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*Large Hadron Collider Project*

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# 13000 A HTS CURRENT LEADS FOR THE LHC ACCELERATOR: FROM CONCEPTUAL DESIGN TO PROTOTYPE VALIDATION

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This report summarizes the conceptual design of the lead and the technological choices made for the different parts of the lead assembly. Particular attention is given to the HTS component on which the results of thermal, electrical, soldering and impregnation tests are reported.

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# 13000 A HTS Current Leads for the LHC Accelerator: from Conceptual Design to Prototype Validation

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## 1. Introduction

The LHC machine includes 1232 main bending dipole and 393 focusing and defocusing quadrupole magnets operating at currents of up to 13000 A. These magnets are connected in series strings, giving in total 24 electrical circuits, 8 for the main dipole and 16 for the quadrupole magnets, the focusing and defocusing units being separately powered to allow flexibility of tuning and optics [1]. These 24 electrical circuits together with the energy extraction systems at the centre of the dipole circuits will require in total sixty-four 13000 A leads transferring all together a current of more than 800 kA.

After a R&D program culminating in the test of various HTS materials and 13000 A HTS prototype leads [2] CERN has designed, assembled and tested in-house a pair of 13000 A HTS current leads. The work was done to validate design and technological choices prior to launching the industrial production of the 64 series components.

This report summarizes the conceptual design of the 13000 A HTS lead, the technological choices made for the different parts of the lead assembly and the first test results.

## 2. Conceptual design

The lead operates in a temperature range between room temperature and the saturated liquid helium bath. It consists of a resistive section, convection cooled by helium gas available in the LHC machine at a nominal temperature of about 20 K, and a superconducting section, self-cooled by the vapour generated by the heat conducted by the lead itself at 4.5 K. The two circuits are hydraulically separated. The warm end of the superconducting section is maintained at 70 K in stand-by operation and about 50 K in operation with current [3].

### *2.1. Normal conducting section*

Analytical models are available in the literature for the optimization of conventional self-cooled leads [4]. They use simplifying assumptions such as: ideal heat transfer between the lead and the gas or finite heat transfer expressed by a constant parameter of efficiency and Wiedemann-Franz law or constant thermal and electrical properties for the conductor. These models give acceptable solutions for the sizing of the conductor provided a sufficient surface of heat exchange is ensured in the final design. The self-sustained condition, which links the heat conducted into the liquid bath to the mass flow cooling the lead, is adopted and used for the optimization of the geometry: the heat conducted into the bath is minimized to reduce the cooling load of the refrigerator. The correspondent temperature profile of the conductor has zero derivative at room temperature.

All these assumptions are not valid for a gas-cooled lead. The helium mass flow is a variable and the inlet temperature of the gas is not identical to that of the lower end of the lead. Moreover, the resistive conductor operates over a range of temperature, above about 50 K, where the various grades of copper have similar and strongly temperature dependent thermal conductivity and electrical resistivity.

The resistive part of the 13000 A HTS lead consists of a fin-type copper alloy heat exchanger. This choice was linked to optimization of the mechanical design [5].

The optimum thermal and electrical performance was initially calculated by solving numerically a system of three differential equations expressing respectively the derivative with respect to length of the copper temperature, of the gas temperature and of the heat conducted along the lead. These equations are derived from the steady state, one-dimensional, heat balance equations between the lead and the helium gas. Boundary conditions are the temperature at the bottom of the heat exchanger, the inlet temperature of the gas and the heat conducted to the lower end. The temperature dependence of the properties of helium and copper was taken into consideration. For the convection heat transfer coefficient in laminar flow, the relation Nu = 3.8 was adopted, where Nu is the Nusselt number.

A parametric study has shown that in the gas cooled configuration there is also an optimum geometry of the conductor represented by an optimum shape factor (length times current divided by cross section). The corresponding minimum helium mass flow rate gives a copper temperature profile having room temperature and a zero derivative at the top of the lead. For a fixed temperature of the inlet gas, the shape factor increases when the temperature at the bottom of the heat exchanger decreases. This model enables us to calculate the optimum shape factor of the lead, the minimum mass flow rate and the characteristic of the hydraulic circuit.

A two-dimensional model was also made to optimise the geometry of the fins.

Two heat exchangers were considered in the calculations made using copper with RRR = 30 and copper with RRR = 90 (RRR is the ratio between the electrical resistivity at room temperature and liquid helium temperature). It was determined that for a length of 0.5 m and a current of 13000 A, the current carrying cross section should be 890 $mm^2$ and 730 $mm^2$ respectively. The voltage drop at maximum current is 55 mV. The corresponding helium mass flow rate is 0.7 g/s. In stand-by operation, the resistive section requires a flow rate of 0.22 g/s for a temperature range between 70 K and room temperature, provided a power of 360 W is supplied at the top of the lead and exchanged with the helium gas. This is necessary to prevent condensation and ice formation at the top of the lead in operation with zero current.

### *2.1.1 Control of flow*

A valve controlled by a temperature sensor incorporated into the lower end of the copper heat exchanger regulates the helium flow cooling the normal conducting section. This temperature sensor also indicates the temperature of the warm end of the HTS element.

The lead is optimised for a performance corresponding to an inlet temperature of the helium gas of 20 K and a temperature at the warm end of the HTS element maintained, at any current, at a set temperature equal to 50 K. These are the nominal parameters for most of the HTS leads in the LHC machine. However, as the inlet temperature of the nominally 20 K helium gas depends on the position in the LHC ring, varying between 4.5 K to 20 K, it is necessary to adapt the set points of the temperature at the top of the HTS section [3]. A reduction of flow rate due to a decrease of inlet temperature of the helium gas can create a thermal run-away of the resistive part. The temperature set point is therefore adjusted to be between 30 K and 50 K for a gas inlet temperature varying between 5 K and 20 K.

### *2.2. Superconducting section*

The superconducting section consists of 36 stacks, 350 mm long, each containing 7 BSCCO 2223 tapes.

The multi-filamentary tapes for the prototypes were purchased from American Superconductor. In order to limit the heat conduction the tapes, which are about 4 mm wide and 0.2 mm thick, feature a silver alloy matrix having 5.3 wt % of gold. The critical current of the tape was ≥ 75A at 77 K and in self-field (1 μV/cm criterion).

The tapes are soldered into stacks. The stacks are supported on a stainless steel cylinder. The cylinder has copper terminals brazed at both ends, and the stacks are soldered into longitudinally machined grooves. The cylindrical geometry was chosen to orient the self-field parallel to the tape surface. This self-field component is 49 mT at 13000 A.

The reduction in critical current of a stack, at 77 K, due to its own magnetic field was calculated to correspond to about 18 % of the current obtained by multiplying the number of tapes times the critical current of the tape in its own self-field. Critical currents of about 726 A (77 K, self-field) were measured on stacks of 7 tapes having each an average critical current of 126 A (77 K, self-field).

The total cross section given by the silver alloy of the tapes and the stainless steel support provides the stabilizer necessary to by-pass the current in case of a resistive transition of the HTS element. The cross section of the stabilizer matches the requirements of the magnet chain powered by the leads, whose longest time constant, corresponding to the dipole circuit, is 120 s. The discharge of the magnets is assumed to start when the voltage across the HTS part reaches 3 mV.

The heat load into the 4.5 K helium bath was calculated to be ≤ 1.5 W/lead at nominal current. At their lower end the stacks are soldered to Low Temperature Superconducting (LTS) wires. On the basis of the design, a contact resistance between the HTS and the LTS of 2 nΩ, at 4.5 K, was assumed as a feasible low-resistance value.

## 3. Prototype manufacture and assembly

A pair of 13000 A HTS prototype leads were manufactured and assembled at CERN. As mentioned above, the two leads incorporate respectively a heat exchanger made from copper with RRR = 30 and a heat exchanger made from copper with RRR = 90.

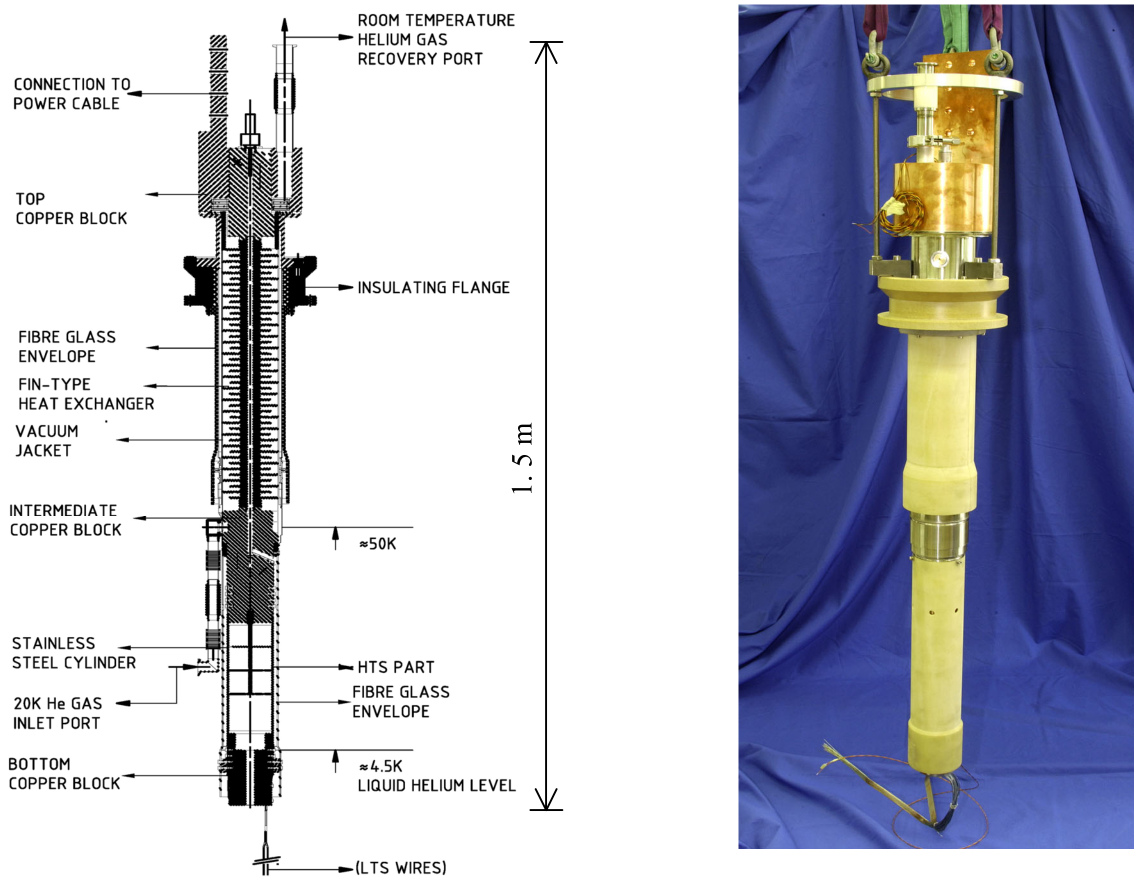



**Figure 1.** 13000 A lead schematic and prototype

The assembly of the lead involves a sequence of vacuum brazing, vacuum soldering, electron-beam and TIG welding procedures the good quality of which is essential for the success of the lead design. These operations were performed at CERN.

The lead consists of three main sub-assemblies: a top copper block, the fin type heat exchanger with its vacuum jacket and the superconducting section.

### *3.1. Normal conducting section*

The normal conducting includes the fin-type heat exchanger made from copper of measured RRR. In order not to change with heat treatments its thermal and electrical properties, properties which were used as input in the calculations, the electron beam welding method has been chosen to join the top copper block and the superconducting part.

The top copper block is made of OFE copper with stainless steel inserts assembled by vacuum brazing using silver-based, low vapour pressure brazing alloys. It contains also a heat exchanger made of punched thin copper plates assembled by vacuum diffusion brazing.

### *3.2. Superconducting section*

The superconducting section consists of a rigid support and superconducting stacks and wires. The support comprises two copper blocks and a stainless steel cylinder at the extremities of which the copper blocks are vacuum brazed. This supporting unit features

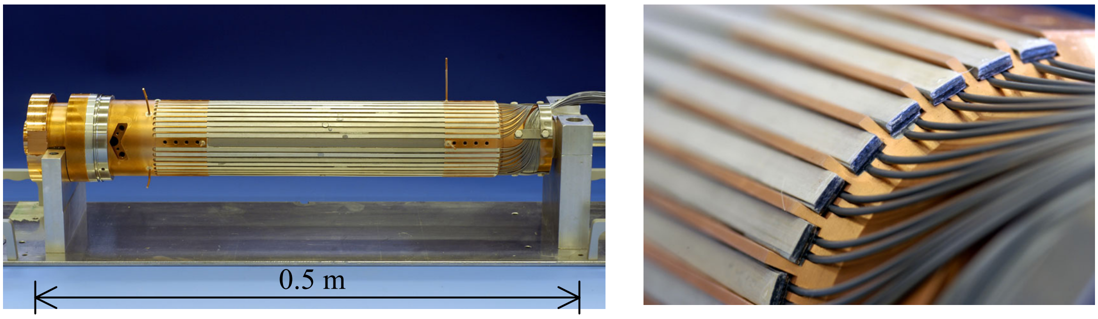



**Figure 2**. 13000 A superconducting part

grooves onto which the stacks and the LTS wires are positioned and vacuum soldered. The solder alloy used is Sn-Pb37 eutectic.

Vacuum soldering was chosen to avoid use of flux, to provide gradual and homogeneous heating of the superconducting part and to guarantee cleanliness of the result. Abrasive cleaning procedures were avoided to prevent damaging of the stacks. The maximum temperature reached on the stacks during soldering was 200 °C for about 15 minutes. The duration of the adopted heating cycle has shown not to create prejudicial effects such as dissolution of base material into the solder. The grooves machined in the stainless steel tube are copper-plated before soldering the stacks. The quality of the joint between stacks and copper and between stacks and LTS wires was found to be good.

To assure current sharing in case of resistive transition of the HTS element, the stacks are vacuum soldered on the supporting unit over the whole length.

### *3.2.1 Stack preparation*

The use of stacks instead of tapes facilitates the final assembly of the superconducting part and the handling of the HTS conductor. Stacks of sintered tapes were initially considered as a valid option. Micrographs performed on some sintered stacks (see Figure 3) have shown that micro-cracks can propagate through the superconducting filaments during the sintering operation and empty spaces can be present at the interface between the tapes. While the first problem was not drastically compromising the critical current of the stacks initially, there was a fear that cracks might propagate in time; the second problem was also considered as a possible cause for degradation of the electrical contact at the interface between the stacks and the copper end-caps or LTS wires.

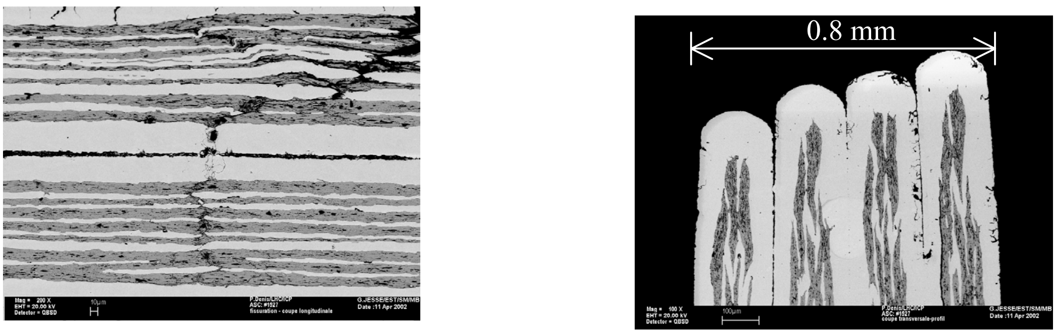



**Figure 3.** Micrographs performed on sintered stacks of 4 tapes

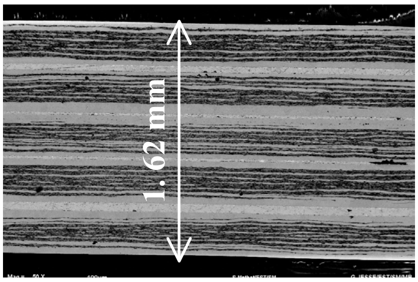



**Figure 4.** Micrograph performed on a vacuum soldered stack of 5 tapes

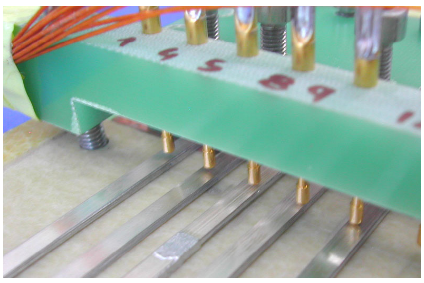
It was therefore decided to make the stacks by soldering the tapes together. This work was done at CERN. As for the assembly of the stacks and the LTS wires onto their supporting unit, vacuum soldering technology was adopted. The solder alloy chosen was Sn-Ag3.5 eutectic. Tapes with interleaved foils of this solder were positioned in grooves machined in graphite blocks and compressed with a uniform pressure of about 150 g/cm$^2$. A peak temperature of 240 °C was maintained during about 15 minutes. The average thickness of the stacks after soldering was 1.62 mm. Microscopic analysis made after soldering have confirmed the good quality of the contact between the tapes (see Figure 4).

*3.2.2 Electrical characterization*

Each tape soldered in a stack and each stack integrated in the leads was electrically measured in a saturated liquid nitrogen bath. Tooling was built to measure the critical current of 10 tapes or stacks in series. To avoid soldering to HTS conductor, the electrical contacts at the ends were clamped. The voltage taps were spring-loaded needles fixed to a removable glass fibre structure and positioned on the HTS conductors, at their two extremities, after assembly of the conductors to a supporting tooling (see Figure 5). The minimum critical current of the stacks was 450 A at 77 K and in self-field (1 μV/cm criterion).

*3.2.3. Thermal conductivity measurements*

The thermal conductivity of the tapes and of the stacks was measured at CERN in a dedicated test set-up using the static measurement method [6]. The sample is inserted in a vacuum chamber that is immersed in a saturated liquid helium bath. While one extremity of the sample is maintained, via a heater, at a fixed temperature, which can vary from 5 K to about 70 K, a heat source is applied to the other extremity. Thermocouples, fixed on the sample, measure the temperature difference induced by the heat flow across a measured length. A temperature difference of the order of 0.03 K was found to be appropriately adapted to the resolution of the measurement set up.



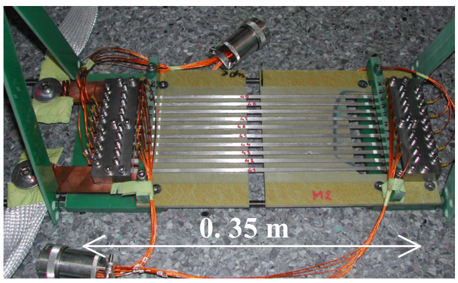



**Figure 5.** Tooling for electrical characterization of HTS tapes and stacks

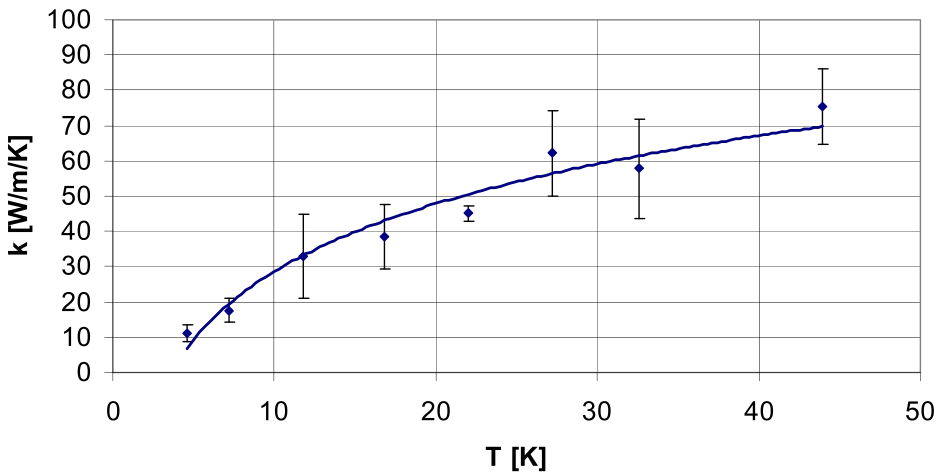



**Figure 6.** Thermal conductivity measured on a vacuum-soldered stack of 7 tapes

The thermal conductivity value is deduced from the Fourier law of heat conduction. In Figure 6 the value of thermal conductivity (k) measured on a stack of 7 tapes as a function of temperature (T) is reported.

*3.2.4. Protection against ballooning*

To protect the HTS part against the "ballooning effect" [7], due to penetration of liquid cryogen through the silver alloy matrix, the superconducting part of the lead was vacuum impregnated at room temperature with a layer, about 20 µm thick, of Parylene® C coating. The impregnation takes place after vacuum soldering of the stacks and of the LTS wires to the supporting structure.

Microscopic analysis [8] performed on samples which were coated with Parylene® C and than submitted to 30 thermal cycles from liquid helium and liquid nitrogen to room temperature have shown that the polymer bonds with a uniform layer to the tape surface. Some samples were left several hours in a helium bath, warmed up to room temperature and then tested electrically to confirm impermeability of the coating. No "ballooning effect" was observed on coated conductors.

## 4. Validation of thermal and electrical performance

The two prototype leads have been tested in nominal operating conditions.

The leads were connected in series and powered up to 13000 A. At 13000 A, for a helium inlet temperature of about 10 K and a temperature at the top of the superconducting section of about 40 K, the helium flow rate necessary to operate stably the normal conducting section was 0.64 g/s. The corresponding pressure drop was of the order of 20 mbar. The total voltage drop across the fin type heat exchanger was 55 mV. The top part of the lead was stable at room temperature without the need of additional heating, which proves that the heat exchanger was correctly dimensioned. The contact resistance between the HTS section and the LTS wires was measured to be < 1.5 nΩ. The heat load in the helium bath was measured to be < 1 W/lead.

In stand-by operation the mass flow required to operate the normal conducting part between 70 K and room temperature was about 0.24 g/s. Cartridge heaters integrated in the top copper block of the lead were able to maintain the temperature of the copper and of the gas at about 300 K. No condensation was observed at the top of the lead.

The measurements have shown that performance of the heat exchangers made from copper with different RRR were similar.

Transient measurements have proved that the HTS element is able to withstand a resistive transition followed by a discharge at the nominal current decay rate without exceeding a maximum voltage of 10 mV.

The effect of fast neutron irradiation on current transport properties of the tapes has also been studied in a dedicated set-up and is presented elsewhere [9].

## 5. Conclusion

Thermal, electrical, soldering and impregnation tests have been performed on BSCCO 2223 tapes to validate performance and assembly procedures. A pair of 13000 A HTS leads has been successfully designed, assembled and tested at CERN. The tests in nominal operating conditions have confirmed the calculated performance. On the basis of this work, a call for tenders has been issued to European companies for the construction of the series components. The 258 HTS leads for powering the insertion dipole and quadrupole magnets of the LHC machine at about 6000 A are of a similar design.

The BSCCO 2223 tape for all the HTS leads, about 30 km in total, is being purchased by CERN. The stacks for the complete series of leads will be manufactured at CERN and supplied to the lead manufacturer.


## Aknowlegments

The realization of the prototype leads has involved several activities performed at CERN. The authors wish to thank the Main Workshop and in particular D. Valero' and J.M. Geisser for the coordination of the mechanical activities, J. Favre, Th. Tardy and J.P. Brachet for the welding and the optimisation of the welding parameters. The electrochemistry & surface treatments experts made an excellent job on the surface treatments involved in different phases of the lead assembly. Microscopic analysis was made by the metallurgy team. The cryogenic measurements were performed with the able collaboration and support of R. Van Weelderen, L. Metral and V. Fontanive. The detailed drawings have been handled professionally by Th. Strauli and F. Roqua. And last but not least we wish to thank P. Chambouvet and L. Poyet for their untiring support in the search for practical solutions, in the participation in prototype assembly and in the performance of numerous tests.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