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JT-Cooler Developments at STFC: 2K-30K Coolers in Support of Space Science Missions

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3rd Dec 2020

Cryogenics in support of Science Missions

- Medium and Large category science missions are typically requiring a more varied and bespoke cryogenic approach than for smaller/Earth observation missions

- Very low temperatures
  - 50 mK for some detectors driving a need for sub-Kelvin cooling in space
  - complex ‘cryo-chain’ – cascading cooling technologies of ever decreasing temperature

- Spacecraft and instrument architectures
  - Sensitive detectors (EMC and mechanical) and extended architectures can require ‘remote cooling’
  - Congested detector regions require small cold tips with routing constraints

- A speciality of cryocooler developments at STFC Rutherford Appleton Laboratory, Joule-Thomson type coolers are proving to be very useful in offering a great deal of flexibility for the solution of these issues

- This presentation highlights some of the benefits of JT-Coolers, with examples of recent developments at RAL:
  - 4K cooler previously flown on the Planck mission
  - 30K cooler being developed for the Ariel mission
  - 2K cooler in support of the Athena mission

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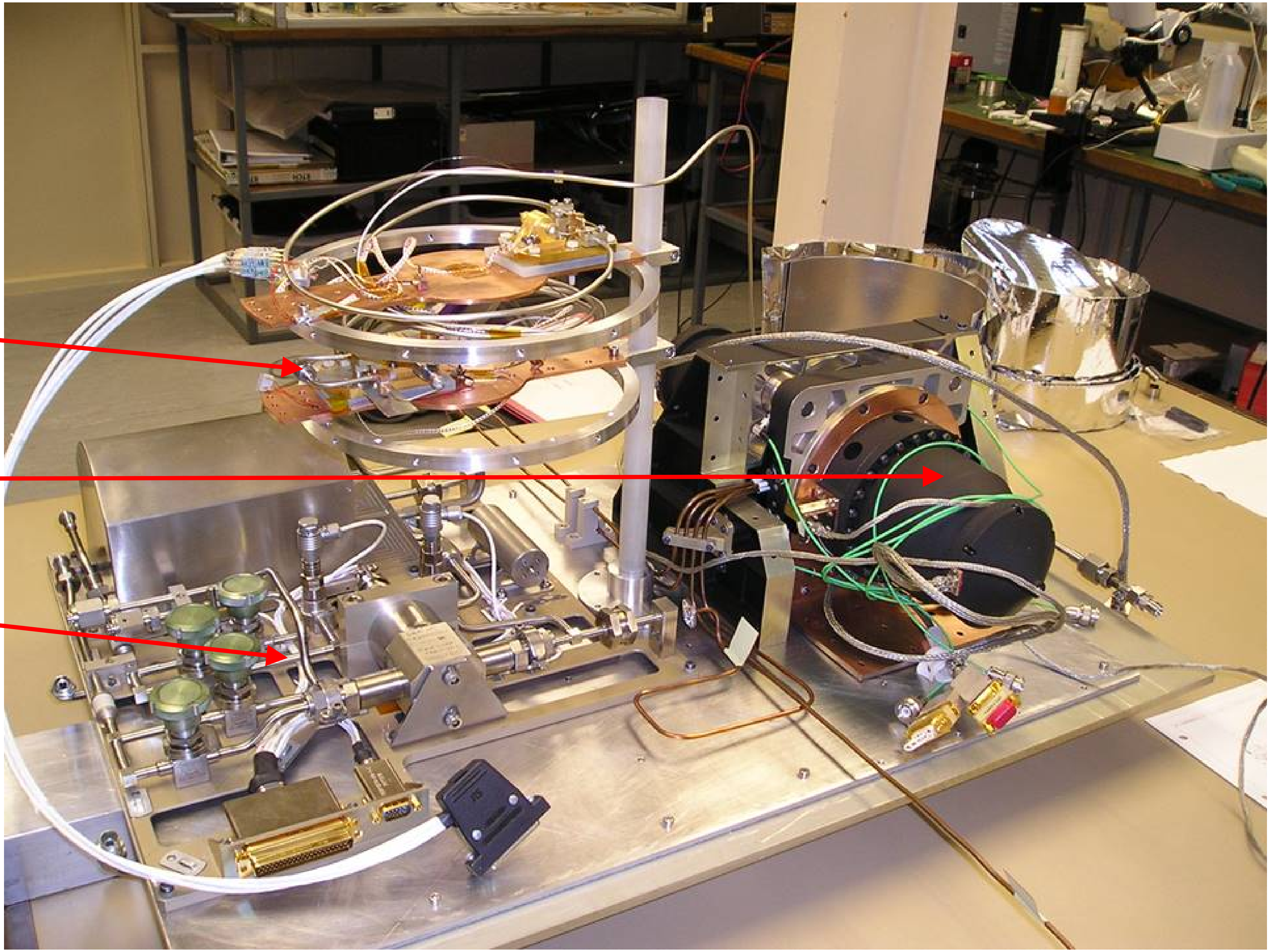
Closed-cycle JT-Cooler – General Overview

Basic working principle

- Joule-Thomson cooling realised by performing an expansion of the working fluid across a restriction (15-50 µm orifice)
- Heat exchangers are used to facilitate the cycle and improve efficiency
- Compressors are used to drive the working fluid around the loop
- Some gas handling is needed
- Control electronics are needed (not shown)



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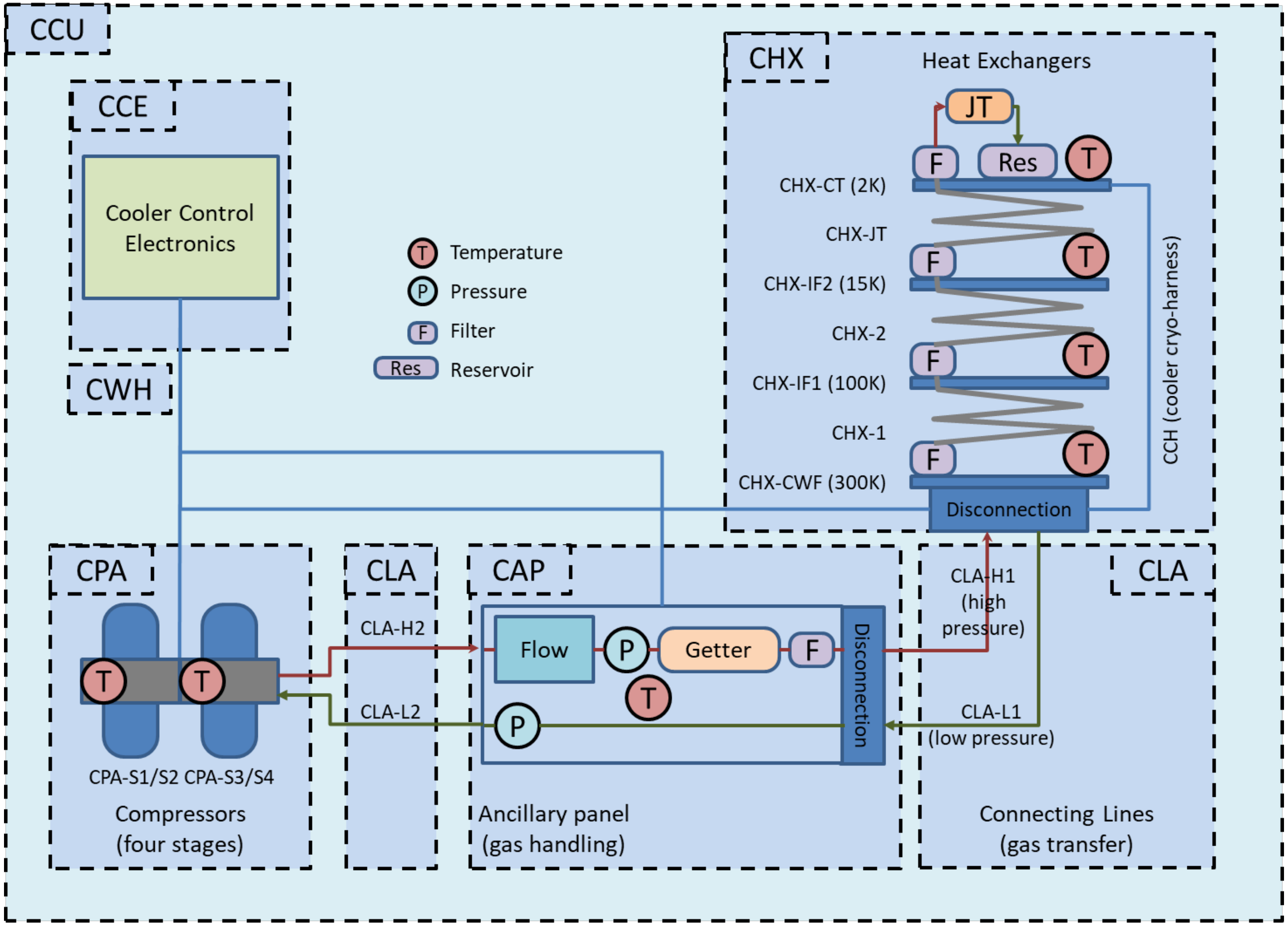
Closed-cycle JT-Cooler – Schematic

- Architecture lends itself to an extended accommodation
- Cooler can be conceptually and physically split into ‘warm units’ and ‘cold units’



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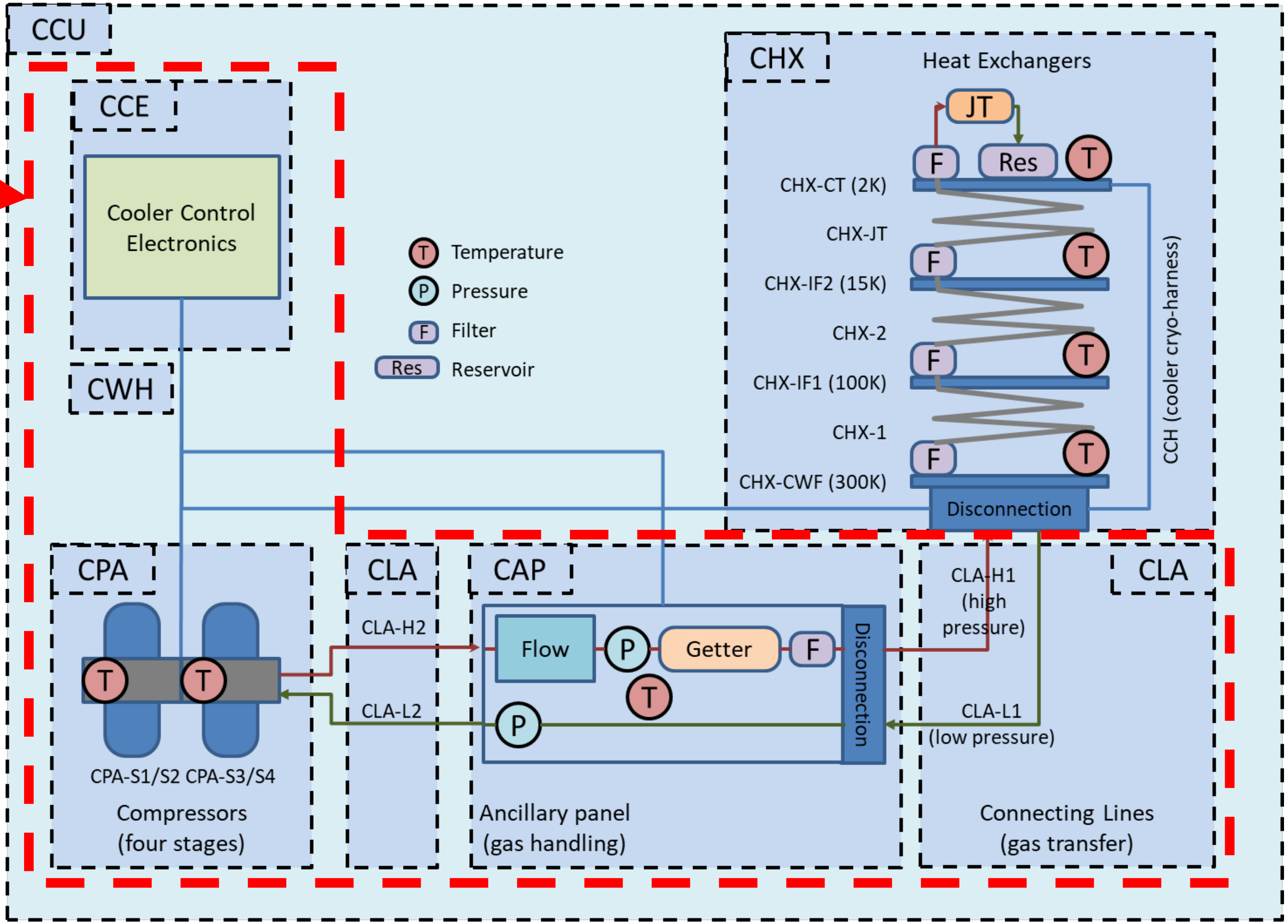
Closed-cycle JT-Cooler – Warm Units

- Warm Units
- Can be sited remotely (several meters) from sensitive instrument detectors to reduce impact of low level mechanical and electrical disturbances
- Can be installed separately to the cryogenic parts of the payload



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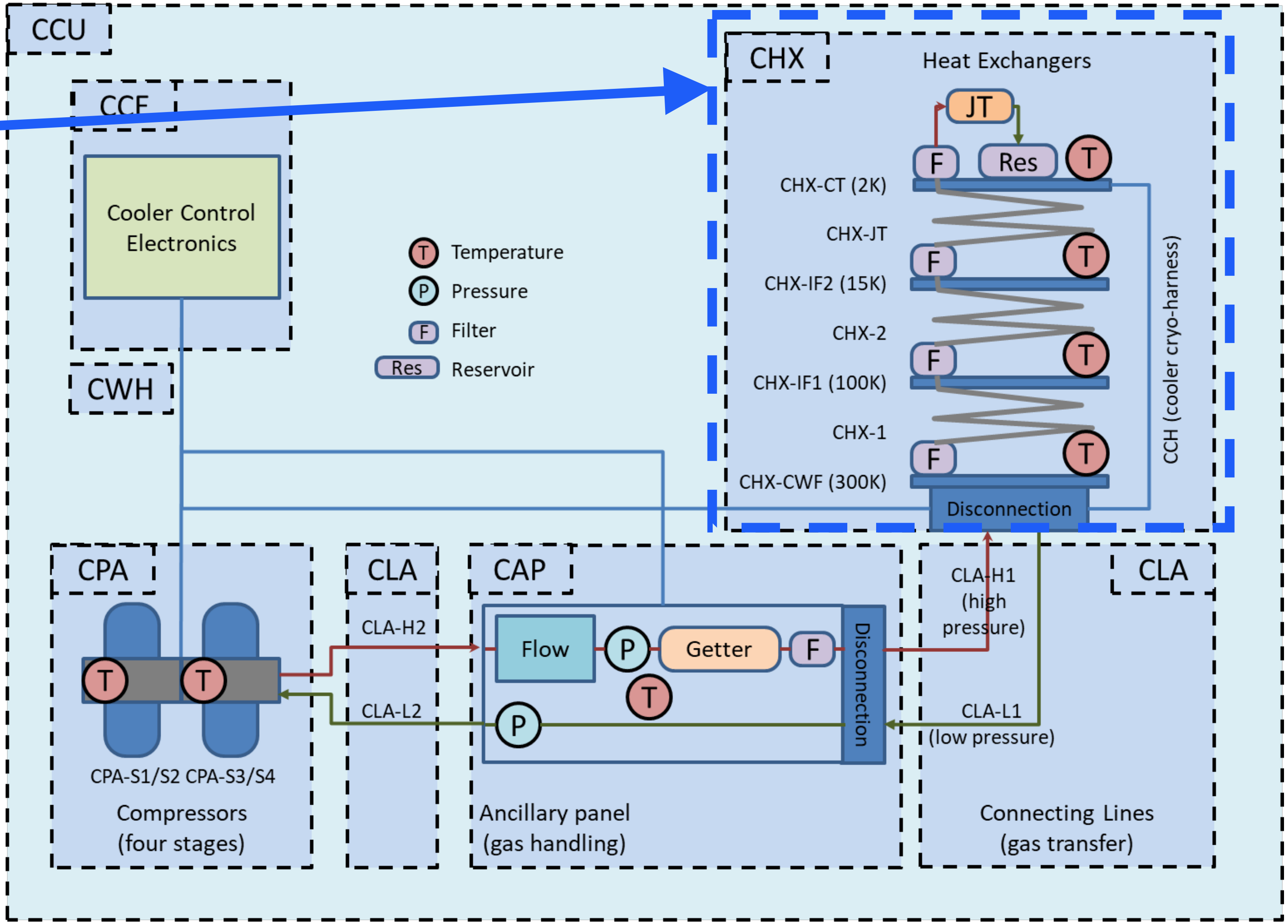
Closed-cycle JT-Cooler – Cold Units

- Cold Units
- No mechanical or electrical disturbances
- Can be installed into the cryogenic payload separately from the rest of the cooler
- Disconnection boxes to physically split the cooler during integration



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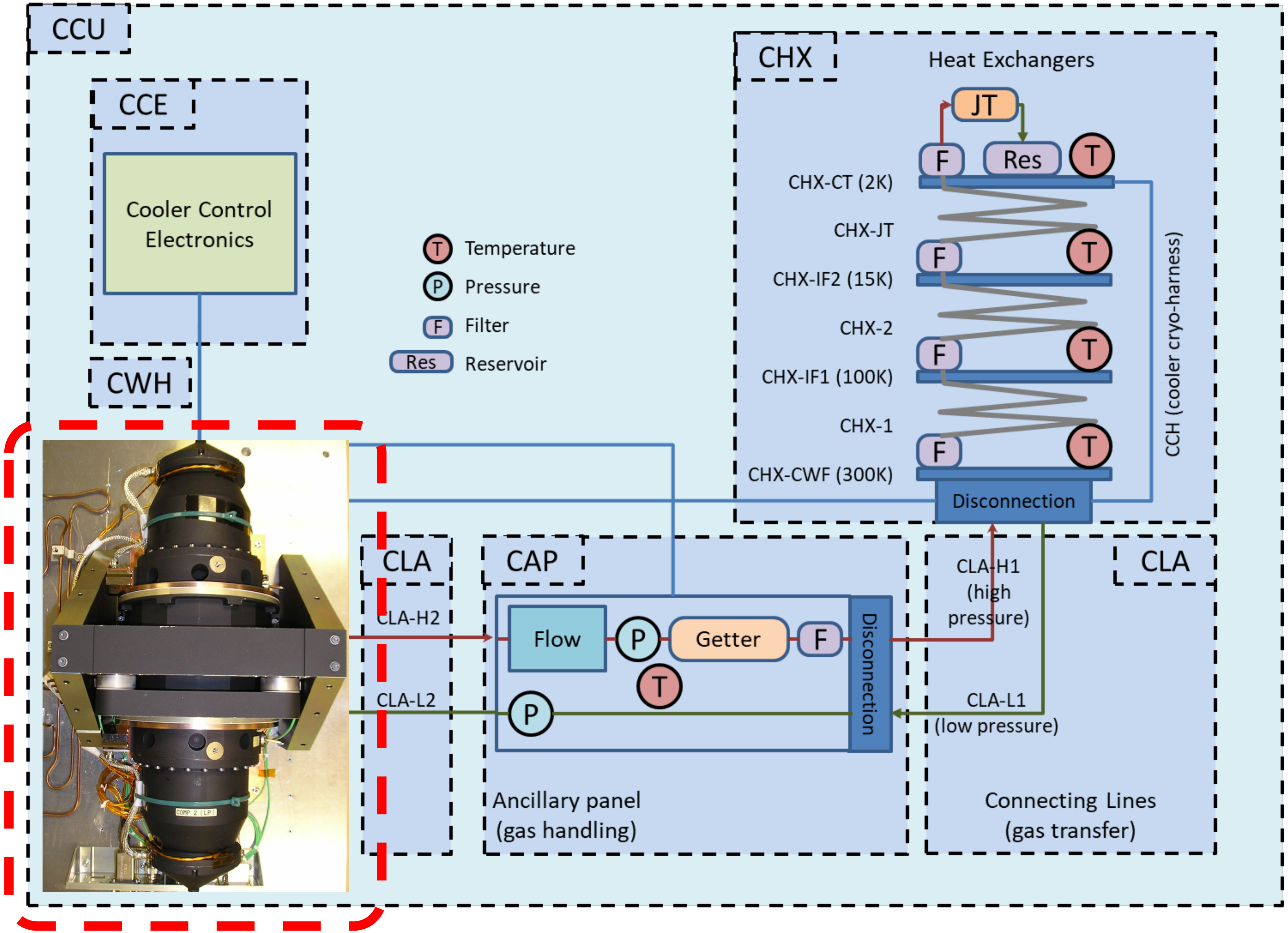
Closed-cycle JT-Cooler – Compressors

Compressor Assembly (CPA)

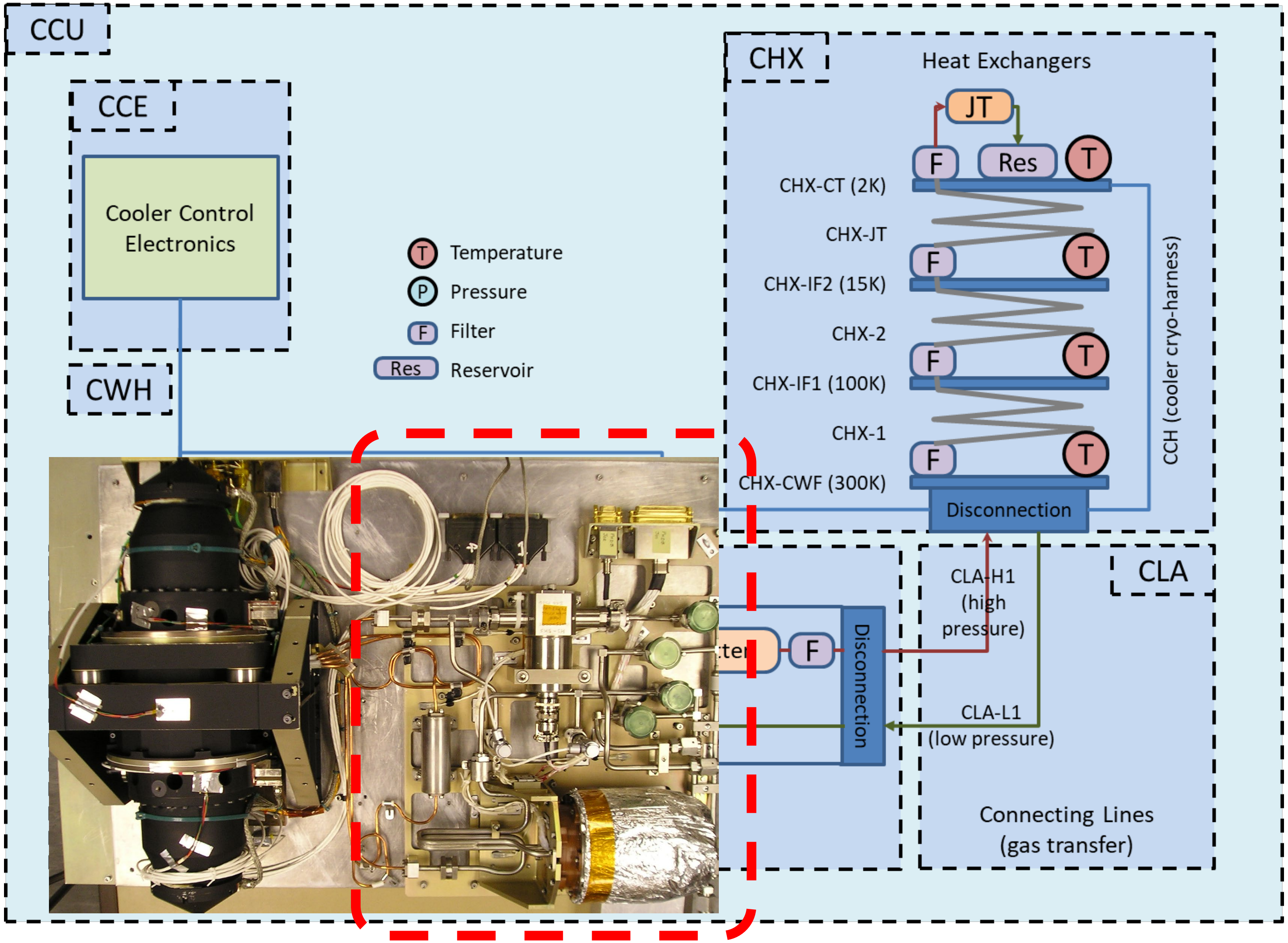
- Drives working fluid around the system and develops a pressure ratio and mass-flow across the restriction
- Moving coil linear motor reciprocating mechanisms
- Reed valves to rectify mass-flow
- Non lubricated, non-contact moving parts
- 10 µm piston/bore clearance seal maintained by a flexure bearing suspension system
- Zero maintenance high reliability. >10E+10 cycles demonstrated (20 years at 40Hz)
- Multiple stages arranged as pairs in a head to head configuration to minimise exported vibrations



Closed-cycle JT-Cooler – Ancillary Panel

Ancillary Panel Assembly (CAP)

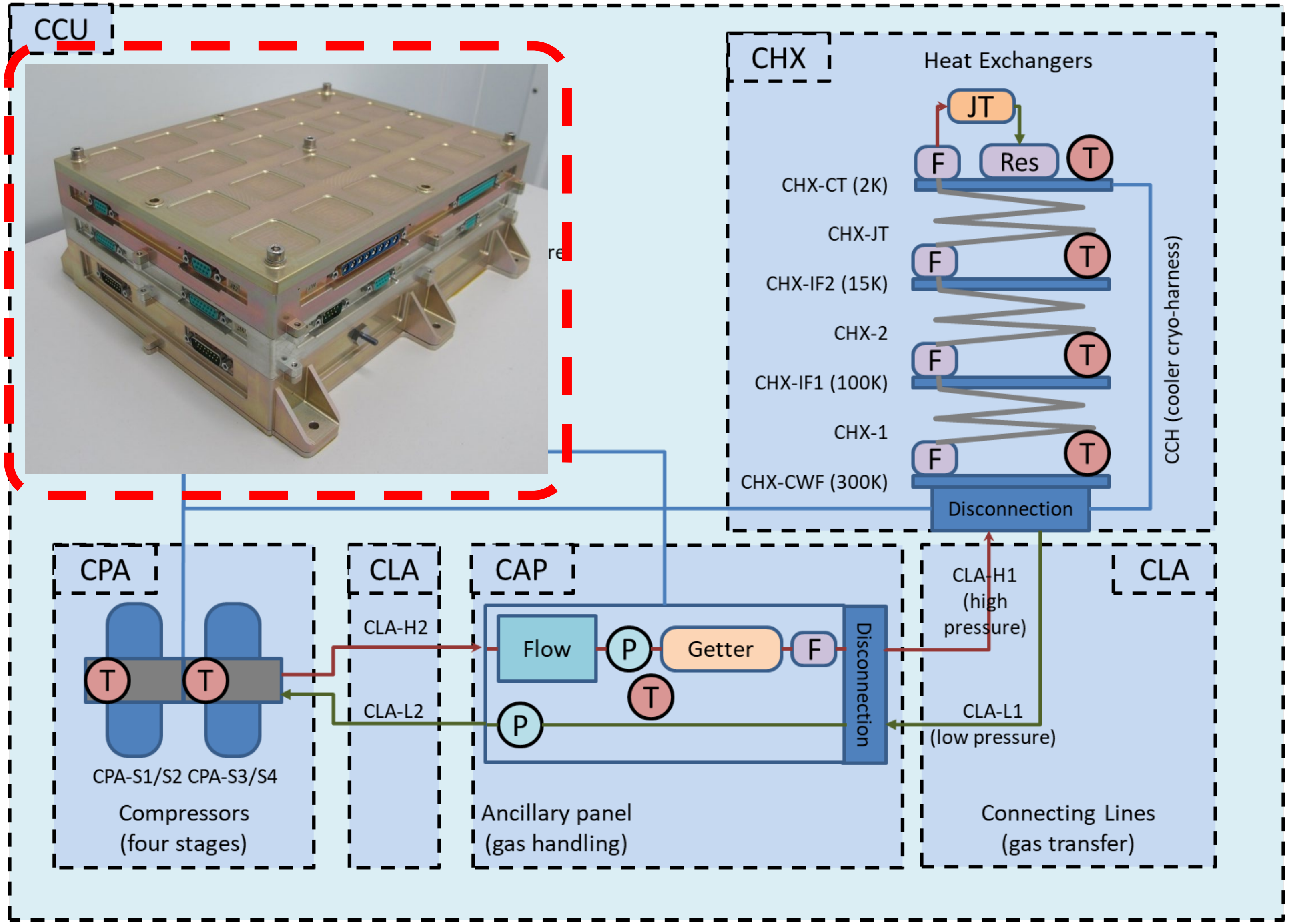
- Provides gas handling, purification and housekeeping functions
- Getter maintains gas cleanliness over the lifetime of the cooler
- Filters prevent migration of particulates
- Pressure transducers and mass-flow meter for health monitoring
- Compressors and ancillary panel are delivered as a single sealed assembly
- Disconnection provided for isolation



Closed-cycle JT-Cooler – Control Electronics

Cooler Control Electronics (CCE)

- Provides command and control
- Compressors driven in a closed position loop
- Compressor active vibration control – typically up to 600Hz in piston axis
- Sensor power and signal conditioning
- Failure detection isolation and recovery
- Communications with spacecraft



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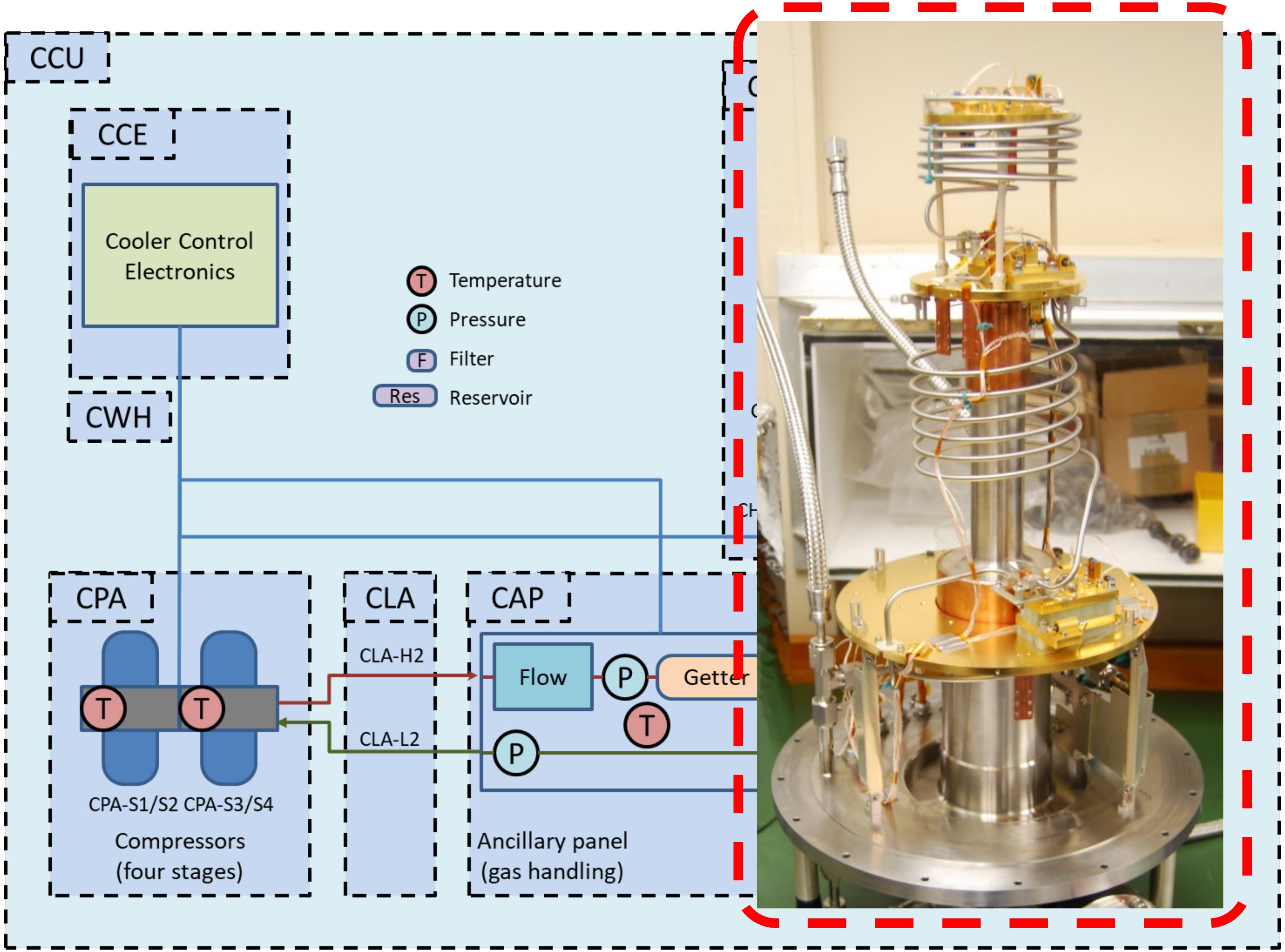
Closed-cycle JT-Cooler – Heat Exchangers

Heat Exchanger Assembly (CHX)

- Interfaces for precooling the working fluid
  - must be below inversion temperature for JT-Cooling to occur
- Preference to operate sub-critical for temperature stability
  - liquid accreted and contained in reservoir
  - Temperature determined by vapour pressure
- Tube-in-tube counter-flow heat exchangers between each pre-cooling stage
  - Low pressure return gas used to cool high pressure flow gas
- Filters at each pre-cooling stage to trap molecular and particulate contamination
- Total length 5-8 m and easily manipulated
  - can be coiled into compact configuration
  - can be arranged into convoluted routing

- Expected to be delivered as independent assembly for integration
- Disconnection provided for isolation
- Connecting lines of any reasonable length allow remote accommodation of cold and warm units



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Planck Cryo-chain

Planck mission mapped fluctuations in the CMB (2009-2013)

- HFI instrument bolometric detectors needed to be cooled to 0.1 K
- Operation of the cryo-chain was one of the most important technological achievements of the mission

- Passive cooling chain from 300 K to 50 K
  - L2 orbit location – good thermal conditions
  - Series of three v-groove radiators to reach successively lower temperatures

- 3 stage active cooling chain from 50 K to 0.1 K
  - Closed cycle H_2 sorption cooler to 17 K
  - Closed cycle ^4He JT-cooler to 4 K
  - Open cycle $^3He/^4He$ dilution refrigerator to 0.1 K

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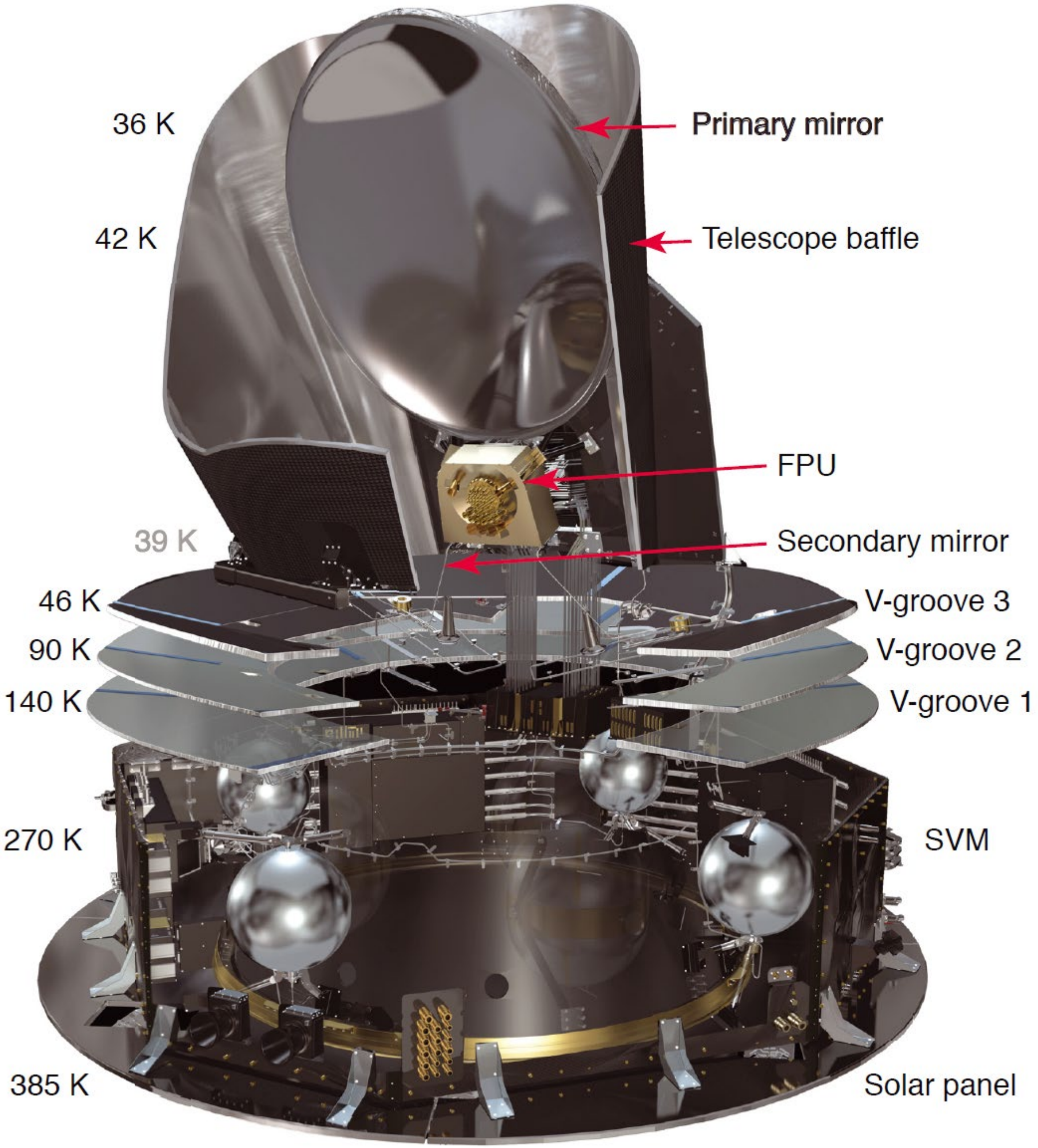


Planck 4K JT-Cooler

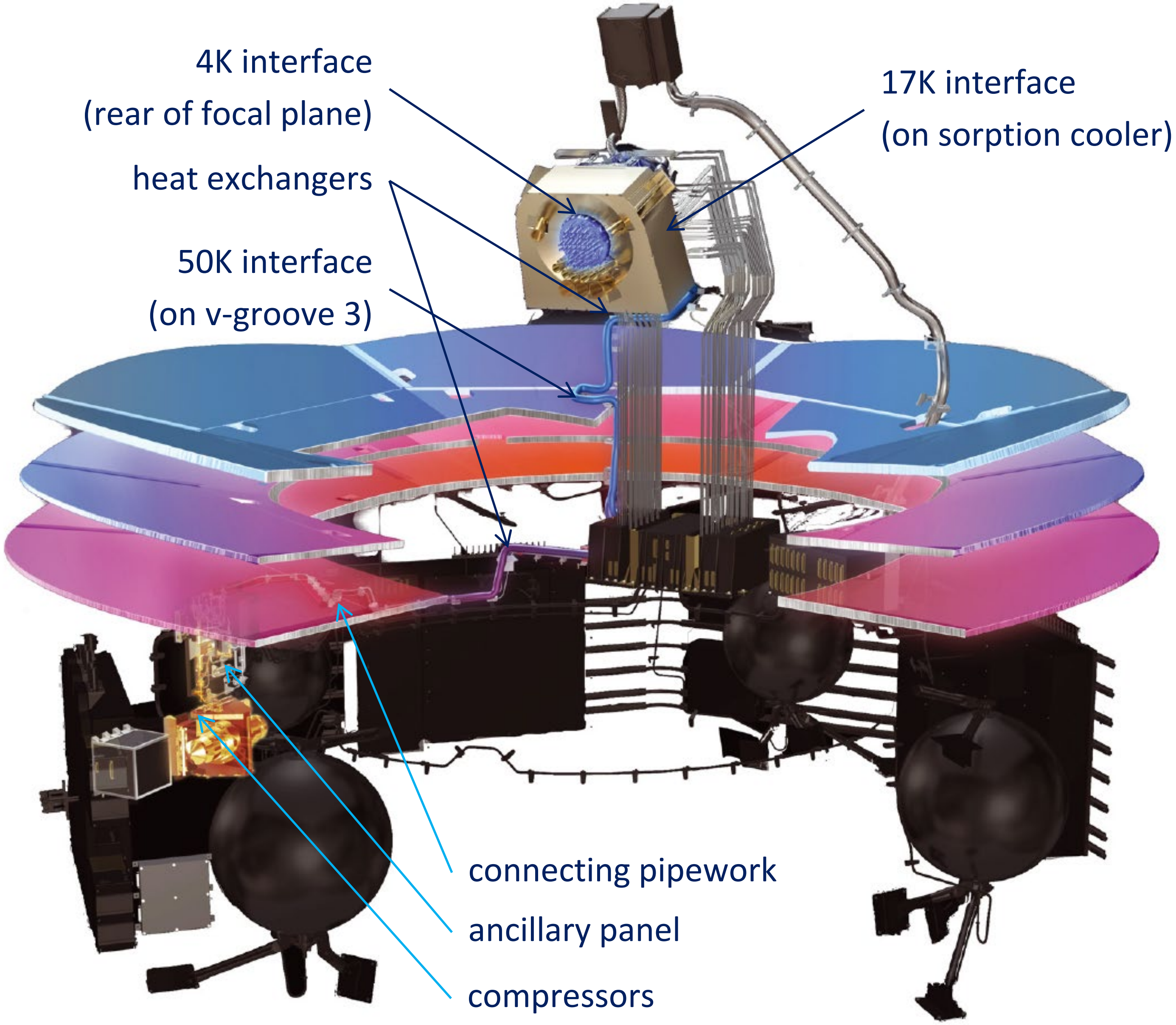
- ^4He working fluid
- High pressure = 10 bar
- Low pressure = 1.3 bar ≡ 4.5 K
- Cooling power 20 mW with 17 K pre-cooler

- 1st stage pre-cooling from v-groove 3 at 50 K
- 2nd stage pre-cooling from sorption cooler at 17.5 K

- Heat exchanger pre-formed and installed in early integration stages
- V-groove 'petals' closed around pipework

- Warm units delivered separately, installed on hinged panel
- Panel closed and connecting pipework mated warm and cold units
- Final fill of ^4He on spacecraft with specialised rig

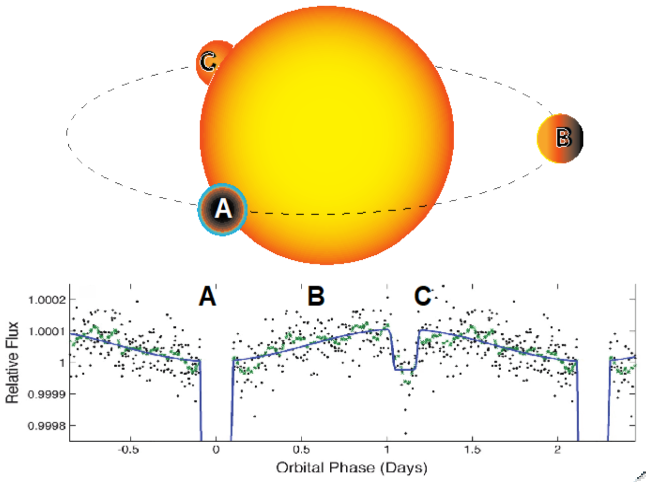
- Planck 4K cooler is still the only closed cycle JT-Cooler to have demonstrated long term operation in orbit

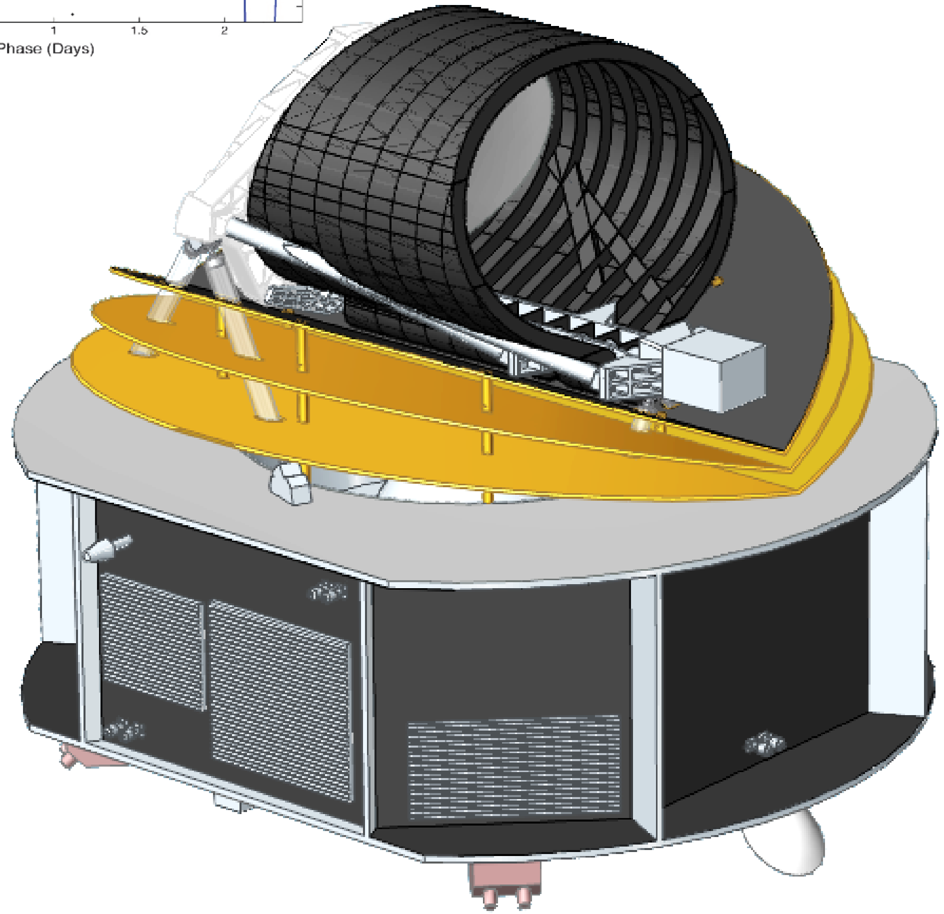


30K JT-Cooler for Ariel

Ariel mission will observe transiting exoplanets in Visible and IR (2029-2033) (+2yrs)

- AIRS instrument MCT detectors need to be cooled to <42 K
- Very similar architecture to Planck
- Passive cooling chain from 300 K to 55 K
  - L2 orbit location
  - Series of three v-groove radiators
- Very much simpler active cooling chain
  - Temperature requirement leads to selection of Ne as the working fluid
  - Closed cycle Ne JT-cooler to 32 K
- Cooler accommodation and integration will be very similar to Planck





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Ariel 30K JT-Cooler – Design Considerations and Trade-offs

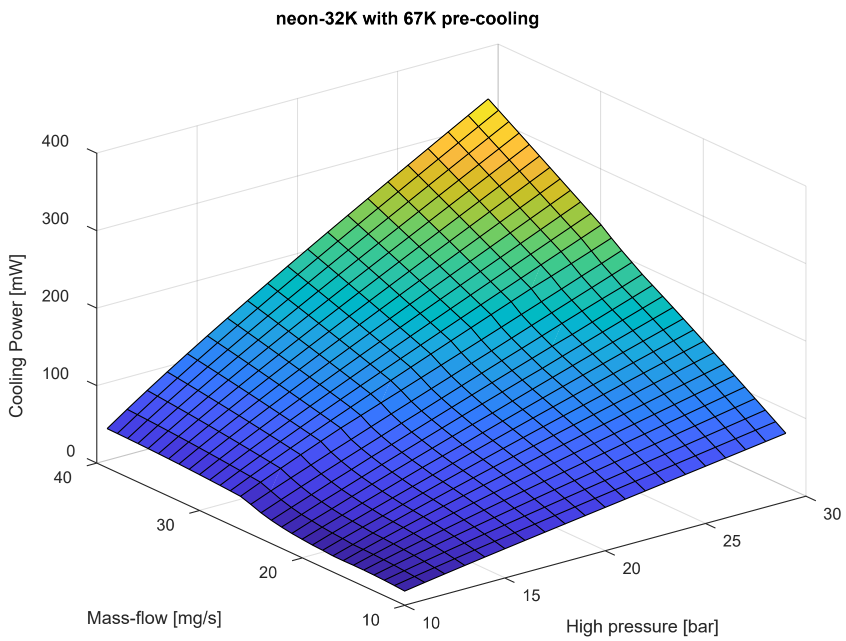
Working fluid considerations

- Ne has high critical temp and pressure compared to ^{4}He
- Return line pressure determines temperature 3.5 bar ≡ 32 K
- Flow line pressure and mass-flow determine cooling power

Wider system considerations

- Cooling power sharply increases with mass-flow and high pressure
- …BUT…
- Increasing mass-flow increases heat rejected to v-grooves impacting the passive cooling performance
- Increasing high pressure rapidly increases compressor input power and the number of compression stages required

- Cooling power requirement – 88 mW at 32 K
  - Many possible solutions - trade-off has selected operation at 20 bar high pressure and 20 mg/s mass-flow
  - two stages of compression
  - Three stages of pre-cooling (all three v-grooves)
- Compressor and heat exchangers optimised for these conditions



High pressure [bar]	Low pressure [bar]	Mass flow [mg/s]
15	3.5	29.0
20	3.5	19.8
25	3.5	14.3

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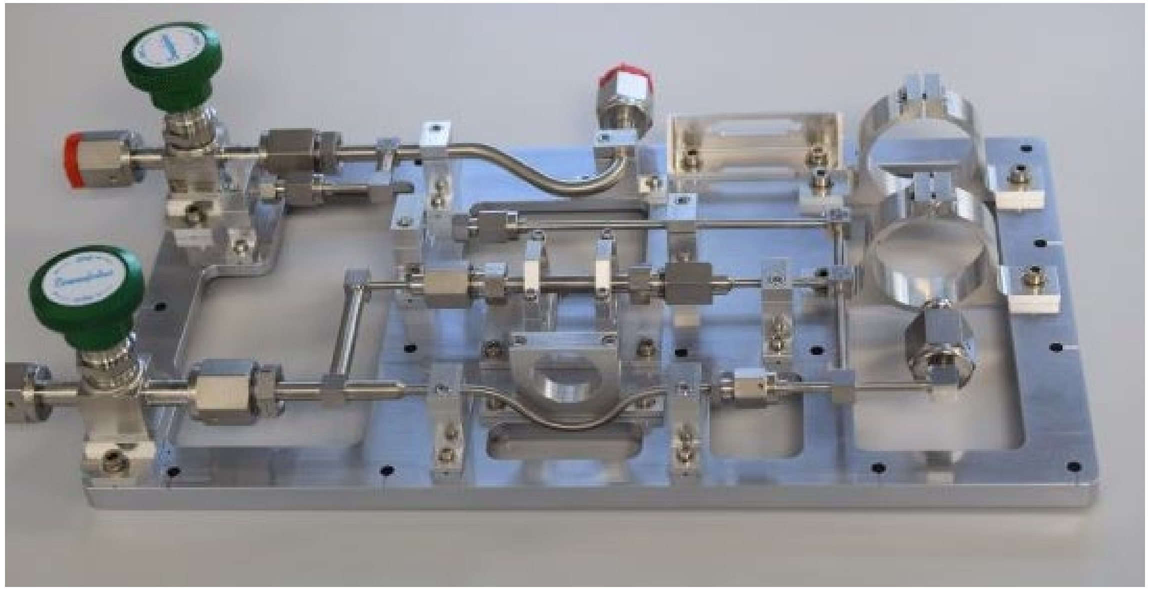
Ariel 30K JT-Cooler – Current Status

Compressors

- Design optimisation completed
  - Resonant operation for maximum efficiency
- Identical mechanisms for each compression stage
  - Minimum exported vibrations
- Demonstration model currently in manufacture
  - Linear motor mechanism shown



Ancillary Panel

- Demonstration model has been manufactured and sensors are being installed

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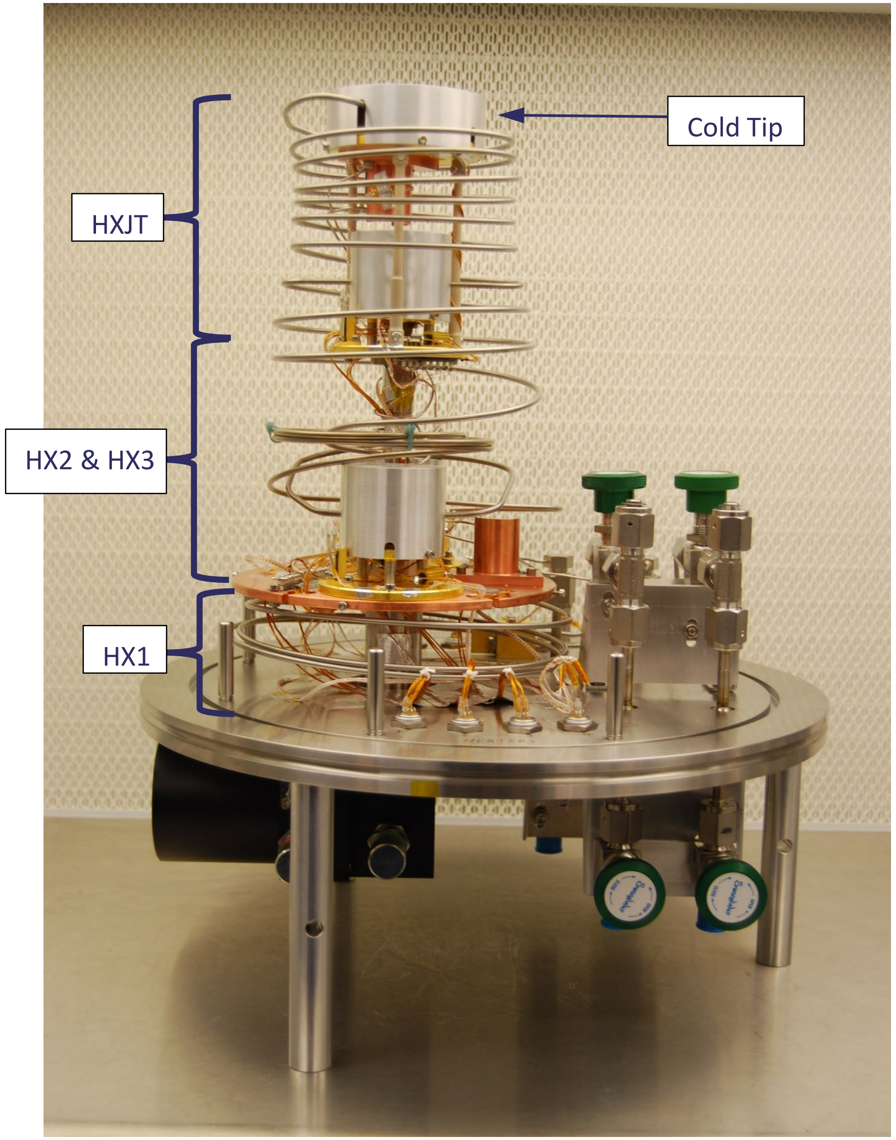
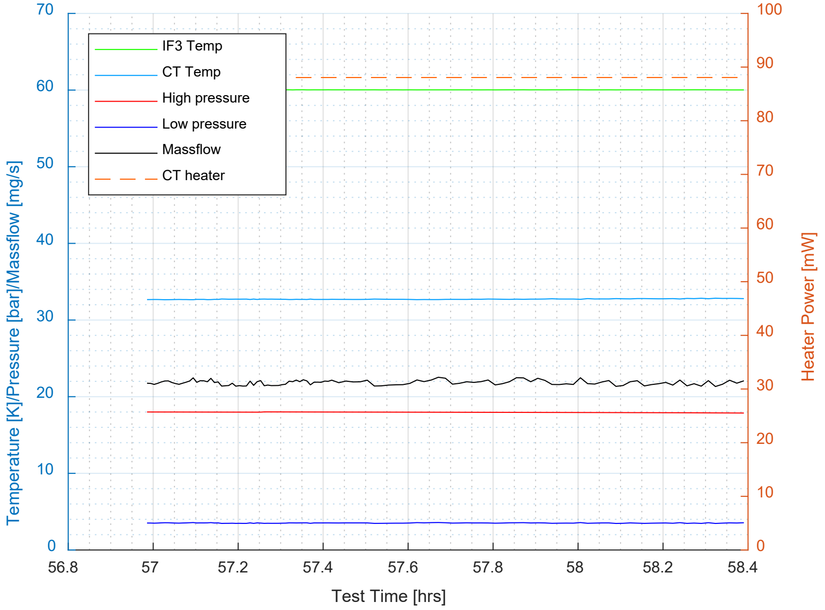
Ariel 30K JT-Cooler – Current Status

Heat Exchangers

- Manufacture and test of DM completed
  - Open loop botte test
  - Pre-cooling using commercial cryo-cooler
- First time demonstration of CHX with Ne as working fluid
- Cooling power requirement met at the compressor design point





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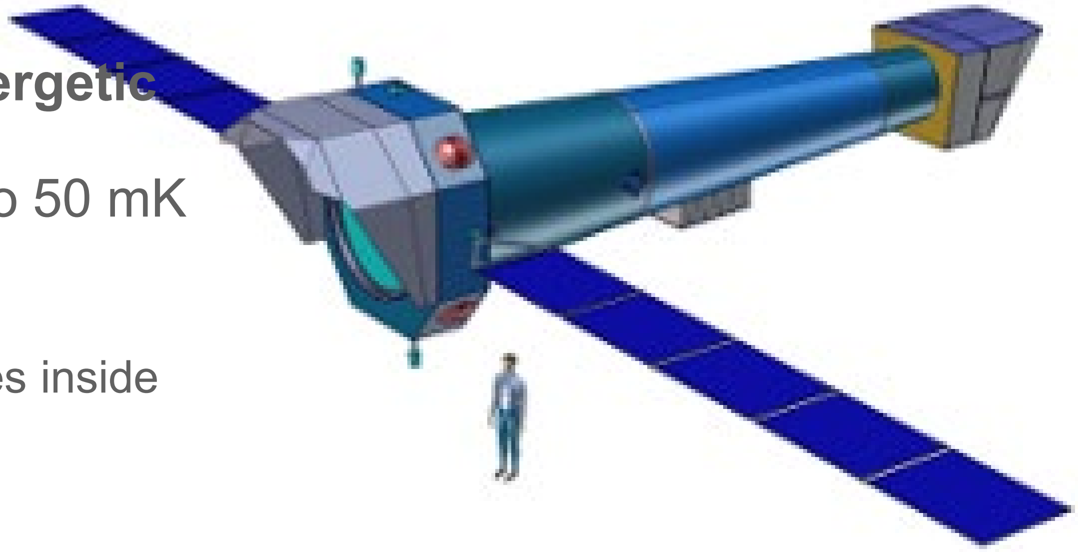
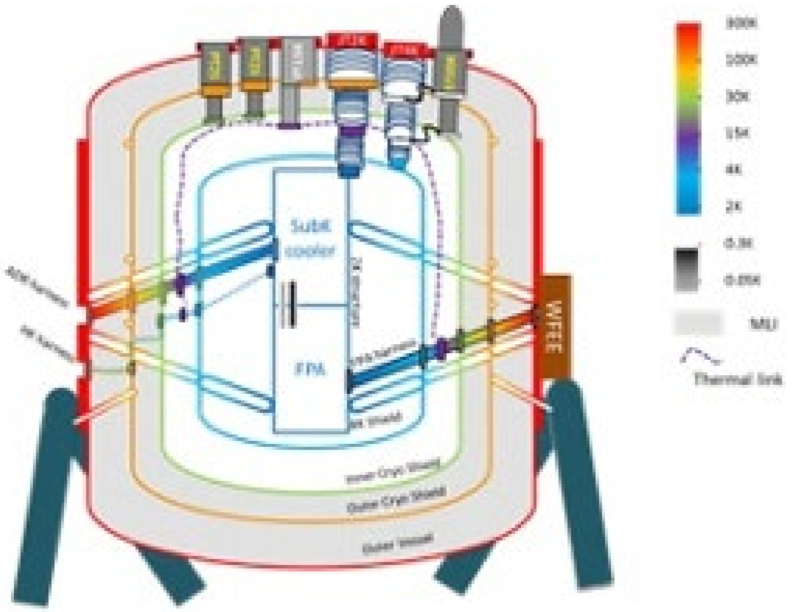
2K JT-Cooler in support of Athena



Athena mission - X-ray observatory for the hot and energetic Universe

- X-IFU instrument TES micro-calorimeter needs cooling to 50 mK
- Different architecture to Planck and Ariel
  - no passive cooling, cryo-chain housed inside a Dewar
  - Traditional Russian doll architecture - decreasing temperatures inside each ‘doll’ (radiation shields)
- Very complex cryo-chain
  - Two stage Stirling coolers precooling 4K JT-Coolers
  - Two stage pulse tube coolers precooling 2K JT-Coolers
  - 2K and 4K JT-Coolers act as pre-coolers and allow re-cycling of a hybrid sub-Kelvin cooler
  - Hybrid ^3He sorption cooler providing 300 mK coupled to an Adiabatic Demagnetisation Refrigerator providing 50 mK
- JAXA providing JT-Coolers - RAL 2K JT-cooler being developed as back-up solution



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2K JT-Cooler – Design Considerations and Trade-offs

Working fluid considerations

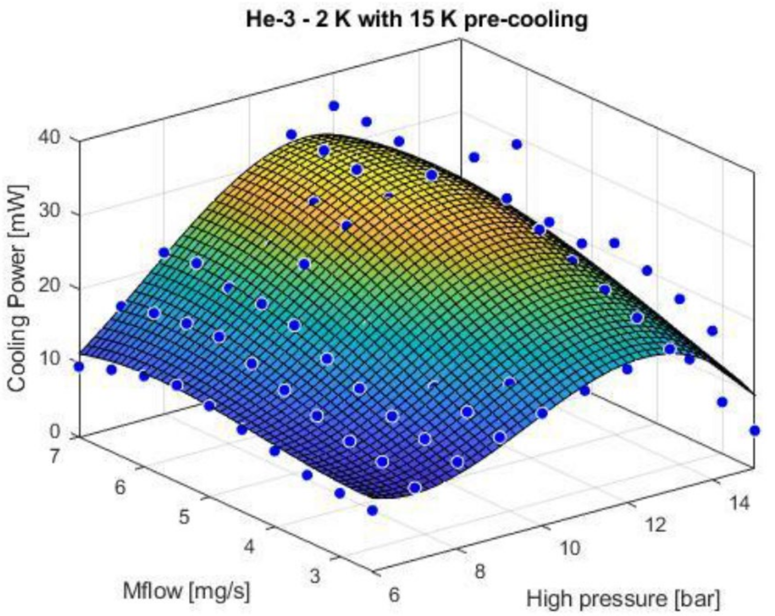
- ^{4}He unsuitable - very low vapour pressure and transition to superfluid 48 mbar ≡ 2.17 K
- ^{3}He saturation curve 200 mbar ≡ 2 K, 110 mbar ≡ 1.7 K
- Pre-cooling is needed at <15 K and at ~100 K for reasonable performance

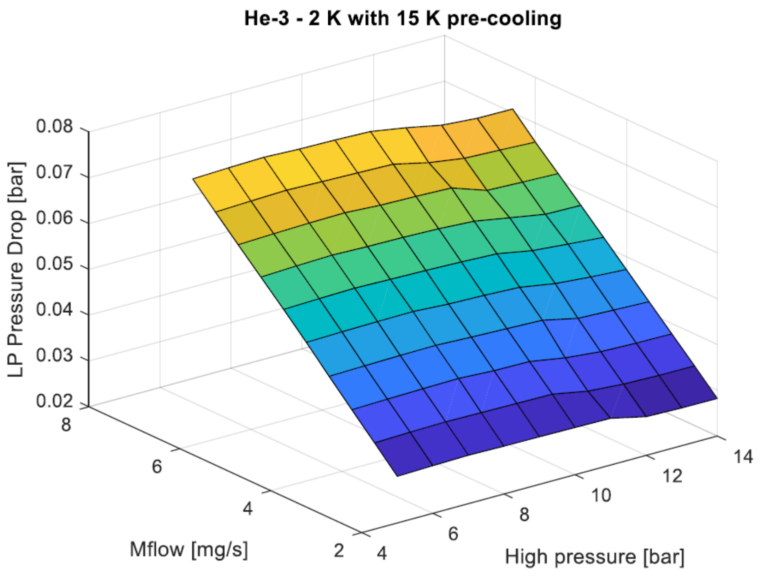
System considerations

- Cooling power increases rapidly with lower pre-cooling and increasing mass-flow and high pressure
- …BUT…
- Diminishing returns with for a given CHX configuration
- Increased heat rejection with increased mass-flow overwhelms capacity of low temperature pre-coolers
- Increased mass-flow rapidly increases compressor capacity to maintain pressure differential
- Increased pressure drop with mass-flow in return line increases cold tip temperature
- Increased heat exchanger efficiency (length) increases pressure drop

Operating Conditions

- High pressure 10 bar, low pressure 0.1 bar, mass-flow 4.4 mg/s (four compression stages needed)





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2K JT-Cooler – Current Status

Demonstration Model manufactured and tested

- 20 mW at 2 K with 12 K pre-cooler
- 14 mW at 2 K with 15 K pre-cooler
- Environmental test campaign successful
  - Thermal cycling
  - Mechanical environment (launch)

Engineering Model currently in manufacture

- Increased compressor capacity
  - utilising same linear motor mechanism as Ariel compressors for all four stages
- Increased heat exchanger capacity
  - 20 mW at 2 K with 15 K pre-cooler
- Improvements to cold tip thermal performance
- Improvements to heat exchanger manufacturing processes

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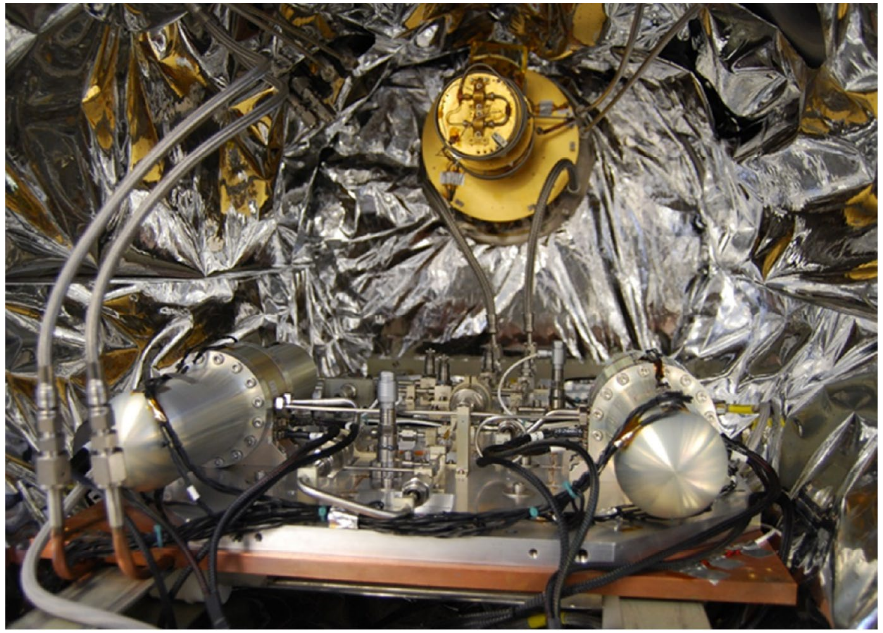

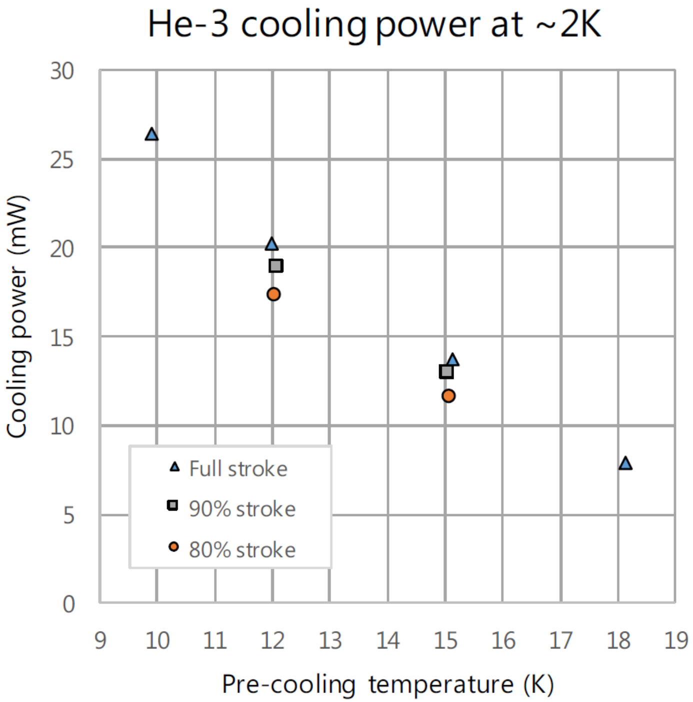

JT-Coolers at RAL – Next Steps and Future Work

Ariel 30K JT-Cooler

- System tests of heat exchanger with compressors Q1/Q2 2021
  - Cryogenic performance
  - Mechanical environment
  - Thermal vacuum, including thermal cycling
- Build of Qualification Model system to start in 2022
  - Will be tested with Payload Engineering Model
- Demonstration model upgraded to life-test model 2023 until launch and beyond

2K JT-Cooler

- Ariel cooler has priority
- System tests of heat exchanger with compressors Q3/Q4 2021
  - Cryogenic performance
  - Mechanical environment
  - Thermal vacuum, including thermal cycling
  - Life-test

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