Hybrid model for laser interaction with low-density foams

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Abstract

We propose a novel hybrid model that describes laser-driven homogenization of individual foam elements as a competition between isothermal expansion (due to volumetric heating by electron heat flux) and surface ablation by the incident laser. The model is formulated in terms of ordinary differential equations for mass, momentum, and energy conservation and its parameters are chosen according to the detailed PIC simulations of laser-cylinder interaction. Cross-sections for laser absorption and scattering are calculated from the Mie theory for electromagnetic scattering on sub-wavelength cylindrical particles. The proposed micro-scale model is implemented in the PALE hydrodynamic code for laser-plasma interaction modeling. The capabilities of the hybrid model are demonstrated by successfully reproducing experimental data for several experiments at PALS facility.

Plasmas created by laser ionization of foams have attractive properties for research in the field of inertial confinement fusion (ICF). The addition of an extra foam layer to the ICF target capsule can improve implosion symmetry and suppress the excitation of hydrodynamic instabilities in direct drive ICF or increase the efficiency of laser to X-ray conversion for radiography purposes. However, hydrodynamic modeling of the foam target as a homogeneous material, i.e. without the influence of the internal foam micro-structure, results in heat-front velocities that are considerably faster than those observed experimentally.

Dedicated two-scale sub-grid models [1, 2, 3] are therefore needed to correctly describe laser propagation in foam and to correctly capture the partition of absorbed energy between electrons and ions in the plasma created behind the ionization front. These models often describe the laser-foam interaction in terms of volumetric heating and expansion of planar/cylindrical foam microstructure, however, such a physical model is not universally applicable as the assumptions of volumetric heating are not justified for foams with solid elements thicker than the skin depth.

In our novel approach [4], we develop a single-pore model according to the results of kinetic simulations of laser absorption in a single cylindrical foam element [5]. Each foam pore is divided into two regions with separate densities, masses, and temperatures. The central region is the expanding cylinder of radius a, mass m_{cyl}, and density ρ_{cyl}. The outer region corresponds to the ambient plasma created by the ablation of the solid element.

The **ablation of the cylinder** is described by the stationary ablation model [6, 7] and characterized by the laser and thermal ablation velocities

$$v_{\mathrm{abl,las}} = \frac{(2q_{\mathrm{abl,las}}\rho_{\mathrm{cr}}^2)^{1/3}}{2\rho_{\mathrm{cyl}}}, \qquad v_{\mathrm{abl,th}} = \frac{3q_{\mathrm{abl,th}}}{2\rho_{\mathrm{cyl}}(\varepsilon_{\mathrm{pe}}+\varepsilon_{\mathrm{pi}})}.$$

Our main assumption is that all the mass removed from the surface of the cylinder is immediately redistributed uniformly across the volume of the pore, which increases the density of the ambient plasma. The mass ablation is expressed by a differential equation for the mass of the cylinder

$$\frac{\mathrm{d}m_{\mathrm{cyl}}}{\mathrm{d}t} = -\frac{2(v_{\mathrm{abl,las}}+v_{\mathrm{abl,th}})}{a}m_{\mathrm{cyl}}.$$

The **expansion of the cylinder** controls the movement of the boundary between the cylinder and ablated plasma, changing the cylinder radius and density, but not affecting its mass. The expansion rate depends on the cylinder internal energy and the characteristic expansion velocity v_{exp} is calculated according to the model of self-similar isothermal expansion [8, 9]

$$\frac{\mathrm{d}v_{\mathrm{exp}}}{\mathrm{d}t} = \frac{4}{3}\frac{\varepsilon_{\mathrm{cyl}}}{a}.$$

The radius of the cylinder a changes due to the combination of self-similar expansion, laser ablation and thermal ablation

$$\frac{\mathrm{d}a}{\mathrm{d}t} = v_{\mathrm{exp}} - v_{\mathrm{abl,las}} - v_{\mathrm{abl,th}}.$$

The density of the cylinder is initially equal to the solid density. Expansion and ablation both contribute to the equilibration of the cylinder and plasma density, and the homogenization of each pore ends when these two densities become equal to the average foam density. The microscale model is complemented by the equations for energy conservation and then connected to the macroscale hydrodynamics. A detailed description can be found in [4].

The hybrid model has three distinct regimes of the single-pore dynamics that are determined by the energy partition between bulk heating and cylinder ablation. If all incident energy is used for cylinder bulk heating (i.e. for volumetric laser absorption in the cylinder), we reach the **expansion dominated regime**. It is similar to the sub-grid models [1, 2, 3] due to its isothermal expansion and fast homogenization. If all absorbed laser energy is spent on the cylinder ablation (which could occur in the case of surface laser absorption), we obtain the **combined ablation-expansion regime**. This regime has an intermediate homogenization time and it is the best match to the PIC results [5]. The **ablation dominated regime** occurs when the cylinder heating by electron heat flux is reduced, suppressing the expansion completely. It is the best-performing regime for multi-pore simulations due to its slow single-pore homogenization.

Results

The hybrid model is implemented in the PALE hydrodynamic code, and applied to simulate experiment at the PALS laser, see [10] for more information about the setup. The results for the temporal dependence of the simulated heat front position are depicted in Figure 1 for the TAC foam targets with average density of 9.1 mg/cm^3 and 4.5 mg/cm^3. We compare the ionization front propagation of the different regimes to a simulation of a homogeneous target of equivalent density and to the experimental burn-through time.

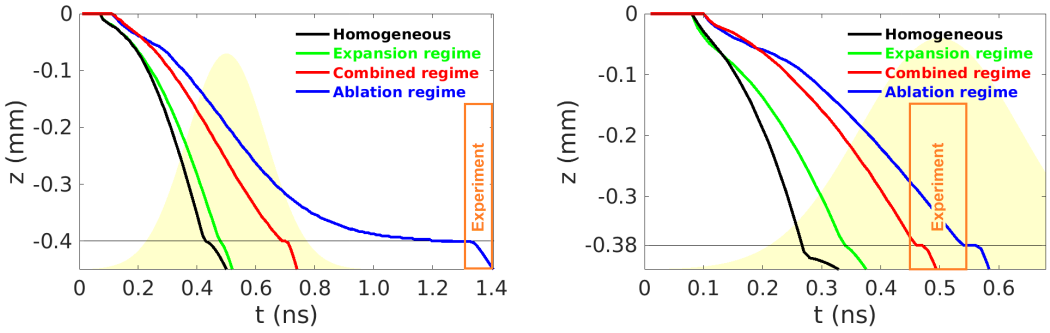

Figure 1: *The position of the ionisation wave front in the simulations of 9.1 mg/cm^3 (left) and 4.5 mg/cm^3 (right) foam targets. The laser temporal profile is shown in yellow.*

The results demonstrate that by varying the fraction of the energy flux used for the cylinder ablation, one can efficiently control the laser propagation velocity and reduce it up to 3 times compared to the homogeneous simulation. The ablation regime is the optimal regime for the denser 9.1 mg/cm^3 foam as it can match the experimental burn-through time of 1.4 ns, while the combined regime is closer to experimental data for the 4.5 mg/cm^3 foam. The latter can be explained by thinner solid elements for which a regime with stronger bulk heating might be more appropriate. As can be seen from the simulated average temperatures in Table 1, the inclusion of cylinder ablation has an important consequence on the energy repartition in the resulting plasma. The dissipation of the kinetic energy of ablated particles causes a strong ion heating and results in an elevated ion temperature. The ratio of T_i/T_e in the 9.1 mg/cm^3 foam simulation is around 3.6 for the combined regime and about 5 for the ablation regime. These numbers are comparable to the ratio $T_i/T_e \sim 4$ that was observed experimentally for the 9.1 mg/cm^3 foam from the emission spectrum; the approximate average value of ion temperature $T_i \simeq 3$ keV was measured from the Doppler broadening of the intercombination He-α_γ line of chlorine dopant, and the electron temperature was measured at around $T_e \simeq 0.7 - 0.9$ keV. For the 4.5 mg/cm^3 foam, the combined regime with the temperature ratio $T_i/T_e = 4.2$ relates the best to the experimental and theoretical estimations. No direct comparison is available in this case due to the absence of ion temperature measurements.

	T_i(keV)	T_e(keV)	η_{abs}(%)	T_i(keV)	T_e(keV)	η_{abs}(%)
homogeneous	0.35	0.46	85.7	0.30	0.41	43.2
expansion	0.77	1.21	89.6	0.76	1.0	55.1
combined	4.27	1.20	95.3	4.6	1.1	63.1
ablation	4.57	0.88	93.2	7.1	1.1	76.6
	9.1 mg/cm^3 foam			4.5 mg/cm^3 foam		

Table 1: *Average ion temperature T_i, average electron temperature T_e, and laser absorption efficiency η_{abs} obtained from the simulations of the PALS experiment.*

Conclusions

We developed a novel approach to foam modeling that combines a self-similar expansion of cylindrical elements with a surface ablation by laser [4]. The approach is inspired by the results of kinetic simulations of foams [5]. Based on the settings of its parameters, hybrid model can operate in three distinct regimes - expansion, combined, and ablation dominated regime. Hybrid model has been successfully applied to simulate experiments at PALS laser, and two of its regimes produce results close to the experimentally observed propagation of ionization front. It also predicts that ion temperature is larger than electron temperature in foam targets, which is consistent with experimental data.

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