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DYNAMIC TESTING AND CHARACTERIZATION OF ADVANCED MATERIALS IN A NEW EXPERIMENT AT CERN HIRADMAT FACILITY*

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Abstract

An innovative and comprehensive experiment (named "*Multimat*") was successfully carried out at CERN HiRadMat facility on 18 different materials relevant for Collimators and Beam Intercepting Devices. Material samples, tested under high intensity proton pulses of 440 GeV/c, exceeding the energy density expected in HL-LHC, ranged from very light carbon foams to tungsten heavy alloys, including novel composites as graphite/carbides and metal/diamond without and with thin-film coatings. Experimental data were acquired relying on extensive integrated instrumentation (strain gauges, temperature sensors, radiation-hard camera) and on laser Doppler vibrometer. This allows investigating relatively unexplored and fundamental phenomena as dynamic strength, internal energy dispersion, nonlinearities due to inelasticity and inhomogeneity, strength and delamination of coatings and surfaces. By benchmarking sophisticated numerical simulations against these results, it is possible to establish or update material constitutive models, which are of paramount importance for the design of devices exposed to interaction with particle beams in high-energy accelerators such as the HL-LHC or FCC-hh.

INTRODUCTION TO THE EXPERIMENT

The High Luminosity upgrade of the LHC (HL-LHC) [1] will increase the energy stored in the circulating beams by almost a factor of two (from 360 to 680 MJ). In the case of new proposed accelerators such as the hadron-hadron version of the Future Circular Collider (FCC-hh) [2], the beam stored energy will be even higher, up to 8500 MJ. Among the components interacting with particle beams, collimators [3] are particularly exposed to risks of accidental beam impacts, e.g. in case of asynchronous dumps or injection errors. For HL-LHC and FCC-hh, the thermal loads predicted for the collimator jaws exceed energy densities of 10 kJ/cm^3 [4], potentially leading to material melting or vaporization in the impacted region, and intense pressure waves which may induce plasticity or fracture in nearby regions [5].

This requires an experimental validation of materials and coatings exposed to such extreme conditions. Additionally, ad-hoc experiments are required to derive the constitutive material models necessary to reliably simulate high energy beam impacts. This can only be done through dedicated tests in experimental facilities using high energy beams. In this context, a new comprehensive experiment, named "*Multimat*" [6], was successfully performed in autumn 2017 at CERN HiRadMat facility [7].

MULTIMAT EXPERIMENT LAYOUT

Multimat, which profited from the experience gathered in previous experiments such as HRMT-14 [8], [9], aimed at offering a modular and reusable platform to test advanced collimator materials and coatings developed in recent years [10], [11], under high brightness beams at energy densities equalling or exceeding HL-LHC values. The main goal of Multimat was the derivation and/or validation of little known material properties, such as mechanical response at high strain rates, dynamic strength, internal damping, effects of porosity, anisotropic wave propagation, dynamic behaviour of coatings.

Figure 1: View of the Multimat test-bench. Beam comes from the left traversing embarked beam monitors (in black). The rotatable barrel is visible behind the camera window.

The test-bench (Figure 1) featured a leak-tight aluminium vessel hosting 16 target stations, each 1 m long, mounted on a rotatable barrel. Each target station hosted a varying number of material specimens, in the form of

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slender bars, with cross sections ranging from 8×8 to 12×11.5 mm^2 and lengths of 120 or 247 mm; in total, 81 specimens, made of 18 different materials, were tested. They were extensively instrumented, with 335 strain gauges and 112 thermal sensors; a rad-hard, high-definition camera, mounted on a translating support outside the vessel, was used to inspect the target stations through a large window; a laser Doppler vibrometer (LDV) was placed in a shielded bunker ~40 m away from the test-bench, targeting material specimens through a system of mirrors and a dedicated viewport.

One target station was devoted to a proof of concept of an adaptive collimator jaw design, under development at University of Huddersfield and CERN, devised to monitor and correct in realtime jaw distortions induced by beam in operation.

The rotatable barrel (Figure 2) was enclosed in a leak-tight vessel to prevent contamination to the external ambient. A forced flow of argon was provided by a closed circuit to ensure an inert atmosphere, limiting materials oxidation, while decreasing the cooling time of specimens after impact to ensure a faster pulse repetition rate. Each target station could be finely aligned with respect to the beam by a precise actuation system. Beam position and profile were acquired by two Beam Position Monitors (BPM), including one based on a Glassy Carbon OTR system, withstanding the highest available beam intensity [12].

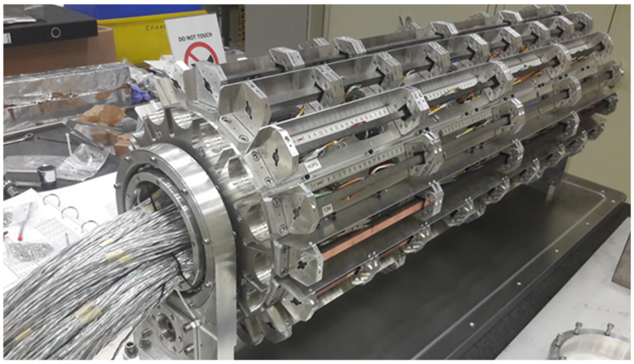

Figure 2: Rotable barrel with mounted target stations. Note shielded cables for onboard instrumentation.

Specimens were supported at the two extremities on graphite restraints, with pressed contact granted by springs.

Tested specimens can be grouped in seven categories:

- *Pure carbon materials*, i.e. 2D Carbon/Carbon (CFC), isotropic and pyrolytic graphite, carbon foams [13].
- *Metal carbide – graphite composites,* featuring a graphitic matrix reinforced by molybdenum (MoGr) or titanium carbides (TiGr), with the addition in some grades of short carbon fibres [14], [15].
- *Titanium alloy*, produced by SLM Additive Manufacturing (AM), with an apparent density of ~1.6 g cm^{-3}.
- *Copper – diamond (CuCD)*, two different grades [16].
- *Silicon carbide*.
- *Heavy alloys*, namely TZM molybdenum, tantalum-tungsten (TaW) and tungsten heavy alloy (Inermet 180) [17], [18].
- *Monitoring and actuating devices* for correction of the beam-induced jaw deflection.

Some carbon-based specimens were coated with copper, molybdenum or titanium nitride (TiN) thin films, namely R4550 isotropic graphite (Cu), AC150K CFC (Mo), MG-6403Fc MoGr (TiN), MG-6541Fc (Mo), MG-6530Aa (Cu). Coating thicknesses were 8 µm for Mo, 2 µm (with an additional 0.5 µm Ti flash) for Cu and 5 µm for TiN.

EXPERIMENTAL/NUMERICAL RESULTS

The Multimat experiment was carried out in early October 2017: some 2.25×10^{15} protons were delivered on target in 478 pulses. Pulse intensity ranged from one to 288 bunches, with a typical bunch intensity of 1.3×10^{11} p. Nominal beam rms sizes were 0.25×0.25, 0.5×0.5 and 2×2 mm^2. Good beam stability and repeatability were obtained: this was particularly important for grazing impacts in which high position accuracy was sought.

Specimens were submitted to three different types of impact (Figure 3): axially centred impacts, intermediate offset and, where a coating was present, grazing impacts.

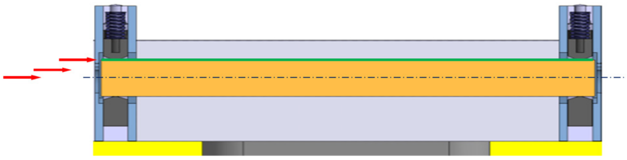

Figure 3: Typical specimen configuration, showing a scheme of beam impacts: centred, offset and grazing on coated surface (in green).

The specimen aspect ratio allowed generating signals in which the footprint of different phenomena, at distinct timescales, could be easily detected. In the first 1÷10 µs, a signal rise time, associated to the pulse duration, occurs: in this phase the highest strain rates are attained, with values as high as 10^4 s^{-1}. Subsequently, an axial wave, with a distinct trapezoidal pattern and a period in the order of 100 µs, is generated [19]: this regime is particularly useful to study material elastic constants, internal damping and axial strength. If the impact is transversely offset, lateral oscillations are also excited: these have a period in the range of 1 ms and are useful to determine the flexural strength and plasticity. Finally, temperature evolves on a significantly longer timescale, 0.1 s or more for the considered dimensions: this is why most of the dynamic phenomena can be reasonably considered as quasi-instantaneous and adiabatic [20].

An impressive amount of data was acquired and is presently being post-processed. Experimental data and numerical simulations were compared: results for a few selected cases are presented below.

In Figure 4, axial strain measured on the most loaded TaW specimen, with dimensions of 10×10×247 mm^3, are compared to values obtained from simulations, assuming a purely elastic model. TaW was submitted to a 2-bunch pulse, with intensity of 2.19×10^{11} p, rms sigma of 2 mm and vertical offset of 2.2 mm . The axial strain is taken at the specimen center on its bottom face. The propagation of a trapezoidal axial wave is clearly visible. Two numerical simulations were performed: with and without damping. It can be observed that a better agreement can be obtained assuming a Rayleigh damping ratio $\zeta = 0.002$; in the numerical model this was introduced through a stiffness-weighted damping constant $\beta = \frac{\zeta}{\pi f}$, taking for f the value of the high-frequency transversal vibrations.

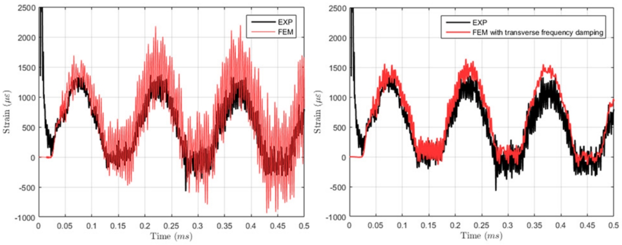

Figure 4: Numerical (red) and experimental (black) comparison for axial strain in TaW with (right) and without (left) internal damping.

In Figure 5, the flexural oscillations for CuCD grade 1, impacted by one bunch with 1.43×10^{11} p, sigma 0.5 mm, offset 3.1 mm are reported. The left plot shows a comparison between purely-elastic and elastic-plastic models and experimental data; the right plot reports numerical results with a damping ratio $\zeta= 0.08$, estimated from the logarithmic decrement of measured oscillations.

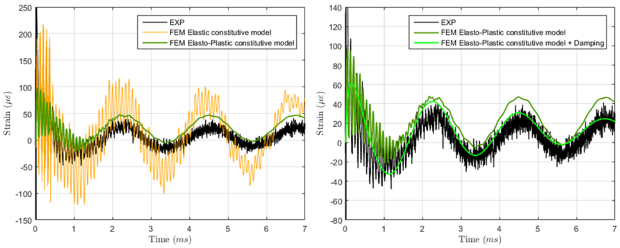

Figure 5: Flexural oscillations in the most loaded specimen of CuCD-grade 1. Numerical/experimental comparison.

As mentioned, grazing impacts were also performed to probe the robustness of coatings applied on some low-Z materials. Electrically conductive thin films are considered to further reduce the transverse wall impedance of LHC and HL-LHC collimators, which make up for the highest impedance contribution for these accelerators.

In Figure 6 the damage induced on Mo coating applied on CFC and MoGr is shown; test conditions are reported on the figure. As it can be noticed, a surface scratch is present in both materials; the extent of the coating ablation for 288 bunches is comparable, with a width estimated to ~2 mm.

As can be observed in Figure 7, the damage extent in CFC is a factor 2 larger than the thermally affected area in Mo, defined as the region above 200° C; this ratio increases to a factor of 5 or more, if one considers the area exceeding Mo melting point. A similar behaviour can be found in the case of MoGr. This effect is to be further studied, but may be due to the strong accelerations induced on the coated layer by the free surface reflection of the stress wave originated at the impact centre.

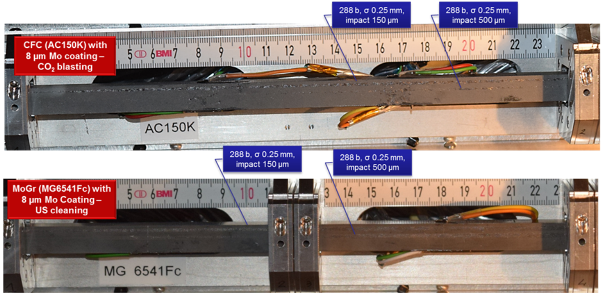

Figure 6: Damage induced on Mo coating applied on CFC (top) and MoGr (bottom) by 288 bunch grazing impacts.

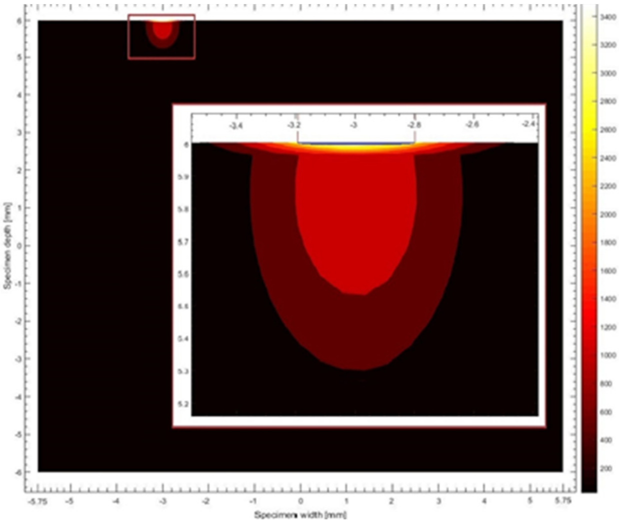

Figure 7: Temperature distribution induced on the most loaded cross section of Mo-coated CFC by a 288 b impact.

The energy density corresponding to the highest intensity pulses (288 b) exceeds the one predicted for the HL-LHC both for standard and Batch Compression Merging and Splitting (BCMS) schemes [21]. Based on these results, the choice of Mo (and to a lesser extent of Cu) for HL-LHC secondary collimators coatings, as to robustness, was validated.

CONCLUSIONS

A complex, comprehensive experiment was carried out at CERN aiming to explore the dynamic behaviour of 18 different materials relevant for collimators and beam intercepting devices, hit by 440 GeV/c intense proton pulses, with centred, offset and surface grazing impact parameters. A selection of measurement results was presented to illustrate the potential of this setup. Collected data are encouraging, well matching results of advanced computations, when previously unknown material properties are plugged back into numerical models. A large amount of information is being treated and will help improving constitutive models for the less known composite materials.

The dynamic behaviour of coatings applied on advanced composites was probed under conditions which exceeded, in terms of energy density, the value expected in HL-LHC, validating the material solution for collimators to be installed during LS2. The modularity and reusability of the test-bench will permit performing additional tests in the future.

REFERENCES

[1] High-Luminosity Large Hadron Collider (HL-LHC). Technical Design Report V.0.1, edited by G. Apollinari, I. Bejar Alonso, O. Brüning, P. Fessia, M. Lamont, L. Rossi, L. Tavian, CERN Yellow Reports: Monographs, Vol.4/2017, CERN-2017-007-M (CERN, Geneva, 2017).

http://dx.doi.org/10.23731/CYRM-2017-004

[2] M. Benedikt, F. Zimmerman, "Future circular colliders", Proc. Int. Sch. Phys. Fermi 194 (2016) 73-80 CERN-ACC-2015-164.

[3] F. Carra *et al.*, "Mechanical engineering and design of novel collimators for HL-LHC", in *Proc. 5th Int. Particle Accelerator Conf. (IPAC'14)*, Dresden, Germany, Jun. 2014.

[4] A. Bertarelli, "Beam-induced damage mechanisms and their calculation. CERN Yellow Reports", v. 2, p. 159, Jan. 2016. ISSN 00078328.

[5] A. Bertarelli *et al.*, "Behaviour of advanced materials impacted by high energy particle beams", Journal of Physics: Conference Series, Vol. 451, conference 1.

[6] F. Carra *et al.*, "The Multimat experiment at CERN HiRadMat facility: advanced testing of novel materials and instrumentation for HL-LHC collimators". Journal of Physics: Conference Series, Vol. 874, Issue 1, 20 July 2017, Article number 012001.

[7] I. Efthymiopoulos *et al.*, "HiRadMat: a New Irradiation Facility for Material Testing at CERN", IPAC11, San Sebastián, Spain, 2011.

[8] A. Bertarelli *et al.*, "An experiment to test advanced materials impacted by intense proton pulses at CERN HiRadMat facility". Nuclear Instruments and Methods in Physics Research B, Vol. 308, pp. 88–99, 2013.

[9] A. Bertarelli *et al.*, "High Energy Tests of Advanced Materials for Beam Intercepting Devices at CERN HiRadMat Facility", HB2012, Beijing, China, 2012.

[10] E. Quaranta, "Investigation of collimator materials for the High Luminosity Large Hadron Collider", PhD Thesis, Politecnico di Milano, Italy, 2017.

[11] A. Bertarelli, F. Carra, N. Mariani and S. Bizzaro, "Development and testing of novel advanced materials with very high thermal shock resistance", Tungsten, Refractory and Hardmetals Conference, Orlando, USA, May 2014.

[12] S. Burger *et al.*, "Scintillation and OTR screen characterization with 400GeV/c proton beam in air at the CERN Hiradmat facility", Proceedings of the International Beam Instrumentation Conference, Barcelona, Spain, 2016, p. 268

[13] L. Peroni, M. Scapin, F. Carra, N. Mariani, "Investigation of Dynamic Fracture Behavior of Graphite", Key Engineering Materials, Vols. 569-570, pp. 103-110, 2013.

[14] N. Mariani, "Development of Novel, Advanced Molybdenum-based Composites for High Energy Physics Applications", PhD Thesis, Politecnico di Milano, Italy, 2014.

[15] A. Bertarelli *et al.*, "Innovative MoC – graphite composite for thermal management and thermal shock applications", Thermal Measurement, Modeling & Management Symposium (SEMI-THERM), San José, USA, 2015.

[16] A. Bertarelli *et al.*, "Research and development of novel advanced materials for next-generation collimators, IPAC11, San Sebastián, Spain, 2011.

[17] M. Scapin, C. Fichera, F. Carra, L. Peroni, "Experimental investigation of the behaviour of tungsten and molybdenum alloys at high strain-rate and temperature", EPJ Web of Conferences 94, 01021 (2015).

[18] M. Scapin, L. Peroni, F. Carra, "Investigation and Mechanical Modelling of Pure Molybdenum at High Strain-Rate and Temperature", J. dynamic behavior mater. (2016) 2: 460.

[19] A. Bertarelli, A. Dallocchio, T. Kurtyka, "Dynamic Response of Rapidly Heated Cylindrical Rods: Longitudinal and Flexural Behavior", J. Appl. Mech. 2008.

[20] F. Carra, "Thermomechanical Response of Advanced Materials under Quasi Instantaneous Heating", PhD Thesis, Politecnico di Torino, Italy, 2017

[21] HL-LHC Engineering Change Request, Beam/Machine Parameters in Collision – Update, CERN, LHC-_-EC-0039, EDMS n. 1908458