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Novel diagnostic of low-Z shock compressed material

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Abstract

An experiment was performed using high-energy protons, generated by an intense short laser pulse, to try to characterize in situ, the spatial and temporal evolution of a laser-driven shock propagating through a low-Z material. Radiography of the shock propagating through the low-Z transparent material could lead to density determination under compression. A first test of a proton radiography of the rear-side released state of a shocked aluminum foil has also been tried.

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1. Introduction

The knowledge of Equation of State (EOS) and related parameters of dense matter is important in several fields of physics. For instance, in astrophysics the star evolution is mainly governed by the thermodynamic properties of matter. Planet cores EOS is also fundamental for the knowledge of their internal structure [1]. Inertial Confinement Fusion (ICF) success is also directly related to the understanding of shell pellet implosion and the final core compression. Both of these processes necessitate a precise knowledge of the microballoon material and the fuel (deuterium) EOS at very high pressures [2] (>100 GPa).

Shock-wave-EOS experiments require that two parameters, usually the shock and fluid velocities, be measured to infer the thermodynamic properties of the material. While a few experiments have used X-ray radiography on low-Z materials to determine both velocities [3], most of them [4,5] rely on the

shock velocities measurement (via optical interferometry in transparent media or by observation of shock breakout times on steps of known thickness in optically opaque materials). The latter technique results in indirect EOS determinations through a method known as impedance matching. In opaque high/mean Z materials, it is not possible to get information about the shock characteristics inside the sample and then to measure fluid velocities directly. In this case, impedance matching is the only route to get data. Moreover, in measurements based on velocity determination, it is impossible to have a good precision on such an important physical quantity as density due to error amplification going through Rankine–Hugoniot relations. The development of direct probing techniques to obtain information on another shock parameter, such as density, would allow precise absolute EOS determinations and represent a real breakthrough in this field.

A first attempt was therefore conducted using high-energy protons, produced by the interaction of an intense laser pulse, in a point projection imaging scheme, to characterize in situ the spatial and temporal evolution of a laser-driven shock propagating through a low-Z material. The particular properties of laser-driven protons beam (small source, high degree

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of collimation, short duration) make them of great interest for radiographic applications [6]. The proton profile in the beam should undergo due to collisional stopping power the density profile in the crossed matter leading to the determination of the density in the shock. Experiments similar to one described here, but in a different context, have been conducted using high explosives to drive a shock in a metal and a high-energy proton beam (800 MeV) from conventional accelerators to probe it [7]. These experiments were dedicated to the study of spallation, i.e., in a pressure regime much lower than the one we are interested in.

2. Experimental principle and setup

The experiment was performed on the 100 TW laser facility at the Laboratoire pour l'Utilisation des Lasers Intenses (LULI). The shock was generated by focusing a 60 J – 550 ps Gaussian pulse – at 1053 nm on a multilayer target. To eliminate large scale spatial intensity modulations and to obtain a flat intensity profile in the focal spot, we used a phase zone plate [8]. The resulting focal spot had a 300 μm FWHM diameter with a 150 μm flat top profile, leading to a maximum average intensity about $6 \times 10^{13} \text{ W cm}^{-2}$. The target (Fig. 1) was composed of a low-Z ablator (4–6 μm CH) to minimise preheating and a pusher (25 μm of aluminum). A low-Z material sliver (Lexan, quartz, diamond, LiF) was glued on this foil. This material was chosen to limit the protons scattering in the sliver, which could reduce significantly the spatial resolution. Due to the maximum intensity achievable, the ablator–pusher thicknesses were designed to give a maximum pressure in the pusher about 5 Mbar, as steady as possible. In order to infer directly the shock velocity in the transparent material, two VISAR [9] were implemented around the target chamber. The probe laser beam was 8 ns long and we used two colours ($\lambda = 1064, 532 \text{ nm}$) scheme as recently developed at LULI [10].

The proton beam was generated with an ultra high intensity short pulse 30 J – 350 fs – 1053 nm focused by an F/3 off-axis parabola. The resulting focal spot was about 15 μm leading to an average intensity of $3 \times 10^{19} \text{ W cm}^{-2}$. The proton

Fig. 1. Target design: the CH layer is the ablator, the aluminum foil the pusher. The shock generated by the long pulse beam propagates in the low-Z sliver. Proton beam probes the shock perpendicularly as it propagates into the sliver.

beam was created by irradiating a thin 15 μm aluminum foil [11,12] and detected through a stack of several layers of radiochromic film. A 25 μm thick aluminum filter was placed in front of the first radiochromic film layer giving minimum detectable proton energy about 3–10 MeV. The proton source was 2 mm away from the main target, the RC film being in a position such that the magnification was about 12 (Fig. 2).

3. Shock data

Because of the too short transverse dimension of the sliver, the shock strength (i.e. the achieved point in the phase diagram along the principal Hugoniot curve) could not be inferred by the VISAR. Therefore we performed several shots on aluminum stepped targets in order to determine the achievable pressure and to associate the laser energy to the numerical intensity used in our hydrodynamic code (MULTI [13]) to reproduce the data. We were therefore able to get a relation between the shock velocity and the intensity needed in our 1D code to get a good agreement between simulation and experiment. For instance, in shots made on stepped target (2.5 μm CH, 8.5 μm Al, 3.7 μm Al step), the delay observed (Fig. 3) in the shock breakouts was $\Delta t = 150 \text{ ps}$ resulting in a shock velocity about $D = 23 \text{ km/s}$. Such a velocity corresponds to

Fig. 2. Experimental setup.

Fig. 3. VISAR image obtained with an aluminum step target. Fringes extinction corresponds to the shock breakout. From the time difference between the top and the bottom of the step, the mean shock velocity in aluminum is deduced.

a pressure ≈ 8 Mbar for an intensity of $6 \times 10^{13} \text{ W cm}^{-2}$. We also performed some shots on thicker targets, with the same thickness than our ablator–pusher ones (20 μm CH, 20 μm Al, 10 μm Al step). In that case, the shock mean velocity in the step is lower (17 km/s) being obviously non-steady due to the “short” duration of our long pulse beam. However, we could reproduce accurately this data with the code, according to the laser energy, so the state of the targets (Fig. 1) can be inferred numerically with a good confidence.

4. Propagation of the shock in quartz

Among the different shots we performed on the transparent materials, the quartz case represents a paradigm, the sliver quality being excellent and the results corresponding to typical trend. Fig. 4 shows a 6 MeV proton image of the shock propagating in the quartz sliver. On this image, only half of the proton beam is observed, the other part being cut by the

ablator–pusher part and the target holder. In the rectangular part representing the sliver, the protons are slow down and scattered by the quartz. The question is whether we could infer the density in the shock during its propagation through the quartz sliver or not. Protons are slowed down while they are crossing the sliver and the beam intensity decreases at the same time. The bright region outside the sliver acts as a reference for the original beam intensity. As shown in Fig. 4, the high compression induced by the shock wave is not visible on the proton image whatever the protons energy is (only the 6 MeV image is presented here). The line profile (dotted line) presented in Fig. 4b is obtained along the axis as presented in Fig. 4a. It shows the 6 MeV protons intensity directly coming from the proton target and crossing the quartz sliver. The profile presents a strong decrease that corresponds to the proton propagation in the quartz. Propagation in the quartz slows down the incoming protons. For example 6 MeV protons will lose, due to collisions, around 2 MeV while crossing 150 μm SiO_2 [14]. Proton angular distribution being highly sensitive to its energy [15], adding the effect of the scattering in the sliver, it does explain the important difference between the proton profile crossing the sliver and the proton propagating on its side.

The absence of signature in the proton profile of the shock wave could be explained by the scattering of the protons in the sliver. Monte Carlo simulations were made using density profile of the shock in quartz given by 1D simulations (Fig. 5). It calculates energy loss and scattering of protons while propagating into the shocked matter. In this figure black curve represents 22 MeV proton profile and the blue curve 7 MeV proton profile in the detector plan. It shows that the decrease in proton profile induced by the overdensity in the shock front is visible only if the energy proton is high enough to limit the scattering effect. Otherwise the spatial resolution is so strongly reduced than the shock front signature in the proton profile disappears.

5. Release state of an aluminum foil

In the direct drive scheme, a precise knowledge of the state of the expanding plasma at the backside of the imploding shell

Fig. 4. (a) Proton image on the quartz sliver when a shock is propagating into. The square shadow corresponds to the proton absorption in the sliver, the bright circle to the protons around it. (b) The curve corresponds to the protons profile along the white axis in (a). Distances are taken in the detector plane, including the magnification.

Fig. 5. Density profile in the quartz 7 ns after the long pulse peak given by 1D simulation. MC calculation for the proton beam that propagates through the quartz using the 1D density profile is presented in the same figure. Blue curve correspond to 7 MeV proton profile and the black curve to 25 MeV proton profile. The decrease in the proton profile observed on the black curve correspond to the shock front position, it is not visible on the blue curve (7 MeV proton) because of the strongest effect of the scattering at this lower energy (for interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

is required. Development of instabilities is related to uniformity [9] of the compression, therefore, studies have been carried out to diagnose the effect of laser imprints on the homogeneity of the compression at the backside of an aluminum foil [16] and also influence of preheating on the backside expansion of an aluminum foil [17]. During this experiment, the release of a single aluminum foil (15 μm) was probed 7 ns after the rear-side breakout (Fig. 6). A highly contrast boundary between vacuum and the moving expanding foil is observed. From Fig. 6, the shift of the foil was determined by considering that the edge of the image denotes its initial position. We found a value equal to 100 μm , which corresponds to a mean velocity of 14 km/s.

In principle this could be caused by two effects: (1) a rapid density jump causing proton density enhancement at the edge

[18]; (2) an electric field at the edge of the slowly expanding plasma deflecting the protons outwards [19].

In order to discriminate between these two possible effects, we compared the experimental results to simulations including both 1D hydro code (for the foil status 7 ns after the pulse) and Monte Carlo (MC) for the proton propagation in the shocked expanding foil (Fig. 7). The large scale spatial dimensions observed on the proton image were consistent with the results of the 1D hydro code. The density foil decreases from 2.7 g/cc to about 0.5 g/cc and its width expands from 20 μm to 80 μm . The foil position after 7 ns (100 μm) is also consistent with the hydro calculations.

Nevertheless, the MC calculations cannot reproduce the observed proton pile-up using the density profile given by the hydro code. The result (Fig. 7) shows an absorption of the proton beam due to the density jump. However, the scattering is then too low to explain the experimentally observed phenomenon. Simulations have been made to reproduce the experimental profile, the density shape given by hydro code is modified so that the dose profile exhibits a pile-up. The results are presented in Fig. 8. In this case, the simulated dose fits the experimental one, but the hydro profile is slightly modified from the initial one presented in Fig. 7. The proton profile is highly sensitive to the steepness of density gradient.

Second possibility is the existence of an electric field, for example to a strong diffusion effect of electrons as compared to ions due to their small mass [17]. Estimation of the electric field at the front shock could be realized using Ref. [17]. Assuming a 5 eV temperature and a density around 10^{23} cm^{-3} , electric field strength is in the order of 10^7 V/m . Assuming that protons probe this field on a 400 μm length, resulting deviation of the proton trajectory is 20 μrad which is not visible on RCF film. From the MC simulations and the electric field estimation, we can conclude that this pile-up observed in the proton profile is induced by a sharp density profile that our hydro code (MULTI) cannot reproduce.

6. Conclusions

A novel diagnostic has been developed to probe highly compressed matter. A short – 1 ps – laser generated proton

Fig. 6. (a) Proton image of an aluminum foil 7 ns after the long pulse beam. (b) Distribution of the proton beam intensity along the axis shown in the left figure. The pile-up of the protons corresponds to the position of the foil 7 ns after the long pulse interaction.

Fig. 7. Density profile given by 1D hydro simulations and proton profile given by MC calculations using the hydro profile. On the same image the experimental curve is shown in red. Using the profile given by the hydro code, the simulated dose profile does not fit the experimental PDS density profile (for interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

beam has been used to probe a laser generated shock-wave propagation in the quartz sliver or released from an aluminum foil. This first attempt shows that to probe a shock wave propagating in a quartz sliver the proton mean energy has to be high enough (around 25 MeV) to limit the scattering in the sliver.

Proton imaging of release state of a shocked aluminum foil gives a high contrast imaging of motion of a supercritical density surface. Monte Carlo simulations show that the hydro

profile given by the 1D hydro code MULTI has to be modified so that the simulation fits the experimental data. This mismatch between the experimental data and the simulation point out some limitation in the description of the release state by hydrodynamical simulations at these late times (7 ns after the peak of the laser). More attention should be focused and specific design should be made in further experiment to study this particular state of matter (release), which has many implications in several branches of physics.

Fig. 8. Density profile given by 1D hydro simulations and proton profile given by MC calculations using the hydro profile. On the same image the experimental curve is shown in red. The density profile has been modified so that the simulated profile (in red) fits the experimental one. The position is magnified and is in microns (for interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

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