LETTER TO THE EDITOR

Shock impedance matching experiments in foam–solid targets: implications for ‘foam-buffered ICF’

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Abstract. The influence of foams on laser-produced shocks has been studied experimentally using sub-ns laser pulses smoothed with phase zone plates and focused on layered foam–aluminium targets. A strong pressure increase was measured when the foam was present in comparison with that obtained by focusing the beam directly onto the aluminium target, due to impedance mismatch at the aluminium–foam interface. Results are compared with computer simulations. The impact of these measurements on the possible use of ‘foam-buffered targets’ for direct-drive inertial confinement fusion is briefly discussed.

1. Introduction

As is well known, the problem of uniformity of energy deposition in direct-drive inertial confinement fusion (ICF) is of the utmost importance in order to obtain ignition and high gain. To improve the uniformity of laser illumination, optical smoothing techniques have been introduced in the last few years, which include, for instance, the use of random phase plates [1], phase zone plates [2], kinoform phase plates [3] smoothing by spectral dispersion [4] or induced spatial incoherence [5]. Despite the considerable success of all such techniques, they are in principle unable to deal with the problem of laser non-uniformity at very early times during the laser–target interaction. This has been called the ‘laser imprints’ problem [6, 7] and may have important consequences on compression uniformity at later times (and in particular on the development of Rayleigh–Taylor instability [7]) even if optical smoothing is used.

In this context, recently the use of low-density foams has been proposed as a means of producing a uniform energy deposition in direct-drive ICF. A low-density foam is inserted between the target itself (the payload material) and the laser, producing a long plasma where laser non-uniformities are effectively removed by thermal smoothing. The scheme was first proposed by Dunne et al [8] who carried out preliminary experiments using a plastic foam with density $\rho = 50 \text{ mg cm}^{-3}$ and thickness $d = 50 \mu\text{m}$, illuminated by a laser beam at intensity $I_L \leq 5 \times 10^{14} \text{ W cm}^{-2}$. Despite encouraging results, much work remains to be done, and many details must be studied before such a scheme may really be considered for ICF applications. In particular, the smoothing capability of foams is not the
only critical parameter. Indeed, the introduction of foams should not create a plasma where laser instabilities are likely to develop and also the hydrodynamics of such foam-buffered targets should be studied in order to verify that no appreciable degradation of the laser–target coupling, i.e. of the compression efficiency of the pellet, occurs.

The last problem has been considered in [8] but the diagnostics used in the experiment allowed the study of the hydrodynamics of layered foam–solid targets at late times only. The authors showed that the time histories of the target motion with and without a foam layer were substantially the same, but this is exactly what is expected since the target motion at long times is determined only by its mass and by the laser ablation pressure which is relatively independent of the ablated material, as derived from simple models.

Moreover, the details of shock propagation in foams and the transmission of the momentum to the payload material need also to be studied. In ICF, it is very important to minimize the drive energy by compressing the target along a low isentrope in order to reach a high gain. Thus the generation of too strong a shock, which could preheat the thermonuclear fuel and make its compression more difficult, must be avoided, especially in the early stage of the implosion [9].

Hence more precise diagnostics are needed to study how the target is set in motion and not only its motion at late times. With this particular aim we have studied the influence of introducing a foam layer on laser-produced shock, studying the shock breakthrough from layered targets made of a foam layer on the laser side and a stepped aluminium layer on the rear side. A streak camera was used to detect shock breakthrough at the base and at the step of the aluminium target, allowing the shock velocity to be determined, following the method described in [2]. Of course, aluminium is not a realistic payload material for ICF targets, but it is a typical reference material for pressure determination since its equation of state is well known. Also, what is really important in this context is the transmission of the shock from the low-density foam to a denser payload material which is strictly proper to the principle of foam-buffered ICF itself.

2. Experimental set-up

The experiment was performed using three of the six beams of the LULI laboratory Nd laser (converted at $\lambda = 0.53 \, \mu m$, with a maximum total energy $E_{2\omega} \approx 100 \, J$) focused onto the same focal spot. The laser pulse was Gaussian in time with a FWHM of 600 ps. Each beam had a 90 mm diameter and was focused with an $f = 500 \, \text{mm}$ lens. The scheme of the experimental set up is shown in figure 1.

We used the phase zone plates (PZPs) [2] to eliminate large-scale spatial intensity modulations and produce a flat-top intensity profile in the focal spot. Hence shocks with a very planar front were produced. Despite the smoothing effect introduced by foams, the use of PZPs was necessary in our experiment in order to have the same irradiation parameters for any foam density, the parameter which was changed during the experiment. The characteristics of our optical systems (PZP + focusing lens) were such that we produced a total focal spot of 400 $\mu m$ FWHM, with an $\approx 200 \, \mu m$ wide flat region in the centre, corresponding to a laser intensity $I_L \approx 6 \times 10^{13} \, \text{W cm}^{-2}$. Such large focal spots were needed in order to reduce 2D effects because the total thickness of the target was of the order of 80 $\mu m$. 
3. Target production

The foam layers of the targets were realised with a technique developed at Dundee University [10, 11]. The targets are filled with a monomer solution containing a photo-initiator, and then polymerized in situ using UV light.

The monomer used in our experiments was TMPTA (trimethylol propane triacrylate, with chemical formula C₁₅H₂₇O₆). Starting from a liquid chemical solution, foams were formed inside a brass ring of ≈ 60 µm thickness, closed at one end with the stepped aluminium foils. The brass ring determined the final thickness of the foam which was checked again by optical microscopy. One essential stage in the preparation was critical point drying; indeed, any other drying method would damage the structure of the foam.

Such a technique produces foams in the required position in the target without the need for machining or handling, thereby reducing the risk of damage to the foam. Foam densities from 5 to 900 mg cm⁻³ can be produced. The polymerization is a free-radical process and produces homogeneous foams with uniform submicron pore sizes (see figure 2).

The stepped targets were produced at the Target Preparation Laboratory in CEA–Limeil with an electron gun deposition technique [12]. The accurate target-fabrication technique allowed sharp step edges to be obtained and a precise determination of step heights. The aluminium base thickness was in the range 10–12 µm, and the step was in the range 4–6 µm. The typical step width was 75 µm, while separation between steps was 45 µm so that we were sure to have at least one step inside the flat region of the focal spot on each shot (as can be seen in figure 3).

4. Experimental results

Figure 3 shows two streak camera images. In both cases it is possible to see a time fiducial at the top right of the image obtained by sending a portion of the laser beam onto the streak camera slit with an optical fibre. In figure 3(a) a stepped aluminium target without foam was used while in figure 3(b) a foam layer was present on the laser side. All the other conditions, including laser pulse energy (E₂₀ ≈ 32 J), were the same.

The pictures show a delayed shock breakthrough, i.e., a longer time between the maximum of the laser pulse (measured through the time fiducial) and shock arrival when the foam is present. This corresponds to the time needed for the shock to travel through
the thick foam. The pictures also show that the shock velocity inside the aluminium target, and hence the pressure generated in the aluminium, increases (the values of pressure have been deduced from shock velocity by using the SESAME tables for aluminium [13]). Such effects have been found to be a function of the foam density and thickness as shown in the experimental results of figure 4. The points corresponding to $\rho = 1 \text{ mg cm}^{-3}$ are really those obtained with stepped targets without foam. The pressure generated in this
Figure 4. Amplification of pressure obtained in aluminium versus foam density $\rho$ in mg cm$^{-3}$.

$P_0$ is the value for simple aluminium targets. Also shown are the results of MULTI simulations. The white circles correspond to targets with carbon overlayer.

Last case ($\approx$ 7 Mbar on average) corresponds approximately to what can be obtained from scaling laws [14, 15] for our laser and target parameters:

$$P \approx 8.6\left(\frac{l}{10^{14}}\right)^{2/3} \lambda^{-2/3} \left(\frac{A}{2Z}\right)^{1/3}$$

where units are in Mbar, W cm$^{-2}$ and $\mu$m, and $A$ and $Z$ are respectively the atomic weight and number of the ablated material. The points for $\rho = 1100$ mg cm$^{-3}$ correspond to targets which have a layer of polymer at normal density. Here the plastic thickness is 15 $\mu$m; indeed, the use of a 60 $\mu$m layer in this case would have implied the shock pressure is not maintained, our laser pulse duration being too short.

Figure 4 also shows some experimental points obtained by adding a carbon overlayer on the targets on the laser side. Such shots were performed in order to address the question of a possible influence of laser shinethrough in the transparent foam layer. Such points do not exactly correspond to the others from a quantitative point of view, due to the effect of the carbon layer on hydrodynamics. Indeed the carbon layer needed to be non-transparent was rather thick ($\geq 1 \mu$m) implying a significant additional mass. However, they have the same qualitative behaviour, showing a negligible effect of laser shinethrough.

Finally, typical error bars are reported in figure 4. Errors on experimentally determined pressures are of the order of $\pm 8\%$, corresponding to an experimental error on shock velocity of $\pm 4\%$, due to the approximately quadratic dependence of $P$ on shock velocity. Such errors arise from different sources:

- calibration of streak camera sweep (1\% ) which was done with a train of femtosecond laser pulses as described in [16].
- measurement of step thickness ($\approx \pm 0.05 \mu$m) corresponding to 1.3 \% [17].
- streak camera resolution ($\pm 5$ ps) due to the value of slit width (100 $\mu$m) and the streak sweep used (100 ps mm$^{-1}$).
- measurement of shock breakout time due to shock front planarity and reading error ($\leq 10$ ps) [2].

The errors on the horizontal axis are due to the foam fabrication procedure ($\pm 5\%$).
5. Discussion

The principle of pressure increase relies on an impedance mismatch between foam and aluminium. Upon the arrival of the shock wave at the interface, a shock is transmitted in aluminium and another one is reflected into the foam. The different materials on the two sides have the same pressure and fluid velocity, this common point being at the intersection of the aluminium shock polar and the foam polar for reflected shocks [18]. By decreasing the foam density, the impedance mismatch between the two materials increases and one would expect that the shock pressure in aluminium would become bigger. Indeed, for instance, using the impedance mismatch relations in the perfect gas approximation we find

\[ \frac{P}{P_0} = 4\rho_{Al} (\sqrt{\rho_{Al}} + \sqrt{\rho})^{-2} \]  

where \( \rho_{Al} = 2.7 \text{ g cm}^{-3} \) and \( \rho \) is the foam density. We note, however, in figure 4, that for foam densities \( \rho \leq 100 \text{ mg cm}^{-3} \) the behaviour is reversed and the pressure decreases. Several effects contribute to produce this result. Firstly, at the lowest densities, it is not possible to avoid the direct interaction of the laser beam with the metal target behind the foam. This is due to the fast ablation rate of the foam and also to the fact that the foam itself may be undercritical. Simple analytical laws predict the ablation rate [15, 19] as

\[ \dot{m} = 4.5 \times 10^{-6} I_L^{3/4} \lambda^{-1/2} t^{-1/4} \]  

where \( \lambda \) is in \( \mu \text{m} \), \( t \) in ns, \( I_L \) in W cm\(^{-2} \) and \( \dot{m} \) is in g cm\(^{-2} \) s\(^{-1} \). Hence the ablation rate (and hence the shock pressure) is independent of the foam density and the ablation velocity is inversely proportional to it, giving for our laser parameters a limit of about \( \rho \leq 15 \text{ mg cm}^{-3} \). Foams with lower density are completely ablated during the pulse.

Furthermore, direct laser–metal interaction takes place with undercritical foams i.e. if we assume a complete ionization of the low-Z elements of the foam, when

\[ n_e = \rho N_A Z / A < n_c = 1.1 \times 10^{21} / \lambda^2 \]  

where \( N_A \) is the Avogadro number. This fixes a limit at \( \rho \leq 12 \text{ mg cm}^{-3} \) (for \( \lambda = 0.53 \mu \text{m} \)). A partial ionization is not likely, considering the high temperatures reached in the foam (as shown in numerical simulations) but it would mean that an even higher foam density would be required to reach critical density. These two effects contribute to gradual lowering of the shock pressure to the value measured in simple metal targets, hence bringing a meaningful continuity of physical results. The residual measured pressure increment for such low densities is probably due to the partial confinement of the expanding aluminium plasma by the foam, as observed in shocks produced from focusing lasers on the surface of targets immersed in water or under a layer of transparent material [20].

For the denser foams, in the range 20 to 100 mg cm\(^{-3} \), the pressure generated at the interface is increased due to impedance mismatch, but other effects arise which justify the behaviour of shock pressure versus foam density. Firstly, the shock initially accelerates and hence it may be transmitted to the aluminium layer before maximum pressure has been reached. By using shock relations for ideal gases, it is possible to show analytically that in this case for a fixed foam thickness the pressure generated in aluminium decreases with density. Secondly, the pressure generated at the interface is not maintained due to the fast transit times of the reflected shock followed by the unloading wave. The laser intensity sustains a pressure given by formula (1) in the foam which is then increased in the aluminium due to the impedance mismatch. The reflected shock travels rapidly back through the foam and is then reflected as an unloading wave at the critical surface. This unloading wave will also travel rapidly through the hot foam and aluminium [18] and may reach the initial shock in the aluminium before this breaks out from the rear surface. This
effect results in a decrease in the pressure inside the metal as a function of time and so we measure a shock velocity which is smaller than that which corresponds to the maximum pressure determined by the impedance mismatch conditions. Moreover, the experiment measures the average velocity inside the step, hence giving a lower velocity than at the bottom of the step.

In order to simulate our data we used the hydrocodes MULTI [21] and DUED [22]. Simulations clearly show that for densities below 100 mg cm\(^{-3}\), a very high pressure is reached at the aluminium–foam interface but it is not maintained and begins quickly to decay as the relaxation wave from the ablation front reaches the slower shock propagating in the aluminium. The simulation results, shown in figure 4, are affected by radiation transfer. Radiative effects are evidenced in the simulations, as already described in literature [18, 23, 24]. By comparison with an equivalent mass of normal plastic, the foam is heated to higher temperatures by the compression and, being very low density, is also more transparent to radiation. Hence, even though not much XUV radiation is produced (foams being made of low-Z elements only) preheating ahead of the shock front is non-negligible. Moreover, because of the higher temperatures and higher transparencies of the foam relative to normal plastic, the interface between foam and metal will preheat more since radiation propagating in the foam will be stopped due to the much higher absorption in the metal. Hence a slight modification of the plasma profile is expected at the interface. However, in our case such radiative effects are not dominant.

It is evident from figure 4 that while the simulations describe the overall behaviour of experimental data qualitatively well, the fine details are not explained. The lack of detailed agreement may be in part connected to the fact that foam opacities, and foam equation of state (EOS) are not sufficiently well known. We have used the simple analytical EOS model [22], the Los Alamos opacity data [25] and the SESAME EOS for plastic. In this last case, we have artificially lowered the initial density [13] to fit the appropriate foam density. Finally, the computer simulations used to interpret our experimental results show that, at least in the first approximation, the ablation pressure is independent of foam density and equal to that in aluminium. This shows again that target motion at late times, as studied in [8], is not enough to discriminate the effects due to the presence of the foam.

6. Conclusions

We conclude that shock propagation in foam is a complex hydrodynamic phenomenon and that at foam–solid boundaries a key role is played by the pressure increase due to the impedance mismatch. We have shown how the presence of a foam layer can strongly increase the pressure reached in an adjacent layer of a denser payload material. In our case the effect is slightly increased by the use of Al which has a larger mismatch with foam as compared with more realistic payload materials. However, our results, obtained at intensities typical of the NIF and LaserMegajoule footpulses, have important consequences for the concept of foam-buffered targets which has been proposed for ICF to remove the initial imprint by thermal smoothing. Shock enhancement at the foam–solid boundary moves the target material off the isentrope with a consequent significant loss of compression efficiency. Hence such an effect must be considered carefully in order to estimate the shock enhancement and optimize the target design.

Finally, we want to point out that, despite the fact that simple models give a good qualitative description of our results, both the equation of state and the opacity of the foam can play significant roles in the dynamics of the shock propagation. This means that precise foam EOS and opacity data are needed to improve computer codes, not only in order to
perform accurate quantitative simulations of our experimental results, but above all to ensure reliability of future foam-buffered ICF targets.

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References