PRELIMINARY ASSESSMENT OF BEAM IMPACT CONSEQUENCES ON LHC COLLIMATORS

M. Cauchi[#], CERN, Geneva, Switzerland and University of Malta, Msida, Malta
R. Assmann, A. Bertarelli, R. Bruce, F. Carra, A. Dallocchio, D. Deboy, N. Mariani, A. Rossi, CERN, Geneva, Switzerland
L. Lari, CERN, Geneva, Switzerland and IFIC (CSIC-UV), Valencia, Spain
P. Mollicone, N. Sammut, University of Malta, Msida, Malta

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, the robustness of the collimators plays an important role. An accident, which causes the proton beam to hit a collimator, might result in severe beam-induced damage and, in some cases, replacement of the collimator, with consequent downtime for the machine.

In this paper, several case studies representing different realistic beam impact scenarios are shown. A preliminary analysis of the thermal response of tertiary collimators to beam impact is presented, from which the most critical cases can be identified. Such work will also help to give an initial insight on the operational constraints of the LHC by taking into account all relevant collimator damage limits.

INTRODUCTION

One of the main goals of the LHC collimation system is to keep the highly energetic beam (7TeV at nominal conditions) under control by ensuring that any particle losses that occur stay at a safe level [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, for instance due to an asynchronous beam dump, one or more high-energy density bunches might directly impact on a collimator with possible serious consequences. This effect might be even further amplified in the presence of slight misalignment errors concerning the collimator jaw inclination.

On impact, abnormal beam loss processes result in very fast energy deposition within the jaws, thus provoking a thermo-mechanical dynamic response of the system including the development of shock waves within the affected structure [2]. As the high-energy protons impinge on the collimator jaw, they produce particle cascades that deposit their energy in matter. This leads to an intense thermal load developed within the collimator jaws that causes an increase in temperature, the latter being determined by the particle shower developed within the jaw as well as by the thermal properties of the jaw material.

[#]marija.cauchi@cern.ch

Consequently, in view of the highly destructive nature of the beam as well as the likelihood of accident scenarios, the mechanical response of the collimator structure to energy deposition is deemed extremely important.

ACCIDENT SCENARIOS

One of the most probable accident scenarios is an asynchronous beam dump, where a mis-kick of the kicker magnet at Point 6 of the LHC, which is devoted to the Beam Dumping System, may cause one bunch of the beam to directly impact on the collimator jaw and penetrate it at a certain transverse offset, known as the impact parameter. Furthermore, other accident cases have been identified to investigate what happens if, in addition, the impacted jaw has a slight inclination of a few mrad due to misalignment errors of the collimator installation at the beamline (see 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.

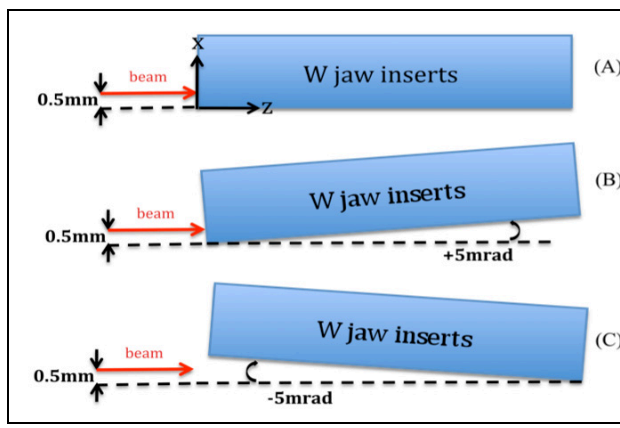

Figure 1: Schematic diagram of the studied accident scenarios. (A) Ideal case: perfect alignment of jaw with beam direction (0mrad angle). (B) & (C) Cases with jaw inclination due to misalignment errors.

Case Studies

Eight different cases were derived from these scenarios, with varying beam energies and impact angles. In all cases, the bunch has the same impact parameter (0.5mm), charge (1.3×10^{11}p) and beam size (0.3mm(σ_x)×0.3mm(σ_y) RMS). Relevant parameters for the studied cases are provided in Table 1.

Table 1: List of studied accident cases.

Case	Energy [TeV]	Angle [mrad]	Deposited energy on 1 jaw [kJ]	TNT equivalent [g]
1	7	0	48.50	11.56
2	7	+5	12.11	2.89
3	7	-5	10.32	2.46
4	3.5	0	23.08	5.50
5	3.5	+5	6.39	1.52
6	3.5	-5	5.22	1.24
7	7	-1	29.73	7.09
8	3.5	-1	14.18	3.38

It is necessary to point out that a jaw inclination of 5mrad in either direction is regarded as the maximum misalignment error that can be present and thus, these scenarios are studied as limiting cases.

NUMERICAL ANALYSIS

The fast and complex thermo-mechanical phenomena induced by the interaction of beam particles with matter make the implementation of a numerical approach through finite element analysis highly necessary [3]. Non-linear, transient analyses were thus performed to correctly evaluate the temperature distribution due to the different beam impacts. Such analyses were conducted using the ANSYS® Finite Element code. These ANSYS analyses are complemented by non-linear hydrocodes simulations [2] when phase changes and the presence of shock waves must be accounted for.

A FLUKA [4, 5] model of the jaw inserts was set up and full shower simulations 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.

Geometry

Simulations were performed on a TCTH collimator jaw. Since the considered beam impact leads to a symmetrical energy deposition in the longitudinal plane, it was only necessary to model the lower half of the collimator structure (see Figure 2).

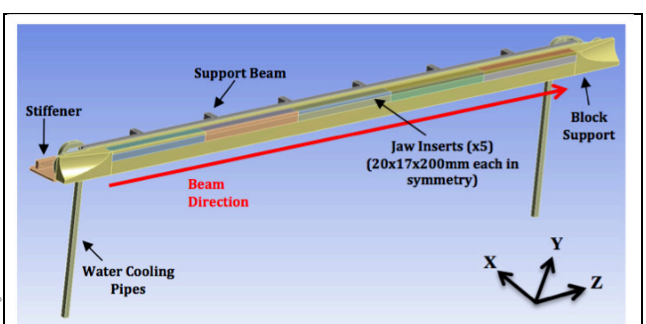

Figure 2: Lower symmetrical half of the collimator structure.

Finite Element Discretization

In finite element modelling, one way to obtain a mesh that satisfactorily balances accuracy and computational resources is a mesh convergence study. The FLUKA results have 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 region around the beam impact.

Material Modelling

The thermal material properties implemented in the model are temperature-dependent. In reality, the material of the jaw inserts is a W(95%)-Ni(3.5%)-Cu(1.5%) alloy, known as Inermet 180. However, in the simulations, the material adopted for the jaw inserts is pure tungsten (W). Such an assumption is considered acceptable for the thermal analyses to be performed in this study.

Loading and Boundary Conditions

Thermal load is applied as an internal heat generation caused by the beam impact; since the bunch length in time is 1ns, the thermal shock duration is considered to be of the same value. Thermal analyses were performed for the collimator structure, accounting also for the convection of the cooling system.

RESULTS

A first, preliminary assessment of the extent of beam-induced damage can be done by evaluating the maximum temperatures reached as well as the dimension of the molten region on the jaw inserts.

During the 1ns beam impact duration, the system receives all the energy and reaches the maximum temperature on the W inserts. Figure 3 portrays the different peak temperatures reached as well as their different locations.

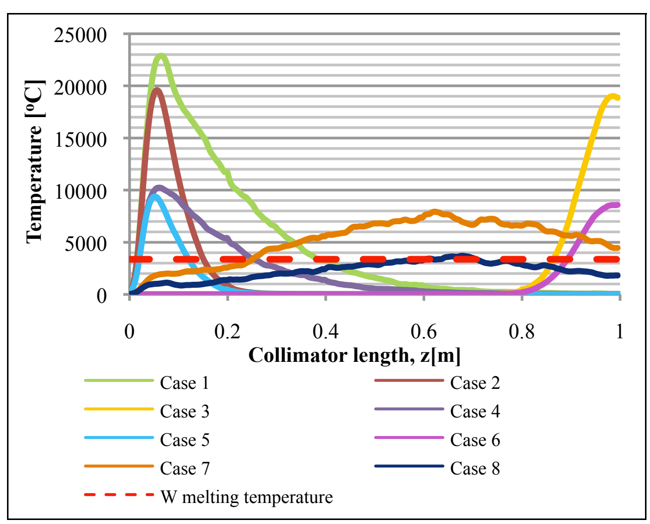

Figure 3: Temperature peak profiles within the jaw inserts along the beam direction for the different accident cases.

The effect of the beam impacting at different angles on the cross-sectional temperature distribution can also be seen in Figure 4 where the most loaded case (Case 1) and the least loaded case (Case 7) at 7TeV can be compared.

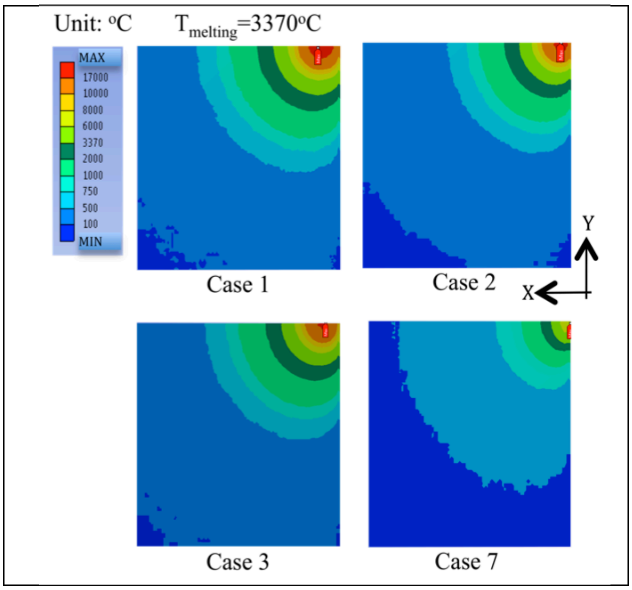

Figure 4: Comparison of the cross-sectional temperature distribution at T_{max}-slice just after the impact at 7TeV. Note that the region from the dark green edge towards the corner is above the melting temperature.

A proton population study (see Figure 5) was also performed for the ideal 0mrad case (see Figure 1A) at 7TeV (Case 1), this time varying only the number of p/bunch while keeping all other parameters constant. The purpose is to give an idea of the number of p/bunch that will cause melting of the jaw material. Such a study will thus serve to support future studies on the onset of damage.

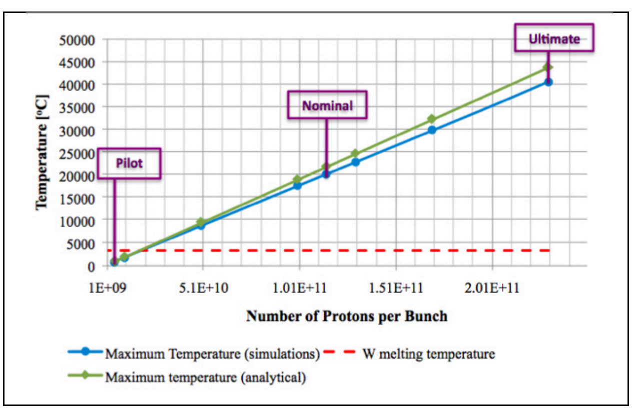

Figure 5: Variation in maximum temperatures reached with different proton populations (at 7TeV, 0mrad case).

The maximum temperatures in each case were verified with a simple analytical calculation (1), where P_{Max} is the maximum power density, τ is the thermal shock duration, ρ is the density of pure tungsten, c_p is the specific heat capacity and T_{REF} is the reference temperature (22°C).

$$T_{MAX} = \frac{P_{Max}.\tau}{\rho c_p} + T_{REF} \qquad (1)$$

It can be observed that there is good agreement between the analytical and numerical values for the maximum temperatures, which also implies the choice of a sufficiently fine mesh at the location of the beam impact. Any discrepancies can be due to the fact that Equation 1 assumes adiabatic conditions.

CONCLUSIONS

The purpose of this preliminary study was to evaluate the thermal response of tertiary collimators in view of these newly defined accident scenarios and to start identifying the most critical load cases for further detailed analyses.

Comparison of the peak temperatures reached and of the extent of the molten region indicates that the most loaded case is when the beam impact occurs on jaw inserts that are perfectly aligned with the beam direction.

Significant peak temperatures are also observed when the jaws are slightly inclined, with the main concern here being that in the presence of small angles, significant melting at the impacted insert corner might result in the detachment of a part of the jaw insert.

In the case of a jaw inclination of 1mrad far away from the beam, it can be noticed that no region with very focused energy deposition exists, leading to a lower peak temperature. Moreover, for this case at 3.5TeV, it is seen that with the same nominal bunch as other impact scenarios, the melting temperature of the jaw material is still not exceeded.

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 each of the accident cases.

ACKNOWLEDGEMENTS

The work of H. Richter (CERN, DGS/RP) and D. Campanini (CERN, EN-MME) in developing and making available FLUKA-ANSYS interfaces is acknowledged.

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