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DESIGN DEVELOPMENT AND R&D FOR CERN'S HL-LHC EXTERNAL BEAM DUMP

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Abstract

The energy stored in the Large Hadron Collider (LHC) circulating beams must be safely absorbed in external beam dumps (Target Dump External, TDE). High Luminosity (HL) LHC is a planned upgrade of the machine which will increase this stored energy to 680 MJ, compared to 150 MJ in LHC Run 1 and 540 MJ during Run 3.

The TDE design has changed only slightly since Run 1; it is a cylindrical stainless-steel vessel with an absorbing core made of graphite. During long shutdown 2 (LS2), upgrades were made to the TDEs to address issues found during Run 2 and to prepare for the higher intensity of Run 3.

Further upgrades will be needed for HL due to some key challenges: increased vessel vibration will lead to higher stresses; graphitic materials able to withstand energy densities up to 5.7 kJ/g (as determined by FLUKA Monte Carlo simulations) are required; and a new TDE cooling system is necessary, so that temperature build up following consecutive dumps will not affect the LHC's availability.

This paper describes work completed to develop a conceptual design of the HL TDE and planned future work. Results of Finite Element (FE) simulations of the TDE's response to the beam energy deposition and CFD simulations of the cooling system will be presented.

LHC BEAM DUMPS

Two external beam dumps (TDEs) are in operation in the CERN LHC, one for each beam. Their purpose is to safely and repeatedly absorb the beam's energy [1] when the beam has to be disposed from the collider.

Their current design [2], following LS2 (2018-2022) upgrades, is an 8.5 m long, 0.7 m diameter duplex stainless steel grade 318LN (SS 318LN, ref 1.4462 [3]) vessel, containing graphitic materials (Fig. 1). The upstream (US) and downstream (DS) windows are forged Ti6Al4V (ASTM Ti Grade 5, UNS R56400 [4]) and contain the nitrogen gas atmosphere preventing graphite oxidation.

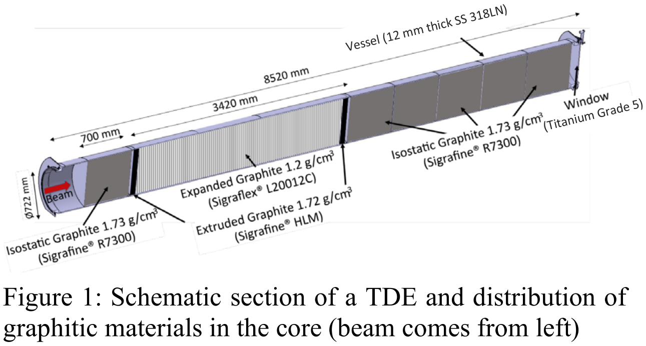

Figure 1: Schematic section of a TDE and distribution of graphitic materials in the core (beam comes from left)

The purpose of the 3.4 m section of low density (LD) Sigraflex® expanded graphite is to reduce the peak energy density (3.4 kJ/g for a HL nominal dump) and thereby limit the adiabatic temperature rise. Away from the peak, high density (HD) Sigrafine® graphite blocks are used. The rigidity of Sigrafine® allows it to be firmly shrink fit in the vessel, increasing heat transfer and aiding cooling, whereas Sigraflex® sheets can only be loosely placed inside.

A series of magnets is employed in the LHC beam dump system (LBDS) [5], firstly to direct the beam toward the TDE via LHC extraction lines, then to sweep the beam in a spiral pattern over the face of the TDE to reduce energy density. Partial failure of the dilution kickers may lead to a peak energy density of up to 5.7 kJ/g in the graphite in the worst-case failure scenario considered. Complete failure of the dilution system is deemed to be very unlikely.

Following LHC Run 3 (2022-2024) [6] , upgrades to accelerator systems will start with the aim of increasing the LHC's luminosity [7] in the framework of the HL-LHC upgrade. Higher beam intensity and energy will lead to a 26% rise in stored energy compared to Run 3, necessitating TDE design enhancements in three areas: vessel integrity, graphite resistance, and a more effective cooling system.

VESSEL INTEGRITY

While the core configuration and dimensions of the beam dump are not yet fully defined, simulations were conducted based on an analogous core configuration to the current operational TDE to explore vessel conceptual design ideas. This was considered reasonable because sensitivity studies indicated that minor variations in core configuration have little impact on the vessel's dynamic response.

The particle shower generated by beam impact with the core materials induces a fast temperature rise in the vessel [2], exciting radial, longitudinal and flexural vibration modes. In particular, the ~200 Hz longitudinal mode has caused leaks, permanent displacement of the TDE [2] and damage to the retaining plates of the LD graphite [8] during Run 2. The high velocities it induces at the ends of the vessel also lead to high-amplitude cyclic stresses in the window [2]. The DS window typically experiences higher stresses because the US window receives much lower energy deposition. The central LD segment of the vessel sees the highest amplitude stress oscillations.

The highly dynamic nature of this event requires an explicit mechanical model to correctly simulate the phenomena. A weakly coupled thermal-structural FE model has been developed in LS-Dyna® for this purpose.

Firstly, differences in the response of the TDE to full-intensity dumps in Run 3 and HL were assessed. Results are shown in Table 1. The 28% increase in beam intensity is reflected in a corresponding increase in the amplitude of the longitudinal extension and the peak stresses in the central part of the vessel. The average temperature in this part following the energy deposition is 140°C. At this temperature, the yield stress of SS 318LN is 374 MPa [9], giving a safety factor of 1.06. Estimation of the fatigue life of the current TDE design if used at HL conditions will be investigated in future work.

Table 1: Vessel Performance in Run 3 vs HL Nominal Conditions, With the Same SS 318LN Vessel

Run	**Extracted Intensity (protons)**	**Peak longitudinal extension (mm)**	**Max LD stress (MPa)**
Run 3 (6.8 TeV)	4.9E+14	5.60	297
HL (7.0 TeV)	6.3E+14	7.24	353

To potentially mitigate these issues, vessel design changes have been explored using the developed FE model, including different vessel materials and geometry changes. Among the possible materials, a promising alternative is the same Ti Gr5 as currently used for the windows. A comparison of the pertinent mechanical properties of SS 318LN and Ti Gr5 indicates several thermomechanical advantages. Firstly, Ti's lower density and atomic number induce lower interaction with the particle shower generated by the dumped beam and lower total energy deposition. Its smaller coefficient of thermal expansion (CTE) leads to lower expansion for a given amount of heating, which with a lower Young's modulus gives a great reduction in stress while having a significantly higher yield stress. A comparison between the results of the simulation using the current 318LN vessel and using Ti is presented in Table 2. The reduction in deposited energy will also reduce the residual dose rate in the vessel at the end of service life.

Table 2: Vessel Performance in HL, SS 318LN vs Ti Gr5

Material	**Peak longitudinal extension (mm)**	**Max LD stress (MPa)**	**DS window max stress (MPa)**
SS 318LN	7.24	353	262
Ti Gr5	3.79	153	222

When the vessel material is changed to Ti Gr5, a 48% reduction in the peak longitudinal extension of the vessel is achieved. The maximum moves from 7.2 mm to 3.8 mm (Table 2). The reduction in cyclic stress amplitude in the LD sector is shown in Fig. 2.

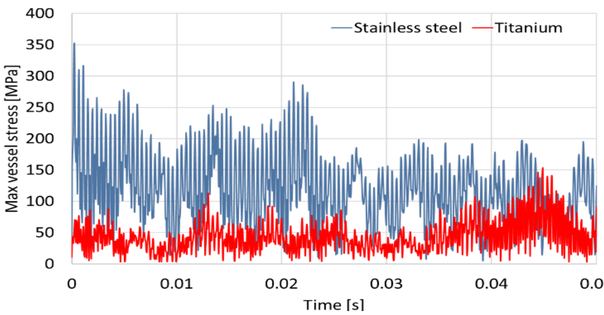

Figure 2: Stress evolution in the most highly stressed element in LD section, SS 318LN vs Ti Gr5, HL conditions

Notably, peak stress in the LD sector decreased from 353 MPa for SS 318LN to 153 MPa for Ti Gr5. This gives a safety factor of 5 against Ti Gr5's yield strength of 759 MPa at 135 °C (average LD sector temperature following a dump) [10]. 153 MPa is well below the material's fatigue limit of approximately 500 MPa [11]. The reduction in extension is only partly reflected in the decrease in window peak stress (-15%) because the energy deposited in the window is relatively unaffected by the vessel.

Geometry changes were also evaluated. The possibility of shortening the assembly length was initially thought promising for its potential to reduce the overall vibrating mass and the vibration amplitude. To investigate this, a dump configuration was simulated with the last two 70 cm long Sigrafine® blocks and corresponding vessel sections removed. This comparison is shown in Table 3.

Table 3: Comparison Between a Vessel With the Current Length and One That is Two Blocks Shorter

Length	**Peak longitudinal extension (mm)**	**Max LD stress (MPa)**	**DS window max stress (MPa)**
Current	7.24	353	262
-2 blocks	7.09	351	712

Despite lower vessel length and mass, there was little change in peak extension, as the LD segment of the vessel which is subject to the peak energy deposition was still present. Removing the last two blocks only reduced total energy deposited in the vessel by 8%. However, the vessel's stiffer response and lower mass increased the longitudinal frequency from 185 Hz to 214 Hz. The peak energy density and total energy deposited in the DS window both approximately doubled, due to reduced particle shower containment, which along with the higher vibrational acceleration resulted in a 270% increase in DS window peak stress.

An increase in vessel length, while likely to lower stress in the DS window, was not studied due to the increased quantity of material required and the additional complexity of installing it in the cavern. The effect of increasing the thickness of the vessel was also studied. This stiffened the vessel, but the additional material also interacted with the beam particle shower and total energy deposited in the vessel increased by 33%, giving 10% increase in peak extension and 3% increase in peak LD stress.

While Ti Gr5 seems to offer many benefits for the TDE's performance, the associated procurement, welding and assembly processes must be studied over the coming year.

All models presented here considered the vessel to be continuous. This is not the case for the current operational TDEs, which employ 6.65 mm partial penetration socket welds in between the HD segments of the 12 mm thick vessel. Recent studies [12] found a stress concentration factor associated with this thickness reduction of as much as 3.3, which would prove unacceptable for the HL dumps. An R&D study is underway to develop the processes necessary to implement full-penetration welds in the vessel. In particular, Electron Beam Welding could be advantageous, if facilities are available large enough to contain several metres of vessel.

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GRAPHITIC MATERIALS

The HiRadMat-56-HED (HRMT-56) experiment [13] tested the performance of carbon-based materials up to an energy density of 3.2 kJ/g with four beam impacts. Sigraflex® sheets withstood these conditions when assembled in a stack. However, out of plane deformations were identified on single non-stacked sheets, while severe delamination was found in HiRadMat-43 [14] . All tested Carbon-Fibre-Reinforced-Carbon (C-C) materials were deemed promising since they survived with no observable damage. No isostatic graphite grades were tested.

A follow-up experiment, taking advantage of higher intensities available for the HiRadMat facility (up to 288 bunches with 2.1E11 protons per bunch) is planned for 2024. The aims of this experiment are:

- to test material in three categories (isostatic and flexible graphite, and C-C) across a wide range of relevant industrial grades as candidates for the HL TDE core;
- with a number of pulses representative of the number of full intensity dumps expected over the TDE's lifetime, at the nominal energy density of 3.4 kJ/g;
- with beam optics inducing stress gradients representative of those generated in the operational TDE;
- including specimens subjected to one (or multiple) shots at the failure scenario energy density of 5.7 kJ/g.

Targets subjected to a high number of shots will have to be cooled to prevent temperature build-up. The higher intensities of 440 GeV/c protons will mean long targets with shallow energy gradients (Fig. 3) can be used, giving better experimental statistics and removing the need for diluters to increase energy deposition by initiating particle shower.

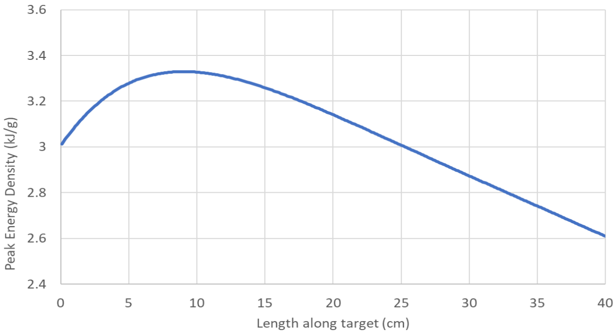

Figure 3: FLUKA Energy density along a 40 cm target for the nominal case

The results of this experiment will inform the selection and procurement of graphitic materials for the HL TDE.

TDE COOLING UPGRADE

To prevent temperature build-up between consecutive dumps, the TDE employs a cooling system that currently consists of a series of nozzles (Fig. 4) which blow air along the underside of the vessel, cooling the TDE down to ambient temperatures in around 12 hours. Given the HL energy increase, cooling improvements are required to avoid the TDE overheating and limiting the LHC's availability.

A CFD model developed to benchmark the current design showed that effective cooling is limited to the immediate impingement area (Fig. 4). There is low heat extraction on the top surface and reheating effects from warmed air flowing over cooler areas.

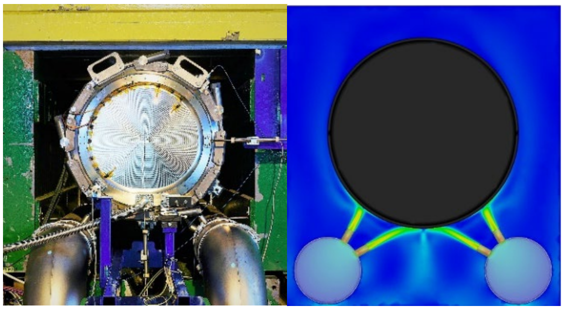

Figure 4: Current TDE cooling system with air ducts below (left); CFD model velocity magnitude contours (right)

A candidate design (shown in Fig. 5) is to place a sleeve around the vessel, through which air is fed in a longitudinal direction achieving higher average air velocity over the whole dump surface. It will be assessed using CFD, while the feasibility of integrating new structures inside the existing shielding will be investigated in parallel.

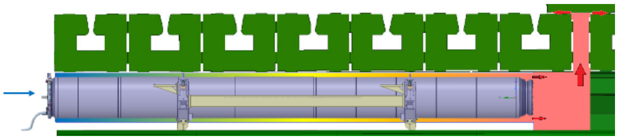

Figure 5: Example of an improved cooling system design using annular sleeve and chimney at rear of shielding

CONCLUSIONS

The HL-LHC upgrade following Run 3 will increase the beam stored energy by an additional 26%. TDE upgrades are required to ensure: sufficient vessel service life; that selected graphitic materials withstand both repeated nominal dumps and accidental scenarios; sufficient cooling.

An explicit FE analysis of beam impact on the TDE revealed that the current design would have a safety factor of 1.06 against material yielding in the central LD sector, limiting its potential lifetime. Of the vessel design changes studied, a move to Ti Gr5 was shown to give significant improvements in terms of stress (a safety factor of 5) and longitudinal displacement (48% reduction). A feasibility study of the associated procurement, welding and disassembly challenges has therefore been initiated. Other changes, including to the vessel length and thickness and number of Sigrafine® blocks showed no benefits, while some increased DS window stress substantially.

A successor to the HRMT-56 experiment is planned for 2024, to investigate the resistance of candidate graphitic materials for the HL TDE in nominal and accidental scenarios. Conceptual design of this experiment is underway, including cooling of the target to a high number of pulses.

Finally, a CFD model was developed to benchmark the performance of the current TDE cooling system. To give greater velocity airflow over most of the dump surface, the performance and feasibility of a new design using an annular duct is being investigated.

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