LHC BEAM IMPACT ON MATERIALS CONSIDERING THE TIME STRUCTURE OF THE BEAM

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Abstract

In this paper we report numerical simulations of the thermodynamic and the hydrodynamic response of a solid carbon cylindrical target that receives the full impact of the 7 TeV/c LHC proton beam. The calculations have been done in two steps. First, the energy loss of the protons is calculated using the FLUKA code assuming solid material density. Second, this energy loss data is used as input to a two–dimensional hydrodynamic code, BIG2, to simulate the hydrodynamic effects. As the material is heated due to the energy deposition, hydrodynamic motion sets in that modifies the density distribution in the absorption region. This modified density distribution is then used in the FLUKA code to calculate the corresponding energy loss distribution. The new energy loss data is again used in the BIG2 code and the two codes are thus run iteratively with an iteration interval of 2.5 μs. These simulations have shown that as the target density decreases substantially due to the hydrodynamic motion, the protons that are delivered in the subsequent bunches penetrate deeper into the target, thereby increasing the proton range significantly. It has been found that using this dynamic model, the LHC protons penetrate up to 25 m in solid carbon whereas the corresponding static range of the protons and the shower in solid carbon is about 3.5 m.

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, each with a momentum of 7 TeV/c. The bunch length is 0.5 ns and two neighboring bunches are separated by 25 ns while intensity distribution in the radial direction is Gaussian with a standard deviation, σ = 0.2 mm. The total duration of the beam will be of the order of 89 μs and the total number of protons in the beam will be 3×10^{14} which is equivalent to 362 MJ energy, sufficient to melt 500 kg copper. Safety of operation is a very important issue when working with such extremely powerful beams. The machine protection systems are designed to safely direct the beams into a graphite absorber by the beam extraction kicker, at then end of each fill an in case a failure is detected [1].

An accidental loss of even a small fraction of the beam energy can severely damage the equipment. A worst case scenario could be loss of the entire beam at a single point. The likelihood of occurrence of an accident of this magnitude is quite remote, nevertheless it is important to quantify the consequences if it ever happens. One of the failure modes is a wrong deflection of part of the beam by the extraction kicker. A 4 m long absorber, the TCDQ, is installed to capture the particles. In this paper we address the question if this absorber can absorb the entire beam in case that the extraction kicker deflects the beam by a wrong angle.

The calculations presented in this paper have been done in two steps. First, the energy loss of the LHC protons, assuming solid carbon density, is calculated using the FLUKA code, 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 to calculate the beam–target interaction that causes hydrodynamic motion which leads to density reduction at the target center. The modified density distribution obtained from the BIG2 code is then used in the FLUKA code to calculate the corresponding modified energy loss distribution and the two codes are thus run iteratively using an iteration interval of 2.5 μs. The results are presented below.

SIMULATION RESULTS

FLUKA Simulations

For the study presented in this paper, the geometry for the FLUKA calculations was a cylinder of solid carbon with radius = 5 cm and length = 6 m. The density of the carbon is assumed to be 2.28 g/cm^2. The energy deposition is obtained using a realistic two–dimensional beam distribution, namely, a Gaussian beam (horizontal and vertical σ_{rms} = 0.5 mm) that was incident perpendicular to the front face of the cylinder.

In Fig. 1 we present the energy loss per proton in GeV/g using solid carbon density which shows that the range the shower is about 3.5 m in the target and the peak of the distribution is about 12 GeV/p/g. The FLUKA calculations show that about 54 % beam energy will escape while 46 % will be absorbed in the target.

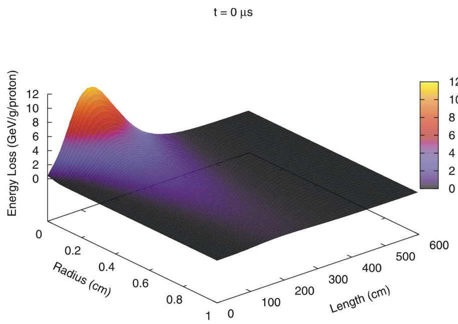

Figure 1: Energy loss distribution using FLUKA at solid carbon density.

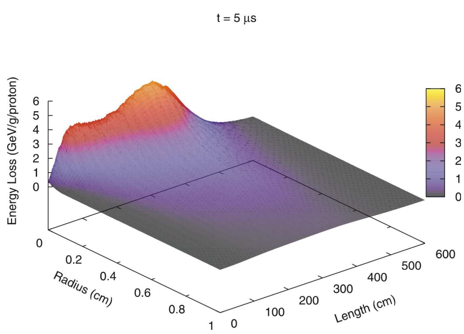

Figure 2: Energy loss distribution using FLUKA considerin the BIG2 density distribution at t = 5 μs (third iteration).

In Fig. 2 we present the energy loss distribution calculated by FLUKA using the density distribution provided by BIG2 at t = 5 μs (third iteration). It is seen that the energy deposition distribution has been substantially modified showing significant broadening of the energy peak that indicates deeper penetration of the protons and the shower into the target. Moreover, the distribution has two peaks and the higher peak lies in the beam direction where the material density is much higher.

The energy loss distribution plotted in Fig. 3 has been calculated by FLUKA using the density distribution obtained from BIG2 at t = 10 μs (fifth iteration). This figure

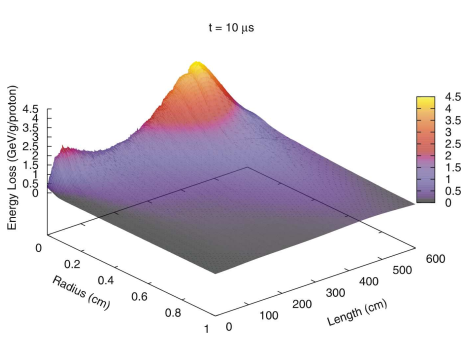

Figure 3: Energy loss distribution using FLUKA considerin the BIG2 density distribution at t = 10 μs (fifth iteration).

shows even longer penetration of the projectiles and the shower and the contrast between the two peaks becomes much more pronounced.

BIG2 Simulations

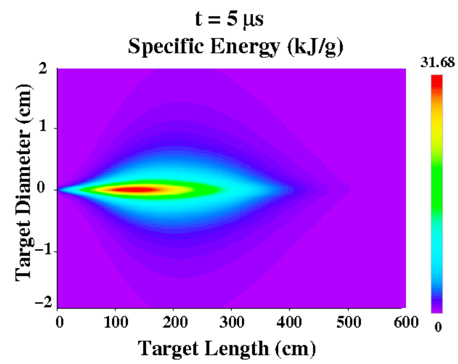

Figure 4: Specific energy deposition distribution at t = 5 μs.

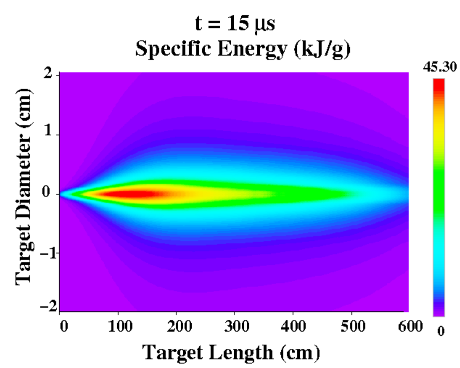

Figure 5: Specific energy deposition distribution at t = 15 μs.

In Fig. 4 we plot the specific energy deposition distribution in the target at t = 5 μs which shows that the maximum specific energy deposition is of the order of 30 kJ/g and the length of the deposition region is around 4 m. Figure 5 shows that the maximum specific energy deposition at t = 15 μs is about 45 kJ/g while the deposition region extends to the entire length of the target. This means that the LHC protons and the shower penetrate 6 m into the carbon target in 15 μs. It is also to be noted that since the energy is distributed in larger mass due to longer penetration, the maximum specific energy deposition is limited to about 45 kJ/g.

The corresponding temperature and pressure distributions at t = 15 μs, are shown in Figs. 6 and 7, respectively. It is seen from Fig. 6 that the maximum temperature is about 9000 K and the material in this region is in gaseous state that indicates severe material damage.

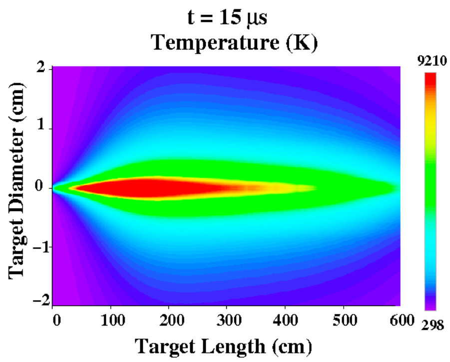

Figure 6: Temperature distribution at t = 15 μs.

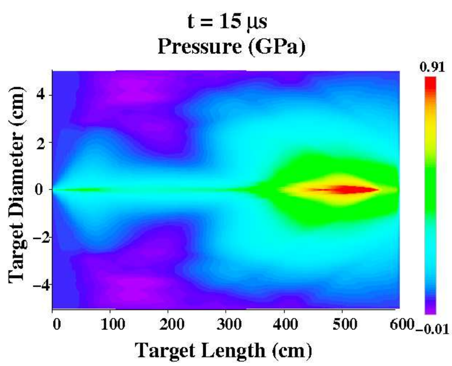

Figure 7: Pressure distribution at t = 15 μs.

Figure 7 shows interesting behavior of the pressure distribution as the maxima of the distribution occurs at the end of the target in the beam direction. This is because of the higher density in that region. Moreover, the reflection of the pressure waves from the target surface and the target expansion in the radial direction is also seen. The density distribution at t = 15 μs is presented in Fig. 8 which shows that the density in a significant region around the axis has been substantially reduced to a value of 0.11 g/cm^3 due to the hydrodynamic effects and the beam has tunneled through the entire length of 6 m within 15 μs. We note that energy deposition, target heating and density depletion are localized phenomenon and therefore we show these variables only within the inner 2 cm radius of the target. The pressure, on the other hand, drives compression waves throughout the target and we therefore present the pressure distribution in the entire target.

The density profiles along the axis at different times are plotted in Fig. 9 which show that after 6 μs, the density depletion front moves along the axis with a constant speed of about 25 cm/μs. This means that during the remaining 83μs of the beam, the penetration depth will be 20.75 m. Since in the first 6 μs, the beam has penetrated up to 4 m, the total penetration depth will be around 25 m.

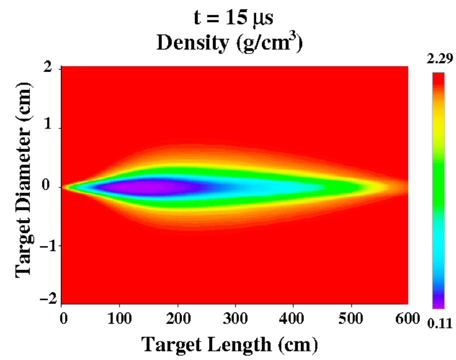

Figure 8: Density distribution at t = 15 μs.

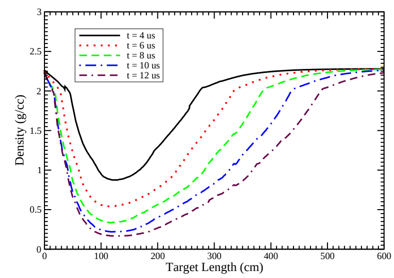

Figure 9: Density profiles along the axis at different times.

CONCLUSIONS

Simulations of the damage caused to a solid carbon cylidrical target by the full impact of the LHC beam have been performed by running the FLUKA and the BIG2 codes iteratively using an iteration interval of 2.5 μs. This allows consideration of the effect of the density changes in the target due to hydrodynamics on calculations of the energy loss by the FLUKA code in a correct manner. This is a significant improvement on our previous work [2] where we only used the solid density energy loss data provided by FLUKA in the hydrodynamic simulations, although some approximations were used to account for the effects of the density changes. The study presented in this paper has shown that due to the onset of hydrodynamics, the protons and the secondary particles penetrate much deeper into the target in comparison to solid material and a much larger part of the target is severely damaged. This has important implications on the consequences of an accidental beam loss as well as for the design of a sacrificial beam stopper that needs to have a length of more than 20 m.

REFERENCES

[1] R. Schmidt et al., New J. Phys. 8 (2006) Art. No. 290.
[2] N.A. Tahir et al., Phys. Rev. E 79 (2009) 046410.