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The Large Hadron Collider (LHC) will need some 800 superconducting magnets to correct the orbit of the particle beams. These magnets will be individually powered and each needs a pair of current leads to the ambient temperature. To minimize the heat loss through these leads, the magnets have been designed for a very low current of about 25 amperes and the leads could be made with high Tc material. In the recent past, a theoretical study was made to investigate different types of high Tc leads. Since then, a prototype has been built which combines a low heat loss with an extremely simple design. The design, the test set up and the results are described in this paper.

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Design and test of the prototype high T_c current leads for the Large Hadron Collider orbit correctors

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Abstract—The Large Hadron Collider (LHC) will need some 800 superconducting magnets to correct the orbit of the particle beams. These magnets will be individually powered and each needs a pair of current leads to the ambient temperature. To minimize the heat loss through these leads, the magnets have been designed for a very low current of about 25 amperes and the leads could be made with high T_c material. In the recent past, a theoretical study [1] was made to investigate different types of high T_c leads. Since then, a prototype has been built which combines a low heat loss with an extremely simple design. The design, the test set up and the results are described in this paper.

I. INTRODUCTION

The LHC will be equipped with some 800 orbit corrector dipoles which must be powered individually whereas practically all the other magnets are powered in series through cold superconducting busbars. We therefore have to bring the current leads of each of these corrector magnets out from the cold mass of 1.8 K to the ambient temperature. If this is done with conventional current leads from 4.2 K to 300 K and if we assume that the heat leak from 4.2 K into the 1.8 K cold mass can be neglected then the 25 A leads add an overall heat load of some 40 W to the machine cryostats and this demands a "Carnot" liquefying power of some 13 kW. Assuming an efficiency of 16 % the electricity consumption will be 81 kW. Using high T_c material on the cold end of the lead (typically between 1.8 and 77 K) its low thermal conductivity will reduce the heat leaking into the liquid helium to practically zero. However cooling is still necessary to maintain the 77 K at the connection between the high T_c material and the conventional top part of the lead. One can expect a reduction in refrigeration power by a factor 3 to 4. In addition, thanks to the high T_c material, it is possible to simplify significantly the design and the installation of the lead in the crowded cryogenic service area of the magnets.

II. CHOICE OF THE TYPE OF CURRENT LEAD

An evaluation has been made [1] of different possible configurations of high T_c current leads. In principle two types can be distinguished characterised by the way of cooling of the normal part of the lead (see Fig. 1).

Fig. 1. Two types of lead design

The first is a current lead where the normal part from 77 to 300 K is cooled with helium gas of 50 to 70 K flowing along the lead from low to high temperature. One might be tempted to use cold gas boiling from the helium bath. This is in the present case not possible but it is also of little interest as it reduces the cooling power by only 20% compared to a conventional lead. The second type is cooled by conduction of heat into a heat sink. The sink can be one of the helium tubes with gas of 50 to 70 K used in the LHC for the cooling of the thermal screens.

A. The Cooling of the Copper Part

Figure 2 compares the theoretical "Carnot" cooling power necessary for each of the two types assuming that the heat leak through the high T_c material can be neglected. For the forced gas flow cooling, we considered an optimized lead. To calculate the cooling power at a temperature T , we cut the colder part of the lead, maintain the same gas flow but bring it in at temperature T and have the downward conducted heat absorbed by the gas supply tube. The latter carries a sufficient amount of gas to absorb this heat without a noticeable temperature change. The cooling power calculated, is plotted relative to that of a usual lead optimized between 4.2 and 300 K and which amounts to 0.354 W/A.

If the normal part is cooled with a flow of helium gas of 50 to 70 K, then the relative cooling power will be about 23 %. This factor is 37% for the thermalisation type of cooling. Figure 2 also compares the cooling power for the case where the current is zero, a situation that may be frequent for such corrector magnets. Phosphorus de-oxidized copper has been assumed and the cooling requirement reduces typically by a factor of 2 for both types of lead. For the corrector magnets, the ease of installation is an important argument and therefore we opted for the thermalisation cooling. The advantages are that we do not need a gas tube around the lead nor tubes

Black squares: forced gas cooling
Black diamonds: forced gas cooling (no current)
White squares: thermalisation cooling
White diamonds: thermalisation cooling (no current)

Fig. 2. Calculated cooling power as a function of the temperature T_c

outside the cryostat to recuperate the gas. In addition we do not need to control a gas flow, the only demand is that the heat sink always stays at or below 77 K. The disadvantage is that the cooling requirement is slightly higher than the gas cooled version. A second disadvantage is that current feed-throughs will be necessary to transfer the current from the atmosphere into the insulation vacuum and from this vacuum into the helium vessel.

B. The Cooling of the High T_c Part

The material chosen for the high T_c part is a melt-casted BSCCO-2212 rod from Hoechst, Germany. It can be obtained with silver end caps to facilitate the connections. Thanks to its low thermal conductivity and the absence of a metal backing the heat conducted into the helium bath can be strongly reduced. A calculation has been made of the "Carnot" cooling power, necessary to take the heat out of the 1.8 K bath. The temperature at the "warm" end of the high T_c rod has been varied, choosing at each temperature the minimum cross section. The critical current of this material increases about linearly with decreasing temperature. For this calculation, we approximated this behaviour as:

$$J_c = 282 - 3.5 T \quad (\text{A/mm}^2) \quad .$$

where T is temperature in degree Kelvin ($35 < T < 75$ K).

The results for rods of 100 mm length can be seen in Fig. 3. At lower temperature the cross section decreases thanks to the higher critical current and this reduces the heat leak. The lower temperature span over the length of the bar reduces the heat leak too. As a result, one can see that the cooling power at 77 K is about 2.3 per cent of the cooling power of an optimised conventional lead. At 60 K this is even a factor ten lower and becomes negligible. In other words, if one designs to work at a temperature somewhat

Fig. 3. Calculated heat flow through 100 mm BSCCO-2212 rods

lower than the boiling temperature of liquid nitrogen (i.e. 60 instead 77 K), and this is possible because we cool with helium gas, the heat leak into the liquid becomes negligible and the cross section of the high T_c rod can be chosen with a large safety margin. The figure has been calculated neglecting the effect of the self field which is an acceptable assumption for the present low current. An appreciable advantage of working at a slightly lower temperature is that the critical current becomes less sensitive to magnetic fields.

III. DESIGN OF THE CURRENT LEAD

The current lead can be seen in Fig. 4. From warm to cold it consists of the following elements: A ceramic current feed-through, a copper braid, a rod of BSCCO-2212 high T_c material and a final ceramic feed-through. Parallel to the BSCCO-2212 rod (the black part, left on the photograph) one can distinguish a spiral of stainless steel wire used as a safety lead. The length and cross section of the braid have been optimized for minimum cooling power. The length of the BSCCO-2212 material has been chosen 100 mm. The cross section for 25 A at 77 K could be 2.6 mm². At the moment such a small cross section cannot be produced and we took the smallest available of 19.6 mm² (diam. 5 mm). The heat leak through the high T_c lead will therefore be much greater than needed, in fact the lead could take much higher currents and the test lead can only be used to check the principles, not to prove the optimum.

The ceramic feed-throughs are insulators that contain a hollow metal tube of NiFe 42 in which we tin-soldered a conductor; a copper wire on the warm end and a copper-NbTi superconducting wire on the cold end. All current carrying connections have been made by indium soldering. The connection with the braid on its warm end has been made by opening the braid and slide it around the end cap before the soldering. On its cold end a superconducting wire (NbTi

Fig. 4. Prototype current lead

embedded in copper) was spiralled around the silver end cap and then soldered.

The thermalisation has been obtained by clamping a copper piece around a helium gas tube which has previously been insulated with 2 layers of 0.025 mm polyimide. The braid was then clamped against this copper piece. Table 1 gives the most important parameters.

IV. THE TESTS

The aim of the tests has been to evaluate the following aspects of the lead:

- The connection techniques for low contact resistance
- The efficiency of the thermalisation cooling
- The reliability of the ceramic feed-throughs
- The protection of the high T_c material by means of a safety lead.

A test cryostat has been equipped to measure the temperatures, voltages and heat flows on the current lead. Measurements are at present going on and some preliminary results are given below.

A. The Connection Techniques

The quality of the connection at the cold end of the high T_c lead is important because a bad connection generates ohmic heat and can considerably increase the heat flow into the liquid helium. Different types of connections were made on trial pieces and measured after dipping these into liquid nitrogen. The results are typically the following: at 300 K, the resistance from the metal conductor to the BSCCO

TABLE 1
MAIN PARAMETERS OF CURRENT LEAD

	Material	Cross section	Temp.	Heat flow
40 mm	Copper rod	11.0 mm ²	300 K	0 W
	Copper braid	6.0 mm ²	300 K	0 W
			60 K	1.15 W
820 mm	Polyimide	3000 mm ²	60 K	1.15 W
	(2 x 0.025 mm thick foil around O.D. 50 mm st.st. tube)			
100 mm	BSCCO rod	19.5 mm ²	60 K	0.012 W
			1.8 K	0.012 W
	St. steel wire	1.4 mm ²	60 K	0.0005 W
	(length 822 mm)		1.8 K	0.0005 W
50 mm	Cu-NbTi wire	11.0 mm ²	1.8 K	0.0125 W

material ranges from 2 - 12 m Ω , at 77 K this reduces to 0.5 - 5 $\mu\Omega$. Finally the contact at the 1.8 K end showed a resistance of less than 0.1 $\mu\Omega$ at 1.8 K. We can conclude that the ohmic heat generated at each of the connections is negligible, less than 1 % of the local heat flow.

B. The Efficiency of the Thermalisation Cooling

The temperature step from the copper braid through the polyimide insulation to the stainless steel tube was measured to be 0.9 K. One should keep in mind that all has been mounted in vacuum and the heat is only conducted through the contact.

C. The Feed-throughs

The feed-throughs should be safe. In particular a leak of helium into the insulation vacuum would destroy this vacuum and cause a warm up of the magnet. We tested six feed-throughs of a type used at CERN for room temperature applications (Frialit, Friedrichfeld, Germany) quenching them ten times into liquid nitrogen and measuring the helium tightness. They all withstood this test. Then we took new ones to equip the cryostat and they were found to be helium tight when installed on the helium vessel filled with 1.8 K superfluid helium. To avoid mechanical damage to these feed-throughs once installed, we designed a protection around the feed-throughs which at the same time is used for the mechanical fixation and the thermalisation of the indium soldered contact between the NbTi wires.

D. The Safety Lead

The safety lead must be able to carry the current during the time of unloading of the magnet in case of a failure of the high T_c part of the lead. It has been designed to stand the

current during 3 seconds, heating from 77 to 300 K without causing a voltage drop of more than 10 V. At present we rely on the calculations but in the near future we will be able to check these numbers by tests.

V. CONCLUSIONS

Calculations have been made that show that a current lead with high T_c material on the cold end should give a reduction in cooling power of a factor of 3 to 4.

A choice has been made for a current lead design that combines a great simplicity of construction and installation with an appreciable cooling power reduction of about a factor three. Prototypes of such leads have been made for a nominal current of 25 A. It has been shown that a safety lead can be applied without introducing important thermal losses. The connection techniques have been mastered and the ceramic feed-throughs appear to be reliable. Tests in a test cryostat will go on to study in more detail the effect of different thermalisation temperatures and the influence of different screening temperatures. We also have the intention to continue the development for higher currents (up to 12 kA if possible).

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- [1] A. Ballarino, A. Ijspeert, "Expected advantages and disadvantages of high T_c current leads for the Large Hadron Collider orbit correctors", *Advances in Cryogenic Engineering*, Vol. 39, 1994.