

INTERACTION OF THE CERN LARGE HADRON COLLIDER (LHC) BEAM WITH CARBON COLLIMATORS AND ABSORBERS

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Abstract

The LHC will operate at an energy of 7 TeV with a luminosity of $10^{34} \text{cm}^{-2}\text{s}^{-1}$. This requires two beams, each with 2808 bunches. The energy stored in each beam of 362 MJ. In a previous paper the mechanisms causing equipment damage in case of a failure of the machine protection system was discussed, assuming that the entire beam is deflected into a copper target [1, 2]. Another failure scenario is the deflection of beam into carbon material. Carbon collimators and beam absorbers are installed in many locations around the LHC to diffuse or absorb beam losses. Since the collimator jaws are close to the beam, it is very likely that they are hit first when the beam is accidentally deflected. Here we present the results of two-dimensional hydrodynamic simulations of the heating of a solid carbon cylinder irradiated by the LHC beam with nominal parameters, carried out using the BIG-2 computer code [3] while the energy loss of the 7 TeV protons in carbon is calculated using the well known FLUKA code [4]. Our calculations suggest that the LHC beam may penetrate up to about 10 m to 15 m in solid carbon, resulting in a substantial damage of collimators and beam absorbers.

INTRODUCTION

The CERN Large Hadron Collider (LHC) is a 26.8 km circumference proton synchrotron with 1232 superconducting magnets, accelerating two counter-rotating proton beams. When the maximum particle momentum of 7 TeV/c is reached, the two beams will be brought into collisions. The total number of protons in the beam will be 3×10^{14} and the beam will have a very fine time structure. The beam consists of a 89 μs long train of 2808 bunches.

The machine protection systems are designed to safely extract the beams in case of a failure [5]. The accidents discussed in this paper are extremely unlikely and beyond the design of the machine protection systems. However, in view of the large amount of energy stored in each beam (362 MJ), it is important to quantify the consequences assuming some worst case scenarios that have been discussed in [6].

EXAMPLES FOR FAILURE SCENARIOS

In case of a beam dump request, the beam is extracted from the LHC by the extraction kicker with a nominal de-

flexion angle of 0.275 mrad into a graphite target 800 m downstream. Several failure scenarios could lead to a deflection with a different angle, leading to the beam being deflected into one of the graphite absorbers that are installed to protect the septum magnet and the ring aperture. If the deflection angle is very small, say, less than 0.02 mrad, the beam will stay in the aperture but might impact on carbon collimators downstream. A similar deflection angle could be produced by the injection kicker magnets if they ever would fire at 7 TeV.

During normal operation of the beam dumping system, 10 pulsed magnets will be used to sweep the extracted beam along an e- shape path on the upstream face of the absorber graphite core. Calculations have been made of the effect of the absence of dilution [7]. No dilution can locally lead to an energy deposition above the vaporisation limit where phase changes will occur, but the studies claim that the beam would not pierce a hole in the target [8].

SIMULATION RESULTS

In this section we present numerical simulation results of full impact of one of the LHC beams on a carbon cylinder with a radius of 5 cm. These simulations have been carried out using a two-dimensional hydrodynamic computer code, BIG-2 [3]. The LHC beam will consist of a bunch train with every bunch consisting of 1.15×10^{11} protons. The total number of bunches will be 2808, so that the total number of protons in each beam will be 3×10^{14} . The bunch length will be 0.5 ns and two neighboring bunches will be separated by 25 ns while the radial power profile in the beam spot will be Gaussian with a typical standard deviation of 0.2 mm. The total duration of the beam is of the order of 89 μs .

It is well known that energetic heavy ions deposit their energy in the target as a result of Coulomb collisions, mainly with the target electrons [9, 10]. An energetic heavy ion beam induces strong radial hydrodynamic motion in the target that drastically reduces the density in the beam heated region. The reduced density leads to a much longer range for particles in the material. For the interaction of the LHC proton beams with a target a similar effect is expected.

The 7 TeV protons, on the other hand, when incident on matter, will generate particle cascades in all directions and one needs to calculate the energy deposited by all these dif-

ferent particles in the target. For this purpose we have used the well known particle interaction and transport Monte Carlo code, FLUKA [4]. This code is capable of calculating all components of particle cascades in matter from TeV energies down to that of the thermal neutrons. The energy deposition profile calculated by the FLUKA code is used as input to the BIG-2 code. The target geometry for the FLUKA simulations is considered to be a cylinder of solid carbon that is 5 m long and has 1 m radius.

In Fig. 1 we plot the specific energy deposited by a single bunch of 7 TeV protons and their cascade particles, calculated by the FLUKA code in solid carbon which is compressed powdered graphite with a density of 2.2 g/cm^3 along the beam axis. It is seen that the maxima of energy deposition occurs at a longitudinal position, $L = 135 \text{ cm}$ and is 0.16 kJ/g . In Fig. 2 are plotted specific energy deposition vs transverse coordinate at four different values of $L = 40 \text{ cm}$, 135 cm , 240 cm and 350 cm respectively.

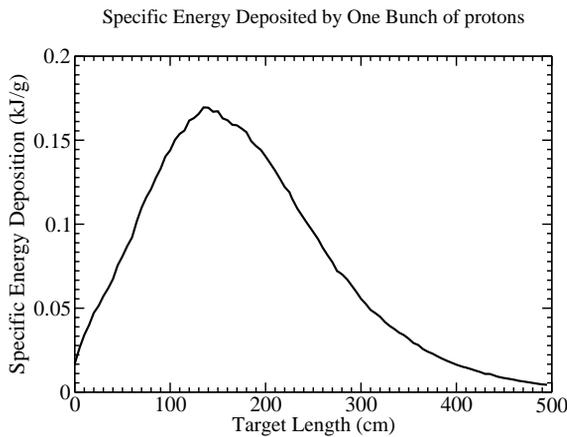


Figure 1: Specific energy deposited in solid carbon by a single LHC bunch along the axis.

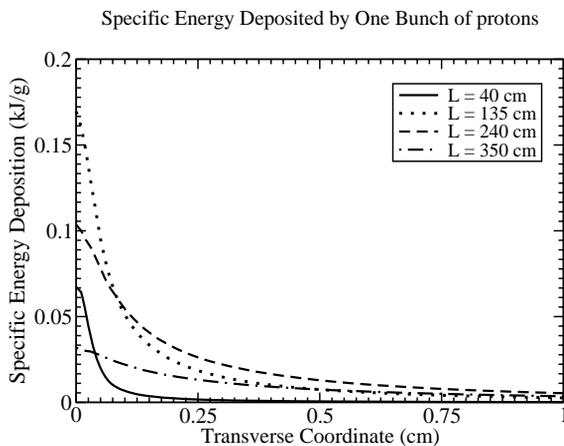


Figure 2: Specific energy deposited in solid carbon by a single LHC bunch in transverse direction at four different longitudinal positions.

Using the energy deposition data provided by the

FLUKA code as input to the BIG2 code, we have calculated the hydrodynamic and thermodynamic response of a solid carbon cylinder whose one face is irradiated with the LHC beam. We note that the energy deposition profile generated by the FLUKA code is three-dimensional while the BIG2 code is two-dimensional. To overcome this difficulty we consider four different longitudinal positions and study the hydrodynamic and thermodynamic response of the target along the transverse direction.

In Fig. 3 we plot the target temperature vs transverse coordinate corresponding to the energy deposition profiles shown in Fig. 2 at $t = 5 \text{ microsecond}$. By this time, only 200 out of 2808 bunches have been delivered. It is seen that a maximum temperature of 7000 K has been generated at the beam axis at $L = 135 \text{ cm}$, where the maximum of energy deposition occurs. This leads to a maximum pressure of the order of 0.7 GPa , as is seen from Fig. 4. This high pressure drives a radially outgoing shock wave that leads to a substantial reduction in density (0.4 gm/cm^3) which is shown in Fig. 5. This means that the protons will penetrate further into the material thereby increasing the penetration depth of the beam. The energy deposition peak that lies at $L = 135 \text{ cm}$ for solid density will continuously shift along the longitudinal direction.

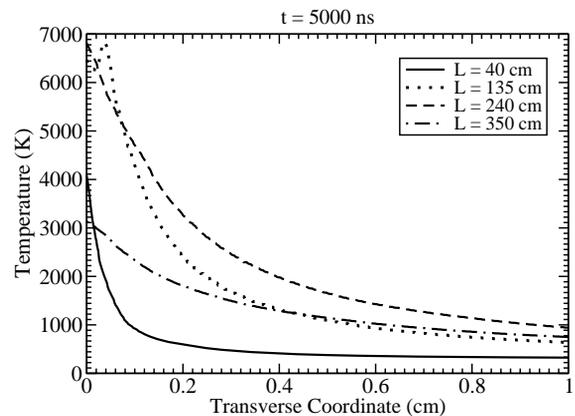


Figure 3: Temperature vs transverse coordinate at $t = 5 \text{ microsecond}$ at four different longitudinal positions.

Due to lower energy deposition at other longitudinal position, the material damage is relatively lower. We note that as the energy material density is reduced at a given position, the production of the secondary particle decreases that leads to a reduction in specific energy deposition. This in turn will slow down the hydrodynamic expansion of the material in transverse direction. This effect however is not included in the present calculations and is intended for the future work. We estimate that the LHC beam may penetrate about 10 m to 15 m in solid carbon.

CONCLUSIONS

For the impact of the 7 TeV LHC beam on a target, two-dimensional numerical simulations of thermodynamic and

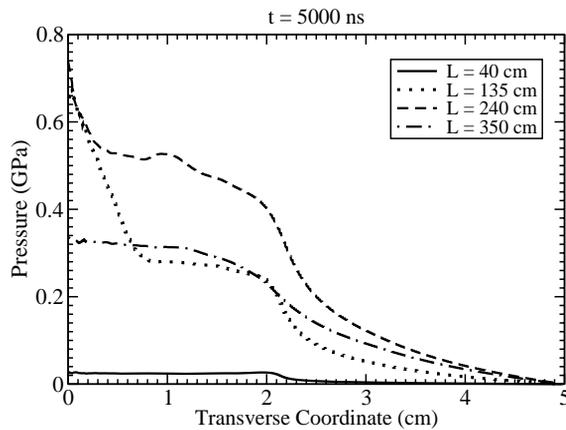


Figure 4: Pressure vs transverse coordinate at $t = 5$ microsecond at four different longitudinal positions.

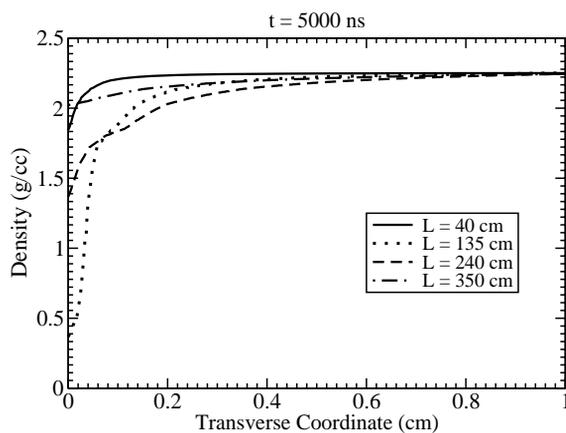


Figure 5: Density vs transverse coordinate at $t = 5 \mu\text{s}$ at four different longitudinal positions.

hydrodynamic response show that the target density decreases after the impact of part of the beam. The simulations presented in this paper allow comparing the results for beam impact on carbon with the results published in [1] on copper.

The maximum energy deposition in copper is 2.3 kJ/g after a distance of 20 cm into the target, and for carbon only 0.17 kJ/g after 135 cm. For copper, after about 2.5 μs when only 100 out of 2808 bunches have delivered their energy to the target, the density at the center of the beam heated region is reduced by about a factor of 10 due to the hydrodynamic expansion. For carbon, the reduction is only a factor of 4 after 5 μs . The extension of the energy deposition in the transverse dimensions is larger for carbon than for copper.

For both materials, the bulk of the protons that will be delivered in the subsequent bunches will penetrate deeper into the target that means that the effective length of the material needed to stop the beam will be significantly longer than predicted by using static conditions. For copper, the penetration depth was found to be between 10 m and 40 m.

For carbon, the penetration depth is expected to be less, between 10 m and 15 m.

The length of carbon absorbers installed in LHC is in the range of 1 m (collimators) to about 8 m (beam dump block). The simulation presented here were performed with a beam size of $\sigma=0.2$ mm. Since the beam impact and the beam size depends on the failure scenario, there is no general conclusion if an absorber would survive a failure and more simulations are required. As an example, the undiluted beam impacting on the beam dump block would have a width of $\sigma=1.5$ mm. The case of beam impact close to the edge of a block needs also further studies.

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