A hybrid (ablation-expansion) model for low-density foams

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Introduction and overview

Hydrodynamic simulations of laser-foam interaction:
Homogeneous simulation overestimates laser propagation - Foam microstructure have to be included

Direct simulations [Kapin et al (2006), Milovich et al (2021)] - computationally expensive, limited foam types

Two-scale models = conventional macroscale hydrodynamics + simplified microscale interaction model
- CTU+CELIA [Velechovský et al (2016)]: expansion of 1D layer, *closed-pore foams only*
- ENEA [Cipriani et al (2018), Gus'kov et al (2015)]: viscosity-dampened decompression, *overcritical foams*
- LLNL [Belyaev et al (2020)]: self-similar isothermal expansion, *small-pore light foams* $\varrho_{av} < 5$ *mg/cm*^{3}

Our area of interest: wire-like chemical aerogel foams/ artificial ("3D printed") foams ~ 10 mg/cm^3

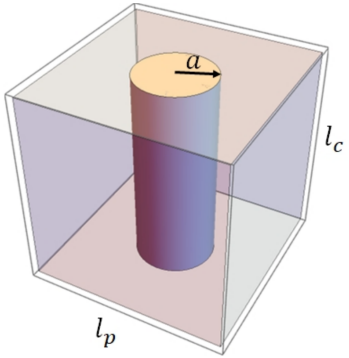
size of solid elements $\gg$ laser skin depth $\rightarrow$ **surface absorption and ablation**
size of solid elements comparable to laser wavelength $\rightarrow$ wave-based description

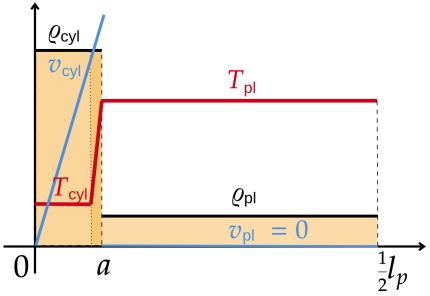
Interaction of laser with sub-wavelength sized cylinder - PIC/hydro simulations by S. Shekhanov and A. Gintrand
as a basis for **Ablation-expansion microscale model**

Microscale model

Conservation laws (PDEs) → integration over volume of the pore → ODEs for averaged values

6 equations for cylinder radius $a(t)$ and mass $m_{\mathrm{cyl}}(t)$, expansion velocity $v_{\mathrm{exp}}(t)$, and internal energies $\varepsilon_{\mathrm{cyl}}$, $\varepsilon_{\mathrm{pe}}$, $\varepsilon_{\mathrm{pi}}$





Expansion of the cylinder (controlled by cylinder temperature)

Ablation of the cylinder (external flux controlled) - removes mass from the cylinder surface

Pore homogenisation finished when density of cylinder and plasma equilibrate (at average foam density)

Energy conversion process - 3 steps: laser absorption by electrons → kinetic energy of accelerated mass → ion-ion collisions in plasma → ion internal energy (≈ instantaneous in our model, uniform redistribution of mass inside pore)

Laser absorption and scattering

The total absorption rate per unit length

$$K_{\mathrm{tot}} = K_{\mathrm{cyl}} + K_{\mathrm{pl}}$$

Absorption in the plasma

$$K_{\mathrm{pl}} = K_{\mathrm{ib}}(\varrho_{\mathrm{pl}}, T_{\mathrm{pe}}) \left(1 - \frac{\pi a^2 l_c}{V_{\mathrm{pore}}}\right)$$

Inverse bremsstrahlung weighted by volume

Absorption in the cylinder

overcritical cylinder $\varrho_{\mathrm{cyl}} > \varrho_{\mathrm{cr}}$

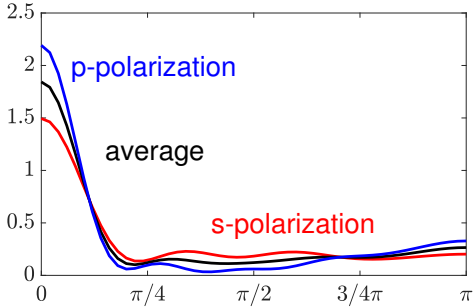
$$K_{\mathrm{cyl}} = Q_{\mathrm{abs}} \frac{2 a l_c}{V_{\mathrm{pore}}}$$

effective cross-section

subcritical cylinder $\varrho_{\mathrm{cyl}} < \varrho_{\mathrm{cr}}$

$$K_{\mathrm{cyl}} = K_{\mathrm{ib}}(\varrho_{\mathrm{cyl}}, T_{\mathrm{cyl}}) \frac{\pi a^2 l_c}{V_{\mathrm{pore}}}$$

weighted inverse bremsstrahlung



Laser scattering on cylindrical foam elements: Angular distribution

$$p_{\mathrm{sca}}(\theta) = \frac{s(\theta)\, P_{\mathrm{sca}}}{l_p l_c l_{\mathrm{las}}} \approx s(\theta) \left[1 - \exp\left(-Q_{\mathrm{sca}} \frac{2a}{l_p}\right)\right]$$

Cumulative distribution function $\approx$ two-step profile

Efficiency factors $Q_{\mathrm{abs}} \simeq 0.5 - 1.0$, $Q_{\mathrm{sca}} \simeq 1 - 3$ from Mie theory of electromagnetic scattering on cylindrical particles [H. C. van der Hulst, Light scattering by small particles (Dover Publ., 1957)]

Energy fluxes

Macroscale ray-tracing use K_{tot} to calculate the total power deposited to pore P_{las}

Absorbed power in cylinder $P_{\mathrm{cyl}} = \eta_{\mathrm{cyl}} P_{\mathrm{las}}$ Absorbed power in plasma $P_{\mathrm{ib}} = \eta_{\mathrm{ib}} P_{\mathrm{las}}$

$$\eta_{\mathrm{cyl}} = \frac{K_{\mathrm{cyl}}}{K_{\mathrm{tot}}}, \qquad \eta_{\mathrm{ib}} = \frac{K_{\mathrm{pl}}}{K_{\mathrm{tot}}}, \qquad \eta_{\mathrm{cyl}} + \eta_{\mathrm{ib}} = 1$$

The energy flux entering the surface of the cylinder

$$q_{\mathrm{cyl}} = \frac{P_{\mathrm{cyl}}}{2\pi a l_c} + q_{\mathrm{th}}$$

Local electron heat conduction between plasma and cylinder

$$q_{\mathrm{th}} = f_{\mathrm{lim}} \frac{Z_{\max} \varrho_{\mathrm{pl}}}{m_i} k_B v_{\mathrm{te}} (T_{pe} - T_{\mathrm{cyl}})$$

(calculated as a fraction of a free-streaming limit)

Heating of cylinder

$$q_{\mathrm{heat}} = \zeta_{\mathrm{las}} \frac{P_{\mathrm{cyl}}}{2\pi a l_c} + \zeta_{\mathrm{th}} q_{\mathrm{th}}$$

Ablation

$$q_{\mathrm{abl}} = \underbrace{(1 - \zeta_{\mathrm{las}}) \frac{P_{\mathrm{cyl}}}{2\pi a l_c}}_{q_{\mathrm{abl,las}}} + \underbrace{(1 - \zeta_{\mathrm{th}}) q_{\mathrm{th}}}_{q_{\mathrm{abl,th}}}$$

Parameters ζ_{las}, ζ_{th} control the splitting of the fluxes $\rightarrow$ determines the regime of operation

Expansion and ablation

Radius of the cylinder - combined effect of expansion and ablation:

$$\frac{\mathrm{d}a}{\mathrm{d}t} = v_{\mathrm{exp}} - v_{\mathrm{abl}}$$

Self-similar expansion [Belyaev et al (2018)]

$$\frac{\mathrm{d}v_{\mathrm{exp}}}{\mathrm{d}t} = \frac{4}{3}\frac{\varepsilon_{\mathrm{cyl}}}{a}\,\Theta(T_{\mathrm{cyl}} - T_{\mathrm{exp}})$$

- expansion suppressed for low temperatures (foam not sufficiently ionised)

Stationary ablation model [Manheimer et al (1982)]

- two contributions: laser and local heat flux

Laser ablation

$$v_{\mathrm{abl,las}} = \frac{(2q_{\mathrm{abl,las}}\rho_{\mathrm{cr}}^2)^{1/3}}{2\varrho_{\mathrm{cyl}}}$$

Thermal ablation [Betti et al (2001)]

$$v_{\mathrm{abl,th}} = \frac{3q_{\mathrm{abl,th}}}{2\varrho_{\mathrm{cyl}}(\varepsilon_{\mathrm{pe}} + \varepsilon_{\mathrm{pi}})}$$

$$v_{\mathrm{abl}} = \xi_a v_{\mathrm{abl,las}}\,\Theta(\varrho_{\mathrm{cyl}} - \varrho_{\mathrm{cr}}) + v_{\mathrm{abl,th}}$$

- laser ablation turned off in subcritical cylinder
- average over laser polarisations, additional factor $\xi_a \approx 0.5$

Mass of the cylinder:

$$\frac{\mathrm{d}m_{\mathrm{cyl}}}{\mathrm{d}t} = \underbrace{-2\pi a l_c v_{\mathrm{abl}}\varrho_{\mathrm{cyl}}}_{\text{mass ablation rate}} = -\frac{2v_{\mathrm{abl}}}{a}m_{\mathrm{cyl}}, \qquad m_{\mathrm{pl}} = m_0 - m_{\mathrm{cyl}}$$

Energy balance

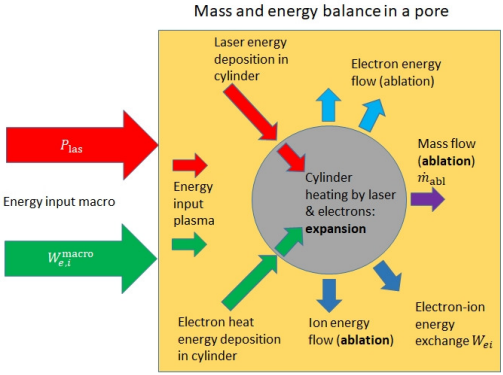
Specific internal energy of cylinder:

$$\frac{\mathrm{d}\varepsilon_{\mathrm{cyl}}}{\mathrm{d}t} = \underbrace{-\frac{1}{2a} v_{\mathrm{abl}} v_{\mathrm{exp}}^2}_{\text{kinetic energy of cylinder expansion}} - \frac{2}{3}\frac{v_{\mathrm{exp}}}{a}\varepsilon_{\mathrm{cyl}}\Theta(T_{\mathrm{cyl}} - T_{\mathrm{exp}}) + \underbrace{\frac{2\pi a l_c}{m_{\mathrm{cyl}}} q_{\mathrm{heat}}}_{\text{cylinder heating}}$$

Electron/ion internal energy of plasma inside the pore:

$$\frac{\mathrm{d}\varepsilon_{\mathrm{pe}}}{\mathrm{d}t} = -\frac{2v_{\mathrm{abl}}}{a}\frac{m_{\mathrm{cyl}}}{m_{\mathrm{pl}}}\varepsilon_{\mathrm{pe}} + \underbrace{\frac{2v_{\mathrm{abl}}}{a}\frac{m_{\mathrm{cyl}}}{m_{\mathrm{pl}}}(1-\zeta_i)\left(\varepsilon_{\mathrm{cyl}} + \frac{1}{2}v_{\mathrm{exp}}^2\right)}_{\text{initial energy of the ablated mass}}$$
$$+\underbrace{(1-\zeta_i)\frac{2\pi a l_c}{m_{\mathrm{pl}}} q_{\mathrm{abl}}}_{\text{energy from the ablation flux}} - \underbrace{\frac{2\pi a l_c}{m_{\mathrm{pl}}} q_{\mathrm{th}}}_{\text{local HF}} + \frac{P_{\mathrm{ib}}}{m_{\mathrm{pl}}} - W_{\mathrm{ei}} + \underbrace{W_e^{\mathrm{macro}}}_{\substack{\text{electron heatflux from} \\ \text{neighbouring pores}}}$$

$$\frac{\mathrm{d}\varepsilon_{\mathrm{pi}}}{\mathrm{d}t} = -\frac{2v_{\mathrm{abl}}}{a}\frac{m_{\mathrm{cyl}}}{m_{\mathrm{pl}}}\varepsilon_{\mathrm{pi}} + \underbrace{\frac{2v_{\mathrm{abl}}}{a}\frac{m_{\mathrm{cyl}}}{m_{\mathrm{pl}}}\zeta_i\left(\varepsilon_{\mathrm{cyl}} + \frac{1}{2}v_{\mathrm{exp}}^2\right)}_{\text{energy of the ablated mass}}$$
$$+\underbrace{\zeta_i\frac{2\pi a l_c}{m_{\mathrm{pl}}} q_{\mathrm{abl}}}_{\text{energy from the ablation flux}} + W_{\mathrm{ei}} + \underbrace{W_i^{\mathrm{macro}}}_{\substack{\text{ion heatflux from} \\ \text{neighbouring pores}}}$$



Free parameter ζ_i controls the repartition of energy between electrons/ions ($\zeta_i \approx 0.6$ in PIC simulations)

Microscale-macroscale connection

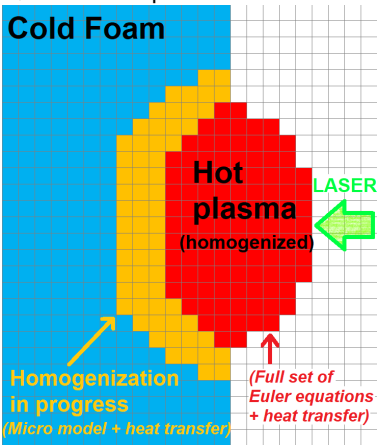
Macroscale - two-temperature Euler equations with the electron/ion heat conductivity, electron-ion energy exchange, and laser source term (in fully homogenised cells)

In non-homogenised cells: microscale model + laser absorption + heat transport

Modifications to the macroscale hydrodynamics:

- Laser deposition is calculated using a modified absorption rates/coefficients
- Hydrodynamic motion is suppressed in non-homogenised cells
- ODEs for the microscale model solved (with a reduced timestep) using RK4 method
- Internal energy and the kinetic energy of the expanding cylinder "hidden" from macroscale, added at the end of homogenisation:

$$\Delta\varepsilon_e = \frac{m_{\mathrm{cyl}}}{m_0}\frac{Z_{\mathrm{cyl}}}{Z_{\mathrm{cyl}}+1}\varepsilon_{\mathrm{cyl}}, \qquad \Delta\varepsilon_i = \frac{m_{\mathrm{cyl}}}{m_0}\left(\frac{1}{Z_{\mathrm{cyl}}+1}\varepsilon_{\mathrm{cyl}} + \frac{1}{4}v_{\mathrm{exp}}^2\right)$$

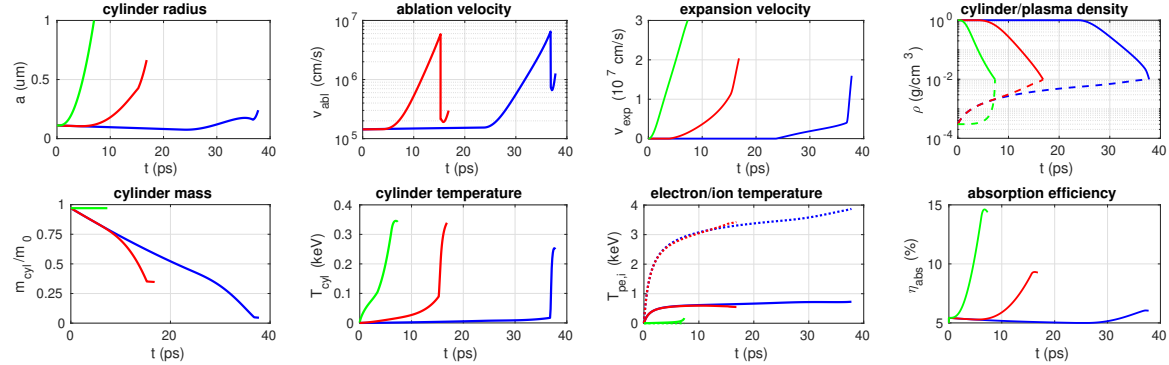


Hybrid model implemented in **PALE** (Lagrangian/ALE code) and **FLASH** (Eulerian code)

Simulation in one foam pore

One-pore test for the laser intensity 10^{14} W/cm^2; no interaction with neightbouring cells/pores
Foam target similar to [V. Tikhonchuk et al, (2021)]

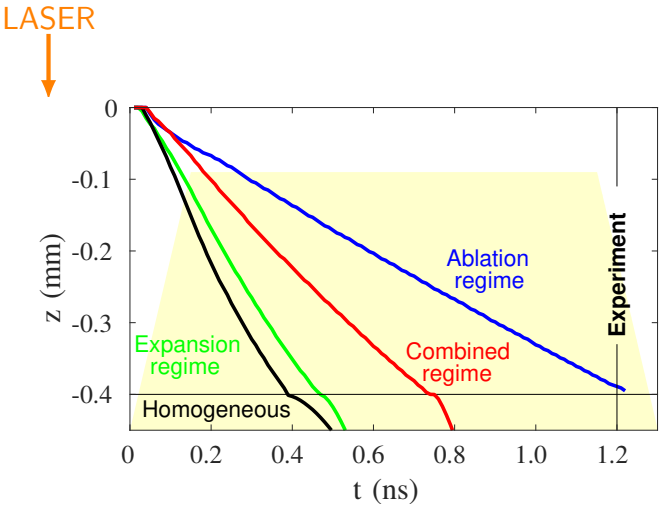
The free parameters of the model determine the regime of operation:
Expansion dominated regime ($\zeta_{\mathrm{las}} = 1$) - fast, 7 ps homogenisation time
Combined regime ($\zeta_{\mathrm{las}} = 0$, $\zeta_{\mathrm{th}} = 0.5$) - intermediate, 16 ps
Ablation dominated regime ($\zeta_{\mathrm{las}} = 0$, $\zeta_{\mathrm{th}} = 10^{-2}$) - slow, 38 ps



Other parameters: $Q_{\mathrm{abs}} = 0.5$, $\xi_{\mathrm{abl}} = 0.5$, $\zeta_{\mathrm{i}} = 0.5$, $T_{\mathrm{exp}} = 5$ eV, $f_{\mathrm{lim}} = 0.03$

Comparison of hybrid model results to the experimental data

Ionisation wave front propagation



Experiment at the Shenguang III prototype laser [V. Tikhonchuk et al (2021)]

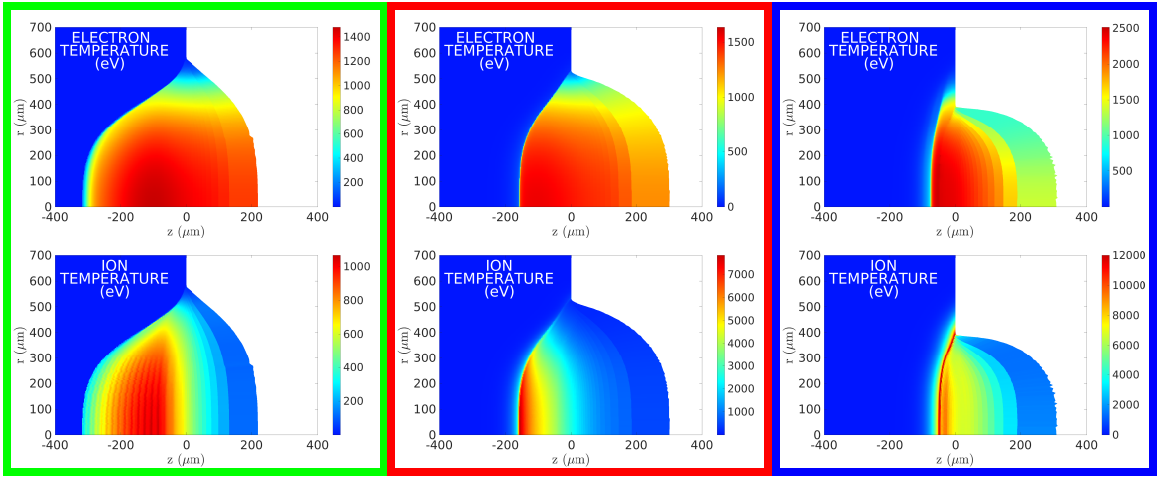
0.4 mm thick target
10 mg/cc TMPTA foam, 2 μm pores
Laser energy 835 J / 1.3 ns pulse
Peak laser intensity $2 \cdot 10^{14}$ W/cm^2
4th order super-gaussian spatial profile

Target burned-through at 1.2 ns

Results from PALE code, front edge of target at $z = 0$ mm
(scattering on foam microstructure enabled)

2D results

Expansion regime | **Combined regime** | **Ablation regime**



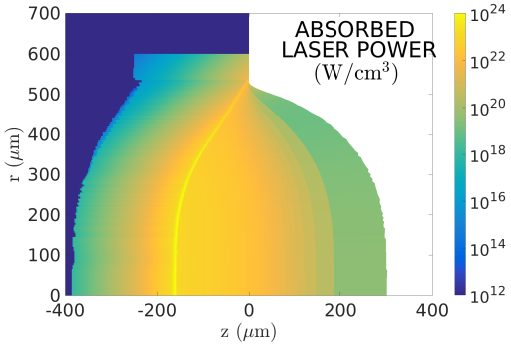
Temperature profiles at 300 ps

ion temperature $T_i \approx 4T_e \approx ZT_e$

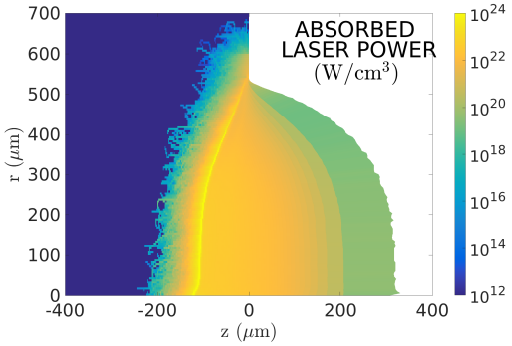
The influence of random foam scattering

Random scattering decreases laser penetration through foam layers
Smaller width of the homogenisation region → decreases propagation speed by 20-25 %

Without scattering



With scattering



Deposited laser power at 300 ps

Conclusions

- We presented a novel approach to the foam modelling that combines a self-similar expansion of cylindrical elements with a surface ablation by laser
- Three regimes of operation have been demonstrated in one-pore test of the model
- The hybrid model has been applied to simulate the experiment at the Shenguang III prototype laser
- The inclusion of foam-induced laser scattering is crucial for the foam simulations as it reduces the laser penetration and decreases the width of the homogenisation zone

Thank you for your attention