Laser interactions with low-density plastic foams

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Outline

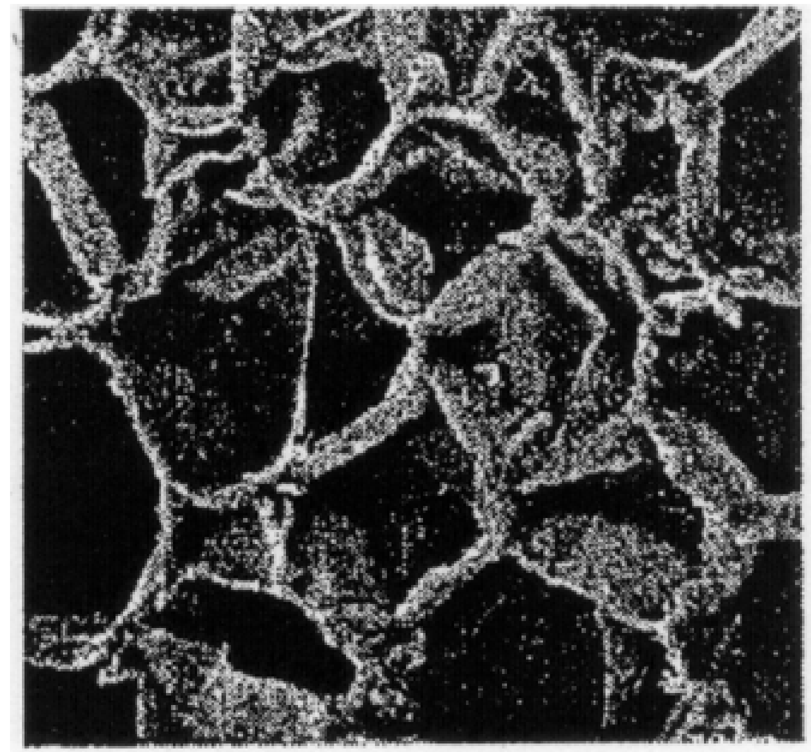
- Motivation and aim
- Experimental results
  - X-ray streak measurement of thermal transport in foam
  - 3-frame optical interferometry to measure foil acceleration
  - Preliminary experiment on shock break-through (opt.streak)
- 2D hydrodynamic simulations of experiments
- Analytical model of experiments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

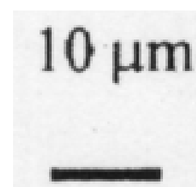
Motivation

- 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)

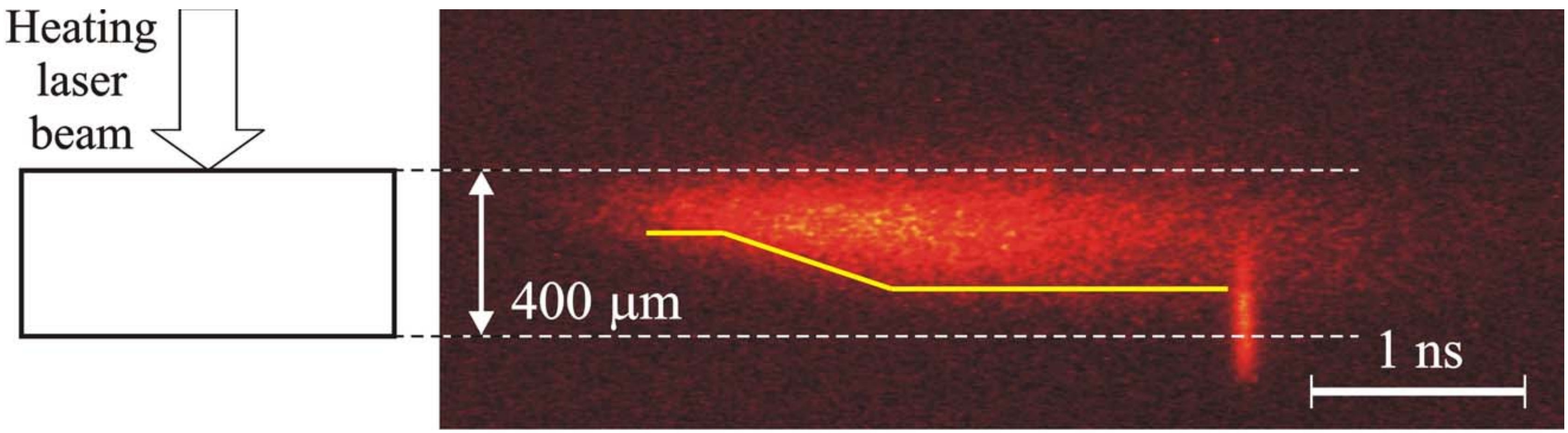




Aim

- 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

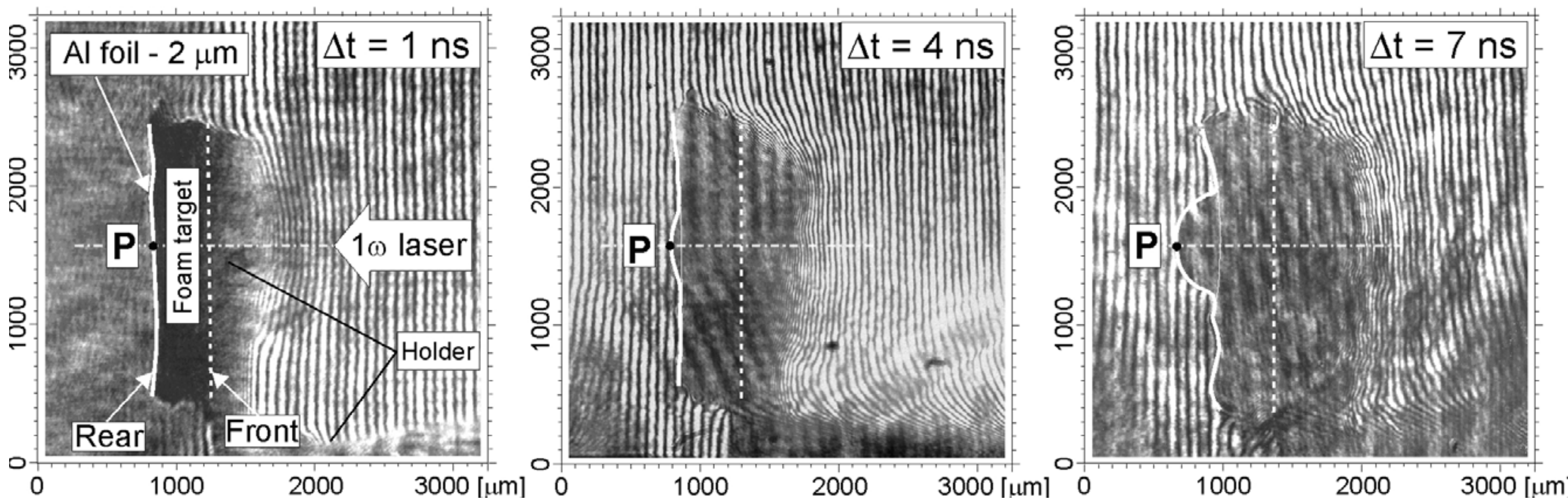
X-ray streak records of lateral slit image



Interaction of 400 ps iodine laser (λ=1.32 µm) pulse of energy 92 J and radius 150 µm with 400 µm thick polystyrene foam of density $\rho \approx 9$ mg/cm^3 and pore diameter $D_p \approx 50 – 70$ µm, 2 µm thick Al foil is placed at the target rear side.

- Images above the sensitivity limit of the streak could be re-gistered only for foams with the largest pore diameter
- Laser penetration depth can be estimated from the immediately heated layer thickness ~ 130 µm
- Heat wave propagates later with velocity 1.4 x 10^7 cm/s
- No x-ray emission near the target rear side is observed

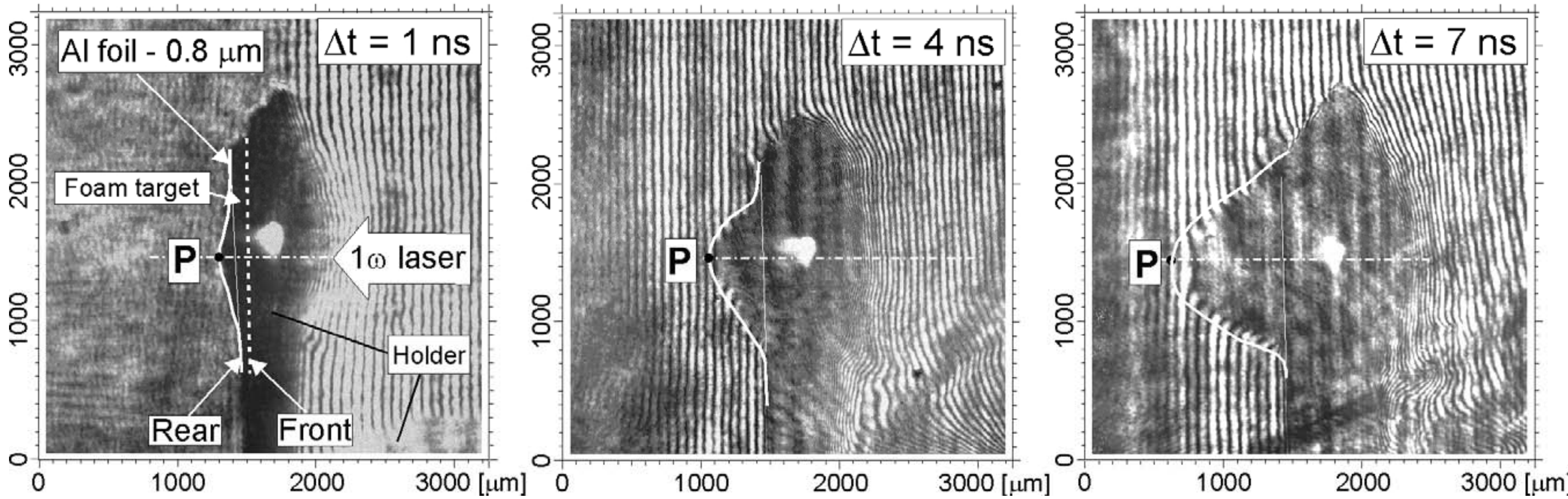
Three-frame optical interferometry



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 8×10^6 cm/s between 4 and 7 ns after laser

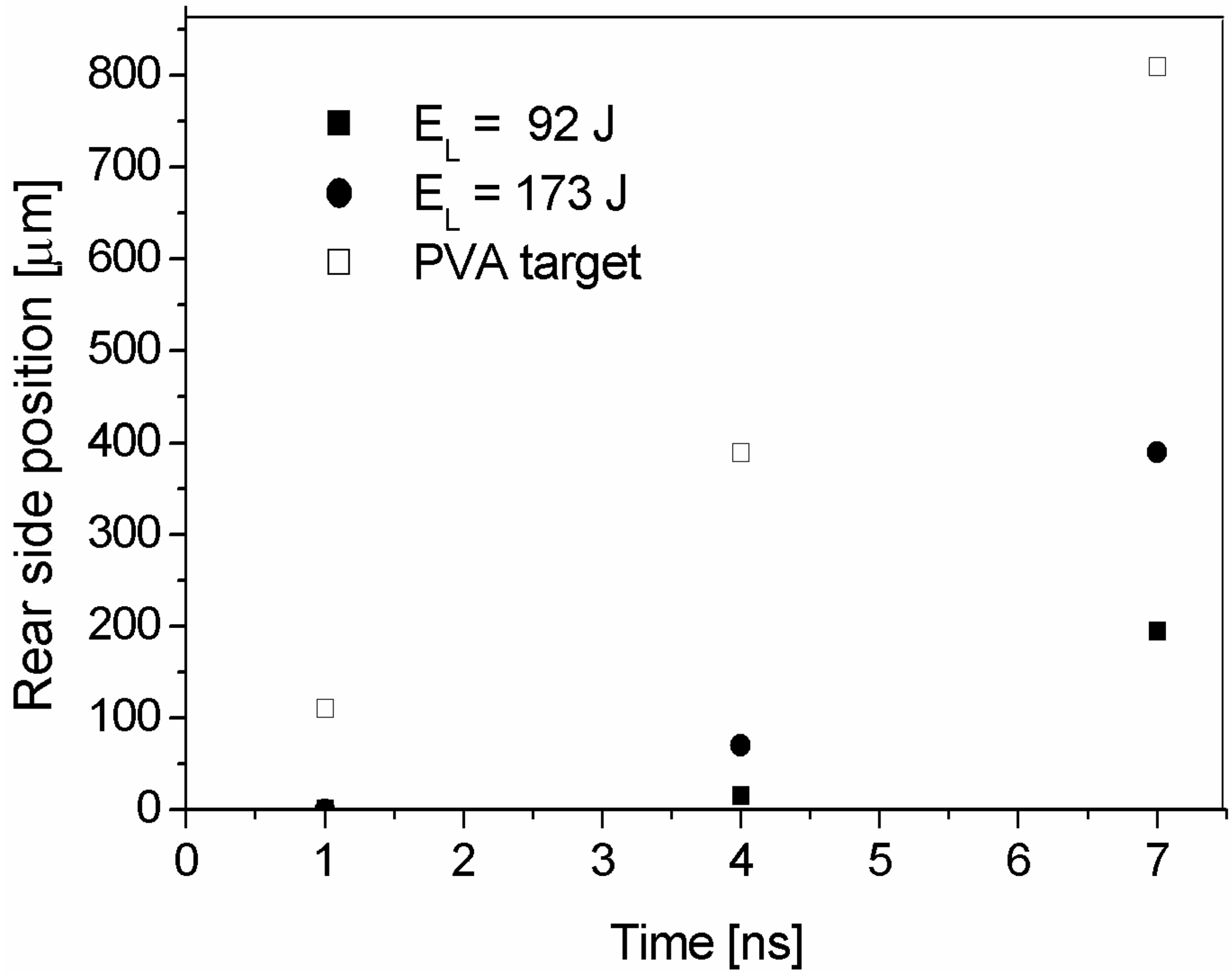
Three-frame optical interferometry (PVA foam)



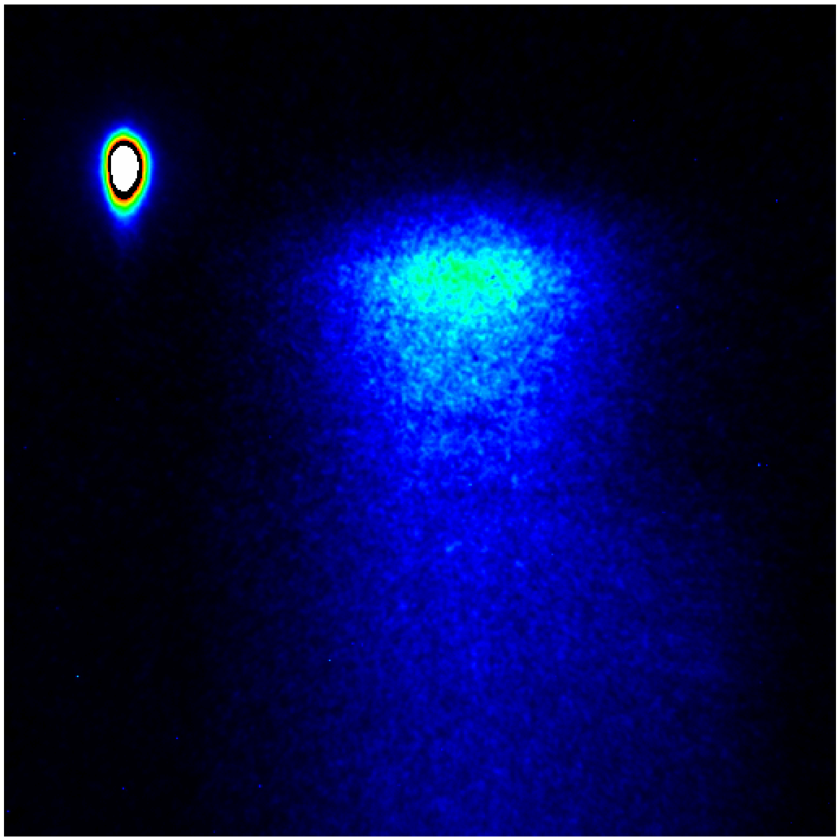
Sequence of 3 interferograms recorded in one shot in instants 1, 4 and 7 ns after the main 400 ps FWHM laser pulse maximum. Laser wavelength 1.32 μm and beam radius 150 μm on the PVA (polyvinylalcohol) foam of ρ ~ 5 mg/cm^3, D_p ~ 5 μm, 100 μm thick with 0.8 μm thick Al foil at its rear side. Laser energy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

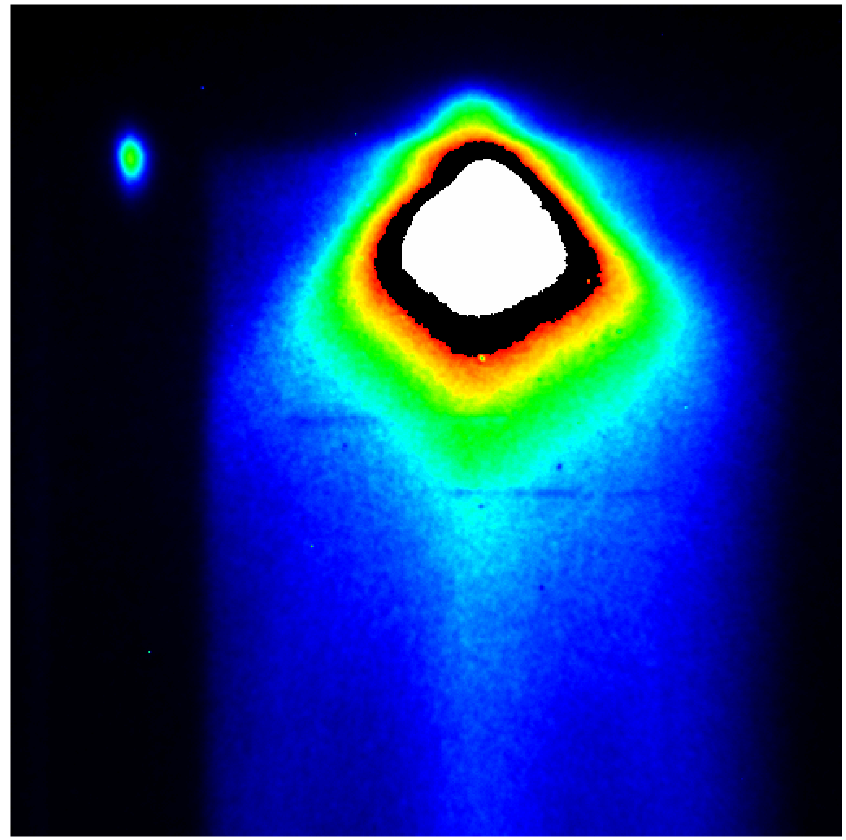
- Target rear side (foil) expansion observed
- Smooth shape of accelerated foil
- Rear side motion starts during laser pulse
- Point P moves with velocity $1.4\mathrm{x}10^7$ cm/s between 4 and 7 ns

Measured evolution of point P position



Preliminary optical streak record of self-emission from target rear side





Left – foam 700 μm + 5 μm Al foil

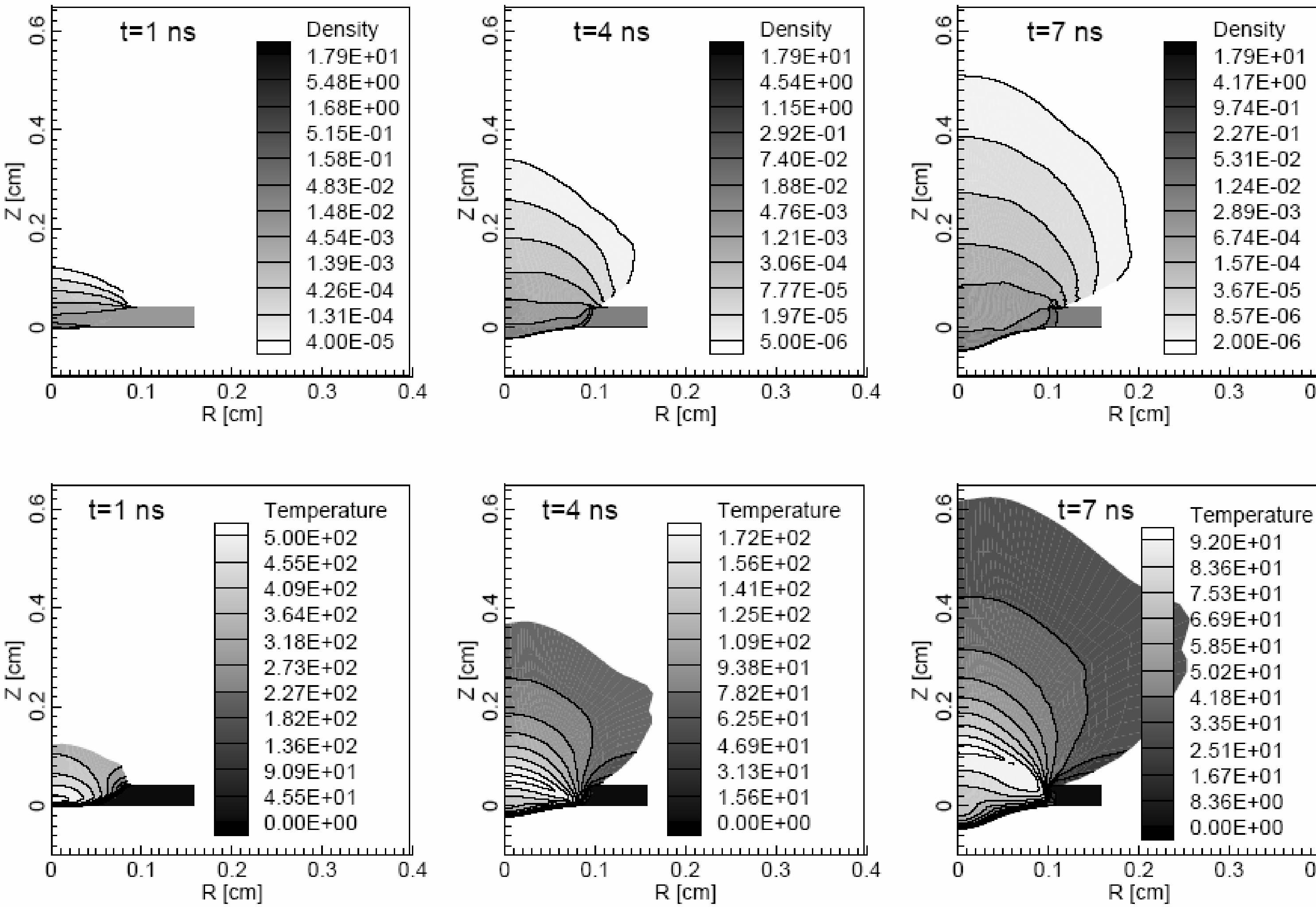
Right - 5 μm Al foil only

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 $\Rightarrow$ speed of hydrothermal wave may be overestimated

Results of 2D hydrodynamic simulations



Density (in g/cm^3) 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

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

Foil maximum velocity

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

where $c_0 = (\gamma \cdot P_0/\rho_f)^{1/2}$

Comparison of experiment, simulations and analytical theory

Laser energy	Target	v_{exp} (cm/s)	v_{simul} (cm/s)	V_{max} (cm/s)
92 J	$(CH)_n$	6.0×10^6	4.9×10^6	4.8×10^6
173 J	$(CH)_n$	8.0×10^6	8.2×10^6	6.7×10^6
238 J	$(CH)_n$	------	1.1×10^7	8.2×10^6
238 J	PVA	1.4×10^7	3.5×10^7	1.32×10^7

- 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 be foam homogenization
- Fast homogenization stage needs $t_s \sim (D_p - b)/V_s$ (~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, ρ = 10 mg/cm^3

$$t_h = \frac{\left(D_p - b\right)^2}{\lambda_i V_s} \approx 10^{-9} \times \frac{D_p^2 \rho_f}{T^{3/2}}$$

Conclusions

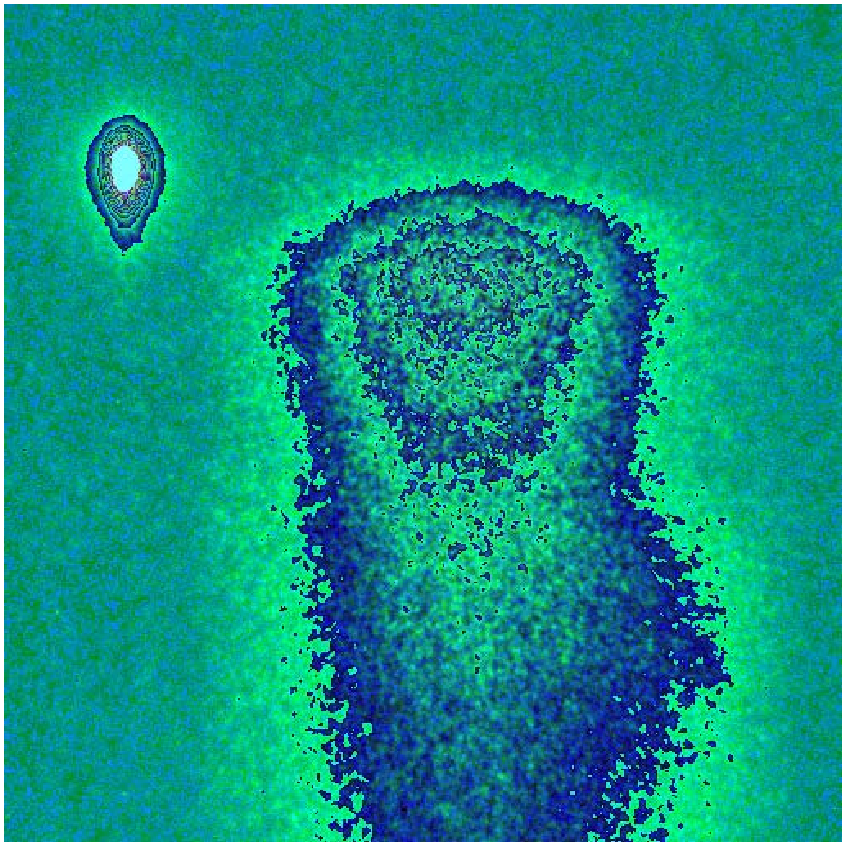
- *Depth of laser absorption region and speed of heat wave in foam measured by x-ray streak*
- *Foil acceleration observed by 3-frame interferometry*
- *Preliminary measurement of shock wave arrival*
- *2D hydrodynamic simulations and analytical model applied, but foam fine structure not taken into account*
- 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

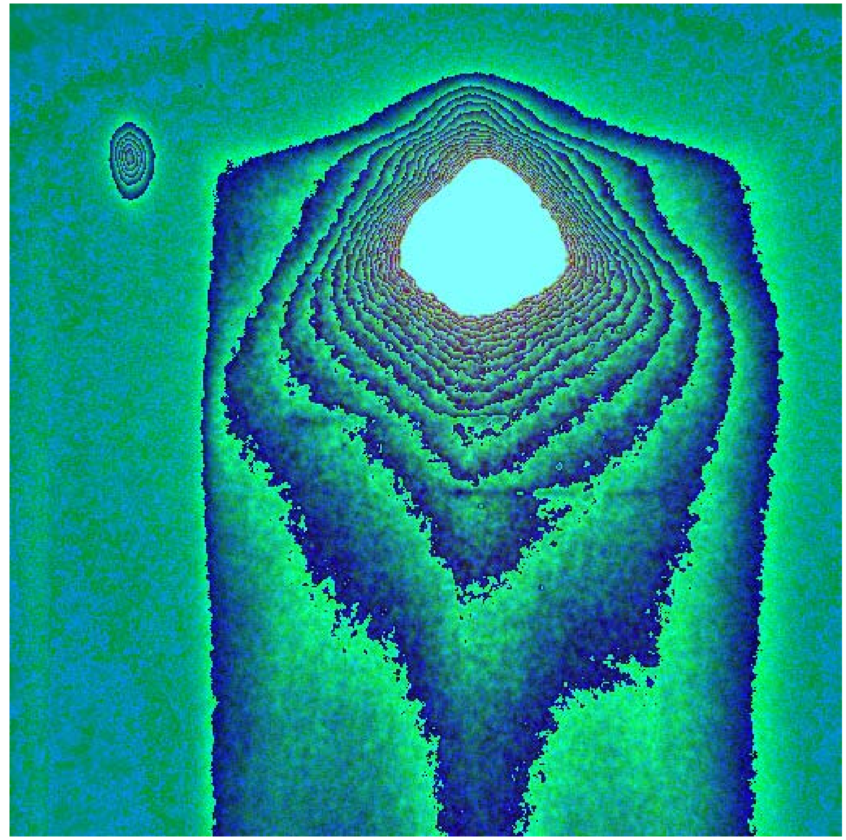
Plans for future

- 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 1ω
- 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