東北大学機関リポジトリ
TOUR
Tohoku University Repository

A Cryocooler Cooled 6T NbTi Superconducting Magnet with Room Temperature Bore of 220 mm

著者	渡辺 和雄
journal or publication title	IEEE Transactions on Magnetics
volume	32
number	4
page range	2594-2597
year	1996
URL	http://hdl.handle.net/10097/47212

doi: 10.1109/20.511404

A Cryocooler Cooled 6T NbTi Superconducting Magnet with Room Temperature Bore of 220mm

K.Watazawa, J.Sakuraba, F.Hata, T.Hasebe, C.K.Chong, and Y.Yamada*
Sumitomo Heavy Industries, Ltd., 63-30 Yuhigaoka, Hiratsuka 254, JAPAN

K.Watanabe, S.Awaji, and T.Fukase
Institute for Materials Research, Tohoku University, 2-1-1 Katahira, Aoba-ku, Sendai 980-77, Japan

Abstract **- We are developing a cryocooler cooled 6T superconducting magnet without liquid helium and/or liquid nitrogen. This magnet, which is directly cooled by two 4K Gifford-McMahon(GM) cryocoolers in vacuum, consists of an graded NbTi coil, Bi-based oxide superconducting current leads and a persistent current switch. The coil is made using two types of NbTi wires and a copper bobbin. The coil with an inner diameter of 260mm, an outer diameter of 329mm, and a height of 334mm, is impregnated with grease to ensure a good heat conduction. The operating current for a central field of 6T in the 220mm room temperature bore is 152A. A mechanical persistent current switch is used to limit the load from the switch into the 4K GM cryocooler. Designed temperature of the magnet is 4.9 K at the operating current of 152 A.**

I. INTRODUCTION

A large bore superconducting magnet system which is easy to operate is necessary for advanced research in biological, chemical, and medical sciences. However conventional superconducting magnets need cooling by liquid helium. As it is difficult to continuously operate a superconducting magnet over many hours, because of a limited supply of liquid helium, the realization of a superconducting magnet without liquid helium is of great advantage for a wide applications of superconducting magnets [1].

We have already developed cryocooler cooled superconducting magnet systems without liquid helium and/or liquid nitrogen. A $(Nb,Ti)_3Sn$ superconducting magnet system has generated a magnetic field of 4.6 T in a 38 mm room temperature bore using a 10 K GM cryocooler and Bi-based oxide current leads [2,3]. This system has operated continuously at a field of 3.7 T for 1200 hours. Then, NbTi superconducting magnet system has been developed by using a 4 K GM cryocooler and Bi-based oxide current leads, by the successful development of 4 K GM cryocoolers. This system has generated a magnetic field of 5.0 T in a 51 mm room temperature bore [4]. The magnet has operated continuously at a field of 5.0 T for 100 hours.

On the basis of these developments, we are developing a cryocooler cooled 6T superconducting magnet with a larger room temperature bore of 220 mm and a vertical penetration for various scientific applications. This magnet consists of a graded NbTi coil, Bi-based oxide superconducting current leads, two 4K GM cryocoolers, a mechanical persistent current switch, and a vacuum chamber. In this paper, we present the design and the construction.

II. DESIGN OF MAGNET SYSTEM

A. NbTi Superconducting Coil

The superconducting coil consists of an inner and an outer section. The inner coil with an inner diameter of 260 mm, an outer diameter of 288 mm, and height of 334 mm is wound using NbTi wire with a cross section of 0.8 x 1.6 mm and copper to superconductor ratio of 1.5. The outer coil with an inner diameter of 288 mm, an outer diameter of 330 mm, and height 334 mm is wound NbTi wire with a diameter of 0.8 mm and copper to superconductor ratio of 1.5.

The inner coil generates a magnetic field of 1.4T and the outer coil generates 4.6T in the center of a room temperature bore of 220 mm at the normal operating current of 152 A. The peak fields in the inner coil and in the outer coil are 6.6 T and 4.9 T, respectively. Inductance of the coil is 35 H and the stored energy is 400 kJ. If the coil quenches at 152 A, the stored energy will be thermally absorbed by the coil which weighs 120 kg, the temperature of the coil will rise to 120 K.

Figure 1. shows the load lines of the inner and outer coil, and the field dependencies of the critical current (I_c) vs. magnetic field (B) characteristics at various temperatures.

Manuscript received June 13, 1995.

*present address : Faculty of Engineering, Tokai University, 1117 Kitakaname, Hiratsuka 259-12, Japan

0018-9464/96$05.00 © 1996 IEEE

Authorized licensed use limited to: TOHOKU UNIVERSITY. Downloaded on March 04,2010 at 00:18:45 EST from IEEE Xplore. Restrictions apply.

The I_c-vs-B curves in Figure 1 are estimated by the scaling law based on flux pinning theory [5]. The critical temperature corresponding to the operating current of 152 A is 6.0 K for the inner coil and 6.3 K for the outer coil. As the temperature of the coil is estimated to be 4.9 K at the operating current of 152 A, the temperature margin is 1.0 K for the inner coil and 1.3 K for the outer coil.

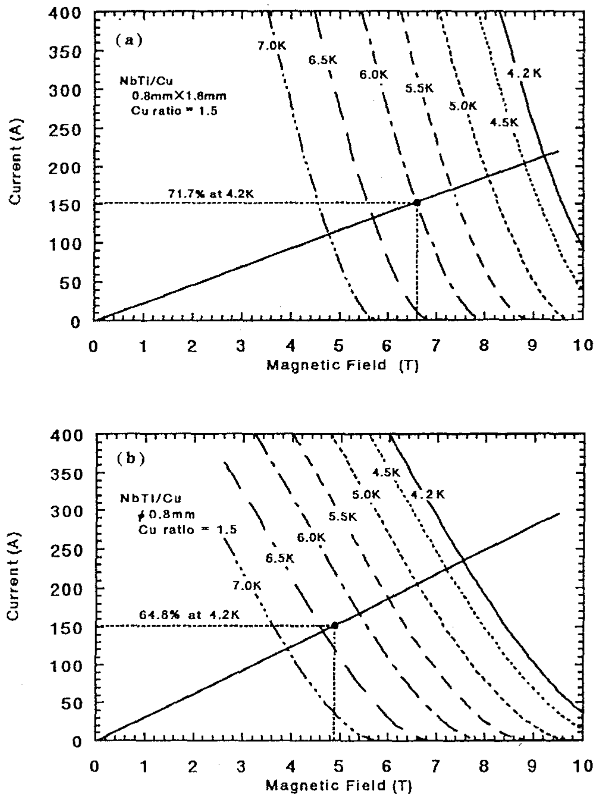

Fig. 1. Critical current versus magnetic field at various temperatures for NbTi wires and the load line for (a) inner coil and (b) outer coil.

B. Bi-based Oxide Current Lead

In order to reduce the heat load to the cryocooler, Bi-based oxide current leads are used. The composition of the current lead which has an outer diameter of 23 mm, an inner diameter of 20 mm, and a length of 190 mm, is $(Bi,Pb)_2Sr_2Ca_2Cu_3O_{10}$.

Since a room temperature bore is large, stray magnetic field from the coil is about 1T at the cold end of the Bi-based oxide current leads and about 0.3T at the warm end. Figure 2. shows distribution of the stray magnetic field intensity at the current leads. The critical current of the current leads is over than 1000 A at 1T and 4.9 K which is the design temperature of the cold end [6]. The critical current is more than 800 A at 0.3T and 45 K which is the design temperature of the warm end [7]. Thus these current leads have enough current margin for this magnet system.

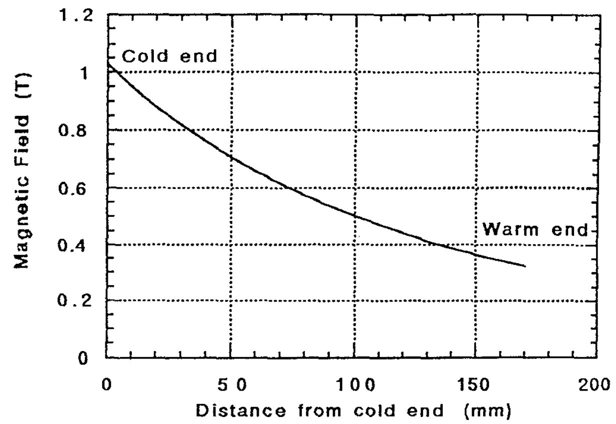

Fig. 2. Distribution of stray magnetic field intensity at Bi-based oxide current lead.

C. Cryocooler

Two double stage 4K GM cryocoolers are utilized for the superconducting magnet system. Regenerative material for the 1st stage displacer is copper mesh, and material for the 2nd stage displacer is lead and ErNiCo spheres. Figure 3 shows the measured temperature of the stages of the cryocooler. When heat loads of the 1st and 2nd stages are 0 W, the 1st stage cools at 30 K and the 2nd stage cools at 3.65 K.

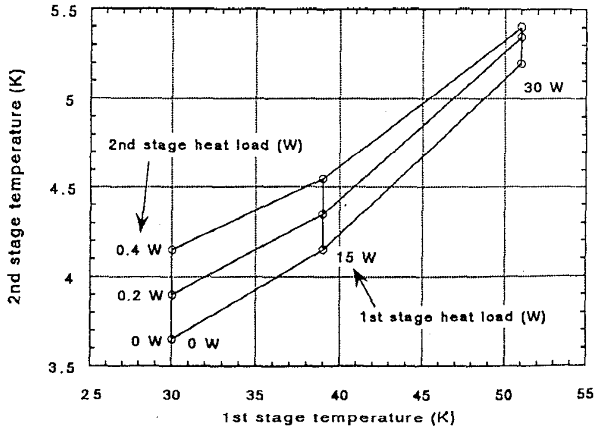

Fig. 3. Measured temperature of the stages of the cryocooler.

Authorized licensed use limited to: TOHOKU UNIVERSITY. Downloaded on March 04,2010 at 00:18:45 EST from IEEE Xplore. Restrictions apply.

D. Mechanical Persistent Current Switch

Figure 4. shows the details of the mechanical persistent current switch. When the copper block attached a GFRP rod is driven by air pressure, the block shorts two NbTi wires at the 2nd stage. The NbTi wires and the copper block are plated with silver. The design resistance between the NbTi wires in the persistent current mode is under 1 μΩ, and the rate of decease of the current is 1.0 x 10^{-4} / hour.

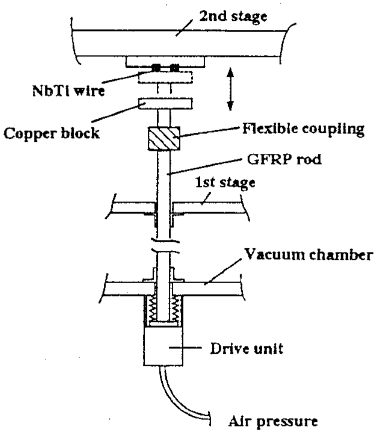

Fig. 4. Details of the mechanical persistent current switch.

III. STRUCTURAL DESIGN

The sectional view of the cryocooler cooled magnet is shown Figure 5. The outer diameter and the height of the magnet system is 610 mm and 1575 mm, respectively. In order to obtain good access for experiments, the top the magnet is flat, and working space is secured at under area. The NbTi superconducting coil, Bi-based oxide current leads, two cryocoolers, copper current leads, the mechanical persistent switch, and radiation shield are installed inside of a vacuum chamber.

To ensure a good heat conduction, 1) the coil form is made of copper, 2) the superconducting coil is impregnated with grease, 3) the coil is set onto the 2nd stage by bolting, 4) the coil is surrounded by two copper blocks which are mounted on the 2nd stage. The superconducting coil and 2nd stage whose total weight is 120 kg, are supported on the 1st stage by two cryocoolers and two GFRP pipes.

The current leads are connected between the 1st stage and superconducting coil. The warm ends of Bi-based oxide current leads are soldered to copper mesh wires to avoid thermal stresses.

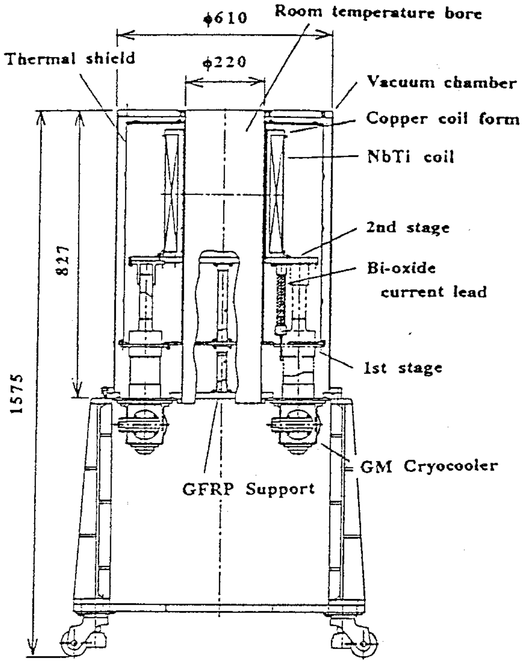

Fig. 5. Sectional view of the cryocooler cooled 6T NbTi superconducting magnet with room temperature bore of 220 mm.

IV. THERMAL DESIGN

Table 1 shows the calculated heat loads on the cryocoolers at the operating current of 0 A and 152 A. The total heat loads are 42.8 W at the 1st stage and 0.61 W at the 2nd stage at 152 A. Estimated temperatures of 1st and 2nd stages from these heat loads and cryocooler's cooling capacity (Fig.3.) are 45 K and 4.9 K, respectively.

TABLE 1
CALCULATED HEAT LOADS

	at 0 A	at 152 A
1st stage		
Copper current leads	: 7.2 W	11.8 W
Heat radiation	: 25.9 W	25.9 W
Wires for measurement	: 0.3 W	0.3 W
Joule heating	: 0.0 W	2.3 W
GFRP Supports	: 2.5 W	2.5 W
1st stage total	: 35.9 W	42.8 W
2nd stage		
Bi-based oxide current leads	: 0.06 W	0.06 W
Heat radiation	: 0.03 W	0.03 W
Wires for measurement	: 0.11 W	0.11 W
Joule heating	: 0.00 W	0.19 W
GFRP Supports	: 0.06 W	0.06 W
AC loss	: 0.00 W	0.16 W
2nd stage total	: 0.26 W	0.61 W
1st stage temperature	: 43 K	45 K
2nd stage temperature	: 4.6 K	4.9 K

Authorized licensed use limited to: TOHOKU UNIVERSITY. Downloaded on March 04,2010 at 00:18:45 EST from IEEE Xplore. Restrictions apply.

V. CONSTRUCTION

An inside and outside view of the magnet system is shown in Figure 6 and Figure 7. Table 2 shows the parameters of the magnet system.

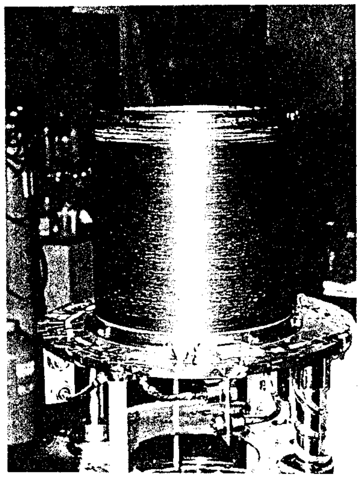

Fig.6. Inside view of the magnet system.

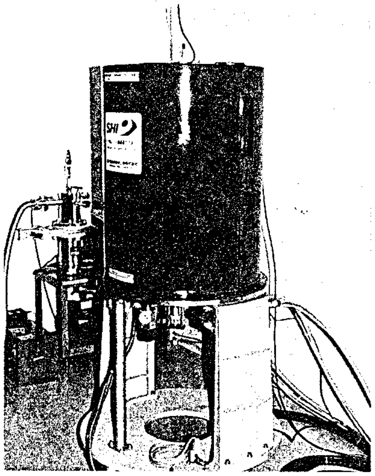

Fig.7. Outside view of the magnet system.

VI. CONCLUSIONS

We have designed and constructed a cryocooler cooled superconducting magnet with a room temperature bore of 220 mm. The magnet consists of a graded NbTi coil, two 4K GM cryocoolers, Bi-based oxide superconducting current leads, a mechanical persistent current switch, a radiation shield, and a vacuum chamber. The magnet generates a magnetic field of 6T in a 220 mm room temperature bore at a calculated coil temperature of 4.9 K, and an operating current of 152 A. We will finish the peformance test of the magnet system within the year.

TABLE 2
PARAMETERS OF A CRYOCOOLER COOLED SUPERCONDUCTING MAGNET WITH A ROOM TEMPERATURE BORE OF 220mm

Magnet System	
Central field	: 6.0 T at 152A
Room temperature bore	: 220 mm
Dimensions	: Outer diameter 610 mm Height 1575 mm (including support)
Weight	: 330 kg
Superconductor for coil	
Material	: NbTi/Cu
Dimensions	: 0.8mm x 1.6mm for inner coil(bare) ϕ 0.8mm for outer coil (bare)
Copper/NbTi ratio	: 1.5
Superconducting coil	
Inner coil	: ID 260 mm, OD 288 mm 3211 turns
Outer coil	: ID 288 mm, OD 330 mm 10990 turns
Both coil	: Height 334mm
Inductance	: 35 H
Bi-based oxide current leads	
Materials	: $(Bi,Pb)_2Sr_2Ca_2Cu_3O_{10}$
Dimensions	: OD 23 mm x ID 20 mm x L 190 mm
Critical current	: Over 1000 A at 77K, 0T
Cryocooler	
Type	: GM cycle
Number	: Two
Refrigeration capacity	: 0.4 W / 4.5K, 15 W / 40K (per one)

REFERENCES

[1] T.Kuriyama, M.Urata, T.Yazawa, K.Yamamoto, Y.Ohtani, K.Koyanagi, T.Masegi, Y.Yamada, S.Nomura, H.Maeda, H.Nakagome and O.Horigami, "Cryocooler Directly Cooled 6 T NbTi Superconducting Magnet System with 180 mm Room Temperature Bore", Proceedings of the 15th ICEC, 1994, pp.643-646

[2] K.Watanabe, Y.Yamada, J.Sakuraba, F.Hata, C.K.Chong, T.Hasebe and M.Ishihara, "$(Nb,Ti)_3Sn$ Superconducting Magnet Operated at 11 K in Vacuum Using High-Tc $(Bi,Pb)_2Sr_2Ca_2Cu_3O_{10}$ Current Leads", Jpn. J. Appl. Phys. Vol.32, 1993, pp. L488 - 490 Part2, No.4 April 1993.

[3] F.Hata, J.Sakuraba, C.K.Chong, Y.Yamada, T.Hasebe, M.Ishihara, and K.Watanabe, "A Conduction Cooled Superconducting Magnet Using High-Tc Oxide Current Leads", IEEE Trans. on Mag, Vol.30, No.4, July 1994, pp.1903-1906

[4] J.Sakuraba, F,Hata, C.K.Chong, Y.Yamada, K.Watanabe, and K.Yokoo, "Liquid Helium-Free Superconducting Magnet for Millimeter Wave Gyrotrons", The 19th IR & MM WAVES Conference Digest, 1994, pp.220

[5] E.J.Kramer, "Scaling Laws for Flux Pinning in Hard Superconductors", J. Apply. Phys., Vol.44, No.3, 1973, pp.1360

[6] Y.Yamada, T.Yanagiya, T.Hasebe, K.Jikihara, M.Ishizuka, S.Yasuhara, and M.Ishihara, "Superconducting Current leads of Bi-based Oxide", IEEE Trans. on Apply. Superconductivity, Vol.3, No.1, pp.923-926

[7] T.Hasebe, T.Tsuboi, K.Jikihara, S.Yasuhara, J.Sakuraba, M.Ishihara, and Y.Yamada, "Dependence on Temperature and Magnetic Field of Transport Current of Bi-2223 Bulk", ICMC Topical Conference, Honolulu, October 24-26, 1994

Authorized licensed use limited to: TOHOKU UNIVERSITY. Downloaded on March 04,2010 at 00:18:45 EST from IEEE Xplore. Restrictions apply.