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HTS CURRENT LEADS FOR THE LHC MAGNET POWERING SYSTEM

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Abstract

Among the different applications of the emerging High Temperature Superconducting (HTS) technology, current leads represent a key development component. In this field the state of maturity of the conductor is such as to satisfy both a wide range of design requirements and those of economic viability. The LHC superconducting magnets will be powered through HTS current leads transferring in total more than 3 MA of current. The R&D program undertaken at CERN and in industry to experimentally validate different design assumptions has led to major progress towards design choices for the different HTS leads of the LHC magnet system. Test results, merits of design variants and major milestones for the LHC leads manufacture will be reported.

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HTS current leads for the LHC magnet powering system

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Abstract

Among the different applications of the emerging High Temperature Superconducting (HTS) technology, current leads represent a key development component. In this field the state of maturity of the conductor is such as to satisfy both a wide range of design requirements and those of economic viability. The LHC superconducting magnets will be powered through HTS current leads transferring in total more than 3 MA of current. The R&D program undertaken at CERN and in industry to experimentally validate different design assumptions has led to major progress towards design choices for the different HTS leads of the LHC magnet system. Test results, merits of design variants and major milestones for the LHC leads manufacture will be reported.

Keywords: Current leads; High temperature superconductors; Accelerator technology; Cryogenics

1. Introduction

To accelerate and collide 7 TeV proton beams in the existing LEP tunnel, the LHC will require about 8000 superconducting magnets operating at superfluid helium temperature [1]. The total excitation current of up to 1.7 MA will be transferred via current leads housed in ad hoc designed cryostats (Distribution Feed Boxes) located, in the LHC tunnel, right and left of each of the eight interaction points. In view of the large amount of current to be carried into the cryogenic environment and the potential saving in liquefaction power induced by the use of High Temperature Superconducting (HTS) material, CERN has decided to employ HTS current leads in the LHC [2]. Over the last 8 years an extensive R&D program has been undertaken at CERN to validate both the viability of today commercially available HTS materials and technical choices (cryogenic, electrical and mechanical) in the design of the complete lead. The results of the measurements performed on 13 000 and 600 A HTS prototype leads are reported together with the corresponding analysis.

2. HTS leads R&D program

Already in early 1995 CERN was testing, in collaboration with Oxford Instruments, HTS elements designed for carrying currents as high as 12 500 A [3]. These tests were made with elements operating in a vacuum environment between liquid nitrogen temperature and liquid helium temperature. Small 600 A HTS samples were tested at CERN. Studies made in parallel to optimise the HTS lead design for the LHC machine [4] resulted in the choice of using the available 20 K helium gas to cool the upper, heat exchanger section of the leads, and in the issuing, in April 1997, of a technical specification for the design and manufacture of 13 000 A prototype leads. Ten companies were selected, world wide, to each provide one pair of 13 000 A HTS leads.

In June 1998 a technical specification was issued for the design and manufacture of one assembly of four 600 A HTS prototype leads. Twelve companies were selected, world wide, to design and manufacture each one assembly of four 600 A HTS leads. Two test cryostats were built at CERN for the thermo-electrical characterisation of the prototypes [5], and in-depth measurements have been performed on the prototypes in different operating conditions (stand-by, nominal and transient operation, thermal and electrical cycling) [6].

The principal features of the prototype HTS current leads are described elsewhere [2,7,8].

3. Test results

The HTS prototype leads consist of an upper, restive part and a lower, HTS part, which are hydraulically separated. Helium gas at 20 K (1.3 bar) cools the resistive part while the HTS element, whose cold end dips into liquid helium, operates in self-cooling conditions using the vapour created by the lead at 4.5 K.

3.1. Resistive heat exchanger

3.1.1. Optimisation

The temperature at the interface between the cold end of the resistive heat exchanger and the warm end of the HTS (T_{HTS}) was specified to be $\leqslant 50$ K. A theoretical optimum shape factor (F_{OPT} = current $\times$ length/cross section) [9] defines the geometry of the resistive heat exchanger which allows to operate the lead with the minimum 20 K helium flow [4]. Operation with higher flows would result in over-cooled leads while operation with lower flows would imply sub-cooled leads with consequent thermal run-away for flows below the critical one. F_{OPT} depends not only on the material properties, as for conventional self-cooled resistive leads, but also on the inlet temperature of the helium gas and on T_{HTS}. Fig. 1 represents the calculated 20 K helium flow rate as a function of F for different values of T_{HTS}. Each isothermal curve corresponds to a fixed temperature T_{HTS}. The F_{OPT} for $T_{HTS} = 60$, 40 and 30 K is represented respectively by the points O^{I}, O and O^{II}. Point D represents an over-cooled lead operating with $T_{HTS} = 40$ K. The change of flow on a lead optimised to operate with a given T_{HTS} (point C if $T_{HTS} = 40$ K) moves the operation point on a colder isothermal curve (point B for higher flow, $T_{HTS} = 30$ K) or on a warmer isothermal curve (point A for lower flow, $T_{HTS} = 60$ K). The reduction of flow and the corresponding operation with higher T_{HTS} are limited by requirement for lead stability against thermal run-away.

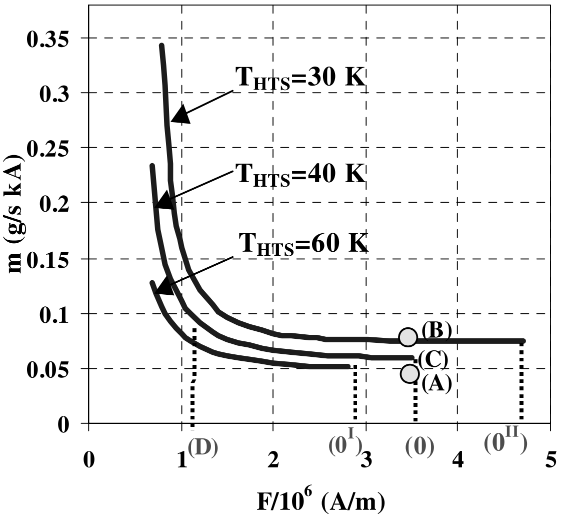

Fig. 1. Dependence of 20 K helium flow from lead shape factor.

The operational temperature of the warm end of the HTS for the LHC current leads has been designed to be 50 K. It corresponds to an optimum both in terms of sensible use of currently available HTS materials (current density and sensitivity to magnetic field) [7] and in terms of cryogenic power consumption (minimum total cooling power) [4,7].

3.1.2. Resistive sections of the 13 000 and 600 A prototypes

The resistive heat exchangers tested in the prototype leads have various configurations. They

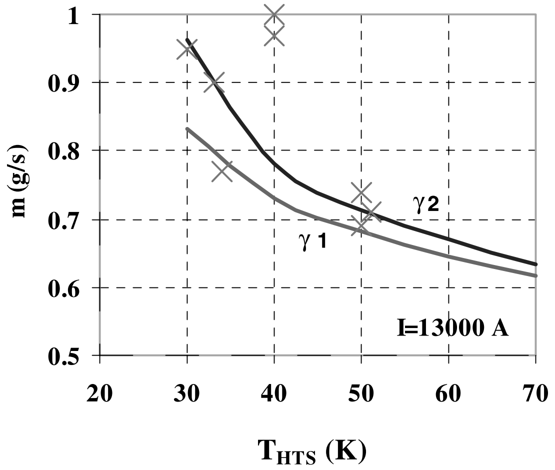

Fig. 2. 20 K helium flow calculated and measured on 8 different prototype leads. For $\gamma 1$ and $\gamma 2$ see text ($\gamma 1 = 1 \times 10^{-7}$ m^2/A^2, $\gamma 2 = 1 \times 10^{-8}$ m^2/A^2).

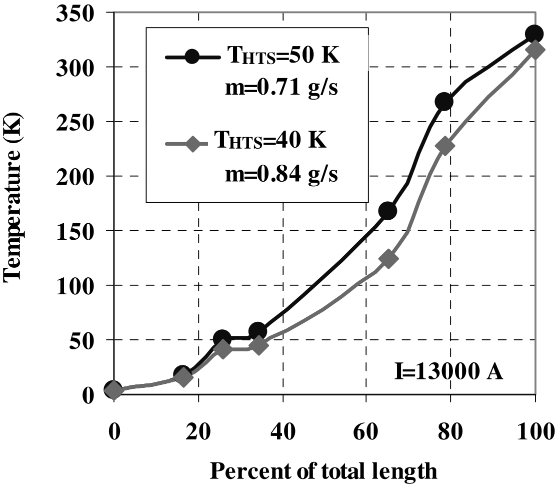

Fig. 3. Measured temperature profile of prototype lead (temperature as function of % of total lead length).

include: cable in conduit conductors, jelly-roll conductors, assemblies of tubes, assemblies of plates, central rods with fins and braids.

In Fig. 2 are reported the results of the measurements performed on eight 13 000 A prototype leads operating, with different T_{HTS}, at nominal current. Among the 10 pairs of prototypes, one pair was never cold tested, due to leak problems detected during the warm measurements, and one did not reach the nominal current. The two curves of Fig. 2 indicate, for two different efficiencies of the resistive heat exchanger, the predicted minimum 20 K helium flow required for running 13 000 A leads optimised for different values of T_{HTS} [4]. The parameters $\gamma 1$ and $\gamma 2$ relate to the efficiency of the resistive heat exchanger ($\gamma \propto (1/D_{eq})^2$, where for laminar flow $D_{eq} \propto k_{He}/h$. D_{eq} is the equivalent diameter of the circuit, k_{He} is the thermal conductivity of the helium and h is the coefficient of heat exchange between the helium and the conductor). As can be seen from Fig. 2, two leads running with $T_{HTS} = 40$ K were over-cooled ($m \approx 1$ g/s). An attempt to reduce that flow by about 10% gave rise to thermal run-away. All the other prototypes required about the minimum predicted helium flow rate. In Fig. 3 is reported, as an example, the temperature profile measured on one prototype, operating at nominal current, in optimum conditions ($T_{HTS} = 50$ K) and in over-cooled conditions ($T_{HTS} = 40$ K). Controlled at 40 K operation, this lead requires a flow (0.84 g/s) that is higher than the optimum of Fig. 1.

In stand-by operation (zero current), T_{HTS} is kept constant by decreasing the flow to a value varying from 0.2 to 0.45 g/s, depending from the material used for the design of the heat exchanger. To avoid condensation, the temperature at the top terminal of the lead is maintained at room temperature by means of thermostatically controlled heaters (about 1 kW power for 13 000 A leads).

The 20 K flow (calculated and measured) for running a 600 A HTS lead is about 30 mg/s.

3.2. The HTS element

A full range of HTS materials were studied in the prototype leads: BSCCO 2223 tapes with various percentages of Au in the Ag alloy matrix (supplied by ASC, NST, Sumitomo, BICC), DIP coated (supplied by OST) and bulk melt cast processed (MCP) BSCCO 2212 (supplied by Nexans), Accordion folding method (AFM) BSCCO 2223 (supplied by Enel) and bulk melt textured (MT) YBCO 123 (supplied by Haldor Topsoe) for the

Table 1
Heat load measured at 4.5 K (13 000 A leads)

Material	T_{HTS} (K)	$Q_{4.5\ K}$ (W/lead)	
		0 A	13 000 A
Bi-2223 tapes	50	0.88	0.95
Bi-2223 tapes	50	1.16	1.74
Bi-2212 MCP	50	1.15	1.3
Bi-2223 AFM	40	1.62	1.68
Bi-2223 tapes	40	0.64	0.715
Bi-2223 tapes[a]	40	1.11	–
Y-123 MT	30	0.75	0.95
Bi-2212 DIP	30	0.82	1.3
Bi-2223 tapes	30	0.81	1.1

[a] 13 000 A not achieved.

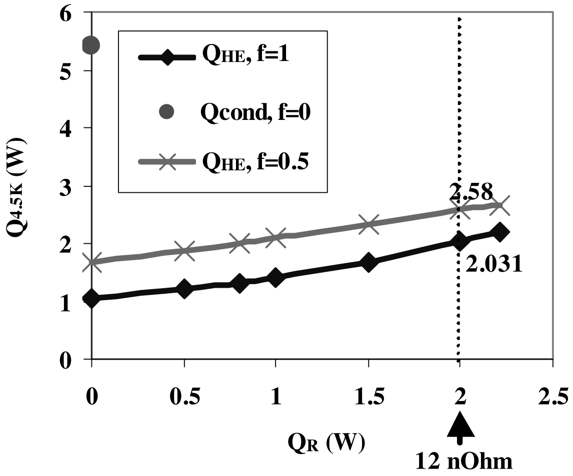

Fig. 4. Heat load at 4.5 K as a function of power dissipation of cold joint of HTS.

13 000 A prototypes. In addition, in the 600 A prototypes bulk Ceramo Crystal Growth (CCG) YBCO 123 (supplied byATZ) and Laser Floating Zone (LFZ) BSCCO 2212 fibres (supplied by the University of Saragoza) were tested. The results of the measurements on the 13 000 A samples are summarised in Table 1.

As can be seen in Table 1, the heat load into the helium bath does not depend on the type of HTS material chosen for the design of the lead. Taking into account that a conventional 13 000 A self-cooled lead would conduct about 14.3 W to the 4.5 K bath [9], a reduction in this heat load of up to a factor of 20 has been measured for these HTS leads. Moreover, all these HTS elements included the metal stabiliser required to satisfy quench protection requirements (circuit time constant of 120 s).

The heat load measured at nominal current includes both the thermal conduction from T_{HTS} to 4.5 K and the ohmic dissipation of the cold joint between the HTS and the low temperature superconductor. For such high current ratings, a contact resistance of few nΩ must be assured to avoid spoiling the thermal performance. Resistances lower than 2 nΩ, at 13 000 A and 4.5 K, have been measured on several prototypes and thus proved to be achievable. The calculated heat load into the helium bath ($Q_{4.5\,K}$) for a 13 000 A (BSCCO 2223) prototype as a function of the power (Q_R) dissipated by the cold joint contact resistance is shown in Fig. 4. In conduction cooling conditions, the heat load (Q_{COND}) at zero current ($Q_R = 0$ W) would be of the order of 5.4 W; with self-cooling, this heat load can be reduced to values of the order of 1 W, depending on the efficiency, *f*, of heat exchange. The static heat load measured on that prototype is about of 1.2 W and, as can be seen in Fig. 4, the heat load due to Joule heating in the joint cannot be simply added to the heat load due to thermal conduction at zero current. The enhanced gas cooling reduces the input due to conduction and also the expected total power dissipation. Thus the use of helium gas for cooling the HTS element has the clear advantage of both reducing the static heat load and reducing the effect of higher contact resistance.

The same considerations are valid for the 600 A prototype leads, the test results of which are summarised in Table 2.

3.3. Control of 20 K helium flow

The 20 K helium flow rate is regulated by a warm valve controlled by a temperature sensor integrated at the warm end of the HTS. In Fig. 5 is reported the measured time dependence of T_{HTS} and 20 K helium flow during a ramp to 13 000 A (ramp rate = 50 A/s). T_{HTS} is set equal to 50 K.

Table 2
Heat load measured at 4.5 K (600 A leads)

Material	T_{HTS} (K)	$Q_{4.5\ K}$ (W/lead)	
		0 A	600 A
Bi-2223 tapes	50	0.079	0.092
Bi-2223 tapes	50	0.085	0.085
Bi-2223 tapes	50	0.072	0.079
Bi-2223 AFM	50	0.099	0.1
Bi-2212 fibers	50	0.17	0.21
Y-123 CCG[a]	50	0.23	0.38
Bi-2212 MCP	40	0.089	0.11
Y-123 MT[b]	40	0.1	0.11
Bi-2223 tapes	40	0.09	0.1
Bi-2212 DIP	30	0.053	0.078
Bi-2223 tapes	30	0.07	0.07

[a] Test of two leads: one cold joint deteriorated.
[b] Test of two leads: one HTS sample broken.

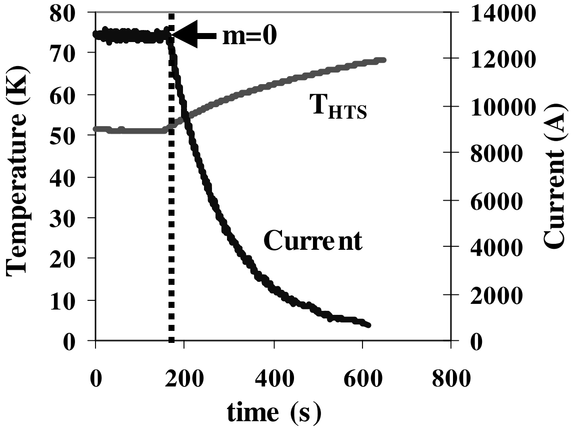

Fig. 6. Increase of T_{HTS} during a 20 K helium coolant loss measurement.

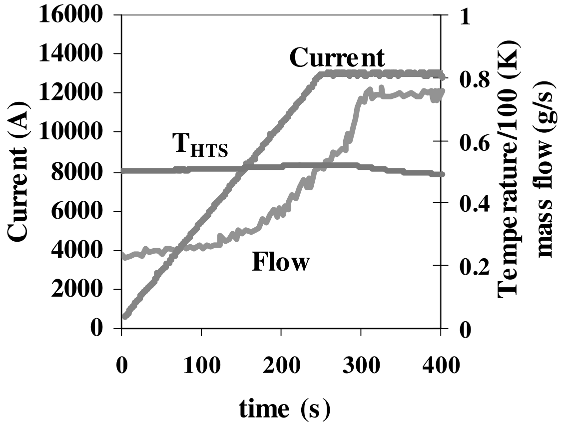

Fig. 5. Measured time dependence of current, T_{HTS} and 20 K helium flow during a ramp from 0 to 13000 A, with temperature control of the helium flow.

The response of the flow is perfectly adequate: T_{HTS} stays constant while the flow increases, during the ramp, up to the nominal value (0.76 g/s).

3.4. Transient measurements

Quench measurements have been performed on all the prototype leads. The HTS elements were brought to critical temperature by warming up the HTS warm end via heaters integrated on the leads for this purpose. Most of the prototypes had critical temperatures above 80 K. Voltages up to 0.25 V have been measured without degradation of the HTS characteristics [10].

Measurements of 20 K coolant loss have been performed on all the prototype leads (Fig. 6). After having closed the 20 K helium supply valve, the current was made to decay exponentially with the time constant of the LHC electrical circuit. In all the prototype leads, T_{HTS} stayed below the critical value during this transient.

Most of the prototypes have undergone up to 4 complete thermal cycles, from room temperature to operating temperature, and up to 100 electrical cycles. No degradation has been measured on the prototype leads.

4. Conclusion: lessons from prototype tests and challenge for the series production

The extensive work carried out on prototype leads has endorsed the predicted design parameters such as size of the lead, thermo-electrical optimisation, and the cryogenic and electrical performance of both the resistive and the HTS parts. It has also allowed to acquire experience with the operation of this equipment and to gain confidence in the HTS material performance by addressing such problems as quench protection of the HTS element and resistance of joints. Six 13 000 A and seven assemblies of four 600 A prototype leads are now integrated in the String 2 test facility, a full size model of the LHC cell where the leads will power dipole, quadrupole and corrector magnet electrical circuits.

The work performed on each different prototype (some of them were delivered and repaired several times) has allowed to identify critical parts in the engineering design of the lead, leading to technical solutions to be integrated in the LHC HTS current lead design for the series production [11]. Requirements of compactness and ruggedness have been emphasised in the lead design. Regarding the resistive part, the choice has converged on a fin-type heat exchanger, which offers a big surface of heat exchange, thermal stability in transient operation and simple electrical connections at its extremities. For the HTS part, BSCCO 2223 in a silver–gold matrix appears to be the most suitable material in view of its good thermal performance, established quality control procedures associated with industrial scale production and the facility of making low resistance joints. Moreover, current by-pass in the event of a resistive transition is ensured by the metal alloy matrix, which makes for an inherently reliable design. Leak tight plugs providing electrical insulation, which were a source of problem in the prototype tests, have been replaced by welded, brazed or soldered joints. The number of electrical joints have been minimised both in the resistive and HTS parts.

A technical specification based on a CERN reference design will be issued toward the end of 2001. The present LHC layout (machine optics version 6.3) calls for 64 × 13 000 A, 310 × 6000 A and 750 × 600 A HTS current leads. The delivery of the leads of the corresponding three series will have to conform to the LHC installation schedule which presently foresees the start of integration into the final cryostats in 2003. Everything is due to be installed by the end of 2005.

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