AN EXPERIMENT ON HYDRODYNAMIC TUNNELLING OF THE SPS HIGH INTENSITY PROTON BEAM AT THE HiRadMat FACILITY

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Abstract

The Large Hadron Collider (LHC) and the future linear colliders operate with very high energy stored in the beams (in the order of several hundred MJoules for LHC) or very high power (for linear colliders). Beam sizes are small, for the LHC down to 10 µm, for linear colliders below one µm. It is important to understand the damage potential of such high energy beams to accelerator equipment and surroundings. What are the consequences of a full LHC beam impact in material, e.g. in case the extraction kickers for the beam dump would deflect the beam with wrong angle?

Simulations have shown that in case of an impact of the full LHC beam onto a solid copper target the beams can penetrate up to 35 m [1] as compared to 140 that is the typical penetration length for 7 TeV protons (hydrodynamic tunneling). For this simulation, a typical Gaussian transverse intensity distribution with $\sigma = 0.2\,\mathrm{mm}$ was assumed. The total number of protons per beam is 3×10^{14} that corresponds to an amount of energy of $362\,\mathrm{MJ}$, sufficient to melt $500\,\mathrm{kg}$ copper. Calculations of the impact of dense high intensity proton beams into material have been presented in several papers [1, 2, 3, 4].

How confident are we in these simulations? This paper introduces an experiment designed to reproduce the hydrodynamic tunneling effect that is predicted by simulations and describes the layout of the experiment and the instrumentation. The experiment was performed at the High Radiation to Materials (HiRadMat) facility at the CERN-SPS from the 22nd of June 2012 to the 12th of July 2012.

Results consistent with tunneling of protons in matter are presented. However, further analysis, new simulations with parameters similar to those in the experiment and postmortem inspection are required to precisely evaluate the tunneling depth and propagation speed.

MOTIVATION

Extensive simulation studies of the full impact of the ultra-relativistic proton beam generated by the Large Hadron Collider (LHC) on solid targets of different materials of interest have been carried out over the past years. The response of a solid copper cylindrical target that was facially irradiated by one LHC beam along the axis was simulated. These simulations were done using a two-dimensional hydrodynamic computer code, BIG2 [5]. The energy deposition of the 7 TeV/c protons in copper was calculated with the FLUKA code [6] assuming solid target density. This data was used as input to the BIG2 code. This study showed that the high pressure produced in the deposition region after energy deposition by only 100 proton bunches generated a radially outgoing shock wave that led to a substantial reduction in the density at the center. In practice, the protons in subsequent bunches will penetrate much deeper into the target. It was predicted that the LHC protons can penetrate between 10–40 m in solid copper.

The experimental verification of the numerical simulations is very important from the machine protection point of view. However, this is not possible with the LHC beam. Already in 2005, a beam impact experiment [7] was performed in the CERN-SPS TT40 extraction line. Up to 8×10^{12} protons were shot onto a target and the onset of damage was measured. FLUKA simulations and experimental observations agreed, however these results cannot be extrapolated to LHC regime since the beam intensity was far below the onset of hydrodynamic tunneling.

For this purpose, an experiment was performed at an experimental facility named HiRadMat [8] (High Radiation Materials). To assist designing of suitable experiments, extensive numerical simulations of heating of solid copper cylinders using the SPS beam were performed [1]. Hydrodynamic tunneling effect is also clearly observed in these simulations. Confirmation of the existence of this phenomenon in the HiRadMat experiments will partially validate the simulations for the LHC beam.

The experimental main objective is to reproduce the hydrodynamic tunneling effect observed in simulations. Further objectives are to measure density, temperature and shock waves during the beam-target interaction. However, the success of the experiment was not linked to the operation of the detectors since a thorough investigation of the target after the experiment will show if there was hydrodynamic tunneling. The additional information gathered with the instrumentation will improve the understanding of the experiment.

SPS-HIRADMAT

The HiRadMat facility is dedicated to beam shock impact experiments. It is designed to allow testing of accelerator components, in particular those of LHC, to the impact of high-intensity pulsed beams. It provides a 440 GeV proton beam or a 497 GeV/A ion beam. The proton beam has a minimum focal size of 0.2 mm, thus providing a very dense beam (energy/size). The transversal profile of the beam is considered to be Gaussian with a tuneable sigma ranging from 0.2 mm to 2 mm.

This facility allows to study High Energy Density physics as the energy density is high enough to create plasma in the core of materials such as copper or tungsten and to produce strong enough shock waves that creates a density depletion channel along the beam axis (hydrodynamic tunneling effect) [9, 10].

SPS-HIRADMAT EXPERIMENT

Target Description

Figure 1 and 2 show the target setup. The target consists of three assemblies of fifteen copper cylinders each, called target 1,2 and 3. The cylinders within a assembly are aligned and separated from one to another by 1 cm. Each cylinder has a radius of $r = 4\,\mathrm{cm}$ and length of $L =$10 cm. These values have been chosen as a compromise between materials cost ($\sim r^2$), waste material ($\sim r^2$) and safety ($\sim r$, $\sim L$). The three assemblies of cylinders are enclosed in an aluminum housing that provides rigidity to the setup and at the same time prevents contamination of the facility. The front and rear faces of the target are covered with an aluminum cap. In this way, only those faces are exposed to the air. The caps have a radius of $r = 4\,\mathrm{cm}$, a length $L = 18.5\,\mathrm{cm}$ and an entrance hole of radius $r =$1 cm that allows the beam to pass through.

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

The target is mounted on a moveable table. The table can be transversally moved to four different positions: target 1, target 2, target 3 and off-beam position (the motion system uses a DC motor, a variable resistor and a set of switches to control the position). The entire setup has been built in a way that it can be remotely opened with a crane. After an adequate cool down period of at least four months, the target will be opened and inspected.

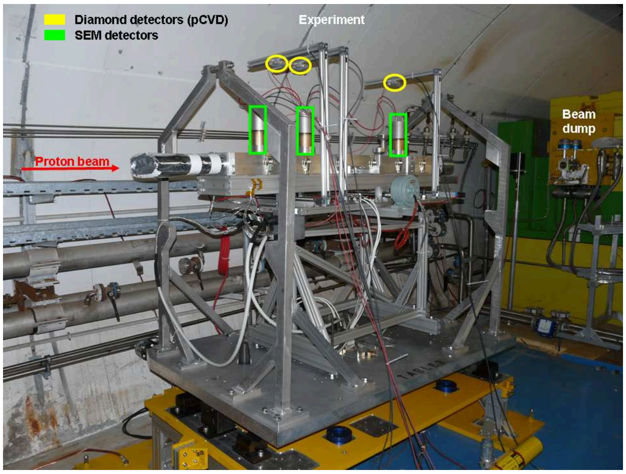

Figure 2: Experiment setup on the movable table at HiRadMat.

Detector Description

The setup is equipped with several types of detectors to obtain additional information during and directly after the beam interaction time (which takes about 7.2 µs for beams with 144 bunches).

- Three diamond detectors (pCVD) for measuring the scattered particles during the beam passage are placed at 50 cm above the 4th, 5th and 13th cylinders, longitudinally along the beam axis. The detectors do not move with the table and are fixed to the beam axis position. The detector's face is oriented perpendicular to the beam direction. Diamond detectors are radiation hard monitors with nanosecond resolution and a large dynamic range, that can be used to detect single particles (the conditions under which they were operated in the experiment exceeds the regimes found in literature). Each detector has an effective area of $7\,\mathrm{mm}^2$ and a thickness of $\sim$100 µm. The rounded gold electrodes have a 1.5 mm radius. The bias voltage between the gold electrodes is 1 Vµm. The expected fluence, from simulations, ranges from 10^8 to $10^9\,\mathrm{particles/cm}^2$ for the impact of a single proton bunch. The expected diamond signal is $\sim$5 A, which gives $\sim$250 V across the oscilloscope internal resistance. As this is too high, a set of current dividers (20 dB and 40 dB) has been used during the experiment.

- Three Secondary Electron Emission (SEM [11]) detectors are placed on top of the aluminum sheet, due to the lower efficiency than pCVD, over the 3rd, 6th and 13th cylinders. The bias voltage for the SEM detectors is 1.5 kV.

- A minute after the beam impact, the temperature of each block is determined by the penetration of the beam. The longitudinal temperature profile of the third target can be measured and compared to simulations, to get an independent estimation of the penetration range. PT100 temperature sensors are glued to the second block of each target. Five more PT100 sensors are glued to the 4th, 6th, 8th, 10th and 12th cylinders of the third target.

- Strain gauges measure the vibration on the surface of the cylinder. The frequency and strength of the vibration can be deduced. A set of four strain gauges are placed on the third cylinder of the second target.

Experimental Phases

Phase I.a On the 22nd of June, 2nd and 3rd of July th target was irradiated with low intensity beams, with on bunch of $5\times10^9 - 2\times10^{11}$ and a beam size of $\sigma \approx$0.2 mn During this phase, the correct operation of the detecto was verified. Reproducibility and linearity of the diamon detector signal was also tested. Figure 3 shows the diamond response at the oscilloscope for $\sim 8.9\times10^9$ protons at target 2. Figure 4 shows a very good linearity between the diamond detector No.3 signal and beam intensity. The beam intensity was measured with a beam current transformer in the SPS.

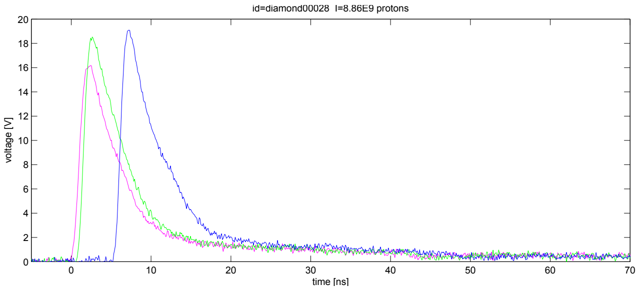

Figure 3: Signal from diamond detector 1(pink), 2(green) and 3(blue) during the impact of one low intensity shot on target 2.

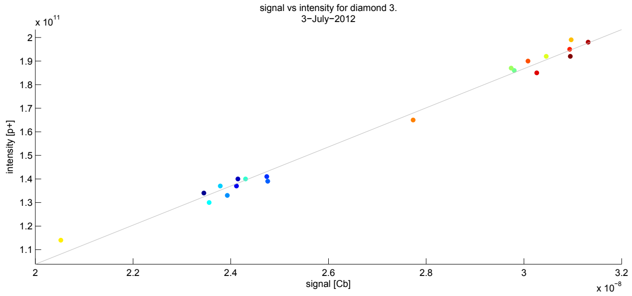

Figure 4: Diamond detector 3 linearity (signal vs beam intensity).

Phase I.b As the first shots with low intensity single bunch beams were successful. On the 6th of July, the target was irradiated with a series of beams with six and twelve high intensity bunches in order to verify that the bias voltage of the diamond detectors does not decrease due to an insufficient capacity on the high voltage side. It was also verified that the time between bunches, 50 ns, was sufficiently large for the diamond to recover its initial state e.g. that the diamond can resolve single pulses within a batch. It was observed that a 50 mV offset grows during the first 2 bunches, and remains stable for the rest of the pulse. The process behind this offset is not yet understood, it is most likely due to charging of a parasitic capacity. Figure 5 shows the diamond signals during the irradiation of the target with six high intensity bunches. The above discussed stability of the bias voltage and the growth of the signal offset can be seen here.

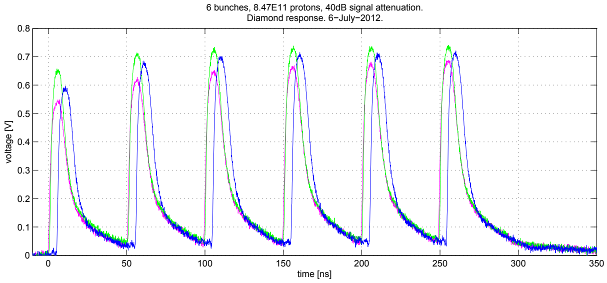

Figure 5: Signal from the diamond detector 1(pink), 2(green) and 3(blue) during the impact of six high intensity bunches on the target.

Phase II The destructive irradiation of the target during phase 2 of the experiment to demonstrate hydrodynamic tunneling was performed on the 12th of July. Target 1 was irradiated with 144 bunches of 1.5×10^{11} protons per bunch separated by 50 ns. The beam sigma was very large, about 2 mm in both planes (hor. and ver.). Target 2 and 3 were irradiated with 108 and 144 bunches of 1.5×10^{11} protons per bunch and a small beam size of σ =0.2 mm on both planes (ver and hor). The separation between bunches was 50 ns.Hydrodynamic tunneling is expected on target 2 and 3. As the beam size during the irradiation of target 1 was relatively big, tunneling was not expected. This data can therefore be used to calibrate the readout for the other two targets.

Phase III After the target was irradiated it is left for cool down for at least 4 months. A preliminary study [12] of the activation of the copper cylinders shows that after a 4 month period it will decrease to ∼90 µSv/h on the surface and to ∼375 µSv/h in the center. The target will be remotely open, using the crane, for visual inspection. For the moment, it is not foreseen to do any destructive test on the copper targets.

Experimental Results

Figures 6–8 show the diamond response during the irradiation of target 1 (large size beam, no tunneling). The expected diamond signal is constant with time. However, the obtained signal decreases with time. This behavior can be explained by a progressive discharge of the high voltage capacitor that keeps the bias voltage across the diamond electrodes. This decrease provokes a decrease in the collection charge efficiency and an increase of the collection time.

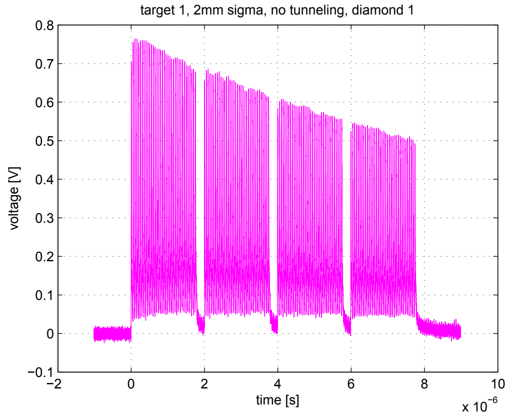

Figure 6: Signal from the diamond detector 1 and target 1 (large beam).

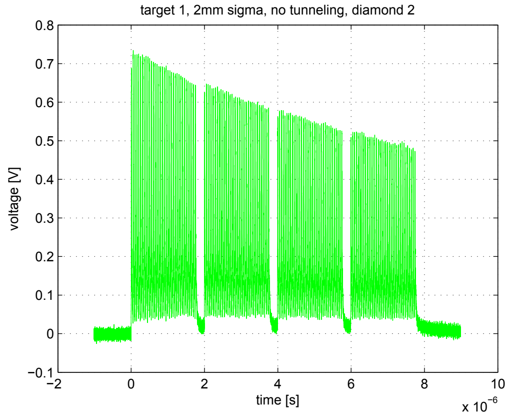

Figure 7: Signal from the diamond detector 2 and target 1 (large beam).

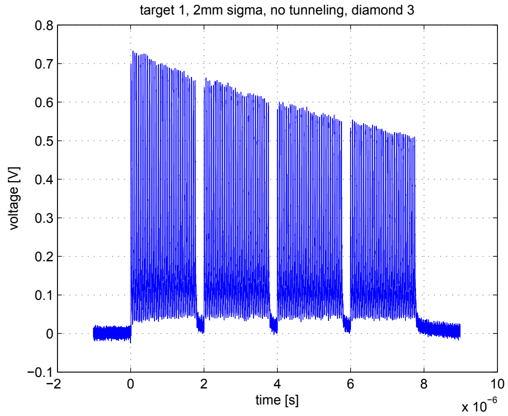

Figure 8: Signal from the diamond detector 3 and target 1 (large beam).

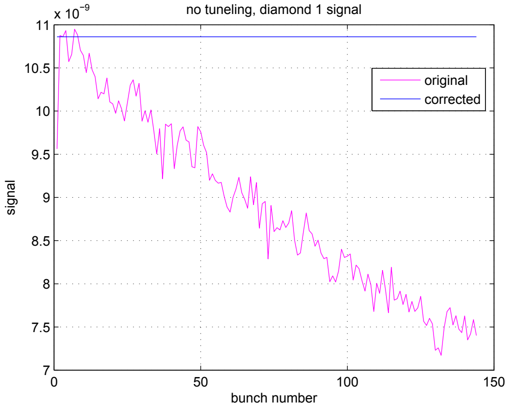

Figure 9: Target 1, diamond 1 corrected integrated signal per bunch.

Assuming that all bunches have the same intensity and should give the same signal, we can correct for this effect. The correction uses the information of the signal per bunch but it does not correct individually the amplitude or the FWHM. The corrected signal per bunch is shown in Figure 9 and the correction factors as a function of the bias voltage drop are shown in Figure 10.

These correction factors are applied to correct the diamond signals recorded during the irradiation of target 2 and 3 (small beam size, tunneling expected). Figures 11–13 show the measured and corrected signal. The signal from the first diamond points to a decrease in the number of secondary particles with time. On the contrary the signal from the third diamond points to an increase in the number of secondary particles. The signal from the second diamond does not show an increase or decrease of the signal with time.

According to simulations, detectors placed in the upstream part of the target will experience a decrease of signal while the ones placed at the downstream part will experience an increase of signal. The signal of the detectors located at the middle, close to the maximum of the fluence, will not experience a significant change with time [13].

The measurement results indicate that hydrodynamic tunneling took place during the irradiation of target 3. Compared to the simulations performed earlier the tunneling progressed slower.

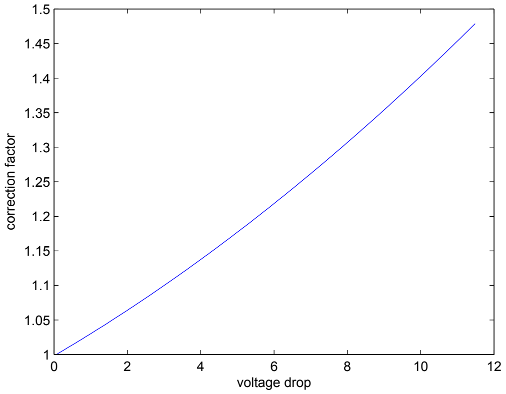

Figure 10: Target 1, diamond 1 correction factors.

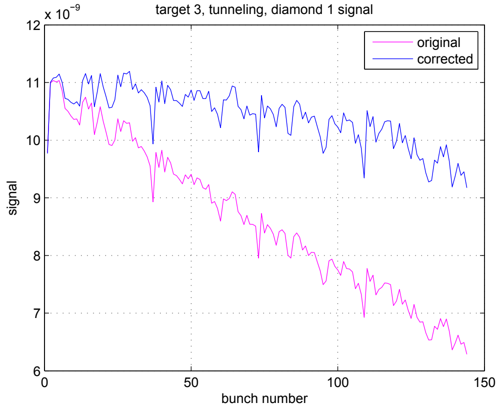

Figure 11: Target 3, diamond 1 corrected integrated signal per bunch.

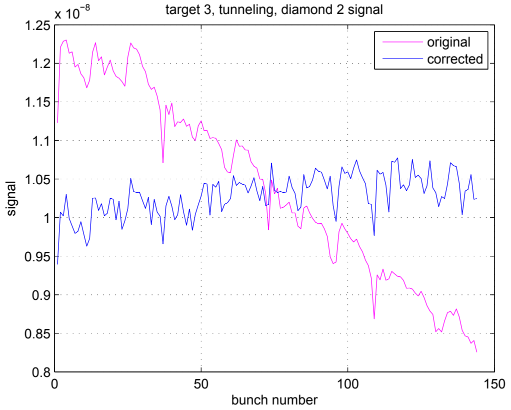

Figure 12: Target 3, diamond 2 corrected integrated signal per bunch.

To further understand this behavior it is planned to repeat the simulation with the exact beam parameters used during the experiment. In addition the experiment will be opened and the targets will be inspected visually after a sufficient cool down time to verify in what target hydrodynamic tunneling has been created.

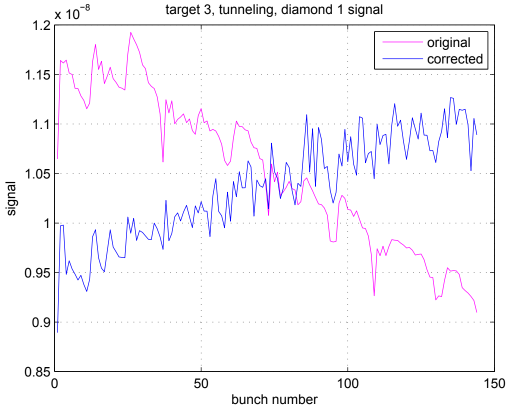

Figure 13: Target 3, diamond 3 corrected integrated signal per bunch.

Results from the other instruments (PT100, SEM and strain gauge sensors) are still being analysed and will be subject of a future publication.

CONCLUSIONS

It is the first time that a hydrodynamic tunneling experiment with a high-intense and high-dense beam has been done.

The experiment was a success. Results show evidence of hydrodynamic tunneling on a High-Z material using a high intensity high brightness beam from the SPS. This result is qualitatively in line with expectations from simulations. For the time being it is not yet possible to precisely evaluate the penetration depth and tunneling speed. However, a post-mortem analysis will be performed when the target will be opened before the end of year 2012 to address these questions. It is also planned to redo the simulations with the same parameters as used during the experiment and to further analyse the data from the different detectors.

During the tests, diamond detectors developed together with CIVIDEC [14] have demonstrated, under extreme conditions, to be a very attractive option due to their radiation hardness, speed, dynamic range and simplicity.

The knowledge acquired during the preparation and realization of the experiment will help to design and perform future experiments. 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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