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Results of an Experiment on Hydrodynamic Tunneling at the SPS HiRadMat High Intensity Proton Facility

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Abstract

To predict the damage for a catastrophic failure of the protections systems for the LHC when operating with beams storing 362 MJ, simulation studies of the impact of an LHC beam on targets were performed. Firstly, the energy deposition of the first bunches in a target with FLUKA is calculated. The effect of the energy deposition on the target is then calculated with a hydrodynamic code, BIG2. The impact of only a few bunches leads to a change of target density. The calculations are done iteratively in several steps and show that such beam can tunnel up to 30-35 m into a target. Validation experiments for these calculations at LHC are not possible, therefore experiments were suggested for the CERN Super Proton Synchrotron (SPS), since simulation studies with the tools used for the LHC also predict hydrodynamic tunneling for SPS beams. An experiment at the SPS-HiRadMat facility (High-Radiation to Materials) using the 440 GeV beam with 144 bunches was performed in July 2012. In this paper we compare the results of this experiment with our calculations of hydrodynamic tunneling.

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To predict the damage for a catastrophic failure of the protections systems for the LHC when operating with beams storing 362 MJ, simulation studies of the impact of an LHC beam on targets were performed. Firstly, the energy deposition of the first bunches in a target with FLUKA is calculated. The effect of the energy deposition on the target is then calculated with a hydrodynamic code, BIG2. The impact of only a few bunches leads to a change of target density. The calculations are done iteratively in several steps and show that such beam can tunnel up to 30-35 m into a target. Validation experiments for these calculations at LHC are not possible, therefore experiments were suggested for the CERN Super Proton Synchrotron (SPS), since simulation studies with the tools used for the LHC also predict hydrodynamic tunneling for SPS beams. An experiment at the SPS-HiRadMat facility (High-Radiation to Materials) using the 440 GeV beam with 144 bunches was performed in July 2012. In this paper we compare the results of this experiment with our calculations of hydrodynamic tunneling.

INTRODUCTION

The Large Hadron Collider beam at 7 TeV has 362 MJ of stored energy, enough to melt 500 kg of copper. At the end of a physics fill or in case of a failure, the beams are safely deposited by extracting them into a 700 m long transfer line, diluting the density and finally absorbing the energy in large graphite blocks. Several failures could lead to the beam deflected with non-nominal angle, into a 10 m long graphite absorber, into a septum magnet, or into superconducting magnets [1].

Extensive simulation studies of the full impact of the ultra-relativistic proton beam generated by the LHC on solid targets of different materials (e.g copper) have been carried out over the past years. A study performed for a copper target show that the high pressure produced in the target after the energy deposition by only 100 proton bunches generates a radially outgoing shock wave that lead to a substantial reduction in the density at the center. The protons in subsequent bunches will penetrate much deeper into the target. It was predicted that the LHC protons can penetrate up to 25 m in solid copper [4].

To validate the simulation method, an experiment was performed at the HiRadMat facility using the 440 GeV beam from the CERN Super Proton Synchrotron (SPS) [3], providing beams with a Gaussian width (sigma) ranging from 0.2 mm to 2 mm.

To assist designing of suitable experiments, extensive numerical simulations of heating of solid copper cylinders using the SPS beam were performed [4]. A hydrodynamic tunneling effect is also observed in these simulations. The main objective of the experiment was to reproduce the hydrodynamic tunneling effect. Further objectives was to develop instrumentation for performing such experiments. The preliminary results of the experiment were already reported in [5].

SPS-HIRADMAT EXPERIMENT

Setup of the Experiment

The target consists of three assemblies of fifteen copper cylinders each, spaced by 1 cm. Each cylinder has a radius of $r = 4$ cm and length of $L = 10$ cm. The three assemblies of cylinders are enclosed in an aluminium housing that provides rigidity to the setup and prevents any contamination of the facility. The front and rear faces of the target are covered with an aluminium cap. The caps are made of cylinders of 4 cm radius and a length of $\sim$ 18.5 cm. Each cap has a 1 cm hole that allows the beam to pass through. Fig. 1 shows the target before the installation into HiRadMat. The target is mounted onto a moveable table. The table can be moved to four different positions: target 1, target 2, target 3 and off-beam position.

The setup was equipped with pCVD diamond particle detectors, PT100 temperature sensors, strain gauges and secondary electron emission particle detectors to obtain additional information during the beam interaction time of about 7.2 μs for beams with 144 bunches and 50 ns bunch spacing. A detailed analysis of the measured pCVD diamond particle detector signals is discussed in [6].

Experimental Phases

The experiments were performed in July 2012. Initially, the target was irradiated with low intensity beams, with single bunches of $5\times10^9 - 2\times10^{10}$ and beam sizes of $\sigma = 0.2\,\mathrm{mm}$. In a next step the target was irradiated

Figure 1: Target with 3 assemblies, each with 15 copper cylinders. The aluminium enclosure and caps are not shown.

Table 1: Beam parameters of the destructive tests for the three targets.

Target	# bunches	Beam size σ [mm]	Stored beam energy [MJ]	Peak energy density [kJ/cm^3]	Expectation
1	144	2.0	1.52	63.3	no tunneling
2	108	0.2	1.14	181.6	some tunneling
3	144	0.2	1.52	242.2	tunneling

with a series of six to twelve high intensity bunches up to $1.8{\times}10^{11}$ protons.

The last part of the experiment, the destructive test to demonstrate hydrodynamic tunneling, was performed with high intensity beam (see table 1). The beams had a bunch spacing of 50 ns and intensities of $\sim 1.5 \times 10^{11}$ p/bunch. After the target was irradiated it was left for cool down for 8 months and opened in February 2013.

Results from Opening the Target

When the copper melts or vaporizes, material escapes through the spaces between the copper cylinders and the entry hole created by the beam in the first cylinder. This material is visible, both in the caps and outside the target. Fig. 2 shows the front aluminium cap after the irradiation of the target. Splashes of target material projected back into the front cap are clearly visible. The cap in front of target 1 shows no splashes. For target 3 there was significantly more material projected into the cap than for target 2. This result is confirmed by a visual inspection of the front surfaces of the three targets, which showed that the front face of target 1 was not damaged. For target 2 a slight damage was observed, and for target 3 a hole at the position of the beam impact was clearly visible.

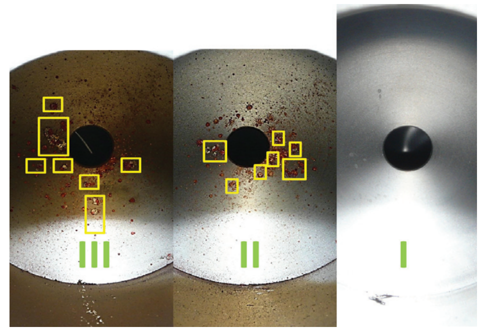

Figure 2: Splashes on the front aluminium cap (III=target 3, II=target 2, I=target 1), indicating that the front face of target 1 was not damaged. For target 3 there is significantly more material projected from the first cylinder into the aluminium cap than for target 2.

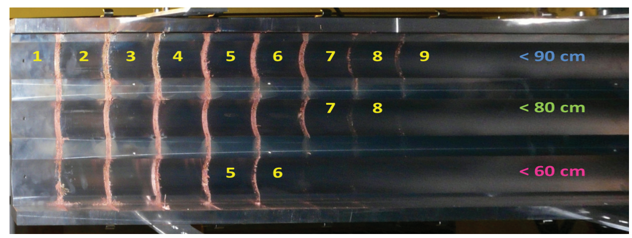

Figure 3: Top cover of the experimental set-up after the irradiation. Traces of projected copper between the 10 cm long cylinders of the targets indicate the length of the melting zone. For target 1 (bottom) the molten zone ends in the 6th cylinder, i.e. the copper was molten over a length of 55 ± 5 cm. For target 2 (mid) the molten zone goes up to cylinder 8, i.e. 75 ± 5 cm. For target 1 (top) the molten zone goes up to cylinder 9, i.e. 85 ± 5 cm.

The targets are enclosed in an aluminium housing. After beam impact molten material is projected to the outside, in particular against the top cover (see Fig. 3). These projections allow to estimate the depth of the damaged zone without a destructive analysis of the cylinders or a tomographic scan and provide an idea if hydrodynamic tunneling took place or not. The traces of projected copper between the 10 cm long cylinders of the targets are clearly visible. For target 1 (bottom) the molten zone ends in the 6th cylinder, i.e. the copper was molten over a length of 55 ± 5 cm. For target 2 (mid) the molten zone goes up to cylinder 8, i.e. 75 ± 5 cm. For target 3 (top) the molten zone goes up to cylinder 9, i.e. 85 ± 5 cm.

As the updated simulations with the combination of FLUKA [7] and the hydrodynamic code, BIG2, are still ongoing, FLUKA simulations have been performed with the beam parameters of the experiment to calculate the expected energy deposition in the three targets. The expected length of the molten zone without hydrodynamic tunneling when reducing the beam size from 2 mm to 0.2 mm was calculated.

Table 2: Comparison of the expected and measured length of molten zone. The simulations were solely performed with FLUKA, thus, the results show the expectations if no hydrodynamic tunneling takes place.

Target	Simulated	Δ to target 1	Measured	Δ measured-simulated
	[cm]	[cm]	[cm]	[cm]
1	49 ± 5	-	55 ± 5	6
2	65 ± 5	16	75 ± 5	10
3	69 ± 5	20	85 ± 5	16

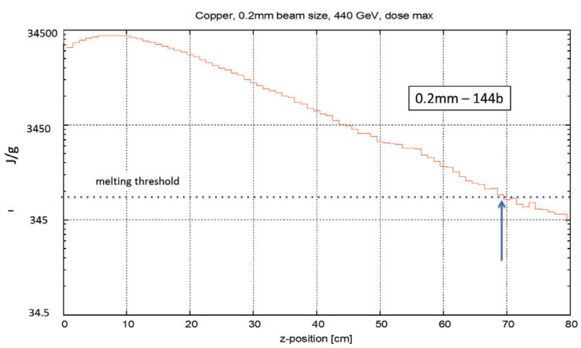

Figure 4: Simulated energy deposition in a copper target along the beam axis. The beam parameters are the same as for target 3 ($\sigma = 0.2$ mm, 144 bunches of $\sim 1.5 \times 10^{11}$ p/bunch). The dashed blue line indicates the melting point of copper (620 J/g). This simulation shows that the length of the molten zone would be expected to be 69 ± 5 cm without hydrodynamic tunneling.

Fig. 4 shows the energy deposition in the copper target along the beam axis for the beam parameters of target 3. The dashed blue line indicates the melting threshold of copper. The expected length of the molten zone without hydrodynamic tunneling is derived from these simulations. Table 2 compares the expected lengths of the molten zone to the measured lengths. For target 1 the measured molten zone is similar to what is expected. The length predicted by the simulation increases to 65 cm for beam impacting on target 2 and to 69 cm for beam impacting on target 3.

This is significantly different from the experiment, where the measurements show an increase of the length of the molten zone with respect to the simulations by 16 cm for target 3 and 10 cm for target 2. Thus, this is a strong indication of hydrodynamic tunneling.

CONCLUSIONS

A material damage experiment to verify the simulation of high intensity beam impacting on material predicting hydrodynamic tunneling has been successfully performed in CERN's HiRadMat facility with different beam sizes and intensities. The visual inspection of the target in February 2013 allowed to determine the length of the molten zone for the three different targets. Preliminary FLUKA simulations, which only take into account the energy deposition, show that the length of the molten zone in target 3 measured after the experiment can only be explained by an additional effect of hydrodynamic tunneling. A final answer to what extent hydrodynamic tunneling has been observed can only be given when the results for the combined FLUKA and BIG2 simulations with the beam parameters used during the experiment are available. Further investigations of the copper cylinders of the target e.g. with ultrasonic tomography could reduce the uncertainties in the length of the molten zone and therefore ease the understanding of the experimental results.

The knowledge acquired during the preparation and realization of the experiment will help to design and perform future experiments. Especially the diamond particle detectors used in the experiment have shown to be excellent tools for on-line monitoring of beam impacts. The SPS HiRadMat facility has a huge potential to further investigate and understand the damage potential of the LHC and future accelerator beams.

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REFERENCES

[1] J. Uythoven et al.. Possible Causes and Consequences of Serious Failures of the LHC Machine Protection Systems. Proceedings of EPAC 2004, Lucern, Switzerland, 2004.

[2] N.A. Tahir et al. J. Appl. Phys, vol. 97, p. 083532, 2005.

[3] I. Efthymiopoulos et al. A new irradiation facility for material testing at CERN. Proceedings of IPAC2012, New Orleans, NM, USA, 2012.

[4] N.Tahir et al. Impact of high energy high intensity proton beams on targets: Case studies for Super Proton Synchrotron and Large Hadron Collider. Phys. Rev. Special Topics Accel. Beams, vol. 15, p. 051003, 2012.

[5] J. Blanco et al. An experiment on hydrodynamic tunneling of the SPS high intensity proton beam at the HIRdmat facility. Proceedings of HB2012, Bejing, China, 2012.

[6] F. Burkart et al. Diamond Particle Detectors Properties during High Fluency Material Damage Tests and their Future Applications for Machine Protection in the LHC. Proceedings of IPAC2013, Shanghai, China, 2013.

[7] G. Battistone et al. The FLUKA code: Description and benchmarking. AIP Conference Proceeding 896, 31-49 (2007), 2007.