# Experimental Studies and Theoretical Interpretation of Hydrodynamic Tunneling of SPS Protons in Solid Targets *

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The phenomenon of hydrodynamic tunneling has been experimentally studied at the CERN HiRadMat facility using the SPS beam [1]. The beam parameters include, proton energy = 440 GeV, bunch intensity = $1.5 \times 10^{11}$, bunch length = 0.5 ns, bunch separation = 50 ns and $\sigma$ of the transverse intensity distribution = 0.2 mm. In two experiments, 108 and 144 proton bunches, respectively, were used and the protons were delivered in sets of 36 bunches each while a separation of 250 ns was considered between the bunch packets.

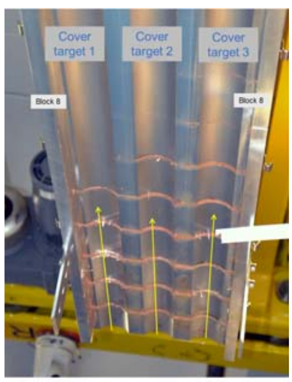


Figure 1: Photograph of the Al target cover

The target was composed of 15 identical solid copper cylinders, each 10 cm long having a radius of 4 cm, placed in a row. For diagnostic purposes, a gap of 1 cm was left between two neighboring cylinders. The beam is irradiated transversely at the face of the first cylinder.

The results of the experimental measurements are presented in Fig. 1 which is a photograph of the Al cover that was placed on the top of the target. It is seen that in the case of the experiment using 108 bunches, the material is deposited up to the gap between cylinder 7 and cylinder 8 whereas in the experiment with 144 bunches, the deposition of the melted/gaseous material is up to the gap between cylinders 8 and 9. To understand these results, detailed numerical simulations have been carried out running the FLUKA and BIG2 codes iteratively. For simplicity, we considered a single solid copper cylinder 150 cm long with a radius of 4 cm. This is a good approximation to the target used in the experiments.

In Fig. 2 are plotted $\rho$ and T vs target axis at t =5800 ns when 108 bunches have been delivered. It is seen that the

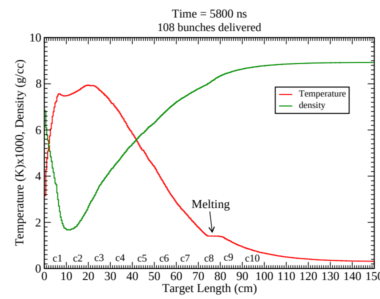


Figure 2: $\rho$ and T vs target axis at t = 5800 ns [108 bunches]

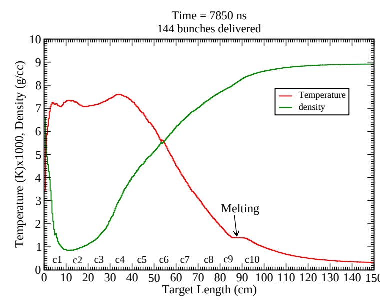


Figure 3: $\rho$ and T vs target axis at t = 7850 ns [144 bunches]

flat part of the temperature curve that represents melting, lies within the second half (RHS part) of the eighth cylinder. This means that the material in the LHS half of the cylinder has been melted. The melted 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 and is deposited on the target cover. This is in full agreement with the experimental observations.

Fig. 3 shows same variables as Fig. 2, but at t = 7850 ns when 144 bunches have been delivered. The melting region now lies in the RHS half of cylinder 9 while the left half part has been melted. The simulations thus predict material deposition at the target cover in the region between cylinder 8 and 9, in full agreement with the experimental measurements. These experiments therefore fully confirm the existence of the hydrodynamic tunneling.

## References

[1] R. Schmidt et al., Proceedings of IPAC13, Shanghai, China, 2013.

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