CEC 2023

Effects of Working Fluid on Performance of 4.5 K JT Cooler

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7/10/2023

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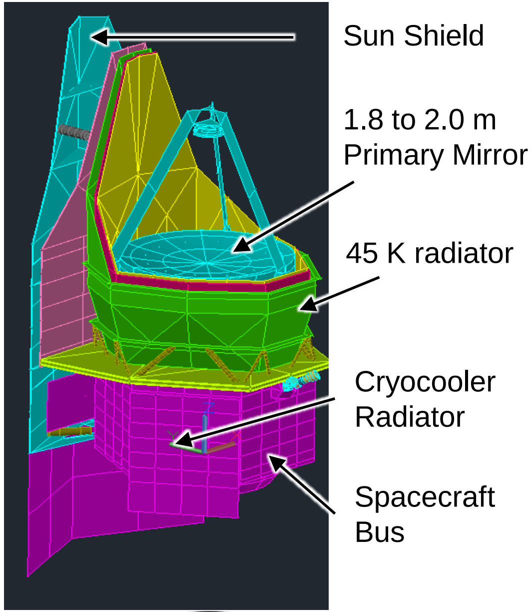
Background

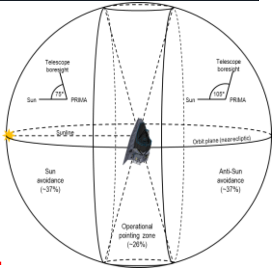
- PRIMA mission
  - The PRobe far Infrared Mission for Astrophysics (PRIMA) is a mission concept for a NASA cryogenic observatory
    - Far IR spectrometer and multi-band imager using superconducting MKID detectors
    - Probe-class astrophysics mission with a target launch date in 2030
  - Earth-Sun L2 halo orbit
- PRIMA instrument operating temperatures

Heat Loads at Low Temp. Stages	18K Stage for bi-pod heat intercept, actively cooled shield and LNAs	4.5 K Stage for primary mirror, relay optics and their structural support, ADR, FTS and scan mirror actuators, and harness	1.0K Stage for detector enclosure support and harness	0.10K Stage for detector harness and support
CBE Loads	106.5 mW	27.9 mW	350 μW	5.16 μW
Required Capability for 100% Margin	213 mW	47.8 mW (8 mW from ADR does not require margin because it is for >2x loads at 1.0K and 0.1 K)	700 μW	10.3 μW

<u>Margin = 100% * {[System capacity/CBE heat load] - 1}</u>

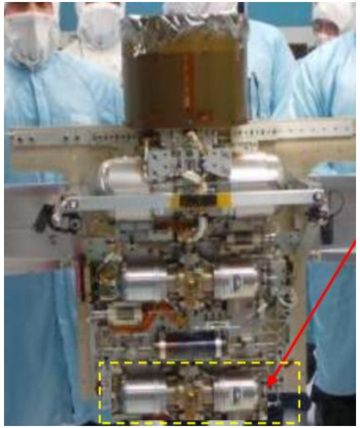
- Performance of existing TRL9 mechanical cryocoolers is not adequate
  - Cooling power from existing TRL9 coolers is < 50 mW
    - MIRI, Sumitomo Hitomi and Planck JT coolers



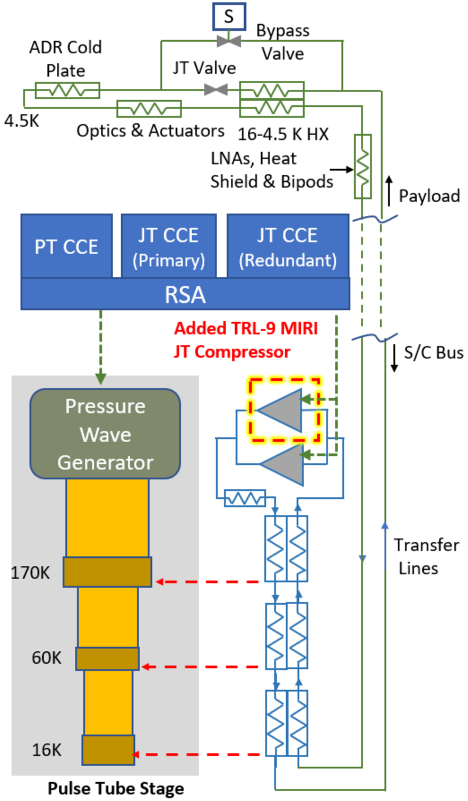


Development Paths using MIRI Flight Spare Cooler

- Leverage existing MIRI flight spare cooler
- Candidate JT stage configurations
  - Two-stage compression system with ^{4}He to achieve a PR > 9
    - Require a lower stage compressor with volumetric flow rate ~ 3x MIRI compressor
      - Decrease JT restriction outlet pressure from 4 bar to about 1.2 bar
      - Require technology maturation of lower stage compressor from TRL4 to TRL6
  - Single-stage compression system with ^{3}He
    - Two parallel MIRI compressors to increase flow rate
      - ^{3}He JT stage does not benefit from a high pressure ratio
    - No need for new compressor technology development
    - All components and subsystem hardware are at TRL 9
- Control electronics
  - Cross-strapped JT compressor CCEs
    - One CCE can drive two compressors
    - One as redundant
  - One PT CCE (no redundant) for Class C mission



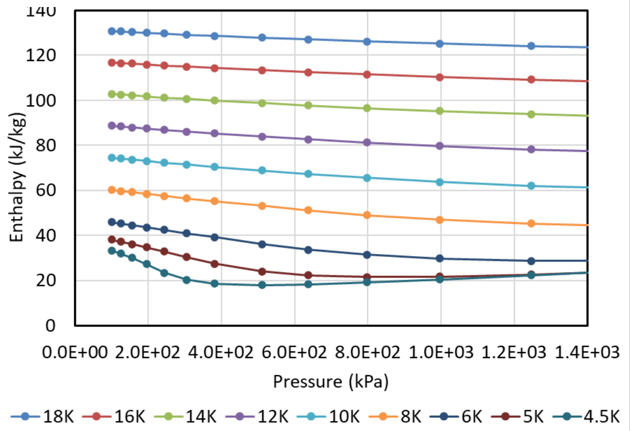
DC input power: 410W. Estimated cooler mass is 68 kg, including CCEs



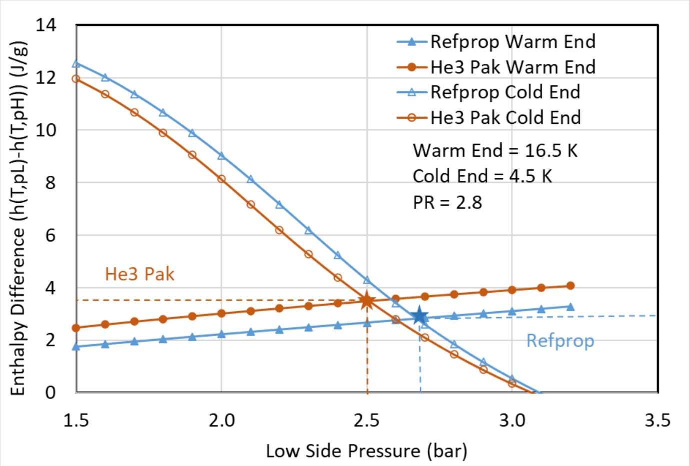
Thermodynamic Cycle Analysis

- Goal: Maximize JT stage cooling capacity
  - Within compressor thermal and stroke limits over a wide range of operating conditions
- At 4.5 K, ^{3}He enthalpy reaches a minimum value at about 4.8 bar based on REFPROP
  - ^{3}He JT stage would not benefit from a 2-stage compression system
- Predicted optimum suction pressure is about 2.5 bar with He3Pak, and 2.7 bar with REFPROP
  - For fixed PR of 2.8, corresponding to a PR of 3.3 across compressors
- PRIMA conservatively uses properties from REFPRO since it predicts a lower JT effect than He3Pak
  - Will verify ^{3}He properties by testing during Step 1 study

^{3}He Enthalpy-Pressure Diagram from REFPROP



Flow Stream Enthalpy Difference vs JT P_{Outlet}



JT Stage Losses

- Actual performance depends on
  - Pressure drops in warm recuperators
    - Reduce PR across the lowest stage recuperator and JT restriction
  - Loss in lowest stage recuperator due to recuperator thermal ineffectiveness
    - Directly reduces cooling power at 4.5 K
    - PRIMA cooler is more sensitive to this loss since ^3He specific cooling capacity is lower than MIRI ^4He
  - Losses due to ineffectiveness in warm recuperators, and enthalpy flow into cold end of each recuperator due to non-ideal gas effect
    - Increase loads on PT cooler and thus JT precooling temperature
- Total pressure drops reduce JT restriction PR from 3.3 to 2.8
  - Due to higher volumetric flow rate than MIRI
  - Reduce flow cooling capacity by 19%
- Thermal effectiveness of recuperators in both systems are near identical
- Enthalpy flow due to non-ideal gas effect is higher for MIRI ^4He in 60-18K recuperator
- Overall JT precooling heat loads on PT stages are very similar

Predicted PRIMA Cooler Performance

- Cooling power of 53 mW @4.5 K and 235 mW@ 18 K with 275 K heat sink, and optimized JT restriction
  - > 2x of CBE heat loads at these temperatures
  - 49 mW if using existing JT restriction in MIRI cooler, still above 2x CBE load re
- Require a compression ratio of 3.3 and mass flow rate of 20.66 mg/s
  - Well within scaled capability of MIRI JT compressors
- CBE DC input power: 410 W (PT: 334 W + JT: 76 W)
  - For comparison, MIRI cooler bus nominal input power of 400 W at SS and 475 W during cooldown
- CBE cooler mass is 68 kg, including CCEs
  - Additional JT compressor mass and CCE mass of 4.1 kg and 3.8 kg (not incl. structural support)

Cases	Total Bus DC Power (W)	T_{sink} (K)	$P_{Low,comp}$ (bar)	$P_{High,comp}$ (bar)	$T_{precool}$ (K)	Q_{ext_load} at $T_{Precool}$ (mW)	$T_{c\text{—}JT}$ (K)	Q_{JT} (K) (mW)	Flow Rate (mg/s)
Existing JT Restriction	400	275.0	2.448	8.152	16.21	236	4.5	48.7	16.58
Optimized JT Restriction*	410	275.0	2.443	8.135	16.66	236	4.5	52.8	20.66

*The mass flow rate with optimized JT restriction is used as the requirement for compressors

Performance Sensitivity Study

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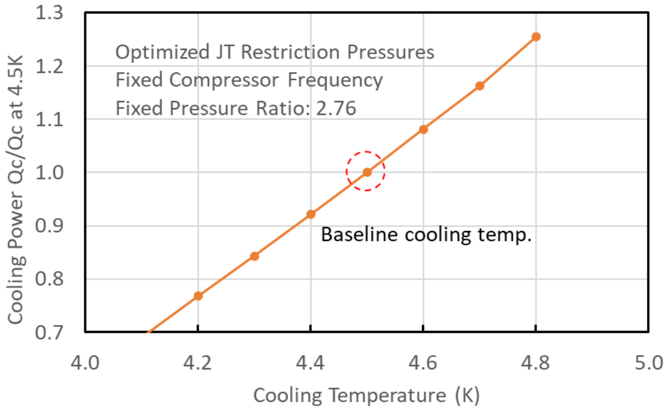
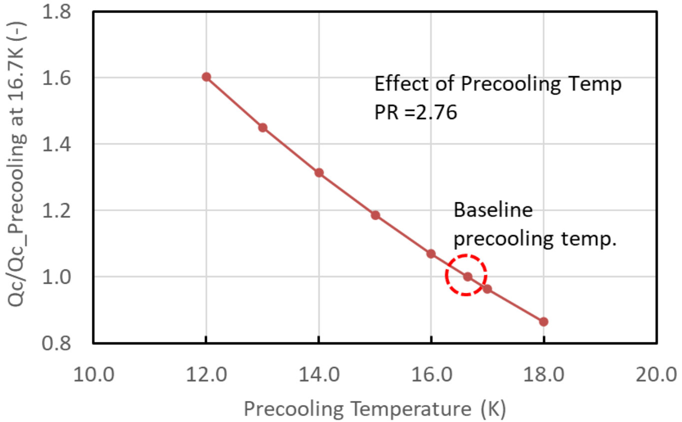
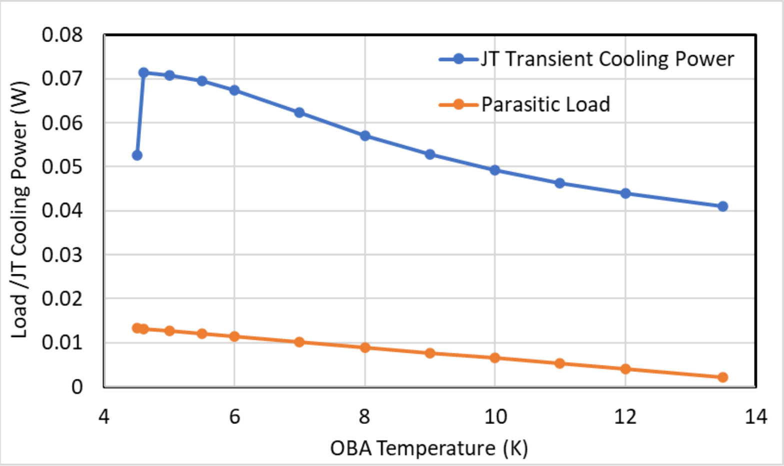
- Heat sink temperature
  - Lowering T_{sink} increases compressor mass flow rate
  - Lowering T_{sink} enhances PT precooler performance and thus decreases JT precooling temperature
  - 273 K is baseline T_{sink} to enhance cooling power
    - 29% higher cooling power at 4.5 K than with a 314 K heat sink
- Precooling temperature
  - Reducing $T_{precooling}$ from 18K to16K increases cooling power by about 23.7%.
- JT stage cooling temperature
  - Increases cooling power by about 8% for every 0.1K increase





Cooldown through JT Pinch Point

- Payload parasitic is very low at beginning of JT stage cooldown because
  - Entire payload is in an environment at JT stage precooling temperature
  - All active heat loads are not turned on
  - Much more benign conditions than MIRI where it has no bipod heat intercepts
- Net available cooling power for payload is high right after Pinch Point traverse
- Even with a very large mass of 550 kg, predicted cooldown time from 14 K to 4.5 K is only about 2 days
  - After ~30 days of cooldown from 150 K to 14 K using passive cooler and active cooler
- Traversing the Pinch Point is not a concern for PRIMA



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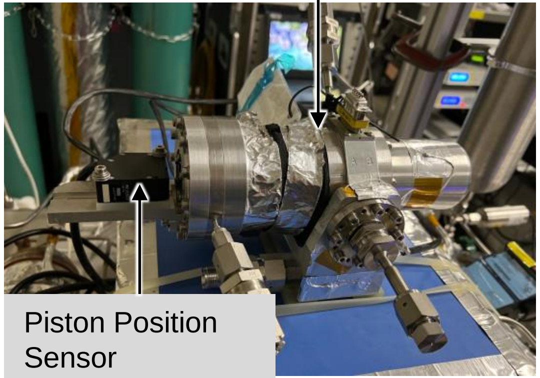
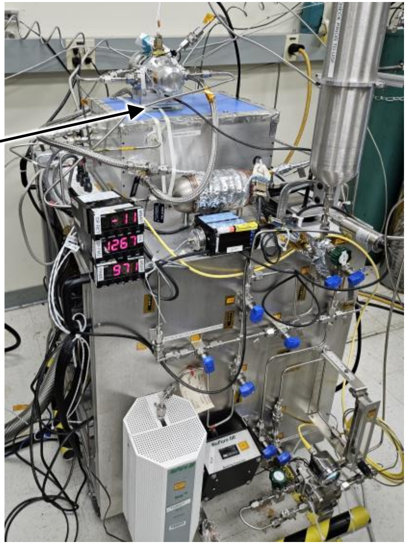
MIRI DM Compressor Testing

- Motivation
  - PRIMA design pressures are lower than MIRI operating condition
    - Lower gas spring stiffness for pistons, reducing piston resonance frequency
    - Decrease mass flow rate
  - ^{3}He as working fluid instead of ^{4}He in MIRI cooler
    - Assume same volumetric flow rate capability in initial study
  - Directly measure flow rate capability and power input to reduce risk
- MIRI JT compressor Development Model (DM)
  - Nearly identical to flight MIRI compressor
  - Has piston position sensor (NOT in flight model) to
    - Provides critical information needed for safe operation
    - Allows direct measurement of piston stroke margin
    - Provides key information to adjust piston DC position

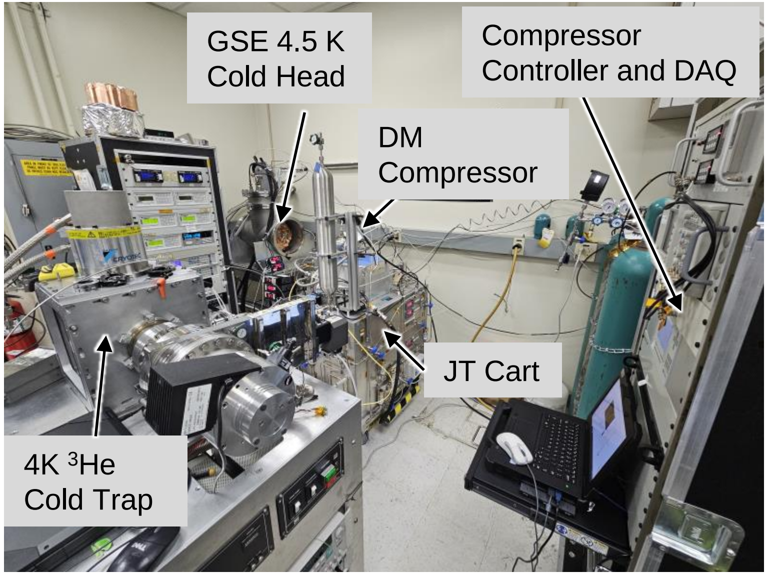


JT Cart with Support Equipment



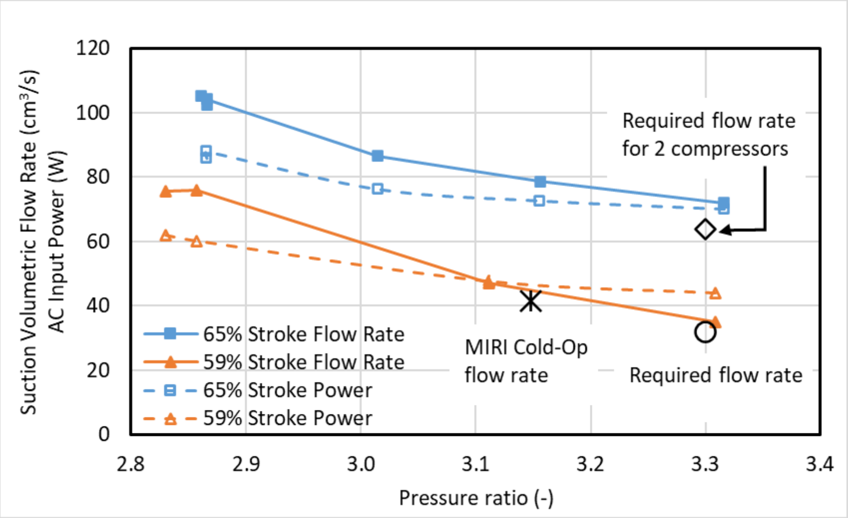
Test Facility

- Based on an existing facility developed for MIRI cooler
  - COTS electronics controls compressor operation and records flow conditions
  - Chiller and HXs control compressor and inlet and outlet flow temperatures
  - Vacuum pump system, particulate filters and a getter to remove contaminants
  - Mass flowmeters, pressure transducers and temperature sensors
- Plumbing system to
  - Pneumatically determine piston hard stops and max stroke length
  - Bleed valve to adjust piston backside pressure and their DC position
- Have features to support subsequent ^{3}He tests
  - COTS GM cooler and recuperator for JT effect testing
  - ^{3}He cold trap for pressure boosting and gas recovery



Compressor Performance

- Natural frequency
  - 74 Hz at P_{in} = 2.31 bar and P_{out} = 7.79 bar
    - 13% lower than MIRI's 85 Hz at P_{in} = 3.83 bar and P_{out} = 12.90 bar
- DM compressor has substantial performance margin against flow rate requirement at target pressure ratio of 3.3
  - Can achieve more than 2x required flow rate with piston DC position slightly biased toward fore end
    - Piston stroke is still < 70% distance between hard stops
    - Motor I^2R loss is much below 28 W limit
    - Compressor AC input power is only 63 W at 2x volumetric flow rate
  - Flow rate increases very quickly as stroke length increases
  - Will determine actual flow rate margin with flight-like piston DC offset control over a range of operating conditions



Discussion

- Flight CONOPS may require a higher stroke margin than preliminary ground test to date
  - Piston DC position will change with compressor temperature and system pressures
  - Require additional stroke margin
    - To meet steady-state cooling requirement over a wide range of sink temperatures
    - Accommodate transient operation during cooldown
- Test data from integrated flight spare cooler acceptant test during Cold-Op also confirms FM flow rate capability
  - DC offset and piston stroke were controlled by MIRI CCE flight software
  - 41.6 cm^3/s suction flow rate is 30% higher than required value of 31.9 cm^3/s for 1 compressor
    - Assume suction volumetric flow remains the same for ^3He

Date & time completed	T_{sink} (K)	P_{Low} (bar)	P_{High} (bar)	$T_{precool}$ (K)	3rd PT Stg. Ext. Load (mW)	$T_{c\text{—}JT}$ (K)	Q_{JT} (K) (mW)	M_{dot} (mg/s)	V_{dot} (cm^3/s)
2/19/16 2:19	249.0	2.64	8.31	17.693	203.32	5.540	56.47	21.2	41.6
Requirement for 1 ^3He Compressor	275	2.44	8.14						**31.9**

Conclusions

- PRIMA cooler is a slightly modified JWST MIRI cooler
  - Adding one MIRI JT flight compressor/CCE to an existing spare flight MIRI cooler
  - ^{3}He instead of ^{4}He working fluid to lower cooling temperature
  - All key subsystem and component hardware are at TRL 9
  - Predicted cooling power: 53 mW at 4.5 K and 230 mW at 18 K
    - >2x CBE heat loads
  - Mass: 68 kg, including CCEs and relay
  - CBE bus input power: 410 W
- Feasibility of achieving design suction volumetric flow rate has been demonstrated with ^{4}He
  - Compressor can achieve a flow rate much higher than requirement at target pressure ratio, while still meeting compressor input power and stroke margin requirement
  - Actual margin in flight model might be lower but still higher than requirement
- Next steps:
  - Characterize compressor flow rate capability with ^{3}He
  - Measure ^{3}He JT effects under PRIMA design conditions