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BEAM-IMPACT VALIDATION OF HL-LHC COLLIMATOR MATERIALS: THE "MULTIMAT-2" EXPERIMENT*

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Abstract

In 2017, a proton-impact test on HL-LHC collimator materials was carried out in the HiRadMat facility at CERN. The experiment, called "*MultiMat*", enabled the testing of uncoated and coated material composites and alloys, in most of the cases developed at CERN, for different beam collimation functionalities. Manufacturing of these materials was then passed to industry, leading to a series production for use in the collimators installed in the LHC during Long Shutdown 2 (LS2). The industrial versions of bulk and coating materials were tested in HiRadMat in 2021 in the "MultiMat-2" experiment, that efficiently re-used the same experimental test bench as for "*MultiMat*". This new experiment demonstrated the reliability of the absorbers installed in LS2, and confirmed the possible use of alternative materials and coatings for the next LS3 collimator production. This paper describes the preparation and beam parameters of "*MultiMat-2*", the experimental setup and the main results of the experiment.

INTRODUCTION

The LHC High-Luminosity upgrade (HL-LHC) means almost doubling the energy stored in the proton beams, from 360 to 680 MJ [1]. The collimation system [2] will also evolve, adopting materials able to dissipate the increasing power load, and reducing the RF impedance, thanks to an improved electrical conductivity of the collimator surfaces. The collimation upgrade is structured in two main phases: during Long Shutdown 2 (LS2, 2019-2021), a first series of low-impedance secondary collimators (TCSPM) was built and installed. During the future long shutdown (LS3, 2026-2028), more TCSPM, as well as new collimators for the Interaction Regions (IR), will be produced, including tertiary collimators [3]. The *MultiMat* proton-impact experiment [4] took place at the CERN HiRadMat facility [5] to validate, before LS2, the resistance to beam impact of the materials and coatings developed at CERN for the HL-LHC collimators. The experiment was successfully completed in October 2017. The test bench could host up to 16 target stations, each one embarking up to eight target rods, see Fig. 1. The experiment successfully validated the resistance of the materials under beam impacts that were equivalent or more severe than the HL-LHC design scenarios [6].

After *MultiMat*, the manufacturing of such materials and coatings was outsourced to industry, for production during LS2. Moreover, in recent years, new material solutions have been proposed for the LS3 collimators [7]. A second experiment, named *MultiMat-2*, was devised and completed in 2021, to validate the industrial grades developed for LS2 collimators, as well as new solutions proposed for the LS3 production. *MultiMat-2* successfully employed the same test bench of *MultiMat*, allowing to test in an economic way new uncoated and coated targets.

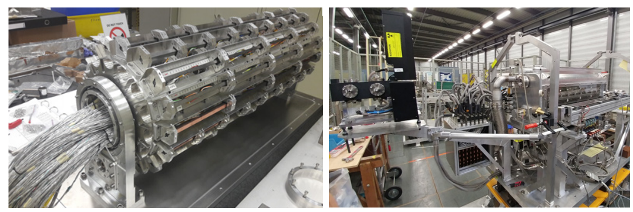

Figure 1: Left: *MultiMat* rotatable sample holder and target stations. Right: test bench on its supporting table.

MATERIALS

MultiMat-2 targets had a length of 125 or 250 mm, with rectangular cross section ~1 cm^2 (Fig. 2). They included:

Molybdenum-Graphite (Nanoker MoGr) [8][9], uncoated as in LS2 primary collimators (TCPPM) and coated with a 6 µm Mo layer obtained by HIPIMS [10] as in LS2 TCSPM.

Isotropic graphite (SGL R7550) [11], uncoated and coated with a 6 µm Mo layer, or with a 0.5 µm Ti + 3 µm Cu double-layer, both obtained by HIPIMS [10], considered as a cheaper solution for LS3 TCSPM.

Copper-Diamond (Nanoker CuCD) [12], uncoated, beam-impact robust alternative for LS3 tertiaries.

Additional materials of interest for high-end applications: Carbon-Fibre-Carbon (CFC), denser MoGr, Chromium-Graphite (CrGr) [13][14].

In this paper we focus on HL-LHC solutions or alternatives [7]: Mo-coated MoGr, Cu-coated graphite and CuCD.

Figure 2: Top left: Mo-coated MoGr. Top right: Mo and Cu-coated graphite. Bottom: CuCD.

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Inermet 180, the material choice for several HL-LHC collimators (TCLPX, TCTPXH, TCTPXV, TCLP, TCTPM), has been extensively tested in past HiRadMat experiences [15][16][4] and was thus not re-evaluated in *MultiMat-2*, as it was found to explode under absorbed energies one order of magnitude lower than the HL-LHC design case [17].

IMPACT PARAMETERS

To be considered suitable for operation in collimators, carbon-based materials adopted in TCPPM and TCSPM must survive the beam injection error scenario, while CuCD, of interest for tertiary collimators, requires withstanding without damage an asynchronous beam dump [1]. In this case, it is estimated that a single HL-LHC bunch may reach and impact the collimator jaw. Parameters of the two scenarios are summarized in Table 1.

Table 1: *HL-LHC* Collimator Design Accidental Scenarios

Design Case	Beam Type	Beam Energy [TeV]	Pulse Intensity [p]	Beam Emittance [µm]	RMS beam size [mm]
Injection Error	LIU BCMS	0.45	5.8×10^{13}	1.3	0.61
Asynchronous Beam Dump	HL-LHC	7	2.3×10^{11}	2.1	0.6

These parameters, in terms of beam energy and intensity, are beyond the reach of HiRadMat. It is, however, possible to mimic the expected damage, which depends on Damage Parameter Indicators (DPI) such as energy density (U_{max}) and average energy per target cross-section ($\bar{U}_{max}$) [4][18]. U_{max} equivalent to the HL-LHC design case can be reproduced in HiRadMat by reducing the beam size, whereas an equivalent $\bar{U}_{max}$ can be achieved by reducing the target cross-section with respect to a full-scale collimator absorber size. In a nutshell, materials that must withstand the injection error are tested in HiRadMat under a pulse of 288 bunches, with ~10^{11} p/bunch, and a beam sigma of 0.25 mm. As for the asynchronous beam dump, the damage equivalence is obtained with a pulse of 48 bunches and a beam sigma of 0.5 mm, at the intensity of ~10^{11} p/bunch. As shown in Table 2, these impacts produce DPI that are equivalent, or more severe, than in the case of HL-LHC.

Table 2: Comparison *MultiMat-2* / HL-LHC in Terms of DPI [kJ/cm^3], Calculated with FLUKA [19-21]

Material	MultiMat-2		HL-LHC Design Case	
	U_{max}	$\bar{U}_{max}$	U_{max}	$\bar{U}_{max}$
MoGr	7.35	0.48	6.09	0.46
Graphite	4.69	0.30	-*	0.12**
CuCD	4.70	0.85	4.81	0.15

** Not simulated; expected to be lower than MultiMat-2, since same beam as of MoGr case. **Extrapolated from CFC by density scaling.*

POST-IRRADIATION EXAMINATION

Analyses done on the targets after the experiment included visual inspection, surface topography, optical and scanning-electron microscopy (SEM), micro-computed tomography (µCT) and coating adhesion.

Visual Inspection and Topography

Analyses were performed in a metrology room at controlled temperature (20°C ±1°C). Pictures were acquired with an HD camera. Topography was performed, on the coated samples impacted with grazing impacts, with a contactless profilometer (VEECO WYKO – NT 3300).

In the case of Mo-coated MoGr, the beam impact strips a coated surface with an average width of 2 mm. Topography shows that the impact leaves a trace with depth ~8 µm. Since the coating thickness is 6 µm, this means that the material ejection starts 2 µm inside the MoGr substrate (Fig. 3).

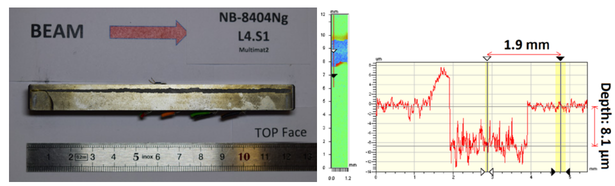

Figure 3: Mo-coated MoGr. Left: visual inspection. Right: surface topography at a longitudinal coordinate of 60 mm.

Cu-coated graphite also shows a trace produced by the beam on the coating; a peak of about 9 µm is visible, and a narrow valley, close to it, of about 12 µm (Fig. 4).

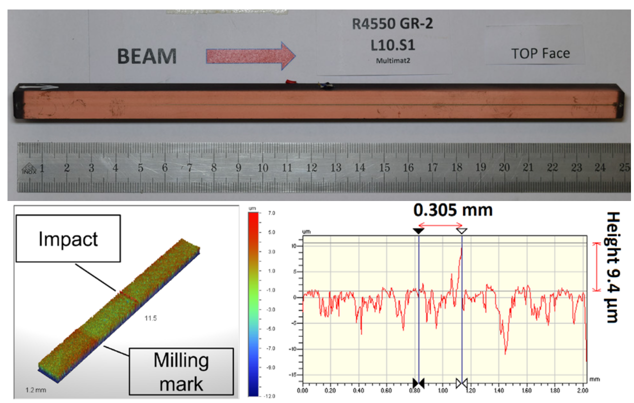

Figure 4: Cu-coated graphite. Top: visual inspection. Bottom left: surface topography at a longitudinal coordinate of 237 mm. Bottom right: profilometry in the same position.

CuCD does not show any trace of the beam impact after a pulse reproducing the asynchronous beam dump (Fig. 5).

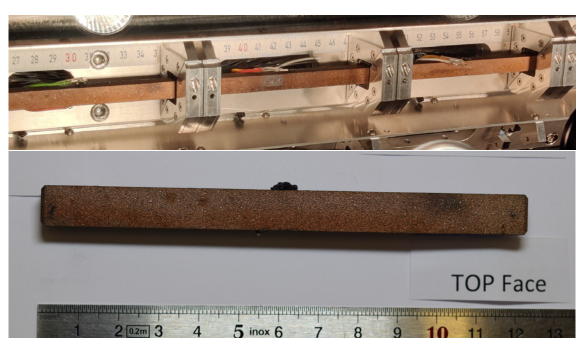

Figure 5: CuCD. Top: in-tunnel visual inspection of the target line. Bottom: HD image of the most loaded sample.

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Microscopy

The macrography and SEM (Fig. 6) show that the stripe visible on the Cu-coated graphite is made of molten and re-solidified copper. The titanium interlayer also gets visible. The stripe composition was verified via EDS spectroscopy.

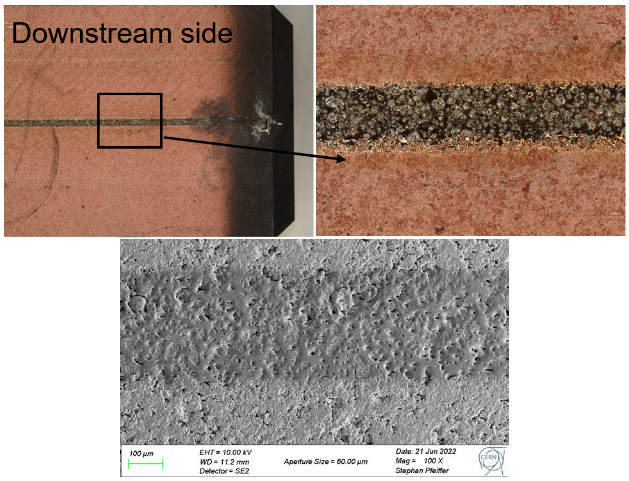

Figure 6: Cu-coated graphite. Top: optical microscopy (left) with zoom on the beam trace area (right). Bottom: SEM.

In MoGr, SEM confirms the good quality of the interface coating/substrate, and that the ejection originated in the first microns of the substrate, due to the higher density of MoGr with respect to graphite (Fig. 7).

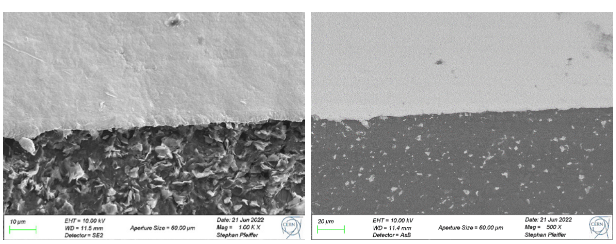

Figure 7: Mo-coated MoGr, SEM. Left: interface between intact and ejected surface areas. Right: backscattered electron image showing Mo carbides in MoGr.

Micro-Computed Tomography (µCT)

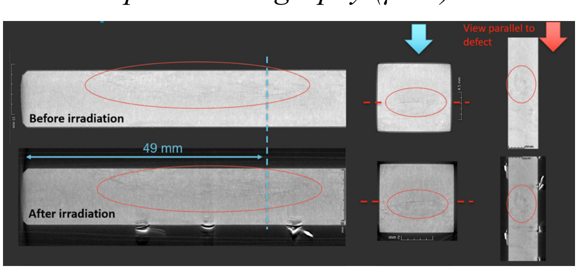

Figure 8: MoGr target examined by µCT. A defect was identified after irradiation, but careful examination of the pre-irradiated target showed the same defect, likely generated during sintering of the sample.

The presence of internal cracks in the impacted targets was studied via µCT. This technique allows detecting cracks and defects in the order of a few microns. MoGr, graphite and CuCD targets were scanned over all the length and compared with the µCT observations performed on the same samples prior to the experiment. No change was detected due to the beam impact. Figure 8 shows an example of a MoGr measurement.

Coating Adhesion Test

As mentioned, beam impacts on coated samples generated a local detachment of the coating, as in Mo-coated MoGr, or its local melting and re-solidification, as in Cu-coated graphite. Primary and secondary collimators support a movement orthogonal to the collimation plane (5th axis), that can be used, if needed, to expose a fresh, untouched coating surface to the beam. However, it is important to ensure that the coated regions around the affected impact area maintain a good adherence with the substrate. This was verified with adhesion tests, according to the norm ASTM D4541, evaluating the maximum stress sustainable by the coated interface. The tests showed that the fracture always occurs in the material substrate, confirming the good quality of the coating interface also after beam impact. Also, a hardening of the substrate after impact was observed, more significantly in the coating graphite case (Fig. 9).

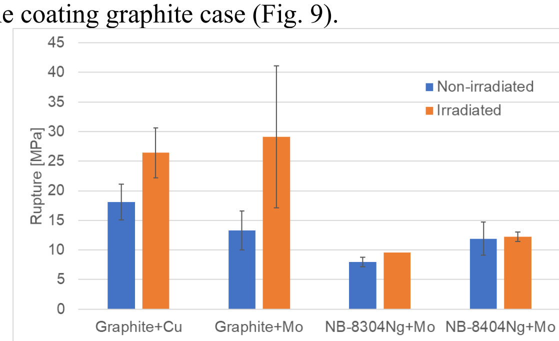

Figure 9: Adhesion strength of coated samples after beam impact, around the ejected or melted coating area.

CONCLUSIONS

After the previous experiment on HL-LHC collimator materials and coatings performed in 2017 (*MultiMat*), a new test, named *MultiMat-2*, was completed in HiRadMat in 2021. All bulk materials survived without damage following beam impacts equivalent or more severe than the HL-LHC design scenarios. All coating options show traces after grazing impacts, with lower damage in the case of graphite with respect to MoGr thanks to the lower energy absorption. However, the local effect produced on the coating can be recovered, in case of need, via the collimator 5th axis. Moreover, coating adhesion tests show that the areas surrounding the beam impact are unaffected, and they even show higher strength than before the test, likely due to a hardening phenomenon.

For these reasons, Mo-coated MoGr, Cu-coated graphite and CuCD are validated, from the robustness point of view, for use in the HL-LHC collimation system. Based on these results, Cu-coated graphite will be employed in LS3 TCSPM.

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