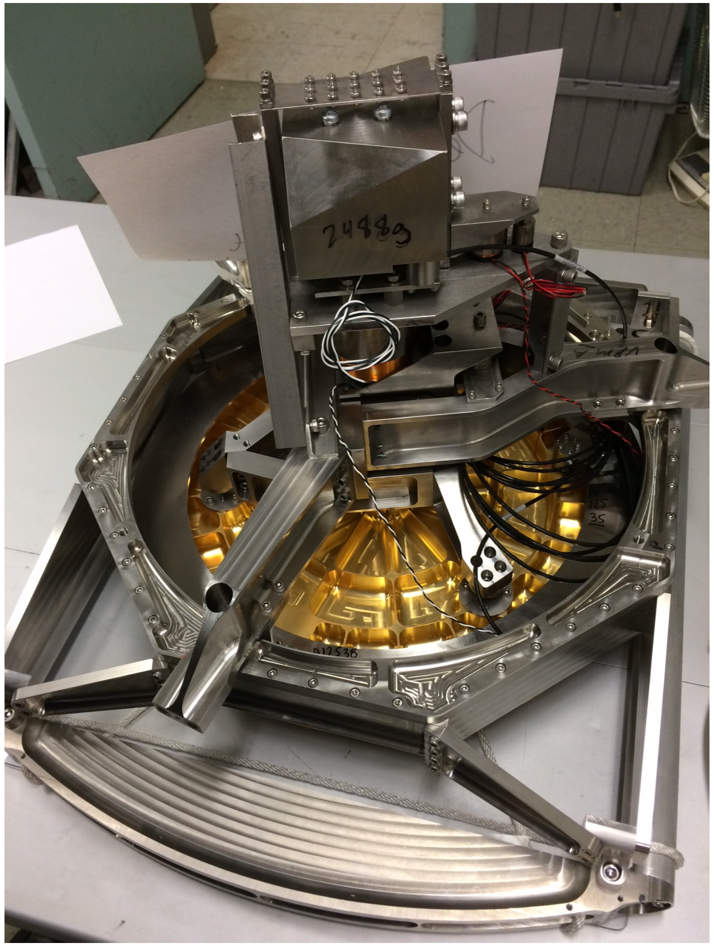
Thank you!



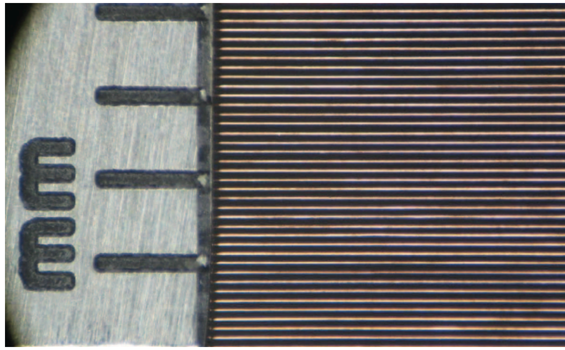
S (J/K)
2.5
2.0
1.5
1.0
0.5
0.0
10^{-1}
10^{0}
Temperature (K)
Temperature (K)
10^{0}
10^{-1}
Field (T)
10^{0}
10^{-1}
0
2
4
6
8
10
Time (sec)

PIPER Variable-delay polarization modulator (VPM)

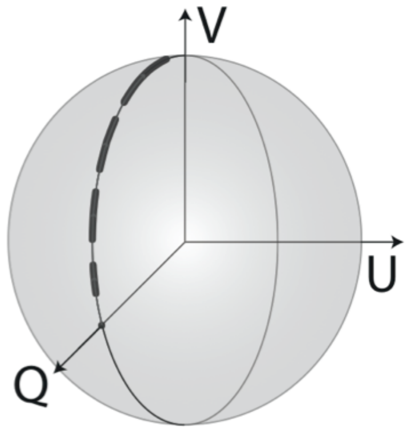




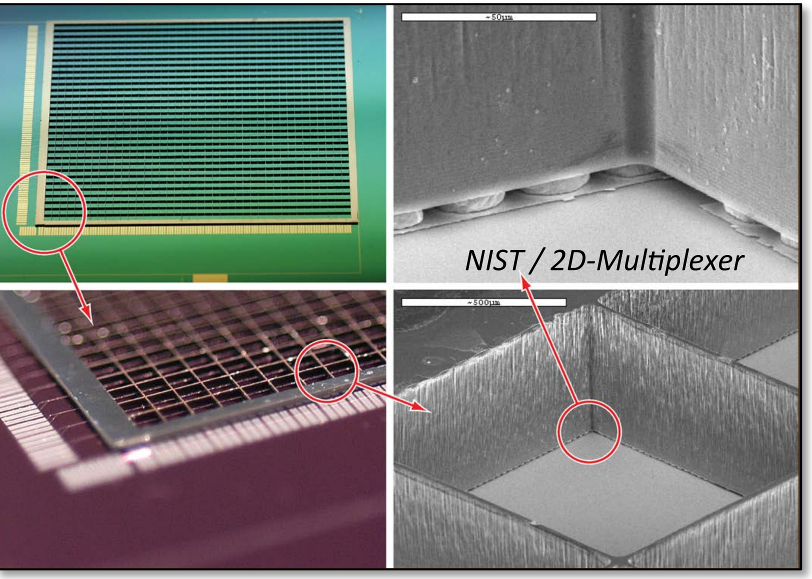
Voice coil and counter-weight
Read with capacitive distance sensors



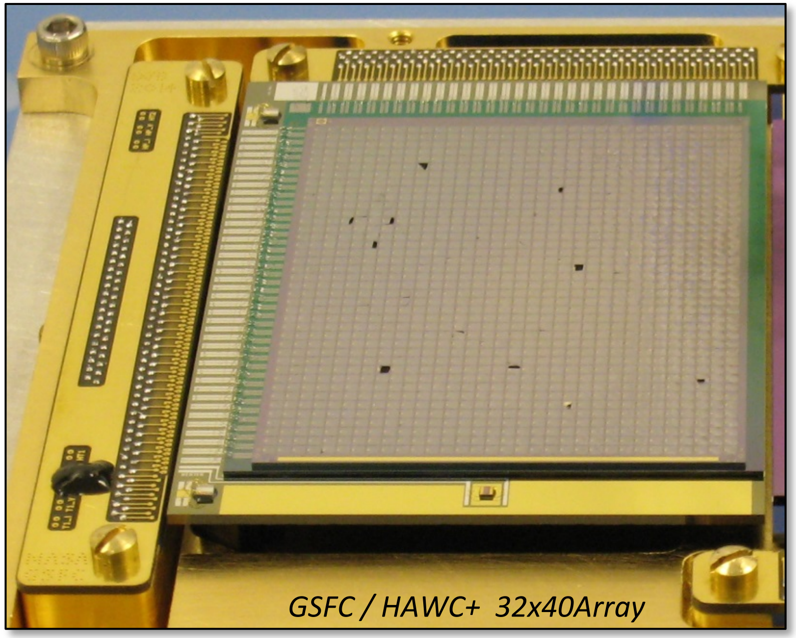
36 μm diameter wire
110 μm pitch
40 cm clear aperture



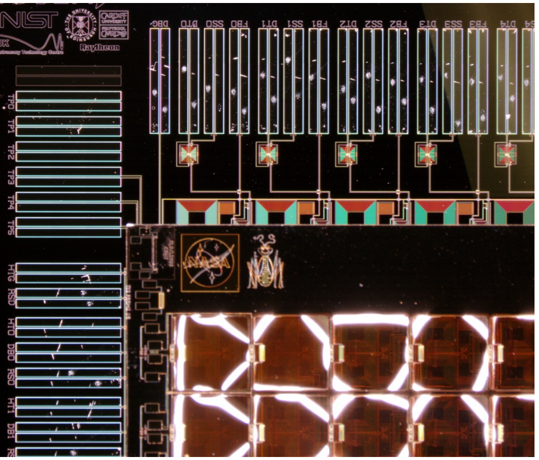
Detectors and Integrated SQUID Readout



NIST / 2D-Multiplexer



GSFC / HAWC+ 32x40Array



TES array is hybridized to a 2D MUX wafer through superconducting indium bump bonds.

The series array is off-chip.

PIPER detector parameters:

Pixel Pitch	1135 μm
Base Temperature	100 mK
Absorber Temperature	140 mK
Power Loading	0.5 pW
Thermal Conductance	29 pW/K
Time Constant	21 ms
NEP	3.8×10^{-18} W $Hz^{-0.5}$

Stage properties

S4b:

- G(nc) ~ 10 uW/K
- G(cond) ~ 40 mK/K

S34:

- G(nc) ~ 70 uW/K (~20 uW/K expected)
- G(cond) ~ 5 mw/K (~2 mW/K expected)

S23:

- G(nc) ~ 17 uW/K
- G(cond) ~ 2 mw/K (~10 mW/K expected)

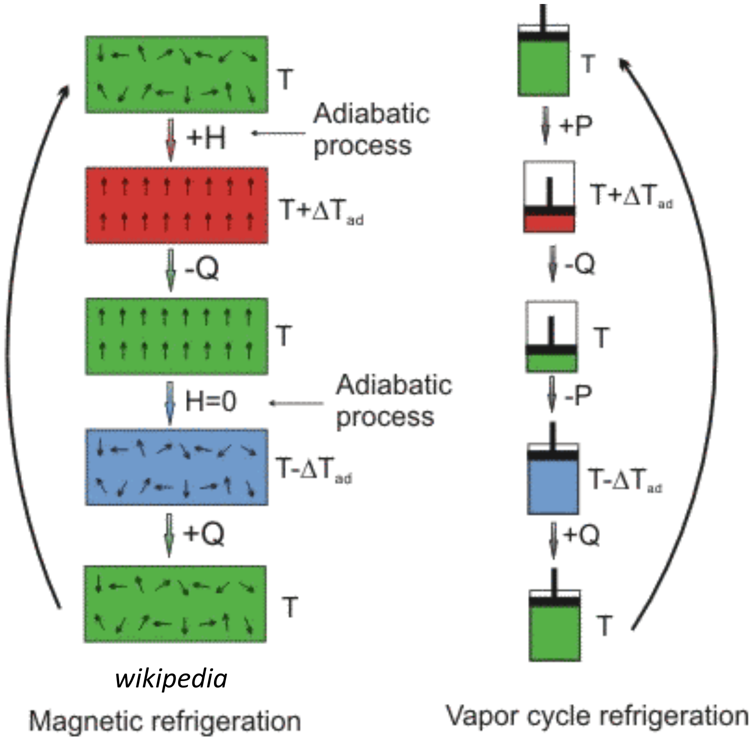
S12:

- G(nc) ~ 20 uW/K
- measured G(cond) ~ 1 mW/K (~10 mW/K expected)

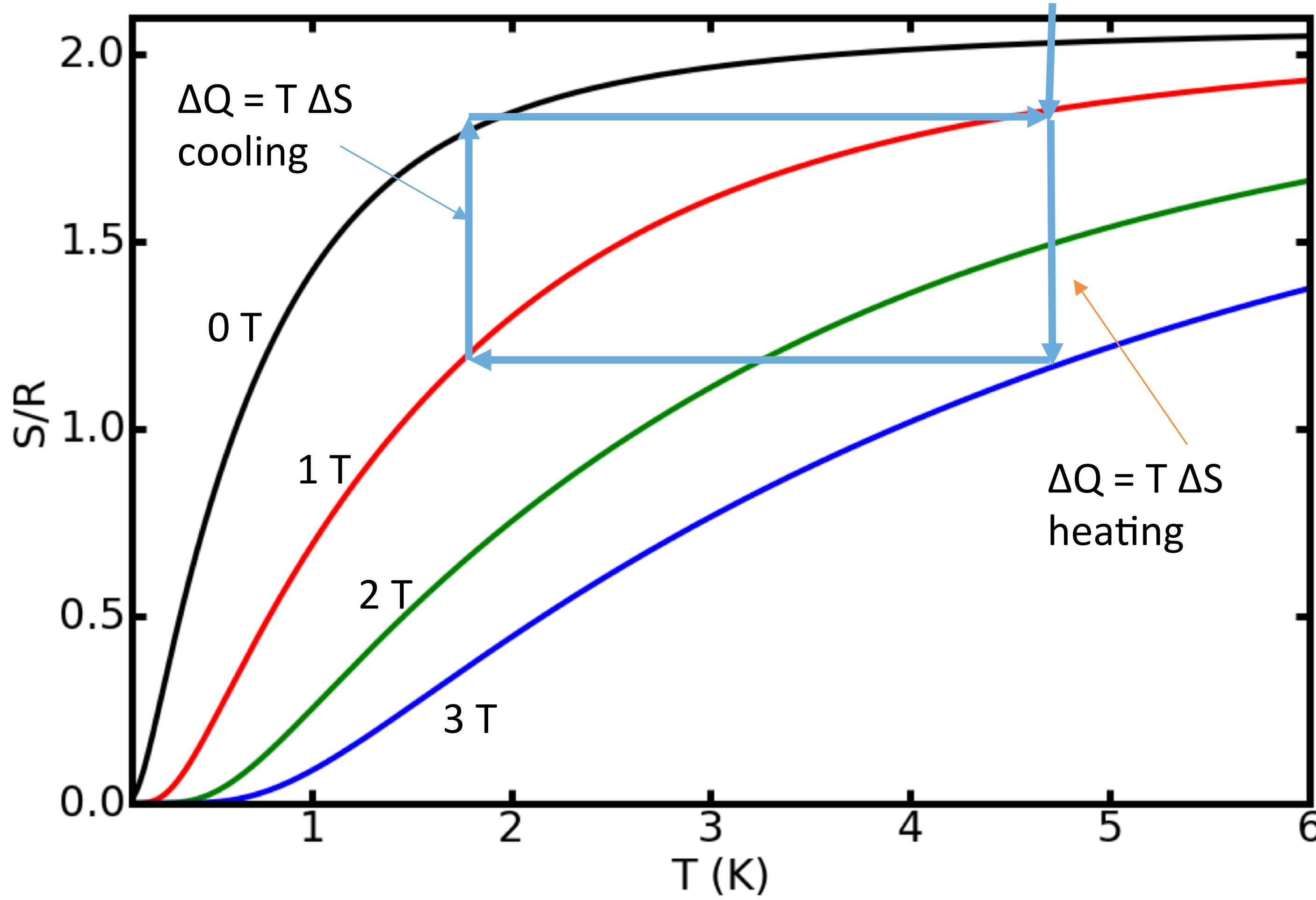
From 2.2K bath:

- S1 and S2 loading ~5 uW (2.2K bath), ~20 uW (4.3K bath)
- S4, S3 loading is ~50 uW (4.3K bath)

ADR thermodynamic cycle



$\Delta Q = T\,\Delta S$



Accept ΔS isothermally at operating point
Reject ΔS isothermally to the bath, or upper stage

Entropy of GGG