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Sigraflex® STUDIES FOR LHC CERN BEAM DUMP: SUMMARY AND PERSPECTIVE

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Abstract

The Large Hadron Collider (LHC) external beam dump (TDE, Target Dump External) is required for safe and reliable operation of the collider. It absorbs particles extracted from the accelerator whenever required. The original design of the TDE dates from the early 2000s and it is constituted of an eight-meter-long cylindrical stain-less-steel tube, filled with low-Z carbon-based materials from different grades and densities. Sigraflex®, an ex-panded low-density graphite, is employed in the middle section of the TDE core. Due to unexpected behaviour observed in the past LHC runs, several major upgrades were recently implemented in order for the TDE to be ready for LHC Run 3 (2021-2024), where up to 555 MJ beam energy is expected to be dumped every few hours. According to simulations, temperatures in the Sigraflex® core will reach locally up to 1500 °C in the regular dump cases, and above 2300 °C for failure scenarios. The objective of this contribution is to summarize the LS2 hard-ware upgrades and the plan for the evaluation of the Sigraflex® performance during LHC Run 3. This work will also detail the last experimental and numerical findings applied to the Sigraflex®, and possible alternative materials for the future.

INTRODUCTION

The LHC Beam Dump System (LBDS) is critical for the safe operation of the LHC. The LBDS is based on a fast extraction system placed in Point 6 [1]. The two counter-rotating beams are deviated from the LHC ring by a series of 15 kickers (MKD) and 15 septum magnets (MSD) to a tangential extraction line (one per beam). At the end of the beam line (700 m length) the Target Dump External (TDE) block is placed, where each beam is finally absorbed. Because of the high energetic beams 10 fast-pulsed dilution kickers are used to sweep the high focused beam in a pseudo-elliptical spiral path in order to spread out its energy in the TDE core [2]. In addition, TDE is surrounded by a steel shielding (> 1000 tons) that helps to reduce residual dose rate in the dump caverns.

The design and manufacturing of the current operational TDE dates from early 2000's. The beam energy and intensity has been ramped up during the successive Runs 1 and 2 (Table 1). For the coming Run 3 the total beam energy will be increased significantly by nearly 74%, exposing the TDE to more powerful beams, even above the maximum energy considered during the original de-sign phase (540 MJ) [3].

Table 1: Overview of the Nominal Beam Parameters over Different Runs and HL-LHC Era

	Run 2	Run 3	HL-LHC
Energy [TeV]	6.5	6.5 – 7	7
Max. # bunches	2556	2748	2748
Max. bunch intensity [ppb]x10^{11}	1.2	1.4 – 1.8	2.3
Beam stored Energy [MJ]	319	431 – 555	709

The TDE block consists in a stainless (Uranus-45) vessel, 8500 mm long and diameter 722 mm. The core is made of a series of six isostatic polycrystalline graphite blocks (SGL Sigrafine® 7300) 700 mm long with a nominal density of 1.73 g/cm^3 and shrink fitted into the vessel. The central region is assembled with ~ 1630 Sigraflex® sheets (L20012C) 2 mm thick and 1.2 g/cm^3 density, stacked together and supported by two end SGL Sigrafine® HLM plates (80 mm thick and 1.72 g/cm^3 density) located in the vessel by two steel rings. The vessel is filled with N_2 gas at a slight over-pressure in order to provide an inert atmosphere for the graphite and, since the LS2 upgrades [4], it is closed by two titanium alloy windows (see Fig. 1).

When the beam impacts the TDE, it generates a sudden energy deposition as result of the beam-matter interaction phenomenon. Graphitic materials are one of the most suitable materials for beam absorption because of their good thermo-mechanical performance at high temperature and low atomic number, that in turn means a progressive beam energy absorption [5]. In particular, the low density of Sigraflex® plays a major role controlling and reducing the energy peak deposition in the core. This is the most exposed sector, reaching a peak dose of 2.5 kJ/g for Run 3 at nominal conditions and up to 4.1 kJ/g in case of dilution failure (equivalent to a temperature increase of 1500 °C and 2300 °C, respectively). This phenomenon lasts only ~ 86 µs (nominal dilution time), exposing the TDE core to extremely high thermo-mechanical loads.

Sigraflex® belongs to the expanded graphite family and its properties significantly differ from standard graphite grades (commonly used in Beam Intercepting Devices (BID)) [6]. To the best knowledge of the authors, the TDE is the only BID employing Sigraflex® as core material. Each of the

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operational TDEs has been impacted with more than 9000 beam dumps during all previous Runs. The assessment of the thermo-mechanical response and soundness of the core is critical for ensuring the future safe operation of the TDE.

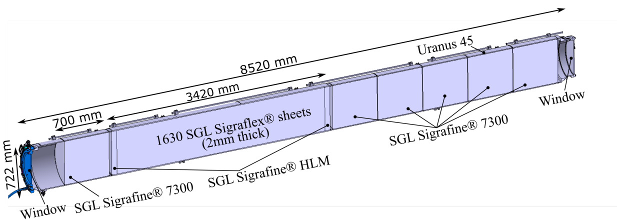

Figure 1: Schematic illustration of the TDE Dump.

LS2 HARDWARE UPGRADE

With the increase of the energy in the system during Run 2, a series of issues started to appear from 2015 related to N_2 leaks. Operational interventions during Technical Stops revealed loosening of the fasteners, damage of the seals and permanent movements of the entire TDE assembly.

Post-processing the data of the instrumentation system, which consists of several interferometers, showed that the TDE exhibits violent vibrations during beam impacts [4, 7]. Numerical analysis of the entire TDE block confirmed that the beam impact induces two different phenomena: a fast vibration due to the excitation of natural frequencies of the system and a quasi-static thermal expansion because of the high among of energy deposited on it.

A major upgrade was recently done during Long Shut down 2 (LS2) aiming at mitigating these issues [4, 8]. The upgrade was mainly focused on measure for the reduction of the constraint forces on the TDE: uncoupling it from the LHC extraction beam line and designing a novel supporting system compatible with such dynamic response. Current operational TDEs were replaced by the two spare ones and the windows were upgraded (based on Ti Grade-5). A more advanced instrumentation system was installed in order to assess the dynamic behaviour of TDE. No actions were performed on the TDE graphite core itself.

LAST EXPERIMENTAL AND NUMERICAL FINDINGS

Sigraflex® is a flexible exfoliated graphite. It is produced from natural graphite flakes, which are expanded via chemical processes in the crystalline c-axis direction. The crystal basal planes of the flakes get separated, generating an exfoliate structure, worm-shaped, with a size increment of x300 thicker. Then, the “worm” units are compressed by rolling, producing Sigraflex® sheets. The result is a porous material with a strong orthotropy [6, 9]. It exhibits a relatively high thermal conductivity in the plane direction (compared with standard graphite), whilst it is practically an insulator with low permeability out of plane. Regarding mechanical properties, Sigraflex® behaves like viscous-elastic material, with a response similar to a porous media in the off-plane direction.

Several attempts to characterize it through quasi-static standard tests can be found in the literature [9–12]. Nevertheless, in the context of BIDs they are exposed to strong thermo-mechanical loads involving wave propagations. A collaboration with NTNU and SINTEF institute has been established aiming at dynamically characterizing Sigraflex® and developing a numerical model (based on the Finite Element Method). Preliminary tests revealed that Sigraflex® mechanical behaviour is highly nonlinear, asymmetric and results strongly depends on test conditions (temperature, strain rate, heating rate, etc.), inferring that standard tests and standard FEM models may be not suitable in describing the material’s mechanical behaviour in its operational conditions [6]. Moreover, the proton beam is very focused and the micro-scale features of Sigraflex® may play a role. In this context, a new approach is being developed relying on Multi-Scale Methods together with Deep Material Network technique (Fig. 2).

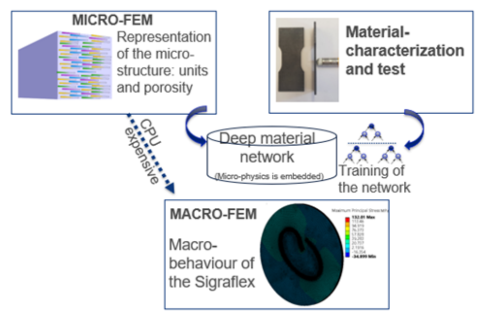

Figure 2: Numerical approach for Sigraflex®.

During the LS2 upgrade, an endoscopic analysis was performed on the used TDEs aiming at assessing the core status. The upstream isostatic graphite block seems to be not damaged at first sight. Nevertheless, graphite powder was found on the bottom of the vessel and a macro crack was observed on the Sigrafine® HLM plates (Fig. 3). The accessibility was very limited and the central region of the Sigraflex® could not be inspected unfortunately. Although these observations are not conclusive, the dynamic phenomenon of TDE should be analysed carefully.

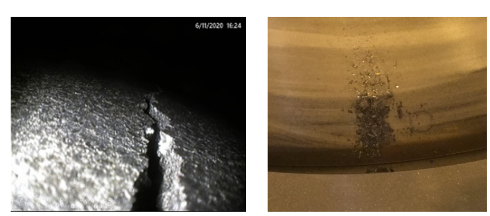

Figure 3: Postoperational diagnosis of the used (Run 2) TDE core: (left) crack on the Sigrafine® HLM plate and (right) graphite powder found on the vessel.

As part of HiRadMat-43 experiment [13], four samples of Sigraflex® F05010TH (0.5 mm thick sheets, 1.0 g/cm^3) were

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irradiated in the HiRadMat falcilities [14, 15] at different intensity levels aiming at assessing the integrity resistance of this material when exposed to peak energy densities close to those of LHC Run 3 case (1.85 – 2.5 kJ/g). Post-irradiation tests showed damage on all samples presented at the beam exposed area, these being more serious on the most exposed samples (Fig. 4). Profilometry analysis on the samples revealed an out-of plane deformation of up to 200 – 250 µm. Moreover, micro-Computerized Tomography (CT) analysis showed the presence of interlaminar spaces created by the beam.

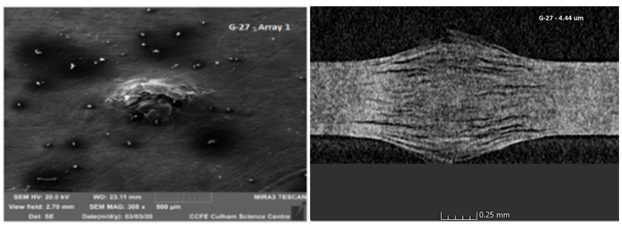

Figure 4: UKAEA SEM Results (left [16]) & CERN micro-CT scan (right) on the HRMT-43 Sigraflex® sample.

RUN 3: PLANS FOR PERFORMANCE ASSESSMENT

The previous observations and HRMT-43 Sigraflex® results raised questions about its soundness and ability to withstand the LHC Run 3 period. In order to solve some of these questions, an autopsy of the past-operational Run 2 Dumps, allowing direct access to the Sigraflex® sector, is being evaluated from the safety and technical point of view to be performed at end of 2021. The autopsy would involve an overall analysis of the Sigraflex® sector, assessing the stacking arrangement, and a local analysis of several Sigraflex® sheets extracted from different zones via FIB-SEM, High resolution optical microscopy, Contactless profilometry and eventual Micro tomography.

In October 2021, a dedicated HiRadMat experiment, HRMT-56 (“HED”) [17, 18], will be carried out to reproduce conditions for different LHC beam-exposure scenarios on low density Carbon-based materials. Dedicated targets within the experiment will assess both Sigraflex® for LHC-Run 3 performance and HL-LHC Beam Dumps alternative core materials.

With respect to Sigraflex® testing targets, there will be samples tested receiving Run 3 peak energy density values (2.5 kJ/g) and HL-LHC peak energy density values (3.2 kJ/g). Sigraflex® behaviour will be assessed depending on different production parameters such as thickness (0.5 – 2 mm) and density (1.0 – 1.2 g/cm^3). Moreover, different boundary conditions will also be experimentally evaluated, impacting single sheets, unpressed sheets stacks and sheets stacked through a pre-imposed compression load (5% of compaction). Finally, different assemblies will also be tested under different environments, such as under vacuum or in nitrogen gas (1 bar).

ALTERNATIVE MATERIALS

As Sigraflex® has shown its limitation when exposed to highly energetic beams, other materials are under consideration for the low-density region core of the future HL-LHC dump. Carbon-Fibre-Reinforced-Carbon (CFRC) [5] materials are being studied as an alternative to Sigraflex®. These Carbon-based materials also present low densities but their superior manufacturing technology results in much higher mechanical properties and non-brittle behaviour.

CFRCs are made by stacking layers of Carbon-fibre tissues or fabrics having their fibres oriented differently forming the structure or preform. These preforms are then further densified via two methods: Liquid Impregnation (LI) or Chemical Vapour Infiltration (CVI), forming the Matrix. Then the assembly is Graphitized to transform most of the carbon into graphite. Material properties, especially density is used as a tailoring parameter with the objective of accommodating the required density variations within the core region materials.

The grades being studied will also be tested during HRMT-56 (see Fig. 5) to understand and assess beam induced phenomena on each material. The objective is to test these materials as close to HL-LHC peak energy densities as possible (3 – 3.2 kJ/g). For this, denser diluter elements have been included upstream and between the targets, increasing the energy density deposition. Additionally, targets will have samples for each material stacked together to represent and reproduce the future interfaces of the possible dump design. The experiment will include a thorough campaign of Pre & Post-Irradiation Examinations on the samples by several techniques (micro-CT, Profilometry, Mass measurements).

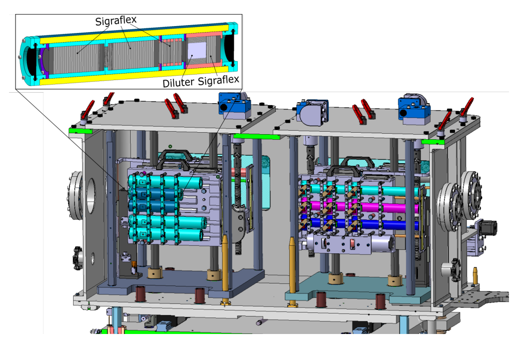

Figure 5: HRMT-56 (“HED”) tank and Sigraflex® target.

CONCLUSIONS

Several R&D activities have been launched to analyse the past operational performance of the LHC-TDE core during Run 2 and to assess its suitability for Run 3. The behaviour if Sigraflex®, as the main element in the LHC-TDE core, needs to be further understood, characterized, and modelled. CFRC materials present themselves as solid and promising materials for the low-density region core of the future HL-LHC Dump. HRMT-56 presents the ideal opportunity to test both Sigraflex® performance as well as future candidates for the HL-LHC Dump design.

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