PRELIMINARY THERMO-MECHANICAL ANALYSIS OF ANGULAR BEAM IMPACT ON LHC COLLIMATORS*

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Abstract

The correct functioning of the LHC collimation system is crucial to attain the desired LHC luminosity performance. However, the requirements to handle high intensity beams can be demanding. In this respect, accident scenarios must be well studied in order to assess if the collimator design is robust against likely error scenarios. One of the catastrophic - though not very probable - accident scenarios identified is an asynchronous beam dump coupled with slight angular misalignment errors of the collimator jaw. Previous work presented a preliminary thermal evaluation of the extent of beam-induced damage for such scenarios, where it was shown that in some cases, a tilt of the jaw could actually serve to mitigate the effect of an asynchronous dump on the collimators.

This paper will further analyze the response of tertiary collimators in presence of such angular jaw alignments, with the aim to identify optimal operational conditions.

INTRODUCTION

The LHC collimation system consists of several collimators placed in 7 out of 8 LHC IPs (interaction regions), having the two essential functions of beam cleaning and machine protection. In fact, in case of accident scenarios, when the highly energetic beam (7TeV at nominal conditions) is out of control, collimators are strategically positioned in order to absorb the particle impact, thus serving as a protection for other critical structures such as the downstream superconducting magnets [1]. Being in close proximity to the beam, the collimator jaws are continuously exposed to direct interaction with high-energy particles. Moreover, in case of an accident, one or more high-energy density bunches might directly impact on a collimator with possible serious consequences.

The work presented in [2] initiated a parametric study to investigate the effect of the beam hitting the collimator jaw at a small angle due to slight misalignment errors of the collimator installation at the beam-line. It was shown that not all collimator misalignment angles have the same effect when it comes to beam-induced damage. In fact, the outcome was that a jaw inclination of 1 milliradian (mrad) away from the beam, could actually mitigate the effect of the beam-induced damage in case of an accident. This was a very interesting observation as it could mean that the collimator jaw could actually be inclined at this angle on purpose in order to dilute any impact effects.

The mechanical response of the collimator structure to energy deposition is deemed extremely important [3]. Consequently, in view of the highly destructive nature of the beam, it was considered essential to determine whether this inclination angle could be further optimized.

ACCIDENT SCENARIOS

This study will continue to focus on an asynchronous beam dump. This refers to a spontaneous misfiring of one of the horizontal extraction kicker magnets (MKDs) that causes a trigger outside the abort gap. In these cases, some bunches are kicked at an angle that is smaller than the nominal kick, and consequently they circulate for 1 turn before being kicked out. If the collimators are set up correctly, sensitive equipment is in the shadow of the TCDQ block and is thus well-protected.

Indeed, this study focuses on a combined error case in which, following an asynchronous kick (in the right phase advance) of the kicker magnet, and due to a setup error of the TCDQ, one bunch of the LHC directly impacts on a collimator jaw and penetrates it at a certain transverse offset, known as the impact parameter. Moreover, in the accident cases studied in this paper, the impacted jaw has a slight inclination of a few mrad (Figure 1). This particular study focuses on accidents involving horizontal tertiary collimators (TCTHs) due to the fact that a mis-kick accident can only act on the horizontal plane.

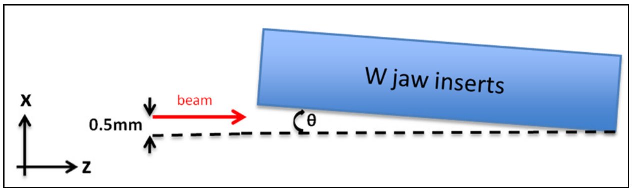

Figure 1: Schematic diagram of the studied accident scenarios. The jaw is inclined as shown due to misalignment errors. The angle θ ranges from 0mrad in which case the jaw is perfectly aligned with the beam direction to -1mrad which is the configuration shown in the diagram.

This paper presents some general cases based on these very realistic, although not so probable, combined error scenarios for which general inputs have been used to investigate what happens to the collimator structure. In all studied cases, the beam energy is 3.5TeV, and the

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bunch has the same impact parameter (0.5mm), charge ($1.3\text{x}10^{11}$p) and beam size (0.3mm(σ_x) × 0.3mm(σ_y) RMS). Simulations were carried out covering the range of jaw inclinations from 0mrad to -1mrad in steps of 0.1mrad, with the inclinations that gave the most interesting results being presented here.

NUMERICAL ANALYSIS

Tools & Geometry

The fast and complex thermo-mechanical phenomena induced by the interaction of beam particles with matter, as well as the complexity of the collimator structure, make the implementation of a numerical approach through finite element analysis highly necessary [4]. Non-linear, transient analyses were thus performed to correctly evaluate the temperature distribution and other thermally-induced effects due to beam impact. Such sequential analyses were conducted using the ANSYS® Finite Element code.

FLUKA [5,6] models were set up and full shower simulations [7] provided energy deposition distributions for the defined accident cases. These 3D maps were then loaded in the ANSYS 3D model through dedicated subroutines in order to provide the input thermal load in terms of power density distribution.

Simulations were performed on the lower symmetrical half of a TCTH collimator jaw (Figure 2) since the considered beam impact leads to a symmetrical energy deposition in the longitudinal plane (x-z plane in Figure 2).

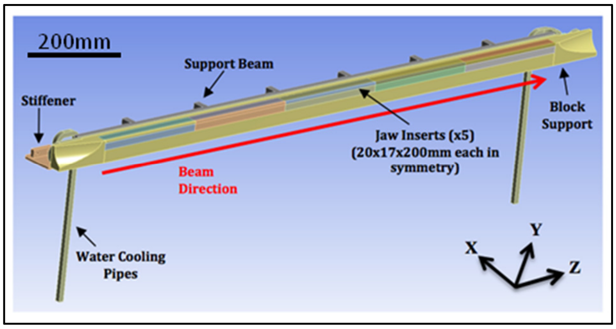

Figure 2: Lower symmetrical half of the collimator structure.

Finite Element Discretization

The energy deposition profile results from FLUKA justified the choice of the element size as well as its location for simulations in ANSYS. The finest mesh size with dimensions 0.1mm(x) × 0.1mm(y) × 5mm(z) was only necessary in the beam impact region. The same mesh was employed for thermal and structural analyses in order to facilitate sequential analyses.

Material Modelling

Temperature-dependent thermal material properties were implemented in the model. In reality, the material of the jaw inserts is a W(95%)-Ni(3.5%)-Cu(1.5%) alloy, known commercially as INERMET 180. Unfortunately, literature data providing properties of such an alloy at high temperatures is very scarce. A full thermal characterization of this alloy has however been performed [8]. Therefore, unlike previous simulations [2] where the material adopted for the jaw inserts was pure tungsten, the new measured values for INERMET 180 were used to define the thermal properties for the material model of the collimator jaw inserts in this work (Figures 3-5).

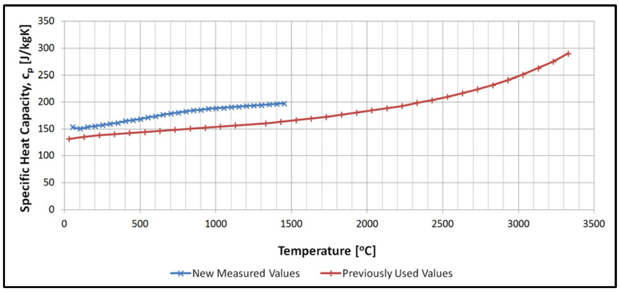

Figure 3: Specific heat capacity as a function of temperature used for the TCTH jaw inserts [8].

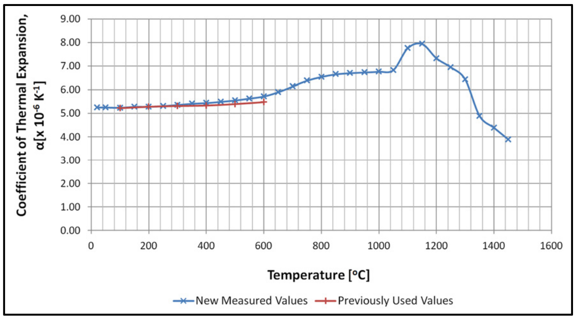

Figure 4: Coefficient of thermal expansion as a function of temperature used for the TCTH jaw inserts [8].

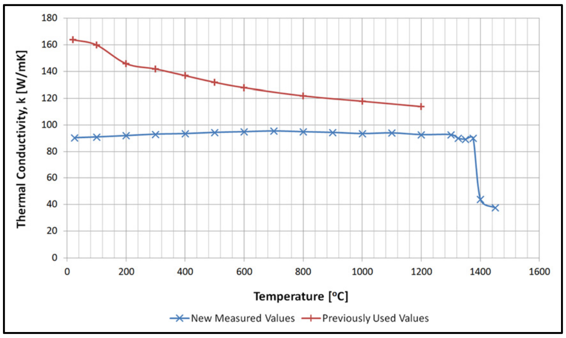

Figure 5: Thermal conductivity as a function of temperature used for the TCTH jaw inserts [8]. The sharp drop in the thermal conductivity above 1300°C is due to sintering effects which cause the sample thickness to decrease leading to such data becoming highly uncertain at temperatures higher than onsets like this.

Loading and Boundary Conditions

Thermal load is applied as an internal heat generation caused by the beam impact with duration of 1ns. Thermal analyses were performed for the whole collimator structure, accounting also for the convection of the cooling system by specifying a convection coefficient on the inner wet surface of the cooling pipes.

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RESULTS

A first, preliminary assessment of the extent of beam-induced damage can be done by evaluating the maximum temperatures reached and consequently the extent of the molten region. Figure 6 shows the different peak temperatures reached along the jaw as well as their different locations for the newly defined misalignment angles. During the 1ns beam impact duration, the system receives all the energy and reaches the maximum temperature on the jaw inserts (Figure 7).

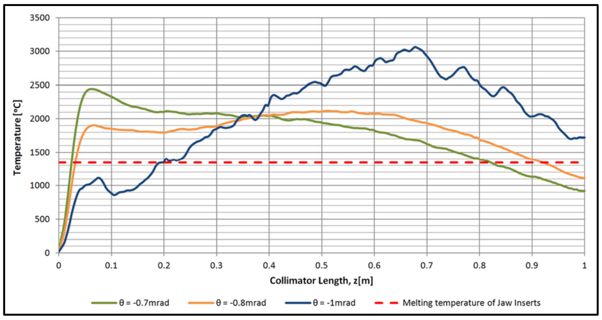

Figure 6: Temperature peak profiles within the jaw inserts along the beam direction for the different angles.

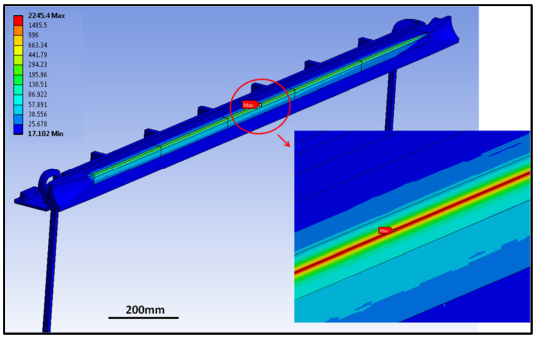

Figure 7: Temperature distribution on the lower symmetrical half of the collimator jaw assembly after 1ns for the -0.8mrad misalignment angle. The temperature values in the legend are in ^{o}C.

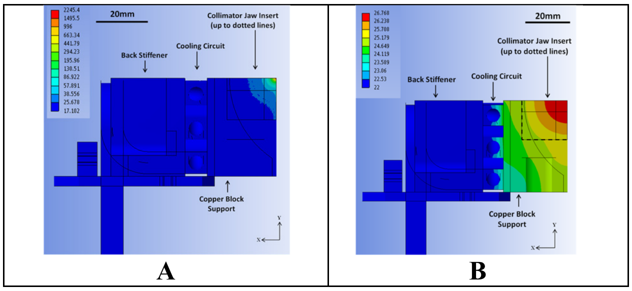

Figure 8: Temperature distribution at the hottest cross-section for the -0.8mrad misalignment angle. The temperature values in the legend are in ^{o}C. (A) After 1ns. (B) After 5s.

It can be observed that compared to the -1mrad case, an inclination of -0.8mrad yet again imposes a better temperature distribution on the jaw. Figure 6 thus shows that by varying the jaw inclination, one can minimize the extent of the molten region and beam-induced damage by obtaining a more uniform temperature distribution on the collimator structure. Moreover, at the end of the energy deposition, only the collimator jaw inserts experience a rise in temperature since thermal diffusion does not play an important role during this short time-range, resulting in very localized heating (Figure 7). However, from this time on, the temperature distribution tends to become more uniform because of thermal diffusion, thus resulting in most of the collimator structure components experiencing an increase in temperature (Figure 8).

CONCLUSIONS

The purpose of this study was to evaluate the response of horizontal tertiary collimators to beam impact in view of newly defined misalignment angles with the use of new and more suitable thermal material properties. A jaw inclination of -0.8mrad proved to be optimal in spreading the effect of the beam all along the jaw edge, resulting in an overall lower peak temperature. This means that having the same impact parameter and beam conditions, one can vary the misalignment of the collimator jaw in order to mitigate the effect of the beam-induced damage. However, the amount of escaping high energetic protons, which can potentially be lost in the superconducting magnets located downstream of the impacted collimator, must also be taken into account.More detailed thermal as well as structural analyses are foreseen in the near future to further investigate the thermally-induced dynamic response of the collimator structure in these scenarios.

ACKNOWLEDGEMENTS

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