

SIMULATIONS OF THE FULL IMPACT OF THE LHC BEAM ON SOLID CU AND C TARGETS

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Abstract

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} 7 TeV 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 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. 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. Fortunately, 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. This important question is addressed in the present article.

INTRODUCTION

The machine protection systems are designed to safely extract the beams in case of a failure [1]. 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 have a reasonable estimation of the consequences assuming some worst case scenarios that have been discussed in [2].

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 [3], 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 [4] to calculate the beam-target interaction. In this study we have considered solid Cu and solid graphite targets and the results are presented below.

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SIMULATION RESULTS

Solid Copper Target

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 $\sigma_{rms} = 0.2$ mm) that was incident perpendicular to the front face of the cylinder.

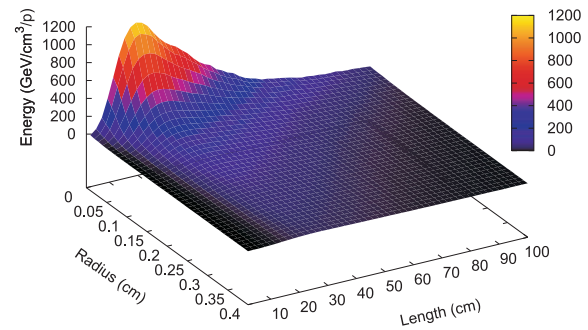


Figure 1: Energy deposition in a solid copper cylinder by a single 7 TeV proton per unit volume.

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/cm³ occurs at L = 16 cm that corresponds to a specific energy deposition of 2.6 kJ/g [5, 6] per bunch.

In the following 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 [4] 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.

The energy deposited by few tens of proton bunches leads to strong heating that generates a pressure of the order of 30 GPa in the beam heated region. This high pressure generates a strong outgoing shock wave that moves material outwards, thereby leading to strong density reduc-

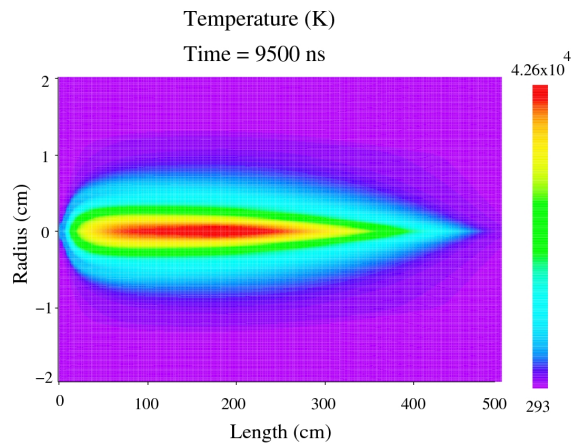


Figure 2: Temperature distribution in copper target at $t = 9.5 \mu\text{s}$

tion along the target axis. As a consequence, the protons that are delivered in subsequent bunches and the particle shower they generate penetrate deeper into the target causing significant range lengthening, the so called "tunneling effect".

In Fig. 2 we present the temperature distribution in the target at $t = 9.5 \mu\text{s}$. It is seen from Fig. 1 that the range of the 7 Tev protons and the secondary particles in solid copper is about 1 m. However, Fig. 2 shows that due to the tunneling effect, the beam heated region extends to 5 m and the maximum temperature is of the order of 10^4 K.

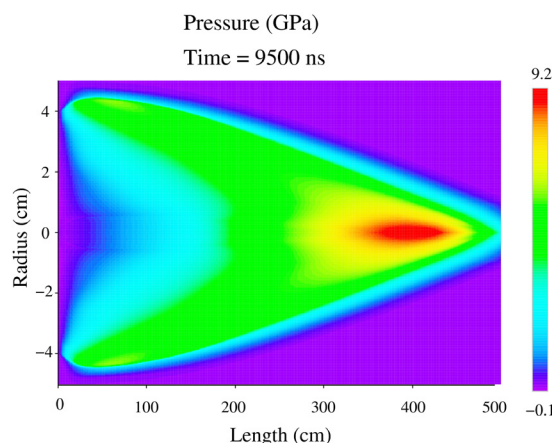


Figure 3: Pressure distribution in copper target at $t = 9.5 \mu\text{s}$

In Fig. 3, is presented the pressure distribution at $t = 9.5 \mu\text{s}$ which shows the radial propagation of the shock wave as well as deeper penetration of the protons in longitudinal direction due to the tunneling effect. The maximum pressure is about 9 GPa.

The corresponding density distribution is shown in

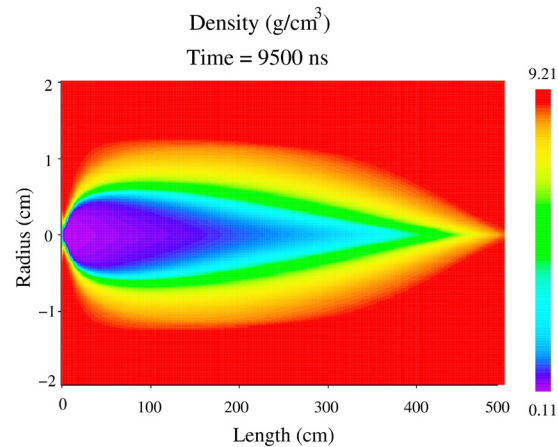


Figure 4: Density distribution in copper target at $t = 9.5 \mu\text{s}$

Fig. 4. It is seen that substantial reduction in the density has taken place and at the target center, the density is about 1 per cent of the solid copper density. These simulations thus demonstrate that the target is severely damaged by the beam. From these calculations it is estimated that the LHC beam will penetrate up to 35 m in solid copper in $89 \mu\text{s}$. Further details can be found in [7]. It is also to be noted that the material in the beam heated region is converted into High Energy Density (HED) matter. The LHC can therefore also be used as a tool to study the interesting subject of HED physics [5, 6, 7].

Solid Graphite Target

The energy loss per proton per unit volume in solid graphite is presented in Fig. 5. The beam and the target parameters are the same as considered in the case of a copper target. It is seen that in graphite, the maximum energy deposition is about 30 GeV/proton/unit volume which is significantly lower than in copper. Moreover, this peak occurs at $L = 110$ cm and range of the protons and the shower is about 3.5 m into solid graphite. This marked difference in the energy deposition in the two materials is due to the difference in their densities.

For the hydrodynamic simulations we consider a cylindrical target with $L = 10$ m and a radius = 2.5 cm. In Fig. 6 we present the temperature distribution at the end of the beam ($89 \mu\text{s}$) that shows that the beam has penetrated the entire length (10 m) of the target. The temperature at the central part of the target is of the order of 10^4 K. Therefore the material in the heated zone will be in a gaseous state which means that the target will be severely damaged.

The corresponding pressure distribution is presented in Fig. 7 which shows the propagation of the radial shock. In Fig. 8 we present the density distribution which again shows density reduction at the target center. However in this case the density has only been reduced by a factor of 4.

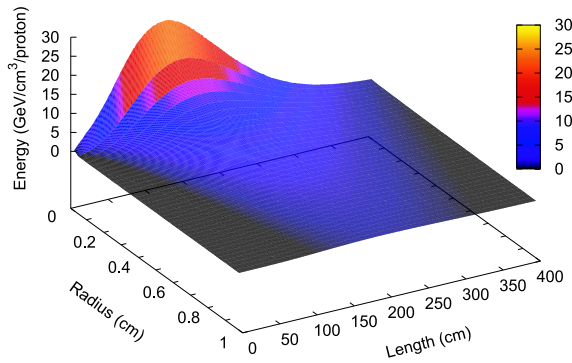


Figure 5: Energy deposition in a solid graphite cylinder by a single 7 TeV proton per unit volume.

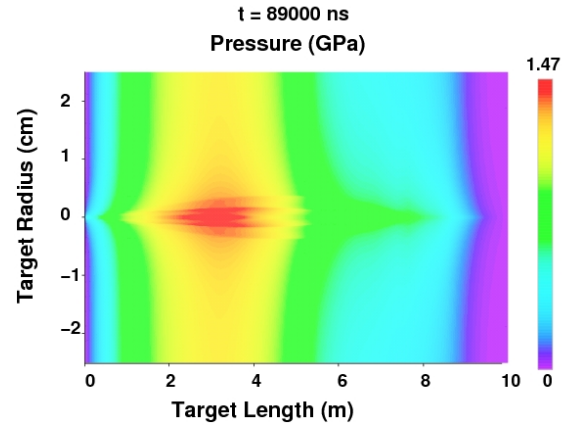


Figure 7: Pressure distribution in graphite target at $t = 89\mu\text{s}$

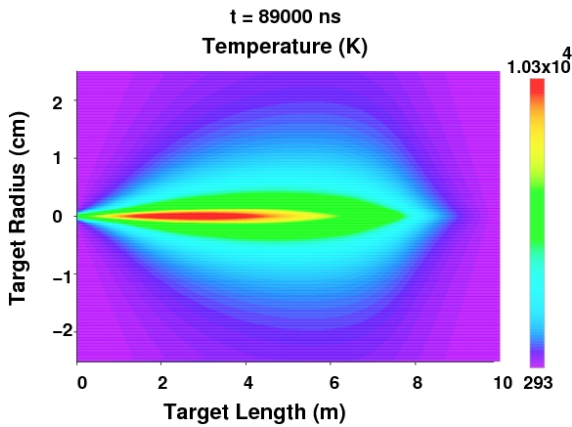


Figure 6: Temperature distribution in graphite target at $t = 89\mu\text{s}$

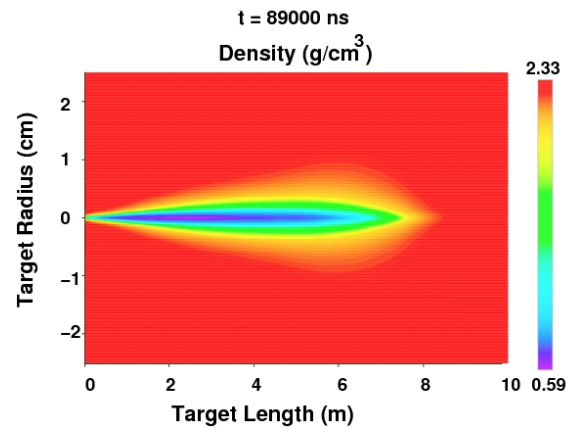


Figure 8: Density distribution in graphite target at $t = 89\mu\text{s}$

CONCLUSIONS

Simulations of interaction of one LHC beam with solid Cu and solid graphite cylindrical targets have been done. These calculations have been performed in two steps. First the energy deposition by the LHC protons and the shower is calculated using the FLUKA code [3]. This data is then used as input to a 2D hydrodynamic code, BIG2 [4]. A full self consistent treatment of this problem requires coupling of the FLUKA code with the BIG2 code. This work is currently in progress.

It has been 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. This has important implications on the consequences of an accidental beam loss as well as for the design of a sacrificial beam stopper. We simulate this effect by normalizing the specific energy deposition with respect to the line density along the axis in each simulation cell at every time step. Our simulations show that the protons will penetrate up to about 35 m in solid Cu and 10 m in solid graphite.

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