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Optical smoothing techniques for shock wave generation in laser-produced plasmas

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Shock wave experiments have been performed at the Laboratoire pour l'Utilisation des Lasers Intenses in a regime of interest for inertial confinement fusion and equation of state measurements. Laser beams have been optically smoothed either with random phase plates or with phased zone plates. This last technique allowed the production of a flat-top intensity distribution in the focal spot and hence of flat shock fronts. High quality shocks have been produced and used with stepped targets to allow direct measurements of shock velocity by time-resolved imaging of shock breakthrough at the rear of irradiated targets.

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I. INTRODUCTION

The study of shock wave dynamics is very important in the framework of laser-driven inertial confinement fusion. Moreover, it is important to study the equation of state (EOS) of materials in extreme pressure conditions (P_s of the order of some tens of Mbar to 1 Gbar). Hugoniot and shock relations indeed allow the determination of one EOS point once two shock related quantities (such as shock velocity, fluid velocity, shock temperature, etc.) have been measured. But before such measurements can be performed, it is necessary to produce very high quality shocks (i.e., very flat in space and with constant pressure in time) to allow quantitative results on EOS determination. One of the main problems in realizing high quality shocks is inherent to the use of coherent laser light, which produces lack of uniformity in the irradiation due to beam modulations by interference effects. Such nonuniform illumination produces strong pressure nonuniformities which, in the past, have prevented the use of lasers as a quantitative tool in high pressure physics, even if several experiments [1–3] have clearly demonstrated that very high pressures were indeed obtained.

There are two possibilities of overcoming such a difficulty. The first one is based on the conversion of coherent laser radiation into incoherent soft x rays inside a laser heated cavity (*Hohlraum*). Thin foil targets are then uniformly irradiated by exposure to the intense soft-x-ray Planck radiation emitted from such a cavity. Recently this approach, with the use of the colliding foil technique, has allowed estimated pressures of about 0.75 Gbar to be obtained [4]. In this case anyway the authors do not discuss in detail the quality of the shocks they obtained. In another experiment performed by Lower and co-workers [5,6], much lower pressures were obtained (≤ 10 Mbar with the single foil technique) but shock quality was carefully checked.

General problems of the indirect approach are its low efficiency due to the intermediate step of x-ray conversion, and an induced x-ray preheating of the shocked target. The second solution, which constitutes the main subject of this article, is to use direct-laser drive with optically smoothed laser beams.

Our results have been obtained with single foil targets by looking at shock breakthrough with time-resolved rear imaging of the thin irradiated targets with a visible streak camera. Initially the laser beam was smoothed with random phase plates (RPP's). Such a well known technique [7] assures a very good control of laser energy deposition and laser focal spot shape, allowing reproducible results, but unless very large focal spots are used, which is not feasible with our laser energy, does not allow the production of the flat shocks needed for precise studies on shock wave dynamics and EOS. Hence in the development of the experiment, we used the new technique of phased zone plates (PZP's) [8] which allowed the production of a flat-top intensity distribution of laser light in the focal spot and hence of flat shock fronts.

II. EXPERIMENTAL SETUP

The experiment has been performed at the Laboratoire pour l'Utilisation des Lasers Intenses (LULI), Ecole Polytechnique, and some preliminary results have been presented in [9,10]. It is based on the detection of the emissivity, in the visible region, of the target rear face, illuminated on the other side by the laser beam. A photographic objective imaged this face onto the slit of a visible streak camera in order to record the variations in time of this emission. The system magnification was $M=22$, allowing a ≈ 5 μm spatial resolution which was measured imaging a suitable grid. We note that according to diffraction theory, the elementary speckles, produced with both RPP's and PZP's, are smaller than our resolution and hence cannot be evidenced in our experimental results.

Thin aluminum foils (5–25 μm) were used as targets. We used either simple foils to check the shock quality (especially to control the flatness of the shocks produced with PZP's) or stepped targets to measure shock velocities. In this last case, to achieve a good accuracy in the measurement of the shock breakthrough time in the two steps, it is very important to have a step as sharp as possible (step gradient of only a few μm) [11].

The experiment has been performed with three of the six LULI laser beams (converted in second harmonic, $\lambda=0.53$

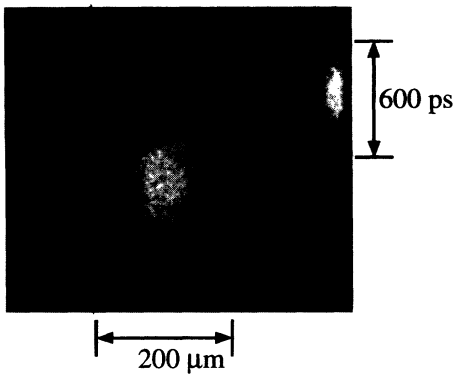

FIG. 1. Rear side shock breakthrough for a 18 μm Al target. Optical smoothing is realized with RPP's giving a measured focal spot diameter FWHM=106 μm. Time fiducial is on the right of the image.

μm, with total laser energy $E_{2\omega}\approx 100$ J) focused onto the same focal spot. The temporal behavior of the laser pulse was Gaussian with a full width at half maximum (FWHM) of 600 ps. A fourth beam, also converted to 2ω, was used as temporal fiducial. Each beam had a $\Phi = 90$ mm diameter and was focused on target with a $f=50$ cm lens.

An equivalent plane diagnostic was implemented for controlling the laser focal spot. The system was based on an imaging objective (Olympus 50 mm, 1/1.2, the one used to image the target rear side onto the streak camera slit) and a charge-coupled-device (CCD) camera (12 bits, 512×512 pixels). A removable mirror allowed the image to be directed to the CCD or to the streak camera, so that we had an almost "on line" control of the focal spot shape which could be very easily checked between two shots on targets.

Finally an active x-ray pinhole camera looking at the target on the laser side, at 22.5° with respect to the laser beam plane, was used to check plasma formation and image the focal spot in the x-ray domain.

III. MEASUREMENTS WITH RPP'S

In the first experiment, the beams were optically smoothed with RPP's to produce a homogeneous Gaussian focal spot. A large focal spot ($\geqslant 100$ μm) was used in order to reduce two-dimensional (2D) effects giving an intensity on target $I_L \leqslant 3\times 10^{14}$ W/cm^2. Figure 1 shows a typical streak camera image obtained with a 18 μm Al target. These data were obtained with the streak camera scale of 100 ps/mm. Shock velocities were of the order of $D\approx 30$ μm/ns with a typical dispersion of $\pm 10\%$. By carefully checking laser energy and foil thickness, we obtained more reproducible results allowing the use of a 50 ps/mm time scale and achieving a ≈ 5 ps time resolution (working with a 100 μm slit on the streak camera).

The shape of the image is due to the Gaussian focal spot (at the edge, the laser intensity is lower and shock waves travel at lower speed). Such a shape is reproducible "shot by shot" with no evidence of localized earlier shock breakthroughs due to hot spots.

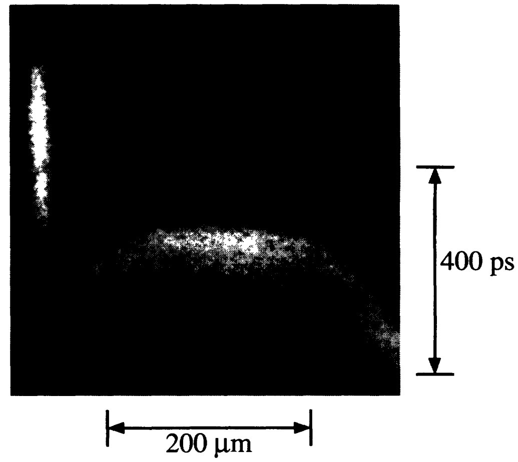

FIG. 2. Rear side shock breakthrough for a 13.8 μm Al target. Optical smoothing is realized with PZP's giving a measured focal spot diameter FWHM=400 μm. Time fiducial is on the left of the image.

IV. MEASUREMENTS WITH PZP'S

Even if RPP's can assure a good spatial control of laser energy deposition and focal spot shape, the Gaussian shape of the focal spot makes difficult the use of produced shocks for EOS measurements. Hence in our second experiment we used the PZP beam smoothing technique obtaining a top-hat intensity distribution in the focal spot. As a result, 2D effects are almost completely eliminated (around the center of the focal spot) and high quality flat shock waves are generated as otherwise can be produced only be indirect x-ray drive.

Phased zone plates [8] are made of a Fresnel lens array, each with a very long focal length $f_Z = r_0^2/\lambda$. The combined focal length is hence $f_T \approx f$, and the focal spot diameter $d = d_Z f/f_Z$, where r_0 is the inner zone diameter, d_Z the diameter of each Fresnel lens, and f the focal length of the focusing lens. Also Fresnel lenses are randomly dephased of 0 or π to break the laser beam spatial coherence and give smoothing effects as in RPP's.

With PZP's, our focal spot diagnostic system becomes important to find the best position. At a given distance from the geometrical focus we found the "best" focal spot composed of a 200 μm top-hat intensity distribution and Gaussian edges. The total focal spot FWHM is 400 μm and the corresponding laser intensity is $I_L \leqslant 10^{14}$ W/cm^2. Figure 2 shows a "flat" shock breakthrough obtained with PZP's. The flat region in the picture extends over a ≈ 180 μm length.

Pinhole camera images are recorded on each shot which allows a control of the focal spot in the x-ray domain, since we verified the good correspondence (shape and dimensions) with the far-field image. Unlike the images we got when using RPP's (or usual plasma images) which have a typical Gaussian distribution of emissivity, we obtain a clear "flat" emissivity region whose dimensions are ≈ 180 μm, in good agreement with the flat region in the streak camera picture (Fig. 2).

To test the quality of the shock waves produced with PZP's we looked at the spatial "flatness" of the shock wave and hence at the temporal "flatness" of its breakthrough. Shock breakthrough showed typical differences in time cor-

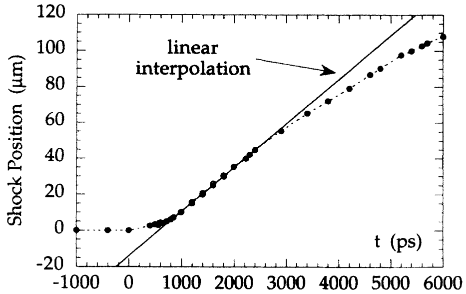

FIG. 3. Shock position as a function of time in Al target according to 1D code FILM simulations ($I_L = 7\times10^{13}$ W/cm^2, peaked at $t = 1$ ns, FWHM=600 ps). The linear interpolation corresponds to a shock velocity $D = 24$ μm/ns.

responding to $\Delta t = \pm 7$ ps, or a shock wave whose velocity uniformity is better than $\pm 4\%$ across a ≈ 180 μm diameter in the sample.

Also, if we take a densitometry of the streak camera image of Fig. 2 as a function of time, we see that the rear side luminosity is characterized by a very steep rise followed by a long decay. As observed by Lower *et al.* [6], this behavior is typical of shocks when preheating is negligible (no preshock signal), but in their case only relatively thick targets, $d \geqslant 17$ μm, were free of such preheating (caused by the hard primary x rays coming from the cavity), while for us this is true for much thinner targets.

V. MEASUREMENTS WITH STEPPED TARGETS

Simple foil targets only allow measurements of the shock breakthrough time and hence shock velocity can only be deduced by comparison of results obtained with the same conditions but different thicknesses. Owing to laser energy fluctuations this method is time-consuming and not sufficiently accurate. Stepped targets instead allow direct "shot to shot" measurements of shock velocity. Of course this method is relevant only if (a) shock pressure is the same on the two sides of the step, and (b) shock pressure, and hence shock velocity, are constant (in time) in the step.

The point (a) shows again how it is important to get flat shock fronts such as those which may be produced with PZP's. For (b) we performed some simulations with the 1D hydrodynamic Lagrangian code FILM developed at Ecole Polytechnique. They show that with our laser and target parameters a nearly constant shock velocity is obtained for targets with thickness $d \geqslant 10$ μm. It differs from a constant slope for large thicknesses (over our range of interest). Figure 3 shows shock position as a function of time in a thick target: there is a clear "linear" region where shock velocity is approximately constant. Outside this region, since the measured velocity is a mean velocity, stepped targets are not very useful. Figure 4 shows a shock breakthrough with PZP's and stepped targets.

Measured shock velocities are now of the order of $D \approx 24$ μm/ns, due to the larger focal spot and thus lower intensity. Comparisons with FILM simulations, using the SESAME EOS tables, show that these velocities correspond to pressures $P_s \approx 11$ Mbar in Al [9]. This result can also be

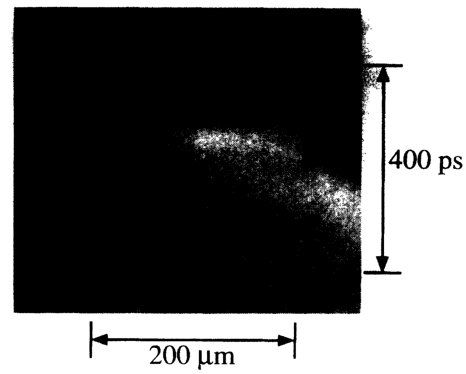

FIG. 4. Rear side shock breakthrough for an Al target with a 7.5 μm basis and a 2.8 μm step. Optical smoothing with PZP's.

qualitatively obtained with a simple analytical model. Indeed in the perfect gas approximation of a plasma, shock velocity and pressure are related by the formula [12]

$$D^2 = 1.33 P/\rho_0$$

in cm/s, where $\rho_0 = 2.7$ g/cm^3 is the unperturbed Al density and P_s is the shock pressure (in Mbar) which is given by [12]

$$P_s = 12.3 (I_L/10^{14})^{2/3} \lambda^{-2/3} (A/2Z)^{1/3},$$

where λ is the laser wavelength (in μm). Here $I_L \approx 7\times10^{13}$ W/cm^2 is needed to get $D \approx 24$ μm/ns. These formulas are valid in the 1D case with flat-top laser pulses; hence in our case they are useful only as order of magnitude estimates.

VI. CONCLUSIONS

These preliminary experiments have shown the possibility of obtaining reproducible and quantitative measurements on shock waves with optically smoothed laser beams. The use of PZP's has allowed the production of high quality, flat shock fronts, while stepped targets allowed direct measurements of shock velocity. The use of a direct drive scheme for EOS experiments, considering the optical smoothing technique of PZP's, has the advantage of a better efficiency to generate higher pressures than indirect drive for the same laser energy available. Moreover, problems due to primary x-ray preheating of the target are strongly reduced. The method presented in this paper for the generation of "flat" shock waves is now applied to two-step, two-material targets. This allows direct and simultaneous measurement of shock velocities and a comparison of the EOS in the two materials [13].

ACKNOWLEDGMENTS

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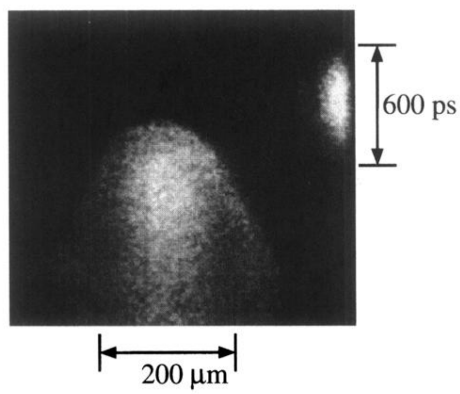
[1] R. J. Trainor, J. W. Shaner, J. M. Auerbach, and N. C. Holmes, Phys. Rev. Lett. **42**, 1154 (1979).
[2] R. Fabbro, B. Faral, J. Virmont, H. Pepin, F. Cottet, and J. P. Romain, Las. Part. Beams **4**, 413 (1986).
[3] B. Faral, R. Fabbro, J. Virmont, F. Cottet, J. P. Romain, and H. Pepin, Phys. Fluids B **2**, 371 (1990).
[4] R. Cauble *et al.*, Phys. Rev. Lett. **70**, 2102 (1993).
[5] Th. Lower and R. Sigel, Contr. Plasma Phys. **33**, 355 (1993).
[6] Th. Lower *et al.*, Phys. Rev. Lett. **72**, 3186 (1994).
[7] Y. Kato *et al.*, Phys. Rev. Lett. **53**, 1057 (1984).
[8] R. M. Stevenson *et al.*, Opt. Lett. **19**, 363 (1994).
[9] B. Faral, M. Koenig, V. Malka, J. M. Boudenne, D. Batani, and S. Atzeni, in Rapport Annuel LULI 1992 (unpublished), p. 34.
[10] B. Faral, M. Koenig, V. Malka, J. M. Boudenne, D. Batani, and S. Atzeni, in Proceedings of the 22nd ECLIM, Paris, 1993 (unpublished), p. 4/2.
[11] B. Faral, J. M. Boudenne, M. Koenig, M. Belingard, F. Zielinski, and J. P. Perrine, in Rapport Annuel LULI 1993 (unpublished), p. 309.
[12] R. Fabbro, Thèse, Université d'Orsay, 1982.
[13] M. Koenig, B. Faral, D. Batani, A. Benuzzi, S. Bossi, and S. Atzeni, in Rapport Annuel LULI 1993 (unpublished), p. 82.



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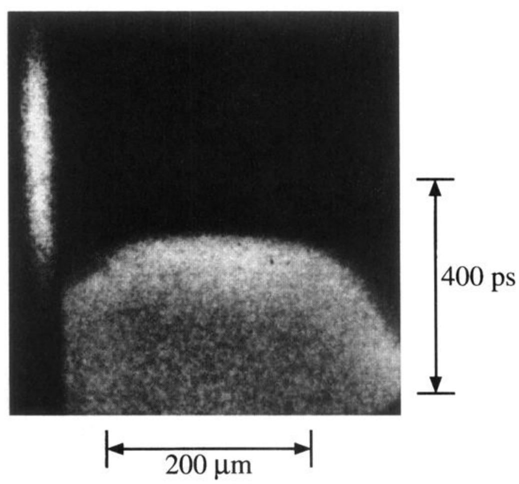

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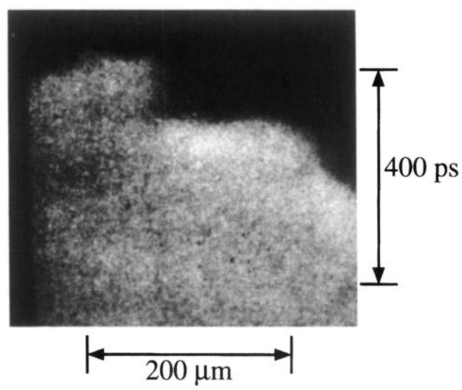

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