Heat Transfer in the LHC Main Superconducting Bus Bars

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CERN is performing a systematic analysis of the interconnecting bus bars of the Large Hadron Collider (LHC) main magnets. Their thermal, electrical, mechanical and hydraulic performances are addressed. In the frame of these studies, the heat transfer between the main superconducting (SC) bus bars and the surrounding He bath is investigated. It represents a key parameter in the comprehension of the bus bars stability and quench propagation mechanisms, thus crucial for the analysis of the 2008 incident which was triggered by a defective bus bars joint. This paper reports on the experimental tests and relative analysis aiming at describing the thermal behavior of the LHC main bus bars.

INTRODUCTION

The LHC incident occurred in September 2008 triggered a systematic analysis of the interconnecting bus bars aiming at determining safe operating conditions for the accelerator [1]. This work includes experimental and theoretical studies of defective bus bar joints [2,3], identified as the cause of the incident.

As part of this study, the heat transfer between the 13 kA main bus bars and the helium bath was investigated. The heat extraction plays indeed an important role in the bus bars stability and quench propagation mechanisms, hence an appropriate effort was paid to obtain a good insight of the underlying thermal phenomena. Heat transfer tests were performed on a bus bar sample both in helium-II and helium-I bath. The analysis of the measurements allowed identifying the transient and steady-state driving heat transfer mechanisms. A complete overview of the bus bar thermal behaviour was therefore provided.

EXPERIMENTAL SETUP

The sample was prepared from an insulated piece of main bending (MB) dipoles bus bar, whose cross-section is shown in Figure 1(a). The insulation of the LHC bus bar is made of two polyimide tapes 20 mm wide and 50 µm thick, both overlapped by 50 % and wrapped in opposite direction with respect to each other, covered by an ISOPREG EP2047 tape 12 mm wide and 120 µm thick, wound with a 3 mm spacing between adjacent turns and cross-wrapped with respect to the second polyimide tape.

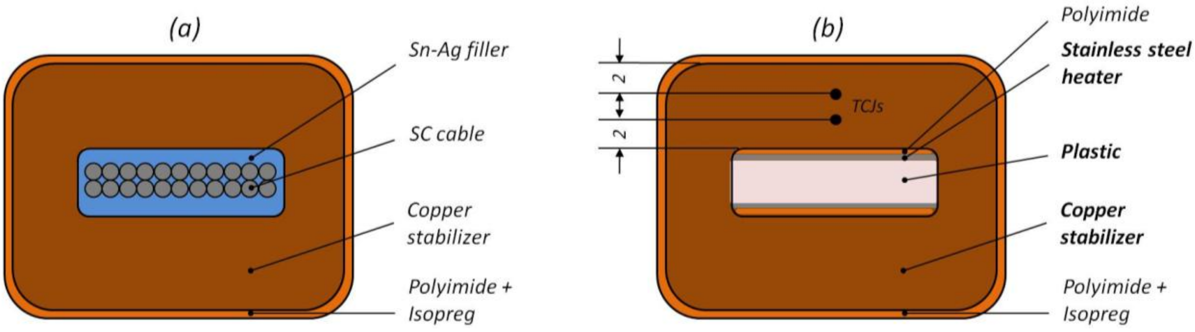

Figure 1 Scheme of the bus bar cross section (a) and of the middle cross-section of the sample (b)

The SC cable and the Sn-Ag filler were removed from the central hole of the hollow Cu profile. A stainless steel strip was placed in the hole, and electrically insulated from it through polyimide foils. The strip was connected to a current supply, in order to simulate a constant heating of the bus stabilizer, uniform over its length, due to a resistive transition of the SC cable. The dissipated power was calculated using the measurement of the voltage at the strip extremities and of the injected current. The hole was filled with teflon, foam and fiberglass plates to keep a good thermal contact between heaters and Cu profile that, in the real bus bar, is ensured by the Sn-Ag solder. Figure 1(b) shows a sketch of the sample cross-section.

The bus stabilizer was instrumented with $AuFe_{0.07at\%}$-Chromel thermocouple junctions (TCJs) that were hosted in holes previously drilled in it. Small squares of insulation were removed, allowing the varnish insulated TCJs to be installed and then sealed using epoxy resin. The average position of the TCJs, considered for the analysis, is shown in Figure 1 (b). The relative error of the measured temperature difference between bus bar and bath was evaluated to be less than 5 mK in He-II and less than 10 mK in He-I bath. The sample preparation was completed by adding epoxy resin plugs on its extremities to prevent longitudinal parasitic cooling. Finally, the sample was installed in a Claudet-bath cryostat, where all its faces were in direct contact with the 0.1 MPa pressurized He-II or saturated He-I bath. No stress was applied on the sample faces. The bath was stabilized within 0.5 mK in He-II and 0.8 mK in He-I, using Ge temperature sensors. The measurements aim at correlating the bus bar steady-state temperature increase to the power dissipated in the heater, to determine the overall heat transfer coefficient (HTC) through the insulated bus stabilizer. Contrary to the expectations, the observed time constants were not below 1 s. This feature required the development of a transient model, described in the next Section.

MODEL DESCRIPTION

The numerical simulation of the measurements was performed using the CryoSoft code THEA [4]. The original 1-D model with lumped parameters was modified into a quasi 2-D model by taking into account the temperature gradients across the polyimide components. Hence, besides the temperature dependent material properties of the three thermal components (see below), the thermal resistances between them is also considered as temperature dependent. Three thermal components were defined, as shown in Figure 2:

the copper bus stabilizer (*Cu*), the stainless steel heaters (*SS*), and a plastic element (*Pl*) representing the plates located in the *Cu* central hole, with homogenized thermal properties of the different materials.

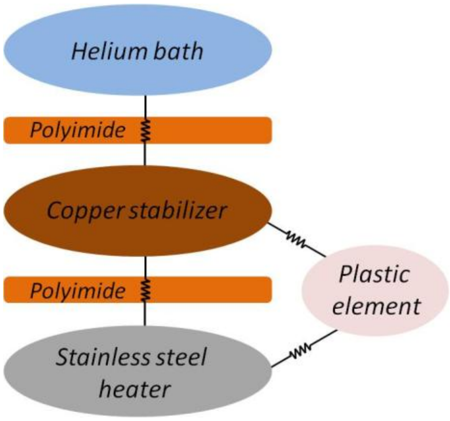

Figure 2 Scheme of the lumped parameters model

Table 1 Geometric parameters of the sample

Heat transfer length		(mm)	150
Cross sections:	*Cu*	(mm^2)	266.64
	SS	(mm^2)	0.8
	Pl	(mm^2)	45.28
Contact / wetted perimeters:			
	SS - Cu, *SS - Pl*	(mm)	32
	Cu - Pl	(mm)	5.66
	Cu - He	(mm)	74.37

The following heat balance equation was solved for each component *i* :

$$A_i \rho_i C_i \frac{\partial T_i}{\partial t} = \dot{q}_i' + \sum_{\substack{j=1 \\ j \neq i}}^{3} p_{ij} h_{ij} (T_j - T_i) - p_{ih} h_{ih} (T_i - T_h) - Q_{He-II}, \tag{1}$$

where the subscripts i and j refer to the thermal components and h refers to the He bath. A_i is the cross-section of the component, ρ_i its density, C_i the specific heat and T_i the temperature. p_{ij} and p_{ih} are the contact/wetted perimeters between two thermal components or between the bus stabilizer and the external He bath, respectively. q_i' is the external heating in the *SS* component. The HTC between two thermal components h_{ij} and between bus stabilizer and bath h_{ih} before the film boiling formation are defined as:

$$h_{ij} = \frac{1}{\delta_{ij} \cdot (T_j - T_i)} \int_{T_i}^{T_j} k_{ij}(T) dT, \qquad h_{ih} = \frac{1}{\delta_{ih} \cdot (T_i - T_h)} \int_{T_h}^{T_i} k_{ih}(T) dT. \tag{2}$$

δ_{ij} is the distance between two adjacent thermal components, equal to the polyimide thickness for the *Cu*-*SS* link and to the *Pl* half-thickness or half-width for the other links. δ_{ih} is the insulation thickness, considered to be made of only polyimide material. k_{ij} is the temperature dependent thermal conductivity. h_{ih} is described by pure conduction through the bulk of the dielectric insulation before the film boiling formation, otherwise a film boiling layer (HTC of 250 W/m^2 K [5]) is considered in series with the pure conduction mechanism. The Kapitza resistance at the interfaces between the components and the He bath is neglected. Q_{He-II} represents the superfluid contribution to heat transfer between the stabilizer and the external bath, occurring through the micro-channels located between the insulation tapes. This mechanism, well known for the polyimide insulations of SC cables [6,7], cannot be neglected despite the quite sealed insulation scheme. This is probably also due to the lack of applied stress on the bus bar faces. Q_{He-II} is evaluated from the measured steady-state temperatures, and is assumed decoupled from the conduction mechanism. It is only present for small powers at 1.9 K, and its ratio with respect to conduction is comparable to that measured in similar conditions [7]. Table 1 reports the sample geometric parameters.

RESULTS AND ANALYSIS

Transient State

The measured temperatures as a function of time are reported in Figure 3, for a bath temperature of 1.9 K on the left and of 4.25 K on the right. The results obtained using the described model are also shown. Different powers are considered in both cases: 1, 1.5, 2 and 6 W at 1.9 K, 1 and 6 W at 4.25 K.

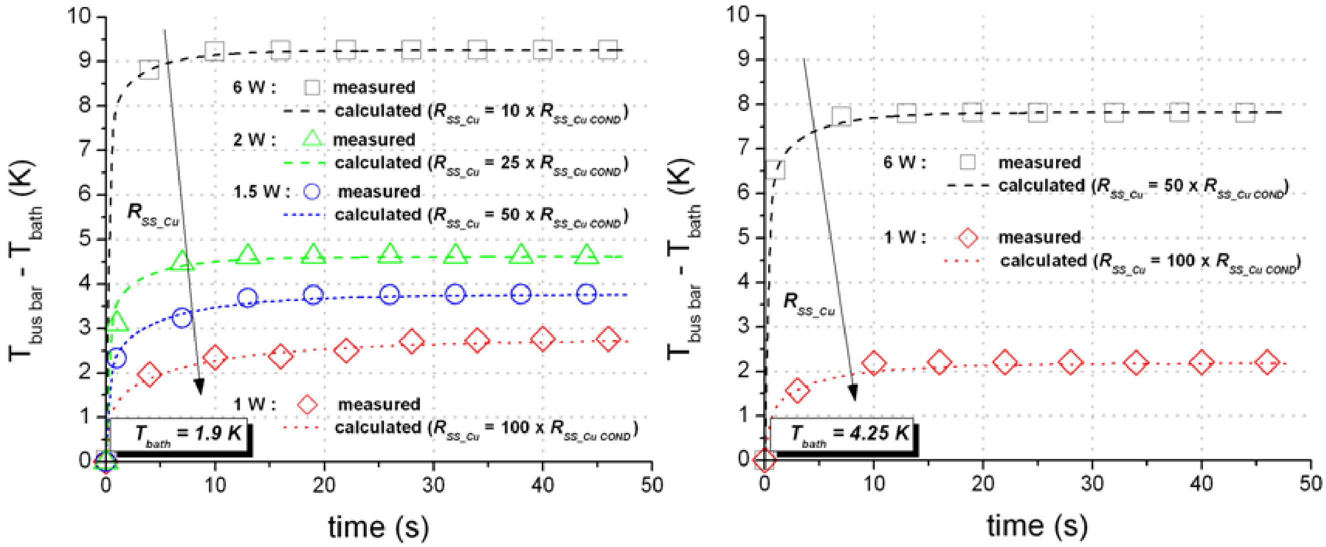

Figure 3 Measured and calculated temp. difference vs. time (see text). 1.9 K bath on the left, 4.25 K on the right

In order to reproduce the experimental data it was necessary to tune the thermal resistances between heaters and bus stabilizer (R_{SS_Cu}): a value of R_{SS_Cu} larger than the resistance due to only solid conduction across the polyimide bulk ($R_{SS\_Cu\ COND}$) has to be taken into account. In this case the heat transfer between heaters and bus stabilizer is indeed limited, thus yielding a lower temperature increase of the bus stabilizer and a bigger temperature increase of the heaters. Moreover, the heat transfer increases with time driven by the heaters temperature increase and by the corresponding decrease of thermal resistance R_{SS_Cu}. This increase of heat transfer is the cause of the temperature increase with time, and the higher R_{SS_Cu} is, the slower is the process. R_{SS_Cu} must be 10 to 100 times larger than the polyimide bulk thermal resistance. This cannot be explained in terms of thermal boundary resistance: although dependent on the properties of the contact materials and on the surface topography, literature does not show such large values of thermal boundary resistance [8]. We believe the reason of the large thermal resistance is the larger thermal contraction of the plastic components with respect to the copper. They are supposed to push the heaters against the copper, but the differential thermal contraction can cause a detachment of the components in the central hole: the lower the temperature is, the larger is the cleavage, thus the higher is R_{SS_Cu}. Furthermore, the possible presence of the superfluid contribution in parallel with the conduction one (at 1, 1.5 and 2 W at 1.9 K), or the series between the conduction and the film boiling (at 6 W at 1.9 K, at 1 and 6 W at 4.25 K) was deduced from the steady-state results discussed in the next sub-section. The transient analysis of the tests showed that the observed time constants are due to the experimental setup, and are not characteristic of a well soldered LHC bus bar, i.e. entirely filled with Sn-Ag (as shown schematically in Figure 1(a)).

Steady State

Figure 4 reports the measured steady-state temperature difference between bus bar and bath as a function of the power dissipated in the 150 mm long sample. The results obtained with two heat transfer models are also shown, based on conduction through the polyimide insulation, and on the series between conduction and a film boiling layer. This approach allows identifying the different heat transfer mechanisms.

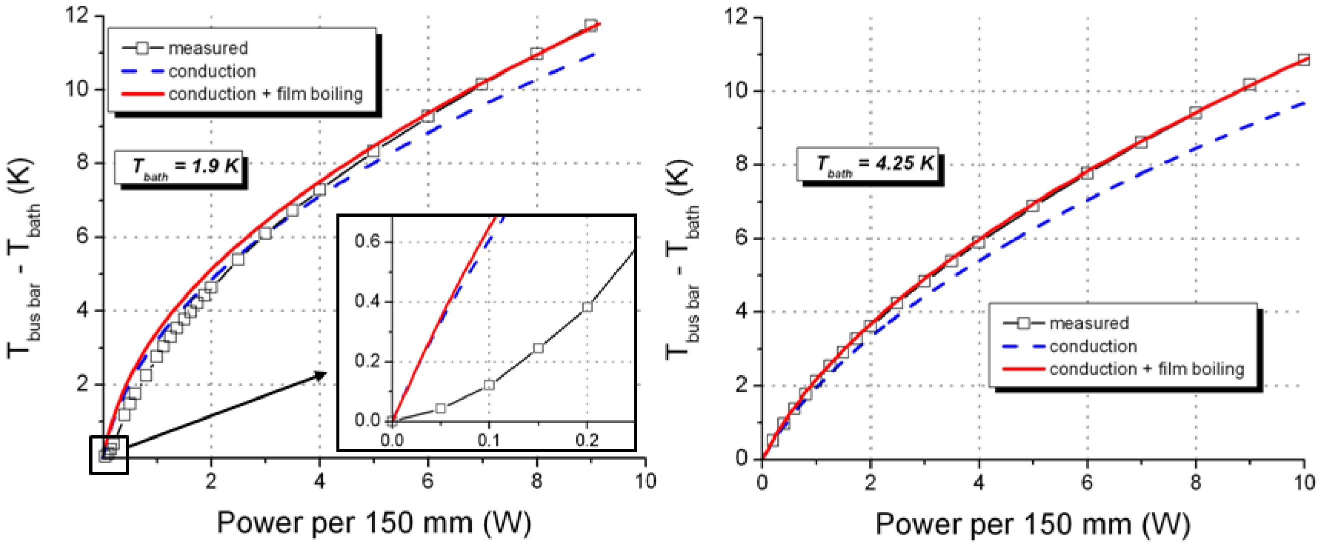

Figure 4 Measured steady-state temperature difference vs. dissipated power. Bath at 1.9 K on the left, at 4.25 K on the right. Two heat transfer models are considered: conduction and series between conduction and film boiling

In 1.9 K bath the He-II permeating the micro-channels between the insulation layers contributes to cooling for small powers. The effect of this contribution amounts to two to eight times the solid conduction one. It decreases with increasing the power, until the point (at around 3 W) where the measured curve crosses the calculated conduction curve. It is worth noting that this point where $Q_{He\text{-}II}$ becomes negligible corresponds to a bus bar temperature much higher than the He λ transition temperature. This might be related to the large temperature gradient associated to the thick insulation scheme. Above 3 W the measured curve tends towards the calculated conduction + film curve, which it reaches at around 7 W. It seems therefore possible to describe the heat transfer above 7 W by the series between conduction and a film boiling layer blanketing the bus bar external surface. This is more evident for the 4.25 K bath because always the case from the smallest measured power of 0.2 W. The film boiling thermal barrier effect is more significant at high temperatures, where the thermal resistance associated to the conduction mechanism

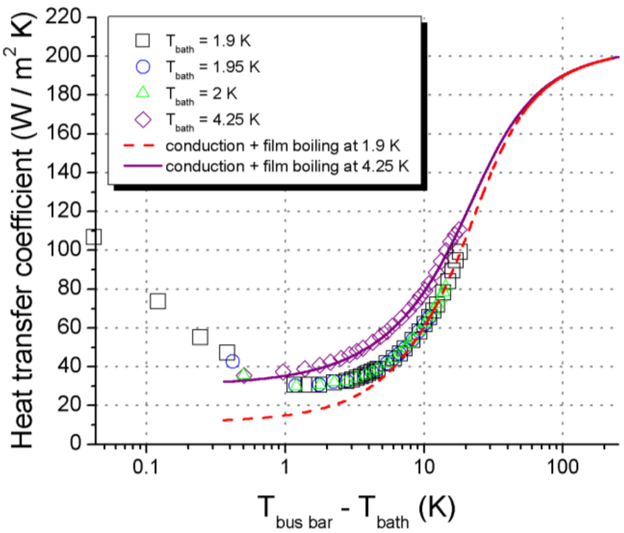

Figure 5 HTC for bath at 1.9, 1.95, 2 and 4.25 K. The conduction + film boiling model is also shown

decreases and the film boiling becomes the limiting mechanism.

The HTC is reported in Figures 5 for bath temperatures of 1.9, 1.95, 2 and 4.25 K. The results using the conduction + film boiling model both at 1.9 and 4.25 K are also shown: they aim at extending the results to larger temperatures, where the HTC saturates at a value of 200 W/m^2 K for both the 1.9 K and 4.25 K bath. The HTC does not show differences for bath temperatures of 1.9, 1.95 and 2 K but for the small temperatures region, where the He-II plays a significant role. Except for this region, the HTC in 4.25 K bath is always larger than in 1.9 K bath, thus confirming the relevance of the solid conduction mechanism, due to the large insulation thickness.

Because of the normalization over the heat transfer area, all considerations concerning the HTC are valid for both the MB dipoles and main quadrupoles (MQ) bus bars. These results will be used to analyze in terms of local HTC the tests reproducing defective interconnections [2]. This will allow improving the reliability of the stability calculations of the bus bars interconnection [3].

CONCLUSIONS

The modeling of the LHC interconnecting bus bars, following the 2008 incident, called for better understanding of the heat transfer from the bus bar to the cooling He bath.

Dedicated measurements were carried out on a bus bar sample in He-II and He-I bath. The relative analysis allowed describing the transient temperature behavior. The steady-state heat transfer was determined and the driving mechanisms identified. In particular, the effect of superfluid helium was shown, as well as that of conduction through the bus bar insulation and the film boiling formation. A complete picture of the LHC main dipoles and quadrupoles bus bars heat transfer coefficient was obtained.

REFERENCES

1. Rossi L., Superconductivity: its role, its success and its setbacks in the Large Hadron Collider of CERN, Superconductor Science and Technology (2010), 23 034001

2. Willering G. et al., Thermal Runaways in LHC Interconnections: Experiments, to be presented at Applied Superconductivity Conference, Washington, USA, 2010.

3. Granieri P.P. et al., Stability Analysis of the Interconnection of the LHC Main Superconducting Bus Bars, to be published.

4. Bottura L., Rosso C., Breschi M., A general Model for Thermal, Hydraulic, and Electric Analysis of Superconducting Cables, Cryogenics (2000), 40 617-626

5. Schmidt C., Review of Steady State and Transient Heat Transfer in Pool Boiling He I, International Institute of Refrigeration: Commision A1/2-Saclay, France, (1981) 17–31

6. Granieri P.P., Fessia P., Richter D., Tommasini D., Heat Transfer in an Enhanced Cable Insulation Scheme for the Superconducting Magnets of the LHC Luminosity Upgrade, to be published on IEEE Trans. Appl. Sup.

7. Baudouy B. et al., He II heat transfer through superconducting cables electrical insulation, Cryogenics (2000), 40 127–136

8. Gmelin E., Asen-Palmer M., Reuther M., Villar R., Thermal boundary resistance of mechanical contacts between solids at sub-ambient temperatures, J. Phys. D: Appl. Phys. (1999), 32 19-43