Foams in direct-drive fusion: Laser-supported ionizing heat wave in gases and foams

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experiments - S. Depierreux, C. Labaune, E. Krouský, T. Pisarczyk,
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foam targets - N. G. Borisenko, W. Nazarov

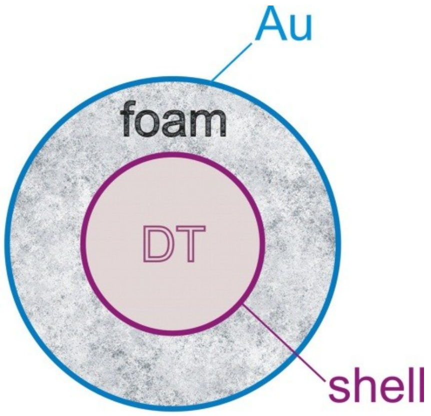
OUTLINE

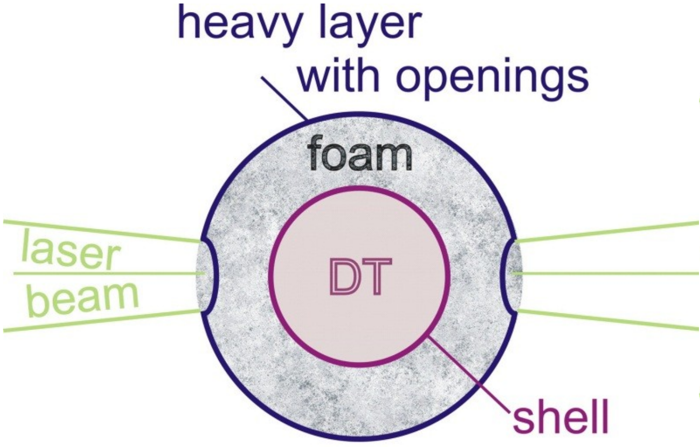
- Applications of low density media
- Low-density media properties
- Experiments – ionizing heat wave, laser smoothing
- Laser-supported ionizing heat wave in homogeneous media
- Laser-supported ionizing heat wave in foams
- Comparison with experiment
- Proposal for modeling foam via homogeneous media – delay in absorption coefficient

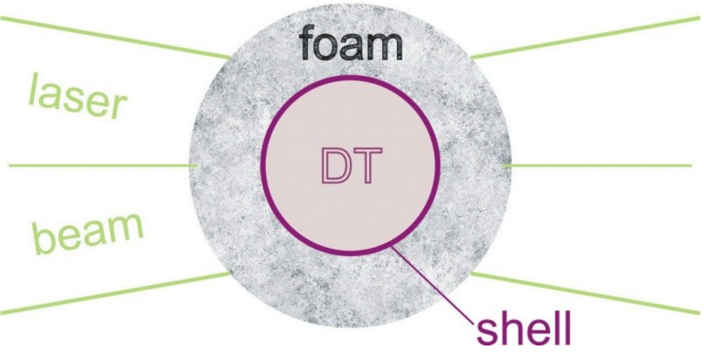
Applications of low density media in laser interactions

- **Direct-drive ICF targets** – ablation pressure **smoothing**
- **DD** - **imprint** mitigation – if laser-supported ionizing heat wave is ***supersonic***
- Dynamic phase plate for laser beam homogenization
- Enhancement of shock wave pressure for EOS studies
- Ion acceleration by fs pulses – efficiency enhancement
- Atomic physics and X-ray spectroscopy studies and X-ray sources

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

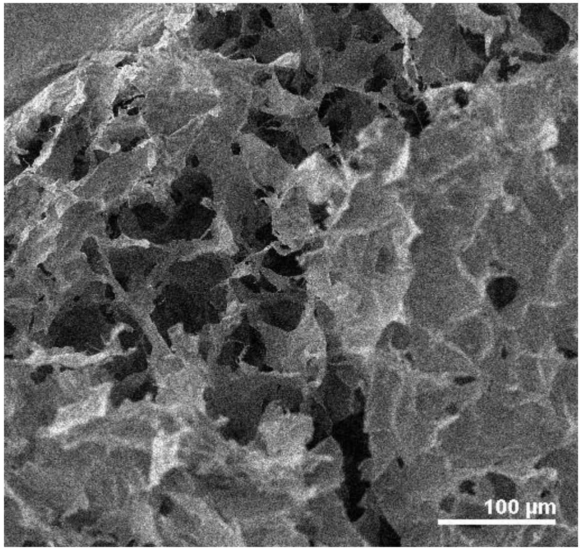
Imprint mitigation

Low-density media

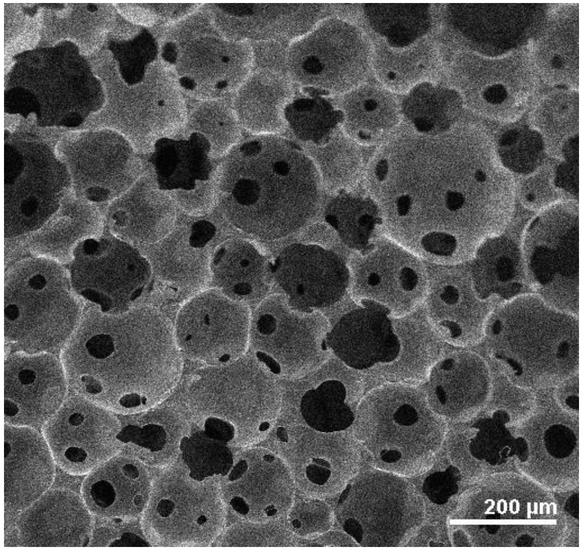
- Low density solid materials have to be inhomogeneous – porous - they have to contain spaces inside
- Various structures are possible - closed, semi-closed, open cells, (foam and fiber-like structures)
- Plastic foams, plastic foams doped with higher Z elements, deuterated plastic foams
- Alternatively 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)

Foam Structures

Semi-closed cells (usually large pores)



Agar-agar – 10 mg/cm^3



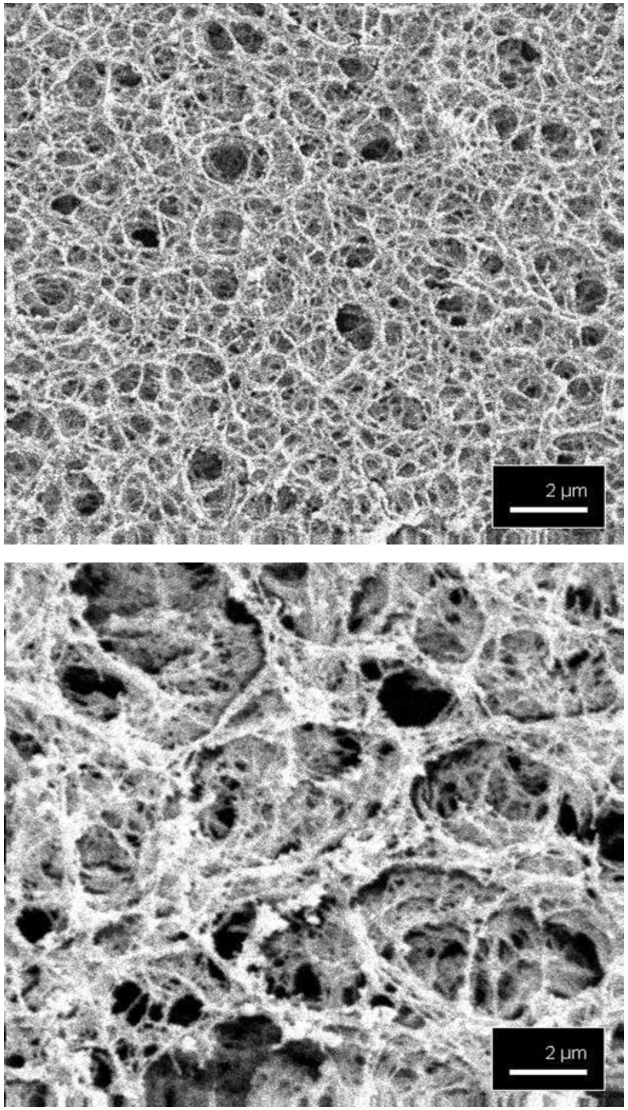
Polystyrene – 20 mg/cm^3

Porous media with open cells (aerogels) – pore size ~ 1 μm, $\rho \geq 2.25$ mg/cm^3

TMPTA (Nazarov), TAC (Borisenko) both C,H,O

additions (Cl, Cu, SnO_2) possible

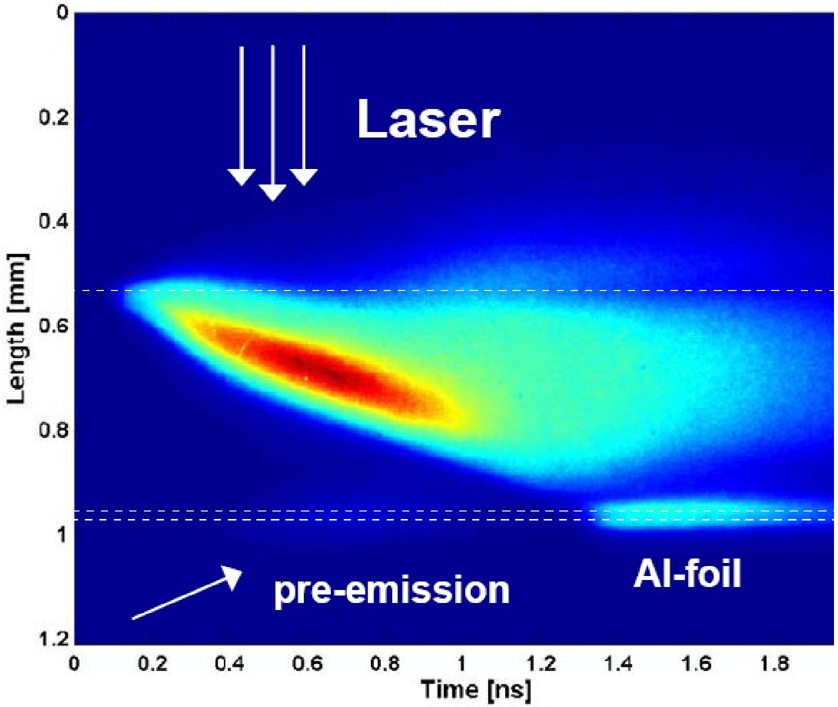
Open cells (3D networks)



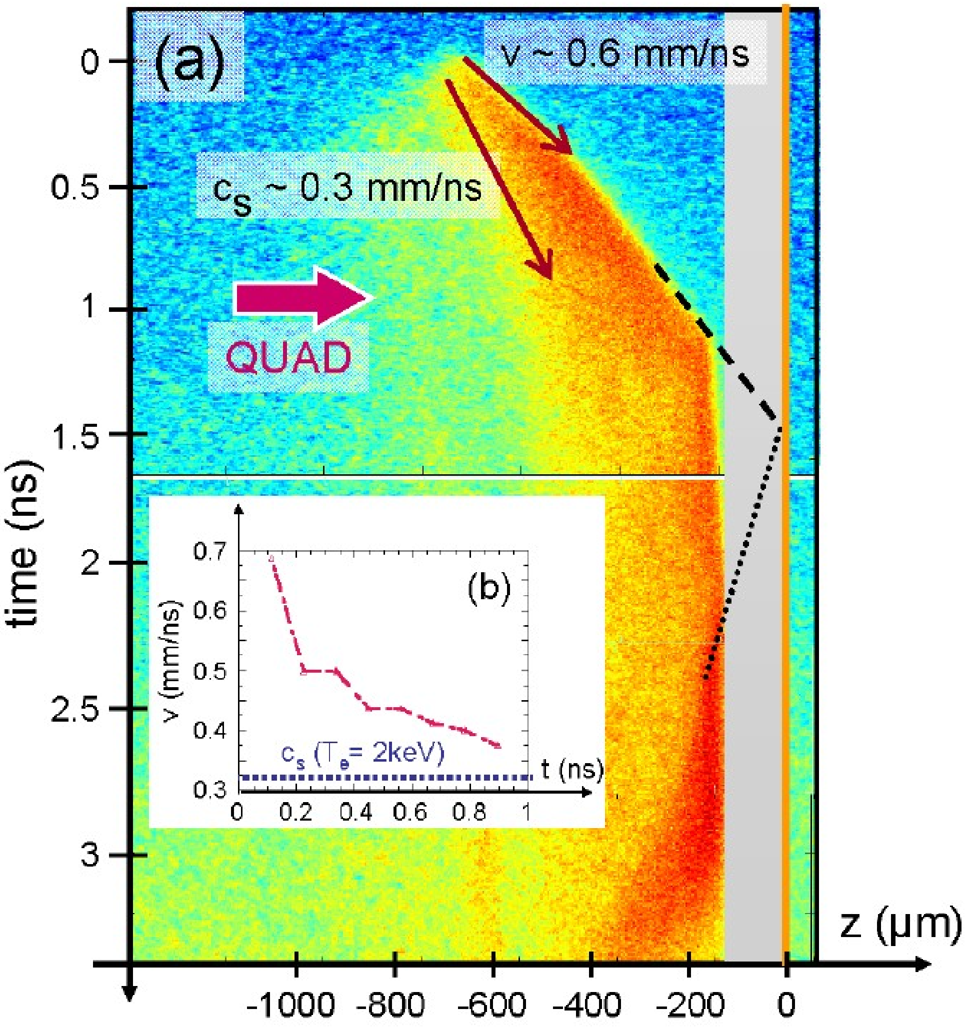
TAC – 9 mg/cm^3
upper – pure,
lower – 10 % Cu
(weight)

Experiment – ionizing heat wave

PALS

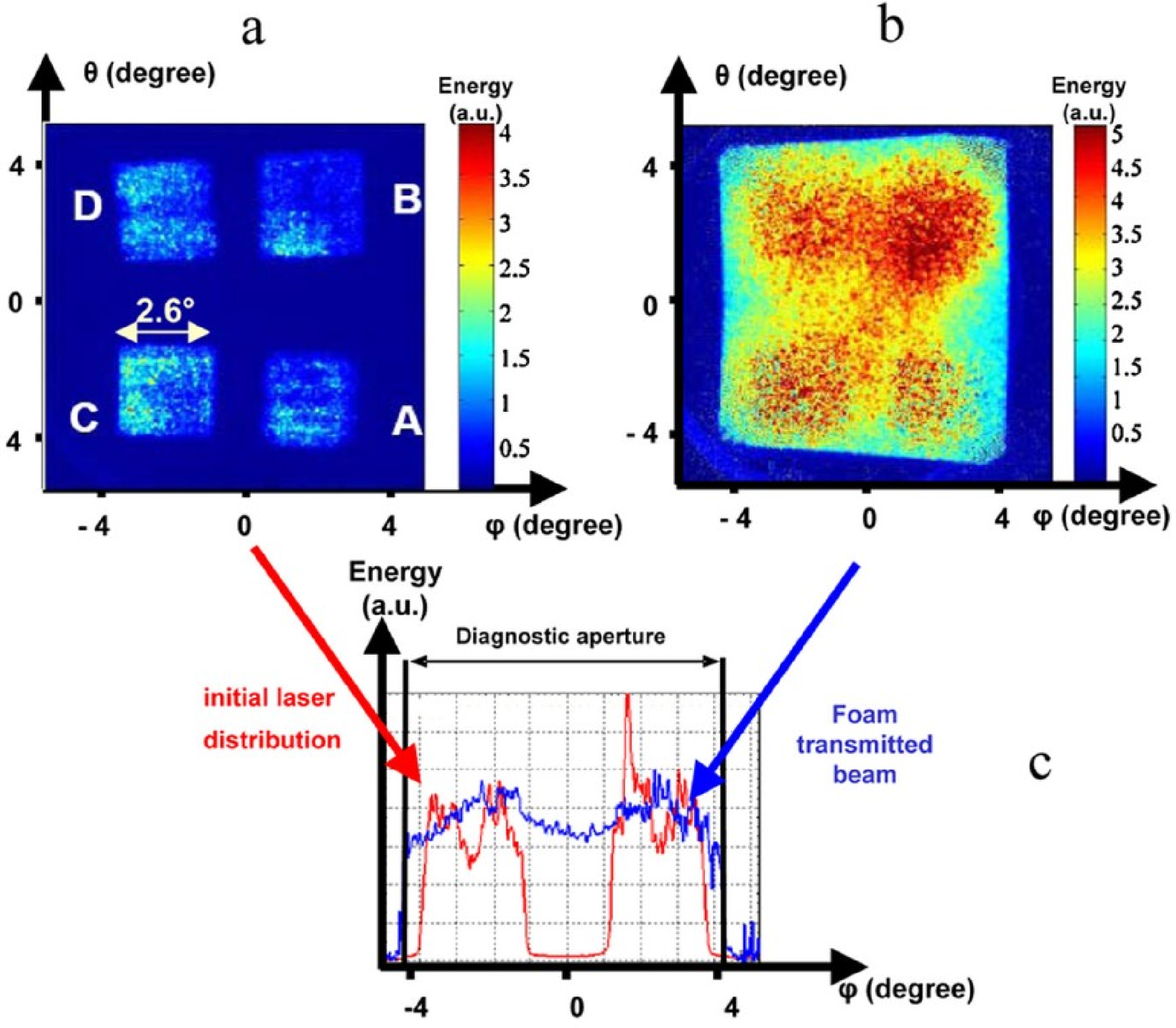


LIL



Laser-supported ionizing heat wave at PALS (300 ps, 170 J, λ = 439 nm, TAC, 9 mg/cm^3) and at LIL (laser quad from left, 2.7 ns square pulse, 12 kJ, 351 nm, TMPTA, 10 mg/cm^3),

Experiment – laser smoothing



Time integrated near field images of the laser beam. (a) in vacuum; (b) after propagation through foam (900 μm, TAC, 6.5 mg/cm^3)

Angular divergence growth due to either scattering on residual inhomogeneities in foam plasma or forward stimulated Brillouin scattering (FSBS) or filamentation or self-focusing. Smoothing is efficient till the end laser pulse when residual inhomogeneities are negligible. Simulation indicate FSBS important.

S. Depierreux et al., Phys. Rev. Lett. ***102****, 195005 (2009)*

Laser-supported heating wave in homogeneous media

- Plasma heating and laser absorption in planar geometry

$$\frac{3}{2} n_a \frac{\partial}{\partial t}\left(Z_{av} T_e \right) + n_a \chi_{[Z_{av}]+1} \frac{\partial Z_{av}}{\partial t} = \kappa_{ei} I_L = -\frac{\partial I_L}{\partial z}$$

The coefficient of collisional absorption is $\kappa_{ei} = \kappa_0 T_e^{-3/2}$

- Fully ionized plasma - analytical solution *(Denavit & Phillion 1994)*

$$T_e^{3/2} = \frac{3\kappa_0}{2}(z_f - z) \qquad I_L^{3/2} = I_0^{3/2}\left(1 - \frac{z_f}{z}\right) \qquad V_{ft} = \frac{\mathrm{d}z_f}{\mathrm{d}t} = \frac{2I_0}{3n_e}\left(\frac{3\kappa_0}{2} z_f\right)^{-2/3}$$

incident laser intensity $I_0(t) = I_L(0,t)$, z_f is the heat front position

  - for the constant incident laser intensity I_0

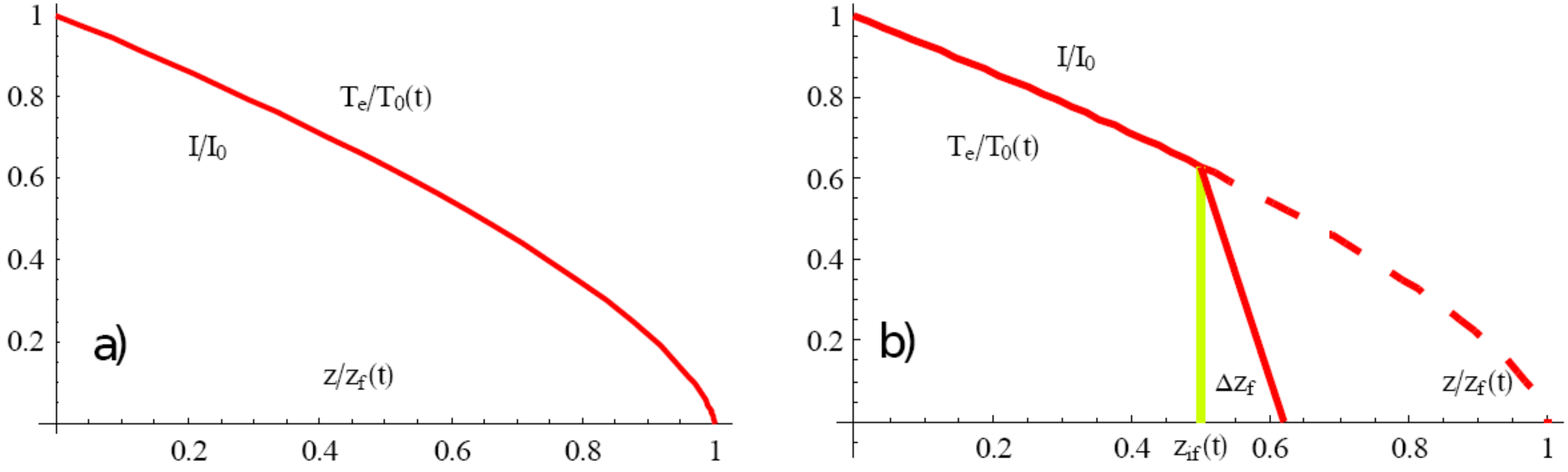
$$T_e(0,t) = \left(\frac{5 I_0 \kappa_0 t}{3 n_e}\right)^{2/5}, \quad z_f = \left(\frac{2}{3\kappa_0}\right)^{2/5} \left(\frac{10 I_0 t}{9 n_e}\right)^{3/5}, \quad V_{ft} = \left(\frac{2}{5\kappa_0 t}\right)^{2/5} \left(\frac{2 I_0}{3 n_e}\right)^{3/5}$$

Ionization front (homogeneous media)

- When plasma is not fully ionized, equation for mean ion charge

$$\frac{\partial Z_{av}}{\partial t} = Z_{av} n_a S_{[Z_{av}]+1}\left([Z_{av}]+1-Z_{av}\right)\Psi\left(\frac{T_e}{[Z_{av}]+1}\right)$$

Denavit & Phillon 1994 solved laser-supported wave with ionization numerically



Fully ionized plasma

Non-ionized homog. medium

Spatial distribution of the laser intensity and the electron temperature in the thermal/ ionization wave. Here, Δz_f is the ionization front width and z_{if} is the point where the ionization is terminated and the ionization front joins the thermal wave.

Simplified model of ionization

- **Simplifications:** $\Psi(x) \approx 0.2\, H(x-1)$ (Heaviside step function), ionization potential is $\chi_Z \approx \chi_H Z^2/n^2 \approx \chi_H Z^2/4$, ionization rate

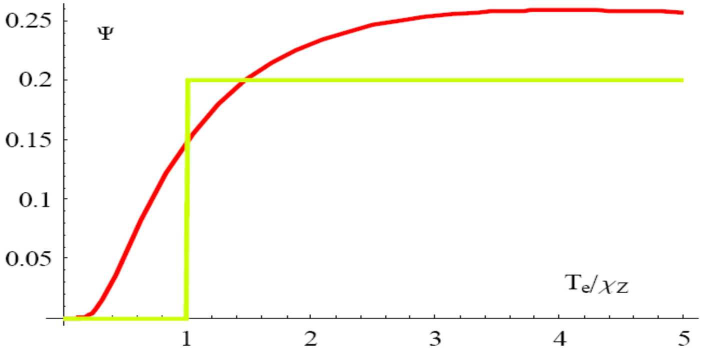
$$n_a S_Z \approx \nu_{ion} Z_{av}^{-3} \qquad \nu_{ion} \approx 2\times 10^4 \rho_a / A \quad \text{ps}^{-1}$$

, where

$$\frac{\partial Z_{av}}{\partial t} = \frac{\nu_{ion}}{Z_{av}^2} \quad \text{if} \left(T_e \geq \tfrac{1}{4}\chi_H Z_{av}^2 \text{ and } Z < Z_m \right), \quad \text{and} \quad \frac{\partial Z_{av}}{\partial t} = 0 \quad \text{otherwise}$$

Ionization energy is small compared to thermal, dimensionless temperature

$$\theta = T_e/\chi_1 = 4\, T_e/\chi_H,$$



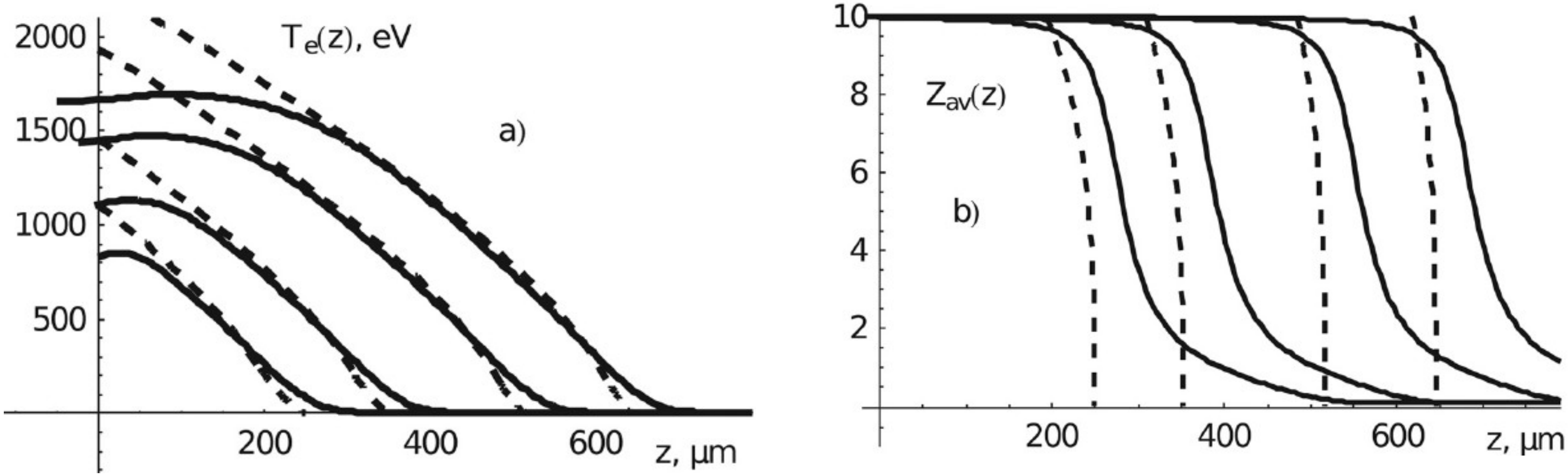
Temperature dependence of the ionization function $\Psi(T_e/\chi_Z)$ and its interpolation.

Energy conservation rewritten

$$\frac{\partial}{\partial t}\left(Z_{av}\theta \right) \approx \nu_h Z_{av}^3 \theta^{-3/2} \qquad \nu_h \equiv \xi_h I_L \approx 5.1\times 10^6 I_{14} \lambda_L^2 \rho_a / A \quad \text{ps}^{-1}$$

Ionization wave (homog. media)

- **Low laser intensities** - $I_0 \leq I_B = 3\nu_{ion}/\xi_h$ (ionization faster)
  - Ionization equilibrium in each moment $Z_{av}^2 = \theta$
  - Temperature increases linearly with time $\theta = Z_{av}^2 = \int \nu_h \mathrm{d}t \approx \nu_h t$
- **High laser intensities** - $I_0 > I_B = 3\nu_{ion}/\xi_h$ (heating faster)
  - Mean ion charge less than in equilibrium (overheated plasma)
  - Mean ion charge $Z_{av} \simeq (3\,\nu_{ion} t)^{1/3}$ until it reaches Z_m



Electron temperature (a) and mean ion charge in the neon gas of 5 mg/cm^3 at the moments 25, 50, 100, 150 ps: dashed lines (model), solid (numerical simulation)

Laser propagation in underdense foam

- Porous structure slows down laser propagation in foams via the filling the pore of size δ_0 by expanding solid elements
- The front advances for one pore size δ_0 after time τ_f when the expanding solid elements become underdense ($n_e < n_{cr}$)
- Foam structure of average density ρ_a – mixture of thin membranes and wires of solid density ρ_s and thickness δ_s.

$$\delta_s \simeq \delta_0(\rho_a/\rho_s)^\alpha$$

α=1 for foil-like, α=1/2 for wire-like foam, $\alpha \approx 0.8$

α – fractal number

- Solid foam element thickness δ_s less than or comparable with the laser skin depth $\Rightarrow$ element heated homogenously
- The front velocity is $V_p = \delta_0/\tau_f$
- In solid elements ionization rate heating rate small ($\nu_{ion} > \nu_h$), and thus, ionization is in equilibrium $Z_{av}^2 = \theta$

Ionization wave velocity in foam

- Element expansion starts after full ionization is reached
- For 1D expansion, the maximum density decreases with time and solid element becomes transparent at time

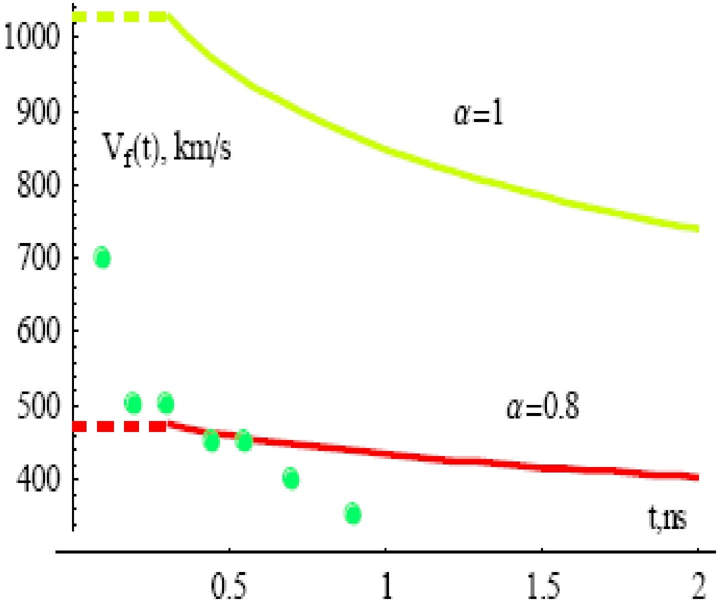
$\tau_f = \delta_s Z_m n_s / n_{cr} c_s$ where $c_s \simeq (I_L t / 4 m_i n_s \delta_s)^{1/2}$

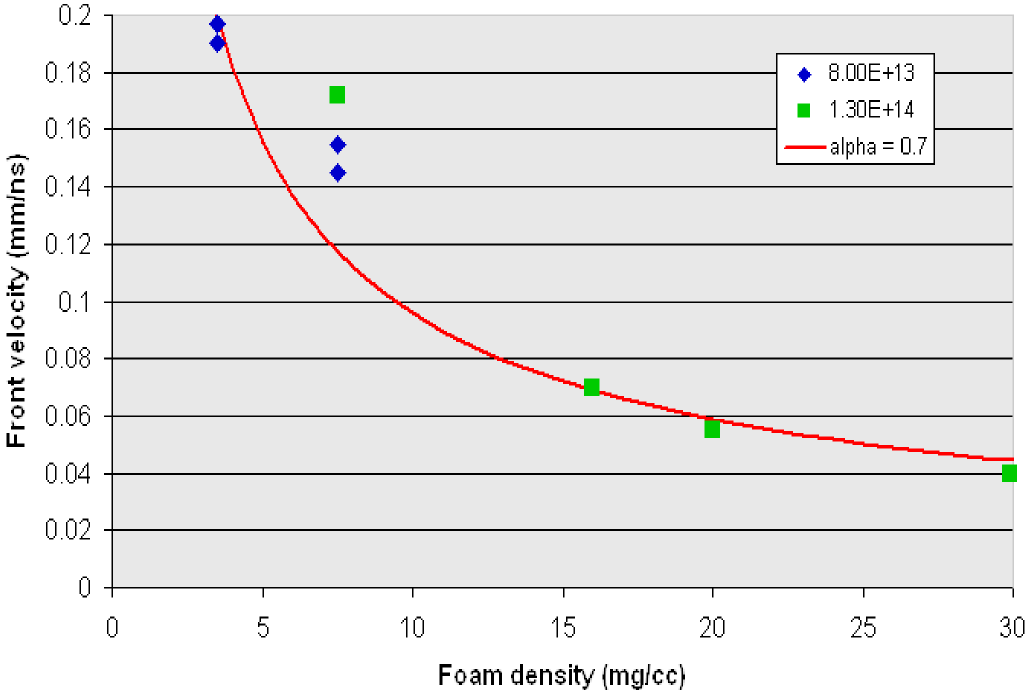
- Then $\tau_f \simeq \delta_s \left(\frac{4 m_i Z_m^2 n_{cr}}{I_L} \right)^{1/3} \frac{n_s}{n_{cr}} \simeq \delta_0 \left(\frac{4 m_i Z_m^2}{I_L} \right)^{1/3} \frac{n_a^\alpha n_s^{1-\alpha}}{n_{cr}^{2/3}}$

- The velocity V_p of the ionization front in underdense foam is

$$V_p \simeq \frac{n_{cr}^{2/3} I_L^{1/3}}{(4 m_i Z_m^2)^{1/3} n_a^\alpha n_s^{1-\alpha}} \approx 9.7 \times 10^4 \frac{A^{2/3} I_{14}^{1/3}}{Z_m^{2/3} \lambda_L^{4/3} \rho_a^\alpha \rho_s^{1-\alpha}} \ \mathrm{cm/s}$$

Comparison with the experiment





Supersonic front speed dropping from 600 to 400 km/s.
Polymer TAC foam ($C_{15}H_{20}O_6$), the average density ρ_a = 6 mg/cm^3, thickness 500-900 μm and pore size of 1-2 μm; laser λ_L = 351 nm, I_0 = 4× 10^{14} W/cm^2, 3ns square pulse (laser energy 10-12 kJ at LIL). Derived parameter α ≈ 0.8.
(Depierreux et al., PRL 2009)

Ionization front velocity versus foam density for intensities 8x10^{13} W/cm^2, and 1.3x10^{14} W/cm^2. Experiment at LULI in 2011 (not yet published).
Laser 2 ω_0, 1.5 ns, 2 different RPP, the derived parameter α ≈ 0.7.

Model of laser absorption in foams

- Laser interaction simulation including detailed 3D foam microstructure is extremely difficult due to difference in scales
- Using homogeneous material of average density and compositions leads to overestimated ionization wave speed
- We propose to introduced temporal delay in the absorption coefficient in homogeneous media substituting foam
- Foam is absorbing with low reflectivity ⇒ laser intensity

$\partial I_L/\partial z = -\kappa_{ef} I_L$ κ_{ef} – effective absorption coefficient

- Laser absorbed in 1 layer of non-evaporated foam $\kappa_{ef} \simeq \delta_0^{-1}$
- The variation of absorption coefficient during time delay τ_d

$$\tau_d = t_{exp} + \tau_f \qquad \int_{-\infty}^{t_{exp}(z)} c_s \mathrm{d}t = \delta_s, \quad \int_{-\infty}^{\tau_f(z)} c_s \mathrm{d}t = \delta_s \left(\frac{n_s}{n_{cr}} - 1 \right)$$

- Up to $\tau_d(z)$ - $\kappa_{ef} = 1/\delta_0$, then absorption in plasma with effective density

$$\rho_{ef} = \max \left(\rho_a, \frac{\delta_s \rho_s}{\int^t c_s \mathrm{d}t} \right)$$

Conclusions

- Underdense foam layers may be important in targets for DD
- If laser-supported ionizing heat wave is supersonic, laser beam smoothing may be achieved without laser imprint
- One-dimensional **analytical** model of laser-supported ionizing heat wave in underdense gases and foams developed
- Ionizing heat wave in homogeneous media - narrow **ionization front** and **thermal wave** behind it
- In foams ionizing heat wave slowed down due to delay caused by **homogenization** of porous media
- Empirical model for foam substitution by homogeneous media proposed – uses **delay** in absorption coefficient