Development of Superconducting Magnets with Current Leads without Gas Cooling

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ABSTRACT: The superconducting magnets (SCM) of electromagnetic vibration apparatus for MAGLEV ground coils operate in a persistent current mode for long periods of time. In addition, almost all of the time, the current lead of the SCM acts as a route for heat leak to the inside; therefore, the authors have developed low-heat-load current lead equipment. This equipment consists of a high-temperature superconductor (HTS) lead and the low-duty metallic lead allows the SCM to magnetize and demagnetize without a gas cooling system. This realizes a simplification of work procedure and reliable operations for magnetizing and demagnetizing the SCM. This result is also valuable for further improving the SCM of the MAGLEV vehicle.

1 INTRODUCTION

Railway Technical Research Institute (RTRI) has worked on the long-term durability and reliability of the key technology parts for the superconducting MAGLEV system, and invented the electromagnetic vibration apparatus for the ground coil (Fig.1) . To increase vibration power and to extend a test period, the superconducting coil of this apparatus requires the status of high magnetomotive force for a long operation under the persistent current mode.

Fig.2 shows operation pattern of the SCM with a persistent current mode. It is only at the time of magnetization and demagnetization that the current leads need to be electrified from a power supply. This shows that the current leads behave as an invasion route of heat leak to inside of the SCM in almost time.

Then we have aimed to improve the current lead system and achieved the performance of not requiring gas cooling, which brings a simplification of work procedure and reliability at the time of magnetization and demagnetization. In this report, the details and test results of this lead system are described.

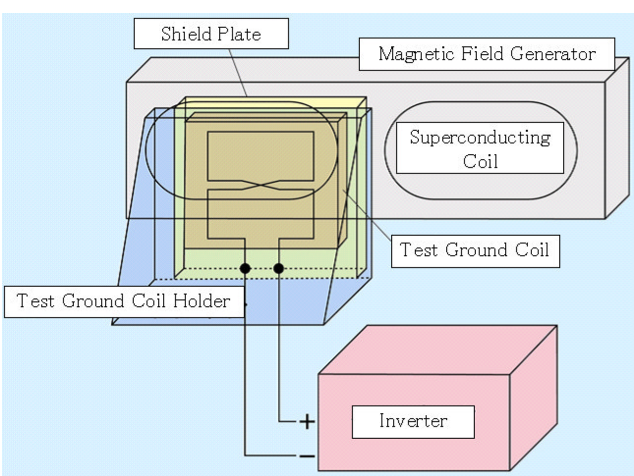


Figure 1. Electromagnetic vibration apparatus for ground coil.

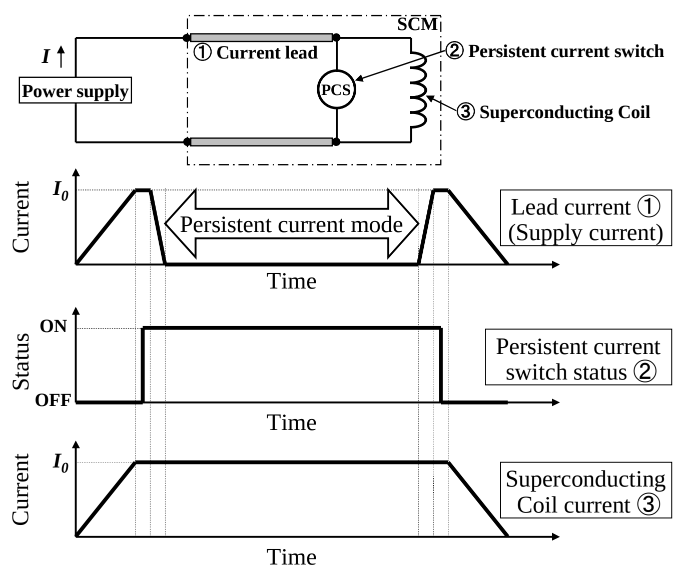


Figure 2. Operation pattern of SCM with persistent current switch.

2 STRUCTURE OF CURRENT LEADS WITHOUT GAS COOLING

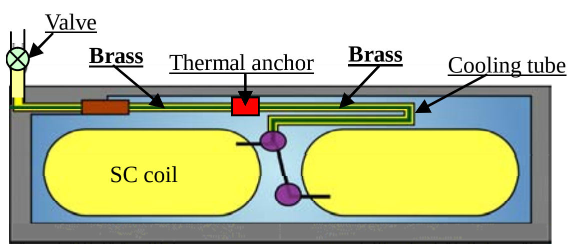
2.1 Merits of gas cooling free

When magnetizing a SCM with conventional current leads requiring gas cooling, five procedures as follows were necessary. (a) Supplying the cooling gas by valve operation. (b) Confirming the leads were cooled. (c) Magnetizing a SCM with supplying the cooling gas. (d) Confirming the leads were cooled after magnetization. (e) Turning off the cooling gas by valve operation. According to current leads not requiring gas cooling, procedures of (a), (d), (e) become unnecessary and the cooling gas is no longer in need at procedure (c).

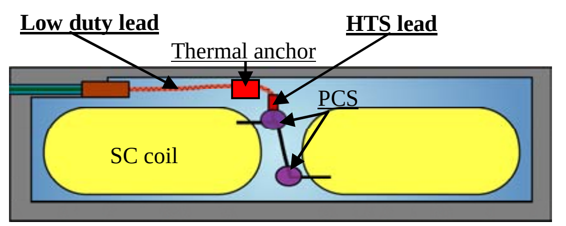
As a result, a large simplification of work procedure and improvement of reliability at magnetization are realized. In addition, a reduction of gas piping equipment and an increase of freedom for current leads design contribute to downsizing, lightweighting, simplifying for SCM structure.

2.2 Comparison of current leads composition

Fig.3 shows the current leads composition of previous type and this work. Superconducting coil made of NbTi alloy is as cooled by liquid helium and attached persistent current switch. In this work, a thermal anchor is installed between the HTS lead at a low temperature and a low duty lead at high temperature. By comparing with previous setup, it is possible to reduce the lead length and to remove the gas cooling tubes.



(a) Previous setup



(b) Present setup

Fig. 3 Schematic comparison of current lead composition.

2.3 HTS lead

The HTS lead made of HTS bulk is installed between a thermal anchor (77 K) and a superconducting coil (4.2 K). This temperature condition enables the HTS bulk to keep the superconducting state.

2.4 Low-duty lead

The low-duty lead is installed between a thermal anchor (77 K) and a terminal of normal temperature (300 K). Now a low-duty signifies a short time electrifying rating. Since this section is a temperature domain, unable to sustain a superconducting state by the present HTS bulk performance, the conventional lead made of copper alloy is used in this section. In addition, for removing the gas cooling tube, a careful design of heat leak estimation against Joule heat and conduction heat at electrifying is essential for this lead.

3 DEVELOPMENT OF HTS LEAD

3.1 Target performance

In consideration of superconducting MAGLEV system, the performances of HTS lead were set a highest temperature at a hot end of 85 K, a maximum current of 600 A, and a maximum magnetic field at 0.5 T.

3.2 HTS bulk materials and lead composition

Since the current leads are the parts of the SCM that generates a high magnetic field, the rare earth (RE:Rare Earth) HTS bulk (RE-Ba-Cu-O) that has a high critical current density under a high magnetic field was selected for HTS bulk material. And the Dysprosium (Dy) that has a characteristic of very low thermal conductivity was adopted as the RE element.

Fig.4 shows the HTS lead. The outside sizes are 130 mm in length, 20 mm in width and 10 mm in thickness. The HTS lead is assembled so that the transport current and ab-plane of crystal structure become the same direction. The connecting method

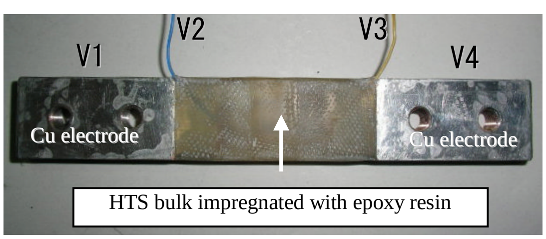


Fig. 4 HTS lead.

with the copper electrode of at both sides and HTS bulk of 30 mm length is soldering. The target value of connecting resistance is less than 1 micro ohm per one side. Moreover, the whole HTS lead is as formed by vacuum impregnation of epoxy resin so that the mechanical property of the HTS bulk is improved.

3.3 Properties measuring system for HTS lead

Soaking the HTS lead into liquid nitrogen was a popular method for evaluating the HTS lead. However, using the boiling point of cryogen, there was the problem that this method cannot confirm the temperature characteristics of the HTS lead broadly. For this reason, the properties measuring system for HTS lead was developed.

Fig.5 shows the schematic diagram of this system and Table 1 describes the main specifications. Using a permanent magnet (Nd-Fe-B), the magnetic field of 0.5 T is impressed to the space of 50 mm in width, 36 mm in height, and 90 mm in length. Maximum test current is 1000 A. By GM cryocoolers and heaters

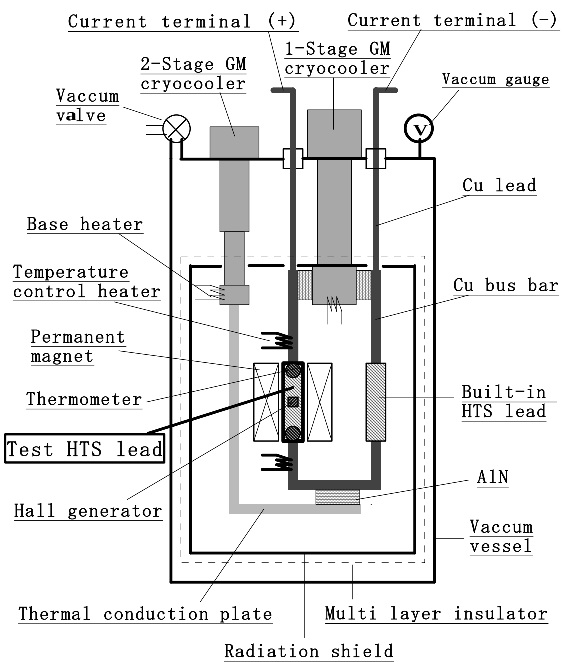


Fig.5 Schematic diagram of properties measuring system for HTS lead.

Table 1 Specifications of properties measuring system for HTS lead

Transport current	1,000 A (max)
Temperature	40-100 K (Hot end of HTS lead) 9- 40 K (Cold end of HTS lead)
Magnetic field	0.55 T (max)
Measurement of heat leak	1 W (max)
Test space for HTS lead	50×50×300 mm (50×36×90 mm: 0.5 T warranty)

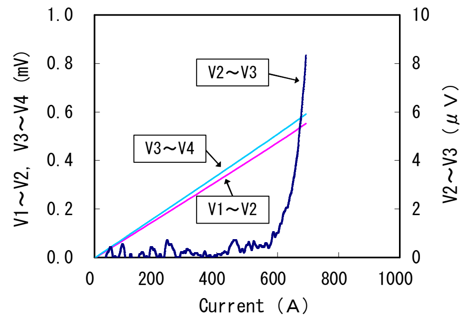


Fig.6 Test results of I-V characteristics at 88 K for both ends of HTS lead (Fig.4) with imposed magnetic field of 0.5 T perpendicular to c-axis.

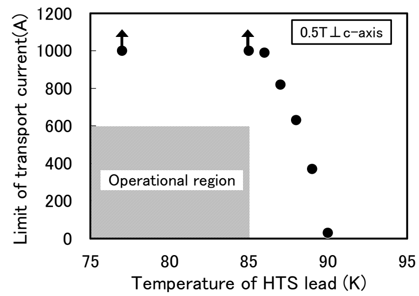


Fig.7 Test results of critical current in HTS lead with imposed magnetic field of 0.5 T perpendicular to c-axis.

for temperature control, it is possible to set up the temperature of both end of the HTS lead individually, from 40 K to 100 K for hot end, from 9 K to 40 K for cold end. In addition, the measurement of heat leak of the HTS lead is possible by change of the bus-bar composition.

3.4 Test results of HTS lead

The critical current (Ic) measurement of the HTS lead shown in Fig.4 was carried out with condition of a same temperature at both ends of lead as magnetic field of 0.5 T was impressed in the direction of vertical to c-axis. The I-V characteristic at 88 K is shown in Fig.6. Here, we decided to transport the current from the left to the right of Fig.4. The voltage of V2-V3 rise began at near 600 A, and changed to rapid rise after that. This rise shows the transition to the normal conducting state from the superconducting state of the HTS bulk. In this case, the Ic is 631 A, the connection resistance between HTS bulk and copper electrode of 0.79 micro ohm at plus side and 0.85 micro ohm at minus side are both in target value.

The test results of the Ic measurement with temperature conditions from 77 K to 90 K is shown in Fig.7. According to the results, the HTS lead usable to highest temperature of hot end at 85 K, maximum current at 600 A and maximum magnetic field at 0.5 T was obtained.

4 DEVELOPMENT OF LOW-DUTY LEAD

4.1 Target performance

At the SCM using persistent current mode shown in Fig.2, it is advantageous to cryocooler to decrease the heat leak of the current lead at no electrifying. Therefore, the performances of low-duty lead were decided that a heat leak from room temperature current terminal to thermal anchor is at less than 10 W, and a metal conductor is exposed to vacuum space.

4.2 Heat Analysis simulation

The transport current pattern is shown in Table 2, and Fig.8 shows the analytical model. It was set that the material of the low-duty lead is brass, the temperature of hot end (T_H) is 300 K, and cold end (T_L) is 80 K. Hereafter, it is set that basic composition of the low-duty lead is of cross section A= 60 mm^2, of length L= 72 mm, and for ease, A and L are set with A= 1 and L= 1.

Since the theoretical optimum heat leak (Qopt) of the steady lead (optimum dimension IL/A= 720 A/mm) is 27 W when the transport current I= 600 A, the maximum heat leak (Qmax) of the low-duty lead at electrifying must be less than Qopt. Fig.9 shows the simulation result of parameter survey as to Qmax by A and L both made no dimension. Then it turns out that it is necessary to be A> 1.5 and L> 1.0 for Qmax< Qopt, and the combination of A and L can be chosen according to Qmax.

Fig.10 shows the simulation result of heat leak electrifying the low-duty lead with A= 4.0 and L= 3.0. It turns out that the maximum heat leak comes 10 W which is less than 27 W of steady lead, and the heat leak at no electrifying become 5 W which is

Table 2 Transport current pattern

Operating current	Sweeping rate	Hold time
600 A	3 A/s	120 s

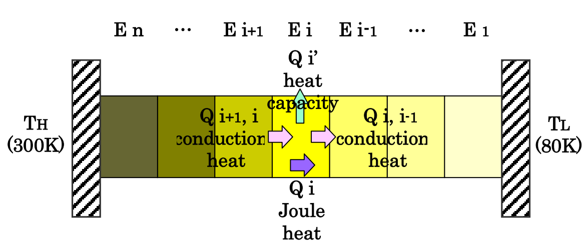


Fig.8 Analytical model of low-duty lead.

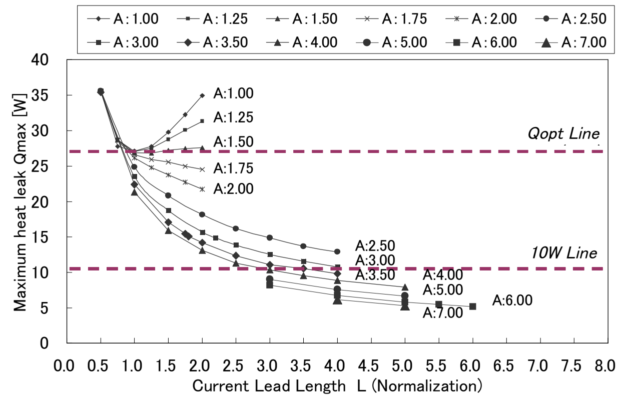


Fig.9 Simulation results of parameter survey for maximum heat leak in low-duty lead.

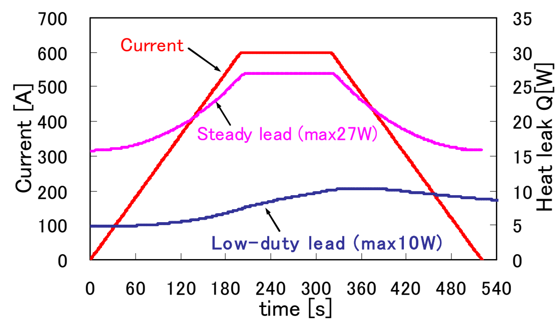


Fig.10 Simulation results of heat leak electrifying low-duty lead(A＝4.0,L＝3.0).

approximately one-third of steady lead. In such a way, the guideline of the low-duty lead which is of a low heat leak and unnecessary for gas cooling was obtained.

4.3 Test results of actual size sample

The actual size sample of brass which has 240 mm^2 of cross section and 864 mm of length corresponding to A= 4.0 and L= 3.0 was tested. Fig.11 shows the test results of the temperature distribution along full length at set electrifying with the condition of T_H= 300 K and T_L= 80 K. Fig.12 shows the test results of

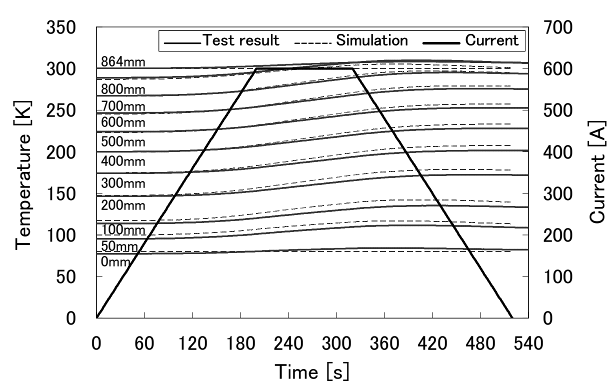


Fig.11 Test results of temperature distribution for actual size low-duty lead sample.

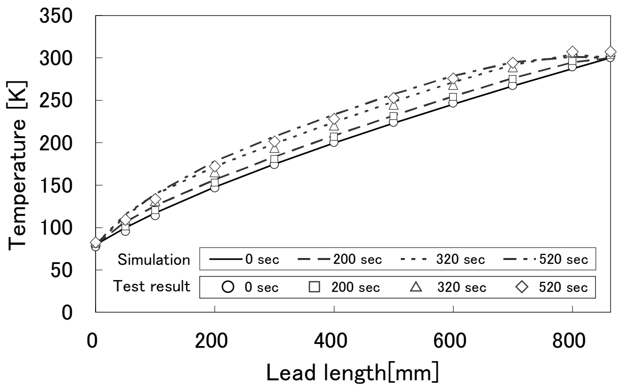


Fig.12 Test results of temperature gradient for actual size low-duty lead sample.

the temperature gradient along the lead length. These show that the maximum temperature of the low-duty lead is 305 K at most and the test results are consistent with the simulation results.

Then, we verified the validity of low-duty lead design. In addition, the low-duty lead, which is unnecessary for gas cooling, and into 10 W of maximum heat leak at set electrifying was obtained.

5 SCM WITH CURRENT LEADS WITHOUT GAS COOLING

5.1 Specifications

The current lead without gas cooling consisting of the HTS lead and the low-duty lead was installed in the SCM of electromagnetic vibration apparatus for the ground coil. Fig.13 shows the SCM and table 3 shows the main specifications.

5.2 Test results of actual low-duty lead

Fig.14 shows the test results of temperature properties of the actual low-duty lead at the point of 0 mm, 100 mm, 400 mm and 800 mm from the cold end with electrifying as table 2.

Test results show that the temperature properties of the actual low-duty lead is in good agreement with simulation, and hot end temperature of the HTS lead get 78.5 K at most, then the actual SCM with the HTS lead and the low-duty lead has no problems at magnetizing and demagnetizing without gas cooling.

6 CONCLUSIONS

After the SCM with current lead without gas cooling was completed, it has been working satisfactorily as a

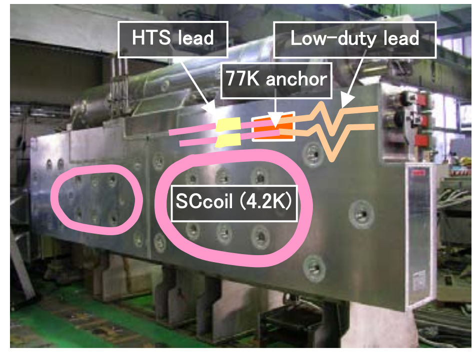


Fig.13 SCM with current leads without gas cooling.

Table 3 Specifications of SCM

Magnetomotive force	800 kA
External dimensions	3,430×1,240×500 mm
Coil conductor	NbTi
Coil dimensions	1,070×500 mm (racetrack shape)
Current lead	HTS bulk (4 K ～ 80 K)
	Brass (80 K ～ 300 K)
HTS lead dimensions	130×20×10 mm
Cryocooler	GM+JT (4 K ref.),GM (80 K ref.)

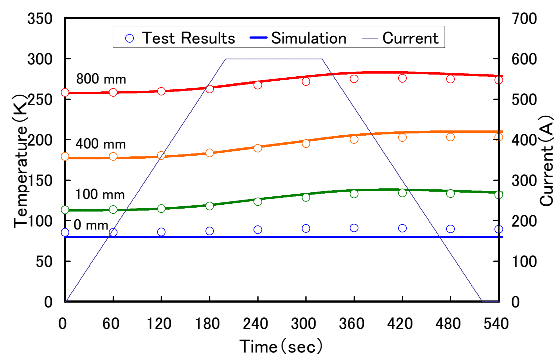


Fig.14 Test results of thermal properties of actual low-duty lead.

magnetic field generator of the electromagnetic vibration apparatus for the ground coil.

Finally, the contents of this report are summarized as follows:

(1) The structure of the current leads of the low heat leak and without gas cooling for a magnetic field generator of the electromagnetic vibration apparatus for the ground coil was discussed.

(2) The HTS lead consisting of rare earth HTS bulk was developed and its critical current properties were disclosed by properties measuring system for HTS lead.

(3) The outline of the low-duty lead was obtained by heat analysis simulation and this was confirmed by testing an actual size lead sample.

(4) The SCM with current leads consisting of the HTS lead and the low-duty lead was developed and it was confirmed that the temperature properties of an actual low-duty lead was consistent with simulation,

and the operation of magnetizing and demagnetizing the SCM without gas cooling was realized.
(5) The authors consider that this current lead system will be valid to replace the conventional lead system of superconducting MAGLEV.

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