Uniform Multimegabar Shock Waves in Solids Driven by Laser-Generated Thermal Radiation

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Uniform shock waves were driven into solid gold and aluminum samples via ablation of material by intense thermal radiation. The radiation was generated by laser heating of 1–3 mm size gold cavities to radiation temperatures of up to 150 eV. Shock wave velocity and uniformity were measured using flat, single-step, double-step, and wedge samples. Pressures of up to 20 Mbar were achieved.

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The prospects to generate extremely high pressures in the laboratory by the action of a focused laser beam attracted considerable attention as soon as powerful pulsed lasers became available. In particular it is hoped to study the equation of state of dense matter at very high pressures by launching intense, laser-generated shock waves into solid material. Experiments with solid samples [1] have indeed demonstrated the formation of shock waves with pressures up to 100 Mbar in solid samples directly irradiated by pulsed laser light; even higher pressures were reported in impact experiments using laser-accelerated thin foils [2]. However, for quantitative applications, the shock waves should be spatially uniform, of constant velocity, and preheating in the material ahead of the shock front should be avoided [3]. It turned out that shock waves driven by direct laser irradiation of a sample could not achieve adequate uniformity due to the spatial intensity modulations of laser beams which arise from the coherent nature of laser light. In this Letter we demonstrate that this difficulty may be overcome by driving the shock wave not directly by laser ablation, but by incoherent, laser-generated thermal x rays. We report below the generation of planar shock waves of very high spatial uniformity with pressures up to 20 Mbar in solid samples which were heated by the thermal radiation from a laser-heated cavity. The observations were made with a detection system which provides background-free registration of the sample luminosity with high spatial and temporal resolution. We demonstrate that preheating of the sample may be minimized by proper cavity design.

We note that early work [4] provided evidence for the existence of shock waves driven by laser-generated x rays. Recently the subject found new interest [5,6]. However, the work reported by Campbell [5] has not been described in detail. The very recent work by Hammel *et al.* [6] takes a different approach.

The principle of the experiments is to heat a mm size cavity by pulsed laser light and to generate in this way intense thermal soft x rays. The radiation temperature depends on cavity size and available laser power; in the present experiments it is in the range 90–150 eV. The intense thermal radiation ablates material from the shock sample and generates a shock wave in it. The flash of light emitted by the shock-heated material during shock breakout at the outer surface is registered by an optical streak camera. The velocity of the shock wave is determined from the time delay of shock arrival between areas of the sample with different thicknesses.

An estimate for the expected pressures may be readily obtained from the self-similar solution for the ablative heat wave [7] in the case of a gold sample which is integrated into the wall of a gold cavity:

$$p(\text{Mbar}) = 44 S_s^{10/13} t^{-3/26} . \quad (1)$$

Here S_s is the temporally constant source flux in units of 10^{14} W cm^{-2} and t time in ns. The source flux may be calculated by dividing the injected laser power through the inner surface of the cavity, and multiplying with the conversion efficiency of laser light into x rays.

Experiments were performed using the ASTERIX iodine laser at Garching and the GEKKO XII laser at Osaka. In the ASTERIX experiments the laser delivered a single beam with an energy of up to 250 J, a pulse duration of 450 ps, and a wavelength of 0.44 μm. The focused beam was injected through a laser inlet hole into spherical gold cavities with 1 mm diameter as shown in Fig. 1(a). In the ASTERIX experiments the diagnostics were developed and radiation driven shock waves with pressures up to 7 Mbar were observed and investigated [8]. Based on this experience a second series of experiments was then performed with the GEKKO laser using the same diagnostics. The larger energy available from this laser allowed not only an extension of the parameter range of the experiments to higher pressures, but also, equally important, more flexibility in the cavity design which may be used to improve the "cleanness" of the experiments by optimizing the cavity shape. In the GEKKO experiments four beams with a total energy of up to 2.2 kJ, a pulse duration of 0.8 ns and a wavelength of 0.35 μm were used to heat the type of cavities shown in

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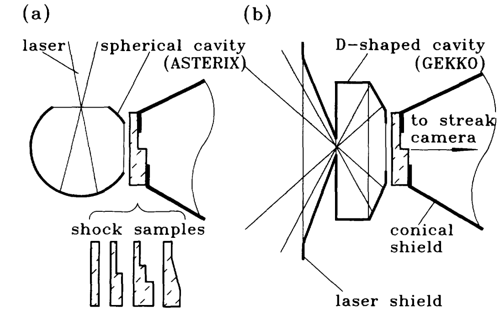

FIG. 1. Arrangement of laser-heated gold cavity and shock sample. (a) Spherical cavity irradiated by the single beam ASTERIX laser. Bottom: The various types of shock samples used in the experiments. (b) D-shaped, rotationally symmetric cavity irradiated by four beams from the GEKKO laser. The independently adjustable conical shield provides a light-tight connection to the streak camera (see text).

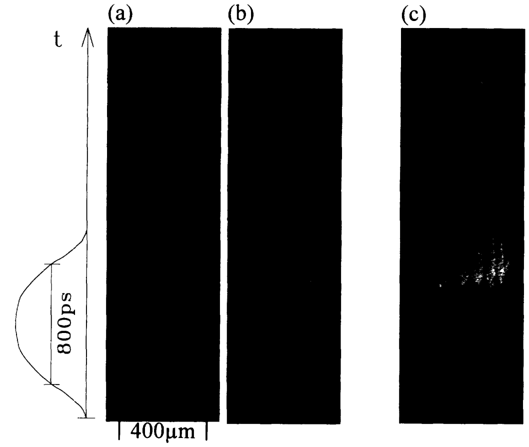

FIG. 2. Streak camera records of visible light emitted by the shock sample. On the left-hand side the temporal shape of the GEKKO laser pulse is shown as derived from a simultaneously registered fiducial. (a) Record from a single-step gold sample mounted on a 2 mm GEKKO cavity. The signal preceding shock arrival on the thin side of the sample is due to temporary light transmission through a pore in the black glue holding the sample. (b) Record from a gold wedge sample mounted on a 2 mm GEKKO cavity. (c) Record obtained in the case of direct laser irradiation of a flat sample by the ASTERIX laser beam. The shock wave shows small-scale modulations.

Fig. 1(b). Design criteria for these cavities were to position the sample for optimum x-ray irradiation uniformity, to minimize heating of the sample by x rays from the laser-irradiated areas in the cavity and by laser light reflected from them, compactness to achieve a high temperature for a given energy input, and compatibility with other experiments performed on the cavity in the same shot. The cavity design shown in Fig. 1(b) is a compromise in these respects. The shock sample is located on the axis of the cavity, where an extremum for the radiation flux and hence optimal uniformity are expected.

The cavities were made of gold by electroplating (wall thickness 15 μm) and etching suitable brass mandrels. The cavities of the GEKKO experiments were used in three equivalent sizes which had the same inner surface area as hollow spheres with 3, 2, and 1 mm inner diameter. For optimal surface quality the shock samples of gold or aluminum were fabricated by diamond turning of either electroplated gold or massive aluminum. The root-mean-square surface roughness was less than 0.06 μm. As shown in Fig. 1(a), flat, single-step, double-step, and wedge samples were used. The material thicknesses ranged from 3 to 30 μm in gold and from 10 to 70 μm in aluminum.

One of the major experimental difficulties consists in the measurement of the relatively weak shock signals in an environment of very intense scattered laser light (to which the streak camera is sensitive) and of plasma luminosity, both sources being typically 10^8 times more intense than the shock wave signal. In order to obtain clear, background-free signals we protected the diagnostics light path by a light-tight metallic tube. The adjustable tube carries at its front end a disposable gold cone on which the sample is fixed with opaque glue. The tube also contains the imaging objective ($f/2$, $F=100$ mm) in which an exchangeable planar glass plate serving as debris shield and vacuum window is integrated. The position of the sample relative to the cavity can be adjusted with an accuracy of better than 10 μm.

The sample is imaged with fivefold magnification onto the $S20$ photocathode of a Hadland Imacon 500 streak camera. Spatial resolution corresponds to 50 line pairs per mm in the sample plane, temporal resolution of 10 ps for the streak speed applied in the experiments.

Results obtained in the GEKKO experiments with gold samples are shown in Fig. 2. Figure 2(a) was obtained with a gold step foil of 8 and 15 μm thickness mounted on a 2 mm diam gold cavity of the type shown in Fig. 1(b). The observed area is limited by the hole in the cone with a diameter of 400 μm. It is seen that the shock wave is very uniform; to within ± 5 ps it arrives simultaneously over the whole observed area on the thin as well as on the thick side of the sample. The delay introduced by the 4 μm thickness difference is 790 ps, corresponding to a shock velocity of $v_s = 0.86\times 10^6$ cm s^{-1}. The shock velocity is hence uniform to better than $\pm 0.6\%$. Since $p \propto v_s^2$, a velocity variation translates, according to Eq. (1), into a source flux variation 26/10 times larger; i.e., the irradiation uniformity is better than $\pm 1.6\%$. Calculations of radiative transfer in the cavity of the type described in Ref. [9] are underway to verify the uniformity found in the experiment.

The uniformity of the shock wave makes it possible to determine the time history of the shock wave in a single experiment using a wedge sample (wedge samples were first used in experiments of this type in Ref. [5]). Figure 2(b) was obtained with a gold wedge whose thickness varies linearly from 9 to 21 μm over a distance of 300

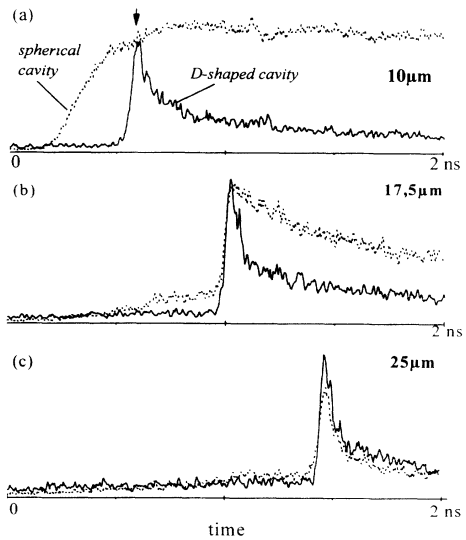

FIG. 3. Streak records (linear scale) of aluminum samples obtained with a D-shaped cavity under similar drive conditions. The signal from the D-shaped cavity has been multiplied by a factor of 2. The data were obtained in only two experiments using double-step targets with step thicknesses of (a) 10 μm, (b) 17.5 μm, and (c) 25 μm. The preshock signal in the case of the spherical cavity is attributed to radiative preheating (see text).

μm. The wedge is bounded on both sides by flat parts; in fact shock arrival in the flat parts of the sample may be seen in Fig. 2(b) near the right and left boundaries of the field of view. The straight shock wave trajectory indicates a constant velocity up to the full thickness of the wedge. This observation is in approximate agreement with theoretical estimates [3].

For a direct comparison with x-ray drive, in some experiments shock waves of comparable strength were driven into flat aluminum samples by direct laser irradiation. The shock signal presented in Fig. 2(c) was obtained with the ASTERIX laser which has a good beam quality with intensity modulations of less than $\pm 10\%$. Nevertheless, strong nonuniformities of the shock wave are evident. We note that laser-driven shock waves may find renewed interest as beam smoothing techniques become mature [10].

The shock wave signals obtained in aluminum x-ray-drive experiments with the two types of cavities show interesting differences related to preheating of the sample. Figure 3 presents shock wave signals obtained in the two cases under similar drive conditions; the sample was in both experiments an aluminum double-step sample with thicknesses of 10, 17.5, and 25 μm.

The signals obtained with the D-shaped cavity (GEKKO) are independent of the sample thickness as expected for a shock wave traveling into a medium with uniform properties. By contrast the experiment with the spherical cavity (ASTERIX) shows a preshock signal, which for the 10 μm thick part of the foil has become so strong at the time of shock arrival that the jump in the signal can hardly be recognized [see Fig. 3(a); the arrival time is marked by an arrow]. In the thicker parts of the foil the signals approach those observed with the D-shaped cavity.

TABLE I. Comparison of predicted [from Eq. (1)] and measured shock wave pressures in gold.

Laser	GEKKO			ASTERIX
Cavity size (mm)	1	2	3	1
p [Eq. (1)] (Mbar)	23	8.4	4.5	7
p (expt.) (Mbar)	19	7.5	3.4	6

We attribute the preshock signal seen in the experiment with the spherical cavity to thermal emission from the rear surface of the sample which is caused by x-ray preheating. Calculations using cold aluminum opacities show that the dominant contribution to preheating comes from the x rays emitted by the laser-produced plasma in the cavity which fall into the spectral window of aluminum below its K edge (1.56 keV); a somewhat smaller contribution is due to the M-band emission of gold around 2.5 keV from the same source. In the spherical cavity, where these x rays fall at an angle of 45° onto the sample, we estimate a rear-side temperature of about 3 eV. In the D-shaped cavity the situation is much more favorable because the x rays fall nearly tangentially onto the sample (under an angle of 75° to the normal). Our calculations suggest that in this case x-ray preheating should be well below the estimated detection limit of about 0.5 eV blackbody temperature of our streak camera. In fact no preheating signal has been observed in the experiments with the D-shaped cavity. Thus our comparative study leads to the interesting conclusion that radiative preheating may be minimized by a suitable choice of the cavity shape and laser irradiation geometry.

Using single-step targets we performed one experiment for each cavity size and for each of the two materials with the GEKKO laser, and several using the ASTERIX laser. From the measured shock wave velocities we determined the shock wave pressures with the help of Hugoniot curves calculated from SESAME equation-of-state data [11]. For aluminum we obtained pressures of 20, 9.5, and 3.6 Mbar in the D-shaped cavities and 7 Mbar in the spherical cavity. Assuming that the equation of state is accurately known, the measured pressure may be used to infer the cavity temperature, either by numerical simulation of the x-ray-driven shock wave or by using the analytical theory of Hatchett [12]. The temperatures obtained in this way are in good agreement with those measured by x-ray spectroscopy. For gold the measured pressures are listed in Table I together with the predictions of Eq. (1). A conversion efficiency of 0.5 was assumed for the calculation of the source flux from the incident laser energy. If one keeps in mind the approximate nature of Eq. (1), the agreement appears quite satisfactory and confirms our previous conception of laser-heated cavities

[13] now with respect to pressure generation. A more detailed analysis will be presented elsewhere.

Summarizing, we have demonstrated that with the help of lasers uniform, high-quality shock waves can be generated in dense matter in a pressure range which otherwise is not accessible in the laboratory. The progress is due to the conversion of the laser light into incoherent thermal soft x rays. In this way not only small scale modulations of the shock front may be eliminated, but also, as we have shown, a high degree of uniformity may be achieved on macroscopic samples. As experiments using two different types of cavities and lasers have shown, radiative preheating effects may be minimized by proper cavity design and irradiation conditions. Using the methods described here it should be possible to make relative measurements of shock adiabats using the so-called impedance-match technique [14] at pressures exceeding those obtained in the laboratory by conventional methods. By making use of the impact of thin foils accelerated by x-ray ablation, absolute measurements and an extension of the parameter range may be realized; in fact pressures approaching the gigabar range have been demonstrated very recently using this approach [15]. It is thus conceivable that high-pressure generation by x-ray ablation might become a new tool in high-pressure physics.

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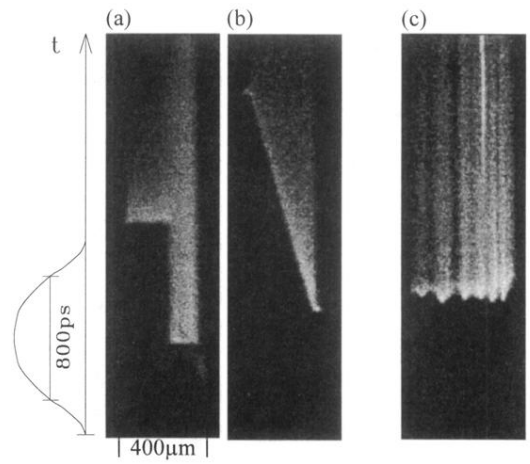

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