Design of Superconducting Magnet for Background Magnetic Field

Qiuliang Wang, Yinming Dai, Baozhi Zhao, Souseng Song, Shunzhong Chen, Luguang Yan, and Keeman Kim

***Abstract*—For the advanced testing of High Temperature Superconducting (HTS) wire/tape and sample coils, a wide bore conduction-cooled superconducting magnet with the available warm bore of ϕ186 mm and a center field of 5$\sim$6 T for background magnetic field applications was designed and fabricated. The magnet is composed of four coaxial coils. All the coils were connected in series and can be powered with a single power supply. The maximum magnetic field is 5.5 T. In order to support the high stress in superconducting magnet a detailed finite element (FE) analysis with electro-plastic model has been performed. A compact cryostat with a two-stage GM cryocooler was designed and manufactured for the magnet. The detailed design of magnet system is described in this paper.**

***Index Terms*—Conduction-cooled, high magnetic field, magnet.**

I. Introduction

A conduction-cooled high magnetic field superconducting magnet possesses many advantages over the pool cooling superconducting magnet. The development of conduction-cooled magnet technology allows the generation of high fields without the use of liquid helium and nitrogen for cooling. The technology can provide the customer access to high magnetic fields in applications or locations, where the use of liquid helium is difficult or expensive [1]–[3]. In order to study the characteristics of Bi2223 high temperature superconducting tape, we are developing a test device with high magnetic field in a large warm bore. The cryogenic test devices for more than 1000 A critical current measurement with improved performance and a safe procedure of sample mounting in a large size warm bore superconducting magnet without the need of helium logistics was designed and fabricated. For superconducting magnet applications in the advanced testing of HTS wires and sample coils, a wide bore conduction-cooled superconducting magnet with a warm 186 mm providing a center field of 5–6 T as background magnetic field is developed by our laboratory. This allows measurements to be performed in a repeatable and reliable fashion.

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Q. Wang is with the Key Laboratory of Applied Superconductivity, Institute of Electrical Engineering, Chinese Academy of Science, Beijing 100080, China (e-mail: qiuliang@mail.iee.ac.cn; qiuliangw@hotmail.com).

Y. Dai, B. Zhao, S. Song, S. Chen, L. Yan, and Y. Bai are with the Institute of Electrical Engineering, Chinese Academy of Science, Beijing 100080, China (e-mail: ymdai@mail.iee.ac.cn; lgyan@mail.iee.ac.cn).

K. Kim is with the Korea Basic Science Institute, Korea 305-333 (e-mail: kkeeman@kbsi.re.kr).

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TABLE I
Major Parameters of NbTi Superconducting Strands

Type	Inner wire FSW-MF-100B	Outer wire FSW-MF-65B	compensating wire FSW-MF-65B
Wire dia. (mm)	1.00±0.01	0.65±0.01	0.65±0.01
Cu/Sc ratio	2.0±0.1	2.0±0.1	2.0±0.1
Filamentary dia. (μm)	13	8.5	8.5
Twist pitch (mm)	18±2	15±2	15±2
Insulator	PVF	PVF	PVF
Critical current (A)	≥670A (5T)	≥280A (5T)	≥280A (5T)
	≥530A (6T)	≥220A (6T)	≥220A (6T)
	≥400A (7T)	≥170A (7T)	≥170A (7T)
R R R	≥100	≥100	≥100
Wire length (m)	5713	9536	9536

II. Design of Background Superconducting Magnet

The specifications of the conduction-cooled high magnetic field superconducting magnet are described as follows: warm bore size over ϕ180 mm; the central field is over than 5 T; field uniformity $\Delta B/B$ should be lower than 1% within a central region of $\phi 50\times 50$ mm and lower than 5% within $\phi 100\times 100$ mm; the ramping rate of superconducting magnet is about 0.12 T/min to the full field operation; total cooling time for the system is about 90 hrs.

In the cryogenic test device several solenoid-type NbTi coils are use to generate the background field. To achieve the required uniformity in the sample space for the test of HTS wires and coils compensation coils are used to compensate the drop of the field towards the ends of the solenoids. Moreover, the solenoid coil is designed with current density grading using different superconducting wires. An operating temperature of 5.5 K has been selected for the superconducting magnet taking into account the temperature rise during charging. Two kinds of wires are used in the background magnet design. One wire is chosen as a ϕ1.0 mm NbTi/Cu wire to wind the inner layers, another is a ϕ0.65 mm NbTi/Cu wire to wind the outer layers. The two compensation coils are to be wound with the thinner one. The critical currents of the two wires at 5 T and 4.2 K are 670 A and 280 A, respectively. Both wires have a copper/superconductor ratio of 2. Main parameters of superconducting wire are listed in Table I. The magnet is to be manufactured with four coaxial superconducting coils, the inner coil, the outer coil and two compensation coils. These four coils are connected in series and powered with a single power supply.

The parameters of the background superconducting magnet are listed in Table II. The four coils of the background superconducting magnet are denoted as the coil-1, 2, 3 and 4 in the

TABLE II
MAJOR PARAMETERS OF NbTi SUPERCONDUCTING MAGNET

Parameter	Coil 1	Coil 2	Coil 3	Coil 4	Magnet
I.D./mm	245	276.4	313.9	313.9	237
O.D./mm	272.4	303.9	341.4	341.4	392
Height /mm	350	350	80	80	380
Wire Dia./mm	1.0	0.65	0.65	0.65	1.0/0.65
Turns	4264	9860	2260	2260	18644
Weight /kg	~ 22	~ 24	~ 6.2	~ 6.2	~ 116.5

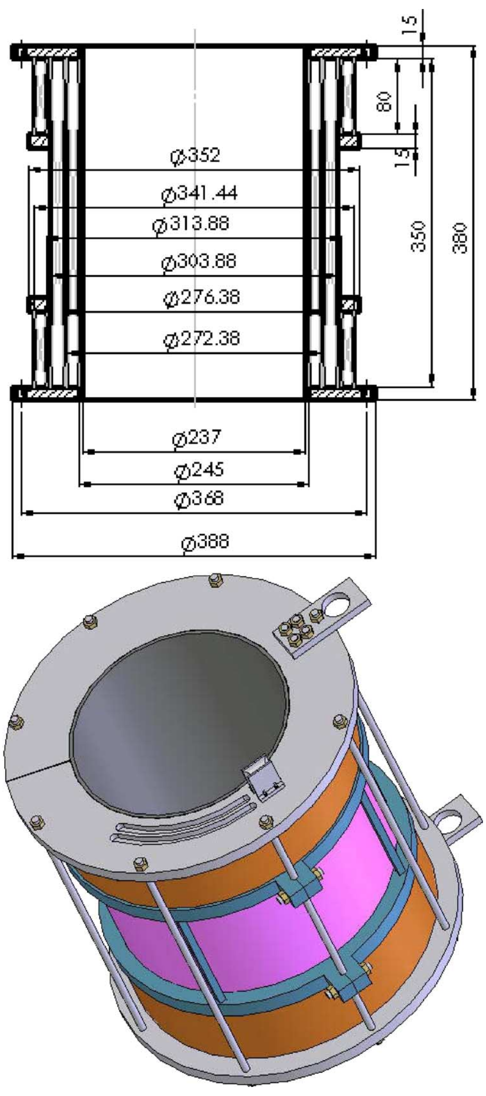

Fig. 1. Overall configuration of the superconducting magnet.

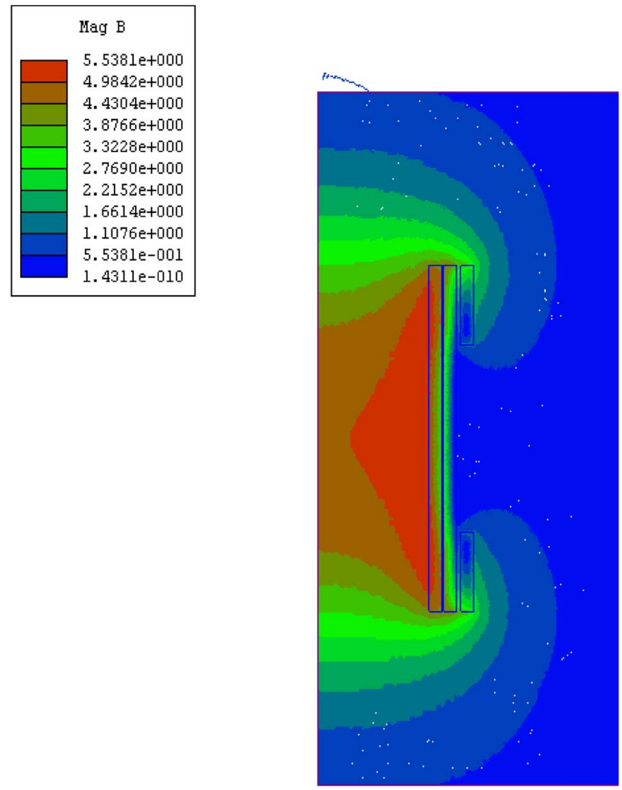

Fig. 2. Magnetic field distribution of magnet (unit: Tesla).

magnet structure. The coils are to be wound directly onto a brass former which serves as the coil supporting and thermal conduction structure. Two end plates are used to fix the magnet to the cryostat. After finishing the windings, the two magnet end plates are bolted together to form a rigid structure. The designed coil configurations are shown in Fig. 1. Sizes of the solenoid former are set as 4 mm thick and 380 mm high. Two end plates are set as the thickness in 15 mm. The former and the end plates are to be welded together. The accessorial supporting structures for winding the two compensation coils are two pair bolted collars. The collar thickness is 20 mm.

III. ELECTROMAGNETIC AND THERMAL ANALYSIS FOR SUPERCONDUCTING MAGNET

The electromagnetic simulation of the background magnet is based on a finite element method (FEM) code. The magnetic field distribution was calculated by executing an ANSOFT 2-D program. When the operating current is set as 104.88 A, the central magnetic field of the magnet is 5 T, which is the requirement for HTS sample space. The magnetic field of the background magnet is plotted in Fig. 2. The results show that the magnetic field intensity and uniformity meet the requirements well in the HTS sample space. The maximum field deviations from 5 T are 0.435% in the ϕ50 mm $\times$ 50 mm and 1.828% in the ϕ100 mm $\times$ 100 mm HTS sample space, respectively. The maximum magnetic field for the coil 1 is 5.5 T located at its inner surface with a displacement of 119 mm from the midplane. For the two compensation coils, the maximum magnetic field is only 3.76 T. The operational safety margin for 5.5 K operating temperature of the background superconducting magnet can be determined as 79% and 82% for coil 1 and coil 2 respectively. The load lines of the two superconducting coils are depicted in Fig. 3.

Inductance of the background superconducting magnet is estimated as 53.22 H. Total magnetic energy storage is 0.3 MJ when the magnet is charged to the full operational current of 104.88 A.

The quench is not a rare phenomenon for operating a superconducting magnet. After quench at the operation current of 104.88 A, the currents in the magnet coils decay through their shunt diodes. The profiles of current in each coil are presented

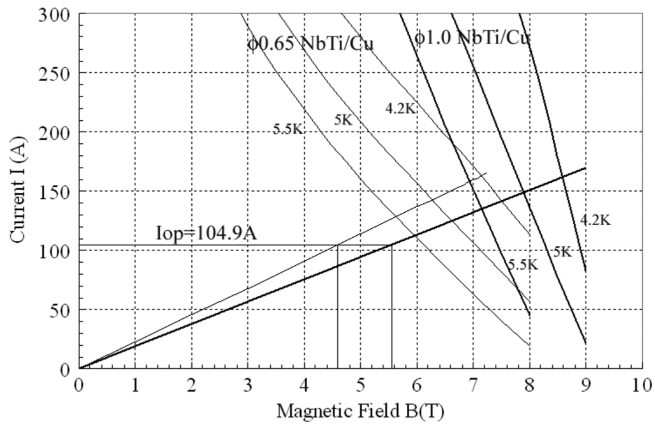

Fig. 3. Load lines for the superconducting magnet.

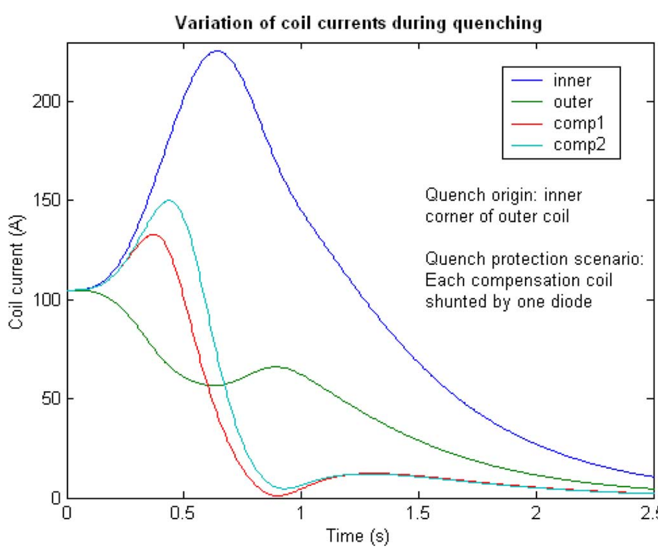

Fig. 4. Profiles of current with respect to time after quench in one of coil.

in Fig. 4. It shows that the quenched outer coil induces a higher current inside the nearest adjacent inner coil.

The simulation results on the hot spot temperature after magnet quench shows that the maximum temperature is lower than 170 K for the outer coil in which the normal zone is initiated. The normal zone will propagate first to the nearest inner coil, which is located at the relative high field region. The higher hot-spot temperatures in the inner coil are caused by the induced current. It is expected that the hot-spot temperatures in the coils are reasonable for the total stored energy of 0.3 MJ. The diode protection set design reduces the complexity of the protection structure and enhances the reliability, as shown in Fig. 5.

The finite element analysis on axial-symmetric stress in the magnet was studied by using ANSYS software. The detailed model for material characteristics is employed in the analysis. The calculating results are shown in Fig. 6. The hoop stress in the superconducting coils is computed. The maximum hoop stress in the inner coil is about 88.0 MPa. The material of the frame is brass. The material of sticks is stainless steel.

The inner plates of compensation coils are composed of two pairs of arc plates which are bolted together. 8 supporting

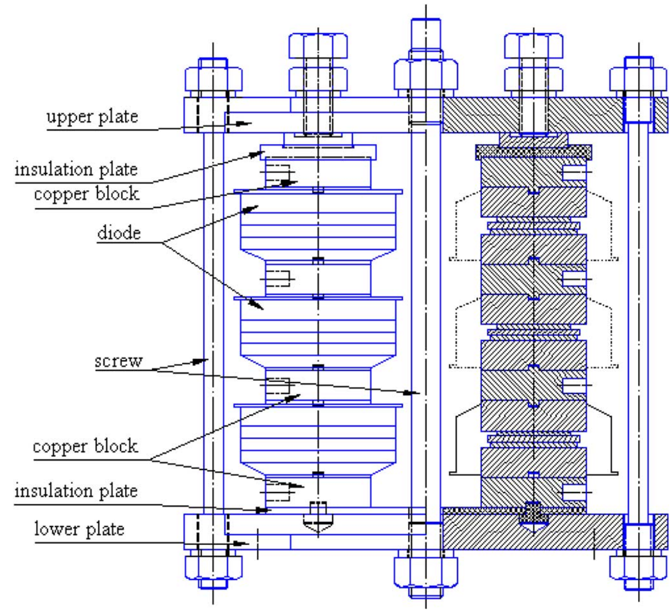

Fig. 5. Protection diode structure for whole magnet system.

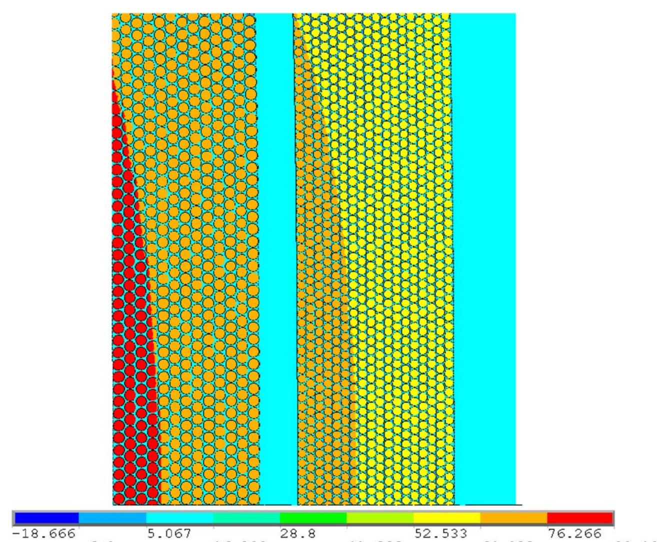

Fig. 6. Hoop Stress in superconducting coil based on detailed model (unit MPa).

rods are fixed between top and bottom plates. The size of the rod is $\phi 8$ mm. The space between coil 1 and coil 2 is filled with fiberglass band and epoxy resins with the thickness in 2 mm. The space between coil 2 and compensation coils are filled with fiberglass band and epoxy resins. The structure with high thermal conduction characteristics might generate eddy losses during charging the superconducting magnet. In order to reduce the heat load for the bobbin, a slit will cut along the axial direction of bobbin.

IV. Cryostat for Superconducting Magnet

The whole cryostat is illustrated in Fig. 7. The magnet will be cooled to 4.2 K with a 1.5 Watt cryocooler. The cryostat has a penetrating room-temperature bore of 186 mm in diameter.

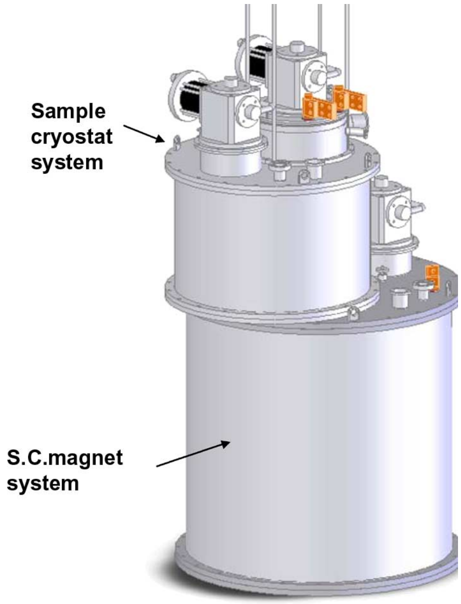

Fig. 7. Configuration of superconducting coil support and sample cryostat.

The cryostat consists of thermal radiation shield, superinsulation, pull rod, thermal connection and inner pipes. The cryostat is fabricated by using 316 stainless steel. It has an outer cryostat vessel on which the GM cryocooler is mounted used to cool the thermal radiation shield with temperature in 40 K. The magnet is cooled down to 4 K by the second stage. The GM cryocooler accepted in the superconducting magnet system is conventional and commercially available with RDK-415D. The cooling capacity of the cryocooler is 31 W at 40 K on the first stage and 1.5 W at 4.2 K on the second stage, respectively.

To avoid refrigeration capacity deterioration caused by the stray field of the superconducting magnet, the cryocooler is mounted on one side of the magnet, and the cold head is arranged at a position where the leakage magnetic field was lower than 0.3 T.

The magnet is cooled down by using copper braid for a flexible thermal link that connects the magnet with the second stage of the cryocooler. The magnet is mechanically fixed to the thermal radiation shield with low thermal conductivity suspension structures. Super-insulation materials are applied to the thermal shield to minimize the radiation losses.

In order to reduce heat leakage from the room temperature environment to the superconducting magnet, a pair of HTS current lead is to be used to charge the magnet. The Bi-2223 ceramic cylinder HTS current leads are soldered to the terminals of superconducting magnet. The upper ends of the HTS current leads are to be anchored to the thermal radiation shield.

All thermal shield structure materials are the copper, and the reinforcements are the stainless steel. The thermal radiation shield is mounted on the flange of first-stage of cryocooler to reduce heat radiation to the superconducting magnet. To keep the radiation shield in a rigidity state, two reinforce rings are integrated into the upper and bottom ends of the thermal shields. Besides, an extra thermal shielding tube is introduced between the magnet clear bore and the cryostat warm bore. Multi-layer super-insulations are applied to the thermal shielding to reduce thermal radiation losses. All these components are kept in a vacuum environment of $10^{-5} \sim 10^{-6}$ Pa.

TABLE III
CALCULATED HEAT LOADS OF CRYOCOOLER

Operating current in magnet	0A	105A
First-stage of cryocooler		
Copper Current leads	5.714 W	9.87 W
Support sheet	1.21 W	1.21 W
Radiation	1.78 W	1.78 W
Joule heating	0	2.2 W
Total	8.7 W	15.06 W
Second-stage of cryocooler		
Bi-2223- current leads/support	0.192	0.192
Support sheet	0.0093	0.0093
Measuring wires	0.0011	0.0011
Radiation	0.032	0.032
Joule heating	0	0.12
Total	0.2346W	0.3564W

For the design of a conduction-cooled magnet system, it is essential to calculate all heat loads in order to reach a temperature which is low enough for steady state and to maintain sufficient margin of cooling power to absorb the losses during magnet ramping. The heat loads into the first-stage and second-stage of cryocooler are the thermal conduction through copper current leads, instrument wires, solid conduction through structural supports, thermal radiation from room temperature, Joule heating caused by connection resistance of the current and residual gas conduction. Table III lists the calculated heat loads for each stage of the cryocooler. Further, a thermal reservoir to absorb heat generation from the field ramping rate will be considered in the construction of the cryostat.

V. CONCLUSION

The design and fabrication of conduction-cooled background superconducting magnet system for advanced HTS sample test devices are introduced. The magnet is composed of four coaxial coils which two of them serve as the main coil to produce the required 5$\sim$6 T background magnetic field. Together with the two compensation coils, the magnet can provide the field uniformity of 1% within a central space of ϕ50 mm $\times$ 50 mm in the warm bore.

REFERENCES

[1] Q. Wang, L. Yan, B. Zhao, and S. Song, "Development of a wide-bore conduction-cooled superconducting magnet system for material processing applications," *IEEE Trans. Appl. Supercond.*, vol. 14, no. 2, pp. 372–376, 2004.

[2] K. Watanabe and K. Takahashi *et al.*, "Cryogen-free hybrid magnet for magnetic levitation," *PhysicaC*, vol. 386, pp. 485–489, 2003.

[3] Q. Wang, Y. Dai, S. Song, Y. Lei, B. Zhao, H. Wang, C. He, H. Wang, L. Yan, and L. Lin, "High magnetic field superconducting magnet technology and its applications," in *Materials Science Forum*, 2007, vol. 546–549, pp. 1935–1940.