HIGH ENERGY TESTS OF ADVANCED MATERIALS FOR BEAM INTERCEPTING DEVICES AT CERN HIRADMAT FACILITY

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Abstract

Predicting by simulations the consequences of LHC particle beams hitting Collimators and other Beam Intercepting Devices (BID) is a fundamental issue for machine protection: this can be done by resorting to highly non-linear numerical tools (Hydrocodes). In order to produce accurate results, these codes require reliable material models that, at the extreme conditions generated by a beam impact, are either imprecise or non-existent.

To validate relevant constitutive models or, when unavailable, derive new ones, a comprehensive experimental test foreseeing intense particle beam impacts on six different materials, either already used for present BID or under development for future applications, is being prepared at CERN HiRadMat facility.

Tests will be run at medium and high intensity using the SPS proton beam (440 GeV). Material characterization will be carried out mostly in real time relying on embarked instrumentation (strain gauges, microphones, temperature and pressure sensors) and on remote acquisition devices (Laser Doppler Vibrometer and High-Speed Camera). Detailed post-irradiation analyses are also foreseen after the cool down of the irradiated materials.

THERMALLY INDUCED DYNAMIC PHENOMENA

The interaction of energetic particle beams with matter provokes dynamic responses in the impacted element [1]. Several parameters can affect intensity and time scale of the response: deposited energy, maximum energy density, interaction duration and strength of the impacted material are the principal ones.

Three regimes are identified at increasing deposited energy, namely Elastic Stress Waves, Plastic Stress Waves and Shock Waves.

Elastic Wave Regime

- Waves propagate at elastic sound speed
- Negligible change of density
- Can be treated with implicit FEM codes [2] and with analytical tools [3]

Plastic Wave Regime

- Wave velocity lower than elastic sound speed
- Limited change of density
- Can be treated with implicit FEM codes [4]

Shock Wave Regime

- Shock waves appear above a critical pressure
- Waves propagate at velocity higher than elastic sound speed
- Significant change of density
- Special explicit, non-linear numerical tools required: Hydrocodes

HYDROCODES

As opposed to a standard, implicit FEM code, hydrocodes usually rely on complex material constitutive models, able to encompass a much larger range of densities and temperatures, including changes of phase. Strength and failure models are also more complicated, as they take into account effects of strain rate, temperature, density change etc.

Equations of State

An Equation of State (EOS) is integrated in the hydrocode to model the behaviour of materials under any state and condition. It provides the evolution of pressure as a function of density, temperature and internal energy. Most used analytical EOS are Shock, Tillotson and Mie-Gruneisen, however their application is limited since analytical modelling can describe only a single phase region of the EOS [5].

Strength Models

To model the behaviour of materials in the extreme conditions due to shock wave propagation, an advanced yielding criterion is needed. The model must take into account, in addition to strain, the strain rate and the temperature. Most used models are Johnson-Cook [6], Steinberg-Guinan [7] and Johnson-Holmquist [8].

Failure Models

On the same basis, dynamic failure models must take into account many factors such as strain, strain rate, temperature, maximum and minimum pressure, fracture toughness. In addition, failure criteria also depend on the type of failure and on the mesh used for the simulation.

NUMERICAL SIMULATIONS OF ENERGY BEAM IMPACTS

Analyses methods for complex components under extreme conditions have been developed in recent years at CERN and Politecnico di Torino, partly in the frame of the European Collaboration for Accelerator Research and

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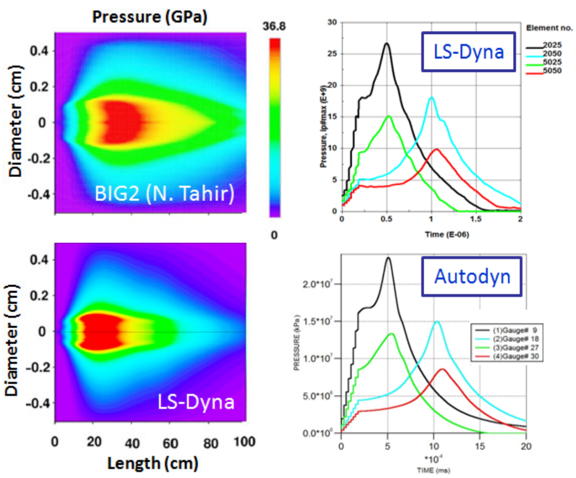
Development (EuCARD), adopting state-of-the-art hydrodynamic codes, namely Autodyn® and LS-Dyna®. A preliminary benchmarking between these two Hydrocodes and another explicit code, BIG-2, developed by GSI, was performed. The reference case was a copper cylindrical sample impacted by nominal LHC bunches [9]. The results obtained showed good agreement between the three codes (Fig. 1).



Fig

Figure 1: Comparison between LS-Dyna, BIG-2 and Autodyn.

Analysis of a LHC Tertiary Collimator (TCT)

One such extensive computation has been performed at CERN to simulate the consequences of accidental beam impacts on a Tertiary Collimator for the LHC [10]. The analysis has been carried out making use of Autodyn® and simulating the whole collimator jaw (Fig. 2). The jaw section directly interacting with the beam is composed of five Inermet® 180 blocks, each 200 mm long, fixed with stainless steel screws to a support made of OFE-Cu. The Copper support is in turn brazed to cooling pipes made of Copper-Nickel alloy (90% Cu – 10% Ni), while these are brazed to a back-stiffener (made of Glidcop®, a Dispersion Strengthened Copper).

Two complementary 3D models were implemented in Autodyn® based respectively on a) Lagrangian (full jaw assembly) and b) Smoothed Particle Hydrodynamics (SPH) algorithms (for the most loaded W block).

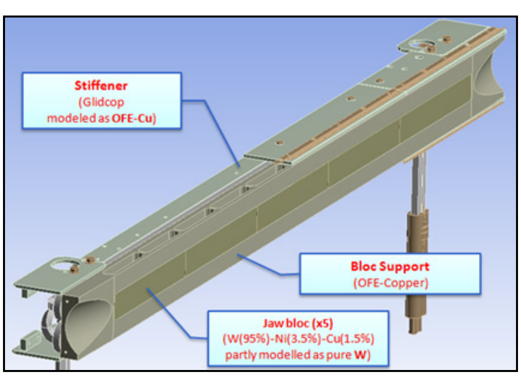


Figure 2: Jaw assembly of a TCT Collimator.

Seven accident cases, with different degrees of severity and probability, were identified. All of the cases are based on an asynchronous beam abort event [11], assuming that each bunch has the same impact parameter (2 mm).

Table 1: List of Accident Cases

Case	Beam Energy [TeV]	Norm. Emittance [μm rad]	No. of Impacting Bunches	Energy on Jaw [kJ]	TNT Eqv. [g]
1	3.5	3.50	1	38.6	9.2
2	5	7	1	56.2	13.4
3	5	3.5	1	56.5	13.5
4	5	1.75	1	56.6	13.5
5	5	1.75	2	111.3	26.6
6	5	1.75	4	216.1	51.6
7	5	1.75	8	429.8	102.7

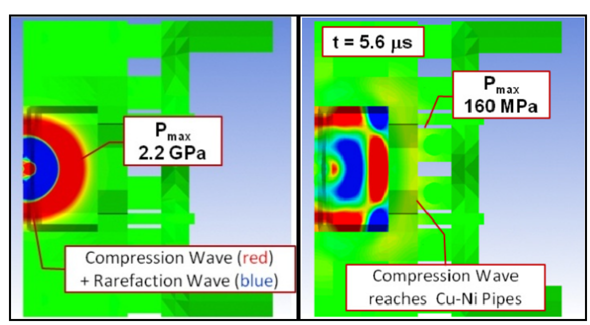
A complete FLUKA [12], [13] model of the collimator was set up and full shower simulations were carried out for each case to provide the deposited energy distribution (considering the expected optics functions at the TCTS).

To determine consequences on the collimator and LHC operation, three different damage levels were defined:

- Level 1 – Collimator not to be replaced. Limited jaw damage: an intact spare surface can be found relying on the 5th axis movement, which permits a maximum vertical shift of +/- 10 mm. Negligible permanent jaw deformation.
- Level 2 – Collimator to be replaced. Damage to the jaw incompatible with 5th axis travel; other components may also be damaged (e.g. screws).
- Level 3 – Long down time of the LHC. Very severe damage to the collimator leading to water leakage into beam vacuum.

Results

All the single-bunch cases, both at 3.5 and 5 TeV, fall within Damage Level 1. No appreciable difference is found when varying the beam emittance.



Figures 3–4: Case 4. Propagation of the shock wave in the jaw assembly.

The so-called shock impedance between W and Cu, defined as $Z = \rho_0 U_s$ (with ρ_0 initial density, U_s shock velocity), plays an important role in limiting the damage, confining most of the wave energy inside the W block (Figs. 3-4).

For cases 5 and 6 the jaw damage cannot be compensated by 5th axis travel (Damage Level 2). Severe

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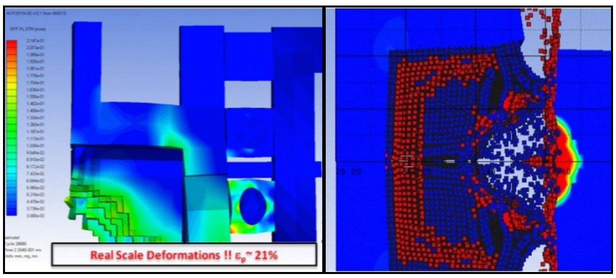
plastic deformations can be observed on cooling pipes and screws, although visible failures are not detected.

The SPH simulations anticipate permanent damage on the opposite jaw, provoked by W particles impacting at elevated velocity.

The only case studied leading to Damage Level 3 is case 7. In this scenario one may expect: a) water leakage due to very severe plastic deformation on the pipes (Fig. 5); b) extended eroded and deformed zone on the W jaw; c) projections of hot and fast solid W bullets (T~2000 K, V_{max}~1 km/s) onto the opposite jaw with slower particles hitting tank covers at velocities just below the ballistic limit; d) risk of permanent bonding between the two jaws due to the projected re-solidified material (Fig. 6).



Figures 5-6: Case 7. Plastic strain in Cu and Cu-Ni (left) and damage extension on the two jaws (right).

EXPERIMENTAL VALIDATION IN THE HIRADMAT FACILITY

As shown above, Hydrocodes are powerful tools which allow treating extremely complex dynamic phenomena, but also require, in order to provide reliable results, a material modelling accurate over the whole operational range.

Unfortunately, the material models, in particular at the extreme conditions generated by high-energy beam impacts, are far from being readily available and/or experimentally validated. This is in particular true for non-conventional alloys, compounds and composite materials presently used or likely to be used for future LHC Collimators.

In order to obtain experimental data upon which building and/or validating reliable constitutive models for relevant materials, a direct material characterization is to be performed in HiRadMat facility [14] in late 2012. The experimental setup consists of a multi-material sample holder allowing to test six different materials under particle beams of different intensity.

Table 2: HiRadMat Beam Parameters

	Protons	Ions (Pb^{82+})
Energy	440 GeV	173.5 GeV/u
Bunch Intensity (max)	1.7e11	7e9
N. Bunches (max)	288	52
Pulse Intensity (max)	4.9e13	3.6e9
Pulse Energy (max)	3.4 MJ	21 kJ
Bunch Length	11.24 cm	11.24 cm
Bunch Spacing	25/50/75/150 ns	100 ns
Pulse Length	7.2 µs	5.2 µs

HRMT14-LCMAT EXPERIMENT SET-UP

The test bench is designed to permit the most possible complete material characterization; most of the relevant measurements are acquired in real time and made available online. Physical quantities to be measured are axial and circumferential strain, radial velocity and temperature. Microphones and vacuum pressure gauges will also be installed; particle projections generated by the beam impact will be filmed by a high-speed camera.

The material sample holder (Fig. 7) is constituted by a vacuum vessel and a specimen housing featuring 12 material sample tiers arranged in two arrays of six. The housing will be accurately positioned via a two degree-of-freedom actuation system: the 300-mm vertical travel permits to centre on the beam axis each of the six tiers, while the 120-mm lateral movement allows switching between the two arrays.

Specimens are made of materials currently used for BID such as Inermet® 180, Dispersion Strengthened Copper (Glidcop® AL-15 LOX) and Molybdenum, as well as novel materials currently under development (Molybdenum-Copper-Diamond, Copper-Diamond and Molybdenum-Graphite composites) [15].

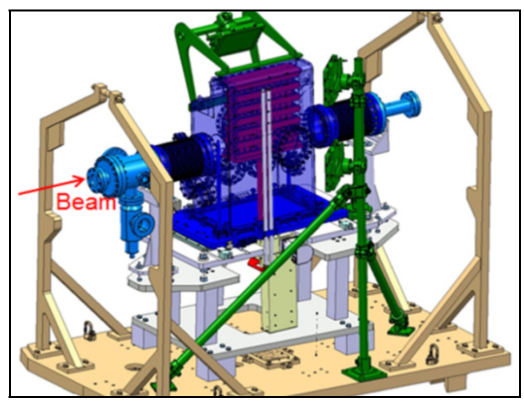
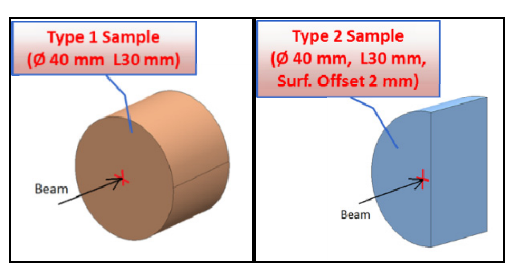


Figure 7: General assembly of the sample holder.

Material Specimens

Two types of specimen shapes are foreseen for each material (Figs. 8-9): full cylinders for medium intensity tests (measuring shockwave propagation, benchmarking simulations) and cylinders with a half-moon cross section for high intensity tests (to visualize impact-generated material projections through a high-speed camera).



Figures 8-9: Type 1(left) and type 2 (right) material sample shapes.

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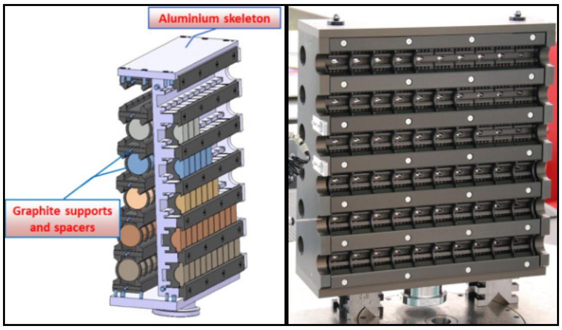
Specimen Housing

Material specimens will be kept in place by restraints made of graphite, in order to minimize the propagation of shock waves into the housing (Figs. 10-11).



Figures 10-11: Specimen housing of the material sample holder.

Vacuum System

The vacuum vessel is made of AISI304L stainless steel (Fig. 12), equipped with a series of view ports on its sides to allow online measurements and offline observations. Each of these ports houses a transparent optical window, designed to withstand internal vacuum and particle projections.

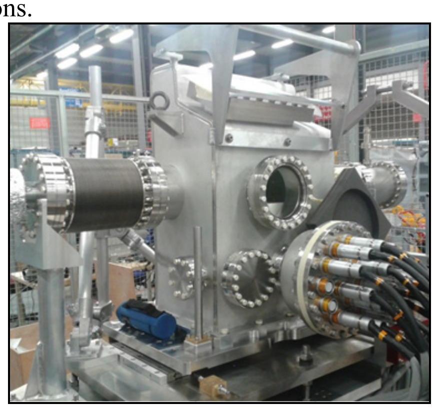


Figure 12: Stainless steel vacuum tank.

One view port allows the transmission of a laser beam for the Laser Doppler Vibrometer (LDV) measurements of type 1 specimens (lateral window). A second port is dedicated to the image acquisition of type 2 samples while exposed to high intensity shots (top window). The vessel is equipped with UHV beryllium windows at the beam entry and exit ports.

Primary vacuum (≤ 1 mbar) is required for the experiment. After installation in the tunnel, a pump placed on the table will operate to maintain adequate vacuum level, even after possible outgassing provoked by beam impacts.

Embarked Instrumentation

Part of the instrumentation is installed directly on the specimens; to benchmark time-dependent simulations, the most important physical quantity to be acquired is the strain produced on samples by shockwave propagation. This acquisition will be made by radiation-hard **resistive strain gauges** placed on the cylindrical external surface of both type 1 and type 2 samples (Fig. 13); axial and circumferential strains will be measured at a sampling rate of 2.5 MHz, with amplitudes up to 20.000 μm/m.

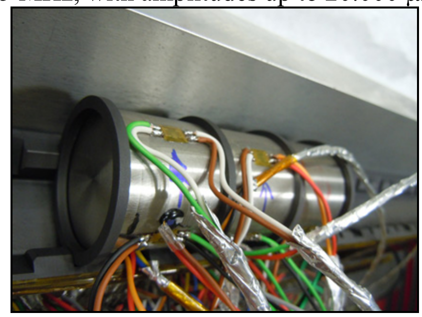


Figure 13: Strain gauges mounted on Inermet® specimens.

Measured values will be then compared to numerical simulations (Fig. 14).

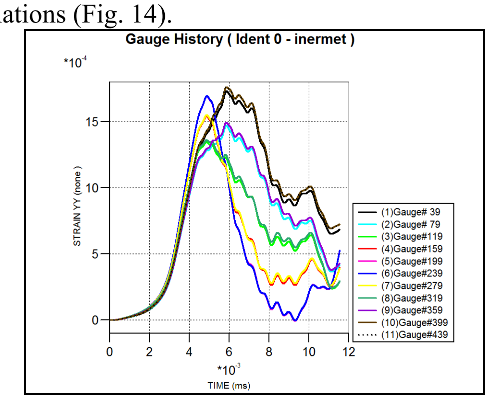


Figure 14: Expected circumferential strain in different axial positions for Inermet®, 440GeV energy, 3e12 protons/pulse.

Temperature sensors, **vacuum pressure gauges** and **microphones** will also be installed inside or in the vicinity of the tank.

Remote Instrumentation

The most sensitive instrumentation will be installed in a radiation-protected bunker, 40 m upstream of the sample holder.

A **Laser Doppler Vibrometer (LDV)** will measure the radial velocity on the outer surface of one cylindrical sample per tier. It is capable of acquiring velocities of up to 24 m/s with a sampling rate of 2.5 MHz. The laser beam will be reflected back to the vibrometer by a system of aligned mirrors.

A **high-speed camera** will be used to film the particle projection produced by high intensity impacts. The capture rate will be 20000 fps, with an exposure time of 5 μs. The high intensity illumination necessary for the camera acquisition will be provided by a battery of xenon flashes mounted outside the tank.

POST-IRRADIATION ANALYSES

In addition to real-time data acquisition, a series of observations and tests is foreseen on the material

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specimens after the end of irradiation. With the sample holder still on the test bench, remote observation of impacted specimens will be possible with Wi-Fi cameras, profiting of three different tank portholes.

According to Monte Carlo simulations performed for the experiment radiological assessment [15], a cool-down time of several weeks before dismounting the specimens and performing non-destructive analyses will be required. Approximately four months will then be necessary before destructive tests and metallurgical observations in an adequately equipped laboratory.

Table 3: Maximum Residual Dose Rate within Material Specimens

Cooling period	Residual dose rate [μSv/h]
1 hour	7.40e6
1 day	3.11e5
1 week	1.92e4
1 month	2.52e3
2 months	1.50e3
4 months	1.02e3

CONCLUSIONS

The experimental validation of advanced simulations of particle beam impact on Beam Intercepting Devices carried out at CERN and Politecnico di Torino, is a crucial issue for LHC machine protection. The HiRadMat facility offers the unique opportunity to test materials at conditions similar to those provoked by the direct impact of LHC beams.

A test bench has been designed to allow the characterization of six different materials. The design of such experiment has posed severe challenges: in particular the data acquisition, at the extreme conditions induced by beam impacts, has required innovative solutions in terms of lighting, support stabilization, radiation resistance and noise control.

The experiment will be carried out in late 2012; while most physical quantities are to be acquired in real time, roughly four months will be necessary before being able to directly handle the impacted specimens and conduct the metallographic cuts and observations.

A complementary experiment (HRMT09-LCOL) has been performed during July 2012 in the HiRadMat facility, by impacting with particle beams a complete LHC Tertiary Collimator (TCT) in order to extend the test of collimator materials to a full-scale device [17]. Results of the two experiments will be cross-checked, validating the robustness of TCT in case of accident.

REFERENCES

[1] A. Dallocchio, G. Belingardi, T. Kurtyka, A. Bertarelli, "Study of Thermo-Mechanical Effects Induced in Solids by High Energy Particle Beams: Analytical and Numerical Methods", PhD Thesis, Politecnico di Torino, Turin 2008; CERN-THESIS-2008-140; http://cdsweb.cern.ch/record/1314219/

[2] A. Bertarelli *et al.*, "Mechanical Design for Robustness of the LHC Collimators", PAC'05, Knoxville, May 2005.

[3] A. Bertarelli, A. Dallocchio, T. Kurtyka, "Dynamic Response of Rapidly Heated Cylindrical Rods: Longitudinal and Flexural Behaviour", Journal of Applied Mechanics, May 2008, Volume 75, Issue 3, 031010, pp. 1-13.

[4] A. Bertarelli *et al.* "Permanent Deformation of the LHC Collimator Jaws Induced by Shock Beam Impact: an Analytical and Numerical Interpretation", EPAC'06, Edinburgh, July 2006.

[5] M. Meyers, "Dynamic Behavior of Materials", Wiley-Interscience, 1994.

[6] G. R. Johnson, W. H. Cook, "A Constitutive Model and Data for Metals Subjected to Large Strains, High Strain Rates and High Temperatures", Proc. 7th Int. Symp. on Ballistics, 1983.

[7] D. J. Steinberg, S. G. Cochran, M. W. Guinan, "A Constitutive Model for Metals Applicable at High-Strain Rate", J. Appl. Phys. 51 (3), 1498–1504, 1980.

[8] G. R. Johnson, T. J. Holmquist, "An Improved Computational Constitutive Model For Brittle Materials", High-Pressure Science and Technology, 1994.

[9] M. Scapin, L. Peroni, A. Dallocchio, "Thermo-mechanical modelling of high energy particle beam impacts", Proceeding ACE-X 2010, July 2010.

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

[11] T.Kramer et al., "Performance Studies for Protection against Asynchronous Dumps in the LHC", IPAC'10, Kyoto, May 2010.

[12] G. Battistoni, *et al.*, "The FLUKA code: Description and Benchmarking", Proc. of the Hadronic Shower Simulation Workshop 2006, Fermilab, AIP Conference Proceeding 896, 31-49, 2007.

[13] A. Fassò, A. Ferrari, J. Ranft, and P.R. Sala, "FLUKA: a Multi-particle Transport Code" CERN-2005-10 (2005), INFN/TC_05/11, SLAC-R-773.

[14] I. Efthymiopoulos *et al.*, "HiRadMat: a New Irradiation Facility for Material Testing at CERN", IPAC'11, San Sebastián, September 2011.

[15] A. Bertarelli *et al.*, "Research and Development of Novel Advanced Materials for Next-generation Collimators", IPAC'11, San Sebastián, September 2011.

[16] N. Charitonidis, C. Theis, S. Roesler, "Radiological assessment of the Collimator Materials tests at HiRadMat in 2012", EPFL-Report-178219; http://infoscience.epfl.ch/record/178219.

[17] D. Deboy *et al.*, "TCT collimator test in HiRadMat", presented at the LHC Collimation Working Group #146, July 2012; https://indico.cern.ch/conferenceDisplay.py?confId=201418.

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