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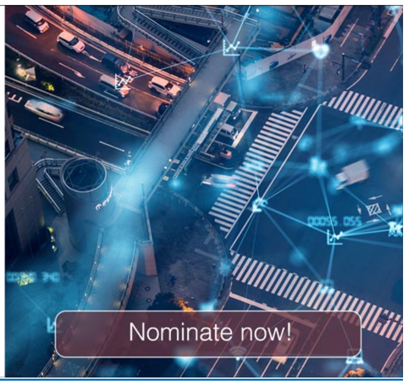

Mechanical robustness of HL-LHC collimator designs

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Abstract. Two new absorbing materials were developed as collimator inserts to fulfil the requirements of HL-LHC higher brightness beams: molybdenum-carbide graphite (MoGr) and copper-diamond (CuCD). These materials were tested under intense beam impacts at CERN HiRadMat facility in 2015, when full jaw prototypes were irradiated. Additional tests in HiRadMat were performed in 2017 on another series of material samples, including also improved grades of MoGr and CuCD, and different coating solutions. This paper summarizes the main results of the two experiments, with a main focus on the behaviour of the novel composite blocks, the metallic housing, as well as the cooling circuit. The experimental campaign confirmed the final choice for the materials and the design solutions for HL-LHC collimators, and constituted a unique chance of benchmarking numerical models. In particular, the tests validated the selection of MoGr for primary and secondary collimators, and CuCD as a valid solution for robust tertiary collimators.

1. Introduction

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 In recent years, a novel design was proposed for LHC collimators [1], to cope with the requirements imposed by the High-Luminosity upgrade of the LHC (HL LHC). Such requirements encompass material robustness under higher beam stored energy (from 360 MJ to 680 MJ), as well as a reduction in impedance [2]. A new collimator jaw (see Figure 1) was developed to ease manufacturing and assembling, compared to the previous configuration [3]. The new design features a common platform for the three halo cleaning families (primary, secondary and tertiary collimators), which enables using different absorbing materials with the same supporting structure [4].

Primary collimator jaws make use of molybdenum carbide graphite (MoGr) [5], offering a significant reduction of impedance compared to the 2D carbon fibre reinforced carbon (CFC) used so far. In secondary collimators, where the thermal loads are less concentrated, a 5 µm molybdenum coating is applied on MoGr to further reduce the impedance. Finally, copper diamond (CuCD) [6] is proposed as a more robust solution compared to the tungsten heavy alloy currently used in tertiary collimators.

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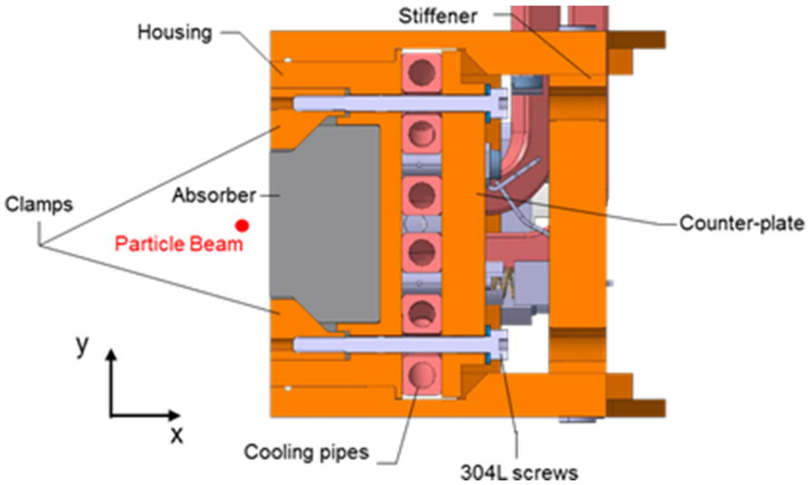


Figure 1. HL-LHC collimator jaw section view.

2. HiRadMat experiments

In order to validate the mechanical design and the material choices, two experiments were performed in 2015 and 2017 at CERN HiRadMat facility [7]. During the first experiment, named "Jaws" [8], two full scale HL LHC collimator jaws in MoGr and CuCD were built, largely instrumented and installed in a vacuum chamber together with a standard LHC collimator in CFC (Figure 2). The test aimed at assessing the thermomechanical response under beam impact of the key elements such as absorbing blocks, taperings, BPMs and cooling circuit.

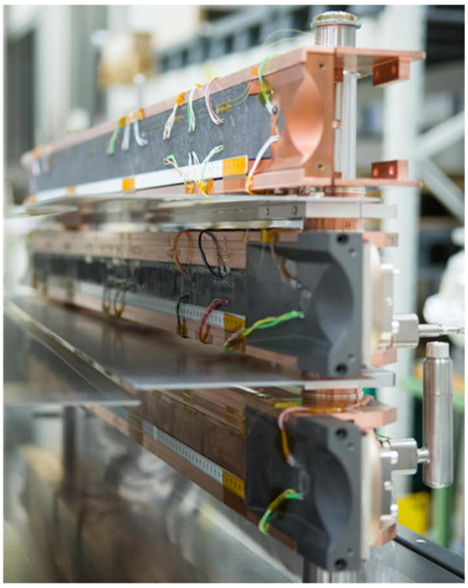


Figure 2. Configuration of Jaws, with, from top to bottom, CFC, MoGr and CuCD jaws.

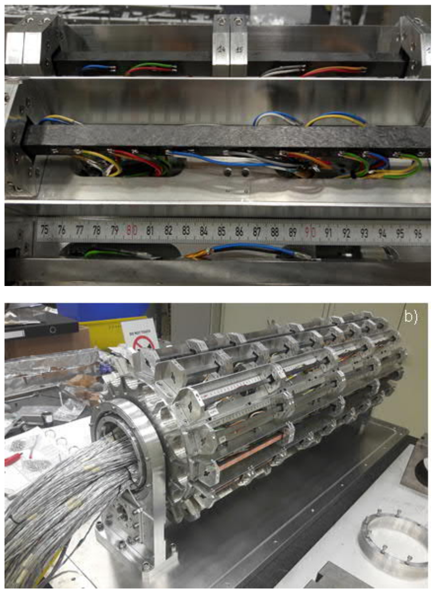


Figure 3. Configuration of Multimat.

The second experiment, "Multimat" [9], featured several material samples, also including MoGr and CuCD, with the goal of determining the material models to adopt in numerical simulations (see Figure 3). Moreover, in *Multimat*, profiting of the sample geometry, it was possible to reach dynamic strains on the most loaded specimens significantly higher than what expected in the HL-LHC accidental scenarios (Table 1). Additionally, *Multimat* aimed at evaluating, under proton impacts, the adherence of coatings made of molybdenum, copper and titanium nitride, applied to MoGr, CFC and isotropic graphite. The parameters of the two experiments, together with those expected in the

HL-LHC accidental scenarios, *i.e.* beam injection error (BIE) and asynchronous beam dump (ABD) [10], are reported in Table 1 where n_{tot} is the pulse intensity, σ is the beam transverse dimension, η is the impact parameter, ε is the impact depth, $E_{d,max}$ is the energy density peak, simulated with FLUKA [11], and $\varepsilon_{R,max}$ is the maximum dynamic strain evaluated at the most loaded cross section of the target [12]. In the two experiments, the energy density peaks, which are related to local damages in the material, expected during the HL-LHC accidents, were exceeded by transversally squeezing the proton beam.

Table 1: *Jaws* And *Multimat* Testing Parameters and HL LHC Accidental Scenarios. The Required Energy Density of The ABD Scenario is Mimicked by Compensating Lower SPS Energy With Higher Intensity.

	Material	n_{tot} (p)	σ min-max (mm)	η min-max (mm)	$E_{d,max}$ (kJ·cm^{-3})	$\varepsilon_{R,max}$ (μm·m^{-1})
Jaws	MoGr	3.80×10^{13}	0.35÷0.61	0.18÷3.05	5.66	2550
	CuCD	1.73×10^{13}	0.35÷0.61	0.18÷3.05	13.8	2590
	CFC	3.79×10^{13}	0.35÷0.61	0.18÷5.00	3.16	910
Multimat	MoGr	4.03×10^{13}	0.27÷0.75	0.15÷6.00	7.68	6050
	CuCD	2.89×10^{12}	0.49÷1.91	1.00÷5.00	2.71	2650
	CFC	3.72×10^{13}	0.30÷0.72	0.15÷6.00	3.76	3090
	Graphite	4.04×10^{13}	0.29÷0.72	0.15÷6.00	4.15	1320
HL-LHC BIE	MoGr	6.62×10^{13}	0.61	0÷3.05	6.09	2870
	CFC	6.62×10^{13}	0.61	0÷3.05	2.55	1140
HL-LHC ABD	CuCD	6.07×10^{12}	0.61	0÷3.05	4.81	850

3. Absorbing blocks

Absorbing blocks were subjected to visual inspection, metrology, 3D topography and computed tomography.

3.1. Molybdenum-Graphite

The MoGr jaw was impacted with six pulses at the maximum intensity available in the facility, reaching an energy density equivalent to that of the HL LHC BIE accident scenario (Table 1). Detailed visual inspections show only minor traces of the beam passage on the block active face (see Figure 4). The mark was produced by a grazing impact (0.5 σ impact parameter) with maximum energy density achieved on the material (σ = 0.35 mm, see Table 1). Any increase in the beam sigma, impact parameter, or decrease in the intensity, did not produce traces on the block surface.

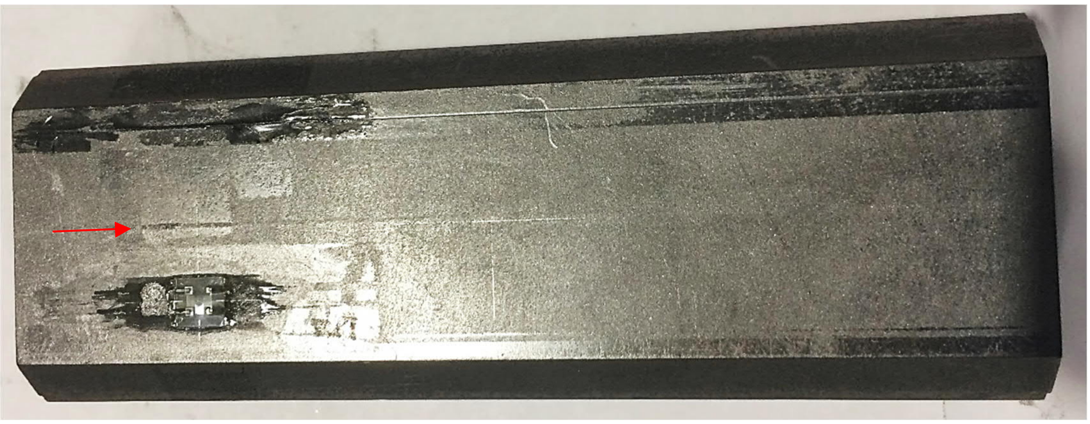


Figure 4. Visual inspection of most loaded MoGr block (#2). Red arrow indicates beam-induced mark. The other visible horizontal signs are optical fibre grooves and the glue used to fix them. Strain gauges are also visible.

Flatness measurements and 3D topography determined that the height of the mark shown in Figure 4, is in the order of 15 µm, with the block flatness error (including also the manufacturing tolerance) that remains below the specification of 40 µm (see Figure 5). Microtomography excluded the presence of internal cracks in the blocks.

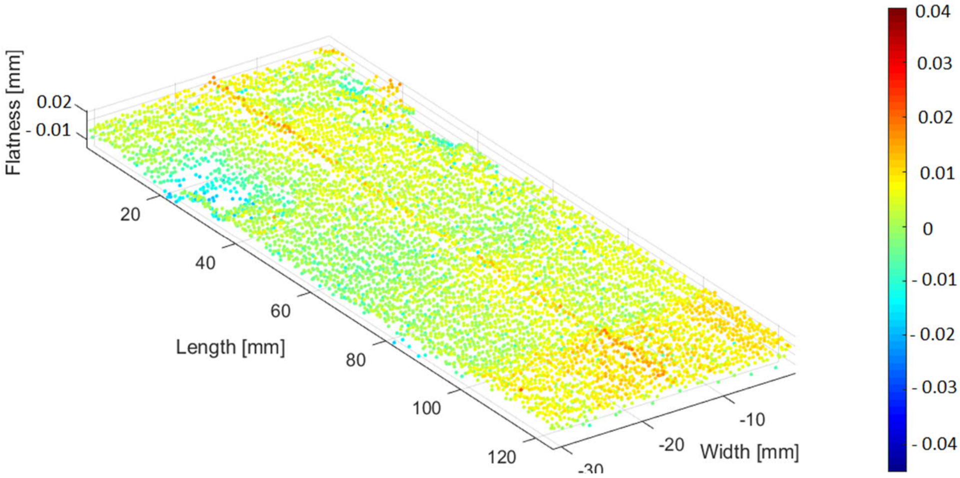


Figure 5. Flatness measurement of MoGr block #2.

3.2. Copper-Diamond

The CuCD jaw was submitted to ten impacts entailing energy densities equal or higher than the design accidental scenario (HL-LHC ABD). The *Jaws* highest intensity pulse surpassed in intensity the HL-LHC ABD by a factor of 3, and generated a scratch with local material fissuring, melting and detaching (see Figure 6). However, the metrology measurements showed that the functionality of the collimator, in case of such damage, can still be guaranteed by shifting the collimator assembly by ±10 mm, exposing a pristine flat region of the jaw to the beam (see Figure 7). This is possible thanks to the so called 5th axis, which can be activated in a collimator in case of accidental impact during operation. Comparing this result with those observed on a standard tertiary collimator during HiRadMat tests in 2013 [13], a factor ~14 of increase in robustness, when moving from Inermet180 to CuCD, could be estimated [8].

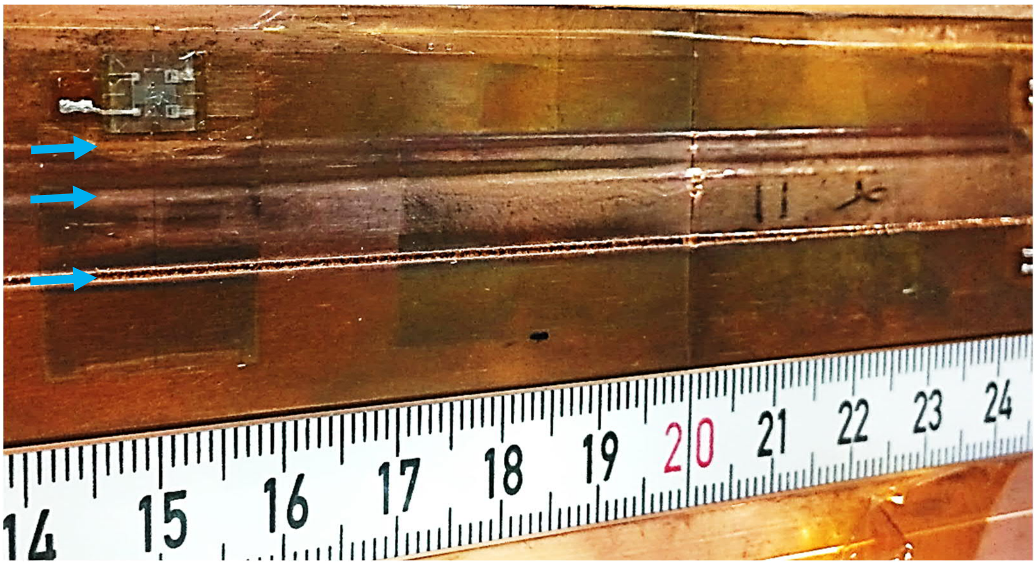


Figure 6. Visual inspection of CuCD jaw. Effects of the grazing impacts are indicated by the blue arrows.

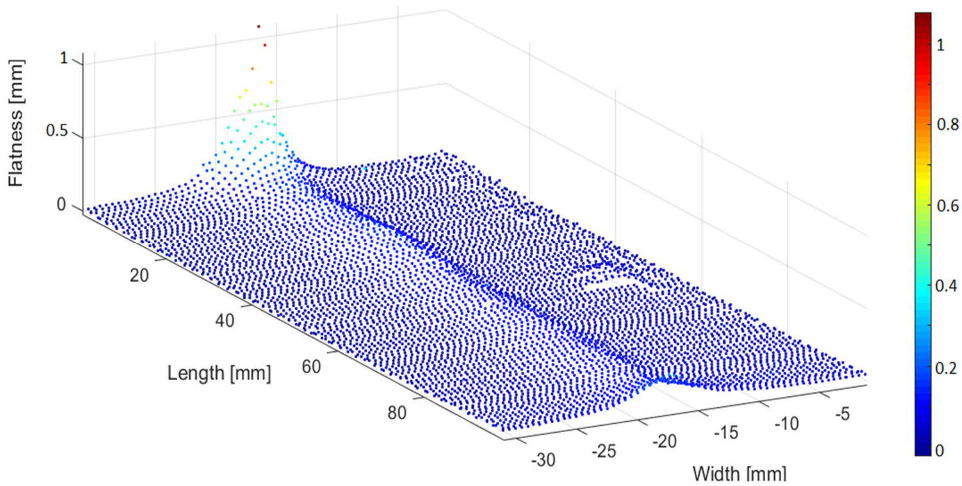
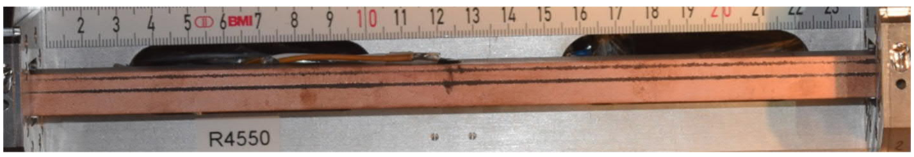


Figure 7. Flatness measurement of CuCD block #5, showing the area affected by the most severe impact, a factor of 3 above the ABD accident scenario.

3.3. Coating on MoGr

Coating adherence was investigated in *Multimat*. Results (see Figure 8) show that, in spite of the energy density peak higher than what expected in the BIE accident scenario, only minor scratches were produced on the thin films. The largest scratch occurs on copper coating, and is 1.9 mm wide. Molybdenum behaves better (1.1 mm scratch), thanks to its higher melting point. For all the tested solutions, the limited scratch width can be compensated, in case of impact, by shifting the collimator jaw with the 5th axis, exposing a pristine coated surface to the beam.



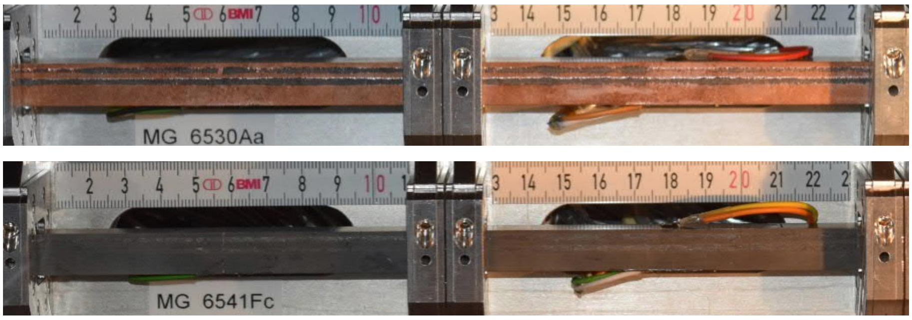


Figure 8. Visual inspection of Multimat targets: Cu-coated graphite (top), Cu-coated MoGr (center) and Mo-coated MoGr (bottom).

4. Taperings

In *Jaws*, MoGr taperings were installed in the MoGr and CuCD jaws, while Glidcop was used for the CFC jaw. The downstream Glidcop tapering locally melted (see Figure 9), with a produced crater of ~4×7 mm^2 size, as a consequence of an impact with intensity 3.8×10^{13} p and depth 5 mm. No damage was observed in the taperings made of MoGr (Figure 10), which has now become the baseline choice.

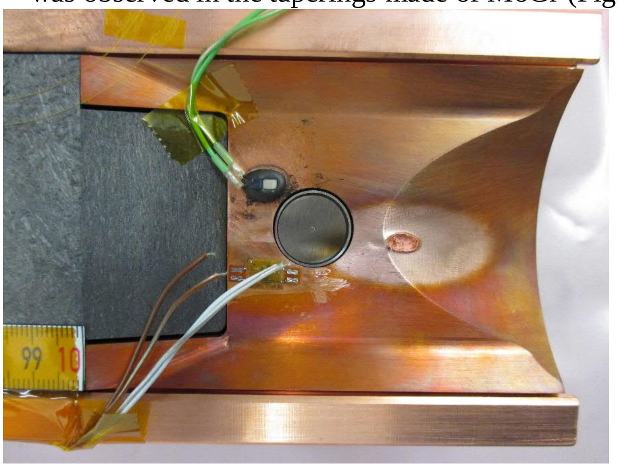


Figure 9. Jaws downstream taperings in Glidcop.

Figure 10. Jaws downstream taperings in MoGr.

5. Housing and cooling circuit

The jaw housings were measured before and after the experiment, to determine the variation in flatness provoked by the beam impact. The residual deflection was equal to 80 µm in the MoGr jaw and 50 µm in the CuCD jaw. This is a result of the multiple impacts at or above the design scenario. Assuming a linear contribution of each pulse above thresholds, the jaw deflection provoked by one pulse at nominal design intensity is estimated in 5 to 15 µm [8].

To guarantee a good heat transfer, the jaw cooling pipes are brazed to the Glidcop housing. Ultrasonic tests (UT) were performed to demonstrate that the proton impacts during Jaws had provoked no damage at the brazed interface (see Figure 11): the dark areas indicate optimal contact between housing and cooling pipes). After the experiment, the cooling pipes of the circuit were tested under internal water pressure of 10 bar. No leaks were observed.

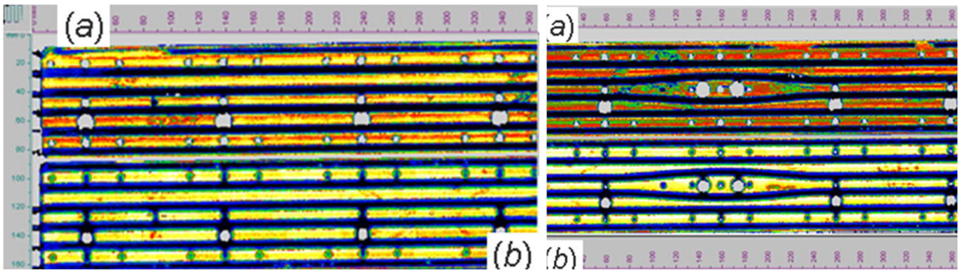


Figure 11. UT of MoGr (a) and CuCD (b) brazed interfaces, over different lengths: 200-550 mm (left) and 490-840 mm (right).

6. Beam position monitors (BPMs)
The performance of BPM installed in the *Jaws* taperings was measured before and after the experiment. The only BPM which failed during the test was the one installed in the Glidcop downstream tapering (**Error! Reference source not found.** and discussion in the previous "Taperings" chapter), as a consequence of the high deposited energy induced by the metallic surroundings. To further reduce energy absorption, in the final design, on top of using MoGr for the taperings, the BPM material was changed from stainless steel to titanium.

Table 2: Capacitive measurements on *Jaws* BPMs.

BPM location	T_{max} (°C)	Aspect	Impulse response change before and after experiment (%)
MoGr upstream	25	ok	1.6
MoGr downstream	400	ok	0
CuCD upstream	25	small black dot on one side	0.2
CuCD downstream	50	ok	0.1
CFC upstream	25	slight trace	0.6
CFC downstream	900	broken	13.7

7. Conclusions
An extensive characterization of the new collimator designs for the HL-LHC upgrade was carried out at CERN. The mechanical response under beam impacts of key elements, such as absorbing blocks, taperings, BPMs, housing, cooling pipes and brazed interfaces, was assessed in two experiments (*Jaws* and *Multimat*) at HiRadMat. The outputs of the experiments led to the validation, from a mechanical standpoint, of the final design choices. Given the limitations in terms of maximum intensity available at HiRadMat, the equivalence with the HL-LHC accidental scenarios on the full-scale equipment was mainly achieved by equalling or exceeding the peak energy density on the absorbing materials. The authors consider important to repeat similar experiments when higher-intensity LIU beams will possibly be available at HiRadMat.

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