UPDATED ROBUSTNESS LIMITS FOR COLLIMATOR MATERIALS

A. Bertarelli, R. Bruce, F. Carra, A. Dallocchio, M. Guinchard, N. Mariani, L. Lari, S. Redaelli, A. Rossi, CERN, Geneva, Switzerland

Abstract

State-of-the art complex numerical methods based on advanced wave propagation codes have been developed to study the extreme phenomena induced in Beam Intercepting Devices (BID) by accidental beam impacts. A first study, based on these methods, led to the identification of damage thresholds for LHC Tertiary Collimators which were presented at Chamonix workshop in 2011. However, numerical simulations were unavoidably affected by uncertainties due to the limited knowledge of the material constitutive models; two experiments in the HiRadMat facility were proposed to address this issue: the destructive test of a complete tertiary collimator for a thorough, integral assessment of beam accident consequences (HRMT09) and a controlled test on a multi-material test bench hosting a variety of specimens conveniently instrumented for online and offline measurements (HRMT14). Both experiments were very successful and confirmed the effectiveness of numerical methods and material models to reliably predict beam-induced damages. Preliminary data acquired during HRMT14 provided interesting results on the ability of various materials to withstand extreme accidents. These tests also highlighted additional potential machine protection issues, on top of mechanical damage, induced by the projection of fragments out of the tungsten jaw: these include UHV degradation, chamber pollution, contamination, etc. In line with updated accident scenarios, new damage limits are proposed for LHC Tertiary Collimators.

INTRODUCTION

At Chamonix 2011 workshop, a thorough numerical analysis of a Tertiary Collimator (TCT) was presented. It relied on advanced simulations performed with the wave propagation code Autodyn® [1], applied to a complex 3D model [2]. Several asynchronous beam abort cases were studied with different values of beam emittance, energy and intensity. The main results were:

- Single-bunch accidents at 3.5 and 5 TeV induce jaw damage which does not require collimator replacement, provided that the full collimator movement parallel to the jaw surface is available (so called “5th axis”).
- Multi-bunch accidents always require collimator replacement.
- Risk of very severe damage leading to long LHC downtime above four bunches (risk of water leakage detected at 8 bunches).

The most important issue of these simulations concerned the reliability of adopted constitutive material models, especially at the extreme conditions as to temperature, pressure and energy induced by the beam impact. In order to probe and evaluate such models, two experiments have been performed in the HiRadMat facility in 2012 [3]. The first experiment, known as HRMT09, entailed the destructive test of a complete tertiary collimator, in order to assess not only the mechanical damage provoked to the structure but also other consequences of the beam accident, such as degradation of vacuum pressure in the beam line, contamination of the inner tank, impacts on collimator dismounting procedure, etc. In the second experiment (HRMT14), six different materials, already used in collimators or under intensive R&D for future applications, have been tested at different beam intensities. For a comprehensive characterization, online measurements were carried out both with embedded instrumentation and remote devices.

Data gathered by these two experiments were used to refine the numerical material models; new simulations were then performed in order to determine the damage limits for LHC Tertiary Collimators, considering updated and more realistic accident scenarios [4].

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HRMT09 EXPERIMENT

The goal of the experiment was to verify the robustness and performance integrity of a fully assembled TCT direct beam impact [5]. Three different tests were performed, with different beam intensity and different goals (Fig. 1):

- **Test 1**: to investigate the effects of asynchronous beam dump with impact equivalent to 1 LHC bunch at 7 TeV.
- **Test 2**: to identify the onset of plastic damage.
- **Test 3**: to reproduce a destructive scenario, inducing severe damage on the collimator jaw (damage on the collimator equivalent to 4 bunches at 5 TeV [2]).

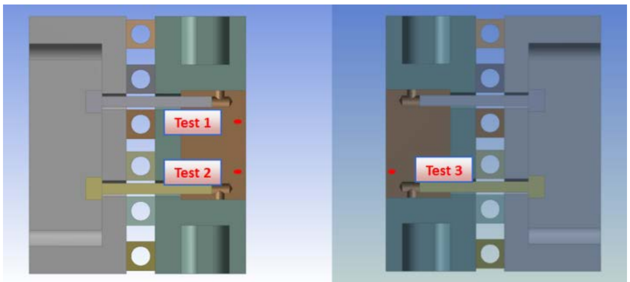

Figure 1: Schematic diagram of the three tests performed on the TCT during HRMT09 experiment. Impact locations are shown in red.

Table 1 resumes the parameters of each test. For each of the three tests, the equivalence between SPS and LHC energies is done in terms of mechanical damage induced to the jaw. For example, a SPS pulse with 3.36×10^{12} protons produces a mechanical damage on the jaw equivalent to one LHC nominal bunch at 7 TeV [6].

Table 1: Beam parameters and impact positions of tests performed during HRMT09.

	Test 1	**Test 2**	**Test 3**
Beam energy	440 GeV	440 GeV	440 GeV
Pulse intensity	3.36×10^{12} p	1.04×10^{12} p	9.34×10^{12} p
N. bunches	24	6	72
Bunch spacing	50 ns	50 ns	50 ns
Beam size [$\sigma_x \times \sigma_y$]	0.53 x 0.36 mm^2	0.53 x 0.36 mm^2	0.53 x 0.36 mm^2
Impact location	Left jaw +10 mm	Left jaw -8.3 mm	Right jaw -8.3 mm
Impact depth	2 mm	2 mm	2 mm
Jaws half-gap	14 mm	14 mm	14 mm

A post-irradiation visual inspection was performed at the beginning of 2013 (Fig. 2). The damage provoked by Test 1 and Test 3 is clearly visible; the observation also highlighted other possible issues:

- Contamination of bellows, tank, and vacuum chambers, due to activated tungsten particles; scenarios for future intervention and regular maintenance must take this into account.
- Ejected particle could affect the correct functionality of movable parts (RF fingers sliding on upper and lower rails).
- Degradation of ultra-high vacuum (UHV) along the beam line.

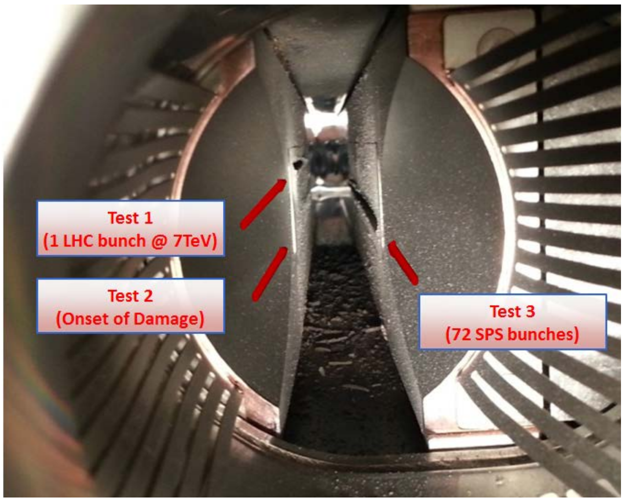

Figure 2: Post-irradiation visual inspection. Note the impressive quantity of tungsten ejected (partly bonded to the opposite jaw, partly fallen on tank bottom or towards entrance and exit flanges).

Qualitative comparison with Autodyn® simulation is given in Figs. 3, 4, 5. Simulations of Test 1 and Test 3 show good accordance with visual inspections, while it is impossible to visualize the plastic deformation produced by Test 2. The zone is, in fact, covered with particles ejected from the opposite jaw during Test 3, which reached a velocity of about 1 km/s according simulations; the damage produced during Test 2 will be evaluated during future metallographic inspections once the radiation dose rate will be low enough.

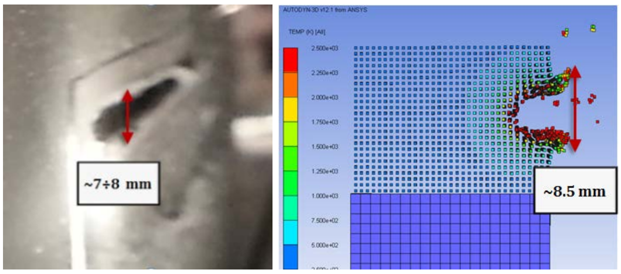

Figure 3: Qualitative numerical benchmarking of the damage generated by Test 1 beam impact.

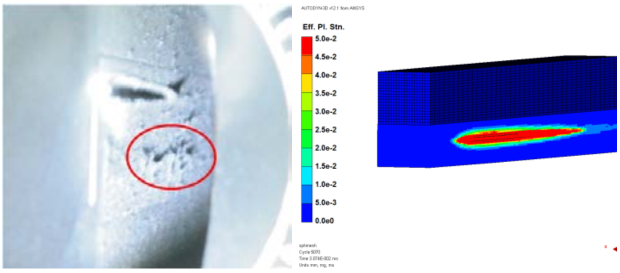

Figure 4: Qualitative numerical benchmarking of the damage generated by Test 2 beam impact. Note that the impacted zone is covered by particles ejected from the opposite jaw during Test 3.

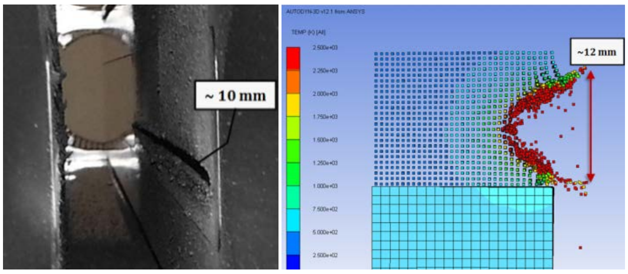

Figure 5: Qualitative numerical benchmarking of the damage generated by Test 3 beam impact.

HRMT14 EXPERIMENT

The goal of the HRMT14 experiment was to derive new material constitutive models collecting, mostly in real time, experimental data from different acquisition devices: strain gauges, laser Doppler vibrometer (LDV), high-speed video camera, temperature and vacuum probes [7].

The material sample holder was constituted by a vacuum vessel and a specimen housing featuring 12 material sample tiers arranged in two arrays of six (Fig. 6).

Specimens were made of materials currently used for collimators such as Inermet® 180 (tungsten heavy alloy), Glidcop® AL-15 LOX (dispersion-strengthened copper) and Molybdenum, as well as novel materials under development (Molybdenum-Copper-Diamond, Copper-Diamond and Molybdenum-Graphite composites) [8].

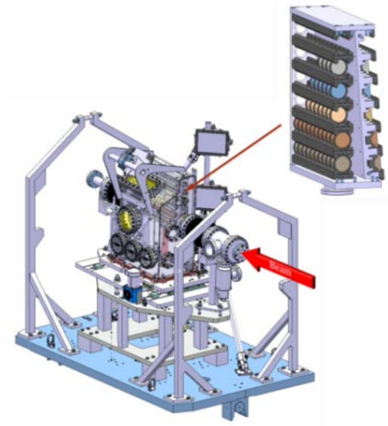

Figure 6: General assembly of the HRMT-14 test-bench.

Two different specimen shapes were chosen for each tested material: cylindrical disks (type 1) for medium-intensity tests, to measure axially-symmetric shockwaves; cylinders with a half-moon cross section (type 2) for high-intensity tests, allowing extreme surface phenomena (melting, material explosion, debris projections, etc.) to be visualized and optically acquired (Fig. 7).

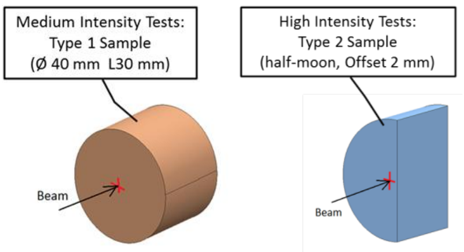

Figure 7: Material specimen shapes for medium intensity (type 1 - left) and high intensity (type 2 - right).

Part of the instrumentation was installed directly on the specimens; resistive strain gauges measured the strain produced on samples by shockwave propagation, to benchmark time-dependent simulations (Fig. 8). Temperature sensors, vacuum pressure gauges and microphones were also installed inside or in the vicinity of the tank. Optical devices (LDV and high-speed camera) were installed remotely in a concrete bunker, in order to protect them from the effects of radiation. The LDV acquired the radial velocity on the outer surface of one cylindrical sample per tier. The high-speed camera filmed the particle projection produced by high-energy impacts on type 2 specimens; the lighting necessary for the acquisition was provided by a battery of radiation-hard xenon flashes mounted atop the tank.

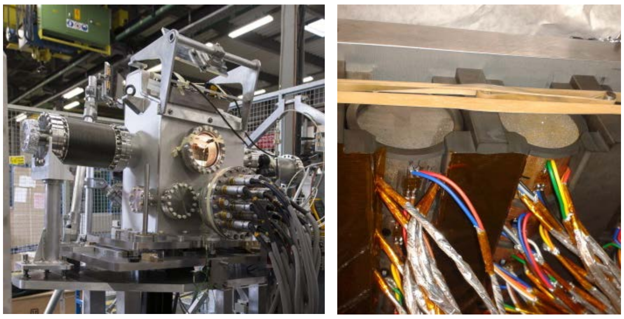

Figure 8: Assembled test-bench with DAQ cables and connectors (left); strain gauges mounted on Molybdenum-Copper-Diamond and Copper-Diamond (right).

Table 2 reports the characteristic values of the impacting beam during tests on Inermet® 180. Numerical simulations adopted the same parameters, except for the beam transverse dimension which was set to 2.5 x 2.5 mm^2.

Table 2: Beam parameters for tests performed on Inermet® 180 during HRMT-14 experiment.

	Medium intensity test	**High intensity test**
Energy	440 GeV	440 GeV
N. bunches	24	72
Bunch spacing	25 ns	25 ns
Pulse intensity	2.7×10^{12} protons	9.05×10^{12} protons
Energy on most loaded specimen	8.35 kJ	25.1 kJ
Impact point	Centre of *type 1* specimen	2 mm from *type 2* flat surface
Beam size [σ_x x σ_y]	1.4 x 2 mm^2	1.9 x 1.9 mm^2

Medium intensity tests

Strain gauges measured axial and hoop strains on the external surface of type 1 samples, while the LDV acquired the radial velocity. Acquired raw data were then compared to the results of numerical simulations (Fig. 9).

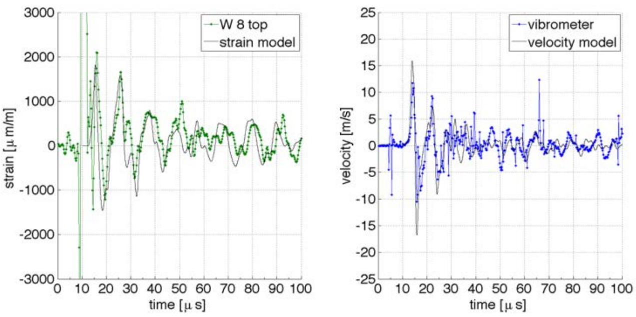

Figure 9: Comparison at r = 20 mm, L = 15 mm, measurements (dotted lines) vs. simulations (continuous lines); axial strain (left) and radial velocity (right).

A strong electromagnetic noise induced by the particle beam perturbed the strain gauge measurements during the first few microseconds after the impact, concealing the first deformation peak. However, this effect was limited to the beam impact duration, allowing to capture the remainder of the phenomenon. Measured and simulated signals are in good accordance, especially during the first three reflections of the shockwave. Random spikes in the signal of gauges and LDV will be treated during more accurate signal processing.

High intensity tests

The high-speed camera system allowed for the first time, to the best of authors' knowledge, to record images of the impact of a proton beam on solid targets and of the effects induced. As shown in Fig. 10, a large quantity of hot material was ejected at high velocity from the two most loaded Inermet® 180 samples; high temperatures reached are confirmed by the intense light emitted by the fragments during a few hundred microseconds.

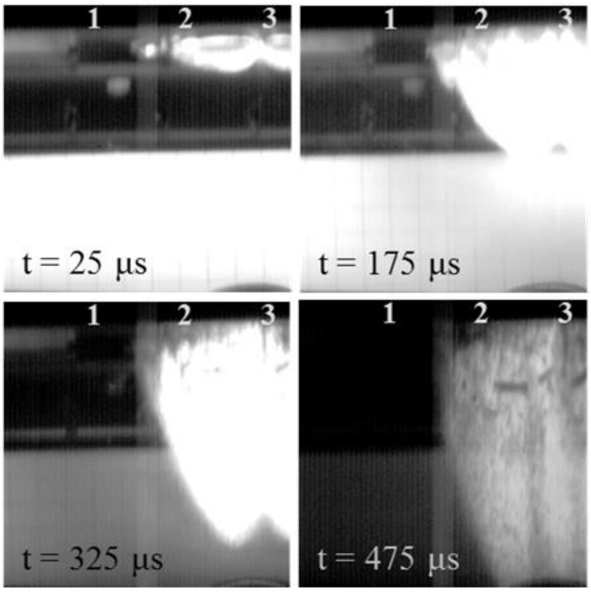

Figure 10: Image sequence of the impact on Inermet® 180 at high energy; three samples are partially visible.

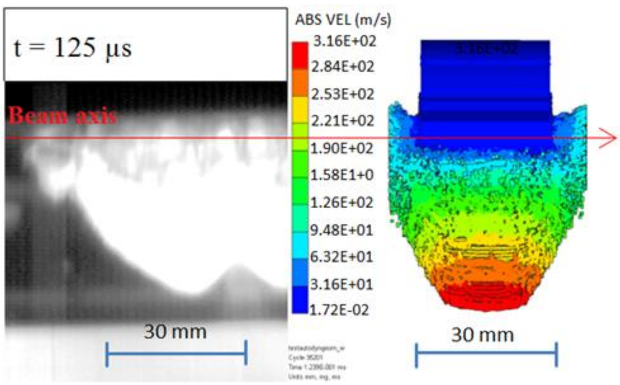

Figure 11: Comparison between simulation (SPH method) and acquired image ~125 µs after the impact.

Smoothed-particle hydrodynamics (SPH) simulation results are consistent with the camera acquisition (Figs. 11-12), even considering the differences in beam size between real and simulated scenarios. The acquired velocity of the fragment front has been estimated by measuring the displacement between two successive frames and is about 275 m/s, well matching the simulated velocity of 316 m/s (difference is about 15%).

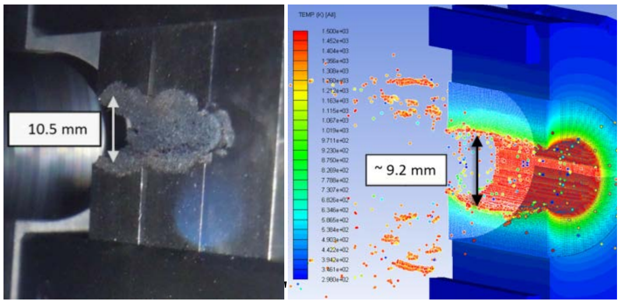

Figure 12: Post-mortem observation of Inermet® 180 samples (left) and simulated failure (right).

UPDATED ACCIDENT SCENARIOS

Preliminary results of the experimental tests performed show that the numerical methods and material models adopted to simulate beam impact accident scenario on a TCT are reliable (the error band is about 25%).

Actually, up-to-date beam parameters for asynchronous dump scenarios foresee fractions of several bunches impacting the jaw [4] but, at the moment, FLUKA [9] simulations are not yet available for this accident case. Nevertheless, new Autodyn® simulations have been performed considering one bunch with variable intensity impacting the jaw with a fixed impact parameter.

Three damage thresholds have been identified:

- **Threshold 1: onset of plastic damage**. Below this threshold, no permanent deformation is induced on the collimator jaw.
- **Threshold 2: limit for W fragment ejection.** The beam impact induces plastic deformation of the jaw without ejection of tungsten particles (no contamination or vacuum degradation).
- **Threshold 3: limit for 5th axis compensation.** The impact generates severe plastic deformation with projection of tungsten particles, but the mechanical damage can still be compensated by moving the collimator through the 5th axis (i.e. parallel to the jaw surface), therefore guaranteeing the required flatness (it should be noted that the vacuum quality will be affected by such an accident and the collimator will be contaminated by radioactive tungsten fragments).

Simulation parameters and results are summarized in Table 3. The calculation confirms the results presented at Chamonix 2011 workshop: the impact of a nominal LHC bunch is critical enough to require the collimator replacement (Figs. 13-14).

Table 3: Thresholds identified in case of accident on TCT (asynchronous beam dump).

	Threshold 1	**Threshold 2**	**Threshold 3**
Beam energy	7 TeV	7 TeV	7 TeV
N. bunches	1	1	1
Impact depth	0.5 mm	0.5 mm	0.5 mm
Beam size [σ_x x σ_y]	0.5x0.5 mm^2	0.5x0.5 mm^2	0.5x0.5 mm^2
Jaws gap	20 mm	20 mm	20 mm
Pulse intensity	***5x10^9 p***	***2x10^{10} p***	***1x10^{11} p***

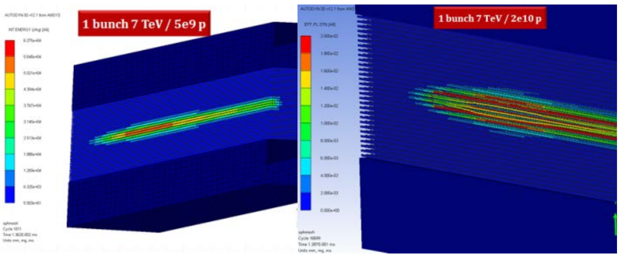

Figure 13: Threshold 1, 5x10^9 p: no plastic deformation induced (left); Threshold 2, 2x10^{10} p: a crack is generated, but without ejection of tungsten particles.

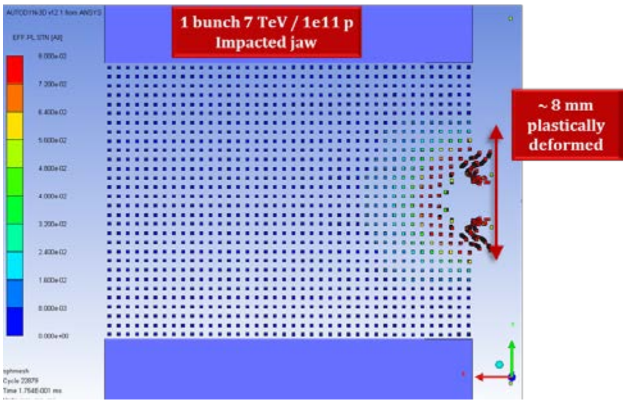

Figure 14: Threshold 3, 1x10^{11} p: groove generated in the jaw; Below this threshold the damage can still be compensated through 5th axis movement.

CONCLUSIONS AND FUTURE ACTIONS

A state-of-the art numerical method based on advanced wave propagation codes was developed in the last years at CERN in order to study beam-induced extreme phenomena including phase transitions, spallation, and explosions. The method was applied in 2011 to identify the beam-induced damage limits on LHC Tertiary Collimators. However, this complex numerical approach required a dedicated experimental validation: two different tests were therefore performed at the CERN HiRadMat facility. The first experience entailed the destructive tests of a complete TCT; in the second experiment, six different materials were characterized under intense beam impacts.

The two experiments confirmed the effectiveness of the numerical methods and material models to reliably predict beam-induced damages, also highlighting additional potential machine protection issues on top of mechanical damage, due to the projection of fragments from the impacted components.

New damage limits were then proposed in line with updated accident scenarios on TCTs, considering one bunch with variable intensity impacting the jaw with a fixed impact parameter.

- Onset of plastic damage : 5x10^9 p
- Limit for fragment ejection: 2x10^{10} p
- Limit for 5th axis compensation (with fragment ejection): 1x10^{11} p

These simulations will be refined, to consider asynchronous dump scenarios where fractions of several bunches impact the jaw in different points, once FLUKA energy deposition maps will be available.

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