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IRRADIATION OF LOW-Z CARBON-BASED MATERIALS WITH 440 GeV/c PROTON BEAM FOR HIGH ENERGY & INTENSITY BEAM ABSORBERS: THE CERN HiRadMat-56-HED EXPERIMENT

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Abstract

The beam stored energy and the peak intensity of CERN Large Hadron Collider (LHC) will grow in the next few years. The former will increase from max. of 320 MJ for Run2 (2015-2018) to almost 555 MJ during Run3 (2022 onwards) and 709 MJ during the HL-LHC era, putting stringent requirements on beam intercepting devices, such as absorbers and dumps. The HiRadMat-56-HED (High-Energy Dumps) experiment performed in Autumn 2021 executed at CERN HiRadMat facility employed the Super Proton Synchrotron accelerator (SPS) 440 GeV/c proton beam to impact different low-density carbon-based materials targets to assess their performance to these higher energy beam conditions. The study focused on advanced grades of graphitic materials, including isostatic graphite, carbon-fibre reinforced carbon and carbon-SiC materials in addition to flexible expanded graphite. Some of them precisely tailored in collaboration with industry to specific properties. The objectives of this experiment are: (i) to assess the performance of existing and potentially suitable advanced materials for the currently operating LHC beam dumps and (ii) to study alternative materials for the HL-LHC main dump or for the Future Circular Collider dump systems. This contribution will detail the R&D phase during design, the execution of the experiment, the pre-irradiation tests as well as the first post irradiation examination of the target materials. Lessons learnt and impact on operational devices will also be drawn.

INTRODUCTION

The LHC operates with a Beam Dumping System (LBDS) that is critical for its safe operation. The LBDS [1] is based on a fast beam extraction system made of a series of kicker and septum magnets used to deviate the two counter-rotating beams from the LHC ring towards two extraction lines. Each one of these extraction lines finishes on a different Target Dump External (TDE) unit.

The LHC TDE beam absorbing core is composed of six blocks of isostatic graphite (SGL Sigrafine® 7300), two 50 mm extruded graphite plates (SGL Sigrafine® HLM) and 1630 sheets, each 2 mm thick, of flexible expanded graphite (SGL Sigraflex® L20012C). The TDE core is designed to dilute and diffuse the energy of the beam [2]. The stored energy of the LHC beam during Run3 (2022-2025) will be higher than original LHC ultimate design values (523 MJ) [3].

The operational challenges encountered in LHC Run2 (2015-2018) on the two LHC TDE units were solved during Long Shut Down 2 (LS2) by a thorough programme of upgrades on the TDE spare units, which then became the main in-operation units [4, 5]. Nevertheless, experimental results from HiRadMat-43 (2018) [6], highlighted the importance of finding low-density Carbon-based alternatives to be used within the TDE core. During this experiment (HRMT-43), four Sigraflex® sheets received 440 GeV/c proton beam impacts to assess their performance to Run3 peak energy density values (2.35 kJ/g - 2.5 kJ/g). These sheets delaminated, bursting within their bulk, and causing permanent deformations of up to 250 μm on both sheet sides [6,7]. As options for the TDE low-density region [8], Carbon-Fibre-Reinforced-Carbon (CC) grades were considered due to their low density, good mechanical and thermo-mechanical properties and their non-fragile behaviour [9]. Moreover, HiRadMat-56-HED experiment included CCs currently implemented in two LHC beam extraction absorbers (TCDQ [10] and TCDS [11]). Finally, the design and material choices for the FCC-ee dumping system spoiler were assessed [12]. To fulfil all the experiment objectives a R&D campaign was carried out.

EXPERIMENT R&D

The HiRadMat [13, 14] beam (extracted from the SPS) was not capable of delivering by default the peak energy densities expected during Run3 and HL-LHC (> 2.5 kJ/g) on the targets, this triggered thorough R&D studies. The temperature and thermal strain fields obtained for HiRadMat-56 samples simulations had to represent the conditions calculated for the HL-LHC operational cases. To approach the experiment results to simulations, a deep R&D campaign was performed where beam diluters (used to increase the peak energy density on targets), specific targets and beam optics were designed for the HMRT-56 experiment and installed inside an Aluminium tank [8].

The proposed target design (Fig. 1 – (a)) features three disks of CC stacked together, inside an aluminium hollow cylinder. These targets axis is collinear with the beam trajectory, allowing to send four beam pulses at their centre. CC disks are axially constrained with Sigraflex® washers, contact springs and Titanium bolts.

Figure 1: CC Target model (a) & Diluter model (b) [10].

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Beam diluters (Figure 1 – (b)) were used for the first time in a HRMT experiment. Each diluter is made of a stack of Titanium diboride cylinders (TiB_2), each 20 mm diameter and 20 mm long. Sigraflex® washers are placed in between each cylinder to dump their axial deformation during beam impact. Sigraflex® thin foil is wrapped around the assembly and then it is inserted in a Ti grade 2 tube closed on both ends with CC disks. There are several diluters in length, some made of Titanium Carbide (TiC), instead of TiB_2 allowing to use different optics.

Sigraflex® samples were tested both in vacuum (2x10^{-3} mbar) and in nitrogen (1.05 bar absolute) to match the TDE operational requirements [8]. Different sheet distributions – varying density and sheet thickness – were tested under different configurations (stacked with and without compression, and single sheets). Figure 2 shows Sigraflex® targets type 1 and 2 models and the values of peak energy density for each region within the targets. The whole HRMT-56-HED experiment was finally made of 32 C-based cylindrical samples, 14 long diluters, 21 short ones and 5 Sigraflex® targets to be irradiated.

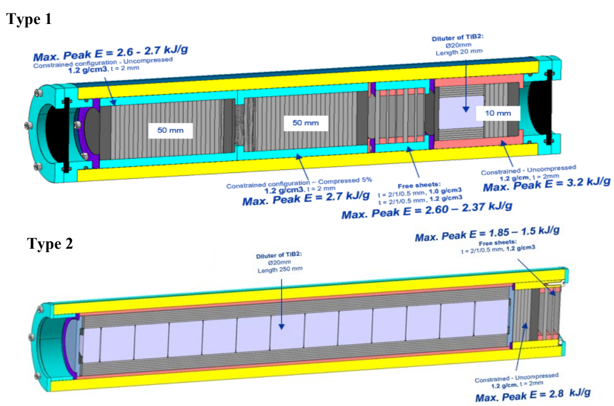

Figure 2: Sigraflex® HRMT-56 target type 1 and 2.

FLUKA Simulations

FLUKA [15] simulations were used to calculate energy deposition distributions in the target materials. Simulations were used to find the optimised target design, aiming at replicating the energy density conditions expected in Run-3 operation and beyond with HRMT beam. The presence of diluters, thanks to their higher proton inelastic cross-section, enhances the shower build-up, where protons interact producing secondary particles leading to the broadening of the target exposed area and the increase of the energy density deposited in the targets. The choice of diluter's materials was based on their fusion/sublimation temperature, technical feasibility, cost, and market availability. Two beam spot-sizes (at 1σ) on the targets [250x250 μm^2] and [1000x340 μm^2] were chosen. Most focused beam allowed to get high energy densities, whereas the asymmetric beam gave wider energy distribution profiles to match the simulated stress-fields still at high energy densities thanks to the diluters.

Figure 3 shows an example of a FLUKA simulation result applied to target train (assembly of targets + diluters place in beam trajectory) when impacted by the asymmetric SPS beam.

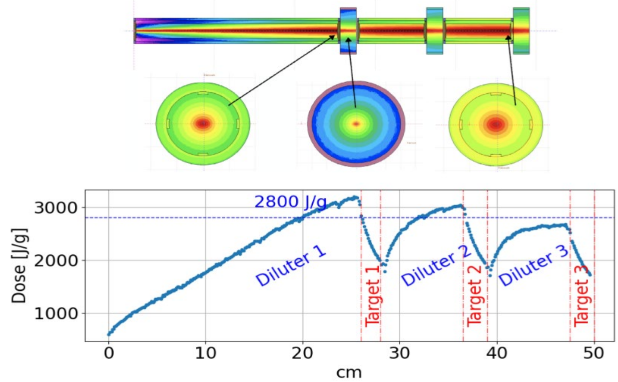

Figure 3: Example of a target station train peak energy density deposited versus length. Max. on targets: 2.8 kJ/g.

The plot above shows the peak energy density as function of length. Peak energy densities of about 2.8 kJ/g, 2.6 kJ/g and 2.3 kJ/g are respectively reached in the three targets. Figure 4 reports the peak energy densities ranges at which each one of the material families has been tested.

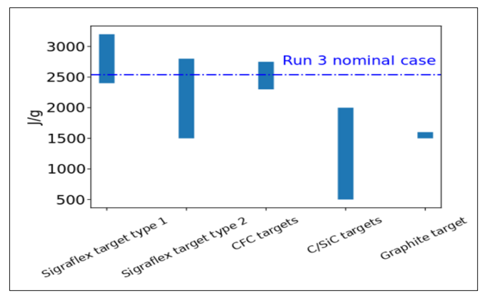

Figure 4: Peak Energy densities within the experiment.

PRE- AND POST-IRRADIATION (PIE) EXAMINATION & INSTRUMENTATION

Targets have been analysed before and after irradiation. Analyses included micro-CT scans with CERN CT scanner [16], accurate mass measurements, HD pictures, IET test and profilometry scans with CERN Veeco® optical profilometry device. Internal and external Laser-Doppler-Vibrometers (LDV) have been implemented for online measurement of two targets surface accelerations as well as temperature sensor on diluters.

OPERATIONAL DETAILS & RESULT

The experiment was aligned with the beam trajectory using geodetic metrology techniques. Beam-based alignment (BBA) and LDV-based alignment were performed to ensure the correct positioning of the proton beam with respect where the LDV laser pointed on the targets. The experiment was completed during week 44 - 2021. The Pulse List [17] is made of 72 pulses spread over all different targets for a total of 2.69 x 10^{15} protons.

Results on CC Targets

None of the grades of CC irradiated during this HRMT experiment show any damage or trace of the beam impacts nor visually neither under the u-CT scanner up to the resolution of this technique on these targets (15 μm) [18]. Moreover, mass measurements and HD pictures taken

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Pre/Post irradiation show no major beam induced effect. All CC targets received four impacts with the asymmetric beam at their centre. Figure 5 shows the results for u-CT scans on one sample of CC before & after beam impacts.

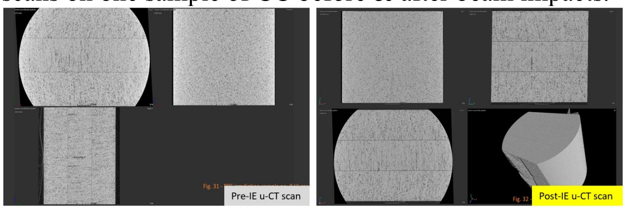

Figure 5: CC μ-CT results - before (L) and after (R) beam.

Results on Sigraflex®

The Sigraflex® PIE shows that, when assembled as a stack, sheets do not present any visible defect or delamination (checked with micro-CT) as observed for instance in [18]. Importance shall be given to this configuration as inside the TDE, layers are stacked together. This result is valid for any of the conditions tested – symmetric/asymmetric beam optics, N_2/vacuum atmosphere, different peak energy densities –. Figure 6 shows undamaged u-CT scans of one of the stacked layers sub-assemblies (L) and on one of the layers within the stack, scanned at high resolution – 10 µm – (R).

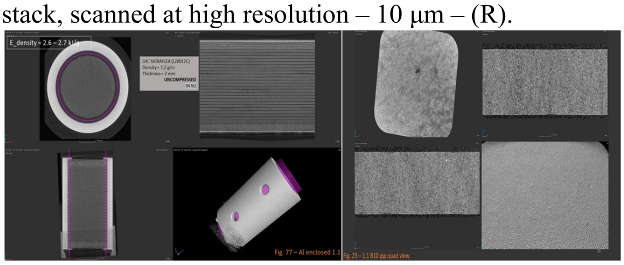
Figure 6: Stacked Sigraflex® u-CT examples.

When single Sigraflex® sheets (with a gap of 0.5 mm before/after each sheet) were irradiated, the material demonstrated damages on the front/back surfaces under the symmetric beam. Moreover, the effect of three pulses versus one pulse was studied as well as the effect of the atmosphere in which they were irradiated. Figure 7 (left) shows Sigraflex® sheets out of plane deformation (normalised with the thickness), after beam impacts all in N_2, for different sheets thicknesses. For each sheet, upstream (positive) and downstream (negative) faces deformations are plotted. Blue bars are normalised deformations for three beam impacts and yellow ones for a single impact. The material is slightly more damaged for three pulses events than for a single pulse event. Figure 7 (L) shows how samples in N_2 burst more out of plane than samples under vacuum. In addition, the thinner and less dense samples show a higher value of normalised deformation hence damage. Remarkably these symmetric-beam irradiated single layers do not show any delamination in the bulk as samples irradiated in air during HRMT-43.

Finally, one point of contact was found between previously damaged Sigraflex® samples at HiRadMat 43 [6] and the current experiment. Single sheets irradiated with asymmetric beam when in N2 show failure and delamination in the bulk.

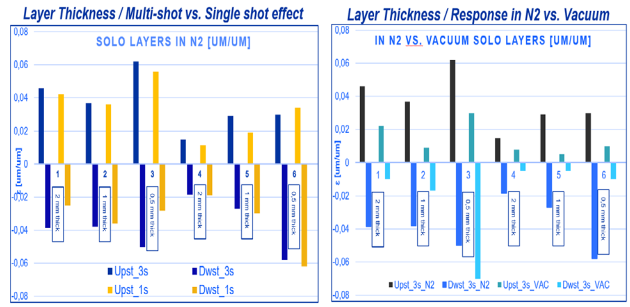

Figure 7: Single (SOLO) Sigraflex® sheets out of plane normalised deformation with symmetric beam impacts.

This delamination is more pronounced for the thinnest samples (0.5 mm) and at three beam pulses spot. However, these samples received lower values of peak energy density (1.5 – 1.85 kJ/g) than HRMT-43 samples [19] (and different beam spot size). The reasons for these differences in results are still being investigated. Figure 8 shows the failure for one single sheet (R) against an unaffected stacked layer example (L).

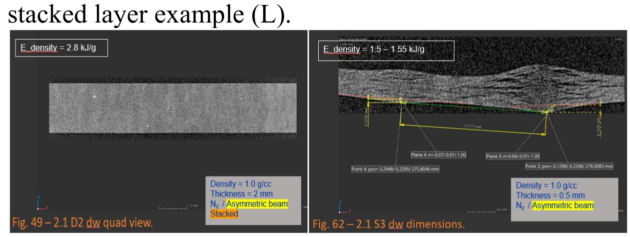

Figure 8: Damaged 0.5 mm Sigraflex® sheet (b) and untouched 2 mm stacked layer (a) micro-CT scan results.

CONCLUSIONS

HRMT-56-HED experiment allowed to assess the performance of different C-based materials to high-energy beam impacts. All CC grades performed well when impacted a limited number of times with a high energy proton beam (up to 2.7 kJ/g of peak energy density per pulse and 4 pulses in total each). This enables to establish grounds for the absorbing materials of high-energy beam dumps and beam absorbers for LHC Run3 and HL-LHC.

Sigraflex® demonstrated its capability to withstand 4 (3 -at the centre- + 1 -3mm from centre-) beam impacts up to 3.2 kJ/g of peak energy density when in stacked configuration in any atmosphere and with symmetric or asymmetric beam. Moreover, several different stacked sheets sub-assemblies received between 2.5 kJ/g and 2.7 kJ/g of peak energy density with no observed damages. These energies correspond to nominal Run3 conditions for the low-density segment of the TDE. Some out of plane deformations have been identified on single Sigraflex® layers exposed to symmetric and asymmetric beams that need to be further investigated. Single layers irradiated in N_2 with asymmetric beam experienced severe delamination in the bulk as in HRMT-43 experiment (2018).

Results of HRMT-56 are still being studied and interpreted at the moment of writing this contribution.

Main remaining question is what the performance of these materials would be at HL-LHC equivalent scenarios after hundreds of shots. For this reason, a follow-up experiment is already being prepared to take place in 2024.

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