EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH
European Laboratory for Particle Physics

Large Hadron Collider Project

LHC Project Report 691

CONDUCTION-COOLED 60 A RESISTIVE CURRENT LEADS FOR LHC DIPOLE CORRECTORS

A. Ballarino

Abstract

The powering of the LHC close orbit dipole corrector magnets will be made via 752 electrical circuits rated for a maximum current of 60 A. A total number of 1504 current leads will transport the current, through the cryostat main vacuum insulation, from room temperature to the 1.9 K superfluid liquid helium bath. This report summarizes the lead's optimisation principle, including the cooling method and the choice of material, as well as the integration issues and the results of the measurements performed on prototype leads manufactured and assembled at CERN.

Accelerator Technology Department

CERN
CH - 1211 Geneva 23
Switzerland

Geneva, 5 March 2004

1. Introduction

Conventional low current self-cooled leads, with optimised thermal and electrical performance, are well-known, commercially available, components. They can be integrated in any system that provides as boundary conditions: a path preferably straight from the ambient temperature environment down to the liquid helium bath, an active system to control the helium gas cooling the lead and a recovery line to collect the warm gas escaping at the top of the lead. The use of conduction-cooled leads becomes attractive if any of these constraints do not represent the optimum choice for the system within which the leads must operate. In the LHC machine, the operation of 1504 self-cooled leads rated for a maximum current of 60 A would require kilometres of piping and more than a thousand control valves. In addition, the leads will be integrated in a cryostat where stringent space constraints dictate the need of a flexible and compact design.

The drawback of a conduction-cooled lead design is the higher heat load into the cryogenic system. A conventional optimized self-cooled lead conducts into the helium bath about 1.1 W/kA while an optimized conduction-cooled lead conducts, from room temperature down to the 1.9 K liquid helium bath, about 46 W/kA.

For the 60 A LHC dipole corrector leads, the design of intermediate heat sinks and a proper optimisation of the conductor's geometry and material allow reducing the 46 W/kA by a factor of about 16, satisfying the cryostat's thermal and geometrical constraints and profiting from the economic savings associated with the conduction-cooled design.

2. Conduction-cooled leads

Wiedemann and Franz observed that at a given temperature the ratio of thermal (k) to electrical (σ) conductivity is approximately the same for all metals. Lorentz extended this to a finding that at not too low temperatures this ratio is directly proportional to the thermodynamic temperature, the constant of proportionality being fairly independent of the particular metal. The relation is in agreement with the quantum theory of thermal and electrical conductivity [1], which, under certain assumptions, yields:

$$L_0 = \frac{k}{\sigma T} = \frac{\pi^2}{3}\left(\frac{k_B}{e}\right)^2 = 2.443 \cdot 10^{-8}\left[\frac{W\Omega}{K^2}\right] \tag{1}$$

k_B = Boltzmann constant
e = electron charge
L_0 = Lorentz number

The above expression is usually referred to as Wiedemann-Franz (WF) law and an ideal metal that follows it exactly is referred to as WF metal. The assumptions which lead to this simplified formulation are that the electronic contribution dominates the phonon conduction in the heat conduction, and that the collision averages are the same for the electrical and thermal conductivities. The first of these assumptions is not valid for impure metals and disordered alloys and the second is invalid at low temperatures (< 100 K).

The mono-dimensional heat balance equation for a conduction cooled lead made of a WF metal is easily solvable and, despite its limitations, is often used in elementary analysis and provides a useful benchmark. An optimised lead of this type, designed to carry a current

(I) from room temperature (T_W) to cold temperature (T_C) has a minimum heat-inleak at the cold end of:

$$Q = I \cdot \sqrt{L_0 \cdot \left(T_W{}^2 - T_C{}^2\right)} \qquad [W] \tag{2}$$

This heat in-leak is independent of the material and corresponds to an optimum ratio of length to cross-section of the conductor, which depends on the material's properties [2]. For T_W = 293 K and T_C = 1.9 K, the heat load is 46 W/kA. Each of the 1504 dipole corrector leads needs to pass 60 A on a continuous basis, and the corresponding heat load of 2.8 W is more than 40 times that of a standard self-cooled lead recovering the boil-off vapour. This was considered to place an unreasonable load on the cryogenic system.

For the purpose of this study the heat balance equation was solved for various materials using tabulated thermal and electrical properties as a function of temperature [3]. An idea of the differences which are revealed by this more accurate evaluation is given in Table 1. The heat load at zero current (Q_{0A}) was calculated for a lead 1.4 m long optimised for carrying 60 A. To reduce the heat load, there is an interest in choosing a material whose function $k(T)\cdot\rho(T)$, where ρ is the electrical resistivity, stays below $L_0\cdot T$ (see Fig. 1).

MATERIAL	**Q_{min} [W/kA]**	**Q_{0A} [W]**
Al 1100	40.72	1.71
Cu RRR = 300	43.5	2.11
Cu RRR = 20	44.12	1.8
WF	46	-
Cu85-Zn15	50.4	1.82
Stainless steel	60.55	2

Table 1. Minimum heat load (Q_{min}) at 1.9 K

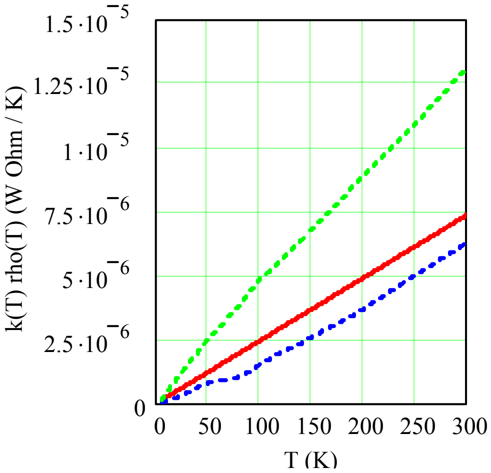

Fig. 1. $k(T)\cdot\rho(T)$ for: stainless steel (top), WF material (middle) and Al 1100 (bottom)

Clearly, while the choice of material is important, this alone does not enable to reduce significantly the heat load into the liquid helium and other measures are called for.

3. Conduction cooled leads with intermediate heat sinks

In the LHC machine, the helium gas in the lines C’ and E, used for the cooling of the beam screen and of the thermal screen, makes it possible to intercept the heat at 4.5-20 K and 50-75 K. The heat load into the 1.9 K liquid helium bath can therefore be reduced by intercepting the heat at these intermediate temperature levels. In this case the lead shall ideally be optimised in each of the three temperature intervals 293 K→50-75 K, 50-75 K→4.5-20K, 4.5-20 K→1.9 K. The optimum ratio of the length to the cross section is different in each of the three temperature intervals, because the material properties and extreme temperatures are different. Moreover, the intermediate lengths are imposed in practice by the space available in the cryostat. In order to achieve low heat inleak, the cross section of the lead should therefore change along its length.

A significant reduction in heat load cannot be obtained, for safe operation, by optimising the lead geometry for operation without heat sinks and simply adding heat intercepts for reducing heat inleaks. In such a lead, which is over-dimensioned toward the cold end, the thermal performance is poor since it is dominated by the heat conduction at zero current. For example, a 60 A lead made of Cu with RRR = 20 and 1.4 m long, which is the physical length available in the LHC cryostat, has a diameter of about 5 mm when optimised for operating without heat sinks. It would conduct about **2.64 W** at 60 A and **1.8 W** in stand-by operation at 1.9 K. If a 20 K heat sink is introduced into such a design, the conduction into the bath at zero current is reduced to **0.45 W**. This value depends on the length of the conductor and was calculated for 0.3 m, which is the maximum length achievable for the 20-1.9 K interval in the LHC cryostat and adopted for the final design of the lead.

To reduce the heat load into the helium bath to the given budget of less than 0.1 W/lead in stand-by operation [4], it is necessary to have both heat sinks and a conductor cross-section variable along its length. In this way, it is possible to profit from the increased current carrying capacity of the material at lower temperatures and, as mentioned above, optimise the lead geometry and thermal performance between each intermediate temperature level. In the same way that a self-cooled lead must be protected in case of a problem with the helium flow, such a lead will require protection in case that a heat sink becomes inoperative.

4. Conductor

4.1. Impact of material properties

The increase in current density from the top to the bottom of the conductor due to a variable cross section improves the thermal performance but it has a number of drawbacks that strongly compromise the lead design: lead stability in case of thermal run-away and efficiency of the heat sinks. The diameter of a tapered copper lead (Cu RRR = 300) optimised for operating at 60 A decreases from 3.6 to 0.68 mm. The thermal performance, calculated assuming perfect heat sinking at 50 K and 20 K, is summarized in Table 2 for Cu with RRR of 300 and 20. The diameters of the top warm and bottom cold part of the lead are respectively $\phi 1$ and $\phi 2$.

Material	Q_{60A}50K [W]	Q_{60A}20K [W]	Q_{60A}1.9K [W]	Q_{0A}1.9K [W]	ϕ1 [mm]	ϕ2 [mm]
Cu RRR = 300	2.58	0.34	0.19	0.09	3.6	0.68
Cu RRR = 20	2.6	0.38	0.2	0.088	3.9	2.3

Table 2. Thermal performance of a lead made from a tapered copper conductor

The study of the thermal run-away consequent to the loss of a heat sink shows that the high purity copper lead is highly unstable. In the case of Cu with RRR = 300, the lead reaches a peak of temperature of about 700 K in about 2 minutes. Clearly with a lower RRR the transients become longer: in the case of Cu with RRR = 20, the lead reaches room temperature in about 15 minutes.

The insulated conductor is contained in a thin stainless steel tube, which provides the separation between the liquid helium and the cryostat main vacuum insulation environment. The thermalization is made by clamping the lead to the two heat sinks. The clamping crimps the tube (see section 5) to provide good heat transfer by thermal conduction from the conductor to the heat sink. The tapered solution described above would require a tapered stainless steel tube, with a consequent complication of the design and increase in price of the component.

Alloys such as Constantan (Cu57-Ni43), Cupro-Nickel (Cu60-Ni10), Manganin (Cu84-Mn12-Ni4), Silicon bronze (Cu96-Si3-Zn1), ordinary brass (Cu63-Zn37), stainless steel and Al 2024 have been examined for this current lead design, but because of their high electrical resistivity and consequent larger cross section of the conductor, have been excluded in view of the cryostat's space constraints and of the requirements of flexibility and shaping.

4.2. Material choice

To achieve low heat losses into the cryogenic environment and guarantee the stability of the component in transient operation, a hybrid conductor has been investigated and chosen. It consists of a copper plated brass rod (red brass, Cu85-Zn15): the brass has a constant diameter while the copper thickness of only few 1/10 of mm decreases along the length. The advantages of this solution are the following:

- an almost constant conductor cross section in which the copper, which carries the current in nominal operation, produces a low heat in-leak while the brass, which is a poorer thermal conductor, acts as a support for the copper without compromising the global thermal performance,
- good stability thanks to the presence of the brass which performs as a shunt in case of thermal run-away,
- a constant diameter for the insulating sheet and the stainless steel tube thanks to the small variation in the external diameter of the conductor's cross section providing also a suitable diameter for clamping.

The hybrid conductor has an equivalent thermal conductivity and electrical resistivity $k_{eq}(T)$ and $\rho_{eq}(T)$ that are a function not only of the copper and brass properties but also of the ratio of copper to brass in total cross section. The product $k_{eq}(T)\cdot \rho_{eq}(T)$ can be tuned along the conductor's length by changing this ratio. The effective RRR of the conductor changes from the top to the bottom of the lead.

The values of $k_{eq}(T)\cdot\rho_{eq}(T)$ for a 3 mm brass rod copper plated, with a ratio copper cross section to brass cross section equal to 1.56 in the top half part and 0.152 in the bottom half part of the lead, stay below those pertaining to a WF material (Fig. 2). The thermal performance of such a lead design is summarized in Table 3. The heat load can be tuned to be slightly better than the one obtained for the tapered optimised lead reported in Table 2.

	Q 50K [W]	**Q 20K [W]**	**Q 1.9K [W]**
I = 0 A	1.6	0.13	0.085
I = 15 A	1.63	0.15	0.09
I = 30 A	1.75	0.24	0.11
I = 60 A	2.48	0.28	0.17

Table 3. Thermal performance of the hybrid conductor

In case of a thermal run-away, created by the malfunctioning of the two heat sinks, the performance of the hybrid conductor is strongly influenced by the presence of the brass. The temperature profile developed along the lead during such a transient is shown in Fig. 3. At 60 A, which is the maximum current the lead has to transport, the conductor reaches room temperature after about 1 hour. Unlike a conventional self-cooled lead, the peak of temperature is localised in the lower part of the lead, where the lead's cross-section is smaller. At 25 A, the lead takes about 7 hours to reach a maximum temperature of about 340 K while at 18 A the lead can operate stably, with no heat sinks, without overheating. These considerations are important in view of the fact that it is estimated that the average current in a corrector magnet will be about 15 A and that in a normal run about 2/3 of the magnets will be operating at less than this current. The long time constants simplify the protection of the circuit against heat sink failure.

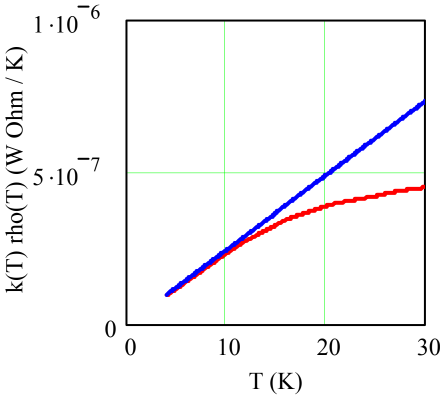

Fig. 2. k(T)·ρ(T) for: WF material (top) and hybrid conductor (bottom)

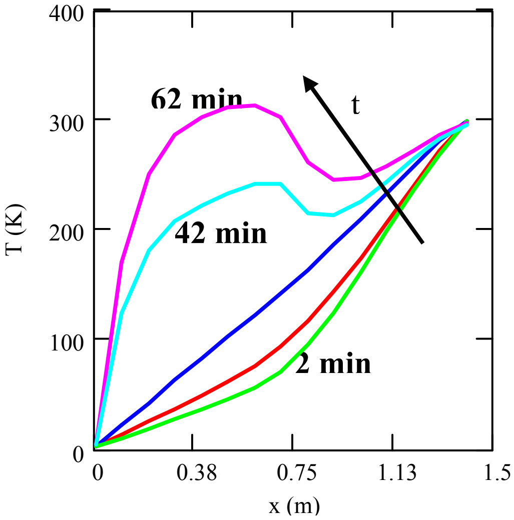

Fig. 3. T(x,t): temperature profile of the hybrid conductor transporting 60 A during a transient following the loss of the two heat sinks (t = 2, 8, 32, 42, 62 minutes)

A tapered copper lead (Cu RRR = 300 in Table 2) with comparable thermal performances would start over-heating at about 8 A and, as mentioned above, at 60 A it would reach high temperatures in few minutes, allowing little time for redistributing the current in the other LHC corrector magnets for stable operation of the stored proton beams.

The choice of the hybrid conductor is also supported by price considerations: while the copper electrolytic deposition is a well-known and relatively cheap process, the need of a conductor and a stainless steel tube both of variable cross section implies an important increase in the price of the components, as turned out from some model work at CERN.

5. Engineering design

The engineering design of the 60 A leads [5,6] was based on the optimisation principles presented in the previous sections. Prototype leads have been built at CERN and a number of tests have been performed to prove the lead's performance and reliability (see section 6).

The general concept of the lead design is based on an electrical insulation principle that excludes the use of cold vacuum-tight ceramic feedthroughs for providing both the electrical insulation and the separation between the superfluid liquid helium bath and the cryostat main vacuum insulation environment. As a consequence, the lead has been designed as an electrically insulated hybrid conductor contained in a thin stainless steel tube welded, at the two extremities, to the supporting flanges.

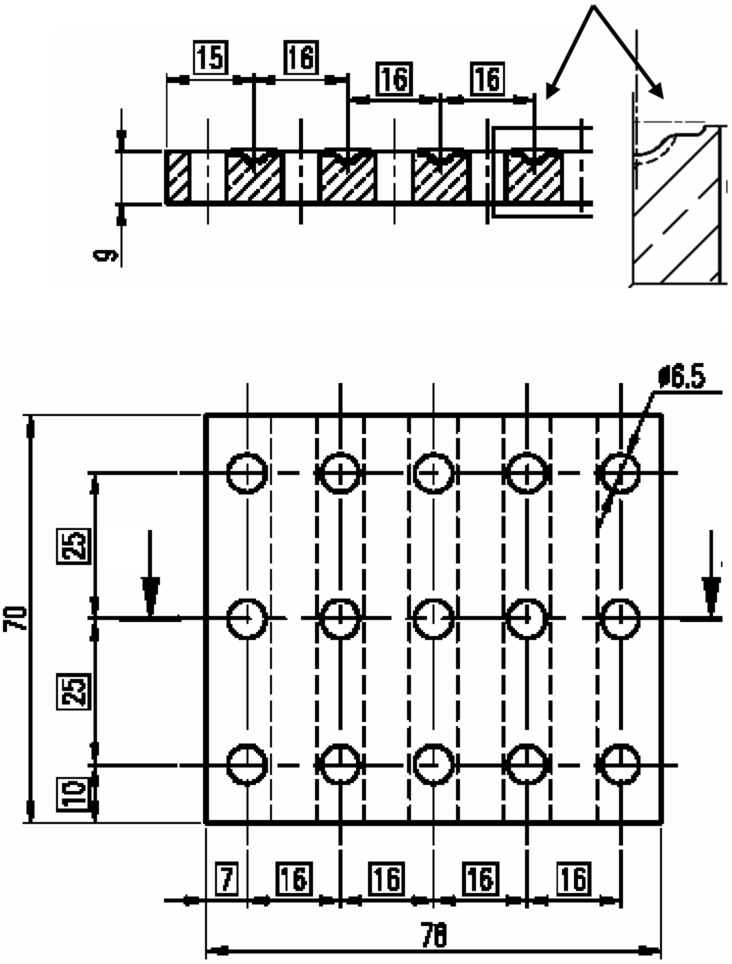

Fig. 4. Design of the thermalization block showing the grooves for housing the lead tubes

The electrical insulation is made with a Kapton® tube (thickness 4×25µm), between the tubular envelope (0.2 mm thick stainless steel tube) and the conductor. Welded seals guarantee the leak tightness with respect to the vacuum environment.

The cold end of the stainless steel tube is open to the liquid helium bath and static helium gas stratifies inside the tube. The leak tightness between the helium and the outside environment is made at the room temperature and with standard rubber (NBR) O-rings.

5.1. Design of the heat sinks

The heat sinks are made by clamping the leads between two metallic plates fixed to the cryogenic lines E and C'. This clamping assures the heat transfer (see Table 3) by thermal conduction from the hybrid conductor, through the Kapton® and the stainless steel tubes wall, to the metallic plates welded to the tubes carrying helium gas at intermediate temperatures and housed in the main cryostat vacuum insulation.

The metallic plates contain a groove for housing the lead. The shape of the groove is such as to allow and guide a smooth deformation of the stainless steel tube during clamping (see Fig. 4).

Tests have been made in collaboration with the CERN Main Workshop (EST-MS) and the TIS Commission to prove that such a deformed tube can withstand the required pressure and electrical tests without degradation of the lead properties.

In addition, a pre-series lead assembly with the stainless steel tubes compressed at the position of the heat sinks has been submitted to 10 thermal cycles down to liquid nitrogen. Micrographies have been made of different sections of the lead that prove that no degradation of the stainless steel tubes and of the electrical insulation happens due to shaping, thermal contraction and/or compression [7]. Prototype assemblies have been submitted to several pressure tests up to 2.5 MPa. Two assemblies of 60 A leads have been operational in the Short Straight Section (SSS) No.3 and No.4 of String 2.

Tests performed in a cryostat where the intermediate temperatures were provided by cryocoolers have shown that the thermal resistance between the thermalization block and the hybrid conductor are about 0.1 K/W @ 50 K and 0.7 K/W @ 20 K when the torque applied for the fixation of the metallic plates and the crimping of the leads are about 1.6 kg·m and 1.3 kg·m respectively.

5.2. Lead assembly

In view of the important number of 60 A leads and of the strong space constraints imposed by the cryostat's configuration, the leads are assembled in groups of four on common stainless steel flanges. Each electrical insulated conductor is inserted in a stainless steel tube and pre-shaped as required for the integration in the cryostat. The tubes are then welded, in groups of four, to the supporting stainless steel flanges.

The 60 A lead assemblies are the last components to be integrated into the densely packed QQS module of the SSS (Fig. 6). This constraint added a number of complications in the definition of the shape and of the interfaces (size of connection flanges, length and size of the lead, position of heat sinks and thermalization blocks). The lead interfaces and integration procedure in the cryostat are described in a separate document [8].

Fig. 5 shows a final assembly of four 60 A leads which were manufactured and assembled at CERN. The total length of each conductor is about 1.4 m. The diameters of the warm and cold flanges, supporting the leads, are about 120 mm and 70 mm respectively.

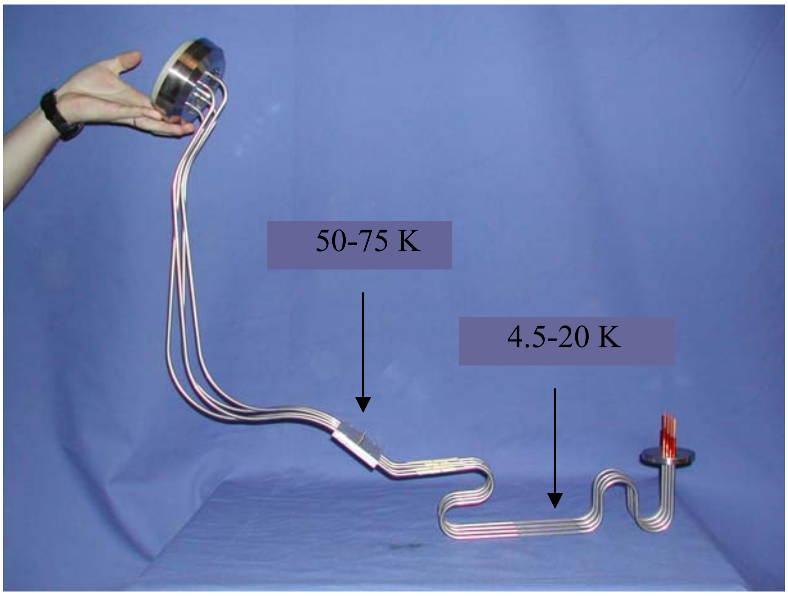

Fig. 5. Assembly of four 60 A conduction cooled leads ready for installation. The arrows show the position of the heat sinks.

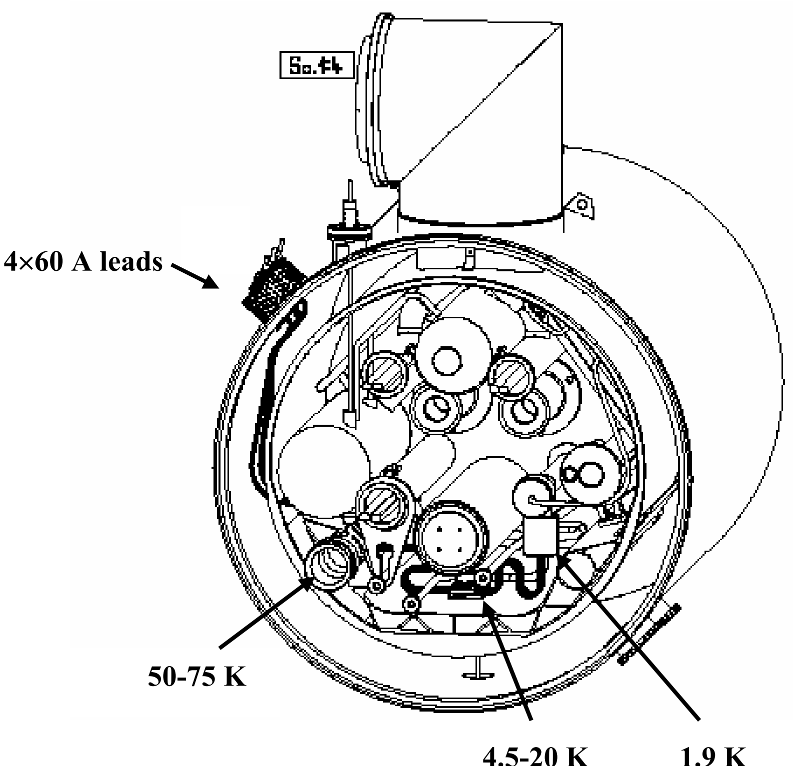

Fig. 6. Assembly of four 60 A leads integrated in the final cryostat

6. Manufacture and assembly

The leads will be manufactured in industry according to a precise technical specification [6]. The manufacturing process includes the shaping of the leads, their welding to the flanges, the crimping of the tubes around the insulated conductors at the 4.5-20 K intercept, and subsequent pressure testing (up to 2.5 MPa), leak testing (the integral of leak detected shall be < 10^{-11} Pa m^3 s^{-1}) and voltage testing (up to 1 kV). For the voltage test the lead is filled with helium gas. In order to avoid eventual twisting during installation, the crimping (which is only slight) of the tubes at the level of the 50-75 K heat intercept is done in situ. The design has been validated through a number of prototypes, built and tested at CERN, some of which are already installed and operational in SSS No.3, SSS No.4 and SSS No.5.

7. Protection

It is important to protect the lead against thermal run-away because a lead failure would not only render the corresponding corrector magnet unusable but also cause a loss of the cryostat insulating vacuum due to the almost certain arc melting of the stainless steel envelope. With their long time constant, however, the leads can be equipped with a simple and robust fault detection and protection. The voltage drop across the lead is monitored by using the voltage tap at the magnet terminal and the one at the top of the lead. It is proposed to issue a warning which allows up to 30 minutes to redistribute currents in the machine: if no corrective action is taken and the temperature reaches the second level the power converter is shut down. The protection of the current leads will be incorporated in the power converters.

8. Conclusions

A design of the 60 A dipole corrector leads has been made which satisfies the thermal, electrical and geometrical requirements of the LHC machine. It is a conduction-cooled design that allows a number of savings with respect to a conventional self-cooled lead design.

The LHC machine requires additional current leads rated for a maximum current of 120 A, which will be integrated in the SSS of the Dispression Suppressor and of the Maching Section regions. The design of those leads is being extrapolated from the 60 A leads, by increasing the diameter of the brass rod from 3 to 5 mm while keeping the same thicknesses of the copper plating.

9. Acknowledgements

The realization of the pre-series leads has been achieved with the able support of the CERN workshop. In particular, I wish to thank Guy Bonnefond for the realization of the tooling for shaping the leads, for the follow-up of the pre-series production and for the remarkable enthusiasm he has shown during the realization of this work and Ian Sexton for the realization of the weldings and the optimisation of the welding parameters. Davide Milani gave considerable help with the literature search and calculations regarding the choice of materials. The detailed designs and drawings have been handled professionally by Thierry Strauli and Fabien Roqua. And last but not least I wish to thank Philippe Denis for his untiring support in the search for practical solutions, in the preparation and performance of numerous tests.

10. References

1. Introduction to Solid State Physics, Ch.Kittel, 1971
2. Superconducting Magnets, M.Wilson, Clarendon press, Oxford, 1983, pp 256-267
3. The thermal and electrical properties from cryogenic to room temperature of the different materials analysed in this study have been taken from several sources including:

-Properties of copper and copper alloys at cryogenic temperature, NIST, Monograph 177, N.J.Simon, E.S.Drexel, R.P.Reed

-R.R.Conte, Elements de Cryogenie, Masson & Cie, 1970

-Electrical resistivity of some engineering alloys at low temperature, A.F.Clark, G.E.Childs, G.H.Wallace, Cryogenics 10, 1970, 295-305

-Low temperature properties of resistance wires, Furakawa et al., 1964; Lerner and Daund, 1964; Feldman et al., 1977

-Low Temperature Electrical Resistance of Fifteen Commercial Conductors, O.E.Park, M.M.Fulk, M.M.Reynolds, NBS Report 3517, 1954

-Selected Cryogenic Data Notebook, J.E.Jensen, R.B.Steward, W.A.Tuttle

-Thermophysical properties of matters, Vol.1, Y.S.Touloukian, IFI Plenum, 1970

4. Heat Load Working Group, 14-09-2000; Powering Review, 28-11-2000
5. Current Leads for the LHC Magnet System, A.Ballarino, presented at MT-17 conference, IEEE Transaction on Applied Superconductivity, Vol.12, No.1, 1275-1280
6. Manufacture and Supply of Assemblies of 60 A Resistive Current Leads for the LHC Dipole Corrector Magnets, IT-2901/LHC/LHC, EDMS No. 348434
7. EST/SM-ME, EDMS No. 343346
8. Interface requirements and integration procedure of the Dipole Corrector Feedthroughs in the LHC Short Straight Section, LHC Project Document No. LHC-DFLD-ES-0001, EDMS No. 32899