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Thermal Characterization of the HeII LHC Heat Exchanger Tube

D.Camacho[(1)], S.Chevassus[(2)], C.Policella[(3)], J.M.Rieubland[(3)], G.Vandoni[(3)], R. van Weelderen[(3)]

Abstract

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(1) Detached to CERN under the program Subprograma de Especialización en el Laboratorio Europeo de Física de Partículas, Ministerio de Educación y Cultura, C/Serrano N°150, 28071 Madrid, Spain
(2) AMSE, 7 Allée des Morilles, 74960 Meythet, France
(3) CERN, LHC Division

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Administrative Secretariat
LHC Division
CERN
CH - 1211 Geneva 23
Switzerland

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D.Camacho[(1)], S.Chevassus[(2)], C.Policella, J.M.Rieubland, G.Vandoni, R. van Weelderen,
CERN - LHC Division, CH - 1211 Geneva 23, Switzerland
[(1)] Detached to CERN under the program *Subprograma de Especialización en el Laboratorio Europeo de Física de Partículas*, Ministerio de Educación y Cultura, C/Serrano N°150, 28071 Madrid, Spain
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The LHC magnet cooling scheme is based on a HeII bayonet heat exchanger, which acts as a quasi isothermal heat sink. In order to assess the thermal performance of the oxygen free, annealed/cold worked copper tube, measurements of the total thermal conductance of the tube were performed in a laboratory set-up. This paper describes the experimental technique, which permits to separate the contribution of the Kapitza interface resistance from the total transverse conductance. The influence of the surface treatment on the Kapitza resistance is also discussed.

1 INTRODUCTION

The Large Hadron Collider (LHC) makes use of superconducting magnets operating in pressurized helium II at 1.9 K and 0.1 MPa for bending and focusing the particle trajectories. The heat generated in the cold mass is transported by conduction to a heat exchanger tube running all along the string of magnets [1], which works at a temperature difference less than 50 mK. Inside the tube, a flow of saturated helium II absorbs the heat by vaporization of the liquid.

Recently, a simplification of the cryogenic scheme was adopted [2], which increased the length of the cooling loops from a half-cell (53 m) to a full-cell (107 m). Doubling the length of the heat exchanger without changing its geometry would have lead to an unacceptable increase in pressure drop and hence to a decrease of its thermal performance. To avoid this, the design of the exchanger outer pipe has been changed from one with a corrugated cross section to one with a cylindrical section of larger hydraulic diameter. The thermomechanical optimization of the material leads to the choice of oxygen free high-conductivity (OFHC) copper with 21% cold work, instead of deoxidized high phosphorous (DHP) copper. The tube has an outer diameter of 58 mm for 2.3 mm of wall thickness.

The size of the tube has been determined under the assumption that the transverse thermal impedance be independent of the copper quality. The main scope of the present work is to verify this hypothesis. Additionally, since the thermal impedance is largely dominated by the Kapitza resistance across the interfaces between the solid and the superfluid, a study of the effect of the copper surface treatment has been undertaken.

2 EXPERIMENTAL METHOD AND RESULTS

The tube sample is filled with pressurized heliumII (see figure 1), and immersed in a bath of saturated heliumII. Applying heat $\dot{Q}$ to the inner bath, a temperature difference ΔT appears across the walls of the tube. The transverse thermal conductance of the exchanger tube is defined as $C_{th}^{tube} = \dot{Q} / \Delta T$. The thermal impedance R_{th}^{tube} is its inverse value. Three terms in R_{th}^{tube} can be identified: the Kapitza resistance R_K [3] of each liquid-solid interface, and the thermal resistance of the bulk copper, R_{Cu}. The bulk thermal resistance R_{Cu} can be considered constant over the small temperature range considered in our measures, whereas R_K depends strongly on temperature, following a T^{-3} law. Therefore, the total transverse thermal resistance for the tube, R_{th}^{tube}, is expressed as

$$R_{th}^{tube} = R_{Cu} + 2 \cdot R_K = \frac{e}{S\lambda_{Cu}} + 2 \cdot \frac{1}{C_K S} \cdot \frac{1}{T^3} \qquad (1)$$

where e is the wall thickness, S the interface surface, λ_{Cu} the thermal conductivity for copper and C_K the Kapitza coefficient characterizing the interface. We assume an equal value of the Kapitza resistance for the outer and the inner surfaces, yielding the factor 2 in equation (1). The measurements have been performed in the temperature range 1.7 K-2.0 K. Measuring ΔT for an applied power $\dot{Q}$, $R_{th}^{tube}(T)$ can be calculated from the slope of a $\Delta T - \dot{Q}$ graph at constant temperature T. Plotting R_{th}^{tube} versus $1/T^3$, we obtain a straight line. The values of C_K and λ_{Cu} are in principle deduced from its slope and intercept.

Actually, the bulk conductivity of OFHC copper with 21% cold work can be estimated relating tabulated RRR values and thermal conductivity values [4-5], yielding 200 W/K·m, or a thermal resistance of ~$5 \cdot 10^{-5}$ K·m/W. We shall see that this value is of the same order of magnitude as experimental uncertainty, hence it can be neglected with respect to the Kapitza component of the resistance, by setting the intercept equal to zero.

Notice that the measurement is performed in an inverse configuration compared to the LHC cryogenic scheme, where heat flows from the outer –pressurized– helium bath to the inner –saturated– helium bath. This inversion simplifies the layout of the experiment, without affecting the determination of the transverse thermal conductance, because of the only slight variation of the heliumII density between saturation and 1 bar. Since the exchange surface of the tube is fully wetted, we shall obtain the maximum heat that can be extracted from the cold mass for a given ΔT.

Figure 1 shows a schematic view of the experimental set-up. The 10 cm long sample is suspended in the cryostat using three long support rods and a circular support copper plate. The stainless steel end caps are 1 cm thick, to minimize heat leak through these to the bath.

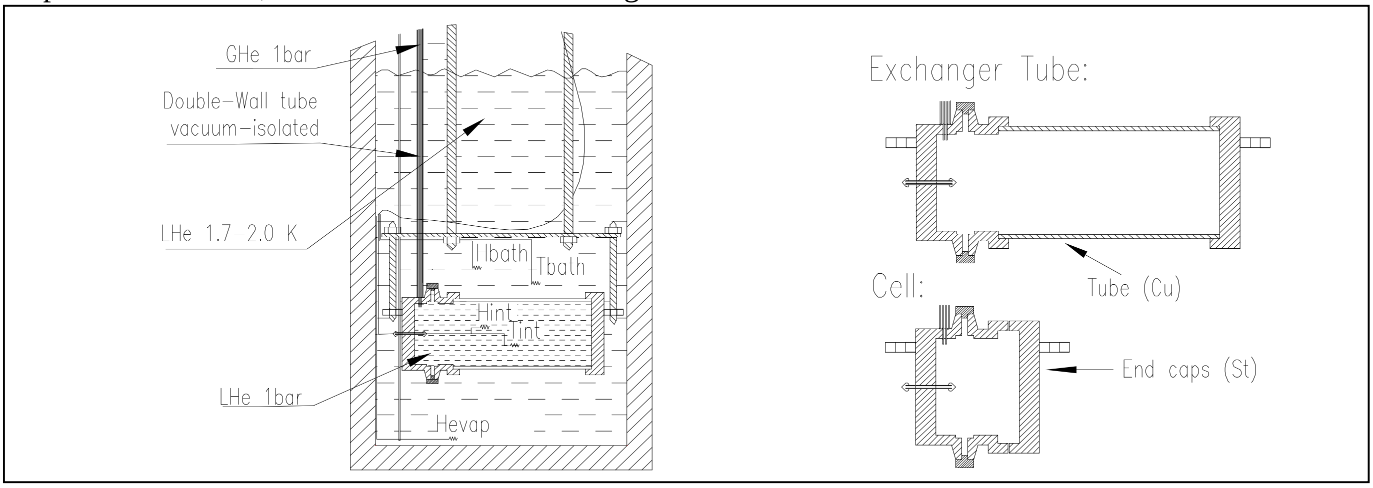

Figure 1: Layout of the experimental set-up. The insert shows the exchanger tube in the measuring configuration, compared to the calibration cell, where only the stainless steel end caps are mounted.

A 2 m long stainless steel capillary connects the tube to a gas bottle. The capillary is vacuum-insulated and thermalized to the lowest copper screen of the cryostat (not shown on figure 1), itself cooled by convection at ~2 K. This configuration reduces the heat leak through the superfluid column in the capillary to ~20 mW, while minimizing the heat leak from the inner bath to the outer bath.

Three calibrated carbon sensors (470 Ω at 273 K) fed with 1μA measure the pressurized bath temperature inside the tube (T_{int}), the saturated bath temperature (T_{bath}) and the temperature of the lowest cryostat screen. The absolute temperature of the bath is measured with an accuracy of ±3 mK. The error in ΔT is estimated to be ~0.5 mK. A resistor (H_{int}) is used to add heat inside the sample from 0 W to 1.2 W, with an error of 1%. The bath temperature is manually regulated keeping the pumping speed constant and controlling the power applied to a resistor (H_{bath}), yielding a stability better than 1 mK. All the signals are measured with a computerized acquisition system based on a Keithley 2000 scanner with a nominal resolution of 1 μV.

In order to account for the fraction of heat flowing through the stainless steel end-caps, a cell constituted by the end-caps alone is constructed and measured (see figure 1), following the same procedure as for the complete sample. This isolates the transverse conductance of the end-caps, allowing the correction of the data for the complete set-up by applying $C_{th}^{tot} = C_{th}^{tube} + C_{th}^{end-caps}$ (parallel heat flow). The heat flowing through the end-caps is thus found to account for less than 5% of the total heat flow (see table 2).

The Kapitza resistance depends strongly on the quality of the surface [3], therefore the cleaning method applied to the exchanger tube can affect its thermal performance. In order to study this effect, three samples with different surface treatments have been measured. Table (1) summarizes the treatment applied to each of the three samples. After cleaning, samples #2 and #3 were handled with gloves and stored in plastic bags. Sample #1 was handled without any special precaution.

	Sample #1	**Sample #2**	**Sample #3**
Description	Not treated	Degreased with Biosane SL 80 and deoxidized with Hydrochloric acid	Degreased with Biosane SL 80

Table 1: Cleaning treatment applied to the three tube samples.

Figure 2 shows a typical set of raw measurements in the $\Delta T - \dot{Q}$ plane. Every curve is taken at constant T_{bath}, and displays a linear behavior. The slope of each curve is the total thermal resistance, at constant bath temperature, the inverse of it is the total thermal conductance. Subtracting the end-cap conductance, we obtain the conductance of the copper tube alone. Values of this conductance at 1.9K are displayed in table 2, for all tested samples, as well as for the sole end-caps.

Over the whole temperature range, the transverse conductance of the untreated sample is about 30% smaller than that of the cleaned samples, which show essentially the same value. Figure 3 shows a plot of the thermal resistance of the tube alone, versus T^{-3}. Setting the intercept equal to zero in account of the small value of the bulk resistance, and interpolating linearly the data points, we obtain the values displayed in the second line of table 2. By statistical analysis, we estimate the error in C_{th}^{tube} to ~5%, and the error in C_K to ~3%. The copper resistance contribution amounts to 4% of the total resistance, which justifies that it is neglected in the linear interpolation.

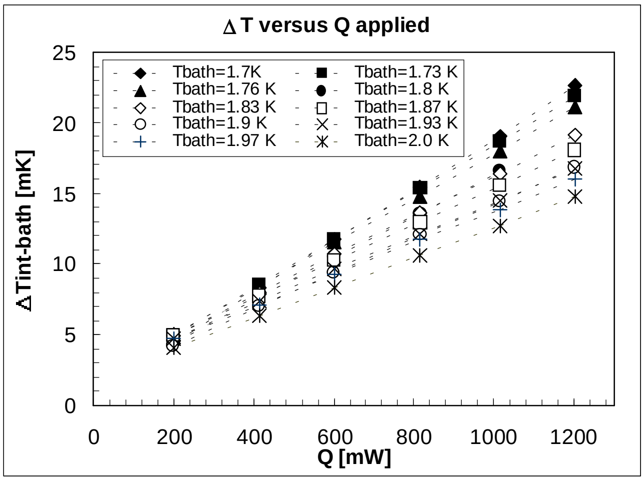

Figure 2: Measured temperature difference as a function of applied heating power, for different bath temperatures. From the slope of the curves, $R_{th}^{tube}(T)$ is deduced

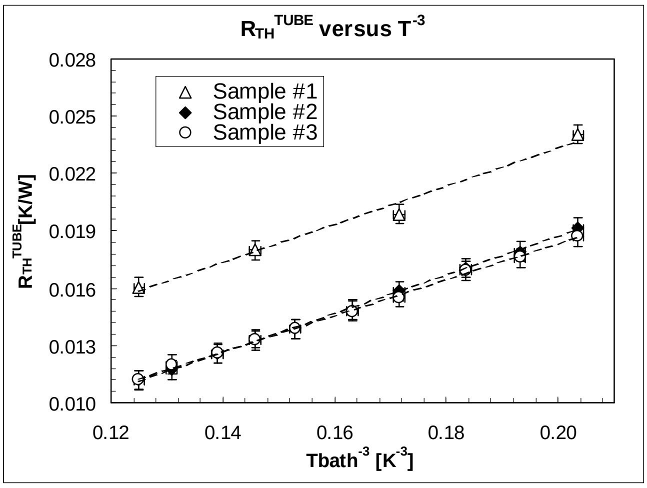

Figure 3: R_{th}^{tube} versus $1/T^3$. Applying (1), and assuming the intercept to be equal to zero, C_K can be calculated from the slope of the linear fit.

	Sample #1	**Sample #2**	**Sample #3**	**End-caps**
C_{tot} [W/K m] @ 1.9K	556 (± 25)	749 (± 30)	754(± 30)	37
C_K [W/K^{4}m^2]	914 (± 37.6)	1193 (± 30.1)	1205 (± 29.7)	

Table 2: Values of the tube transverse conductance, and of the Kapitza conductance obtained from a linear fit of $R_{th}^{tube}(T)$ versus $1/T^3$.

The measurements demonstrate that the different surface treatment for samples #2 and #3 do not result in a different transverse conductance. This shows that the oxidation of sample #1 due to exposure to the atmosphere is more important in determining the Kapitza coefficient than the effect of deoxidation with respect to degreasing.

A review of literature shows that the values obtained for C_K are higher than published data. Values of C_K for copper in the range 400-900 W/K^{4}m^2 are reported in [3], whereas previous measurements realized at CERN [6] on the corrugated DHP copper tube yielded values in the range 824-890 W/K^{4}m^2. These were the values retained to evaluate the behavior of the heat exchanger in the simplified cryogenic LHC scheme. It is possible that cold work, which is known to reduce the Young modulus by creating mobile dislocations [4][7], influences the Kapitza conductance by the same mechanism of increased elasticity. The influence of bulk rigidity on the Kapitza conductance appears clearly from the relation between C_K and the Debye temperature Θ_D, $C_K \propto T^3 \Theta_D^{-n}$, $n \approx 1$ [3], the latter being a good empirical parameter of the stiffness of the solid.

3 CONCLUSIONS

The total transverse conductance of the LHC cold mass heat exchanger tube is measured as a function of temperature, in the range 1.7 K-2 K, and for samples to which a distinct surface cleaning has been applied. It yields a value of 750 W/K m at 1.9 K, for degreased and/or deoxidized samples, and of 560 W/K m for the untreated sample. The surface cleanliness determines an increase in the transverse conductance of about 30%. Disentangling the Kapitza conductance from the total transverse conductance, we obtain values of C_K of 920-1200 W/K^{4}m^2. Larger values of the Kapitza conductance with respect to literature can possibly be accounted for by the amount of cold work. This work shows that the estimation of the total transverse conductance of the cold mass exchanger, which has been applied to evaluate the simplified LHC cryogenic scheme, is conservative.

4 REFERENCES

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