PREPARATION AND TESTING OF PROTOTYPE 12.5 kA HIGH TEMPERATURE SUPERCONDUCTING CURRENT LEADS FOR THE LHC AT CERN

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Abstract

In most high current superconducting magnet systems, the largest cryogenic losses are associated with the leads which carry current from the room temperature power supply to the cold circuit. High temperature superconducting (HTS) materials combine low thermal conductivities with the ability to carry currents without ohmic dissipation at temperatures up to 100 K, and so offer the possibility of drastically reducing the consumption of cryogens. Oxford Instruments have been investigating the potential for the use of HTS materials in current leads for several years. In 1995, this work was a starting point for a collaboration with CERN to demonstrate the feasibility of HTS leads for powering the proposed Large Hadron Collider (LHC) dipoles at currents of 12.5 kA. This paper presents results and analysis from tests on leads incorporating HTS materials under simulated LHC conditions at currents up to 13 kA.

1 INTRODUCTION

Very low loss current leads for superconducting magnets were among the earliest potential applications to be recognised following the discovery of the first HTS compounds[1].

Conventional copper leads, if optimised for continuous energisation, leak heat to the 4.2 K part of the system at a rate of 1.04 W/kA[2]: a magnet operating at 12.5 kA will therefore suffer a heat load of 26 W due to the leads alone. The LHC will have more than 8000 superconducting magnets operating at currents up to 12.5 kA. If the current lead losses can be minimised the reduction in operating cost and cryogenic infrastructure will be significant.

2 REQUIREMENTS OF A LEAD

For a lead to be useful, it must fulfill a number of criteria. These include:

- Ability to carry the full current at the necessary temperature and field
- Substantially lower losses than a conventional lead
- Ability to withstand repeated thermal and current cycles with no performance degradation
- Ability to withstand fault conditions, such as a loss of coolant, without damage or degradation.

3 CANDIDATE MATERIALS

Although a number of HTS materials of different types and with various properties have been discovered, only a few have been produced in a form suitable for carrying very large direct currents. When the present collaboration between Oxford Instruments and CERN began, just two suitable European candidates were identified; melt cast BSCCO-2212 produced by Hoechst in Germany, and YBCO-123 produced by Haldor Topsøe in Denmark. The BSCCO was available in cylinders of various diameters and current ratings, and the YBCO in thin, rectangular-section plates.

4 PRELIMINARY RESULTS IN LIQUID NITROGEN

Before starting the collaboration with CERN, Oxford Instruments had already carried out tests on samples of both materials in liquid nitrogen. A simple test rig was built, which allowed the conductors to be immersed and currents up to 4 kA to be applied.

The cross section of the YBCO sample was 69 mm^2, and it was supplied with flexible copper braids attached for connection to the test rig. As the current was applied, sensors on the sample indicated that the temperature was rising due to resistive heating in the braids. The current was increased slowly in small steps until the lead suddenly became resistive at 3570 A, at a current density of 51.74 A/mm^2. The temperature at which superconductivity was lost was measured at 89 K: the critical temperature for the material was later determined to be 90.5 K. When the lead was removed from the test rig, it was found to have broken, and there were clear signs of intense heating on the fracture surface.

The BSCCO lead was tested under virtually identical conditions except that the cooling arrangements were improved, ensuring that the lead temperature remained below 77.5 K for the duration of the test. The cross section of this lead was 6400 mm^2, and it carried a current of 1890 A (current density 0.30 A/mm^2) before it suddenly became resistive and broke.

These experiments were useful in highlighting one of the major problems with using HTS materials for current leads. Thermal analysis shows that, if a normal zone develops in the lead, the rate of propagation of that zone is very slow. This results in rapid heating of a very small region and can lead (as in these cases) directly to the destruction of the lead.

5 CONTACT TESTING

In a HTS current lead, the heat load to 4.2 K is almost entirely due to conduction through the lead and the resistance of the contact between the superconductor and normal metal. The conducted heat is essentially a property of the HTS material: the cross section is determined by the maximum allowable current density at the warmest point on the lead, and the heat load follows directly from the length and thermal conductivity.

Transfer of current from the superconductor is generally achieved through a layer of silver coating the surface. Solder can then be applied to the silver to connect either to conventional superconductor or to normal metal. The contact resistance depends on the nature and integrity of the bond between the silver and the superconducting ceramic, and on the area it covers. It is usual to compare contacts in terms of a specific joint resistance - generally measured in $\mu\Omega cm^2$ - which accounts for both of these factors.

New samples of the YBCO and BSCCO materials were cooled to 4 .2 K and currents up to 240 A applied while voltages across the leads and contacts were monitored. The BSCCO lead, being rather large due to its low current density capability, had a much lower contact resistance than the much smaller YBCO lead. The specific resistances were 0.3 $\mu\Omega cm^2$ for the YBCO and 0.07 $\mu\Omega cm^2$ for the BSCCO. For a given dissipation, the contact on the YBCO would therefore have to cover an area 4 times larger than that on the BSCCO.

6 TEST FACILITY

For work on current leads to be directly applicable to the LHC, it has been necessary to build a specialised test facility to reproduce as closely as possible the expected environment in the accelerator. A suitable system has been designed and manufactured by Oxford Instruments. It features two separate helium vessels and a nitrogen vessel, with all of the associated equipment for cryogen transfer, monitoring and safety. The HTS lead is mounted between heat sinks connected to the nitrogen vessel and one of the helium vessels. The liquid helium maintains the temperature at the bottom of the lead at 4.2 K. The pressure of the nitrogen can be reduced by pumping, which means that the top end of the lead can be controlled at a temperature between 65 K and 77 K. The lead operates in vacuum, and can be demounted easily.

For the LHC, it is anticipated that a safety lead will be connected in parallel with each HTS lead to protect the magnets in case the lead breaks. A similar lead has been incorporated in the test facility. It has been manufactured from a standard aluminium alloy, featuring low thermal conductivity to reduce the heat load conducted to 4.2 K.

The return current path is provided by a resistive current lead, cooled by vapour from the second helium vessel.

7 HTS LEAD DESIGN

The design of the experimental lead was deliberately made simple, so that the maximum information could be gathered about the performance of the conductors. Since larger conductors were not immediately available, a pair of 70 mm diameter BSCCO tubes were obtained from Hoechst. These were soldered in parallel into copper end-pieces using a mixture of Woods metal and indium. This particular solder had been recommended[3] because of its very low melting point (55 °C) which allows the contacting process to be carried out without any risk of superconductor degradation. It was not known how effective the solder would be at very high currents. The copper end-pieces were then bolted into the test facility.

8 TEST RESULTS

Power was supplied to the lead through resistive bus bars. The current was increased in steps of 1 kA, with a pause of several minutes at each step for data analysis. The maximum current of the power supply - 13 kA - was reached on the first attempt, with the ends of the HTS lead held at 70 K and 4.2 K.

After a complete thermal cycle from the operating temperature to room temperature and back again, the tests were repeated. The performance of the lead was found not to have changed. The current was then raised to 10 kA while the pump on the nitrogen vessel was switched off, allowing the temperature to rise. When the temperature at the warm end of the HTS lead reached 80 K, the voltages on the system began to rise sharply, indicating that at least one of the superconductors had started to go normal. By pressing the emergency button on the power supply, the current was reduced to zero within a few seconds. When the system temperatures had all stabilised again, the current was raised to 13 kA once more, indicating that the lead had not been damaged.

Next the current was raised to 12 kA and held while the nitrogen temperature was allowed to rise as before. On this occasion the voltages began to increase when the warm end temperature reached 79 K, and again the current was reduced to zero within a few seconds.

On the next attempt to apply current, the lead became fully resistive at about 7 kA. After removal from the test facility, it was found that both superconductors had broken near to the contact at the 70 K end.

9 ANALYSIS

The rate of helium boil-off due to the HTS lead was monitored throughout the experiments, and was found to be rather higher than had been expected. When the data from the voltage taps on the lead was examined, it was found that the resistance was dominated by the solder joining the silver contact on the HTS tubes to the copper end-pieces. This resistance was also a strong function of the lead current, probably because of self-heating. At 12.5 kA, the resistance for both superconductors was approximately 0.4 $\mu\Omega$. The heat generated in these soldered joints was therefore 31 W. This may be compared with the conducted heat due to the safety lead and HTS lead together, which was around 1.7 W.

Close examination of the voltage data revealed that the chain of events in both lead quenches was the same. One of the leads went normal in a region near the contact at the 70 K end. A small amount of current (about 200 A) was then shunted into the safety lead while the rest transferred into the other superconductor.

The second quench (from 12 kA) seriously damaged both superconductors. This was fully expected, both from the early work on nitrogen-cooled conductors and from thermal analysis using finite difference (FD) techniques.

10 CONCLUSIONS

A test facility has been constructed which may be used to model the anticipated environment for current leads in the LHC. Current, voltage, temperature and cryogenic data may all be collected for the analysis of prototype leads.

The results obtained with this experimental lead show that it is feasible to transport large currents - of the magnitude required for the LHC - using HTS leads. Our lead accommodated a limited number of thermal and current cycles up to 13 kA with no apparent degradation in performance. With an improved solder formula it will be possible to reduce the 4.2 K heat load very significantly. If the superconductor geometry is optimised as well, the target of 1.3 W for a 12.5 kA lead should be within reach.

The problem of lead fracture if coolant is lost remains. No attempt was made in this work to protect the lead from quenching, although it was encouraging that it was able to survive a quench from 10 kA for at least a few seconds. Recent work at CERN[4] has also had success in protecting 600 A leads of the same material from damage caused by quenching.

This successful collaboration between Oxford Instruments and CERN will form a foundation for continuing development of HTS leads. Future work will include investigation of leads incorporating superconductors made from different materials and using alternative processes, as well as ageing trials. Now that the current carrying capability has been proven, the survivability of leads in a quench must be given high priority.

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