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**Cryocooler Application for Accelerator and
Development Status of Powerful Cryocooler
at SHI Ltd.**

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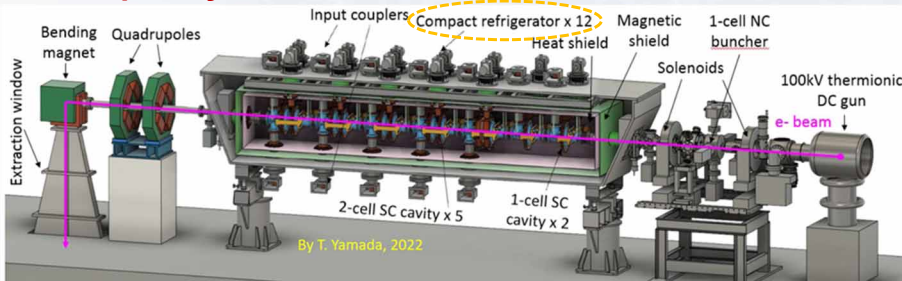
Sumitomo Heavy Industries, Ltd

- Introduction
- Concepts of development and features of GM-JT
- GM-JT system configuration and main specifications
- Evaluation result of prototype model
- Conclusion and feature works

Advances in recent Nb_3Sn cavity development makes possible to operate the cavity at 4.3 K and to design SRF accelerator in which the cavities are cooled directly with small mechanical cryocoolers instead of using LHe cryoplants.

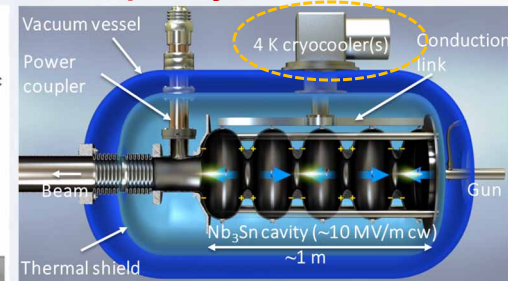
→ Conduction-cooling with cryocoolers greatly simplify the overall design and also contribute for cost saving of an SRF accelerator.

Developed by KEK



- H. Sakai *et al.*, "CONCEPTUAL DESIGN OF THE HIGH-POWER ELECTRON BEAM IRRADIATOR USING NIOBIUM-TIN SUPERCONDUCTING CAVITY", in *proc. IPAC2023*
- O. Tanaka, "Design and beam dynamics study on compact Nb_3Sn accelerator", *TTC2022*

Developed by Fermilab



- J. Thangaraj, "Conduction-cooled SRF accelerator development for industrial applications at Fermilab", *TTC2022*

- However, since the cooling capacity of current cryocooler is small (1~2W at 4.2K), multiple units will be used in combination.
- Larger cooling capacity and higher efficiency is preferable, in terms of power consumption, footprint and maintenance costs.

We have been developing a large-capacity and high-efficiency **4KGM-JT cryocooler system** in the **10 W class at 4.2 K**.

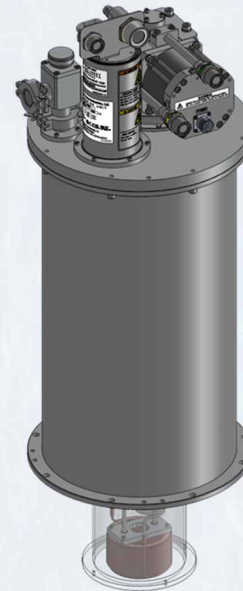
Concepts

- Achieve the world's largest cooling capacity at 4.2K and COP with mechanical small cryocooler.
- Contribute to the development of science and technology by saving energy and reducing CO2.

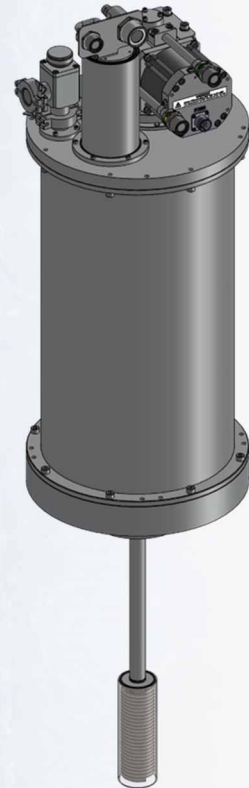
Contributing to the SDGs



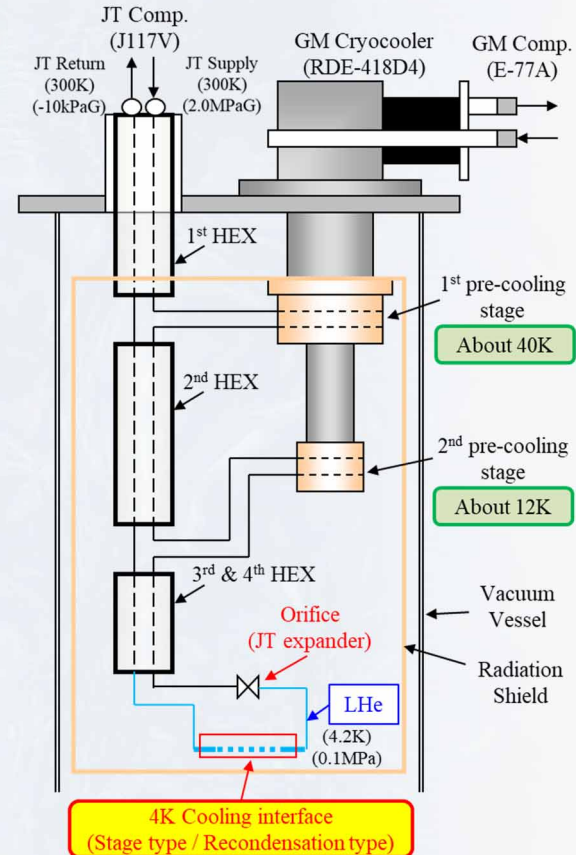
**RJT-100ST
(Stage)**



**RJT-100RC
(Recondenser)**



- GM-JT cryocooler is Joule-Thomson (JT) cryocooler using two-stage Gifford-McMahon (GM) cryocooler as pre-cooler of GHe.
- The 4K cooling capacity utilizes the latent heat of LHe, and its features are **large capacity and high efficiency** compared to GM and Pulse Tube (PT) cryocoolers.
- Due to the large capacity, **the number of cryocoolers can be reduced** at customer system, it's leading to **reduction in maintenance costs**.
- There is no pressure pulsation due to valve like GM, so **temperature fluctuation is very low**.

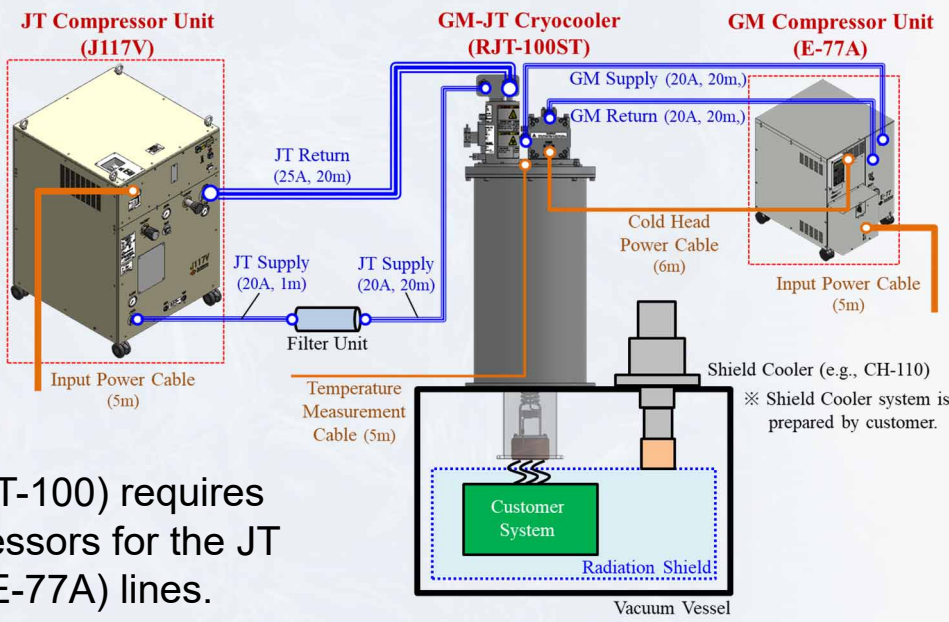


GM-JT Cryocooler System Configuration



	Specification
Cooling Capacity	9W @4.2K
Power Consumption	14.1kW or less※ (GM:7.5+JT:6.6)

※Except for shield cooler system.



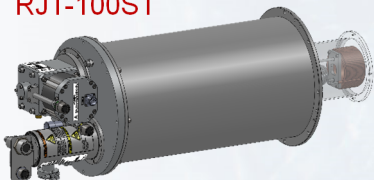
- GM-JT cryocooler (RJT-100) requires two separately compressors for the JT (J117V) and the GM (E-77A) lines.
- Shield cooling against radiation heat requires a separately shield cooler. (Shield cooling system is prepared by customer.)
- Since compressor units have inverters, **this system can adjust cooling capacity and power consumption to lower value than above.**

Main Development Specifications

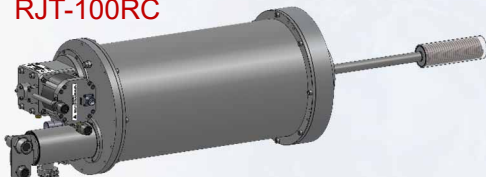
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GM-JT cryocooler

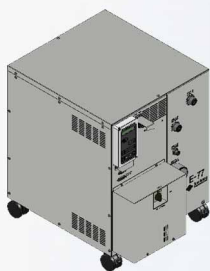
RJT-100ST



RJT-100RC



Compressor



E-77A (For GM)



J117V (For JT)

	Specification
Cooling Capacity	RJT-100ST(Stage type): 9.0 W @4.2 K RJT-100RC(Recondensation type): 8.5 W @4.2 K
Power Consumption	14.1 kW or less (J117V: 6.6kW + E-77A: 7.5kW)
Compressors Input power	<ul style="list-style-type: none"> LV : AC200V class at 50/60Hz, 3 phase HV : AC400V class at 50/60Hz, 3 phase
Compressors Cooling System	Water cooling (Both J117V and E-77A)
Environmental Condition	Indoors (without dew) Ambient temperature: 5 ~ 28 deg.C Humidity: 25 ~ 85 %RH
Outside Dimensions, (Mass)	<ul style="list-style-type: none"> RJT-100ST : Φ350mm H: 1040mm (60kg) J117V : W:690mm D:800mm H:1070mm (340kg) E-77A : W:450mm D:485mm H:601mm (120kg)
Standards	<ul style="list-style-type: none"> UL : RJT-100→UL 471 J117V→UL 60335-2-89 CE Machinery Directive : 2006/42/EC CE EMC Directive : 2014/30/EU CE RoHS Directive : 2011/65/EU+2015/863/EU UKCA
Maintenance	Frequency: Every 10,000h (※shortest object)

Specification comparison of SHI line-up



	GM: RDE-418D4	PT: RP-182B2S	GM-JT: RJT-100ST
Compressor unit	F-50 × 1	F-100 × 1	E-77A (For GM) × 1 J117V (For JT) × 1
Cooling capacity	2.0 W at 4.2 K	1.5 W at 4.2 K	9.0 W at 4.2 K
Power consumption	7.5 kW	14.5 kW	14.1 kW
COP ※1	2.7×10^{-4}	1.0×10^{-4}	6.4×10^{-4}
Cool down time ※2	<1 h	<1 h	Approx. 13 h
Reaching temperature	<3.5 K	<2.8 K	4.2 K
Limit of max. heat load	No limit	No limit	9.0W or less
Orientation	Free	Vertical	Vertical Horizontal ※3

※1: COP=4.2K cooling capacity(W) / Power consumption(W)

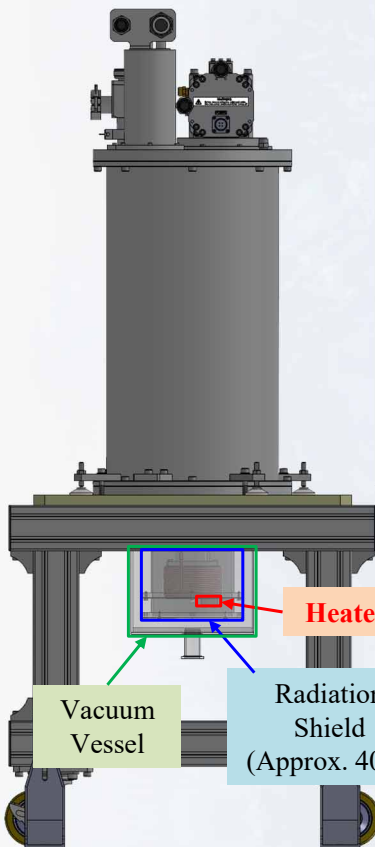
(Catalog spec)

※2: These values are without heat load.

※3: Horizontal is available optionally. The cooling capacity is almost constant regardless of the Cryocooler orientation.

4K cooling capacity and COP of GM-JT are better than GM and PT.

Evaluation Results of Prototype Model (RJT-100ST)



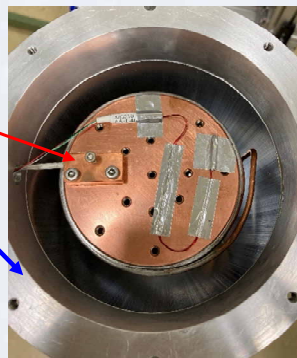
Conditions (Standard)

«Filling pressure»
 J117V: 1.23MPaG (20deg.C)
 E-77A: 1.72MPaG (20deg.C)

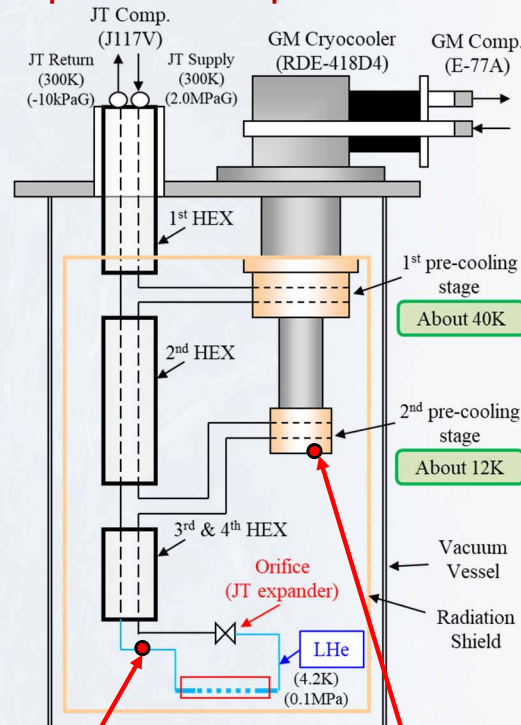
«Operating frequency»
 J117V
 Comp.1: 78Hz, Comp.2:41Hz
 E-77A
 Comp. : 60Hz, C/H: 60Hz

«Cryocooler orientation»
 Vertical

«Temperature measurement»
 Sensor: Cernox CX-1050-AA

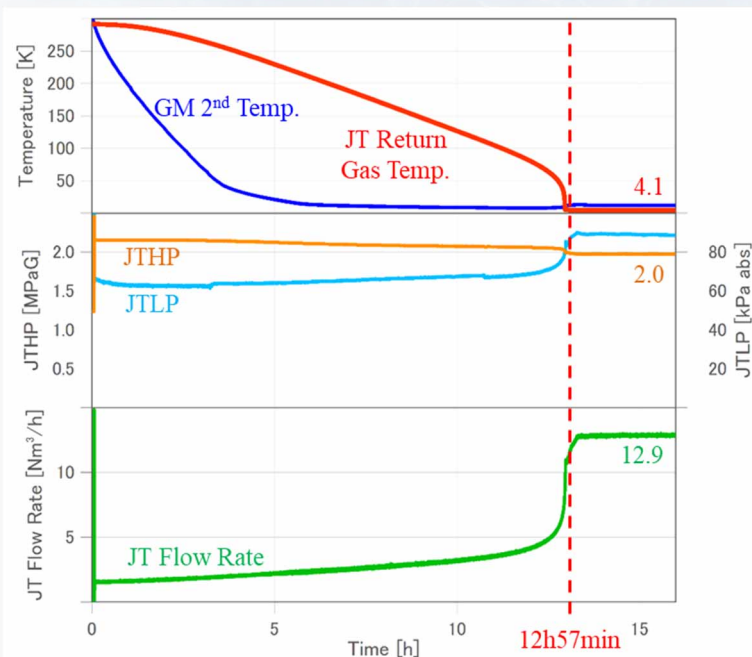


Temp. measurement position



JT Return Gas Temp. **GM 2nd Temp.**

※These sensor are included in the products.

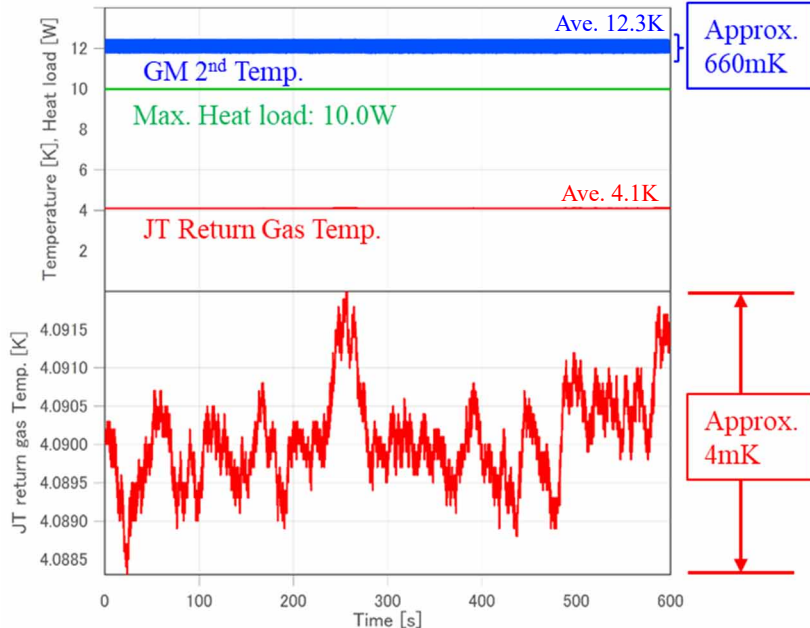


«Cool down process»

- Cooling started at about 300 K.
↓
- JT line was gradually pre-cooled and JT flow rate gradually increased.
↓
- When the JT line was pre-cooled to around 40 K, temperature drops rapidly due to the JT expansion, also JT flow rate rapidly increased.

Cool down time is defined as the time it takes for the JT return gas temp. to reach 4.3K, The cool down time was approx. 13 hours without heat load.

※ Cool down time will vary depending on the heat capacity and the heat penetration of the object to be cooled.



- The heat load was increased in 0.1 W increments to obtain the maximum heat load that could be kept 4.2K or less.
- At a heat load of 10.1 W, JT return gas temp. kept rising due to overheating.

- The cooling capacity achieved **10.0 W at 4.2 K or less**.
- The temperature fluctuation's amplitude of GM-JT was **about 4 mKp-p and 1/165 smaller** than that of our GM because it uses latent heat of helium and there is no pressure pulsation.

Capacity Control (Save Mode)

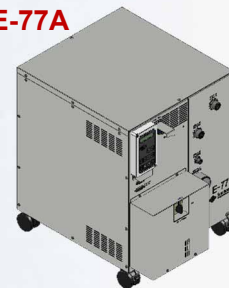


In actual operation, it is preferable to be able to reduce the cooling capacity by capacity control according to usage **to reduce the power consumption.**

→ This system has a **capacity control (Save mode)** function.

Cooling Capacity	Power Consumption	E-77A Comp. Frequency	J117V Operation Mode
Maximum (9.0W)	Maximum (14.1kW)	60Hz	Standard
Middle range		30Hz ~ 60Hz	Standard
Minimum		30Hz	Save mode

E-77A



J117V



«Adjusting method»

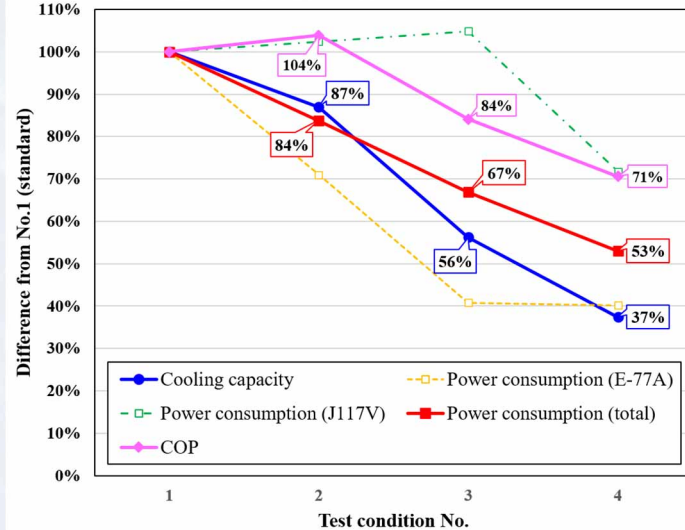
- To adjust “Middle range”, please change only the comp. operating frequency of E-77A between 30Hz and 60Hz **by operating touch panel or using serial (RS232C) communication.**
- To adjust “Minimum”, please also change the operation mode of J117V to “Save mode” **by operating front panel switch or using remote I/O port.**

Performance of Capacity Control

We evaluated under 4 conditions to confirm the relationship between cooling capacity and power consumption in case of capacity control.

Test conditions

No.	E-77A Comp. Frequency	J117V Operation
1	60Hz (standard)	Standard
2	45Hz	
3	30Hz	
4	30Hz	Save mode

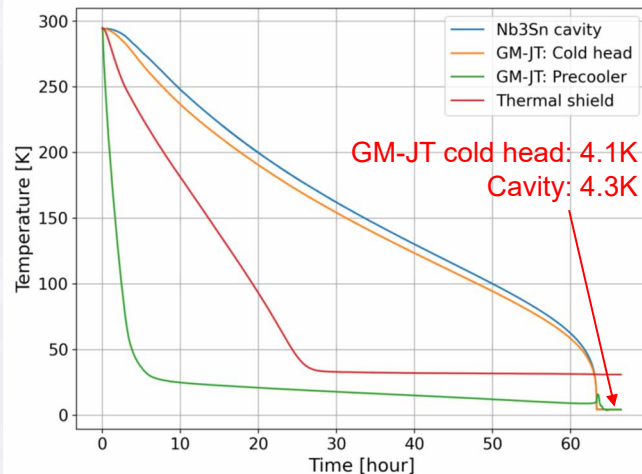
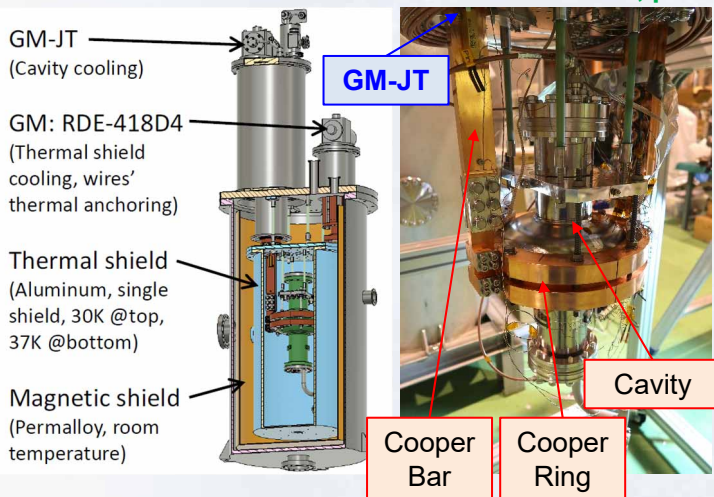


- When only the operating frequency of the E-77A was reduced to 30 Hz (No.3), the **cooling capacity was reduced to 56 %** and **total power consumption was reduced to 67 %** of standard condition (No.1)
- When the operation mode of J117V was also changed to 'save mode' (No.4), the **cooling capacity was reduced to 37 %** and **total power consumption was reduced to 53 %** of standard condition (No.1).

Nb₃Sn Cavity Cooling Result (at KEK)

We lent the prototype of GM-JT cryocooler to KEK, and first conduction cooling test of Nb₃Sn cavity was performed by KEK.

For details of this evaluation, please refer to KEK Yamada-san's report (WEPWB081).



- Copper bar from the GM-JT's 4K cold head was connected to the copper rings surrounded cavity equator, and cavity is cooled.
- Cavity was successfully cooled down to 4.3 K in 63 hours.

We will continue to study to shorten the cool down and to investigate the effect of vibration of GM-JT in customer system.

Conclusion

We have been developing a large-capacity and high-efficiency 4KGM-JT cryocooler system in the 10 W class at 4.2 K, and we evaluated the performance using prototype of RJT-100ST.

- The cooling capacity achieved 10 W at 4.2 K or less and the temperature fluctuation's amplitude was extremely small at 4 mKp-p.
- By reducing the cooling capacity to 37 % of the standard condition due to capacity control, the power consumption can be reduced to maximum 53 % of the standard condition.
- We lent the prototype of GM-JT cryocooler to KEK, and first conduction cooling test of Nb₃Sn cavity was performed by KEK. Cavity was successfully cooled down to 4.3 K in 63 hours.

Future Works

- To study to shorten the cool down time.
- To investigate the effect of vibration of GM-JT in customer system.

- We are working on standards compliance and products evaluation.
- Orders will be accepted from the end of October 2023.

※Development schedule is subject to change without notice.



Thank you for your attention.