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A Cryocooler Cooled 5 T Superconducting Magnet with a Horizontal and Vertical Room Temperature Bore

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Abstract—We designed and constructed a cryocooler cooled 5 T superconducting magnet with a horizontal room temperature bore of 50 mm and a vertical room temperature bore of 90 mm without liquid helium. The magnet, which is directly cooled by 4 K Gifford-McMahon cryocooler in vacuum, consists of NbTi coil, Bi(2223) bulk current leads and cryostat. The coil with an inner diameter of 130 mm, an outer diameter of 301 mm, a height of 66 mm and a gap of 80 mm is made using NbTi wires and Cu-plated SUS bobbin. Bi(2223) bulk current leads are thin-walled sintered cylindrical tube. The outer diameter, height and weight of the magnet are 510 mm, 730 mm and 260 kg, respectively. The magnet is cooled down to 3.8K in approximately 62 hours. A continuous operation at 5 T, which is generated by an operating current of 122 A, has been performed.

I. Introduction

Since we have developed a cryocooler cooled 4.6 T superconducting magnet without liquid helium [1], we have designed and constructed several types cryocooler cooled superconducting magnets[2]. One of the merits of the cryocooler cooled superconducting magnet is it is easy to operate. Therefore many researchers who have never handled liquid helium may utilize high magnetic fields and perform several types experiments under high magnetic field. When studying phenomenon under a high magnetic field, a magnet with horizontal and vertical bore access is very useful. Because one bore is for the specimen, the other can be utilized for observing the specimen and applying X-ray and/or laser.

In this paper we describe the design and the test results of a cryocooler cooled 5 T superconducting magnet with a cross room temperature bore.

II. Design

A. Magnet system

This magnet consists of NbTi superconducting coil, Bi(2223) bulk current leads, 4K Gifford-McMahon (GM) cryocooler, GFRP support pipes, thermal radiation shield and vacuum chamber. The outer diameter and height of the cryostat are 510 mm and 730 mm. The weight of the cryostat is 260 kg. There is horizontal room temperature bore of 50 mm and a vertical room temperature bore of 90 mm. The main parameters of the magnet system are shown in Table I.

TABLE I
PARAMETER OF A CRYOCOOLER COOLED 5 T SUPERCONDUCTING MAGNET WITH A HORIZONTAL AND VERTICAL ROOM TEMPERATURE BORE

Cryostat	
Horizontal room temperature bore	50 mm
Vertical room temperature bore	90 mm
Dimensions	Outer diameter 510 mm Height 730 mm
Weight	260 kg
NbTi coil	
Inner diameter	130 mm
Outer diameter	301 mm
Height	66 mm
Coil gap	80 mm
Number of turns	6385 x 2
Operating current	122 A
Central field	5 T
Maximum field	6.8 T
Critical temperature	5.8 K
NbTi conductor	
Dimension	0.65 x 1.20 mm
Copper ratio	2.1
Filament diameter	ϕ14.4 μm
Twist pitch	19 mm
Critical current	750 A at 4.2 K, 5 T
Bi(2223) current lead	
Composition	(Bi,Pb):Sr:Ca:Cu = 2:2:2:3
Dimensions	ID 20 / OD 23 x L190 mm
Critical current	over 1000 A at 77 K, 0 T
4K GM cryocooler	
Regenerator of 1st displacer	Cu meshes and Pb spheres
Regenerator of 2nd displacer	Pb spheres and Er_3Ni spheres
Cooling capacity	0.7 W at 4.2 K for 2nd stage 40 W at 46 K for 1st stage

B. NbTi coil

The NbTi coil is split type coil with a coil gap of 80 mm. Each coil has an inner diameter of 130 mm, an outer

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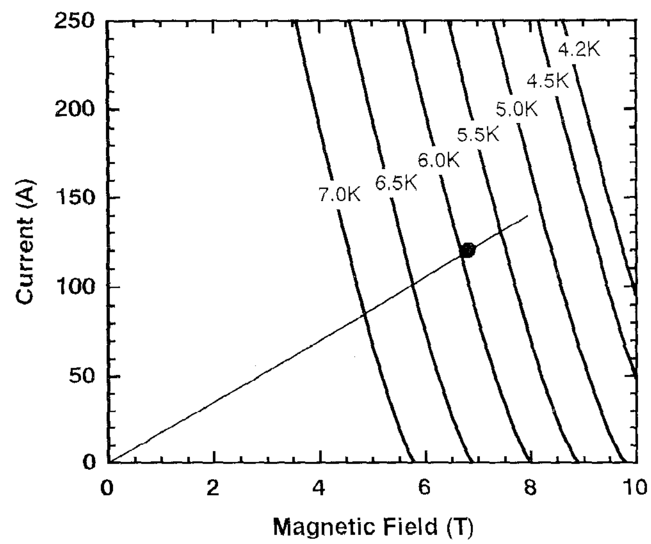

Fig. 1. Ic-vs.-B characteristics of NbTi conductor and a load line of the NbTi coil. A closed circle shows the operating point.

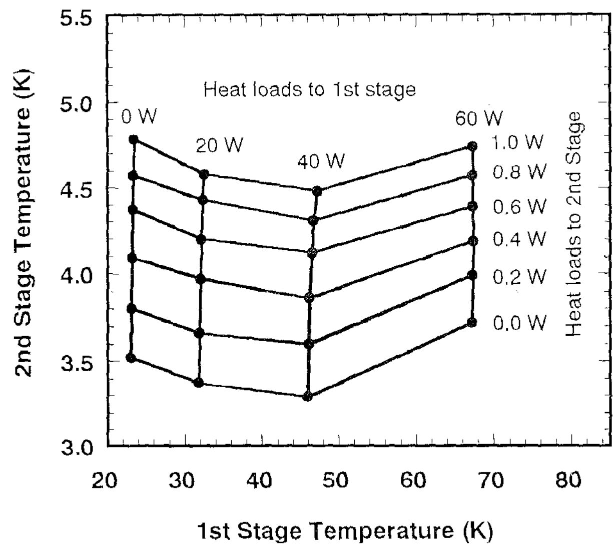

Fig. 2. The load map of the 4K GM cryocooler

diameter of 301 mm and a height of 66 mm which was wound upon Cu plated SUS bobbin using a commercial NbTi/Cu conductor. Dimension of the NbTi/Cu conductor is 0.65 x 1.20 mm with a Cu/non-Cu ratio of 2.1. The critical current of the conductor is 750 A at 4.2 K in a field of 5 T. A central field of 5 T is generated at an operating current of 122 A. Fig. 1 shows the dependence of the critical current (Ic) vs. the magnetic field (B) characteristics from 4.2 K to 7.0 K and the load line of the coil. The Ic-vs.-B curves were estimated by the global pinning scaling laws [3]. The critical temperature of the NbTi coil is estimated at 5.8 K.

C. Bi(2223) current leads

The Bi(2223) bulk current leads with an inner diameter of 20 mm, an outer diameter of 23 mm and a length of 190 mm were fabricated by intermediate cold isostatic pressing process [4]. Each end of the bulk was made into an electrode by Ag plasma splay. The critical current of the bulk was over 1,000 A at 77K in absence of a filed. A contact resistance between Bi(2223) bulk and Ag electrode was below 1 x 10^{-6} ohm at 77 K. The cantilever bending strength of the bulk leads at room temperature were approximately 20 MPa.

D. GM cryocooler

The cryocooler is a two stage GM cycle cryocooler. The regenerator of 1st displacer is Cu mesh and Pb spheres, and those of 2nd displacer is Pb spheres and Er_3Ni spheres. The load map of the cryocooler is shown in Fig. 2. The typical cooling capacity is 0.7 W at 4.2 K for the 2nd stage and 40 W at 46 K for the 1st stage.

E. Thermal design

The calculated heat load into the 1st stage and the 2nd stage of the cryocooler are listed in Table II. The heat loads into the 1st stages are due to thermal conduction through Cu current leads, measuring wires and GFRP support pipes, thermal radiation from room temperature, and joule heating of connection resistance. The heat loads into the 2nd stages are due to thermal conduction of Bi(2223) bulk current leads,

TABLE II
CALUCULATED HEAT LOADS TO CRYOCOOLER AND ESTIMATED TEMPERATURE

	Current at 0 A	Current at 122 A
1st stage		
Cu current leads	6.8 W	8.3 W
Measuring wires	0.1 W	0.1 W
Radiation	31.7 W	31.7 W
Joule heating	0.0 W	2.9 W
Support pipes	0.2 W	0.2 W
Total	36.8 W	43.3 W
2nd stage		
Bi(2223) current leads	0.082 W	0.082 W
Measuring wires	0.038 W	0.038 W
Radiation	0.099 W	0.099 W
Joule heating	0.000 W	0.030 W
A.C. losses	0.000 W	0.061 W
Support pipes	0.015 W	0.015 W
Total	0.234 W	0.325 W
1st stage temperature	44 K	50 K
2nd stage temperature	3.7K	3.9 K

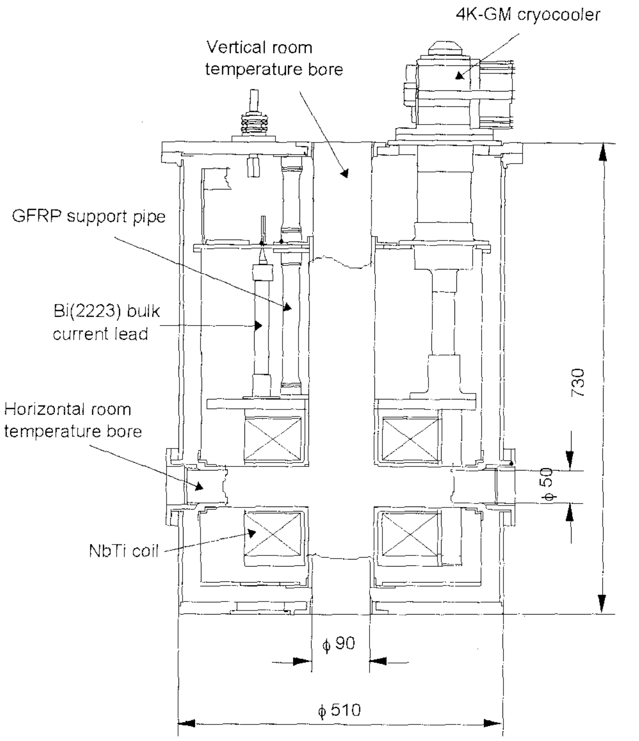

Fig. 3. Cross sectional view of the cryocooler cooled superconducting magnet with a horizontal and vertical room temperature bore,

measuring wires and GFRP support pipes, thermal radiation from the radiation shield plate temperature, joule heating of connection resistance and a.c. losses of NbTi wire. Estimated heat loads are 36.8 W for the 1st stages and 0.234 W for the 2nd stages at an operating current of 0 A, and 43.3 W for the 1st stage and 0.325 W for the 2nd stage at an operating current of 122 A. The temperature of the 1st and the 2nd stage are estimated to be 44 K and 3.7K at an operating current of 0 A, and 50 K and 3.9 K at an operating current of 122 A, respectively, from the load map of the 4K GM cryocooler shown in Fig. 2.

F. Cryostat

Fig. 3 shows the cross sectional view of the magnet system. The NbTi coil was set onto the 2nd Stage of the cryocooler. The bobbins of the upper and the lower coil were connected by bolts. The outer surface of coil was tightly covered with a Cu thin plate which was anchored to the 2nd stage. The cold end of the Bi(2223) bulk current lead was soldered to a Cu electrode anchored to the 2nd stage of the cryocooler through a ceramics insulator. The warm end of the Bi(2223) bulk current lead was connected to a flexible Cu braided wire which was anchored to the 1st stage of the cryocooler and connected to a Cu current lead from room temperature. Leakage fields at the cold end and the warm end of the Bi(2223) bulk current lead are estimated at 1.0 T and 0.23 T, respectively. When the magnet generates 5T, the Bi(2223) bulk leads experiences a bending load of 1.0 MPa by the electromagnetic force. As mentioned above, the Bi(2223) bulk lead has a bending strength of 20 MPa, therefore safety coefficient to static load is 20.

The 2nd stage was supported by two GFRP pipes with an inner diameter of 25 mm and an outer diameter of 29 mm and the 2nd cylinder of the cryocooler. The radiation shield is connected to the 1st stage.

III. Test Results

A. Cool Down

Initial cooling characteristics are shown in Fig. 4. The NbTi coil was cooled down to 3.8 K in approximately 62 hours. The 1st stage temperature was saturated at about 50 K in approximately 12 hours, while the temperature slightly rose around 60 hours, and finally reached 47 K. The measurement temperatures of the 2nd and the 1st stage agree well with the estimated temperatures shown in Table II.

B. Magnet Performance

After training 8 times, the magnet generated 5 T at an operating current of 122 A in a center of a room temperature bore .

Fig. 5 shows the typical excitation pattern. The operating current was increased up to 122 A with a ramp rate of 0.1 A/sec. The coil temperature rose up linearity to 4.15 K in the low field of 1 T, then rose up to 4.3 K with a curve of secondary degree. We considered that these were caused by A.C. losses of the NbTi conductor. The coil temperature went down to 4.1 K after holding the field at 5 T at an

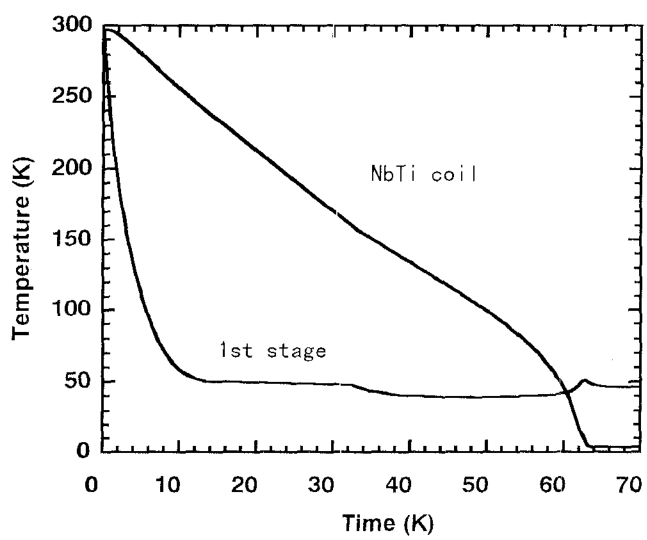

Fig.4. Initial cooling characteristics of 5 T magnet system

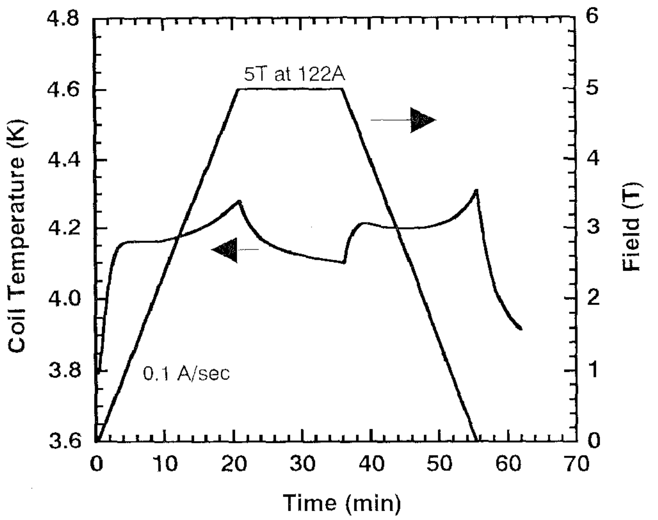

Fig. 5 The lower coil temperature of the magnet operated at 5 T in operating current of 122 A with a ramp rate of 0.1 A/sec.

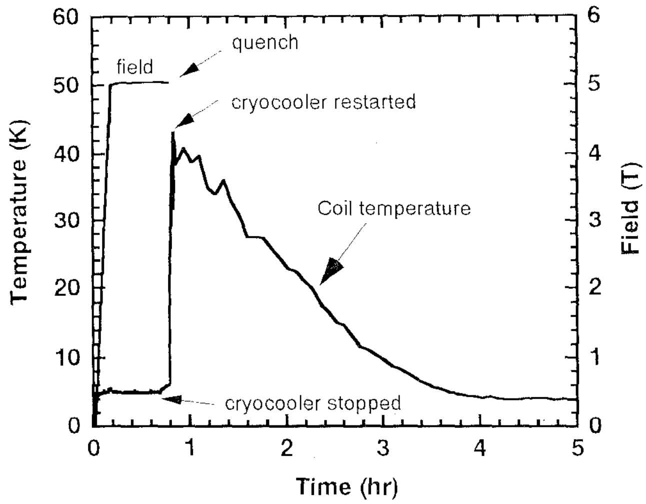

Fig. 6. The lower coil temperature after stopping and restarting the cryocooler

operation current of 122 A for 15 minutes. But the coil temperature didn't saturated while holding the field for 15 minutes. The operating current was decreased down to 0 A with a ramp rate of 0.1 A/sec. The coil temperature rose up to 4.32 K, at this time.

Fig. 6 shows the coil temperature when the cryocooler was stopped at the generating filed of 5 T. The lower coil temperature increased up to 6.2 K in 6.5 minutes after stopping the cryocooler and then the coil quenched in the upper coil. The temperature of 6.2 K is 0.4 K higher than estimated temperature of 5.8 K from Ic-vs.-B curves shown in Fig.1. After quench, the coil temperature rose up to 42 K. The magnet was protected against a quench by diode protection circuits. A pair of diodes were connected in parallel with each coil. When a quench occurred, the stored energy was absorbed by the cooling mass. The cooling mass which is the NbTi coils, bobbins, the flange of the 2nd stage and the diodes is about 130 kg. The coil inductance is 17.5 H and the stored energy is 130 kJ at 5 T at an operating current of 122 A. The temperature of the coil, after quench, is estimated at 43 K. The measurement temperature of 42 K agree well with the estimated temperature. Thereafter the cryocooler was restarted, it took 4 hours to cool down to the initial temperature.

IV. Conculutions

A cryocooler cooled superconducting magnet with a horizontal and vertical room temperature bore consisting of the NbTi split coil, Bi(2223) bulk current leads and 4K GM cryocooler was designed and constructed. The NbTi coil was cooled down to 3.8 K in 62 hours. A central field of 5 T was successfully generated at an operating current of 122 A. After a coil quench at 5 T, it took 4 hours to cool down to the initial temperature.

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