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COMPARISON OF THE RESULTS OF A HYDRODYNAMIC TUNNELING EXPERIMENT WITH ITERATIVE FLUKA AND BIG2 SIMULATIONS

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Abstract

In 2012, a novel experiment has been performed at the CERN HiRadMat facility to study the impact of a 440 GeV proton beam generated by the Super Proton Synchrotron (SPS), on extended solid copper cylindrical targets. Substantial hydrodynamic tunneling of the protons in the target material has been observed.

Iterative FLUKA and BIG2 simulations with the parameters of the actual experiment have been performed. In this paper the results of these simulations will be discussed and compared to the experimental measurements. Furthermore, the implication on the machine protection design for high intensity hadron accelerators as the current LHC and the future circular collider (FCC) will be addressed.

INTRODUCTION

Previous theoretical work on beam–target heating has shown that in case of an extended bunched particle beam, like the one delivered by the LHC, energy deposited in the target by the protons delivered in the first few tens of bunches and the proton shower, causes strong heating of the solid material that leads to substantial increase in the temperature [1]. The heated material undergoes phase transitions that include liquification, evaporation and even conversion into weekly ionized strongly coupled plasma. The high temperature in the absorption zone generates high pressure that launches a radially outgoing shock wave which causes substantial density depletion on the axis. As a consequence, the protons that are delivered in the subsequent bunches, penetrate much deeper into the target, a phenomenon which is called "hydrodynamic tunneling". The continuation of this process during the irradiation, leads to a significant lengthening of the projectile range. This phenomenon therefore has very important implications on the machine protection system design. In order to check the validity of these theoretical considerations, especially the existence of the hydrodynamic tunneling, experiments have been performed at the HiRadMat facility using the SPS proton beam.

EXPERIMENTAL SETUP

Figure 1 shows the target used in the experiments before its installation in the HiRadMat facility. It consists of three targets, each comprised of fifteen copper cylinders with a spacing of 1 cm in between that allows for visual inspection of the target after the irradiation. Each cylinder has a radius of 4 cm and a length of 10 cm. The three assemblies of cylinders are enclosed in an aluminum housing that provides rigidity to the setup and prevents any contamination of the facility. The front face of the first cylinder and the rear face of the last cylinder in the three target assemblies are covered with cylindrical aluminum caps.

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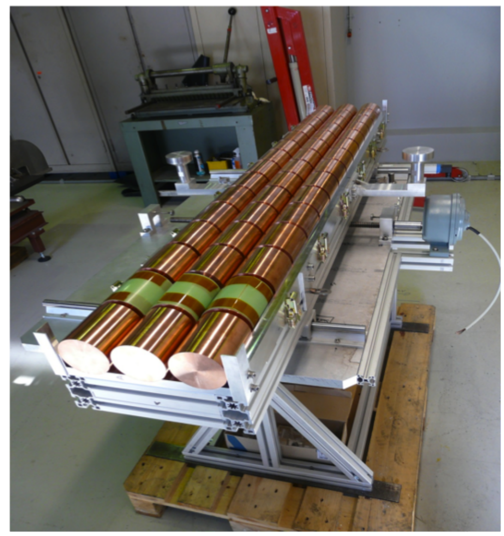

Figure 1: Target in the assembly hall, each target is consists of 15 Copper cylinders with 10 cm length and 4 cm radius.

The experimental beam parameters were 440 GeV, bunch intensity of 1.5E11 protons per bunch, bunch length of 0.5 ns and a bunch separation of 50 ns. Target 1 was irradiated with 144 bunches with a beam focal spot characterized by σ = 2 mm. Target 2 was irradiated with 108 bunches whereas target 3 was irradiated with 144 bunches while in both these cases, the beam had a much smaller focal spot size characterized by σ = 0.2 mm. A summary of the beam parameters used in these three experiments is presented in table 1.

Table 1: Beam Parameters During the Experiment in the HiRadMat Facility

Target	Number of bunches	Beam σ (mm)	Beam Energy (MJ)	expectation
1	144	2.00	1.52	Some tunneling
2	108	0.20	1.14	Moderate tunneling
3	144	0.20	1.52	Significant tunneling

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EXPERIMENTAL RESULTS

The target was opened for visual inspection after 8 months of cool down in February 2013. Droplets and splashes of molten and evaporated copper have been found on the copper cylinders, the aluminum housing at the position of the gaps between cylinders and in the front aluminum caps. Figure 2 shows the top cover of the experimental setup.

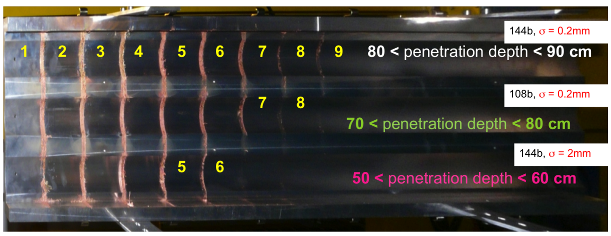

Figure 2: Top cover of the experimental setup after the irradiation. Traces of molten on the cover indicate the penetration depth of the proton beam.

After the beam impact, molten/evaporated material is projected outwards and is deposited against the top cover. The traces of the projected copper between the 10 cm long cylinders are clearly visible. It is seen that in case of the first target using 144 bunches and beam focal spot σ = 2.0 mm (Figure 2 - bottom), the splash of molten copper occurs up to the gap between the fifth and the sixth cylinder. That means that the material was molten/evaporated over a length of 55 ± 5 cm. In the second target with 108 bunches and beam focal spot, σ = 0.2 mm (Figure 2 - middle), the molten/evaporation zone goes up to the eighth cylinder that means a damage length of 75 ± 5 cm. In the third target with 144 bunches and beam focal spot, σ = 0.2 mm (Figure 2 - top), the molten/evaporation zone extends to the ninth cylinder that means a length of 85 ± 5 cm.

STATIC FLUKA SIMULATIONS AND COMPARISON TO EXPERIMENTAL RESULTS

Figure 3 shows the specific energy deposition along the target axis calculated with the FLUKA code [2–4] (excluding hydrodynamics) for target 1 and target 3. The red and blue-dashed lines indicate the amount of the specific energy needed to melt and to evaporate the copper, respectively. It is seen that in case of the first experiment using 144 bunches and σ = 2 mm, the beam deposits sufficient specific energy between L = 6–47 cm, to melt the target. It is also seen in Figure 3 that melting occurs along the axis up to L = 47 cm, whereas the corresponding experimentally measured length is 55 ± 5 cm, in this case. For Case 3 in the figure which uses parameters of target 3, namely 144 bunches and σ = 0.2 mm, the simulations show that the material is melted/evaporated along the axis to up to L = 67 cm, but the corresponding experimental measured length is 85 ± 5 cm. A comparison between these simulations that are based on a static model

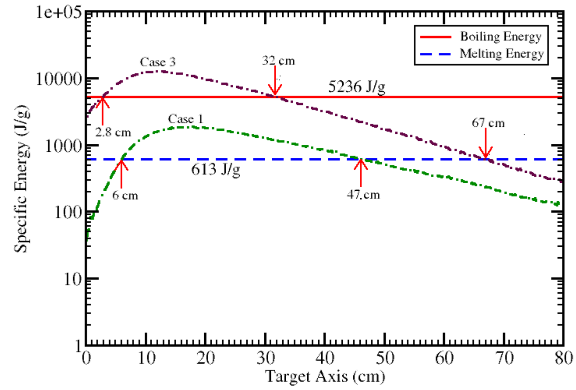

Figure 3: Specific energy deposition along the target axis calculated by static FLUKA simulation. Case 1 shows the energy deposition for 144 bunches, each $1.5 \cdot 10^{11}$ protons, σ=2 mm. Case 3 shows the energy deposition for 144 bunches, each $1.5 \cdot 10^{11}$ protons, σ=0.2 mm.

and the experimental measurements for the three experiments, is provided in Table 2.

Table 2: Comparison Between Measured and Expected Length of the Molten Zone, Simulations were Performed with a Static Model, Without Hydrodynamics

Target	Simulated length of molten zone	Measured length of molten zone
1	47 cm	55 cm ± 5 cm
2	64 cm	75 cm ± 5 cm
3	68 cm	85 cm ± 5 cm

HYDRODYNAMIC TUNNELING SIMULATIONS

Table 2 shows a significant discrepancy between the experimental measurements and the simulations based on a static approximation. In order to have a better understanding of the problem, detailed numerical simulations have also been carried out using the above beam parameters (Table 1) and running the energy deposition code FLUKA [2–4] and a 2D hydrodynamic code, BIG2 [5] iteratively, using an iteration step of 700 ns. This is the time during which the target density decreases by about 15 percent at the target centre due to the hydrodynamic processes. For the simplicity of calculations a single solid copper cylindrical target with 150 cm length and 4 cm radius was considered. The 1 cm gaps between neighbouring cylinders do not affect the energy deposition. Moreover, the over all hydrodynamics will not be affected as the hydrodynamic processes are much stronger in the radial direction than in the axial direction in this type of problems. It is to be noted that the BIG2 code is equipped with a semi–empirical, multiphase Equation–of–State [6] to model different phases of the target during and after the irradiation. Figure 4 shows the energy deposition calculated by the FLUKA code at t=6050 ns (121 bunches delivered)

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in GeV/g per primary particle. For this case a peak energy of 2.9 GeV/g per primary particle was evaluated.

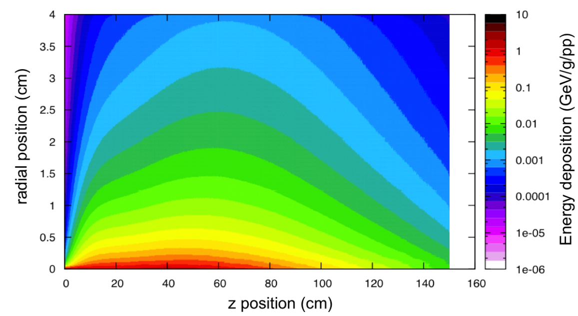

Figure 4: Simulated energy deposition in GeV/g and primary proton at t=6050 ns (121 bunches delivered).

Figure 5 shows the density and temperature along the axis at t = 5800 ns, when 108 bunches had been delivered for the second target. The flat part of the temperature curve represents the melting region and lies within L = 75 and 80 cm which is equivalent to the RHS half of the eighth cylinder. The temperature curve also shows that the material along the axis up to 75 cm is liquefied or even evaporated, depending on the temperature. Liquefied material escapes from the left face of cylinder number 8 and collides with the melted/gaseous material ejected from the right face of cylinder number 7. As a result of this collision, the material is splashed vertically and is deposited at the inner surface of the target cover above the gap between cylinder number 7 and 8. The simulations are therefore in full agreement with the experimental observations.

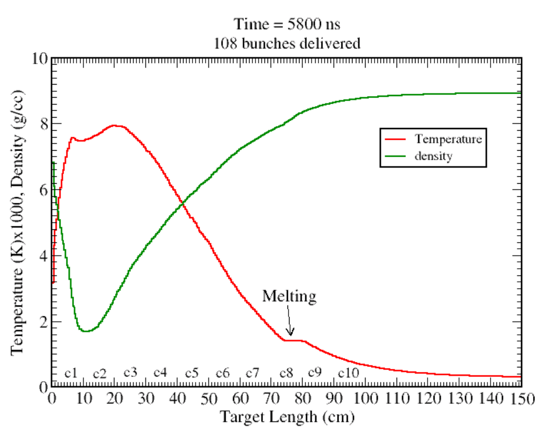

Figure 5: Simulated density and temperature vs. target axis at t = 5800 ns (108 bunches delivered) coming from iterative FLUKA-BIG2 simulations. Final result for target 2.

Figure 6 shows the same variables as Figure 5, but at t = 7850 ns, after 144 bunches had been delivered. The melting region now lies between L = 85 and 90 cm, which is the RHS half of cylinder 9, while the left half part (L = 80–85 cm) has been liquefied. The simulations, thus, predict material deposition at the inner surface of the target cover above the region between cylinder 8 and 9, which is in full agreement with the experimental measurements.

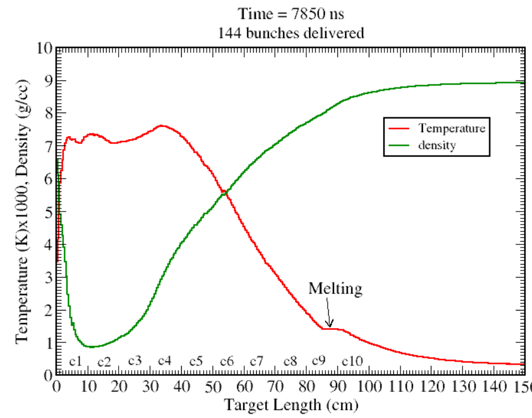

Figure 6: Simulated density and temperature vs. target axis at t = 7850 ns (144 bunches delivered) coming from iterative FLUKA-BIG2 simulations. Final result for target 3.

CONCLUSION

First experiments have been carried out on the impact of highly relativistic, high intensity, bunched proton beam from the SPS onto extended solid copper cylindrical targets. Significant hydrodynamic tunneling of the protons has been established that substantially increases the projectile range. The experimental measurements show excellent agreement with numerical simulations. This provides confidence in the simulations done in the case of the 7 TeV LHC proton beam. A very interesting outcome of this work is that the SPS beam can be used to study HED physics at the HiRadMat facility. Simulations with Future Circular Collider (FCC) beam parameters were just started.

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