Modeling of a Dynamic Thermal Load Generated by a 7 TeV Proton Beam Impacting the Beam Dump of the Large Hadron Collider at CERN

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Abstract. The two beam dumps of the Large Hadron Collider (LHC), made up mostly of low-density graphite, are responsible for absorbing the high-energy particle beams when ejected from the accelerator. In the framework of the project to improve the luminosity in the LHC, the beam intensity will be increased by a factor of around two in the coming years. The dominant load on the dump assembly is the energy deposited in the material by the 7 TeV proton beam. Thermomechanical simulations have to be performed to ensure the safe operation of the dump through assessing the integrity in the future. To date, the particle beam contains an average energy of 370 MJ, which is sent to the dump in a sweep movement within around 80 μ s. Based on the large dimensions of the dump core and considering the highly dynamic nature of this load, an explicit code like LS-Dyna[®] was deemed to be best suited for these studies. This paper presents the methodology proposed to model the discrete time structure of the load, caused by the interaction between the particle beam and the dump. Results of the application of this technique, to determine the temperature, stresses and wave propagation on the downstream wall of this device, are described here. In addition to the methodology of the load application, the results of standard quasi-static material tests on the low-density graphite material in the beam dump are presented, to assess the general nature of the material behavior. These experiments will be the basis for a dynamic test campaign to construct a comprehensive material model, as the graphite used in this device has never been fully characterized under such loading conditions.

1 Introduction

The LHC beam dumping system is designed to extract the proton beam from the Large Hadron Collider (LHC) to an external dump block (TDE), which is located in a cavern at the end of a separate 650 m long vacuum beam pipe. The TDE itself intercepts the particle beam, which results in the deposition of energy in the absorbing material. The core of the TDE has a cylindrical shape, with a total length of 8.4 m and a diameter of 0.7 m. The core consists of several distinct blocks of two different graphite grades. One grade is Sigrabond[®] R7300 P500 with a density of 1770 kg m⁻³ and the other one is Sigrflex[®] L20012-C, a flexible grade of graphite with a density of 1200 kg m⁻³ [1, 2]. SGL Carbon GmbH produces both grades. The graphite is contained in a stainless steel housing (EN 1.4462) to keep it in a N₂-atmosphere at a positive pressure (200 Pa). Two disks made of solid material close the housing to keep the pressure inside the core. They separate the TDE from the ultra-high vacuum at the upstream end, and from the atmosphere in the cavern at the downstream end. Usually, these disks are referred to as *windows* [3, 4].

Figure 1 shows an illustration of the dump core and its housing. The second block from the back in the figure rep-

Fig. 1. Model of the dump core and its different grades of graphite with its stainless steel housing.

resents the low-density graphite, whereas the other blocks are made of the higher density grade. In reality, the low-density sector of the dump is not homogeneous. It consists of around 2800 sheets of Sigrflex[®] with a thickness of 2 mm, which are piled up upon each other. During the interaction with the proton beam, energy is deposited in the material, which causes a sudden temperature increase. The low-density sector of the dump reaches the highest temperatures during operation [4].

Installed in 2007, the TDE is again the focus of more detailed thermomechanical studies in the framework of the

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High Luminosity LHC (HL-LHC) project. The objective of the project is to increase the luminosity in the experiments by a factor of 10 beyond the LHC's design value [5]. The luminosity is a measure of the number of events per unit of surface per second. The higher the luminosity, the more collisions are produced in the experiments to be detected. The accelerator complex will be improved in several ways to achieve the increase of the luminosity. Some will, for example, increase the beam intensity by a factor of around two or reduce the beam diameter, with the aim to increase the overall particle density in the beam. It is clear that these improvements will also increase the peak temperature in the TDE, as the deposited energy density increases. Thermomechanical finite element (FE) studies will be performed to evaluate the performance of the TDE under these new loading conditions. This paper presents the elaborate modeling of the load which is caused by the intercepted proton beam. The proper load definition is an essential part of a methodology which aims at obtaining reliable simulation results to assess the performance of the dump after 2025 when the HL-LHC is expected to be in operation. This paper also presents the results of quasi-static material tests on the low-density graphite used in the TDE. Those experiments were performed to assess the general nature of the material response, aiming at being able to design future high-strain-rate and high-temperature tests, to establish a reliable material model for future simulation studies.

2 Load Description

2.1 Proton Interaction with Matter

The impinging proton beam induces the main load on the dump structure. The protons of the beam undergo a series of interactions with the nuclei of the dump material in the course of their passage through the dump. These interactions give rise to coupled hadronic and electromagnetic radiation showers, leading to deposition of energy in the dump, observable as a thermal load on the macroscopic scale [6].

2.2 Distribution of Protons on the TDE

The protons within the particle beam of the LHC are structured with a time dependency. This structure is established during the passage of the protons through the accelerator complex at CERN. In reality, the protons are spread over single packages, so-called *bunches*, which follow each other in bunch *trains*. A whole proton beam in the LHC consists of several of these bunch trains. The LHC accelerates different proton beams, which are characterized by their intensity and their proton distribution over time. After the upgrade of the accelerator complex, the beams will have a total intensity of around 6×10^{14} protons, divided between 2 600 to 2 800 bunches, which follow each other with a time spacing of 25 ns. At the end of the acceleration process, each proton will have a total energy of 7 TeV. Table 1 describes two examples of planned proton beams

in the LHC after the upgrade [7]. Here, a round geometry of the beam spot is assumed.

Table 1. Beam parameters for HL-LHC 25ns beams.

	"Standard"	"BCMS"
Beam Energy in TeV	7	7
No. of protons per bunch	2.3×10^{11}	2.3×10^{11}
Number of Bunches	2 748	2 604
Total Intensity	6×10^{14}	5.7×10^{14}
Norm. emittance in $\mu\text{m rad}$	2.08	1.37

In addition to the variation of the particle density during the impact, the location of the beam impact on the TDE depends on time, too. The time dependency of the impact location is a result of the usage of a system of horizontal and vertical dilution kickers in the vacuum line. It sweeps the proton beam in an "e" shaped form on the upstream face of the TDE, to reduce the energy density in the dump during the impact. The variation of both – intensity and impact location – has to be modeled to retrieve the correct material response from the simulation.

3 Developed Modeling Technique of the Thermal Load

3.1 Basic Concept

To model the thermal load in the FE-simulation, the energy deposition caused by the beam is necessary as an input. One way to get this input is through FLUKA simulations, which are widely used at CERN for various projects. FLUKA is a Monte Carlo code to simulate the interaction and transport of particles in a wide range of energies. A detailed description of this code is given in [8]. To illustrate the sweep movement of the beam and to show the capabilities of the FLUKA code, Figure 2 shows the simulated maximum transverse energy density deposited in the dump core by a proton beam after the upgrade of the LHC [4].

In this simulation with FLUKA, the deposited energy density per averaged proton of the full beam was scaled with the overall intensity of the beam, so that the result of the simulation represents the combined deposited energy density after the full beam impact, including the sweep movement. Consequently, the presented result has no information about the time structure of the beam. However, to be able to simulate the correct material response of the TDE to the beam impact, the time structure of this load is crucial. For this reason, this contribution uses the simulation result of an averaged proton in one single bunch as a starting point. FLUKA generates a 3D-matrix which is the used for the simulation in LS-Dyna®. It represents the bucketed field of the deposited kinetic energy density in the simulated geometry. The deflection and the bunched character of the beam are then considered with a time-depending translation of this matrix, according to the coordinates of the sweep movement over time. This approach

Fig. 2. Transverse energy density distribution in the TDE core for a regular dump of a HL-LHC beam (2748 bunches with 2.3×10^{11} protons per bunch, an Energy of 7 TeV per proton and an emittance of $2.1 \mu\text{m rad}$)[4].

assumes that the relative positions of the protons are constant within the bunch, that the influence of the deflection angle is negligible and that each proton interacts with the same material thickness during the sweep. Figure 3 illustrates this concept.

Fig. 3. Concept of the load application: The energy deposition of one bunch is translated according to a predefined sweep pattern.

The purpose of the presented method is to model the load on the TDE in LS-Dyna®. During the interaction with the particle beam, no shock waves are expected in the material due to the moderate temperature increase. Based on this assumption, the solution of the thermal problem is only weakly coupled with the solution of the mechanical problem. Consequently, the energy deposited in the material is only considered as heat generation in the structure, which causes a temperature increase. Based on a temperature-dependent specific heat, the temperature is evaluated with the thermal solver and is then used as an input for the structural solver to evaluate the thermal stresses with a temperature-dependent thermal expansion coefficient and Young's modulus. The material density is assumed to be constant. There are other options available for LS-Dyna® to retrieve the material response, where the deposited energy is considered in an equation of state directly. These options are then also valid for beam-induced

shock waves [9]. Taking into account that the aim is to model each bunch in a discretized way, a decoupled approach seems to be more time efficient, because, for each bunch, a new simulation would be started by Matlab®, with new load-dependent material properties for new subsets of elements.

LS-Dyna® uses time-dependent load curves to define the heat generation rate per volume. These load curves must describe the load during the whole time covered by the simulation. The load also depends on the varying beam impact position; hence the load curves are different for every finite element in the model if energy is deposited. Based on this fact, a single load curve must define the thermal load for each finite element.

To build the load curves, the heat generation rate per volume on the FE-mesh, caused by the translated 3D-matrix from FLUKA, is extracted for each element. After each bunch, a text file stores the retrieved data. The generation of the mesh and also the data extraction is performed in ANSYS®. This is because ANSYS® interpolates the data from the imported 3D-matrix on each element, much faster than anything that would be possible to implement directly in Python. Afterward, a Python 3 script processes the generated files to build the load curves.

3.2 Mapping of the FLUKA Output on the Finite Element Mesh

APDL snippets are used in ANSYS Workbench® to extract the energy deposited in the mesh. The 3D-matrix of the energy deposition is saved in an ASCII-file as a continuous data stream:

Listing 1. Typical FLUKA output file that is used in ANSYS.

```
Cartesian binning n. 1 "ECoFine " , generalized particle n. 208
Information about the binning dimensions
Data follow in a matrix A(ix,iy,iz), format (1(5x,1p,10(1x,e11.4)))
3.4166E-02 3.1591E-02 2.8669E-02 2.7887E-02 2.6041E-02 . . .
1.6862E-02 1.5238E-02 1.3124E-02 1.1779E-02 . . .
5.7502E-03 5.1293E-03 4.6540E-03 . . .
5.8332E-02 5.9764E-02 . . .
5.1285E-02 . . .
```

This data stream is read in a *table* in ANSYS®, scaled by a constant, so that it represents the heating power of a complete bunch in SI-units. This table is then used to apply a body force on the FE-mesh. The usage of an ANSYS® table has two advantages:

- Linear interpolation between the stored data points is possible. Consequently, a value for the density of the energy deposition is defined for each coordinate inside the space of the original 3D-Matrix,
- The table has its local coordinate system. As a result, the position is variable in global coordinates during the simulation.

Additional to the 3D-matrix of FLUKA, another input is needed to model the sweep movement: the locations of the bunch impact positions over time. These locations redefine

the origin of the local coordinate system of the bunch during the sweep. The impact positions are read from a CSV-file to redefine the origin of the load table in ANSYS, accordingly. Afterward, the defined heating power per bunch is requested at each element and extracted to a file. Thereafter, the next coordinates are used to model the following bunch impact. An APDL snippet defines all these steps. Finally, after the extraction of all data, the SOLVE command is replaced by a selection of all elements, to prevent the actual solution of the FE-problem.

3.3 Generation of the Load for LS-Dyna®

An example problem, with a mesh of 500 000 elements and 2 748 bunches applied, leads to the creation of 1.374×10^9 data points with this approach, where the majority of these points are equal to zero. All unnecessary zero-values should get excluded from the definition of the load curves in LS-Dyna®. Therefore the implemented function in the script has to contain a filter. Based on the amount of data which has to be read before the filtering, it was necessary to implement the request of data in Python as an iterator over each element. The iterator constructs the required data for one element only upon request [10]. In this way, it was possible to optimize the use of computational resources during the execution of the Python script. After reading the data, two levels of the filter are introduced to remove the unnecessary zero-values during the output:

- The first level checks the necessity to write the load curve for the respective element in general. If the maximum data value in the yielded data is larger than 0, the load curve is used in the output. In this case, the data values are duplicated within one load curve, to model a constant heating power during the impact of one bunch,
- After the decision to write a load curve, the second level of the filter checks which data points are necessary within a single curve. A data point is necessary, if the previous or following data point is larger than 0 or if it is the very first data point of the curve.

The deposited energy is summed per element. After the generation of all load curves, the largest amount of deposited energy is printed out to enable the user to compare the maximum generated load with the original load from FLUKA.

3.4 Example for the Application

As an example, to apply the presented method, a thermomechanical simulation of the window behind the TDE was performed. The window consists of Titanium (Grade 2) with a diameter of 700 mm and a thickness of 10 mm. The finite element mesh contained 299 075 hexagonal elements. The raw data for the Python script had a size of 14.5 GB. With an average usage of 2.4 GB of RAM it took 1:30 h to process the data in Python where the reading and writing process on the HDD took the largest amount of time. Finally, the resulting output file had a size of

38.6 GB. It took 18:08 h to solve the created finite element problem with LS-Dyna®, where 18 CPUs and around 33 GB of memory were used. The simulation covered 400 μ s and the defined material model used the parameters shown in Table 2 and Table 3. Only a linear elastic material model was implemented.

Table 2. Thermal material data for Titanium (Grade 2) [11].

Temperature	Property		
	Therm. conductivity W/mK	Specific heat J/kgK	Therm. expansion $10^{-6}/K$
20 °C to	7.23	523.4	8.28
93 °C	7.68	544.3	8.64
204 °C	10.12	565.2	9.00
260 °C	11.53	575.7	9.18
538 °C	12.93	669.9	9.63

Table 3. Mechanical material data for Titanium (Grade 2) [11].

Temperature	Property		
	Young's modulus GPa	Poisson's ratio 1	Mass density kg/m ³
20 °C – 538 °C	106.9	0.31	4429.9

The maximum deposited energy density in the finite element model is 349.8 J cm^{-3} . Compared with the original deposition of 356 J cm^{-3} evaluated in FLUKA, the load is underestimated by 1.7 % in LS-Dyna®. Figure 4 shows a contour plot of the resulting equivalent v. Mises stress at the time when the maximum stress occurs.

Fig. 4. Stress response of the titanium window to an impact of the standard beam presented in Table 1.

In addition to the eq. stress, Figure 5 shows the principal stress components and the temperature over time to further evaluate the stress state at the point in the material where the maximum v. Mises stress occurs. The first temperature rise is based on the halo of the showers around the beam. The passing beam causes the highest peak in the equivalent stress, which is also observable in the much higher rise of temperature. After the first peak, several other vibrations in the material cause a variation of stress with different frequencies.

Fig. 5. Time development of different stress components and the temperature at the material point where the maximum stress occurs.

4 Quasi-Static Material Tests

The low-density sector of the TDE consists of Sigraflex[®] sheets, which is a graphite-based material used as a seal against different media. In contrast to other graphite grades, Sigraflex[®] appears to be flexible and has a significant porosity. The choice of this material was made based on its low density as well as its high resistance against radiation and thermal shocks. The raw material used to produce Sigraflex[®] is natural graphite flakes. These flakes are expanded in a thermal process and get compressed into foils. Based on the alignment of the graphite particles and their planar structure, the thermomechanical properties of Sigraflex[®] have a directional dependence. Different tests were performed on two grades of Sigraflex[®] at room temperature. The tests were performed at CERN. The tested grades of Sigraflex[®] were: L20010C, with a thickness of 2.0 mm and a density of 1.0 g cm⁻³ and L25012C, with a thickness of 2.5 mm and a density of 1.2 g cm⁻³.

4.1 Uniaxial Compression Test

Uniaxial compression tests were performed to determine the stress-strain behavior of the material. The specimens were square with a thickness determined by the grade of Sigraflex[®], and a edge length of 5 mm. The specimens were tested at a constant crosshead speed of 1 mm/min and with a preload of 1 N mm⁻² according to ISO 604. A Zwick/Roell 20 kN load cell to measure the force, and a Zwick/Roell LaserXtrens optical transducer was used to measure the displacement. Figure 6 shows the stress-strain response of all tested samples, sorted by the respective grade of Sigraflex[®]. For all samples, the material did not show an apparent linear range in its stress-strain behavior and after unloading, the majority of the deformation is residual. Nevertheless, the curves of the different samples show good reproducibility. For a 2 mm sample, three loading-unloading cycles were performed. It is evident that the material stiffness is dependent on the already induced strain.

Fig. 6. Stress-strain response under compression [12].

4.2 Three-point Flexural Test

Three-point flexural tests were performed to assess the stress-strain behavior of the material grades in a different load case. The tests have been designed following EN ISO 178 where possible. The samples had a length of 180 mm and a width of 4 mm. No preload was applied to the samples, and the loading rate was 1 mm min⁻¹ for one half of the specimens and 0.5 mm min⁻¹ for the rest. The material orientation was marked on each sample. The maximum flexural stress on the outer surface of the test specimens was evaluated with

$$\sigma = \frac{3Fl}{2bh^2}$$

F is the force acting on the specimen and h , b and l define the height, the width and the span length of the specimen. The strain was evaluated afterward with

$$\epsilon = \frac{600sh}{l^2}$$

Here s represents the measured distance between the test specimens top surface and its original position. The evaluated strain is valid, assuming a linear-elastic material response as well as a symmetric tension and compression response. However, for this material these assumptions were not appropriate. During the tests, no stretching of the outer surface of the specimens was observed, and the specimens broke after less than 1 % of strain. Nevertheless,

Figure 7 shows the calculated stress-strain response of the specimens sorted by the thickness of the used Sigraflex® grade. There are two sets of curves for each grade observ-

Fig. 7. Stress-strain response during the flexural tests [12].

able. To date, there is no explanation available why this is the case. The material orientation was the same for each test, and no dependence on the loading rate was observed.

5 Conclusion

This paper presented a method for the definition of thermal loads for LS-Dyna® caused by proton-beam-induced heating. Additionally, investigations on the mechanical properties of Sigraflex® were shown. Even though the resulting output, which is used for the solution with LS-Dyna®, is quite extensive, the overall performance of the implemented method appears to be practicable within a simulation workflow. The performed quasi-static material tests showed a non-linear material response under mechanical loads. The collected material data will not be used for a definition of a material model because they are not applicable to the expected loading conditions in the TDE. However, the data will support the design of further test setups by giving an order of magnitude for the expected material response.

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