Design Of 12.5 kA Current Leads for the Large Hadron Collider using High Temperature Superconductor Material.

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The Large Hadron Collider will be equipped with about 8000 superconducting magnets. Some 2600 current leads will feed the currents ranging from 25 to 12500 A. CERN aims to reduce the consumption of liquid helium, using high temperature superconductors in these leads. A development of leads for 12.5 kA is being conducted in collaboration with Oxford Instruments. The design options for these leads are described. A test rig and prototype lead have been made according to one of the options. Electrical contact tests are in progress on BSCCO-2212 and YBCO-123 samples. In the first run, the prototype carried 13000 A.

INTRODUCTION

The Large Hadron Collider (LHC) will be equipped with more than 8000 superconducting magnets. The number of circuits, according to the present powering scheme, is more than 1300. This implies a need for more than 2600 current leads. The currents range from 25 to 12500 A, the present total being distributed among the different ratings as shown in figure 1.

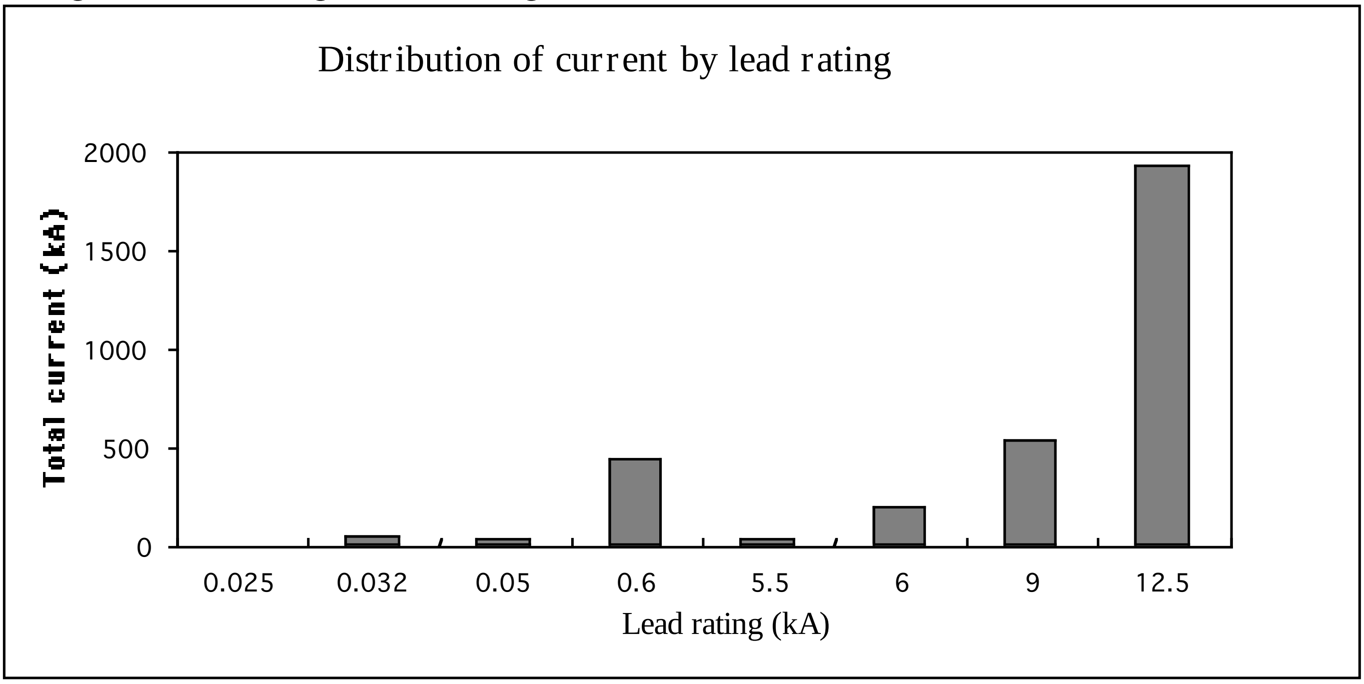

Figure 1 Distribution of current among different lead ratings.

The proportion of the current taken by the leads rated 12.5 kA is by far the largest.

The total current going into and coming out of the cold (1.9 K) mass amounts to some 3200 kA. Normal vapour cooled leads cause a heat load of 1.2 W/kA into the 4.5 K He bath. They operate between ambient temperature and 4.5 K. This works out to more than 3800 W at 4.5 K for all the leads. It represents a substantial load on the cryogenic equipment and causes a considerable He boil-off.

CERN aims to reduce this load by a factor up to ten using hybrid leads. Such a lead consists of a normal conducting part, above, say 70 K and a high temperature superconductor (HTS) below 70 K. The HTS has a low thermal conductivity and no ohmic heat generation, making the heat load reduction possible.

For the normal conducting part, different alternatives may be considered. For the HTS there are several options regarding the choice of material.

DIFFERENT DESIGN OPTIONS

Two conceptional designs of hybrid leads have been studied [1]. The difference concerns the cooling of the normal conducting part (Cu Phosphorous Deoxidized), which can be either conduction cooled or gas cooled. Both methods can be applied, given the cooling capacity of the cryogenic system, which offers two sources [2]: high pressure 50-75 K He gas, used to cool the Thermal Shield and the Magnet Supports, and 20 K He gas, used to cool the Beam Screen.

Type 1: conduction cooled lead

The normal part of this type is conduction cooled. It can be very compact, since its geometry (L/A) is not determined by cooling requirements. The shape factor for phosphorous deoxidized Cu (IL/A) is 1700 A/mm. The 60 K He gas heat-exchanger intercepts the heat produced by ohmic losses in the upper stage. An optimised 12.5 kA lead, with zero slope in the temperature profile at 300 K conducts 575 W into 60 K. This amount of heat can easily be absorbed by a compact heat exchanger, thanks to the large flow of high pressure He gas (see Fig. 2a). At zero current, the lead conducts 316 W.

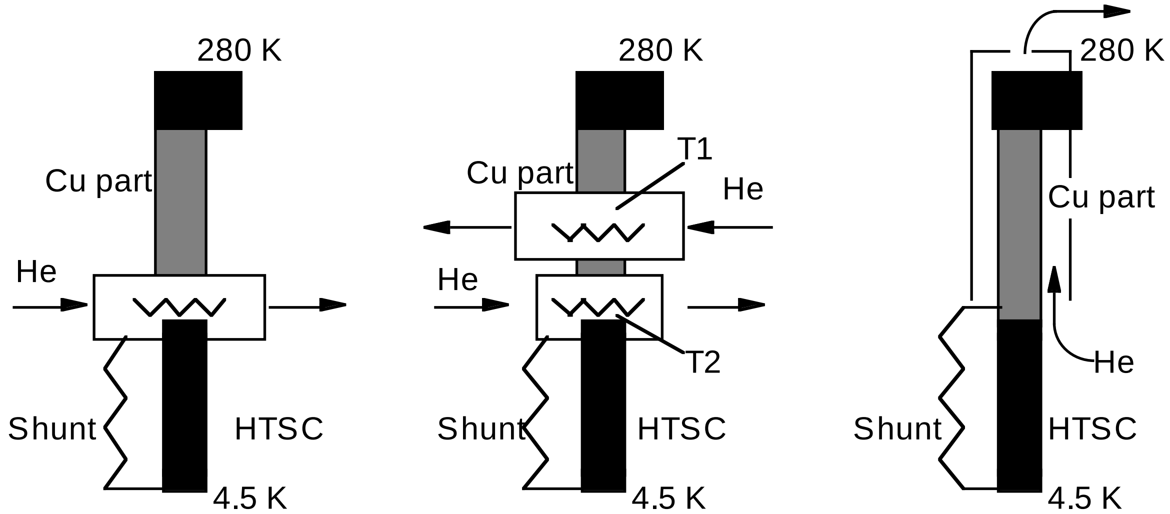

Figure 2a, b and c cooling methods

The leads are grouped inside the the electrical feedboxes (DFB)s, which interface to the machine, (see fig. 3). CDL is the cryogenic distribution line.

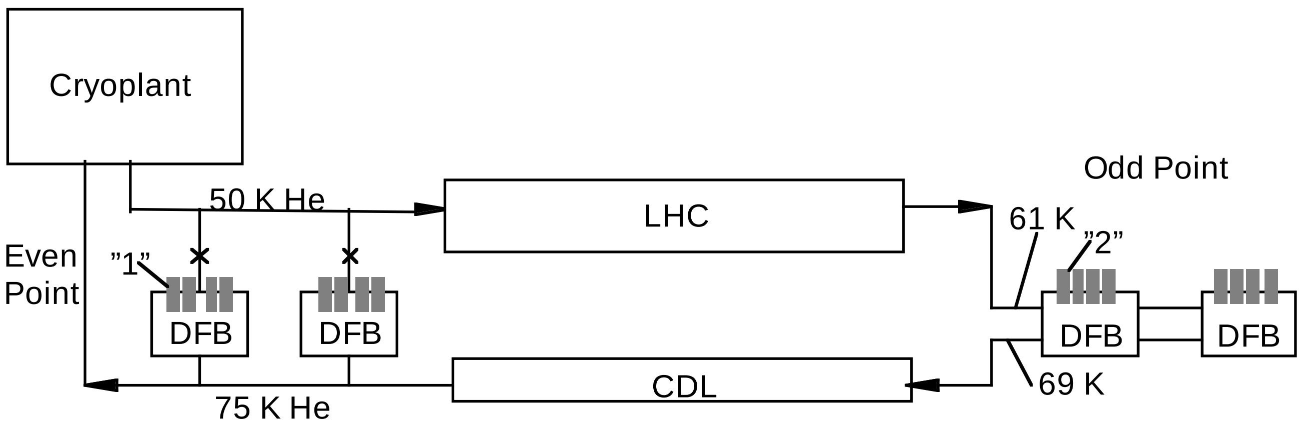

Figure 3 location of current leads with respect to their cryogenic supply.

As the He gas absorbs the heat from the different loads, its temperature increases from 50 to 75 K. An important increase in critical current density can be achieved by a small reduction of the HTS temperature. A temperature lower than 75 K at the warm end of the HTS can be obtained by going to two heat-exchangers (see Fig.2b). The lower heat-exchanger fixes the temperature below 65 K, using the incoming gas. The upper heat-exchanger absorbs the heat produced in the normal part of the lead. Table 1 summarizes the calculated heat loads at the two different temperature levels. Lead 1 refers to the lead closest to the cryoplant, lead 2 is the first lead directly at the He outlet of the LHC, as indicated in figure 3. These leads have the largest heat flow at their lower heat-exchangers of their respective groups. Most of the heat is taken by the upper heat-exchanger.

Table 1 Heat load when using two heat-exchangers (figure 2.b.)

	T1 (K)	Q1 (W)	T2 (K)	Q2 (W)
Lead 1	75	569	50	109
Lead 2	69	571	63	55

The characteristics of this design compared to a conventional vapour cooled lead in self cooling condition can be summarized as follows:

• compact upper stage of the lead, a surface for heat exchange is not required. A normal self cooled lead needs 1.04 m length for reaching an exchange surface of ~ 1 m^2 (100 disks, 8 cm diameter) [3],

• no need of return gas lines,

• no need of gas control valves,

• simplicity and economy of design,

• needs electrical insulation of the He lines.

Type 2: gas cooled lead
The He gas in forced flow cools the resistive part of the lead of this type all along its length. The cold end of the lead has a fixed temperature of 60 K, obtained by flow control, while the gas enters at 50 or 20 K, depending on the source of cooling chosen (see Fig.2c). These temperatures are determined by the boundary conditions given by the cryogenic installation.

The calculation of the temperature profiles, both of the lead and of the gas, consists of solving the heat balance equation numerically, taking into account the dependence of the He and metal properties on temperature. The calculated cross-section of the phosphorous deoxidized Cu lead is 22.5 cm^2. The cross-section of the cooling tube is 30 cm^2. The length of the lead is adjusted to reach 280 K at the warm end with a zero slope in the temperature profile at nominal current. The mass flow is 1.022 g/s for 50 K gas and 0.617 g/s for 20 K He gas. The cooled perimeter is 9 meters. In addition to gas return lines and control valves, these types of lead require:

• temperature control at the warm end,

• temperature control at the cold end.The cold end temperature of a conventional self cooled lead is fixed thanks to the presence of liquid helium. The use of helium gas for the cooling requires a more complex control system to guarantee a stable 60 K temperature,

• electrical insulation of the He lines.

COOLING POWER

The theoretical (Carnot) cooling power of each of these leads necessary to compensate for the heat loads has been calculated using for the He gas the steady state formula of a reversible process:

$$P_{min} = \dot{m}(T_0 \cdot \Delta s - \Delta h),$$

where P_{min} is the minimum cooling power, Δs is the change of entropy of the gas, Δh is the change of enthalpy of the gas, T_0 is the room temperature and $\dot{m}$ is the mass flow.

Table 2 summarizes the reduction in cooling power of the hybrid leads.

Table 2 Cooling Power necessary to compensate for the heat loads

	Normal lead	Type 1 55 K	Type 2 $T_{He\ in}$ 50 K	 $T_{He\ in}$ 20 K
P cooling normal conducting part (W/kA)	430	207	123	137
P cooling at 4.5 side HTSC (W/kA)	-	7.7	7.7	7.7
∗Compression power (W/kA)	-	-	73.5	-
Ptotal (W/kA)	430	214.7	204.2	144.7
% of conventional vapour cooled lead	100	50	47.4	33.6

The cooling power for the HTS part depends on the material properties. We took a specific heat of 5 % of a conventional lead.

∗ Power necessary for recompressing the cooling gas in the return cryogenic line from 4 to 20 bar.

PROTOTYPE CONSTRUCTION

A prototype lead for 12.5 kA of type 1 has been designed and constructed in collaboration between CERN and OXFORD INSTRUMENTS. A cryostat has been built to test such a hybrid conduction cooled lead. The return of the current is done by means a conventional vapour cooled lead. The normal and the hybrid lead have separate He vessels to distinguish the heat leak of each. The heat-exchanger of the normal conducting part has been replaced with a nitrogen bath. The boiling temperature of the N_2 is lowered by pumping down the pressure. The high Tc lead works in vacuum between 70 and 4.2 K. It consists of two parallel BSCCO-2212 melt cast cylinders, 70 mm diameter and 8 mm wall thickness. The cross-section is overdimensioned, to obtain a safety margin at the nominal temperature. One tube can carry 7.5 kA at 77 K, with a current density of 470 A/cm^2, [4]. The length of 140 mm makes the lead very compact. The tubes have integrated silver contacts. The contacts are soldered with a mixture of woods-metal and indium. The Cu end caps have been silver plated before soldering. The safety lead is made in a cheap aluminium alloy design and can take an exponential decaying current with a time constant of 130 s, in case of a quench of the HTS part. A second sample is made from YBCO-123. It consists of two rectangular rods glued onto each other in a T-shape. They will be embedded in a support cylinder for mechanical rigidity. The current density in the YBCO will be about 8900 A/cm^2.

MATERIAL CHOICE

The selected BSCCO-2212 and YBCO-123 have about the same current density/heat conductivity ratio, giving a very low heat conduction into the 4.2 K He bath.

Material in other forms, such as filamentary BSCCO and silver-backed or silver-sheated thin film may also prove to be viable alternatives (provided the conductivity of the silver is sufficiently reduced by suitable alloying).

Some prelimary tests on contact resistances were performed. Two representative 70 mm diameter BSCCO-2212 tubes were tested at currents up to 240 A. The tubular silver contacts on the leads have been formed in slightly different manners: one was "folded" and the other "punched". In each case the contact area was 63 cm^2. The "folded" contact showed no measureable resistance at 4.2 K, the measurement limit is1 nΩ. At 60 K it measured 100 nΩ. The "punched" contact resistance at 4.2 K was approximately 15 nΩ. The specific joint resistance of the better sample was therefore less than 0.06 $\mu\Omega\cdot cm^2$ at 4.2, and 6$\mu\Omega\cdot cm^2$ at 60 K.

A sample of YBCO-123 was tested under similar conditions. The contact was in the form of a silver coating on the surface of the superconductor. In this case the specific joint resistance from the superconductor to the silver was 0.3 $\mu\Omega\cdot cm^2$ at 4.2 K.

FIRST TEST RUN

The first test was recently performed in Oxford. The current was ramped up in steps of 1000 A. The lead successfully conducted current of 13000 A, which was the limit of the power supply. The test will be repeated and detailed results will be presented at a future conference.

CONCLUSION

A theoretical study of different lead design options has been made. A hybrid prototype lead has been assembled and tested: it recently successfully carried 13000 A at 70 K in vacuum. Other lead designs and other HTS materials will be tested and evaluated in the near future.

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