INTERACTION OF LARGE HADRON COLLIDER 7 TeV/c PROTON BEAM WITH A SOLID COPPER TARGET

N. A. Tahir, GSI, Planckstr. 1, 64291 Darmstadt, Germany
R. Schmidt, CERN-AB, 1211 Geneva, Switzerland
A. Shutov, I.V. Lomonosov, V.E. Fortov, IPCP, Chernogolovka, Russia
A. R. Piriz, University of Castilla-La Mancha, 13071 Ciudad Real, Spain
D.H.H. Hoffmann, TU Darmstadt, Germany

Abstract

In previous papers, the mechanisms causing equipment damage in case of a failure of the machine protection system were discussed, assuming that the entire beam of 7 TeV/c protons generated by the Large Hadron Collider (LHC) is deflected onto a copper target [1, 2]. However, a simplified model was considered in these calculations in which the thermodynamic and hydrodynamic response of a solid cylindrical copper target that was facially irradiated with one LHC beam was studied in radial direction at given positions at the axis. Using these simulation results, analytic models were developed that allowed one to estimate the penetration depth of the protons in the target which was between 10 – 40 m. Recently, substantial progress has been made in this work by carrying out simulations considering r–Z geometry that show that the beam penetrates up to 35 m in the target. The target is severely damaged and is converted into a large sample of High Energy Density (HED) matter. A very interesting outcome of this work therefore is that the LHC can also be used to study HED physics which is a very important and very active field of research. For further details see [3].

INTRODUCTION

The CERN Large Hadron Collider (LHC) is by far the most powerful accelerator in the world. It is a 26.8 km circumference proton synchrotron with 1232 superconducting magnets, accelerating two counter-rotating proton beams. When this accelerator will achieve its full capacity, each beam will consist of a bunch train with 2808 bunches and each bunch comprising of 1.15×10^{11} protons. The bunch length will be 0.5 ns and two neighboring bunches will be separated by 25 ns while intensity distribution in the radial direction will be Gaussian with a standard deviation, σ = 0.2 mm. In the center of the physics detectors the beam will be focused to a much smaller size, down to a σ of 20 μm. The total duration of the beam will be of the order of 89 μs. The total number of protons in the beam will be 3×10^{14}. When the maximum particle momentum of 7 TeV/c is reached, the two beams will be brought into collisions.

The machine protection systems are designed to safely extract the beams in case of a failure [4]. 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 [5].

The calculations presented in this paper have been done in two steps. First, the energy loss of the LHC protons is calculated using the FLUKA code [6], which is an established particle interaction and Monte Carlo package capable of simulating all components of the particle cascades in matter, up to multi-TeV energies. Second, this energy loss data is used as input to a sophisticated two–dimensional hydrodynamic code, BIG2 [7] to calculate the beam–target interaction. The results are presented in the following sections.

PROTON ENERGY LOSS IN COPPER

For the study presented in this paper, the geometry for the FLUKA calculations was a cylinder of solid copper with radius = 1 m and length = 5 m. The energy deposition is obtained using a realistic two–dimensional beam distribution, namely, a Gaussian beam (horizontal and vertical σ_{rms} = 0.2 mm) that was incident perpendicular to the front face of the cylinder.

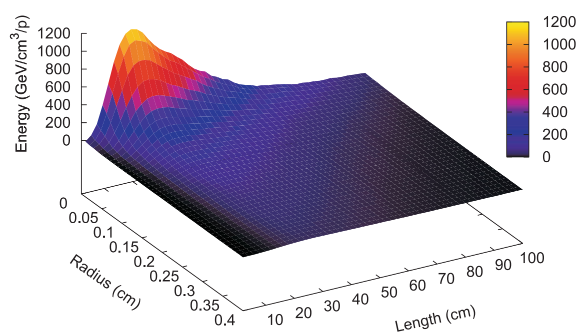

Figure 1: Energy deposition in a solid copper cylinder by a single 7 TeV proton per unit volume.

In Fig. 1 we present energy deposition in GeV per proton per unit volume in solid copper as a function of the depth into the target and the radial coordinate. It is seen that although we consider a target radius of 1 m, the effective energy deposition takes place within a radius of about 0.5 cm. A maximum energy deposition of 1200 GeV/p/cm^3 occurs at L = 16 cm that corresponds to a specific energy deposition of 2.6 kJ/g [1, 2, 3] per bunch.

SIMULATION RESULTS

In this section we present hydrodynamic simulation results of beam–target interaction. The data presented in Fig. 1 is converted into specific energy deposition (in kJ/g that is deposited in the target) which is used as input to the BIG2 code to study heating and hydrodynamic expansion of the material. The target geometry for the BIG2 calculations is assumed to be a solid copper cylinder having a length, L = 5 m and a radius, r = 5 cm.

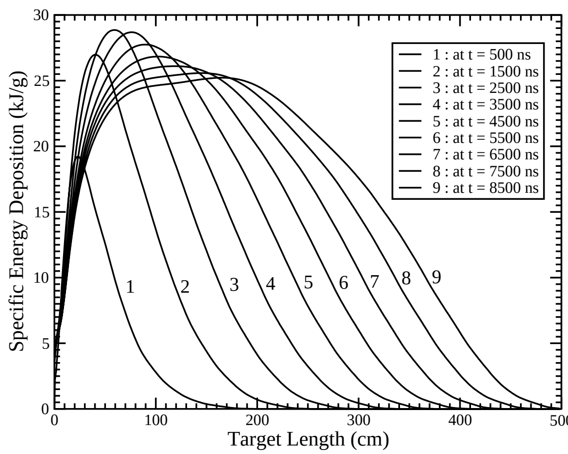

Figure 2: Specific energy deposition along the axis (at r = 0.0) at different times during irradiation, time interval between two consecutive lines is 1 μs.

In Fig. 2 we plot the specific energy deposition along the axis (at r=0.0) at different times during the target irradiation. It is seen that at t = 500 ns (curve labeled 1), when about 20 out of 2808 bunches have been delivered, a maximum specific energy deposition of about 17 kJ/g has been deposited and this peak lies at a longitudinal position, L = 16 cm. It is seen that at t = 1.5 μs, the peak energy deposition is 24 kJ/g and the location of the peak has shifted towards the right. The curve labeled with 3 shows that at t = 2.5 μs, the maximum energy deposition is on the order of 28 kJ/g and the peak lies at a position of L = 1 m. Subsequent curves show that the specific energy deposition saturates around a value of 25 kJ/g and at t = 8.5 μs, the entire target length is heated by the beam, although the range of the 7 TeV/c protons in solid copper is of the order of 1 m. The reason for this range lengthening is as follows.

The energy deposited by first few tens of proton bunches strongly heat the target material as shown in Fig. 3 where we plot the target temperature along the axis (r = 0.0) at different times during irradiation. This high temperature generates very high pressure (see Fig. 4, curve labeled 1 which shows a maximum pressure of 30 GPa) that drives an outgoing radial shock wave. This leads to a density reduction in the beam heated region and consequently the protons that are delivered in subsequent bunches penetrate further and further into the target, the so called ”tunneling effect”.

Figure 3 shows that the temperature profiles follow the behavior of the specific energy deposition profiles shown in

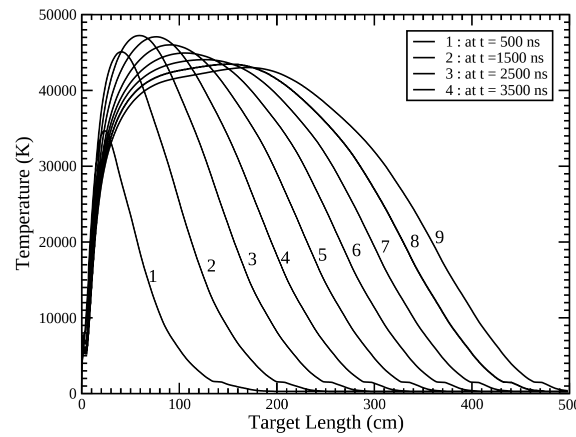

Figure 3: Temperature along the axis (at r=0.0) at different times during irradiation, time interval between two consecutive lines is 1 μs.

Fig. 2. The temperature increases to a maximum values of 48000 K (see curve labeled 3) and then saturates at a value of 40000 K. It is also seen that at the end of each curve (to the right), there is a small flat part which represents a constant temperature. This is due to the melting of the target and this region shifts towards the right as the beam penetrates further and further.

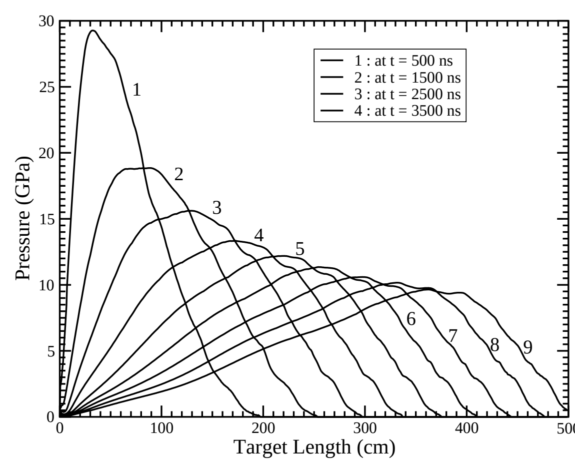

Figure 4: Pressure along the axis (at r=0.0) at different times during irradiation, time interval between two consecutive lines is 1 μs.

Figure 4 shows the pressure profiles along the axis at different times during the irradiation. It is seen that a maximum pressure of about 30 GPa is generated at t = 500 ns when the target density is high in the beam heated region, but at later times when the density is substantially reduced, the pressure is significantly lower.

The corresponding density profiles are presented in Fig. 5 which clearly shows the reduction in the target density due to the outgoing radial shock wave that quantitatively demonstrates the tunneling of the protons into the target.

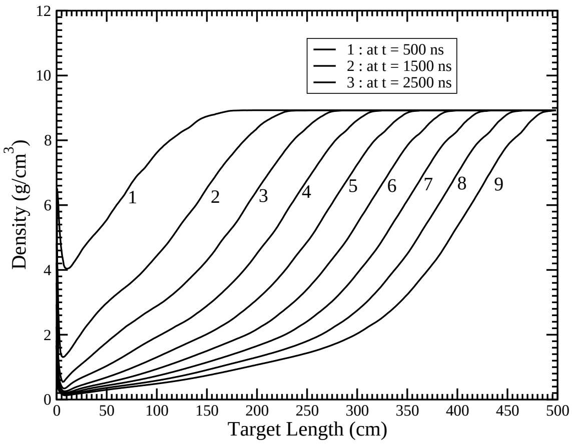

Figure 5: Density along the axis (at r=0.0) at different times during irradiation, time interval between two consecutive lines is 1 μs.

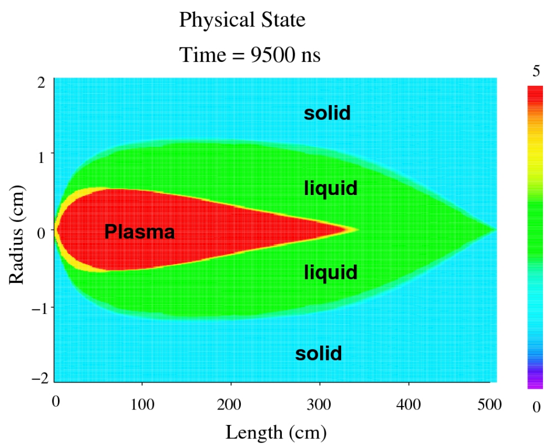

Figure 6: Physical state of the target shown at t = 9.5 μs.

The physical state of the target at t = 9.5 μs is shown in Fig. 6. It is seen that a large region at the target center that extends up to L = 3 m is converted into a strongly coupled plasma state that is surrounded by an extended region of liquid state. The LHC therefore can be used as a tool to study HED physics.

CONCLUSIONS

Numerical simulations of interaction of one LHC beam with a copper cylindrical target have been carried out. These calculations have been performed in two steps. In the first step, energy deposition by the LHC protons and the shower in the target is calculated using the FLUKA code [6]. In the second step, this data is used as input to a two–dimensional hydrodynamic code, BIG2 [7]. A full self consistent treatment of this problem requires coupling of the FLUKA code with the BIG2 code. This work in currently in progress. The energy deposited by first few tens of bunches generates a very high pressure along the axis that launches a radial shock wave outwards. This leads to depletion in the density at the central part of the target and the protons that are delivered in later bunches therefore penetrate deeper into the target. This effect was observed before in case of ion beam heated targets [8]. The density reduction in the beam heated region and the deeper penetration of the protons continues within the pulse duration. This so called ”tunneling effect” has important implications on the consequences of an accidental beam loss as well as for the design of a sacrificial beam stopper. In our study we simulate this effect by normalizing the specific energy deposition in the target with respect to the line density along the axis at every time step. Our simulations show that the protons will penetrate up to about 35 m in solid copper.

In is also interesting to note that the target is severely damaged by the beam and a huge sample of HED matter is generated. Due to the importance of this subject to numerous areas of basic and applied physics and due to its great potential for very useful industrial applications, HED physics has been a very active field of research over the past decades. Our work has shown that the LHC could be an additional tool to research this important branch of science. Further details about this work can be found in [3].

ACKNOWLEDGEMENTS

The authors wish to thank the BMBF for providing the financial support to do this work and to R. Assmann, A. Ferrari and M. Brugger for many useful discussions.

REFERENCES

[1] N.A. Tahir et al., J. Appl. Phys. 97 (2005) 083532.

[2] N.A. Tahir et al., Phys. Rev. Lett. 94 (2005) 135004.

[3] N.A. Tahir et al., Phys. Rev. E 79 (2009) To be published.

[4] R. Schmidt et al., New J. Phys. 8 (2006) Art. No. 290.

[5] J.Uythoven et al., Possible Causes and Consequences of Serious Failures of the LHC Machine Protection Systems, Proc. EPAC 2004, Lucern.

[6] A. Fasso, et al., The physics models of FLUKA: status and recent development, CHEP 2003, LA Jolla, California, 2003.

[7] V.E Fortov, B. Goel, C. -D. Munz, A. L. Ni, A. Shutov, O. Yu. Vorobiev, Nucl. Sci. Eng. 123, 169 (1996).

[8] N. A. Tahir, A. Kozyreva, P. Spiller, D. H. H. Hoffmann, A. Shutov, Phys. Rev. E 63, 036407-1-8 (2001).