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CRYOCOOLER APPLICATION FOR ACCELERATOR AND DEVELOPMENT STATUS OF POWERFUL CRYOCOOLER AT SHI Ltd.

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Abstract

Advances in recent Nb3Sn cavity development makes possible to operate the cavities with Qo ~ 1xE10 at 4.3 K and to design SRF accelerator in which the cavities are cooled directly with small mechanical cryocoolers instead of using liquid helium. Conduction-cooling with cryocoolers greatly simplify the overall design and also contribute for cost saving of an SRF accelerator, making the SRF technology feasible for industrial accelerators. However, in the case of using current cryocooler systems (like Gifford-McMahon cryocooler, Pulse-Tube cryocooler, etc.) for the conduction-cooling, since the cooling capacity per unit is small, multiple units will be used in combination depending on the required cooling capacity, it will cause problems in terms of power consumption (efficiency), footprint, and maintenance costs. Therefore, SHI have been developing a large-capacity and high-efficiency 4KGM-JT (Gifford-McMahon-Joule-Thomson) cryocooler system in the 10 W class at 4.2 K. This contribution will report the overview of this cryocooler system and its status of development.

INTRODUCTION

Currently, SRF accelerators require liquid helium (LHe) cryoplants, often subcooled to 2 K, to cool the cavities well below the superconducting transition temperature. Whereas niobium (Nb) has been the material of choice for SRF cavities, Nb_3Sn has emerged as a viable alternative in recent years [1]. Since the critical temperature of Nb_3Sn is 4.3 K, instead of 2 K of Nb, it makes possible 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, making the SRF technology feasible for industrial accelerators.

However, in the case of using current cryocooler systems (like Gifford-McMahon cryocooler, Pulse-Tube cryocooler, etc.) for the conduction-cooling, since the cooling capacity per unit is small (1~2 W at 4.2 K), multiple units will be used in combination depending on the required cooling capacity, it will cause problems in terms of power consumption (efficiency), footprint, and maintenance costs.

Therefore, SHI have been developing a large-capacity and high-efficiency 4KGM-JT (Gifford-McMahon-Joule-Thomson) cryocooler system in the 10 W class at 4.2 K [2]. In this contribution we present the overview of this cryocooler system and its status of development.

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OUTLINE OF 4KGM-JT CRYOCOOLER SYSTEM

RJT-100 4KGM-JT Cryocooler

Figure 1 shows the schematic of RJT-100 4KGM-JT cryocooler. RJT-100 is Joule-Thomson (JT) cryocooler using RDE-418D4 two-stage Gifford-McMahon (GM) cryocooler as pre-cooler of gas helium (GHe). Normal temperature and high pressure GHe supplied from JT compressor unit (J117V) is pre-cooled by RDE-418D4 and Four heat exchangers (HEX). The pre-cooled GHe is expanded by fixed orifice (JT expander) and part of GHe is liquified at 4 K cooling interface. Heat exchanged GHe with the customer system at 4 K cooling interface is returned to J117V after heat exchange with the high pressure GHe at HEX. Note that the temperature of the 4 K cooling interface is uniquely determined by saturated vapor pressure of helium, and in this system, the temperature is controlled 4.2 K or less by adjusting the JT return pressure of J117V to a constant.

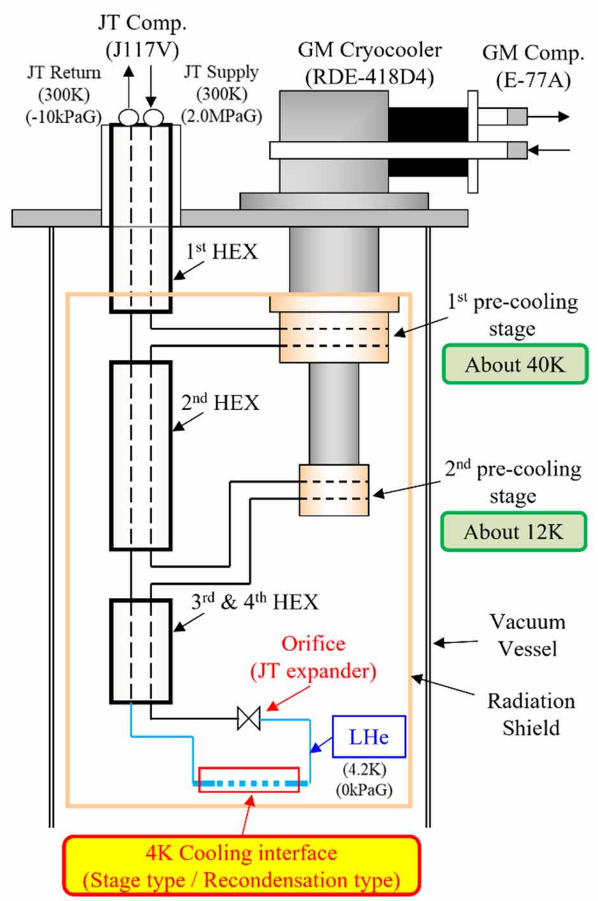

Figure 1: Schematic of RJT-100 4KGM-JT cryocooler.

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Since the 4K cooling capacity of RJT-100 utilize the latent heat of LHe, its features are large capacity and superior efficiency compared to GM and Pulse Tube (PT) cryocoolers. And the number of cryocoolers can be reduced at customer system, it's leading to reduction in maintenance costs.

System Configuration

Figure 2 shows the 4KGM-JT cryocooler system configuration. This cryocooler system consists of RJT-100 4KGM-JT cryocooler and two separately compressor units J117V (for JT line) and E-77A (for GM line). And this cryocooler system requires a separately shield cooling system against radiation heat. However, the required cooling capacity of the shield cooler depends on the customer system, so the shield cooling system is prepared by customer.

E-77A is mounted with a helium compressor, which supplies high-pressure GHe to RDE-418D4 and also provides power to operate the cold head motor. This compressor unit can adjust the operating frequency of the compressor and the cold head motor using an inverter, and the former can be used for capacity control as described later.

J117V has two helium compressors connected in series for two-stage compression of GHe, and like the E-77A, the operating frequency of each compressor can be adjusted by inverters. In addition, since GHe is liquified in the RJT-100 due to the JT expansion, large capacity buffer tanks are mounted between JT supply and JT return line to prevent GHe shortage during cooling, and also JT supply and JT return pressure can each be regulated to a constant pressure using pressure regulators mounted both ends of buffer line.

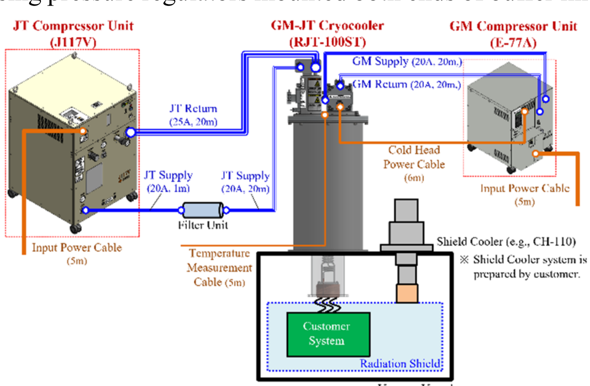

Figure 2: 4KGM-JT cryocooler system configuration.

4KGM-JT CRYOCOOLER SYSTEM MAIN DEVELOPMENT SPECIFICATIONS

Table 1 shows the main development specifications of 4KGM-JT cryocooler system. The 4 K cooling interface are available in stage type (RJT-100ST) or recondensation type (RJT-100RC) and outlines are as shown in Fig. 3. The stage of RJT-100ST can cool customer system with conduction cooling, and the recondenser of RJT-100RC can condense GHe into LHe in customer's helium pot.

The cooling capacity of RJT-100ST is 9.0 W or more at 4.2 K and that of RJT-100RC is 8.5 W or more at 4.2 K, which is achieved with a total (J117V and E-77A) power consumption of 14.1 kW or less. Note that, in the case of RJT-100RC, the cooling capacity is decreased from 9.0 W to 8.5 W due to the influence of heat penetration from ambient into recondenser.

Table 1: Specifications of 4KGM-JT Cryocooler System

Specifications	
4K cooling interface	Stage type (RJT-100ST) Recondensation type (RJT-100RC)
Cooling capacity	RJT-100ST: 9.0 W at 4.2 K RJT-100RC: 8.5 W at 4.2 K
Power consumption	Total: 14.1 kW or less (J117V: 6.6 kW + E-77A: 7.5 kW)
Power requirements	J117V: 13 kVA or more E-77A: 12 kVA or more
Environmental condition	Indoors (without dew) Ambient temperature: 5 ~ 28 deg.C Humidity: 25 ~ 85 %RH
Comp. cooling	J117V and E-77A: Water cooling
Outside dimensions	RJT-100ST: ϕ350 x H1040 mm RJT-100RC: ϕ350 x H1435 mm J117V: W690 x D800 x H1070 mm E-77A: W450 x D485 x H601 mm
Mass	RJT-100ST: 60 kg RJT-100RC: 70 kg J117V: 340 kg, E-77A: 120 kg
Maintenance	Frequency: Every 10,000 h (Above is the shortest object)

*Values in the table are T.B.D.

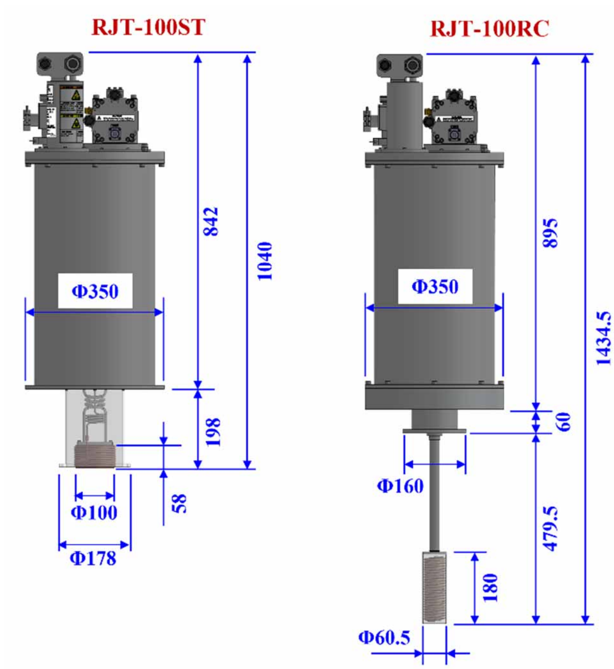

Figure 3: 4K cooling interface of RJT-100.

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The required power line voltage of J117V and E-77A are 3 phase 200 V class (LV) or 400 V class (HV), and the required power of J117V is 13 kVA or more and that of E-77A is 12 kVA or more. Installation is possible indoors at ambient temperatures 5~28 deg.C and relative humidity from 25~85%RH without dew. The cooling system of both J117V and E-77 are water cooling. The shortest maintenance cycle is every 10,000 hours that correspond replacing the GM cold head's parts and JT gas cleaning, but each component has its own maintenance cycle.

Table 2 shows the specifications comparison with GM and PT cryocooler of SHI line-up. The 4.2 K cooling capacity and COP of GM-JT cryocooler are better than GM and PT cryocooler. However, the cool down time is longer, it takes about 13 hours without heat load. In addition, since GM-JT cryocooler utilizes the latent heat of LHe, the reaching temperature does not change (stable at 4.2 K) due to the heat load unlike GM and PT cryocooler, and the limit heat load is 9.0 W or less. About the orientation of GM-JT cryocooler, the 4 K stage is oriented vertical downward as standard, also horizontal is available optionally, and the cooling capacity is almost constant regardless of the orientation.

Table 2: Specifications Comparison with GM and PT Cryo of SHI Line-up

Item	4KGM RDK-418D4	4KPT RP-182B2S	4KGM-JT RJT-100ST
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 at 60 Hz (F-50 x 1)	14.5 kW at 60 Hz (F-100 x 1)	14.1 kW at 60 Hz (E-77A x 1, J117V x 1)
COP [1]	2.7 x 10^{-4}	1.0 x 10^{-4}	6.4 x 10^{-4}
Cool down time [2]	< 1 h	<1 h	Approx. 13h
Reaching temp.	< 3.5 K	< 2.8 K	4.2 K
Limit heat load	No limit	No limit	9.0 W or less
Orientation	Free	Vertical	Vertical, Horizontal [3]

EVALUATION RESULTS OF PROTOTYPE MODEL OF RJT-100ST

Test Configuration

Figure 4 shows the test configuration of prototype model of RJT-100ST. The 4 K stage is covered by radiation shield cooled by GM 1st stage to about 40 K and the heat load is inputted by heater mounted on the surface of 4 K stage.

Table 3 shows the test conditions of prototype model of RJT-100ST. Note that these filling pressures and operating frequencies are decided to be proper pressure balance in each line during the operation.

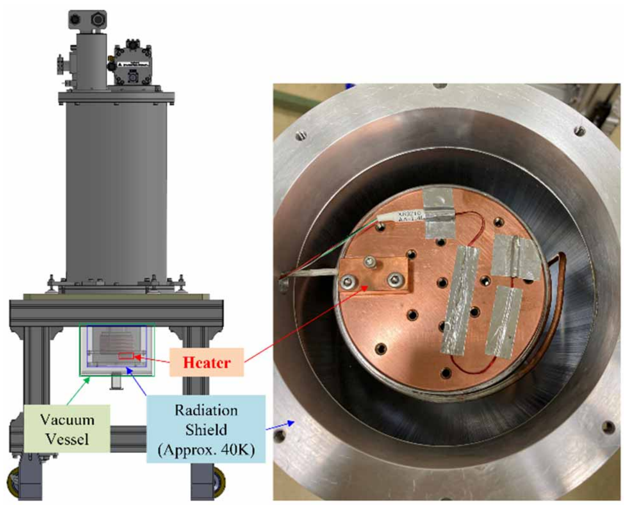

Figure 4: Test configuration.

Table 3: Test Conditions

Item	Condition
Filling pressure	J117V: 1.23 MPaG at 20 deg.C E-77A: 1.72 MPaG at 20 deg.C
Operating frequency (Standard)	J117V 1st Comp.: 78 Hz, 2nd Comp.: 41 Hz E-77A Comp.: 60 Hz, Cold Head: 60 Hz
Orientation	Vertical
Temperature measurement [4]	Sensor: Cernox CX-1050-AA Point 1: JT return gas temp.[5] 2: GM 2nd stage temp.

1 COP = 4.2 K cooling capacity (W) / Power consumption (W)
2 These values are without heat load.
3 Horizontal is available optionally. The cooling capacity is almost constant regardless of the orientation.

4 These sensors are included in the products and customer is available to measure temperature.
5 This sensor is mounted downstream of the 4K cooling interface and this temperature is almost same as the 4K stage temperature.

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Performance of Cool Down

Figure 5 shows the time-series of JT return gas and GM 2nd stage temperature, JT supply and JT return pressure, and JT flow rate during the cool down process. Cooling started at room temperature (about 300 K) and JT flow rate gradually increased as the JT return gas temperature gradually decreased. The cool down time is defined as the time it takes for the JT return gas temperature to reach 4.3 K, and it was 12 hours 57 min. Note that this result was obtained without heat load, and it will vary depending on the heat capacity and the heat penetration of the object to be cooled.

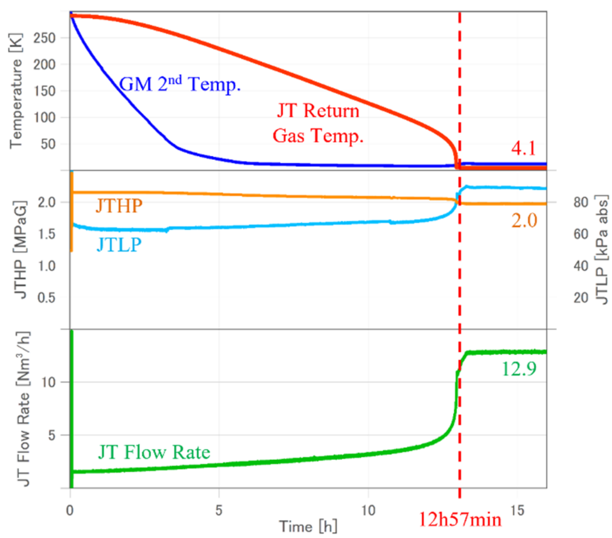

Figure 5: Performance of cool down.

Cooling Capacity and Temperature Fluctuation

Upper side of Fig. 6 shows the time-series of JT return gas and GM 2nd stage temperature, inputted heat load when the heat load was maximum, and lower side shows the magnification of JT return gas temperature. The cooling capacity achieved 10.0 W at 4.2 K or less. And the temperature amplitude of RJT-100ST was about 4 mKp-p and 1/165 smaller than that of GM 2nd stage temperature (about 660 mKp-p) because it uses latent heat of LHe and there is no pressure pulsation.

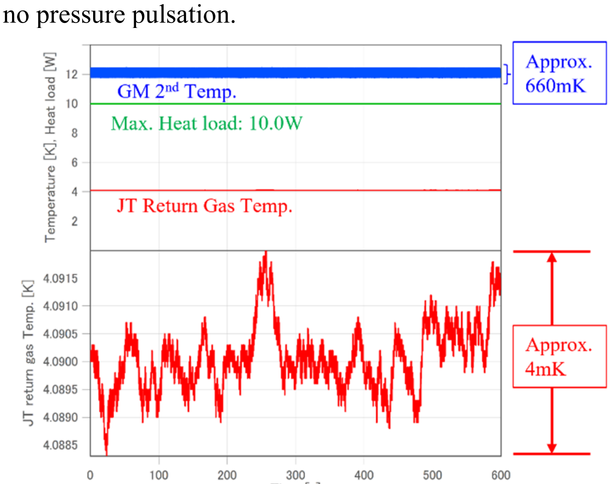

Figure 6: Performance at maximum heat load.

Performance of Capacity Control (Save Mode)

Although this 4KGM-JT cryocooler system can achieve the cooling capacity 9.0 W or more at 4.2 K with the power consumption 14.1 kW or less, considering actual operation, it is preferable to be able to reduce the cooling capacity by capacity control according to usage to reduce the power consumption. For this reason, this cryocooler system has a capacity control function. For capacity control, 'only E-77A' or 'both E-77A and J117V' settings must be changed according to the required cooling capacity.

In this evaluation, the system was operated four conditions shown in Table 4 to confirm the relationship between cooling capacity and power consumption in case of capacity control. First, No.1 was the standard condition same as in Table 3. Then, No.2 and No.3 were changed only the compressor operating frequency of E-77A to 45 Hz and 30 Hz from No.1. Finally, No.4 was changed the operation mode of J117V to 'save mode' from No.3.

Note that when the operation mode of J117V is changed to 'save mode', the JT supply line is throttled and the JT supply pressure of RJT-100 is decreased, which lowers the JT flow rate and reduces the cooling capacity. However, because the JT flow rate is reduced, the J117V compressors operating frequency must be lower to ensure proper pressure balance, which also reduces the power consumption consequently.

Table 4: Test Conditions of Capacity Control

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

*Other conditions are the same as in Table 3.

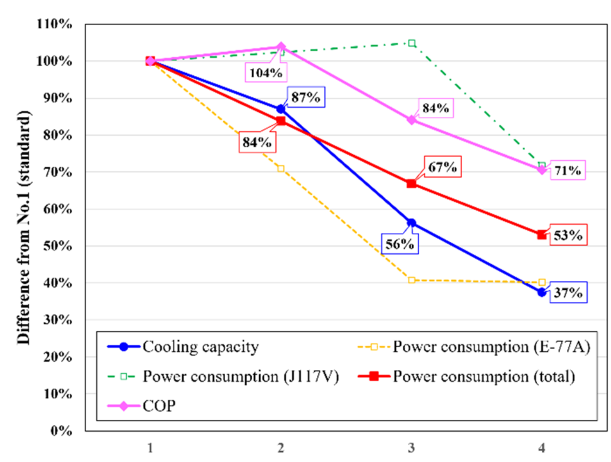

Figure 7: Performance of capacity control.

Figure 7 shows the result of performance of capacity control. 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

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67% of standard condition (No.1). In addition, 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). Also, the COP was reduced to 71% of the standard condition by capacity control, which is because this system is designed to be more efficient in the standard condition.

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 model of RJT-100ST.

Although the cool down time was about 13 hours without heat load, we confirmed that 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.

Also, we confirmed that by reducing the cooling capacity to 37% of the standard condition, the power consumption can be reduced to maximum 53%.

In the future, we will continue to investigate the effect of vibration of GM-JT cryocooler in customer system and to study to shorten the cool down time.

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