# Development of Testing Device for Critical Current Measurements for HTS/LTS

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***Abstract*—For the goal of superconducting magnet applications in the advanced testing device for high temperature superconducting (HTS) wire and sample coils, a wide bore conduction-cooled superconducting magnet with available warm bore of $\phi$186 mm and center field of 5 T for the background magnetic field applications was designed and fabricated and tested. A sample cryostat with two GM cryocoolers is inserted in the background magnet. The system allows measurements to be performed in a repeatable and reliable fashion. The detailed design, fabrication and thermal analysis are presented in the paper.**

***Index Terms*—Conduction-cooled superconducting magnet, electro-plastic model, HTS test devices.**

## I. Introduction

THE conduction-cooled high field superconducting magnet is very convenience for the user [1]–[3]. In order to study the characteristics of Bi-bismuth HTS, we are developing a test device with high magnetic field in a large warm bore and full conduction-cooled insert cryostat which can be contained the HTS sample and sample coil. The cryogenic test device for more than 1000 A critical current measured devices with improved performance and a safe procedure of sample mounting in a large bore of superconducting magnet without the need of liquid helium logistics is designed and fabricated. For superconducting magnet applications in the advanced testing of HTS wire and small sample coils, a wide bore conduction cooled superconducting magnet with a warm bore of $\phi$186 mm providing a center field of 5 T as background magnetic field is developed by our laboratory. The magnet system is automated by using the house software, which includes all the necessary operational states. This allows measurements to be performed in a repeatable and reliable fashion. The sample cryostat system consists of removable sample device (sample, one cryocooler, current leads, copper rod) and sample cryostat (another cryocooler, thermal radiation shield, vacuum vessel) and other accessories (temperature sensors, vacuum valve an so on). To meet the requirements of easy mounting/change of the sample (one sample per day), removable sample device is independent from sample cryostat. So sample with one cryocooler and all other accessories can insert from the top of cryostat. Four guide rods will be mounted on the top of cryostat so that removable sample device goes in and out easily and quickly.

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TABLE I
SPECIFICATION FOR SUPERCONDUCTING MAGNET

| No | $R_1$ | $R_2$ | $Z_1$ | $Z_2$ | $I_{opt}$ | $B_m$ | Margin |
|---|---|---|---|---|---|---|---|
| | cm | cm | cm | cm | (A) | T | 5 K |
| 1 | 12.25 | 13.619 | 10 | 45 | 123.5 | 5.54 | 72.8 |
| 2 | 13.819 | 15.263 | 10 | 45 | 123.5 | 4.39 | 64 |
| 3 | 15.763 | 17.259 | 10 | 18 | 123.5 | 3.61 | 55.26 |
| 4 | 15.763 | 17.259 | 37 | 45 | 123.5 | 3.61 | 55.26 |

## II. Background Superconducting Magnet for the Test Device for LTS/HTS Wire

The background superconducting magnet for the cryogenic test device is designed by using two coaxial NbTi solenoid coils to generate the 5 T central field. To achieve the required the uniformity in the sample space for the test HTS wires and coils, two additional compensation coils are used to compensate the drop of the towards the ends of the solenoids. Moreover, the solenoid coils are designed with current density grading using difference superconducting wires [4].

The operating temperature has been selected as 5.5 K for the superconducting magnet taking into account the temperature rise because of AC losses during charging. The thermal equilibrium between the heat generation of the magnet and the cooling power of the cryocooler is analyzed to define the ramping rate, operating current level and the temperature margin of the superconducting magnet. Two kinds of wires are used in the background magnet design. The magnet is to be fabricated with four coaxial superconducting coils, the inner coil, the outer coil and two compensation coils. These four coils will be connected in series and powered with a single power supply. After finishing the windings and bindings, the two end plates are bolted together to form a rigid supported structure. Dimensions of the solenoid former are set as 4 mm thick and 380 mm high. Two end plates are set as 15 mm thick. The former and the end plates

Fig. 1. Measurement and control system for the Superconducting magnet.

TABLE II
SPECIFICATIONS FOR SAMPLE CRYOSTAT

| | | |
|---|---|---|
| 1 | Type of cryostat | Vessel with Cryo-cooled sample holder to be inserted in warm bore of the magnet |
| 2 | Maximum sample length | System to be designed to allow for maximum sample length according to warm bore diameter. |
| 3 | Sample geometry | (a) straight sample with field either perpendicular or parallel to tape<br>(b) solenoid type sample coil |
| 4 | Temperature range | 4 K – 110 K. |
| 5 | Temperature measurement accuracy | ±0.1 K |
| 6 | Temperature stability | $T < \pm 0.5$ K during the I-V-curve |
| 7 | Sample Current Capacity | $I_{sample}(T) = \begin{cases} 1000A\ (T = 10K - 48K) \\ 1780 - 16.2 \cdot T\ (T = 48K - 110K) \end{cases}$ |
| 8 | Sample Current Accuracy and Stability | $I/I < \pm 2\%$ |
| 9 | Temperature sensors | Temperature sensors for controlling and monitoring the sample temperature in the whole temperature range (♦). |

are to be welded together. Parameters of the background superconducting magnet are listed in Table I. The averaged model of finite element method for material characteristics is employed in the analysis. The hoop stress for superconducting winding is about 88.9 MPa.

The general configuration view of the designed cryostat for the background superconducting magnet system is cooled to 4.2 K with a 1.5 Watt cryocooler. The cryostat has a penetrating room-temperature bore of 186 mm in diameter. The cryostat consists of thermal radiation shield, super-insulation, pull rod, thermal connection and inner dewar pipes. The cryostat is constructed by using 316 stainless steel. It has an outer vacuum vessel and thermal shield in which a two-stage GM cryocooler is mounted. The thermal radiation shield is cooled down to 40 K by the first stage of the cyocooler and the magnet be 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. All these components are kept in a vacuum environment of $10^{-5} \sim 10^{-6}$ Pa.

While the superconducting magnet quenched, there are eddy currents in the copper shield radiation of warm-hole induced by the varying magnetic field. The electromagnetic force is strong enough to generate deformation in the copper radiation shield if it is not strong. The induced eddy currents generate the deformation of the thermal radiation shield. The time of current decayed to zero from operating level is about 0.5 s. The maximum strain is about 0.3%. The deformation magnitude of the material is in the elastic limit which can recover to normal state after the load be removed.

The whole measurement and control system for the superconducting magnet are shown in Fig. 1. Five temperature sensors are attached to the thermal radiation shield, the first and second stages of the GM cryocooler, top and bottom of the superconducting magnet. There is an electronic instrumentation port for the current leads and temperature sensors. Four Rhodium-Iron Resistance sensors and one Platinum Resistance sensor are used to monitor the temperature changing of the magnet system. These temperature sensors are located on the upper flange of coils, lower flange of coils, the first-stage and the second-stage of cryocooler, the farthest position of the thermal radiation shield, respectively.

Hardware for the temperature measurement system we prefer a high-sensitivity data acquisition instrument which can be used in the relevant temperature and magnetic field range with the temperature measurement accuracy about $\pm 0.01$ K. a user-friendly temperature measurement interface of data acquisition software using LabView by National Instruments and Visual Basic by Microsoft is used. It not only shows the temperature of magnet and the first stage cold head and the second cold head in magnet cryostat, but also shows the temperature of sample holder and first-stage cold head and second-stage cold head in the sample cryostat. The software can save all of temperature data constantly when system operating and display other temperature data if we requiring in other interface.

## III. DESIGN OF SAMPLE CRYOSTAT FOR TEST LTS/HTS

The sample cryostat includes the two GM cryocoolers with the second stage operated at 10 K and 4 K, the hybrid current leads, holder of sample and other parts. It is an important to assure temperature stability during measurement $(T < 0.5\ \mathrm{K})$ to achieve the accurate measurement of the critical current in the HTS. The sample cryostat and holder are equipped with all necessary wires for currents, voltages and temperature measurements. The temperature sensors are attached to check directly the sample temperature during measurement. The main requirements of the sample cryostat are listed in Table II. The work status for sample cryostat is: the sample cryostat and sample holder should be designed in a way to enable easy mounting and change of the sample (one sample per day). The sample should be no any degradation due to mounting, cool-down and warm-up. It is reliable and reproducible measurements of the current-voltage characteristics (noise level <100 nV) and determination of the critical current. The installation sample cryostat for the high current cryogenic test bed for the high temperature

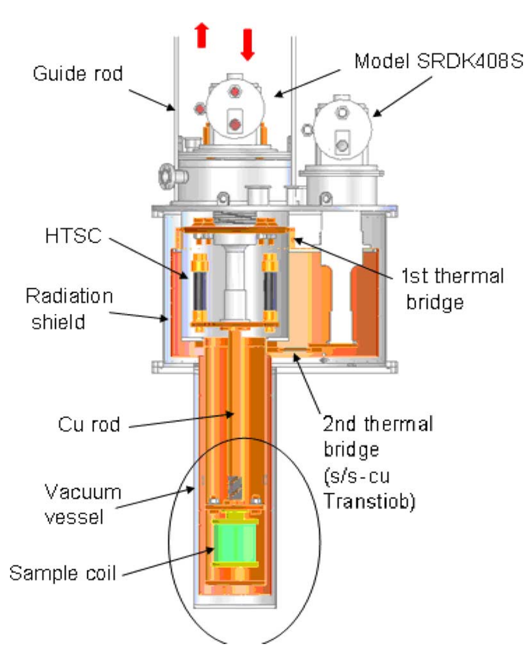


Fig. 2. Configuration of sample cryostat for HTS wire and sample coils.

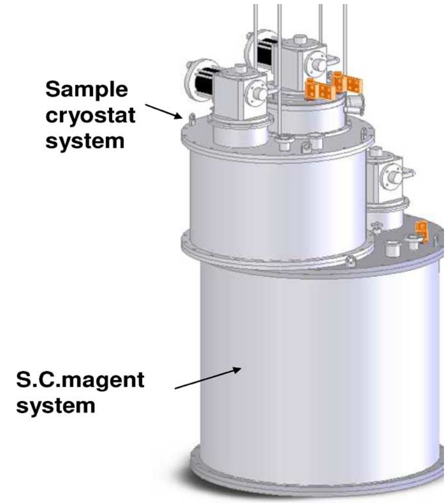


Fig. 3. Configuration of sample cryostat and background magnet.

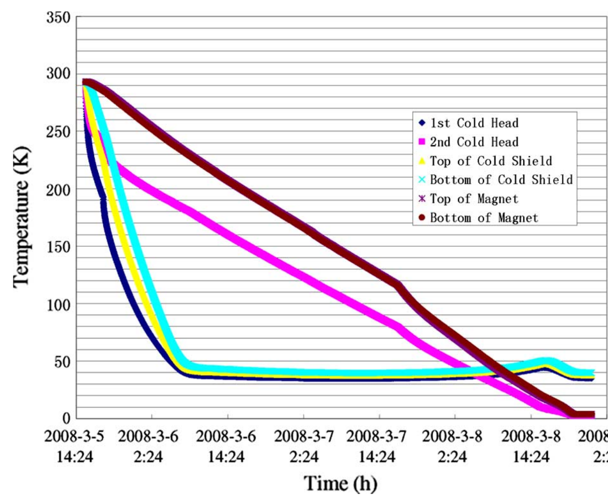


Fig. 4. Cooling superconducting magnet from room temperature to 4 K.

superconducting tape or coils is illustrated in Fig. 2. Total weight of the sample cryostat system with two cryocoolers is about 130 kg. To meet requirements of easy mounting or change of the sample every day, removable sample device is independent from the vacuum system and thermal shield in the sample cryostat. The GM cryocoolers and all the other sections can be inserted from the top in the cryostat of superconducting magnet. Four guide rods are mounted on the top of the cryostat of superconducting magnet so that the testing sample device can be removed in and out easily and quickly from the sample cryostat. When the testing sample is changed, the cryostat can be maintained its vacuum condition continuously. The first-stages of the two cryocoolers are employed to cool down the copper current leads and the second stage to cool down sample or small sample holder through the way of conduction cool with copper rod. The sample is fixed in vacuum without small holder and in exchanges helium gas with small container. The current leads for the sample cryostat are designed to operate in 1000 A. The copper sections conduct the currents between the room temperature and the upper ends of HTS current leads cooled by first-stage of the two cryocoolers. According to the load map of the GM cryocoolers, the temperature of the first-stage of GM cryocooler is below 60 K so long as the total heat load is less than 100 W. Assume the temperature drop at the thermal anchors is about 5 K, then temperature of the lower ends of the copper current leads is taken to be 65 K. It can calculate that the cross-section area in 116 $\mathrm{mm}^2$ can obtain the lowest heat load of 91.6 W. To decrease the heat leaking of the copper current leads, the most important factor is to reduce the temperature of the warm end of the copper current leads. The copper wires with the diameter in 0.5 mm are used to form the copper section. The GFRP pipes are attached to the copper strips and Bi-2223 tapes to sustain electromagnetic force. The structure of frame for the sample coil should be determined on the basis of users. The temperature control of sample holder and the thermal shield are realized by the regulation of heating power with two resistance heaters through using commercial temperature controllers. The resistance heaters are made of manganese wire of about 0.35 mm diameter winding on the copper rod and the shield to control temperature of sample. The sample cryostat is assembled in the background magnet as shown in Fig. 3.

## IV. Test the Superconducting Magnet

The superconducting magnet is cooled by GM cryocooler and keeps the operating temperature of 3.9 K. It takes about 76 h. The temperature of cooling processing for the superconducting magnet is shown in Fig. 4.

After the current of the superconducting magnet to its operating current, the temperature of superconducting coils is about 4.65 $\sim$ 4.77 K. Test of the center field in the superconducting magnet is about 5.127 T with operating current 124 A. The ramping rate is about 0.05 A/s, it takes about 41.16 minute to its full operating currents. The homogeneities of superconducting magnet are 0.2% for the region in $\varphi 50\ \mathrm{mm} \times 50\ \mathrm{mm}$, and $\varphi 100\ \mathrm{mm} \times 100\ \mathrm{mm}$ in 1% as shown in Fig. 5. The magnet

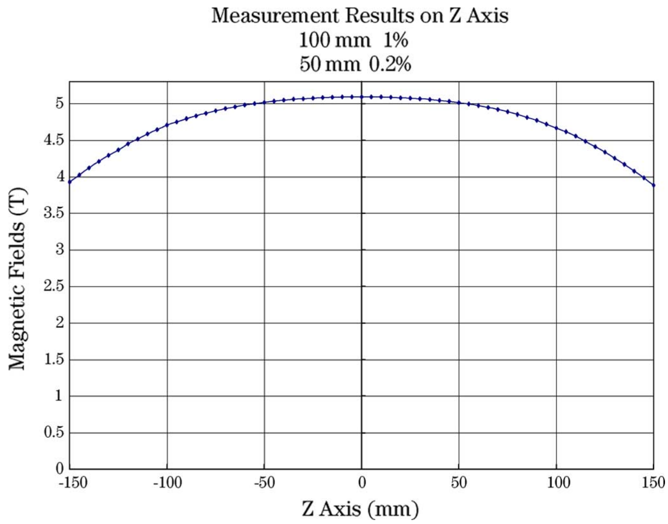


Fig. 5. Magnetic field distribution along the axis in the magnet.

is continuously operating over 24 hours with very stable magnetic field, current and temperature, after that, we shunt down the power supply, it shows that the superconducting magnet can stably operate for a long time. The profiles of the temperature in the superconducting magnet system are shown in Fig. 6. The temperature inhomogeneity in the whole coil is lower than 0.12 K during the magnet operating at full field.

## V. Conclusion

A test device for LTS and HTS wire was designed and fabricated. The superconducting magnet and sample cryostat are full cryofree testing system. It is easy to operate for the user. The superconducting magnet was tested for magnetic field and operation.

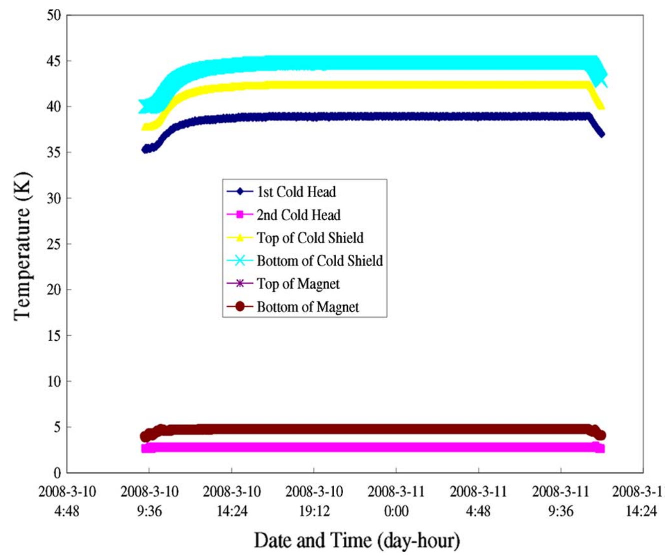


Fig. 6. Charging the magnet system, the temperature versus time.

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