A Superconducting Magnetization System With Hybrid Superconducting Wire for the Study and Application of Superconductivity

S. D. Chen, Y. T. Yu, J. C. Jan, F. Y. Lin, C. S. Hwang, I. G. Chen, C. H. Du, T. M. Uen, and C. Y. Chang

***Abstract*—For the study of high-temperature superconductors and for the application of superconductivity, a superconducting high-field magnetization system with a hybrid superconducting coil was designed. This coil is composed of superconducting wires of three kinds—HTS YBCO 2G-wire, high-field and low-field NbTi wires. Three principal purposes of building this system are to inspect the characteristics of disk-shape bulk YBCO, to develop a HTS-bulk undulator, and to magnetize a portable HTS-bulk high-field magnet for application to a resonant X-ray scattering experiment. With four steps of temperature decrease, a two-stage GM-type cryocooler and liquid nitrogen provide cooling for the magnetization system. The hybrid superconducting coil, two cryogenic systems for the magnetization system and the portable HTS-bulk magnet, and the control and monitor systems that were designed are discussed.**

***Index Terms*—GM-type cryocooler, HTS 2G wire, magnetization system, superconducting undulator, YBCO bulk.**

I. INTRODUCTION

A HIGH-FIELD magnetization system is necessary for the investigation of the material characteristics of high-temperature superconductor YBCO [1]. It was planned to build a stronger magnetizing system to replace the existing system, which is 9 T with a bore of 2.8 cm diameter [2]. An important issue for the future development of YBCO bulk is to enlarge the size of the bulk, for which purpose a large-bore magnetization system with sufficient intensity of magnetic flux and uniformity of field is preferred and should be required. Beyond the investigation of the YBCO bulk disks, the magnetization system is expected to be available for two other applications. In research towards a high-temperature superconducting undulator [3], YBCO bulk disks in an array are to produce a sinusoidal magnetic wave [4]; this long-series magnet array of YBCO cuboids should be magnetized in an uniform field of high quality, which lengthening the solenoid achieves. Another research is directed to provide a strong magnetic field for an eight-direction diffraction instrument [5]. Two YBCO bulk disks with cryostat will be cooled with an individual portable cryo-cooler system and then magnetized with this system to produce a strong magnetic field [6]–[10]. The geometry of the entire system should match the space limitations of the eight-direction diffraction instrument, taking into account that the length of the magnetization solenoid is limited. With all requirements considered, the specifications of the magnetization solenoid were set as magnetic field 12 T, field uniformity $\Delta B/B \leq 0.15\%$ over 100 mm, a solenoid of total length less than 300 mm, and a bore of 80 mm diameter. The solenoid was constructed as a multi-coil structure, in which wires of three kinds—HTS 2G YBCO wire, high-field and low-field NbTi—were used [11].

An easily operable cooling system is preferable for this magnetization system. Each of two traditional cooling methods—either a cryo-cooler or $LN_2 - LHe$—has its own features. The operation of the LHe cooling method is tedious, and the operation cost is great for an experiment; a hybrid cooling system with a cryo-cooler [12] and liquid LN_2 was hence designed. A cooling system for the portable high-field magnet with large-diameter bulk YBCO was also designed. Its weight was minimized and the bulk YBCO will replace the rare-earth permanent magnet.

II. HIGH-FIELD AND HIGHLY UNIFORM MAGNETIZATION SYSTEM

As the magnetizing solenoid was planned to be compatible with various experiments, its dimensions and specifications should be set appropriately for all those experiments. A solenoid with magnetic field up to 12 T and a region of uniform field of length 10 cm were designed and optimized. The specifications were finally set as in Table I. The design of the solenoid coil and containing superconducting wires of various kinds is shown in Fig. 1. The magnet is comprised of five coils. Table II presents the design parameters and the specifications of the superconducting wire in each coil. A Cu sheet of 0.1 mm thickness is placed between two neighboring coils to improve the cooling efficiency. The first coil, a split coil, of the solenoid acts as a trim coil with HTS 2G wire, which helps to decrease

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C. S. Hwang, J. C. Jan, and F. Y. LinD. J. Huang are with National Synchrotron Radiation Research Center, Hsinchu 30076, Taiwan (e-mail: cshwang@nsrrc.org.tw).

S. D. Chen and T. M. Uen are with Department of Electrophysics, National Chiao Tung University, Hsinchu 30076, Taiwan.

Y. T. Yu is with Graduate Program for Science and Technology of Accelerator Light Source.

C. Y. Chang is with Department of Electronic Engineering, National Chiao Tung University, Hsinchu 30076, Taiwan.

D. J. Huang is with the National Synchrotron Radiation Research Center, Hsinchu 30076, Taiwan. He is also with the Department of Physics, National Tsing Hua University, Hsinchu 30043, Taiwan

Z. W. Huang is with the Department of Physics, National Tsing Hua University, Hsinchu 30043, Taiwan.

I. G. Chen is with Department of Materials Science and Engineering, National Cheng Kung University, Taichung, Taiwan.

C. H. Du is with Department of Physics, Tamkang University, Taiwan.

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TABLE I
SPECIFICATIONS OF MAGNETIZING SOLENOID

Total length of solenoid (mm)	289
Magnetic field strength (T)	12
Field uniformity on solenoid axis	<0.12 % in ±50mm
Inner bore diameter (mm)	80
Multi-coil solenoid[a] (from inner to outer)	5 coils (YBCO, YBCO, YBCO, NbTi, NbTi)
Number of power supplies	2

[a] The first coil was made from two short coils; the distance between them is 51.8 mm. Other coils are long solenoids.

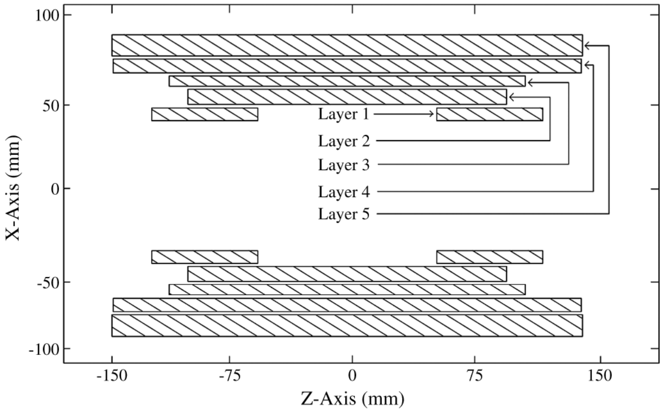

Fig. 1. Cross section of magnetizing solenoid coil structure.

TABLE II
DESIGN PARAMETERS OF THE FIVE COILS [a]

Coil #	**1**	**2**	**3**	**4**	**5**
Wire type	2G-wire	2G-wire	2G-wire	High-field NbTi	Low-field NbTi
Dimension including insulation(mm^2)	4.35*0.35	4.35*0.35	4.35*0.35	Ø1.04	0.78*0.54
Inner radius (mm)	40	49.7	60.8	69	79.3
Outer radius (mm)	47.7	58.8	67	77.3	92.3
Length (mm)	65.3	195.8	218.1	287	288.6
Operating current (A)	370	370	370	176	176
Maximum field on wire Bs (T)	⊥ 2.2 //12.5	⊥ 2.4 //12.0	⊥ 2.5 //9.3	7.0	6.0
Critical current at 4.2K (A)	423@⊥ 2.2T	387@⊥ 2.4T	378@⊥ 2.5T	537@7T	311@ 6T
Number of turns	(15x22) *2	45x26	49x20	276x8	370x24
Field increment (T)	0.41	2.43	1.8	1.52	5.85

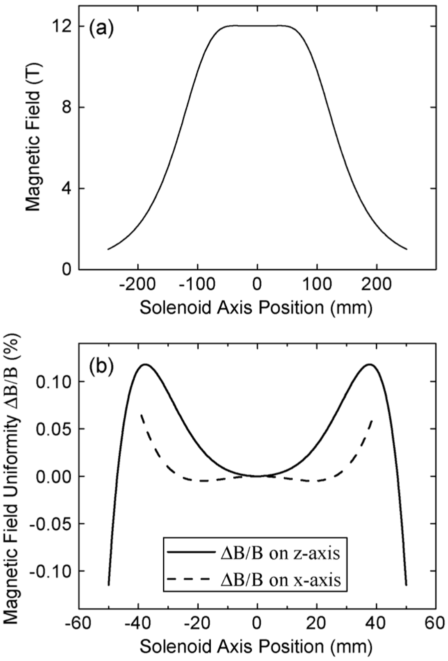

Fig. 2. (a) Longitudinal field along the solenoid axis. (b) Field uniformity in ±5 cm.

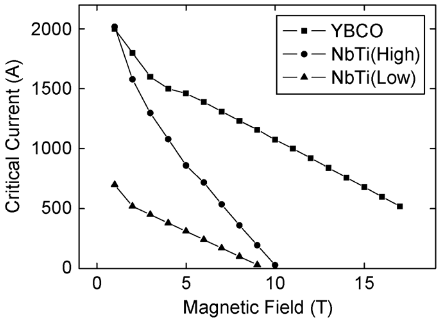

Fig. 3. Characteristic of superconducting wires.

the total length of the solenoid and enlarges the field of uniform region. After optimization, the calculated distribution of the magnetic field along the longitudinal axis is shown in Fig. 2(a); Fig. 2(b) shows the field uniformity on the transverse and axial axes. The geometry of each coil was optimized and the critical current density should match the specification of the superconducting wires. The characteristics of the wires are shown in Fig. 3, which reveals that 2G-wire is appropriate for a high field and NbTi for a low field; for this reason the inner coil is the HTS 2G wire. The coils are all operated at 4.2 K. Two power supplies are necessary for this compound solenoid magnetization system, one for the HTS 2G wires and the other to charge the NbTi wires. The uniformity of the magnet field on the axis of the solenoid can be fine-tuned by adjusting individually the currents of the two power supplies.

III. YBCO WINDING TEST

Two HTS 2G coils were manufactured, one with insulation and the other bare, both of 88 turns (4 × 22 turns) of HTS coils. With no insulation layer, the turns can be nearer the center, producing a stronger field with the same number of turns. Theoretically, at low temperature in the superconducting state, the resistant of zero-resistant YBCO is much less than that of copper material, and current flows only along YBCO, so insulation might be unnecessary. Two coils were constructed to understand the real reaction and tested in a LN_2 vessel; the construction pictures appear in Fig. 4 before they were charged in the LN_2 cryostat. The wire thickness with insulation is 0.35 mm and without insulation is 0.1 mm. The insulated coil quenched at operating current 34.5 A; the field strength was 417 Gauss as measured with a Hall probe. The quenching current is reproducible. The

Fig. 4. (a) 88-turn coil without insulation. (b) 88-turn coil with 0.05-mm Kapton insulation (50% overlap).

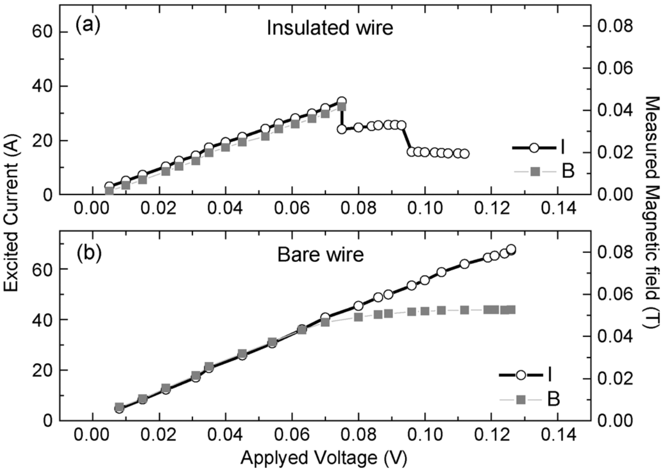

Fig. 5. Measurement data of two testing coils in the liquid nitrogen dewar.

bare coil was excited up to 67 A, but the strength of its magnetic field fails to increase with increasing current. Its magnetic field attains about 500 G at 41 A; as current increases to 67 A, the magnetic field failed to increase as expect, but remains around 500 ~ 530 G. The strength of the magnetic field at the center of the coil was measured and is shown in Fig. 5. For the insulated wire, the current decreases were due to the increasing resistance, and the stepped pattern indicates that quenching occurs at local points, not along the entire coil. For bare wire, part of the operating current generate no magnetic field, but flows in the copper and generates extra heat inside the (bare) coil. For that reason, insulation was indicated to be necessary.

TABLE III
HEAT LOADS OF THE MAGNETIZATION SYSTEM

	80 K	50 K	4.2 K
Instrumentation wiring conduction (W)	0.82	0.45	0.03
Radiation (W)	8.4	3.64	0.02
Current leads - 480A (Q_c) (W)	31.04	7.2	0.1
Current leads - 480A (Q_e) (W)	30.84	7.2	None
Current leads - 200A (Q_c) (W)	13.8	3.42	0.1
Current leads - 200A (Q_e) (W)	12.4	2.66	None
Cryo-cooler (W)	None	-45	-1.5
Liquid Nitrogen (L/h)	3.94	None	None

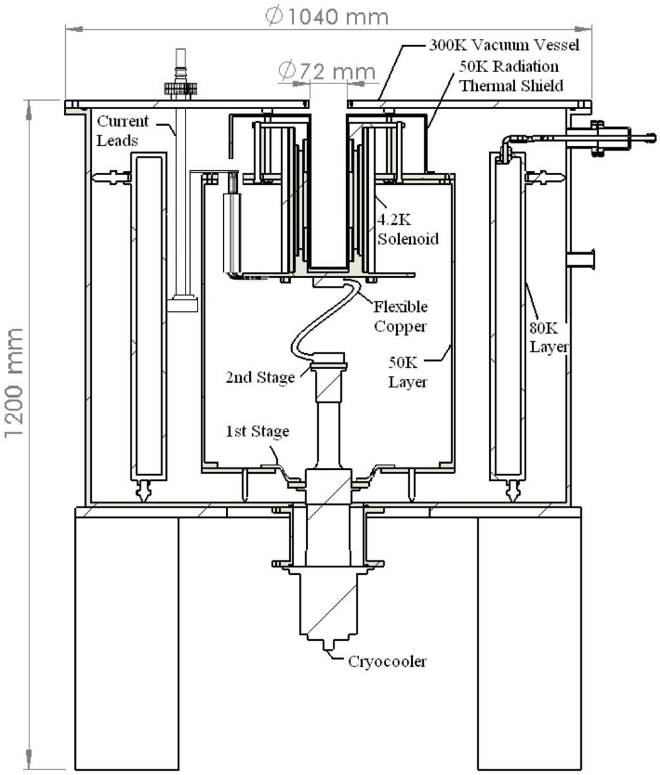

Fig. 6. Layout and the structure design of the magnetization system.

IV. 4.2-K VACUUM VESSEL OF THE MAGNETIZING SYSTEM

A hybrid cooling system in which one cryo-cooler and a liquid-nitrogen vessel were introduced was designed for a magnetization system. If the pure cryo-cooler system were chosen, two cryo-coolers would be necessary in this magnetization system as the heat load at the 50-K shield exceeds the capacity of the first stage of the cryocooler. The heat load on the 50-K intercept comes mainly from the two pairs of current leads. Table III lists the estimated heat loads of the magnetization system, but the duration of cooling from 300 K to 4.2 K is two days. Another liquid cooling system, a LHe filling system, was rejected because of the complicated operation and the expense of liquid helium.

For the convenience of assembly of the entire system, some parts, including the superconducting solenoid, the current leads and the cover of the thermal shielding at 50 K, are connected with the cover of the thermal shielding at room temperature, and these parts can be removed and lifted up by a hoist. Fig. 6 shows a schematic drawing of the magnetization system. Because of space limitations in the eight-direction diffraction instrument, the center point of the magnetizing solenoid should be near the top cover of the thermal shield at room temperature. To conform to this requirement, the space between the thermal shielding layers and the thickness of each shielding plate were condensed. The method of connection between the magnetizing solenoid coil and the cover of the thermal shielding at 50 K was also designed to decrease the distance.

The heat loads of each layer were analyzed; the results appear in Table III. The power of the chosen cryo-cooler (Sumitomo SRDK-415D) is shown also in Table III. The structure of the current leads with thermal intercept were designed to match the four steps (300 K, 80 K, 50 K, 4.2 K) for management of the heat load of the hybrid cooling system. Q_c and Q_e is the conduction heat and Joule heat of the current lead, respectively. A partially

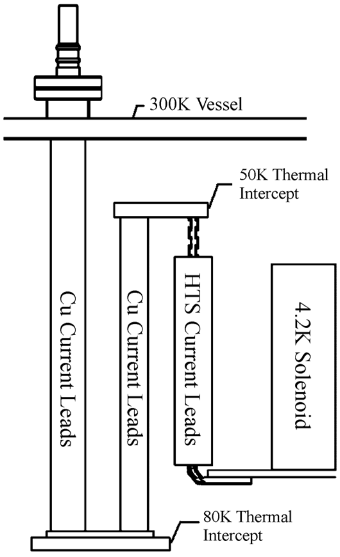

Fig. 7. Schematic layout of current leads and the thermal intercept.

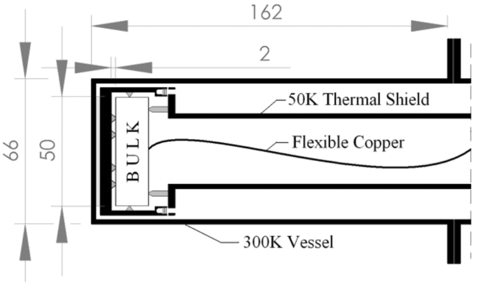

Fig. 8. Cross-sectional drawing of the bulk YBCO cryostat of the portable high-field magnet.

enlarged drawing of the current leads and the thermal intercept appears in Fig. 7.

To minimize the inner radius of the magnetizing solenoid but to remains the large bore of 80 mm diameter, at the inner side of the solenoid, a copper shield of 2 mm thickness at 50 K with 3 layers super-insulation was inserted to replace a standard double-layer shield to decrease the radiation heat load. The inserted system should be cooled to a low temperature to prevent coil quenching; the inserted system should function also as a cover to form a vacuum-sealed vessel.

A low-temperature calibration system with a cryocooler was designed and set up to calibrate the temperature sensor between 300 K and 4 K. One calibrated sensor was placed in a copper plate, to serve as a reference sensor. All other non-calibrated sensors were placed in the same copper plate that was cooled with the cryocooler.

V. CRYO-COOLER SYSTEM FOR THE BULK YBCO

A light and portable cooling system was designed that can cool a single bulk YBCO. This system, called hereafter a bulk-cooling system, can be inserted into the core region of the magnetization system, and functions as a cover of the bore of the magnetizing system. The structure of the front end is designed to be easily disassembled and reassembled because the bulk YBCO is easily damaged in a large magnetic field (see Fig. 8).

The length of the front end is considered carefully to match the space limitations of the eight-direction diffraction instrument. To shorten the front end further to match the spatial requirements, the bulk YBCO was placed not at the center of the solenoid but nearer the cover of the magnetizing system. The diameter of front end is 66 mm and the maximum diameter of usable bulk YBCO is 50 mm. The distance between the bulk YBCO and the solenoid center is 40 mm. The magnetic field is reducted at this station to 11 T, 93% of the maximum field at the center of the solenoid. The results of analysis of the heat load are listed in Table IV.

TABLE IV
HEAT LOADS OF BULK YBCO CRYOSTAT SYSTEM

	50 K	20 K
Conduction	4 W	1 W
Radiation	0.5 W	0.5 W
Cryo-cooler	-5 W	-2 W

VI. CONCLUSION

A multi-coil solenoid was designed to achieve a 12-T magnetic field with wires of varied kinds. To achieve a highly uniform region in a small total length, the innermost coil of HTS 2G wire of the solenoid works like a trim coil. An experiment performed to test the YBCO 2G-wire strongly indicated that insulation on that wire is necessary in making the solenoid. The liquid-nitrogen layer was inserted to manage a large heat load from four current leads. To solve the problem of limited space, a special geometry is seen at the top of the magnetization-system chamber.

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