INTERACTION OF THE CERN LARGE HADRON COLLIDER (LHC) BEAM WITH SOLID METALLIC TARGETS

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Abstract

Abstract: The LHC will operate at an energy of 7 TeV with a luminosity of $10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$. This requires two beams, each with 2808 bunches. The nominal intensity per bunch is $1.1 \cdot 10^{11}$ protons. The energy stored in each beam is about 350 MJ, sufficient to heat and melt 500 kg of copper. Protection of machine equipment in the presence of such powerful beams is essential [1]. In this paper a specific failure of the protection system is discussed, resulting in the full beam accidentally being directed towards the accelerator equipment [2]. We carried out two-dimensional hydrodynamic simulations of the heating of a solid copper block with a face area of 2 cm x 2 cm, which is irradiated by the LHC beam with nominal parameters. With the present simulations we estimate that after an impact of about 100 bunches the beam heated region has expanded drastically and the density in the inner 0.5 mm decreases by about a factor of 10. The bulk of the following beam will not be absorbed and continue to tunnel further and further into the target. The results will allow estimating the length of a sacrificial absorber presently under discussion. A very interesting "spinoff" from this work would be the study of high-energy-density states of matter induced by the LHC beam, because a specific energy deposition of 200 kJ/g is achieved after 2.5 μs.

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, each bunch having 1.1×10^{11} protons. The temporal power profile in the bunch will be parabolic with a foot-to-foot duration of 0.5 ns while in general every two neighboring bunches will be separated by 25 ns. The spatial power profile in each bunch will be two-dimensional Gaussian with a typical rms beam size σ of 0.2 mm.

In view of the large amount of energy stored in each beam (360 MJ), it is extremely important to address the question of equipment protection from damage in case of an accident leading to a partial or total beam loss.

It is well known that 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.

In order to assess equipment damage in case of the full beam lost into equipment, we have carried out numerical simulations of the hydrodynamic and thermodynamic response of a solid copper target that is irradiated by one of the LHC beams using a two-dimensional computer code, BIG-2 [3]. The energy deposition profiles resulting from all the particles in the cascade generated by the interaction of 7 TeV protons with solid copper have been obtained using the FLUKA code [4]. The energy deposition data was then used as input to the BIG-2 code. Similar calculations have also been performed for the Superconducting Super Collider (SSC) [5].

The calculations have shown that substantial hydrodynamic expansion of the target material occurs during first 2.5 μs which corresponds to the time during which only 100 out of 2808 bunches were delivered. As a result of this hydrodynamic expansion the material density is substantially reduced (by a factor of 10). The temperature in this region is of the order of 10 eV whereas the pressure is about 15 GPa. The material in the heated region is in plasma state while the rest of the target is liquid. The bulk of the protons that will be delivered in the subsequent bunches will encounter little material to interact. As a consequence these protons will penetrate deeper and deeper into the target, a fact which has also been observed in case of energetic heavy ion beams with long pulse length irradiating solid targets [6]. This dynamic effect must be taken into account while assessing the equipment damage and for the design of a sacrificial beam dump.

NUMERICAL SIMULATION RESULTS

Energy Deposition Profiles Using FLUKA Code

High energy protons impinging on material produce particle cascades [4] that lead to an increase in the material temperature. The temperature increase is determined by the number and energy deposition of the particles in the cascade and by the specific heat capacity of the material. The energy deposited by the 7 TeV/c LHC beam as a function of material and the geometry has been calculated with

FLUKA, an established particle interaction and transport Monte Carlo code capable of simulating all components of particle cascades in matter up to TeV-energies [4].

For the study presented in this paper, the geometry for the FLUKA calculation was a simple cylinder of solid copper with a radius r = 1 m and a length l = 5 m. The FLUKA simulations were made for solid target density. The energy deposition was obtained using a realistic two dimensional beam distribution, namely, a Gaussian beam (horizontal and vertical $\sigma_{\rm rms} = 0.2$ mm) that was incident perpendicular to the front face of the cylinder. The calculated local energy deposition (bin size radial: 0.01cm, longitudinal: 2cm) per proton caused by showering in the first part of the block is shown in Fig.1. The average energy density deposited in cylinders of radius 0.01, 1 and 100 cm is shown as a function of the depth in the target in Fig.2.

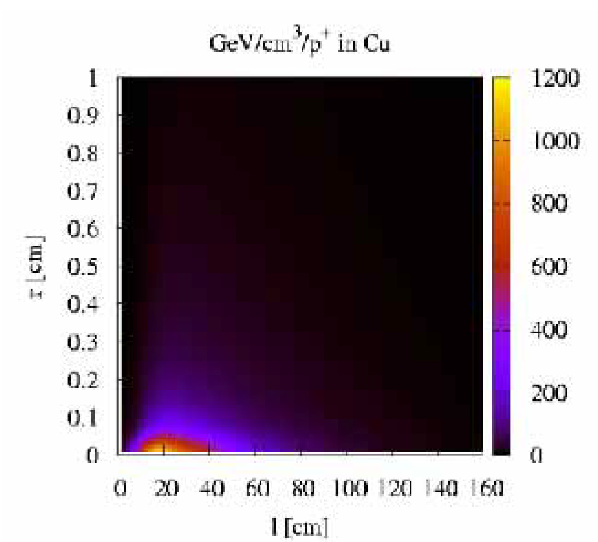

Figure 1: Energy deposition per proton in copper as a function of depth into the target and the radial coordinate.

The energy deposition along the beam axis for one LHC bunch (i.e. after 1 ns) is shown in Fig.3. The longitudinal peak of the energy deposition is about 1200 GeV/cm^3/p$^+$ and occurs at $\sim$15 cm. After 1.5 m the energy deposition is a factor of 1250 lower than in the peak, which indicates that a 1.5 m long copper block would already effectively stop a single LHC bunch. For comparison, the inelastic nuclear scattering length of copper at 7 TeV is about 15 cm so the primary proton beam will be attenuated after a distance of 1.5 m by a factor of exp(150/15) = 22,000.

Hydrodynamic Simulations Using BIG-2 Code

Due to the three-dimensional nature of the problem and the limitation that the BIG-2 code is two-dimensional, we have simulated the thermodynamic and hydrodynamic target response along the transverse direction at various longitudinal positions, L. These include L = 8, 16, 24 and 36 cm. It is seen from Fig.3 that the maximum specific energy deposition occurs at L = 16 cm. In Fig.4 we plot the specific energy deposited by one bunch vs the transverse

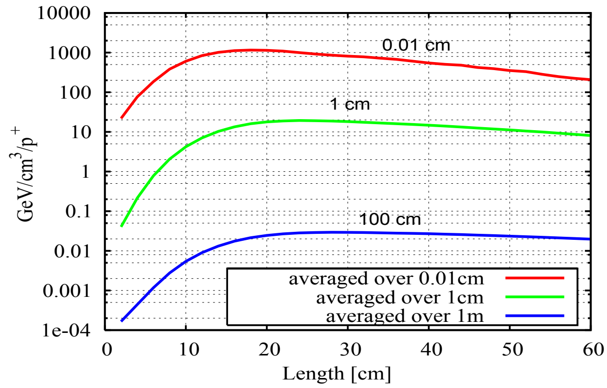

Figure 2: Energy deposition along the beam axis in copper as a function of depth, averaged over circles of 0.01, 0.1 and 100 cm.

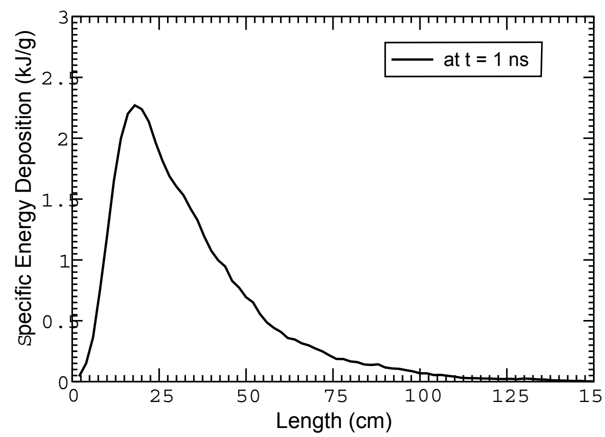

Figure 3: Energy deposition along the beam axis by one bunch.

direction at the above four longitudinal positions. The energy deposited by the following bunches is scaled with the density of the copper target according to the curves shown in Fig.4.

In this study we consider a solid copper block with a facial area = 2 x 2 cm^2 and the beam is directed perpendicular to the face of the target. We consider a transverse cut in the target at given longitudinal positions and study the heating and expansion of the material in the transverse direction.

The impact of the beam onto material leads to an increase in temperature and a corresponding increase in pressure. The high pressure drives a shock wave outwards along the transverse direction. As a result the material is moved from the central part of the beam heated region that leads to a substantial reduction in the density. This is clearly seen from Fig.5 where we plot the target density along the transverse coordinate at different times at L = 16 cm. It is seen that the density has been reduced by a factor of 10 in the central part of the beam heated region after t = 2.5 μs. By this time only 100 out of 2808 LHC beam bunches have been delivered. This means that the bulk of the protons that will be delivered in the subsequent bunches will practically find very little material to interact with and will therefore penetrate deeper into the target. It is

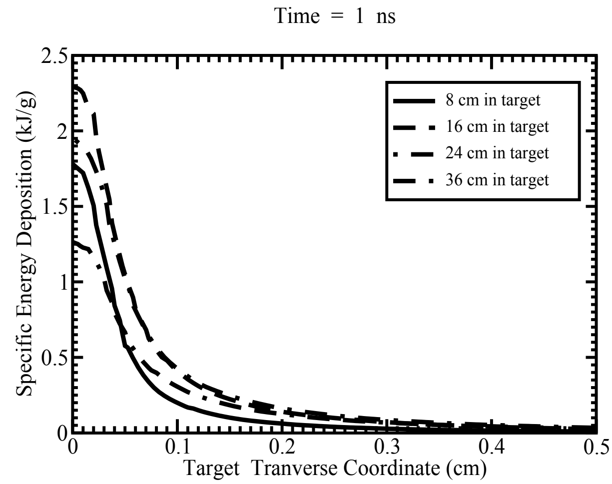

Figure 4: Energy deposition along the transverse coordinate by one bunch at different longitudinal positions.

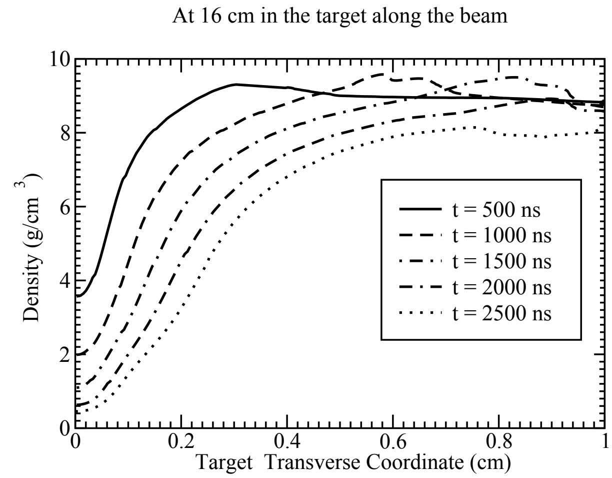

Figure 5: Density vs transverse coordinate at L = 16 cm, at different times.

also interesting to note that by this time the material within a radius of 2 mm is in a plasma state while the rest of the surrounding material is liquid.

These simulation results have been used to estimate the penetration depth of the protons in a copper target. The estimation of the penetration depth is not straightforward.

The energy stored in one LHC beam would be sufficient to vaporise about 60 kg copper, this corresponds to the energy to vaporise a copper target with the same size as the beam and a length of 1500 m.

The average energy deposition of the LHC beam on the axis of a 1 m long copper target on the axis is 400 J/cm^3. The energy to vaporise copper is 5930 J/gm. Assuming that the target becomes transparent after enough energy for vaporisation is deposited, eight bunches would vaporise a 1 m long target. The penetration depth for impact of the entire beam would be about 360 m.

As shown with the BIG-2 simulation, this is by far too pessimistic. The material becomes only transparent after 60-80 bunches are deposited. The penetration length would be at least one order of magnitude less, say, between 10 - 40 m. Details about this work and more accurate estimations will be published in a later paper [7].

The length of a superconducting dipole magnet is 15 m that means in a scenario with the entire beam lost in one spot, up to three magnets may be damaged in such accident.

CONCLUSIONS

This paper presents two-dimensional numerical simulations of thermodynamic and hydrodynamic response of a solid copper target irradiated by one of the two LHC beams.

It has been found that 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 substantially reduced due to the hydrodynamic expansion (about a factor 10 compared to the initial solid density). This implies that 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.

Preliminary estimations based on the simulations indicated that this length may be 10 - 40 m of solid copper.

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