Hydrodynamic simulations of laser/plasma interactions via ALE methods

M. Kucharik[1], J. Limpouch[1], R. Liska[1], J. Nikl[1,2]

[1] *FNSPE, Czech Technical University in Prague, Prague, Czech Republic*

[2] *ELI-Beamlines, Institute of Physics, Academy of Sciences of the Czech Republic, Prague, Czech Republic*

Abstract

Hydrodynamic simulations of laser-produced plasmas represent a useful tool allowing them to investigate processes during laser-plasma interaction, which are often impossible to observe directly during the experiments. They allow not only interpretation of experimental results, but are also often used for designing the experimental setup or detailed analysis of particular processes during the experiment. In this paper, we describe the application of the Arbitrary Lagrangian-Eulerian (ALE) numerical methods, benefiting from the computational mesh moving with the fluid in a Lagrangian manner, while enforcing its geometric quality by a regular mesh smoothing mechanism. The basic ALE algorithm is enhanced by additional physical models (realistic EOS, laser absorption mechanism, heat conductivity model, cylindrical geometry, two-temperature model, phase transition model, magnetic field model, . . .), allowing to perform realistic simulations of laser/target interactions. The performance of the code is demonstrated on selected realistic numerical tests.

Introduction

For detailed understanding of laser/target interactions, numerical simulations are unavoidable, as many intermediate quantities cannot be simply measured during experiments. For full understanding of processes during the interaction, analysis of experimental data, or design of experimental setup, numerical simulation represent a useful tool allowing a deep insight into the problem.

In the hydrodynamic simulations, the choice of the computational mesh is crucial. The classical Eulerian methods using a static computational mesh are not well suited here, as laser-generated plasma significantly changes its volume and shape. Typically, methods based on the Lagrangian concept are used in laser/plasma hydrodynamics, which employ a mesh moving with the fluid, allowing to capture strong material deformations. Unfortunately, the moving mesh can degenerate if vortices or shear flows are present. This is the main reason, why arbitrary Lagrangian-Eulerian (ALE) method [1] have been developed, combining a suitable Lagrangian solver with a rezoning algorithm, keeping the computational mesh smooth, and a fol-

lowing remapping step, conservatively interpolating all fluid quantities from the distorted to the smooth mesh.

This approach has been implemented in the PALE (Prague ALE) code, and proved its applicability for laser/plasma simulations, see for example [2]. For physically relevant results, further models are needed, such as relevant equation of state, heat conductivity model, laser absorption model, etc., which are included in the PALE code either. Another available code is PETE (Plasma Euler and Transport Equations) [3], which is based on the high-order curvilinear Lagrangian FEM framework, and more oriented on the non-local energy transport simulations. This unique combination of available codes allows us to perform a vast range of simulations of laser/plasma interactions.

Numerical models for laser-produced plasmas

The Lagrangian solver in the PALE code is based on the compatible mimetic method in staggered discretization [4]. It solves the set of compressible Euler equations in the Lagrangian formulation

$$\frac{1}{\rho}\frac{d\rho}{dt} = -\vec{\nabla}\cdot\vec{w}, \quad \rho\frac{d\vec{w}}{dt} = -\vec{\nabla}\cdot p, \quad \rho\frac{d\varepsilon}{dt} = -p\vec{\nabla}\cdot\vec{w} - \vec{\nabla}\cdot(\kappa\vec{\nabla}T) - \vec{\nabla}\cdot\vec{I},$$

with scalar quantities (density ρ, pressure p, and internal energy ε) defined in the mesh cells, while the vector velocity $\vec{w}$ is located at the nodes. The last two terms in the energy equation represent heat conductivity and laser absorption, where T is fluid temperature, κ stands for the heat conductivity coefficient, and $\vec{I}$ is laser intensity vector. Winslow rezoning algorithm is typically used for mesh smoothing, followed by swept-based remap and repair method [5] on the subzonal level [6]. The equations are enclosed by a general equation of state (EOS) $p = \mathscr{P}(\rho, \varepsilon)$ through the HerEOS library [7], providing high-order consistent interpolation of a tabulated realistic EOS (QEOS, for example).

The calculations are computed in the axisymmetric cylindrical geometry, well approximating real laser beam geometry. For laser absorption, a wave-based model employing stationary solution of Maxwell equations [8] is preferred. The heat conductivity model is separated by operator slitting, mimetic support operators [9] with the Spitzer-Harm conductivity coefficient $\kappa \approx T^{5/2}$ and heat flux limiter is used. Non-ideal plasma is approximated by a two-temperature model, separating electron/ion energies and including a heat exchange term. Simple phase transition model takes into account latent heat of melting and evaporation, eliminating premature material expansion to vacuum. Most active research is currently performed in the direction towards a universal non-local transport model, approximating long-distance transfer of energy due to

material radiation [10], and towards a magnetic field model, allowing to approximate effects of self-generated magnetic fields in plasma.

Numerical examples

Our codes have been used for simulations of several types of laser/target interactions, see for example [2] for a brief overview. Here, we show one example of a simulation of laser-induced cavity pressure acceleration (LICPA), see for example [11], [12] for further details. In a series of experiments, laser accelerating massive projectiles in a channel covered by cavity maximizing absorbed energy and its transfer to a shock wave in a massive target has been investigated. The setup of one particular experiment and the results of simulations are shown in Figure 1. We can see four different partial simulations of various phases of the experiments
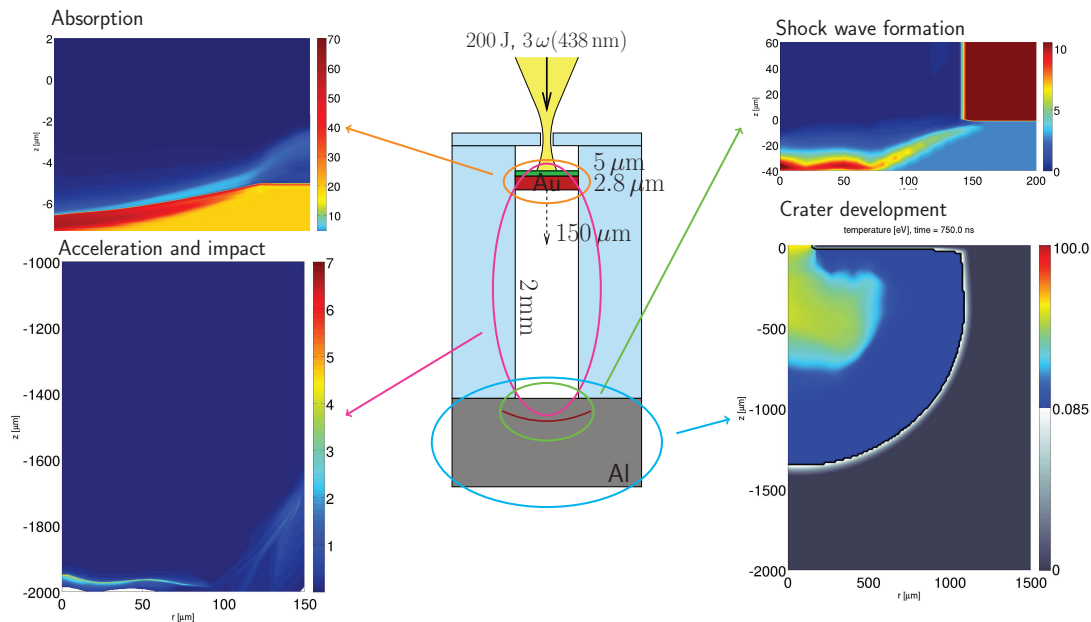

Figure 1: Numerical simulations of different phases of LICPA acceleration shown: absorption, acceleration, impact and shock generation, crater development. Density is shown in first three simulations, electron temperature is shown in the last simulation.

– initial laser absorption and projectile acceleration, its motion through the channel, impact on the massive target at the end of the channel and shock wave formation, and the final crater development. Results of the simulations (impact velocities, crater size) have been compared to the experimental results, a reasonably good agreement can be observed.

Conclusions

In this short paper, we have briefly reviewed abilities of two hydrodynamic codes – PALE and PETE, and the included models of various physical effects. We have shown one selected exam-

ple (LICPA scheme), where simulations have been performed and helped to interpret experimental results. Currently, active research is performed in two directions – non-local transport model and magnetic field model, further improving areas of applicability of these codes.

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