Practical Use of a Liquid Helium-Free Superconducting Magnet(Magnet Technology)

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journal or publication title	Science reports of the Research Institutes, Tohoku University. Ser. A, Physics, chemistry and metallurgy
volume	42
number	2
page range	411-414
year	1996-07-15
URL	http://hdl.handle.net/10097/28639

Sci. Rep. RITU A42 (1996) pp. 411-414
No. 2, May 1996

Practical Use of a Liquid Helium-Free Superconducting Magnet *

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(Received February 15, 1996)

A cryocooler-cooled 4.6 T superconducting magnet with a 38 mm room temperature bore, which consists of a low-T_c Nb_3Sn coil and high-T_c $Bi_2Sr_2Ca_2Cu_3O_{10}$ current leads, has been working in vacuum for about 18000 cooling hours without trouble. It is found that the high-T_c current leads can hold excellent superconducting properties for a long enough time to be practically used. As a next step, we have succeeded in the construction of a 10.7 T-52 mm room temperature bore and a 5.7 T-220 mm room temperature bore liquid helium-free superconducting magnet.

KEYWORDS: liquid helium free, cryocooler, high temperature superconducting current lead, superconducting magnet

1. Introduction

Although liquid helium has enabled us to realize a superconducting magnet, it is holding back high field applications. Liquid helium is troublesome to handle and is expensive to use. In addition, liquid helium requires a large cryostat with a complicated structure to house. To eliminate the use of liquid helium for superconducting magnets, cryocooler-cooled superconducting magnet systems have been designed.[1,2] Since the liquid helium-free magnet is operated in vacuum, it is impossible to adopt the conventional helium gas flow current leads. Therefore, it was very difficult to reduce large heat loads due to copper current leads for the usage of a cryocooler with small refrigeration capacity. Recently discovered high-T_c superconductors are expected to be suitable for current leads, because they have very low thermal conductivity. We demonstrated the compact liquid helium-free superconducting magnet system using $Bi_2Sr_2Ca_2Cu_3O_{10}$ current leads for the first time of the world.[3]

This paper describes a high field and a large bore liquid helium-free superconducting magnet. A 10.7 T-52 mm room temperature bore and a 5.7 T-220 mm room temperature bore liquid helium-free superconducting magnet are successfully realized.

2. $Bi_2Sr_2Ca_2Cu_3O_{10}$ Current Leads

Tubular $Bi_2Sr_2Ca_2Cu_3O_{10}$ current leads with 23 mm outer diameter, 20 mm inner diameter and 140 mm long as shown in Fig. 1 were made by a powder-sintering process. Figure 2 shows the J_c-vs-B characteristics at temperatures from 77.3 K to 4.2 K in fields perpendicular to the transport current direction for $Bi_2Sr_2Ca_2Cu_3O_{10}$ leads. Since the c-axis direction of the lead with a preferred orientation is perpendicular to the tubular surface, it has a weak point for the critical current density at 77.3 K for $B \perp I$. The $Bi_2Sr_2Ca_2Cu_3O_{10}$ leads indicate current capacities of 500 A at 200 G and 77.3 K and 200 A at 1 T and 50 K for $B \perp I$.

The heat load of a pair of $Bi_2Sr_2Ca_2Cu_3O_{10}$ leads is expected to be 0.2 W using the thermal conductivity integral value of about 1 W/cm from 77 K to 4.2 K. An attempt was made to demonstrate a compact superconducting magnet system using large capacity of 500 A current leads. A cryocooler-cooled 11 K-4.6 T superconducting magnet with no use of liquid helium, consisting of a low-T_c Nb_3Sn superconducting coil and high-T_c $Bi_2Sr_2Ca_2Cu_3O_{10}$ current leads, was already realized.[3] The system has been working for about 18000 cooling hours up to now. Some

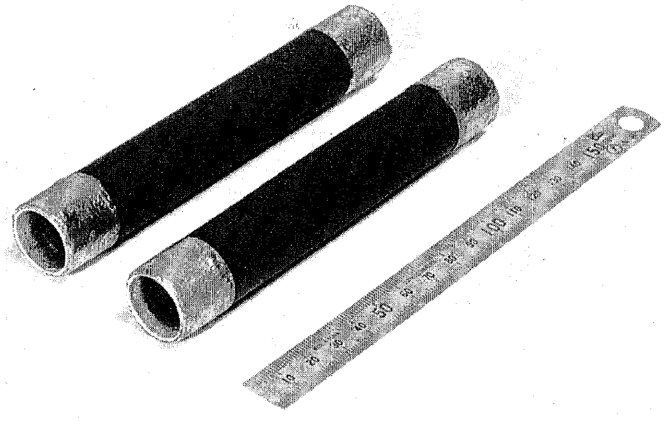

Figure 1 High-T_c superconducting current leads of $Bi_2Sr_2Ca_2Cu_3O_{10}$.

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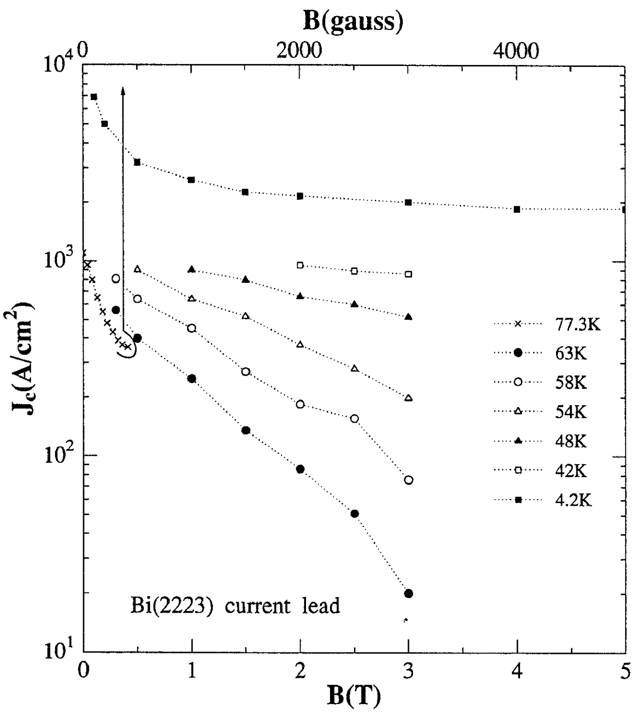

Figure 2 J_c properties in fields at temperatures from 4.2 K to 77.3 K for the Bi(2223) current lead. Magnetic fields are applied perpendicular to the transport current.

experiments were continuously performed for 1200 hours at 3.7 T which is generated by an operating current of 370 A. No variation of the contact resistance for the high-T_c leads was observed. It is found that the $Bi_2Sr_2Ca_2Cu_3O_{10}$ current leads with no reinforcement work excellently in vacuum for a long time.

3. High Field Superconducting Magnet

Recently, a GM-cryocooler with a magnetic regenerator Er_3Ni has been improved, and can provide a refrigeration power of 0.5 W at 4 K. We designed a liquid helium-free high field superconducting magnet which consisted of an outer NbTi coil and an inner $(Nb,Ti)_3Sn$ coil. The critical currents in fields up to 23 T for Nb tube processed $(Nb,Ti)_3Sn$ wires which have wire characteristics of Cu/non Cu ratio of 0.89, filament number of 54, filament diameter of 88 μ m and wire diameter of 0.9 mm were measured. The estimation of the field dependence of I_c at various temperatures is shown in Fig. 3, using the Kramer-type scaling law. The critical current of 200 A is obtainable at 11 T and 8 K. For a NbTi multifilamentary wire, the wire parameters are Cu/NbTi ratio of 1.9, filament number of 1050, filament diameter of 22 μ m and wire diameter of 0.8×1.5 mm^2. The outer coil generates a central field of 4.6 T and a maximum field of 5.2 T at the windings. The critical current of 280 A at 5.2 T and 6.0 K is estimated. We adopted the operating current of 152 A at coil temperature of 6.0 K for the maximum field of 11.2 T.

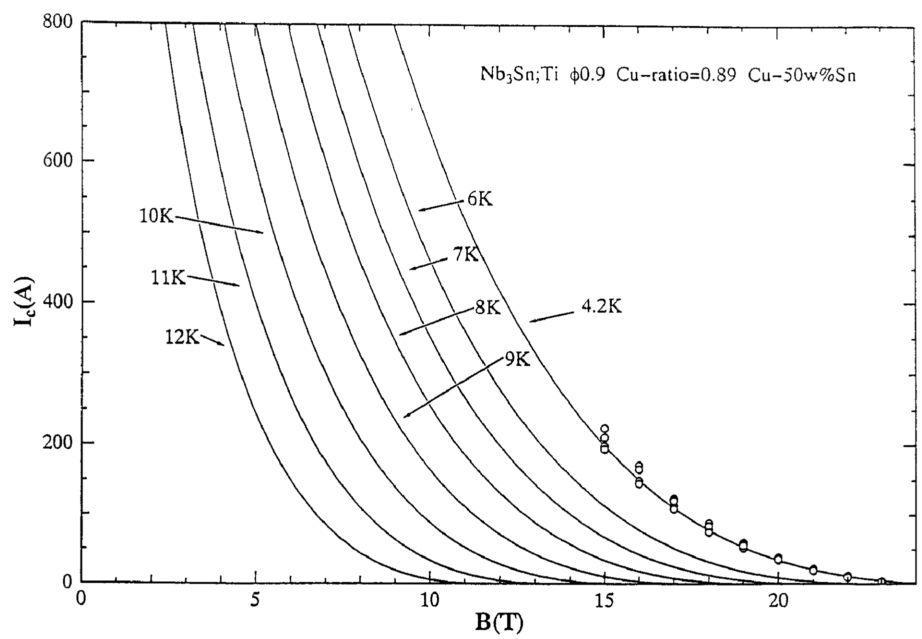

Figure 3 I_c- vs- B properties at various temperatures for Nb tube processed multifilamentary $(Nb,Ti)_3Sn$ superconducting wires.

Figure 4 shows an outline of the liquid helium-free 11 T superconducting magnet. Heat loads are estimated to be about 0.30 W for a second stage with Bi(2223) leads and about 30 W for a first stage with copper leads of the cryocooler. An experimental room temperature bore of 52 mm is available. The $(Nb,Ti)_3Sn$/NbTi coil was cooled down to 4.3 K in 40 hours from room temperature using two GM-cryocoolers. In a performance test, the coil temperature increased to 6.6 K for the inner $(Nb,Ti)_3Sn$ coil and 5.9 K for the outer NbTi coil while sweeping a field at 0.43 T/min. We succeeded in generating a central field of 10.7 T at maximum and holding 10.5 T for 5 hours. This liquid helium-free high field magnet will be superior to traditional 8 T NbTi superconducting magnets immersed in liquid helium.

4. Large Bore Superconducting Magnet

The high field superconducting magnet with a large experimental room temperature bore is of importance for a number of practical applications. A great interest is recently being focused on chemical or biological effects in high field. In order to offer an easy- operation of such a large bore superconducting magnet, a 6 T- 220 mm room temperature bore superconducting magnet without use of cryogenic fluids is constructed. The outline of the cryocooler-cooled large bore superconducting magnet is shown in Fig. 5. The coil is set onto the second stage of two GM-cryocoolers whose total refrigeration power is about 0.8 W at 4 K. Total heat loads for the 1st stage at 40 K and for the 2nd stage at 4 K of GM-cryocoolers are 23.4 W and 0.24 W, respectively. Main heat loads are due to current leads, and are 13 W for the 1st stage from 300 K to 40 K and 0.08 W for the 2nd stage from 40 K to 4 K. Since the coil mass is about 150 kg, the initial cooldown time from room temperature to 4 K is estimated to be within 44 hours. The coil graded into two sections is wound employing multifilamentary NbTi superconducting wires. The multifilamentary NbTi wires are composed of 4,200 filaments with size of about 10 μm and twist pitch of 18 mm. The superconducting magnet wound by these NbTi wires has a temperature rise of 0.45 K at a field-sweep speed of 6 T/25 min. We adopted a coil temperature of about 5 K. Figure 6 shows the load line together with the magnetic field dependencies of I_c at various temperatures which are calculated from a scaling characteristic using I_c data at 4.2 K. The operation current I_{op} is 152 A

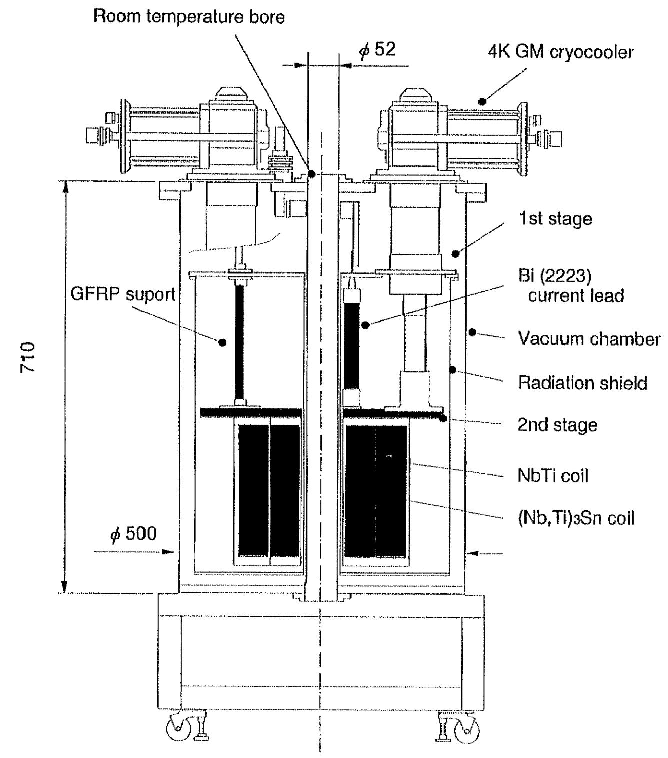

Figure 4 Liquid helium-free 11 T high field superconducting magnet system with the compact cryostat of outer diameter of 500 mm, room temperature bore of 52 mm and cryostat height of 710 mm.

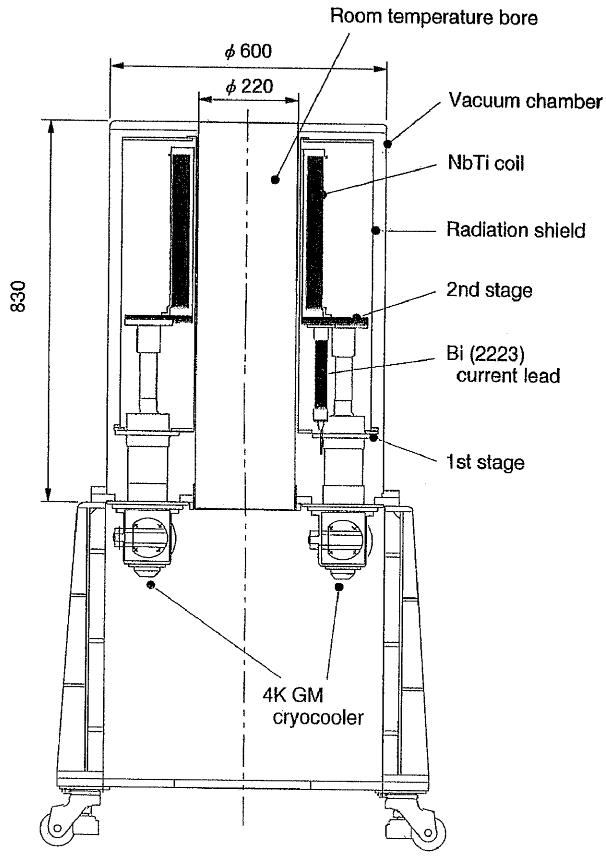

Figure 5 Liquid helium-free 220 mm room temperature bore superconducting magnet system.

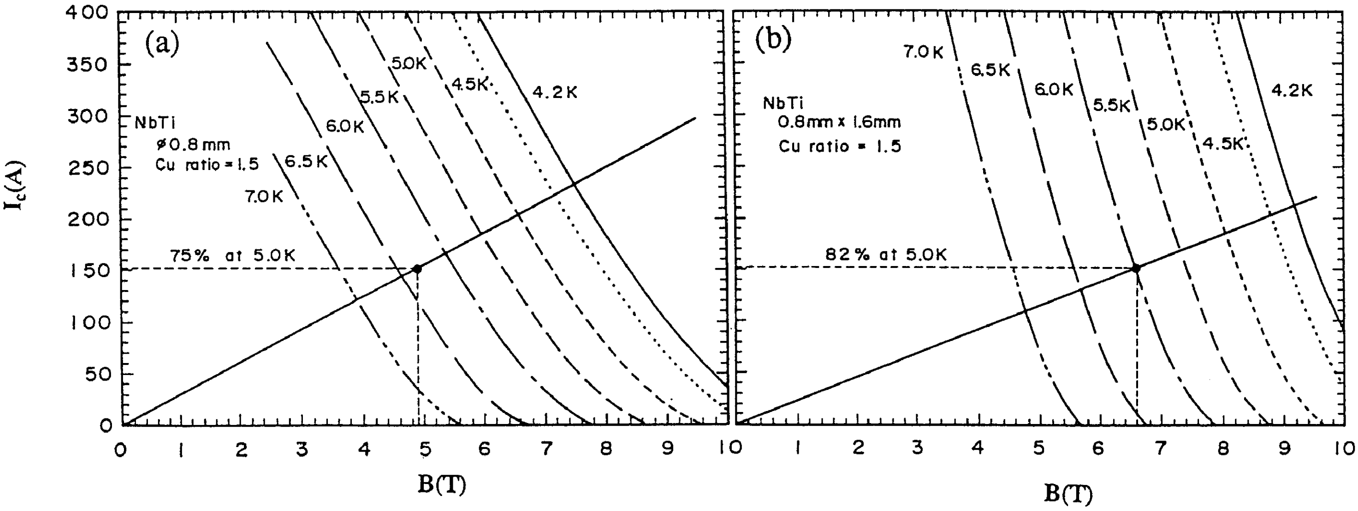

Figure 6 I_c-vs- B properties at various temperatures for multifilamentary NbTi superconducting wires and the load line of a 6 T large bore superconducting magnet for (a) outer coil and (b) inner coil.

at 6 T which corresponds to a design where the current margin at 5.0 K is $I_{op} \approx 75\ \%\ I_c$ for an outer coil and 82 % I_c for an inner coil. In the case that the coil quench occurs at 6 T, the stored energy of 400 kJ is absorbed by the coil and then the coil temperature is estimated to be about 120 K under the adiabatic condition. In a performance test, the coil was initially cooled down to 3.8 K. The coil temperature increased to 5.0 K at a sweeping rate of 0.12 T/min near 5.7 T. A central field of 5.7 T at maximum was generated in a 220 mm room temperature bore, and holding at 5.5 T was tested for 1 hour. The liquid helium-free large bore superconducting magnet will be provided as common use for all those who intend to carry out frontier sciences such as biological, chemical and medical researches in high fields.

Acknowledgements

This work is supported by Toray Science Foundation, and Grant-in-Aids from Scientific Research from the Ministry of Education, Science and Culture, Japan.

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