Coupled Tests of the Closed Cycle Dilution Refrigerator and ^{3}He Compressor for Space

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Motivation

Planck: ^{3}He-^{4}He Open Cycle Dilution Refrigerator (OCDR)

- ^{3}He in + ^{4}He in $\Longrightarrow$ ^{3}He-^{4}He out and rejected into space
- life time + # He on satellite fix: $\dot{Q} = 0.2\,\mu\mathrm{W}$ at $T = 100\,\mathrm{mK}$

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Future: $\dot{Q} = 1\,\mu W$ at $T = 50\,mK$ $\implies$ Closed Cycle DR (CCDR)

- 1 K isotope separator to circulate ^{3}He and ^{4}He $\implies$ ^{3}He pump
- Negative Gravity: sponge confines liquid-vapor interface (NG-CCDR)

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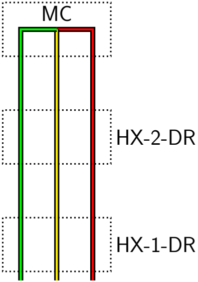
Candidates for space qualified pump

- ^{3}He adsorption pump by Twente University (next talk)
- pump based on ^{3}He compressor for JAXA 1.7 K JT

Goal

breadboard test of NG-CCDR & JAXA pump

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



NG-CCDR setup is . . .

- upside-down OCDR with . . .

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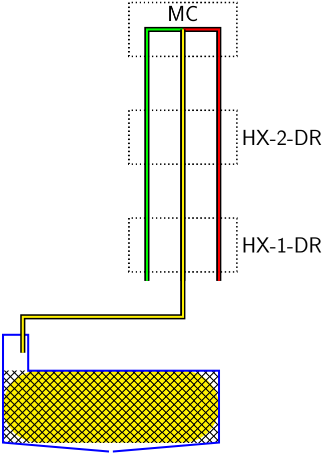

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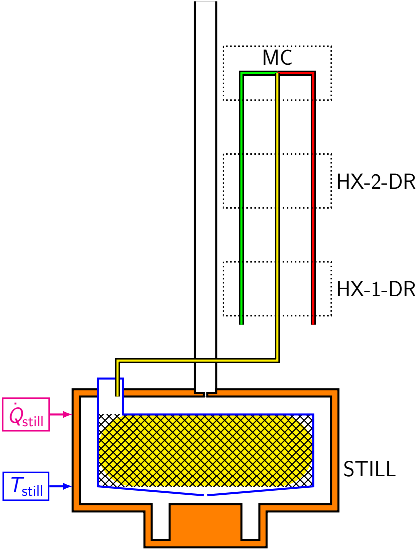

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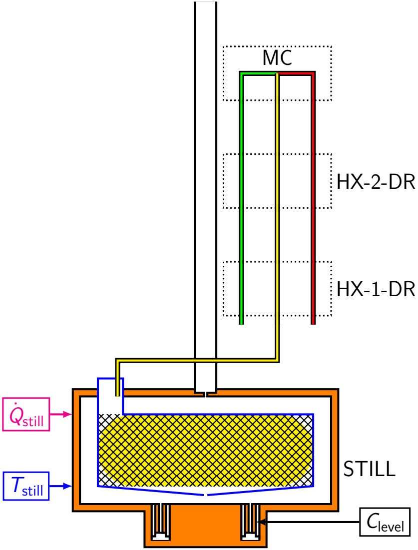

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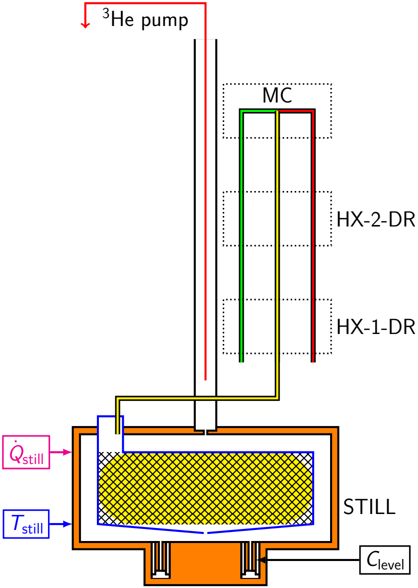

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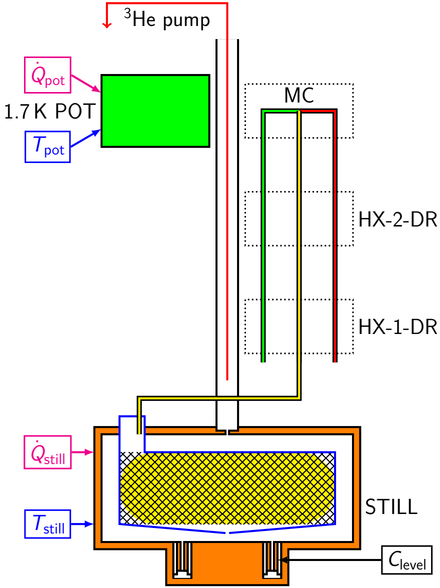

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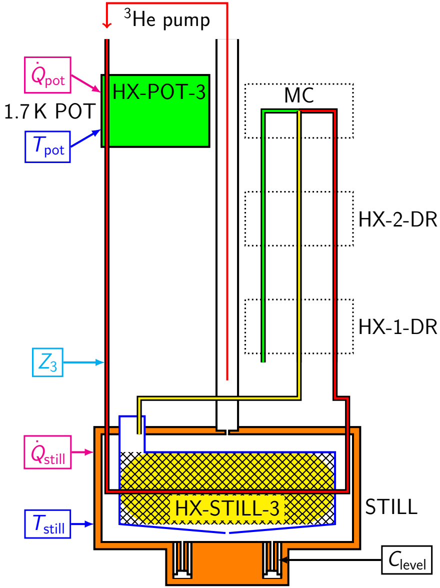

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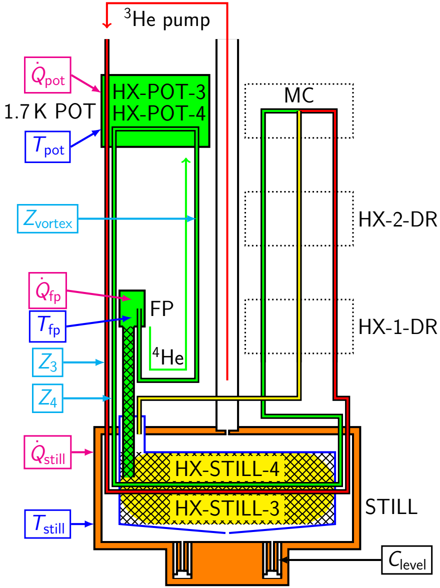

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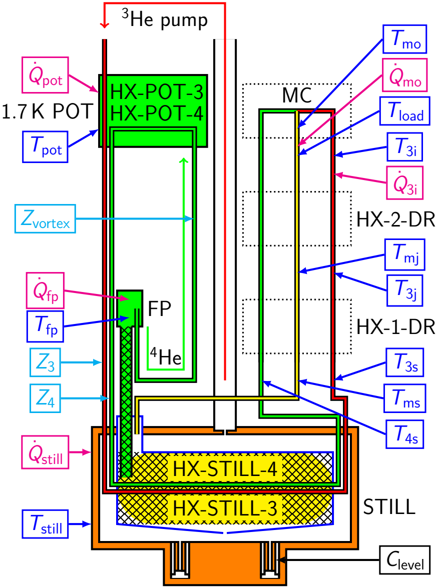

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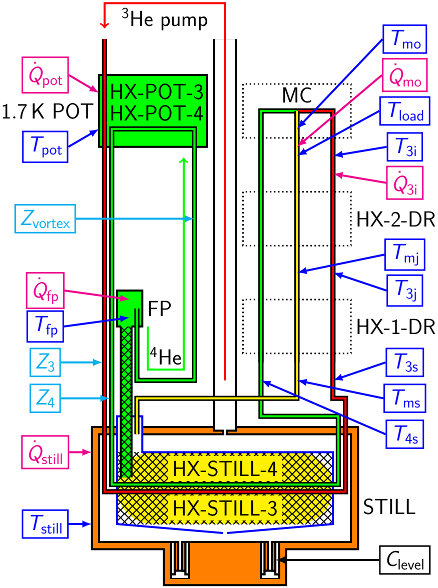

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- ^{3}He in, 2 HX, 1 Z
- ^{4}He pump, 2 HX, 2 Z
- remaining Ts and $\dot{Q}$s
- HX-DR small due to geometry
  $\Longrightarrow$ no $\dot{Q} = 1\,\mu$W at 50 mK

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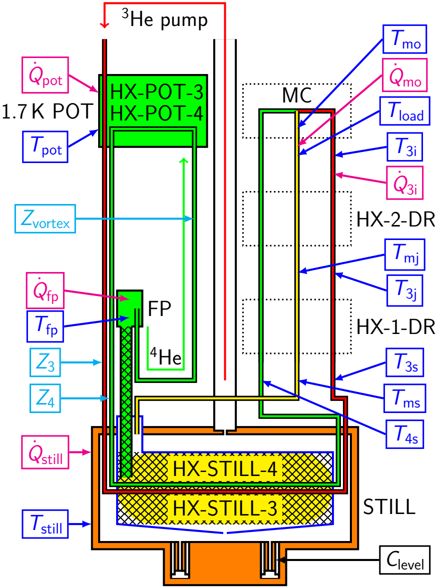

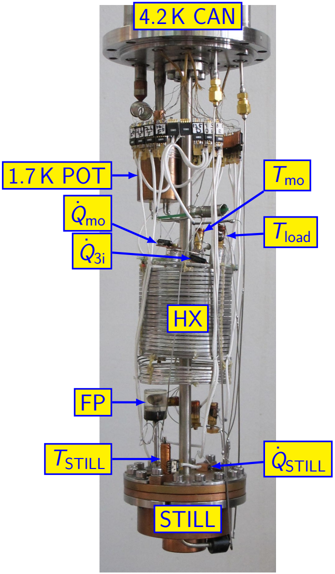

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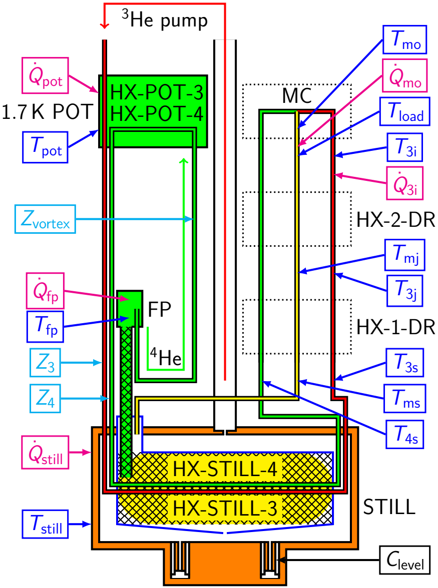

Pre-test CCDR status

- liquid confinement works
- $T_{mo} = 75\,\text{mK} - 80\,\text{mK}$
- $p_{still} = 0.3\,\text{mbar} - 5.0\,\text{mbar}$
  - $p_{still} \uparrow$ is more difficult
  - $\dot{n}_4 = 160\,\mu\text{mol}\,\text{s}^{-1}$ $\times 2$ low
- $T_{POT} = 1.65\,\text{K}$ is OK at $\dot{n}_3 = 21\,\mu\text{mol}\,\text{s}^{-1} - 27\,\mu\text{mol}\,\text{s}^{-1}$ $\times 2$ high

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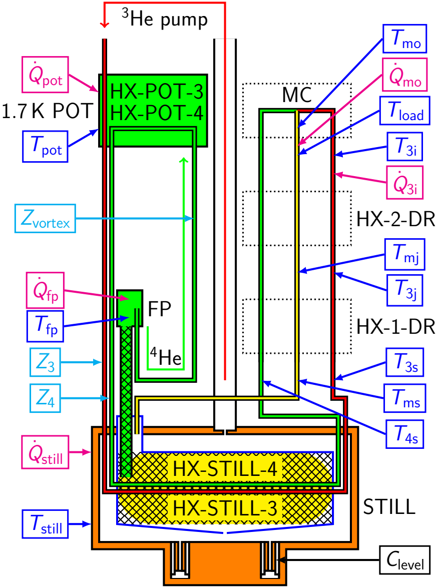

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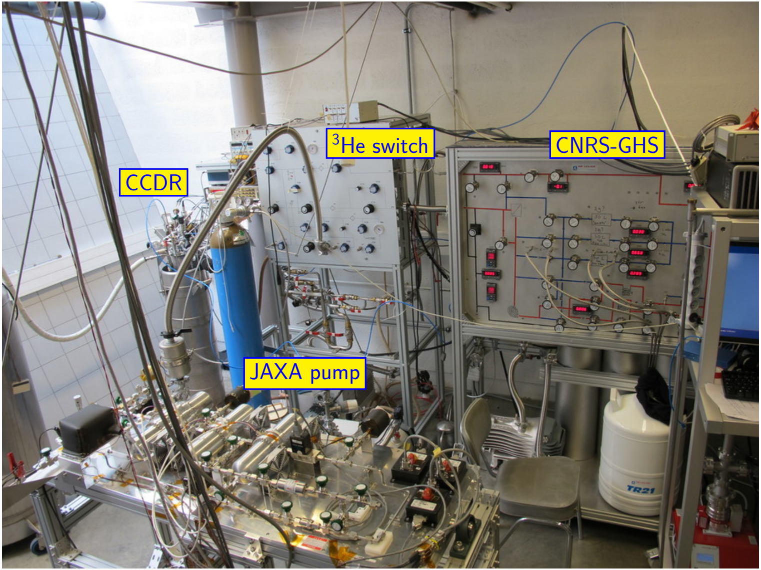
JAXA pump status: $P < 40\,\mathrm{W}$

$\dot{n}_3$ $\mu\mathrm{mol\,s^{-1}}$	p_{in} mbar	p_{out} mbar
20.3	7.8	208
30.7	8.8	195

CCDR with ^{3}He switch to JAXA pump or CNRS-GHS



Key tests in plan

Test conditions

- set $T_{pot} \approx 1.71\,K$
- only JAXA pump circulates ^3He and ^4He through CCDR

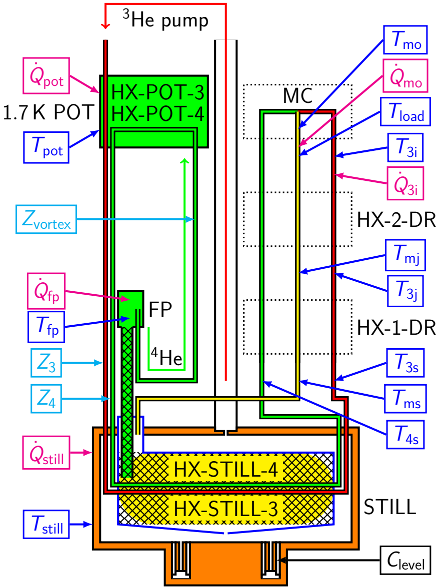
Key tests

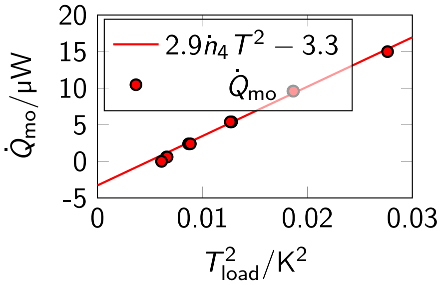
1. cool from $15\,K \rightarrow 0.07\,K$
   - $15\,K \rightarrow 3\,K$ by JAXA pump pushing gas through working 1.7 K POT
   - $3\,K \rightarrow 1\,K$ by condensing ^3He-^4He using JAXA pump
   - $1\,K \rightarrow 0.07\,K$ by applying $\dot{Q}_{fp}$ to drive $\dot{n}_4$ while JAXA pump drives $\dot{n}_3$

   $\dot{Q}_{fp}$ worked after temporarily storing ^3He in tank of CNRS-GHS
2. at 70 mK: step $\dot{Q}_{mo}$ to measure cooling power
3. at 70 mK: step $\dot{Q}_{fp}$ to check still and fountain pump behavior

only time to show data of test 2 and 3

Test 2: cooling power (JAXA pump + $T_{pot} = 1.71\,K$)

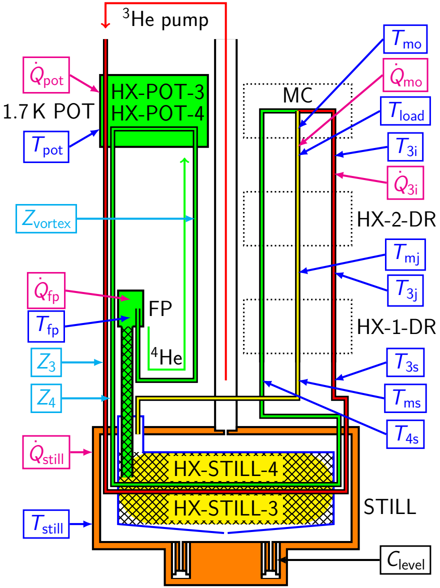




Fit simple 1st order model

- $A\dot{n}_4 T^2_{load} = \dot{Q}_{mo} + \dot{Q}_{leak}$
  - $\dot{n}_4 = 236\,\mu mol\,s^{-1}$
    2nd law using $\dot{Q}_{fp}$ and T_{fp}
  - $A = 2.9\,J\,mol^{-1}\,K^2$
    OK with theory
  - $\dot{Q}_{leak} = 3.3\,\mu W$
    OK with Kevlar suspension

Test 3: FP and STILL (JAXA pump $T_{pot} = 1.71\,K$)



Step $\dot{Q}_{fp}$ and look at

- $\dot{Q}_{fp}$ and T_{fp} $\Longrightarrow$ $\dot{n}_4$
- T_{mo} and T_{load} versus $\dot{n}_4$
- impact of $\dot{n}_4$ on $\dot{n}_3$

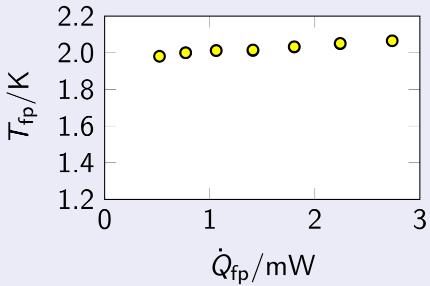
- OK: liquid confinement
- OK: x_{liquid} and x_{vapor}

Test 3: FP and STILL (JAXA pump+ $T_{pot} = 1.71\,\mathrm{K}$)

$\dot{Q}_{fp}$ and $T_{fp} \implies \dot{n}_4$

2nd Law of Thermodynamics $\implies$

$$\dot{n}_4 = \frac{\dot{Q}_{fp}}{T_{fp} s_{40}(T_{fp})}$$



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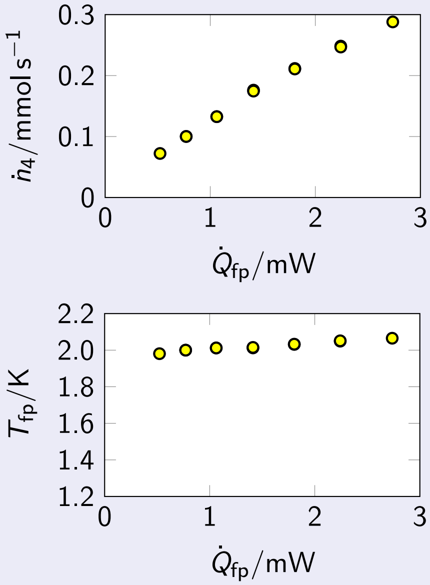

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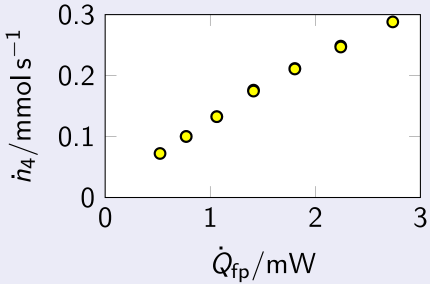

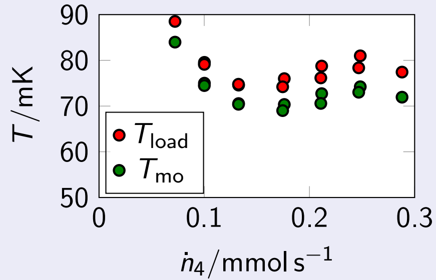

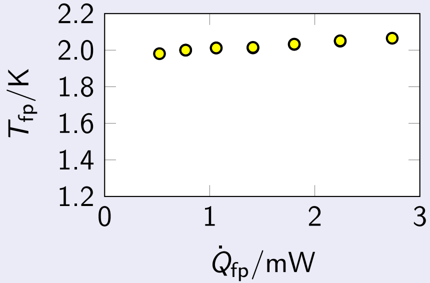

T_{mo} and T_{load} versus $\dot{n}_4$

minimum $T_{mo} = 69\,mK$ at $\dot{n}_4 = 175\,\mu mol\,s^{-1}$ implies $\dot{Q}_{leak} \approx 2\,\mu W$

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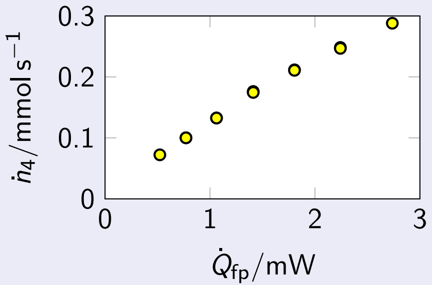

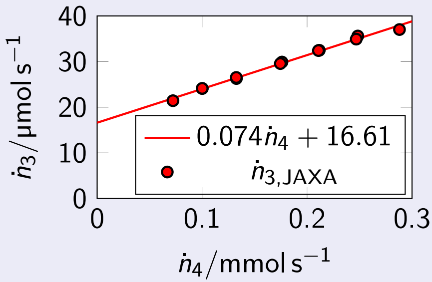

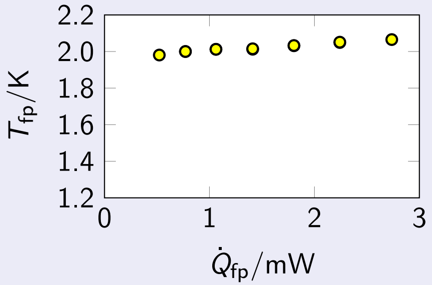

Impact of $\dot{n}_4$ on $\dot{n}_3$

- a heat load on still $\propto \dot{n}_4$
- until today: unable to calculate the slope
- pump specs: $\dot{Q} = 1\,\mu W$ at $50\,mK \implies \dot{n}_4 \approx 400\,\mu mol\,s^{-1}$
  $\implies \dot{n}_3 \approx 45\,\mu mol\,s^{-1}$

Conclusion

JAXA pump specifications

- extrapolation of these tests: $\dot{n}_3 = 45\,\mu\text{mol}\,\text{s}^{-1}$ at $\dot{n}_4 = 400\,\mu\text{mol}\,\text{s}^{-1}$
  - $\dot{n}_4$=$400\,\mu\text{mol}\,\text{s}^{-1}$ needed for 1 μW at 50 mK
  - $\dot{n}_3$ is 50 % higher than our expectations
- $p_{\text{in,JAXA}} = 9\,\text{mbar}$ affects:
  - cryogenic performance
  - starting fountain pump

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Further CCDR development

- NG-CCDR prototype for X-IFU with:
  - 1 µW at 50 mK
  - 20 µW at 300 mK
- demonstration model
- engineering model, designed as CEA-SBT ADR replacement (Air Liquide)