Cryogenic Space Applications

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Néel Institute

Cryocourse 2011-09-23

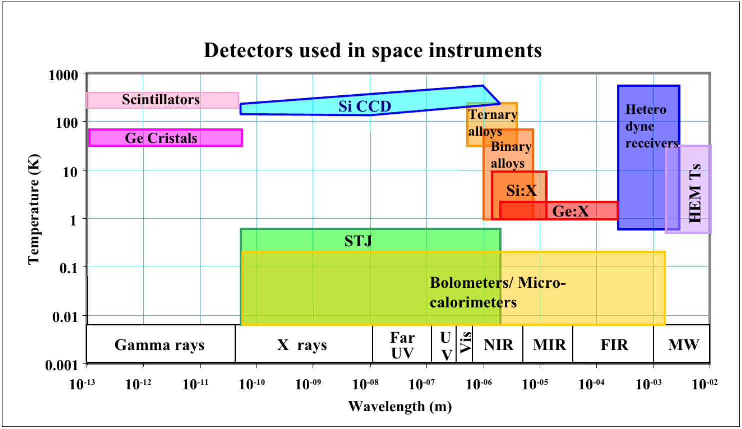
Outline

Applications

Cryogenics is used for:

- propulsion: liquid H_2 and O_2
- biology: cryogenics for ISS and space shuttle
- cooling electronics, superconducting devices, superconducting detectors
  - telecom
  - military
  - science
    - earth
    - metereology
    - astrophysics
- focus on applications below 1 K

Operating Temperatures of Detectors



From B.Collaudin, Estec

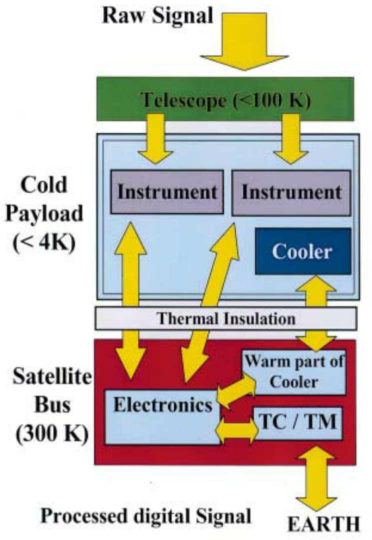
- cryogenics is a technological risk
- need for cryogenics is driven by detectors
- MKID detectors are missing

Specifity of Space Cryogenics

- launch vibrations impose mechanical constraints conflicting with minimization of thermal conductance
  - $a = 20\,\mathrm{m\,s^{-2}}$ to $30\,\mathrm{m\,s^{-2}}$
  - $f = 100\,\mathrm{Hz}$ to $200\,\mathrm{Hz}$
- liquid-gas interface cannot be localized by gravity
- life time of 2 to 10 years is required
- budget:

mission	year	power W	weight kg	cost M€
Herschel	2009	1500	3300	1100
Planck	2009	1600	1950	700
Athena	2020	6000	6000	850

Satellite Architecture



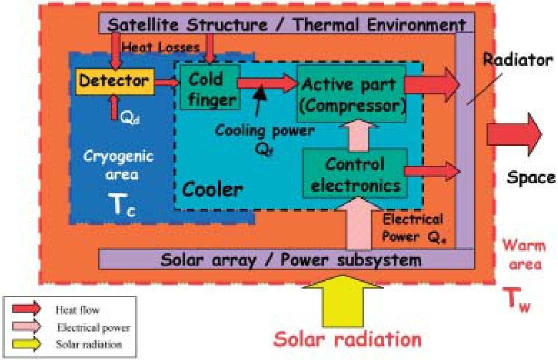
Main parts

1. telescope at $T < 300\,\mathrm{K}$
2. payload with cold focal plane detectors
3. service module at $T = 300\,\mathrm{K}$

Optimization

- power
- weight
- mechanical noise
- electro-magnetical noise
- cost

Cooling Chain Architecture

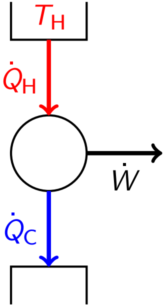


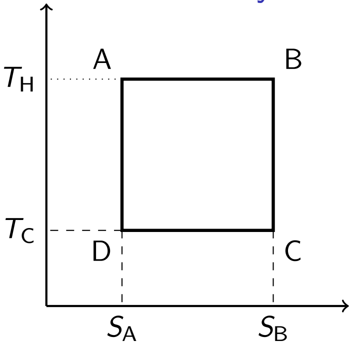
- cold finger interface to focal plane detectors
- active part and control unit linked to radiator
- heat load is minimized

Cooling Methods

- $T > 1\,\mathrm{K}$
  - radiators
  - evaporation and sublimation
  - mechanical coolers
- $T < 1\,\mathrm{K}$
  - ^{3}He sorption coolers
  - open and closed cycle ^{3}He-^{4}He dilution refrigerators
  - adiabatic demagnetization refrigerators

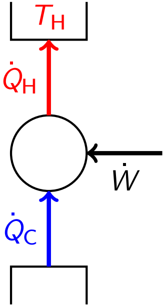
Performance of Engines and Carnot Cycle

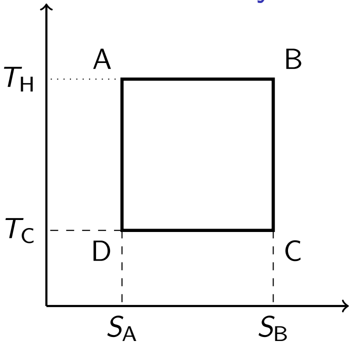




heat engine cycle ABCD: $\dot{W}/\dot{Q}_H = (T_H - T_C)/T_H < 1$

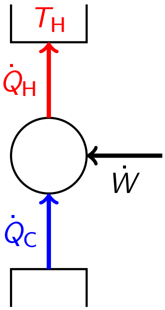
Performance of Engines and Carnot Cycle

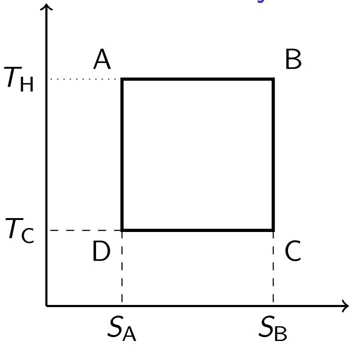




heat pump cycle DCBA: $\dot{Q}_H/\dot{W} = T_H/(T_H - T_C) > 1$
refrigerator cycle DCBA: $\dot{Q}_C/\dot{W} = T_C/(T_H - T_C)$

Performance of Engines and Carnot Cycle





heat pump cycle DCBA: $\dot{Q}_H/\dot{W} = T_H/(T_H - T_C) > 1$

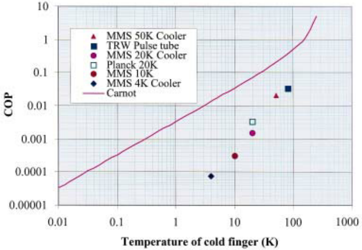
refrigerator cycle DCBA: $\dot{Q}_C/\dot{W} = T_C/(T_H - T_C)$

- Carnot engines are optimum:

$$\frac{\dot{Q}_H}{T_H} = \frac{\dot{Q}_C}{T_H}$$

Coefficient Of Performance (COP)

Carnot = maximum possible COP

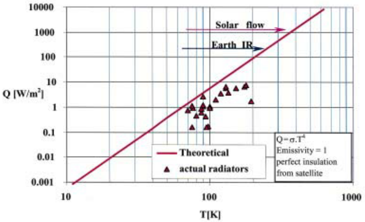


COP for mechanical coolers

- mass is 100 kg to 150 kg
- power is 50 W to 200 W
- minimize vibrations
- cooling power ≈ 1 mW at 4 K for 100 W of input power

Radiators – effect of orbit

$$\dot{Q}_{\text{black-body}} = A\sigma\epsilon(T_H^4 - T_C^4)$$



Close to Earth:

Sun $1.4\,\text{kW/m}^2$

Earth $0.3\,\text{kW/m}^2$

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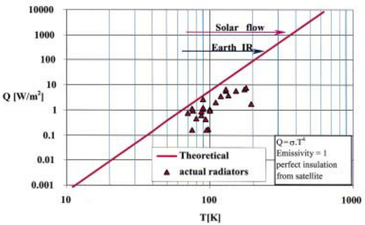

Close to Earth:

Sun $1.4\,\text{kW/m}^2$

Earth $0.3\,\text{kW/m}^2$

LEO 160 km to 2000 km

- 100 K
- International Space Station
- Earth and Sun observation satellites

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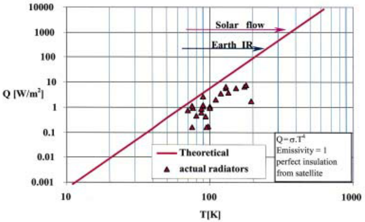

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GEO 36 000 km

- 75 K to 90 K
- communication satellites

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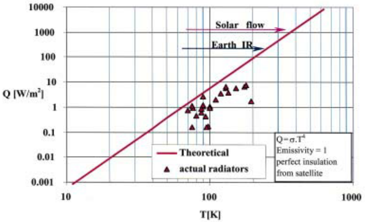

Close to Earth:

Sun 1.4 kW/m^2

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LEO 160 km to 2000 km

- 100 K
- International Space Station
- Earth and Sun observation satellites

GEO 36 000 km

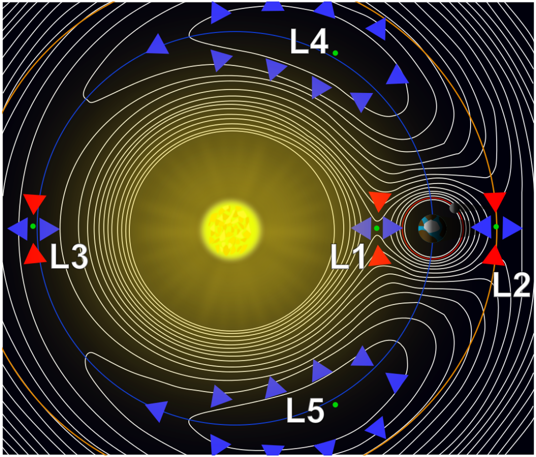
- 75 K to 90 K
- communication satellites

L2 1 500 000 km

- 30 K to 60 K
- science missions

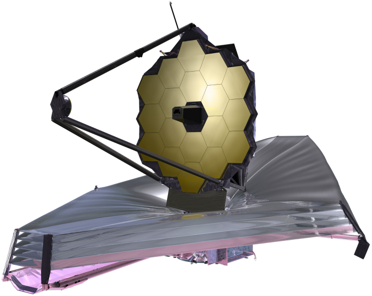
What is L2?

One of the 5 Lagrangian points where the gravitational pull of two big masses equals the centripetal force for a much smaller mass.



V-Groove Radiators Emit to 3 K

James Web Space Telescope

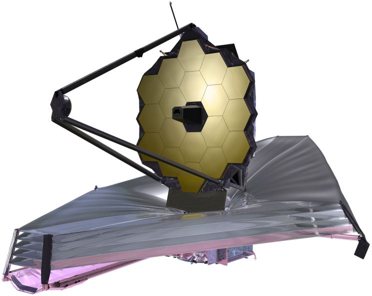


8700 M$

- The diameter of the mirror is 7 m
- The radiators cool the telescope to < 40 K

V-Groove Radiators Emit to 3 K

James Web Space Telescope



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The good and the bad:

- reliability

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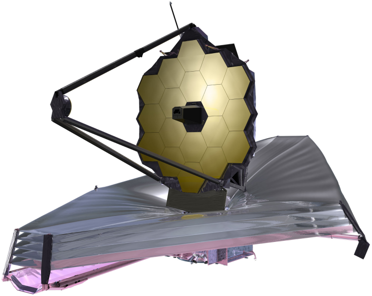

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The good and the bad:

- reliability
- no input power

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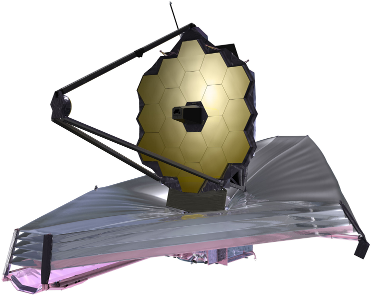

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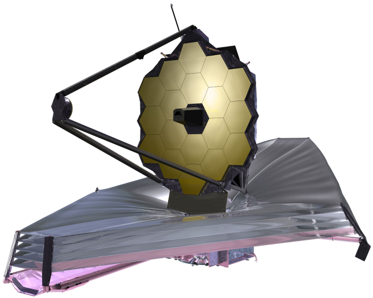

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The good and the bad:

- reliability
- no input power
- limited cooling power
- satellite architecture constraint

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V-Groove Radiators Emit to 3 K

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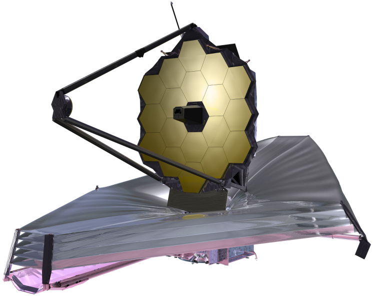

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The good and the bad:

- reliability
- no input power
- limited cooling power
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- orbit and orientation constraints

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V-Groove Radiators Emit to 3 K

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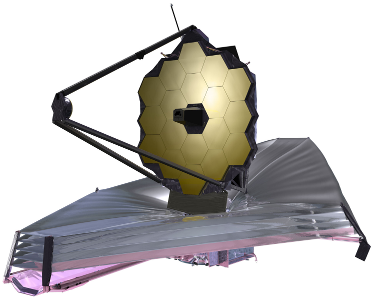

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The good and the bad:

- reliability
- no input power
- limited cooling power
- satellite architecture constraint
- orbit and orientation constraints
- complex ground test

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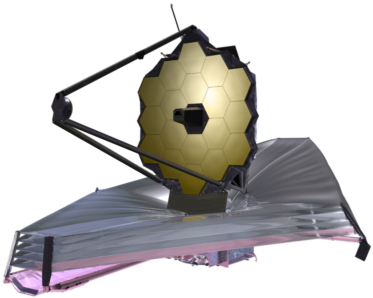


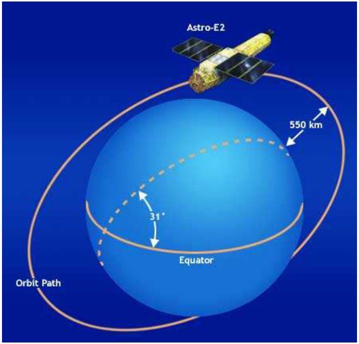
8700 M$

The good and the bad:

- reliability
- no input power
- limited cooling power
- satellite architecture constraint
- orbit and orientation constraints
- complex ground test
- may have to be unfolded after launch

- The diameter of the mirror is 7 m
- The radiators cool the telescope to < 40 K

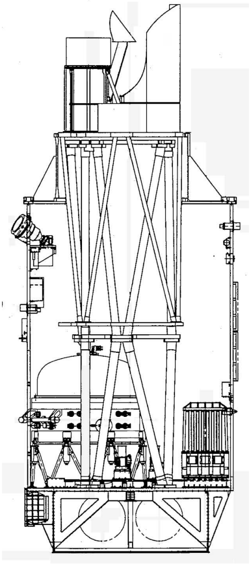
Suzaku – 2 to 3 year lifetime mission

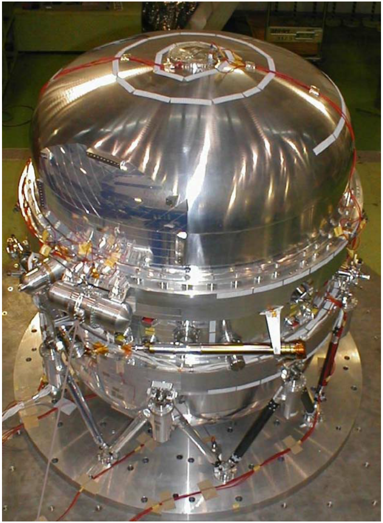


XRS instrument

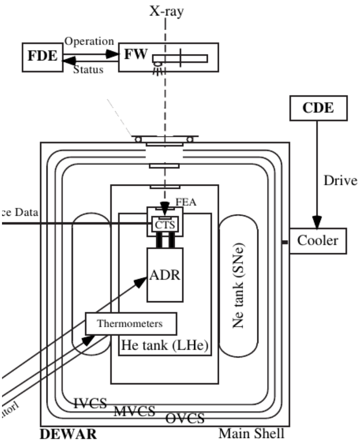
- 32 µcalorimeters with 6 eV resolution from 0.2 keV to 10 keV at 60 mK
- single stage ADR
- 34 L superfluid He dewar
- 120 L solid Ne dewar
- single stage Stirling cooler
- radiator to 230 K

Suzaku – size imposes cryogenic constraints



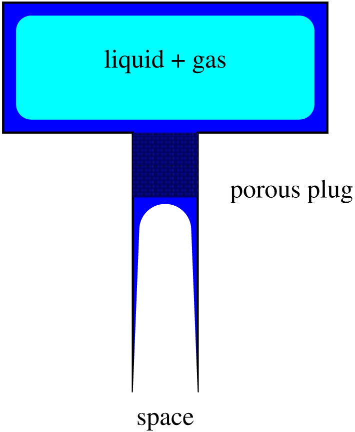


Suzaku – cooling chain



- 2 to 3 year lifetime
- main shell cooled by radiation to 230 K
- OVCS cooled to 100 K with a Stirling cooler
- 120 L Ne dewar
- 34 L He dewar
- $\dot{Q}_{\text{He}} < 1\,\text{mW}$
  - phase separator
  - load $\dot{Q}_{\text{ADR}} < 300\,\mu\text{W}$
- ADR

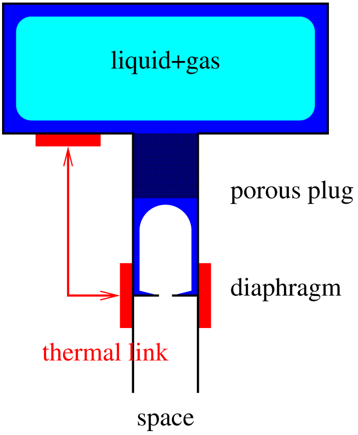
Suzaku – phase separator – 1



How does it work?

- due to capillarity, liquid
  - wets the wall
  - fills the porous plug
- fountain effect
  - ΔT across the plug forces liquid into the cryostat
- reduce heat due to film far from cryostat

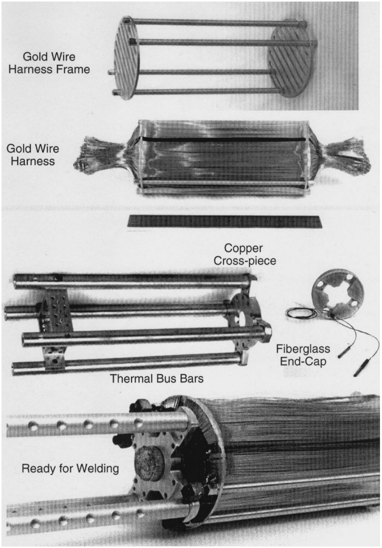
Suzaku – phase separator – 2



Suzaku progress

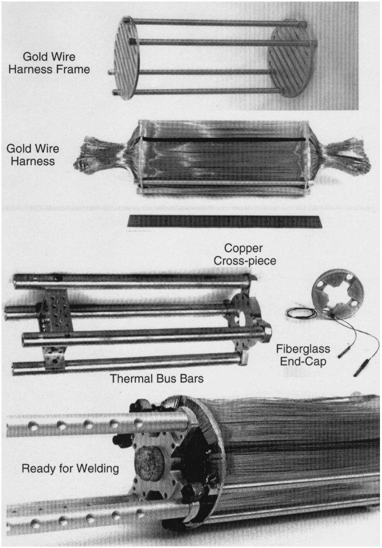
- diaphragm reduces film flow
- cryostat is also cooled by evaporation of the film because of the thermal link
- heat leak of 1 mW instead of 100 mW

Suzaku – ADR



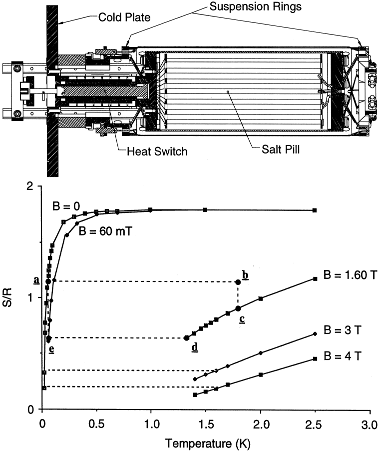
- problems: salt pill
  - ferric ammonium sulfate
  - oxidizes easily
  - corrodes copper

Suzaku – ADR



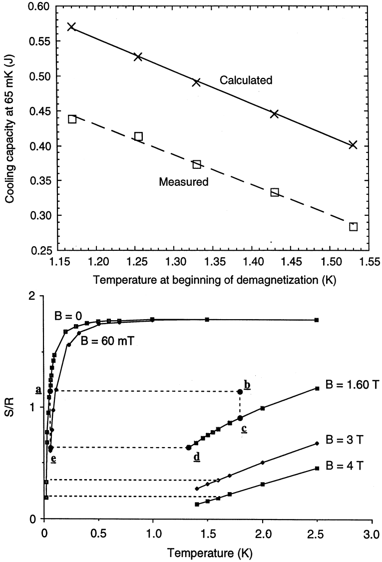
- problems: salt pill
  - ferric ammonium sulfate
  - oxidizes easily
  - corrodes copper
- solution:
  - salt pill has to be sealed
  - $T > 300\,\mathrm{K}$ forbidden
  - gold thermal bus

Suzaku – ADR



- thermal contraction to fix the ADR in the magnet for (cold) launch
- good thermal contact in the stage: 75 % efficiency
- magnet current releases heat to helium
- 2 parallel active gas heat switches with zeolite increase reliability
- $\dot{Q}_{\mathrm{ADR}} = 5\,\mu\mathrm{W}$ at 60 mK for 24 h

Suzaku – ADR efficiency



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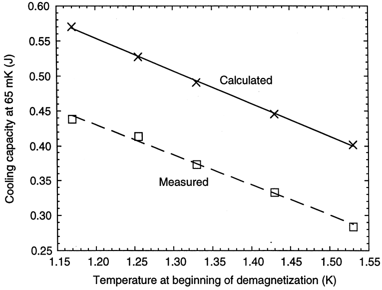
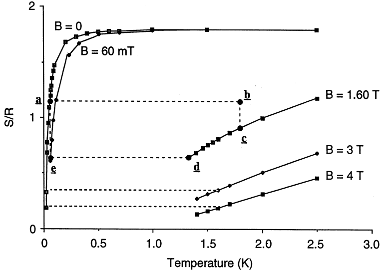
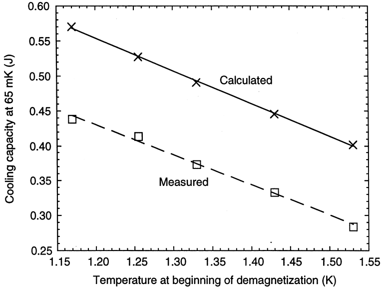
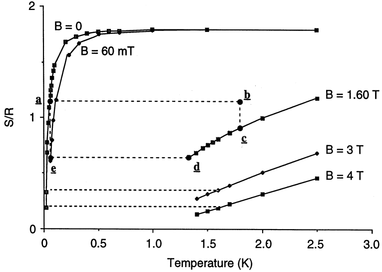




- good thermal contact in the stage: 75 % efficiency
- how does this compare to Carnot?

Suzaku – ADR efficiency





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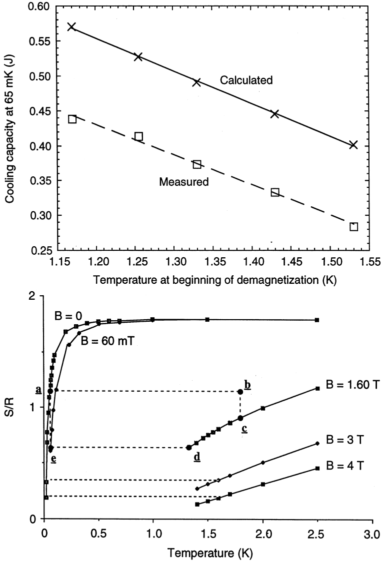
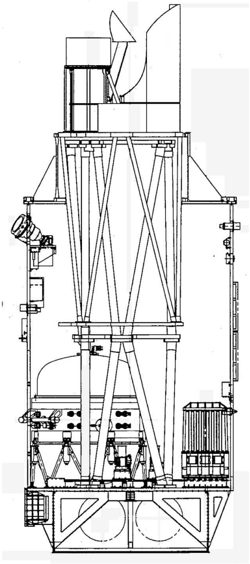
- how does this compare to Carnot?
- ADR can be operated in Carnot cycle and is almost optimally efficient

Suzaku – ADR efficiency



- good thermal contact in the stage: 75 % efficiency
- how does this compare to Carnot?
- ADR can be operated in Carnot cycle and is almost optimally efficient
- helium bath evaporated within 2 weeks due to a bad vacuum

Suzaku – end



- helium bath evaporated within 2 weeks due to a bad vacuum
- opening the vacuum valve of the He bath to improve the thermal isolation caused evaporated helium to leak through it

Herschel – science

Objectives

- galaxy formation and evolution in early Universe
- creation of stars and their interaction with interstellar medium
- molecular chemistry of early Universe

Instruments: 55 µm to 672 µm

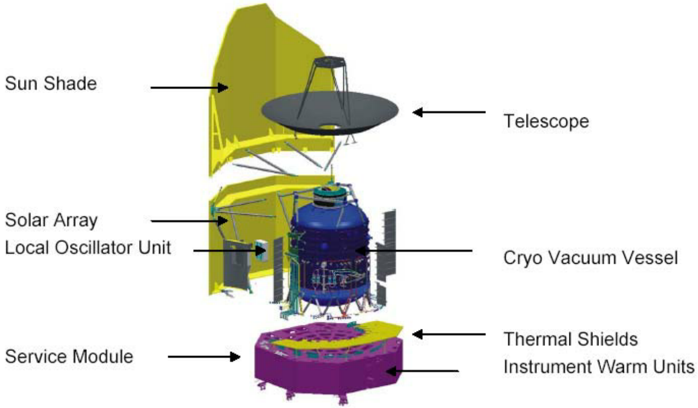
HIFI ?

PACS $T < 300\,\mathrm{mK}$

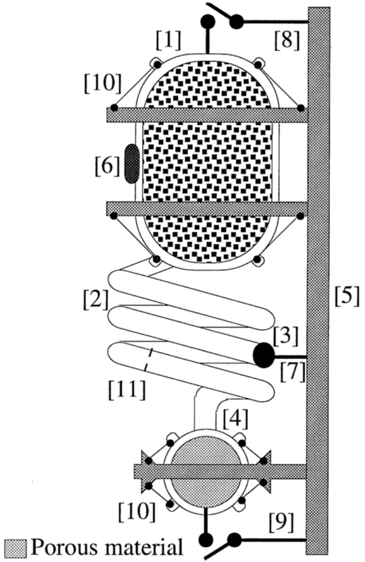
SPIRE $T < 300\,\mathrm{mK}$

$\Rightarrow$ ^{3}He sorption cooler

Herschel – cryogenic chain



Herschel – ^{3}He Sorption Coolers – 1



1. sorption pump
2. pump tube
3. condenser
4. evaporator
5. cold stage
6. heater
7. thermal link
8. heat switch
9. support structure
10. heat switch
11. diaphragm (^{4}He only)

Herschel – ^{3}He Sorption Coolers – 2

- Precooling temperature
  ^{3}He 3 K
  ^{4}He 5 K
- Low thermodynamic efficiency.

Herschel

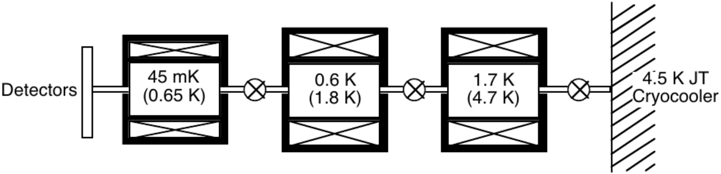
- 46 h hold time with 96 % duty cycle
- $\dot{Q}_C = 8\,\mu W$ at $T_C = 274\,mK$
- $\dot{Q}_H = 2.4\,mW$ at $T_H = 1.8\,K$
- active gas gap switch

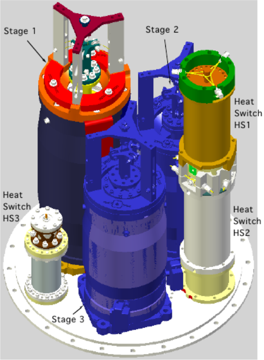
Athena – X rays to study gravitational events.

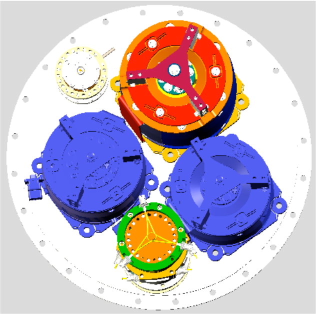
Key instrument: XMS

- microcalorimeter to detect X-rays
- 2 μK at 50 mK
- 90 % operating time

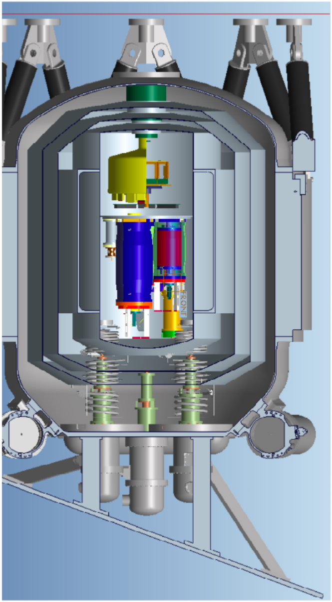
Athena – baseline: NASA ADR + JAXA cryostat



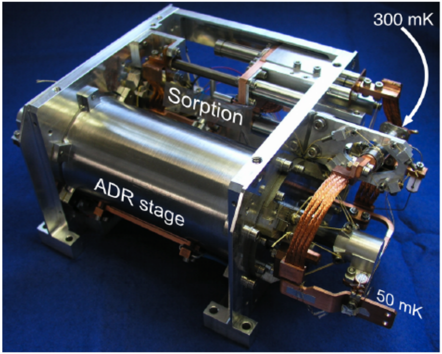


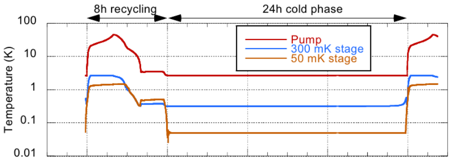


Athena – cryostat



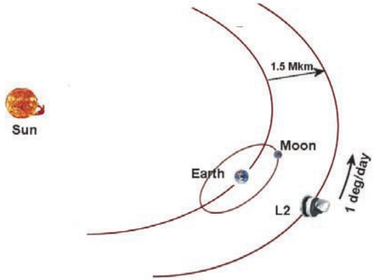
Athena – CEA alternative

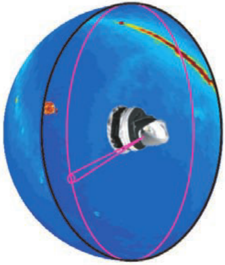




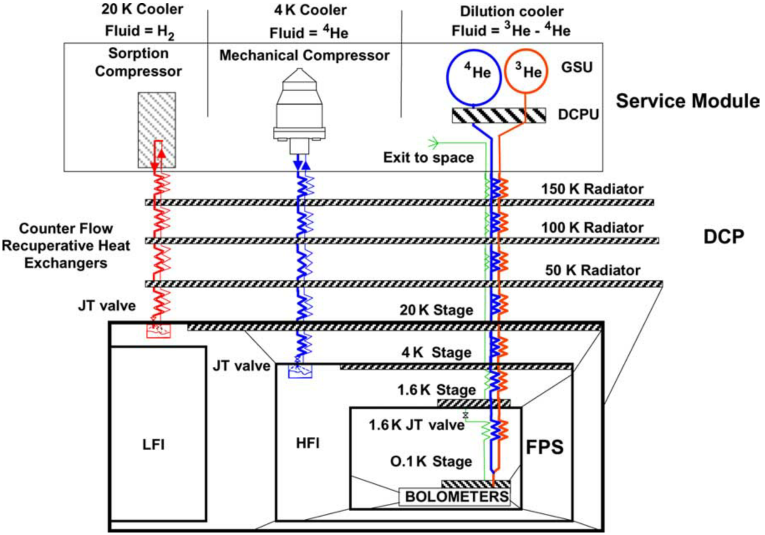
Planck – objective

Reveal the initial conditions for the evolution of the universe by mapping the Cosmic Microwave Background with a resolution of 20′ and about 1 μK from 30 GHz to 850 GHz with LFI and HFI instruments.

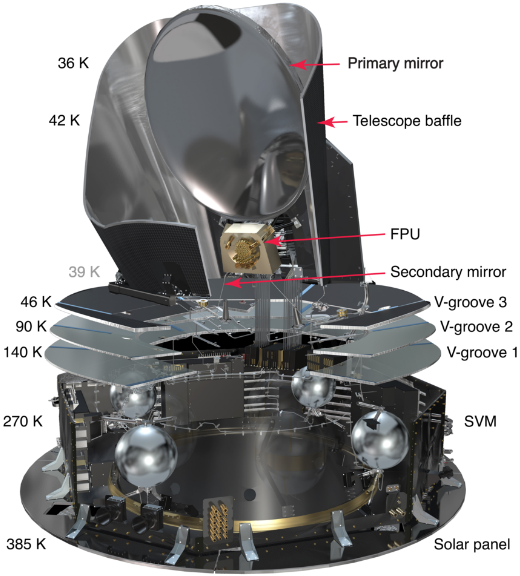




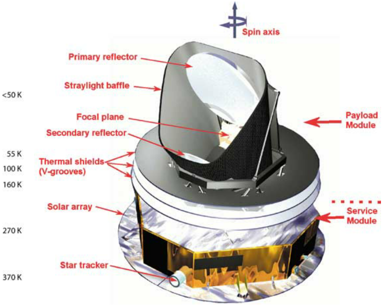
Planck – cooling chain

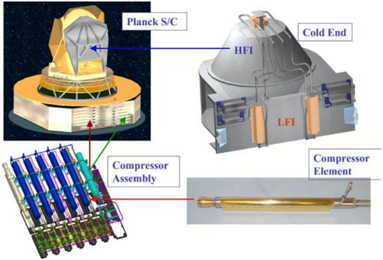


Planck – architecture

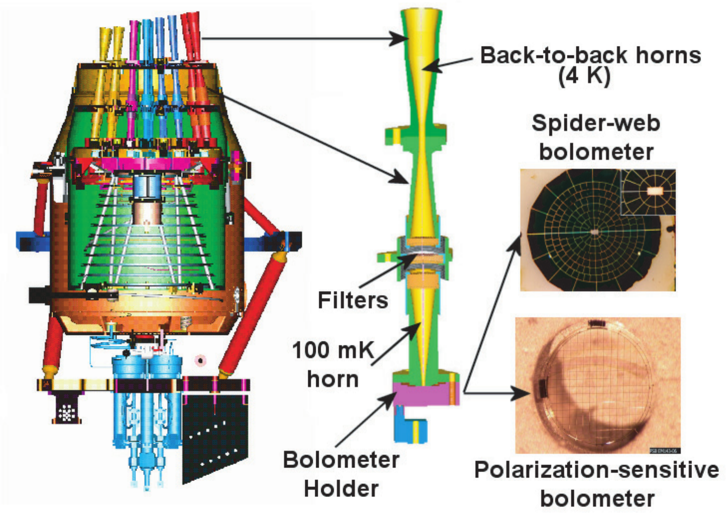


Planck – H_2 Joule-Thompson expansion cooler

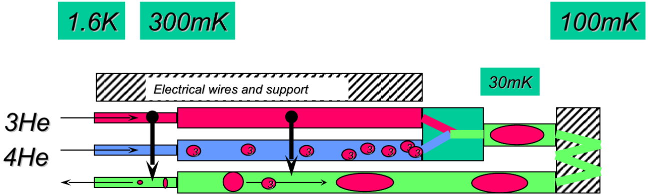




Planck – HFI instrument



Planck – open cycle dilution refrigerator



Mixture extraction

V>Vcrit>20cm/s
D = 40 µ m

Cooling power at 1.6K = 400µW

Dilution 3He -> 4He (bubble interface)

V<Vcrit
1-10 mm/s
D = 300µ m

Cold tip HX

100 nW

5 µmol/s ^{3}He
20 µmol/s ^{4}He

Thermal fluctuations (droplets) damped by a Holmium-Yttrium thermal mass

Scaling the Planck dilution refrigerator

2009: Planck (CMB)

- temperature: 100 mK
- cooling power: 200 nW
- lifetime: 2 years

2019: SPICA and/or IXO

- temperature: 50 mK
- cooling power: 1 μW
- lifetime: 5 years

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  ^{3}He 6 μmol s^{-1}
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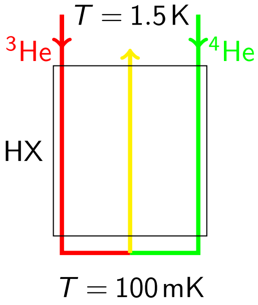
$\Rightarrow$ closed cycle is required!

Overview closed-cycle dilution refrigerator



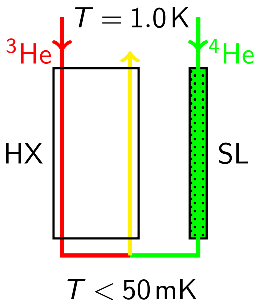
Planck: open cycle dilution refrigerator

- $\dot{n}_3 = 6\,\mu mol\,s^{-1}$
- $\dot{n}_4 = 18\,\mu mol\,s^{-1}$
- JT cooler at mixture exit
- heat load: 10 mW at 4.5 K

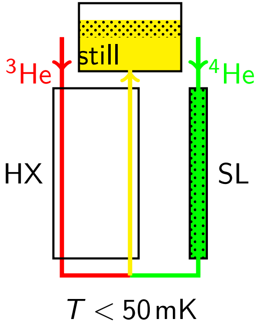
Overview closed-cycle dilution refrigerator

Heat exchanger (HX) optimization

3-tube HX $\Rightarrow$ 2-tube HX and SL in parallel



Overview closed-cycle dilution refrigerator



Heat exchanger (HX) optimization

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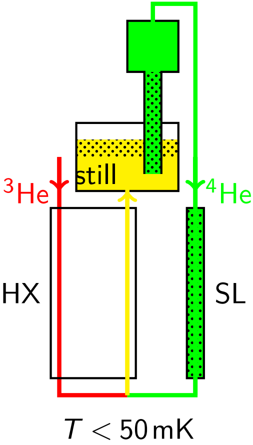
Still with vapor-liquid phase separator

not yet working

Overview closed-cycle dilution refrigerator



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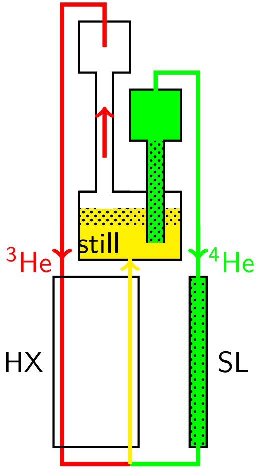
3-tube HX $\Rightarrow$ 2-tube HX and SL in parallel

^{4}He circulation: fountain pump

$\dot{n}_4 \approx 400\,\mu\mathrm{mol\,s^{-1}}$ with $\dot{Q}_{\mathrm{fp}} = 3.5\,\mathrm{mW}$ at $T = 2.1\,\mathrm{K}$

Overview closed-cycle dilution refrigerator



$T < 50\,\mathrm{mK}$

Heat exchanger (HX) optimization

3-tube HX ⇒ 2-tube HX and SL in parallel

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^{3}He circulation, pumps under development

$\dot{n}_3$ from $20\,\mu\mathrm{mol\,s^{-1}}$ to $60\,\mu\mathrm{mol\,s^{-1}}$ for p_{still} from $0.3\,\mathrm{mbar}$ to $15\,\mathrm{mbar}$

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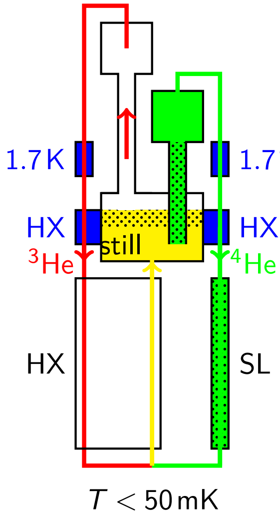

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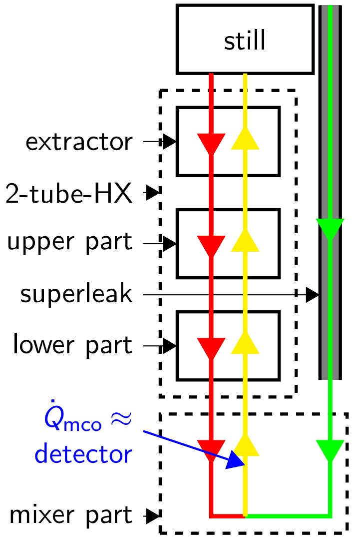
Precooling

heat load is about 5 mW at $T = 1.7\,\text{K}$

Counterflow heat exchanger and mixing chamber



Thermal model is guide

- enthalpy $\propto T^2$
- heat exchange $\propto T^4_{\text{solid}} - T^4_{\text{liquid}}$
- viscous dissipation $\propto 1/T^2$

extractor $d = 0.2\,\text{mm}, L = 1.0\,\text{m}$

upper $d = 0.4\,\text{mm}, L = 3.0\,\text{m}$

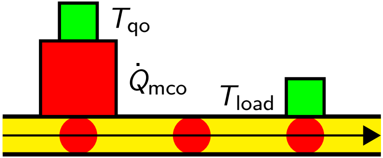
lower $d = 0.6\,\text{mm}, L = 3.0\,\text{m}$

model: $\Delta T_{mc} < 1\,\text{mK}$ for $d = 0.8\,\text{mm}$

superleak $3.0\,\text{mm} \times 2.6\,\text{mm}$ SS316L tube

mixer viscous dissipation

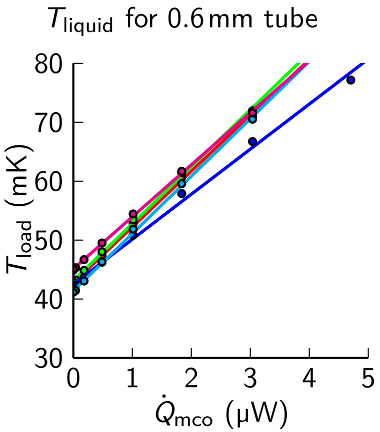
Mixer part heat lift test setup

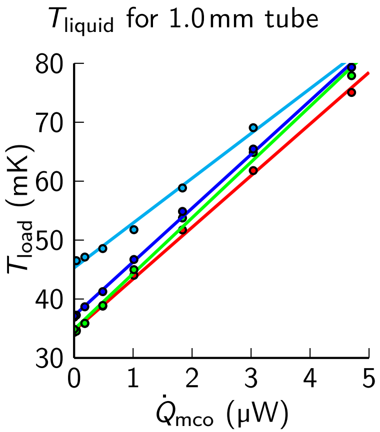


Experiment

Thermometers and heater are mounted on copper cylinders soldered to a spiral of CuNi or Ag tubing

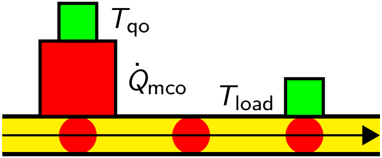
Viscous heating (tube size): 0.6 mm vs 1.0 mm





Lower temperatures with the 1.0 mm tube are due to less viscous heating. Different colors indicate different p_{still}.

Mixer part heat lift (detector) and Kapitza resistance



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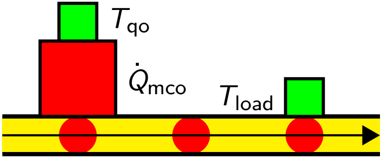

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Kapitza equation

$$\dot{Q} = \frac{A}{4\rho_{\mathrm{K}}}\left(T_{\mathrm{solid}}^4 - T_{\mathrm{liquid}}^4\right)$$

Assumptions

- Kapitza resistance is dominant
- No temperature gradients in in the copper
- Heat is transported by flow only

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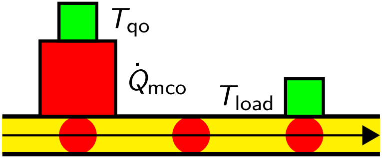

Experiment

Thermometers and heater are mounted on copper cylinders soldered to a spiral of CuNi or Ag tubing

Therefore

- $T_{qo} = T_{solid} = T_{\text{"detector"}}$
- $T_{load} = T_{liquid}$

Kapitza equation

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Assumptions

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- No temperature gradients in in the copper
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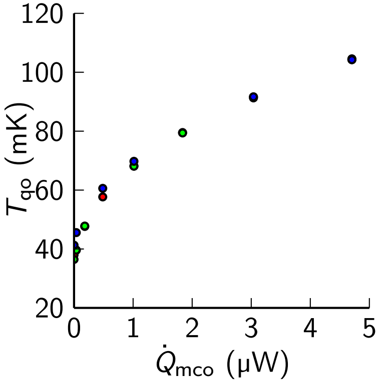
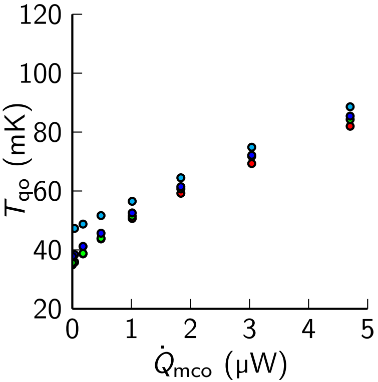
1.0 mm CuNi vs 1.0 mm Ag with 50 µg sinter

$T_{\text{"detector"}}$ for 1.0 mm CuNi



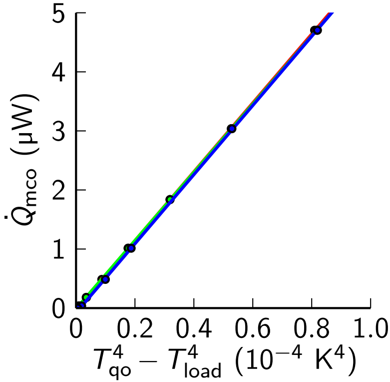
$T_{\text{"detector"}}$ for 1.0 mm Ag



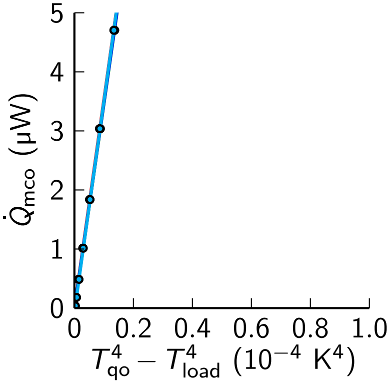
More exchange area decreases $T_{\text{"detector"}}$. For Ag tube red, green, blue, and cyan indicate $p_{\text{still}} = 0.3$, 5, 10, and 15 mbar.

1.0 mm CuNi vs 1.0 mm Ag with 50 µg sinter

Kapitza for 1.0 mm CuNi tube



Kapitza for 1.0 mm Ag tube



Development of ^{3}He circulators

JAXA — Improving the compressor for the ^{3}He compressor for the JT of SPICA

- Improving the check valves

Cooll/Twente — Sorption pump with check valves operating at 15 K

- Check valves are being developed
- Funding is being asked to build a prototype using Darwin compressor cells

CNRS/ALTAL — Holweck compressor (high-pressure stage turbo pump)

- A setup is being built to test our modelization of a commercial pump
- A pump will be built using ball bearings and a commercial motor

Conclusion: current status

- heat lift mixing chamber is 1 μW at $T_{heater} = 51.4\,mK$ and $T_{liquid} = 44.0\,mK$ $\Rightarrow$ interface with a real detector?
- ^{3}He circulator specifications: fridge works better at lower p_{still}, but 10 mbar is still OK:

p_{still} mbar	$\dot{n}_3$ $\mu mol\,s^{-1}$	$\dot{n}_4$ $\mu mol\,s^{-1}$	T_{liquid} mK	T_{heater} mK
0.3	16.7	398	44.0	51.4
5.0	18.5	349	45.0	51.7
10.0	28.8	346	46.7	52.6

- three different ^{3}He circulators are work in progress
- heat load precooler is 5 mW at 1.7 K
- the vapor-liquid phase separator in the still is work in progress