A Cryocooler-Cooled 19 T Superconducting Magnet with 52 mm Room Temperature Bore

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A Cryocooler-Cooled 19 T Superconducting Magnet With 52 mm Room Temperature Bore

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***Abstract*—This paper describes a design of a cryocooler-cooled 19 T superconducting magnet. The technical features of the magnet are a Bi2223 insert coil composed of 25 double pancake coils, Nb_3Sn coils using a Nb_3Sn wire reinforced with Nb-Ti-Cu compound, and a cooling structure using two types of cryocoolers. Coil protection from quenching was confirmed by numerical analysis. A preliminary experiment was carried out in order to investigate the influence of the bending strain upon a maximum permissible hoop stress of Ag-sheathed Bi2223 tape conductor.**

***Index Terms*—Bi2223 coil, cryocooler-cooled superconducting magnet, high magnetic field, reinforced Nb_3Sn coil.**

I. INTRODUCTION

A CRYOCOOLER-COOLED 19 T superconducting magnet with 52 mm room temperature bore is currently under construction by the High Field Laboratory for Superconducting Materials, IMR, Tohoku University. It is planned to be tested for an excitation up to 19 T, whereas it would be operated at 18 T in an ordinary use. Recently, several cryocooler-cooled high magnetic field magnets have been developed [1], [2]. As far as we know, 18–19 T could be the highest magnetic field for a cryocooler-cooled superconducting magnet.

The designed magnet is a hybrid HTS-LTS magnet, which is composed of a Bi2223 insert coil and several layers of LTS coils. Since inner diameter of the Bi2223 insert coil is 90 mm, where a bending strain of Ag-sheathed Bi2223 tape conductor exceeds 0.2%, permissible hoop stress was determined by a preliminary experiment. For the inner LTS coils, two types of Nb_3Sn wires were selected, one for high critical current density and other for high mechanical strength. Recently, many kinds of Nb_3Sn wires reinforced with tantalum [3], Cu-Nb alloy [4], alumina-copper [5], and Nb-Ti-Cu [6] have been developed. Since Nb-Ti-Cu compound has a higher Young's modulus thanthe other reinforcements and a similar thermal contraction to the Nb_3Sn, the Nb_3Sn wire reinforced with Nb-Ti-Cu was selected.

In this paper, we report a design of a 19 T cryocooler-cooled superconducting magnet along with a preliminary experimental result for Ag-sheathed Bi2223 tape conductor.

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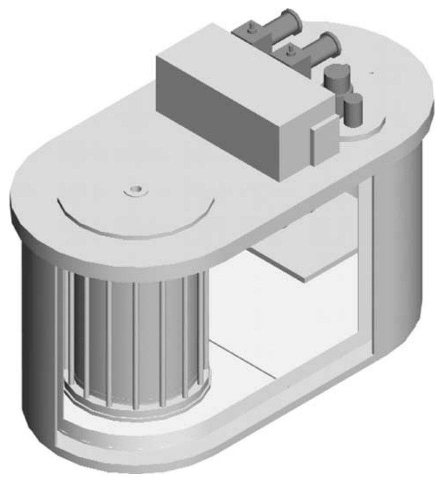


Fig. 1. Schematic of the cryocooler-cooled 19 T superconducting magnet.

TABLE I
SPECIFICATIONS OF THE CRYOCOOLER-COOLED 19 T SUPERCONDUCTING MAGNET

Central field	19 T (target) 18 T (rated value)
Diameter	52 mm (room temperature bore)
Dimensions	1080 mm × 2230 mm × 1190 mm
Weight	5 tons
Inductance	3.8 H / 150 H / 82 H
(HTS/inner/outer) current for 19 T	169 A / 191 A / 449 A
Stored energy at 19 T	11.3 MJ
Charging time for 18 T	40 min
Cryocoolers (two)	GM / JT cryocooler Single-stage GM cryocooler

II. DESIGN OF THE MAGNET

A. Cryostat

Fig. 1 shows a schematic of the cryocooler-cooled 19 T superconducting magnet. The magnet is equipped with two types of cryocoolers: a GM-JT cryocooler to cool superconducting coils and two single-stage GM cryocoolers to cool a thermal shield and current leads. Since the magnet is also equipped with a thermal switch filled with a gas, it is cooled from room temperature to an operating temperature within 10 days.

Dimension of a room temperature bore is 52 mm in diameter. If necessary in future, the insert coil could be taken out easily for exchange.

The magnet is energized up to 18 T within 40 min by three power-supplies. A user of the magnet can operate three power-supplies by a controller. The specifications of the magnet are listed in Table I.

TABLE II
DESIGN PARAMETERS OF THE COILS

	HTS Insert	Inner LTS	Inner LTS	Inner LTS	Inner LTS	Outer LTS
Coil	H1	L1	L2	L3	L4	L5
Superconductor	Ag-sheathed Bi2223 tape	Internal tin processed Nb_3Sn wire	Bronze processed Nb_3Sn wire*	Bronze processed Nb_3Sn wire*	Bronze processed Nb_3Sn wire*	NbTi wire
Dimensions of bare superconductor	4.3 mm × 0.21 mm	Φ 2.0 mm	Φ 1.82 mm	Φ 1.50 mm	Φ 1.35 mm	Φ 1.7 mm
Inner diameter of coil	90 mm	196 mm	273 mm	372 mm	451 mm	519 mm
Coil length	250 mm	316 mm	453 mm	561 mm	617 mm	710 mm
Number of turns	3500	2646	5928	8448	9394	9360
Operating current at 19 T	169 A	191 A	191 A	191 A	191 A	449 A
18 T	160 A	181 A	181 A	181 A	181 A	425 A
Maximum magnetic field at 19 T	19. 1 T	16. 5 T	14. 9 T	12.2 T	9.3 T	7.7 T
18 T	18. 1 T	15. 6 T	14.1 T	11.6 T	8.8 T	7.3 T
Operating temperature	< 4.5 K	< 4.5 K	< 4.5 K	< 4.5 K	< 4.5 K	< 4.5 K
Hoop stress at 19 T	53 MPa	145 MPa	186 MPa	258 MPa	258 MPa	108 MPa

* reinforced with NbTi-Cu

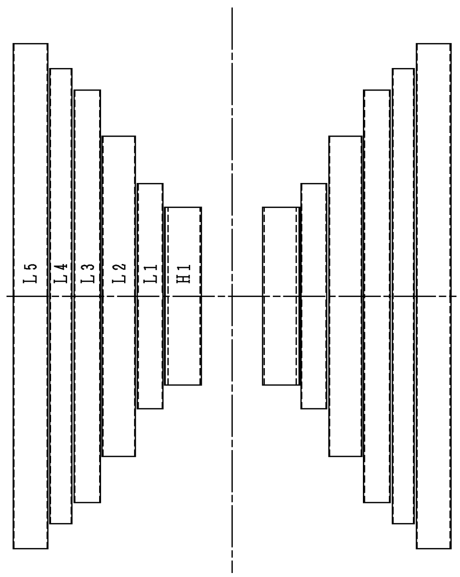


Fig. 2. Cross section of the superconducting coils of the cryocooler-cooled 19 T superconducting magnet.

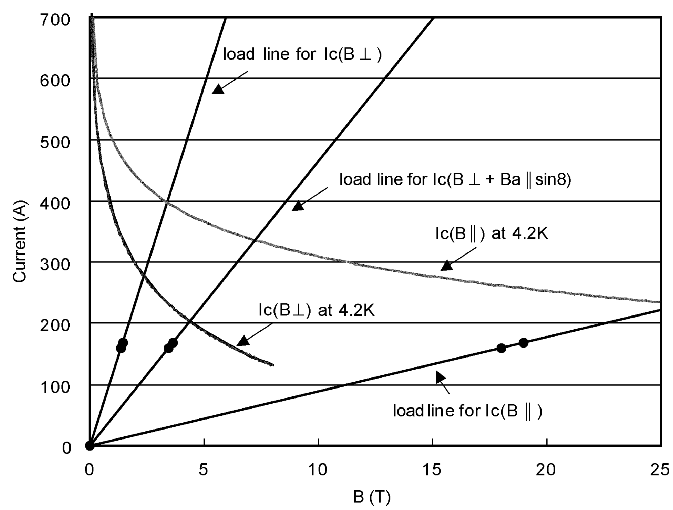


Fig. 3. Critical current versus magnetic field at 4.2 K for Ag-sheathed Bi2223 tape conductor and the load lines for the Bi2223 insert coil (H1). Two operating points on each load line corresponds to the points at 18 T and 19 T.

B. Superconducting Coils

The designed magnet consists of a Bi2223 insert coil, 4 layers of inner LTS coils, and an outer LTS coil. Fig. 2 shows a cross section of the coils and parameters of the coils are listed in Table II.

The Bi2223 insert coil is composed of 25 double pancake coils using Ag-sheathed Bi2223 tape conductor from SEI, with stainless steel tapes for reinforcement. Fig. 3 shows a load line of the insert coil [7]. It is designed for heat generation in a flux flow state not exceeding 0.2 W at 19 T.

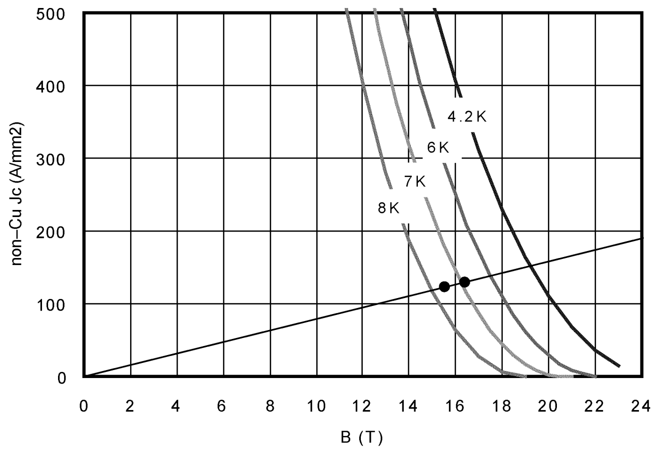
The LTS coils are composed of four Nb_3Sn coils. Since the innermost Nb_3Sn coil requires high critical current density at around 16 T, an internal tin processed Nb_3Sn wire from MELCO is employed. The heat treatment condition of the coil was carefully determined to prevent excessive enlargement of filament diameter. A load line of the L1 coil is shown in Fig. 4(a). Since the other three Nb_3Sn coils of the inner LTS coils require high mechanical strength capable of enduring a hoop stress beyond 250 MPa, a bronze processed Nb_3Sn wire reinforced with Nb-Ti-Cu compound, developed by Watanabe and FEC, was employed. Tensile stress of the wire at 0.3% strain, corresponding to a permissible maximum strain in the design, exceeds 250 MPa. Fig. 4(b) shows load lines of the three of four inner coils.

The outer LTS coil is a NbTi coil, and a load line of the coil is shown in Fig. 5. Since the shape of the outer LTS coil is thin and tall, a heater is placed on the coil surface along a coil axis to accelerate quench propagation.

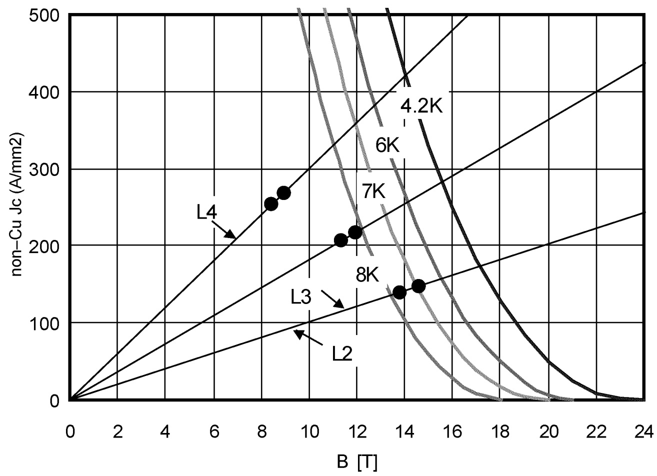
III. COIL PROTECTION

Coil protection from quenching was confirmed by numerical analysis [8]. Fig. 6 shows a protection circuit of the magnet. As shown in Fig. 6, each coil is connected to a pair of diodes. The Bi2223 insert coil (H1) and the innermost LTS coil (L1) are equipped with external resistors, respectively, because a result of quench simulation indicates that an excessive current would be induced without resistors.

Fig. 7 shows a result of simultaneous quenching of all superconducting coils. As shown in Fig. 7, induced currents are suppressed. Fig. 8 shows a profile of voltage between neighboring



(a) L1 coil of the inner LTS coils



(b) L2, L3, and L4 coils of the inner LTS coils

Fig. 4. Non-Cu J_c versus magnetic field at various temperatures for Nb_3Sn wires and the load lines for (a) L1 coil and (b) L2, L3, and L4 coils of the inner LTS coils. Two operating points on each load line corresponds to the points at 18 T and 19 T.

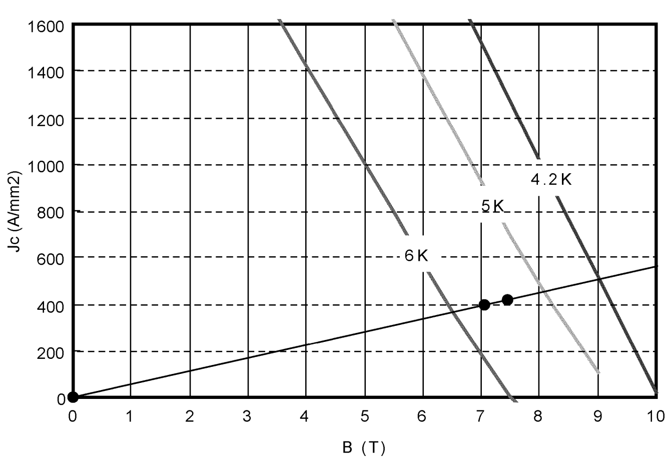


Fig. 5. J_c versus magnetic field at various temperature for L5 coil of the outer LTS coil. Two operating points on the load line corresponds to the points at 18 T and 19 T.

layers of the outer LTS coil when an internal voltage peaks. As shown in Fig. 8, the maximum voltage is reduced by a factor of two, which is a permissible level, by acceleration of quenching propagation with the heater.

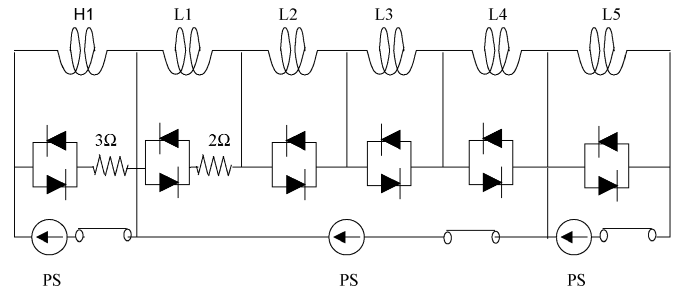


Fig. 6. A protection circuit diagram of the cryocooler-cooled 19 T superconducting magnet.

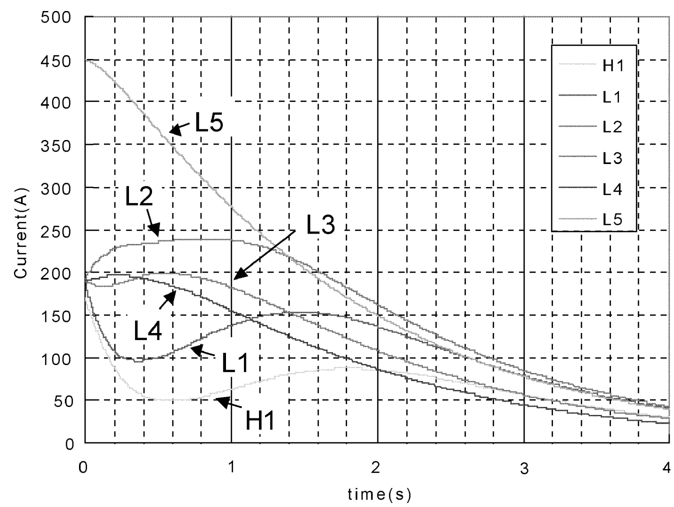


Fig. 7. Change of coil currents after simultaneous quenching of all coils.

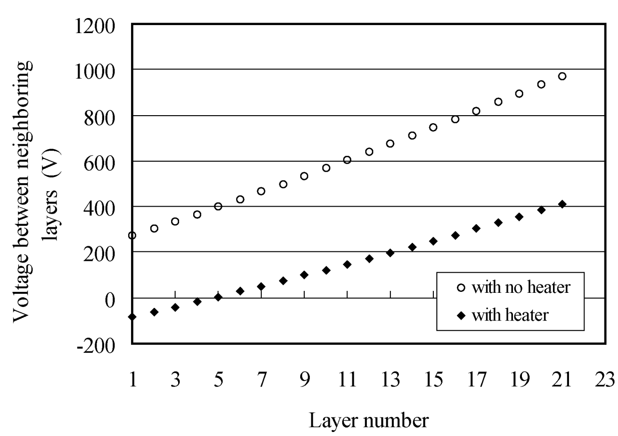
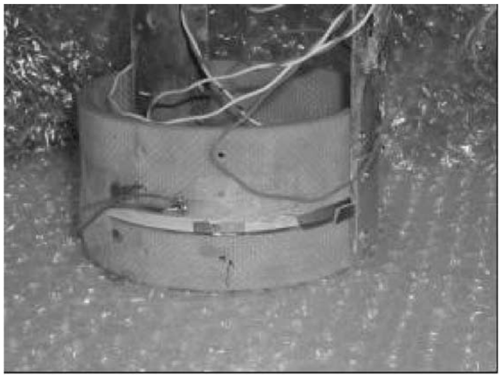


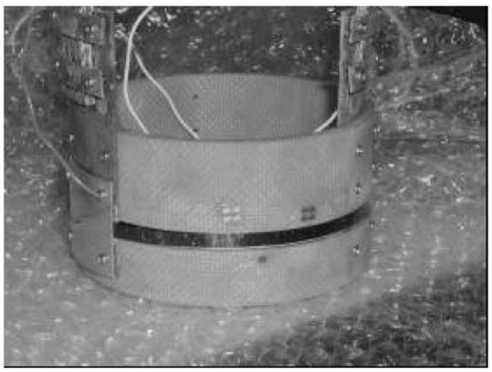
Fig. 8. Profile of voltage between neighboring layers of the outer LTS coil when an internal voltage peaks.

IV. Preliminary Experiment

Since the inner diameter of the Bi2223 insert coil is 90 mm, where a bending strain of Ag-sheathed Bi2223 tape conductor becomes 0.22%, a preliminary experiment was carried out to investigate the influence of the bending strain upon a maximum permissible hoop stress of Ag-sheathed Bi2223 tape conductor. In this experiment, two model coils were prepared. One was a model coil of a bare Ag-sheathed Bi2223 tape conductor, the other a model coil of the conductor with a stainless steel tape for reinforcement. Both of the samples are two-turn coils of 90 mm inner diameter. Fig. 9 shows photographs of the model coils.



(a)



(b)

Fig. 9. Photographs of samples using a preliminary experiment. (a) Two-turn coil of a bare Ag-sheathed Bi2223 tape conductor; (b) two-turn coil of the conductor with a stainless tape for reinforcement.

Fig. 10 shows a relation between hoop stress and the critical current of samples after removal of the hoop stress. As shown in Fig. 10, the critical current of the bare sample starts to degrade at 80 MPa. The stress of 80 MPa is almost in agreement with that of a straight conductor in the SEI report. Therefore, it was found that the bending strain of 0.22% could never degrade performance of the Bi2223 insert coil. An effect of reinforcement with a stainless tape was also confirmed as shown in Fig. 10.

V. Conclusion

A cryocooler-cooled 19 T superconducting magnet with 52 mm room temperature bore was designed. Coil protection from quenching was confirmed by numerical analysis. A preliminary experiment showed that the hoop stress will not degrade the performance of the Bi2223 insert coil despite the bending strain of 0.22%. The magnet is currently under construction.

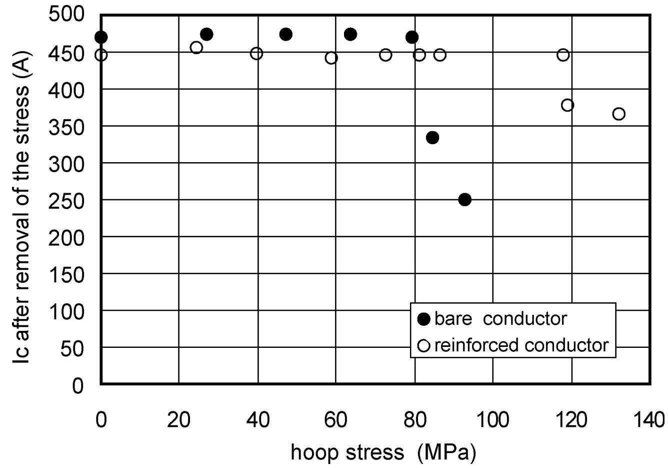


Fig. 10. I_c of Ag-sheathed Bi2223 tape conductor after removal of the hoop stress.

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