Laser Interactions with Foam Targets for Applications in ICF, EOS and X-ray Source Studies

J. Limpouch

Czech Technical University in Prague - FNSPE,
Břehová 7, 115 19 Praha 1, Czech Republic

In collaboration with
P. Adamek¹, N.G. Borisenko², N.N. Demchenko², S.Yu. Gus’kov², M. Kálal¹, T. Kapin¹, A. Kasperczuk³, A.M. Khalenkov², V.N. Kondrashov⁴, V. Kmetik⁵, E. Krouský⁶, J. Kuba¹, R. Liska¹, K. Mašek⁶, Yu.A. Merkul’ev², W. Nazarov⁷, P. Pisarczyk⁸,T. Pisarczyk³, M. Pfeifer⁶, O. Renner⁶, K. Rohlena⁶, V.B. Rozanov², J. Skála⁶, M. Šiñor¹, J. Ullschmied⁵, N.V. Zmitrenko⁹

¹Czech Technical University, Prague, ²Lebedev Physical Institute, Moscow, Russia, ³IPPLM, Warsaw, Poland, ⁴TRINITI, Troitsk, Russia, ⁵Institute of Plasma Physics, AS CR, Prague, ⁶Institute of Physics, AS CR, Prague, ⁷University of St. Andrews, UK, ⁸Warsaw University of Technology, Warsaw, Poland, ⁹Institute of Mathematical Modelling, Moscow, Russia
Outline

• Low-density media – structure, composition, etc.
• Applications of low-density media in laser interactions
  – Direct-drive ICF targets – ablation pressure smoothing
  – Dynamic phase plate for laser beam homogenization
  – EOS studies – amplification of shock wave pressure
  – Atomic physics studies and x-ray sources
  – In short pulse interactions – ion acceleration and initiation of nuclear reactions
• Experiments on PALS laser
  – Laser directly interacting with foam
  – Energy transport and shock wave propagation
  – Foil acceleration by laser heated foam
  – Laser transmission through underdense foam
  – X-ray spectra measurement
• Numerical simulations (1D and 2D)
Low-density media

- Low density solid materials have to be inhomogeneous – porous - they have to contain vacuum spaces inside
- Various structures are possible - closed, semi-closed, open cells, (foam and fiber-like structures)
- Plastic foams, plastic foams doped with higher Z elements, deuterated plastic foams
- Alternatively SiO$_2$ aerogel targets
- Various densities possible – from $<1$ mg/cc to $>1/3$ solid
- Foam is called underdense if homogenized fully ionized foam has electron density less than critical density
- When heated, pore walls expand and fill the pores (fast homogenization stage)
- After collision of mass fluxes, inhomogeneities are damped out by viscosity (slow homogenization stage)
Foams with open cells (3D networks)

- Small-cell plastic foams without and with high-Z additions (Cl, Cu, SnO₂) - TMPTA (Nazarov), TAC (Borisenko)
- SEM microphotographs of TAC (cellulose triacetate) of density 9 mg/cm³ - TAC pure and with 10 weight% of Copper, additions lead to structure roughening
Foams with large semi-closed cells

Agar-agar foam – 10 mg/cm³  Polystyrene foam – 20 mg/cm³
Foams layers in targets for direct-drive ICF

**Target for imprint smoothing**  
*(Dunne M. et al. 1995)*  
Thin (~25 nm) gold foil for x-ray preheat to suppress early imprint of irradiation inhomogeneities  
Foam layer to enhance ablation pressure smoothing

**Greenhouse target (closed variant)**  
*(Gus’kov, Rozanov 1995)*  
Aim is to minimize number of beams in reactor chamber  
High voluminous absorption in thick foam layer  
Ablation pressure smoothing  
Outer layer to suppress expansion, intentional shell thickness variations assumed

**Greenhouse target (open variant)**  
*(Rozanov 1997)*  
Aim is to minimize number of beams in reactor chamber  
Laser absorption in foam is high even for large incidence angles  
Efficient smoothing in foam layer
Aim of Prague experiments

• More information is needed about laser-foam interaction and about energy transport in foam layers for successful design of ICF targets including low-density foam layers
• Laser absorption and energy transport in the foam materials with large ($D_p > 10 \, \mu\text{m}$) and small ($D_p < 2 \, \mu\text{m}$) pores
• Role of high-Z additions in plastic foams is investigated
• Laser transmission measurement is also needed for foam application for smoothing of laser beams
• Sufficient efficiency of thin foil acceleration by the pressure of heated foam matter is demonstrated
• Substantial smoothing of laser inhomogeneities is searched for, but has not been addressed yet
• Comparison of experimental results with numerical simulations and analytical model is important for progress in understanding laser-foam interactions
Energy transport in underdense foam with small (0.5–3 µm) and big (30–100 µm) pores

X-ray streak (side view)–laser $3\omega$, 320 ps FWHM, best focus above target, spot $\varnothing$ 300 µm, 5 µm Al at target rear side

small pore TAC $4.5 \text{ mg/cm}^3 (=n_c/4)$, 380 µm thick, 168 J, fast laser penetration $1.3\pm0.1\times10^8$ cm/s (4 similar shots)

big pore agar $5 \text{ mg/cm}^3 (=n_c/4)$, 570 mm thick, 171 J, laser absorbed in 150 µm thick surface layer, low penetration
Denser \((n_c/2)\) small pore TAC foam

\[9.1 \text{ mg/cm}^3, \ 400 \ \mu\text{m} \text{ thick, } 5 \ \mu\text{m Al at rear side, } 3\omega, 170 \ J, \text{ spot } \varnothing 300 \ \mu\text{m}, \text{ Left – side-on x-ray streak, Right – optical emission from rear side, fiducial (laser pulse) at top left}\]

Small fast preheat – at the same time - optical pre-emission, thermal wave gets to rear side earlier than main opt. emis. starts
TAC foam 9 mg/cm³ with 10 weight% Cu

Laser $3\omega$, 159 J, $\varnothing$ 300 µm, 440 µm thick foam + 5 µm Al

Heat wave similar propagation as for pure TAC (> emission)
Optical prepulse much stronger than for pure foil
Main optical pulse (shock wave arrival) significantly later than for pure TAC (delay 3.7 ns instead of 1.9 ns for pure TAC)
3-frame interferographs for 480 $\mu$m thick TMPTA foam 10 mg/cm$^3$+5$\mu$m Al, $3\omega$, 130 J
Laser $3\omega$, 130 J, focus above target, focal spot $\varnothing \, 300 \, \mu m$, 480 $\mu m$ thick TMPTA foam, 10 mg/cm$^3$, $\sim 1 \, \mu m$ pores+5 $\mu m$ Al left – position of centre of accel. region, $v = 9.5 \times 10^6 \, cm/s$, right – optical streak, fiducial delayed by 3 ns, the start of main optical pulse at 1.9 ns is consistent with acceleration, opt. streaks similar for TAC 9 mg/cm$^3$ and TMPTA 10 mg/cm$^3$
Laser transmission through foam layers

Laser intensity (logarithm scale) – light transmitted through foam compared with fiducial – upper part of figure, \( \sim 160 \) J, \( 3\omega \), TAC foam, 9 mg/cc, left – 200 \( \mu \)m, right – 400 \( \mu \)m
Temporal profiles of transmitted pulses

Laser pulses transmitted through foam as compared pulses propagated without foam 160 J, $3\omega$, TAC foam (pore size 0.5-3 µm)
Left – 9 ng/cc (prev.slide), right – 4.5 mg/cc
Transmission versus foam density and thickness

Laser transmission increases with laser energy

60% transmission for \(\sim1/8 \text{n}_c\) and 100 \(\mu\text{m}\) thick

- Laser penetration decreases with foam density and thickness as expected
X-ray emission from high-Z additions in foam

Emission spectra from Cl-doped TMPTA foam in region of Cl He-a line
Vertical Johann spectrograph using cylindrically bent quartz crystal - 2 mirror-like spectra (photon energy min in centre)
Spectral resolution ~5000
Spatial resolution ~8 µm in vertical direction
Recorded in one shot, 25° from target surface
Lower fig - processed spectra 25 µm below target surface
Region of nearly homogeneous emission found for foam targets
1D and 2D fluid simulations with foam structure

For light (low $\rho \times d$) pore walls - laser is tunneling through walls heating simultaneously several layers, wall expansion in exploding foil regime; fast laser penetration

For heavy walls – laser heats front size of one wall, rest ablatively accelerated, slow penetration

2D simulations – our newly developed ALE code – lateral heat flux not important for our parameters

Foam as set of slabs with void spaces in between laser
$\lambda = 439 \ \mu m$, $3.7 \times 10^{14} \ W/cm^2$, 1 ps rise time
Conclusions

• Fast penetration of x-ray emitting region through significantly subcritical foam (≤1/4 n_c) with small pores (penetration speed ~ 1.3 x 10^8 cm/s), but much slower for ~ same density and big pores, and also for ~ 1/2 n_c and small pores
• Main pulse of opt. emission from rear side starts approximately at the beginning of rear side motion
• The shock transit time (measured by opt. emission) reproducible within ±5% accuracy for TMPTA targets
• The shock transit time increases with density and also for constant density when high Z is added and also when 1ω is used instead of 3ω
• The velocity of accelerated foil and the extent of accelerated region is measured and hydrodynamic efficiency > 10 % has been derived
• Laser transmission through foam (time resolved) and line x-ray spectra (doped Cl He-α) measured