HIGH ENERGY BEAM IMPACT TESTS ON A LHC TERTIARY COLLIMATOR AT CERN HIRADMAT FACILITY*

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Abstract

The correct functioning of the collimation system is crucial to safely operate the LHC. The requirements to handle high intensity beams can be demanding. In this respect, investigating the consequences of LHC particle beams hitting tertiary collimators (TCTs) in the experimental regions is a fundamental issue for machine protection. An experimental test was designed to investigate the robustness and effects of beam accidents on a fully assembled collimator, based on accident scenarios in the LHC. This experiment, carried out at the CERN HiRadMat (High Irradiation to Materials) facility, involved 440 GeV beam impacts of different intensities on the jaws of a horizontal TCT. This paper presents the experimental setup and the preliminary results obtained together with some first outcomes from visual inspection.

INTRODUCTION

The LHC (Large Hadron Collider) collimation system consists of 100 movable collimators placed in 7 out of 8 LHC IPs (interaction points), having the two essential functions of beam halo cleaning and machine protection. In the event of an accident scenario, when the highly energetic beam (7 TeV at nominal conditions) would be out of control, the collimators are strategically positioned in order to be hit by the primary beam particles, thus serving as a protection for other critical structures such as the superconducting (SC) magnets [1]. In the worst accident case corresponding to an asynchronous trigger of the beam dumping system [2], one or more high-energy density bunches might directly impact on a collimator with possible serious consequences.

While the carbon collimators in the warm cleaning insertions are designed to withstand such a scenario without permanent damage, this is not the case for metal-based collimators like the TCTs in the experimental regions that protect the SC triplet magnets [3]. Even though the machine configurations are chosen to minimize this risk in a way that it can only occur in case several unlikely combined failures occur at the same time [4], it is important to understand the implications of the catastrophic event on a TCT. Following simulations for the LHC cases at 5 TeV considered during the LHC run 1 [3], a dedicated beam experiment was setup at the HiRadMat facility to address the nominal 7 TeV case.

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EXPERIMENTAL SETUP

Tertiary Collimator Design

The TCTH (Fig. 1A) consists of two jaws contained in a vacuum tank. Stepping motors allow independent adjustment of jaw tilt, jaw position relative to the beam centre and vertical movement of the whole collimator tank (20 mm full stroke). During the experiment, the jaws were moved remotely via a control application.

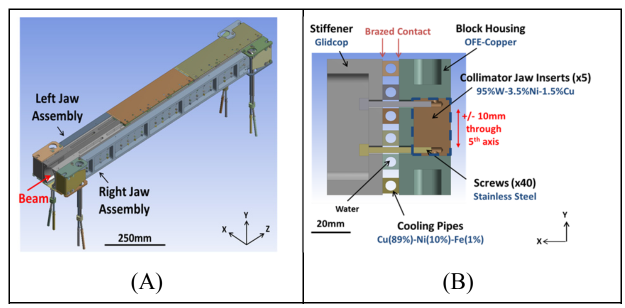

Figure 1: A horizontal tertiary collimator (TCTH). (A) 3D model. (B) Detailed cross-section in the x-y plane of the left jaw assembly.

A detailed view of the jaw assembly is shown in Fig. 1B. Each jaw has a total length of 1.2 m and consists of five inserts made of tungsten heavy alloy. The blocks are then placed into a copper housing and fixed with screws to the assembly. The water cooling pipes are an integral part of the collimator structure and were connected to the external cooling circuit provided in the HiRadMat experimental area. The total flow of the cooling water was adjusted to standard LHC collimators (25 l/min).

HiRadMat Setup for Collimator Test

The tests were run at different intensities using a 440 GeV proton beam, extracted from the CERN SPS (Super Proton Synchrotron). A standard LHC-type horizontal tertiary collimator was tested and its response to the different beam impacts was captured relying on embarked instrumentation. The latter consisted mainly of standard LHC collimator equipment, including stepping motors, position sensors as well as temperature sensors. A vacuum pump and some additional temperature and pressure sensors were also installed on various components of the collimator, specifically for the HiRadMat experiment. Moreover, beam loss monitors (BLMs), beam position monitors (BPMs) and beam current monitors (BCTs) were provided at the test facility in order to monitor the beam orbit and to obtain values for beam intensity and beam losses. Remote instrumentation also included additional equipment that was installed for sound data acquisition [5] at four different points in the tunnel. All sensor read-outs were monitored online and stored for analyses.

OVERVIEW AND GOAL OF TESTS

The goal of the tests was to verify the robustness and performance integrity of a fully assembled TCTH (Fig. 1) following direct beam impact, reproducing unlikely but realistic fast failure scenarios in the LHC. For each case, the beam intensity at 440 GeV was calculated to obtain the equivalent damage level of the 7 TeV accident scenarios [6, 7]. The three tests performed on the TCT are explained here. Details of the tests are given in Fig. 2, where the schematic diagram of the jaw represents the area enclosed within the dotted blue line in Fig. 1B.

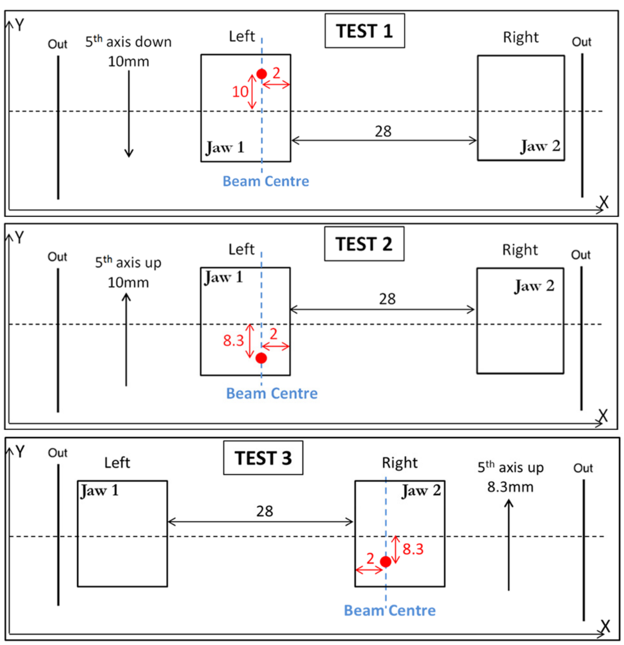

Figure 2: Schematic diagrams for Test 1, Test 2 and Test 3. The impact location is shown in red and all dimensions are in mm.

The objective of Test 1 (energy: 440 GeV, equivalent intensity: 3×10^{12} p) was to investigate the effect of an asynchronous beam dump, inducing impact of one nominal bunch on the TCT jaw. On the other hand, Test 2 (energy: 440 GeV, equivalent intensity: 9×10^{11} p) was aimed to inspect the onset of damage caused by beam impact on the TCT. Finally, Test 3 (energy: 440 GeV, equivalent intensity: 9×10^{12} p) was designed to reproduce a disruptive scenario for asynchronous beam dump, involving the direct impact of 4 LHC bunches at 5 TeV, and to benchmark simulation results presented in [3] against these experimental results.

As indicated in Fig. 2, all tests were performed at an impact parameter of 2 mm in order to ensure that the jaw bulk material was hit. The choice of the locations for the tests was done in such a way as to minimize interference of the high intensity shots in case of material projection. A beam size of 0.5mm (σ_x) × 0.5mm (σ_y) was specified although later it was shown by simulations that small changes in beam size do not affect the damage induced in case of disruptive tests involving high energy.

BEAM TEST RESULTS

Beam-Based Alignment

Prior to each high-intensity test (Tests 1, 2, 3), several low-intensity (on the order of 10^9 p) LHC pilot beam extractions were used to correctly set up the beam line and the experiment. The same setup was performed on every day when measurement campaigns were performed. The left and the right jaws were moved respectively in steps and the developed losses were recorded for each calibration shot. Alignment fits were generated for both jaws from which the beam centre was determined (Fig. 3). This was essential in order to ensure an accurate setup for the tests with the correct impact parameter.

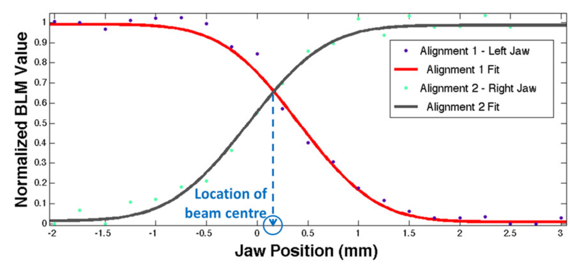

Figure 3: One example of the alignment fits generated for the beam-based setup with the left (L) and right (R) jaws.

Highlight of Experimental Measurements

The beam parameters used for each test, as well as their physical effect on the impacted jaw, are summarized in Table 1. For all tests, the beam energy is 440 GeV and the bunch spacing is 50 ns.

Table 1: Summary of the Test Parameters

Test	1	2	3
SPS extraction intensity [x 10^{12} p]	3.36	1.04	9.34
No. of bunches	24	6	72
Beam size at impact[$\sigma_x \times \sigma_y$ mm^2]	0.53 × 0.36	0.53 × 0.36	0.53 × 0.36
Energy on jaw [kJ]	87.89	27.72	249.87
TNT equivalent [g]	21.01	6.62	59.72

A beam-based setup was performed after Test 1 and Test 2 as an attempt to check the surface integrity of the jaws and the collimator mechanics following the beam shots. As can be observed from Fig. 4, there are no large variations between the beam positions before and after the shot, indicating that there is no critical damage of the jaw surface. It is however difficult to conclude on errors in the range of 100µm

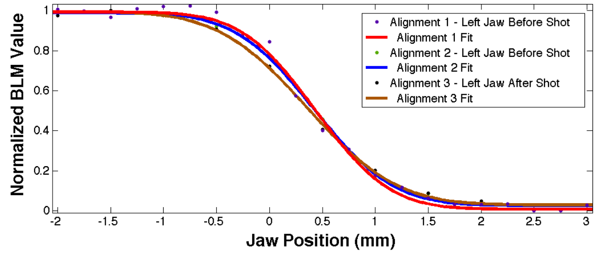

Figure 4: Beam-based alignment of left jaw. Alignment 1 and Alignment 2 are performed before Test 1 while Alignment 3 represents the check after Test 1.

Some of the most significant temperature and vacuum pressure results obtained for Test 1 are presented in Fig.5.

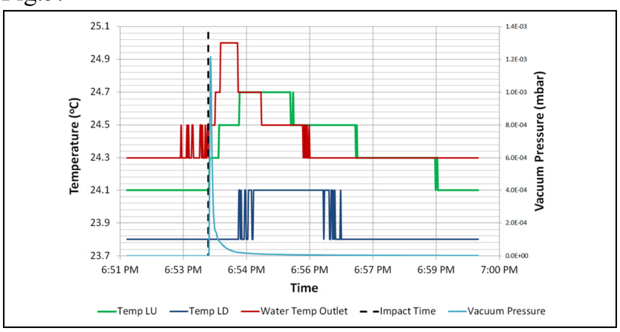

Figure 5: Test 1 temperature profiles captured by the upstream (LU) and downstream (LD) left jaw temperature sensors and by the water outlet temperature sensor. Also, vacuum pressure profile for Test 1. Impact at 6.53.51 PM.

The profiles in Fig. 5 show a temperature rise following the impact, which although small, is clearly observable. The temperature increases recorded are lower than expected and are not really compatible with post-mortem observations presented later. Thus these results have to be handled with care as there are potential issues under investigation. One of the reasons for these discrepancies might be the high thermal resistance (low contact pressure) between the temperature probe and the support to which it is attached, leading to an incorrect temperature recording. A peak in vacuum pressure for Test 1 is observed in Fig. 5 at the moment of impact.

Preliminary Post-Mortem Analysis

After the necessary cool-down of the irradiated collimator, a preliminary visual inspection (Fig. 6) was carried out to give a qualitative damage evaluation before further analysis. Grooves from Test 1 and Test 3 can clearly be identified, showing that there was a local temperature rise exceeding the melting point of the CuNi phase of the jaw insert material (~1343^{o}C). Various fragments and projections of tungsten can be also observed between the jaws. Vaporisation deposit around the molten region is visible, indicating the extent of the damage caused by the beam impacts. The reason why the alignment checks in Fig. 4 did not indicate the presence of such grooves might be because the grooves do not cover the full length of the jaw and the unperturbed part at the end of the jaw still determines the closest point to the beam that determines the alignment.

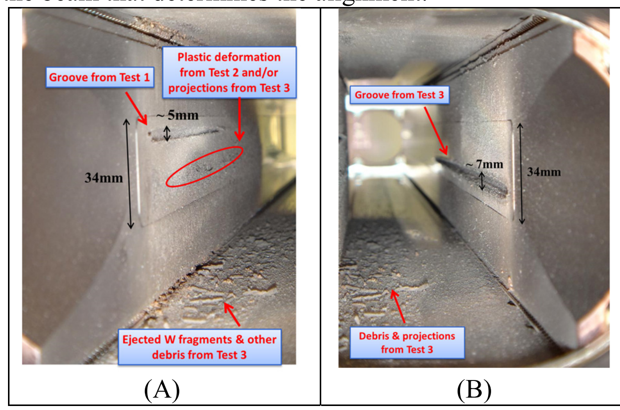

Figure 6: Preliminary visual inspection. (A) Damage on the left jaw caused mainly by Test 1 beam impact. (B) Damage on the right jaw caused by Test 3 beam impact.

CONCLUSIONS

Predicting the consequences of highly energetic particle beams impacting protection devices such as collimators is a fundamental issue in the design of state-of-the-art facilities for high-energy particle physics. The performed tests entailed the controlled impact of intense and energetic proton pulses on both jaws of a tertiary collimator. Preliminary results and visual inspection of the outcome of these tests have been discussed. Moreover, further post-irradiation analyses are foreseen in the near future. Such investigations will provide a thorough, integral assessment of beam accident scenarios together with a more in-depth view of the robustness and effects of beam impacts on a TCT.

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REFERENCES

[1] R.W. Assmann *et al.*, Proc. of EPAC 2002, Paris, France, p.197 (2002).

[2] R.W. Assmann *et al.*, LHC Project Note 293, "The Consequences of Abnormal Beam Dump Actions on the LHC Collimation System", 2002.

[3] A. Bertarelli *et al.*, "Limits for Beam Induced Damage: Reckless or Too Cautious?", Proceedings of Chamonix 2011 Workshop on LHC Performance.

[4] R. Bruce, R.W. Assmann. Presentation in the LHC Machine Committee, 2012.03.28.

[5] D. Deboy *et al.*, these proceeding, MOPWO029, IPAC13, Shangai, China (2013).

[6] F. Carra *et al.*, Presentation in the Collimation Working Group, 2012.07.30.

[7] A. Bertarelli *et al.* Updated Damage Limits for Collimator Materials, Presentation in the LHC Machine Protection Workshop, Annecy, 11-13 March 2013.