AN EXPERIMENT AT HiRadMat: IRRADIATION OF HIGH-Z MATERIALS

J. Blanco Sancho, CERN, 1211 Geneva, Switzerland and
Ecole Polytechnique Federale de Lausanne, 1015 Station 1, Lausanne, Switzerland
C. Maglioni, R. Schmidt, CERN, 1211 Geneva, Switzerland
N. A. Tahir, GSI, Planckstr. 1, 64291 Darmstadt, Germany

Abstract

Calculations of the impact of dense high intensity proton beams into material has been presented in several papers [1, 2, 3]. This paper presents the plans for an experiment to validate the theoretical results. The experiment will be performed at the High Radiation to Materials (HiRadMat) facility at the CERN-SPS. The HiRadMat facility is dedicated to shock beam impact experiments. It allows testing of accelerator components, in particular those of LHC, to the impact of high-intensity pulsed beams. This facility will allow to study High Energy Density physics as the energy density will be high enough to create strongly coupled plasma in the core of high-Z materials (copper, tungsten) and to produce strong enough pressure waves to create a density depletion channel along the beam axis (tunneling effect) [4, 5]. The paper introduces the layout of the experiment and the instrumentation to detect tunneling of protons through the target as well as the expected results based on simulations.

INTRODUCTION

The Large Hadron Collider and future linear colliders deal with very high energy stored in the beams (several hundred MJoules for LHC) or very high power (for linear colliders). Beam sizes are small, for the LHC down to $10\mu m$, for linear colliders below one μm. It is important to understand the damage potential of such high energy density beams to accelerator equipment. Simulations have shown that the full LHC beam impacting on a copper target can penetrate up to $35m$ [3] as compared to about $140cm$ that is the penetration length for a particle shower by $7TeV$ protons as calculated with FLUKA. When working with high energy densities, hydro-dynamic processes leading to a depletion of material in the target must be taken into account. For the calculation, a hybrid approach combining FLUKA [6] and BIG-2 [7] is proposed.

The HiRadMat [8] facility will allow to experimentally validate the simulation we have been carrying out. The experiment aims to demonstrate the density depletion effect along the beam path.

HIRADMAT FACILITY

The HiRadMat facility is dedicated to beam shock impact experiments. The facility has been constructed recently and now it is at the last commissioning stage (high intensity beam commissioning) [9]. Beam properties are shown in table 1. It will provide a $440GeV/proton$ proton beam or a $36.9TeV/ion$ ion beam. The $440GeV$ proton beam will have a focal size down to $0.1mm$, thus providing a very dense beam (energy/size), the size can be tuned ranging from $0.1mm$ to $2mm$.

Table 1: HiRadMat Beam Properties

Parameter	Symbol	Protons	Ions
Particle Energy	E	$440GeV$	$36.9TeV$
Bunch Intensity	N_b	$1.7\cdot 10^{11}$	$7\cdot 10^{7}$
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	$25ns$	$100ns$
Min. beam size (rms)	σ_{beam}	$0.1mm$	$0.1mm$
RMS bunch length	σ_z	$11.24cm$	$11.24cm$
Pulse length	t_p	$7.2\mu s$	$5.2\mu s$

HIRADMAT EXPERIMENT

A previous damage experiment [10], in the SPS TT40 extraction line has shown the damage potential of the SPS beam. It helped validating simulation results which protection systems rely on. As an example, the intensity of a beam that is below damage threshold in case of fast beam loss was derived.

Simulations

Currently, new simulations show that for beam-matter interactions with bunch trains longer than $500ns$, with SPS-beam type, a new process plays a major role, the hydrodynamic motion of matter. The energy density deposited in the target is sufficient to melt and vaporize copper, but also to create a radial pressure wave that transports matter from the target's core outwards.

The simulations presented in this paper with FLUKA and BIG2 assume a cylinder of solid copper with a radius of $5cm$ and a length of $150cm$. The energy deposition is obtained using a realistic two dimensional beam distribution, a Gaussian beam (same size in both planes, horizontal and vertical, either with rms = $0.1mm$ or rms = $0.5mm$) that was incident perpendicular to the front face of the cylinder. As previously introduced, simulations have shown that the LHC beam can penetrate up to $35m$ in copper and up to $25m$ in graphite [11].

Figure 1 and figure 2 show the density of the target after different number of bunches hit the target, for the case of $0.5mm$ sigma beam and $0.1mm$ sigma beam. In both cases the depletion channel grows longitudinally with time. For the $0.1mm$ sigma beam the depletion effect is stronger than for the $0.5mm$, thus the channel grows faster.

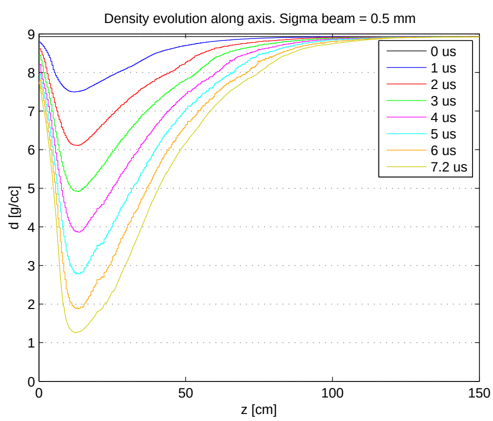

Figure 1: Density profiles along the longitudinal axis for $0.5mm$ sigma beam.

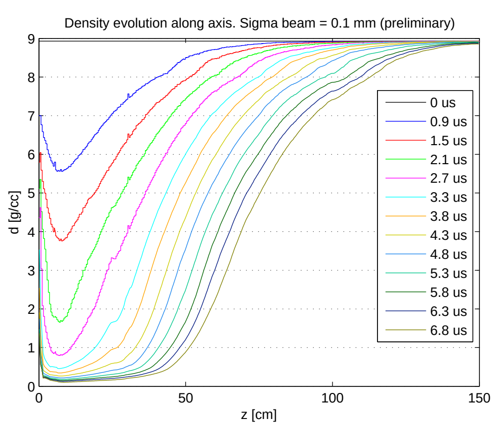

Figure 2: Density profiles along the longitudinal axis for $0.1mm$ sigma beam.

The penetration range of the beam is defined as the length of material damaged by the beam. The damaged area is calculated as the region of the target with a density below the melting point density. The density as a function of time for both profiles ($0.5mm$ and $0.1mm$) exhibit a logarithmic behavior. The asymptote represents the maximum possible penetration range of the beam in the material solely by density depletion processes. This point corresponds to an equilibrium state where the beam energy density is not sufficient to sustain the depletion process. On a larger time scale other thermodynamic processes like thermal conduction will further modify the target.

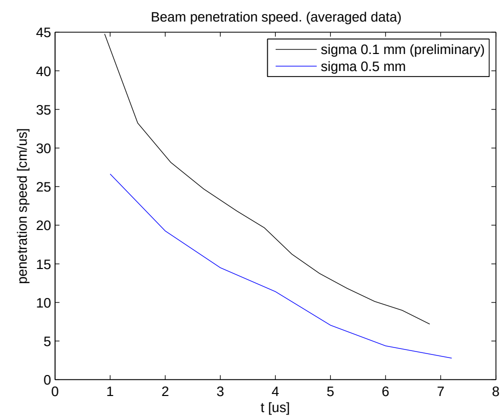

Figure 3: Penetration speed as a function of time.

Experiment

The main motivation for the HiRadMat experiment is to validate these results. The objective of the experiment is to produce the extreme conditions that lead to tunneling, and to measure the evolution of this process.

The target consist of three copper cylinders of $200cm$ length and $4cm$ radius, placed side by side. The radius is slightly different from the radius in the simulation, but this does not change the tunneling. Each cylinder is divided into twenty blocks of $10cm$ length, separated by $1cm$. Figures 4 and 5 show the experiment's front view and the details of the target. For safety reasons, the target is enclosed in an aluminum case. It is being discussed how to seal the front and back side of the case, either by a Boron Nitride window ($1cm$ diameter), or leave it open.

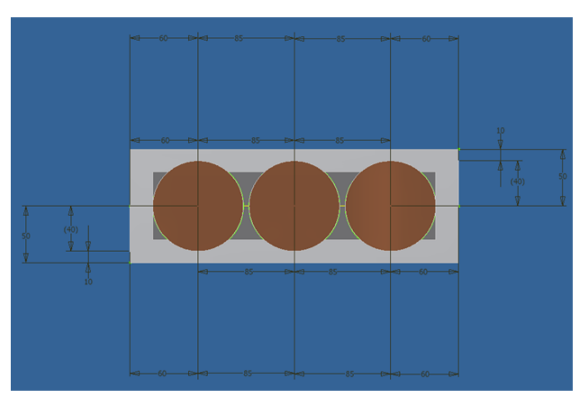

Figure 4: Experiment front view.

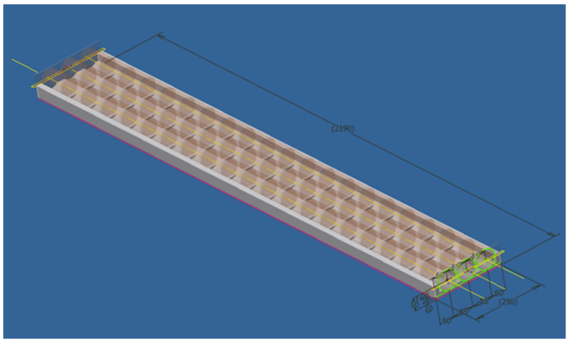

Figure 5: Copper blocks details.

The whole setup is mounted on a movable table with two degrees of freedom.

First, several low intensity single bunches (far below damage threshold) will be directed on the target to calibrate the detectors. Then trains of bunches will complete the calibration. Finally, high intensity shots (above damage threshold) will be directed to each copper target. Different total intensities will be used and different penetration lengths are expected.

Detectors and sensors

The tunneling of beam into the target will be detected using radiation hard diamond detectors with nanosecond resolution and a large dynamic range. The detectors are placed along the longitudinal axis at about $45cm$ distance from the target.

The signal is proportional to the energy deposited in the detector ($13eV/e-h$), proportional to the fluence of particles. Particle fluences around the target change with the tunneling of beam into the target. Each detector has an area of $0.5cm \times 0.5cm$ with an effective thickness of $300\mu m$. The expected average fluence is around $10^{12} particles/cm^2$. The output signal can be measure without amplification with an oscilloscope.

Other ideas for sensors are being discussed, for example temperature sensors attached to each block. The steady state temperature of each block is determined by the penetration of the beam. The temperature profile of a whole target would be measured and compared to simulations, to get an independent estimation of the penetration range. Figures 6 shows the temperature profile along the beam axis as a function of time for the case of $0.5mm$ sigma beam.

After being irradiated, the target will be visually inspected when the activation decays and reaches an acceptable level. As each target is divided into twenty individual blocks, it is possible to identify up to which block the target has been melted (penetration range).

X-ray analysis can show changes in the structure of copper even after if it solidifies. This will show the region of the target damaged by the beam and so the final penetration range can be precisely measured.

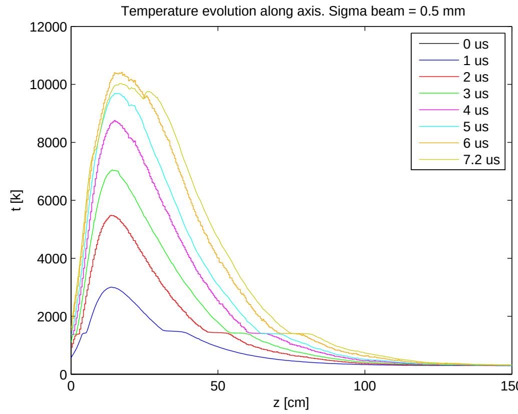

Figure 6: Temperature profile for 0.5mm sigma beam.

CONCLUSIONS

Simulations of beam impact on high-Z materials like copper have shown the appearance of a low density channels that leads to further beam penetration for subsequent bunches. The experiment presented in this paper is expected to detect such tunneling process. This will allow a validation of the simulations that were performed for the experiment. This is required to gain confidence in the simulation tools that have been developed since several years with a variety of beam parameters and materials for SPS and LHC. This is relevant for the assessment of beam induced damage in the LHC if ever a major failure of the protection systems should occur and will be taken into account in the design of beam absorbers.

REFERENCES

[1] N.A. Tahir et al., Laser Part. Beams 27 (2009) 475.

[2] R. Schmidt et al., New J. Phys. 8 (2006) Art. No. 290.

[3] N. A. Tahir et. al., Phys. Rev. E 79 (2009) 046410.

[4] N. A. Tahir et. al., Phys. Plasmas 16 (2009) 082703.

[5] N. A. Tahir et. al., Nucl. Instr. Meth. A 606 (2009) 186.

[6] A. Fasso, et al., The physics models of FLUKA: status and recent development, CHEP 2003, LA Jolla, California.

[7] V. E. Fortov et al., Nucl. Sci. Eng. 123, 169 (1996).

[8] I. Efthymiopoulos, https://espace.cern.ch/hiradmat-sps/

[9] C. Hessler et al., Results from the HiRadMat Beam Line Commissioning, these proceedings

[10] V. Kain, Damage Levels Comparison of Experiment and Simulation, LHC Project Workshop - Chamonix XIV, 2004

[11] N. A. Tahir et. al., Beam Impact On High-Z Materials Taking Into Account The Time Structure Of The Beam, these proceedings