^{3}He-^{4}He Dilution Refrigeration in Space

cooling detectors to study the universe …

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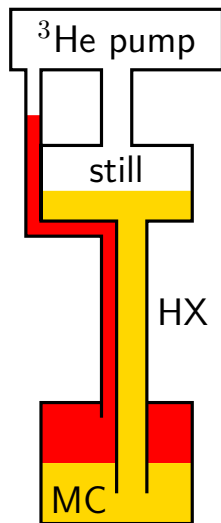
EASISCHOOL, Grenoble, 2019-10-03
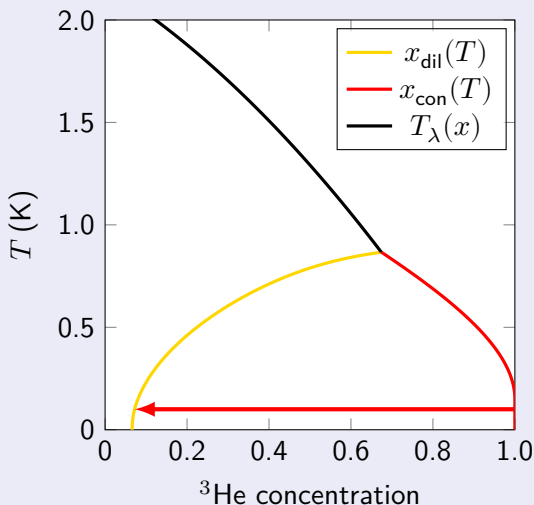
Outline

Gravity and dilution refrigeration on earth

Outline

Open cycle dilution refrigerator for space?
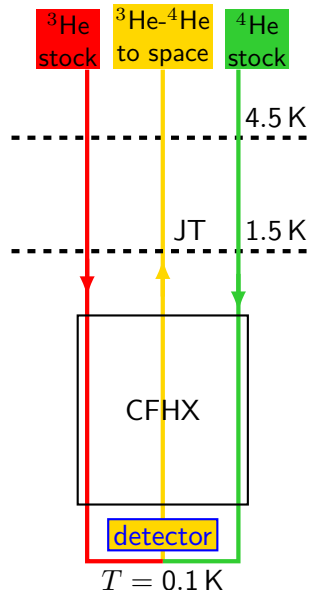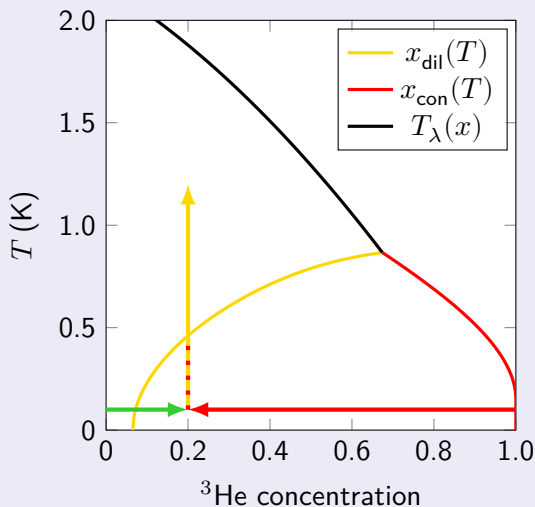
Open cycle dilution refrigerator for space?
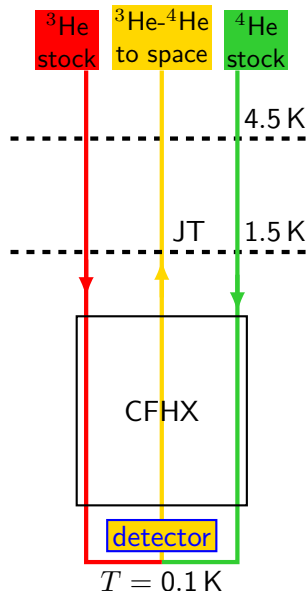
Planck's OCDR

- pre-cooler heat lift specs 10 mW @ 4.5 K
- ^{3}He and ^{4}He stocked on satellite
- space plays role of pump
- capillary forces play role of gravity
  - ingeniously simple solution to zero gravity problems in space
- intrinsic 1.5 K Joule-Thompson cooler
- 100 % duty cycle

Open cycle dilution refrigerator for space?
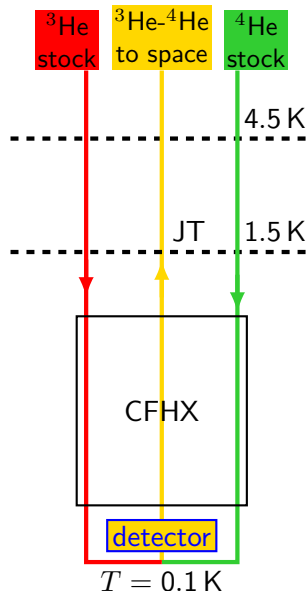
Planck's OCDR

- cooling power: $0.2\,\mu\text{W} @ 0.1\,\text{K}$
- lifetime: 2.5 years
- helium flowrates:
  ^3He $6\,\mu\text{mol}\,\text{s}^{-1}$
  ^4He $18\,\mu\text{mol}\,\text{s}^{-1}$
- high pressure storage on satellite:
  ^3He $12\,\text{m}^3$ STP or 9 M\$ now
  ^4He $36\,\text{m}^3$ STP

Open cycle dilution refrigerator for space?
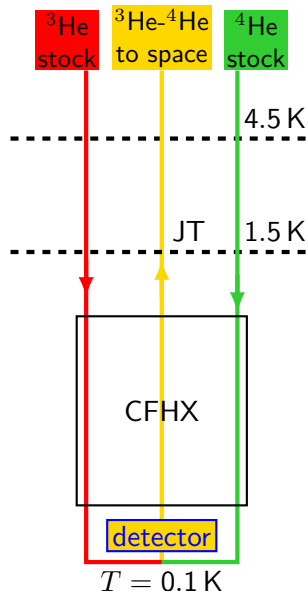
2020–2025: future missions

- cooling power: $1\,\mu W$ @ $50\,mK$
  - X-IFU: $0.8\,\mu W$ @ $50\,mK$
- lifetime: 5 years
- helium flowrates:
  ^{3}He $\,18\,\mu mol\,s^{-1}$
  ^{4}He $\,360\,\mu mol\,s^{-1}$
- high pressure storage on satellite:
  ^{3}He $\,90\,m^3$ STP or $70\,M\$$ now
  ^{4}He $\,1800\,m^3$ STP

Open cycle dilution refrigerator for space?

2020–2025: future missions

- cooling power: 1 µW @ 50 mK
  - X-IFU: 0.8 µW @ 50 mK
- lifetime: 5 years
- helium flowrates:
  ^{3}He 18 µmol s^{-1}
  ^{4}He 360 µmol s^{-1}
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Too heavy and too costly …

- $\implies$ closed cycle is required

Outline

Closed cycle dilution refrigerator for space?
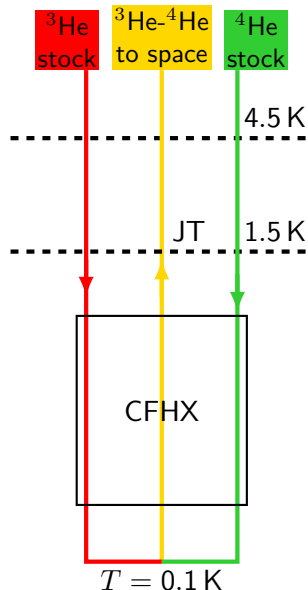
OCDR $\Rightarrow$ CCDR $\Rightarrow$ zero gravity on earth?

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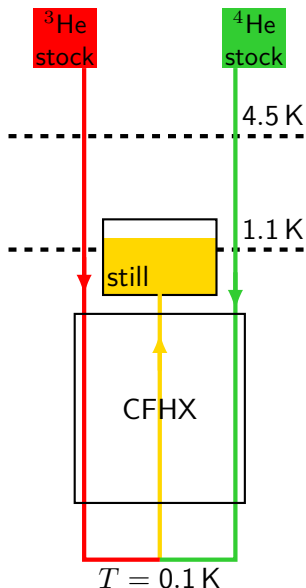
OCDR $\Rightarrow$ CCDR $\Rightarrow$ zero gravity on earth?

1. still: ^{3}He and ^{4}He separator at $T \approx 1.1\,\text{K}$
   - liquid-vapor interface in zero gravity?

Closed cycle dilution refrigerator for space?

OCDR $\Rightarrow$ CCDR $\Rightarrow$ zero gravity on earth?

1. still: ^{3}He and ^{4}He separator at $T \approx 1.1\,\mathrm{K}$
   - liquid-vapor interface in zero gravity?
2. ^{4}He circulation: fountain pump
   - $3.5\,\mathrm{mW}\,@\,2.1\,\mathrm{K} \Rightarrow (0.1-0.4)\,\mathrm{mmol\,s^{-1}}$

- very well understood
- tune ^{4}He flow rate by a factor $0.5-2$

Closed cycle dilution refrigerator for space?

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   - $3.5\,\mathrm{mW}$ @ $2.1\,\mathrm{K} \Rightarrow (0.1-0.4)\,\mathrm{mmol\,s^{-1}}$
3. ^{3}He circulation: pump development
   - $\dot{n}_3 = (20-60)\,\mathrm{\mu mol\,s^{-1}}$ at $p_{\mathsf{still}} = (0.3-15)\,\mathrm{mbar}$
   - determine ^{3}He pump specs

- trade-off between 2 and 3
- collaboration with JAXA for pump: discussion since 2009 and test with JAXA pump in 2015
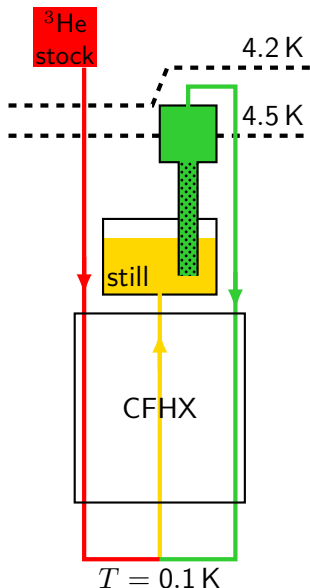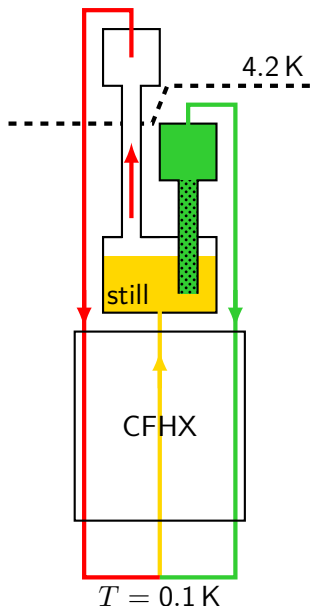
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4. pre-cooling (JAXA SPICA compatible)
   - heat load $\approx 5\,\mathrm{mW}$ at $T = 1.7\,\mathrm{K}$

- JAXA pre-cooler is most suitable available
- lower T is better for 1, 2, 3
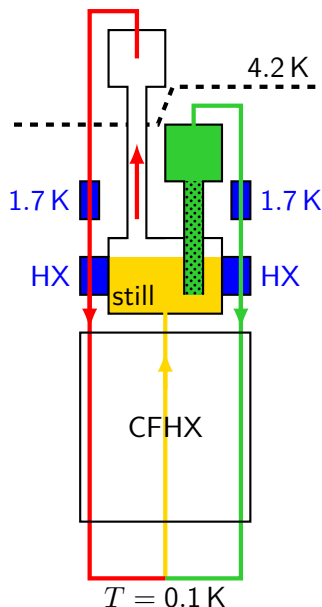
Closed cycle dilution refrigerator for space?

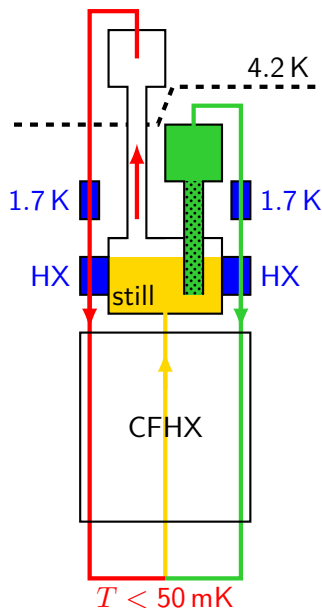OCDR $\Rightarrow$ CCDR $\Rightarrow$ zero gravity on earth?

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Closed cycle dilution refrigerator for space?

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6. optimize detector simulator

Closed cycle dilution refrigerator for space?

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

detector

CFHX

HX · still · HX

$1.7\,\text{K}$ · $1.7\,\text{K}$

$4.2\,\text{K}$

OCDR $\Rightarrow$ CCDR $\Rightarrow$ zero gravity on earth?

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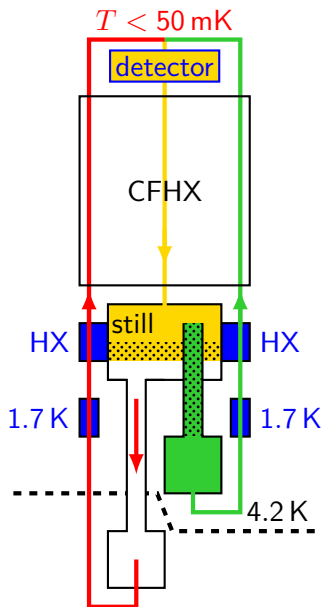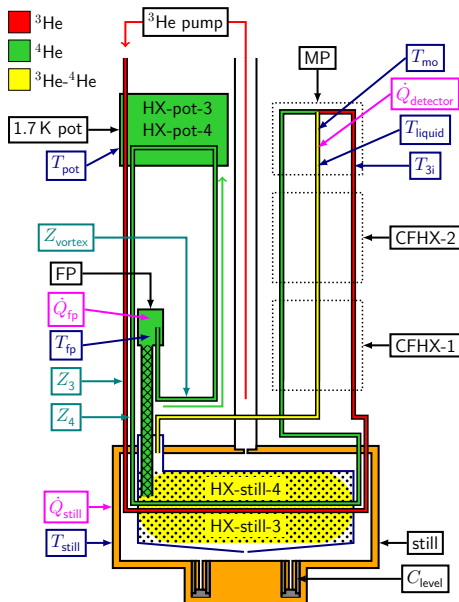5. optimize CFHX to $T < 50\,\text{mK}$
6. optimize detector simulator
7. no zero gravity on earth
   - upside-down or negative gravity

Outline

Negative (not Zero) Gravity CCDR (NG-CCDR)

Upside-down CCDR setup

- sponge confines liquid in still
- capacitance liquid level gauge to detect leaking liquid
- ^{3}He pump circulates ^{3}He gas from sponge to 1.7 K pot (e.g. SPICA) and MP
- fountain pump circulates ^{4}He liquid from sponge to 1.7 K pot and MP
- ^{3}He-^{4}He mixture returns from MP to still

Negative (not Zero) Gravity CCDR (NG-CCDR)
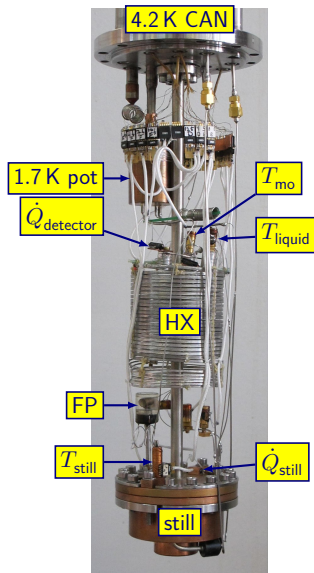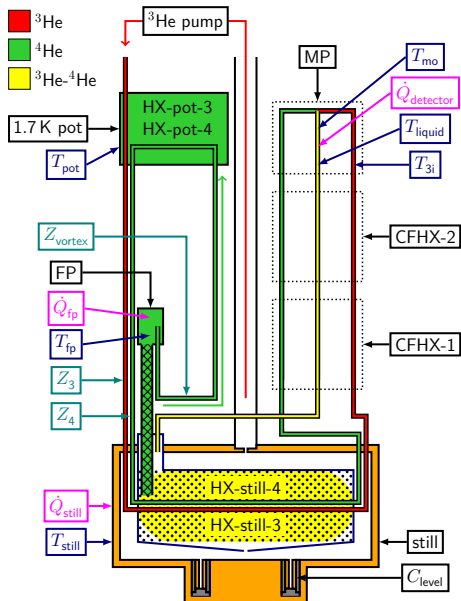
Upside-down CCDR with JAXA ^{3}He circulator
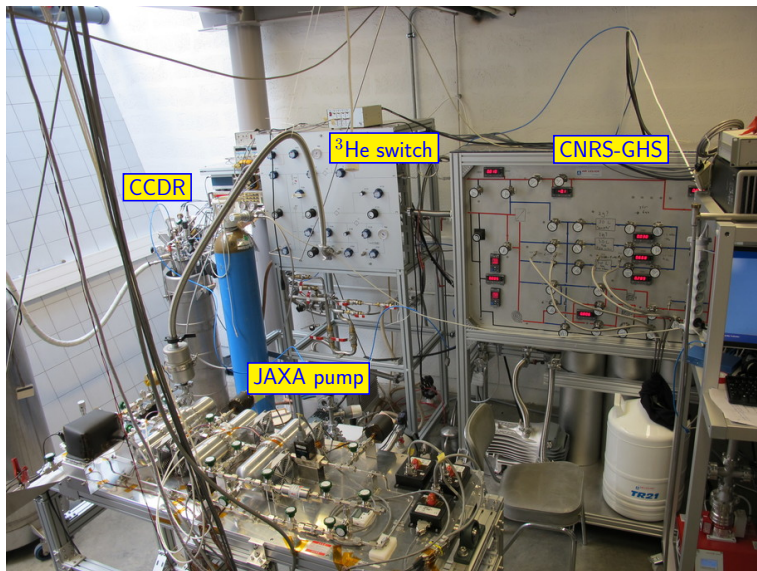
Upside-down CCDR with JAXA ^{3}He circulation pump
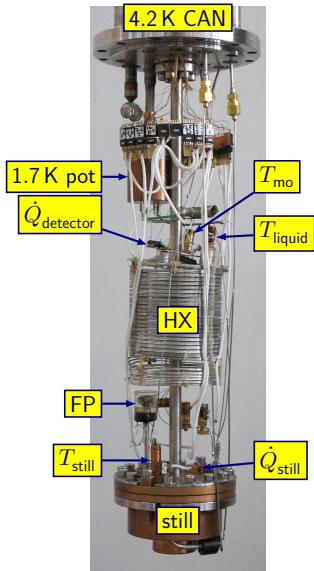
Cooling power result
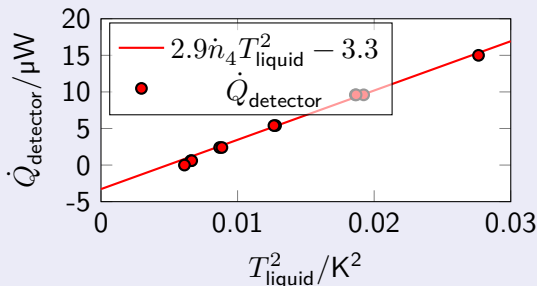
- $\dot{Q}_{\text{detector}} = A\dot{n}_4 T_{\text{liquid}}^2 - \dot{Q}_{\text{leak}}$
  - $\dot{n}_4 = 235\ \mu\text{mol s}^{-1}$ fountain pump physics
  - $A = 2.9\ \text{J mol}^{-1}\ \text{K}^2$ OK with "theory"
- conclusion
  - $3.5\ \mu\text{W} @ 0.1\ \text{K}$ with $\dot{Q}_{\text{leak}} = 3.3\ \mu\text{W}$
  - if $\dot{Q}_{\text{leak}} \approx 1\ \mu\text{W}$: OK for today missions

Outline

Closed cycle dilution refrigerator in simplified cooling chain

cooling power budget

^{3}He-^{4}He
^{3}He
^{4}He

mixing part cools detectors (50 − 100) mK

counter flow heat exchanger (CFHX)

^{3}He-^{4}He still (0.6 − 1.2) K

^{3}He pump 300 K

ADR or ^{3}He JTC 1.75 K

fountain ^{4}He pump (1.8 − 2.1) K

other coolers

^{4}He cooler 5.0 K

thermal-mechanical design issues

- CFHX and mixing part tuning
  - $\dot{Q}_{\text{lift}} \propto {}^4$He and ^{3}He circulation rates $\dot{n}_4$ and $\dot{n}_3$
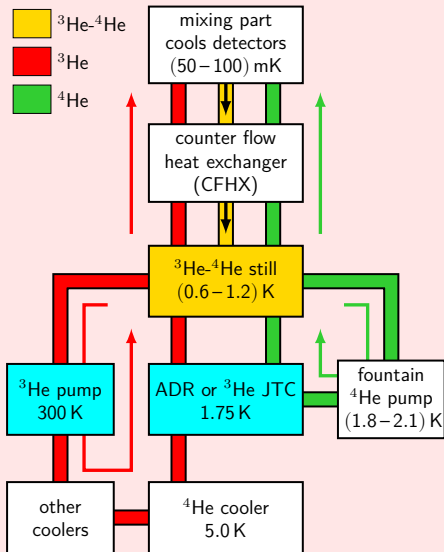- direct CCDR interfaces:
  - ^{3}He circulation pump
  - ^{3}He Joule-Thompson (JTC)
- ^{4}He circulation $\dot{Q}_{\text{load}}$ on
  - ADR or ^{3}He JTC
  - lower T_{still} implies lower $\dot{Q}_{\text{load}}$
- ^{3}He circulation $\dot{Q}_{\text{load}}$ on
  - other coolers
  - ^{4}He cooler
  - ADR or ^{3}He JTC
- CCDR support struts and links to focal plane (launch)

Closed cycle dilution refrigerator in simplified cooling chain

cooling power budget

- ^{3}He-^{4}He
- ^{3}He
- ^{4}He

mixing part
cools detectors
$(50-100)$ mK

counter flow
heat exchanger
(CFHX)

^{3}He-^{4}He still
$(0.6-1.2)$ K

^{3}He pump
300 K

ADR or ^{3}He JTC
1.75 K

fountain
^{4}He pump
$(1.8-2.1)$ K

other
coolers

^{4}He cooler
5.0 K
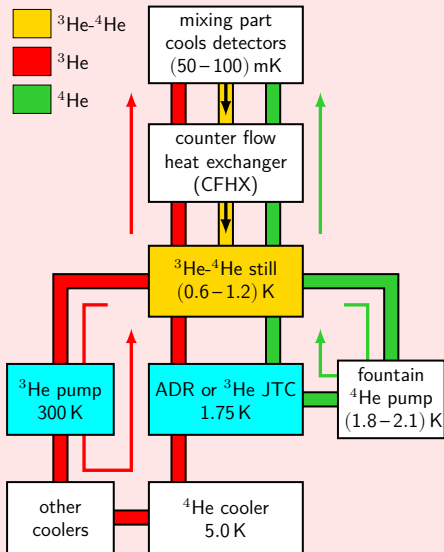
model CFHX and mixing part

❶ flows of enthalpy
  - ^{3}He and ^{3}He-^{4}He thermo
❷ heat exchange (Kapitza)
❸ laminar + turbulent heating
❹ heat loads
  - instrument (focal plane)
  - CCDR support structure

model ^{3}He-^{4}He still

❶ flows of enthalpy including
  - ^{4}He demixing heat < 0
  - ^{3}He evaporation heat > 0

model fountain pump

❶ depends on T_{still} or p_{still}

Closed cycle dilution refrigerator in simplified cooling chain

cooling power budget

LiteBIRD context

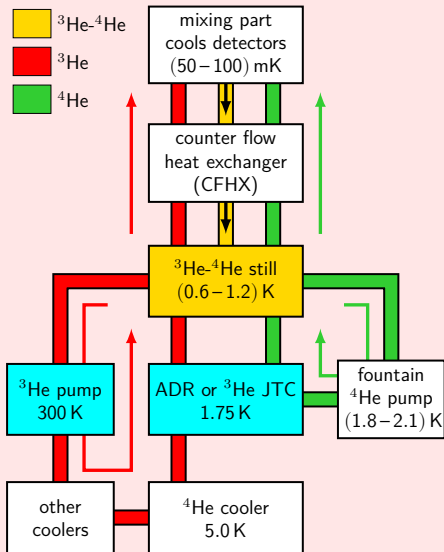- ✔ tuning of CFHX and mixer part: $\dot{n}_4 = 210\,\mu\text{mol s}^{-1}$ & $\dot{n}_3 = 30\,\mu\text{mol s}^{-1}$ give $40.0\,\mu\text{W}\,@\,0.3\,\text{K}$ & $4.0\,\mu\text{W}\,@\,0.1\,\text{K}$ or $7.0\,\mu\text{W}$ with new tested mixing chamber
- ✔ within JAXA ^{3}He pump specs
- ✔ $1.56\,\text{mW}$ load on $5.0\,\text{K}$
- ☞ $2.40\,\text{mW}$ load on $1.75\,\text{K}$
  - $2.5\times$ too high for ADR
- ✘ so far no way without $1.75\,\text{K}$

Closed cycle dilution refrigerator in simplified cooling chain
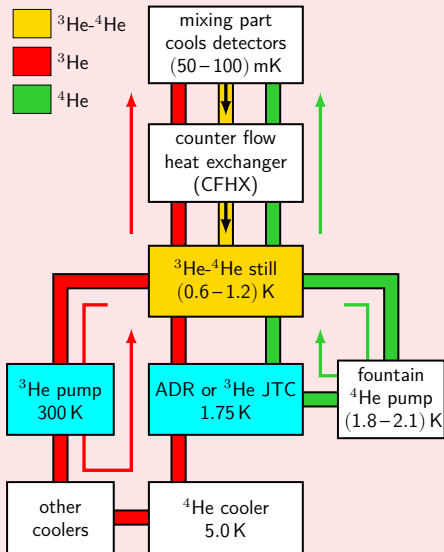
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but, due to JAXA budget cuts

- no JAXA ^{3}He JTC
- no JAXA ^{3}He circulation pump

Outline

Status and conclusion

Status

- we work on a DM (demonstration model) and with the IAS on an EM (engineering model)
- we want an European or French mechanical ^{3}He circulation pump

Comparing ADR and CCDR …

- ideal ADR cycle is a Carnot cycle and a CCDR is less efficient
  - CCDR heat load on 1.75 K is 2.5× higher than that of LiteBIRD's continuous ADR
- LiteBIRD's continuous ADR weighs ≈ 20 kg, CCDR DM ≈ 6 kg, and CCDR EM ≈ 3 kg (IAS, design goal)
  - weight below 4 K has a much bigger negative system impact than weight at 300 K, since stronger implies more conductive heat loads
- TRL of ADR is higher than of CCDR

Thank you and thanks to

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