EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH
European Laboratory for Particle Physics

Large Hadron Collider Project

LHC Project Report 78

Design and Tests on the 30 to 600 A HTS Current Leads for the Large Hadron Collider

A. Ballarino and A. Ijspeert

Abstract

Some 800 correction magnets of the Large Hadron Collider will be individually powered. Each of them needs a pair of current leads. To reduce the heat leak through these leads, the current has been chosen as low as reasonably possible, 30 to 600 A. For the same reason, CERN started in-house a development of current leads using commercial bulk BSCCO-2212 material. This paper discusses the design and the test results of this lead. We tested several prototypes, measured the heat leak through the lead, studied and tested what happens if the lead is brought to critical temperature causing it to quench.

LHC

ICEC'96, Kitakyshu, Japan, 20-24 May 1996

CERN
CH - 1211 Geneva 23
Switzerland

Geneva, 23/10/96

Design and Tests on the 30 to 600 A HTS Current Leads for the Large Hadron Collider

Amalia Ballarino, Albert Ijspeert

CERN, European Laboratory for Particle Physics, CH-1211 Geneva 23, Switzerland

Some 800 correction magnets of the Large Hadron Collider will be individually powered. Each of them needs a pair of current leads. To reduce the heat leak through these leads, the current has been chosen as low as reasonably possible, 30 to 600 A. For the same reason CERN started in-house a development of current leads using commercial bulk BSCCO-2212 material.This paper discusses the design and the test results of this lead. We tested several prototypes, measured the heat leak through the lead, studied and tested what happens if the lead is brought to critical temperature causing it to quench.

INTRODUCTION

Most of the superconducting magnets of the Large Hadron Collider (LHC) are connected in series and powered with relatively high currents which are distributed through superconducting busbars. However, there are quite a number of magnets that need to be powered individually for control of the particle beam. These magnets need individual current leads. The use of High Temperature Superconducting (HTS) material for such leads can make an important reduction of Helium boil-off in the cold (1.9 K) mass. They will be entirely located in the region of insulation vacuum and connected to the cold mass on one side and the ambient on the other side by means of ceramic feedthroughs. The cooling is obtained by thermalising the lead at the warm end of the HTS part to a tube carrying helium gas at 60 K. A metal safety lead gives a current by-pass in case of quench. Such a lead needs no cooling gas control and gas return.
A pair of 30 A [1] leads has been designed and tested on the same principles.

LEAD DESIGN

The 600 A hybrid lead consists of a normal conducting upper part, from room temperature to 60 K, and a high temperature superconducting part, from 60 K to 1.9 K (see fig.1). The normal conducting part is a standard electrolytic copper braid, 75 mm^2 cross section and 390 mm length. The geometry corresponds to the calculated shape factor ($IL/A= 3.12\cdot10^6$ A/m) of an optimum conduction cooled Cu-ETP lead [2]. The temperature profile at nominal current has zero slope at 300 K. At the lower current the lead, for the chosen length and cross section, is no longer fully optimized: heat is entering at the warm end. The braid is thermalised against a stainless steel tube carrying helium gas at 60 K. This is done with a copper ETP block, 5 cm long, which is clamped against the cooling tube and electrically insulated with a Kapton foil 50 µm thick.

The HTS element is a BSCCO 2212 rod, 5 mm diameter and 100 mm length.The measured critical current density of the material at 77 K and in zero field is equal to 1166 A/cm^2 (1 µV/cm criterion). When the temperature of the heat exchanger is lowered to 60 K the lead is able to carry 600 A with a safe temperature margin of ~ 12 K. The BSCCO 2212 rod has integrated silver contacts at both ends,1 cm long. The braid is connected by electron beam welding to a copper sleeve which is then soldered with Indium on the silver contact at the warm end of the HTS. Four parallel low temperature superconducting (LTS) wires (0.84 mm^2 cross section each) are indium soldered on the silver at the cold end. They guarantee a flexible connection at the cold end. They are clamped against a thicker LTS wire that goes through a ceramic feedthrough into the 1.9 K helium bath. A stainless steel casing protects the ceramic feedthroughs from mechanical damage during installation and supports the safety lead and the HTS lead.

A stainless steel safety shunt takes the current in case of an accidental quench of the HTS lead. The geometry of the safety lead is determined by two conditions:

- the heat conduction from 60 K to 1.9 K must be as low as reasonably possible (we specify 5 % of a conventional lead,that is~ 5 W/kA),
- the cross section must be sufficiently large to absorb the Ohmic heat during the 6 seconds of magnet unloading.

The length is then the result of the desired resistance value and the chosen cross section.
The measured resistance at room temperature of the shunt is 4.2 mΩ.

The advantages of this lead design in comparison with a normal lead are basically two: the reduction of cooling power and the suppression of the He ducts and gas return pipe as well as flow control of the conventional leads.

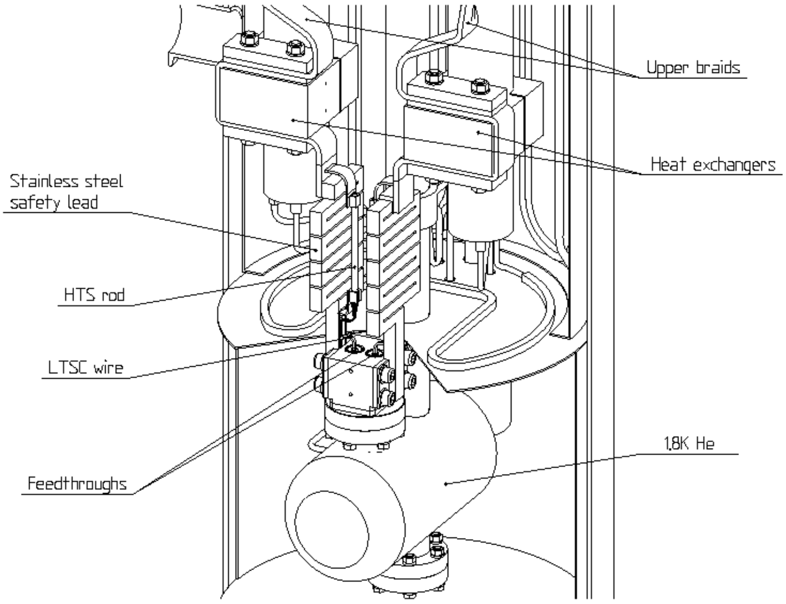

Figure 1 600 A HTS leads in the test stand

TEST OF THE CURRENT LEADS

A cryostat has been built to test two 600 A hybrid leads.It is equipped with temperature probes, voltage taps and a helium level gauge. The cooling of the two 60 K heat exchangers (one for each lead) is independent. The helium gas flow rate, together with the temperature of the helium at the inlet and at the outlet of the heat exchangers, allows us to calculate the heat conducted to the 60 K by the 75 mm^2 copper braid. The cold mass is filled with 4.2 K liquid He and pumped to obtain 1.9 K. All the temperatures and the most significant voltages are recorded.

The heat inleak to the helium due to the cryostat alone has been measured to be 50 mW.
A pair of current leads has been operated steadily at currents of 600 A. At this current, the voltage drop over the braid is 45 mV. The heat absorbed by the heat exchanger is 26.7 W per lead. The heat exchange surface is 45 cm^2. The temperature drop for conduction through the kapton isolation is 5.4 K.

Three methods of heat leak measurements at 1.9 K have been followed to estimate the amount of heat conducted by the HTS lead operating in the cryostat.

- We stop the pump and allow the temperature of the helium to increase for one minute. Then we introduce a known extra heat flow in the bath for one minute. The comparison of the slope of the temperature profiles during these two transients allows to calculate the amount of heat conducted at 1.9 K. The test has been repeated several times, changing the power introduced from the outside.
- Other measurements have been made using the level gauge in the liquid helium.

• The mass flow evaporated of helium at 1.9 K has been measured.
The result gives an average heat leak to the 1.9 K liquid helium of 16 mW per HTS lead.

The contact resistance at the ends of the HTS lead have been measured. For 600 A, the resistance at the warm (60 K) end (Cu-In-Ag-HTS) is 1.2 μΩ. The resistance at the cold (4 K) end (LTSC-In-Ag-HTS) is < 0.03 μΩ.

The measured heat conducted by the safety lead is 12 mW. The total heat inleak at 1.9 K is therefore 28 mW. For comparison, a normal self cooled 600 A lead conducts ~ 660 mW into the liquid helium. The cooling power necessary to cool the 26.7 W at 60 K and the 28 mW at 1.9 K corresponds to 43 % of the cooling power of a 600 A conventional lead.

QUENCH PROTECTION

The resistive zone

The most likely occurrence of a quench would be one caused by a temperature excursion at the top of the HTS section of the lead. We calculated the current distribution in this area at the onset of quench using an empirical description of the critical current density as function of the temperature and the field. Using the data of the BSCCO 2212 measured by the manufacturer we constructed the following equation for the critical current (J_{crit}, A/mm^2), valid for a temperature (T) between 42 K and 78 K and a magnetic field (B) between 0.02 T and 0.1 T:

$$J_{crit} = 3.5 \cdot (80 - T) \cdot \exp\left(\frac{-25000 \cdot B}{(90 - T)^{2.6}} \right)$$

In Fig.2 the distribution is given for the case where the cross sections at the opening of the endcap just becomes resistive. One can see that the critical region is very thin and the length with is partially critical is only a few tenths of millimeters long. The length of the resistive region as found from the quench measurements is about 0.35 mm.

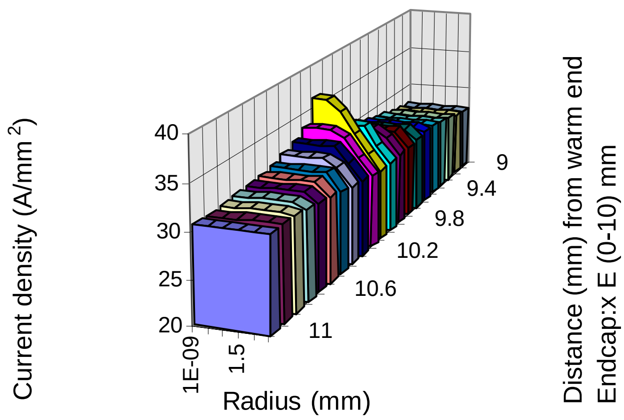

Figure 2 Current distribution in HTC upper end at start of quench

Current sharing and peak temperatures

Although during the quench the safety shunt will take most of the current and will heat up, the quenching lead still takes part of the current and will heat up as well. This may cause fracture of the HTS part of the lead. However,if the heat production in the quenching lead can be cooled away by conduction, about 32 mW for our lead (16 mW to each end), the lead can safely stand the magnet unloading irrespective of the time it takes.

From Ohm’s law the heating in the resistive HTS lead is:

$$\dot{Q} = \left(\frac{I_{magnet} \cdot R_{shunt}}{R_{HTS} + R_{shunt}} \right)^2 \cdot R_{HTC}$$

Introducing the conduction (32 mW) and the known resistance of the shunt we find the relation between the magnet current and the safe HTS resistance where the heat cools away. For 200 A the HTS lead must have a resistance higher than $8 \cdot 10^{-7}$ Ω. Unfortunately the resistance of the leads is very small (we measured $2.5 \cdot 10^{-7}$ Ω) and will only be safe for quenches at currents of 63 A. The measurements showed that one could safely quench up to 200 A limiting the time to 120 s. For higher currents we tried to find a way to create a longer critical zone by covering the end of the lead with a metallic sleeve that distributes the critical temperature conditions over the length it covers. A length of 10 mm was chosen. The tests showed that quenches up to 400 A were safe.

The peak temperatures have been estimated using the pessimistic assumption that the heating of the hot spot has no time to spread significantly and therefore can be assumed adiabatic. The peak temperature (Tmax in table 2) can be obtained from the calculations of the integral I^2 dt over 6 seconds and the values found during the different tests range from $9.9 \cdot 10^3$ to $9.7 \cdot 10^4$ $A^2 \cdot s$. The material cracks when the temperature goes above a certain limit which is about 100 K (measured on the surface of the HTS) for the tests on the 5 mm rods.

The results of the test are shown in table 2. Tq is the temperature at which the quench happened. We should remind that a slight voltage starts to build up already 1.5 K lower where the flux starts to flow. Tmax is the peak temperature calculated from the integral $I^2 \cdot dt$.

Table 2 Results of the quench-test: 6 seconds of quenching period, successfull quench survival

I (A)	Tq (K)	$\int_0^6 I^2 dT$ ($A^2 \cdot s$)	Tmax (K) (adiabatic)	R (mΩ),after t=6 s
100	81.4	$9.9 \cdot 10^3$	120	13
200	77.5	$2.7 \cdot 10^4$	203	12
300	74	$6.9 \cdot 10^4$	400	16
400	70.8	$9.7 \cdot 10^4$	550	16

CONCLUSION

A pair of 600 A hybrid prototype leads has been designed and tested. Heat loss measurements show the important reduction in heat leak at 1.9 K. in comparison with a normal self cooled lead. Tests on the quench protection of the HTS lead have been performed to study the behavior of the BSCCO material in the resistive state and in the future operating conditions. The leads survived the quench of 200 A and 120 seconds of current unloading time. Other materials will be tested in the near future.

REFERENCES

1. Ballarino, A. and Ijspeert, A. Design and Test of the Prototype High Tc Current Leads for the Large Hadron Collider Orbit Correctors IEEE Transactions on Applied Superconductivity (1995) 5 805-808

2. Ballarino, A. and Ijspeert, A. Expected Advantages and Disadvantages of High Tc Current Leads for the Large Hadron Collider Orbit Correctors Advances in Cryogenic Engineering (1994) 39 1959-1966

ACNOWLEDGMENTS

We would like to thank: the Cryogenic Laboratory, in particular P.Gauss and J.M. Rieubland, for the cryogenic expertise and invaluable help, A. Toukhtarov for the design, J. Mazet for the mechanics and G. Peiro for the instrumentation.