Development of superconducting magnet with HTS current lead

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ABSTRACT: The current lead of superconducting magnet (SCM) is a conductor to connect superconducting coil to external power supply. Since the copper alloy usually applied to the current lead, acts as a route of heat leak to the inside of the SCM, we developed high temperature superconductors (HTS) current lead, and estimated the properties by a measuring system for HTS current lead. The properties of the HTS current lead enable the length of the current lead be shortened, and the cooling mechanism of the current lead using evaporated helium gas to be removed. Such advantages of HTS current lead can realize further performances to the SCM.

1 INTRODUCTION

Superconducting magnet (SCM) is a kind of the electromagnet by supplying current. The SCM is electrically connected to external power supply through the current lead. Although the SCM has the feature that a high magnetic field can be generated by a small system compared with a usual electromagnet, in order to use the superconducting state of materials, it is necessary to put a superconducting coil into sufficient low temperature environment. Therefore, a subject that the current lead has to conduct current certainly and also minimize heat leak of itself exists in the current lead for the SCM.

2 PURPOSE OF THIS STUDY

Usually, a copper alloy is used for the material of the current lead for the SCM. This is because that the copper alloy is good conductor of electricity and easy material for availability and processability. However, the copper alloy which is good electrical conductor, is very good thermal conductor simultaneously. Moreover, a Joule heat of the copper alloy which has limited resistance, cannot be disregarded when high current transport.

Then, we turned attention to high temperature superconducting bulk (HTS bulk) for metal material. The HTS bulk is ideal electrical conductor for being in superconducting state under low temperature environment of the SCM. And HTS bulk which is ceramic itself has remarkably small thermal conductivity than metal material. Thus, the HTS bulk is a promising material which has good characteristic to electric and thermal subject of the current lead for the SCM.

From the above thing, it was set as the purpose of this study to realize further performances to the SCM by constituting the current lead for the SCM using the HTS bulk.

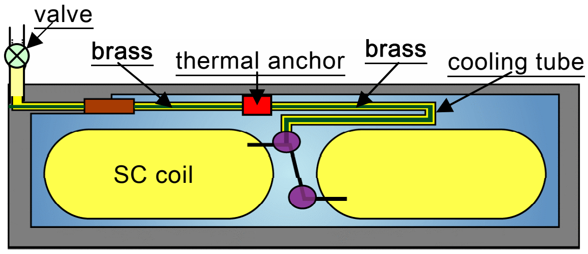
3 CURRENT LEAD COMPOSITION OF THIS STUDY

3.1 *Comparison with the conventional composition*

Fig.1 shows the composition of the current lead for the SCM, which used the HTS bulk. A thermal anchor is between the HTS lead by the side of low temperature and an unsteady type lead by the side of high temperature. By comparing with conventional composition, it is possible to shorten the lead length and to remove the gas cooling tube.

3.2 *HTS lead*

The HTS lead made of HTS bulk is installed between a thermal anchor (77K) and a superconducting coil (4.2K). According to this temperature condition, keeping of the superconducting state of the HTS bulk is possible.



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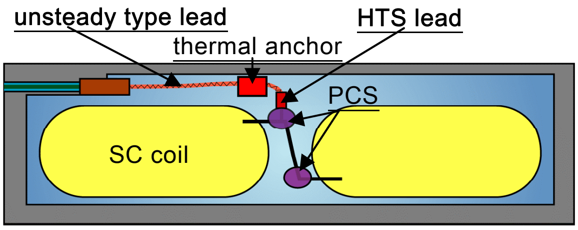

(b) this work

Figure 1: Schematic comparison of current lead composition

3.3 *Unsteady type lead*

The unsteady type lead is installed between a thermal anchor and a terminal of normal temperature. Since this section is the temperature domain which cannot hold a superconducting state by the present HTS bulk performance, the conventional lead which made a copper alloy is used in this section. And for removing the gas cooling tube, a careful design of heat load that the sum of Joule heat and conduction heat at the current transportation may be the minimum is needed for this section lead.

Since the SCM for superconducting MAGLEV builds in the permanent current switch (PCS) is premised on permanent current mode operation, steady transportation of current to lead is unnecessary. For the current lead of these SCM, the heat load design when unsteady transportation of current is at the time of magnetization or demagnetization, becomes an important subject. It is the reason this calls the lead of this section unsteady type lead. In addition, the lead which the optimal heat load design for the SCM on condition of steady transportation of current was made is called steady type lead.

4 DEVELOPMENT OF HTS LEAD

4.1 *HTS lead composition*

Since the current lead for SCM are the parts pertaining the SCM which generates a high magnetic field, the properties of superconductivity stabilized under strong magnetic field is required of HTS bulk. Therefore, the rare earth(RE:Rare Earth) HTS bulk(RE-Ba-Cu-O) which has high

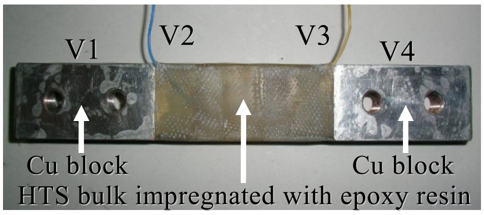

Figure 2: HTS current lead

critical current density under a high magnetic fieldwas made for HTS bulk material. The Dysprosium (Dy) was adopted as the rare earth element. Fig.2 shows this HTS lead. The outside size is 130 mm in length, 20 mm in width, and 10mm in thickness. It constitutes that the direction of transport current of the HTS lead and the direction of ab-plane of crystal structure of the HTS bulk material may become the same, and the whole HTS lead is formed by vacuum impregnation of epoxy resin, raising the mechanical property of a HTS bulk.

4.2 *Properties measuring system for HTS lead*

Fig.3 shows the schematic diagram of this system, and Table 1 describes the main specifications.

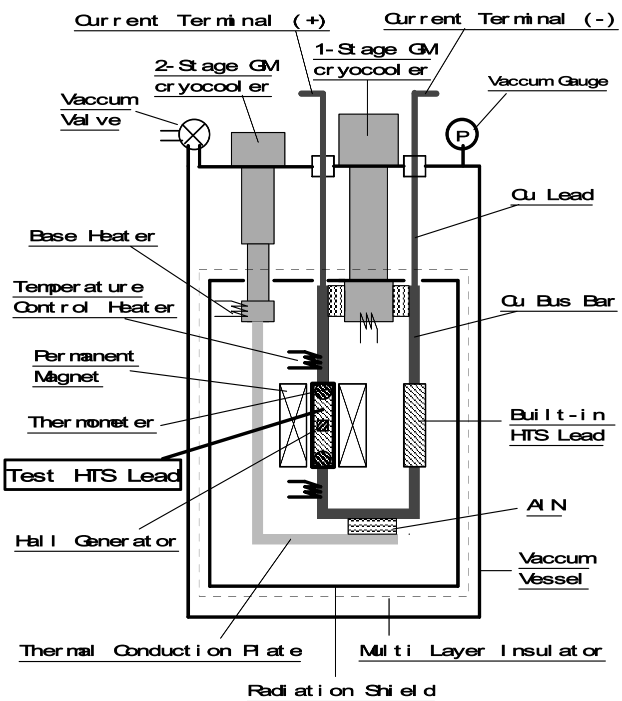

Figure 3: Schematic diagram of properties measuring system for HTS lead

Using a permanent magnet(Nd-Fe-B), where the magnetic field of 0.5T is impressed to the space of 50 mm in width, 36 mm in height, 90 mm in length, the maximum transport current of 1,000 A is made. The direction of the magnetic field impressed can be set up in the arbitrary directions perpendicular to the direction of transport current by rotating the HTS lead for evaluation. By two GM cryocooler and heaters 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 of HTS lead, from 9 K to 40 K for cold end of HTS lead. The heat invasion of radiation is controlled by arranging multilayer insulator and radiation shield plate. In addition, the measurement of heat leak of HTS lead is possible by change of the bus-bar composition. Then the time taken for a sample to become the minimum attainment temperature is about 24 hours after starting the cryocooler.

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)

4.3 Test result

4.3.1 Critical current measurement(condition of a difference temperature at both ends of lead)

The situation of a critical current measurement, which used the commercial HTS lead is shown in Fig.4.

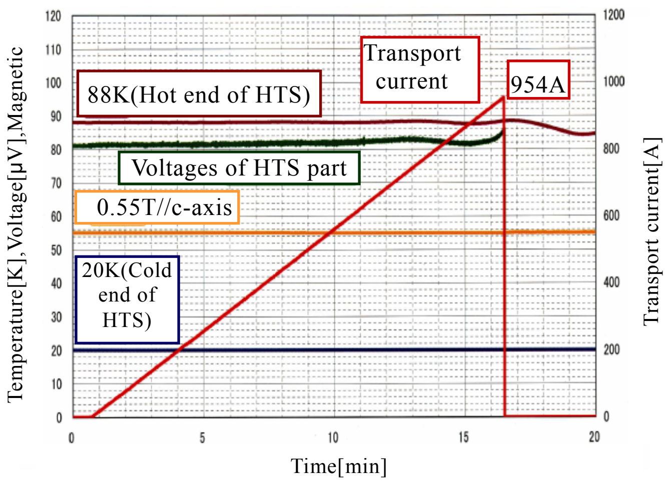

Figure 4: Test result of critical current measurement with different temperature at both ends of HTS lead

The hot end of the HTS lead was set at 88 K, the cold end of the HTS lead was set at 20 K, the magnetic field of 0.55 T was impressed in the direction of c-axis of the HTS bulk material. The voltage of 5 micro V which is equivalent to the normal phase transition criterion of 1 micro V/cm was generated in 954 A. Thus, the temperature of the both ends of the HTS lead was set arbitrarily, and it became possible to grasp the critical properties of the HTS lead by measuring the voltage of the normal phase transition.

4.3.2 Critical current measurement(condition of a same temperature at both ends of lead)

The critical current measurement which used the HTS lead shown in Fig.2 was carried out with condition of a same temperature at both ends of lead as the magnetic field was impressed in the direction of vertical to c-axis. The I-V characteristics at 85 K of both ends of lead is shown in Fig.5 as the impressed magnetic field was 0.5 T and the sweep rate of current was 20 A/s. Here, we decided to transport the current from the left to the right of Fig.2, and to call the potential of plus side copper electrode V1, and to call the potential of plus side HTS bulk V2, and to call the potential of minus side HTS bulk V3, and to call the potential of minus side copper electrode V4. The voltage rise began at near 600 A, and changed to rapid rise after that. This rapid rise of the voltage shows the transition to the normal conducting state from the superconducting state of the HTS bulk.

Thus, the result of critical current measurement which temperature conditions were changed from 77 K to 90 K is shown in Fig.6. The properties that critical current decreases with the temperature rise in the domain more than 81 K was acquired for the first time as a HTS lead.

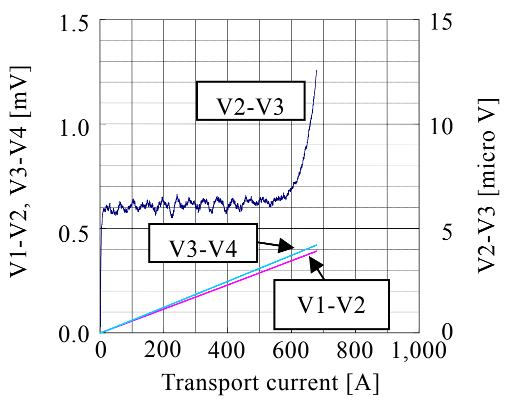

Figure 5: Test result of I-V characteristics at 85 K of both ends of HTS lead(Fig.2) with impressed magnetic field of 0.5 T perpendicular to c-axis

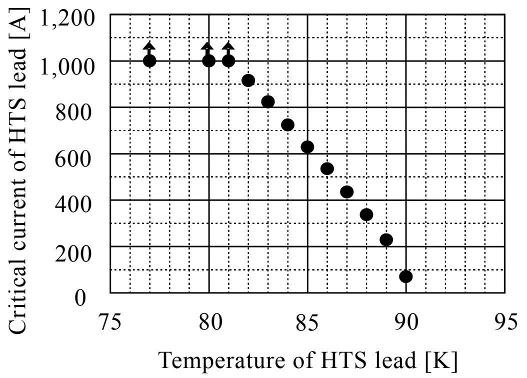

Figure 6: Test result of critical current of HTS lead(Fig.2) with impressed magnetic field of 0.5 T perpendicular to c-axis

5 DEVELOPMENT OF UNSTEADY TYPE LEAD

5.1 Analysis model

The relation of cross section and length of unsteady type lead which make minimum the sum of the heat load by Joule heat and conduction heat when transport the current was studied analytically.

The transport current pattern is shown in Table 2, and the analysis model is shown in Fig.7. It was set that the material of the unsteady type lead is brass, the temperature of hot end (TH) of this lead is 300 K, and cold end (TL) is 80K. Hereafter, it is set that basic composition of unsteady type lead is of cross section A=60mm2, of length L=72mm, and for ease, A and L at this point are set with A=1.00 and L=1.00.

5.2 Simulation result

The result at the condition of A<=1 is shown in Fig.8. The maximum heat load (Qmax) turns the minimum value of 27 W at L=1. Since the theoretical optimum heat load (Qopt) of the optimized steady type lead (IL/A=720 A/mm, here I is the maximum transport current) is 27 W, it turns out when A<=1 that the heat load cannot be smaller than Qopt by every L.

On the other hand, the result at the condition of A>1 is shown in Fig.9. The Qmax cannot be smaller than Qopt when L<1, but when L>=1 and A>=1.5, the Qmax begins to decrease. Therefore, in the conductor design of unsteady type lead below Qopt, it turns out that it is necessary to be A>1.5 and L>1. And it also turns out that the combination of A and L can be chosen at the target of Qmax. As an example, the result of heat load simulation of unsteady type lead when being A=2.5 and L=3.0 is shown in Fig.10. The heat load turns 15 W which is less than 27 W of steady type lead.

Table 2: Transport current pattern for simulation

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

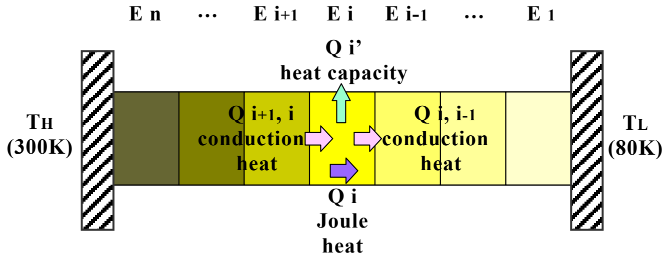

Figure 7: Analysis model

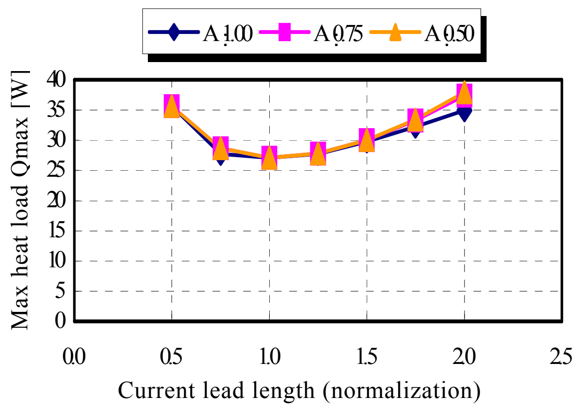

Figure 8: Simulation result (A<=1)

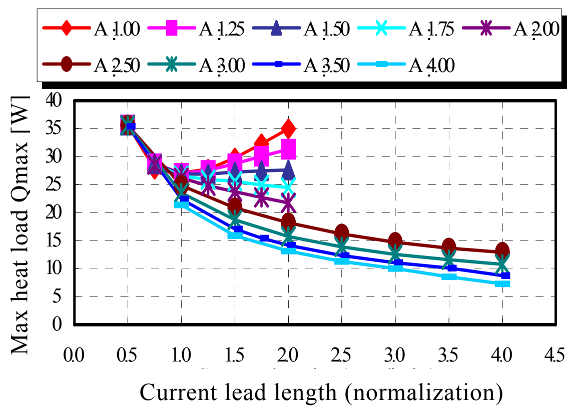

Figure 9: Simulation result (A>1)

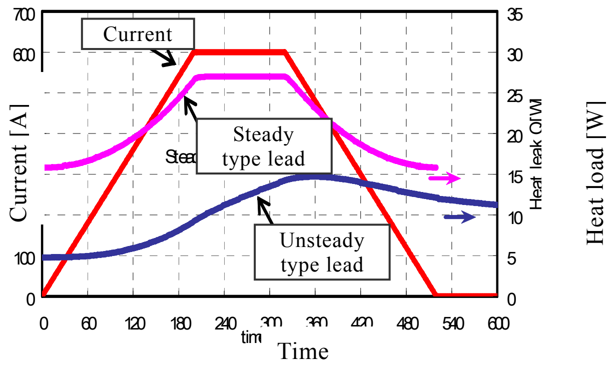

Figure 10: Heat load simulation result of unsteady type lead when A=2.5 and L=3.0

6 DEVELOPMENT OF MGNETIC FIELD GENERATOR WITH HTS LEAD

As the first stage of the development of SCM with HTS lead, we developed magnetic field generator which is a part of electromagnetic vibrating apparatus for ground coil of superconducting MAGLEV. The HTS lead is included in this generator excepting the unsteady type lead. The outside of this generator is shown in Fig.11, and main specifications are shown in Table 3.

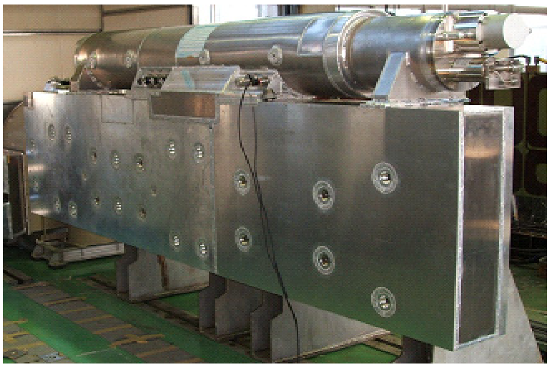

Figure 11: Magnetic field generator with HTS lead

Table 3: Specifications of Magnetic field generator with HTS lead

Magnetomotive force	800 kA
External dimensions	3,430×1,235×490 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	90×40×10 mm
Cryocooler	GM+JT(4 K ref.),GM(80 K ref.)

Although the HTS lead and the copper alloy lead were structured as possible to be cooled by evaporation gas of liquid helium in this generator, the current transport test without gas cooling was carried out, and it was checked that there was no problem in the current transport properties of the HTS lead without gas cooling.

7 PLANS

By accumulating enough data using the properties measuring system for HTS lead, and by feeding back for better design of the HTS lead, we will improve the performances of the HTS lead. In addition, we will forward the development of the unsteady type lead by the guideline of design. Then, we will apply the current lead consists of the HTS lead and the unsteady lead to the SCM.

In addition, for practical use of the HTS lead for SCM, we will also develop the method of reliability and durability evaluation of the HTS lead.

8 SUMMARY

For the further performances of the SCM, it was studied that the constitution and evaluation method of the current lead for the SCM.

The HTS lead made from the rare earth HTS bulk was developed.

The properties measuring system for HTS lead was developed, and the critical current properties of the HTS lead with condition of continuous temperature were acquired for the first time using this system.

By the heat load simulation, the guideline of design for the conductor of the unsteady type lead was acquired analytically.

The magnetic field generator with the HTS lead was developed.

From now on, we will apply the current lead consists of the HTS lead and the unsteady lead to the SCM, and for practical use, we will also develop the method of reliability and durability evaluation of the HTS lead.

9 ACKNOWLEDGEMENT

Lastly, the authors would like to express their gratitude to the people of TOSHIBA CORPORATION who manufactured the properties measuring system for HTS lead and the magnetic generator with HTS lead.

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