SHOCK IMPACT OF HIGH ENERGY/INTENSITY BEAMS WITH MATTER AND HIGH ENERGY DENSITY PHYSICS

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Abstract

The purpose of this study is to assess the damage caused to the equipment (beamdump, collimators etc) in case of an accident involving full impact of the LHC beam. First, the FLUKA code [1] is used to calculate the proton energy loss in solid carbon and this energy loss data is used as input to a two–dimensional hydrodynamic computer code, BIG2 [2] to study the thermodynamic and hydrodynamic response of the target. The BIG2 code is run for 5 μs and the density distribution at the end of this run time is used in FLUKA to generate new energy loss data corresponding to this density distribution. FLUKA and BIG2 are thus run iteratively with a time interval of 5 μs. Previously [3], we carried out hydrodynamic simulations using the energy loss data calculated by FLUKA using solid carbon density, but scaled according to the line density in axial direction. In the present paper, we give a comparison between the results obtained using the two models. Our simulations show that the latter model overestimates the beam penetration. Moreover, the density and the temperature distributions are quite different in the two cases.

INTRODUCTION

When the Large Hadron Collider (LHC) 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, $\sigma = 0.2$ 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 Bunch train will be of the order of 89 μs while the total number of protons in the beam will be 3×10^{14} which is equal to 362 MJ, sufficient to melt 500 kg of copper. When the maximum particle momentum of 7 TeV/c is reached, the two beams will be brought into collisions.

Safety of operation is a very important problem when working with such extremely powerful beams. The machine protection systems are designed to safely extract the beams from the system in case of a failure [4]. However, it is necessary to assess the damage caused to the equipment if the machine protection systems fail. In this paper, we study the scenario in which the entire beam is lost at a single point. Although, the likelihood of happening of an accident of this magnitude is extremely remote and beyond the design of the machine protection systems, nevertheless it is important to know the consequences, if it ever happens.

Previously, we reported calculations of the full impact of the LHC beam on solid carbon [3] and solid copper [5] cylindrical targets. These calculations have been done in two steps. First, the energy loss of the LHC protons is calculated at solid density using the FLUKA code [1], 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 [2], to calculate the beam–target interaction. The decrease in the generation of secondary particles as well as decrease in energy deposition due to the density reduction caused by the onset of hydrodynamics is modeled by using the solid density energy loss scaled with the line density in every simulation cell, at every time step (“analytic approximation”). Recently, we have carried out more advanced simulations in which the FLUKA and the BIG2 codes are run iteratively using an iteration time interval of 5 μs in case of a solid carbon target having a length of 10 m and a radius of 2.5 cm. It has been found that the “analytic approximation” overestimates the beam penetration compared to the iterative calculations. Moreover, the density, temperature and the pressure profiles are noticeably different in the two cases.

PROTON ENERGY LOSS IN CARBON

For the study presented in this paper, the geometry for the FLUKA calculations was a cylinder of solid carbon 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 $\sigma_{rms} = 0.2$ mm) that was incident perpendicular to the front face of the cylinder.

The peak energy deposition is 30 GeV/p/cm^3 which is equal to a specific energy deposition of about 0.3 kJ/g per bunch as shown in Fig. 2 where we plot the specific energy deposited by a single LHC bunch along the axis.

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, Fig. 2) which is used as input to the BIG2 code to study heating and hydrodynamic motion of the material. The

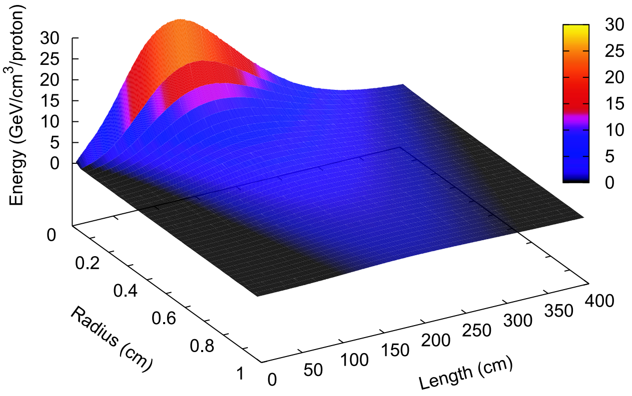

Figure 1: Energy deposition in a solid carbon cylinder by a single 7 TeV proton per unit volume, target length = 5 m, radius = 1 m, and the beam standard deviation, σ = 0.2 mm.

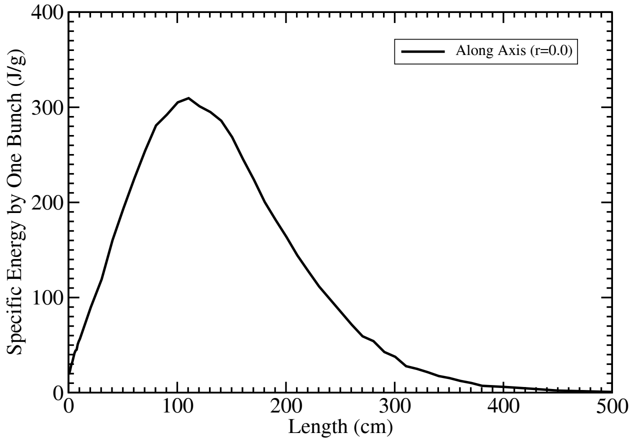

Figure 2: Specific energy deposition by one LHC bunch along the axis (r = 0.0).

equation of state data used to model different material phases in the target is reported in [6]. The target geometry for the BIG2 calculations is assumed to be a solid carbon cylinder having a length, L = 10 m and a radius, r = 2.5 cm with one face irradiated by the LHC beam.

It is to be noted that due to the energy deposited by few tens of the proton bunches, the material in the absorption region is strongly heated that generates a high pressure. This high pressure drives an outgoing radial shock wave. This leads to density depletion at the cylinder center that allows the protons in the subsequent bunches to penetrate deeper into the target material, thereby causing a significant lengthening of the proton range. This so called “Tunneling Effect” can have important implications on the machine protection system, for example, in designing a sacrificial beam stopper. Previously [3] this effect was treated using an analytic approximation in which the solid density energy loss of the protons was scaled by the line density in each simulation cell, at every time step. Recently we have carried out simulations running the FLUKA and the BIG2 codes iteratively with an iteration step of 5 µs. A comparison between the results obtained using the two models is presented in the following. In Fig. 3 we plot the temperature along the cylinder axis (r = 0.0) at t = 10 µs using the two models. It is seen that the maximum temperature is about 4800 K in both cases and the top of both curves is flat. This is due to the fact the material is in a two–phase liquid–gas state in that region. However, it is clearly seen that the calculations done using the analytic approximation show more penetration of the beam as compared to the iterative approach.

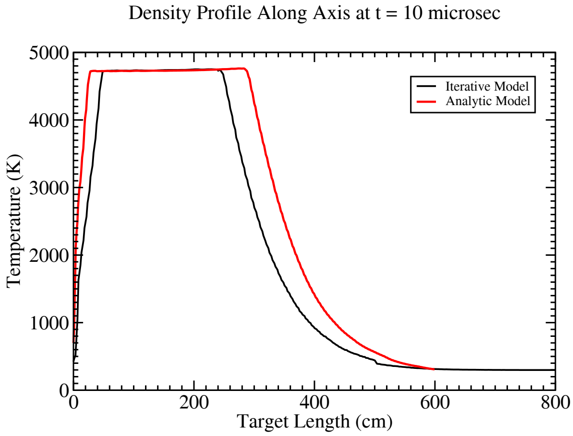

Figure 3: Comparison between two models: Temperature along cylinder axis (r = 0.0) at 10 µs.

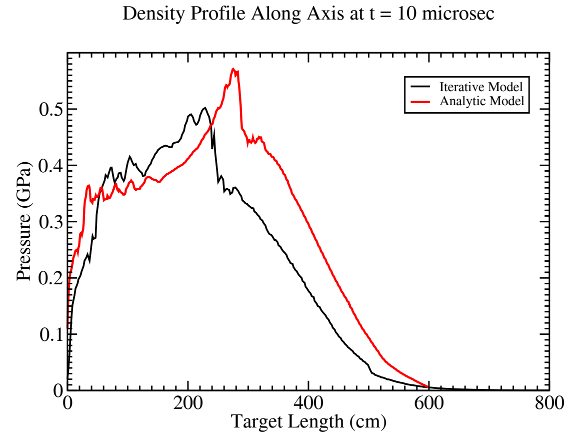

Figure 4: Comparison between two models: Pressure along cylinder axis (r = 0.0) at 10 µs.

The corresponding pressure and density profiles are plotted in Figs. 4 and 5 respectively. It is seen that the pressure and the density profiles have the same qualitative behavior in the two cases while the faster penetration of the beam in case of analytic approximation is clearly evident.

The temperature profiles at t = 50 µs are plotted in Fig. 6 which show a clear deviation in the results in the two cases. The two phase liquid–gas region (with a constant temper-

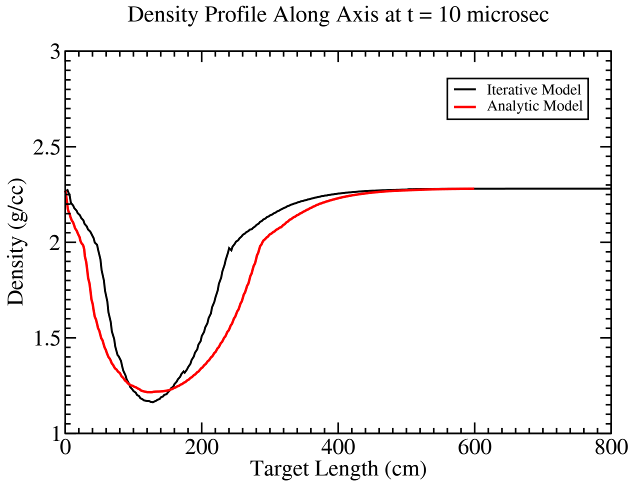

Figure 5: Comparison between two models: Density along cylinder axis (r = 0.0) at 10 µs.

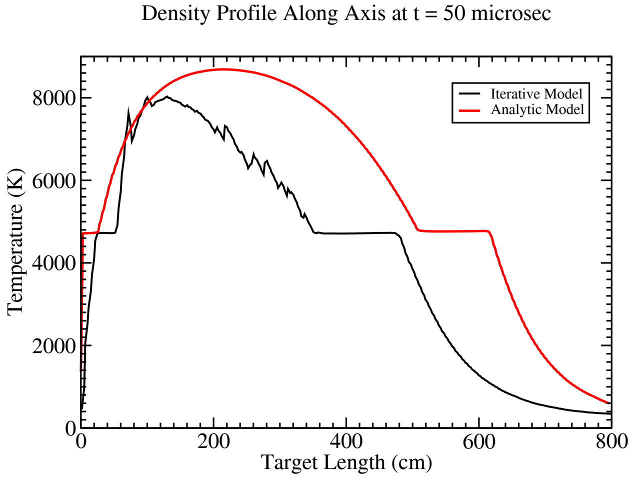

Figure 6: Same as in Fig. 3, but at 50 µs

ature) has been shifted towards the right, but penetration shown by use of the analytic approximation is much more significant compared to the other approach. Moreover, the temperature profiles in the gaseous region of the target are also significantly different while the temperature in case of the analytic approximation is higher.

The corresponding pressure profiles are presented in Fig. 7. It is seen that the maximum pressure achieved using the iterative approach is about three times lower than the other case, although the qualitative behavior of the two is similar.

The density profiles at t = 50 µs are plotted in Fig. 8, which again show the faster penetration of the beam in case of the analytic approximation. It is also seen that there is marked difference in the shape of the two profiles. So far we have calculated up to 50 µs and work is still in progress. Moreover, the density profile obtained using the iterative approach is very similar to that reported in Ref. [7] (on SSC beam interaction with C beam dump).

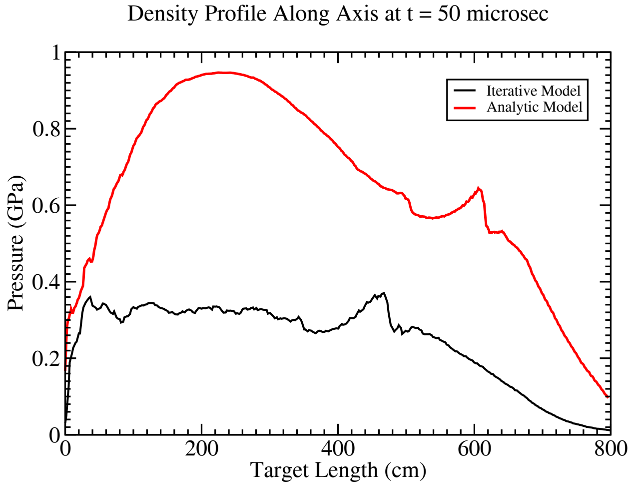

Figure 7: Same as in Fig. 4, but at 50 µs.

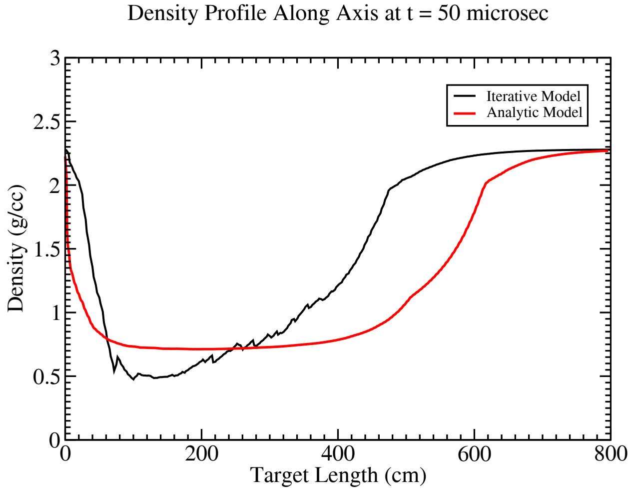

Figure 8: Same as in Fig. 5, but at 50 µs.

Also the LHC beam can be used as a tool to generate high energy density matter [5].

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