14th International Particle Accelerator Conference,Venice, Italy JACoW Publishing
ISBN: 978-3-95450-231-8 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2023-MOPA101

ENERGY DEPOSITION CHALLENGES FOR THE HL-LHC BEAM DUMP*

E. Farina†, T. G. Banks, C. Bracco, M. Calviani, Y. Dutheil, A. Lechner, N. Solieri
CERN, Geneva, Switzerland

Abstract

The LHC beam dump system has the task of safely and reliably disposing of the extracted beams from 450 GeV to 7 TeV. The present dump assembly consists of a multi-segment graphite core, which is contained in a duplex stainless steel vessel with titanium windows. To reduce the energy deposition density in the core and windows, the extracted beams are swept across the dump front face with dedicated dilution kickers. In the High Luminosity-LHC (HL-LHC) era, the dump must withstand beams with a significantly higher stored energy (about 700 MJ) than has been achieved so far (380 MJ). The high temperatures and vibrations generated in the core and vessel require a redesign of the dump assembly to ensure safe operation with HL-LHC beams. This work presents energy deposition studies for the different dump components in case of regular dumps and possible dilution kicker failure scenarios during HL-LHC operation. The impact of different design choices, such as the adoption of titanium as vessel material, on the energy deposition and the leakage of particles from the dump is discussed.

INTRODUCTION

The CERN LHC beam dump (Target Dump External, TDE) is the final element of the LHC Beam Dump System (LBDS), composed of fast extraction kicker magnets, magnetic septa and dilution kickers [1]. The machine accommodates separate dump systems for each of the two counter-rotating beams. In case of a beam abort trigger, the extraction kickers deflect the beam horizontally into the extraction channel, where it receives a vertical kick in the septum field [1]. The dilution kickers (MKB), 4 horizontal and 6 vertical, sweep the beam over the front face of the dump in order to reduce the local energy deposition. The present TDE is composed of a multi-segment graphitic core, contained in a duplex stainless steel vessel with titanium windows. The different core segments have different material densities in order to ensure the maximum shower containment, while minimizing the temperature increase during beam aborts. An open cut view of the current LHC dump is shown in Fig. 1. The dump contains a low-density segment in the center, consisting of more than 1600 flexible graphite sheets (Sigraflex® [2], 1.1-1.2 g/cm^3), each 2 mm thick. The stacked sheets are supported on each side by extruded Graphite plates (Sigrafine® HLM plates). The rest of the core is composed of six 70 cm-long isostatic Graphite blocks (1.7 g/cm^3), one upstream and five downstream of the low-density segment [3]. For a 7 TeV proton beam, the dump geometry accounts for about 15 inelastic interaction lengths (N_λ). Although the dump absorbs a significant fraction of the beam energy, some is carried away by secondary particles produced in hadronic and electromagnetic processes.

In this paper, we review operational conditions of the dump assembly and present studies on the energy deposition in the graphitic core and stainless steel vessel expected in HL-LHC Runs.

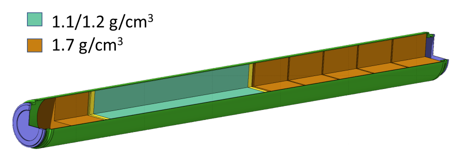


Figure 1: Internal dump structure: a block of isostatic graphite is followed by Sigraflex® (~3 m) and by another 5 blocks of isostatic graphite [3].

OPERATIONAL CONDITIONS

The beam energy stored in the LHC increased throughout the past runs, reaching 380 MJ in 2022, surpassing the original design value of 362 MJ. It is expected that the stored energy will exceed 500 MJ in Run 3, once the target bunch intensity of 1.8x10^{11} protons is reached. The operational conditions will become even more challenging in the HL-LHC era (Run 4), when the beams will carry about 700 MJ. In Table 1 the main LHC beam parameters are reported [4–7].

Table 1: LHC Beam Parameters [4–7]

Parameter	Run 1	Run 2	Run 3	Run 4*
Years	2010-2013	2015-2018	2022-2025	2029-2032
Energy per beam [TeV]	3.5/4	6.5	6.8	7
Bunch spacing [ns]	50	25	25	25
Bunch Intensity at injection [10^{11}ppb]	1.6	1.2	1.8	2.3
Number of bunches	1380	2556	2748	2760
Max Beam energy [MJ]	140	310	540	710

* planned

During operation it is very rare to dump the entire nominal energy as the actual energy is lower due to beam intensity decay during the fill from collisions or since the abort happens during beam injection or before reaching the proton collision energy. Figure 2 shows, for each of the three runs, the median value of the beam intensity which was dumped, normalized to the nominal beam intensity of the run. In Run 1, the median value is below 20% of the nominal beam intensity, rising to about 30% in Run 2. It is, however, possible that the dumps have to cope with several high-intensity

* Research supported by the HL-LHC project
† edoardo.maria.farina@cern.ch

14th International Particle Accelerator Conference,Venice, Italy JACoW Publishing
ISBN: 978-3-95450-231-8 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2023-MOPA101

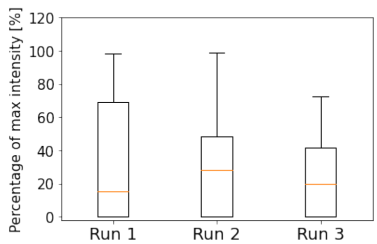


Figure 2: Boxplot of the beam intensity dumped in the TDE in the three Runs, normalized to the maximum beam intensity, showing the median and the first quantile. Run 3 bar only takes into account 2022, when target intensity was not yet reached.

dumps in a row: these scenarios have to be taken into account in the dump design. Considering only Run 1 and Run 2, in total ~200 GJ were dumped (60 GJ in Run 1 and 140 GJ in Run 2), while the maximum dumped energy per day was 800 MJ in Run 1 and 1400 MJ in Run 2.

ENERGY DEPOSITION IN GRAPHITE

FLUKA [8–10] simulations have been carried out to assess the energy deposition in and the particle leakage from the TDE. The simulations indicate that ~78% of the initial proton beam energy is dissipated in the dump itself, whereas the rest is carried away by secondaries (17%). Within the dump, the bulk of the energy is deposited in the low-density Graphite segment (38% of the dumped energy), which contains the shower maximum [3].

Nominal Dilution

In order to reduce the peak particle density impacting the dump, the beam is diluted by the combined contribution of 10 MKBs. Figure 3 shows the bunch position at the front face of the dump in a regular dump scenario (blue). In Fig. 4, the peak energy density deposited in the dump as a function of the dump length is shown, considering a single beam impact at nominal intensity for the different runs. In HL-LHC, ~3400 J/g are reached, equivalent to a temperature rise of about 2000°C. In Run 3, 2500 J/g are expected. The energy density peak occurs at about 3 meters from the front face of the dump. Considering the increased peak load in HL-LHC, several graphitic materials are being investigated (HiRadMat-HED [11] and the planned HiRadMat-HED2 experiments, performed respectively in 2022 and 2024) to identify the best candidates for the dump core.

Dilution Failures

In addition to the nominal case, several accidental scenarios may occur and need to be studied in order to guarantee the safe operation of the dump. Two cases were considered: the loss of one or two dilution kickers due to a flash-over affecting kickers in the same tank and the spontaneous firing of a dilution kicker. For more details, see Ref. [12].

Flash-Over The flash-over of up to two kickers sharing the same vacuum tank might lead to the loss of up to half

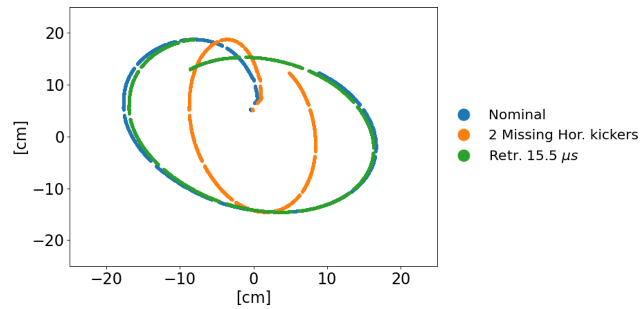


Figure 3: Sweep pattern at the front face of the TDE in three different dilution scenarios, showing the bunch position.

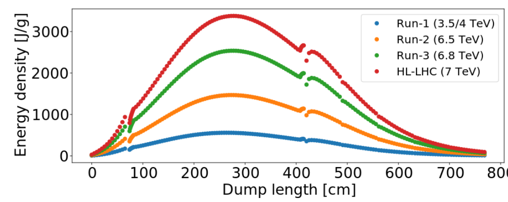


Figure 4: Peak energy density expected in the TDE as a function of the position along the dump, for the different Runs' beam energy and intensity in the case of a nominal sweep. Jumps are due to core density changes.

of the dilution strength, in case the horizontal kickers are affected. An event of this type occurred in 2018 [12]. The sweep pattern resulting from the magnet kicks depends on whether both magnets are affected and the time at which each of the flash-over takes place. The studied worst case scenario is represented by the total absence of two of the four horizontal kickers. The resulting pattern swept over the front face of the dump is depicted in Fig. 3 (orange).

Retriggering The second failure scenario concerns the spontaneous firing of a single kicker, after the detection of which all other kickers are fired and the beam is dumped synchronously at the next abort gap [13]. This implies that the extraction kickers are re-triggered with a time delay after the dilution kickers. This delay accounts for the detection time of the spontaneous firing and for the time needed for the abort gap to reach the extraction region. This can take any value between 0 and 89 μs (1 LHC turn). For each time delay, a different dump sweep pattern is produced. In Fig. 3 (green) the sweep pattern is shown for a time delay of 15.5 μs, which was found to be the most critical condition in terms of energy density in the dump core.

Figure 5 summarizes the maximum energy deposited in the dump for the different failure scenarios. In the scenario of the worst flash-over case (two kickers missing, red), a peak energy density of 5.7 kJ/g is estimated, corresponding to a temperature rise of 3200°C. In the scenario of MKB retriggering (blue, continuous) a peak energy density of 5 kJ/g is found. Material selection for HL-LHC has to take into account these failure cases as well. Finally, as reference, the nominal case is also shown by the dotted blue line which corresponds to a temperature rise of 2000°C.

14th International Particle Accelerator Conference,Venice, Italy JACoW Publishing
ISBN: 978-3-95450-231-8 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2023-MOPA101

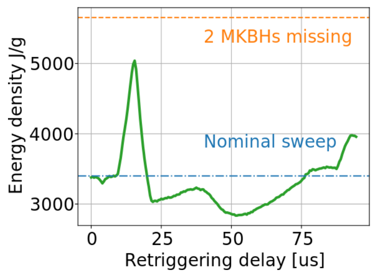
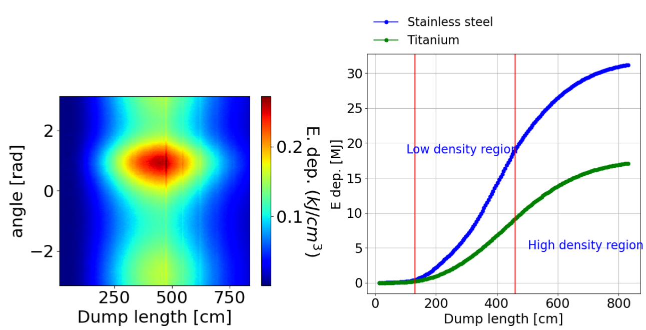


Figure 5: Summary of MKB failure cases: a maximum energy density of 5.7 kJ/g is scored in the core when two horizontal kickers are missing.

ENERGY DEPOSITION IN VESSEL

Another crucial aspect for the safe operation of the TDE is the vessel's response to energy deposition by particle showers, which was found to lead to high frequency vibrations [3]. Figure 6 (a) shows the two-dimensional energy deposition profile in the stainless steel vessel for HL-LHC beams: a clear hot-spot is visible at the location where the bunches along the sweep get closer to the vessel. The cumulative energy deposition is shown in Fig. 6 (b) as a function of the dump length and it reaches 30 MJ (blue). In the same figure, the cumulative energy deposition for a titanium vessel (green line) is also shown: in this case about half of the energy is deposited, which will lead to lower vibration magnitudes in the vessel. Adopting titanium in place of the stainless steel is currently being investigated in view of HL-LHC [14].



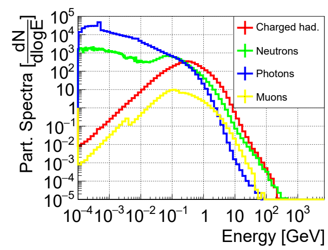
(a) (b)

Figure 6: (a) Two-dimensional distribution (angle vs dump length) of the energy deposited in the stainless steel vessel as simulated by FLUKA in HL-LHC nominal conditions. The peak is located where the beam gets closer to the vessel along the sweep. (b) Cumulative energy deposited in the vessel along the dump.

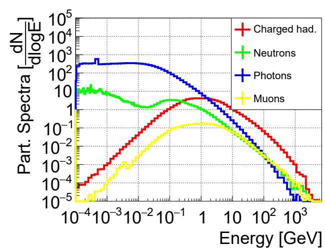
PARTICLE LEAKAGE

Alternative TDE dimensions are being investigated to assess their potential effect on the TDE's thermo-mechanical response; therefore it is important to understand the energy leakage which has to remain within acceptable limits for RP reasons. FLUKA simulations showed that the part of the beam's energy not deposited in the dump is transported by particles escaping either laterally through the vessel (85% of the leakage) or downstream through the window (15%).

In Fig. 7, the energy spectra of the most relevant particles (charged hadrons, neutrons, photons and muons) leaking laterally (a) and downstream (b) are shown. In particular, downstream spectra are characterized by fewer, but more energetic particles. Enlarging the dump diameter from 70 to 80 cm, thus reducing the load on the vessel, leads to a reduction of about 20% of the energy leaking laterally. However this comes with additional material costs, handling and cooling complications and has therefore been discarded. Given that most of the energy is dissipated laterally, one way to reduce costs and weight would be to shorten the dump by removing one block of high-density isostatic graphite downstream. This results in a 2-fold increase of the energy lost downstream. Even in case of a 70-cm shorter dump, lateral leakage still dominates.



(a)



(b)

Figure 7: Energy spectra of particles escaping the dump laterally from the vessel (a) and from the downstream window (b).

CONCLUSIONS

In this study, FLUKA simulations for the LHC TDE dump have been performed in view of HL-LHC operation, focusing in particular on the peak energy density in the graphite core, which is found to be 3.4 kJ/g for a dump event at nominal HL conditions. The exact grade and type of materials to be employed in the HL dump is currently under scrutiny. In HL conditions, the energy deposited in the vessel using the current stainless steel design would be 30 MJ for a nominal dump; thermo-mechanical improvements could be achieved by replacing stainless steel with titanium, reducing energy deposited by about half. Finally, several dilution failure cases have been studied: the worst scenario is represented by the loss of two horizontal kickers, which leads to up to 5.7 kJ/g in the core. Such design failure cases must be considered in the core material choice.

ISBN: 978-3-95450-231-8 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2023-MOPA101

REFERENCES

[1] O. Brüning *et al.*, "LHC Design Report", vol. I, chapter 17: Beam Dumping System, CERN, Geneva, Switzerland, 2004. doi:10.5170/CERN-2004-003-V-1

[2] E. Solfiti *et al.*, "Flexible graphite as beam dumping material in the TDE blocks of the Large Hadron Collider", *Procedia Struct. Integrity*, vol. 28, pp. 2228-2234, 2020. doi:10.1016/j.prostr.2020.11.051

[3] J. Maestre *et al.*, "Design and behaviour of the Large Hadron Collider external beam dumps capable of receiving 539 MJ/dump", *J. Instrum.*, vol. 16, p. P11019, 2021. doi:10.1088/1748-0221/16/11/P11019

[4] M. Lamont, "The first years of LHC operation for luminosity production", in *Proc. IPAC'13*, Shanghai, China, May 2013, paper MOYAB101, pp. 6–10.

[5] R. Steerenberg *et al.*, "Operation and performance of the CERN Large Hadron Collider during proton Run 2", in *Proc. IPAC'19*, Melbourne, Australia, May 2019, pp. 504–507. doi:10.18429/JACoW-IPAC2019-MOPMP031

[6] S. Fartoukh *et al.*, "LHC Configuration and Operational Scenario for Run 3", CERN-ACC-2021-0007

[7] G. Arduini *et al.*, "HL–LHC Run 4 proton operational scenario", CERN-ACC-2022-0001.

[8] C. Ahdida *et al.*, "New Capabilities of the FLUKA Multi-Purpose Code", *Front. Phys*, vol. 9, p. 788253, 2022. doi:10.3389/fphy.2021.788253

[9] G. Battistoni *et al.*, "Overview of the FLUKA code", *Ann. Nucl. Energy*, vol. 82, pp. 10-18, 2015. doi:10.1016/j.anucene.2014.11.007

[10] V. Vlachoudis, "FLAIR: A powerful but user friendly graphical interface for FLUKA", in *Proc. Int. Conf. Math., Comput. Methods & Reactor Phys. (M&C 2009)*, Saratoga Springs, New York, pp. 790-800, 2009.

[11] P. Andreu-Muñoz *et al.*, "Irradiation of Low-Z Carbon-Based Materials with 440 GeV/c Proton Beam for High Energy and Intensity Beam Absorbers: The CERN HiRadMat-56-HED Experiment", in *Proc. IPAC'22*, Bangkok, Thailand, Jun. 2022, pp. 2883–2886. doi:10.18429/JACoW-IPAC2022-THPOTK049

[12] C. Wiesner *et al.*, "Machine Protection Aspects of High-Voltage Flashovers of the LHC Beam Dump Dilution Kickers", in *Proc. 10th Int. Particle Accelerator Conf. (IPAC'19)*, Melbourne, Australia, May 2019, pp. 2418–2421. doi:10.18429/JACoW-IPAC2019-WEPMP040

[13] C. Wiesner *et al.*, "LHC Beam Dump Performance in View of the High Luminosity Upgrade", in *Proc. 8th Int. Particle Accelerator Conf. (IPAC'17)*, Copenhagen, Denmark, May 2017, pp. 2999–3002. doi:10.18429/JACoW-IPAC2017-WEPIK033

[14] G. Banks *et al.*, "Design development and R&D for CERN's HL-LHC external beam dump", presented at the 14th Int. Particle Accelerator Conf. (IPAC'23), Venice, Italy, May 2023, paper TUPM122, this conference.