Concept of a Cryogenic System for a cryogen-free 25 T superconducting magnet

TOSHIBA Leading Innovation

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I. Background

A new 25 T cryogen-free magnet using a REBCO insert coil in the inner coil of outer low-temperature superconducting (LTS) coils wound with NbTi and Nb3Sn is currently under development at Tohoku University. The ac-loss of the REBCO insert coil during the specified field ramping time of 60 min. will produce a heat load of approximately 8.8 W. Meanwhile, to provide protection from the leakage field of high magnetic fields, the cryocoolers must be arranged at positions away from the coils, so that a long-distance cooling technique is required

II. Objectives

We discuss the concept of a cryogenic system for a 25 T cryogen-free magnet, in which the cooling systems of the LTS coils and the REBCO coil are separated. They are independently cooled to different operating temperatures of 4 K and 10 K.

III. Concept of cryogenic system

■ Cooling capacity of cryocoolers

A REBCO coil has a high critical current density in practical use at 10–40 K, and it does not necessarily need to be cooled at 4 K.

Above4 K, a GM cryocooler has a higher cooling capacity of 10 W at 8 K (1.5 W at 4.2 K) than that of a GM/JT cryocooler at 4 K and is cheaper.

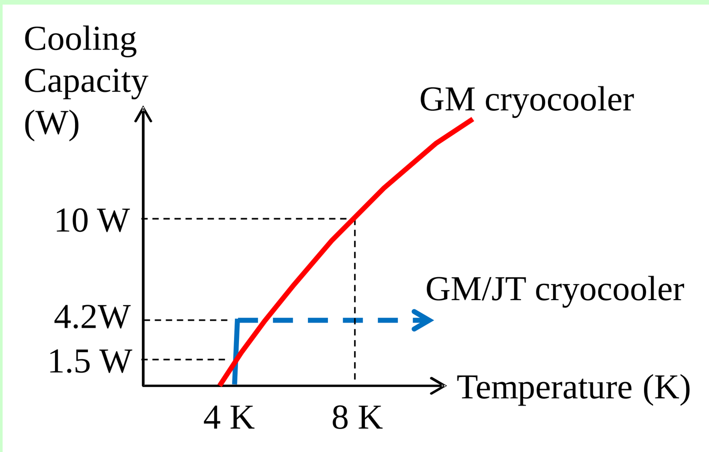

Fig. 1. Schematic drawing of the cooling capacity of the GM and GM/JT cryocoolers.

■ Concept

The cooling systems of the LTS coils and that of the REBCO coil were separated, and the coils were independently cooled to different operating temperatures of 4 K and 10 K.

■ Long –distance cooling

The LTS coils were cooled by GM/JT cryocoolers in which a cooling pipe is extended to the LTS coils, based on the design of the cooling system for the previously developed 18 T and 20 T cryogen-free magnets.

On the other hand, the REBCO coil was cooled by circulating helium gas by using GM cryocoolers and a helium compressor. In both cases, the temperature difference of the heat transfer is independent of the distance over which the helium mist and gas circulate.

Table 1. Specifications of the 25 T cryogen-free magnet

Parameters	HTS	LTS1	LTS 2	LTS 3	LTS 4	LTS5
Conductor	REBCO	Nb3Sn	Nb3Sn	Nb3Sn	NbTi	NbTi
Inner diameter (mm)	102	300	372	458	545	628
Outer diameter (mm)	276	366	452	539	622	712
Coil height (mm)	408	540	628	628	628	628
Magnetic field contribution (T)	11.5	2.43	2.91	2.73	2.69	3.24

IV. Cooling system of the LTS coils

■ Cooling circuit

Since the LTS coils have a large heat capacity compared with the REBCO coil, a large cooling capacity is required for the initial cooling. Although the cooling capacity of the GM/JT cryocooler is large at 4 K, it is small from room temperature to about 4 K. The cooling pipes of the JT system are branched, and this bypass piping is used in the three modes.

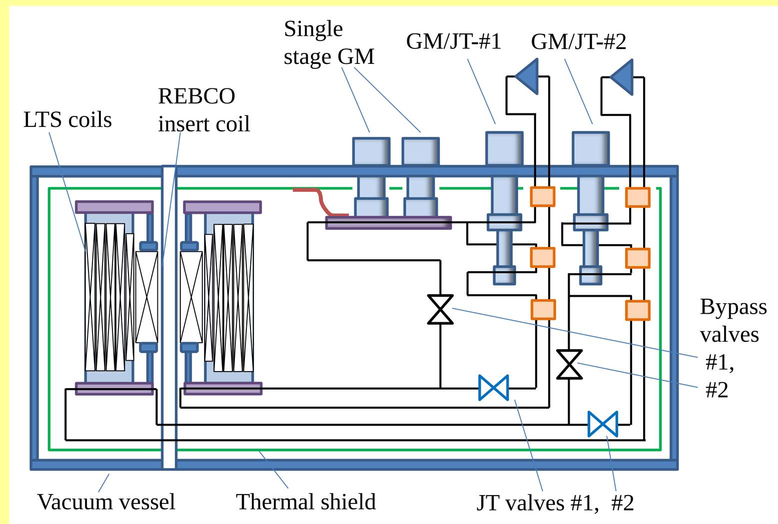

Fig. 2. Cooling circuit of the LTS coils.

Table 2. Opening and closing of the bypass piping in the three modes.

Valve	Mode 1 (300 – 50 K)	Mode 2 (50 – 20 K)	Mode 3 (20 – 4 K)
Bypass-#1	Open	Close	Close
Bypass-#2	Open	Open	Close
JT-#1	Open	Open	Open
JT-#2	Open	Open	Open

■ Initial cooling time

The calculated result of the LTS coil temperature at initial cooling demonstrates that the initial cooling time is estimated at about 312 hours (13.0 days).

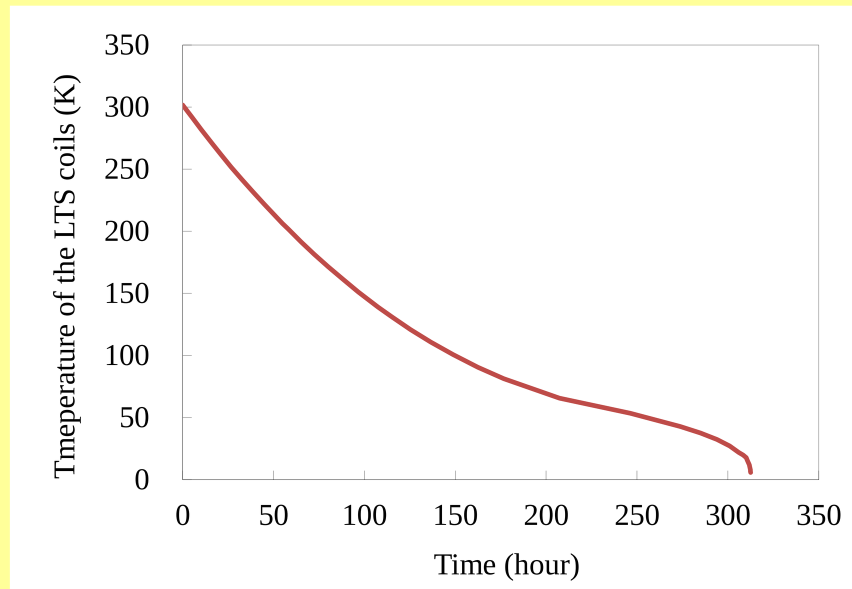

Fig. 3. Calculated result of the time variation of the LTS coil temperature at initial cooling.

■ Heat loads at 4 K

The heat loads to the two GM/JT cryocoolers at 4 K is listed in Table 3. The heat invasion from the support of the REBCO coil is 37 mW, which is small enough compared with the total heat load of 5.6 W. The heat loads can be cooled by the two GM/JT cryocoolers with 4.2 W-class cooling capacities at 4.3 K.

Table 3. Heat loads to the GM/JT cryocoolers at 4 K

Heat load	Value
AC-loss of the LTS coils (W)	2.63
Joule loss of the junctions (W)	0.869
Heat invasion from the support (W)	0.189
Heat invasion from the support of the REBCO coil (W)	0.037
Thermal radiation (W)	0.151
Heat load from the cold stage of the power lead (W)	1.7
Total (W)	5.58

V. Cooling system of the REBCO coil

■ He gas circulating system

For the long-distance heat transfer of about 1.5 m from the cooling head of the GM cryocoolers to the REBCO coil, the circulating helium gas is cooled by the 1st and 2nd cold stages of the GM cryocoolers through the 1st and 2nd heat exchangers. The gas is circulated by a compressor located in a room-temperature area.

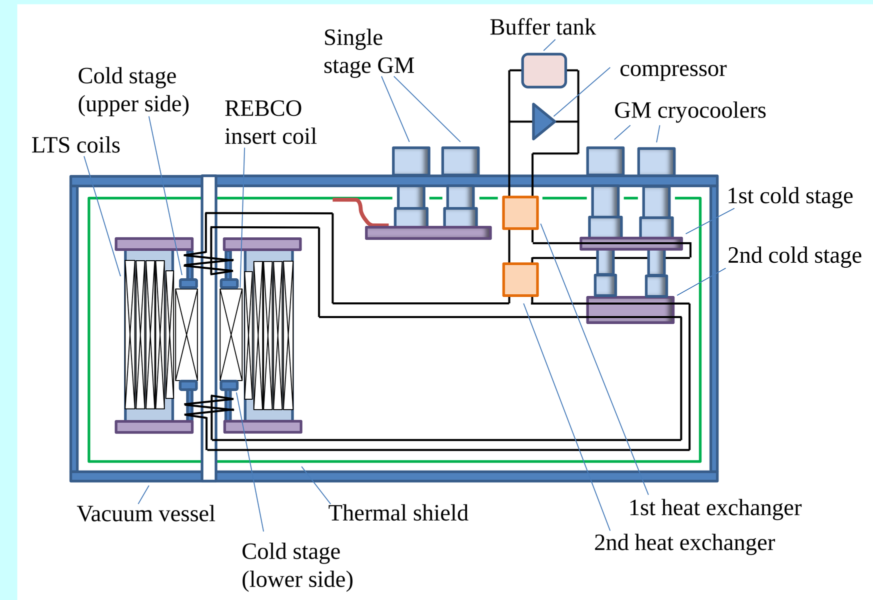

Fig. 4. Schematic diagram of the cooling system of the REBCO coil.

■ Optimization of the gas flow rate at 10 K

The temperatures when the cooling capacity of the GM cryocoolers coincides with the heat loads of 10.3 W listed in Table 4 were calculated at various gas flow rates. The cooling capacity of the two GM cryocoolers is assumed to be 10 W at 8 K (1.5 W at 4.2 K) per unit.

Table 4. Heat loads to the GM cryocoolers at 10 K.

Heat load	Value
AC-loss of the REBCO coil (W)	8.8
Joule loss of the junctions (W)	1.33
Heat invasion from the support (W)	-0.037
Thermal radiation (W)	0.0006
Heat load from the cold stage of the power lead (W)	0.18
Total (W)	10.3

Fig. 6 shows the calculation results of the temperature of the cold stage of the coil and the 1st and 2nd cold stages of the GM cryocoolers. The result shows that the temperature of the cold stage of the coil can be minimized to 8.5 K at a gas flow rate of 0.5 g/s.

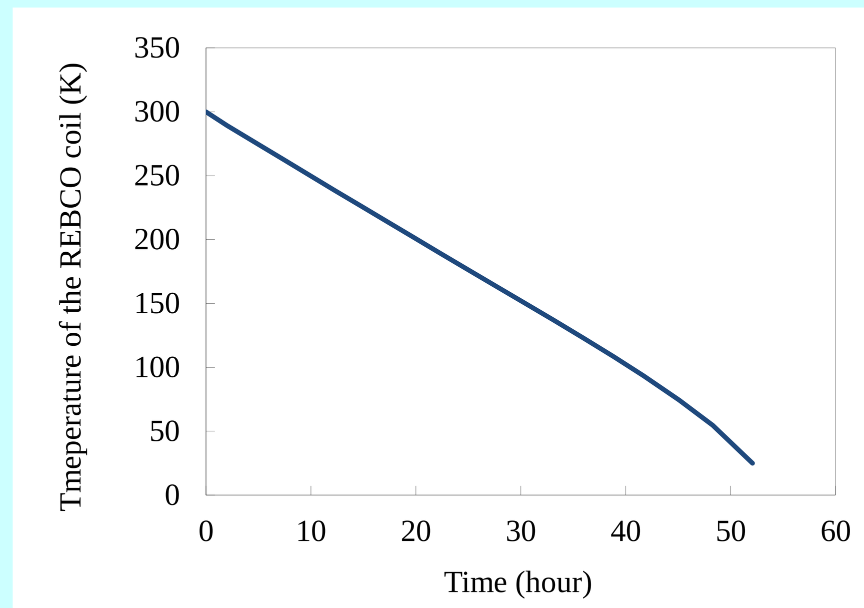

Fig. 5. Calculated result of the time variation of the REBCO coil temperature at initial cooling.

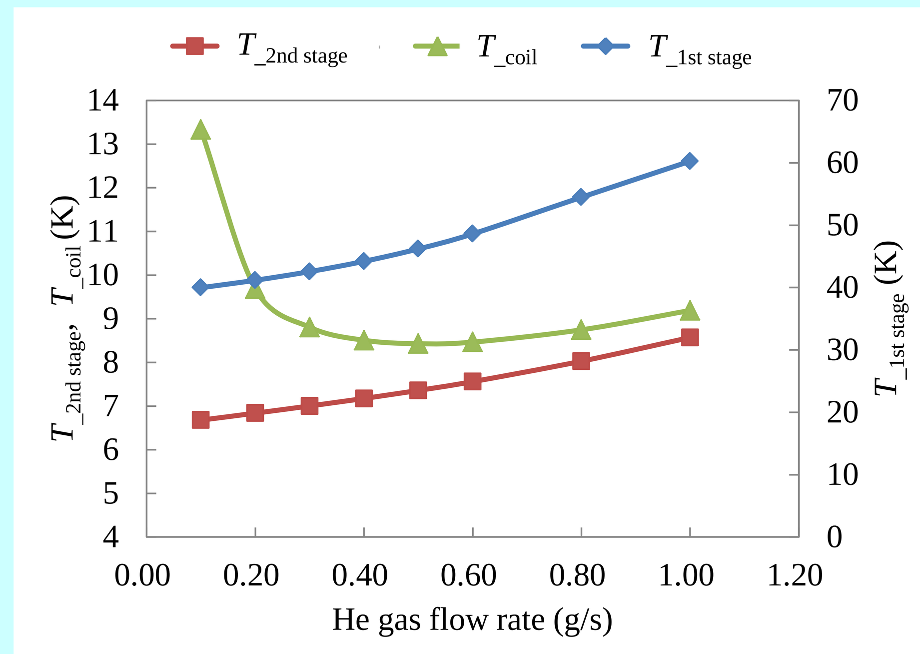

Fig. 6. Calculation results of the temperature of the 2nd cold stage $T_{\_2nd\ stage}$, the temperature of the coil $T_{\_coil}$, and the temperature of the 1st cold stage $T_{\_1st\ stage}$.

VI. Conclusion

- ❖ The LTS coils were cooled by GM/JT cryocoolers using bypass piping, and the initial cooling time was estimated to be about 312 hours (13.0 days). The heat invasion from the support of the REBCO coil was 37 mW, which was small enough compared with the total heat load of 5.6 W. The heat loads of the LTS coils at 4 K can be cooled by the two GM/JT cryocoolers with 4.2 W-class cooling capacities at 4.3 K.
- ❖ For the REBCO coils, we developed a cooling system in which helium gas cooled by the GM cryocoolers is circulated. It was shown that the temperature of the coil cold stage can be minimized to 8.5 K at a gas flow rate of 0.5 g/s by optimizing the gas mass flow.

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