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**Expected Advantages and Disadvantages of High-Tc Current Leads for the Large
Hadron Collider Orbit Correctors**

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Abstract

The Large Hadron Collider (LHC) will be equipped with some 800 superconducting magnets for the correction of the orbit of the particle beams. Each of these magnets will be individually powered and needs a pair of current leads to the ambient temperature. To minimise the heat load due to these leads, a very low operational current has been chosen of about 25 A. A theoretical study has been made of the advantages and disadvantages of leads partly made of high-Tc superconducting materials. The paper gives the results of these calculations comparing normal leads with different current lead options using high-Tc superconducting materials. The results are also immediately applicable to leads for any other current.

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EXPECTED ADVANTAGES AND DISADVANTAGES OF HIGH- T_c CURRENT LEADS FOR THE LARGE HADRON COLLIDER ORBIT CORRECTORS

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ABSTRACT

The Large Hadron Collider (LHC) will be equipped with some 800 superconducting magnets for the correction of the orbit of the particle beams. Each of these magnets will be individually powered and needs a pair of current leads to the ambient temperature. To minimise the heat load due to these leads, a very low operational current has been chosen of about 25 A. A theoretical study has been made of the advantages and disadvantages of leads partly made of high- T_c superconducting materials. The paper gives the results of these calculations comparing normal leads with different current lead options using high- T_c superconducting materials. The results are also immediately applicable to leads for any other current.

INTRODUCTION

Each of the about 800 dipole corrector magnets for the Large Hadron Collider (LHC) will be powered individually and therefore 800 pairs of current leads will be necessary to bring the current from the room temperature environment to the 1.8 K in the cryostats. Although the current for the dipoles has been chosen as low as possible (25 A), these current leads together still cause a heat load comparable to two pairs of 10 kA leads for the main dipoles. Use of high temperature superconductors between 1.8 K and 77 K offers the potential to reduce the cryostat heat inleak.

In this paper the performance of such current leads consisting of a normal metal part on the warm end and a high- T_c superconducting part on the cold end has been analysed and compared with the performance of a conventional current lead. Different designs have been studied with theoretical models adapted to each case. The results can be used for any current and should allow the designer to make a well-considered choice of the current lead that is best adapted to his particular application.

ASSUMPTIONS

Several major assumptions have been made in this analysis.

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Figure 1: Concept of ideal machine

The first is that we took the heat transfer between the lead and the cooling gas to be perfect i.e. at any position along the lead we assume that the lead and the gas have the same local temperature.

Second we assumed that the conventional materials follow the Wiedemann-Franz law which states that the heat conductivity k and the electrical resistivity ρ are related to the temperature T :

$$k(T) \rho(T) = L_0 T \quad \text{where } L_0 = 2.45 \cdot 10^{-6} \text{ W/K}^2 \text{ (Lorentz constant)}$$

Third, to determine the minimum power of cooling for the helium gas the first and the second law of thermodynamics are used. The concept of an ideal machine has been adopted:

In the steady state, for a reversible process,

$$P_{m, rev} = \sum_{in} \dot{m} (U - T_0 s) - \sum_{out} \dot{m} (U - T_0 s)$$

$P_{m, rev}$ represents the maximum power obtainable in a process which produces work or the minimum power needed in a process which requires work.

$(U - T_0 s)$ is called the steady flow available function. U is the "associated energy", that is the sum of the enthalpy, the specific kinetic and the specific potential energy and s is the entropy.

We have taken phosphor deoxydized copper for all the conventional parts of the current leads.

SELF-COOLED LEADS

We call the leads self-cooled when the heat conducted into the liquid helium bath is used to produce the helium vapor flow needed for the cooling along the lead. In a closed system it is then sent to a refrigerator to be re-liquefied

The length and cross-section of the lead can be optimized to obtain a minimum heat inleak into the bath (and thus a minimum gas flow along the lead). It appears that this optimum coincides with a zero heat gradient at the warm end of the lead. As long as the material follows the Wiedemann-Franz law, the minimum heat inleak appears to be independent of the type of material. The lead dimensions can be characterized by an optimized "shape factor" $I L/A$ (where I is the current and L and A are the length and the cross-section of the lead resp). This factor is dependent on the type of material used.

We compared 3 typical cases in increasing order of cooling economy:

Figure 2: three types of self-cooled current leads

Type 1- Conventional lead¹ made from a Wiedemann-Franz material (i.e. phosphor deoxidized copper) and cooled by helium boiling off from the 1.8 K bath.

Type 2- Binary lead composed of a Wiedemann-Franz material on the warm part (from 300 K to 77 K) and a high-T_c material on the cold part (from 77 K to 1.8 K)². Like before the coolant is the helium boiling from the 1.8 K bath.

Type 3- Binary lead like above, but the cooling is different for the warmer and the colder part: the high-T_c material is cooled by conduction of heat into the 1.8 K bath whereas the Wiedemann-Franz material is cooled by nitrogen gas boiling from a liquid nitrogen bath at 77 K^{3,4}.

Although the calculations have been done for an operating current of 25 Amperes, they can readily be adapted to other currents. The different parameters for these optimized leads are given in Table 1 which shows the optimized shape factors, the heat flows at different points along the leads, the mass-flow rates of boiled off gas and the power needed for an ideal refrigeration system to re-liquefy the gas.

Table 1- Thermal performance of three types of self-cooled current leads

	TYPE 1	TYPE 2	TYPE 3
COPPER PART			
Shape factor (IL/A) (A/m)	3.5×10^6	2.21×10^6	1.52×10^4
Heat flow at 300 K (W/A)	0	0	-
Heat flow at 77 K (W/A)	-	0.016	0.0229
Heat flow at 1.8 K (W/A)	0.00104	-	-
Coolant	Helium vapor	Helium vapor	Nitrogen vapor
HTSC PART			
Shape factor (IL/A) (A/m)	-	4.19×10^4	1.70×10^3
Heat flow at 1.8 K (W/A)	-	0.0008	0.000157
Coolant	-	He vapor	Conduction cooled
COOLANT PARAMETERS			
Flow rate (kg/A s)	4.896×10^{-8}	4.168×10^{-8}	1.144×10^{-7}
Heat absorbed (W/A)	0.075	0.064	0.026
Ideal cooling power (W/A)	0.379	0.322	0.099
Power ratio to Type 1	1	0.85	0.263

The table shows that replacing the cold part of a conventional lead by high-Tc material (Type 2 as compared to Type 1) only brings a small reduction in cooling power. The reason is that the high-Tc material cannot be used in an optimum way. In principle we would like to minimize the cross section of this material to just carry the desired current and in this way reduce the heat leak into the bath to a small fraction of that of the conventional lead. However, this reduces the boil off to such an extent that the vapor flow becomes far too small to cool the upper part of the lead. Therefore the cross section of the high-Tc material must deliberately be taken much larger than desired or we must add a metallic strip to bring sufficient heat into the bath and obtain the vapor flow necessary for the cooling of the upper part.

Type 3 takes this limitation away by cooling the upper part with gas boiling off from a 77 K nitrogen bath instead of helium. The cross-section of the high-Tc part can now be minimized for the desired current and the heat conducted into the helium bath now becomes very small, between 0 and 0.0004 W/A. In this way the cooling power can be strongly reduced as compared to the conventional lead. The heat leaking into the helium could be used to boil off some gas and cool the high-Tc part which would still reduce a bit the cooling power. However, the advantage is small and it would complicate the piping in the LHC where it is easier to have it absorbed by the 1.8 K superfluid helium bath in the form of a slight increase of the temperature.

A drawback of the third type of lead is the need for an additional nitrogen circuit which for the LHC machine would mean a network of kilometers of additional pipes which have not been foreseen. However, the LHC cryostats will contain different tubes with helium gas at intermediate temperatures and it may be advantageous to use this gas for a "forced" cooling of the current leads.

One important advantage of the self-cooled leads is the fact that the helium gas flow-rate is self-controlled. When the magnets run at reduced current (and during the operation of the machine each correction magnet may run at a different current, ranging from zero to maximum) the helium boil off will reduce accordingly although it will be higher than the theoretical optimum at that reduced current because the shape factor is only optimized for full current.

FORCED-COOLED LEADS

We might replace the boiling nitrogen cooling of Type 3 by a forced flow of helium gas of similar temperature. In the self-cooled cases this mass flow was a direct effect of the heat leak into the liquid. For forced-cooled leads, this relation disappears and the mass flow can be chosen as an additional degree of freedom. It appears that the optimized solution does not necessarily correspond anymore with a zero temperature gradient at the warm end.

We have studied variants of two basic types of forced-cooled leads shown in figure 3:

Figure 3 - Two basic types of forced-cooled current leads

Type 4 - An adaptation of Type 3 by replacing the nitrogen boil off by a forced helium gas flow along the lead⁴.

Type 5 - Another adaptation of Type 3 replacing the nitrogen bath by a heat sink cooled by helium gas but without any gas cooling along the lead. This allows for a simpler design than Type 4.

For these calculations, the boundary conditions are the 300 K temperature at the warm end of the lead and the 77 K temperature as point where the high-Tc part takes the current over from the conventional top part. In both new cases we cool the high-Tc part of the lead by conduction into the helium bath and renounce for practical reasons to the use of helium gas for the cooling of this lead part.

In a first approach, we supposed that the heat leaking into the high-Tc material and finally into the 1.8 K bath can be neglected. The heat that entered into the nitrogen bath (Type 3) must now be cooled by the helium gas and it appears to be necessary to add to the top part of the lead a prolongation to the cold side ("Copper 2") that does not carry current but serves as a cooling fin to cool this heat away. We can find an optimum solution for the shape factor, the helium mass flow and the initial helium temperature where the cooling power is minimal. This optimum appears to be situated at a helium gas temperature of about 55 K and 70 K for Type 4 and for Type 5 respectively. The results of the calculations are summarized in Table 2, columns 1 and 4, where one can see the similarity in cooling power between Type 4 and Type 3 whereas Type 5 needs a slightly higher cooling power.

Next, to see the effect of the heat leaking into the high-Tc part, we have supposed for simplicity that a fixed amount of heat leaks into the high-Tc part corresponding to the maximum heat leak we would expect. Dependent on the design of the lead, the high-Tc part may be welded to the upper part at 77 K and take the heat out at this level (Type 4A and 5A) or it may be welded from here down to the lower end of the top part and take the heat out there (Type 4 B and 5B). Both cases have been considered in table 2 (columns 2, 3 and 5) where one can see that the optimum does not change very much.

If the helium temperature is different, we can optimise the two other parameters and will obtain slightly higher cooling powers. This is visualised in figure 4, for leads of Type 4 B.

Table 2 - Thermal performance of two types of forced-cooled current leads

	TYPE 4A-B	TYPE 4A	TYPE 4B	TYPE 5A-B	TYPE 5B
COPPER PART 1					
Shape factor (IL/A)1 (A/m)	1.8×10^6	2.2×10^6	2.7×10^6	1.6×10^6	1.6×10^6
Heat flow at 300 K (W/A)	0.048	0.031	0.0173	0	0
Heat flow at 77 K (W/A)	0.008	0.0078	0.0078	0.045	0.045
Coolant	Helium gas	Helium gas	Helium gas	cond. cooled	cond. cooled
COPPER PART 2					
Shape factor (IL/A)2 (A/m)	1.3×10^6	1.4×10^6	2.2×10^4	1.9×10^4	1.8×10^4
Heat flow at 70K (W/A)	-	-	-	0	0.0004
Heat flow at 55K (W/A)	0	0	0.0004	-	-
Coolant	Helium gas	Helium gas	Helium gas	Helium gas	Helium gas
HTSC					
Heat flow Q HTSC (W/A)	0	0.0004	0.0004	0	0.0004
COOLANT PARAMETERS					
Optimized He gas temperature Tg (K)	55	55	55	70	70
Flow rate (Kg/As)	6.8×10^{-8}	6.4×10^{-8}	6.4×10^{-8}	1.23×10^{-6}	1.22×10^{-6}
Ideal cooling power (W/A)	0.092	0.088	0.88	0.136	0.134
Power ratio to Type 1	0.24	0.23	0.23	0.36	0.36

Figure 4 - Optimized cooling power for Type 4 B leads as a function of He gas temperature and flow rate (black markers for heat flow $Q_{HTSC} = 0$, white markers for heat flow $Q_{HTSC} = 0.01$ W)

The same investigations have been done for Type 5 and the results can be seen in Figure 5.

Until here a high- T_c material with a critical temperature of 77 K has been assumed. It is interesting to see how different the optimum cooling power will be for superconducting materials with other critical temperatures. Table 3 gives the results for three different critical temperatures.

Figure 5- Optimized cooling power for Type 5 leads as a function of the He gas temperature and flow rate (heat flow $Q_{HTSC} = 0$ W)

Table 3- Thermal performance of Type 5A leads for HTSC materials of different critical temperatures (heat flow Q HTSC = 0 W)

COPPER PART			
Critical temperature T _c (K)	50	77	90
He gas temperature T _g (K)	45	70	85
Shape factor (L/A) ¹ (A/m)	1.67×10^6	1.60×10^6	1.55×10^6
Shape factor (L/A) ² (A/m)	1.04×10^4	1.91×10^4	4.55×10^4
Heat flow at T _c (W/A)	0.0463	0.045	0.0448
Heat flow at T _g (W/A)	0	0	0
Coolant	Helium gas	Helium gas	Helium gas
Flow rate (kg/As)	1.77×10^{-6}	1.23×10^{-6}	1.17×10^{-6}
Ideal cooling power (W/A)	0.244	0.136	0.108
Power ratio to Type 1	0.64	0.35	0.28

It may be interesting to note that a current lead composed of niobium titanium on the cold end (from 1.8 K to 9 K) and copper on the warm end, cooled by a forced helium gas flow entering at 9 K would give 20 % reduction in cooling power as compared to a normal lead.

If the magnets run at a reduced current and if we do not foresee an adaptation of the helium mass flow as a function of the current, then Type 4 with the constant mass flow will demand a constant cooling power. This makes this solution less attractive because either it needs a flow control or it costs more cooling power than necessary and will need a strong heater on the room temperature side to keep the cable connections ice free. However, even at 0 current, its cooling "power ratio" of 0.24 is still lower than that of a conventional lead at 0 current (0.4). For Type 5 the cooling power reduces when the current reduces even when the helium mass flow is unchanged.

OPTIMIZATION INCLUDING A STAINLESS STEEL PROTECTION TUBE

To bring the current from the outside world at atmospheric pressure to the magnet in the 1.8 K bath at atmospheric pressure, the current lead has to traverse the insulation vacuum. This can be done through feed-throughs which are helium tight but a breakdown of such a feed through on the 1.8 K bath side may cause a major problem. We have checked what would be the thermal effect if the lead is mounted inside a protective stainless steel tube welded to the 1.8 K helium vessel on one end and the outer vacuum vessel on the other end. In several of the cases solved so far, such a tube would be necessary for the guidance of the cooling gas. We supposed this tube to have along the lead the same local temperature as the lead and the gas. It appeared that the cooling power of the conventional part of the lead does not increase very much (some 10%) if this tube is included in the optimization. On the HTSC part, however, this tube would give an additional heat inleak into the liquid.

LEAD BURN OUT

If for some reason the cooling of the lead stops, the temperature of the lead may quickly rise to a level where the materials are destroyed. It is interesting to have an idea of the time during which the lead can take the current before irreparable damage occurs. This time should be long enough for a detection system to switch off the current otherwise it is unsafe to use the lead. For the calculation of this time we assumed adiabatic heating after stop of the cooling which is the most pessimistic assumption⁵. For the high-T_c superconductor we suppose that it becomes immediately normal and behaves like a Wiedemann-Franz material with a "Lorentz" constant of $3.15 \cdot 10^{-8} \text{ W/K}^2$. This value is our estimation but may vary depending on the type of material. The resulting burn-out times are given in Table 4.

Table 4 - Time for a lead to burn out

TIME OF BURN OUT					
	L (m)	A (m ²)	Initial temperature (K)	Final temperature (K)	Time (s)
COPPER PART					
TYPE 1	0.7	5×10^{-6}	300	400	423
TYPE 2	0.7	7.9×10^{-6}	300	400	1060
TYPE 4A	0.7	9.72×10^{-6}	300	400	1596
TYPE 5A	0.7	1.09×10^{-5}	300	400	2024
HTSC PART					
TYPE 1					
TYPE 2	0.2	1.19×10^{-4}	70	150	191
TYPE 4A	0.12	6.2×10^{-6}	70	150	0.5
TYPE 5A	0.12	6.2×10^{-6}	70	150	0.5

CONCLUSIONS

Five principle types of current lead have been compared, starting from the conventional lead up to a binary lead which has a local heat sink cooled by a forced helium gas flow. Binary leads give little advantage (reduction of cooling cost of some 20 %) if the cooling must come from the helium vapor that boils from the bath. However, binary leads can reduce the cooling cost by a factor of 4 when cooled by boiling off nitrogen or by a forced helium gas flow of a temperature of some 55 K. The future LHC will not have a liquid nitrogen distribution system but it has several helium gas pipes at intermediate temperatures, in particular 50 to 75 K, which are interesting candidates for the cooling of the leads of the corrector magnets.

The next step will be the mechanical design and construction of a prototype lead followed by a test to measure the thermal behavior of the binary current lead and assess its reliability.

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