LETTER

3D Carbon/Carbon composites for beam intercepting
devices at CERN

Abstract

3D Carbon/Carbon (3D CC) is a well-known industrial composite material for high-temperature applications. One of its main advantages resides in its ability to maintain good material characteristics at elevated temperatures (higher than 2700°C), which makes it potentially interesting for beam interaction applications where high strength at high temperature is required. The ability of beam intercepting devices to withstand direct impacts of high-energy proton beams is essential for the operation of the Large Hadron Collider (LHC) at the European Laboratory for Particle Physics (CERN). Following successful beam impact tests at CERN, as well as positive vacuum acceptance and metrology tests, several collimators and beam extraction absorbers are currently being equipped with 3D CC composite, as part of the LHC Injector Upgrade (LIU) and High Luminosity LHC (HL-LHC) projects.

KEYWORDS

3D Carbon/Carbon, composite, fibres, matrix, graphite, high temperature, thermal shock, radiation damage

1 | INTRODUCTION

In order to further increase the LHC discovery potential from 2021 onwards, the total integrated number of particle collisions at the experimental insertions will be increased by a factor 10. The High-Luminosity LHC (HL-LHC) and LHC Injector Upgrade (LIU) projects aim to upgrade CERN’s accelerator complex to reach this objective. A wide variety of CERN accelerator components will be exchanged to comply with these projects’ requirements: new magnets, accelerating cavities, collimators, beam instrumentation, etc. Beam intercepting devices (BIDs) play a key role in accelerator operation and personnel safety. During operation, BID active parts are impacted by the high-energy and high-intensity beams, and they need to survive these impacts to prevent any machine downtime. The BIDs are designed with absorbing materials that must have low density and low specific heat in order to minimise the temperature increase during beam impact. Their strength or strain at failure must be as high as possible and their coefficient of thermal expansion (CTE) as low as possible. Their thermal and electrical conductivities need to be maximised for heat extraction efficiency and machine impedance requirements. The impacted materials must be compliant with the machine’s ultra-high vacuum (UHV) requirements, they should present low radio activation potential and high radiation tolerance, and finally, they should be able to be produced in shapes compatible with the machine integration constraints.

2 | BEAM INTERCEPTING DEVICES AT CERN

BIDs represent a large variety of equipment, which can be divided into three categories, based on their function:

Beam stoppers are used for personnel safety, and beam dumps are needed to protect the machine against unsafe beams. These items have to completely absorb all the beam energy, which ranges from 130 J for Linac 4, 100 kJ for the Proton Synchrotron, up to 400 MJ for the LHC. Although beam stoppers must withstand a few shots per machine run (i.e., around 9 months of LHC operation per year), beam dumps can be impacted several times per minute, potentially releasing several hundreds of kilowatts of thermal power. The active parts of beam dumps must ensure a

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progressive beam dilution scheme, which is achieved by using low-density materials at the dump entry point, followed by increasing density materials along the length of the dump. In the LHC main beam dumps, low-density (1.0 g/cm³) flexible graphite sheets are currently used for the front part of the dump, over a length of 7.6 m. 3D CC could be an alternative material, because of its high thermal shock resistance (see Section 3) and because of its 3D construction, preventing to wrap several sheets together (and well compliant with the dump geometry). Its higher density makes it possible to reduce the length of the dump.

For beam cleaning and control, collimators, scrapers, strippers, and slits are used in the CERN accelerator complex. Collimators are active protection systems with roles that include cleaning the beam halo, cleaning physics debris coming from particle collisions in the experimental insertions, and concentrating radiation activation in specific areas of the accelerator complex. A multistage cleaning strategy is implemented, made up of primary, secondary, and tertiary collimators, to clean the beam halo, the secondary beam halo, and the hadronic showers, respectively. Collimator beam absorbing materials need very low electrical resistivity and high thermal conductivity (less than 1 μΩ.m and higher than 230 W/m/K, respectively). In addition, stringent flatness tolerances are needed to guarantee the cleaning and safety roles (typically 20-μm flatness over 1200 mm × 70 mm surfaces). The active parts of the existing LHC primary collimators are typically made of low-density (<1.8 g/cm³) carbon-based materials such as isostatically compressed polycrystalline graphite and 2D carbon/carbon (2D CC).

In order to produce secondary particle beams for physics experiments, particle-producing targets are used. Targets can be continuously impacted by high-energy protons beams, and must retain their material integrity at high temperatures. The absorbing materials making up these devices are also subject to radiation damage, which influences their thermal shock response and modifies certain mechanical and thermo-physical properties. As an example, the CERN CNGS target, made of isostatic graphite 2020 PT from Carbone Lorraine (Mersen), received up to 1.8 × 10²⁰ protons over 6 years of operation, which generated more than 1.5 Displacement Per Atom (DPA) of radiation damage in the graphite core.

For several of these BIDs, the implementation of 3D CC could offer advantages for the reasons explained in Section 3.

3 | 3D CARBON/CARBON SHORT DESCRIPTION

Thermo-structural composites, produced at high temperatures, composed of carbon fibres and a graphitised pyrocarbon matrix, have been widely developed for the aerospace industry. 2D CC composites have large dimensions in the plane (directions 1 and 2) compared with their thickness (direction 3), and their mechanical properties are generally weaker in direction 3. In comparison, 3D CC composites can have relatively large dimensions in the third or Z direction, together with interesting mechanical properties. Two 3D CC (Naxeco Sepcarb from Ariane Group, and the C/C A412 from Mersen) have been recently investigated at CERN by means of direct beam impacts and other tests (see Sections 3 and 4).

The Naxeco Sepcarb 3D CC has been developed mainly for space industry needs. It is a three-directionally reinforced carbon-carbon material, and it is composed of a carbon fibre-based preform. The preform is produced by the superposition of carbon fibre plies in two directions, wound around a large cylindrical mandrel and resulting in a thick
wall cylindrical preform (~2 m long and up to 200 mm thick). Fibres in the third direction are obtained through a radial needling process. Blocks delivered to CERN were extracted from this cylindrical preform, with dimensions shown in Figure 1. Within the blocks, the carbon fibres were then “bonded” together with a very pure pyrolytic carbon matrix obtained via the chemical vapour infiltration (CVI) process. The material density is determined by the amount of CVI processes performed, also called densification steps.

The C/C A412 from Mersen is a high-density carbon-carbon composite with a fine structure and high resistance to oxidation. It is typically used in fusion reactor protection tiles. Its ex-PAN carbon fibres are arranged in three perpendicular directions, and the material is densified through pyrocarbon CVI woven fibre. For this material, a maximum manufacturing thickness of 35 mm in direction 3 necessitated the installation of several consecutive blocks to get enough attenuation length in the BIDs (see Figure 1). To reduce the ash content and improve the thermal performance, thermal treatment at very high temperature (>2600°C) can be applied to 3D CC.

4 | ADVANTAGES OF 3D CC FOR BEAM INTERCEPTING DEVICES
APPLICATIONS

Being industrially produced, a high level of quality in the production process is guaranteed. During the beam impact, the high temperature (close to 2000°C) achieved is not an issue provided that the material is in an inert atmosphere or in vacuum. The beam impact related fast dynamic events (stress waves), and high temperatures are well tolerated because of the material’s high thermal shock resistance (achieved by maximising the material strength and thermal conductivity and minimising the CTE and Young modulus). In addition, in the event of excessive loading, the matrix will fail first, and the resulting crack is stopped when it reaches the next fibre layer, preventing crack propagations by design. In this way, the material could be damaged locally, but should keep its original macroscopic shape, which is a big advantage compared with fragile materials such as isostatic graphite (prone to collapse in case of excessive loading).

In addition, the characteristics can be adjusted based on the application: an optimisation of the fibres’ orientation, combined with an appropriate choice of final thermal treatment parameters (temperature and time) can determine, for instance, the strength and thermal conductivity of the material in the desired directions. The material density can also be chosen within a range close to [1.5–1.85] g/cm³, which is interesting for beam intercepting device applications as it can allow a decrease of the peak energy deposition to reduce the temperature gradient during beam impact. With 48 hours of vacuum firing at 950°C to lower its outgassing rate, 3D CC has been approved for TCDIL collimators and TPSC SPS extraction absorbers, installed respectively in the SPS to LHC transfer lines and in the SPS Machine at CERN.

5 | 3D CC TEST OUTCOMES AT CERN

An experimental set up⁵ has been designed and produced at CERN (Figure 2) to allow testing of the 3D CC material at the HiRadMat facility.⁶ The objective was to assess the 3D CC integrity when impacted by high-energy protons.
beams (3.4 × 10^{13} protons at 440 GeV), representative of the operational beams after the LIU upgrade foreseen during 2019 to 2020. This corresponds to a peak energy deposition slightly higher than 6 kJ / cm³ in the material. Both 3D CC materials described in Section 2 have been selected for the beam impact test. Although vacuum firing has no effect on the material thermal shock properties, this treatment has been applied on the samples prior impact. Thermal treatment at greater than 2600°C has been applied on the Naxeco® Sepcarb® 3D CC sample. All samples have been machined without any lubricant to follow the production rules applied to the BIDs. After several impacts, the material did not show any signs of failure, as shown in Figure 1. In addition, online instrumentation (Optomet Laser Doppler Vibrometer) measured the 3D CC blocks' surface displacement during the impacts. The results are plotted in Figure 3. The proton beam impact led to a local swelling of the material "Top face", appearing all along the beam path. The measured swelling amplitude is 1.7 μm for 3.4 × 10^{13} proton beams and 1.15 μm for 2.6 × 10^{13} proton beams. During the impact phase, the proton beam continuously deposits part of its energy in the absorbing blocks, leading to a local temperature increase and material expansion. The increasing part of the curve lasts 7.8 microseconds (for 3.4 × 10^{13} proton beams), which corresponds to the beam pulse length. Four independent patterns (2 μs long each) in the increasing part of the curve correspond to the SPS beam structure, made up of a train of four independent batches. The nonlinear trend of the curve is also an indication of the material nonlinear mechanical and thermal properties.

6 | PRELIMINARY CONCLUSIONS

3D CC material offers several advantages for BIDs, and the recent CERN SPS beam impact tests confirmed its ability to withstand this kind of thermal loads. The flexibility in the orientation of the fibres allows adjustment of the material properties in a given direction, which potentially makes this material suitable for LHC collimators and dumps. For the fixed temperature gradient loading case (corresponding to beam impact), the material structure, by design, prevents large crack propagations, which is an advantage when compared with the brittle behaviour of polycrystalline graphite. In addition, 3D CC remains expensive and has longer delivery times compared with graphite materials. Ongoing finite elements studies calculating the material response when impacted by a beam will be compared with experimental measurements. The 3D CC material application to other BIDs will be also investigated with this numerical model.

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![Figure 3](image.png)
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