Development of 16 kA HTS current leads for 40 T hybrid magnet application

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Abstract. A pair of 16 kA high temperature superconducting current leads which will serve a 40 T hybrid magnet at the CHMFL was designed, manufactured and performed the factory acceptance test at the ASIPP site. The major design includes the LN$_2$-cooling copper heat exchanger part as well as the HTS module made of BSCCO 2223/AgAu matrix tapes in parallel which allows the operation of the current lead at a minimum coolant mass flow. The paper briefly describes the design of the 16 kA HTS current leads. And the cold test results of current leads are also presented in the paper.

1. Introduction

The 40 hybrid magnet project which was approved in 2008 and will be made by Chinese Magnetic field Laboratory, Chinese Academy of Sciences comprised of a 29 T resistive insert and a 11 T superconducting outsert. The final design\cite{1} was updated in 2013. The insert contain six Florida-Bitter-type coils, which will contribute 33-34 T in a working bore of $\Phi$32 mm. The outsert consists of three Nb$_3$Sn-based CICC solenoid coils, which is cooled by forced-flow supercritical helium of 4.5 K. The superconducting outsert will generate 11.5 T in a room-temperature aperture of $\Phi$800 m. The final hybrid magnet is expected to achieve the magnet field of 44-45 T. A helium refrigerator system (360 W @ 4.5 K in refrigeration mode, 100L/hr in liquefaction mode) is used to cool the superconducting magnet and feeder system including a pair of 16 kA high temperature superconducting current leads which are applied to electrically connect superconducting busbar and room temperature busbar of 16 kA power supply. The HTS leads are assembled at the vacuum cryostat which is remote from magnet distance about 4 meter.

During the past 10 years, the Institute of Plasma Physics, Chinese Academy of Sciences (ASIPP) has developed high temperature superconducting current leads cooled by forced-flow SHe and LN2 in the current range from 10 kA to 90 kA for EAST\cite{2}, ITER\cite{3-4}, Accelerator magnet\cite{5} and so on. Based on the framework of cooperation between Institute of Plasma Physics, Chinese Academy of Science and Chinese Magnetic field Laboratory, two HTS leads rated at 16 kA current were designed, fabricated and cold tested at ASIPP. The paper briefly describes the design and test result of the 16 kA HTS leads.

2. Design

Total length of the current lead is $\sim$ 2 m. The current feeds from the water cool copper terminal through a 0.4 mm thickness copper foils stacked heat exchanger that is cooled by a counter-flow of liquid nitrogen and vaporizing nitrogen. The heat exchanger is connected to an intermediate copper
block, and the HTS section. The HTS section consists of 80 stacks of Bi-2223/AgAu matrix soldered on a stainless steel cylinder that provides mechanical support for the tape stacks and an electrical shunt. The cold end of the HTS section is connected to Nb-Ti strands dis-assembled from the CICC cable. More similar design is in detail described in the [5]. Table 1 shows design requirement of 16 kA current leads. Figure 1 is a design overview of 16 kA current leads.

![Figure 1 overview of 16 kA HTS current leads design](image.png)

| Parameters     | Values         |
|----------------|----------------|
| current        | 16 kA          |
| HTS Temperature| 5~78 K         |
| HEX Temperature| 78~300 K       |
| HTS hotspot    | 200 K          |
| Time constant  | 10 s           |
| HEX’s inlet    | LN2 and vapor  |
| Heat load to 5K| < 5W           |

3. Cold test

3.1. Instrumentation

Figure 2 is a photo of leads before moving into the vacuum cryostat. Figure 3 show the test scheme of HTS tests. Two EAST joints are combined and electrically connected to the cold end of current leads, which are both cooled by liquid helium. Room temperature U-shape copper terminal is connected to a 20 kA power supply. The main HEX is in parallel feed by a 500 L liquid N2 tank.

A temperature sensor is nakedly mounted on the HEX top to monitor and record the temperature profile of the warm terminal. Two temperature sensors (including a backup) mounted at HTS top are used to log the data and monitor the HTS conductor temperature to prevent the HTS quench. In the test, a special temperature sensor is assembled on the HTS at the 90% along the cold end to monitor the quench progress and avoid overheat of the HTS module. A calibrated CERNOX is assembled in the hole of copper cone of the HTS bottom to monitor and record the temperature profile. 5 pairs of voltage taps are soldered on the surface of the lead to get the detail voltage drop including HEX part, HTS module and joint resistance.
3.2. Test results

According to the design requirement, multi-measurements containing joint resistance, conduction heat input to 5 K and loss of flow accident of main HEX are performed after HTS leads is cooled down. Table 2 summarizes the test results of 16kA current leads. Here is mainly focus on the results discussion of loss flow accident test. Figure 4 shows detail data of the temperature/voltage drop response after closing the supply valves of the liquid nitrogen tank for the two leads. It indicated that the current lead can bear more than 6 minutes of holding time of loss of coolant in an accident. The current leads have enough margin of time to remind the operator to take action. The hotspot of the HTS module happens at the 95 % location along the cold end which is similar to the past. In figure 4, we can find that the voltage drop of HTS module goes up to milli-volt level quickly. It indicates that quench current starts to shunt from the superconductor to the matrix or stainless steel. When the HTS 95 % temperature along the cold end is more than 200 K, the power supply is interlocked to cut off. Therefore for the required 10 s time constant of holding time of loss of coolant in an accident, both current leads can meet them. The temperature of room temperature terminal becomes much stable because of water-cool design in the terminal.

![Figure 2 photo of 16kA HTS leads](image1)

![Figure 3 test scheme of HTS leads](image2)

![Figure 4 Temperature and voltage evolution of 16 kA operation and LOFA test](image3)
Table 2 Summary of test result of 16kA HTS leads

| Test items                              | Test results                                      |
|-----------------------------------------|---------------------------------------------------|
| maximum current                         | 16kA@81 K                                         |
| heat load to 5 K end                    | CL1: 3.6 W, CL2: 3.4 W                            |
| Joint resistance of HTS module warm end | CL1: 21.5 nΩ, CL2: 1.3 nΩ                        |
| Joint resistance of HTS module cold end | CL1: 10 nΩ, CL2: 13.6 nΩ                         |
| LOFA time by cutting supply of LN2 tank.| 6 mins without quench. 11 seconds to reach the hotspot of 200 K after quench |

4. Conclusion
A pair of 16 kA HTS current leads was designed and manufactured and performed the factory acceptance test at the ASIPP site. The fruitful development of this two leads provides a significant experience for the next fabrication of 12 kA current leads for the accelerator magnet. These two current leads will be delivered to the end user soon. On-site acceptance test will be performed with the superconducting magnets.

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