Design Construction and Operation of a Conduction Cooling-Type HTS Module Testing System

Kwangmin Kim, Erick Arroyo, Kurtis Cantrell, and John Rogers

***Abstract*—This paper describes the design, construction, and test results of the conduction cooling-type HTS module testing system. The constructed conduction cooling-type HTS module testing system uses two two-stage GM cryo-coolers as the primary cooling source. The 1st stage cold head of the cryo-cooler is responsible for cooling the metal current leads and radiation shields, and the bottom side of the HTS leads. The 2nd stage temperature section is responsible for cooling the Oxygen Free Copper (OFCu) cooling plate and top-side of the HTS leads. The HTS test module is cooled through the OFCu cooling plate. The HTS module testing system controls the temperature of the HTS module under testing from 4 K to 30 K and can supply an operating current of up to 800 A. All operating parameters of the HTS module test system are controlled and recorded using a Data Acquisition (DAQ) system based on LabVIEW.**

***Index Terms*—HTS coil, conduction cooling system, cryo-cooler, HTS module test.**

I. Introduction

CURRENTLY, the National High Magnetic Field Laboratory (NHMFL) is developing a 40 T high-temperature superconducting (HTS) user magnet, and performance evaluation of a large number of HTS modules is expected to be essential for the magnet's development [1]. Typically, each HTS module must undergo performance evaluation after winding and prior to being assembled into the full magnet. Although it is ideal to perform these evaluations under liquid helium (LHe) conditions—matching the final operating environment of the magnet—most evaluations are conducted under liquid nitrogen (LN2) conditions due to constraints in cost and time. However, since the final operation of the HTS magnet takes place in LHe and the performance of HTS tape, which plays a critical role in module performance, does not exhibit linear characteristics between LN2 and LHe temperatures, discrepancies may arise between the performance verified under LN2 conditions and that under LHe conditions. To address this issue, a conduction cooling-based HTS module performance evaluation system has been developed. This paper provides detailed information on the structure, fabrication results, and testing outcomes of the conduction cooling-type HTS module testing system, with the aim of assisting researchers who may require similar equipment in the future. The developed conduction-cooled HTS module testing system utilizes two two-stage Gifford-McMahon (GM) cryocoolers as the primary cooling source. The first-stage cold head of the cryocooler is responsible for cooling the metallic current leads, the radiation shield, and the lower end of the HTS leads. The second-stage cold head cools the oxygen-free copper (OFCu) cold plate and the upper end of the HTS leads. The HTS test modules are cooled via an OFHC cold plate. The testing system is designed to control the temperature of the HTS module under test from 4 K to 30 K and to supply an operating current of up to 800 A. The performance of the system has been verified through actual operation tests.

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The authors are with National High Magnetic Field Laboratory, Florida State University, Tallahassee, FL 32310 USA (e-mail: kwangmin.kim@magnet.fsu.edu).

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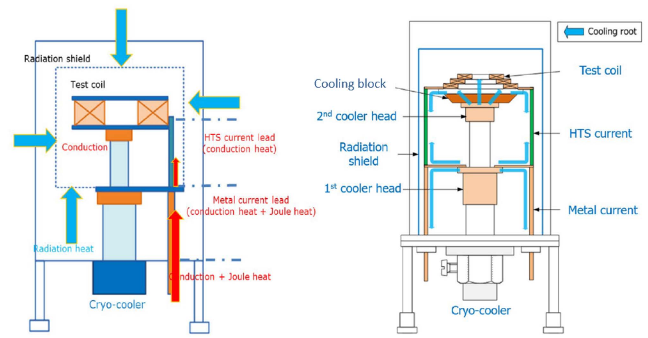

Fig. 1. Conceptual structure and cooling method of the conduction-cooled module testing system: estimated thermal load components (left), cooling path of the system (right).

II. Configuration of the Conduction-Cooled Testing System

Fig. 1 shows the conceptual structure and cooling method of the conduction-cooled module testing system. The types of thermal loads that the cooling system must manage include conduction heat load from the room temperature (RT) region, radiation heat load, and Joule heat generated by the operating current supplied within the system.

The first stage of the GM cryocooler is responsible for cooling the Joule heat generated in the metal current lead parts as well as the conduction heat entering from the RT region. It also cools the radiation shield, which prevents radiative heat intrusion from the RT region to the test coil.

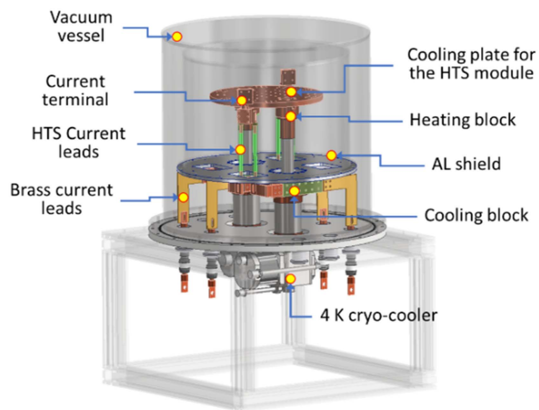

Fig. 2. Detailed 3D design of the proposed conduction-cooled HTS module testing system.

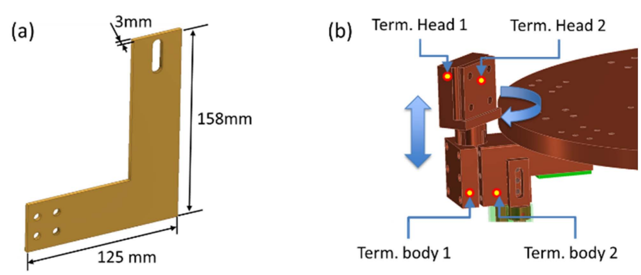

Fig. 3. (a) Brass current lead of the 1st stage of the system, (b) OFHC current terminal at 2nd stage of the system.

The second stage of the GM cryocooler cools the coil under test via the OFHC cooling plate. A cartridge-type heater (with a total power of 100 W) is embedded in a heating block located between the OFHC cooling plate and the second-stage cold head, allowing for temperature control of the cooling plate and, consequently, the test object. HTS current leads are employed at both the first and second stages of the system to block conduction heat load from the first stage and to minimize Joule heating.

Fig. 2 shows the final 3D CAD model of the HTS module evaluation system, reflecting the updated design requirements. As mentioned in the previous system concept, the entire system is divided into a first stage and a second stage based on two two-stage GM cryocoolers.

For the first stage of the system, two pairs of 450 A-class feedthrough current leads are used to ensure vacuum and electrical insulation between the inside and outside of the cryostat. The current path down to the lower terminal of the HTS current lead is formed through a brass current lead [2], a cooling stick, and a flexible copper blade. To prevent mechanical damage at the joints caused by thermal contraction during cooling, a flexible copper blade was used between the lower terminal of the HTS lead and the cooling stick. In the case of the cooling stick, it serves both as an intermediary for conducting current between the brass current lead and the flexible copper blade, and simultaneously provides cooling through its connection with the cooling block. Electrical insulation between the current lead parts and the cold head of the cryocooler is one of the most critical aspects of the system. Fig. 4 illustrates the insulation structure between the first-stage cold head and the cooling stick. A 40 μm-thick Kapton tape was inserted between the cooling stick and the cooling block to secure insulation, and additional insulation was achieved using a G10 plate and tube, which electrically isolate the stainless-steel bolts connecting the parts from the cooling stick and the cooling block.

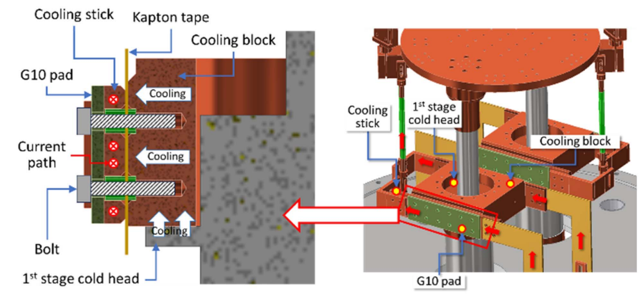

Fig. 4. Insulation structure between the cooling block and the cooling stick.

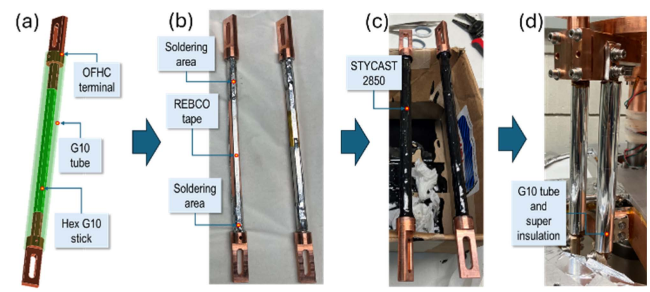

Fig. 5. Fabrication process of the HTS current lead: (a) CAD drawing of the HTS current lead, (b) installation of REBCO tape, (c) application of Stycast 2850, (d) completed HTS current lead installed in the system.

The radiation shield was fabricated by wrapping 15 layers of super insulation around a cylindrical aluminum structure. To improve conduction cooling performance, all parts comprising the first stage—except for the brass current lead and the radiation shield—were fabricated from OFHC.

The second stage of the system consists of a cooling plate for installing and cooling the HTS coil under test, a cooling block for temperature control of the second-stage cold head, current terminals, and HTS current leads.

The cooling block contains two 50 Ω cartridge-type heaters, which apply additional thermal load to the second-stage cold head of the cryocooler, enabling temperature control of the cooling plate. The current terminal (see Fig. 3(b)) is composed of four OFCu pieces: Terminal heads 1 and 2 serve as joints for the current leads from the HTS coil, while Terminal bodies 1 and 2 act both as current joints between the HTS current leads and terminal heads, and as cooling channels that cool the upper terminal of the HTS current lead via the cooling plate. The insulation between the cooling plate and the terminal body adopts the same method used between the first-stage cooling block and the cooling stick.

Fig. 5 shows the fabrication process of the HTS current lead. The HTS current lead functions as the current path for both the first and second stages of the system, while also minimizing thermal intrusion from the first stage.

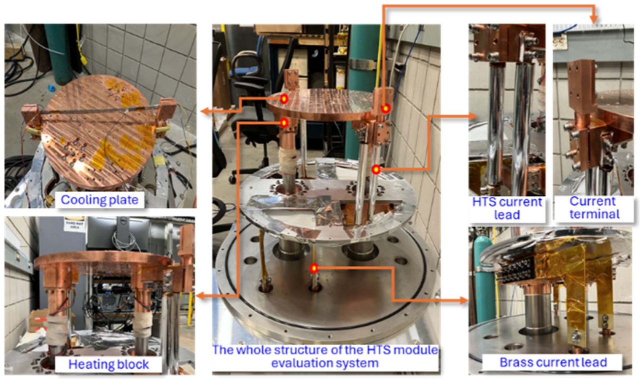

Fig. 6. Final assembly result of the conduction-cooled HTS module testing system.

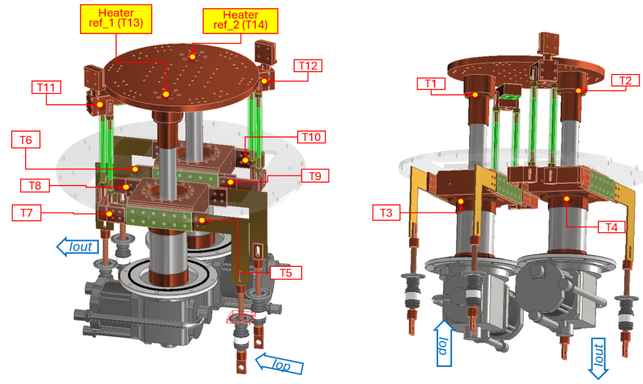

Fig. 8. Sensor placement for system temperature monitoring during performance evaluation.

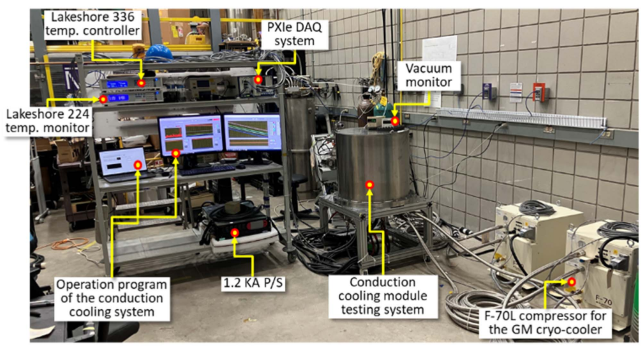

Fig. 7. Full system configuration of the conduction-cooled HTS module testing setup for performance evaluation.

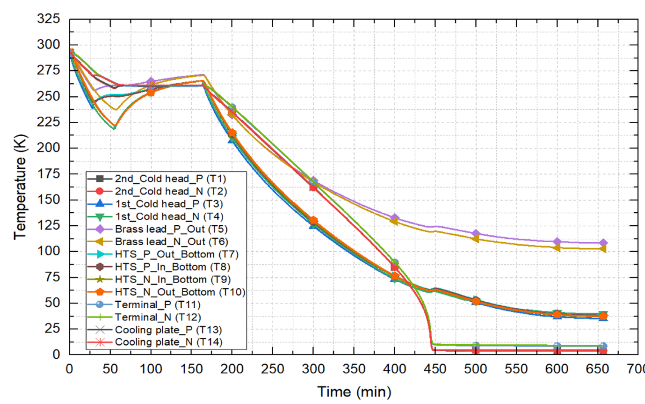

Fig. 9. Final cooling temperature of the conduction cooling testing system under no-load conditions.

To reduce heat conduction from the first stage, the lead body was fabricated in a hexagonal stick form using low-thermal-conductivity G10. To minimize Joule heating, six REBCO tapes were attached—one on each face of the hexagonal stick—and soldered to OFHC terminals located at both ends of the HTS lead. To improve the cooling efficiency of the REBCO tapes, Stycast 2850 was applied to their surfaces. Finally, a G10 tube was used to protect the REBCO tapes from mechanical contact, and superinsulation was added to shield the HTS leads from additional radiation heat load.

Fig. 6 shows the internal configuration of the fully fabricated conduction cooling-type HTS module testing system (excluding the radiation shield), demonstrating that it maintains the same structure as originally designed.

III. Performance Evaluation

Fig. 7 shows the configuration of the system used for performance evaluation of the fabricated conduction-cooled HTS module testing system. To supply the target operating current of 800 A, a Sorensen DC power supply with a capacity of 1.2 kA was utilized. For the operation of the GM cryocoolers, two F70L model compressors manufactured by Sumitomo were employed. A total of twelve DT-670 silicon -diode temperature sensors, produced by Lake Shore, were installed to monitor the temperature of each part of the system.

The temperature readings were monitored using a Lake Shore Model 224 temperature monitor. For temperature control of the cooling plate, a Lake Shore Model 336 temperature controller was used. This controller regulated the current supplied to the cartridge-type heaters embedded in the heating block, based on feedback from two additional DT-670 temperature sensors (T13, T14) used as reference inputs. All data generated during system performance testing were displayed and recorded through a data acquisition (DAQ) system composed of PXIe hardware and LabVIEW software.

Fig. 8 shows the locations of the 14 temperature sensors installed to monitor the cooling performance of the conduction-cooled HTS module testing system. Fig. 9 presents the sensor positions used during the performance evaluation, along with the final temperatures measured under no-load conditions. The test results confirmed that the second-stage cold head reached a temperature of 4.4 K, while the first-stage cold head cooled down to 40 K. The temperatures measured at the cooling plate, current terminals, and HTS leads showed only minor deviations from those of the corresponding stages of the GM cryocoolers, indicating that conductive cooling was effectively maintained across all critical components of the system.

Fig. 10 shows the relationship between the total heater power and the cooling plate temperature.

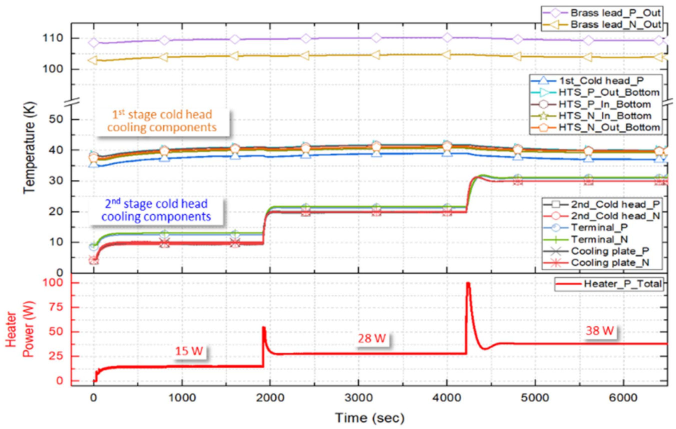

Fig. 10. Cooling plate temperature control results and cartridge heater power.

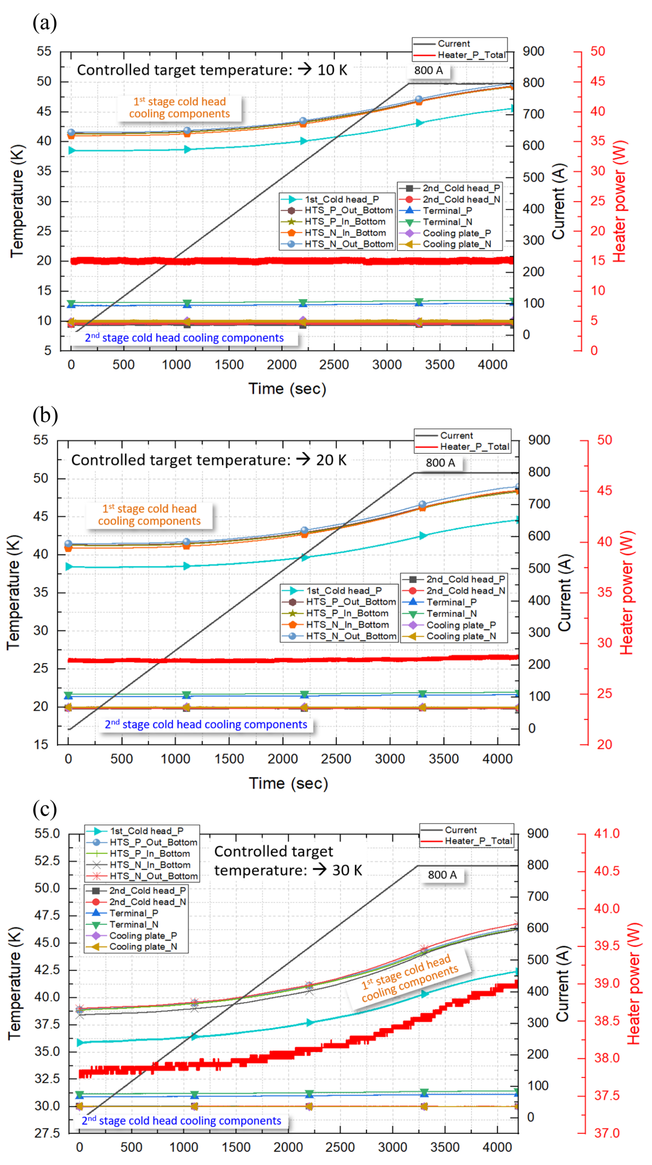

Fig. 11. System cooling temperature during 800 A operation at different cooling plate temperatures: (a) 10 K, (b) 20 K, (c) 30 K.

The cooling plate temperature was regulated using a Lake Shore Model 336 temperature controller in conjunction with two DT-670 silicon diode temperature sensors, with setpoints of 10 K, 20 K, and 30 K. The heater powers required to maintain each temperature were confirmed to be 15 W, 28 W, and 38 W, respectively. Given that the total available heater power in the current system is 100 W, it is anticipated that the system can support temperature control at levels higher than the initial target of 30 K in future applications.

Fig. 11 presents the temperature variation measured at the cooling plate under target temperatures of 10 K, 20 K, and 30 K when a current of 800 A was applied to the system. The current supplied from the Sorensen DC power supply was ramped linearly from 0 A to 800 A at a rate of 0.25 A/sec, and after reaching the target current, the system temperature was monitored for an additional 15 minutes. As the primary objective of the system is to evaluate the performance of HTS modules, continuous operation under the full current condition of 800 A is not required. Therefore, each test was concluded before the first-stage temperature reached full saturation. The results confirmed that, even under increasing current up to 800 A, the cooling plate remained at the initially controlled temperatures (10 K, 20 K, and 30 K). During the entire test period, the bottom temperature of the HTS current lead rose to approximately 50 K. Considering that this value is still about 27 K below the HTS lead's operational limit of 77 K, it is expected that the system could operate for a longer duration under 800 A conditions than demonstrated in this test.

IV. Conclusion

To overcome the limitations of LN_2-based HTS module performance evaluations, a conduction-cooled HTS module testing system was developed using two two-stage GM cryocoolers, designed to enable testing at temperatures below 30 K. Performance test results demonstrated that the fabricated system is capable of stable cooling operation at the target current of 800 A, along with effective temperature control in the range of 4 K to 30 K. Future work will involve the fabrication of additional structures for mounting and cooling HTS modules, as well as the development of an operational procedure based on actual HTS module testing, in order to gain practical experience with system operation.

References

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[2] E. S. Jung, "Optimization of conduction-cooled Peltier current leads," *Cryogenics*, vol. 45, pp. 516–522, 2005.