Laser and Particle Beams (2004), *22*, 59–63. Printed in the USA.

DOI: 10.1017/S0263034604221115

Cold compression of solid matter by intense heavy-ion-beam-generated pressure waves

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(Received 22 July 2003; Accepted 13 November 2003)

Abstract

Experimental investigations of heavy-ion-generated shock waves in solid, multilayered targets were performed by applying a Schlieren and a laser-deflection technique. Shock velocity and the corresponding pressures, temporal and spatial density profiles inside the material compressed by multiple shock waves, and details of the shock dynamics were determined. Important for equation-of-state and phase transition studies, such experiments extend their relevance to inertial confinement fusion and astrophysical fundamental research.

Keywords: Cold compression; Heavy-ion beam; Weak shock waves

1. INTRODUCTION

The shock-wave loading of solids can be accomplished by various means, from explosives and guns to laser and particle beams. Heavy ion beams can be accounted among them as an advantageous tool due to their spatially and temporally well-defined energy deposition profile. The heavy ion synchrotron SIS-18 at the Gesellschaft für Schwerionenforschung (GSI) can supply intense ion beam bunches, of about 5×10^9 particles for U, delivered in 550-ns-long pulses. This leads to a specific energy deposition of about 1 kJ/g in solid matter, which creates solid density plasmas at relatively low temperatures ($\sim$1 eV) and generates a pointlike source of pressure waves in the Bragg peak region. There is a yield of weak shock waves that are generally characterized by velocities just above the speed of sound, imparting to the material behind the shock front a velocity on the order of a 10th of the wave velocity. The material is compressed by only a few percent. The change of the quantities of state occurs isentropically, just as in the case of acoustic waves, from which they differ little. Previous studies on such pressure waves generated by the GSI heavy ion beams (Constantin *et al.*, 2002) indicated that the temperature increase due to shock heating of a sample in multilayered targets does not exceed 4 K, for pressures rising up to 10 GPa. The efficiency of the compression process was obtained by avoiding the direct ion beam heating and enhanced by generation of multiple waves. Reverberations of a primary weak shock on the sample boundaries with the neighboring layers as well as on the interface between coexistent fluid and solid phases of the material heated by the beam lead to an increase of wave strength and compression ratios.

The experiments described herein provide details of the multiple shock dynamics, time history, and structure, and report on measurements of temporal and spatial density profiles for multilayered targets irradiated by different projectiles with similar parameters. The former was investigated by means of a dark-field Schlieren method and the latter by employing a single-laser-beam deflection. The measured shock velocity and density of the compressed material represent a good support for theoretical modeling and equation-of-state analysis of compressed solid matter, with implications in phase transition to metallic states and fundamental research regarding targets for inertial confinement fusion.

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2. TARGET DESIGN AND EXPERIMENTAL ARRANGEMENT

The ion beam was stopped in a metallic plate made of Al, Cu, Fe, or Pb. A few millimeters were added to the calculated location of the Bragg peak to avoid the penetration of the following layer. This was a plexiglass block chosen due to its transparency as an observation window. The metallic absorbent was surrounded by plexiglass to enable two-dimensional visualizations of the shock propagation, both radially and longitudinally. A thin Al layer was affixed to the plexiglass block to keep the target confined during the compression or relaxation processes. The targets were positioned in the interaction point with the ion beam, which was focused down to 0.7 mm by means of a plasma lens (Stetter *et al.*, 1996). Side-on measurements were performed with a cw He-Ne laser of 5 mW power, expanded to a parallel beam of 30 mm diameter for the Schlieren measurements. The recordings of the deflected light of the laser beam were acquired by a streak camera with a temporal resolution of 100 ns, simultaneously with a multiframing camera for two-dimensional imaging. For this purpose the laser beam was split by a half-transmitting mirror just before the detection plane. Both cameras were focused onto the target. A round obstructer of 1 mm diameter, placed in the laser focus, was used to block the entire undeflected, parallel laser beam. An image of the refractive disturbance inside the shocked target is recreated by the deflected rays that pass the obstructer to reach the detectors. In this single-shot experiment, a $^{197}Au^{65+}$ ion beam with a particle energy of 300 AMeV, maximum 2×10^9 particles in a pulse of 700 ns duration was employed.

For the laser deflection diagnostics, a gated diode laser was used, probing the target transversally to the ion beam axis. The laser beam in this case was not expanded, covering a range of 0.5 mm inside the target, at a fixed position. The detection occurs at a large distance from the target (approximately 4 m) where the laser spot size becomes as large as 3 mm. The same type of streak camera was used to image the deflection of the laser spot each time when a shock traversed it. The targets were heated by a $^{238}U^{73+}$ ion beam with a particle energy of 300 AMeV, 8×10^8 particles/pulse, and a pulse duration of 700 ns. According to numerical simulations, such beam intensities can heat material to a few thousand Kelvin and therefore the stopping data in negligibly ionized matter provided by the TRIM code (Ziegler *et al.*, 1996) could be used.

3. SCHLIEREN EXPERIMENTAL RESULTS

Schlieren is a method commonly used for quantitative analysis of cylindrical or spherical indexes of refraction distributions, suitable for the present case. The Schlieren images experimentally obtained provide important information on the dynamics, geometry, and structure of the shock waves traversing the target.

The method works on the principle of the bending of light rays under certain angles due to density gradients transverse to the light propagation direction, translated into detection of spatial variation of the refractive index. The detection takes place at the location of the focused image of the refractive disturbance. The dark-field Schlieren introduces subsidiary elements into the optical system that transform the structurized angular distributions of the deflected rays into

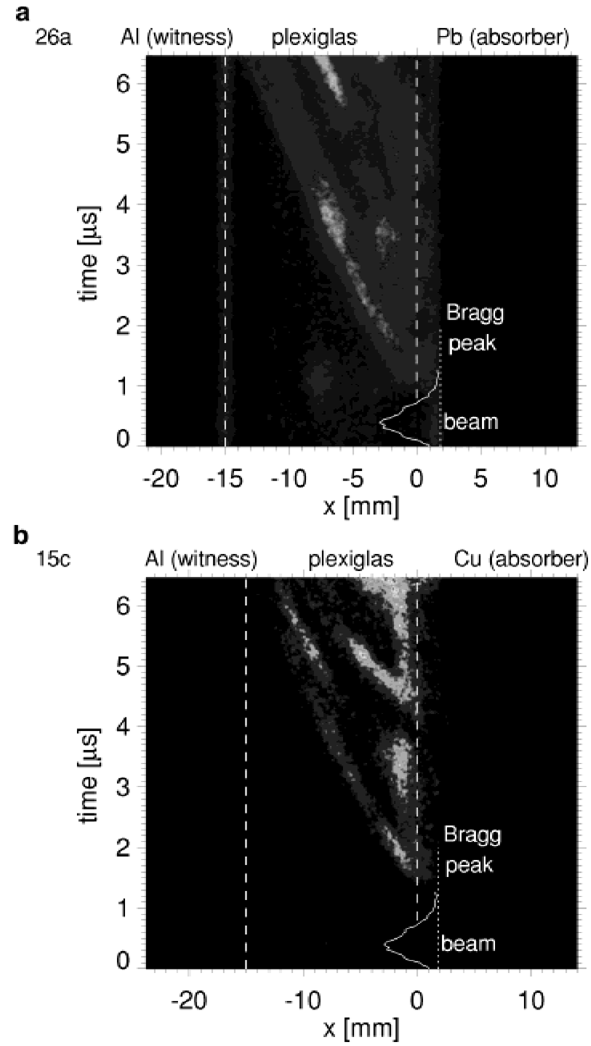

Fig. 1. Schlieren picture of induced shock waves in (a) a Pb-plexiglass-Al target and (b) a Cu-plexiglass-Al target. The temporal ion beam profile is plotted on the picture together with the location of the calculated stopping range (dotted line).

intensity distributions (Decker *et al.*, 1985). Both the front and the back of a shock contribute to the density change in the plexiglass layer, which is ultimately detected as two bright stripes following at close times to one another (see

Table 1. *Shock propagation velocities with the corresponding pressures and delays for the first shock arrival in plexiglass for each absorber material*

Absorbent	v_{max} [km/s]	P (GPa)	t [μs]
Al	3.80	>1.40	0.05
Cu	3.50	>1.40	0.80
Fe	4.00	>1.40	0.30
Pb (focused beam)	3.20	1.19	0.70
Pb (unfocused beam)	2.67	0.19	0.30

https://doi.org/10.1017/S0263034604221115 Published online by Cambridge University Press

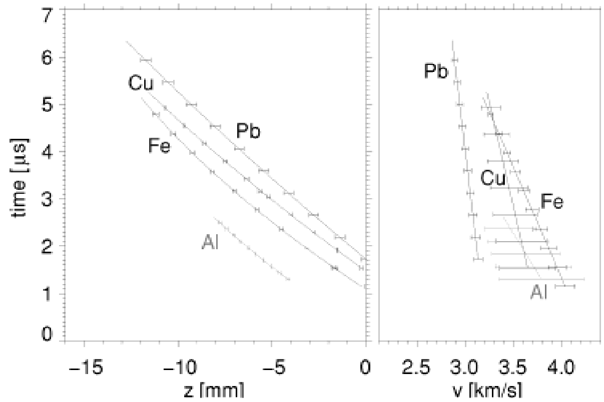

Fig. 2. Comparison of shock wave propagation velocities in plexiglass for targets with Al, Cu, Fe, and Pb absorbents.

Fig. 1a). At later times, an increased intensity of the detected light indicates the presence of some secondary waves (Fig. 1b), propagating in some cases with higher velocities, up to 4.5 km/s. The first shock velocity for all types of targets is above the sound speed in plexiglass at standard conditions, equal to 2.6 km/s. Table 1 gives this values, together with the corresponding pressures taken from literature (Zhang & Mueller, 1984).

The time resolution allowed not only measurements of the mean value of the first shock propagation velocity, but also the change of the velocity curve slope in time for each type of target. Clearly a more pronounced attenuation of the velocity and therefore of the shock strength occurs for the strongest shocks, as can be observed in Figure 2. This was the cases of targets with Al and Fe absorbents.

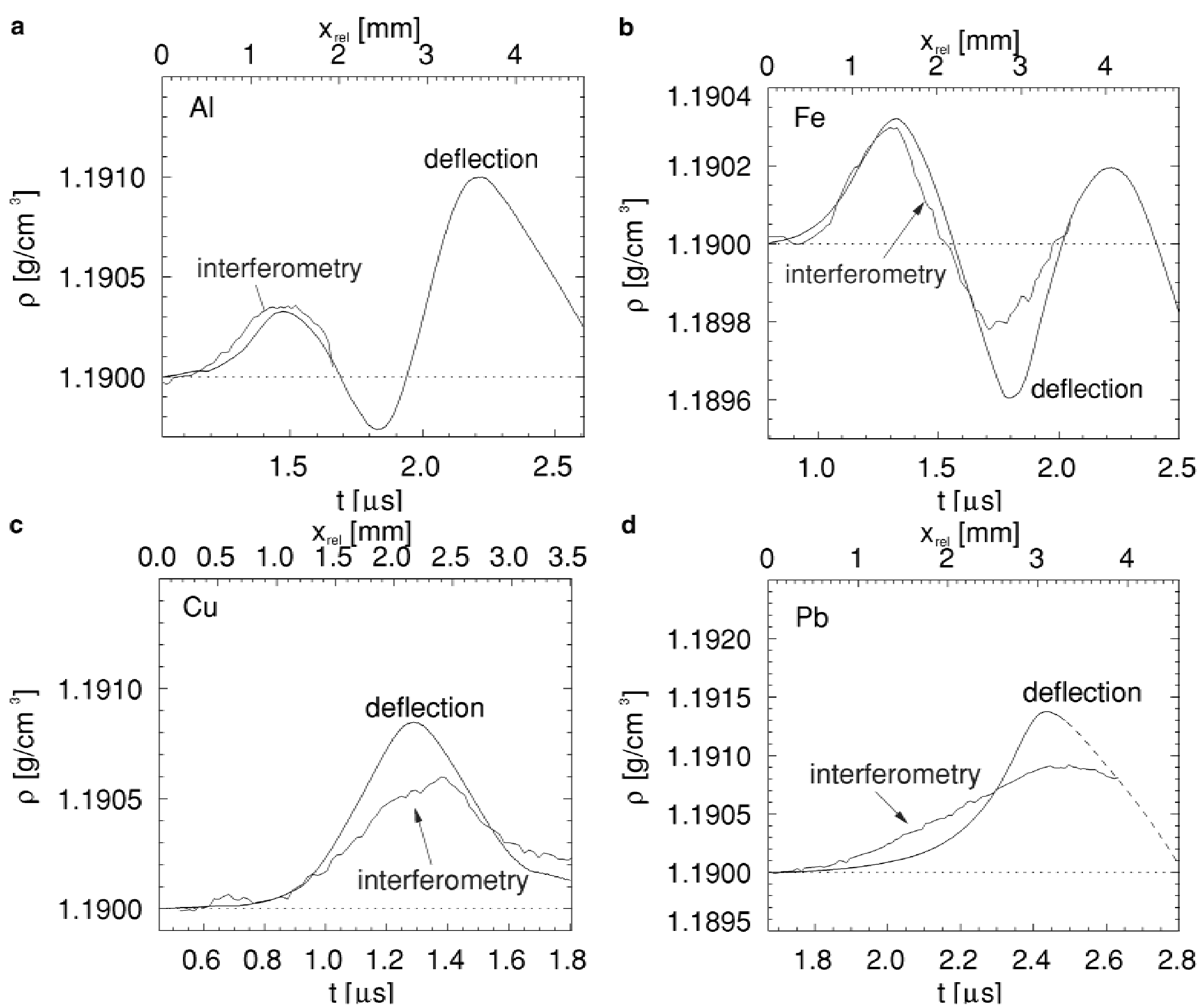

Fig. 3. Temporal and spatial density profiles in plexiglass for targets with (a) Al, (b) Fe, (c) Cu, and (d) Pb absorbents. Overplotted are the density profiles obtained from interferograms recorded simultaneously with the laser deflection pictures.

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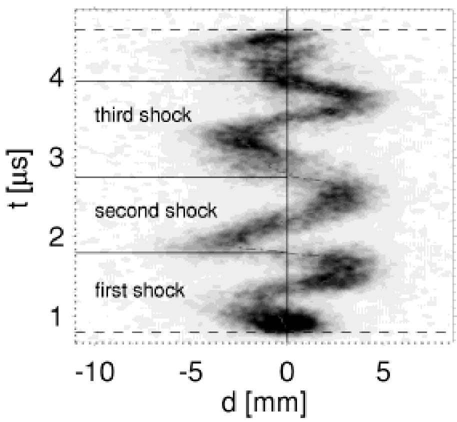

Fig. 4. An image showing the laser spot deflections inside the plexiglass, as the shock waves cross over.

4. LASER DEFLECTION EXPERIMENTAL RESULTS

Although Schlieren is a method that renders a good visual inspection in the refractive behavior of the compressible field of the target, more appropriate quantitative evaluations by means of densitometry are provided by a laser-deflection technique. This was applied together with a Mach–Zehnder interferometer, and thus the results could be cross-checked with the output of the time-resolved interferograms. If the total length from the target to the detection plane l is known and the streak screen is calibrated in millimeters, the spatial displacement, d, of the laser spot from its initial position can be easily measured from the pictures and inserted in the following relation : $d = l \cdot \sin \alpha \approx l \cdot \alpha$. The deflection angle α can be further related to the refractive index by the ray equation (Jahoda & Sawyer, 1971). The refractive index can be converted into densities by using the Clausius–Mossotti relation (Merzkirch, 1971). The results are given in the form of temporal density profiles plotted in Figure 3 for all types of targets. The comparison with interferometric results generally shows a good agreement, especially for the targets with Al and Fe absorbents. The spatial coordinates were calculated using the shock velocities measured interferometrically, which were slightly below the values obtained with the Schlieren method. Also in this case, the images recorded with the streak camera showed the presence of multiple shocks, enhancing considerably the density of the region crossed by the compression fronts (Fig. 3a). One example of such image is shown in Figure 4, which renders the deflections of the laser spot from the initial position, first due to the traversing of the shock front, followed by a deflection in the opposite direction due to the back of the shock.

5. CONCLUSIONS

Low-entropy compression of solid matter by heavy-ion-beam-generated shock waves is an important aspect in the context of equation-of-state studies. There are well-defined advantages that make the use of heavy ions an attractive tool to investigate the behavior of matter in states of high densities and pressures, such as the accurately determined energy deposition profiles, both in space and time. The rather low strength of the created single shocks can be surpassed by formation of multiple shock waves in certain target configurations, in conditions of a cold, efficient compression. To measure the parameters describing the states reached by the compressed material and thus to provide benchmarks for simulation codes, different optical diagnostics were employed. Herein, a dark-field Schlieren and a laser-deflection technique were described, yielding the shock propagation velocity and the temporal changes of the shock dynamics, densities, and pressures, the latter provided by data from literature. Following experiments determined the pressures directly by polyvinylide fluoride pressure gauge measurements. The main features of the stress waves were defined by the measured velocities, which proved to be above the speed of sound in the probed material (plexiglass), with a peak at 4 km/s for the primary shock. The presence of a train of shocks, detected by both diagnostics, lead to an increase of the shock velocity and undisputable enhancement in density, as displayed by the temporal density profiles obtained with the laser-deflection method.

As asserted by numerical simulation, an eventual upgrade of the GSI synchrotron ring, currently under discussion (Gutbrod *et al.*, 2002), would bring about pressures as high as 10 Mbar in solid targets, opening opportunities for investigations of phase transition to metallic states of matter. At this point, target materials of interest due to numerous possible applications are cryogenic crystals made of hydrogen, as well as rare gases, which are already developed in the Plasma Physics Group at GSI. Diagnostics such as those described in this work can be further improved or adapted to match the new conditions.

ACKNOWLEDGMENT

This work was supported by the German Ministry for Education and Research (BMBF).

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