Ultrahigh-Pressure Laser-Driven Shock-Wave Experiments at 0.26 μm Wavelength

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The velocity of strong shock waves, induced by 0.26-μm-wavelength laser pulses, is measured in aluminum, copper, and gold targets. The results lead to an ablation pressure of 3 TPa at 4.5×10^{14} W/cm^2 incident intensity for 450-ps full width at half maximum pulses focused on a 50-μm-diam spot. These first shock-pressure results at 0.26 μm wavelength outline the great interest in short wavelengths for producing ultrahigh pressure in a laser-matter interaction experiment.

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The use of laser wavelengths shorter than one micrometer offers considerable advantages in laser-matter interaction experiments as has been predicted by theoretical analysis.[1] Some recent ablation-pressure experiments[2-4] at wavelengths 1.05 and 0.35 μm have permitted the evaluation of the significant increase of compression efficiency accompanying a threefold reduction in wavelength. For example,[3] at a constant adsorbed intensity of 1.2×10^{14} W/cm^2 with 600-ps pulses focused on a 200-μm-diam spot, a 1-TPa shock pressure is obtained at 0.35 μm and only 0.6 TPa at 1.06 μm. Also, the short-wavelength advantages include increased absorption of laser energy by the target and reduced suprathermal electron preheat.[5] In this work we present the first direct shock velocity measurements in aluminum, copper, and gold targets in a pressure range of several terapascals and at 0.26-μm wavelength.

These experiments were made with the use of the Groupement de Recherches Coordonnées Interaction Laser Matière Nd-glass laser, quadrupled in frequency by potassium dihydrogen phosphate (KDP) crystals with about 20% efficiency relative to the fundamental wavelength (1.05 μm). The available laser energy at 0.26-μm wavelength was 8 J in 450-ps full width at half maximum (FWHM) pulses. The energy distribution in the focal spot was determined with the "burn-paper" technique from impacts at different energy levels on a glass substrate covered with 400 Å of aluminum. The observed impacts are characteristic of the isointensity contours. The focal spot diameter was found to be 50 μm at half energy and 100 μm at 90% of full energy. Then, for an average energy of 8 J, the incident intensity was about 4.5×10^{14} W/cm^2.

The experimental setup is schematically described in Fig. 1. A fast streak camera records the luminous history at the rear surface of a thin metal foil irradiated by the 0.26-μm incident beam. Absolute timing of the streak camera is obtained by use of a fiducial signal, produced by a 0.53-μm-wavelength laser beam. The shock transit time through the target and consequently the shock velocity and shock amplitude are determined by recording the luminosity produced by shock heating of the rear surface of the foil at shock emergence. This system has a time resolution of 100 ps.

The principal measurements were realized with aluminum foils of thickness between 11 and 53 μm with 0.5-μm accuracy. The lower value of 11 μm corresponds to a condition of low preheat effects, and the upper value of 53 μm to a condition of strong shock amplitude decay during the propagation through the target. Consequently, no mea-

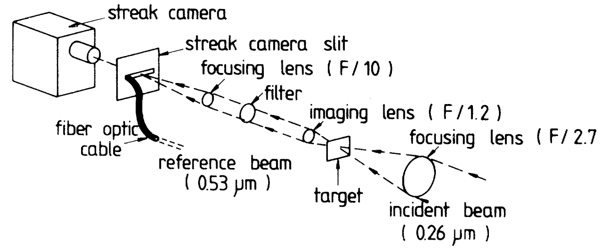

FIG. 1. Schematic configuration of the experimental setup for measurement of laser-induced shock-wave transit time through a thin target.

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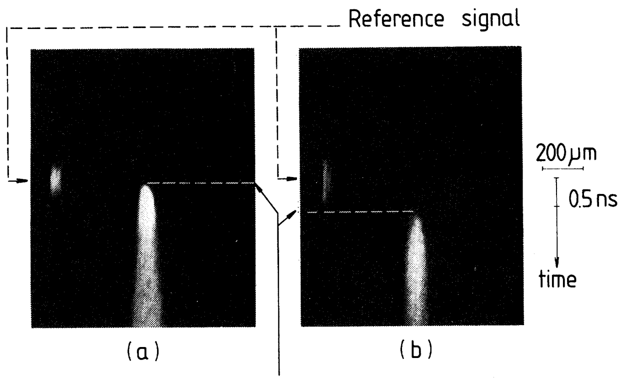

FIG. 2. Streak-camera records of luminosity produced by the emergence of a shock wave at the rear face of a metal target irradiated by a 450-ps-FWHM laser pulse on a 50-μm-diam focal spot at half energy, 4.5×10^{14} W/cm^2 incident energy. (a) 15-μm-thick aluminum foil, (b) 16-μm-thick copper foil.

surements could be made for target thickness larger than 53 μm, because of the too weak shock luminosity at the back face of the foil. In all experiments, wide foils were used to avoid the ablation plasma flow around the foil edges which otherwise disturb luminosity records. Some experiments were made with copper and gold targets for comparison with aluminum. Indeed, from extrapolation of known data at high pressure,[6,7] the shock velocity in the terapascal pressure range is much larger in aluminum than in copper and gold.

Figure 2 shows typical streak records of the shock luminosity at the rear face of (a) 15-μm-thick aluminum foil and (b) 16-μm-thick copper foil. The shock transit time is measured from the interval between the fiducial signal on the left edge of the photograph and the central luminosity corresponding to the shock emergence. These records, realized with the same irradiance conditions —4.5×10^{14} W/cm^2 incident intensity, 450-ps-FWHM duration pulses, and 50-μm-diam spot at half energy— illustrate the above-mentioned great difference between the shock velocities in aluminum and copper.

The experimental values of shock transit time, with respect to the peak of the laser pulse, through aluminum, copper, and gold foils are listed in Table I. These experiments were numerically simulated with an existing[8] one-dimensional hydrodynamic model of laser shock evolution. The variation of applied pressure at the ablation surface (determining the initial conditions of calculations) is modeled in a Gaussian pulse, reproducing the laser pulse shape with the same width at half maximum (450 ps). Equation-of-state data needed in the calculations are the Grüneisen coefficient and the Hugoniot curve of the material, experimentally determined for aluminum,[6] copper,[6] and gold[7] in a pressure range up to 0.3 TPa. Extrapolation of the linear relation between shock velocity and particle velocity up to 3 TPa is consistent with equation-of-state data given by the SESAME equation-of-state library.[9] Planar geometry is used and the free

TABLE I. Shock transit time versus target thickness for aluminum, copper, and gold foils irradiated by 4.5×10^{14}-W/cm^2 pulses focused on 50-μm-diam spot at half energy. The shock transit time is measured with respect to the peak of the laser pulse. In the case of small thickness target (11 μm), the negative value of the transit time corresponds to a shock emergence at the back face of the foil before the arrival of the laser pulse peak at the front face of the target.

Target material	Target thickness (μm)	Number of experiments	Transit times (ns)	Average transit time (ns)
Al	11	3	−0.025, −0.03, −0.04	−0.03
	15	3	0.06, 0.07, 0.09	0.075
	17	2	0.08, 0.12	0.1
	20	3	0.15, 0.2, 0.25	0.2
	27	3	0.34, 0.4, 0.45	0.4
	30.5	2	0.45, 0.45	0.45
	53	2	1.32, 1.37	1.35
Cu	16	2	0.39, 0.47	0.43
	26.5	1	0.8	0.8
Au	20	2	0.82, 0.96	0.89

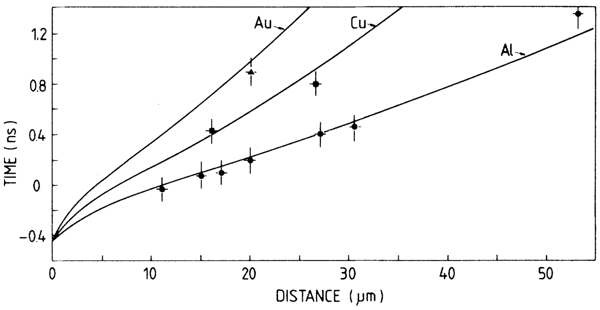

FIG. 3. Experimental points and calculated curves of shock-wave propagation in space-time coordinates for a maximum driving pressure of 3 TPa (zero time with respect to the peak of the laser pulse). The average laser energy is 8 J in 450-ps FWHM on 50-μm-diam spot at half energy at 0.26-μm wavelength.

parameter is the maximum induced shock pressure.

The best simulation of aluminum experimental results, represented in Fig. 3, used a peak driving pressure (or ablation pressure) of 3 TPa, with 0.5-TPa accuracy corresponding to simulated peak pressure limits for a correct adjusting of experimental points. The theoretical fit with experimental data is realized for thickness less than or equal to 30.5 μm, because at a distance of 50 μm the shock propagation is no longer planar. Consequently, the shock decay due to spherical geometry effects is stronger, and the experimental point at 53 μm is above the simulation curve. From the least-squares line fitted to the experimental points between 11 and 30.5 μm, we obtain an average shock velocity of 39 mm/μs corresponding to an average shock pressure of 2.7 TPa, in good agreement with the value obtained from comparison with model calculations.

In the same figure, the calculated curves for copper and gold, with a maximum shock pressure of 3 TPa, are plotted. These simulations show a good fit with the experimental points. Consequently, at fixed irradiance conditions (4.5×10^{14} W/cm^2), the same ablation pressure is induced in aluminum, copper, and gold, and the shock propagation verifies correctly the specific dynamic characteristics of these metals. However, some more experiments in copper and gold should be necessary to confirm the first results on these materials.

The central purpose of present experiments was to demonstrate that extreme high-pressure laser-driven shocks could be generated in a target at 0.26-μm wavelength. Although interaction conditions at 1.05-μm and 0.26-μm wavelength and high irradiance level are different, a comparison can be made on the incident intensity necessary for generating a given ablation pressure. From previous work[3] at 1.05 μm, the same pressure of 3 TPa was produced with about 3×10^{15} W/cm^2 incident intensity focused on 500-μm-spot diameter, instead of 4.5×10^{14} W/cm^2 incident intensity focused on 50-μm-spot diamter at 0.26 μm. Additionally, for small spot diameter (50 μm), experiments[10] at 1.05 μm show an important reduction of ablation pressure attributed to two-dimensional effects. From the present work it appears of great interest to use a very short-wavelength laser to produce ultrahigh ablation pressure: At 0.26-μm wavelength in 450-ps-FWHM pulses, only 8 J, focused on a 50-μm-diam spot, are necessary to induce shock pressures as high as 3 TPa.

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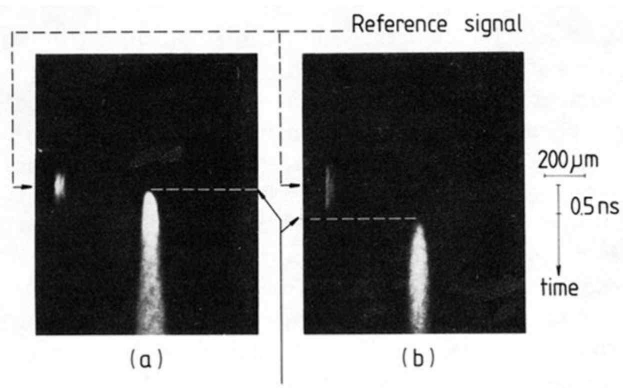

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