Laser interactions with low-density plastic foams

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Outline

• Motivation and aim
• Experimental results
  – X-ray streak measurement of thermal transport in foam
  – 3-frame optical interferometry to measure foil acceleration
  – Preliminary experiment on shock break-through (opt.streak)
• 2D hydrodynamic simulations of experiments
• Analytical model of experiments
• Comparison of experiments, simulation and theory
  – Velocity of accelerated foil
  – Hydrothermal wave transit time though foam
• Conclusions and future plans
Motivation

• Low-density foam layers (mostly overdense plastic foams) have the potential of target design improvement for ICF and other experiments
• Laser imprint may be smoothed out in a relatively thick hot low-density outer layer of target – one approach relies on transport of x-rays generated in a thin high-Z outer layer, while the other approach prefers highly efficient laser absorption in the foam
• Density tailoring of sandwich target including foam layer with distant laser prepulse may suppress RT instability
• Foams are used in EOS experiment to increase pressure due to impedance mismatch on foam-solid interface
• Foam materials are also important in astrophysics dedicated experiments
Foam materials

- Low density materials must be inhomogeneous
- If you want 1% of solid density, you have 1% of solid, and 99% of vacuum
- Here we have basically cubic pores, but filamentary structure also possible
- When heated, pore walls expand (fast homogenization stage)
- After collision of mass fluxes (slow homogenization stage)
Aim

• More information is needed about laser-foam interaction and about energy transport in foam layers for successful design of ICF targets including foam layers

• Laser absorption and energy transport in the foam material with large pores ($D_p > 10 \, \mu m$) is studied here – laser pulse shorter than slow homogenization stage

• Sufficient efficiency of thin foil acceleration by the pressure of heated foam matter is demonstrated

• Substantial smoothing of laser inhomogeneities is searched for

• Comparison of experimental results with numerical simulations and analytical model is important for progress in understanding laser-foam interactions
Interaction of 400 ps iodine laser ($\lambda=1.32 \, \mu m$) pulse of energy 92 J and radius 150 $\mu m$ with 400 $\mu m$ thick polystyrene foam of density $\rho \approx 9 \, \text{mg/cm}^3$ and pore diameter $D_p \approx 50 – 70 \, \mu m$, 2 $\mu m$ thick Al foil is placed at the target rear side.

- Images above the sensitivity limit of the streak could be registered only for foams with the largest pore diameter
- Laser penetration depth can be estimated from the immediately heated layer thickness $\sim 130 \, \mu m$
- Heat wave propagates later with velocity $1.4 \times 10^7 \, \text{cm/s}$
- No x-ray emission near the target rear side is observed
Three-frame optical interferometry

Sequence of 3 interferograms recorded in one shot in instants 1, 4 and 7 ns after the main 400 ps FWHM laser pulse maximum. Laser wavelength 1.32 µm and beam radius 150 µm on the polystyrene foam of $\rho \sim 9$ mg/cm$^3$, $D_p \sim 50 - 70$ µm, 400 µm thick with 2 µm thick Al foil at its rear side. Laser energy 173 J. Parasitic effects of the target holder are denoted in the left picture.

- No sign of the target rear side (foil) expansion observed
- Smooth shape of accelerated foil (~ spherical shock wave)
- Rear side motion starts at about 3 ns after laser pulse
- Point P moves with velocity $8 \times 10^6$ cm/s between 4 and 7 ns after laser
Three-frame optical interferometry (PVA foam)

Sequence of 3 interferograms recorded in one shot in instants 1, 4 and 7 ns after the main 400 ps FWHM laser pulse maximum. Laser wavelength 1.32 µm and beam radius 150 µm on the PVA (polyvinylalcohol) foam of ρ ~ 5 mg/cm³, Dp ~ 5 µm, 100 µm thick with 0.8 µm thick Al foil at its rear side. Laser energy 238 J. Parasitic effects of the target holder are denoted in the left picture.

- Target rear side (foil) expansion observed
- Smooth shape of accelerated foil
- Rear side motion starts during laser pulse
- Point P moves with velocity 1.4x10⁷ cm/s between 4 and 7 ns
Measured evolution of point P position

- $E_L = 92 \text{ J}$
- $E_L = 173 \text{ J}$
- PVA target
Preliminary optical streak record of self-emission from target rear side

Left – foam 700 μm + 5 μm Al foil
Right - 5 μm Al foil only

5 ns/image - time grows downwards, spatial scale 1.5 mm/image, fiducial – left upper corner, 3rd harmonics of iodine laser, energy 240 J, laser spot radius 200 μm
2D hydrodynamic simulations

• 2D Langangian hydrocode “ATLANT-HE” used
• 1 fluid 2 temperature model of plasma with the flux-limited Spitzer’s heat conductivities for electrons and ions
• Advanced treatment of laser propagation and absorption
• Fast electron generation and transport included
• Simulations performed in cylindrical geometry
• Fine structure of the foam is not taken into account, foam approximated as uniform low density medium
• Fast homogenization stage – filling of the pores – lasts about 50-100 ps, i.e less than laser pulse
• Slow homogenization stage – density smoothing – up to several ns ⇒ speed of hydrothermal wave may be overestimated
Results of 2D hydrodynamic simulations

Density (in g/cm³) and electron temperature (in eV) profiles at times 1, 4 and 7 ns after laser pulse maximum calculated numerically for polystyrene foam 400 µm thick with 2 µm thick Al foil and laser energy 173 J.
Analytical model

• Does not take into account fine structure of the foam
• Spherical hydrothermal wave reaches rear side of the the foam in time $t_f$

$$t_f \approx \frac{\Delta_f^{5/2}}{\left[ \frac{3}{2} \left( \frac{5}{3} \right)^2 \frac{(\gamma-1)E_{ab}}{\pi \rho_f} \right]^{1/2}}$$

• Initial pressure on the foil

$$P_0 = P_{ht}(t=t_f) \approx \frac{(\gamma-1)E_{ab}}{\pi \left( \Delta_f + R_L \right)^2 \Delta_f}$$

Foil maximum velocity

$$V_{max} = \frac{c_0 \cdot \rho_f \cdot \Delta_f}{\gamma \cdot \rho_s \cdot \Delta_s}$$

where $$c_0 = \left( \gamma P_0 / \rho_f \right)^{1/2}$$
Comparison of experiment, simulations and analytical theory

<table>
<thead>
<tr>
<th>Laser energy</th>
<th>Target</th>
<th>$V_{\text{exp}}$ (cm/s)</th>
<th>$V_{\text{simul}}$ (cm/s)</th>
<th>$V_{\text{max}}$ (cm/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>92 J</td>
<td>(CH)$_n$</td>
<td>$6.0 \times 10^6$</td>
<td>$4.9 \times 10^6$</td>
<td>$4.8 \times 10^6$</td>
</tr>
<tr>
<td>173 J</td>
<td>(CH)$_n$</td>
<td>$8.0 \times 10^6$</td>
<td>$8.2 \times 10^6$</td>
<td>$6.7 \times 10^6$</td>
</tr>
<tr>
<td>238 J</td>
<td>(CH)$_n$</td>
<td>$\ldots$</td>
<td>$1.1 \times 10^7$</td>
<td>$8.2 \times 10^6$</td>
</tr>
<tr>
<td>238 J</td>
<td>PVA</td>
<td>$1.4 \times 10^7$</td>
<td>$3.5 \times 10^7$</td>
<td>$1.32 \times 10^7$</td>
</tr>
</tbody>
</table>

- Generally good agreement in foil velocities
- Velocity in simulations is overestimated for the case of PVA that is heated up to 800 eV in simulations and foil expansion is faster than in experiment
- Hydrodynamic efficiencies (foil kinetic energy/absorbed laser energy) in range 12 – 14%
- Smooth shape of accelerated region of the foil
Delay in hydrothermal wave propagation

- The hydrothermal wave arrival on the rear boundary is approximately the same in simulations and in theory.
- Experimental time of arrival is by about 2 ns greater for 400 μm thick foam layer.
- Delay may influence laser imprint mitigation.
- Delay may be explained by foam homogenization.
- Fast homogenization stage needs $t_s \sim (D_p - b)/V_s$ ($\sim 100$ ps).
- Final homogenization stage controlled by speed of viscous processes (broadening of shock wavefront).
- Time $t_h$ is about 2 ns for $T = 1$ keV, $D_p = 50$ μm, $\rho = 10$ mg/cm$^3$.

\[
t_h \approx 10^{-9} \times \frac{D^2 p \rho f}{\lambda_i V_s T^{3/2}}
\]
Conclusions

- Depth of laser absorption region and speed of heat wave in foam measured by x-ray streak
- Foil acceleration observed by 3-frame interferometry
- Preliminary measurement of shock wave arrival
- 2D hydrodynamic simulations and analytical model applied, but foam fine structure not taken into account
- Good efficiency of foil acceleration found
- Smooth profile of accelerated foil boundary
- Agreement between theory and experiment in accelerated foil velocities
- Increased experimental delay in hydrothermal wave transit explained by foam homogenization process
- Delay may influence laser imprint mitigation
Plans for future

- Next experiment on PALS laser – November 2004
- Comparison between foams with submicron and large pores will be performed
- Shock wave arrival on the foam rear side for $1\omega$
- Laser reflection to focusing optics will be measured
- Foams containing a medium Z element in order to enhance x-ray emission for x-ray streak measurements will be also used
- High resolution line x-ray spectra of medium Z element in foam will be recorded

Thank you for attention
Preliminary optical streak record of self-emission from target rear side

Left – foam 700 µm + 5 µm Al foil
Right - 5 µm Al foil only

5 ns/image - time grows downwards, spatial scale 1.5 mm/image, fiducial – left upper corner, 3rd harmonics of iodine laser, energy - 75 J, laser spot radius 150 µm