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A Conduction Cooled Superconducting Magnet Using High-Tc Oxide Current Leads

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Abstract - **We demonstrated a conduction cooled $(Nb,Ti)_3Sn$ superconducting magnet system without liquid helium. The magnet system is mainly composed of $(Nb,Ti)_3Sn$ superconducting coil, high-Tc oxide current leads, a GM cryocooler and a cryostat. The $(Nb,Ti)_3Sn$ superconducting coil cooled by the second stage of the cryocooler is operated at 11 K in vacuum. The cylindrical $(Bi,Pb)_2Sr_2Ca_2Cu_3$ oxide current leads were cooled below 77 K by the cryocooler. This system generates a magnetic field of 4.6 T in a 38 mm room temperature bore at the operating current of 465 A. 2 hours holding at the operating current of 400 A were performed.**

I. INTRODUCTION

To maintain the superconductivity for operation, the superconducting magnets are generally immersed in liquid helium, and the cooling system for usage of liquid helium inevitably requires a radiation shield cooled by liquid nitrogen or a subsidiary cryocooler to reduce the vaporization of liquid helium. Resultantly, a cryostat system becomes complicated and the careful attention is required in handling of liquid helium which is quite expensive. These difficulties interrupt the wide spread of a superconducting magnet.

In recent years, the performance of cryocooler is remarkably advanced. As to the Gifford-McMahon (GM) cryocooler, the cooling temperature of 10 K, refrigeration capacity of 1 W, and continuous operation of more than 10,000 hours have been realized. If the heat load of the magnet system can be reduced drastically, it is expected that the superconducting magnet is cooled down by direct contact to the cooling stage of GM cryocooler and the superconducting magnet system without using liquid helium will be realized [1].

Since the discovery of high-Tc superconducting oxides,. these material opened up many potential applications at high temperature. Use of Bi-based oxide for current leads has been actively investigated as promising commercial products. The current lead retains superconductivity below about 110 K and has the critical current of more than 1,000 A under self magnetic field at 77 K [2].

We have developed and tested the conduction cooled superconducting magnet system generating over 4 T in 38 mm room temperature bore, employing $(Nb,Ti)_3Sn$ superconducting coil, Bi-based oxide current leads and a GM cryocooler. In this paper, structural design and performance test results of the conduction cooled superconducting magnet are discussed.

II. COMPOSITION OF THE CONDUCTION COOLED SUPERCONDUCTING MAGNET

This magnet system is composed of $(Nb,Ti)_3Sn$ superconducting coil, double stage cooling type GM cryocooler, Bi-based oxide current leads, copper current leads, radiation shield and cryostat. Table 1 shows the main parameters of the conduction cooled superconducting magnet system. Each composition is described as follows.

TABLE 1
PARAMETERS OF THE CONDUCTION COOLED SUPERCONDUCTING MAGNET

Magnet System	
Central field	: 4.0 T at 400 A
Room temp. bore	: 38 mm
Dimensions	: Outer diameter 320 mm Height 920 mm
Weight	: 190 kg
Superconductor for coil	
Material	: $(Nb,Ti)_3Sn$ (30 % Sn)
Dimensions	: 1.6 mm x 2.4 mm (bare)
Copper/non-copper ratio	: 1.2
Superconducting coil	
Cold bore	: 50 mm
Inner diameter	: 59 mm
Outer diameter	: 164 mm
Coil height	: 188 mm
Number of turns	: 1659
High-Tc superconducting current leads	
Material	: $(Bi,Pb)_2Sr_2Ca_2Cu_3O_{10}$
Dimensions	: OD22.8 mm x ID20 mm x L140 mm
Critical current	: Over 1,000 A at 77 K, 0 T
Cryocooler	
Type	: GM cycle
Refrigeration capacity	: 0.5 W/10 K, 40 W/60 K

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A. (Nb,Ti)$_3$Sn Superconducting Coil

The (Nb,Ti)$_3$Sn superconducting wire with a cross section of 1.6 x 2.4 mm and copper ratio of 1.2 is made by Nb–tube method, and exhibits the critical current of 750 A at 4.2 K and 15 T. The superconducting coil with an inner diameter of 59 mm, an outer diameter of 164 mm, and a coil height of 188 mm was made using a wind and react (W & R) technique. The coil were impregnated with epoxy resin [3][4].

B. Bi–based Oxide Current Leads

Bi–based oxide current leads are the valuable component to decrease heat load to the cryocooler of the magnet system. These current leads are connected between the 1st stage of cryocooler of 60 K level and superconducting coil of 11 K level, and the composition of leads is $(Bi,Pb)_2Sr_2Ca_2Cu_3O_{10}$. The current lead is formed into bulk tubes by cold isostatic pressing and sintered. The tubular current lead with dimensions of 22.8 mm in outer diameter, 20 mm in inner diameter, and 140 mm long is shown in Figure 1. Both ends of each bulk tube were coated with plasma–sprayed silver to form terminals. The critical current of the bulk was measured more than 1,000 A at 77 K and B=0 T.

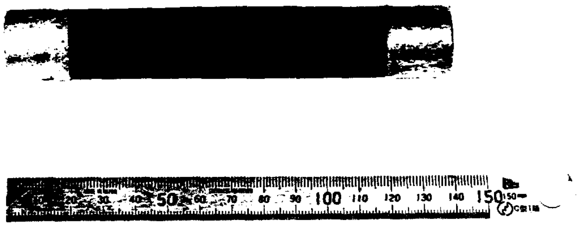

Fig.1. Bi–based oxide superconductor for current leads.

C. Cryocooler

A double stage cooling type GM cryocooler is utilized for the superconducting magnet system. Regenerative coolants of copper mesh for the 1st stage displacer and coolants of spherical lead for the 2nd stage displacer are filled up, and refrigeration capacities are 40 W at 60 K (1st stage) and 0.5 W at 10 K (2nd stage).

D. Magnet system

Figure 2 shows the sectional view of magnet, which is composed of superconducting coil, copper blocks for coil cooling, current leads (Bi–based oxide current leads and copper current leads), radiation shield, magnetic shield and vacuum vessel. Figure 3 presents the detailed constitution of the coil and current lead in terms of thermal anchoring. The superconducting coil and the magnetic shield are placed on the 2nd stage of cryocooler by bolting, and these are surrounded by the copper blocks. Three piece of copper blocks in segmental shape are placed onto contact with the 2nd stage of cryocooler, and coupled in circle with insertion of FRP sheet to prevent eddy current.

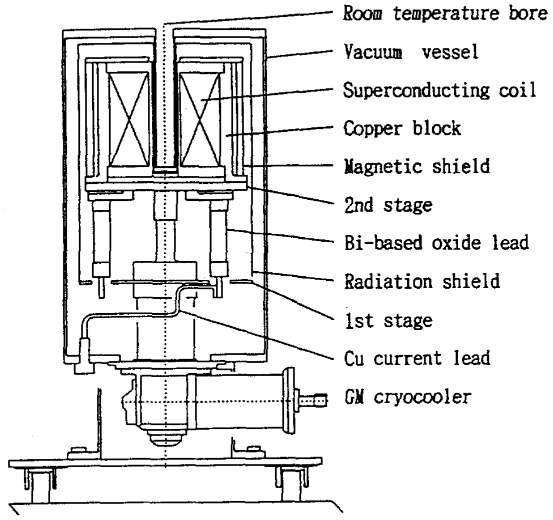

Fig.2. Sectional view of the conduction cooled superconducting magnet using high–Tc oxide current leads.

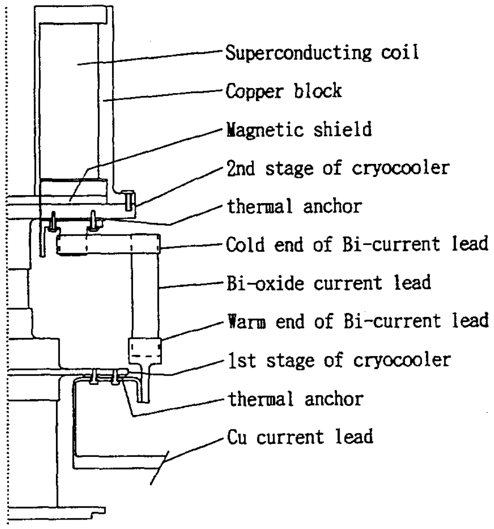

Fig.3. Detailed constitution of the coil and the current lead in term of thermal anchoring.

A pair of copper current leads are fitted spanning the room temperature and 60 K level. Radiation shield is installed on the 1st stage of cryocooler. All these components are kept in a vacuum vessel. The magnet is very compact with an outer diameter of 32 cm, a height of 92 cm and a weight of 190 kg. The room temperature bore in 38 mm diameter is prepared. Figure 4 shows the external appearance of magnet and compressor unit.Figure 5 presents the internal constitution of magnet.

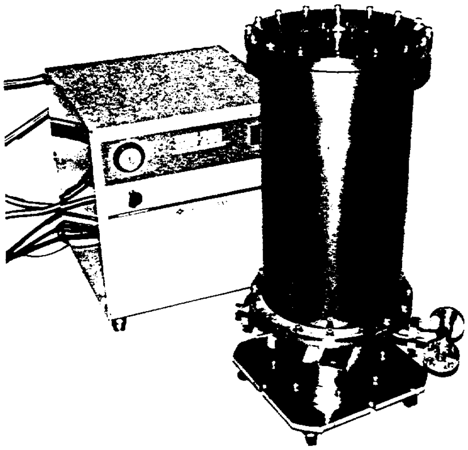

Fig.4. Conduction cooled superconducting magnet and compressor unit.

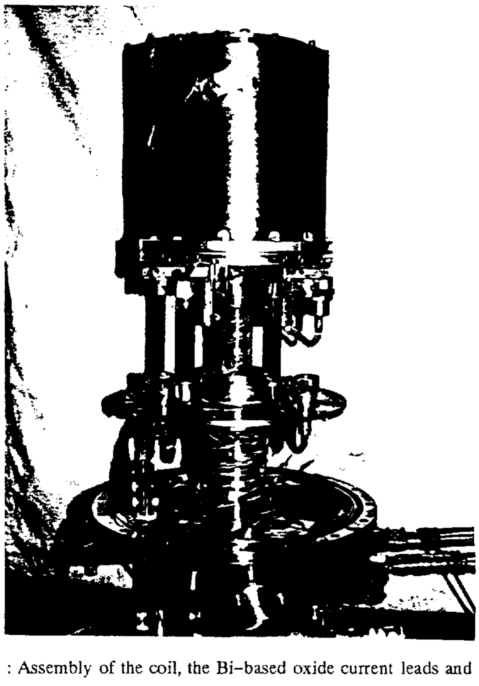

Fig.5 : Assembly of the coil, the Bi-based oxide current leads and the cryocooler in the cryostat.

III. THERMAL DESIGN

Table 2 shows the calculated heat loads of a cryocooler. The heat loads to the 1st stage of cryocooler are invited from copper current leads, wires for measurement, heat radiation, joule heating, while the heat loads to the 2nd stage of cryocooler are brought from Bi-based oxide current leads, wires for measurement, heat radiation, joule heating. In case of 0 A current, the heat loads are 25.5 W (1st stage) and 0.23 W (2nd stage) ,and in case of 400 A current supplied,heat loads are 42.2 W (1st stage) and 0.55 W (2nd stage) respectively. According to the refrigeration capacity, the temperatures for the 1st stage and the 2nd stage corresponds to 54 K, and 9 K respectively at 0 A. And in case of 400 A supplied, temperatures of 62 K and 10 K are estimated.

TABLE 2
CALCULATED HEAT LOADS OF A CRYOCOOLER

	at 0 A	at 400 A
1st stage		
Current leads	: 23.2 W	36.7 W
Wires for measurement	: 0.1 W	0.1 W
Heat radiation	: 2.2 W	2.2 W
Joule heating	: 0.0 W	3.2 W
1st stage total	: 25.5 W	42.2 W
2nd stage		
Oxide current leads	: 0.15 W	0.15 W
Wires for measurement	: 0.05 W	0.05 W
Heat radiation	: 0.03 W	0.03 W
Joule heating	: 0.00 W	0.32 W
2nd stage total	: 0.23 W	0.55 W
1st stage temperature	: 54.0 K	62.0 K
2nd stage temperature	: 9.0 K	10.0 K

IV. EXPERIMENTAL RESULTS

A. Initial Cooldown

The temperatures of the coil, the 1st stage, the 2nd stage, the warm and cold ends of Bi-based oxide current leads were monitored. Measurements were performed by Platinum Resistors and Carbon Glass Resistors. The initial cooling pattern for the magnet system is shown in Figure 6. The temperatures of the 1st stage and the warm end of Bi-based oxide current lead take 10 hours to 60 K, and 80 K respectively. It takes 56 hours to cool the coil, the 2nd stage, and the cold end of Bi-based oxide current leads to about 10 K.

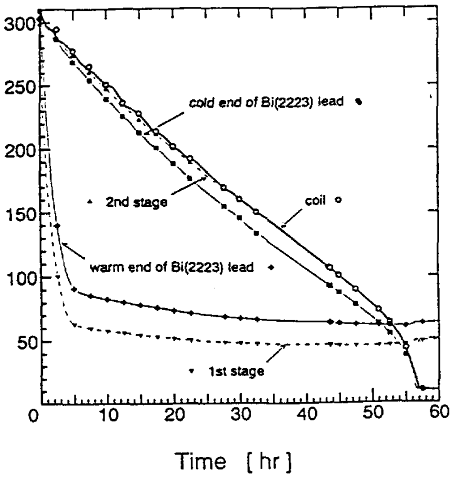

Fig.6. Initial cooling pattern for the magnet system.

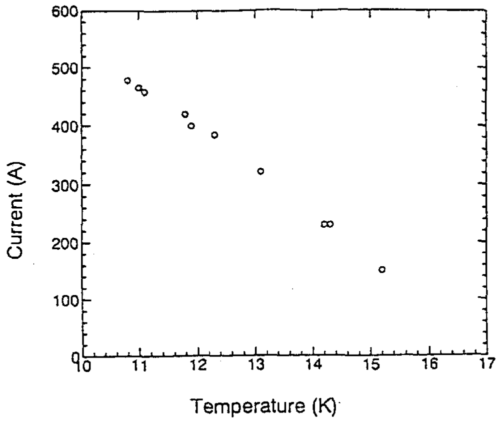

Fig.7. Measured quenching currents of the coil versus the coil temperature.

B. Magnet Operation

The magnet steadily generated the magnetic field of 4 T at operating current of 400 A, and the temperatures measured at 0 A and 400 A are shown in Table 3. The temperatures at operating current of 400 A were measured after holding current for 2 hours. The coil temperature rose from 10.3 K to 11.1 K and the temperature rise caused by joule heating of current supply were also observed in regard to the 1st stage, the 2nd stage and both ends of Bi-based oxide current leads. However, these temperature rise saturated within 2 hours. All heat loads including joule heating were small enough to maintain temperature in steady.

Quench characteristics as a function of coil temperature are shown in Figure 7. Coil temperature was adjusted by resistance heater fitted on the 2nd stage. When the current of 465 A was applied with a sweep rate of 100 A/min, the central magnetic field of 4.6 T were generated at the coil temperature of 10.8 K and the coil quenched. After quenching, the coil temperature rose to about 20 K, and recovered down to 11 K in half an hours. On the other hand, at the coil temperature of 15.2 K, the coil quenched at 150 A (1.5 T). The coil has been quenched more than 50 times, yet no problems have occurred with either the coil or the Bi-based oxide current leads.

TABLE 3
MEASURED TEMPERATURES AT OPERATING CURRENT OF 0 A AND 400 A

	at 0 A	at 400 A
1st stage	: 50.2 K	64.0 K
2nd stage	: 9.2 K	10.2 K
Coil	: 10.3 K	11.1 K
Cold end of oxide current leads	: 10.6 K	12.0 K
Warm end of oxide current leads	: 54.2 K	74.0 K

V. CONCLUSION

We manufactured a conduction cooled superconducting magnet system equipped with $(\mathrm{Nb,Ti})_3\mathrm{Sn}$ superconducting coil, Bi-based oxide current leads and GM cryocooler. The coil was thermally contacted onto the 2nd stage of cryocooler, which has a refrigeration capacity of 0.5 W at 10 K and 40 W at 60 K. The superconducting magnet generated a magnetic field of 4.6 T (465 A) in a 38 mm room temperature bore. 4.0 T (400 A) was continuously generated for 2 hours without any trouble. The high-Tc $(\mathrm{Bi,Pb})_2\mathrm{Sr}_2\mathrm{Ca}_2\mathrm{Cu}_3\mathrm{O}_{10}$ current leads were practically applied to the superconducting magnet, and as a results, a compact magnet without liquid helium was realized.

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