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Density measurement of low-Z shocked material from monochromatic x-ray two-dimensional images

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An experiment on LULI 2000 laser devoted to density determination of shocked plastic from a two-dimensional monochromatic x-ray radiography is presented. A spherical quartz crystal was set to select the He-α line of vanadium at 2.382 Å and perform the image of the main target. Rear side diagnostics were implemented to validate the new diagnostic. The density experimental results given by radiography are in good agreement with rear side diagnostics data and hydrodynamical simulations. The pressure regime into the plastic is 2–3 Mbar, corresponding to a compression between 2.7–2.9.

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I. INTRODUCTION

The knowledge of highly compressed matter ($P > 1$ Mbar) equation of state (EOS) is important in different domains: inertial confinement fusion (ICF), astrophysics and geophysics [1]. Hydrodynamic codes usually use EOS data (e.g., SESAME tables [2]) that come from theoretical calculations and semi-empirical models. Over the last decade, a big effort has been realized to produce EOS experimental data with the aim of validating predictions given by theory or discriminating between different models. Reliable experimental data have been obtained on EOS surfaces up to tens of megabars thanks to laser driven shocks [3–5]. Indeed, the laser shocks are the only tool for studying high pressure regimes. Despite this important progress, the precision of these data is still not sufficient to solve some open questions. An example is the hydrogen controversy, where experimental measurements [6,7] are not able to discriminate between two different theoretical models: a stiffer EOS with a fourfold compression [8–10] or a softer one with a sixfold compression [11] depending on the platform used. To determine EOS in laser shock experiments [7], the fluid and/or shock velocity are measured. In most experiments, only shock velocity is obtained via optical interferometry in transparent media or by observation of shock breakout times on steps of known thickness in optically opaque materials. These measurements result in *indirect* EOS determinations through a technique known as impedance matching [12]. In low-Z materials a few experiments have used x-ray radiography to determine both velocities [13]. Other thermodynamical parameters of shock compressed matter are extracted from Hugoniot–Rankine relations. Unfortunately, this results in amplification of errors, especially on density, as the compression occurs as a multiplier factor.

The development of techniques for direct probing of shocks and for obtaining information on another shock parameter inside the compressed sample (e.g., *density*) simultaneously to the velocities measurements, would represent a real breakthrough in this field. This would allow us to reduce uncertainties and to have an absolute EOS measurement.

An attempt to determine density in the multimegabar regime using a laser shock and time resolved x-ray radiography has been performed by Hammel *et al.* [13]. The shock curvature was not taken into account, leading to an underestimation of the density. More recently, a two-dimensional (2D) point projection image of a shock into a plastic target has been achieved by using a 5 keV x-ray thermal source [14]. The same 2D point projection technique has been used to deduce the density of shocked aluminum by using a hard x-rays source given by Molybdenum K-α radiation at 17 keV [15]. In all previous works, the crucial point to obtain quantitative information on density has been the spectrum knowledge. To free oneself from the spectrum determination, we performed a monochromatic x-ray 2D image of a shock into a plastic sample. We choose plastic since its EOS has been largely investigated in the considered regime of pressure [16]. A precise measurement of plastic density has been obtained and cross checked with results given by other usual diagnostics such as velocity interferometry system for any reflector (VISAR) or self-emission.

II. EXPERIMENTAL SETUP

The two beams of the LULI 2000 facility delivering 400 J at 2ω in 1.5 ns have been used (Fig. 1). One beam, generating the shock, was smoothed by phase zone plate (PZP) and focalized on a 500 μm flat top focal spot, giving an intensity on the target around 5×10^{13} W/cm^2. The main target was composed of an ablator-pusher foil (10 μm CH-10 μm Al-10 μm CH) and a plastic sliver glued on it, where the shock was x-ray imaged. The beam used to generate the x-ray source was smoothed by random phase plates (RPP) and focalized on a 100 μm focal spot to reach intensities around 10^{15} W/cm^2. The backlighter target was a very thin layer of vanadium (0.1 μm) deposited on a plastic support. The aim of the thin layer was to reduce the time duration of

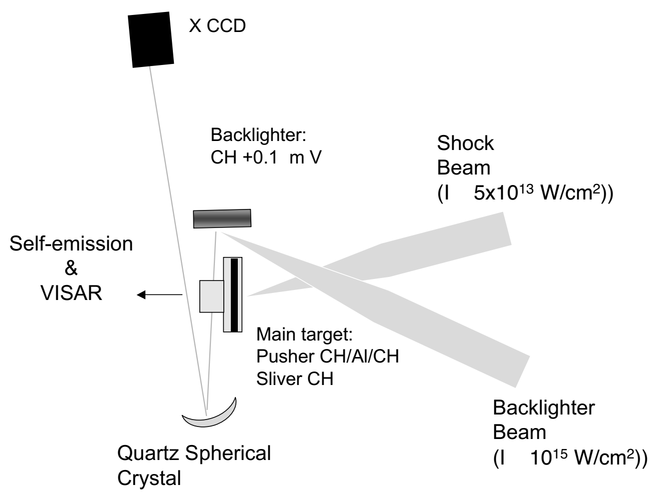

FIG. 1. Experimental setup.

the x-ray emission, as we will discuss below. A spherical quartz crystal (11–20 orientation with $2d=4.9$ Å) with $R=150$ mm was set to select the He_{α} resonant line at 2.382 Å and perform an image with a magnification of $G=10$ of the main target on an x-ray CCD. On the rear side we had self-emission and VISAR diagnostics that allowed us to measure the shock velocity in the plastic and to deduce the compression, independently from the x-ray diagnostic, by using EOS SESAME tables previously validated [16].

The main diagnostic is a monochromatic x-ray backlighting the scheme of which is shown in Fig. 2. Contrary to the traditional backlighting scheme, in which a spherically bent crystal is used near normal incident angle and backlighter source at Rowland circle, the crystal was far enough from normal angles, the backlighter source inside the Rowland circle and the detector between meridional and sagittal foci of the object. Indeed we could not use a traditional scheme (optimized to have a good resolution in the two directions) since the restriction on the angle of incidence limits the wavelength range. Our scheme has been studied to have a good resolution in the direction of shock propagation and to limit astigmatism in the other direction. The resolution depends on source size and magnification. The source size is proportional to the illuminated part of the crystal that determines the wavelength field of view. The choice of a 100 μm source is a compromise between a good resolution and a reasonable field of view. Indeed, a resolution around 10 μm (see Fig. 2) was obtained in the direction of the shock propagation, with a test shot on a gold grid with 400 lines per inch (on the perpendicular direction the resolution was 25 μm). This resolution has been evaluated by taking the spatial interval Δx associated to 90% and 10% of the transmitted values. To distinguish the spectral line to use to image the shock, we performed some preliminary shots with CCD positioned to have all the spectrum around Heα lines. We used the most intense line for our plasma conditions.

Regarding the backlighter source, we choose an *ad hoc* target to minimize the probing time. The x-ray emission duration coincides with the laser pulse duration, so we were restricted to radiograph the shock for 1.5 ns. This time is large enough so the shock typically moves around 30–40 μm according to the measured shock velocities. Therefore, the quality of the image and the precision of density measurement could be seriously affected.

To reduce the probing time, we used a very thin layer of vanadium (0.1 μm) deposited on plastic. In this way, the vanadium is ablated and its electron density very quickly drops down. To determine the x-ray source duration, a calculation based on hydrodynamical simulation coupled with

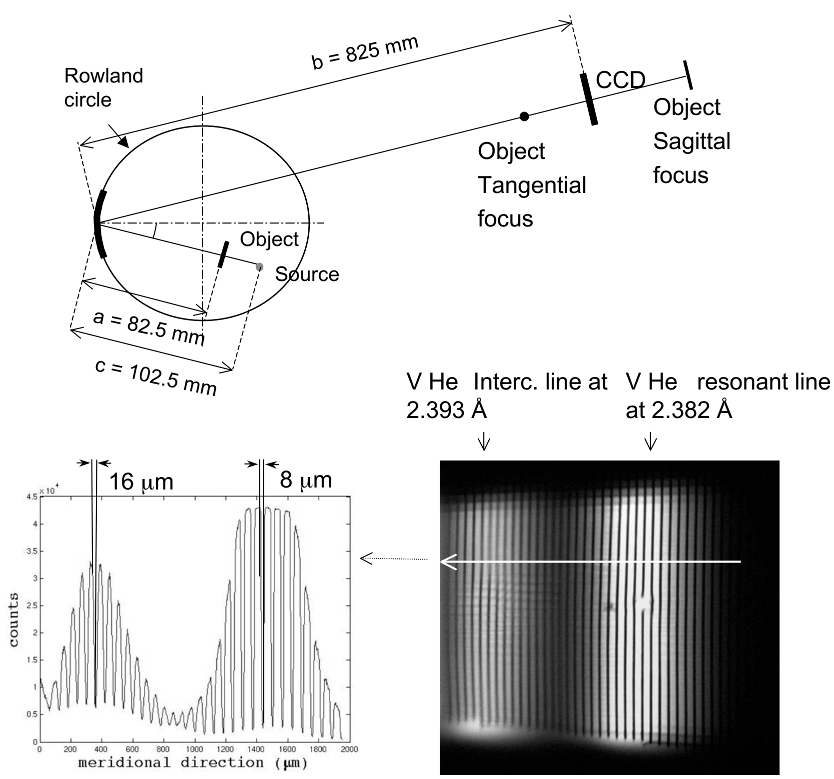

FIG. 2. 2D x-ray imaging diagnostic scheme and 2D image of a gold grid with its profile. One can observe the spatial resolution less than 10 μm in a field of view around 800 μm in the region of the He-α resonant line and less than 20 in the region of the intercombination line. This is due to spherical aberrations.

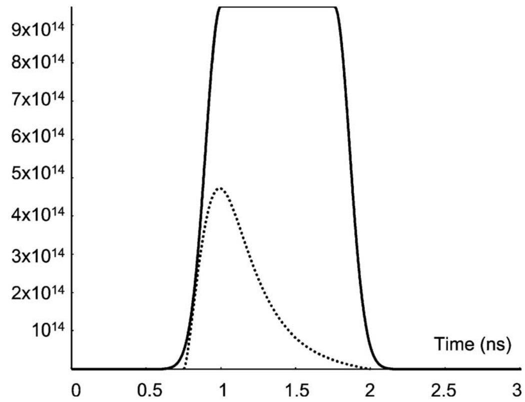

FIG. 3. Solid line: laser pulse. Dotted line: x-ray emission (arbitrary units).

opacities obtained by FLYCHK [17] code has been performed. In this way, we were able to have a "snapshot" of 400 ps of the shock, instead of 1.5 ns (see Fig. 3). Considering the shock velocity to be around 18 μm/ns, the shock front moves 7 μm, which is less than our spatial resolution.

III. EXPERIMENTAL RESULTS AND ANALYSIS

A. Radiography diagnostic

The plastic sliver was probed at different times with respect to the main beam. A mean shock velocity can be deduced by measuring the shock position at two different times (Fig. 4). We obtained 18 km/s, in good agreement with hydrodynamical simulations that predict 19 km/s.

A preliminary estimation of the density can be then performed, if we just consider the transmission profile along the shock propagation axis (see Fig. 5). A transmission of (50 ± 2) % into the cold plastic has been measured, in agreement with tabulated values and (23 ± 2) % of transmission has been detected into the shocked plastic. Now, if we suppose the size of shocked region to be around 300 μm, one can deduce a compression of 2.7 ± 0.3. By this method the compression is underestimated since the curvature of the shock is not taken into account as the shocked region is overestimated.

Therefore, a correct analysis requires one to take into account the curvature of the shock. We can notice that the observed absorption is a line integral of the local absorption, so an inversion must be performed. The shock symmetry, given by using RPP, allowed us to use typical Abel inversion techniques. In the Beer-Lambert law $I/I_0=\exp(-\mu\,\boldsymbol{\rho z})$, only one parameter is not known: the areal density $\boldsymbol{\rho z}$, which is only function of density. Indeed, I/I_0 is the absorption and it

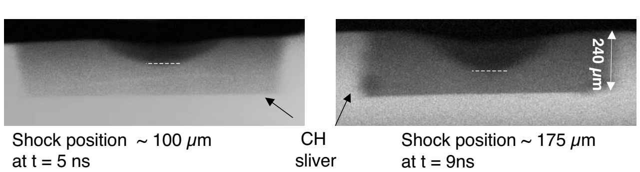

FIG. 4. Two images of the shock, obtained at two different times.

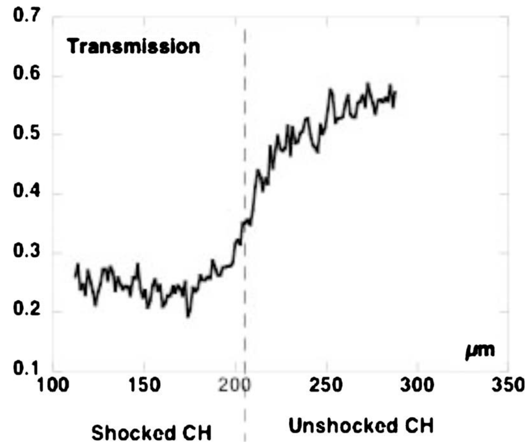

FIG. 5. Transmission along the shock propagation direction.

is measured by analysis images and μ is the opacity, which is obtained by tables. In our case of azimuthal symmetry, the areal density can be expressed into a formula that can easily be Abel inverted. In Fig. 6, we show a profile taken on the front of the shock, perpendicular to the shock propagation axis. On the front of the shock, we measured a compression of 2.85. To evaluate the error bars, we calculated that, by using as input experimental I/I_0 values with an incertitude around 8%, the error propagation through the Abel inversion gives an error around 10% on density. By also including the incertitude on target thickness, the final error is $\pm12\%$ (i.e., the experimental compression is then 2.85 ± 0.34).

B. Rear side diagnostics

Rear side diagnostics allowed us to have independent density determination *via* the measurement of the shock velocity, as the plastic EOS is well known in our pressure regime (2–3 Mbar). In Fig. 7 a typical image obtained with VISAR interferometer is presented. One can notice a sudden dark region beginning at time t_1 and finishing at time t_2. Such a phenomena can probably be associated to a pre-ionization of the glue at the interface between the pusher and the sliver. The glue was a UV-cured optics bond glue and its typical thickness was 1–5 μm. In this way, the plastic becomes opaque when the shock breaks out from the pusher. Similar pre-ionization effects have already been observed and studied by Theobald *et al.* [18]. Anyway, if we compare measured shock velocity, when the fringes reappear, with the

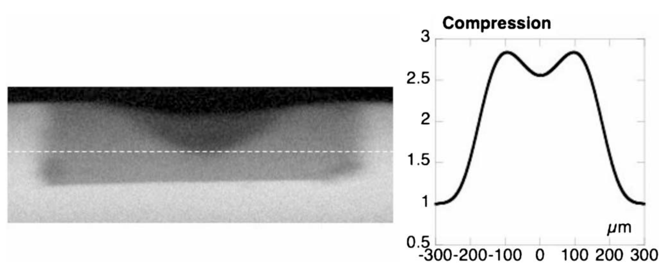

FIG. 6. Experimental 2D x-ray image of the shock with compression profile perpendicular to the shock propagation direction, given by Abel inversion.

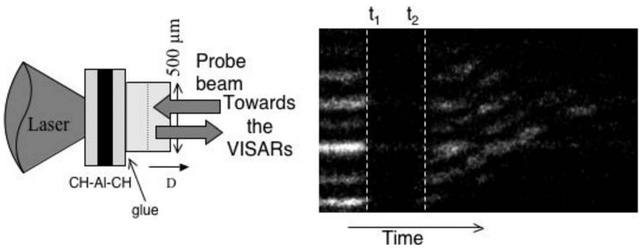

FIG. 7. Typical image obtained with VISAR diagnostic.

shock velocity given by hydrodynamical simulations, we find a very good agreement (as can be seen in Fig. 8). The decreasing velocity as a function of time is due to the nonsteadiness of the shock.

We also extrapolated, by simulation results, the shock velocity at typical radiography time (9 ns after the main laser pulse). We found 17 μm/ns that corresponds to a compression of 2.86, coincident with compression obtained by radiography.

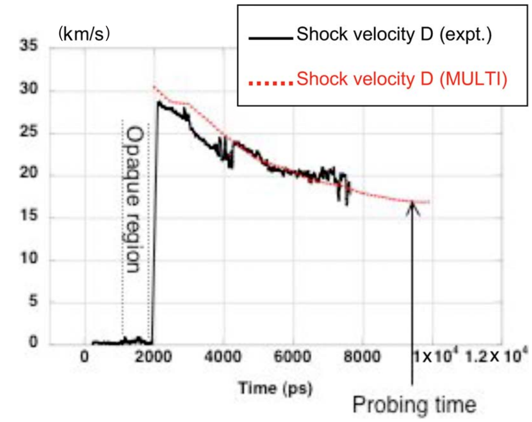

FIG. 8. (Color online) Shock velocity extracted by VISAR image compared with resulting 1D hydrodynamical simulations.

IV. CONCLUSION

We demonstrated that 2D x-ray monochromatic radiography imaging *can be* a reliable diagnostic to measure the density of a low atomic number. Its precision (around $\pm 12\%$) is good compared to usual error bars on density deduced by Rankine–Hugoniot relations in laser shock experiments (typically ± 20–30%) [19]. The crucial point is the data inversion processing that requires a shock symmetry. Advanced Abel inversion methods that took possible deviations from symmetry into account can be applied. Moreover, the precision was not the most important goal of the experiment, but by our results we demonstrated that x-ray 2D monochromatic radiography is a diagnostic with a good potentiality. In particular, the monochromacity makes this technique a high performance diagnostic: then its development for the future is necessary to make significant progress in our knowledge of warm dense matter physics. Moreover, it could be an interesting diagnostic for incoming large facilities such as MégaJoule Laser (LMJ) and National Ignition Facility (NIF) to measure density of low-Z materials used in ICF target designs.

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