Report

Development, Validation and Application of a Novel Method for Estimating the Thermal Conductance of Critical Interfaces in the Jaws of the LHC Collimation System

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Abstract

The motivation for this project arises from the difficulty in quantifying the manufacturing quality of critical interfaces in the water cooled jaws of the TCTP and TCSP (Target Collimator Tertiary Pickup and Target Collimator Secondary Pickup) collimators. These interfaces play a decisive role in the transfer of heat deposited by the beam towards the cooling system avoiding excessive deformation of the collimator.

Therefore, it was necessary to develop a non-destructive method that provides an estimation of the thermal conductance during the acceptance test of the TCTP and TCSP jaws.

The method is based on experimental measurements of temperature evolution and numerical simulations. By matching experimental and numerical results it is possible to estimate the thermal conductance in several sections of the jaw.

A simplified experimental installation was built to validate the method, then a fully automatic Test-Bench was developed and built for the future acceptance of the TCTP/TCSP jaws which will be manufactured and installed in the LHC.

This novel method has shown its validity and has become a decisive tool for the development of the new generation of LHC collimators.

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INTRODUCTION

The operation of the LHC in terms of reliability and luminosity strongly depends on the performance of the LHC collimation system [1]. The jaws interact directly with the beam to clean it from the halo and protect the machine against high-energy impacts [2].

In the TCTP jaw, shown in Figure 1, during cleaning operations, part of the beam energy is deposited in the tungsten inserts screwed against the copper Glicop Al-15 front beam. The heat is then evacuated by means of the cooling system consisting of two copper C70600 U-bend tubes brazed against the front and back copper Glicop Al-15 beams.

The screwed tungsten-copper and the brazed copper-copper interfaces play a critical role in the cooling process since they present a higher resistance to heat flow compared to the beams and cooling tubes.

To avoid excessive deformation of the jaw and to ensure the correct functioning of the collimator the thermal conductance must be high. It is therefore necessary to

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estimate the thermal conductance of these interfaces in order to accept or reject the jaw after the manufacturing process.

This paper presents the method developed for estimating the thermal conductance of an interface using transient temperature evolutions applied to the brazed interface of the TCTP and TCSP jaws.
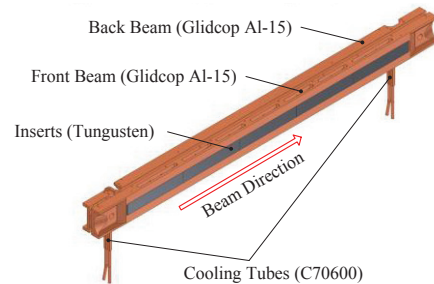

Figure 1: TCTP jaw.

METHODOLOGY

The thermal conductance U (W/m²K), is defined by $U = q''/(T_2 - T_1)$ [3], where q'' is the heat flux (W/m²) and T_2 and T_1 are the temperatures (K) on each side of the interface. In practice, the problem of measuring U would be easily solved using the steady state method [4]. However in this case, it would be very difficult to measure q'', T_2 and T_1 after brazing since the tubes in the middle of the jaw are inaccessible, as shown in Figure 2. It was therefore decided to develop another method in order to estimate U.

Initially, the jaw is at temperature T_{ref} when hot water at temperature T_{hot} starts to flow in the cooling tubes. All the other surfaces are in contact with air at ambient temperature T_{air}.
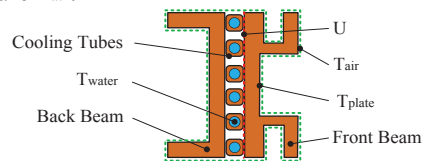

Figure 2: Section view of the TCTP jaw and representation of the 2D model.

Assuming that boundary conditions, geometry and materials are fixed, the transient evolution of temperature $T_{plate\_i}\ (t;\ U)$ is a function of U, as shown in Figure 3. However, the sensibility of $dT_{plate\_i}\ /dt$ decreases when the value U multiplied by the thickness of the interface approaches the thermal conductivity of copper.

Let Δt_i be the time taken to increase from temperature $T_{plate\_i}(t) = T_a$ to temperature $T_{plate\_i}(t) = T_b$, where $T_b > T_a$.

Using an experimental and numerical procedure it is possible to find a numerical correlation of U vs. Δt_i and therefore estimate the experimental value of U.

In the experimental procedure, hot water is injected in the jaw. At the same time, $T_{plate\_i}(t)$ in equally spaced sections of the jaw, inlet and outlet water temperatures, water volumetric flow rate and T_{air} are measured.
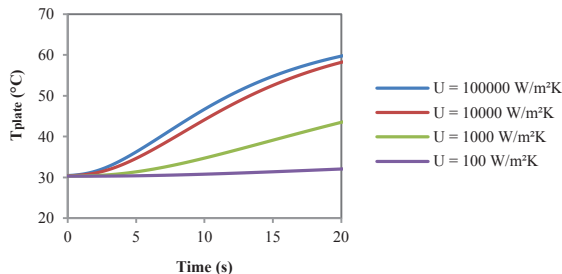

Figure 3: Typical evolutions of T_{plate_i} function of U with fixed boundary conditions using the 2D model.

Subsequently, a 2D model is built for every section of the jaw (the longitudinal heat conduction is negligible for this application) to reproduce the conditions of the experimental set-up. The boundary conditions for the 2D model include water forced convection, air natural convection and radiation losses to the surroundings. For each section of the jaw, a numerical parametric study of U is performed to correlate the evolution of U vs. Δt_i.

Finally for each section of the jaw, the experimental value of Δt_i is found using the measured evolution of $T_{plate\_i}(t)$, and from this the value U can be estimated.

EXPERIMENTAL PROCEDURE

Two Test-Benches were built. The first in a simplified version to validate the principle, while the second is a fully automated version, conform to all safety requirements and CE marked to be used by the factory producing the new LHC collimators, as shown in Figure 4.

The hydraulic circuit of the automated Test-Bench is presented in Figure 5. The electro-valves and less relevant sensors are not represented. The pumps, electro-valves and heaters are software controlled.

Eight Fast Response Thermocouples (FRTs) are placed in equally spaced sections of the jaw to measure $T_{plate\_i}(t)$. The inlet and outlet water temperatures are measured using Resistance Temperature Detectors (RTDs) and the water volumetric flow rate is measured using a magnetic flowmeter.

The hydraulic circuit is composed by two sub-circuits one for heating and one for cooling. In the heating circuit the water is heated at 70 ± 0.5 °C and is injected in the jaw at a flow rate of 5 ± 0.05 l/min. Data is acquired until the minimum temperature in the jaw is greater than 60°C. The cooling circuit is then turned on and heat is exchanged with tap water by the means of a heat exchanger until the jaw reaches $T_{plate\_i}(t) = 30 \pm 0.5$°C.

Figure 4: Pictures of the front and back of the Test-Bench.

This procedure is repeated ten times to improve the statistics of the measurement. Typically, the maximum standard deviation for all temperature signals and flow signals has been measured to be respectively 0.7 °C and 0.25 l/min.
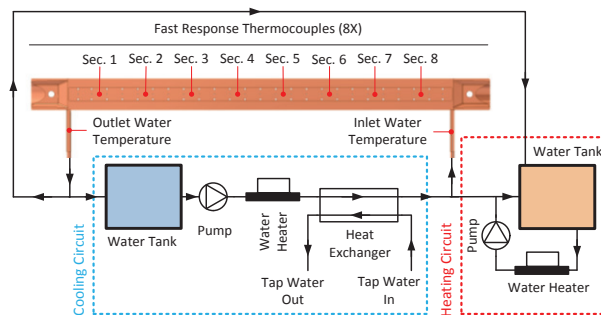

Figure 5: Simplified schematic of the hydraulic circuit.

NUMERICAL PROCEDURE

In this section we describe in detail the numerical procedure used to correlate the value of U to Δt_i and to deduce both from the measured evolution of $T_{plate\_i}(t)$.

The boundary conditions for the 2D model of each section include forced convection in each tube, natural convection in all the surfaces and radiation losses to the surroundings.

The natural convection coefficient $h_{air}(T_{plate})$ calculation is based on the measured value of T_{air} using the Churchill-Chu correlation for vertical plates. T_{air} and emissivity $\varepsilon = 0.2$ (polished copper) are used for the radiation boundary conditions. The water convection coefficient $h_w(t)$ and $T_{water}(t)$ for each tube are used as forced convection boundary conditions. $T_{water}(t)$ is calculated interpolating the inlet and outlet water temperature. $h_w(t)$ is calculated using the Petukhov–Popov correlation, $T_{water}(t)$ and the measured water flow rate. Both $T_{water}(t)$ and $h_w(t)$ vary with the arclength of the tubes and are function of time.

Figure 6 presents typical inlet and outlet temperatures and flow signals.

Figure 7 presents typical signals of $h_w(t)$ and $T_{water}(t)$ for one tube (three crossings) in one section.
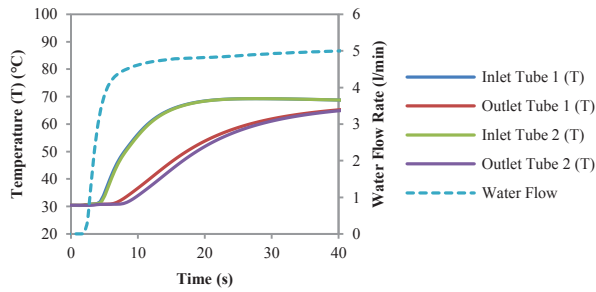
Figure 6: Typical inlet and outlet temperatures and water flow rate signals for the two tubes of the jaw.
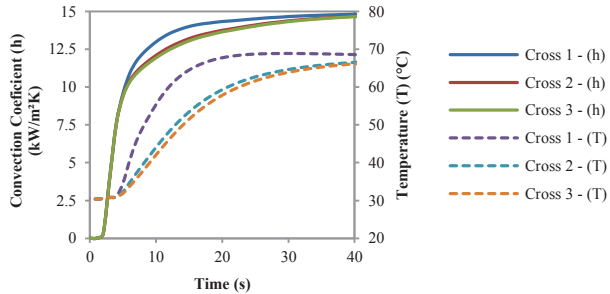

Figure 7: Typical boundary conditions for the 2D model of one tube in one section.

The parametric study of U is performed for each section where T_{plate_i} (t) was measured. Consequently, the numerical correlation of U vs. Δt_i for each section is built from setting T_a and T_b to 35°C and 55°C respectively. Figure 8 presents a typical correlation obtained for sections 1 and 8 in the case of a TCTP jaw.
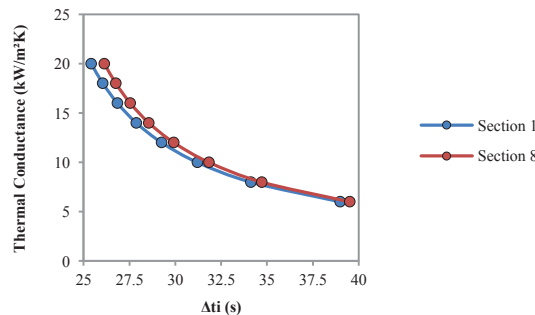

Figure 8: Typical correlations obtained from numerical data in the case of the TCTP jaw.

RESULTS

Although several different jaws were tested, only four TCSP and TCTP cases are presented here for a better visualisation. Figure 9 shows that in the case of the brazed TCSP jaws, U varies from approximately 15 kW/m²K to 8 kW/m²K in the different sections, possibly due to small variations in the brazing process or different flatness tolerances of the contact interfaces.

Concerning the TCTP jaws, the brazed design offers a better thermal conductance (12 kW/m²K) than the screwed design (10 kW/m²K). While it is expected that brazed contacts behave better than screwed ones, the

difference is reduced with respect to theoretical values. Again, this is an indication of the imperfection of the brazed contact that will be further investigated in the future by ultrasound and metallographic tests.
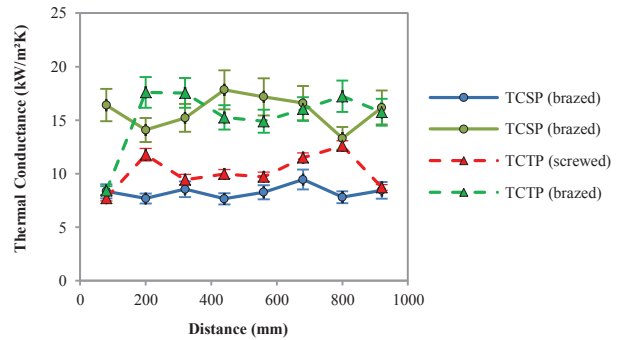

Figure 9: Thermal conductance of four different jaws.

CONCLUSIONS

A novel method to estimate the thermal conductance of contact interfaces for the LHC collimator jaws has been developed.

The results presented show the variability of the brazing quality obtained in different jaws, reinforcing the importance of a jaw acceptance test based on its thermal conductance.

Moreover, this method also allows the comparison of different designs. It has therefore become a decisive tool for the development of the new generation LHC collimators.

ACKNOWLEDGMENTS

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