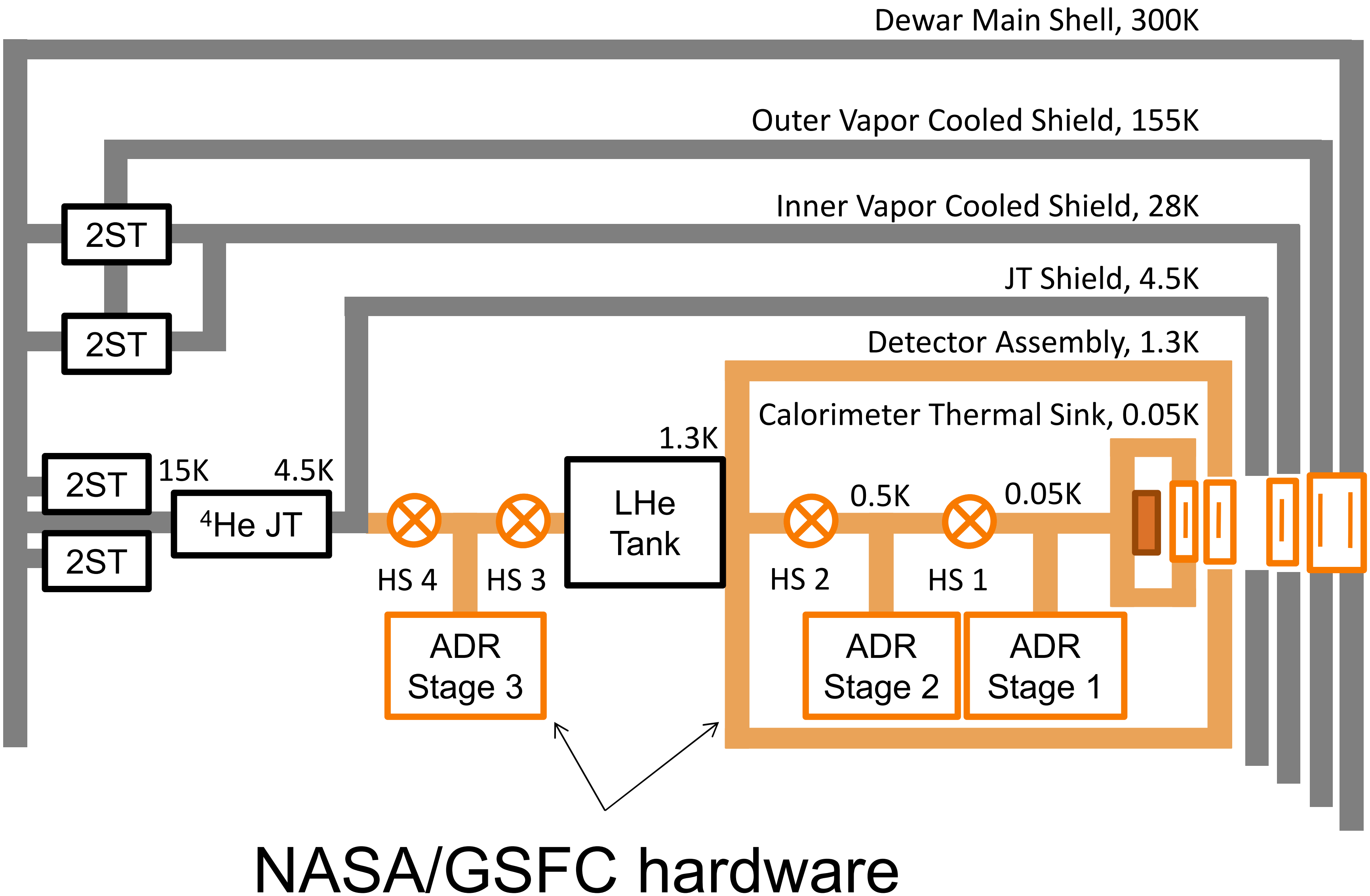
National Aeronautics and Space Administration

Thermodynamic Analysis of the 3-Stage ADR for the Astro-H Soft X-ray Spectrometer Instrument

Peter Shirron

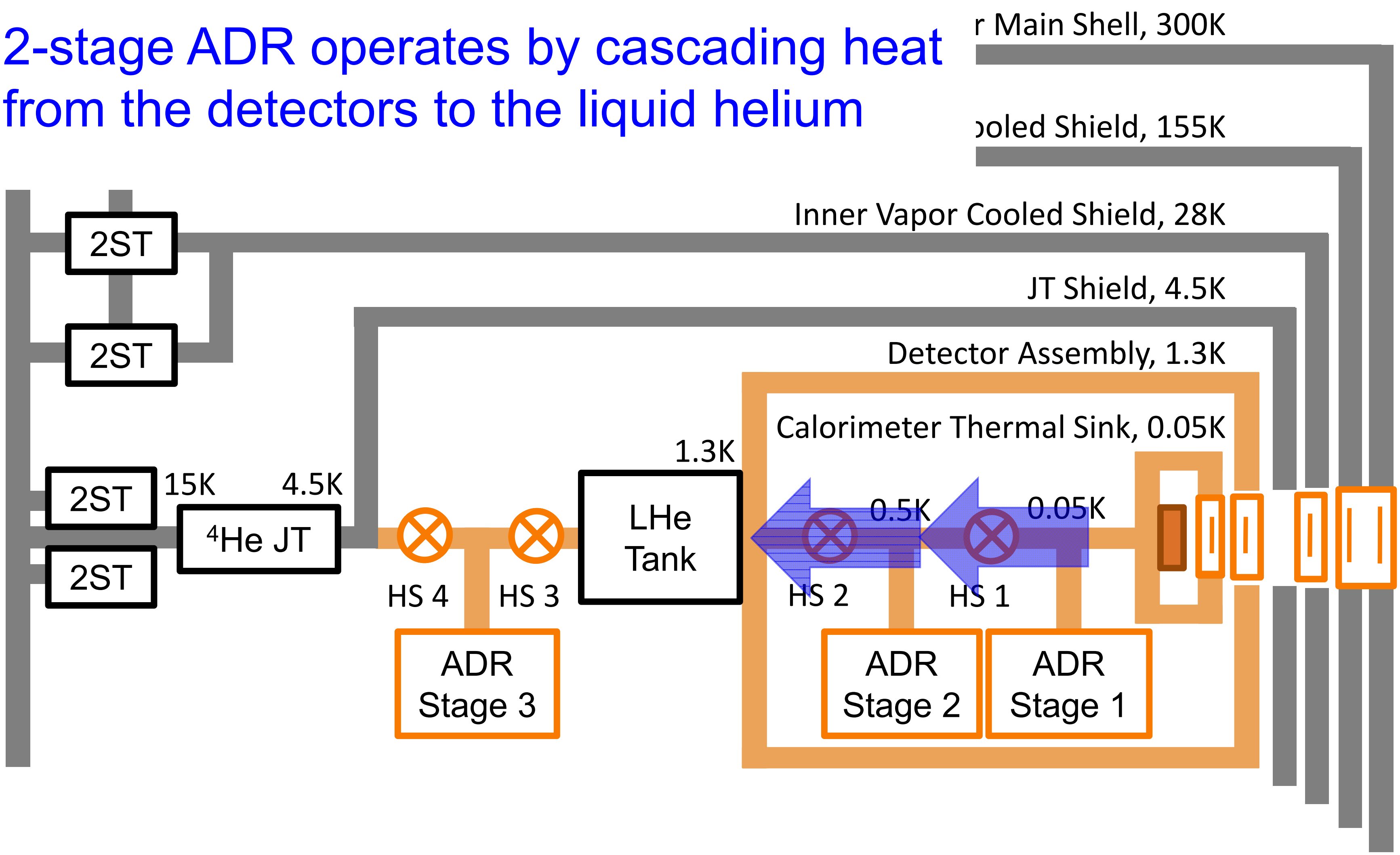
Mark Kimball, Michael DiPirro, Tom Bialas, Gary Sneiderman, Scott Porter, Richard Kelley

Astro-H Cryogenic System



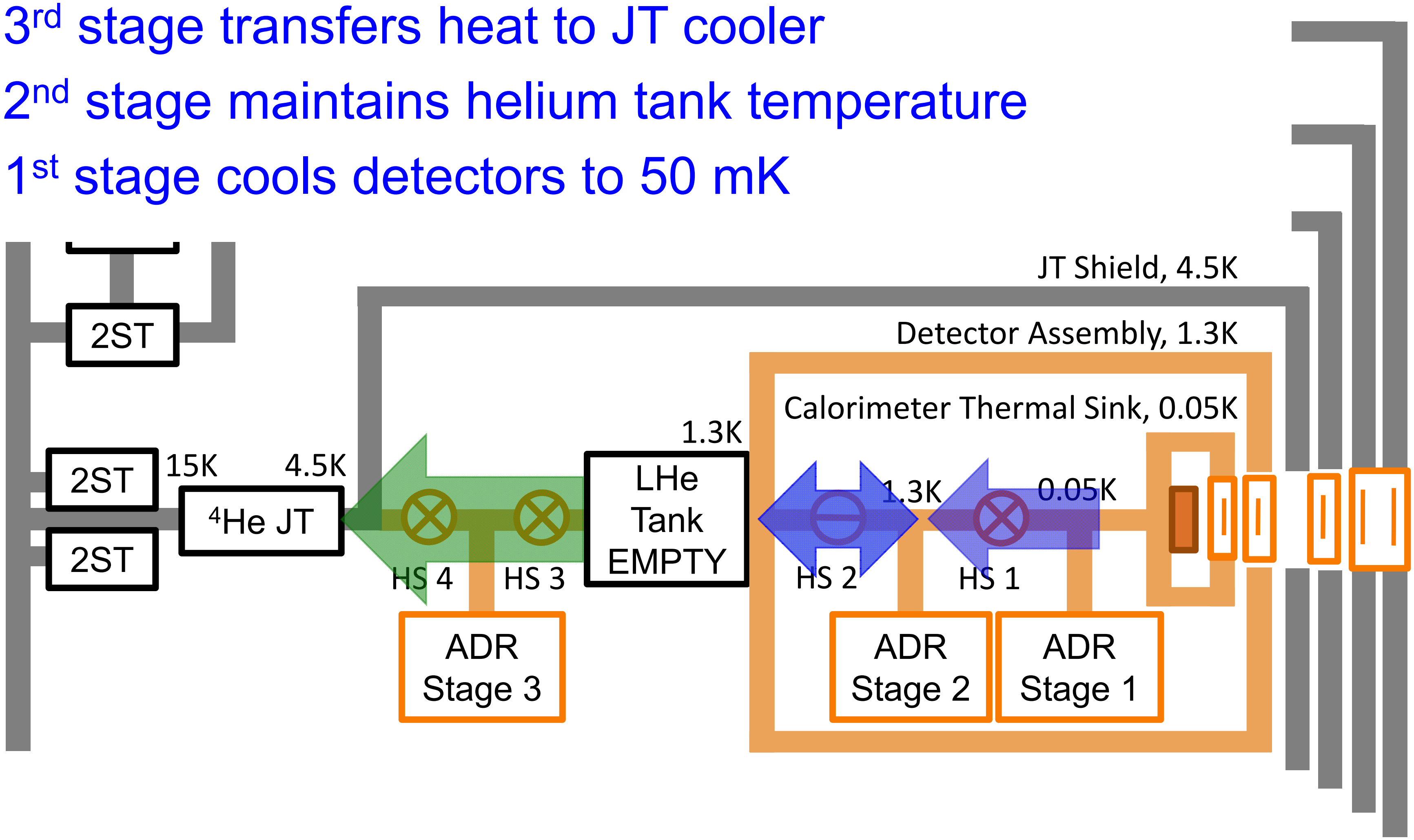
ADR Operation in Cryogen Mode

- 2-stage ADR operates by cascading heat from the detectors to the liquid helium



ADR Operation in Cryogen-Free Mode

- 3rd stage transfers heat to JT cooler
- 2nd stage maintains helium tank temperature
- 1st stage cools detectors to 50 mK



Thermodynamic Performance

For both operating modes:

- Heat lift capabilities
  - Required (detector) cooling power
  - Parasitics heat loads and internal dissipation
- Heat rejected to heat sinks
  - Heat from salt pills
  - Heat switch power
  - Hysteresis heat generation
- Thermodynamic analysis
  - Cooling power or capacity
  - Heat absorption efficiency
  - Cycle efficiency

ADR Design Basis

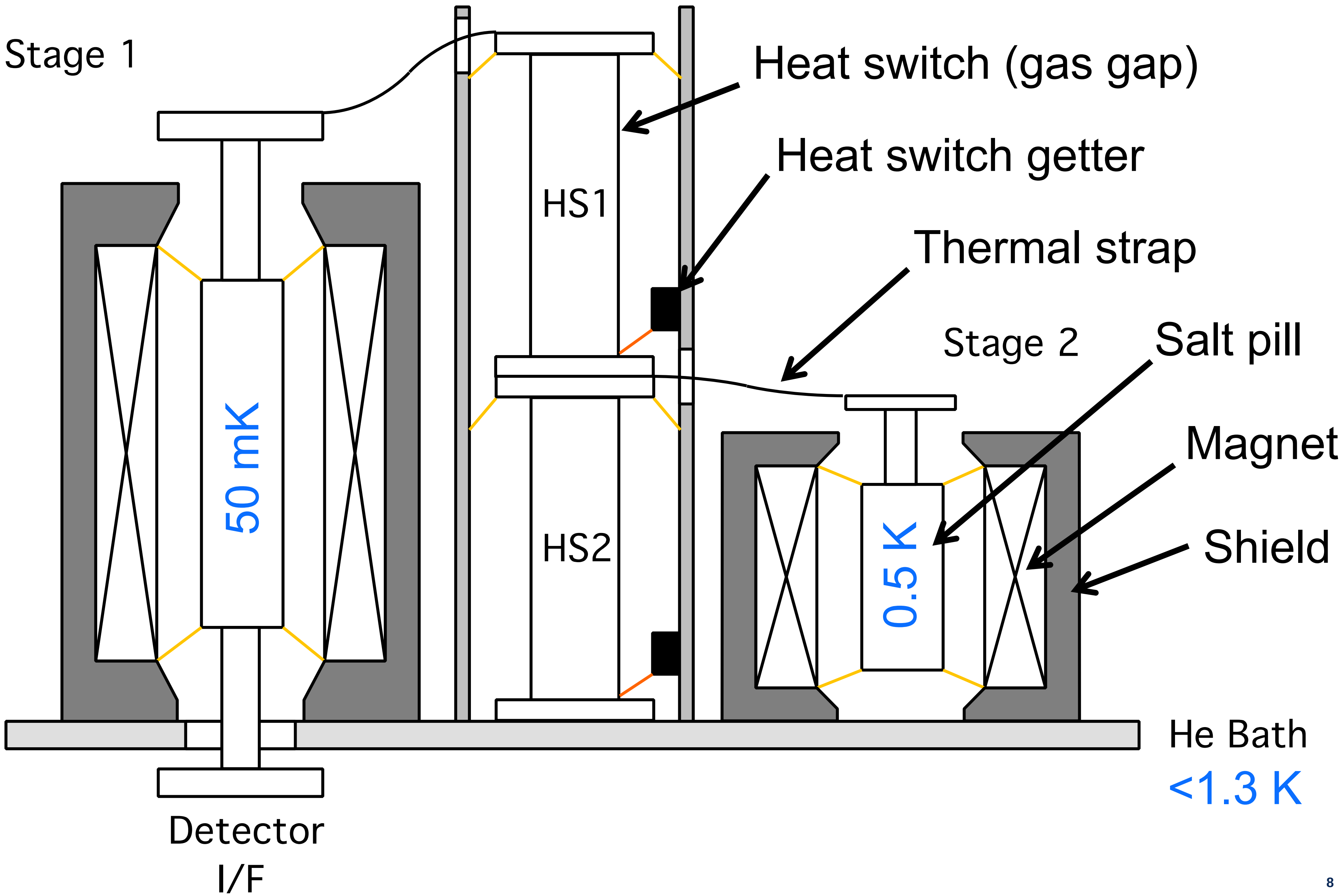
- 2-stage ADR design was based on operation with 1.8 K JT
  - Detector heat load of 0.47 μW
  - Salt pill sized for 2x margin on detector and parasitic heat loads
  - Kevlar loads scaled from Astro-E/E2, based on salt pill mass
  - Heat switch parasitic load significantly reduced by 2-stage configuration
- Total heat load estimated at 0.67 μW
  - 270 grams CPA
  - 2 T magnet
    - 2 amp / 2 T magnet used on Astro-E/E2
  - 0.8 K starting point for demagnetization to 50 mK
  - 48 hour predicted hold time with 1.8 K heat sink with assumption of 70% utilization of entropy capacity

ADR Design Summary

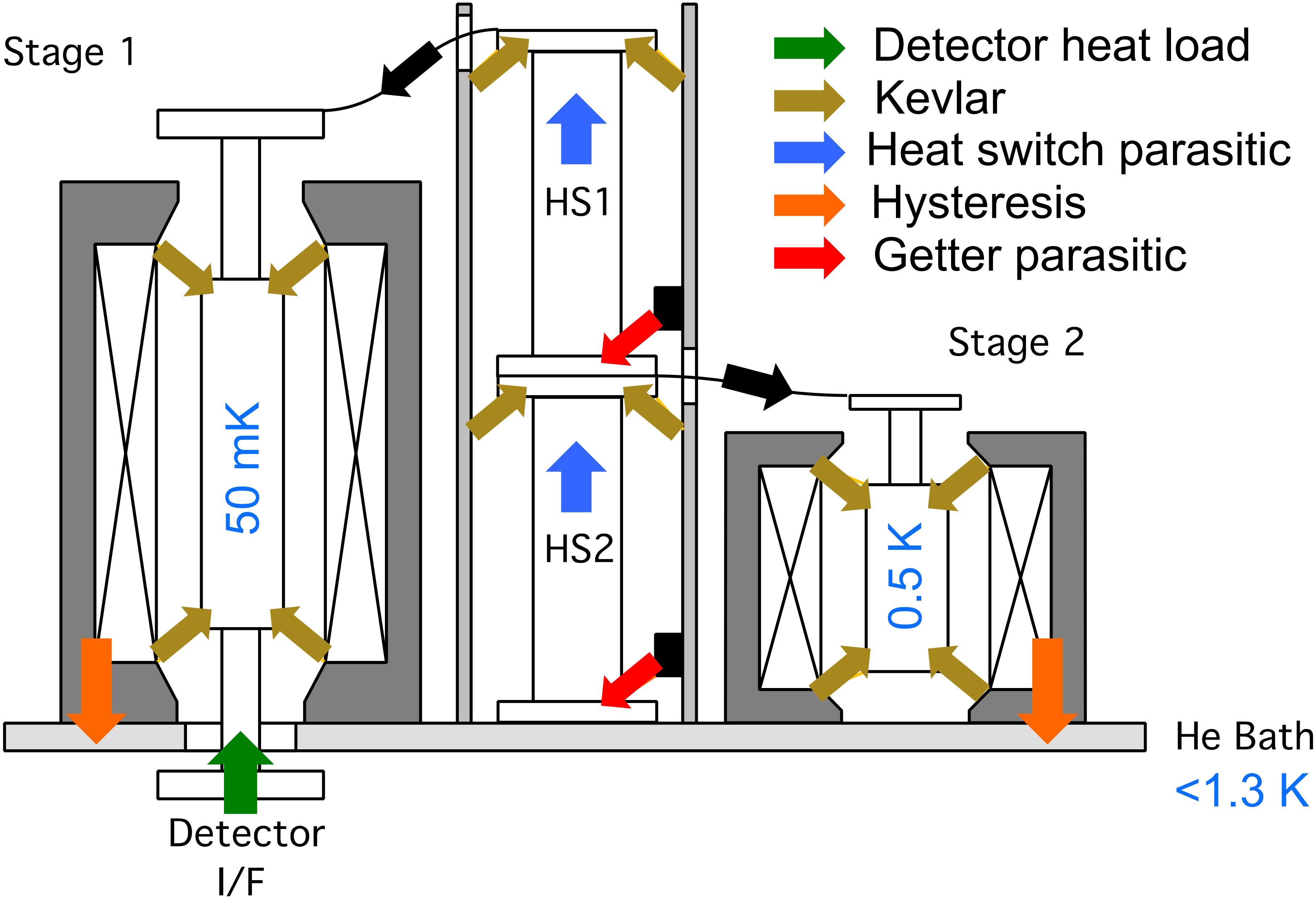
	Stage 1	Stage 2
Salt / mass	CPA, 270 grams	GLF, 147 grams
Peak magnetic field (avg.) (T)	2	3
Demag. Temperature (K)	0.8	1.4
Hold temperature (mK)	50	0.5
Cooling capacity (J)	0.165	
Utilization	70% (0.116 J)	

	Stage 3
Salt / mass	GLF, 147 grams
Peak magnetic field (avg.) (T)	3
Demag. Temperature (K)	4.7
Hold temperature (K)	1.0-1.6

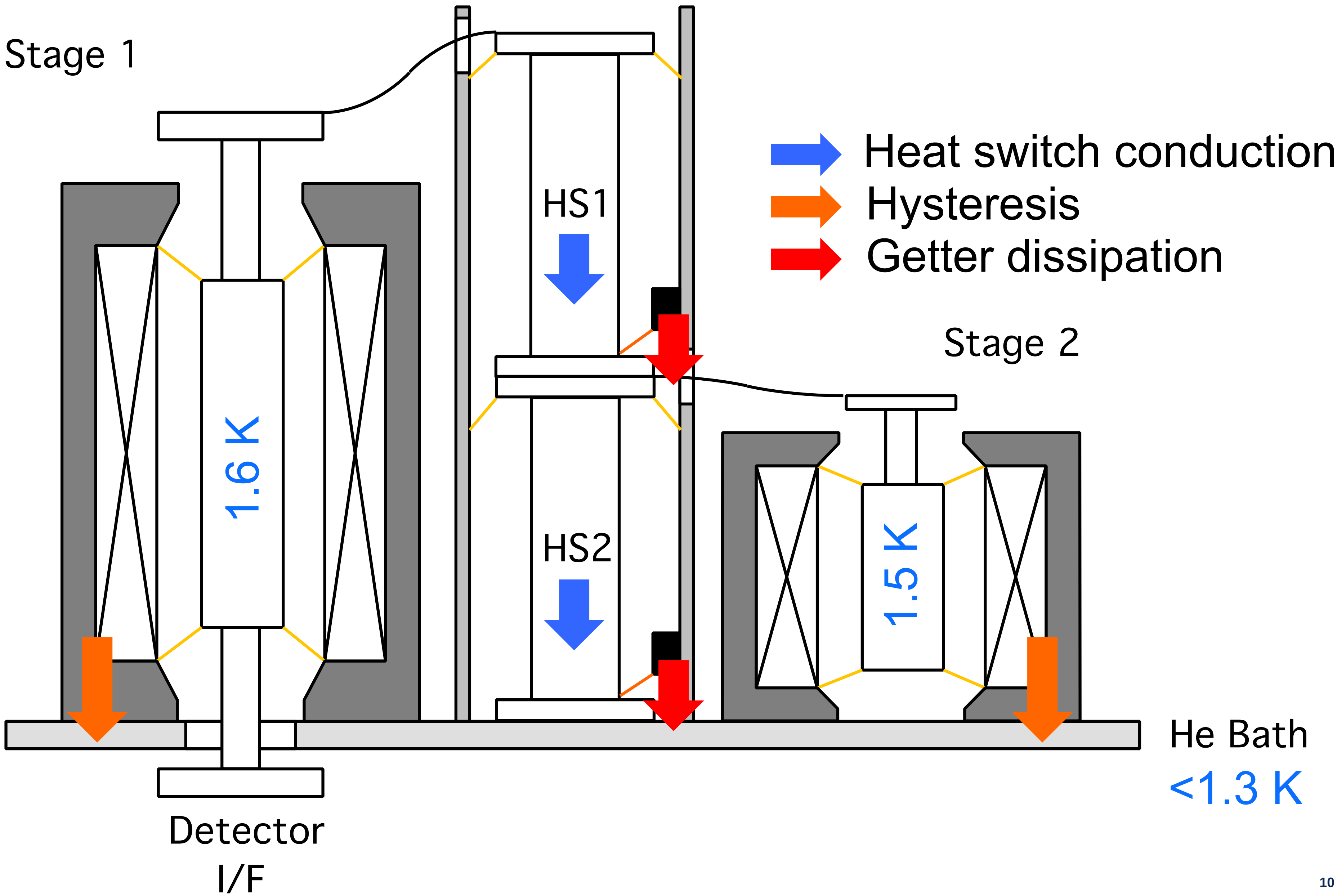
2-Stage ADR Schematic



Cryogen Mode – Heat Flow During Hold

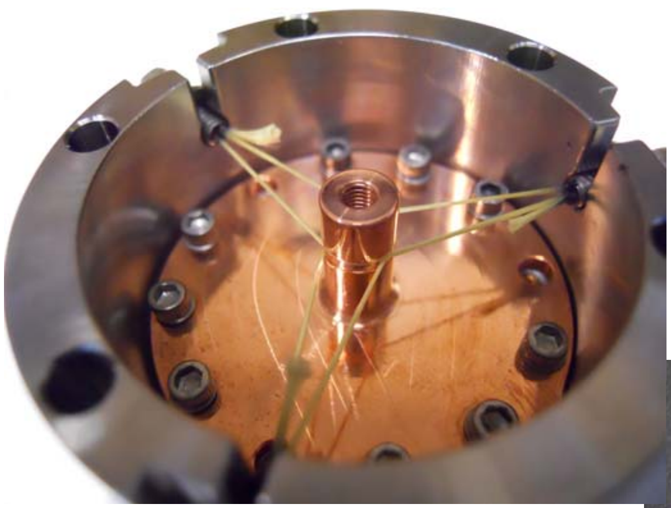


Cryogen Mode – Heat Flow During Recycle



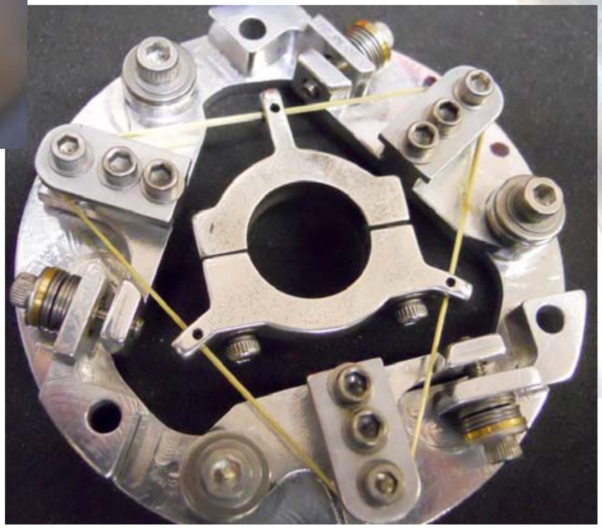
Kevlar Suspension

- Kevlar 49 is used to support salt pills and HS1/HS2 stack
  - Unbraided bundles of 198 denier (134 fibers, 12.5 micron diameter)
  - Number of bundles depends on suspended mass and max g loads



Heat switch: 4

Salt pill "gimbal":
Main loop: 16
Side loops: 12



Salt pill "lateral": 8

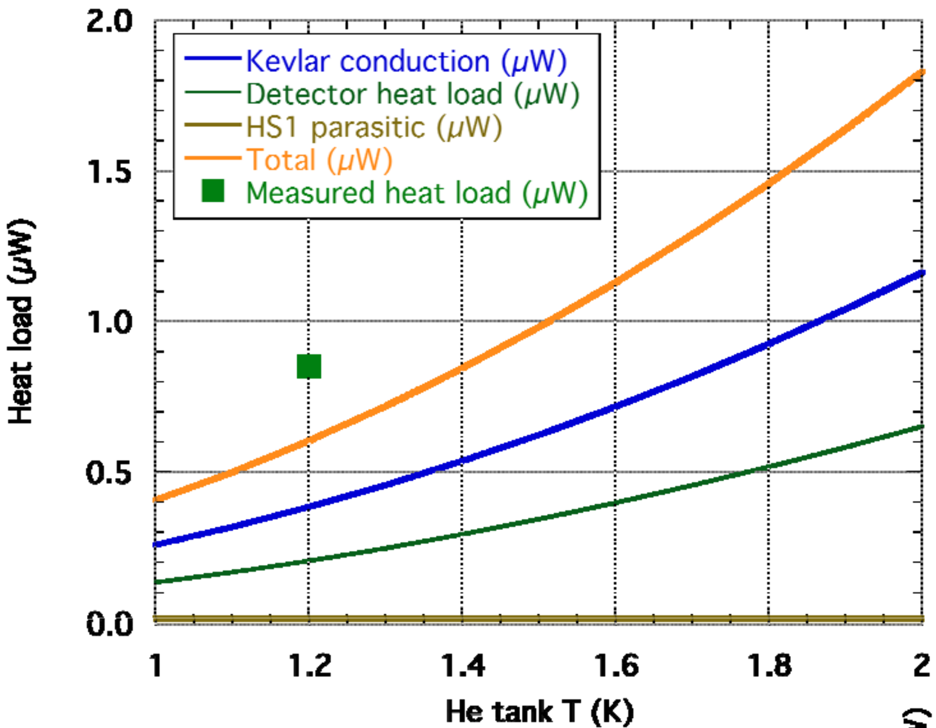
Heat Loads During Hold

- He tank at 1.2 K

Heat load source	Stage 1 (50 mK)	Stage 2 (0.5 K)
Detector array	0.25 µW	
Kevlar suspension	0.38 µW	0.35 µW
Getter parasitic		1.35 µW
Heat switch parasitic	0.02 µW	0.40 µW
Total	**0.65 µW**	**2.10 µW**
Measured loads	**0.86 µW**	**2.20 µW**

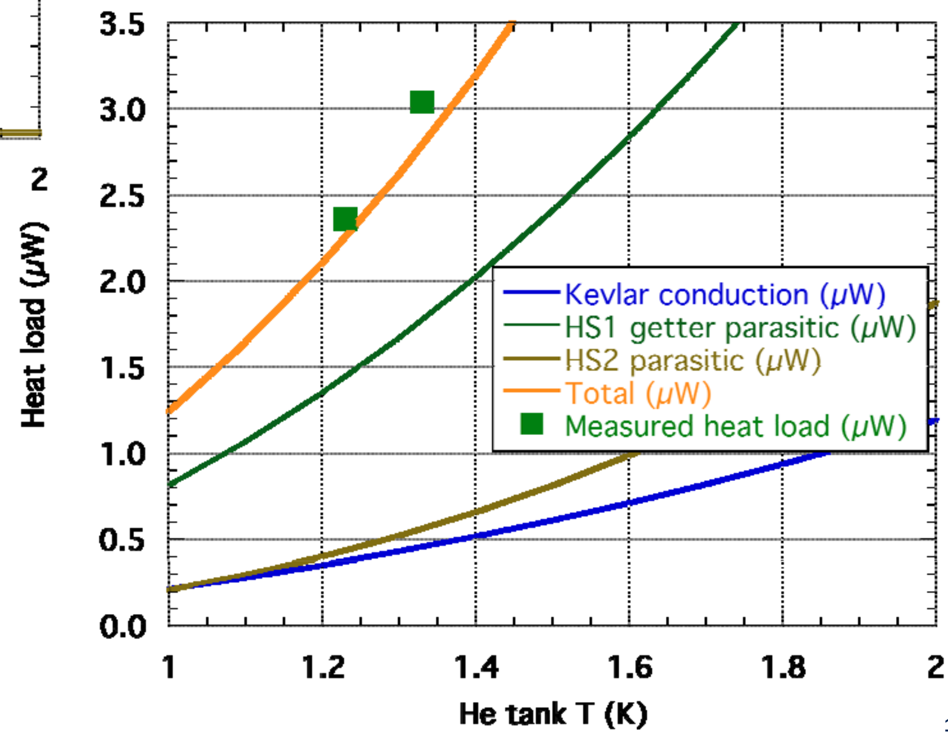
- Possible sources of discrepancy for Stage 1 heat load
  - Detector load or suspension loads are underestimated
    - Considerable uncertainty in literature for Kevlar 49
  - Sensor wiring (heat sunk to Stage 2)
  - Vibrational heating in the Kevlar

Measured vs Expected Heat Loads



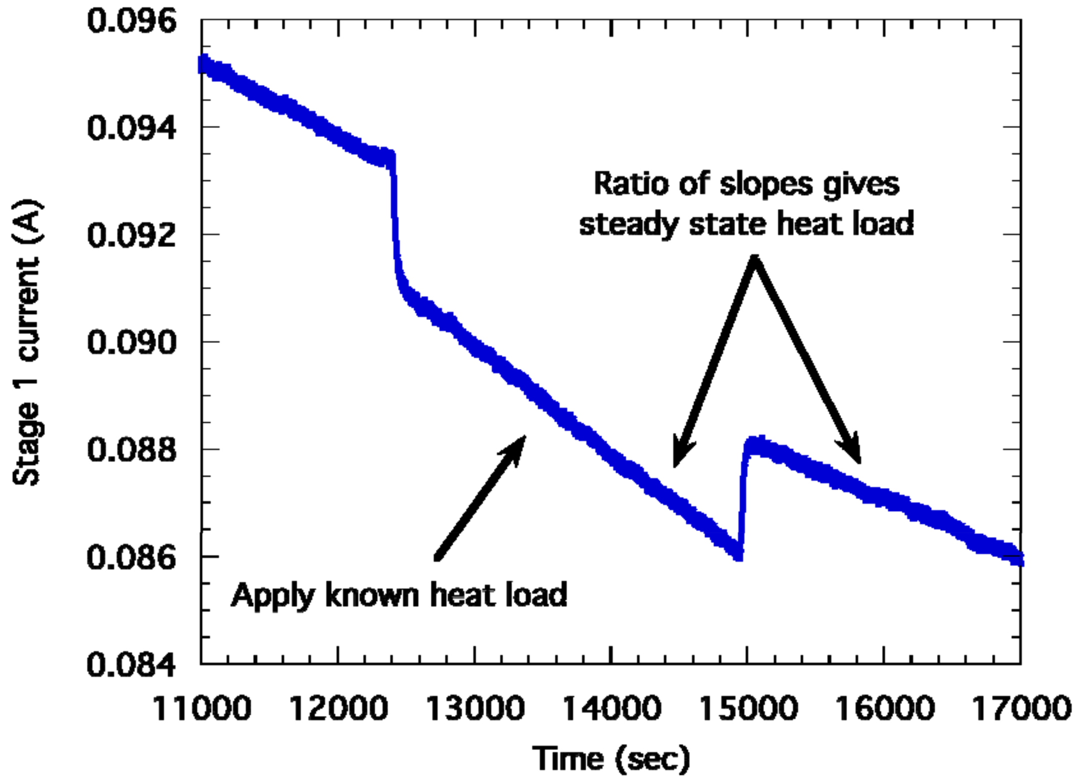
Stage 1

Stage 2



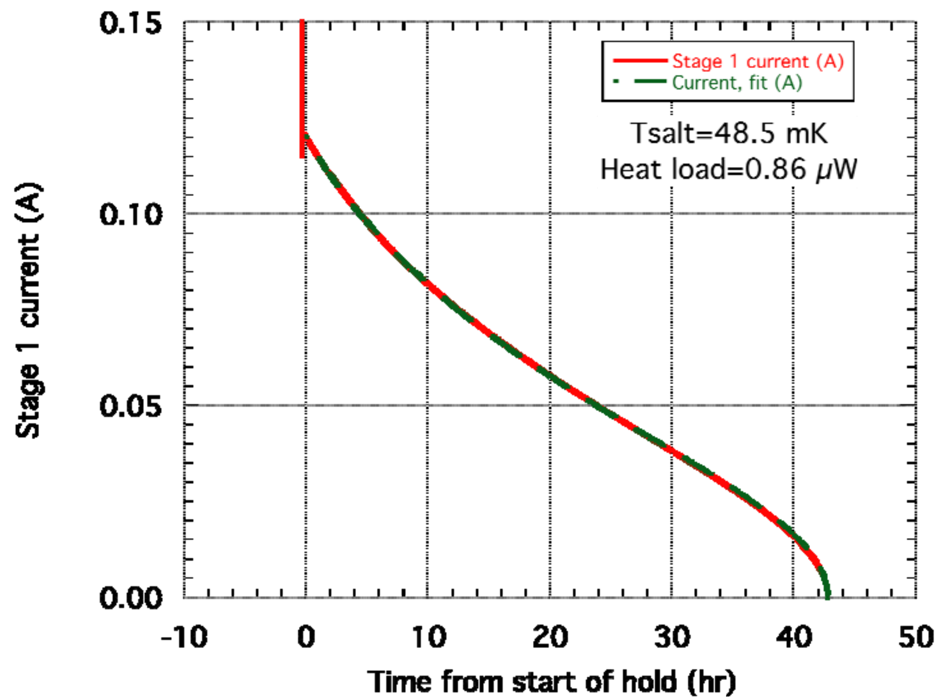
Heat Load Determination

- Measure heat load directly by comparing demagnetization rates with and without applied heat
  - Demag rate is essentially independent of salt temperature
- Establishes an equivalence between dI/dT ⇔ dQ/dT
  - Assumes no degradation over time

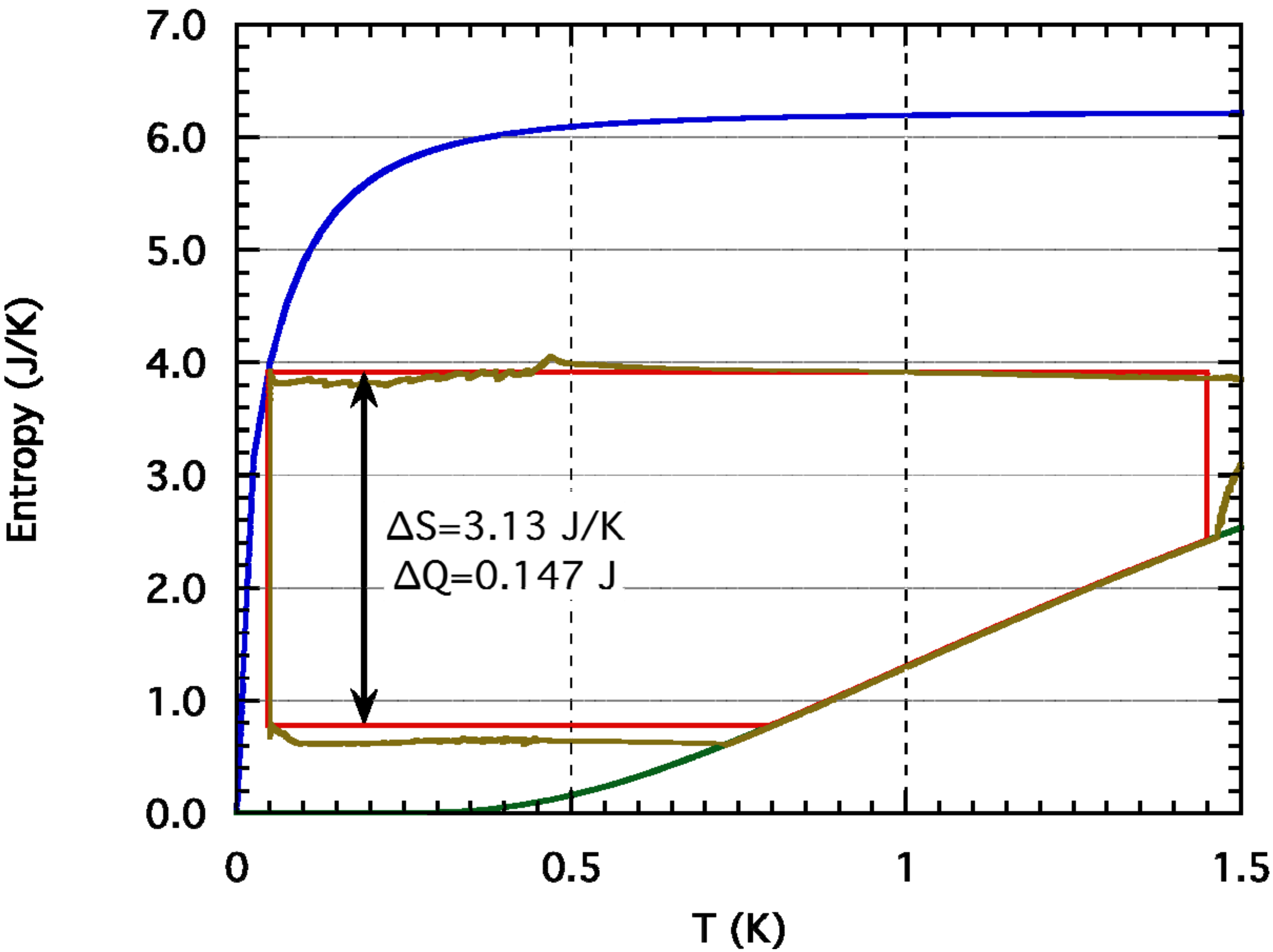


Heat Absorption Efficiency

- Entropy generation: $\dot{S} = \dot{Q}/T$
- Calculate change in salt entropy: $\dot{S}_{salt}(n_{salt}, \dot{B}, T_{salt})$
  – Reflects inefficiencies due to internal gradients and ineffective salt mass
- Determine T_{salt} from fit of *B(t)* to standard curve
  – Requires knowledge of average field to current ratio in salt volume
- Find $\dot{S}/\dot{S}_{salt} = 84\%$



Stage 1 Entropy Diagram



Stage 1 Performance

- Design and actual salt mass is 270 grams of CPA

	Basis		Cooling capacity (J)	Utilization	Usable cooling capacity (J)
	Start point	End point			
Ideal	2T, 0.8 K	0T, 50 mK	0.165	100%	0.165
Design	2T, 0.8 K	0T, 50 mK	0.165	70%	0.115
Actual				80.0%	0.132

	Basis		Max cooling capacity (J)	Actual cooling capacity (J)	Utilization
	Start point	End point			
As built/run	1.92 T, 0.75 K	0T, 48.5 mK	0.160	0.132	83%
As built/run	0.113 T, 48.5 mK	0T, 48.5 mK	0.157	0.132	84%

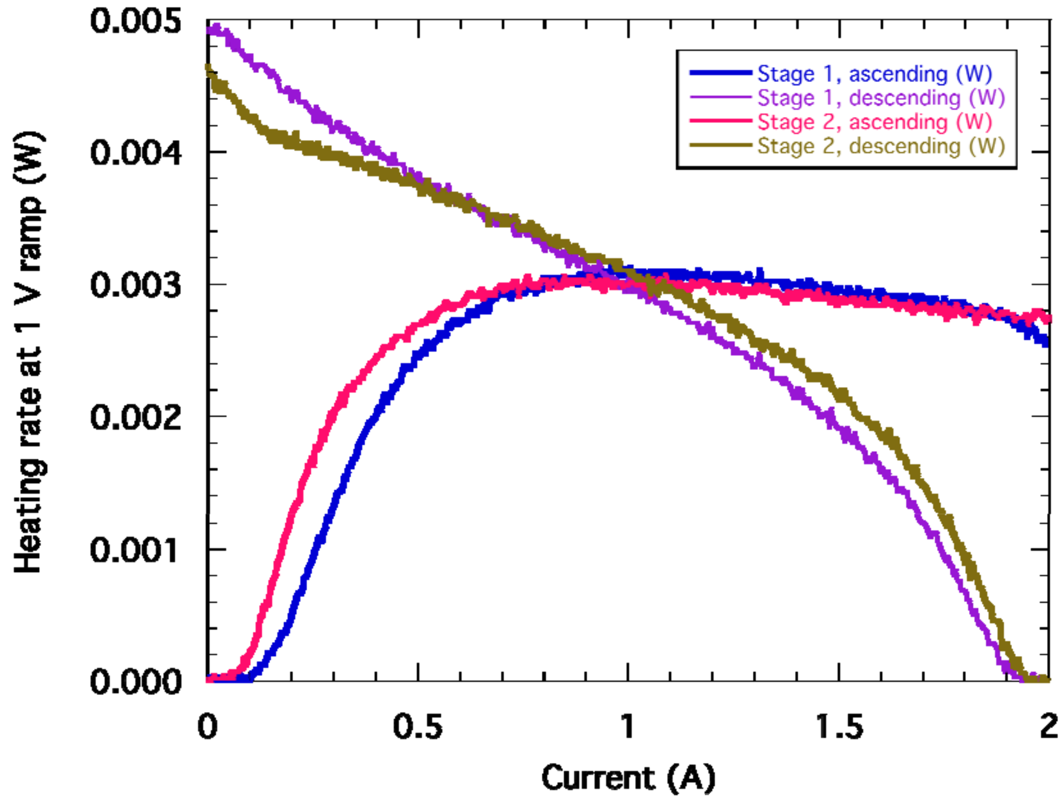
ADR Heat Output (Cryogen Mode)

- Heat sources
  - Salt pill heat
  - Hysteresis
  - Heat switch operation (getter power)

- Salt pill heat can be measured directly using HS2 as a heat meter
  - Thermal conductance is calibrated by measuring temperature difference across the switch with a known heat flow
    - Heat flow is generated by steady magnetization of Stage 1 salt pill
- Hysteresis has been measured as a function of field excursion for both Stage 1 and 2 magnets / shields
- Getter power is known directly from the control setpoint

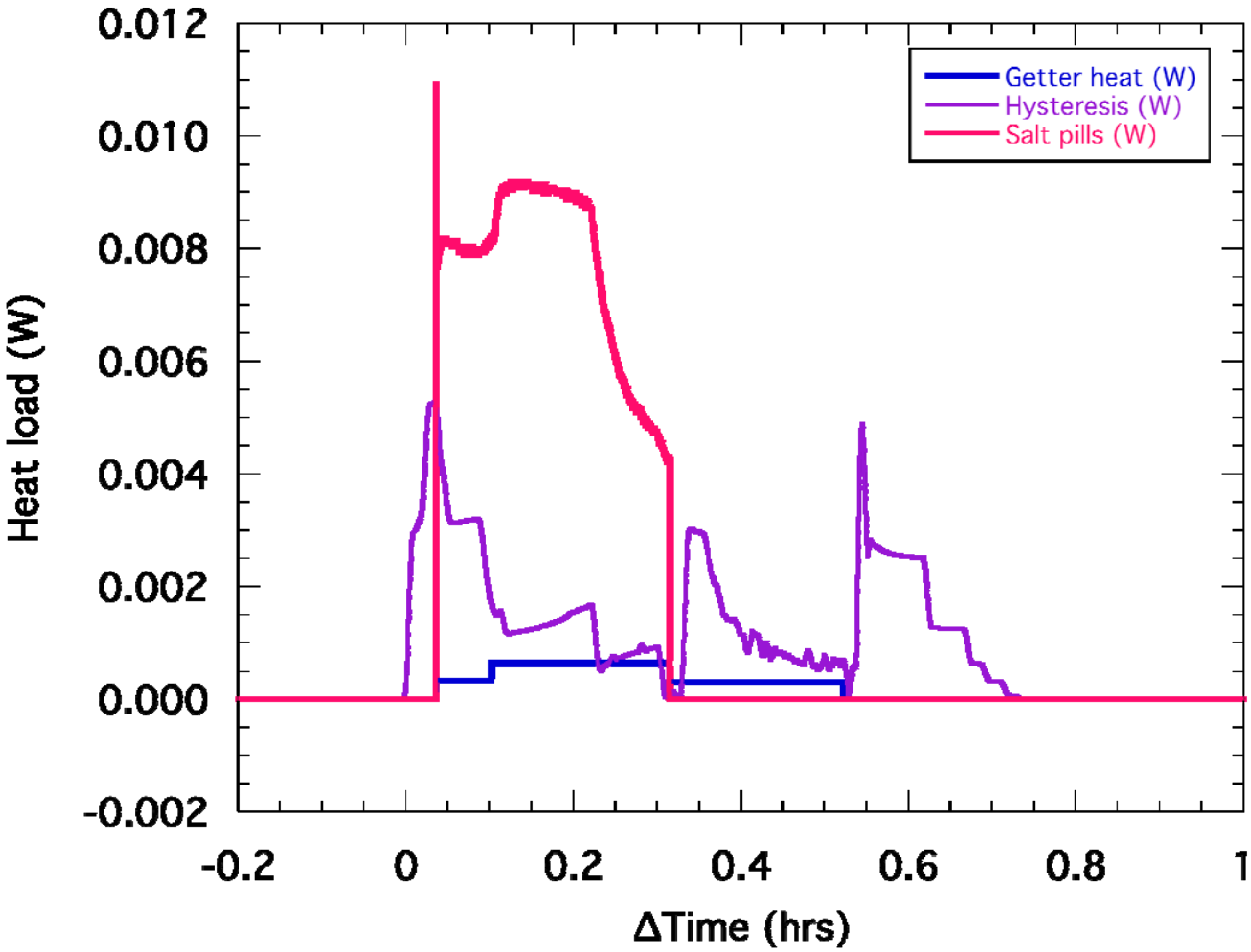
Hysteresis Heat Generation

- Calorimetric measurement of hysteresis heating rate
  - Full He tank at ~1.3 K
  - Calibrate temperature response with known heat input
  - Cycle magnets, 0 to 2 to 0 amps, with heat switches off
- Integrated heat
  - Stage 1: 2.18 J
  - Stage 2: 2.15 J
  - Stage 3 assumed to be the same as Stage 2

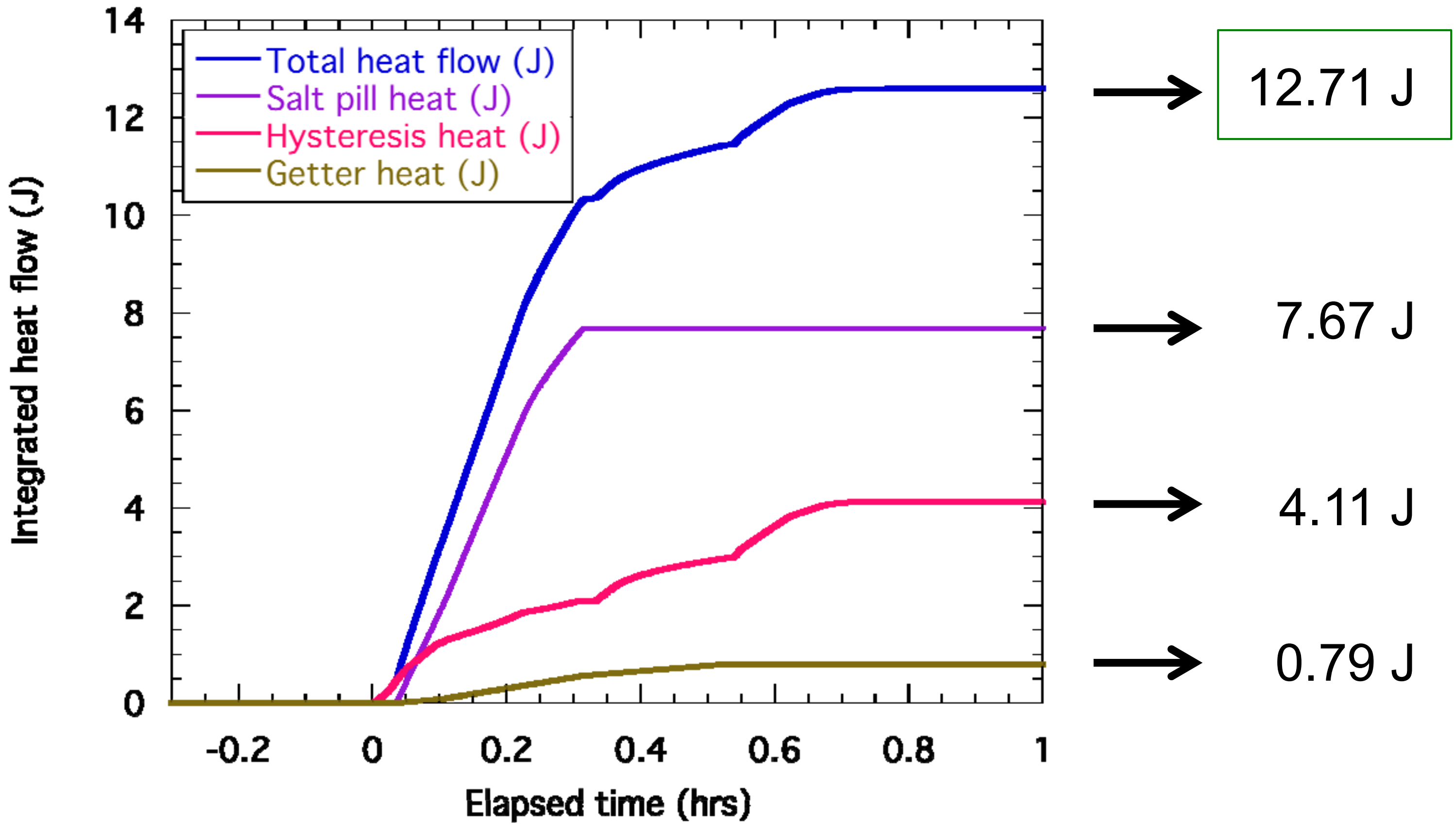


Heat Generation During Recycle

- Heat loads from getter heating, hysteresis and salt pills



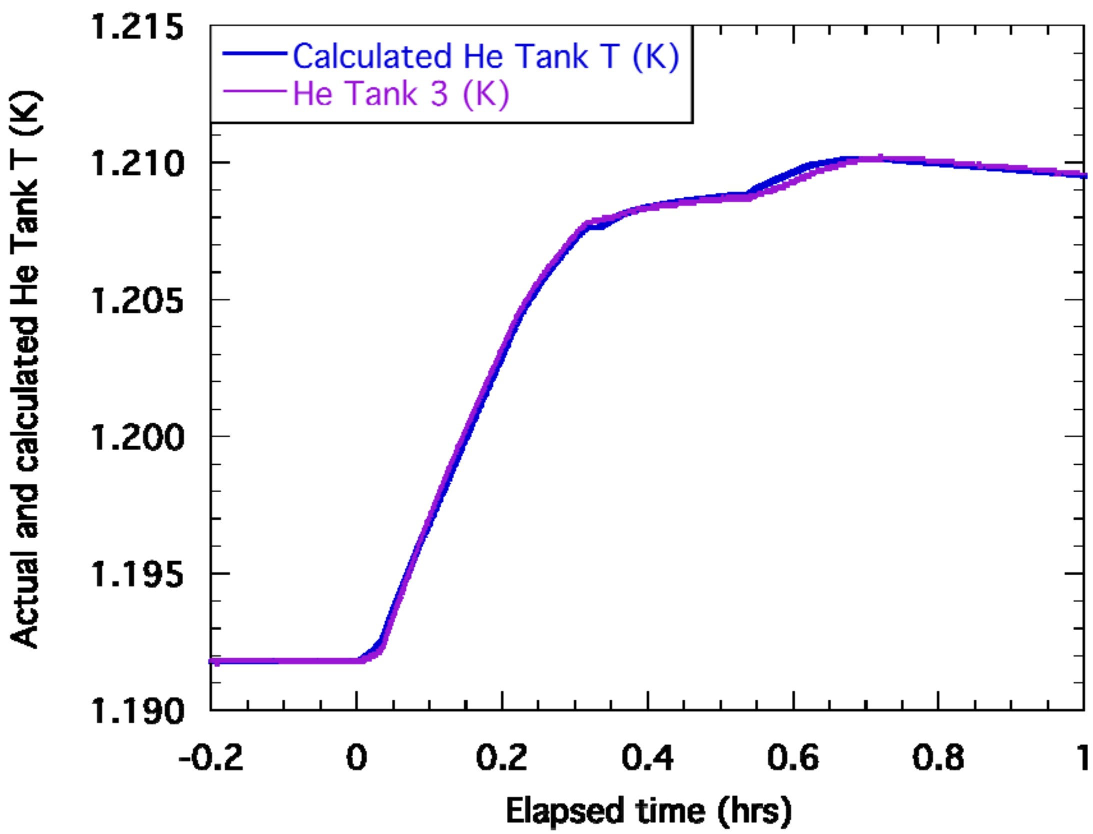
Heat Flows During Cycle

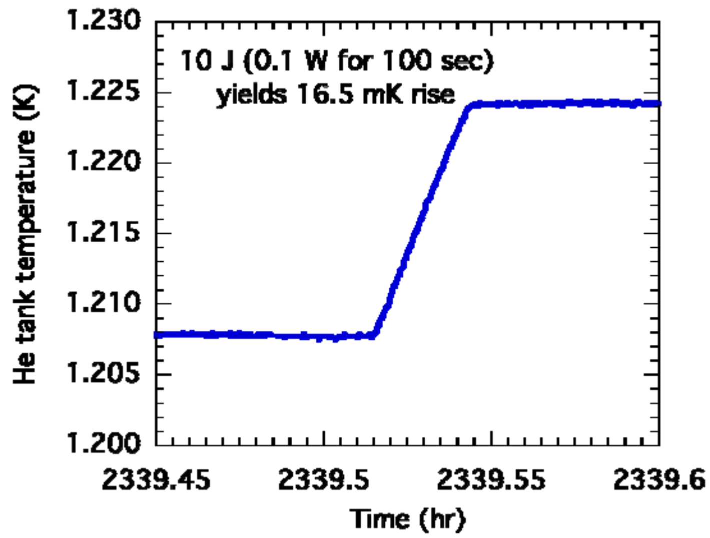


- During hold, additional 0.14 J hysteresis heat is generated
- Cycle period is ~43 hours, giving time average heat rejection rate of 83 µW
  - Requirement is <250 µW
  - Allocation does not include 0.?? mW for HTS leads

ADR Heat Output as Mass Gauge

- Tank response to heat input was calibrated by mass gauge heater
- Tank response to heat from ADR recycle was then calculated
  - Suggests the total heat load and the relative magnitude of each heat load is correct



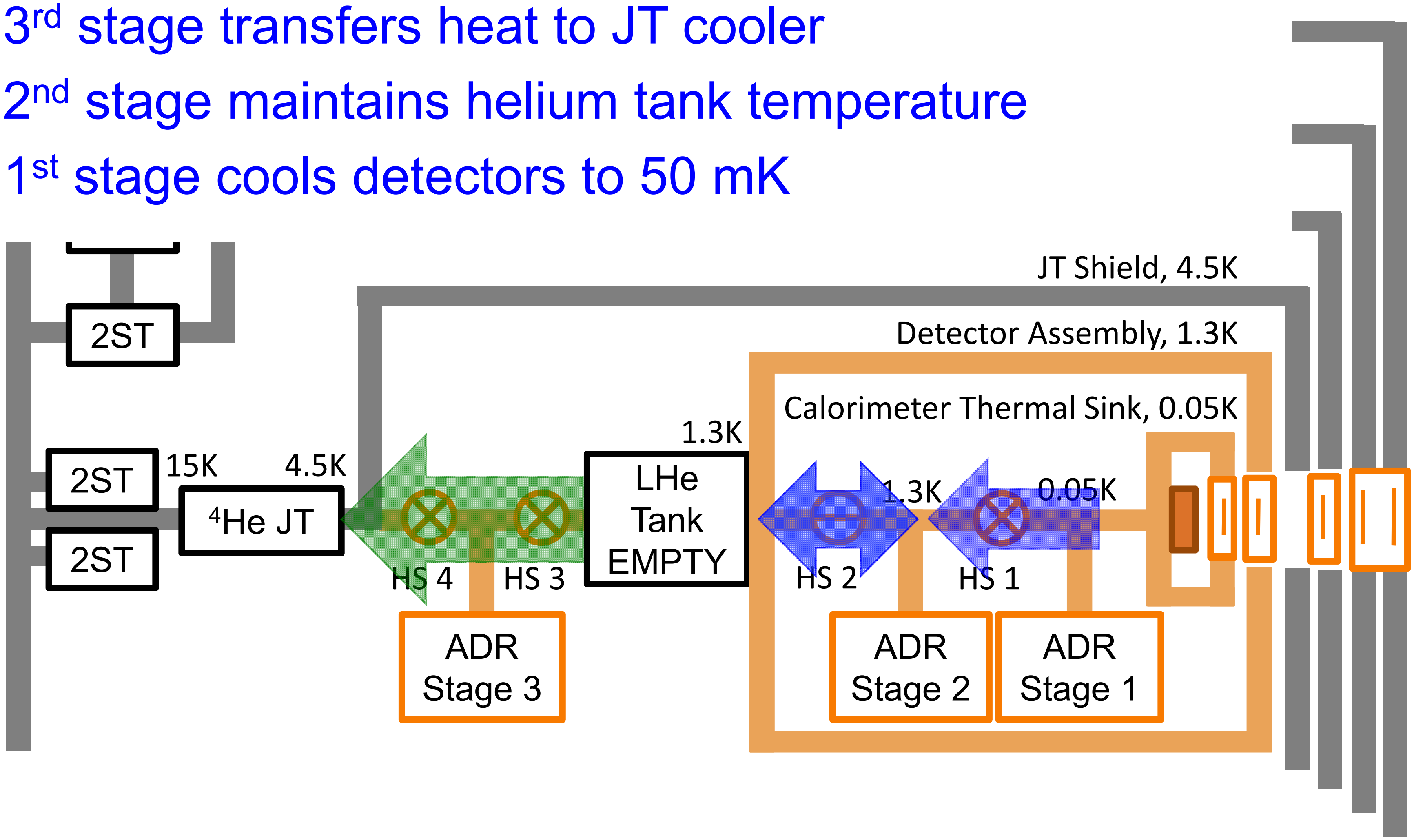


Overall Efficiency

- Average heat load to tank (at 1.20 K) is 80 μW
  - Assumes ADR is recycled after running out of current
  - If ADR is recycled once per day
    - Heat rejection per cycle is 10.0 J
    - Average heat rejection rate is then 116 μW
  - For 3-year dewar lifetime, ADR allocation is <250 μW
- Heat absorption rate at 50 mK is 0.86 μW
  - Excluding HTS magnet leads, efficiency=26% of Carnot
- Detector heat load represents 29% of total load

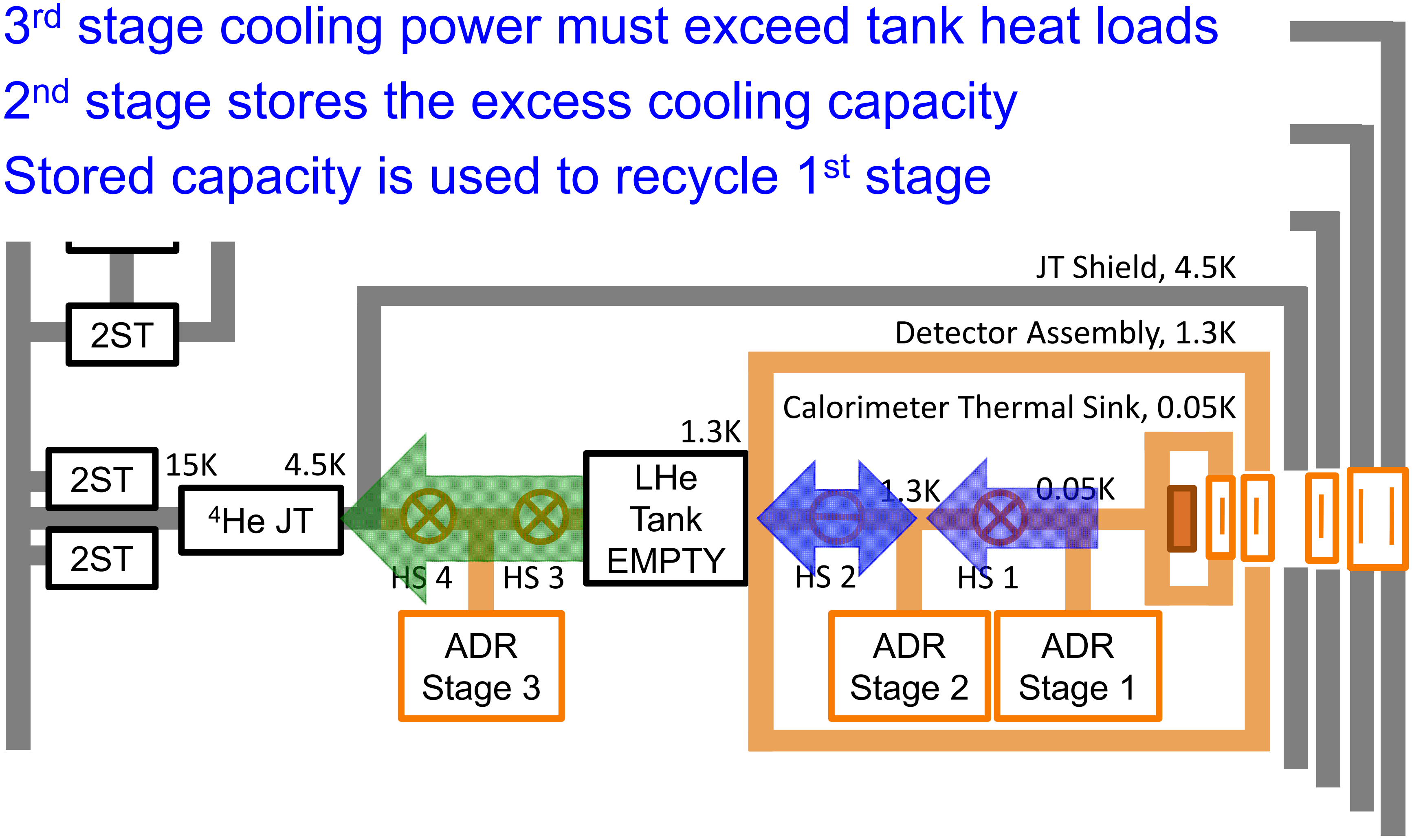
ADR Operation in Cryogen-Free Mode

- 3rd stage transfers heat to JT cooler
- 2nd stage maintains helium tank temperature
- 1st stage cools detectors to 50 mK

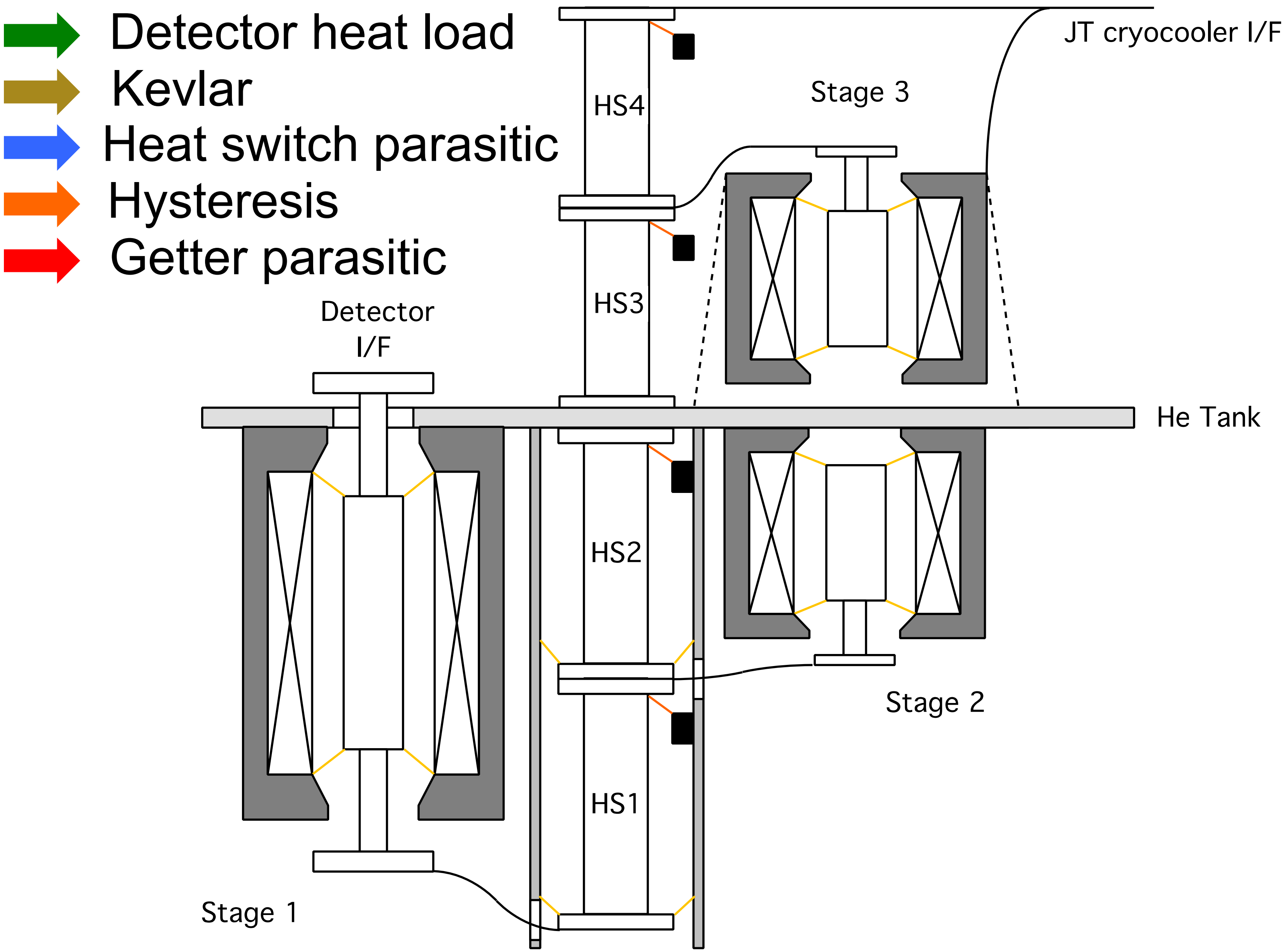


ADR Operation in Cryogen-Free Mode

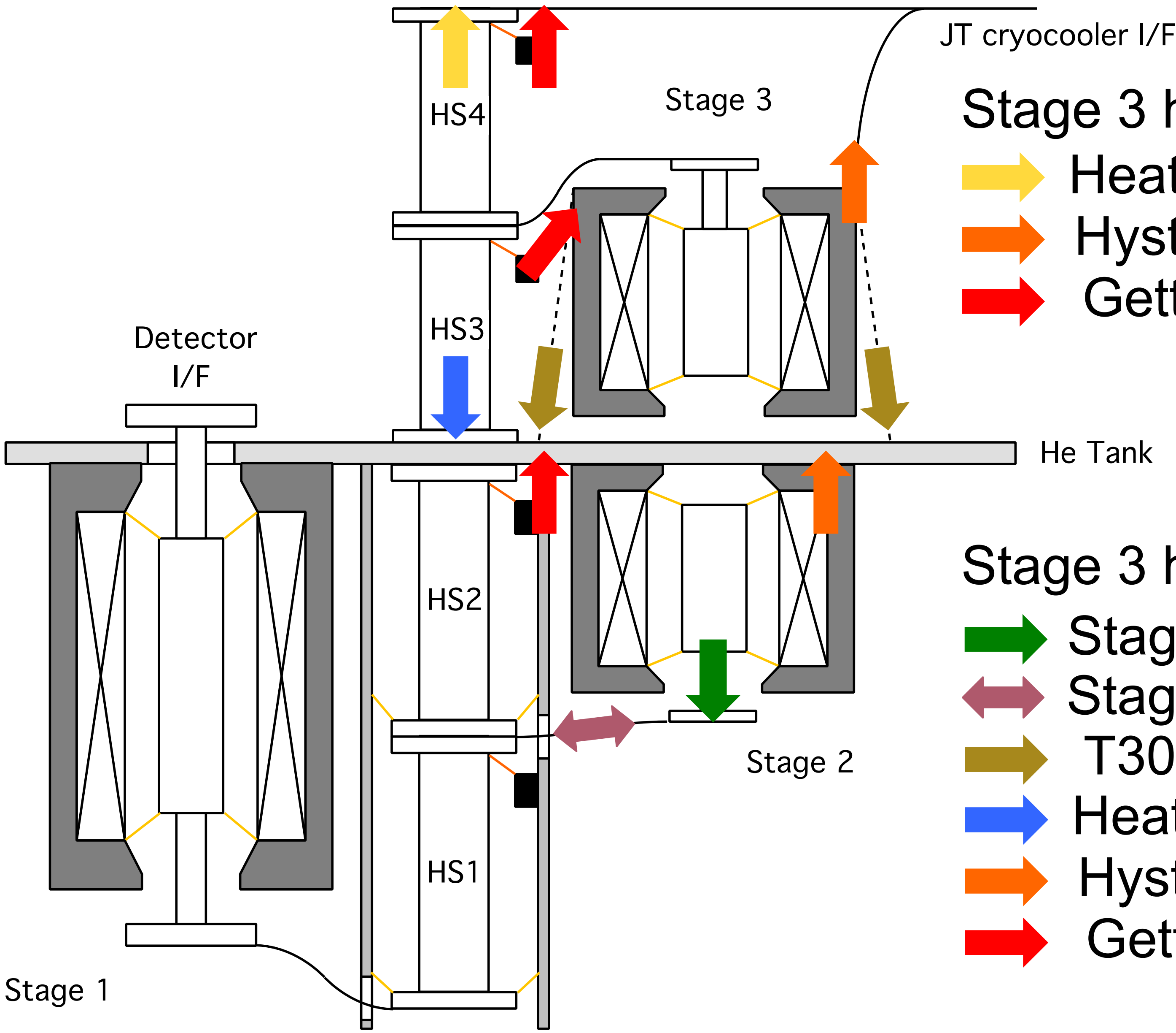
- 3rd stage cooling power must exceed tank heat loads
- 2nd stage stores the excess cooling capacity
- Stored capacity is used to recycle 1st stage



3-Stage Schematic



Stage 2 and 3 Operation



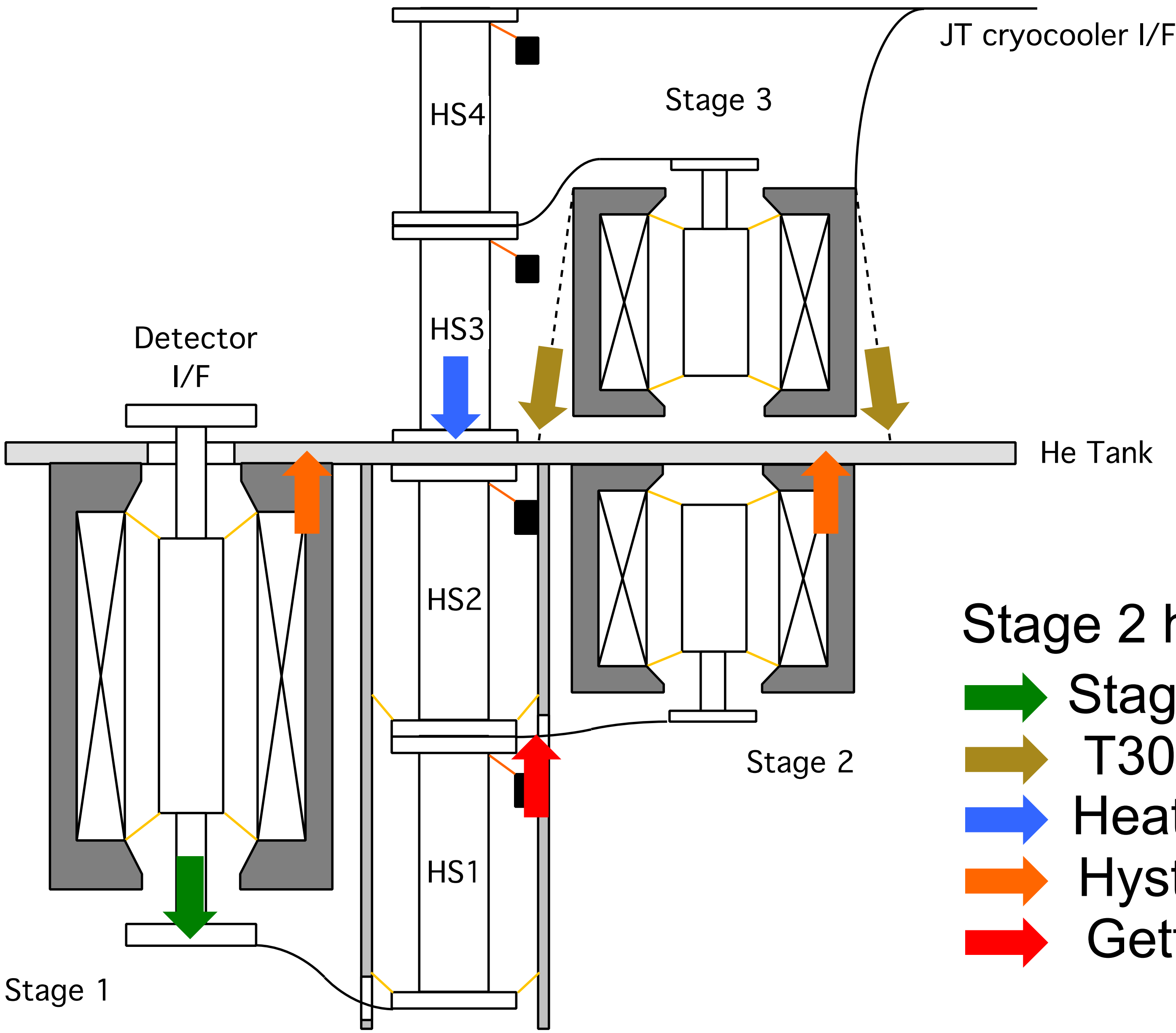
Stage 3 heat rejection

- Heat switch parasitic
- Hysteresis
- Getter heat

Stage 3 heat lift

- Stage 2 charging
- Stage 2 inefficiency
- T300 support
- Heat switch parasitic
- Hysteresis
- Getter heat

Stage 1 Recycling

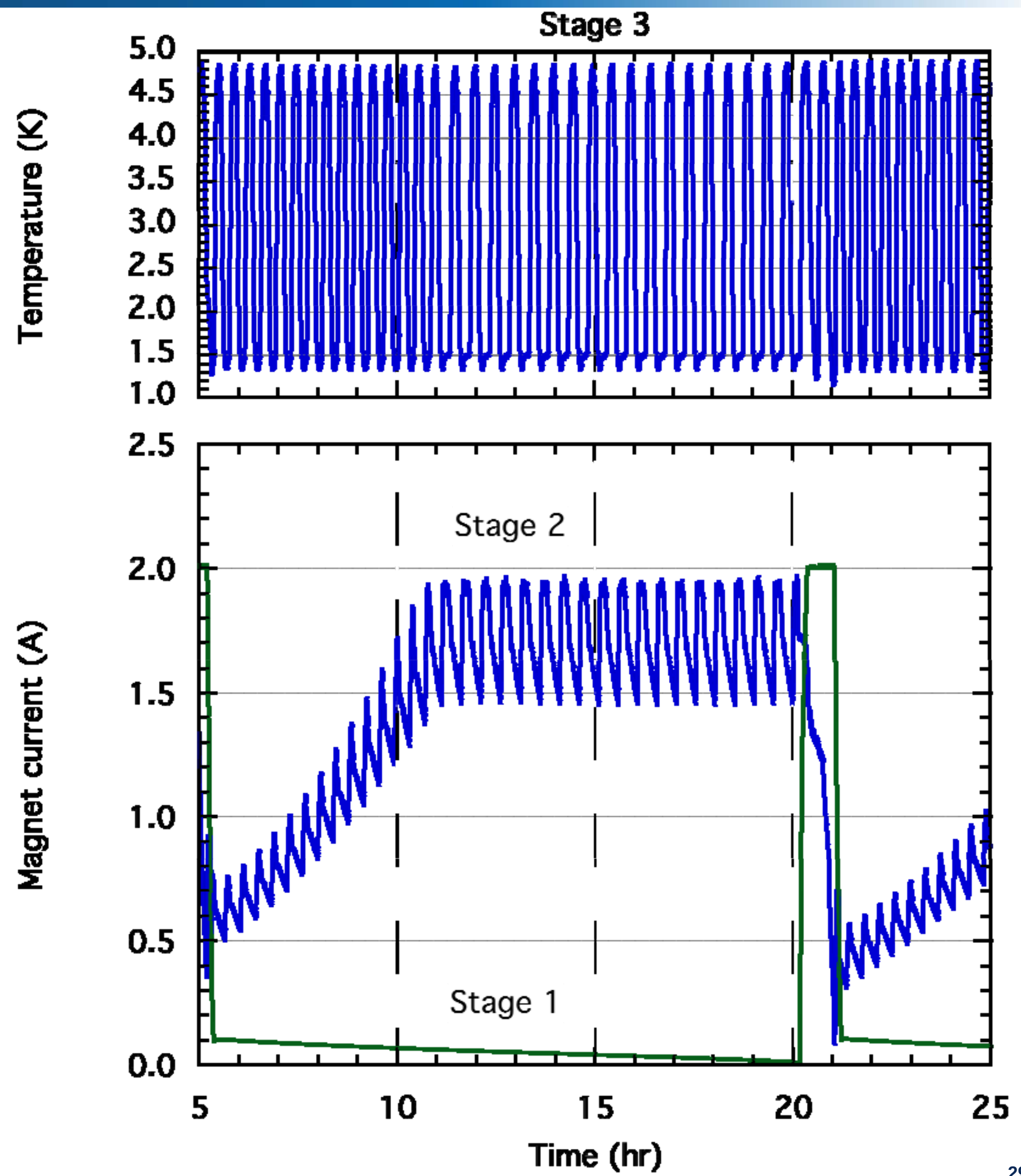


Stage 2 heat lift

- Stage 1 charging
- T300 support
- Heat switch parasitic
- Hysteresis
- Getter heat

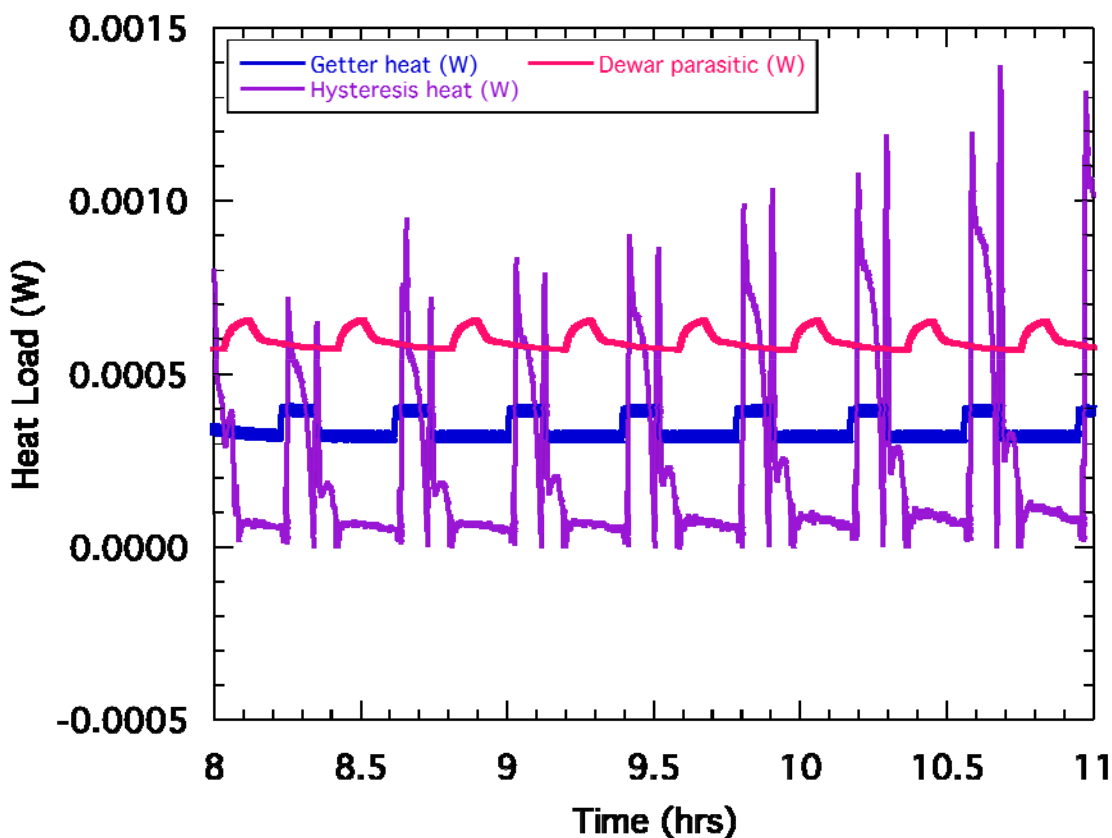
Full Cycle of Stage 1

- He tank heat loads
  - Parasitic loads through dewar structure (static)
  - Parasitic through HS3 (variable)
  - Hysteresis



Heat Loads

- Time average heat loads (Tank=1.625 K)
  - 0.65 mW tank + HS3 parasitic
  - 0.34 mW getter dissipation
  - 0.22 mW hysteresis
  - 0.23 mW S2 inefficiency
- Total=1.51 mW
- S2 charging=0.59 mW
- S3 cooling power
  - 2.20 mW at 1.625 K

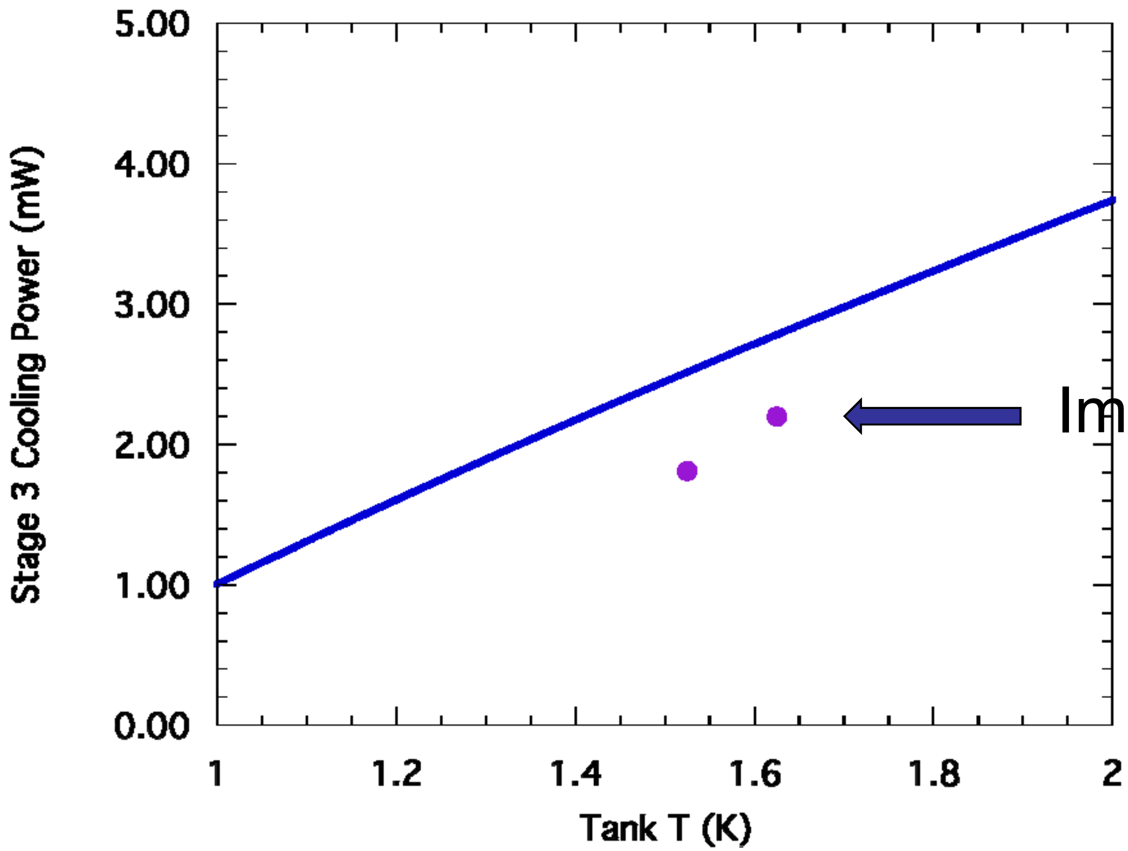


Stage 3 Cooling Power

- Cooling power can be calculated from cycle parameters

$$\dot{Q}_{in} = \left(S(B_{max}, T_{demag}) - S(0, T_{low})\right) \cdot T_{low} \cdot n_{salt} \cdot \varepsilon_{in} / \tau_{cycle}$$

- B_{max}=2.6 T, T_{demag}=4.7 K, T_{low}=0.9•T_{tank}, τ_{cycle}=23 min, $\varepsilon_{in} \leq 1$



Implies ε_{in}~0.79

Stage 3 Heat Rejection

- Heat rejection

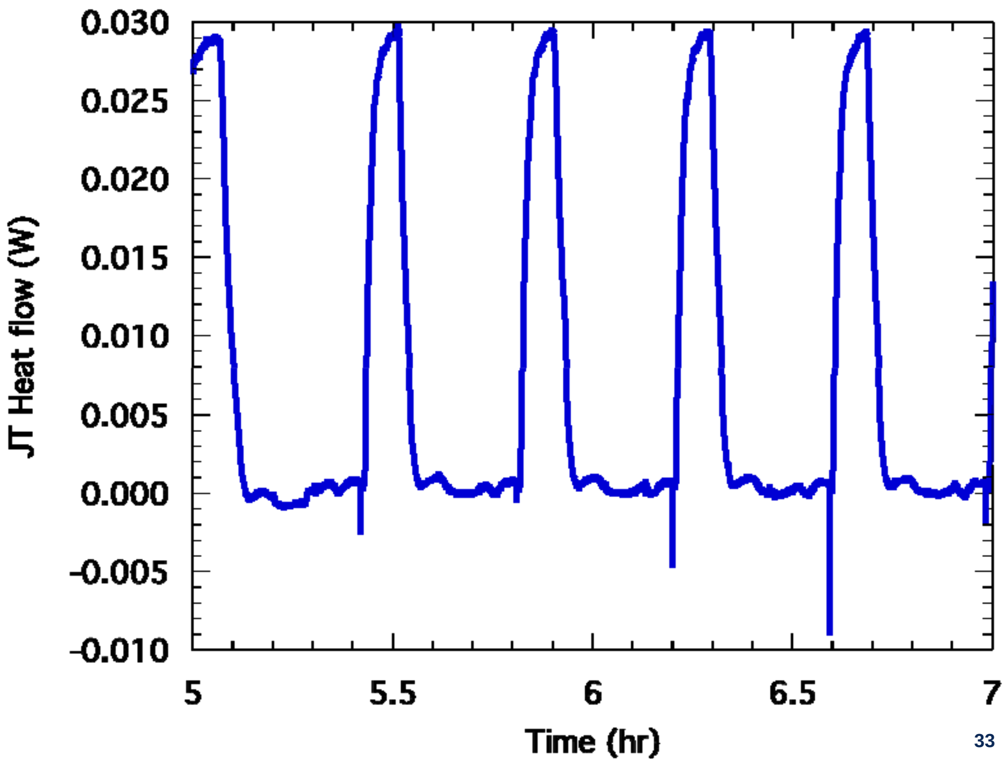
$$\dot{Q}_{out} = \left(\frac{\dot{Q}_{in}}{T_{low}} \right) / \varepsilon_{in} \cdot T_{high}$$

$$\frac{\dot{Q}_{in}}{\dot{Q}_{out}} = \left(\varepsilon_{in} \cdot \frac{T_{JT}}{T_{high}} \cdot \frac{T_{low}}{T_{tank}} \right) \frac{T_{tank}}{T_{JT}} = \varepsilon_{S3} \cdot \frac{T_{tank}}{T_{JT}}$$

- Estimated efficiency ε_{S3}=0.67•0.94•0.90=67%
- Time average heat flow to JT is 8.7 mW
  - 7.2 mW from salt pill plus 1.5 mW hysteresis
- Efficiency at 1.625 K
  - 2.20 mW cooling power and 8.7 mW rejection to 4.5 K
    - 68% efficiency for gross heat lift
  - Useful cooling power of 0.59 mW
    - 18% efficiency overall

Heat Rejection to JT Cryocooler

- Cooling power @ 4.5 K
  - Nominal: 50 mW
  - End-of-helium life: 40 mW
- Steady state heat load to JT in cryogen-free mode is 6 mW
- ADR budget was 18 mW peak, but has been increased to 30 mW peak
- Heat flow is calculated from conductance of thermal strap between ADR and JT



Conclusion

- ADR achieves efficiency needed to operate within its thermal constraints
  - <250 μW average heat load to liquid He
  - <30 mW peak heat load to JT cryocooler
- Design achieves 80% utilization of designed cooling capacity
  - 83% of as-built/as-run cooling capacity
- Salt pill achieves 84% heat absorption efficiency at 50 mK
- In cryogen-free mode, operation of Stages 2 and 3 as a continuous ADR
  - ~2 mW cooling power at ~1.6 K
  - 0.6 mW useful cooling with 8.7 mW rejection to 4.5 K