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Selected Laser Plasma Simulations by ALE Method

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Abstract.
A novel 2D ALE code in Cartesian and cylindrical geometries on logically rectangular quadrilateral meshes was developed for laser plasma applications. We present here simulations of laser interactions with three different types (disc flyer, double foil and foam) of targets used in experiments at the PALS laser. The application of the ALE method proved to be essential as the pure Lagrangian method for these problems fails due to mesh degeneration.

1. Introduction
Laser-matter interactions are typically modeled by Lagrangian hydrodynamics as the Lagrangian computational mesh moving with the fluid is more suitable for the description of expansion or compression regimes appearing frequently in laser plasmas. Selected problems (e.g., those involving shear flows) however cannot be simulated by the pure Lagrangian method as the moving mesh degenerates with some computational cells becoming non-convex or even inverted. One can avoid mesh degeneration by employing Arbitrary Lagrangian Eulerian (ALE) method which either after several Lagrangian time steps or after the substantial mesh quality deterioration conservatively remaps conserved quantities from the old Lagrangian mesh to the new smoothed one.

2. Prague Arbitrary Lagrangian-Eulerian (PALE) Code
Recently developed PALE code models plasma by hydrodynamical equations in Lagrangian coordinates including heat conductivity and laser absorption
\[
\frac{1}{\rho} \frac{d \rho}{dt} = -\nabla \cdot \vec{v}, \quad \frac{d \vec{v}}{dt} = -\nabla \cdot p, \quad \frac{d \varepsilon}{dt} = -p \nabla \cdot \vec{v} - \nabla \cdot (\kappa \nabla T) - \nabla \cdot \vec{I},
\]
where \(t\) is time, \(\rho\) mass density, \(\vec{v}\) speed, \(p\) pressure, \(\varepsilon\) specific internal energy, \(T\) temperature, \(\kappa\) heat conductivity, and \(\vec{I}\) laser energy flux density (Poynting vector). The quotidian equation of state (QEOS) [1] gives \(p = p(\rho, \varepsilon), T = T(\rho, \varepsilon)\). Classical Spitzer-Harm heat conductivity with heat flux limiter is employed. The laser absorption is modeled either by simple absorption on the critical surface or by ray tracing.

The mixed system of hyperbolic-parabolic partial differential equations is treated by splitting into hyperbolic and parabolic parts. The parabolic heat equation is solved numerically by a
mimetic method [2]. The hyperbolic Euler equations are solved by the Arbitrary Lagrangian-Eulerian (ALE) method [3] which after several Lagrangian steps performs rezone/remap step. Staggered conservative discretization method [4] with several types of artificial viscosity is employed for Lagrangian steps. Rezoning smooths the Lagrangian mesh and prevents its distortion. Remapping [5] conservatively interpolates mean values conserved quantities from the original Lagrangian mesh to the new, smoothed one. Our 2D PALE code uses logically orthogonal meshes and supports both Cartesian and cylindrical geometries.

3. Selected Laser Plasma Simulations
Here we present selected PALE code simulations of laser interaction with three different (disc flyer, double foil and foam) targets shown in Fig. 1 simulated by PALE code. The simulated problems model particular experiments performed at Prague Asterix Laser System (PALS) facility. The simulations of such experimental situations by pure Lagrangian codes without employing the ALE method fail due to a severe mesh distortion.

3.1. Disc Flyer Target
The first target (see Fig. 1(a)) consists of a small aluminum (Al) flyer disc with radius $r = 150 \mu\text{m}$ and thickness $d = 6 \mu\text{m}$ or $d = 11 \mu\text{m}$ placed in a distance of $L = 200 \mu\text{m}$ above the massive Al target. The disc is irradiated by 400 ps (FWHM length) iodine laser pulse of energy $120 - 390 \text{J}$ on the first or third harmonics with the laser spot radius on target $125 \mu\text{m}$. The laser accelerates the disc ablatively to velocities of the order of $100 \text{km/s}$. The disc strikes the massive target creating a crater. The chosen parameters (the first harmonics wavelength $1.315 \mu\text{m}$, energy $130 \text{J}$, and disc flyer thickness $d = 6 \mu\text{m}$) correspond to recent experiments performed on the PALS laser [6].

The simulation is split into two phases [7]. The first phase, ablative disc acceleration, is computed until the disc flyer hits the massive target, see Fig. 2(a). The final hydrodynamical data of the first phase are interpolated on the new mesh and serve as initial conditions for the second phase, the disc flyer impact, which models the transformation of the disc flyer kinetic energy into the heat and the crater formation in the target, see Fig. 2(b). For our particular problem the computed average disc flyer impact velocity is $88 \text{km/s}$ while the velocity observed in the experiment is $60 \text{km/s}$. In several other configurations we have found even better agreement of simulated and experimental impact velocities [7]. The deviation of computed (using the temperature distribution) and experimental crater volumes is 9%. The computed crater surface is given by gas-liquid phase interface. The calculated disc impact velocities and the crater volumes and shapes approximate the experimental data reasonably well.

3.2. Double Foil Target
The second target (see Fig. 1(b)) consists of two parallel foils with spacing of $L = 360 \mu\text{m}$. The thicknesses of the upper Al and lower Mg foils are $d_u = 0.8 \mu\text{m}$ and $d_l = 2 \mu\text{m}$, respectively. The
upper foil is irradiated by the 250 ps (FWHM length) laser pulse with energy 78 J in the third harmonics (0.438 µm) and the laser spot radius 40 µm. The heated foil expands upwards and downwards. The foil rapidly burns through, thus the laser is not fully absorbed and irradiates the lower foil through the sub-critical density hole. Consequently, the upper side of the lower foil expands and the two counter-streaming plasma plumes collide between the foils. The simulated hydrodynamic results serve as the input data for modeling the X-ray emission spectra which can be compared with those experimentally observed [8].

3.3. Foam Target
The last target type is 400 µm thick TAC foam with a low-density 9.1 mg/cm$^3$ and 2 µm pores. The simulations were performed using either uniform or structured model of the foam. The uniform model considers the foam to be a material of uniform sub-critical density 9.1 mg/cm$^3$. The structured model (see Fig. 1(c)) approximates the foam target by a series of parallel thin ($d_s = 0.018$ µm) dense ($\rho_s = 1$ g/cm$^3$) slabs separated by thick ($d_v = 1.982$ µm) low density ($\rho_v = 1$ mg/cm$^3$) voids, i.e., this model represents a generalization of the previous double foil target. The laser beam (0.438 µm, 170 J, 320 ps focused to the laser spot radius 300 µm on the target surface) burns gradually through the slabs standing for pore walls. The speed of the laser penetration into such structured foam is controlled by the pore wall areal mass, see 1D results in [9].
The experimentally measured speed of the laser penetration into the foam before the laser pulse maximum is about 600 \(\sim\) 700 \(\mu\)m/ns, the speed derived from the structured-target simulation is about 500 \(\mu\)m/ns (averaged in time interval (0.1, 0.5) ns) and from the uniform-target simulation about 1600 \(\mu\)m/ns (averaged in time interval (0.0, 0.25) ns). Simulation with the uniform low density material target results in too high speed of the laser penetration into the target, while the penetration speed obtained with structured target corresponds to experimental data reasonably well. The environmental conditions in laser-irradiated foams are obviously approximated much better by structured simulations.

\[ \text{Figure 4. Foam problem: (a) laser burning through the target at } T = 10 \text{ eV; (b) density distribution [g/cm}^3\text{] for the structured foam simulation at time of the laser pulse maximum; (c) temperature distribution [eV] for the uniform foam simulation 200 ps before the laser pulse maximum.} \]

4. Conclusion

We have developed the novel 2D hydrodynamic Arbitrary Lagrangian Eulerian code PALE on logically rectangular meshes for plasma simulations in Cartesian and cylindrical geometries. The code has been applied to simulations of the laser interaction with three types of targets: disc flyer, double foil target and low-density foams, for which standard Lagrangian codes fail due to the mesh distortion. Simulated results approximate reasonably well the experimental data.

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