

EXPERIMENTAL AND SIMULATION STUDIES OF HYDRODYNAMIC TUNNELING OF ULTRA-RELATIVISTIC PROTONS*

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Abstract

The expected damage due to the release of the full LHC beam energy at a single aperture bottleneck has been studied. These studies have shown that the range of the 7 TeV LHC proton beam is significantly extended compared to that of a single proton due to hydrodynamic tunneling effect. For instance, it was evaluated that the protons and their showers will penetrate up to a length of 25 m in solid carbon compared to a static range of around 3 m. To check the validity of these simulations, beam-target heating experiments using the 440 GeV proton beam generated by the SPS were performed at the HiRadMat test facility at CERN [1]. Solid copper targets were facially irradiated by the beam and measurements confirmed hydrodynamic tunneling of the protons and their showers. Simulations have been done by running the energy deposition code FLUKA and the 2D hydrodynamic code, BIG2, iteratively. Very good agreement has been found between the simulations and the experimental results [2] providing confidence in the validity of the studies for the LHC. This paper presents the simulation studies, the results of a benchmarking experiment, and the detailed target investigations.

HYDRODYNAMIC TUNNELING

The theoretical investigations of the beam-target heating problem at LHC showed that the energy deposited by few ten proton bunches leads to strong heating that produces very high pressure in the beam heated region. This high pressure generates a radially outgoing shock wave that leads to a continuous density reduction at the target center. As a consequence, the protons of the subsequent bunches, and their hadronic showers, penetrate deeper into the target. Continuation of this process leads to a substantial increase in the range of the projectile particles and their hadronic shower. This phenomenon is called *hydrodynamic tunneling* of ultra-relativistic protons in solid targets. [2] It has an important implications on the machine protection design of every high stored beam energy accelerator.

EXPERIMENTAL SET-UP

Figure 1 shows the three targets used in the experiments before their installation in the HiRadMat facility. Each target comprises 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 set-up and should prevent 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. The experimental beam parameters were 440 GeV, a 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 $\sigma = 2$ mm. Targets 2 and 3 were irradiated with 108 bunches and 144 bunches respectively, in both cases with a beam focal spot size characterized by $\sigma = 0.2$ mm.



Figure 1: Target assembly.

EXPERIMENTAL RESULTS AND COMPARISON TO SIMULATIONS

The experiments were done in July 2012 and the target was opened after a cool-down period of about 10 months for a first visual inspection and the observations made at that time were published in [3,4] together with the theoretical interpretation [5]. This paper focus on the results for target 3. The results of the simulations are shown in Fig. 2. The temperature and the density along the target axis after the irradiation with 144 bunches are shown. It indicates a molten region for $z = 0 - 2$ cm, a

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gaseous state for $z = 2 - 60$ cm, a molten region till $z = 85$ cm and a 2 phase state (molten / solid) for $z = 85 - 90$ cm.

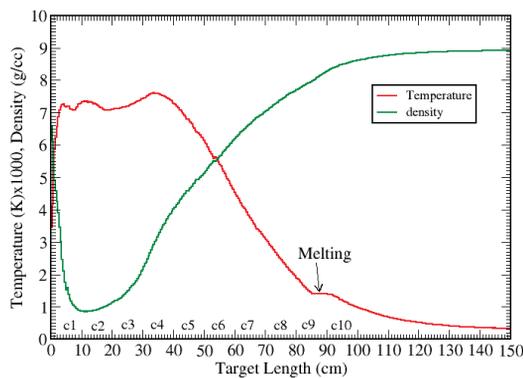


Figure 2: Simulation Results: ρ and T vs target axis at $t = 7850$ ns for target 3, after irradiation with 144 bunches [3].

It was not allowed at that time to physically touch the targets due to radio-protection issues. After cleaning, the targets have been declared safe for further investigations. In Fig. 3 the front and the back face of the third cylinder of target 3 are shown. The copper at the center of this cylinder was in the gaseous state. To investigate in greater detail the beam penetration depth and damage to the target, different parts of the cylinders have been cut for a detailed and thorough visual inspection of the interior of the cylinders.



Figure 3: Front (left) and back (right) faces of the third cylinder of target 3. Re-solidified copper splashes and the hole generated by the beam is visible.

Some material from the cylinders has been ejected with high speed and collided with the material ejected from the following cylinder. These molten copper splashes are partly deposited on the inner side of the aluminum cover and are partly splashed on the opposite faces of the two cylinders. The material deposited on the faces of the cylinders solidified as seen in Fig. 3. It was clearly visible that the beam has penetrated through all 8 cylinders generating holes at both faces of the cylinders and leaving traces of the material that solidifies after ejection. In the 9th cylinder of target 3 only damage on

the front face was visible. This is in complete agreement with the numerical simulations, described in [6]. This cylinder was removed from the target to determine the exact length of the damaged region. In addition, the first cylinder of target 3 was removed and cut along the beam axis. A picture of the surface, made using a standard camera is shown in Fig. 4.

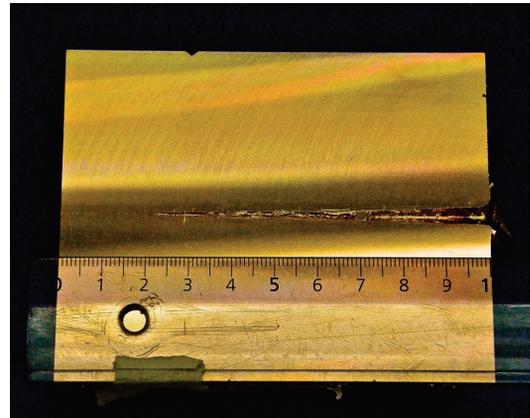


Figure 4: Surface picture of Cylinder 1 of target 3 after cutting it longitudinally. In the first 2.3 cm micro cavities are observed, further downstream a cone shaped hole is clearly visible.

A detailed microscopic analysis of the selected cylinders was carried out in order to inspect the region damaged by the beam. In Fig. 5 different sections of the first cylinder of Target 3 are presented. Figure 5(a) shows the first third, whereas Fig. 5(b) – (c) represent the middle third and the last third of the cylinder.

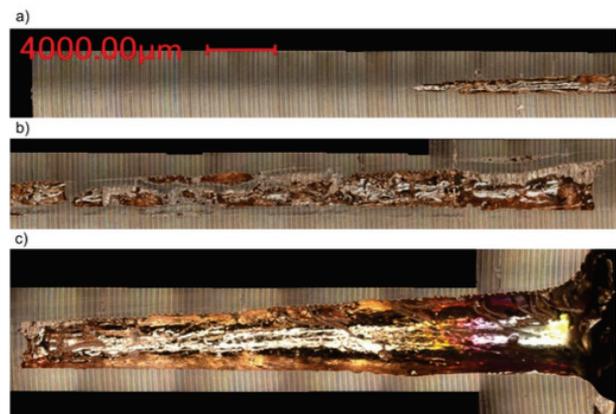


Figure 5: Target 3, Cylinder 1. Microscopic analysis of the hole generated by the beam. a) first, b) second and c) last third of the cylinder.

Figure 5(a) shows that micro-cavities have been formed in the first 2.3 cm. Downstream a bell-shaped hole starts. Figures 5(b) and 5(c) show that the hole continues along the cylinder axis until the end. In addition solidification of liquefied copper is clearly visible. Figure 6 shows three-

dimensional high-resolution pictures of the hole drilled by the beam in the first cylinder of Target 3. On the left side the region between $z = 2.4 - 2.6$ cm and on the right side the region between $z = 9.3 - 10$ cm is shown. The coloring is real. Detailed analysis shows that the radius of the hole on the left side picture is $300 \mu\text{m}$, whereas it is 2.3 mm at the end of the cylinder at $z = 10$ cm, which is in good agreement with the simulations.

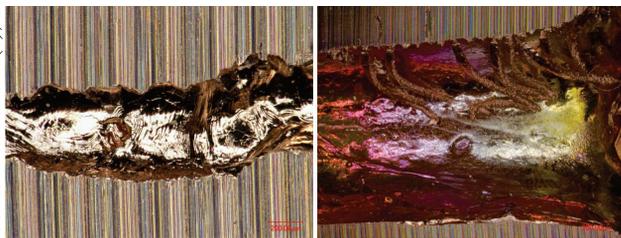


Figure 6: 3D high-resolution pictures of hole drilled by the beam in the first cylinder of Target 3. Left: the region between $z = 2.4 - 2.6$ cm, Right: the region between $z = 9.3 - 10$ cm. The coloring is real. These pictures were made with a magnification of 200x and 50x respectively.

Figure 7 shows a micro cavity found at the end of the damaged region at $z = 85$ cm in target 3. This micro-cavity is located on beam axis. The same kind of micro cavities has been found in the last irradiated cylinder of the other targets; therefore the length of the damaged region was determined by determining the last visible micro-cavity. The measured penetration length of the beam and the results from the hydrodynamic simulations using FLUKA and BIG2 for all targets are summarized in Table 1. Excellent agreement between hydrodynamic simulations and experimental results was found.

Table 1: Simulation and Experimental Results for the Three Targets. No Hydrodynamic Simulations were Performed for Target 1

| Target | Simulation Result (cm) | Experimental Result (cm) | Δ Exp. to Sim. Results (cm) |
|--------|------------------------|--------------------------|------------------------------------|
| 1 | - | 58 | - |
| 2 | 80 | 79.5 | 0.5 |
| 3 | 90 | 85 | 5 |



Figure 7: Micro-Cavity at $z = 85$ cm in Target 3. The area is located on the beam axis with a surface of ~ 1.5 mm^2 .

CONCLUSION

Solid copper cylinders have been irradiated with 440 GeV protons at the HiRadMat facility at CERN. The primary purpose of these experiments was to study the phenomenon of hydrodynamic tunneling of the protons that leads to a substantial increase in the range of the projectile particles and their hadronic showers in matter compared to a single proton. Hydrodynamic simulations using FLUKA and BIG2 were performed. Recently, the targets have been removed from the facility and the state of the interior of the targets has been studied by cutting the most relevant cylinders and a microscopic analysis of these cuts. This provided a high precision of the measurements compared to the previous ones. The simulations showed excellent agreement with the measurements. This work has further deepened the understanding of hydrodynamic tunneling for the LHC beam and has validated the use of the BIG2 code for simulating this effect.

REFERENCES

- [1] R. Schmidt, R. Assmann, B. Dehning, R. Denz, B. Goddard, E.B. Holzer, V. Kain, B. Puccio, B. Todd et al., *New J. Phys.*, vol. 8, p. 290, 2006.
- [2] N.A. Tahir et al., *J. Appl. Phys.*, vol. 97, p. 083532, 2005.
- [3] R. Schmidt, J. Blanco Sancho, F. Burkart, D. Grenier, D. Wollmann, N.A. Tahir, A. Shutov and A.R. Piriz, *Phys. Plasmas*, vol. 21, p. 080701, 2014.
- [4] F. Burkart et al., "Comparison of the Results of a hydrodynamic tunneling experiment with iterative FLUKA and BIG2 simulations," in Proceedings of IPAC14, Dresden, Germany, 2014.
- [5] N.A. Tahir, F. Burkart, A. Shutov, R. Schmidt, D. Wollmann and A.R. Piriz, *Phys. Rev. E*, vol. 90, p. 063112, 2014