Dilution option:

Development of helium-3 compressors and integration test of closed-cycle dilution refrigerator system

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B-mode from space, 10-16th Dec 2015, University of Tokyo, Japan

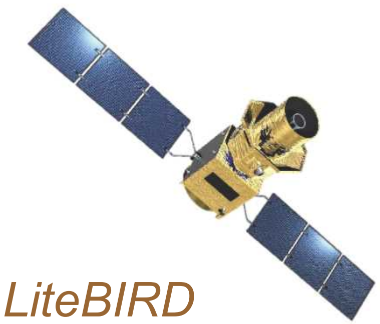
1. Introduction

- There are several methods to cool down below 100mK:
  - Adiabatic Demagnetization Refrigerator (ADR): High thermal efficiency, recycling time (no observational time) is usually needed, high magnetic field.
    - Multi-stage ADR
    - Sorption cooler + ADR
  - Dilution refrigerator: continuous cooling, no magnetic field.

- Closed-Cycle Dilution Refrigerator (CCDR) is a key technology to cool down to 50mK with a comparable cooling power as an ADR but a 100% duty cycle in space.

- Recently, the coupled test between the dilution refrigerator developed by France and the helium-3 circulator developed by Japan has been performed as a breadboard test of CCDR, and successfully achieved to cool down to 70mK.

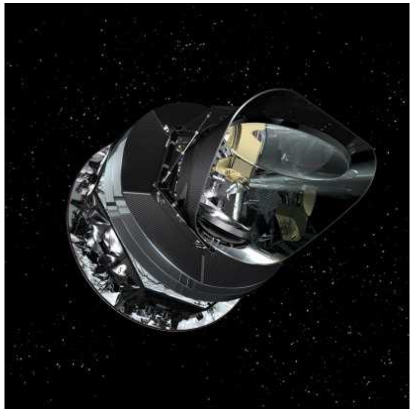
- We believe that CCDR is fully competitive with ADR-based solutions.



LiteBIRD

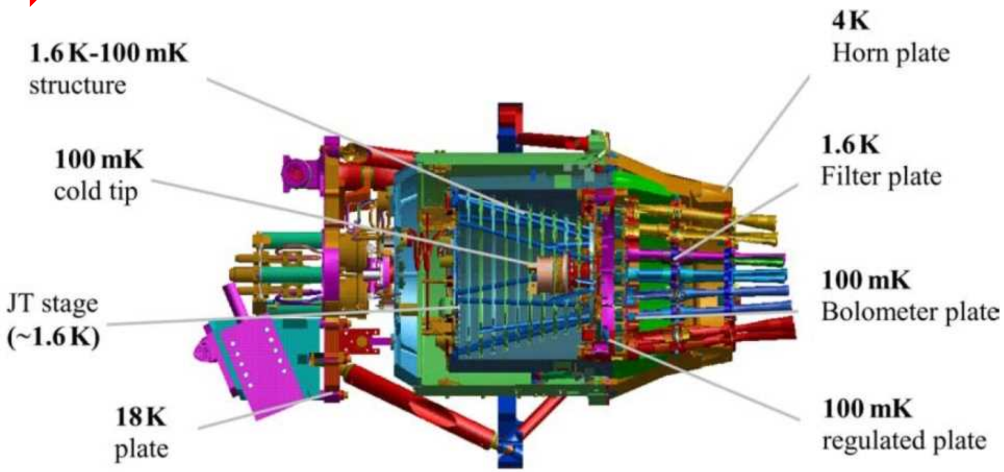
2. Introduction – Planck mission

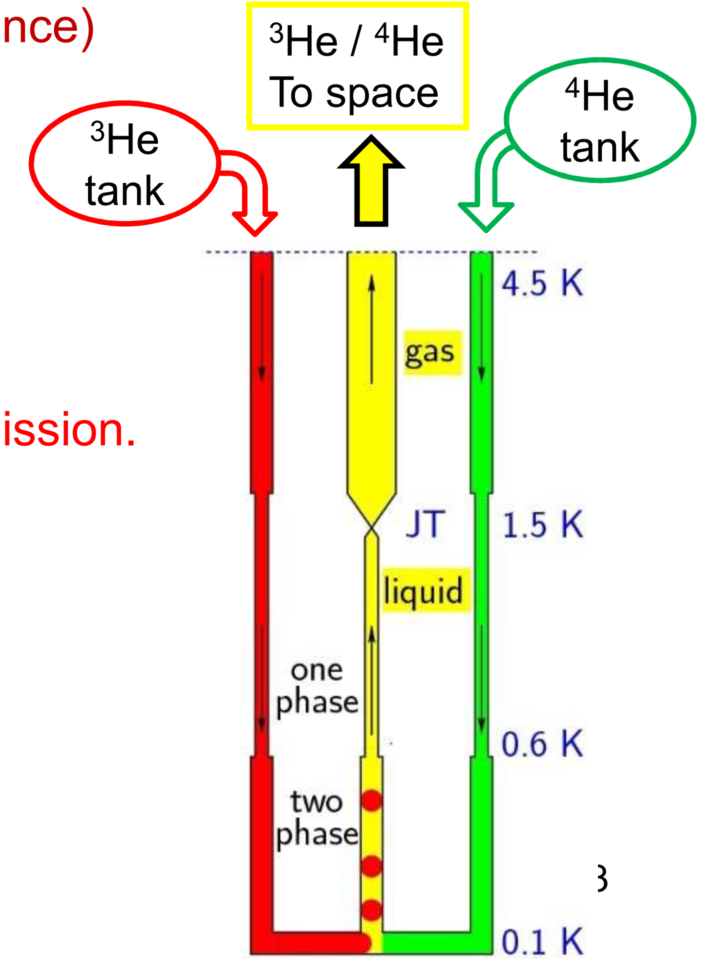
- Cosmic Microwave Background observation
- Launched by Ariane V on May 2009
  - 2nd Lagrangian orbit
  - 40K cooled telescope (1.5m, 30~900GHz)
  - 2 scientific instruments: LFI (20K), HFI (0.1K)



- The open cycle dilution refrigerator (OCDR) – (France)
  - 1st dilution refrigerator in space.
  - Space pump working gas (helium).
  - ^3He as well as ^4He were extracted.
  - Cooling power of only 100nW at 100mK.
  - 12000 L of ^3He and 36000 L of ^4He.
  - 2.5 year's operation.

⇨ Closed cycle dilution refrigerator for future mission.





2. The CCDR development

- Closed cycle dilution refrigerator (CCDR) is desired for next generation space science mission.
  - Operational temperature (<100mK) continuously.
  - No magnetic field.
  - Lower mass and easily designed to optimize the size and assembly according to the detector design.

- Target: Athena, LiteBIRD, etc..
  - Cooling power: 1μW at 50mK, 2μW at 100mK
  - Lifetime: 5 years (requirement)

- The helium-3 compressor is needed to circulate the helium-3 gas. The space qualified low pressure compressor had been successfully developed for 1K-class Joule Thomson cooler in Japan. Therefore, the helium-3 compressor system for CCDR has been developed in JAXA and SHI, as a new challenge of a R & D collaboration between France and Japan in the space development.

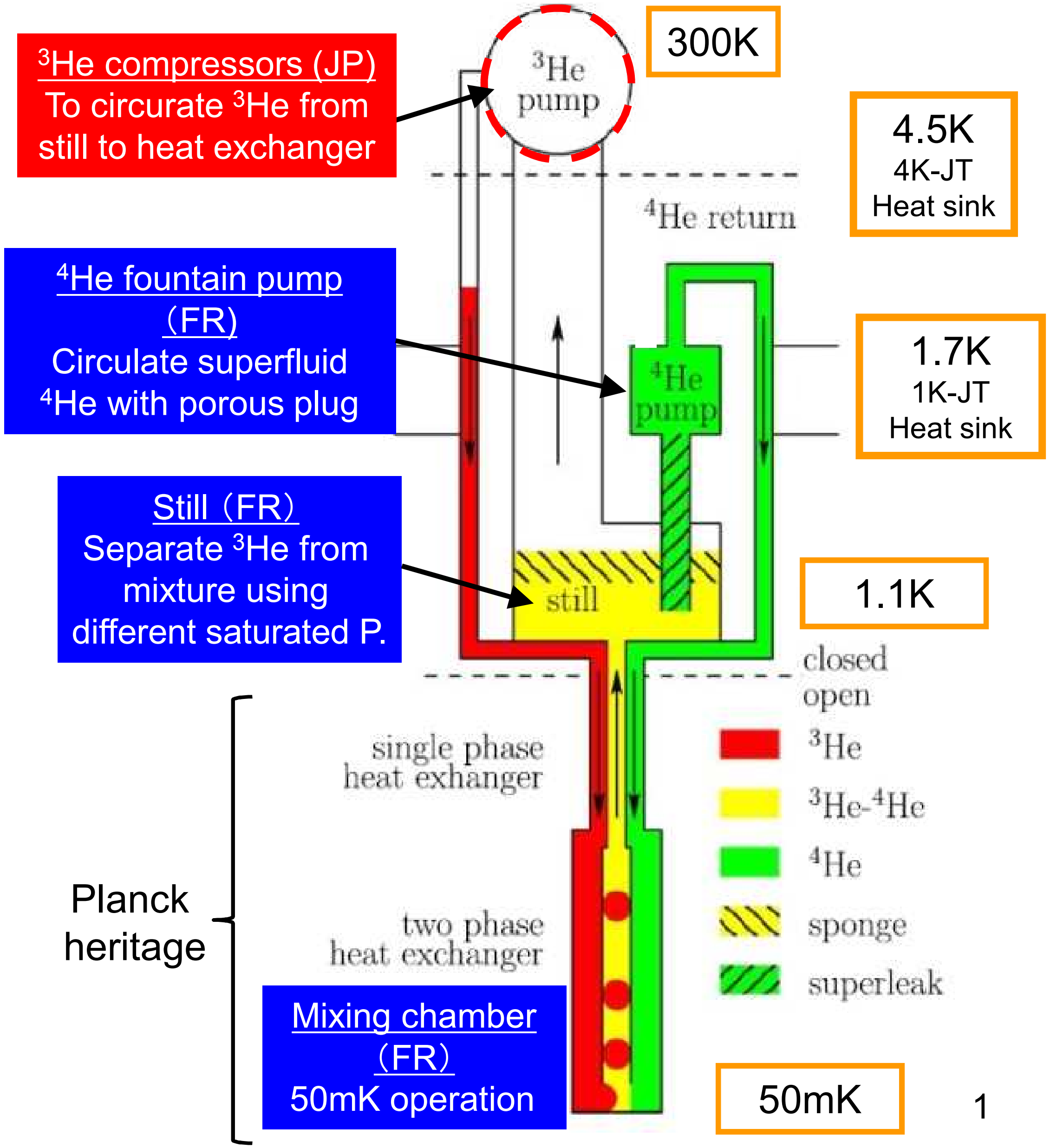
- A ^4He / ^3He separator in a still and a fountain pump to circulate a superfluid ^4He at low temperature are also needed and developed by CNRS, Air Liquide and the CNES.

- We tried to have the coupled test between the helium-3 compressor system and the cold part.

3. CCDR system

- What is a dilution refrigerator ?
  - There are two separated phases at low temperature mixing chamber in principle. ^3He rich phase (c-phase) and ^3He / ^4He mixture (d-phase).
  - Cooling reaction is provided by a transfer of ^3He from c-phase to d-phase.
  - The capillary force is used to separate two phases under microgravity (Planck heritage), while a gravitational force is used in ground.
- A ^3He compressors as well as a still and a ^4He pump have to be developed.
- Because of each technological level, international collaboration is one of best choice.
- Pre-cooler is needed. The use of 1K-class / 4K-class JT cooler developed by Japan are proposed.

- CCDR schematic drawing

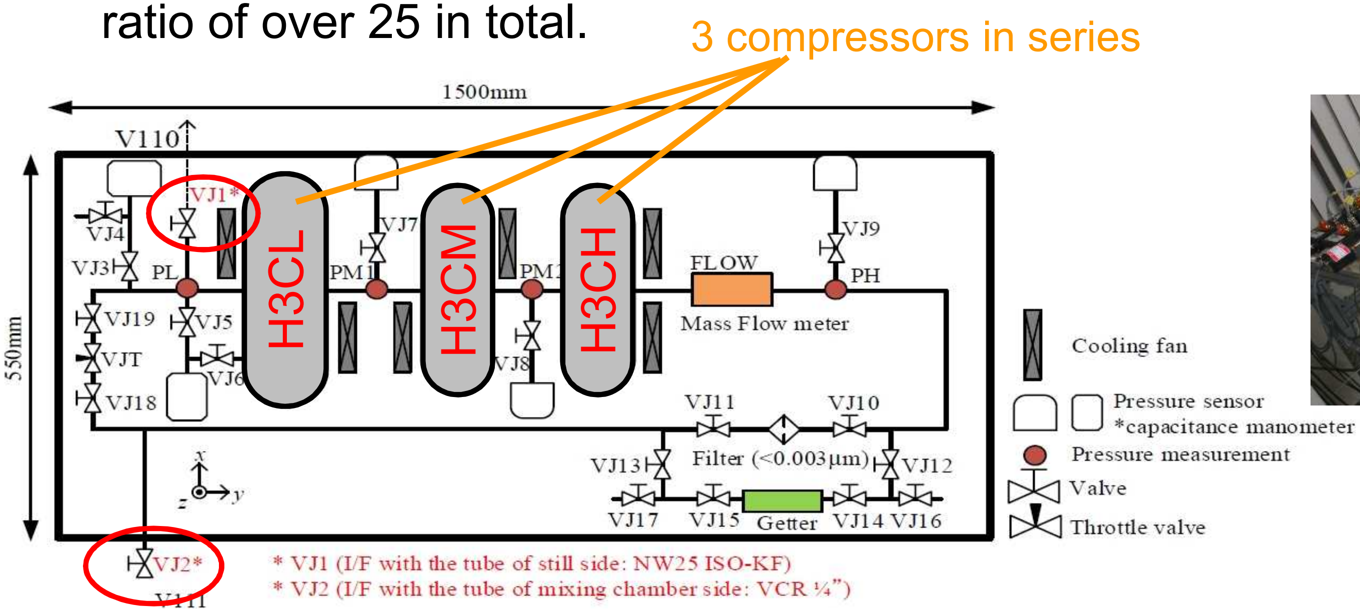


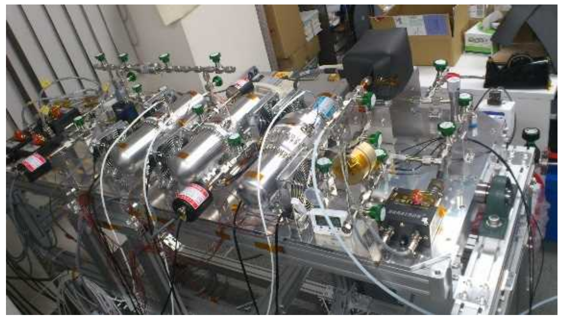
4. ^{3}He compressors system design

- **Pressure target**
  - The heritage of the development of 1K-class Joule Thomson cooler (1K-JT) provided a level of advantage. However, these target performances in particular low inlet pressure (0.8kPa) was challenging issues even when the heritage of 1K-JT was used.

Target	Flow rate*	Required inlet P	Required outlet P
1K-JT	2,232 μg/sec	7 kPa	700 kPa
^{3}He compressors	20 μmol/sec	**< 0.8 kPa**	> 20 kPa

- When actual performance of JT coolers are considered, typical compression ratio of each compressor is 4. Therefore, 3 compressors are needed for the targeted ratio of over 25 in total.



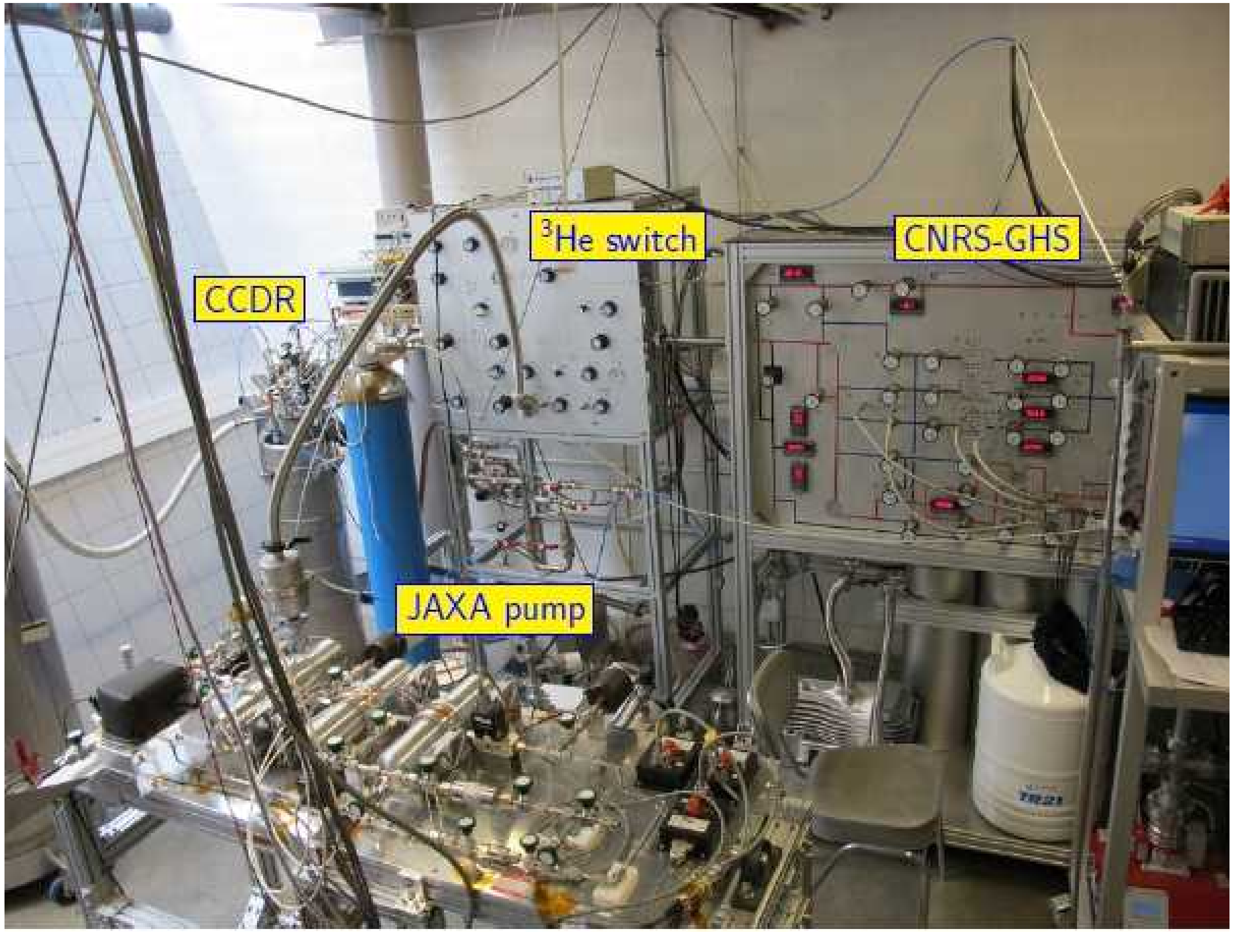


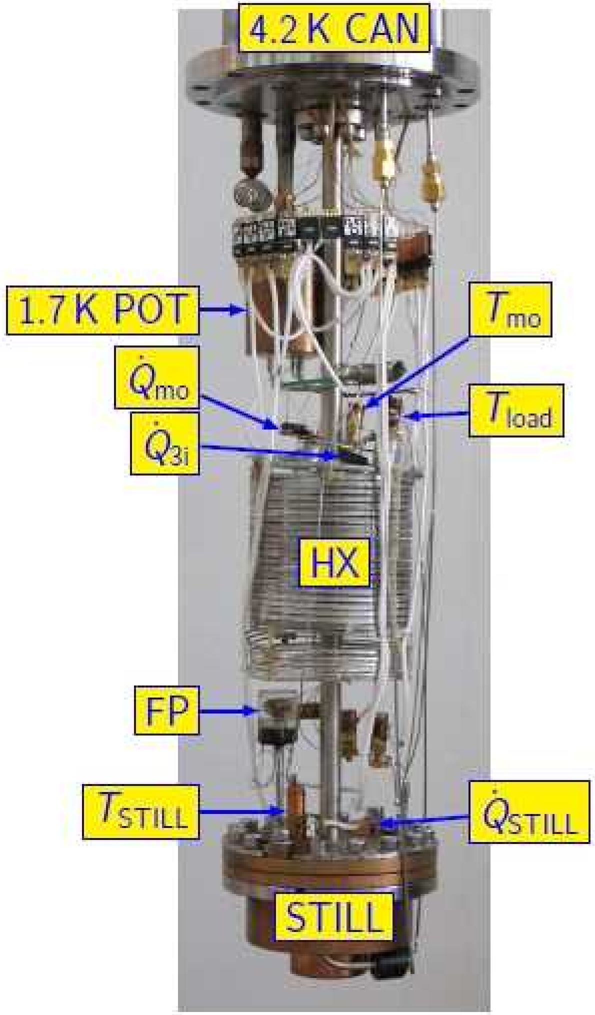
Transportation of ^{3}He compressors system and preparation for the coupled test

◆ Tsukuba Space Center, Tsukuba, Japan

◆ Institute Neel, CNRS, Grenoble, France

Experimental setup for the CCDR coupled test

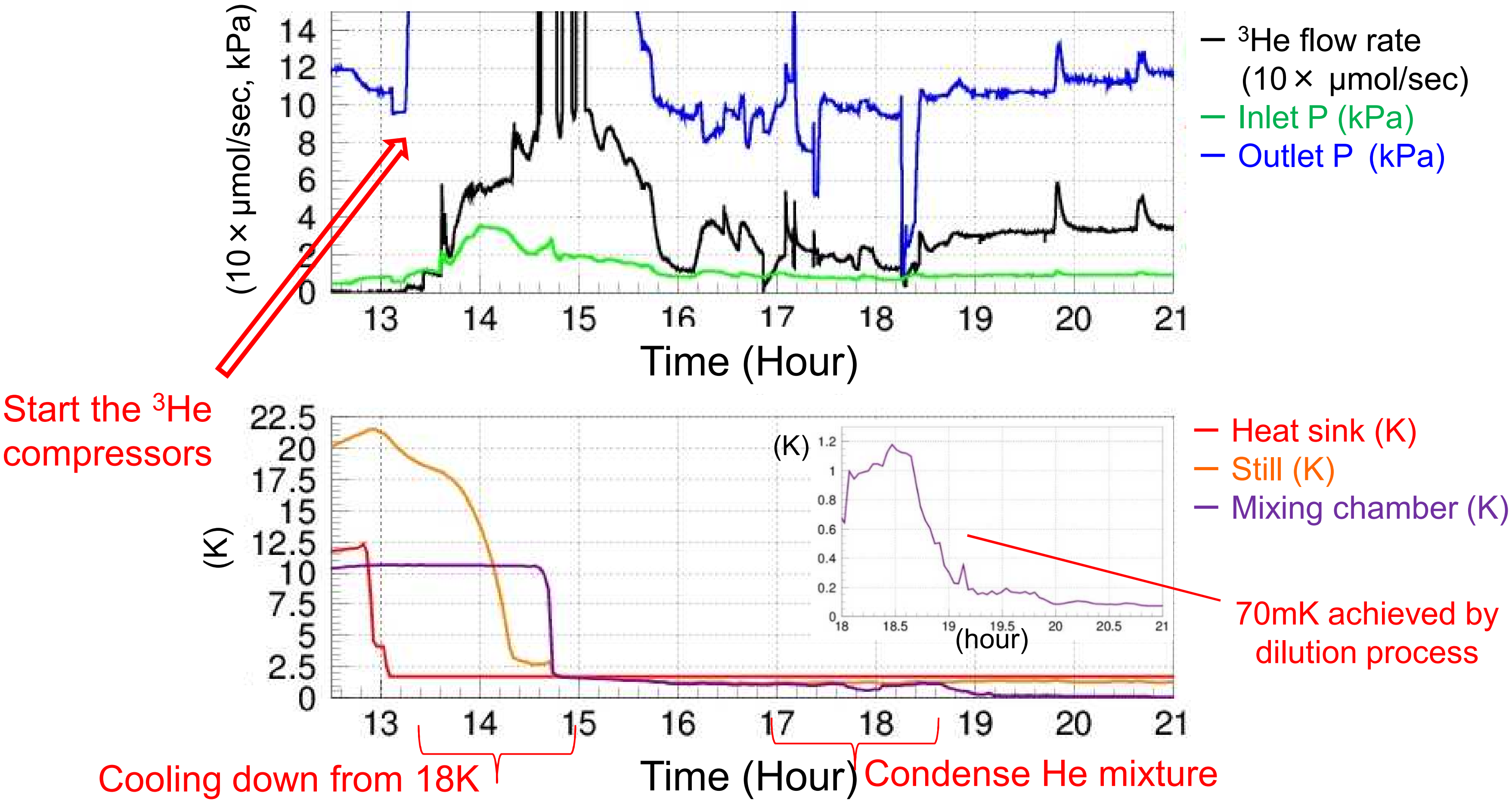




5. Coupled test results (1/2)

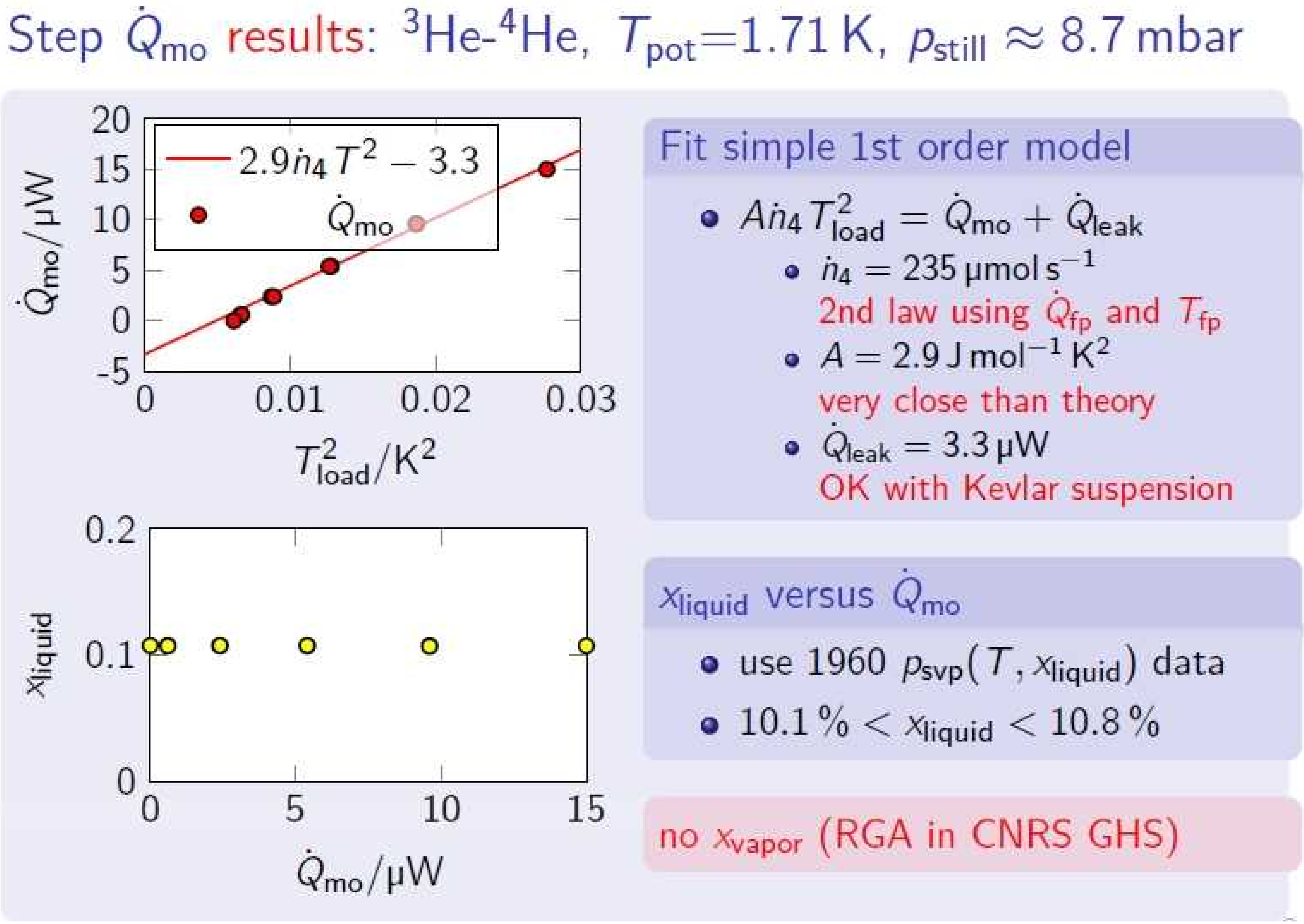
- Goal of the coupled test
  - To achieve lower than 100mK.
  - To demonstrate the feasibility of cooler system with CCDR.

- Coupled test result
  - ^{3}He compressors has to be operated to circulate the working gas in order to cool down the mixing chamber, still and ^{4}He pump from higher than 10K.
  - We could obtained 70mK from 18K with the heat sink of 1.71K



5. Coupled test results (2/2)

- Additional measurement could be obtained after the cool down test
  - Step the mixing chamber heater Q_{mo} to measure the cooling power of the CCDR.
  - Step the fountain pump (fp) heater Q_{fp} to measure the property of the fp.



6. Next step of CCDR development

◆ ^{3}He compressor improvement (TRL4).

- Twice higher flow rate is targeted with lower inlet pressure (<0.4kPa).
- Current performance is assumed to be limited by a leak and a pressure drop around pistons in low pressure compressor.
- ^{3}He reservoir tank is also designed.

◆ Optimization of cold part design (as a prototype, TRL4)

- Parasitic heat load to the mixing chamber
- Reduced flow impedance test between the still and the heat exchanger.
- Recover 1μW at 50mK in negative gravity.

◆ Next coupled test with Demonstration model

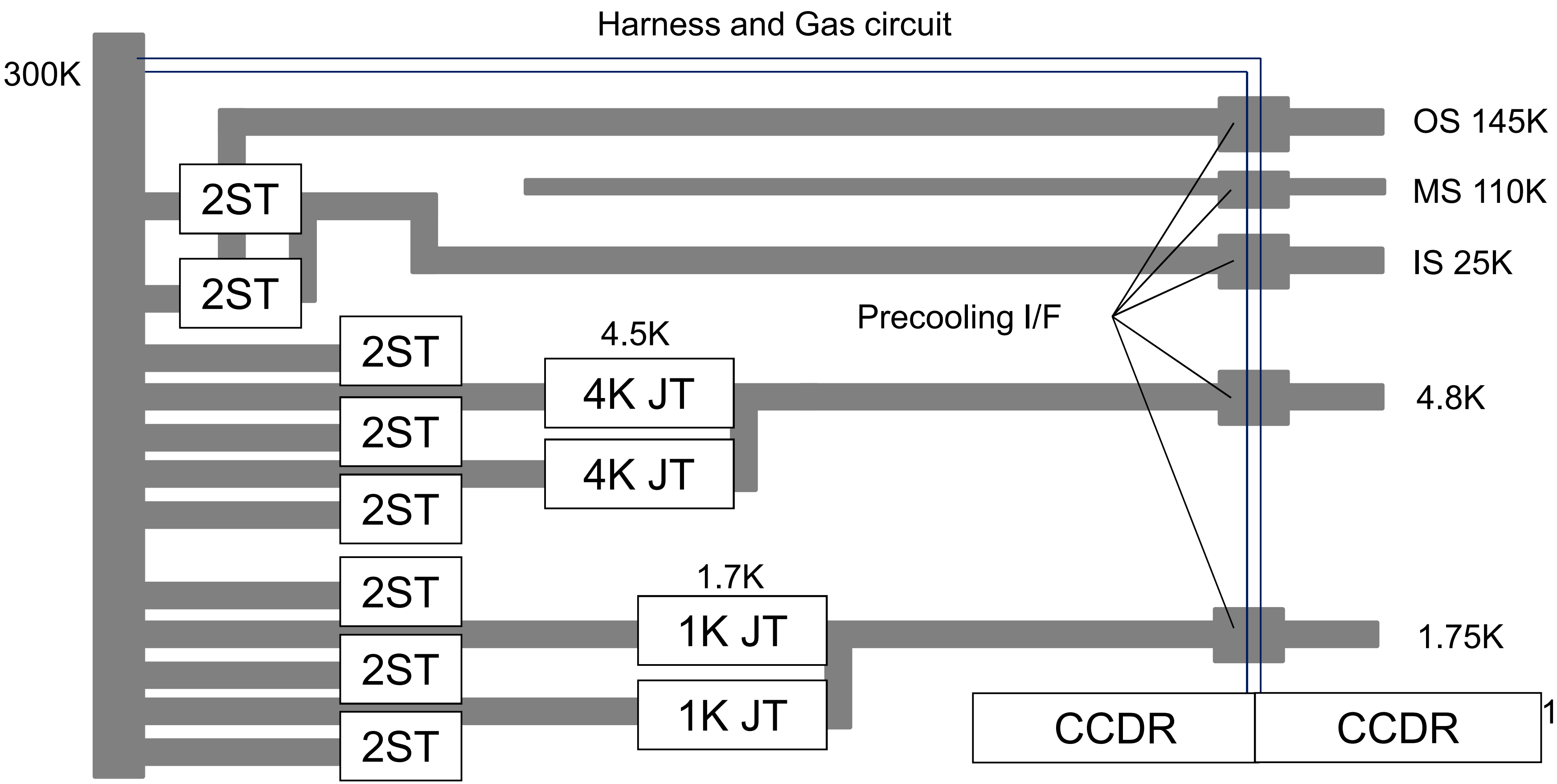
- The CCDR performance test to verify our improvement.
- Validate 50mK I/F and 300mK I/F (including thermal stability).
- Validate launch support structure thermally.
- Validate plug-in compatibility with CEA ADR (sorption cooler + ADR).
- The coupled test between the CCDR and 1K-JT / 4K-JT is also considered.

◆ Engineering model (TRL5)

- Adapted to eventual changes in X-IFU specifications.
- Pre-qualification plan and procedure for all critical components.
- Mechanical testing.

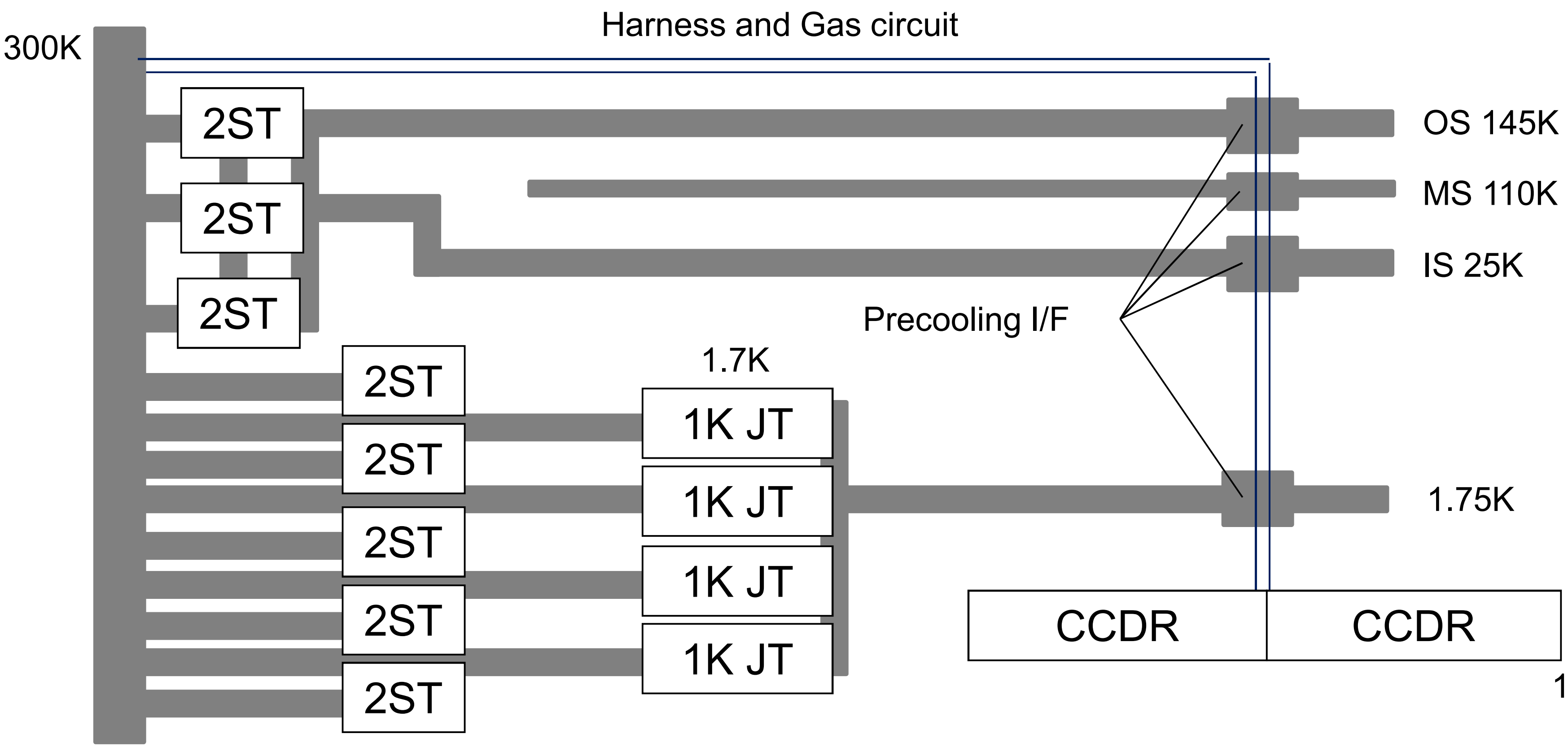
7. Cooling chain with CCDR (1/2)

- 1.75K temperature interface is needed. The heat load is about 5mW.
- (2 × 1K-JT + 3 × 2ST) + (2 × 4K-JT + 3 × 2ST) + (2 × 2ST shield cooler).
- 4K-JT cools the telescope assembly.
- For example, Nominal operation can be done even when one 1K-JT and 4K-JT are both in failure.
- Quite conservative in comparison with other cooling chains.
- More than 20 compressors, electrical power of 730W between 300K and 1.7K.



7. Cooling chain with CCDR (2/2)

- (4 × 1K-JT + 5 × 2ST) + (2 × 2ST shield cooler).
- Easy to verify in the ground test because of few kinds of heat flows in failure modes.
- Heat load to 1K-JTs can be reduced using three 2ST shield coolers.
- More than 24 compressors, electrical power of 700W between 300K and 1.7K.



Summary

- Closed-Cycle Dilution Refrigerator (CCDR) is a key technology to cool down to 50mK with a comparable cooling power as an ADR but a 100% duty cycle in space.

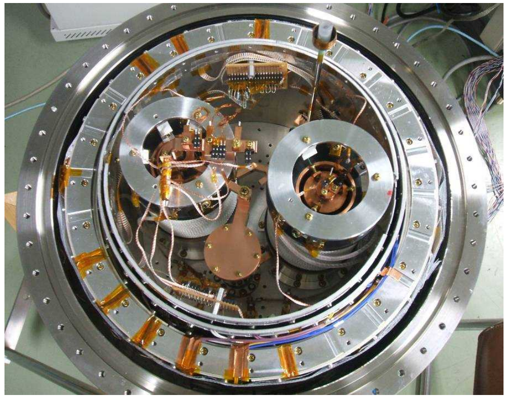
- The coupled test between the dilution refrigerator developed by France and the helium-3 circulator developed by Japan has been performed as a breadboard test of CCDR .

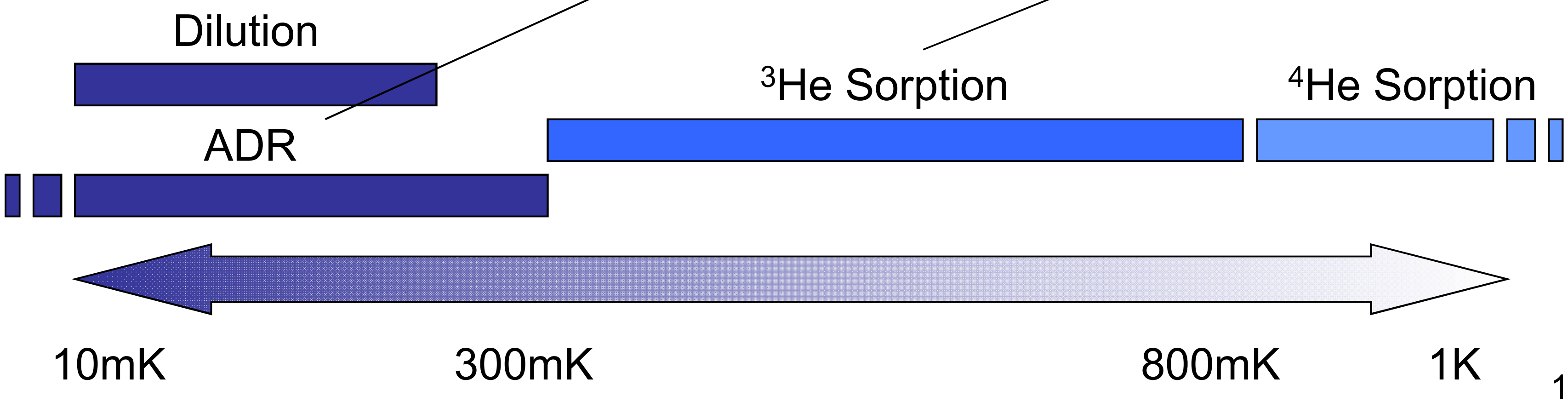
- The coupled test has been obtained 70mK from 18K by circulating the working gas with the ^{3}He compressors system under the heat sink temperature of 1.75K.

- We believe that LiteBIRD has a good opportunity to proceed the CCDR development and to realize the refrigerator in space.

Appendix. 100mK coolers

- ^{3}He (^{4}He) sorption cooler : 300mK --- 1K
- ADR: Adiabatic Demagnetization Refrigerator) : <10mK --- 300mK
- Dilution refrigerator : <10mK --- 200mK





Appendix. Trade off of 100mK cooler

	Pros	Cons
Multi-stage ADR	･Intermediated mass ･Intermediated volume ･possible to be higher starting temperature	･Large magnetic field ･Low cooling power ･Higher rejected heat to pre-cooler
Sorption Cooler + ADR	･Small, low mass ･Large cooling power(300mK)	･Long recycling time, ･Low duty cycle (<80%) ･High pressure ･Not stable temperature(300mK)
Continuous ADR	･Large cooling power ･Intermediated volume ･Continuously operated at 50mK	･Complicated operation ･Large dB ･Concern of number of single point failure
Dilution	･No magnetic field, ･Large cooling power ･Continuously operated at 50mK	･Complicated system ･1K pre-cooler is needed