Continuous sub-Kelvin cooling from an adiabatic demagnetization refrigerator

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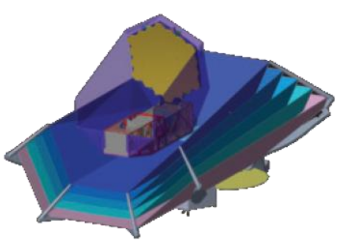
Why the need for sub-Kelvin cooling in space flight?

- Astro-H / XRISM uses an array of 36 bolometers with absorbers tuned to soft-Xray energies. They require 50 mK to reach stated sensitivity less than 7 eV

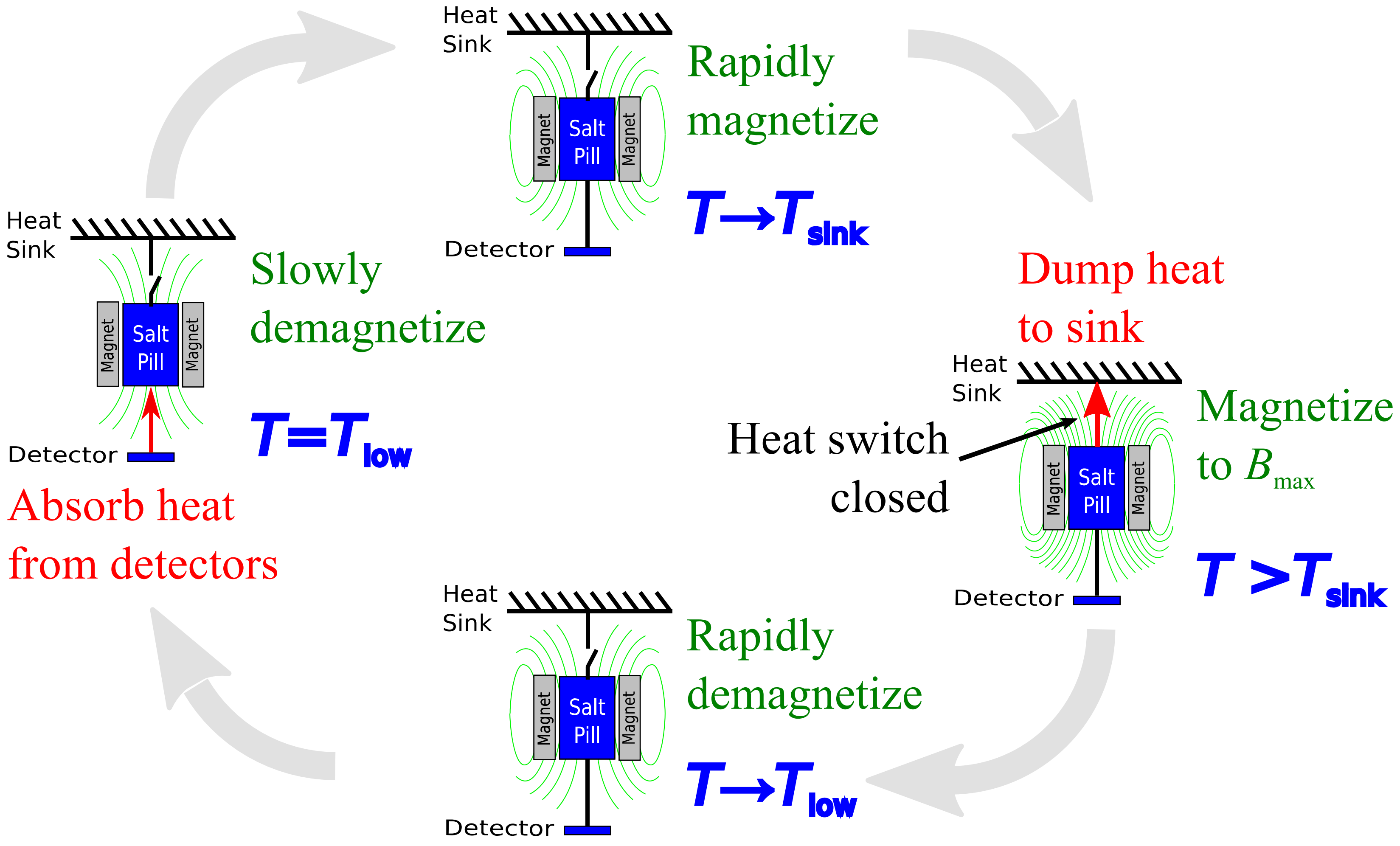
- PIPER uses two Backshort-Under-Grid (BUG) superconducting transition-edge sensors (TES) detectors developed at NASA/GSFC measure signal (> 5000 pixels). TES tuned to ~ 100 mK temperature range

- PIXIE (proposed) will use an array of infrared-sensitive bolometers to measure the polarization of the cosmic microwave background (CMB). Temperature requirement

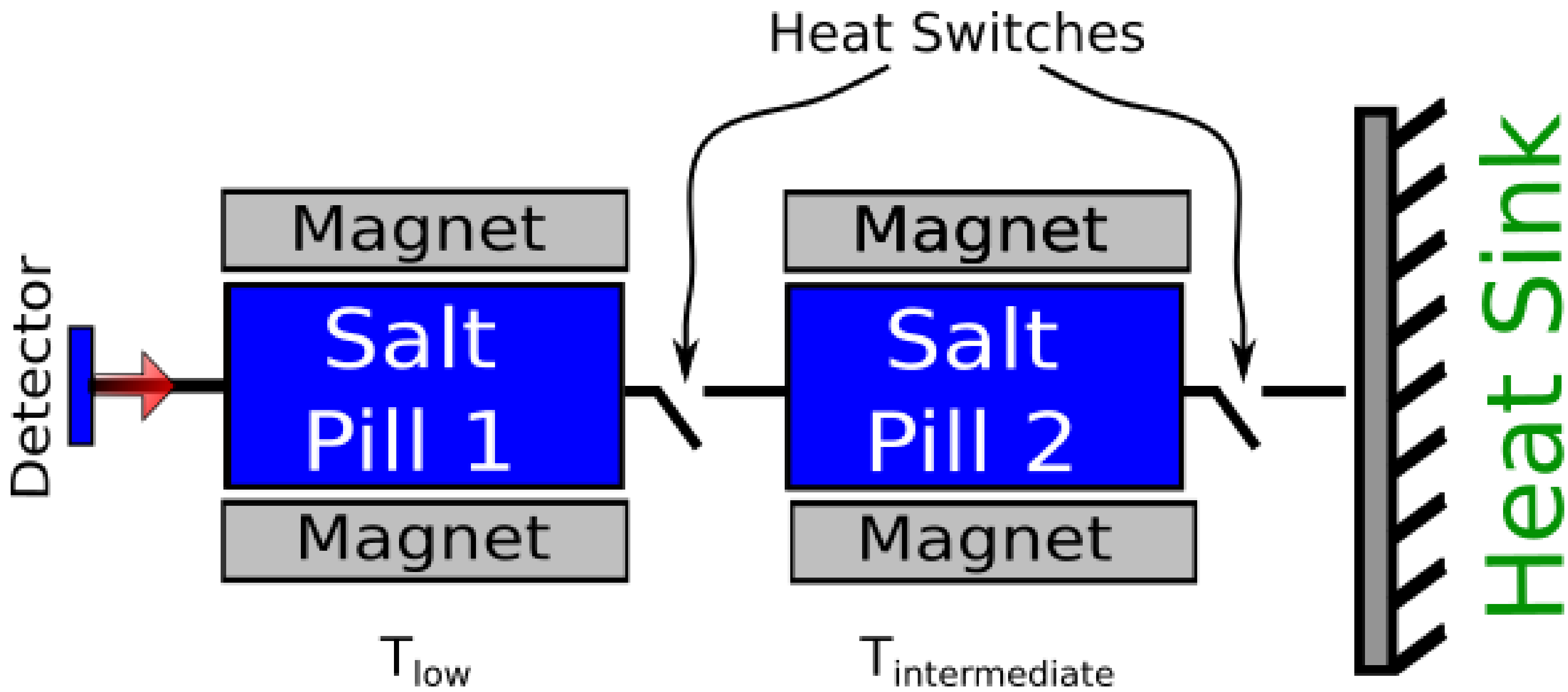


- Origins Space Telescope (proposed) contains three instruments that require sub-Kelvin cooling. All three use TES detectors operating at 50 mK. At this temperature, the sensitivity will be limited by the sky background.

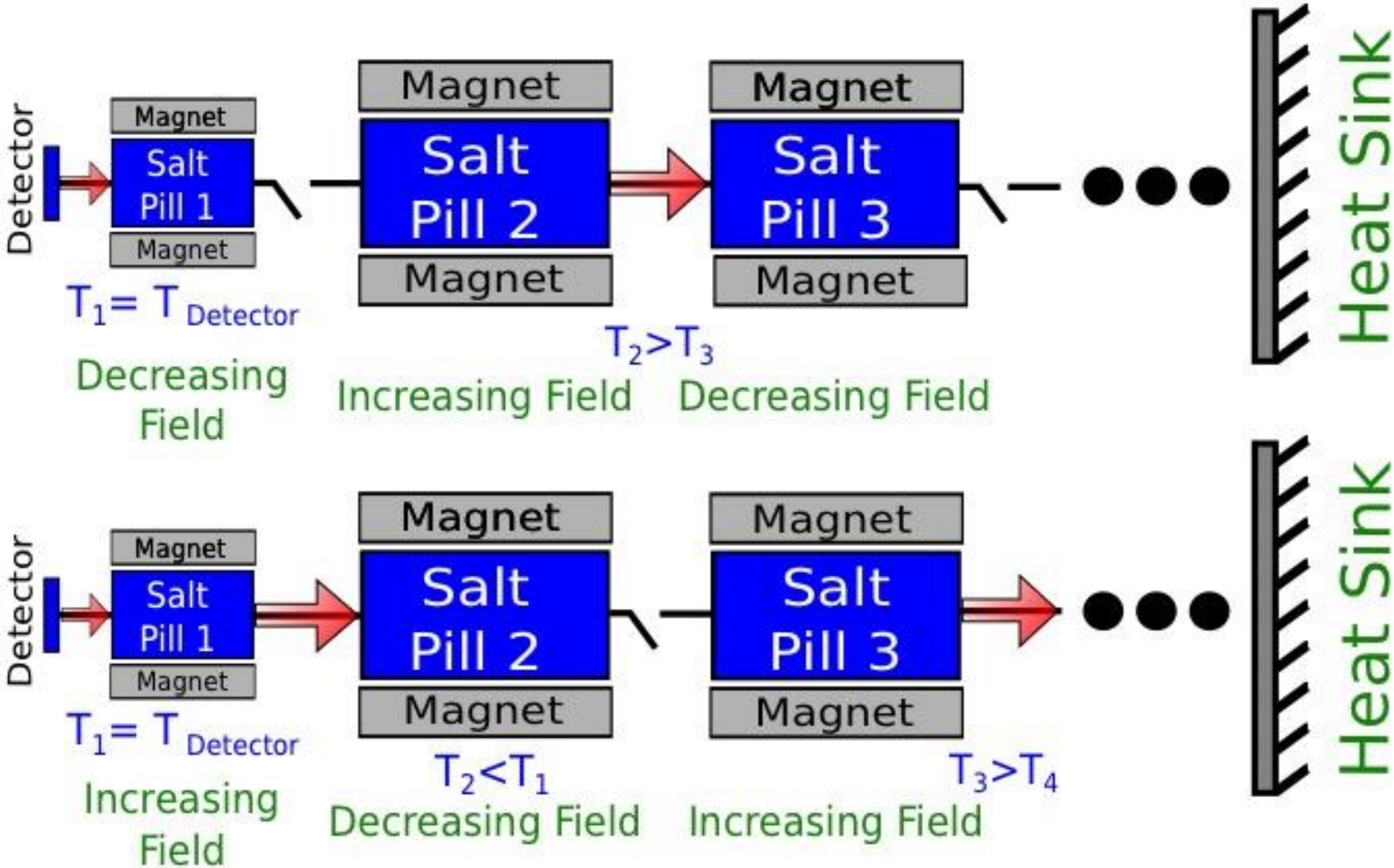
Adiabatic Demagnetization Refrigeration



ADR Multi-Stage System



Continuous ADR



CADR built for External Mission

4 Stages

① 45 g CPA [0.100 K]

② 100 g CPA [0.375 -> 0.09 K]

③ 100 g CPA [1.4 -> 0.275 K]

④ 82 g GGG [4.2 -> 1.2 K]

Heat Switches

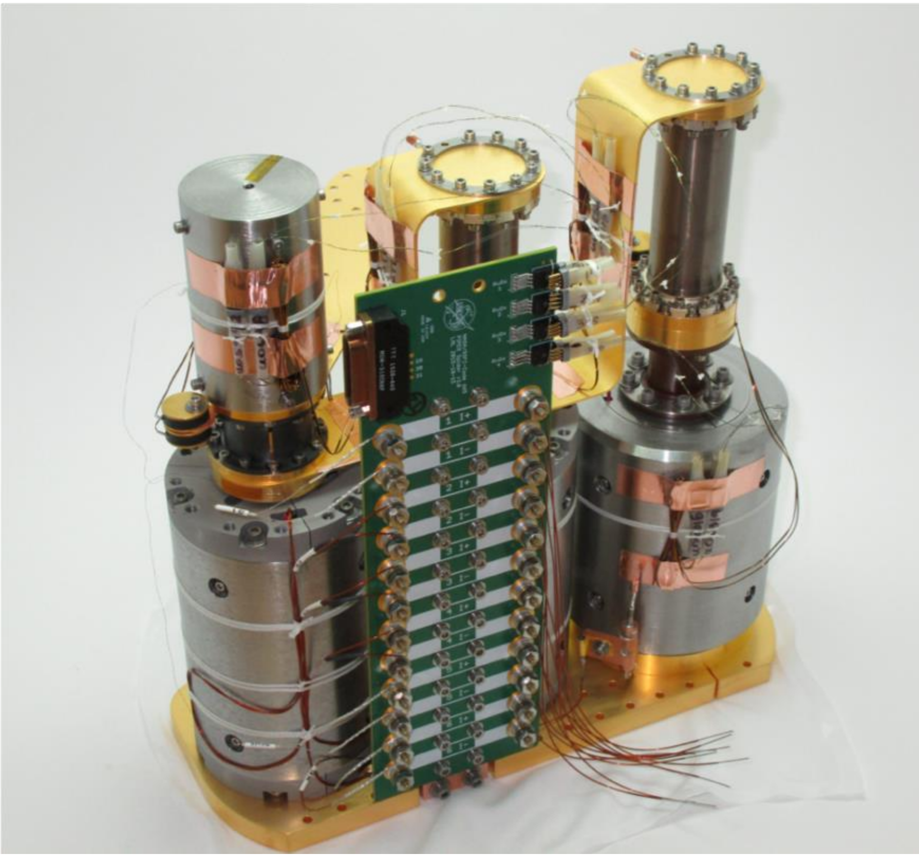
① Superconducting Switch (1 -> 2)

② Passive Gas-Gap (2 -> 3)

③ Passive Gas-Gap (3 -> 4)

④ Internal Passive Gas-Gap (4 -> H.S.)

CADR built for PIPER Mission



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Same CADR; Different Configurations

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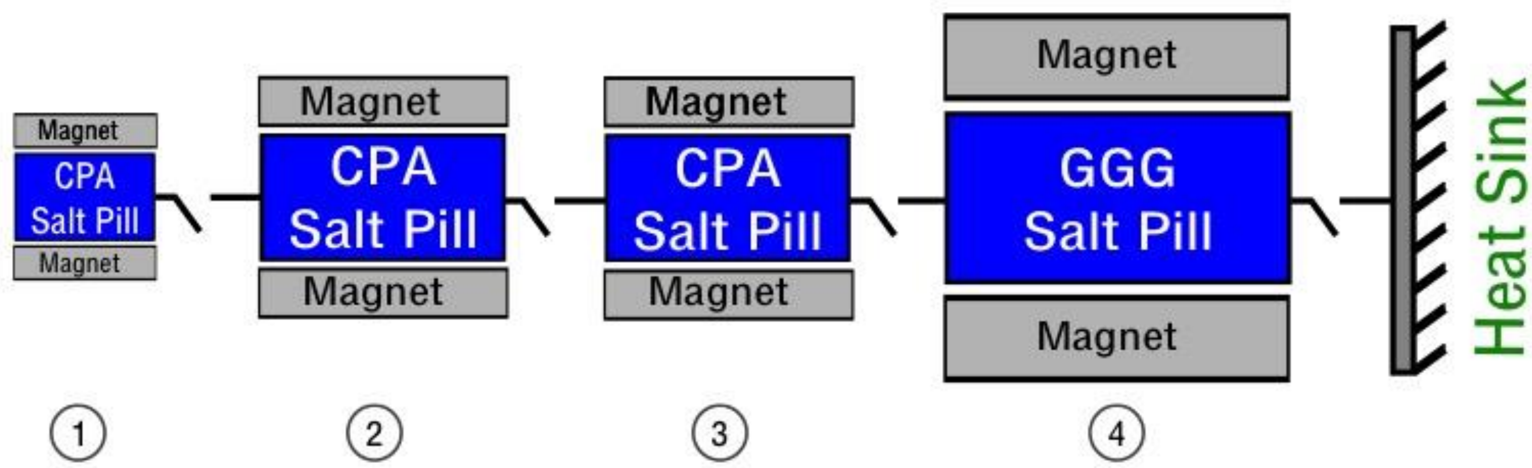
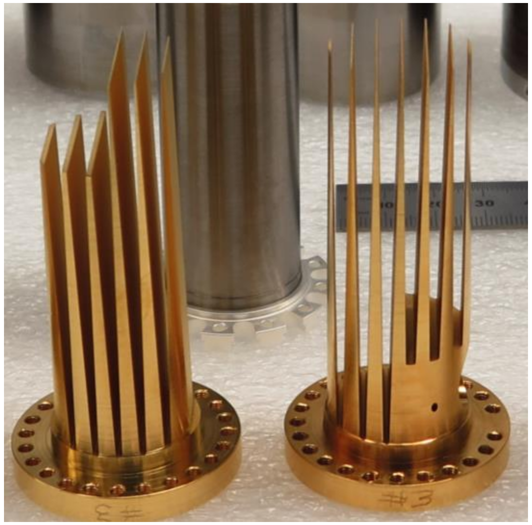
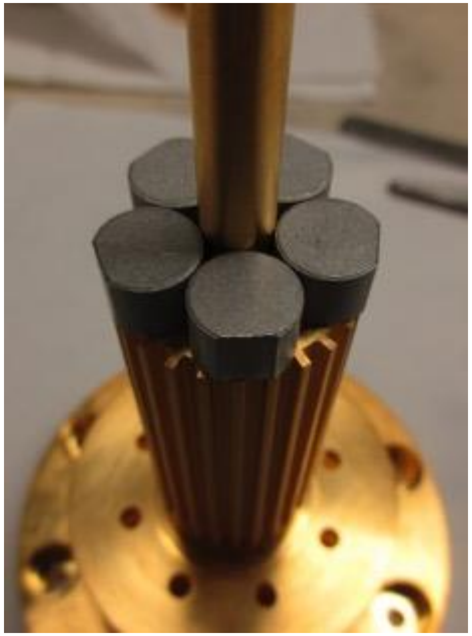


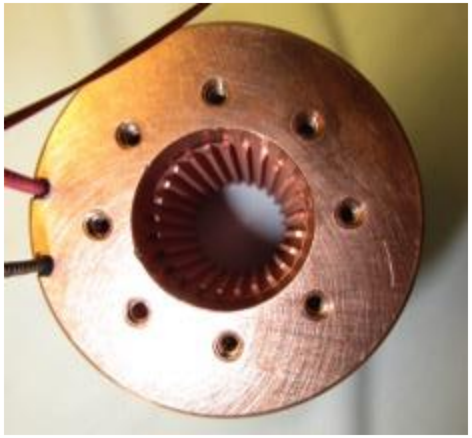
Passive Gas-Gap Heat Switches

- Passively closes when temperature of associated stage warms above some value
  - More thermodynamically efficient since no additional heat added to system to activate
- Thin (0.127 mm) titanium outer shell
- Gold-plated copper innards consist of interleaved fins with a 0.36 mm gap between when assembled
- Getter typically sintered stainless pucks or the copper fins themselves



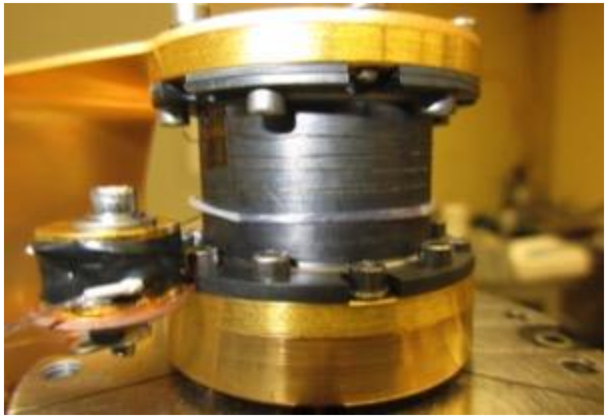
Stage 4 Passive GGHS Internal to Stage

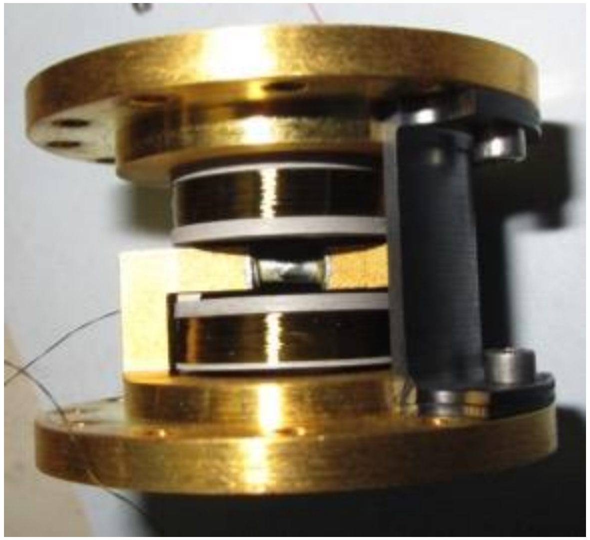




- One set of “fins” is the salt pill
- Other set the magnet itself
  - ~ 0.4 mm gap between adjacent pair of fins
- Sintered 300 CRES getters epoxied onto the pill provide attractive surface for He-3
  - If 3He between sets of fins, switch on
  - When 3He to CRES binding energy greater than some temperature, switch turns off
- Room-temperature fill level sets the transition temperature
  - 4 torr fill provides transition ~ 1.2 K

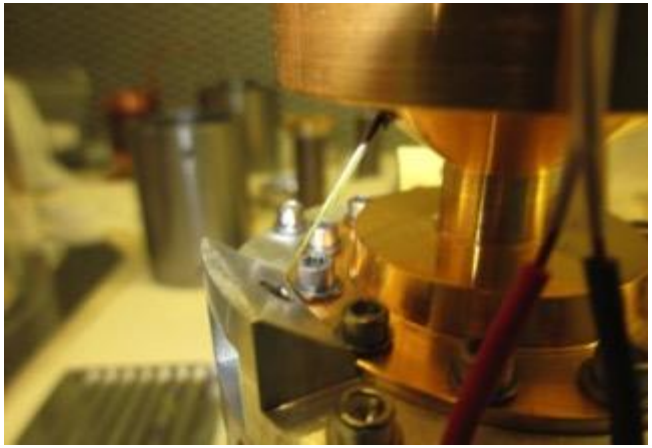
Superconducting Heat Switch

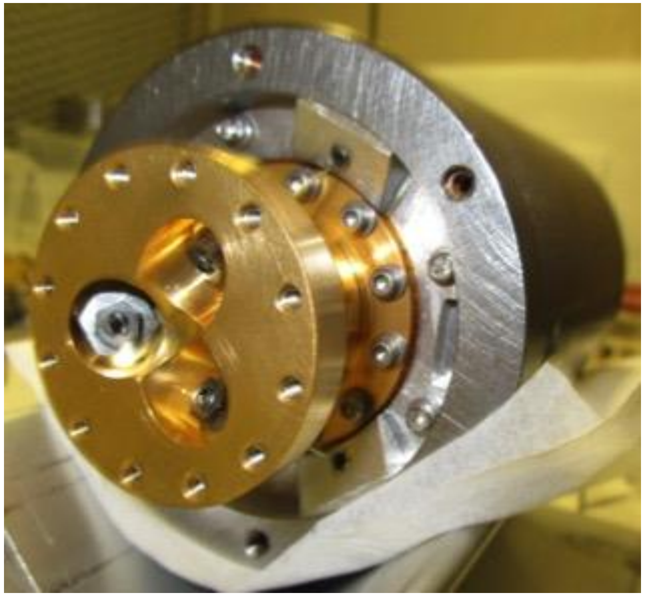




- Positioned between stages 1 and 2
- Two halves of switch separated by a length of lead wire
  - When lead in superconducting state, switch open
  - When lead in normal state, switch closed
  - Magnetic field from Helmholtz coil switches state
- Quick switching time
- Works in a temperature regime where gas in a GGHS is absorbed fully

S2,3 Salt Pill Suspensions

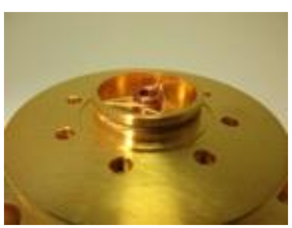


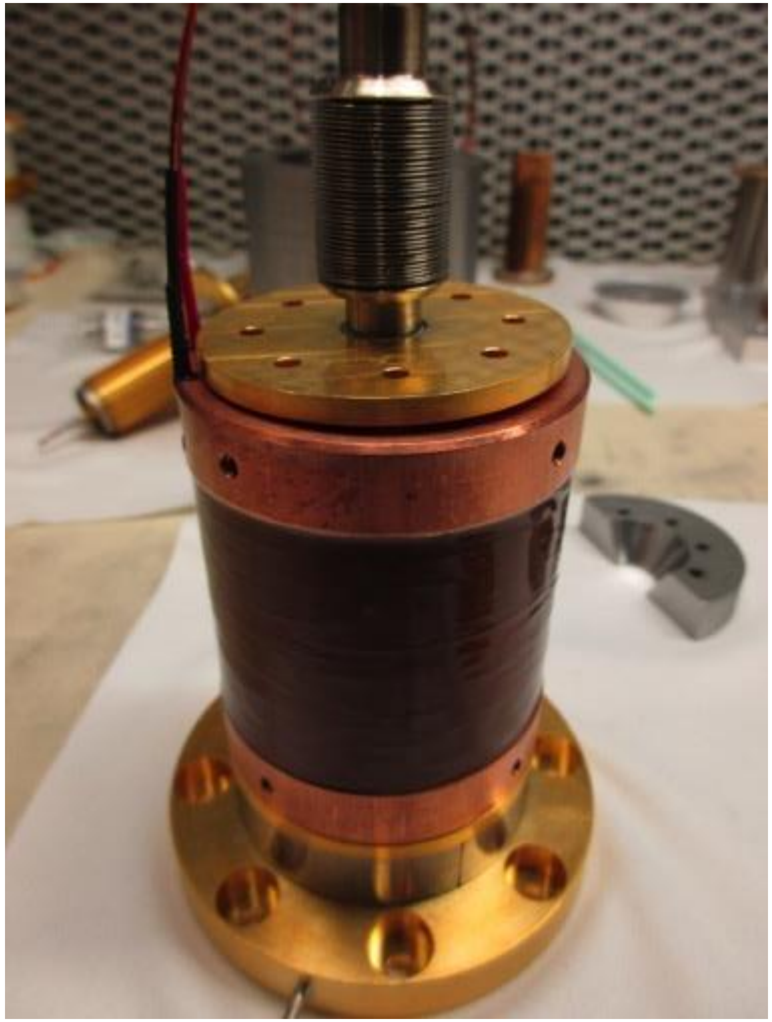


A total of 6 Kevlar bundles suspend the paramagnetic salt pill within the bore of a superconducting magnet

- Magnet temperature: 3 K
- Pill temperatures often below 1 K
- Kevlar assemblies made on the bench then installed
  - Button head screw on outside attachment point
  - "D-shaped" screw threaded through inner attachment point
  - Tensioned via a nut and locked with a second nut
- Estimated heat lead from 3 to 0.1 K: 4.4 µW

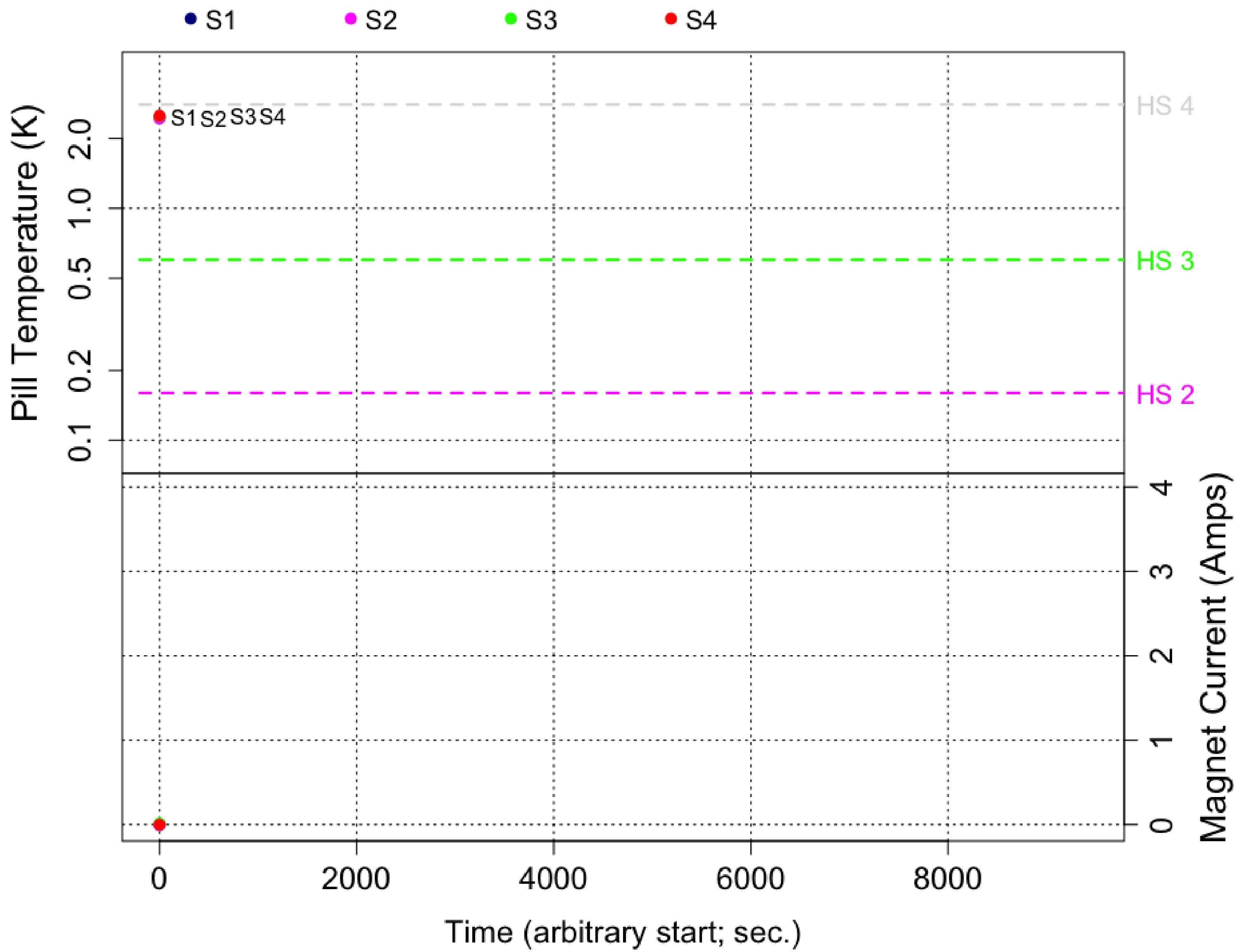
S4 Salt Pill Suspension





- 300 CRES bellows isolates one end
- Thin Vespel SP1 spool provides structural support
- Six Kevlar bundles suspend other end

Plots of Temperatures and Currents



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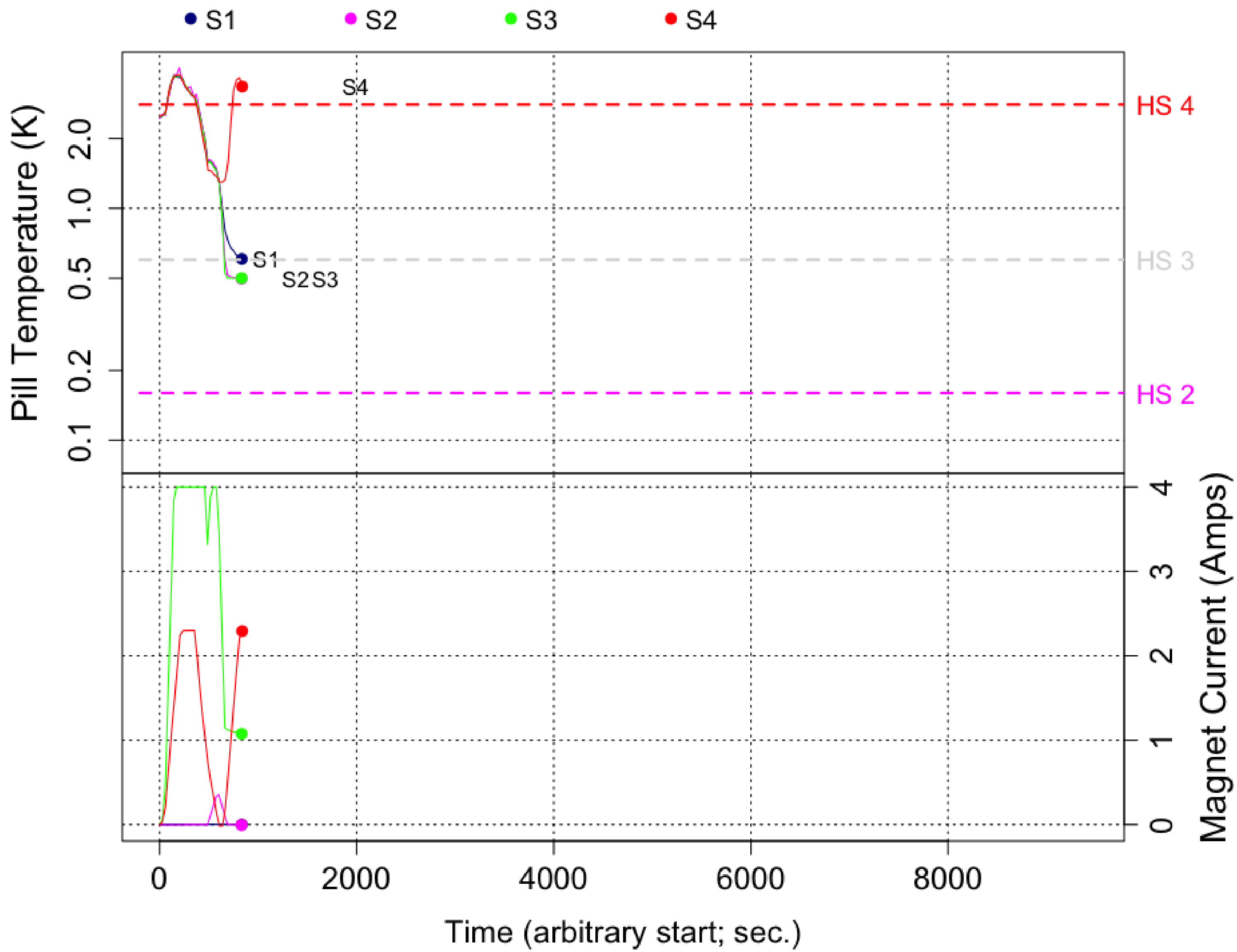

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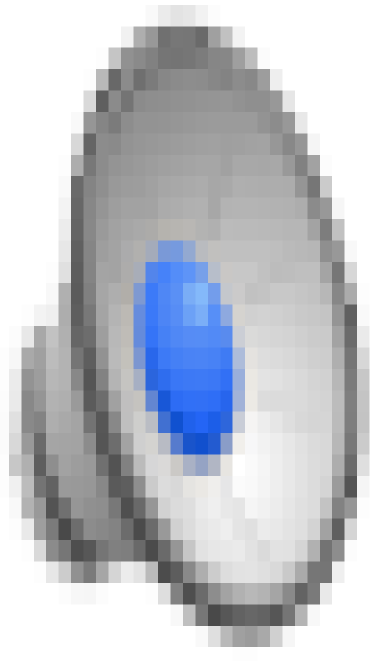
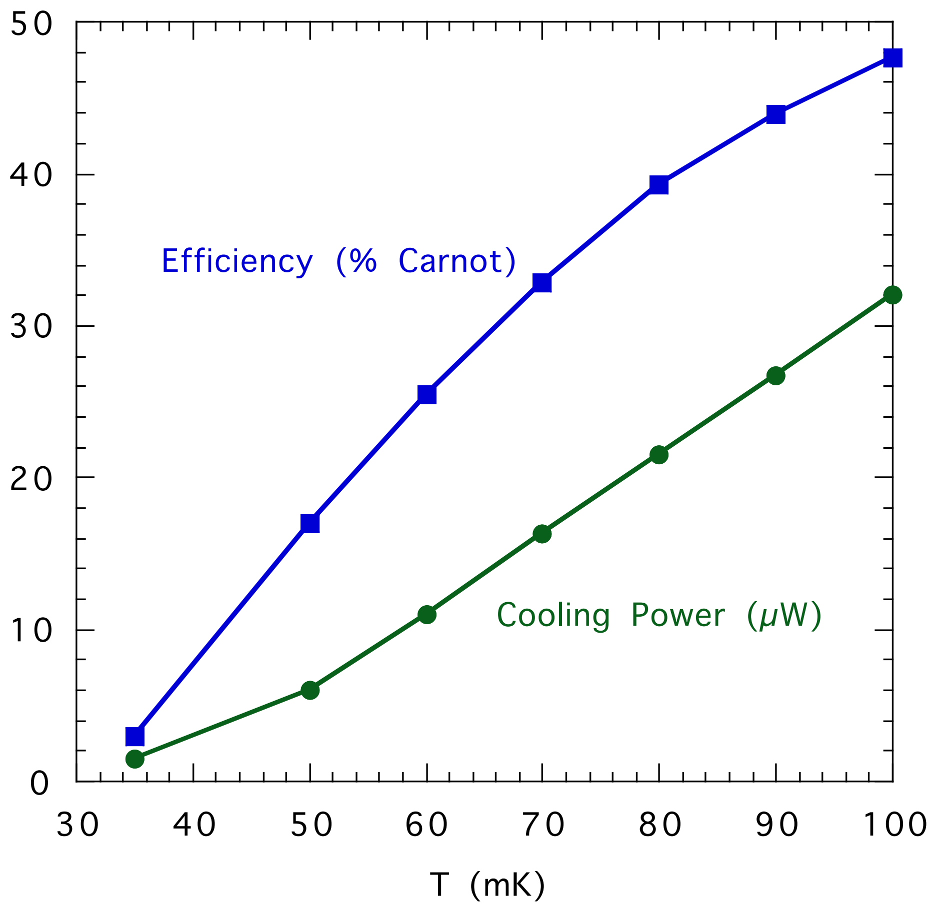


Heat Lift etc.

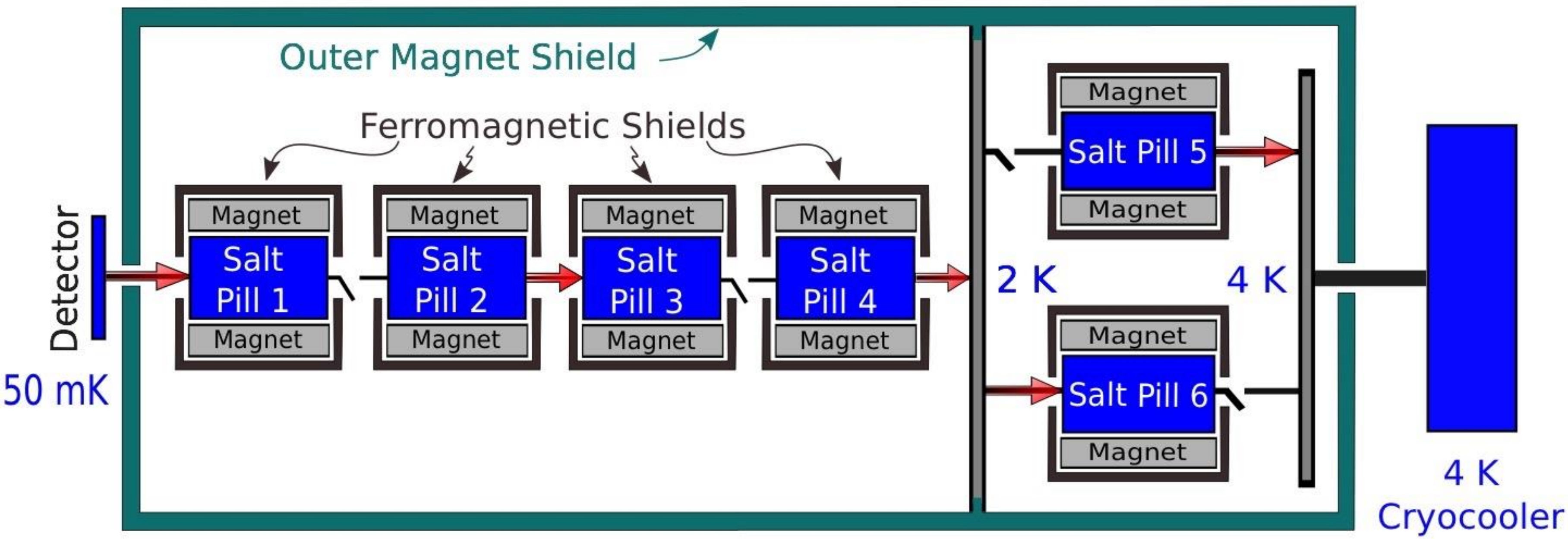


* Cooling power in addition to parasitic heat loads

CADR was developed using research money provided by NASA/GSFC in the early 2000's (Shirron *et al.*)

- Measured cooling powers and overall efficiency measured for that system
- Taking data on new system now and will compare the two systems
    - Expect new system to have a lower available cooling power due to stronger Kevlar suspensions

Many Possibilities



Two, or more, unique continuous temperatures possible

- Asynchronous CADRs
- In this example, one is a 2 K, the other 0.050 K

Summary

- Both 4-stage continuous ADRs built for the PIPER balloon mission and our external partner have completed testing
- One cooler demonstrated continuous operation below 45 mK with a total heat lift of > 5 µW at that temperature
  - Includes parasitic heat to coldest stage two stages
  - Usable cooling power decreased by testing environment (vibrational heating from cooler in one case)
  - Need to modify environment by either dampening cooler or moving to flight Dewar cooled via liquid helium
- Second cooler modified to work from a 4.2 K liquid helium bath
  - Demonstrated greater than 6 µW heat lift in addition to parasitic heating while at 80 mK
- Since the CADR has a higher cooling power for the same mass as a single-shot system, we are now baselining this technology will be baselined for future missions