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

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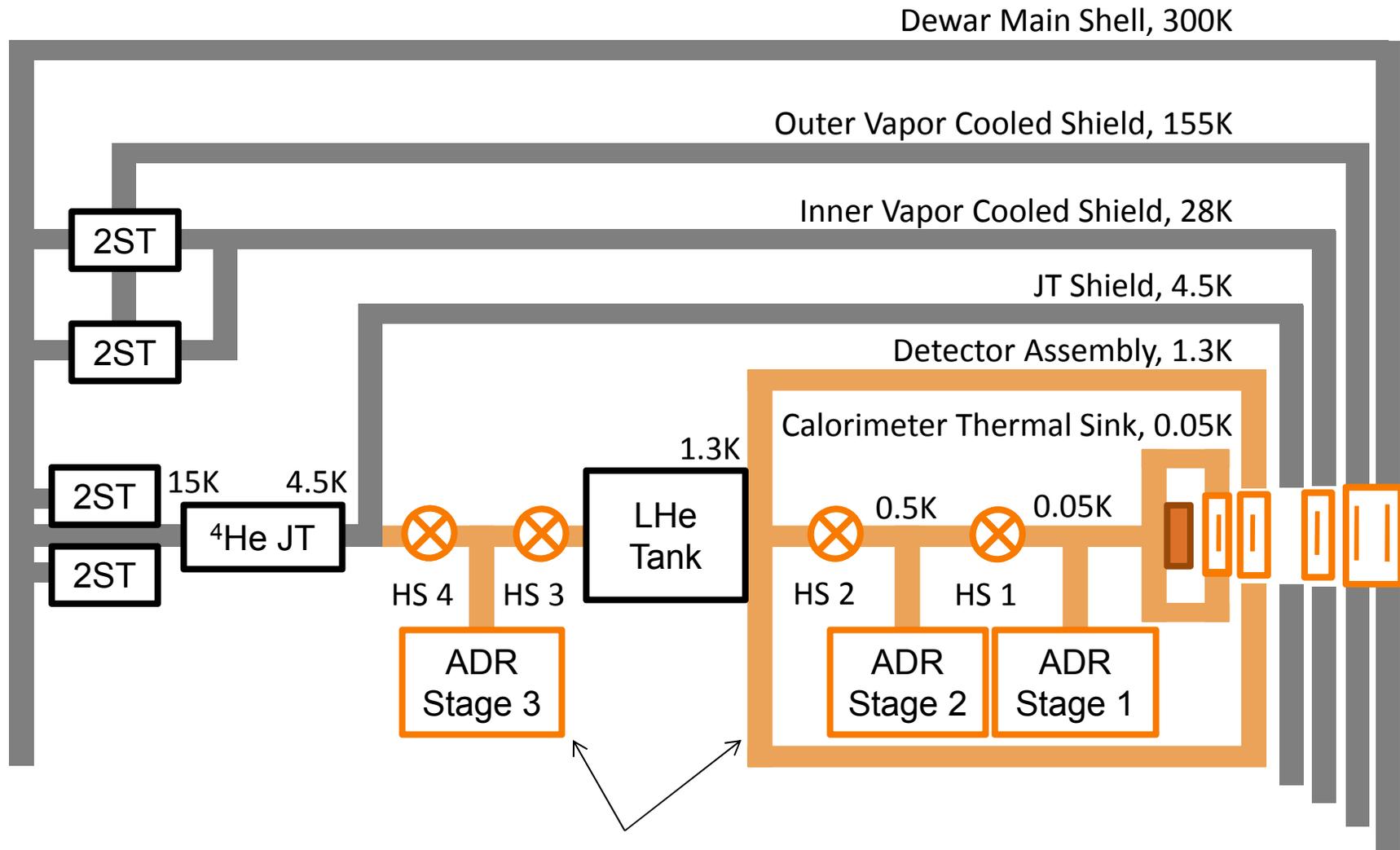
Mark Kimball, Michael DiPirro, Tom Bialas, Gary Sneiderman, Scott Porter, Richard Kelley

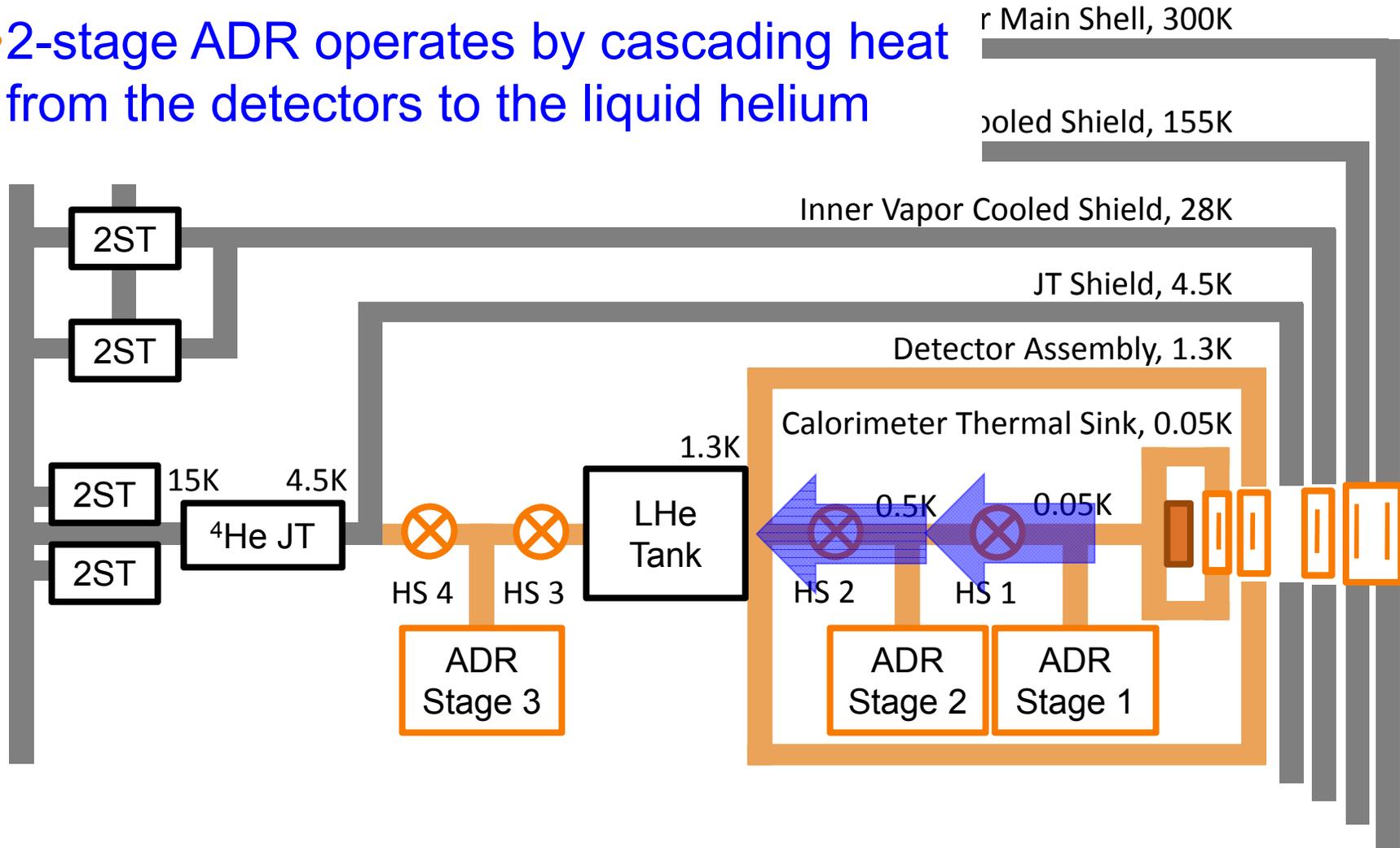Astro-H/SXS   NASA Goddard Space Flight Center

Astro-H Cryogenic System

Dewar Main Shell, 300K

Outer Vapor Cooled Shield, 155K

Inner Vapor Cooled Shield, 28K

JT Shield, 4.5K

Detector Assembly, 1.3K

Calorimeter Thermal Sink, 0.05K

2ST

2ST

2ST

2ST

15K   4.5K

^{4}He JT

HS 4   HS 3

LHe Tank   1.3K

ADR Stage 3

0.5K   0.05K

HS 2   HS 1

ADR Stage 2   ADR Stage 1

NASA/GSFC hardware

ADR Operation in Cryogen Mode

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

Main Shell, 300K

Vapor Cooled Shield, 155K

Inner Vapor Cooled Shield, 28K

JT Shield, 4.5K

Detector Assembly, 1.3K

Calorimeter Thermal Sink, 0.05K

2ST

2ST

2ST   15K   4.5K

^{4}He JT

2ST

HS 4   HS 3

ADR Stage 3

LHe Tank   1.3K

HS 2   0.5K   HS 1   0.05K

ADR Stage 2   ADR Stage 1

3

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
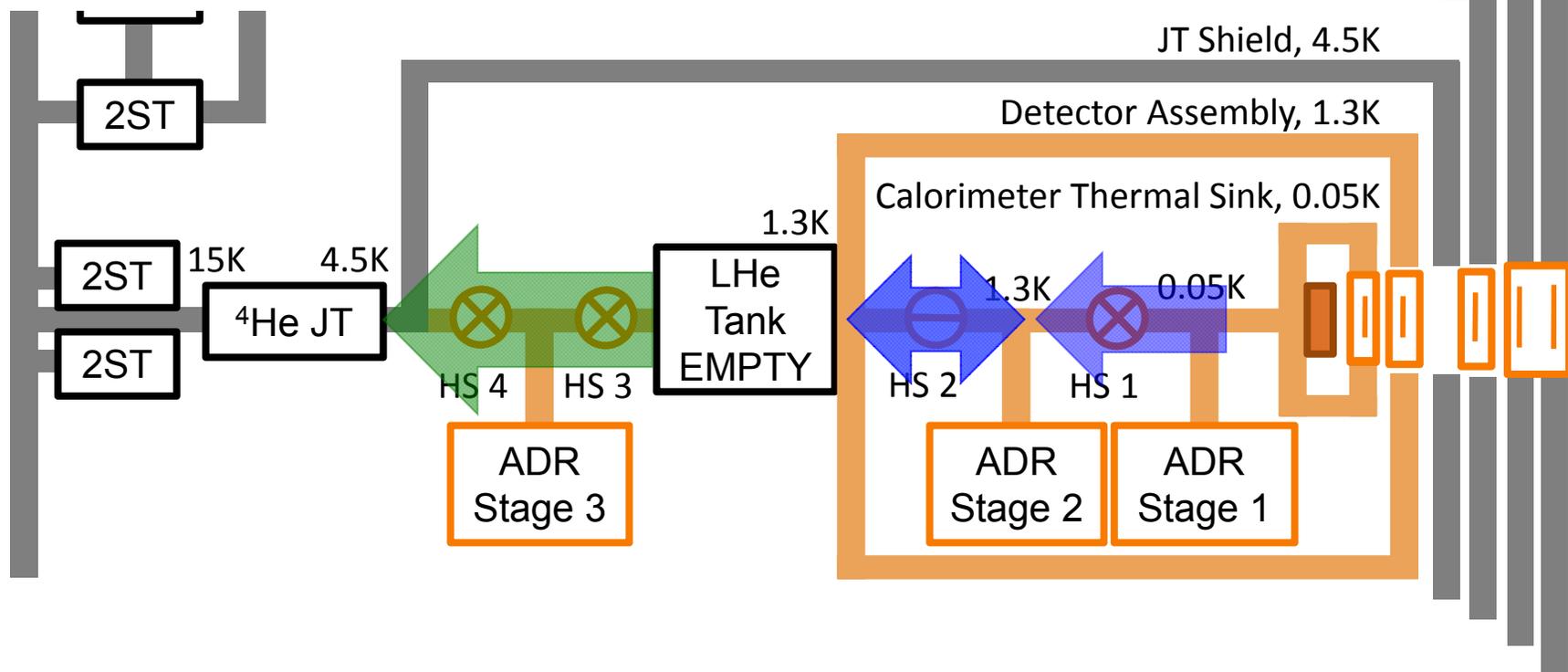
Thermodynamic Performance

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
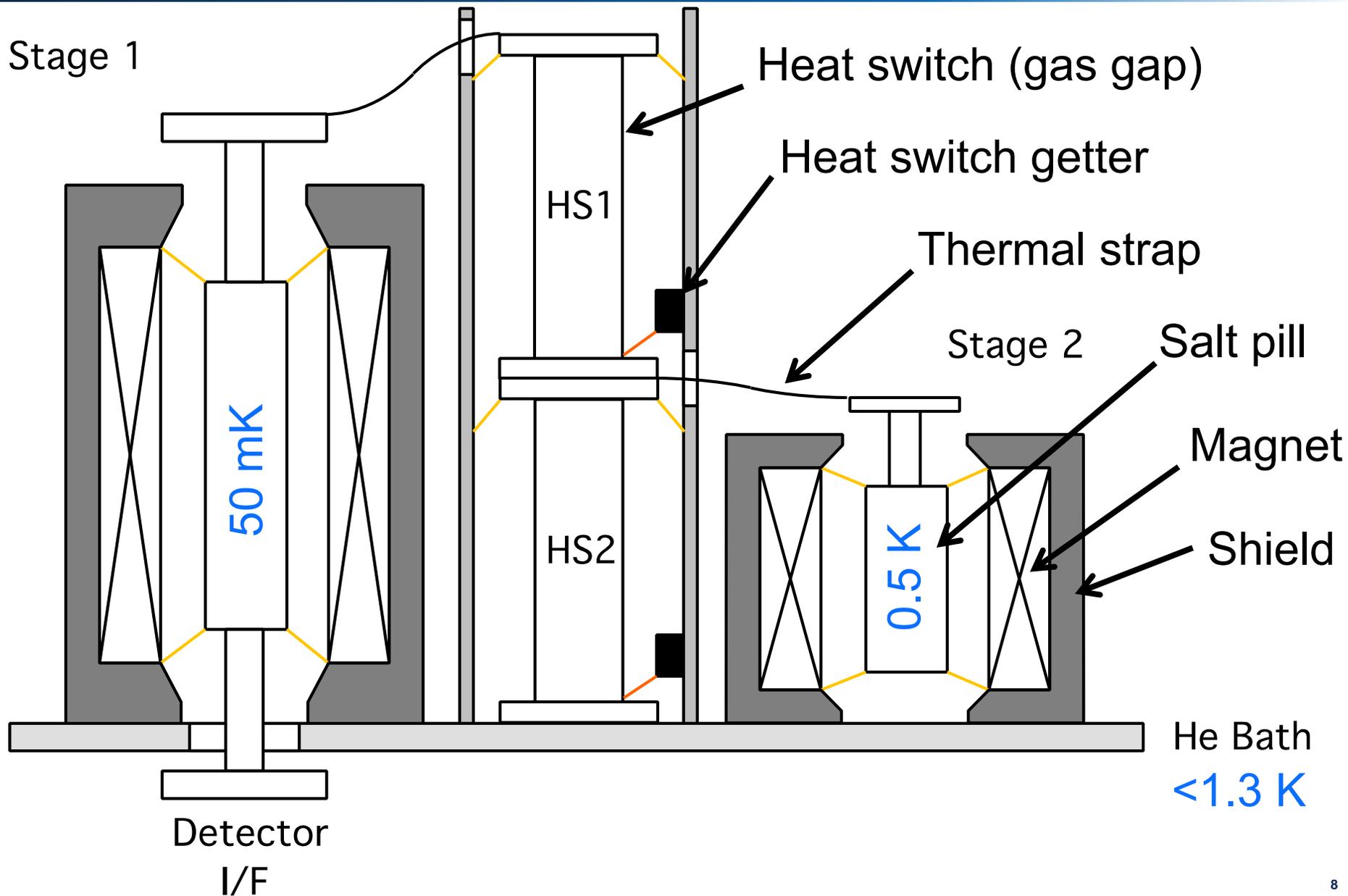 - Cycle efficiency

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
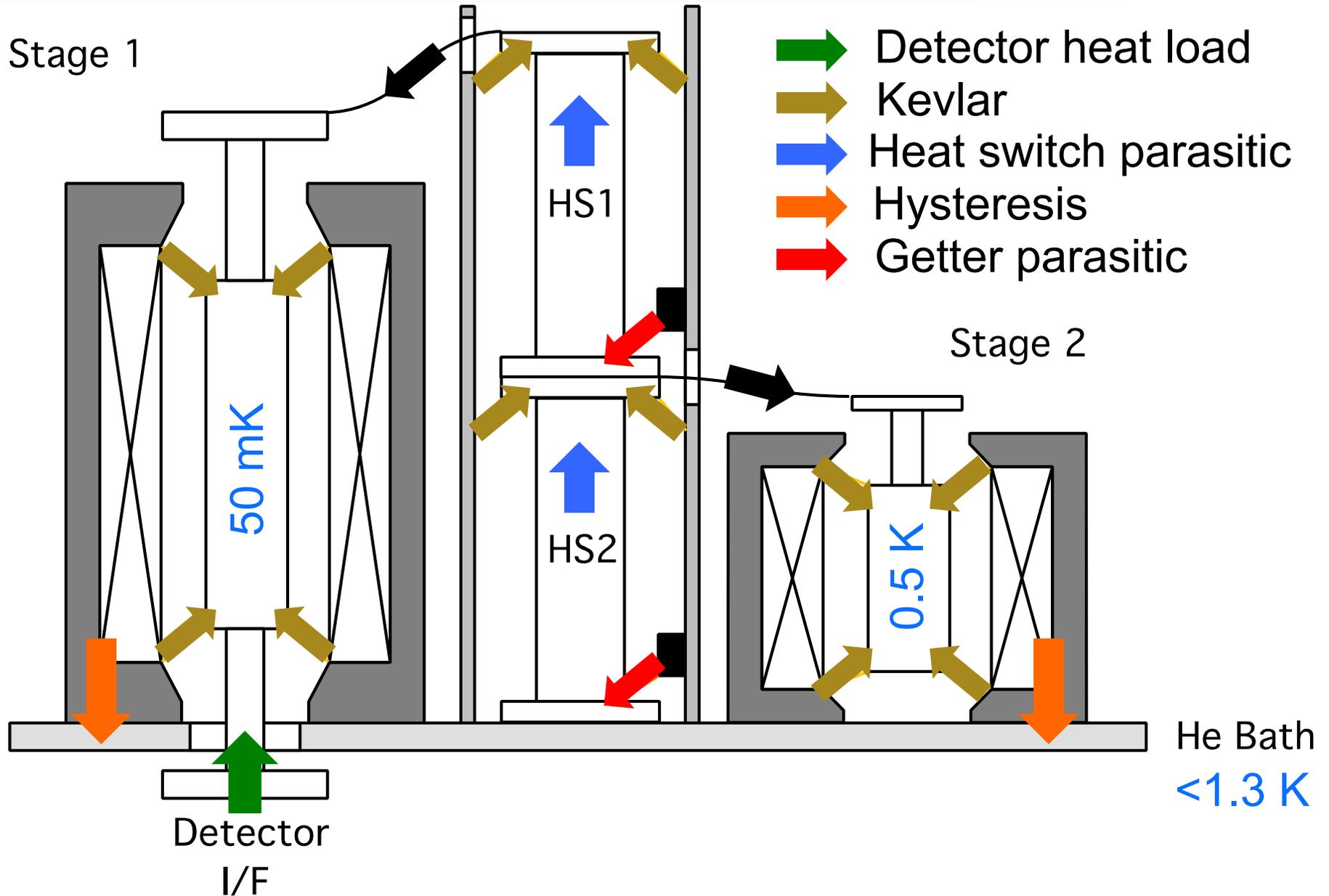
ADR Design Summary

	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

Stage 1

Heat switch (gas gap)

Heat switch getter

Thermal strap

Stage 2

Salt pill

Magnet

Shield

HS1

HS2

50 mK

0.5 K

Detector I/F

He Bath

<1.3 K

Cryogen Mode – Heat Flow During Hold

Stage 1

Stage 2

50 mK

0.5 K

HS1

HS2

Detector I/F

He Bath

<1.3 K

Detector heat load
Kevlar
Heat switch parasitic
Hysteresis
Getter parasitic

Cryogen Mode – Heat Flow During Recycle

Stage 1

HS1

➡ Heat switch conduction
➡ Hysteresis
➡ Getter dissipation

Stage 2

1.6 K

HS2

1.5 K

He Bath

<1.3 K

Detector I/F
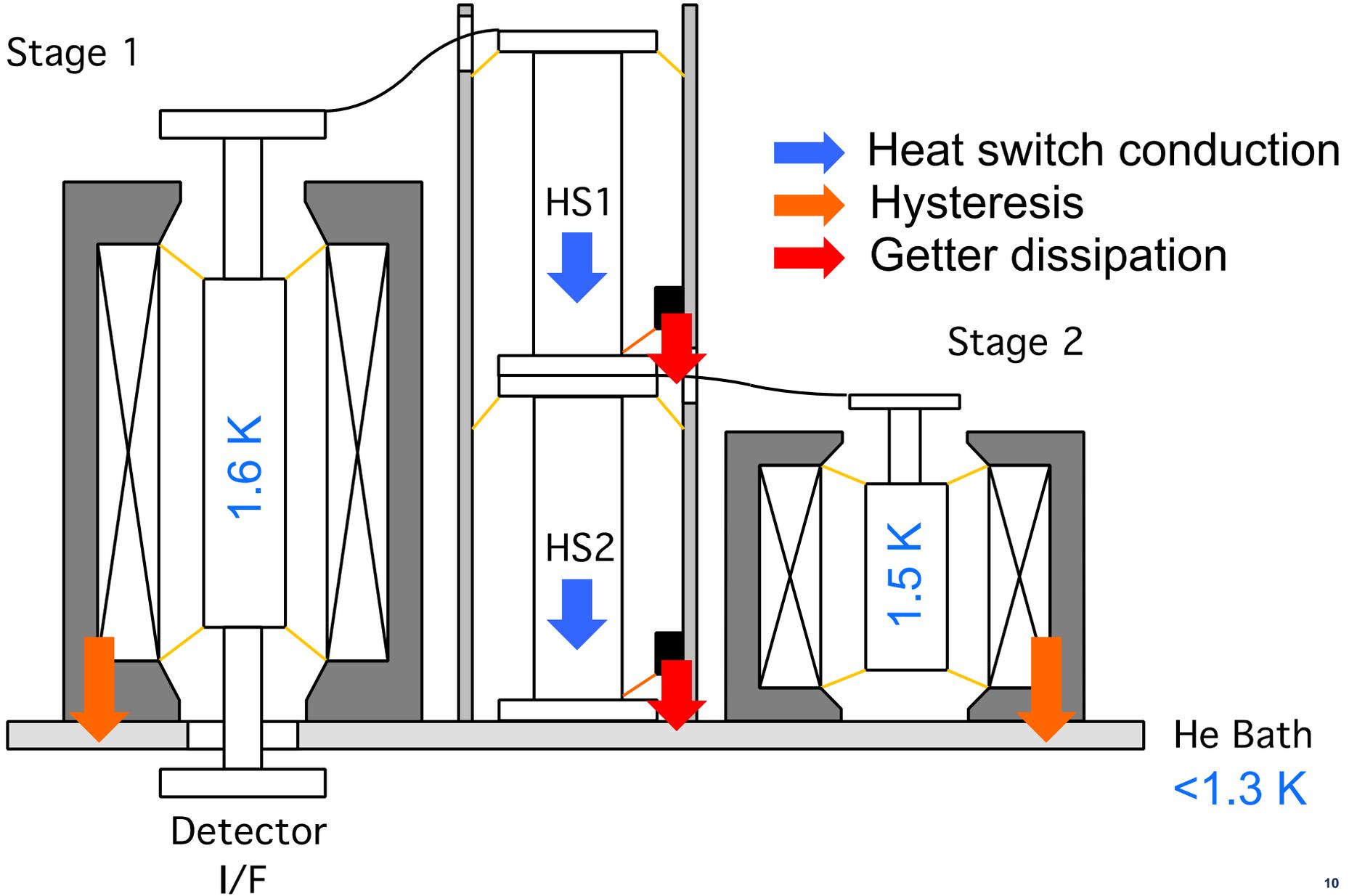
Kevlar Suspension

- 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
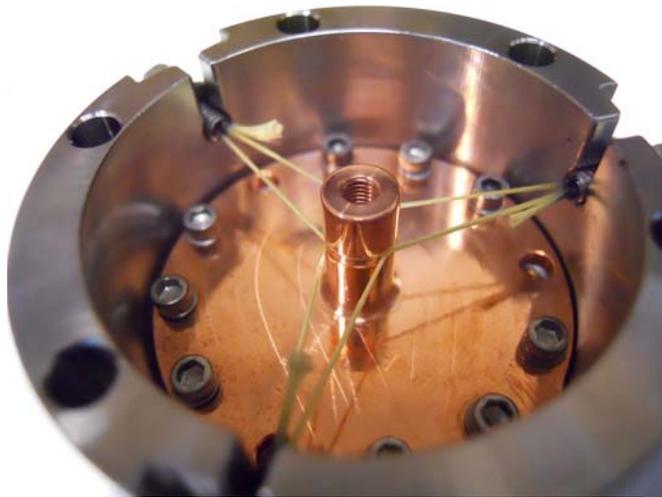
Salt pill "gimbal":
Main loop: 16
Side loops: 12
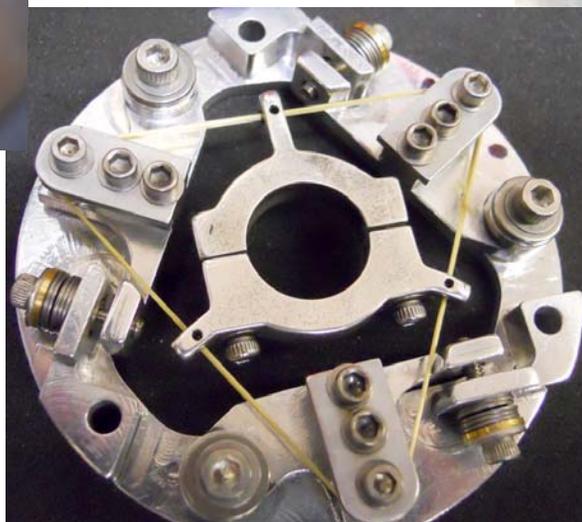
Heat switch: 4

Salt pill "lateral": 8
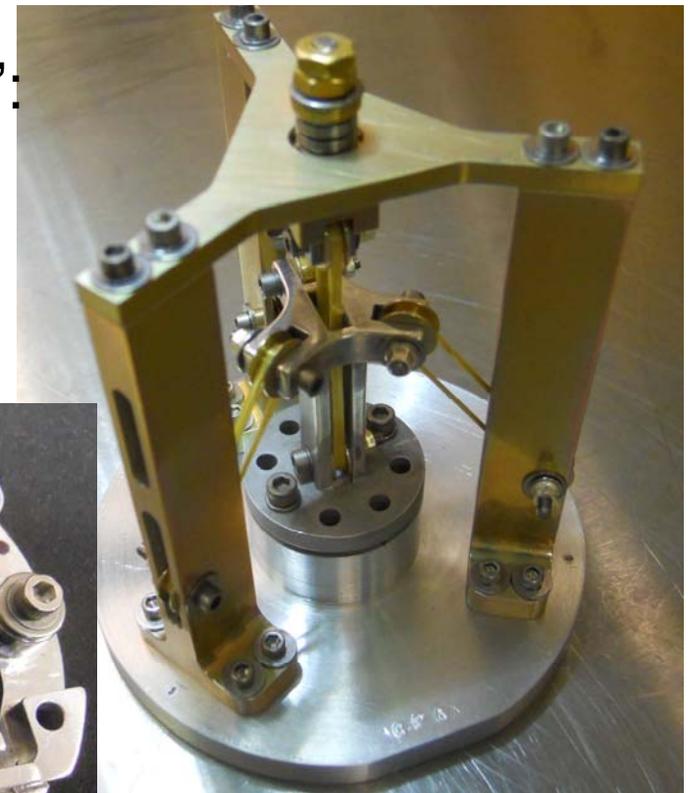
Heat Loads During Hold

- 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
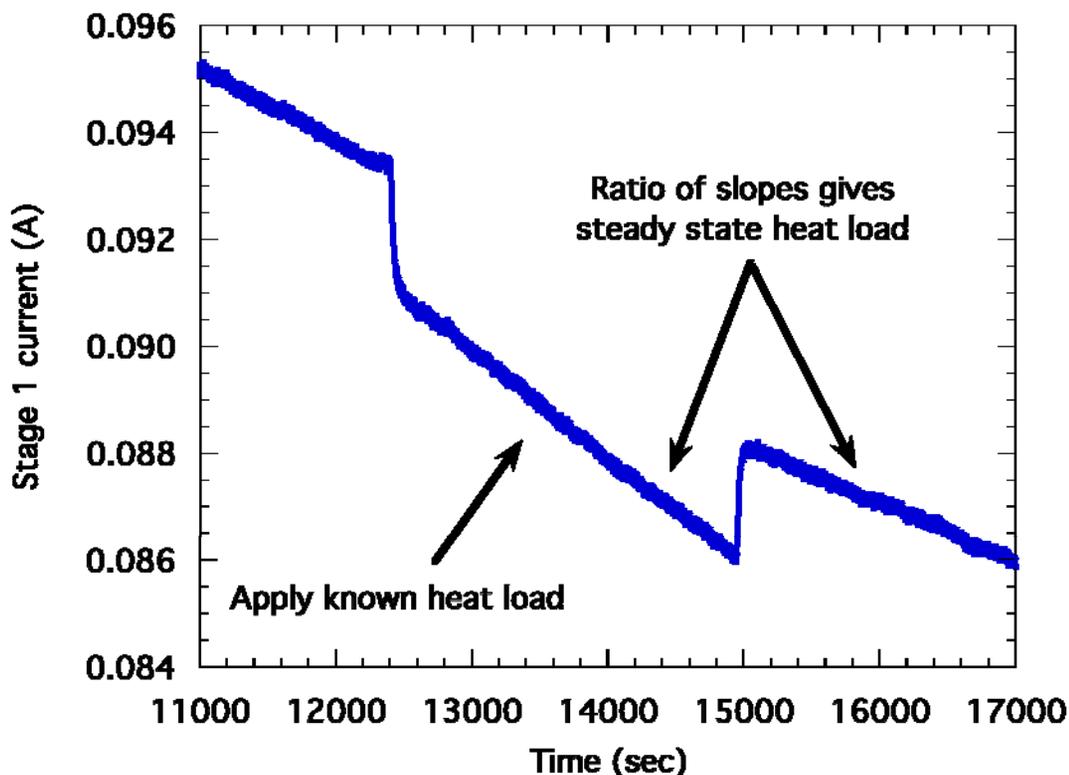
Measured vs Expected Heat Loads
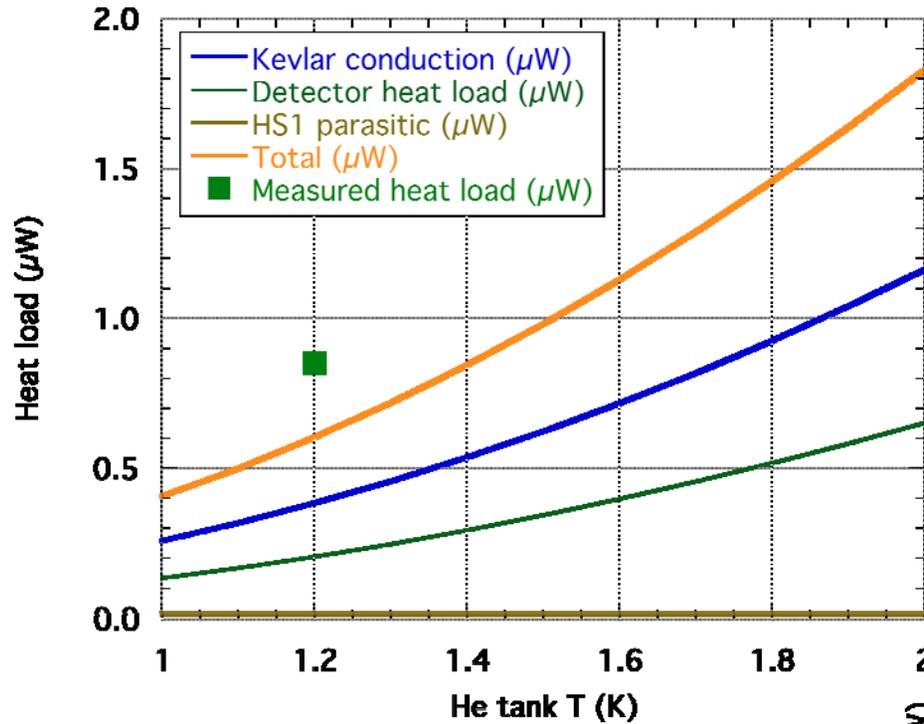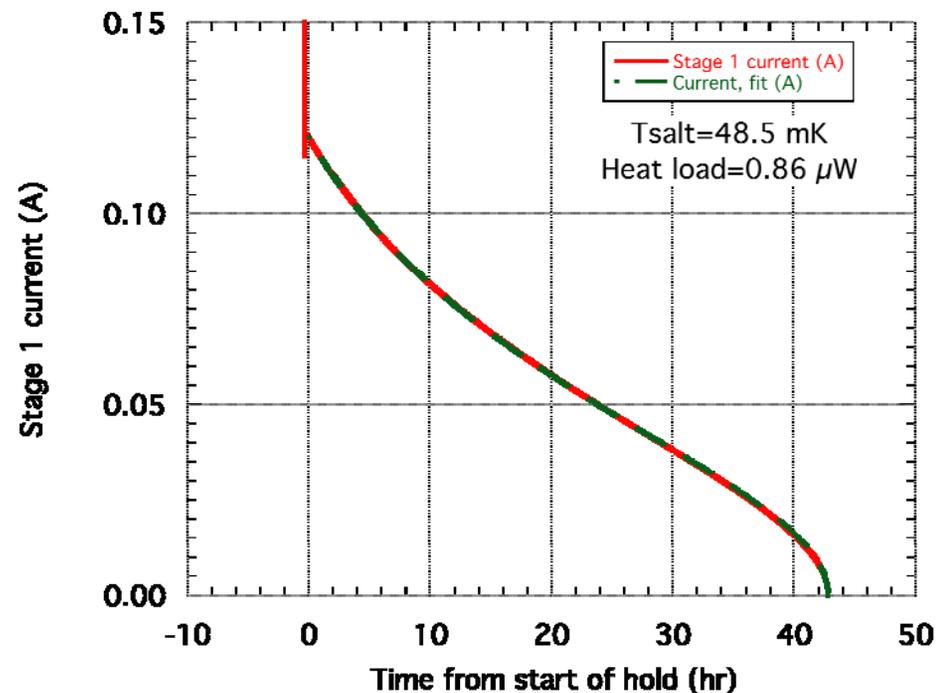

Stage 1

Stage 2
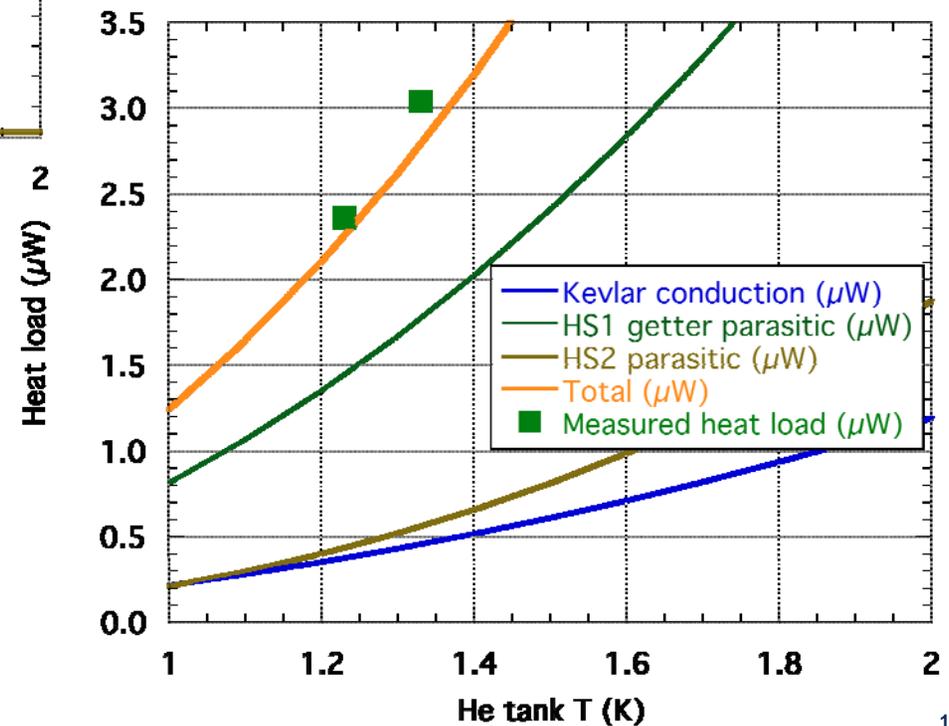
Heat Load Determination

- 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 $\Leftrightarrow$ 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

$\Delta S = 3.13$ J/K
$\Delta Q = 0.147$ J
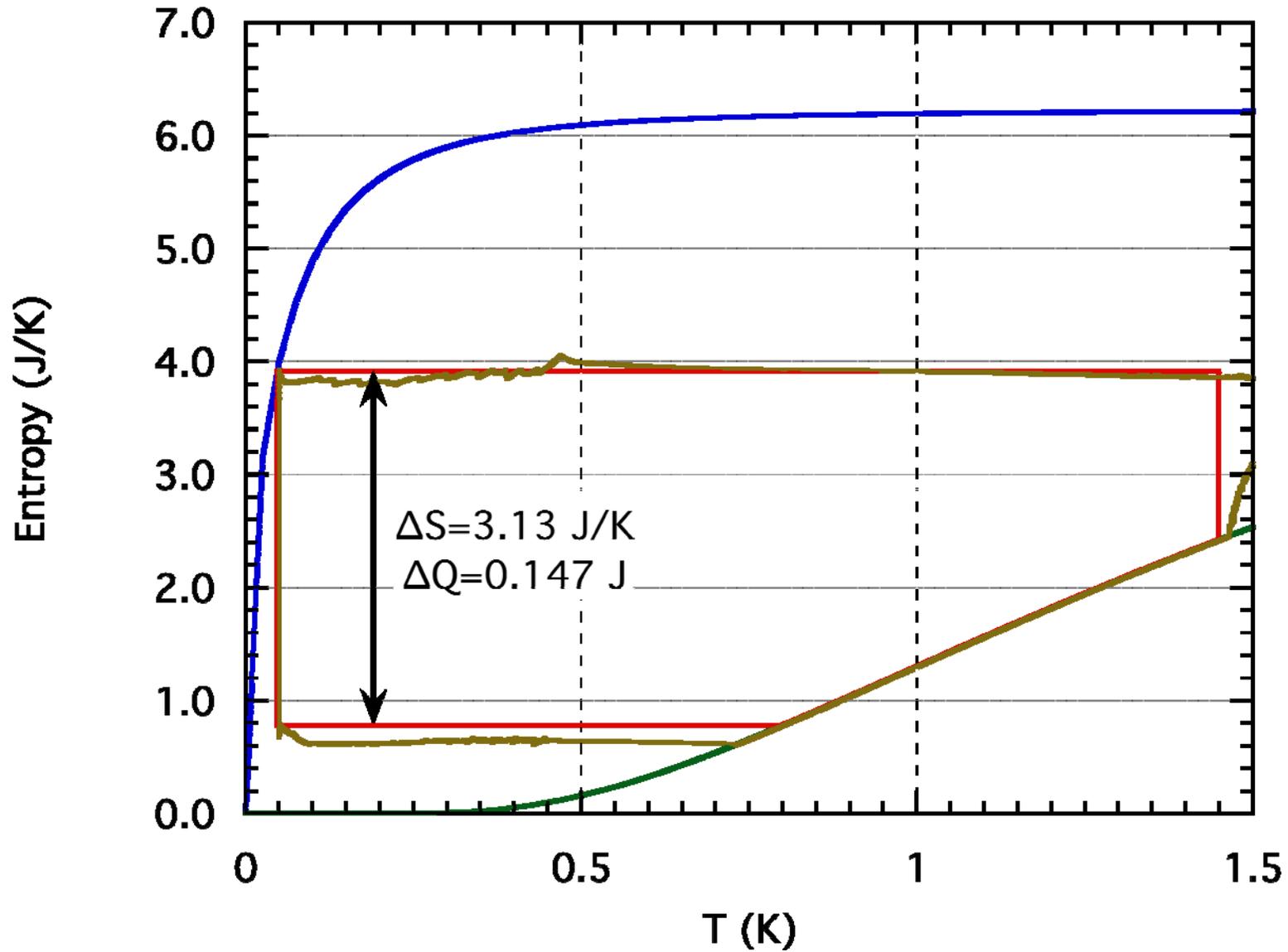
Stage 1 Performance

- 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
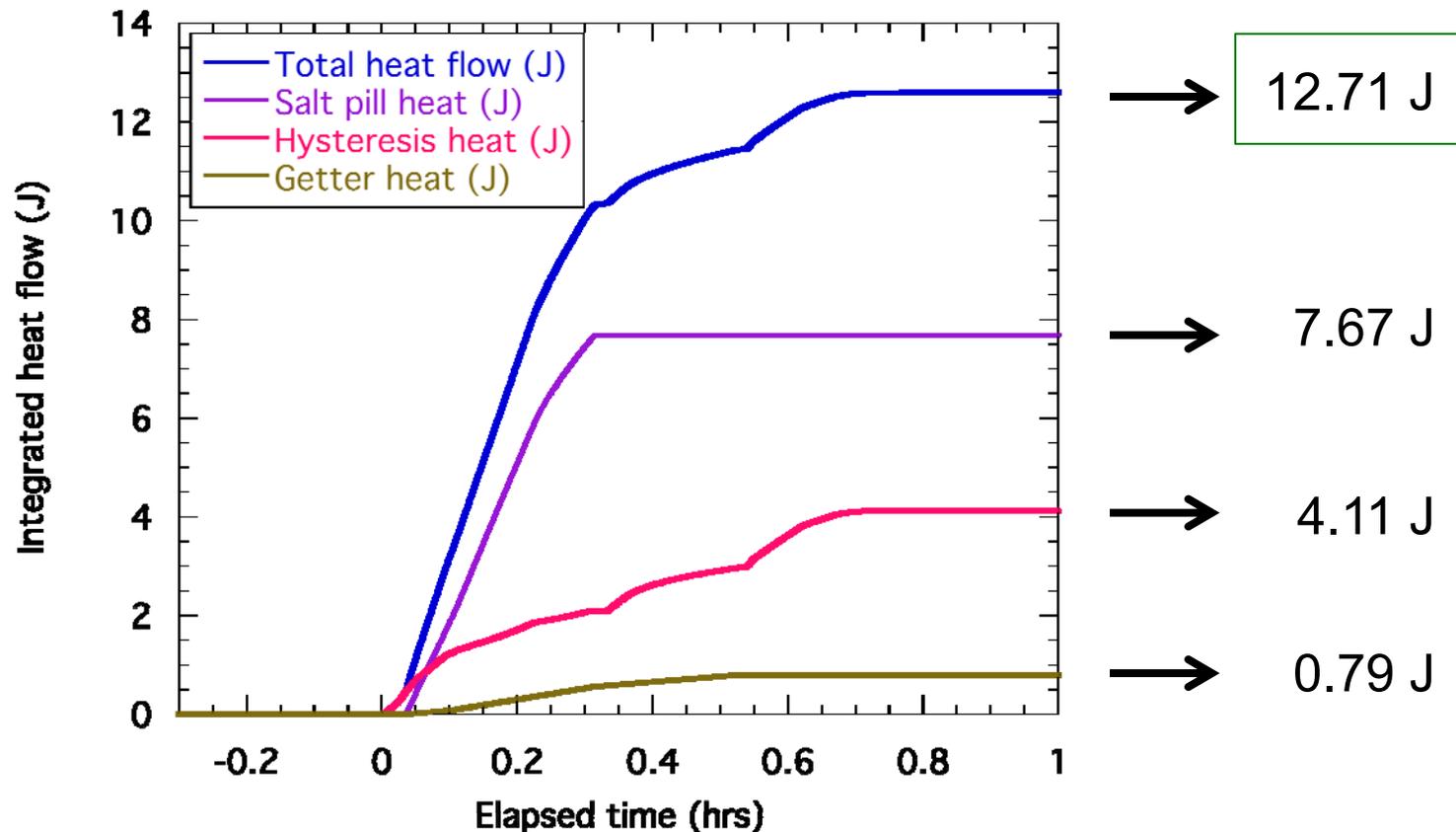 - Stage 3 assumed to be the same as Stage 2
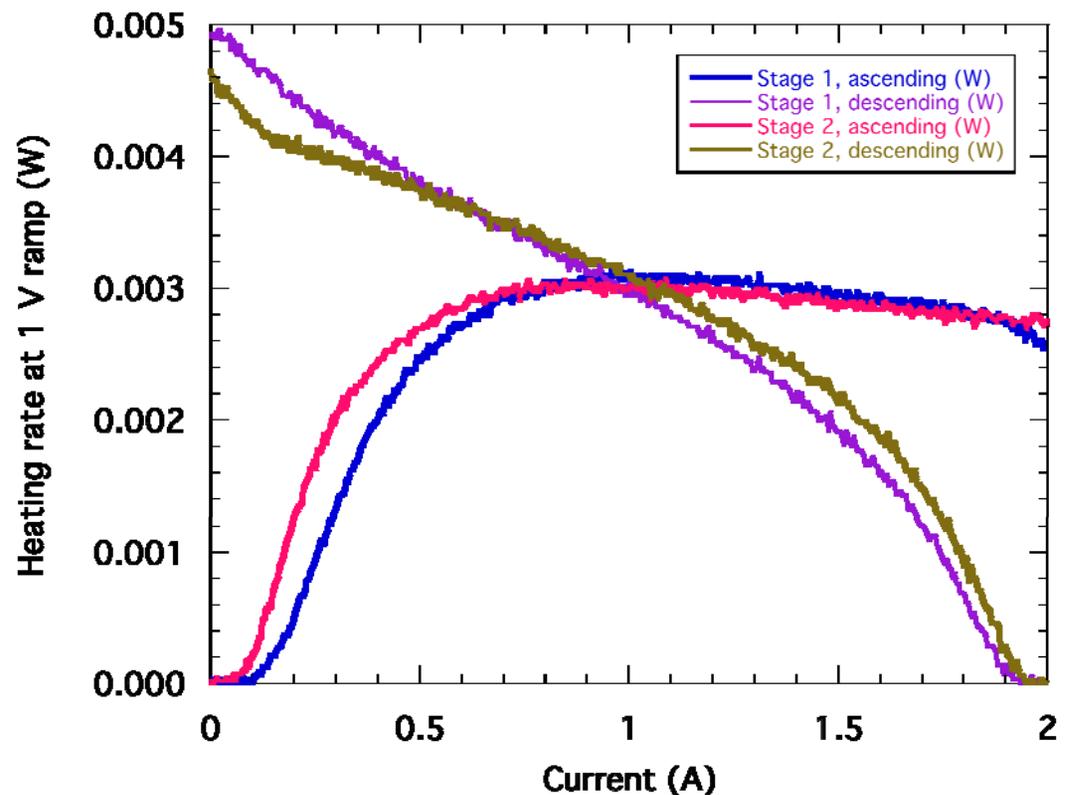
Heat Generation During Recycle

- Heat loads from getter heating, hysteresis and salt pills
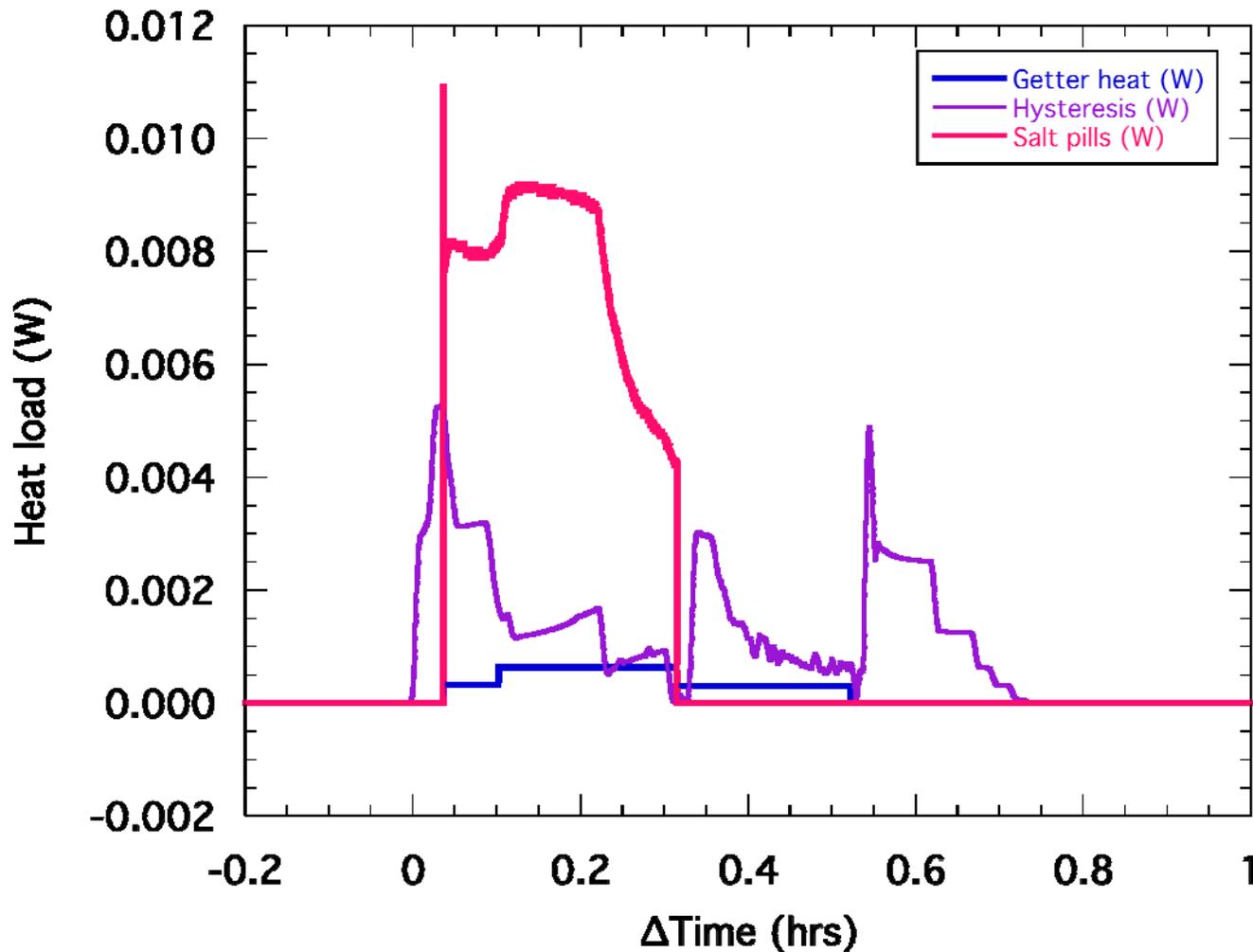
Heat Flows During Cycle

- 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
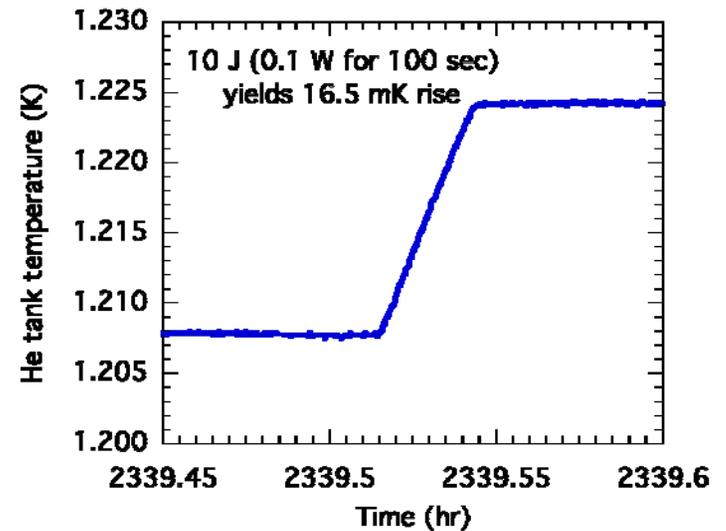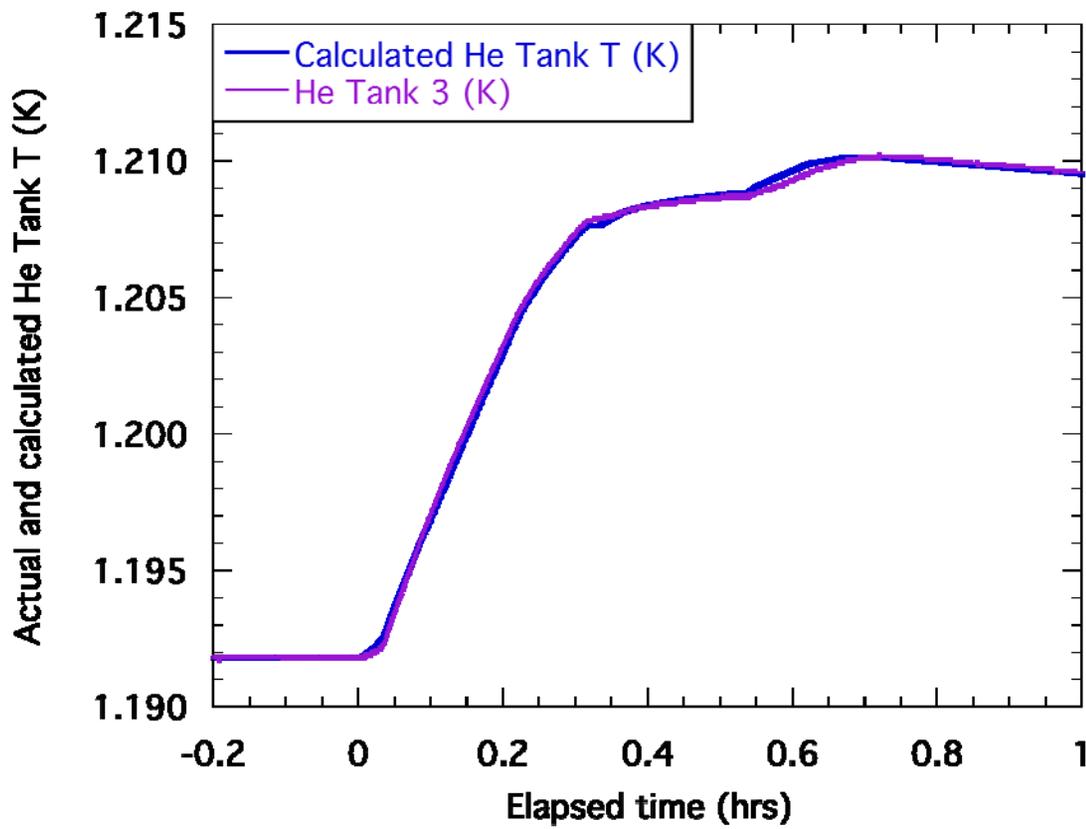
Overall Efficiency

- 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
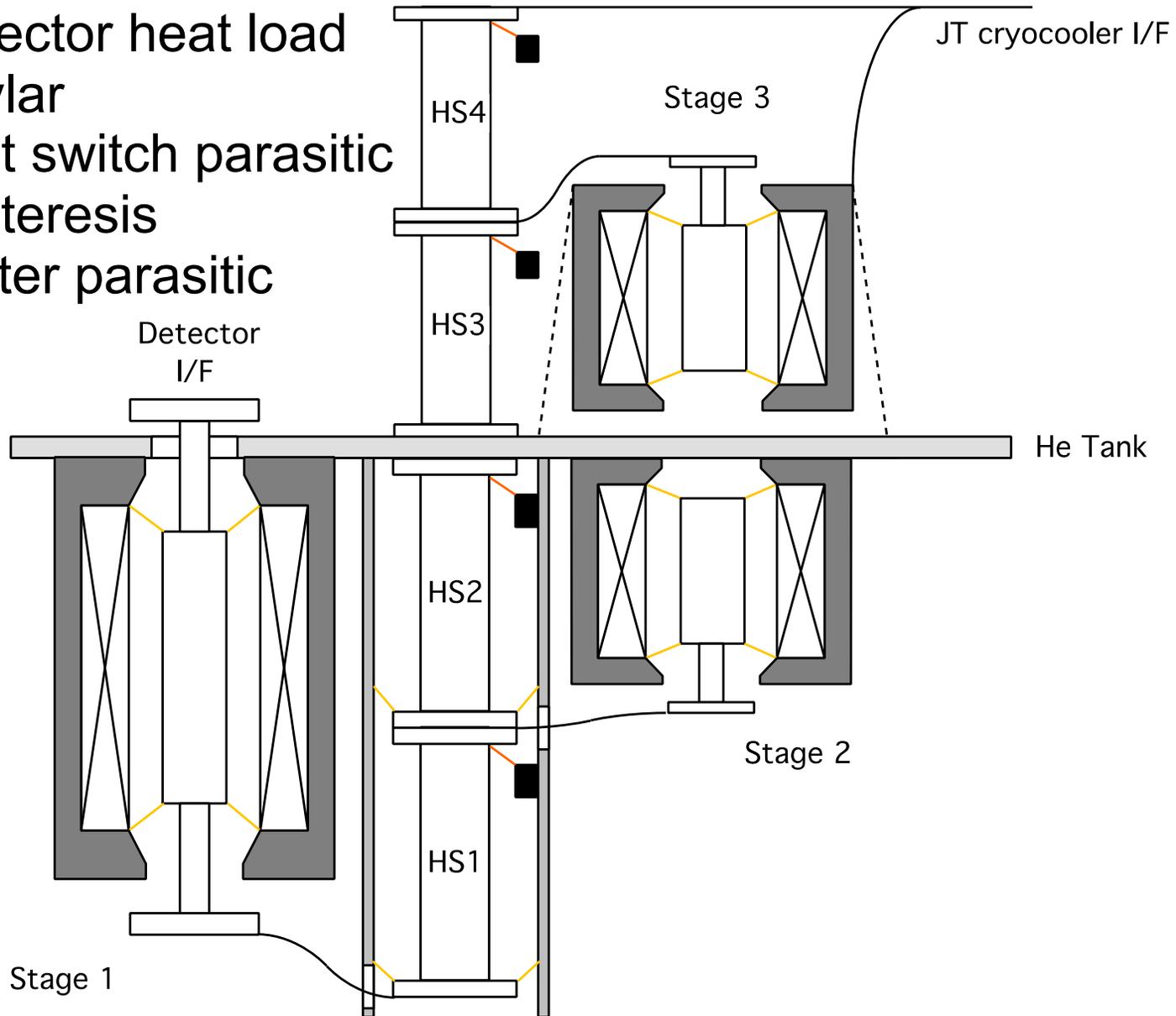- 1st stage cools detectors to 50 mK
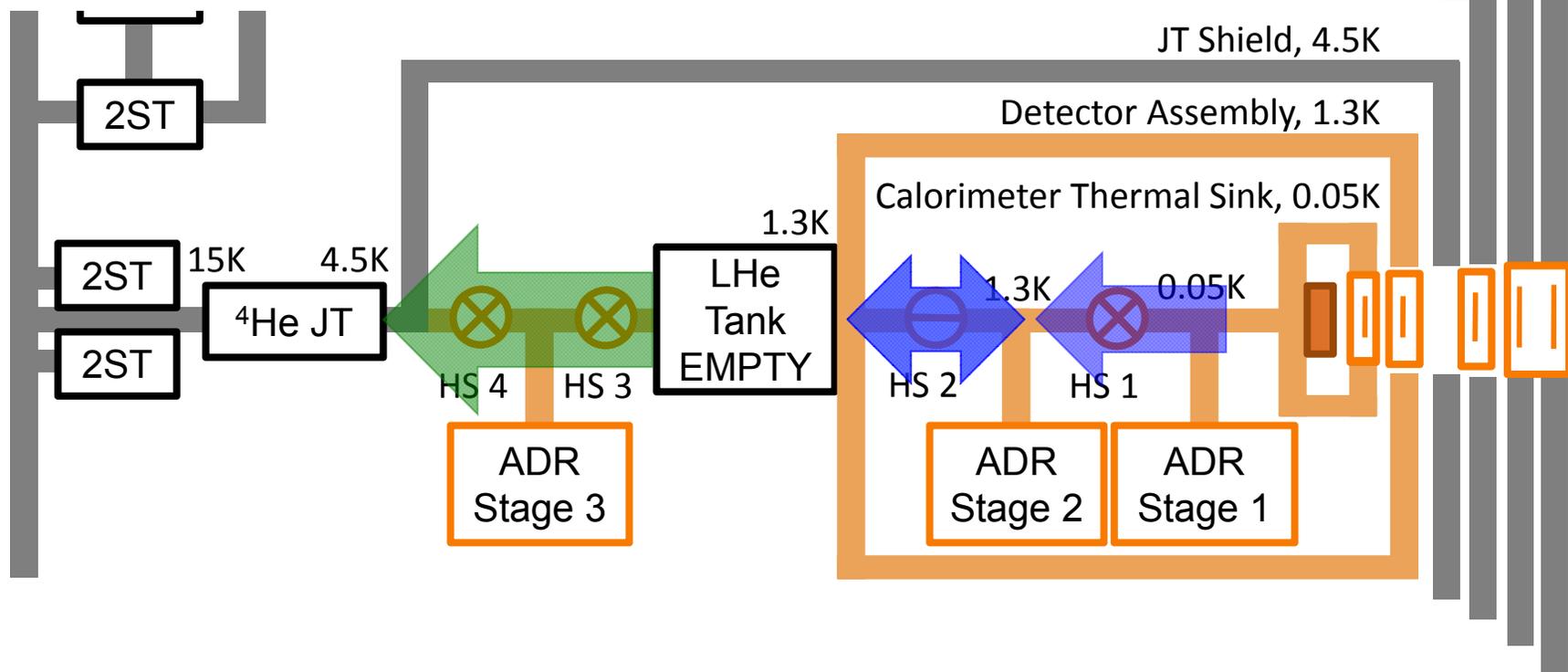
ADR Operation in Cryogen-Free Mode

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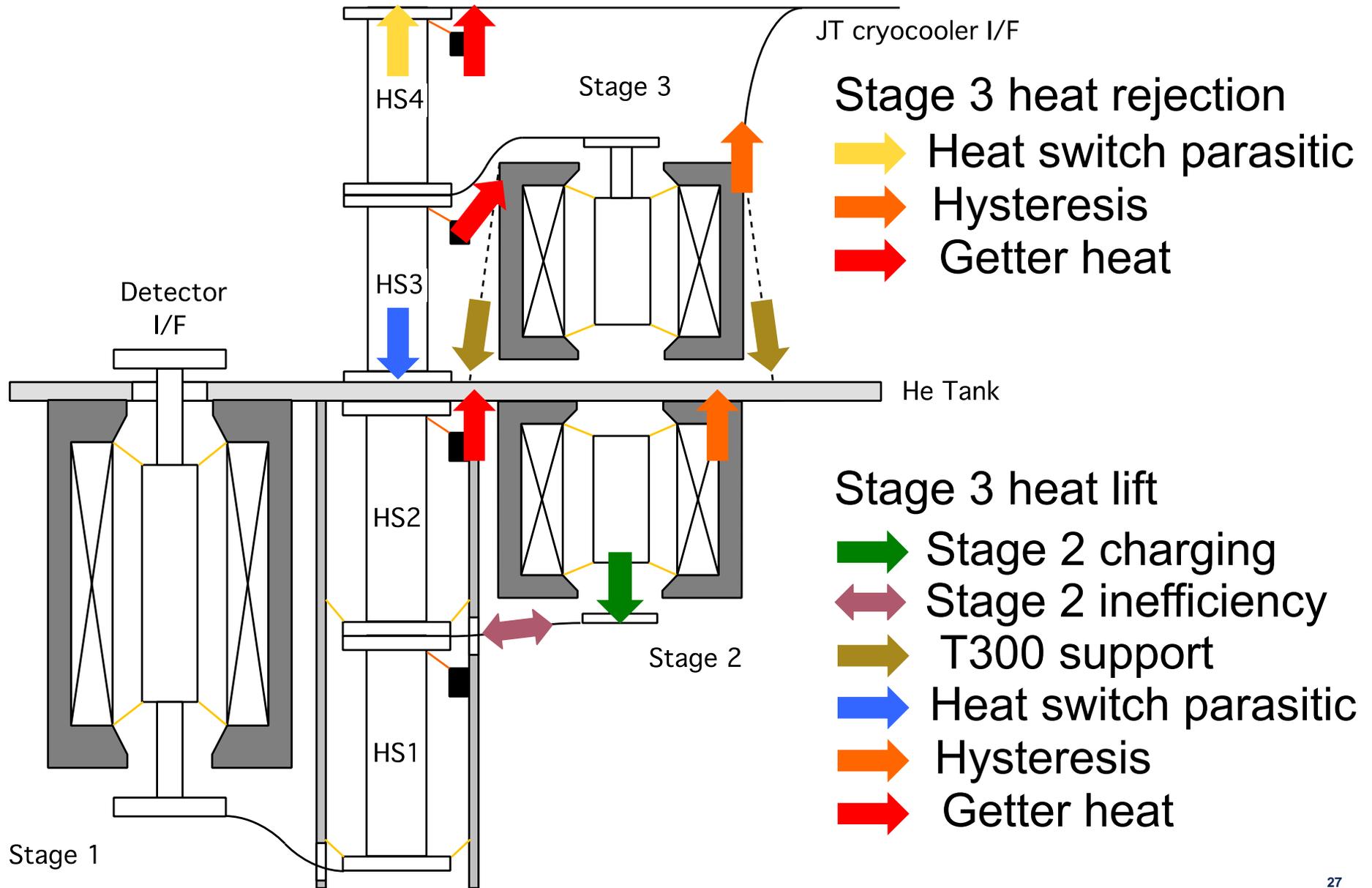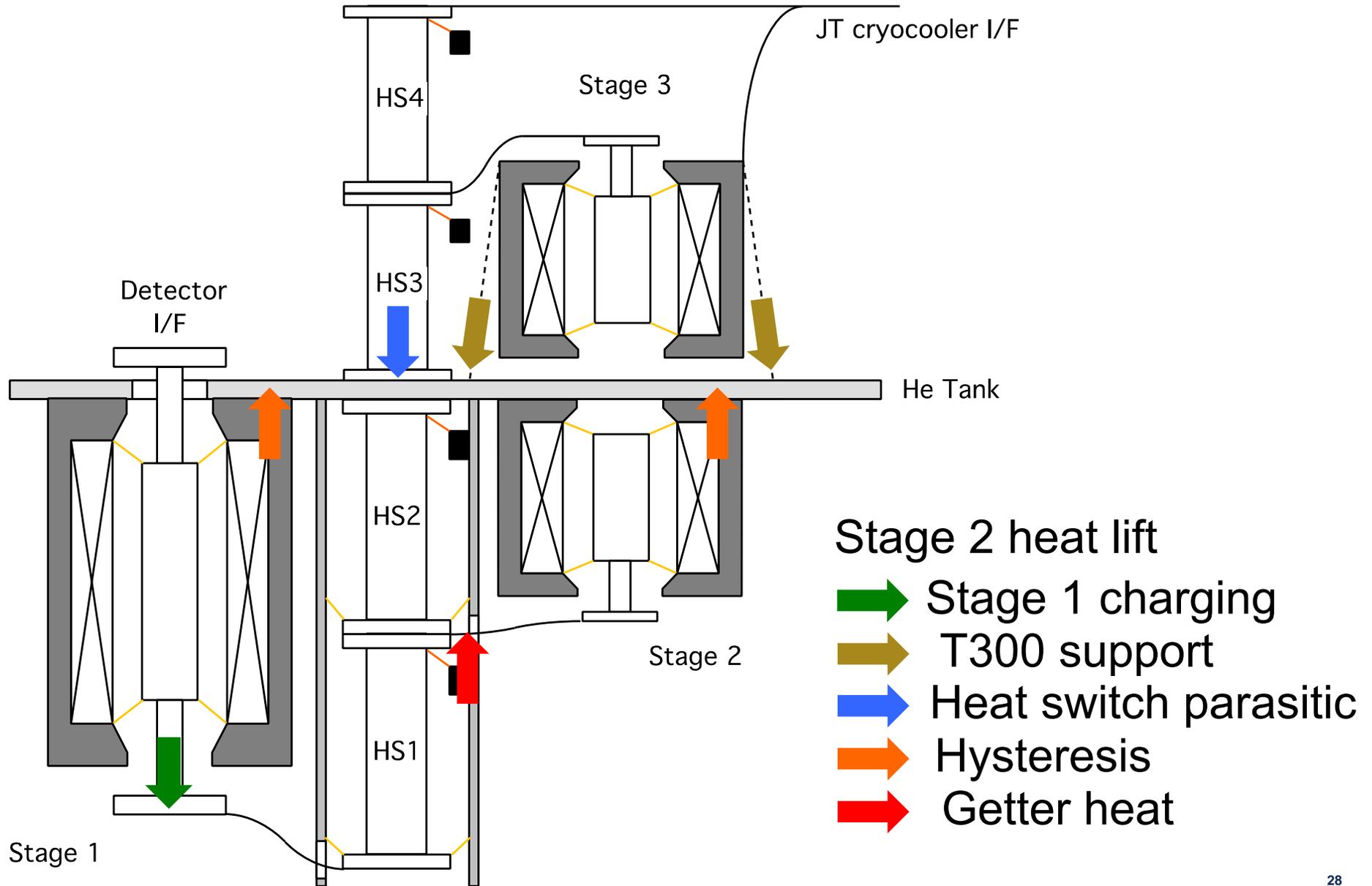- Stored capacity is used to recycle 1st stage
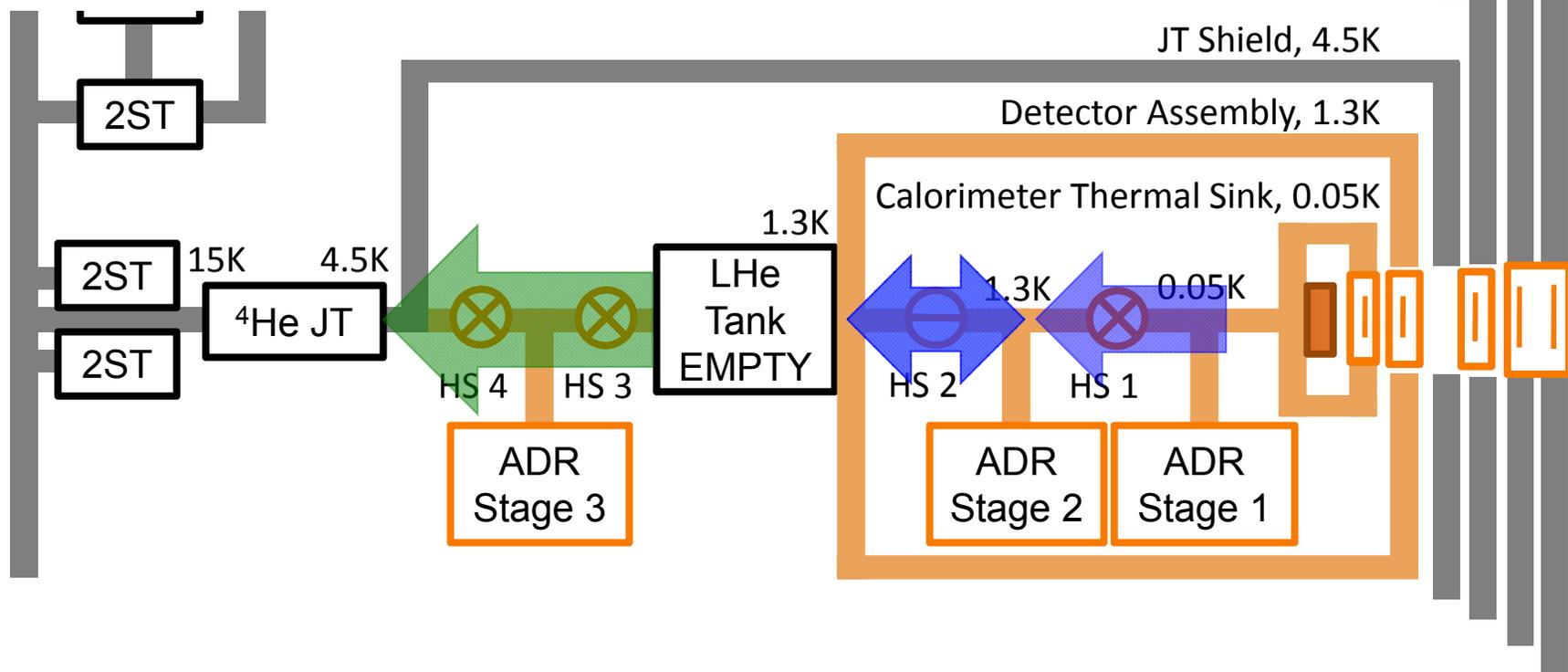
3-Stage Schematic

Detector heat load

Kevlar

Heat switch parasitic

Hysteresis

Getter parasitic

JT cryocooler I/F

Stage 3

HS4

HS3

Detector I/F

He Tank

HS2

Stage 2

HS1

Stage 1

Stage 2 and 3 Operation

JT cryocooler I/F

Stage 3

Detector I/F

HS4

HS3

He Tank

HS2

HS1

Stage 1

Stage 2

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
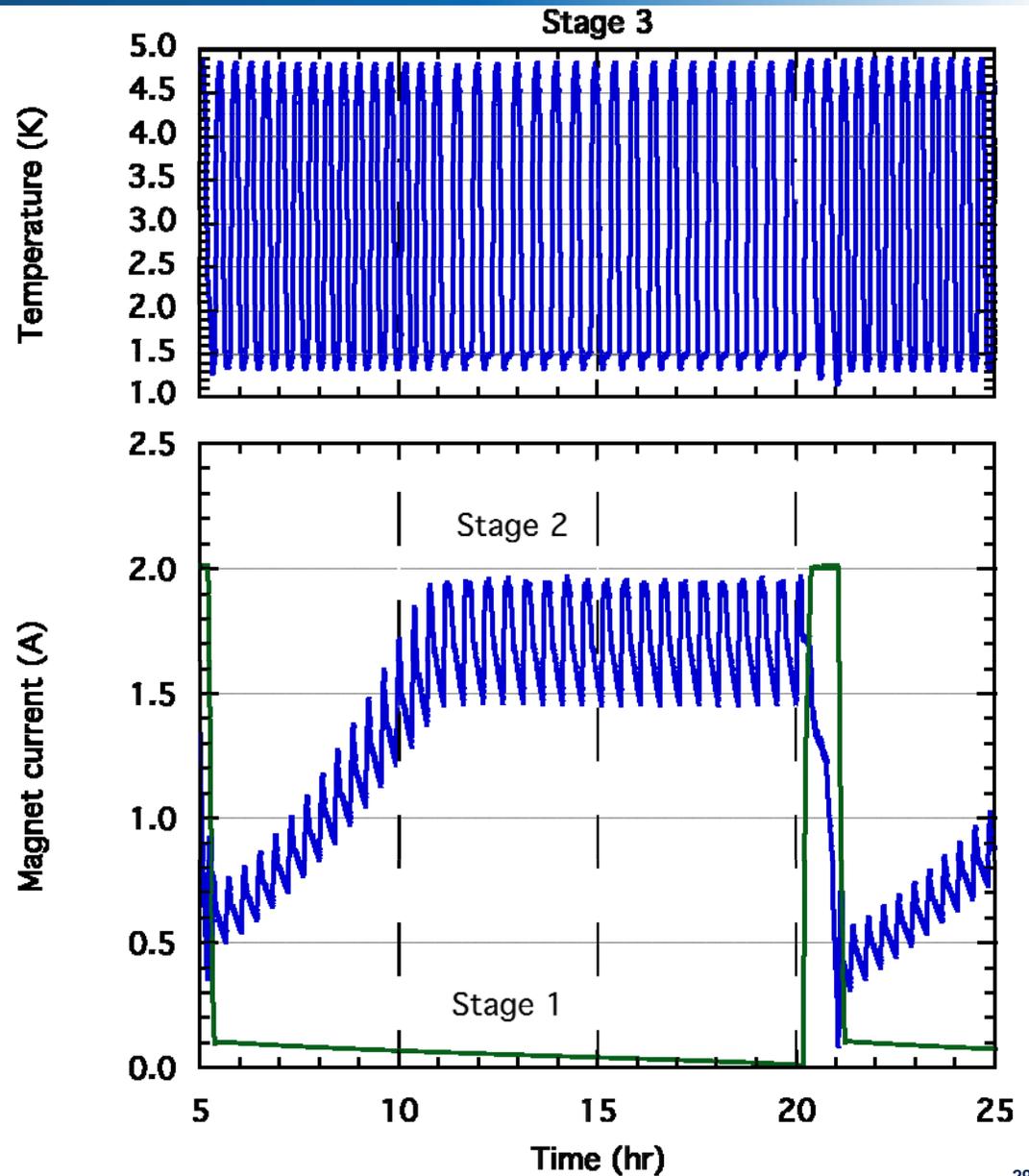- Hysteresis
- Getter heat

Stage 1 Recycling

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

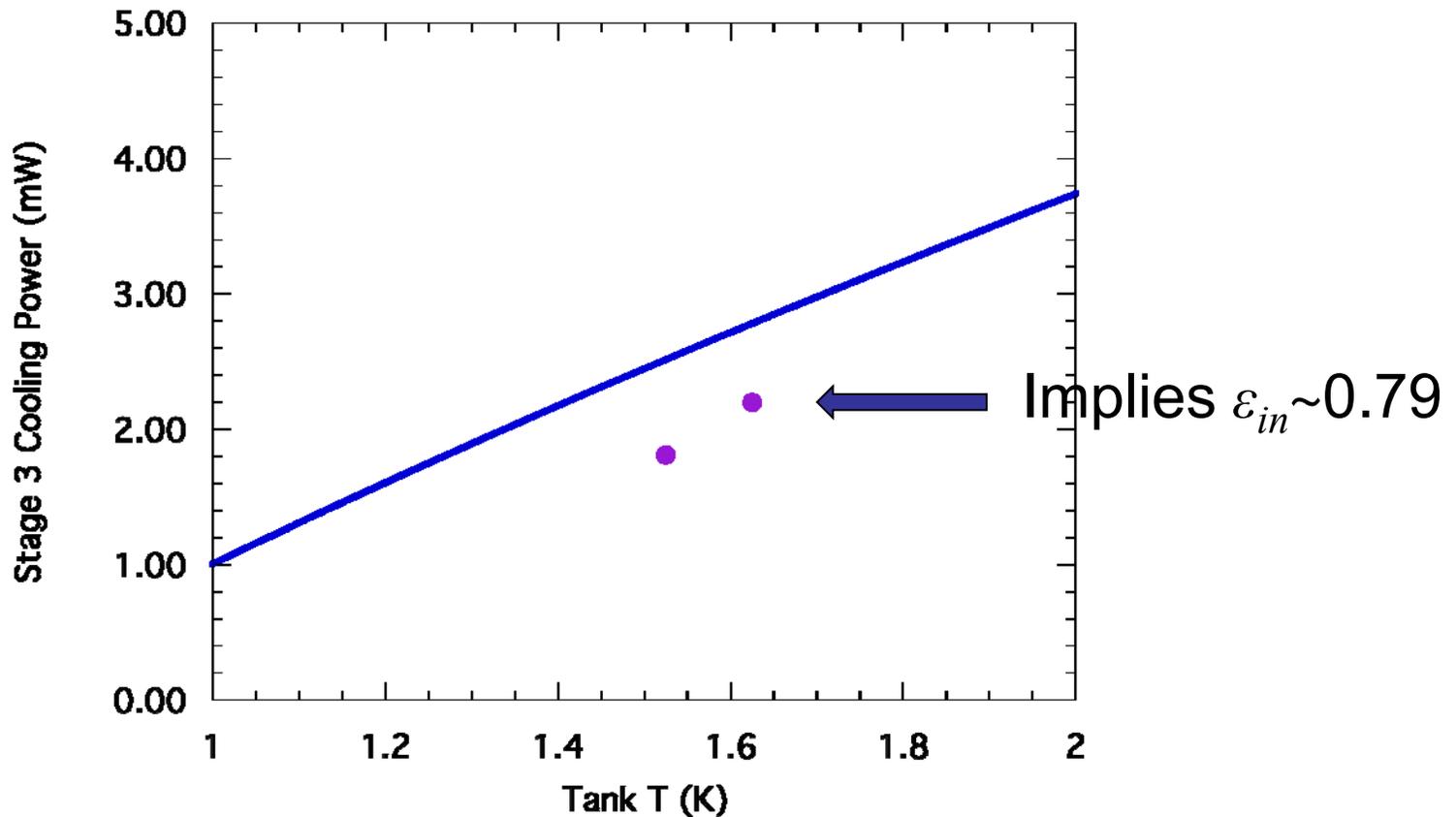- S3 cooling power
  - 2.20 mW at 1.625 K
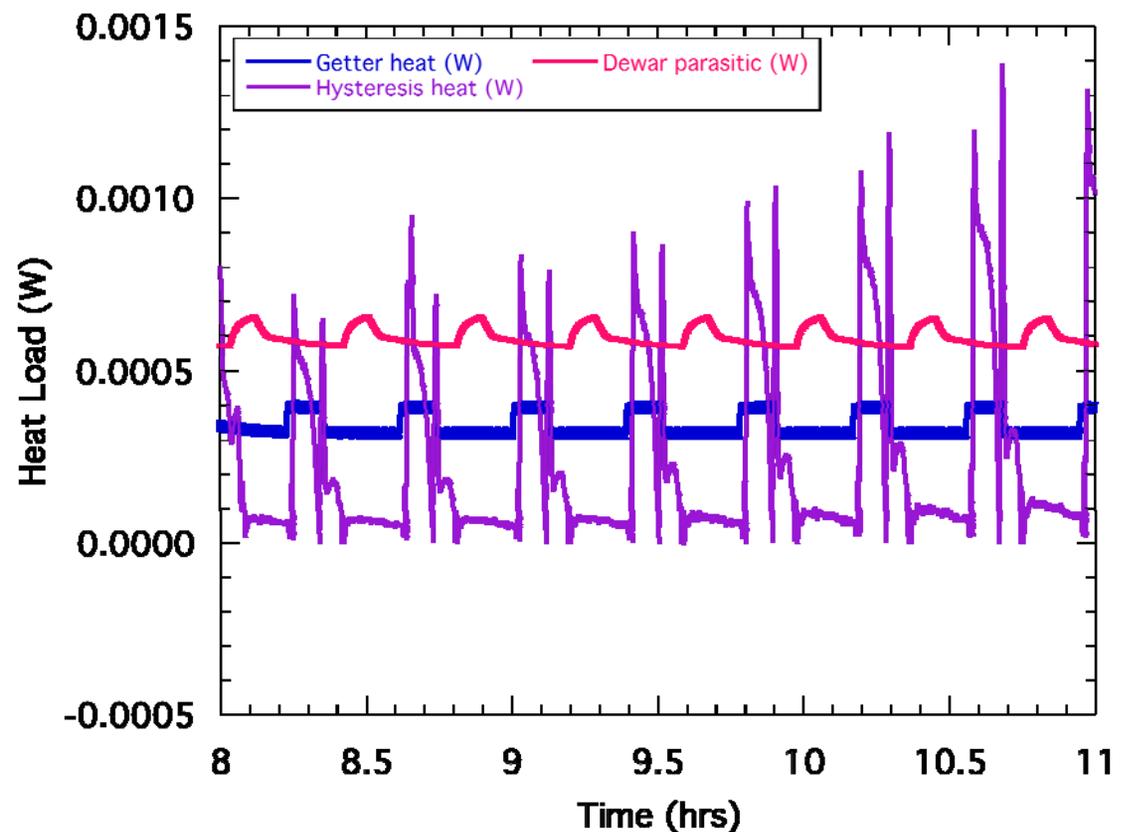
Stage 3 Cooling Power

- 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
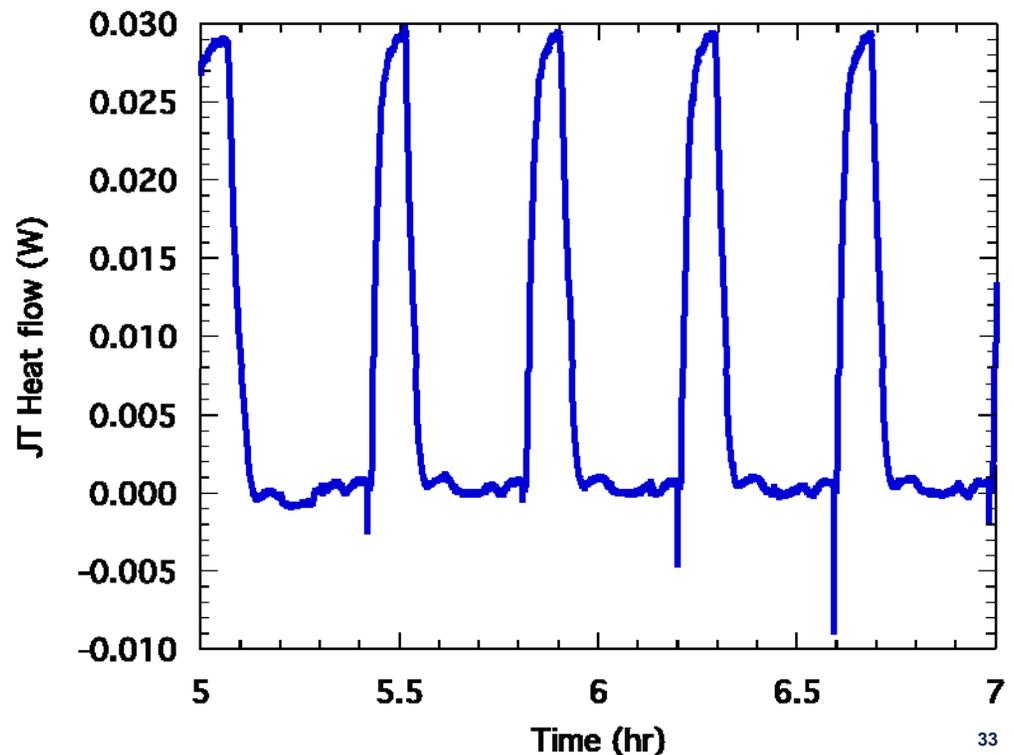
Conclusion

- 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