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THE "MULTIMAT" EXPERIMENT AT CERN HIRADMAT FACILITY: ADVANCED TESTING OF NOVEL MATERIALS AND INSTRUMENTATION FOR HL-LHC COLLIMATORS*

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Abstract

The increase of the stored beam energy in future particle accelerators, such as the HL-LHC and the FCC, calls for a radical upgrade in the design, materials and instrumentation of Beam Intercepting Devices (BID), such as collimators Following successful tests in 2015 that validated new composite materials and a novel jaw design conceived for the HL-LHC collimators, a new HiRadMat experiment, named "HRMT36-MultiMat", is scheduled for autumn 2017. Its objective is to determine the behaviour under high intensity proton beams of a broad range of materials relevant for collimators and beam intercepting devices, thin-film coatings and advanced equipment. The test bench features 16 separate target stations, each hosting various specimens, allowing the exploration of complex phenomena such as dynamic strength, internal damping, nonlinearities due to anisotropic inelasticity and inhomogeneity, effects of energy deposition and radiation on coatings. This paper details the main technical solutions and engineering calculations for the design of the test bench and of the specimens, the candidate target materials and the instrumentation system.

INTRODUCTION TO THE EXPERIMENT

In the next years, the HL-LHC upgrade [1] will increase the energy stored in LHC circulating beams by almost a factor of two (from 360 to 680 MJ). In the case of future proposed accelerators such as the FCC [2], the energy stored will be even higher, in the order of 8500 MJ. Among the components interacting with the particle beam, the collimators, which are used for beam cleaning and machine protection, are exposed to risks of accidental beam impacts, for example in the case of asynchronous dump or injection error. In the case of HL-LHC and FCC, the thermal load expected to be discharged on the collimator jaws will far exceed energy densities of 10 kJ/cm^3 [3], involving potential melting or vaporization of the material in the impacted volume, as well as intense shockwaves propagating towards the surroundings, with risk of plasticity or spallation on the near components. The numerical codes adopted for the simulation of beam impact strongly rely on material models which have to be experimentally benchmarked against the extreme conditions induced by the event. This can take place only in dedicated tests in facilities such as HiRadMat [4].

In 2004 and 2006, carbon collimator jaws were tested and survived the impact of the intense SPS beam [5]. In 2012, an experiment run in the HiRadMat facility allowed deriving the threshold of damage for tungsten tertiary collimators [6]. Finally, in 2015, tests in HiRadMat validated the design of the novel metal-diamond and ceramic-graphite jaws designed for HL-LHC collimators, for beam brightness values beyond LIU [7]. In parallel with the tests on full-scale collimator components, an experiment, known as *HRMT14*, was performed in 2012 [8] on specimens of simple geometry, fully instrumented, to benchmark the numerical results obtained with codes such as ANSYS [9], Autodyn [10] and LS-Dyna [11]. The test confirmed the precision of the numerical results, when the material models, for the extreme conditions produced by the particle beam impact, are well mastered [12,13].

A new experiment of this kind, named *Multimat*, is under preparation for tests in autumn 2017 in HiRadMat. The experiment profits of the experience of HRMT14, aiming at testing at HL-LHC energy densities new collimator materials and coatings developed in recent years [14], in addition to novel instrumentation devices for the monitoring and correction of jaw distortion, under design for HL-LHC and FCC. With respect to past tests, the new experiment will focus on the derivation of less known material properties such as damping, porosity, anisotropic wave propagation, dynamic behaviour of coatings.

The test bench (see Fig.1) features a leak-tight aluminium container (hidden in the figure) hosting 16 target stations, each 1 m long and supported on a rotatable sample holder, separated by protective metal sheets. The target stations will be extensively instrumented (Table 1), with strain gauges, pressure sensors and thermal probes, as well as remote instrumentation such as rad-hard camera and Laser Doppler Vibrometer (LDV) placed in a shielded bunker.

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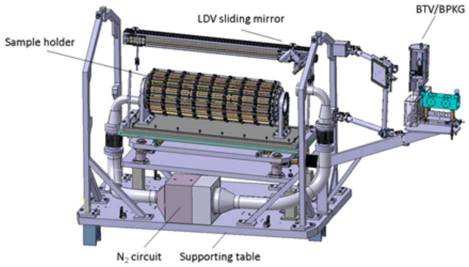

Figure 1: Inner view of the Multimat test bench. The tank is hidden in this view. The beam comes from the right.

Table 1: DAQ Overview

Physical Effect	Amplitude Threshold	Frequency Range	Sampling Frequency	Sensors selected	Acquisition Selected
Axial waves	20 µm/m	50 kHz	1 MHz	Strain gauges	Real time PXI
Bending waves	20 µm/m	2 kHz	1 MHz	Strain gauges	Real time PXI
Temperature	20°C	1Hz	100 Hz	Pt100	Real time PXI
Transverse oscillation	0.05 m/s	2 kHz	1MHz	LDV	Real time PXI
Permanent deformation	0.1mm	Static	Few Hz	FOS strain sensors	Optical nterrogator
Surface damage	-	-	-	Rad-hard camera	-

EXPERIMENT DESIGN

The sample holder is enclosed in a leak-tight aluminium vessel, maintained under inert atmosphere, preventing oxidation of the samples. A forced flow of nitrogen will decrease the cooling time of specimens after each impact. Large windows guarantee the optical access to the specimens for the LDV and the camera. The beamline is equipped with two beryllium windows, reinforced with CFC, designed to withstand the load induced by the beam passage. An actuation system guarantees the rotation of the sample holder and the vertical/horizontal adjustment of the specimen position in the plane perpendicular to the beam line. Stepper motors an leadscrews are used for the horizontal and vertical movement of the whole tank, with an available stroke of ± 15 mm. the accuracty of the actuator is ±10 µm.

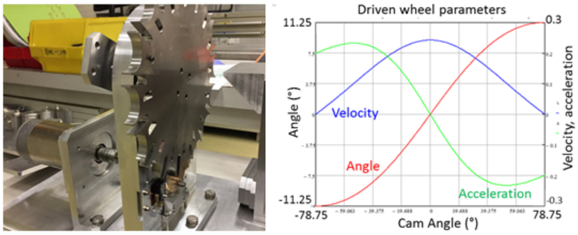

Figure 2: Left: mockup of the Geneva mechanism. Right: driven wheel parameters as function of the cam angle.

The rotation of the sample holder (+/– 180°) is assured by a Geneva mechanism, consisting of a stainless steel driven wheel and a brass cam. Extensive calculations were performed to optimize the geometry and verify the stresses and accelerations on the elements in operation. Moreover, due to the criticality of the mechanism, a mock-up was built and tested, to verify the precision and repeatability of the system after a high number of cycles (see Fig.2). The sample holder is an aluminium rotatable barrel, with 16 positions for material samples and instrumentation (see Fig.3), featuring elliptical holes for the passage of the instrumentation wires.

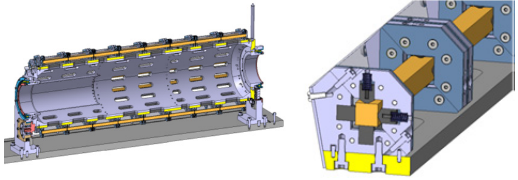

Figure 3: Left: section view of the sample holder. Right: specimen supporting system.

The supporting system hosts targets of variable length, for a total of 1 m per line, and a section with typical dimension comprised between 8 and 12 mm. Supports are adjustable by means of pins, to match the required specific length for each material. The targets can be grouped in six categories:

- *Pure carbon materials*, such as CFC, isotropic and pyrolytic graphite, and carbon foams.
- *Metal carbide – graphite composites,* with a graphitic matrix reinforced by molybdenum and/or titanium carbides, with the possible addition of carbon fibres [15, 16]. Coated samples will also be tested.
- *Copper – diamond*, of different grades, exploring in particular the nature of binders enhancing the resistance of the interface matrix/particle [17].
- *Heavy alloys*, mostly based on molybdenum, tantalum and tungsten [18, 19]. The upgraded compositions do not present a low melting phase, to enhance the robustness to beam impact.
- *Silicon carbide*, possessing high thermo-mechanical robustness, also appealing for other applications outside particle accelerators (aerospace, nuclear plants, braking elements).
- *Monitoring and actuating devices* to correct beam-induced jaw distortion in HL-LHC collimators.

Table 2: 1st Flexural Frequency (Hz) of 5 Target Materials

	Carbon foam	Metal Graphite	Silicon carbide	Pure Mo	Tungsten alloy
Fixed ends	84.2	170.7	1485.0	754.9	592.7
Simply supported	38.3	77.7	676.2	344.4	271.0
Elastic supports	41.4	83.9	729.8	375.7	295.2

The specimens are placed on graphitic elastic supports at the two extremities, with a contact pressure granted by springs with a spring ratio of 1 N·mm^{-1}. A spacer is adopted to change the spring pre-compression adapting the specimen to the desired size. Graphite was chosen because of the transparency to the beam, for its shock damping properties and low shock impedance [20, 15].

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Modal analyses were performed to calculate the flexural frequency of each sample, which will be excited through off-centre beam impacts, and the results show that the system is close to an ideal configuration of simple supports at each end. Table 2 shows the modal results for five different materials.

One target station is dedicated to the testing of a monitoring and actuation system under development at the University of Huddersfield and CERN. Aim of the system is to dynamically correct distortions in the collimator jaws, caused by in-operation events. The distortion detection is performed via Dispersed Reference Interferometry (DRI) by means of optical fibres. The actuation is currently based on piezo-actuators with a rise time in the order of µs, which is the period of flexural oscillations induced on the collimator jaw in case of beam impact. The system is also capable of a static correction of shape errors due to machining tolerances. The principle will be tested on a dedicated target station, correcting the flexural oscillations which will be generated on an aluminium sample (Fig. 4).

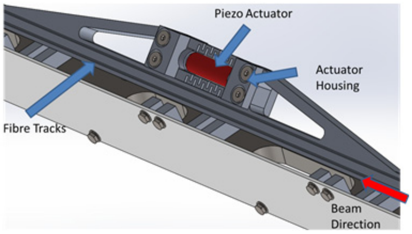

Figure 4: Piezo-actuator for bending correction.

SAMPLE DYNAMIC RESPONSE

Simulations and analytical methods can well predict the behaviour of the material under beam impact [21]. However, these calculations typically include a number of simplifications and assumptions, usually neglecting the dispersive effects due to geometry, impulse shape, material inelasticity, internal friction and porosities. In order to better investigate such mechanisms, the target geometry was optimized to generate uniaxial strains easily detectable by the instrumentation. In HRMT14, measurements on the low-density materials were weak and sometimes in the noise range, as the setup was studied for exciting radial waves, decaying in amplitude with the radius. In Multimat, axial waves will be excited; in this sense, it is important to minimize the dispersion effects due to radial inertia, which affects the quality of the acquired signal and the velocity profile of the wave. This, for a mechanical impulse, can be verified with the *Pochhammer equation* [22]:

$$\frac{c_p}{c_0} = 1 - 3\nu^2\pi^2\left(\frac{r}{\Lambda}\right)^2 \qquad (1)$$

where c_p is the longitudinal wave velocity, c_0 is the sound speed in uniaxial stress condition, ν is the Poisson's ratio, r is the bar radius and Λ the length of the wave. As similar studies for thermal-induced stress waves are scarce in literature, an analytical model not accounting for radial inertia and a numerical one, including radial dispersive components, material nonlinearities, boundary effects, as well as thermal energy distribution variable in z, were built to evaluate the target response. As seen in Fig. 5, for the optimized sample geometry the two models are in good agreement, and the radial inertia contributions are negligible, with the wave travelling at a velocity c_p~c_0. Interestingly, due to the variable energy distribution over z, the two planar waves have a different amplitude.

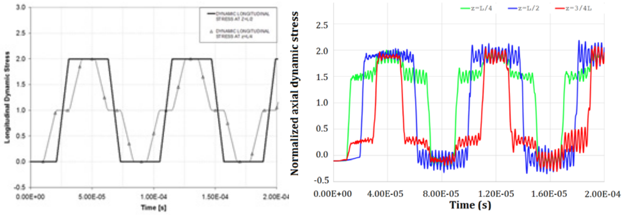

Figure 5: Axial waves in impacted graphite targets: analytical (left) and numerical model (right).

The frequency of the axial wave depends on the material, and ranges from 5 to 50 kHz. An off-centre beam impact will induce a higher amplitude, lower frequency (0.1÷2 kHz) flexural oscillation, which superposes with the axial wave (Fig. 6).

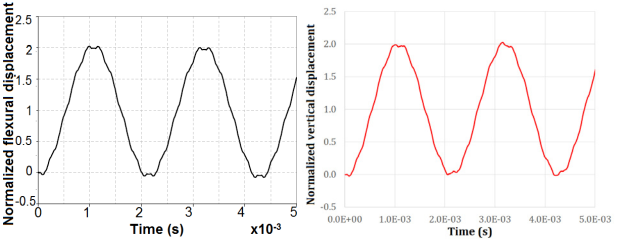

Figure 6: Flexural waves under off-centre impact on graphite targets: analytical (left), numerical model (right).

As mentioned, the numerical model is able to take into account a number of complexities to the problem; however, its validity must be benchmarked against a real scenario, in particular when dealing with novel materials for which strain, temperature and time dependent properties are scarce. Moreover, to the authors' knowledge, no dynamic model exists to predict the behaviour under beam impact of thin coatings, here adopted to increase the material electrical conductivity.

CONCLUSIONS

The energy increase in future particle accelerators calls for the development of unconventional materials and technologies. Although numerical codes can predict the response of a material under particle beam impact, the precision of the results is strongly related to the detailed understanding of the material models, such as the equation of state and the constitutive response. Furthermore, the dynamic behaviour of coatings applied on advanced composites, in the case of quasi-instantaneous heating, is not easy to explore with alternative methods. An experiment is foreseen in the HiRadMat facility at CERN at the end of 2017, to explore unusual properties of beam intercepting device materials, shedding light on the less explored mechanisms of the material behaviour, validating the material solution for HL-LHC.

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