20kA HTS current leads for EAST tokamak project

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Two 20kA current leads are made of different materials. Module 1 consists of melt cast processed Bi-2212 tube and two layers of Bi-2223/Ag-Au alloy tapes as the shunt and also to enhance current-carrying capacity. The critical current of the Bi-2212 tube alone is 9.052 kA at 77 K. After adding 104 Bi-2223 tapes the critical currents increase up to 10.2 kA at 78 K and >20 kA at 70.7K. Module 2 consists of 48 stacks of CryoBlock tapes. The critical currents of 192 tapes reach over 14 kA at 78 K and over 20 kA at 70.7 K.

INTRODUCTION

EAST tokamak (original name HT-7U) under construction in our institute is a full superconducting device for fusion experiments. The tokamak has a major radius of 1.7 m and a minor radius of 0.35 m. The rated currents of 16 D-shaped toroidal field coils made of NbTi/Cu superconductors are 14.3 kA for phase I and 16.5 kA for phase II. There is one pair of current leads for 16 TF coils. In order to obtain a single-hull divertor field configuration the 6 solenoids for Ohmic heating, and 6 round-shaped coils for the divertor field and equilibrium field must be fed power supplies independently. These coils have the same maximum current of 14.5 kA. So 12 pairs of current leads will be equipped for these coils.

EAST tokamak has a total current lead capacity of 33 kA in steady mode and 348 kA in pulsed mode. According to the optimum design of a nominal current lead to cool the leads needs the helium vapor consumption of 1.7 g/s for the TF coils and ~11.6 g/s for all the PF coils (assuming the pulse operation mode to require 2/3 of steady-mode mass flow). It equivalents a refrigeration power about 1.2 kW/4.5K.

According to investigation [1,2] the heat load of HTS current leads (HTSCL) at 4.5K can reduce to 0.1-0.18W/kA of the nominal leads. Using HTSCL for EAST tokamak can reduce refrigeration power of 900 W/4.5K at least and save operating cost greatly. Institute of Plasma Physics, Chinese Academy of Sciences starts developing HTSCL from the 2003 March. Now we design and manufacture two test leads of 20 kA aimed at a cryogenic test facility for EAST coils.

Both Bi-2212 tube and Bi-2223 tape sheathed with Ag-Au alloy are suitable for 15-20 kA leads. The melt cast processed (MCP) Bi-2212 tube has a lower thermal conductivity, lower critical temperature (~92 K) and poor strength. The Bi-2223 tapes have a higher critical temperature (110 K), and Ag-Au alloy sheath possesses much higher thermal conductivity and better stability. In order to compare their heat load at the cold end, contact resistance, stability and performance degradation due to manufacture process and cooldown-warmup cycles. We try to obtain experiences on more HTSCL manufacture and knowledge of making low contact resistance and higher stability, so both HTS materials are selected. In this paper the design consideration, manufacture technology and some test results of 20kA HTSCL are described.

LEAD COOLING MODE AND COPPER SECTION DESIGN

A 500W/4.5K refrigerator is equipped for our test facility for large-scale SC magnets. One pair of 20kA copper current leads spend more than 2g/s of liquid helium, which almost is half of the refrigeration capacity. In order to solve the 4.5K cooling power shortage, the up-ends of the 20kA HTSCL and copper sections will be cooled with liquid nitrogen (LN_2) and vapor, and the lower ends of HTS sections are cooled by 4.5K supercritical helium.

Evaporating latent heat of liquid nitrogen is much greater comparison with liquid helium, and enthalpy difference of nitrogen vapor from 70 K to 280 K is much smaller than helium from 4 K to 280 K. So design and manufacture of the heat exchanger for this kind of copper current leads should be as simple as possible. Helical fins heat exchanger is selected. To decrease vapor flow resistance the surface of heat exchanger is machined three helical parallel cooling channels (see Fig. 1).

The copper lead with lower current density has better stability when over current and coolant stoppage. A low rated current density of 10.9 A/mm^2 for the copper leads is chosen. The ratio of length to cross-section is optimized according to a rated current of 16 kA in order to minimize LN_2 consumption while leads standby. The copper for the section contains total impurity of less than 0.1% and annealed.

Between the heat exchanger and joint with the HTS section there is 27cm-long copper tube immerged in LN_2 as a heat sink to keep temperature of the HTS up-end stable. If the leads carrying current continuously, the tube section should be solder with Bi-2223/Ag tapes to reduce the Joule-heating. Through a buffer in the cryostat LN_2 is supplied to the current leads. To keep LN_2 level in the buffer in a suitable range is important for the normal operation.

The copper section has a vacuum jacket, and also is electrically insulated from coolant transfer pipes and the cryostat.

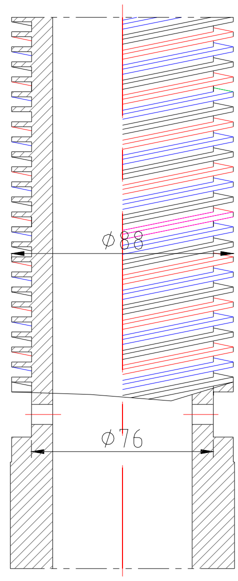


Fig.1 Heat exchanger with tree helical cooling channels

HTS SECTION DESIGN

One of the HTS modules is based on MCP Bi-2212 tube with 80mm outer diameter made by Nexans SuperConductors. According to the data provided by the vendor the critical current (Ic) of the Bi-2212 tube is 9.051 kA at 77K, and increases twice at 70 K. For a lead rated current higher than 5 kA adding a shunt is necessary. The vendor told us that Cu-Ni or Ag-Au alloy sheet could be the shunt material. So we try to use Bi-2223/AgAu alloy tapes for the shunt. Two layers of this kind tapes made by InnoST in China were added. Dimension of the tapes is 4.1 mm wide and 0.21 mm thick, and its Ic is ~ 71 A. So the 106 tapes can enhance current-carrying capacity of ~4kA at 77 K and 6kA at 70 K at least. The sheath of Ag-Au alloy contains 5 wt. % Au. These tapes also can be a shunt when Bi-2212 tube quench. The tapes in two layers are arranged on Bi-2212 tube surface in helical lines (see Fig. 2). The ends of HTS section are directly soldered to the lead copper section and to a copper clamp joint, respectively.

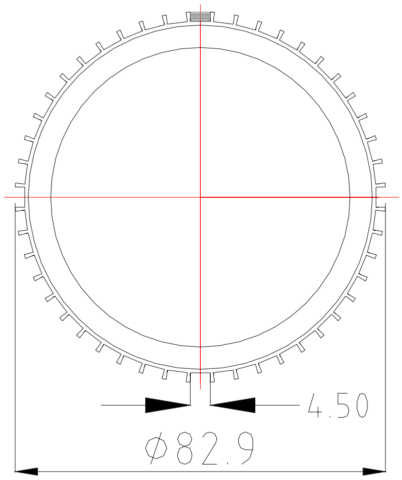
Another HTS module (Fig. 3) is based on Bi-2223 tapes sheathed with Ag-Au 5.3 wt.% alloy (CryoBlock) provided by AmSC. A support cylinder with an outer diameter of 83 mm and 320 mm long consists of two copper terminals and a brass cylinder, which has 48 grooves for tape stacks. The intervals between the stacks should be as small as possible in order to minimize perpendicular field on the HTS tapes and to obtain higher Ic. Each stack consists of 7 CryoBlock tapes. Four of them have full length, and others have shorter length. The tapered configuration can reduce heat leak at 4.5 K and required amount of HTS tape. The tape dimensions are 4mm wide and 0.2mm thick. The Ic of the tapes are not lower than 106 A. The module Ic of more than 20 kA at 70 K is expected. Table 1 lists the major parameters of the two modules.

According to the heat leak data provided by Nexans SuperConductors, the tube with 200 mm length and 8 mm thick has a conduction heat of ~0.5 W at the lower end when up-end at 77 K. It is quite low comparison to the full Bi-2223 wire module.

MCP Bi-2212 tube

Covering with 2 layers of Bi-2223/AgAu tapes

Fig. 2 HTS module 1



Cross-section of support cylinder

Fig. 3 HTS module 2

Table 1. Major parameters of 20 kA HTSCL

	Copper part	HTS module 1	HTS module 2
Effective length (mm)	700	200	320
Effective diameter (mm)	88	81.2	83
Conductor material	Copper	MCP Bi-2212+ Bi-2223/Ag-Au wt.5%	CryoBlock
Configuration	Tube with 3 helical fins	Cylinder	Tapered cylinder
Cooling mode	68K Sub-cooled LN_2 and vapor	4.5K supercritical He	4.5K supercritical He

MANUFACTURE

Soldering is most important technique for HTSCL manufacture and assembling because incorrect soldering results in degradation of HTS Ic and too high contact resistance. To heat and cool HTS tube or tapes must be slow enough, and avoid heating above the temperature limit (300 ℃) for both Bi-2223 wire and MCP Bi-2212. According to the vendor suggestion In-Bi solder was used for module 1. The joints between the HTS module and copper cap and the copper lead part are soldered in atmosphere, and a few of citric acid are applied as flux. The two layers of Bi-2223 tapes are soldered on the Bi-2212 tube in a vacuum vessel. For module 2 62Sn-36Pb-2Ag-paste solder was used between Bi-2223 tape stacks and the support cylinder. This HTS module was soldered into the copper caps also with In-Bi alloy due to its low melt point.

TEST RESULTS OF THE HTS MODULES COOLED WITH LN_2

We concern performance of the HTS modules, the contact resistance of ends and the optimum operation current of the heat exchanger. The two modules were cooled down to 78 K and immerged in LN_2 bath. A computer acquired the potential difference data when current increasing steps by step. For HTS module 2 the critical current was higher than 14kA at 78 K. But for module 1 linear-increasing potential difference appeared when the current higher than 10 kA, it meant more and more current transferred from Bi-2212 tube into Bi-2223 tapes, and Ic of the module 2 was 10.2 kA at 78 K according to 1 μV/cm criterion (see Fig. 4). When LN_2 temperature decreased from 73 K to 70.7 K, the current increased to 20 kA in 2 kA steps. Module 2 showed a stable performance, and had an Ic higher 20 kA at 70.7 K. Module 1 also had an I_C higher than 20 kA at 70.7 K too, but part of current carried by Bi-2223 tapes changed while the temperature decrease (see Fig, 5).

The contact resistances were 130 nΩ for module 1 and 44 nΩ for module 2 at 78 K. The two current leads stayed at 13 kA for 20 minutes. The voltage spanning the heat exchanger was 55 mV. It meant the optimum current near 13 kA for the copper lead, which was smaller than expected. Other measurements require LHe cooling the lower ends of HTSCL, and will be done in future.

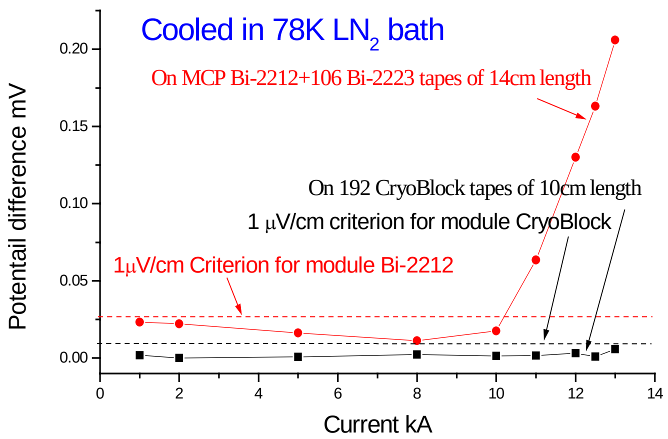


Fig. 4 Ic measurements of HTS modules at 78K LN_2

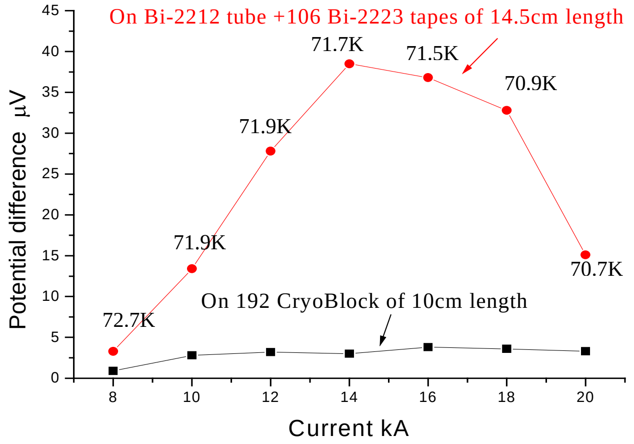


Fig. 5 Ic measurements of HTS modules below 73K LN_2

SUMMARY

The preliminary test results show that module 2 made of CryoBlock has better performance on the higher critical current and lower contact resistance, and the Bi-2223/AgAu alloy tapes as the shunt can enhance current carrying capacity of MCP Bi-2212 tube module to reach 20kA at 70.7K.

Correct solder technique and intervals between the stacks as small as possible are most important for HTSCL to reach a high performance without degradation of Bi-2223/AgAu tapes.

ACKNOWLEDGMENT

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