ISBN: 978-3-95450-227-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2022-WEPOPT015

STUDY OF HYDRODYNAMIC-TUNNELLING EFFECTS INDUCED BY HIGH-ENERGY PROTON BEAMS IN GRAPHITE

C. Wiesner*, F. Carra, J. Don, I. Kolthoff, A. Lechner, R. Rasile, D. Wollmann
CERN, CH-1211 Geneva, Switzerland

Abstract

The design and assessment of machine-protection systems for existing and future high-energy accelerators comprises the study of accidental beam impact on machine elements. In case of a direct impact of a large number of high-energy particle bunches in one location, the damage range in the material is significantly increased due to an effect known as hydrodynamic tunnelling. The effect is caused by the beam-induced reduction of the material density along the beam trajectory, which allows subsequent bunches to penetrate deeper into the target. The assessment of the damage range requires the sequential coupling of an energy-deposition code, like FLUKA, and a hydrodynamic code, like Autodyn. The paper presents the simulations performed for the impact of the nominal LHC beam at 7 TeV on a graphite target. It describes the optimisation of the simulation setup and the required coupling workflow. The resulting energy deposition and the evolution of the target density are discussed.

INTRODUCTION

In order to evaluate the machine-protection systems for high-energy and high-intensity accelerators, the consequences of beyond-design failures (see page 445 in [1]) have to be considered. This includes the accidental, direct beam impact in one location. In this scenario, the damage range in the material can be dominated by an effect known as hydrodynamic tunnelling [2, 3]. The effect is caused by the beam-induced reduction of the material density along the beam axis, which allows subsequent bunches to penetrate deeper and deeper into the target. To take into account the changing material densities for the simulation, it is required to sequentially couple an energy-deposition code and a hydrodynamic code. In this generic study, the worst-case scenario of the direct impact of the full nominal Large Hadron Collider (LHC) proton beam at 7 TeV on a graphite target was simulated [4, 5]. The main aim of the study was to establish an efficient coupling workflow based on the FLUKA code [6–8] and the commercially available Autodyn code [9]. To facilitate future comparisons, similar beam parameters and the same equation of state as in a previous study (see Sec. 5.2. in [2], Sec. V in [10] and Chap. 8.3.2 in [11]), which was performed by coupling the codes FLUKA and BIG2 [12], were chosen.

* christoph.wiesner@cern.ch

SIMULATION SETUP AND PARAMETERS

Beam Parameters

For this study, the nominal LHC beam parameters [1] and a beam size of $\sigma = 0.5$ mm were used. The details of the LHC filling patterns were neglected and a constant bunch spacing of 25 ns was assumed. Table 1 summarizes the main beam parameters.

Table 1: Beam Parameters Used for the Simulations

Particle species	Protons
Beam Energy	7 TeV
Total number of bunches	2808
Protons per bunch	1.15×10^{11}
Bunch spacing	25 ns
Bunch length	0.5 ns
Filling scheme	None
rms beam size (sigma)	0.5 mm

Simulation Workflow

The simulation workflow for this study consisted of three main steps, which had to be performed in a loop:

1. Run the FLUKA simulation.
2. Import the energy-deposition map into Autodyn and perform the hydrodynamic simulation for a certain number of impacting bunches.
3. Update the target densities by interpolating the Autodyn results to the FLUKA regions and create the new FLUKA input file.

The general approach for the coupling simulations is discussed in [13]. For this study, an optimised coupling script [14] was used to update the target geometry of the FLUKA input file. The overall simulation cycle was stopped once it became evident that the propagation speed of the density depletion front in the target reached a near constant value, allowing to extrapolate the total penetration depth after the impact of all the bunches.

FLUKA Setup

The main target and FLUKA simulation parameters are summarised in Table 2. The target was modelled as a graphite cylinder with length of 10 m and a radius of 5 cm with axial symmetry. For the initial simulation step, a uniform target density of 2.28 g cm^{-3} was used. Therefore, no segmentation was required and the FLUKA model was implemented with a single region. However, for all subsequent

ISBN: 978-3-95450-227-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2022-WEPOPT015

simulation steps, the geometry of the target had to be divided into various regions as only a single density value can be assigned to each FLUKA region.

As a compromise between resolution and FLUKA runtime, a model with 13 400 regions was chosen. This implied a running time of up to seven days using at least 50 000 primary protons per simulation step at typically 25 to 30 CPUs on the available cluster at CERN. This resulted in an acceptable relative statistical error of the energy-deposition density below 1.5 % in the beam-heated region.

To ensure a sufficiently high spatial resolution close to the target axis, where the largest density gradients occurred, a radially adapted region size was chosen. For the 40 innermost regions, a radial bin width of 125 µm was chosen, corresponding to one fourth of the beam sigma of $\sigma = 500$ µm. This was followed by 20 regions with a 375 µm radial width, 6 regions with a 1.25 mm radial width, and one 30 mm thick verge region to cover the full 5 cm radial target size.

Table 2: Target and FLUKA Simulation Parameters

Target length	10 m
Target radius	5 cm
Material	Graphite
Initial target density	2.28 g cm^{-3}
Radial region size	Radially increasing (67 regions in total)
Longitudinal region size	5 cm length (200 regions in total)

Autodyn Setup

Table 3 shows the main Autodyn simulation parameters. The material model used for graphite in the Autodyn simulations [15] consisted in a tabular equation of state (EOS) from the SESAME library. This is the most sophisticated type of EOS, as it can express strong nonlinearities and discontinuities between the different parameters. Since, in this impact scenario, pressures are in the order of GPa, the hydrostatic response of the material, controlled by the EOS, is dominant with respect to the deviatoric component, controlled by strength and failure models. For such reason, no strength/failure model was adopted in the simulation.

Table 3: Autodyn Simulation Parameters

Equation of State	Tabular (SESAME) [15]
Strength and failure model	none
Mesh	Eulerian
Longitudinal element size	2.5 cm
Radial element size	125 µm (up to $r = 2$ cm)
Time step	0.5 ns

A Eulerian mesh was used for the model. With respect to a Lagrangian mesh, which was used in previous studies [3], Eulerian methods have the advantage of maintaining a constant element size. This simplifies the FLUKA/Autodyn interaction, and avoids element distortion that, numerically, can lead to high energetic errors, or even to a premature interruption of the simulation. The energy-deposition map per primary proton was loaded from FLUKA into Autodyn and scaled to the required number of impacting protons. Finally, a time step of 0.5 ns was selected in order to be consistent with the bunch length.

RESULTS

Table 4 gives an overview of the performed simulation steps for this study. The first step was stopped after the impact of 70 bunches, corresponding to a density change in the most-loaded mesh element of 16 %. For all subsequent steps, a fixed step size of 100 bunches was used, leading to a reduction of the minimum target density by around 50 % per simulation step.

Table 4: Simulation steps, total number of bunches n_{bun} that have impacted the target at time t_{step}, the resulting peak energy deposition E_{max}, the longitudinal location of the shower maximum $z(E_{max})$, and the minimum graphite density ρ_{min} in the target

Step	n_{bun}	t_{step} **(µs)**	E_{max} **(GeV/g/p)**	$z(E_{max})$ **(mm)**	ρ_{min} **(g cm^{-3})**
0	0	0	8.4	1350	2.28
1	70	1.75	7.2	1450	1.91
2	170	4.25	4.7	2450	0.96
3	270	6.75	4.1	3175	0.51
4	370	9.25	3.9	3925	0.22
5	470	11.75	3.8	4550	0.11
6	570	14.25	-	-	0.07

As discussed below and visible from Fig. 3, the density depletion front at the target axis started to propagate with near constant speed after 4.25 µs, which allowed for stopping the simulations after 6 steps and estimating the total damage range by extrapolating to the impact of all 2808 bunches. Note that the simulation loop was stopped after obtaining the Autodyn results for an impact of 570 bunches, and therefore no energy-deposition map is available for Step 6.

For the 6 coupling steps, a total simulation time of around two months was required, dominated by the running time of the FLUKA simulations. This does not count the time for the simulation setup and for post-processing the final results.

Energy Deposition

Figure 1 shows the longitudinal energy density profile close to the target axis as calculated with FLUKA. For the first simulation step with uniform target density, a peak energy-deposition density of 8.4 GeV/g/proton is reached, and the shower maximum at the target axis is located around $z = 1.35$ m. Due to the depletion of the target density in the beam-heated region, the peak energy-deposition density is reduced to below 4 GeV/g/proton after 9.25 µs. However, the energy is now deposited much deeper into the target. Consequently, the location of the shower maximum moves downstream and reaches approximately $z = 4.6$ m after the impact of 470 bunches. In addition, a double peak structure becomes visible, which is a consequence of the material-depleted region around 2 m inside the target.

ISBN: 978-3-95450-227-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2022-WEPOPT015

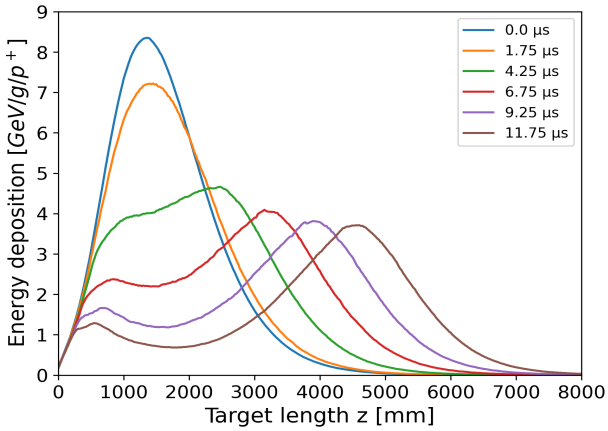

Figure 1: Energy density profiles along the target.

The energy escaping the target volume stayed almost constant during the simulations, changing from 49.4 % after the impact of 70 bunches to 49.7 % after 470 bunches. The simulations showed that a peak pressure of 1.2 GPa was reached after the impact of 170 bunches, while the maximum peak temperature of nearly 8400 K occurred after the impact of 370 bunches [4]. For larger times, the peak pressure decreased because the peak energy-deposition density in the target was reduced due to the hydrodynamic-tunnelling effect.

Density Depletion and Damage Range

Figure 2 shows the graphite density inside the target after the impact of 570 bunches. The density reduction in the beam-heated region close to the target axis is clearly visible.

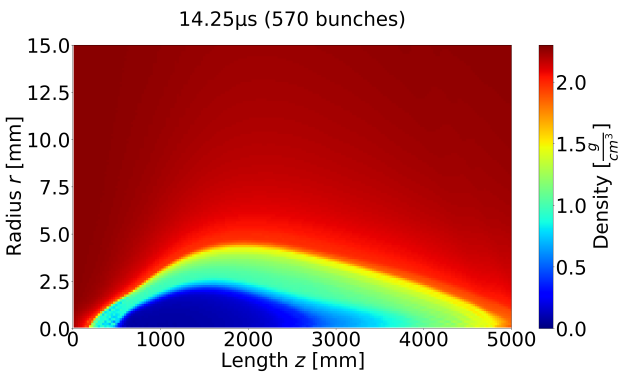

Figure 2: Simulated material density inside the first 5 m of the target after the impact of 570 bunches.

Figure 3 shows the evolution of the material density. The minimum density in the beam-heated region decreases from the initial 2.28 g cm^{-3} to less than 1 g cm^{-3} after the impact of 170 bunches (4.25 µs) and further to 0.07 g cm^{-3} after the impact of 570 bunches (14.25 µs).

It can be inferred from the evolution of the density profiles that after 4.25 µs the density depletion front moves along the axis with a nearly constant speed of 25.5 ± 1.1 cm µs^{-1}. Here, the speed was averaged over the last four steps. This agrees with the value of 25 cm µs^{-1} derived in the previous study (see p. 77 in [2]), which used the BIG2 code.

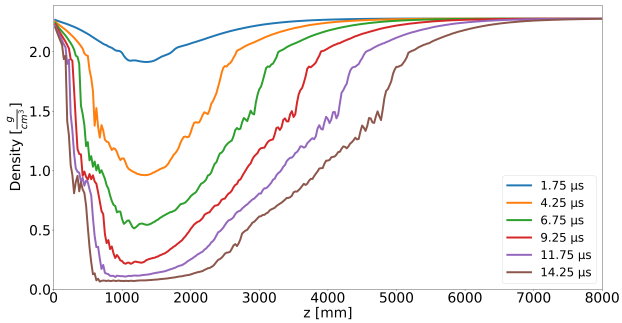

Figure 3: Evolution of the graphite density close to the target axis (i.e. at the innermost mesh line of 125 µm).

Obtaining the speed of the density depletion front is a key result for the machine-protection assessment because it allows to estimate the total damage range as follows: After 4.25 µs, the density is reduced up to approximately 3.5 m into the target. Afterwards, the depletion front moves with a near constant speed until the total number of 2808 bunches have impacted the target, which corresponds to 70.2 µs, assuming a constant bunch spacing of 25 ns. This gives an additional 16.8 m, and, therefore, a total damage range of the LHC nominal beam in graphite of approximately 20 m.

The result confirms that the full impact of the LHC beam is an unacceptable, beyond-design failure that would lead to significant damage to the installed collimators and absorbers and underlines the necessity for highly redundant and reliable protection and dump systems.

CONCLUSIONS AND OUTLOOK

In this study, the spot impact of a proton beam with nominal LHC parameters and a beam size of $\sigma = 0.5$ mm on a cylindrical graphite target was simulated. For this purpose, the energy-deposition code FLUKA was coupled with the hydrodynamic code Autodyn, taking into account the beam-induced density change in the material during the beam impact. In total, 6 simulation steps up to the impact of 570 bunches, corresponding to 14.25 µs, were performed. After 4.25 µs, the density depletion front moved with a near constant speed, allowing to estimate the damage range in graphite for the worst-case scenario of the direct impact of the full nominal LHC beam to be approximately 20 m.

After having successfully established the required coupling workflow, future studies of beyond-design failures using FLUKA and the commercially available code Autodyn are planned. In particular, the effect of the higher intensities of 2.2×10^{11} protons per bunch [16] in the High-Luminosity LHC era on the damage range will be assessed.

ACKNOWLEDEGMENTS

The authors would like to thank Y. Nie, R. Schmidt and N. Tahir for important discussions and insights about hydrodynamic tunnelling.

ISBN: 978-3-95450-227-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2022-WEPOPT015

REFERENCES

[1] O. Brüning (ed.) *et al.*, "LHC Design Report, Vol. I: The LHC Main Ring, CERN, Geneva, Switzerland, Rep. CERN-2004-003, 2004.

[2] N. Tahir, F. Burkart, R. Schmidt, A. Shutov, and A. Piriz, "Review of hydrodynamic tunneling issues in high power particle accelerators", *Nucl. Instrum. Methods Phys. Res., Sect. B*, vol. 427, pp. 70–86, 2018, doi:https://doi.org/10.1016/j.nimb.2018.04.009

[3] Y. Nie *et al.*, "Simulation of hydrodynamic tunneling induced by high-energy proton beam in copper by coupling computer codes", *Phys. Rev. Accel. Beams*, vol. 22, p. 014 501, 2019, doi:10.1103/PhysRevAccelBeams.22.014501

[4] J. Don and C. Wiesner, "Simulation of hydrodynamic-tunnelling effects induced by 7 TeV protons in graphite", MPE Technical Note 2022-01, EDMS Nr. 2739903, May. 2022, https://edms.cern.ch/document/2739903.

[5] R. Rasile, "Dynamic Response of Advanced Materials impacted by MMOD", M.S. thesis, La Sapienza University of Rome, Italy, unpublished, 2022.

[6] G. Battistoni *et al.*, "Overview of the FLUKA code", *Annals of Nuclear Energy*, vol. 82, pp. 10–18, 2015, doi:https://doi.org/10.1016/j.anucene.2014.11.007

[7] C. Ahdida *et al.*, "New capabilities of the FLUKA multi-purpose code", *Front. Phys.*, vol. 9, 2022, doi:https://doi.org/10.3389/fphy.2021.788253

[8] *FLUKA.CERN website*, https://fluka.cern/.

[9] Ansys Inc., *Ansys autodyn*, https://www.ansys.com/products/structures/ansys-autodyn.

[10] N. A. Tahir, J. B. Sancho, A. Shutov, R. Schmidt, and A. R. Piriz, "Impact of high energy high intensity proton beams on targets: Case studies for super proton synchrotron and large hadron collider", *Phys. Rev. ST Accel. Beams*, vol. 15, p. 051 003, 2012, doi:10.1103/PhysRevSTAB.15.051003

[11] J. Blanco Sancho, "Machine Protection and High Energy Density States in Matter for High Energy Hadron Accelerators", Ph.D. Thesis, École Polytechnique Fédérale de Lausanne, Lausanne, Switzerland, https://cds.cern.ch/record/1704466, 2014.

[12] V. E. Fortov, B. Goel, C.-D. Munz, A. L. Ni, A. V. Shutov, and O. Y. Vorobiev, "Numerical Simulations of Nonstationary Fronts and Interfaces by the Godunov Method in Moving Grids", *Nucl. Sci. Eng.*, vol. 123, no. 2, pp. 169–189, 1996.

[13] C. Wiesner, F. Carra, J. Kruse-Hansen, M. Masci, Y. Nie, and D. Wollmann, "Efficient Coupling of Hydrodynamic and Energy-Deposition Codes for Hydrodynamic-Tunnelling Studies on High-Energy Particle Accelerators", in *Proc. IPAC'21*, Campinas, Brazil, May 2021, pp. 119–122, doi:10.18429/JACoW-IPAC2021-MOPAB024

[14] I. Kolthoff, *Coupling script for hydrodynamic-tunnelling studies*, 2021.

[15] N. Tahir, *Equation of state for nominal graphite*, Private Communication, 2020.

[16] O. Aberle *et al.*, *High-Luminosity Large Hadron Collider (HL-LHC): Technical design report*. CERN, 2020, doi:10.23731/CYRM-2020-0010