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About laser shocks dynamics for complex focal spots and structured targets

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Abstract. We have analyzed the laser driven shock behavior in experiments with double focal spots, in particular, its cumulative effect in double layer foam–metal targets, explained by multiple collisions of individual shocks in the structured target. Some of experimental shock dynamics results are in a good agreement with the theoretical and numerical predictions, but others demand for new models.

1. Introduction

The study of the behavior of matter at pressures on the megabars order is relevant both for fundamental science and for many applications. In laboratory conditions, such compression can be realized only by dynamic methods, in particular shock compression with laser driver [1, 2]. Ensuring of the homogeneity and required compression is the key task in such experiments. One of prevailing research directions in this issue is the composite target design with low-density layers of microheterogeneous structure. The study of the propagation and interaction of shock waves in foams has recently received much attention [3–6].

The idea of experiment was to investigate the influence of a low-density ablator on shock compression in the condition of a strong inhomogeneity of the focal spot. The experiments were realized using the PALS (Prague Asterix Laser System) iodine laser [7]. The large-scale non-uniform irradiation was set by splitting the laser beam in two equal parts with a prism and producing a double focal spot on the target.
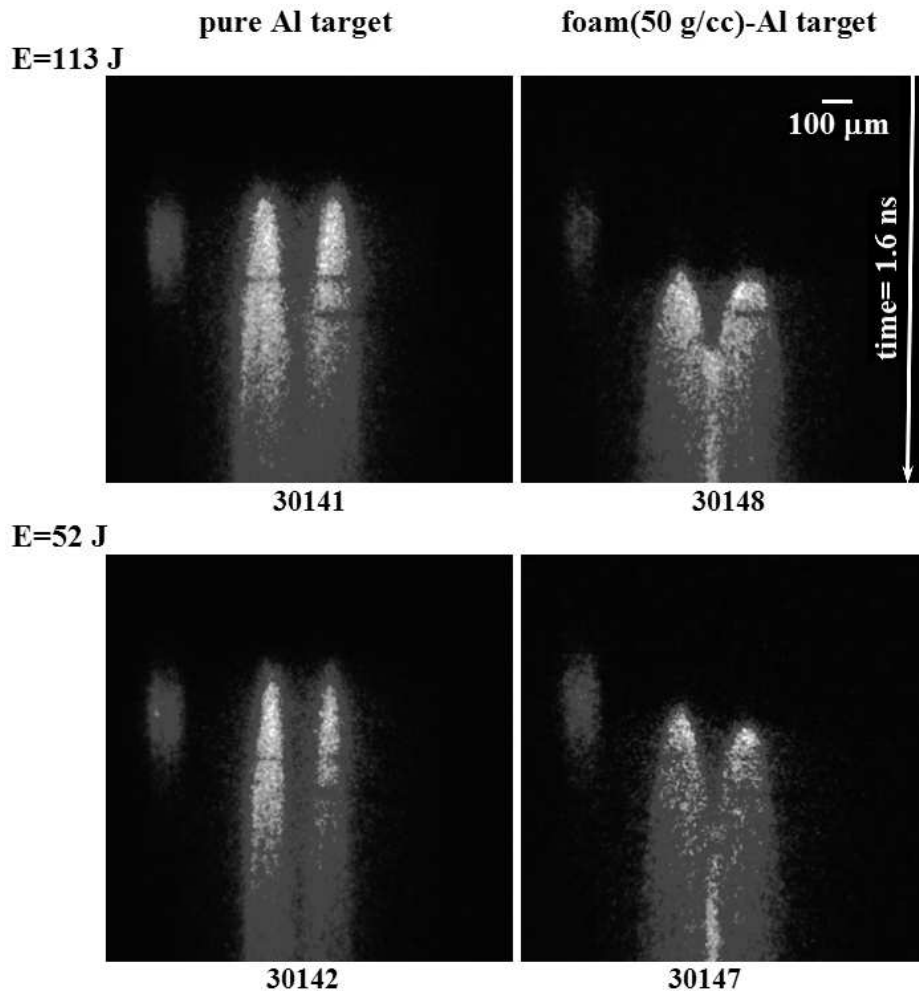
Figure 1. Rear side optical streak camera images. The total time window is 1600 ps (vertical) and the imaged region is 1330 μm wide (horizontal). Time flows from top to bottom. The signal on the upper left part of the image is the time fiducial indicating the arrival of the laser pulse on the front side of the target. The shot number is indicated in the bottom of each image.

In this paper, we focus our analysis on two specific features identified in double-layer targets with a foam density of 50 g/cm^3: (i) the collision between the two shocks originating from each of the two spots, (ii) the shock breakout delay for double-layer targets.

2. Experiment

The experimental set-up and diagnostics system is described in details in our recent papers [8–12]. The characteristics of the laser used in our experiment are the following: the laser pulse at 0.44 μm (the third harmonic of the emission wavelength) is Gaussian in time with a full width at half maximum (FWHM) of about 300 ps and with energy in the range 50–110 J. No phase plates were used in the considered shots. The targets used in the experiment were either flat Al foils (10 μm thick) or double-layer targets made of foam (50 μm thick) and Al (10 μm thick).

Two focal spots, obtained by splitting the laser beam in two equal parts with a prism, had a diameter of about 100 μm and were separated by about 200 μm. A time fiducial to control the time of arrival of the laser beam on the target front side was obtained by sending a small fraction of the incoming laser beam to the streak camera slit with an optical fiber.
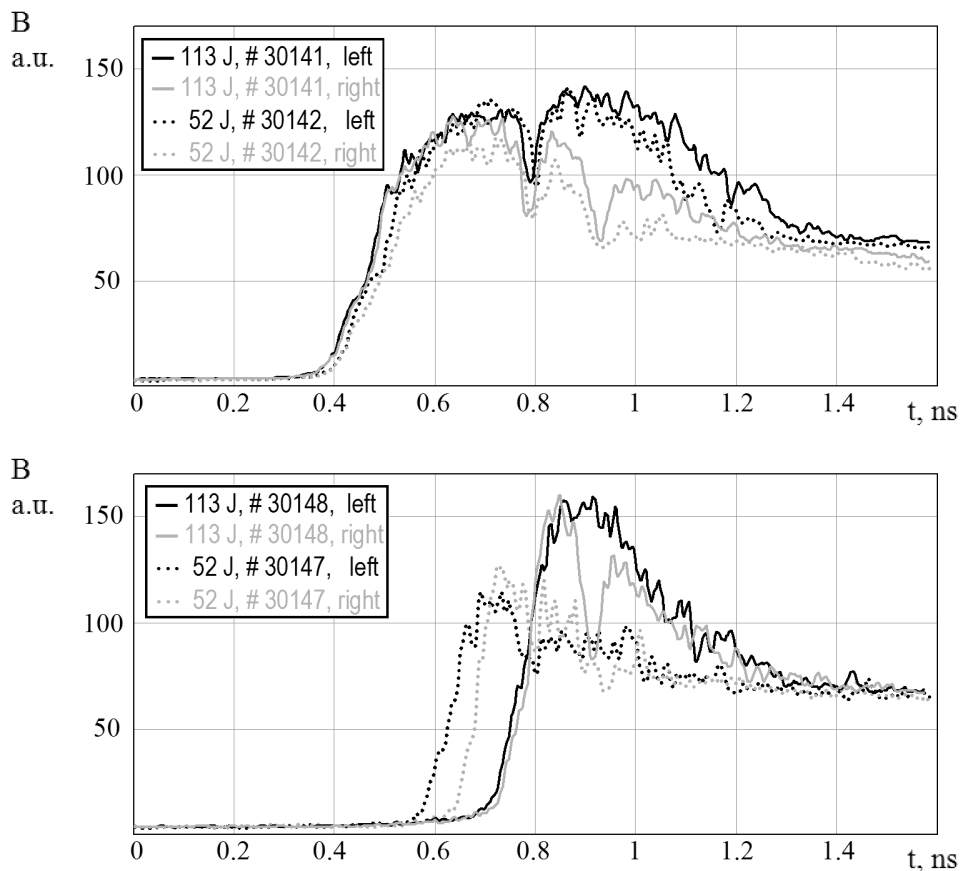
Figure 2. Spatially-integrated time dependences of the rear-side self emission (B, arbitrary units): for left (black) and right (gray) spots (for each image in figure 1), pure Al (top graph) and foam–Al (bottom graph) targets, total energy 113 (solid lines) and 52 J (dot lines). The time for all shots is synchronized by using the correspondent fiducial and taking into account the correction for the different thickness of filters used or different laser energies (about 30 ps). The zero point corresponds to the upper point of the image 30147.

As diagnostics, a photographic objective was employed to image the target rear side onto a streak camera Hamamatsu C7700 with S-1 photocathode to register the time-resolved self-emission signal for the detection of the shock breakout on the target rear side. A red RG60 filter before the streak camera cut out any 3ω light. The spatial resolution of the diagnostic was 2.6 μm and the temporal resolution 3.12 ps.

3. Results and discussion

Typical time-resolved rear-side self-emission images obtained with the streak camera for pure Al and foam–Al targets are presented in figure 1. Here, we present the results for two laser shots of energy 113 and 52 J.

Figure 2 shows spatially-integrated time dependences of the rear-side self-emission for each focal spot. The data for different shots are synchronized by using the fiducial signal. For ease of comparison, the upper graph shows data for the pure Al target, and the graph at the bottom— for foam–Al target. As it can be observed, the results for pure aluminum target are in line with expectations: the shock from the high intensity pulse (total pulse energy $E = 113$ J) is faster than the one at lower intensity (total pulse energy $E = 52$ J). The difference is about 30 ps only
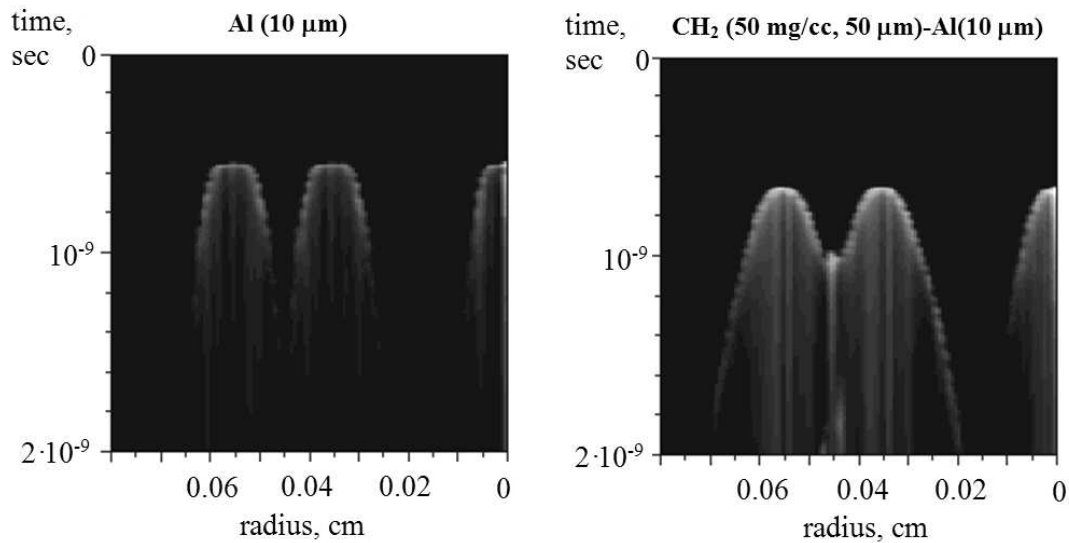
Figure 3. Calculated streak images of the luminescence of the back surface for the simple Al and Al-foam ($\rho_{\mathrm{foam}} = 50$ mg/cm^3) targets. Laser intensity is 10^{14} W/cm^2.

(due to the small target thickness). This is in agreement with predictions from simulations but also within the experimental error bars.

The absolute time of shock breakout was however not reproduced by simulations, which, for the used laser intensity, predicts a must faster shock. This phenomenon was already observed in recent works at similar intensity, performed in the framework of studies on the shock ignition approach to inertial fusion [13]. This points out to the need of including additional processes in the theoretical description of laser–plasma interaction and shock generation [5, 14–18]. In particular, in [18], including the description of parametric instabilities, hot electron generation and transport, and coupling of hot electron energy deposition to hydrodynamics allowed reproducing the experimental results of [13].

Also, as it can be clearly seen from the 2 (bottom), that the shocks in shot No. 30148 (total energy $E = 113$ J) are slower than in the shot No. 30147 (total energy $E = 52$ J). This result can probably be explained, similarly to those of [18], as a consequence of the preheating induced by the energy deposition of hot electrons causing an expansion of the target. The reduced density causes and increase of shock velocity ($D \propto \rho^{-1/2}$) on one side, but on the other side implies that the shock needs to travel a longer distance ($x \propto \rho^{-1}$). Since preheating increases with laser intensity, at a given point this could produce an inverse dependence of the shock speed on the laser energy. Of course these are initial results only and more in depth studying of shock dynamics in this intensity range are needed.

Concerning the results obtained with foam-layered targets, we observe that the size of shock breakout signal appears to be larger than in the Al target. Also the shock breakout arrival time is delayed in foam–Al targets: there is a big time-difference in shock breakout time for pure Al and for foam–Al targets ($\Delta\tau \approx 300$ ps, as seen for example in shots No. 30141 and 30148 with energy on target $E = 113$ J). The longer shock travel time is of course due to the fact that the target is thicker due to the presence of the foam.

Another observed effect, consisting in the appearance of a bright region between the two spots for the shots with double-layer targets, and not detected in the case of targets without the foam ablator, was explained in our recent publications on the base of qualitative 2D MULTI simulations [19, 20] for "ring" [21] and coaxial "double-ring" [22] profiles. The impedance of

aluminium is much higher than the impedance of foam. After the reflection of the shock from the foam–metal interface two shocks with the same pressure are generated, one is transmitted to the aluminium layer and the other reflected back into the foam [23]. The reflected shocks continue to compress the foam-base, and collide in the center. These phenomena produce a compressed central region with higher pressure in the foam layer, which continues to spread into Al layer (in contrast to simple Al foil) implying higher temperatures and higher emissivity in the centre.

A typical result of 2D MULTI simulation illustrating the appearance of a "collision area" in a foam–Al target (in contrast to pure-Al target) is presented in the figure 3. Here, we used a double-ring spatial profile to study the shock collision dynamics and an additional central spot with the same size for a direct comparison with the simulations of a single-spot dynamics.

4. Conclusion
The effect of the increasing of the delay of the shock breakout (i.e. decrease of the shock speed) with the laser energy for double-layer foam–metal targets with a foam density 50 mg/cm^3 and laser intensities about 10^{15} W/cm^2 was observed.

The effect of the generation of larger and more long-lived pressures in the "middle-spot" region for double-layer structured targets with a low-density foam material was observed. This result can be a consequence of the collision between two individual shocks which produce a higher pressures in the collision region.

Further studies on this issue would be of great interest both from a fundamental and an applied point of view. Many questions remain open, and for a complete understanding we should prompt for further experiments. In particular, the use of stepped targets would provide the possibility to calculate the shock speed in the metal layer as well as the use of other measurement techniques such as VISAR, etc would provide more insights on this issue.

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