Laser-driven cylindrical compression above solid density as a testbed for fast-ignition experiments

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Introduction

The fast-ignition approach to the inertial confinement fusion scheme requires a warm and dense plasma in which hot electrons propagate [1]. Until now, many of the experiments carried out on this subject were designed to study transport in cold planar targets at standard density. Such experiments may exhibit a different behaviour of the hot electrons transport issues, compared to the final design. In order to get closer to this objective, the cylindrical geometry can be an important step to be studied as we have access [2]. Very few laser installations are now able to be set up in such a geometry, while having an additional short-pulse beam to produce the hot electrons as necessary for fast-ignition. Two slots on the Vulcan laser facility, within the HiPER project, have been allocated. One of the slots, reported here, consists to cylindrically shock compress a target. The objective of this first part was to determine the characteristics of the compressed matter i.e. its temperature and density at optimal compression. The second part of the experiment will aim to study the electron propagation inside this dense matter.

Experiment setup

Four long-pulse laser beams (4 × 50 J in 1 ns) at 0.53 µm, focused to 150 µm FWHM spots, were used to compress a 200 µm long polyimide tube with a 220 µm outer diameter and a 20 µm wall thickness, as shown on Fig. 1. This tube was filled with plastic at different densities: 0.1, 0.3 g/cc foam, or 1 g/cc solid. Both sides were closed with 20 µm thick foils of Cu and Ni, respectively. The four ns beams timing had been individually set to hit the target at the same time with a precision better than 100 ps. An additional laser (100 J in 1 ps) was used as a backlighting source for the diagnostics. The delay τ between the long pulse

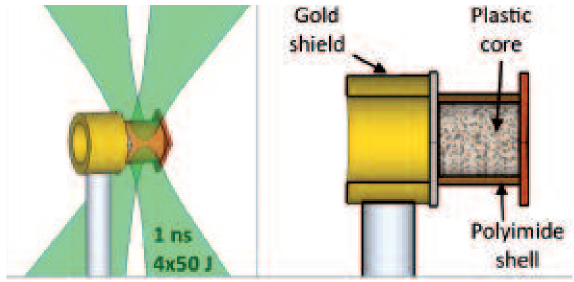

Figure 1. Target and lasers design.

beams and the short pulse one was adjustable from 0 to more than 3 ns. For instance, with τ = 0, the short pulse hit the target when the long pulses just arrived. This delay τ presented a jitter of ± 100 ps.

An absorption spectrometer was set up in order to measure the plasma temperature inside the cylinder, but it will not be reported in this paper as we couldn't extract useful data from it. Side-view point-projection proton radiography was used to measure the target density [3]. The proton source was produced by the short pulse beam focused on gold foils, placed 10 mm away from the target. The detector was a Radio Chromic Film (RCF) stack protected by a 12 µm thick Al foil, placed ~ 50 mm away from the target. Density measurement was also achieved with a X-ray radiography diagnostic [4]. Using Ti foils 10 mm away from the target as backlighters and a quartz crystal to reflect the Ti-K_α radiation (at 4.5 keV) that passed through the compressed target, we obtained a magnification of ~ 10. In order to get an important absorption of these X-rays, the plastic foam was doped, for this diagnostic only, with 30% Cl in mass. The quartz crystal (interatomic distance 1.374 Å) was spherically bent with a radius of curvature 380 mm.

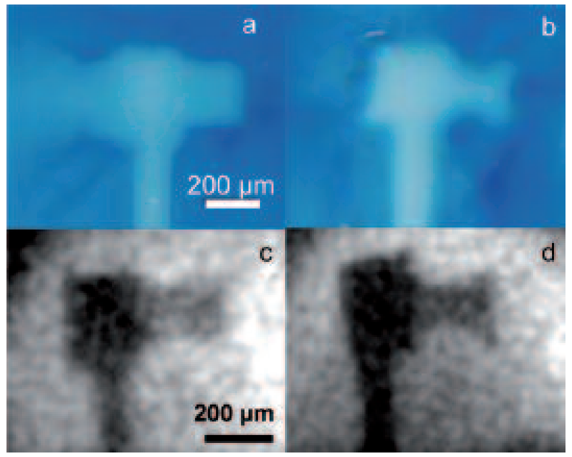

Figure 2. Proton radiography images of (a) an uncompressed target and (b) a compressed one with τ = 2.2 ns. X-ray radiography images (c) 500 ps before maximum compression and (d) at maximum compression (τ = 2.2 ns).

Imaging plates, ~ 2 m away from this crystal, detected the Ti-K_{α} radiation.

In order to predict the cylinder compression, hydrodynamic simulations, using the 2D CHIC code from CELIA, were carried out.

Results and discussion

Proton radiography examples are shown in Fig. 2(a,b). Measuring the cylinder width on the experimental images show that the difference between the uncompressed cylinder and the others denotes noticeable compression. The limited proton energy obtained (< 7 MeV) induced a restricted resolution due to scattering effects. Furthermore, the first RCFs in the stack collect both the protons that were created with a low energy, and the ones that were created with a high energy but slowed down while passing through the plasma. Thus, the protons passing early through the target get mixed with the late ones, giving a decreased temporal resolution. This effect also affects the spatial resolution as the target size evolves with time. In order to take all these effects into account, we developed a monte-carlo code simulating the proton trajectories inside the plasma. This code is a modified version of PROPEL[5]. Given 2D density maps of the compressed cylinder obtained from the hydrodynamic simulations – the outgoing protons gave a resulting profile of the cylinder on the different RCFs, that was compared to the experimental profiles. An example is shown in Fig. 3. The results are well in agreement between experimental data and simulations. One can also notice that the obtained diameters of ~ 150 µm are well above the theoretical diameters of the cylinder core (50 to 100 µm). This is due to the low energy of the protons: they cannot escape from the core, so we obtain an image of the large low-density plasma surrounding the compressed core.

X-ray radiography had the advantage of being able to probe higher plasma densities. The core diameter was more accurately measured thanks to the Cl doping. Examples are shown in Fig. 2(c,d). As for proton radiography, the cylinder FWHM was measured for

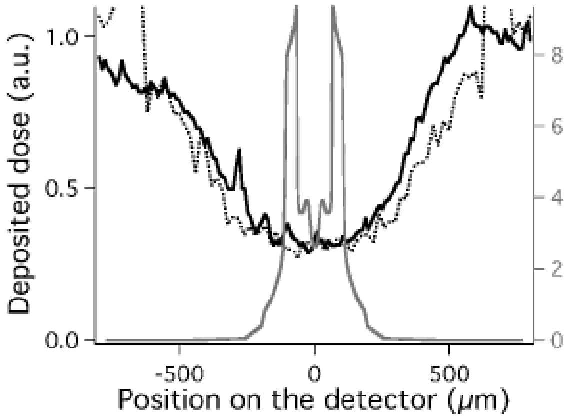

Figure 3. Proton radiography profile. Experimental (dark solid line) and calculated (dotted line) results are plotted. The gray line is the corresponding simulated density profile.

each shot. In order to compare with the hydrodynamic code results, X-ray absorption simulations through 2D density map have been carried out. It shows that the measurement of FWHM is a good estimation of the core diameter. Both experimental and simulated results are compared in Fig. 4. The 0.1 g/cc results are not in perfect agreement with the expected diameter, but the little number of available data makes the comparison difficult. However, the good agreement for 1 g/cc targets indicates an efficient compression, as predicted by the hydrodynamic simulations.

Overall, the simulated evolution of the cylinder radius reproduces well the experimental data for targets initially at 1 g/cc. The density at maximum compression can then be estimated from these hydrodynamic simulations. We obtain a fairly stable mean density in the core of 3 g/cc for τ from 2.2 to 2.7 ns, and an electronic temperature of ~ 15 eV. The peak density in the central area is 8 g/cc.

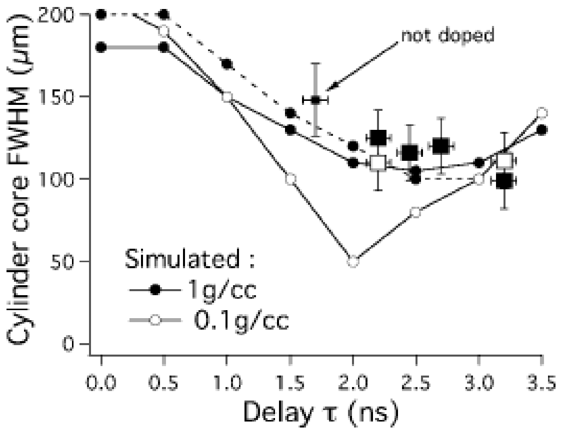

Figure 4. X-ray radiography measurements of the cylinder diameter along time. Solid or open dots correspond to cylinders initially filled with 1 or 0.1 g/cc plastic respectively. The lines with dots correspond to the simulated diameter (dashed line: no Cl doping).

Conclusion

This first phase of the HiPER experiment performed on fast electron transport in cylindrically compressed target showed a final diameter of the cylinder about 100 µm. This value corresponds to expected ones given by the 2D radiative code CHIC for reduced energy in the long pulse beams. In the next phase, the temperature and density deduced from simulations will be used as input for the transport in the compressed core of the cylinder.

Acknowledgements

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