Observation of Laser-Driven Shock Waves in Solid Hydrogen

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The spatial development of laser-driven shock waves in a plane solid-hydrogen target was directly observed by high-speed photography. From the measured shock-front velocity a peak pressure of 2 Mbar is evaluated at the onset of a 10-J, 5-nsec Nd laser pulse. The underlying mechanism of laser ablation and the relevance of such measurements to laser fusion and the behavior of matter at extremely high pressures are discussed.

As is well known,[1] irradiation of a solid target by the focused beam of a powerful pulsed laser leads to the formation of a dense and hot plasma surface layer which exerts a considerable pressure on the neighboring cold material. In this way solid material may be set in motion and compressed to densities well above the solid-state density. Essentially, the concept of laser fusion is based on converging compression waves in a laser-irradiated pellet.[2] To our knowledge, laser-driven compression waves and the pressures involved have been investigated so far only in an indirect manner.[3] In this paper, we report on the direct observation of a laser-driven shock wave in the most accessible geometry, where a single laser beam is focused onto a plane target.

The experiments were performed with the Garching multistage Nd laser system,[1] which was used at an output level of 12 J in 5 nsec (rise and fall time ≈ 1 nsec). The laser radiation was focused by an $f/1$ ($f = 75$ mm) aspherical lens down to a spot size of ≈ 40 μm. For the experiments described here the target consisted of a solid hydrogen stick with a 2 mm square cross section which was extruded from a liquid-helium-cooled cryostat[4] into the evacuated interaction chamber. Similar sticks of polymethyl methacrylate, $C_5O_2H_8$ (Plexiglas), were also used. The front surface was irradiated by the laser at a position close to the narrowest cross section of the beam where the reflection of laser light from the plasma has a maximum. This position is well defined with an accuracy of ± 100 μm[5] and previous measurements of x radiation[6] have shown a maximum electron temperature of the plasma with the target in this position.

The evolution of the shock wave was observed by high-speed photography at 90° to the laser axis with a focused shadowgraph setup. For this purpose, the median plane of the transparent target was imaged on the slit of an ultrafast image-converter streak camera incorporating an image intensifier. Background illumination was produced by the parallel beam of a dye laser ($\lambda = 580$ nm) (the streak camera and dye laser were from Electro Photonics, Northern Ireland). Streak pictures were obtained with the narrow slit of the camera adjusted to view the phenomena occurring along the laser axis and with the dye laser producing a single pulse with a length of ≈ 1 μsec. Framing pictures were obtained with mode-locked operation of the dye laser and a wide-open streak slit. The width of the slit corresponded to the distance which the electron beam of the streak camera sweeps during the interval (2.8 nsec) of two pulses of the dye-laser pulse train. The streak camera then produces a sequence of adjacent frames, each frame being exposed by a single pulse of the mode-locked pulse train. Because sweeping of the camera can be neglected for the ultrashort pulses (≈ 5 psec time duration[7]) applied here, a series of sharp pictures is obtained. Time correlation of the pictures with the laser pulse was provided either by stray laser light or by guiding laser light with a light pipe to the edge of the streak slit. Usually targets with a slightly concave front surface (extruded from an appropriate nozzle) were used to prevent the unavoidable imperfection of the edges from disturbing observation of the vacuum-solid interface. For the magnification used here the spatial resolution was actually limited by the grain of the streak camera to about 20 μm in the object plane.

A typical series of framing pictures obtained with a single laser shot is shown in Fig. 1. The first frame (-2.3 nsec) is taken 2.3 nsec before the onset of laser radiation and shows the undisturbed vacuum-target interface. The cone filled by the incident laser radiation and the focal spot area are schematically indicated. In the second frame ($+0.5$ nsec) a small dent towards the interior of the target is observed in front of the focal spot. Its shape is not yet clearly resolved.

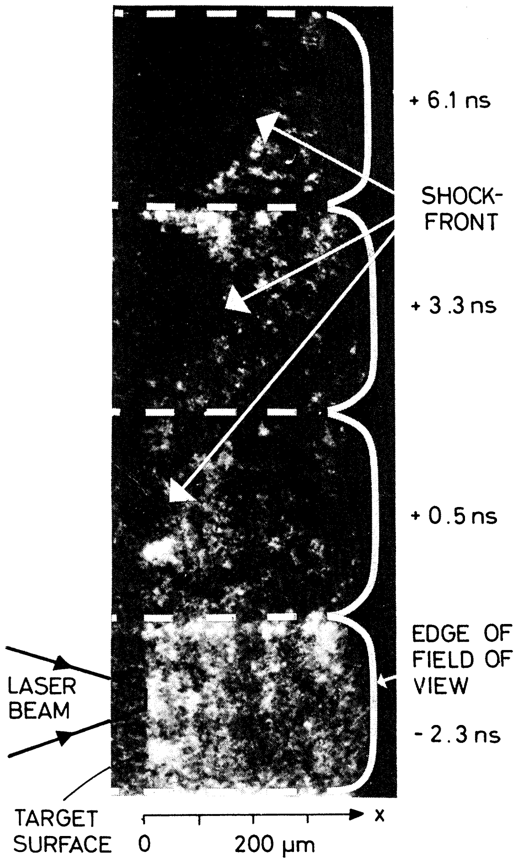

FIG. 1. Framing pictures of a solid-hydrogen target with a mode-locked dye laser as background illumination at 0.5, 3.3, and 6.1 nsec after onset of the laser irradiation.

The third frame (+3.3 nsec) shows an opaque area of hemispherical shape with a depth of 150 μm. The leading edge is believed to constitute the shock front; estimates based on the work of Kerley[8] show indeed that for pressures above 600 kbar the electron density behind the shock front should exceed the critical density (3×10^{21} cm^{-3}) for the background dye-laser illumination and therefore make the shocked material opaque. In the last frame (+6.1 nsec), just after termination of the laser pulse, the shock front has moved to a depth of 215 μm.

The streak pictures (not reproduced here) allow the determination of the shock-front velocity's dependence on time. The velocity is maximum at the beginning of motion, which coincides, within the accuracy of time correlation (±1 nsec), with the onset of laser irradiation and then decreases with time. The maximum shock velocities obtained from the streak pictures were 5.8 $\times10^6$ cm sec^{-1} in solid hydrogen and 2.5×10^6 cm

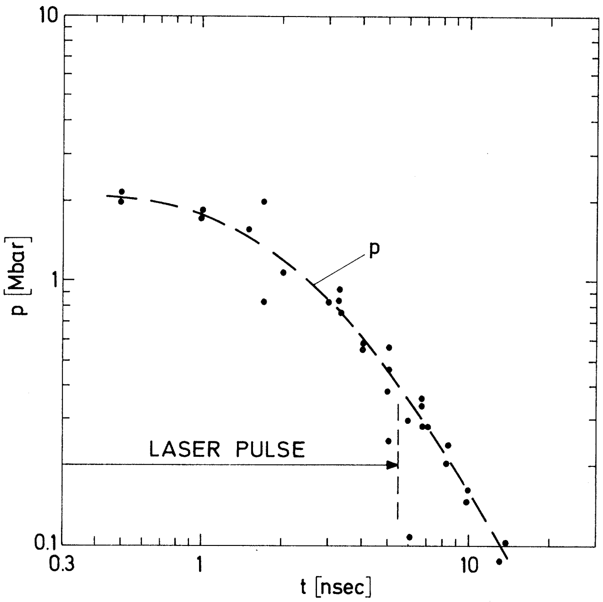

FIG. 2. Pressure p_1 behind the shock wave in solid hydrogen versus time. Data are obtained from five identical shots.

sec^{-1} in Plexiglas.

The measurements of the shock-front velocity allow us to determine the pressure behind the shock front and to relate it to the properties of the laser-plasma interaction region. From mass and momentum conservation across a shock front propagating with a velocity v_s we get for the pressure behind the front

$$p_1 = \rho_0 v_s^2 (1 - \rho_0/\rho_1), \tag{1}$$

where we have neglected the pressure ahead of the front and ρ_0 and ρ_1 are the densities ahead of and behind it. Determination of p_1 requires in principle besides v_s knowledge of the compression ρ_1/ρ_0 which has not been measured in this experiment. From striker-plate experiments[9] and from an analysis of shock compression with the equation of state calculated in Ref. 8 and by van Thiel *et al.*,[10] we expect $\rho_1/\rho_0 \approx 3$ for $p_1 = 100$ kbar and $\rho_1/\rho_0 = 4-5$ for $p_1 = 2$ Mbar. Since for $\rho_1/\rho_0 \gg 1$ the pressure p_1 becomes insensitive to the exact value of ρ_1/ρ_0 according to Eq. (1), we have somewhat arbitrarily set $\rho_1/\rho_0 = 3$ for the evaluation of Fig. 2. The peak pressure in Fig. 2 is therefore slightly underestimated, but probably by not more than 15%. Figure 2 which was obtained from five streak photographs shows a peak pressure of $p_1 = 2$ Mbar at the moment when the motion of the shock wave becomes detectable. It already decreases during the laser pulse and decays rapidly on termination of irradiation.

In the case of Plexiglas, besides determining the pressure, it was also possible to obtain the compression by extrapolating Hugoniot data measured up to 1.2 Mbar.[10] A peak pressure of 3 Mbar and a corresponding compression of $\rho_1/\rho_0 = 2.5$ were evaluated at the onset of shock-wave motion.

Basically shock-wave formation in a laser-irradiated solid target is due to heating and ablation of surface material; this process has been studied numerically in plane (and spherical) geometry, for example by Mulser and co-workers.[1,11] Actually, in the experiment, the gas dynamic flow is two-dimensional, because the plasma radius [expansion velocity (sound velocity) $\approx 2\times10^7$ cm sec^{-1}] and even the shock-wave radius exceed the diameter of the irradiated area considerably with time. A quantitative assessment of the measured pressure and its variation with time requires therefore a two-dimensional, probably numerical simulation (which is underway in our laboratory). At the present time it is nevertheless possible to show that the measured peak pressures are consistent with the previously measured electron temperature in the plasma[12] and to discuss the importance of two-dimensional effects on the background of plane computer calculations.[11]

Laser heating of the material occurs near the critical density $n_c = \rho_c/m_i = \epsilon_0 m_e \omega_L^2/e^2$ ($=10^{21}$ cm^{-3} for $\lambda = 1.06$ μm), where the laser frequency equals the plasma frequency. Part of the deposited heat diffuses into the denser parts of the plasma and provides continuous ablation and acceleration of material. Under the assumption $\rho_0/\rho_c \gg 1$ the pressures at the surface of the solid and the critical layer are related as a result of momentum conservation for a (quasi)stationary, plane flow by $p_1 = p_c(1+M_c^2)$, where M_c denotes the Mach number in the critical layer. The pressure at the critical layer can be determined from the electron temperature $kT_e \approx 500$ eV, measured previously in this experiment.[12] With this value for T_e and assuming $T_i = 0$ we get $p_c = n_c k T_e = 800$ kbar. Comparison of this value with the measured pressure p_1 behind the shock front (2 Mbar) shows that the latter is enhanced appreciably by the recoil of the ablating material. From p_1 and p_c the Mach number at the critical density is calculated to be $M_c = 1.2 \pm 0.5$. The uncertainty is due to the limited accuracy in determining the shock-wave velocity and the electron temperature, determination of the latter from soft x-ray measurements being complicated by the presence of fast electrons in the plasma.[12] For the measured electron temperature a plane computer code based on classical heat-diffusion theory predicts reasonably well the pressure behind the shock front and also the Mach number evaluated above. A strong discrepancy exists with respect to the laser intensity necessary for producing the experimental conditions: According to the computations only 10^{13} W cm^{-2} should be sufficient whereas the intensity applied in the experiment is about an order of magnitude higher ($\approx 2\times10^{14}$ W cm^{-2}). This is interpreted as a reduction of pressure due to two-dimensional plasma expansion, in particular due to an effective enlargement of the heated area by lateral heat conduction. A corresponding enlargement of the plasma diameter has recently been verified by x-ray pinhole photographs of the plasma.[13]

Experiments of the type described here yield immediately the pressure achieved in a solid target under laser irradiation, i.e., the quantity of major importance in laser fusion. If supported by exact two-dimensional computer calculations they could serve to investigate the consequences of collision-free light absorption near the critical density on the compression wave and to assess the practical importance of effects like flux limitation of electron heat transport and fast ion blowoff[14] in regard to dependence on intensity and wavelength. The direct observation of the shock front allows the study of effects which may disturb its shape. As an example we note that self-focusing has been a matter of concern in this experiment (details will be given elsewhere): Streak photographs have shown filaments accompanied by cylindrical shock waves in Plexiglas, particularly if the beam was focused several hundred micrometers inside the target. Streak photographs with solid hydrogen were often completely obscured at the beginning of the pulse, probably by filaments extending along and obscuring the streak slit. Proper control and understanding of such effects might help their avoidance in a less accessible, implosion-type geometry.

We believe that experiments with laser-driven compression waves in solids may also gain interest for basic studies of the behavior of matter under very high pressures. The potential of the method is already obvious in this experiment, where with very moderate laser energies, pressures in the megabar range have been achieved in a light material where corresponding "piston" speeds are difficult to achieve with chemical detonation waves. For example, with a programmed laser pulse it might be possible to observe the transition of solid hydrogen into the metallic state.[15] Although plane waves, achievable by extending the focal spot of a more powerful laser, would be most desirable for such investigations, the small dimensions of such waves do not seem an insurmountable obstacle for modern techniques of high-speed, high-resolution diagnostics.

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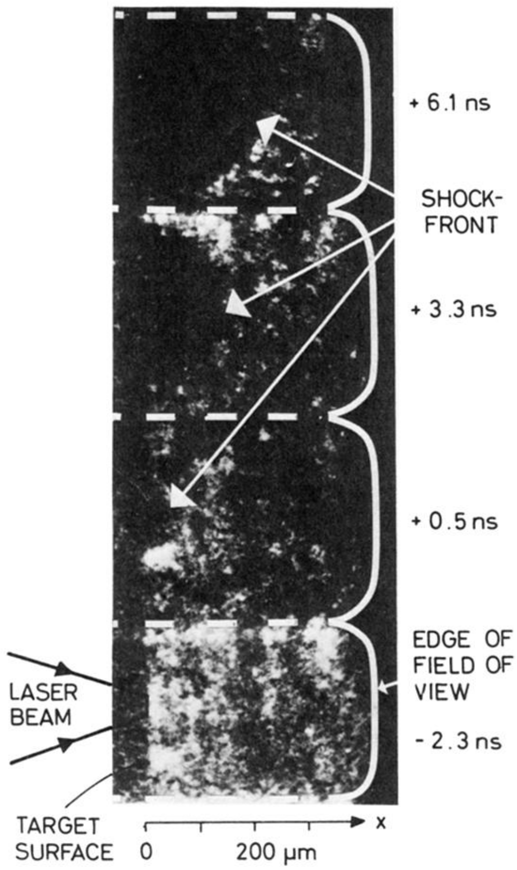

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