

AN EXPERIMENT AT SPS-HiRadMat AS A TOOL TO STUDY BEAM-MATTER INTERACTION

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Abstract

The Large Hadron Collider and the future linear colliders deal with very high energy stored in the beams (on the order of several hundred MJoules for LHC) or very high power (for linear colliders). Beam sizes are small, for the LHC down to $10\ \mu\text{m}$, for linear colliders below one μm . It is important to understand the damage potential of such high energy beams to accelerator equipment and surroundings. Simulations have shown that in case of an impact of the full LHC beam onto a solid copper target can penetrate up to 35 m [1] as compared to 140 cm that is the typical penetration length for 7 TeV protons. It becomes evident that when working with high energy densities, it is no longer possible to neglect the hydro-dynamic process leading to a depletion of material in the target. For the calculation, a hybrid approach combining FLUKA [2] and BIG-2 [3] is proposed to treat HED problems. This approach can improve current simulations. It is foreseen to experimentally irradiate different materials with different beam intensities in the High Radiation to Materials (SPS-HiRadMat) [4] facility at CERN. These experiments will validate the simulation results by reproducing the density depletion along the beam path. The information obtained with these tests will be very useful in the understanding of the consequences of beam-matter interaction. Results could be applied to the LHC Beam Dump system, collimation, etc.

INTRODUCTION

Since the first electrostatic accelerators, 60 years ago, to the actual machines, the energy has been increasing from keV to TeV and currents have gone from mA to A. Actual accelerators, like LHC, operate at energies of some TeV with beam current of some hundred mA. Such multi TeV accelerators with very high current beams are required by particle physics for probing the standard model.

Such energetic beams, 362 MJ per beam in case of the LHC, are a new source of risk to damage the machine in case of failure, which is a major concern. The understanding of the risk is essential in order to design the protection systems of the machine correctly, to set admissible risk levels, and to determine the inventory of the spare parts needed to possibly replace the damaged equipment. The classical approach to address the damage caused by a particle beam is to calculate the temperature increase and induced stress using the energy deposition map obtained by Monte-Carlo

particle transport code. When the beam is long enough (tens of μm) this is no longer valid. Hydrodynamic effects start to play a role. The time constants of the hydrodynamic process are much shorter than the beam duration and thus the target material cannot be considered static during the whole interaction process (dynamic properties). Instead we combine the traditional approach of Monte-Carlo simulations with hydrodynamic simulations.

SPS-HIRADMAT

The High Radiation to Materials (HiRadMat) facility is dedicated to beam shock impact experiments. The project has been approved and the facility is currently under construction at CERN-SPS complex [5]. The facility is also part of the European Coordination for Accelerator Research & Development project (EuCARD). It is designed to allow testing of accelerator components, in particular those of LHC, to the impact of high-intensity pulsed beams. It will provide a 440 GeV proton beam or a 497 GeV/A ion beam. Beam properties are shown in table 1. The 440 GeV proton beam will have a focal size down to 0.5 mm, thus providing a substantial dense beam (energy/size). The transversal profile of the beam is considered to be Gaussian with a tunable sigma ranging from 0.5 mm to 2 mm.

This facility will allow to study High Energy Density physics as the energy density will be high enough to create plasma in the core of some materials (copper, tungsten) and to produce strong enough shock waves creating a density depletion channel along the beam axis (tunneling effect) [6, 7].

ENERGY DEPOSITION IN MATTER

Energy deposition in matter by particles is given by the evolution of the hadronic cascade from several TeV down to thermal energies. Most of the particle production takes place at energies below 1 GeV. Particles lose energy by multiple interaction mechanisms that can be grouped in two. Nuclear interactions (elastic and inelastic) are relatively rare and are treated in a discrete way by Monte-Carlo (MC) codes. The distance traveled by a particle before undergoing a nuclear interaction is modeled using the total cross-section that expresses the probability of interaction between two corpuscles. Energy loss by collisions and radiation, in case of charged particles, are mechanisms that

Table 1: HiRadMat Beam Properties

Parameter	Symbol	Protons	Ions
Beam Energy	E	440 GeV	
Maximum Beam Intensity	N_b	$1.7 \cdot 10^{11}$ protons	$7 \cdot 10^7$ ions
Max. number of bunches per pulse	n_{max}	288	52
Max. pulse intensity	$N_p = n_{max} \cdot N_b$	$4.9 \cdot 10^{13}$ protons	$3.64 \cdot 10^9$ ions
Bunch spacing	Δt_b	25 ns	100 ns
Beam size	σ_{beam}	0.5 mm	0.5 mm
RMS bunch length	σ_z	11.24 cm	11.24 cm
Pulse length	t_p	7.2 μ s	5.2 μ s
Number of pulse per cycle		1	1
Cycle length		18 s	13.2 s

are treated as continuous events by MC codes. A quantitative description of the energy loss by ionization and atomic excitation, or alternatively the stopping power of the material, by a charged particle (excluding electrons) traversing matter is given by the Bethe formula (see Eq. 1).

$$-\frac{dE}{dx} = 4\pi N_A r_e^2 m_e c^2 N^2 Z/A 1/(\beta_L^2) (1/2 \ln \frac{2m_e c^2 (\beta_L \beta_L)^2 T_{max}}{I^2} - \beta_L^2 - \frac{\sigma(\beta_L \gamma_L)}{2}) \quad (1)$$

Radiation is a quantum effect that takes places when particles are deflected; the energy loss is proportional to the second power of the energy over the second power of the particle's mass (Bremsstrahlung).

Particle showers can be categorized into Hadron (HAD) and electro-magnetic (EM) according to the primary interaction channel. HAD-showers are dominated by the strong interaction while EM-showers are dominated by the electro-magnetic force. When the energy of the beam is sufficiently high, above the pion production threshold, a significant amount of energy is transferred from the HAD-shower to the EM-shower via neutral pion production. On the contrary, EM-showers don't develop HAD-showers, if electro and photo nuclear interactions are neglected.

The energy deposition profile around the beam axis is mainly characterized by the stopping power dE/dx and the profile of the superimposed EM cascades associated with the π^0 s. The last part of the energy deposition profile is

characterized by the interaction of low energy neutrons.

CURRENT SIMULATIONS

We are currently simulating the evolution of a carbon target while being irradiated with a 7 TeV proton LHC-type beam. The target length is 1000 cm and the radius in the transversal plane is 5 cm. The initial density is considered to be 2.28 g/cc. The beam has a Gaussian profile with 1mm sigma r.m.s.

As already introduced in the abstract, the classical approach, where an initial energy deposition profile is calculated and later fed to a hydrodynamic code, does not work as soon as we move to a regime where the time structure of the beam is in the same order or bigger as the hydrodynamic processes that occur inside the material. The LHC beam has a total length of 89 μ s while the time needed for a sound wave to reach the surface of the target is 0.05 m/(3901 m/s)=12.8 μ s. One has to consider intermediate steps small where the variation of the material density can be neglected. This adds one level of complexity as there is no equation for the time steps for each iteration. An empirical equation for the time-steps is given in [8], where a step is estimated to 0.2 times the beam spot radius (1σ) divided by the maximum radial velocity in the deposition region. The more the density changes, the smaller the time step should be. Density changes are mainly linked to the radial pressure waves as a consequence of the deposited energy. For materials with a higher energy deposition (smaller nuclear collision length and radiation length), the density will vary faster and the shock waves will be stronger.

Today, we simulated up to 90 μ s of the interaction process, using a time-step of 5 μ s per iteration. Comparisons of each intermediate step with previous simulations are given in [1], where the energy profile was analytically scaled using the line density along the beam axis.

SPS-HIRADMAT EXPERIMENT

A previous damage experiment [9], in the SPS TT40 extraction line has shown the damage potential of the SPS beam and within the expected error bar agreed with the simulations (only FLUKA simulations). Now, it is foreseen to test a new set of material samples at the SPS-HiRadMat facility at CERN. The first experimental objective is to reproduce the "tunneling effect" observed on the simulations results [6, 7]. Further objectives are to measure the density profile, temperature and shock wave strength.

The experiment will consist of a target block made of copper and/or tungsten with a cylindrical shape that will be front face irradiated with a 440 GeV proton beam. The target will be 2000 cm length, long enough to prevent the density channel to reach the end side during the whole beam time, and 10 cm radius that will be sufficient for the target to endure the shock waves.

A test target made of carbon will be used firstly to test

and calibrate the equipment. From simulations, Carbon have shown to endure the impact of the full SPS-HiRadMat type beam and can be considered as a safe test to start with.

Several detectors are foreseen to be placed close to the target. The intention is to be able to capture within ns timescale resolution changes in the density along the target axis along with other parameters. Figure 1 shows a top view of the experimental area. Three particle detectors have been placed around the target: laterally, upstream and downstream of the beam line.

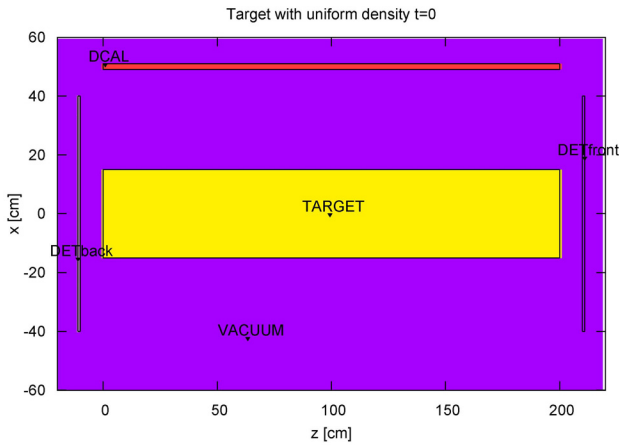


Figure 1: Conical geometry

Simulations have shown that the lateral detector placed at ~50 cm from the beam axis is able to detect changes in the density of the target. In addition, the downstream detector is also able to see changes in the density only if it is placed closer than 20cm from the beam axis. On the contrary, the signal of the upstream detector is sensible to changes in the target density.

It was investigated wherever it is possible to make the signal along the lateral detector flat for the initial situation. By doing this, a change in the material properties would be easily spotted and the calibration of the detectors would be simpler. For a copper target simulations have shown that a cone shape would flatter the detector's signal. Figure 2 shows the charge particle fluence map with the cone geometry superimpose.

Two different scenarios have been studied: the first is the initial situation where the whole target has a constant density; in the second the target has a region, between $z = 21$ cm and $z = 50$ cm, where the density has decreased by a factor of 2. Figures 3 and 4 show the fluence of charge particles on both scenarios. The channel of lower density reduces the nuclear interaction and radiation length and thereby the showers will be enlarged reducing the energy density deposited. This will affect the fluence distribution around and inside the target.

The detector signal is proportional to the fluence of charged particles across it. Figures 5 to 7 compare the signals on the three detectors for each scenario. All three detectors are modeled as an uniform copper object where

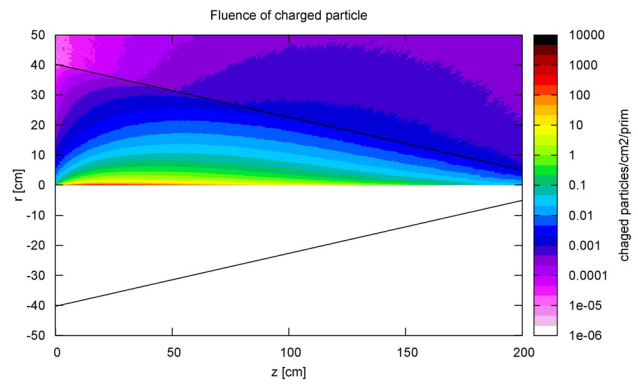


Figure 2: Conical geometry

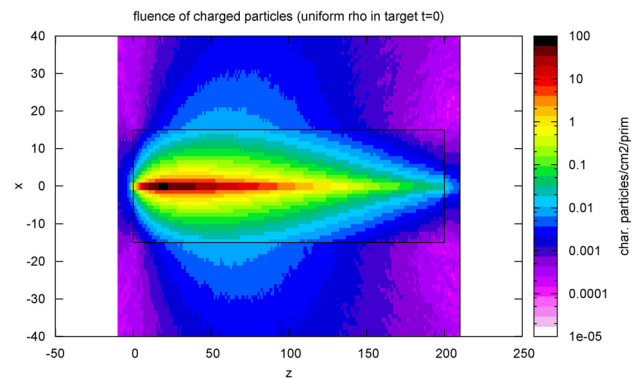


Figure 3: Scenario 1

energy deposition is scored. The hump in the signal of the lateral detector will decrease, flatter and enlarge as the density channel grows. The signal on the downstream detector will increase as the density channel gets larger but the upstream signal will not considerably vary.

The fluence of charged particles with $E > 10$ MeV leaving the target cylinder is shown on Figure 8. Four different solid angles and five energy bins have been sampled. The figure shows the fluence along the lateral side of the target that averaged along the longitudinal direction, so in order to obtain the longitudinal distribution one must weight it.

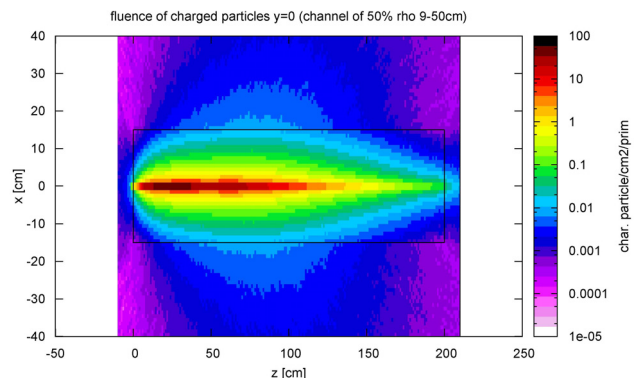


Figure 4: Scenario 2

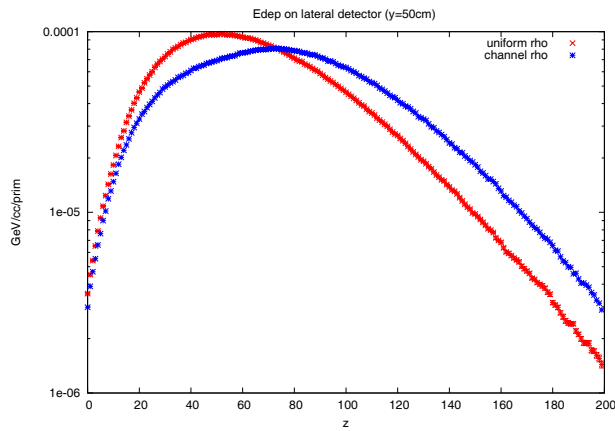


Figure 5: Lateral detector

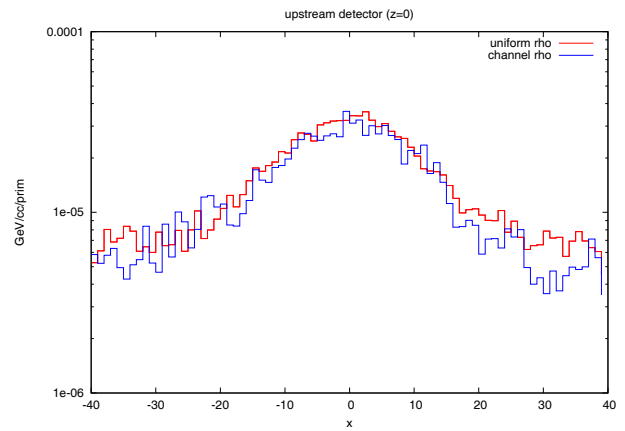


Figure 7: Upstream detector

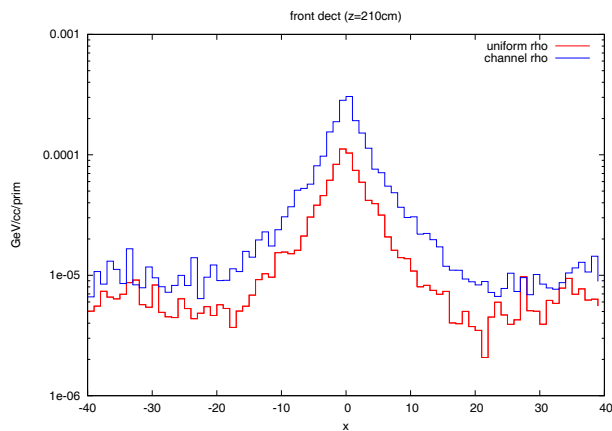
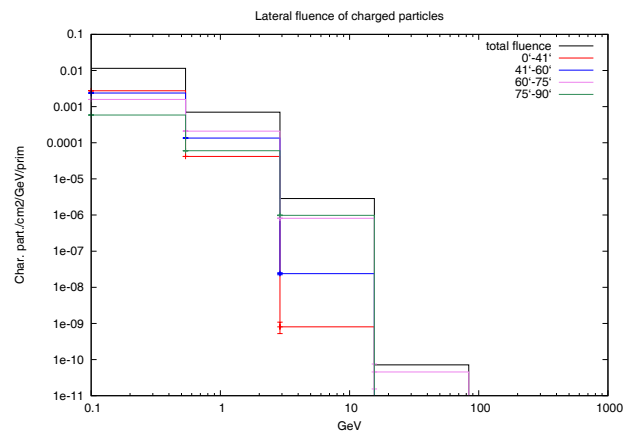


Figure 6: Downstream detector

Figure 8: Fluence $E > 10\text{ MeV}$

The energy deposition on the target could be used to do it.

CONCLUSIONS

Simulations of beam impact on high-Z materials like copper have shown the appearance of a density channel that leads to a further beam penetration and therefore, if an accident, to a greater damage. At present, we are working on an experiment that could reveal the formation and evolution of the density channel; simulations have confirmed that is possible to do it. Now, the effort is placed on the setup of this experiment and all the equipment involved.

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