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Indirect and direct laser driven shock waves and applications to copper equation of state measurements in the 10–40 Mbar pressure range

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High quality shock waves with direct- and indirect-laser drive were generated. We used the phase zone plate smoothing technique in the case of direct drive and thermal x rays from laser heated cavities in the case of indirect drive. The possibility of producing homogeneous, steady shock waves without significant preheating effects with both methods has been proved. By using such shocks, copper equation of state measurements have been performed up to 40 Mbar, which was previously obtained only with nuclear explosions. [S1063-651X(96)03508-8]

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I. INTRODUCTION

The study of equations of state (EOS) of matter in high-pressure conditions (above 10 Mbar) is a subject of great interest for several fields of modern physics. In particular, it is important in the context of astrophysics and inertial confinement fusion research. Some EOS data [1] exist for this pressure range but for a restricted number of materials; moreover, they mainly come from calculations and theoretical models, with only a few experimental data available to validate them. Therefore, the behavior of many materials of interest under high pressure is still unknown. In the past, EOS measurements in the tens of Mbar domain could be performed only by nuclear explosions. Nowadays, it is possible to reach very high pressures in the laboratory by using powerful pulsed laser-generated shock waves in solid material. Earlier experiments have shown the possibility of producing shock waves with pressures up to 100 Mbar [2]. However, in these experiments the poor quality of shocks prevents them from being used as a quantitative tool in high pressure physics.

Flatness of the shock fronts and low preheating in the material ahead of the shock waves are essential to obtain accurate measurements of EOS. Recent experiments [3,4] have proved the possibility of creating spatially, very uniform shocks in solids by using two different methods. The first one consists in producing shock waves by direct-laser drive with optically smoothed laser beams; the second one uses thermal x rays from laser heated cavities to generate shocks (indirect-laser drive). However, these two methods do not ensure a complete absence of preheating of the cold material. In the case of the direct drive, it has been pointed out [5] that the intensity modulations in the focal spot of a smoothed laser beam (the so-called speckles) could produce hard enough x rays to penetrate the material ahead of the shock and preheat it. On the other hand, in the indirect-drive method, the experiments by Löwer *et al.* [4] have clearly shown that the preheating is very sensitive to the geometry of the cavity.

Only if high-quality shocks are obtained is it possible to precisely measure shock parameters. In order to perform EOS measurements, we adopted the impedance-matching technique [6] which consists in measuring the shock velocity in two different materials simultaneously. This technique makes it possible to achieve a relative determination of one EOS point of one material by taking the EOS of the other one as a reference. The reliability of this method, used in the past in nuclear experiments, has been recently proved in laser driven shock experiments [7] allowing, in addition, high pressures (10–50 Mbar) to be reached with lasers of relatively small size (≈ 100 J).

In this paper, we first present a comparison of high-pressure shocks generated either by indirect-laser drive or by direct-laser irradiation with the phase zone plates (PZP) smoothing technique. Such a comparison has been undertaken, in particular, by looking at the time history of the target rear side emissivity, which provides information about the occurrence of x-ray preheating of the targets [4,8]. Then, we used these techniques to perform relative copper EOS measurements in the 10–40 Mbar pressure range. For pressures below a few Mbar the copper EOS is well defined by means of experimental data achieved using gas guns [9] or chemical explosives [10]. Our maximum pressure range has been reached only in nuclear tests [11]. Up to now, all the experimental points obtained with laser-generated shock waves were those by Rothman *et al.* [12] using only indirect-laser drive. In our case, the high efficiency of direct-laser drive allowed us to reach much higher pressures. The experiment was performed at the Max-Planck-Institut für Quantenoptik (MPQ) in Garching, where the high laser energy per pulse allowed experiments to be performed with both methods.

II. EXPERIMENTAL TECHNIQUE AND SETUP

The experiment was performed using the ASTERIX iodine laser of the MPQ, which delivers a single beam, of diameter 27 cm, with an energy of 250 J per pulse at a

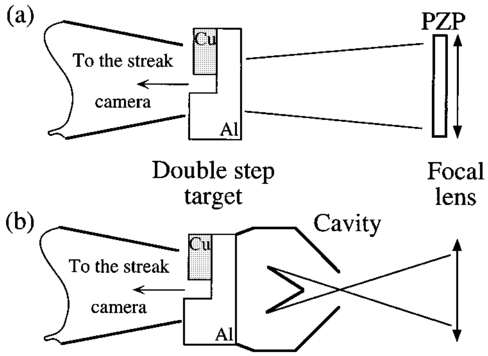

FIG. 1. Schematic arrangements of the two experimental setups. Double-step targets were used to measure the shock velocities D_{Al} and D_{Cu} shot by shot with a visible streak camera. (a) Direct-drive configuration. The laser beam, smoothed with a PZP, was focused onto the target. (b) Indirect-drive configuration. The laser beam was focused in the cavity.

wavelength of 0.44 μm. The temporal behavior of the laser pulse is gaussian with a full width at half maximum (FWHM) of 450 ps. In order to generate the shock wave into the target, we used direct- and indirect-laser drive. Figure 1 shows the two different schematic experimental setups. An important aspect of the experiment was also the ease of switching between direct- and indirect-drive configurations, achieved thanks to the particular cavity design and to the arrangement of experimental diagnostics.

In the direct-laser drive configuration [Fig. 1(a)], the laser beam was focused directly onto the target with a $f_{3\omega}=564$ mm lens. The primary condition of producing high-quality flat shock fronts imposed the use of the PZP [13] optical smoothing beam technique in order to eliminate the large scale spatial intensity modulations arising from the coherent nature of the laser light and to produce a flat-top intensity distribution in the focal spot. The characteristics of our optical system (PZP+focusing lens) were such that we produced a total focal spot of 400 μm FWHM, with a 250-μm-wide flat region in the center, corresponding to a laser intensity $I_L \leq 2\ 10^{14}$ W/cm^2.

In the indirect-laser drive configuration [Fig. 1(b)], we focused the laser beam into a 1-mm-size gold cavity through a small entrance hole. An isotropic radiation is then created [14] whose temperature depends upon the cavity size and the laser power. It can be determined by observing the velocity of a shock wave generated when radiation is absorbed in low-Z material [15]. In our experiment it has been measured to be in the range of 100–150 eV. Our cavity [16] has been designed not only to reach such high temperatures, but also to optimize the irradiation uniformity when only one laser beam is used, and to minimize the preheating of the target, produced by direct primary x rays. Here, a shield with a conical shape has been constructed so that the laser irradiated area and the shocked material were not in direct view of each other, as shown in Fig. 1(b).

In our experiment the impedance-matching technique is applied to two-step, two-material targets. The target is made of a base of aluminum (chosen as reference material), which supports two steps, one of aluminium and the other one of the material to be investigated (copper). The target side corresponding to the base was irradiated directly by the laser or with the thermal radiation, so that, recording the temporal evolution of the rear face emissivity, it was possible to measure the shock emergence time from the base and from the steps. Therefore, this target geometry allows the shock velocities D_{Al} and D_{Cu} to be experimentally determined in the two materials on the same laser shot. By knowing the aluminium EOS and using the impedance-matching conditions [6], we could then find the copper EOS points.

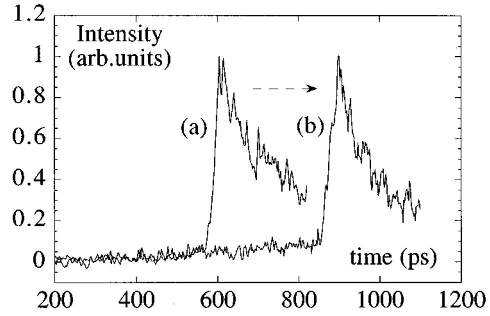

FIG. 2. Flashes, time resolved by a visible streak camera, due to the luminosity of the shock-heated aluminium target. The intensities have been normalized. (a) Signal obtained with direct drive (artificially shifted on the drawing). Shock pressure≈10 Mbar, target thickness=13.5 μm. (b) Signal obtained with indirect drive. Shock pressure≈10 Mbar, target thickness=14.8 μm.

The diagnostic technique used to detect the shock emergence from the target rear face was the same in the two configurations. It consisted of an optical system imaging the rear face onto the slit of a streak camera, operating in the visible region. The temporal resolution was 8 ps and the imaging system magnification was $M=10$, allowing a spatial resolution of 10 μm. A protection system [4] was also used for the diagnostics light path, to shield the streak camera from scattered laser light.

The accurate target fabrication technique [7] allowed sharp step edges to be obtained and allowed a precise determination of step heights. The Al base thicknesses were in the range of 10–12 μm, while the Al and Cu step thicknesses were, respectively, 4–6 and 3–5 μm.

III. RESULT ANALYSIS

Once we checked the spatial flatness of shock waves in the direct- and indirect-drive schemes, we focused our attention on time history of the target rear side emissivity in the two configurations. This point is important since it gives information about the preheating effects that must be minimized in order to perform EOS measurements. Indeed, these effects have been pointed out either in direct [5] or indirect [4] drive. In order to compare the emissivity in the two cases, we considered shocks in aluminium with the same pressure and targets approximately of the same thickness. We observe, as shown in Fig. 2, that the emissivity is similar in the two cases. First, as mentioned in detail in previous papers [4,17], we note that the shapes of the two signals are typical of negligible preheating effects. The rapid emissivity decay proves, in fact, that the peak corresponds, indeed, to the shock breakthrough at an unperturbed step density gradient of solid matter and that the plasma cools in the void without being heated by x rays. In order to confirm this, we per-

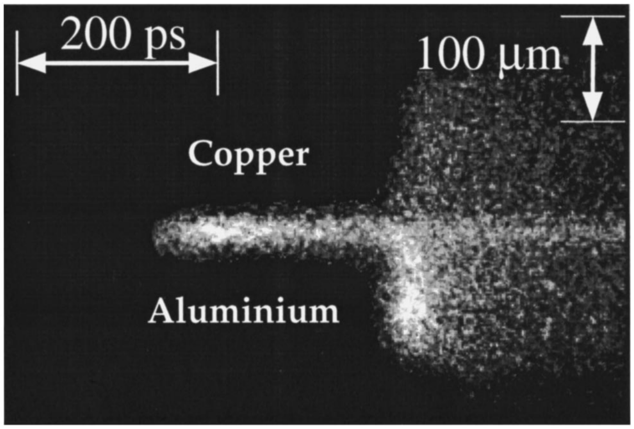

FIG. 3. Streak camera record of visible light emitted by the rear side of an Al-Cu double-step target. Shock has been generated by indirect irradiation.

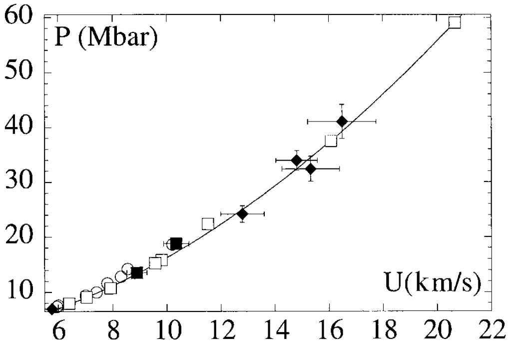

FIG. 4. Copper shock pressure P vs fluid velocity U. Experimental data are compared with the SESAME tables (continuous line). ◆: our points obtained with direct drive; ■: our points obtained with indirect drive; □: Trunin *et al.* [11] points obtained with underground nuclear explosions; ○: Rothman *et al.* [12] points obtained with indirect laser drive.

formed some tests on gold targets with indirect drive. Gold cannot be significantly preheated by our cavity blackbody radiation, which is free of primary hard x rays. We found, again, the same emissivity shape obtained in aluminium. Then, analyzing in more detail the aluminium emissivity time behavior of Fig. 2, one can notice the same growth time and a comparable relaxation. Up to now, theoretical models for the shock emissivity have not been developed because of the difficulties in the calculations of opacities in the visible region, for high densities (≈ 1–4 times the solid density) and low temperatures ($\approx$ a few eV). However, preliminary calculations using a power law for opacities have been performed [17] and suggest $a \approx t^{-0.55}$ dependence of the intensity as a function of time, which approximately corresponds to our experimental results in both the direct- and the indirect-drive scheme. The aluminium emissivity analysis allowed us to choose the base thicknesses so as to make radiation preheating negligible. In this way we ensured that the aluminium and copper steps were not significantly preheated (as one can observe in Fig. 3 where a typical streak image of an Al-Cu target is presented). In any case, the absence of any preshock signals means that a possible preheating should be well below the detection limit of 0.3 eV blackbody temperature of our diagnostic (previously calibrated). Numerical simulations using the one-dimensional (1D) hydrodynamic (with multigroup radiation diffusion) code MULTI [18] have confirmed our results.

After testing the quality of the shocks produced with the two methods, we performed EOS measurements with copper. Our results are presented on the (P,U) plane, as usual, when the impedance-matching technique is used. Figure 4 shows all the copper experimental points obtained up to now. These points are compared with the SESAME EOS. The copper EOS is well defined for pressures below 5 Mbar thanks to the measurements by Mitchell [9] and Al'tshuler [10] performed with gas guns or chemical explosions. The interesting region, where there are few data, as shown in Fig. 4, is beyond 10 Mbar. Our data are displayed in this region together with those by Trunin [11] and Rothman *et al.* [12], which were obtained using nuclear explosions and indirect-laser drive, respectively. One point at low pressure has been obtained at the LULI laboratory in a preliminary experiment with a laser energy of ≈ 30 J. If we consider our experimental results and those of Ref. [12] we find two important differences.

(i) We reached higher pressures (up to 40 Mbar) because we also used the direct-drive configuration, which has a higher conversion efficiency (from the indirect laser energy to the shock energy) than that of the indirect drive, since no energy is lost in the intermediate step of x-ray conversion. A quantitative example of the difference between the two configurations, can be seen by comparing our results with those of Ref. [7]. Here, pressures in aluminium of 10 Mbar were produced with a laser energy on the target of 70 J using the direct-drive scheme, while with the indirect drive, a 250-J-laser energy was needed to reach the same pressure. We recall that shock pressures (in Mbar) are of the order of

$$P_{\mathrm{dir}} \approx 8.6(I_L/10^{14})^{2/3}\lambda^{-2/3},$$

$$P_{\mathrm{ind}} \approx 44(I_C/10^{14})^{10/13}\tau_L^{-3/26},$$

in direct and indirect drive, respectively [19,14]. Here I_C is the primary x-ray flux on the cavity wall (in W/cm^2), τ_L is the laser pulse duration (in ns), λ is the laser wavelength (in μm). Hence the laser pulse energy, E_{ind} (in kJ) needed with the indirect method in order to reach the same pressure of direct drive, is

$$E_{\mathrm{ind}} \approx 0.56(E_{\mathrm{dir}}/\lambda)^{0.87}(R_C^2/R^{1.73})\tau_L^{0.284},$$

where R_C is the effective cavity radius and R the focal spot radius (both in mm). With our parameters and those of Ref. 7 (the different duration of the laser pulse has been taken into account), we find a ratio $E_{\mathrm{ind}}/E_{\mathrm{dir}} \approx 3.5$, corresponding approximately to our experimental results.

(ii) Among our copper data, those produced with the indirect configuration have the same pressures as in Ref. [12]. The relevant difference is that we had 250-J laser energy while their laser delivered 1 kJ. This demonstrates the very good optimization of the cavity developed at the MPQ in order to produce high pressures.

The error bars of our points have been determined considering all the sources of errors in the measurement of D. The causes of possible errors are the uncertainties about the step thicknesses, the shock breakthrough time, and the streak camera sweep speed. The ‘‘cleanliness’’ of the signal (see Fig. 2) enabled us to obtain a precision of ±4 ps in the shock breakthrough time. The step heights of the targets have been measured with an absolute error of 0.03 μm. For what concerns the streak camera sweep speed, we considered the error of 1%, as measured by the constructor. In deducing the error in the copper pressure and fluid velocity, we took into account the relative error in D_{Al} and D_{Cu}, which were determined for each single shot. We obtained a precision better than ±4%. It is possible to show explicitly that the relative errors in fluid velocity and shock pressure are about the same. Moreover, we found that the relative error in the copper pressure is approximately double that in the copper shock velocity, in accordance with the quadratic dependence [6] between the two quantities. Therefore, we determined copper EOS points with a precision better than ±8%.

IV. CONCLUSIONS

In this paper, we have shown the possibility of producing shock with comparable accuracy using the direct- and indirect-laser drive. In particular, in both cases the target rear side emissivity showed that there was no preheating phenomena. In the direct-drive case, a high-quality shock was reached by making use of the PZP smoothing technique. In the case of the indirect drive, it was obtained by taking advantage of the geometry of the cavity, where a shield protected the target from a primary x-ray irradiation. We then presented impedance-matching technique copper EOS measurements performed with these high quality shocks. We investigated a region of the copper EOS surface (beyond 10 Mbar) which is not well known so far. The high efficiency of the direct-drive method allowed us to produce pressures up to 40 Mbar, accessible up to now only by nuclear tests.

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