HIGH INTENSITY BEAM TEST OF LOW Z MATERIALS FOR THE UPGRADE OF SPS-to-LHC TRANSFER LINE COLLIMATORS AND LHC INJECTION ABSORBERS

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Abstract

In the framework of the LHC Injector Upgrade (LIU) and High-Luminosity LHC (HL-LHC) projects, collimators in the SPS-to-LHC transfer lines will undergo important modifications. The changes to these collimators will allow them to cope with beam brightness and intensity levels that are much increased with respect to their original design parameters: nominal and ultimate LHC. The necessity for replacement of the current employed materials will need to be checked by a test in the High Radiation to Materials (HRM) facility at CERN. This test will involve low Z materials (such as graphite and 3-D Carbon/Carbon composite, 3D C/C), and will recreate the worst case scenario those materials could see when directly impacted by HL-LHC or Batch Compression Merging and Splitting (BCMS) beams.

INTRODUCTION

Several absorbers in both the SPS-to-LHC transfer lines (Target Collimator Dump Injection, TCDI) and in the LHC injection region (Target Dump Injection, TDI) are currently being redesigned to cope with the challenging beam parameters anticipated for the HL-LHC era (bunch train intensities of 5.8×10^{13} combined with small emittances [1]).

The TCDI collimators are currently made of Sigrafine® R4550 blocks, which are impacted by the beam in case of out of nominal trajectories.

Thermo-structural simulations have shown that the TCDI collimators graphite blocks are close to the failure point for the future LHC intensities for small impact parameters. As an alternative material, the 3D C/C composite technology is studied.

In order to cross-check and benchmark Finite Elements Analysis (FEA) a collimator-like experimental test bench was designed and constructed at CERN. This test-bench will host an experiment that will be conducted in the High Radiation to Materials (HiRadMat) facility at CERN [2]. This facility is installed in one of the Super Proton Synchrotron (SPS) extraction line.

MATERIAL SELECTION

The main objective of the experiment is the validation of a material with the capability to withstand intense particle beam impacts lasting a very short time (7.2 µs), starting from room temperature configuration (22℃), and reaching temperatures above 1000 ℃. From a material property perspective, this translates into looking for a material with the following properties:

- Light (density close to 1.8 g/cm^3);
- The highest thermal shock resistance coefficient (R_T):

$$R_T = \frac{K\,\sigma_T}{\alpha E}$$

Where:

- K is the thermal conductivity [W.℃$^{-1}$.m^{-1}];
- σ_T is the tensile strength of the material [MPa];
- α is the coefficient of thermal expansion [℃$^{-1}$];
- E is the Young's modulus [GPa].

The density and thermal shock resistance are the two main requirements considered in the material selection phase. Four materials have been selected for the experiment. Average material properties are reported in Table 1:

Table 1: Material Properties at Room Temperature

	Sigrafine® R4550	Graphite 2123 PT	Sepcarb® 3D C/C	C/C A412
Density [g/cm^3]	1.83	1.84	>1.81*	1.7
Thermal Conductivity W.℃$^{-1}$.m^{-1}	100	112	Non-Disclosure Agreement	-
Coefficient of Thermal Expansion 10^{-6} [℃-1]	4	5.6	2	-
Young's modulus [GPa]	11.5	11.4	Non-Disclosure Agreement	15
Tensile Strength [MPa]	30	35	100	60

Sigrafine® R4550 and Sepcarb® 3D C/C material properties provided by manufacturers allowed to perform Finite Element Analysis.

THERMO-STRUCTURAL SIMULATIONS

FLUKA Studies

The bunch trains which can presently be extracted to HiRadMat have a larger emittance and a smaller intensity than the bunch trains which will be transferred from the SPS to the LHC in the HL-LHC era. In order to reproduce the worst case scenario of HL-LHC beams (Run 3, BCMS beam), the SPS beam size had to be squeezed at the HiRadMat focal point (see Table 2).

This allowed to realistically probe the absorber material robustness by achieving similar peak energy densities and temperatures as with HL-LHC bunch trains. The required focal strength was determined by means of FLUKA [3, 4] particle shower simulations.

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* Measured at CERN material characterization laboratory

Table 2: Beam Parameters

	HiRadMat	HL-LHC Beam (Run 3 BCMS)
N. of Protons per bunch	1.2×10^{11}	2.0×10^{11}
N. bunches	288	288
Emittance[$\text{x}10^{-6}$] 1σ*	2.5	1.3
Sigma X [μm]	313	320
Sigma Y [μm]	313	511
Peak per primary [GeV. cm^{-3}.prim^{-1}]	0.66	0.44

Figure 1 shows the longitudinal energy density for the Sigrafine® R4550 block expected in the HiRadMat test and compares it with the worst case impact on a TCDI with future HL-LHC BCMS beam.

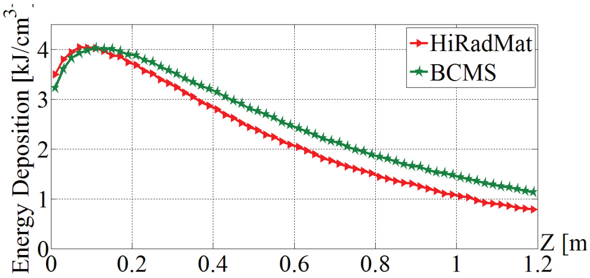

Figure 1: Longitudinal energy density in the Sigrafine® R4550 block.

ANSYS® Studies

The impact of a full 288 bunches beam on a very small spot of the TCDI collimator will create huge temperature gradients as well as high stresses in the structure (see Fig. 2). The produced energy deposition maps (via FLUKA) are used as input to thermo-structural studies performed with the FEA software ANSYS® [5].

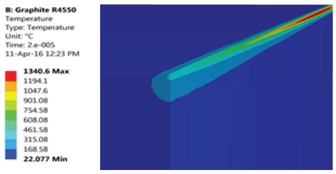

Figure 2: Temperature plot in the Sigrafine® R4550.

For each material a different equivalent stress criteria was used as suggested by the literature [6].

For graphite (brittle material) two different robustness criterion have been used: Mohr-Coulomb (M-C) criterion and the criterion of the maximum and minimum principal stresses. The definition of the two criterion is given below:

Mohr Coulomb safety factor:

$$F_s = \left[\frac{\sigma_1}{\sigma_{Tensile\ limit}} + \frac{\sigma_3}{\sigma_{compressive\ limit}}\right]^{-1}$$

Max/Min. principal stress safety factors:

$$F_{s,t} = \left[\frac{\sigma_{Tensile\ limit}}{\sigma_1}\right]$$

$$F_{s,c} = \left[\frac{\sigma_{Compressive\ limit}}{\sigma_3}\right]$$

Where σ_1 and σ_3 are respectively the maximum and minimum principal stresses at a given point in the material. For the material to withstand a certain stress load, the safety factor Fs (and both Fs,t and Fs,c for the maximum and minimum principal stresses criterion) has to be larger than one.

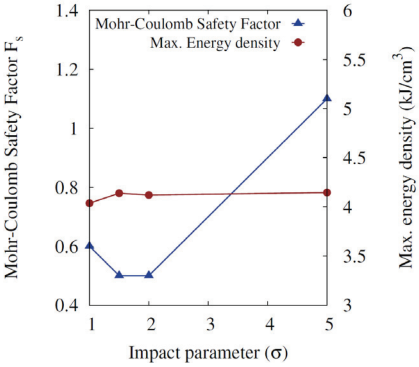

Figure 3: Dependency of M-C safety factor and energy density with impact parameter (in σ).

The minimum Mohr-Coulomb safety factor (worst case scenario) is reached at small impact parameters (about 1.5 σ) as shown in the Fig. 3.

According to these criteria, graphite would probably fail during a HiRadMat impact, while Sepcarb® 3D C/C would withstand the impact (see table 3).

Table 3: Temperatures and Stresses in the Materials Reached After 288 Bunches Hiradmat Beam Impact

	Sigrafine® R4550	Sepcarb® 3D C/C
Max. temperature [℃]	1348	1280
Max. Principal Stress/ Tensile Strength [MPa]	40.1/30	3.4/187
		41/245
		3.6/31
Min. Principal Stress/Compressive Strength [MPa]	-80/118	-13.7/-135
		-23.4/171
		-47/-80
Mohr-Coulomb Safety Factor	0.72	-

This simulations reproduces the expectations of a TCDI hit by a 288 bunches beam during run 3 in the worst case scenario (1 σ impact parameter).

Many uncertainties on the material properties are however still present, in fact static structural material limits are used in the analysis (generally a stain rate between 10^{-4} and 0.5×10^{-4} s^{-1} is used for static material tests) while beam impacts would create dynamic structural loads (strain rate of 5×10^{2} s^{-1}). Static and dynamic material limits for graphite can be very different [7], this being the reason why a test in the HiRadMat facility at CERN was justified.

THE HIGH RADIATION TO MATERIALS EXPERIMENT DESCRIPTION

Design

The design, based on existing collimators, consists of four jaws (one for each material) placed inside a vacuum tank made of stainless steel (as in Fig. 4).

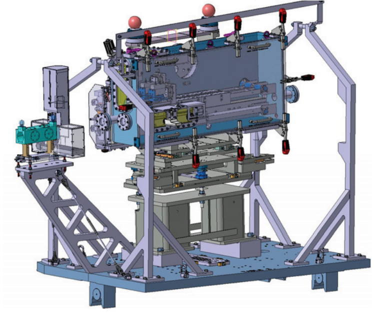

Figure 4: Overall view of the HiRadMat experiment.

Operational Phase

The operational phase of the experiment foresees the following actions:

- Setting up SPS high intensity magnetic cycle parameters (288 bunches beam, 1.2×10^{11} protons per bunch);
- Beam based alignment: Extracting beam to HiRadMat and monitoring with BLMs the particle losses while performing 0.25 σ beam scan steps with the jaws;
- Jaws positioning at 1.5 σ impact parameter;
- Laser Doppler Vibrometer (LDV) horizontal alignment:12 bunches horizontal beam scan;
- High intensity shots: impacting each material with 288 bunches beam.

Preliminary Results

The experiment is equipped with two electrically passive heads of a Laser Doppler Vibrometer (LDV), pointing on the external jaw surfaces, at the impacting beam point. The LDV measures the displacement of the impacted materials during the irradiation phase.

Results, after irradiation of the Sigrafine® R4550 have shown an outstanding agreement between the measured displacements and the simulation results.

The displacements increase linearly during the phase of load application (the beam pulse length lasts about 7.8 μs), then the surface smoothly tends to reach its initial position through small oscillations of about one micrometer of maximum amplitude (see Fig. 5).

In order to align the LDV on top of the particle beam as precisely as possible a beam scan was performed. Figure 6 shows the measurement taken with the LDV during this phase. The vibrometer was aligned with the beam at the 8th beam shot (maximum displacements measured by the LDV). The repetitiveness of the measurements taken was found to be remarkable (see Fig. 6).

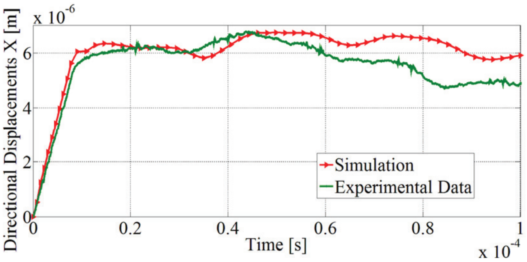

Figure 5: 288 bunches HiRadMat beam impact.

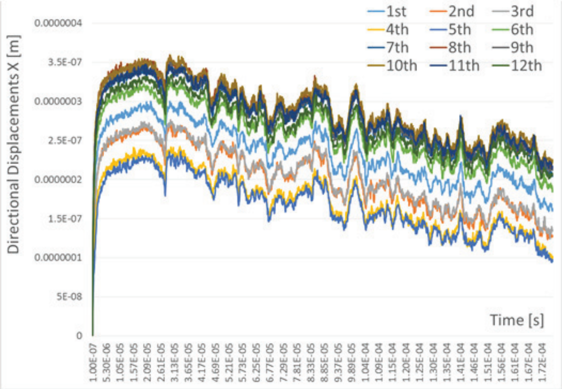

Figure 6: 12 bunches HiRadMat beam impacts.

The experiment is also equipped with high definition cameras, which have allowed to assess the state of the Sigrafine® R4550 (inner jaw in Fig. 7) after the impacts of 288 bunches HiRadMat beam. No visual damage has affected the graphite Sigrafine® R4550 jaw.

Figure 7: Graphite Sigrafine® R4550 before (on the left) and after (on the right) the beam impact.

This scenario suggests that the tensile limit of the graphite is higher with dynamic loads (strain rate: 5×10^{2} s^{-1}) than with static ones (strain rate: 0.5×10^{-4} s^{-1}). The C/C jaws will soon be irradiated.

CONCLUSION

The goal of this HiRadMat experiment is to help the material selection of several absorbers: TCDIs and TDIs.

Simulations have shown that the current TCDIs, made of Sigrafine® R4550, might not survive beam impact with the future LHC intensities (Run 3) for small impact parameters (1-1.5 σ), considering static material limits.

Uncertainties on the material properties were however still present. This is the reason why a test in the CERN HiRadMat was conceived.

The on-line instrumentation installed inside the test-bench has shown very good agreement between the experimental results and simulations during the irradiation of the graphite Sigrafine® R4550. No visual damage has affected the irradiated graphite jaws.

REFERENCES

[1] CERN EDMS Document: N.1296306

[2] HiRadMat, https://espace.cern.ch/hiradmat-sps/

[3] "The FLUKA Code: Developments and Challenges for High Energy and Medical Applications", T.T. Böhlen, F. Cerutti, M.P.W. Chin, A. Fassò, A. Ferrari, P.G. Ortega, A. Mairani, P.R. Sala, G. Smirnov and V. Vlachoudis, Nuclear Data Sheets 120, 211-214 (2014)

[4] "FLUKA: a multi-particle transport code", A. Ferrari, P.R. Sala, A. Fasso`, and J. Ranft, CERN-2005-10 (2005), INFN/TC_05/11, SLAC-R-773

[5] ANSYS® Academic Research, Release 16.2.

[6] Engineering Considerations of Stress, Strain, and Strength by R. C. Juvinall (McGraw-Hill) and Mechanical Engineering Design by J. E. Shigley (McGraw-Hill).

[7] Investigation of Dynamic Fracture Behaviour of Graphite. Lorenzo Peroni, Martina Scapin, Federico Carra, Nicola Mariani, Departement of Mechanical and Aerospace Engineering, Politecnico di Torino and CERN, Geneva Switzerland