



Continuous Adiabatic Demagnetization Refrigerator Systems for CMB Probe+ Mission

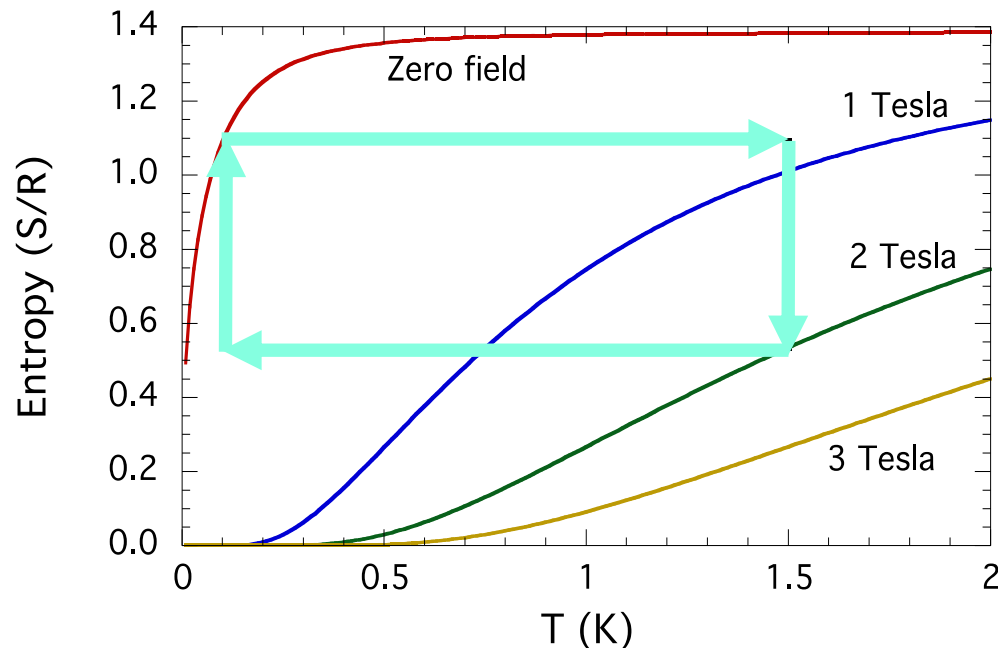
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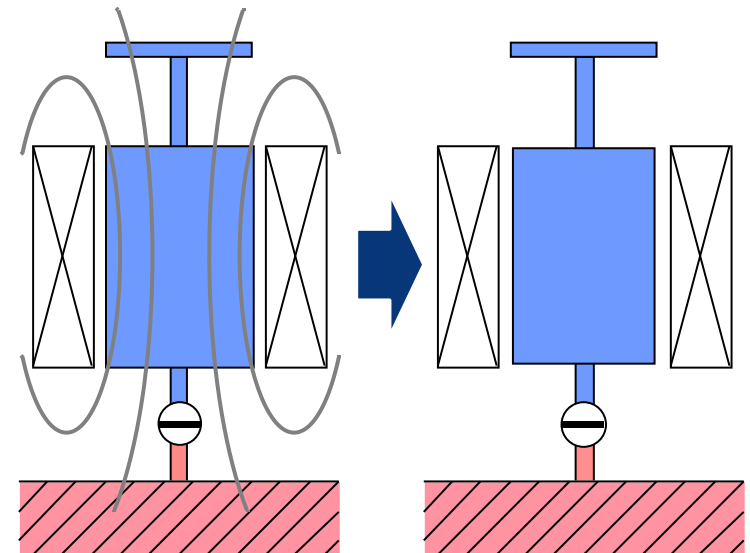


ADR Cycle

- Based on the magnetocaloric effect in a paramagnetic material (“salt pill”)
 - In an increasing magnetic field, salt pill warms or gives off heat
 - In a decreasing magnetic field, salt pill cools or absorbs heat
- Operating temperature is determined by the magnetic field (adjustable on the fly)
- Inherently single-shot, BUT... reversible, so intrinsically high efficiency



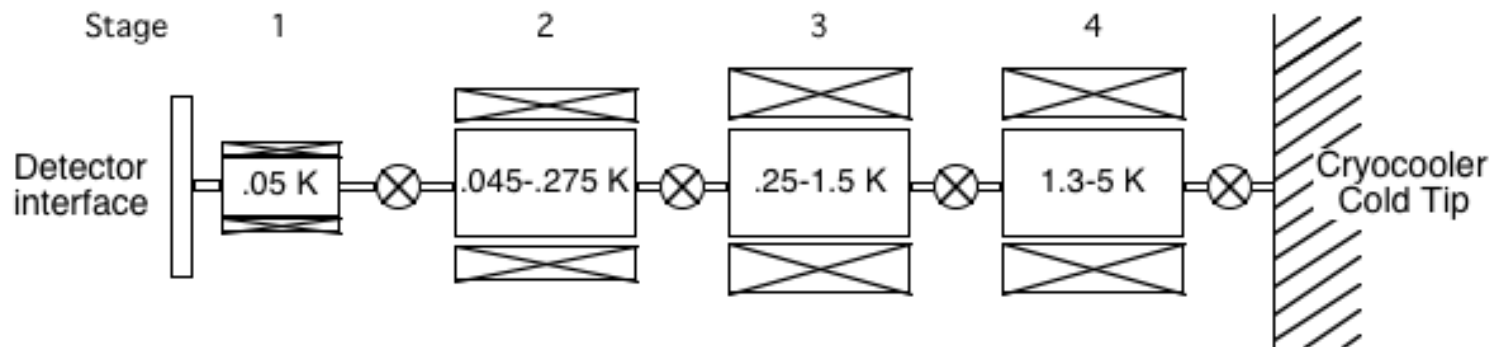
Active field magnetization
demagnetization





Basics of Continuous ADR Cooling

- *Continuous ADR is a very flexible concept, capable of producing continuous cooling at essentially any temperature below the “heat sink”*
 - *Continuous operation significantly increases the cooling power per unit mass*
 - *Essentially no limit on the operating or heat sink temperatures (but there are practical limits)*
- *First implementation (1999-2003) was 4-stage series CADR that produced continuous cooling at 35-100 mK and 4.2 K heat rejection*
 - *Initially the heat sink was a He bath, but eventually CADRs were designed to use flight-worthy cryocoolers*
 - *6 μ W at 50 mK*
 - *8 mW peak heat rejection to 4.2 K*



- *PROBLEM: in this implementation, there is no stable temperature other than the continuous stage (50 mK) and cryocooler (4.5 K)*



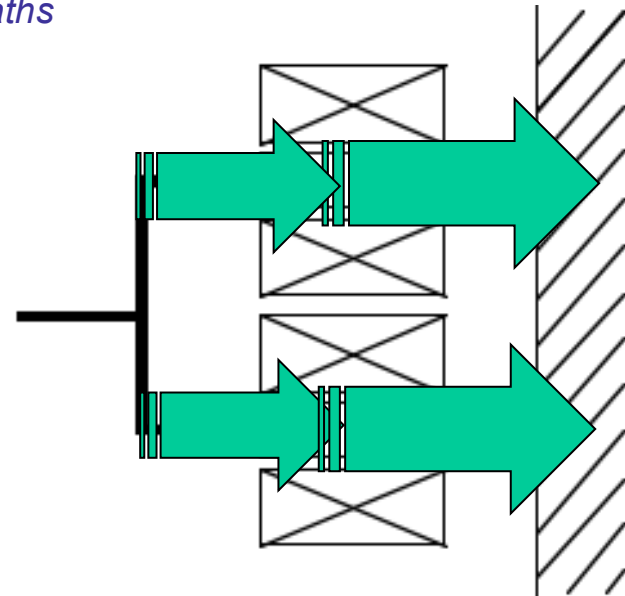
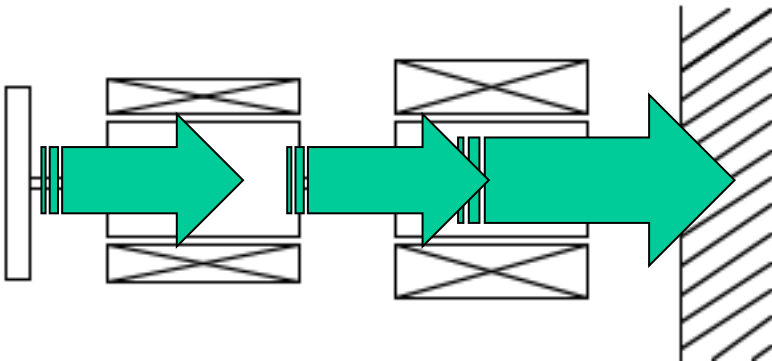
Mission Requirements

- *In developing CADR concepts for multiple mission concept studies (x-ray, IR, CMB probes, etc.), a common requirement was an intermediate stable temperature*
 - *Cooling of optics, amplifiers, support structures for lower T components, etc.*
- *In addition, peak heat rejection must be limited to an acceptable fraction of the flight cryocooler (40-50 mW at 4.5 K)*
 - *Overall system efficiency became a critical consideration*
- *Led to expansion of CADR system designs, considering both series and parallel configurations*



Series vs Parallel CADRs

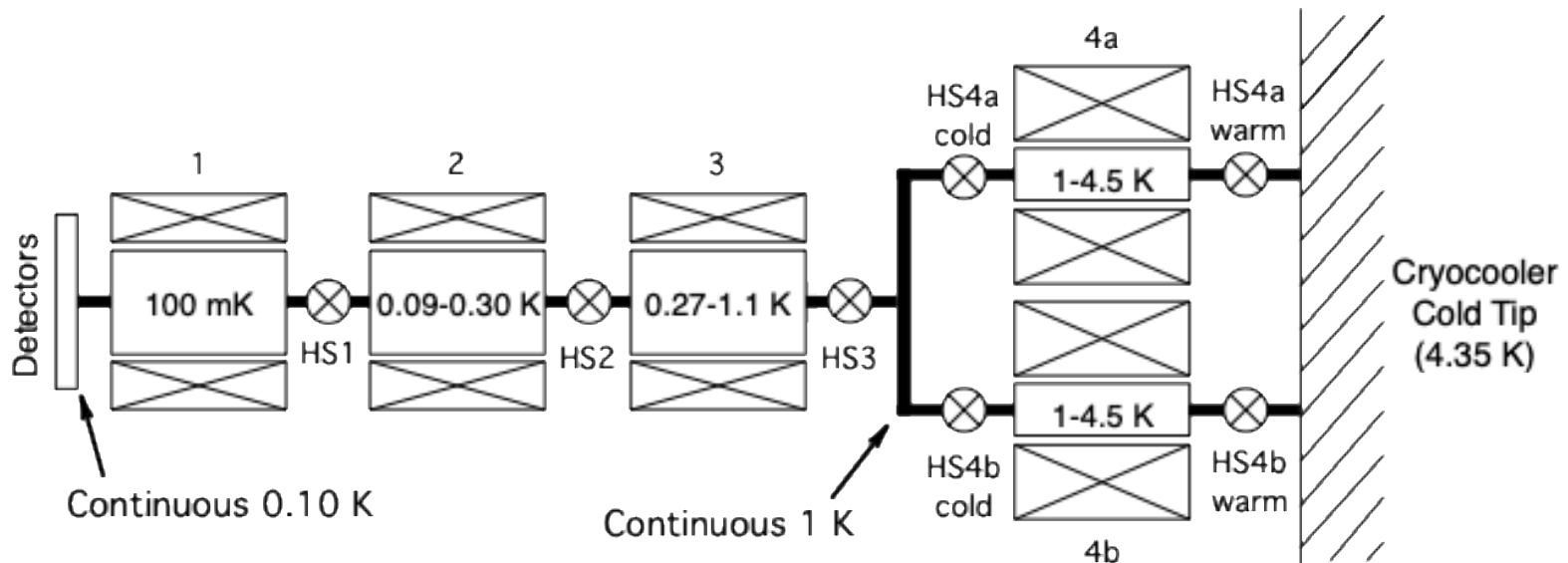
- **Series CADR**
 - Heat is cascaded through upper stage(s)
 - Easily expanded to span wider temperature range with fewer components
- **Parallel CADR**
 - Stages alternate role in cooling the load and rejecting heat
 - Achieves higher average heat reject rate, and therefore capable of higher cooling power
 - More components and more challenging control system
 - Higher parasitic losses due to multiple conduction paths





Concept for CMB Probe+

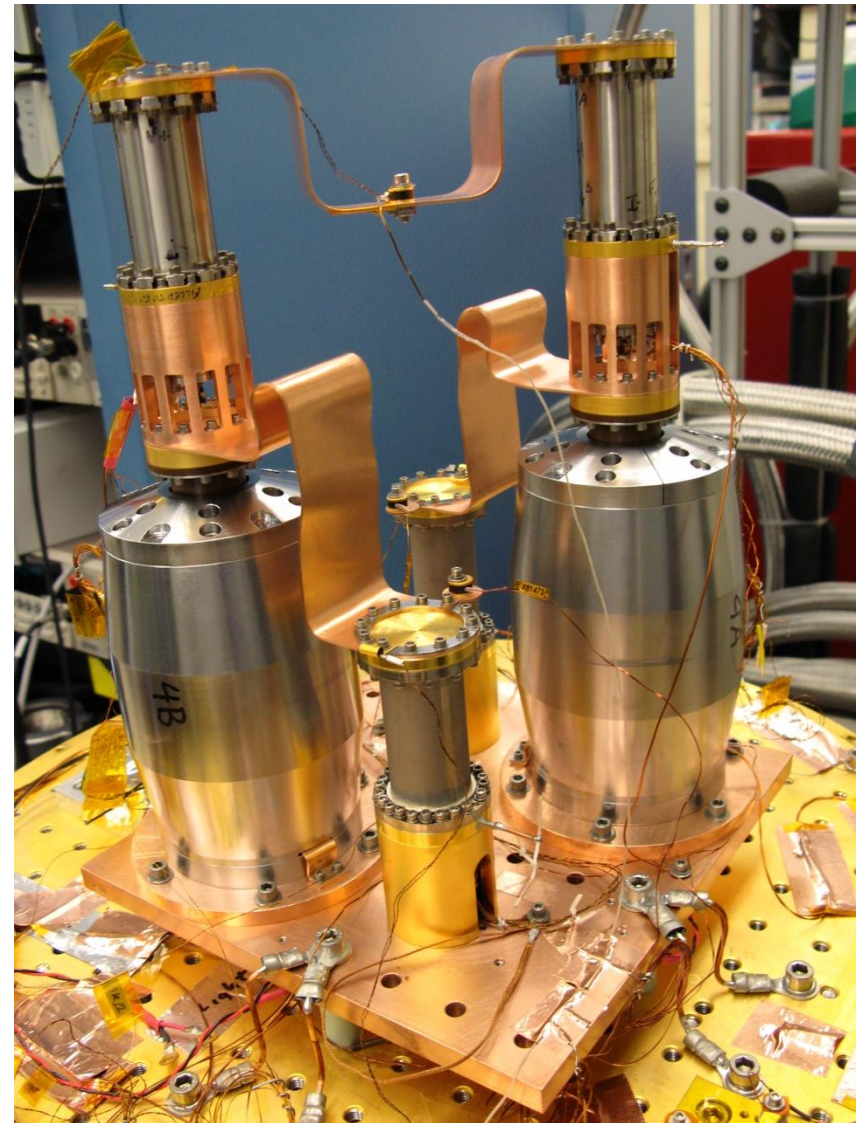
- Combination of series and parallel CADR_s achieves high overall efficiency and cooling powers, with low peak heat rejection
 - Capable of cooling relatively large heat capacities to low T
- Design and operating points can be adjusted for eventual CMB Probe+ requirements
- Performance modeling for CMB Probe+
 - 1 mW at 1 K and 20 μ W at 100 mK both achieve >100% margin on CBE loads





Technology Maturity

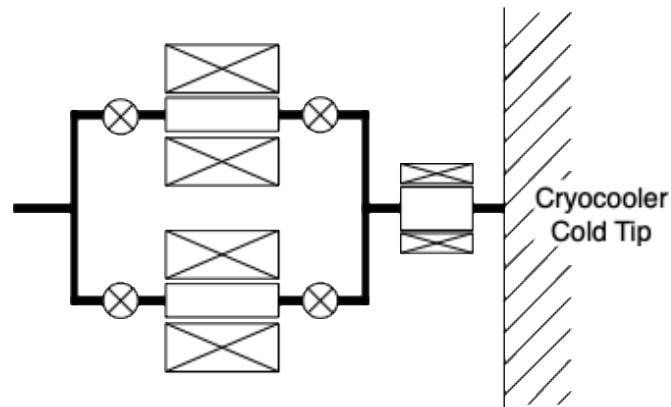
- Have built many (6+) series CADR_s operating at 50-100 mK, rejecting heat to ~1 K
 - Used on PIPER balloon instrument
- A 2-stage series CADR operating at 1.4 K and rejecting heat to 4.5 K cryocooler is currently on orbit (XRISM)
 - ~2 mW cooling power at 1.4 K
 - Not yet demonstrated on orbit
- Recently demonstrated operation of a 2-stage parallel CADR operating at 1 K using a 4.35 K cryocooler heat sink
 - 1 mW cooling power with peak heat rejection of 15 mW





Future Work

- *Continue to refine control algorithms and hardware configurations to improve temperature stability at the continuous platforms*
 - *Depends on particular instrument requirements (esp. spectral densities)*
- *Working on concept for achieving continuous heat rejection*
 - *Reduce peak heat reject rate*
 - *Stabilize cryocooler temperature and any attached components (optics, wiring, etc.), which stabilizes heat loads to lower temperature*





Temperature Stability

- *In CADRs, there is a trade-off between cooling power and temperature stability: faster cycling improves cooling power but leads to larger transients during heat switch transitions*
- *Most common way to state temperature stability is to specify micro- or milli-kelvin rms temperature variation*
- *Distributed nature of many instruments, connected to the CADR with some time constant, suggests specifying requirements based on spectral distribution*

