Thermal Modelling of the LHC dipoles functioning in superfluid Helium

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Abstract

The possible heat sources in the superconducting cable are evaluated and result in a temperature margin of this cable. The electric insulation of the cables plays an important role as heat barrier between the cable and the superfluid helium bath. Numerical and experimental models are presented. Different insulation systems are proposed.

1. INTRODUCTION

The Large Hadron Collider (LHC) [1] to be built at CERN in an existing tunnel requires high field superconducting magnets. Fields in the range of 8 to 10T can be reached using a standard NbTi superconducting cable in a helium bath at a reduced temperature of 1.9K. The helium is then superfluid and has the advantages of a low viscosity and a high thermal conductivity leading to high heat transfer coefficients. If the helium is in close contact with the cable, its high specific heat could compensate for the lower enthalpy of the metallic parts at the reduced temperature.

During the operation of the collider, heat is deposited in the cable, either by beam losses or by electrical losses at ramping. This heat has to flow from the cable to the cold source through the electrical insulation of the cable such that the cable temperature never exceeds the critical temperature of the superconductor at the operational field.

This paper gives estimates of beam losses, ramping effects and temperature margin. Measurements of the temperature increase in a thermal model of the dipole coils are reported for various electrical insulations.

2. TEMPERATURE MARGIN AND LOSSES

2.1 Temperature margin

The coils made of two layers of conductors and the mechanical structure are bathed in the subcooled superfluid helium filling the volume between the cold bore and the helium vessel (Fig. 1). A superconducting cable consisting typically of 28 NbTi strands Ø1.065 mm remains in the superconducting state as long as the temperature, the magnetic field or the current density stay below their critical value. At a fixed current and fixed field, the temperature margin is defined as the difference between the critical temperature and the bath temperature. For the inner layer of a LHC dipole at 8.65T in a 1.9K helium bath, the temperature margin is 1.2K.

2.2 Ramping losses

At ramping and discharge of the current in the dipole magnet, losses occur in the superconducting cables. They are due to hysteresis in the NbTi filaments, interfilament coupling through the Copper matrix and currents circulating between the strands through their contact resistance. The interstrand coupling losses depend on the final resistivity of the copper, the coating of the strands and the compression of the cables. They occur mainly in the winding blocks of the inner layer located near the median plane of the dipole coils where the magnetic field is perpendicular to the cable broad face. For an LHC charging time of 1200 s, the specific power dissipation in these cables is 0.14 mW/cm^3, the total losses have been calculated to be 325 mW per meter length of magnet equivalent to an energy of 400 J/m going into the helium bath. The characteristic time constant associated with the interstrand coupling currents is in the range of 2 to 6 seconds.

2.3 Beam losses

In steady state operation, beam losses occur through proton-proton collisions at each interaction point, as well as through beam-gas scattering all around the machine. Non-linear dynamic effects such as beam-beam interactions and multipolar errors in the magnet field produce an increase of the beam particle oscillation amplitudes, leading to the possible loss of particles on the beam pipe. At LHC nominal operation parameters, 7 TeV and 2835 bunches of 1×10^{11} protons/s, spaced 25 ns, losses of 2×10^9 protons/s per beam have been estimated outside the experimental areas. Even with a highly efficient collimation system, local losses of ~ 10^7 protons/s could be expected in the dipole coils [2].

The distribution of the energy deposit per incident proton inside a LHC dipole has been calculated [3]. Assuming the impact point in the mid-plane of the inner layer, the maximum energy density deposited in the two most exposed cables is approximately 10^{-9} J/cm^3 for an incident proton at 7 TeV. This maximum occurs about 50 cm downstream of the impact point and the two neighbouring cables on both sides of the most exposed cables receive 66%, and the next two cables respectively 25% and 15% of the maximum energy deposit.

Therefore, a local loss of 10^7 protons/s dissipates a power density up to 10 mW/cm^3 in the most exposed part of the cable, corresponding to 0.4W per meter length of cable. Even if the radial energy deposit is not uniform, it is assumed that the temperature is uniform inside the cable cross section as the transverse thermal time constant inside the cable is of the order of 0.2 ms.

3. MODELISATION OF THE THERMAL BEHAVIOUR OF THE CONDUCTOR

3.1 Numerical modelisation

The temperature rise in the cable due to an internal and steady dissipation of power is determined by the thermal link between the conductor and the cold source of helium. The thermal resistance is given firstly by the electrical insulation of the cable and secondly by the thermal path in the superfluid helium bath. This thermal path goes through the annular space of 2 mm between coils and cold bore, the space between the collar plates and the channels in the steel laminations before reaching the heat exchanger tube filled with two phase saturated helium acting as the cold source (Fig. 1).

For a heat dissipation corresponding to a continuous loss of 10^7 protons/s, the temperature rise has been calculated (Table 1). The maximum temperature differences in the helium II bath are negligible compared to those caused by the thermal resistance of the insulation, assumed non porous to helium. The temperature rise of 2.3 K in the most exposed cable calculated with no helium in the insulation is higher than the temperature margin of the cable. But a real insulation has helium porosities, and a better understanding of heat transfer requires an experimental approach.

3.2 *Experimental modelisation*

The aim of the models was firstly to qualify the thermal performance of different insulation systems used in superconducting magnets and to understand the mechanism of thermal transfer in this insulation and helium II environment.

Classically, the insulation is a composite made up of a first wrap, a foil wound around the cable for electric insulation, and a second outer wrap protecting mechanically the inner wrap, creating helium channels and gluing to the next conductor to keep the coil in shape. In the tests described, Kapton® foils were used for the first wrap. For the second wrap, glass fibre prepregs, adhesive Kapton® and, combined with them, dry glass-Kevlar® mixed tapes were employed.

The cables are simulated by stainless steel bars 2.5 x 17 x 150 mm. The low thermal conductivity of the stainless steel helps to suppress the end effects of thermal conduction in the longitudinal direction and the high electrical resistivity allows easy heating of samples. To simulate the strands of the real cable, the surface of the bars are machined over a length of about 120 mm only, to avoid Helium leaks in the longitudinal direction, the ends are not machined. A sample is made of five insulated bars, cured under the same pressure and temperature conditions as the real magnet cable.

It is then mounted in a press jig allowing to maintain the sample under pressure (≈ 60 MPa) during the tests performed in a helium II cryostat. The three inner conductors are equipped with Allen-Bradley-type temperature sensors (10 Ω/mK or 30 µV/mK at 1.9 K) glued into the stainless steel conductor with epoxy resin.

3.3 *Experimental procedure*

The temperature reading is made after attaining the stationary temperature of the conductors heated by passing currents up to 10 A. The temperature outside the conductor, i.e. in the helium bath, is regulated and held constant for the whole run over the range of different power dissipation values. The temperature difference between the conductors and the bath is thus measured versus the dissipated power. This curve characterises the total thermal resistance between the conductor and the cold source (bath temperature T_b). It has to be stressed that the measurements have not been corrected for the non-uniform temperature of the stainless steel bars.

4. RESULTS AND CONCLUSIONS

Only some selected results are presented here (Fig. 3). They permit the comparison of different insulation types (Table 2) [4, 5]

The non-linear variation of temperature differences between the conductor and the helium bath as a function of the power put into the conductor, as well as the sudden change of slope as the conductor temperature reaches 2.16 K, the T_λ temperature, indicate a significant participation of the helium II in the heat transport. The dashed line in Fig.3 representing the heat transport characteristics in presence of helium I has been obtained by extrapolation of measurements made between 2.5 and 4 K. The comparison of the different results show that working in a helium II bath gives a reduction of at least a factor 5 in the temperature increase for heat loads such that the warmest conductor remains in superfluid regime ($T < T_\lambda$).This minimum gain is obtained for the thermally worst performing sample, A16, with a quasi helium-tight insulation.

The comparison of A6 to A15 and A19 to A20 shows that replacing the glass fibre prepreg with Kapton® 140 XRCI-2 for the second wrap of the conductor insulation leads to a lower temperature rise. The polyimide glue on the Kapton® foils does apparently not flow during curing, contrary to the epoxy resin of the prepreg which blocks the helium channels. Also, its dimensional stability seems superior to that of the prepreg. These two characteristics might contribute to maintain helium II pockets of bigger sections acting favourably on the thermal transfer.

The substitution of the 2 mm spacing between the glass fibre prepregs by a dry 10 mm wide glass-Kevlar® tape improved greatly the results, as shown by sample A18. Here, the critical power (maximum power with conductor temperatures below T_λ) is a factor 3 larger than in sample A6 that has a quasi identical helium volume. The dry tissue seems to maintain the helium channels between the conductors so that the heat is conducted directly along the fibres to the helium bath on the small side of the conductors (Fig. 2).

Using dry fibre enables the thermal decoupling of adjacent conductors. Indeed, for A18, A19 and A20, an identical temperature rise for the central conductor has been measured when the central, three or five conductors are heated. The ideal combination seems to be an alternating dry glass-Kevlar® tissue with a Kapton® 140 XRCI tape. The excellent heat transfer of this second wrap allows the increase of the electric insulation thickness for the first wrap from 2 x 25 µm to 2 x 25 µm plus 2 x 12.5 µm (sample A20).

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Table 1: Temp. rise for 10^7 protons/s beam losses with power distributed in magnet components

Magnet components	ΔT [K]
Kapitza resistance cable He II	0.005
He tight insulation	2.3
Annular space coil cold bore	0
20µm spacing of collars	0.0015
Spacing collars steel-yoke	0.017

Table 2: Insulation Systems Characteristics

<table>
<tr><th>Sample Number</th><th>First wrap 50% overlap</th><th>Second wrap</th><th>S mm</th><th>t µm</th></tr>
<tr><td>A6[1]</td><td>Kapton 100 HN 25 µ x 12 mm</td><td>Glass fibre prepreg 125 µ x 12 mm</td><td>2</td><td>70</td></tr>
<tr><td>A16[2]</td><td>Kapton 120XCI-1 33 µ x 9.5 mm</td><td>Kapton 140XRCI-2 38 µ x 9.5 mm</td><td>50% overl.</td><td>105</td></tr>
<tr><td>A15</td><td>Kapton 100HN 25 µ x 12 mm</td><td>2 x Kapton 140XRCI-2 2 x 38 µ x 12 mm</td><td>2</td><td>100</td></tr>
<tr><td>A18</td><td>Kapton 100HN 25 µ x 12 mm</td><td rowspan="2">Alternating glass fibre prepreg 125 µ x 12 mm dry glass-Kevlar 120 µ x 10 mm</td><td>0</td><td>109</td></tr>
<tr><td>A19</td><td rowspan="2">Kapton 100HN 25 µ x 12 mm + Kapton 50HN 12.5 µ x 12 mm</td><td>0</td><td>125</td></tr>
<tr><td>A20</td><td>Alternating Kapton 140XRCI-2 dry glass-Kevlar</td><td>0</td><td>120</td></tr>
</table>

1) HERA type insulation system S = Spacing second wrap
2) SSC type insulation system t = Total thickness after curing

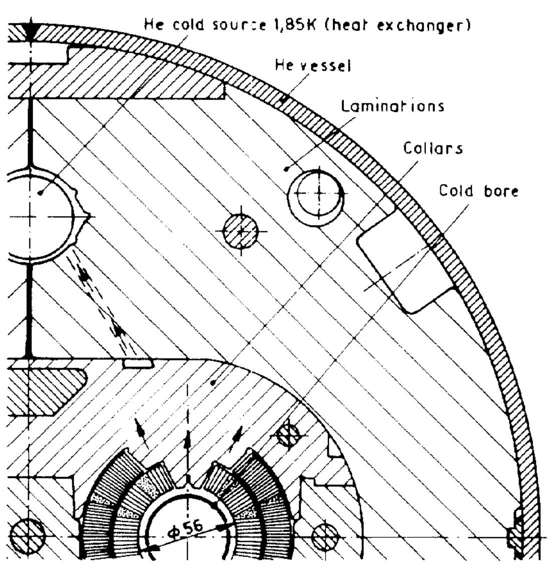

Fig. 1 Cross-Section of dipole quadrant

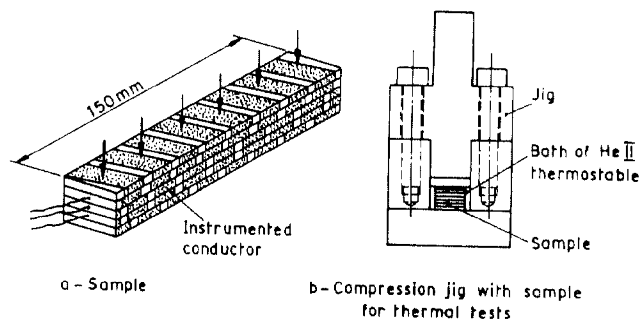

Fig. 2 Test sample

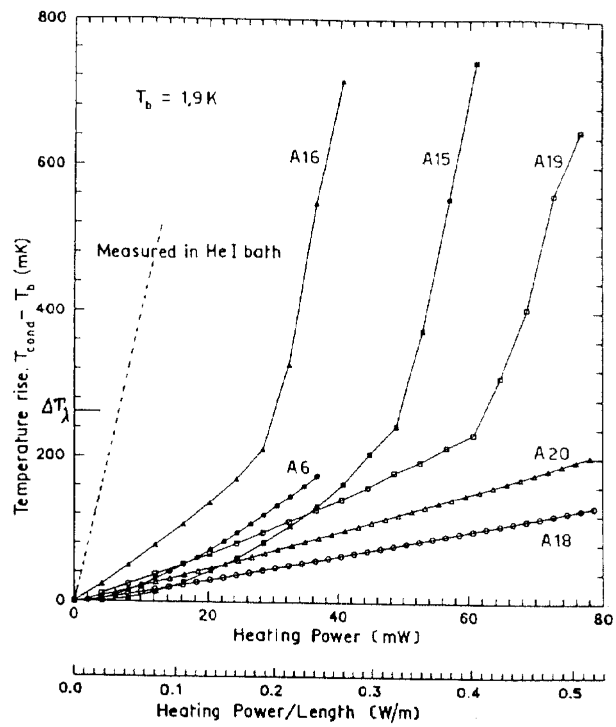

Fig. 3. Thermal qualification of several insulation systems. Temperature rise of central conductor when three conductors are heated.

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7. REFERENCES

[1] LHC Study Group, CERN/AC/93-03 (LHC), Oct. 1993

[2] L. Burnod, J.B. Jeanneret, H. Schonbacher, AC/DI/FA Note 93-06, Nov. 93

[3] L. Burnod, J.B. Jeanneret, LHC Note 167, Sept. 91

[4] C. Meuris, "Heat transport in insulation of cables cooled by superfluid Helium", Cryogenics, Vol. 31, 1991, p. 624

[5] B. Baudouy, C. Meuris, M. X. François, D. Leroy, L. Burnod et B. Szeless, "Transfert thermique dans l'isolation de câbles supraconducteursd'accélérateurs refroidis par hélium superfluide", 4èmes Journées d'Aussois, 1993