Hydrodynamical modeling of targets compression to high densities

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Two different one–fluid one–temperature models, Lagrangian and Eulerian, are employed for modeling target compression to high densities. Numerically, Lagrangian model is treated by support operator method and Eulerian one by composite schemes on moving grid. Both models also include heat conductivity. The quotidian equation of state (QEOS) is used. This equation of state is valid for a very wide range of plasma parameters, it is fast, reliable and consistent. Several particular configurations including targets with several layers from different materials have been simulated. Results for compression of cold liquid/frozen hydrogen by gold flyer correspond reasonably well with fully independent calculations performed by others. We have also simulated a real experiment performed in Lawrence Livermore National Laboratory where liquid hydrogen contained between two sapphire anvils was compressed by a high speed impactor. Reasonably good agreement of our simulation including six layers with experiment has been achieved.

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1 Introduction

Plasmas are any statistical systems containing mobile charged particles. In standard, low density plasmas the long–range Coulombic forces play the key role in establishing for plasma specific collective phenomena. Physics of this form of plasmas is elaborated very completely and serves as a credible basis for many applications.

As the density is increased, the plasma begins exhibiting feature characteristics of a condensed matter, where short–range as well as long–range forces conspire to endow the plasma with a character of strongly coupled many–particle systems [1]. As the temperature is lowered, quantum statistic and dynamic effects start to play a dominant role in the plasma, so that interplay with atomic, molecular, and also nuclear physics becomes a major issue.

Study of strongly coupled systems poses a great challenge for contemporary physics [2], a complex approach based on theory, simulation and experiment is necessary. In this report we describe some preliminary simulation studies of novel methods of strongly coupled plasma generation, based on hydrodynamic modeling.

2 Hydrodynamical model

Both Eulerian and Lagrangian description is used in this study and numerical methods for them are developed.

Here we present Lagrangian formulation which is given by the system

$$\begin{aligned} \frac{d\,\rho}{d\,t} + \rho \operatorname{div} \mathbf{u} &= 0 \\ \rho \frac{d\,\mathbf{u}}{d\,t} &= -\mathbf{grad}\, p \\ \rho \frac{d\,\epsilon}{d\,t} &= -p \operatorname{div} \mathbf{u} - \rho \operatorname{div} \mathbf{W} \end{aligned} \tag{1}$$

where ρ is density, $\mathbf{u}$ is velocity, p is pressure, E is total energy and heat flux $\mathbf{W}$ is given by

$$\mathbf{W} = -\kappa\, \mathbf{grad}\, T \tag{2}$$

where T is temperature and κ is heat conductivity for which we consider Spitzer–Harm [3] and Rozmus–Offenberger [4] approximation however we should note that for most presented computations the heat conductivity is negligible. The above system is coupled with an ordinary differential equation (ODE)

$$\frac{d\,\mathbf{x}}{d\,t} = \mathbf{u},$$

which defines movement of Lagrangian cells ($\mathbf{x}$ denotes the position of a cell).

For numerical treatment of Lagrangian formulation we use support operator method scheme [5] with artificial viscosity given by combination of linear and nonlinear artificial viscosity. Velocities of Lagrangian cell boundaries are updated from the pressure difference in the two neighboring cells and the internal energy inside each cell is updated from local pressure and difference of velocities at both end points of the cell. After moving the cell boundaries, the density is updated from basic Lagrangian assumption that the mass of any cell remains constant all the time.

Our model also includes heat conduction, which introduces a parabolic term into the energy conservation equation. This term is treated by splitting the model into hyperbolic hydrodynamic system and parabolic heat equation which is numerically solved either by explicit method with sub–stepping in time or by implicit method with the same time step as the main hyperbolic part of the model. For low temperatures the heat conductivity is relatively small and thus it allows us to use an explicit method with one or few heat flow time sub–steps per one hydrodynamic time step.

3 Equation of state

We are dealing with hydrodynamic modeling of plasma compression to high densities for which we need an adequate equation of state valid in a broad range of

plasma conditions. We have chosen the quotidian equation of state (QEOS). The QEOS equation of state consists of three main parts [6]: (1) The electron ionization–equilibrium equation of state based on the Thomas–Fermi statistical cell model with scaling property for atomic number and atomic weight. (2) Analytical ion equation of state that combines Debye, Gruneisen, Lindemann and fluid–scaling laws. (3) Empirical term that introduces correction for chemical bonding and is derived from physical properties of a given material.

The QEOS equation of state is valid for a very wide range of plasma parameters, it has an appropriate accuracy for plasma simulations of our interest, and it is fast, reliable and consistent in hydrodynamic calculations. It does not need any external database. The local thermodynamic equilibrium of electrons is assumed. Quantum shell effects and phase transitions are neglected. Material from which plasma is produced can be either pure element or a compound. As input parameters for the QEOS equation of state one needs atomic weight and atomic number of every element, number of atoms of each element in the compound, solid state density and bulk modulus (which describes how the total pressure changes with changing density) at solid state density.

4 Compression of targets to high densities

In order to test implemented numerical hydrodynamical models several particular potential configurations for generation of strongly coupled Coulomb systems have been explored. In all these numerical experiments QEOS equation of state [6] and Spitzer–Harm formula for heat conductivity [3] have been applied. Clearly, this is not fully acceptable approximation in all regions of parameters (density, temperature) of these configurations, but for testing purposes it can be used. Here we present two tests considering compression of hydrogen to metallic state.

4.1 Cold hydrogen compression by gold flyer

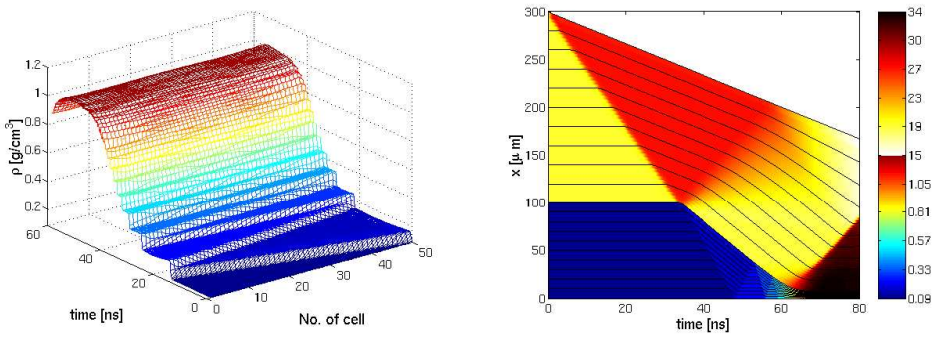
The first numerical experiment has been related to very actual problem: producing metallic hydrogen by using strong shock waves in liquid/frozen planar hydrogen targets. In order to have possibility of quantitative comparison, we have used a configuration with parameters similar to simulation conducted in Max–Planck Institute for Quantum Optics [7] some time ago.

The first configuration here is $100\,\mu$m thick hydrogen layer compressed by $100\,\mu$m thick gold flyer having initial velocity $2.5\,$km/s. Initial densities are $0.088\,\mathrm{g/cm}^3$ for hydrogen and solid state density $19.3\,\mathrm{g/cm}^3$ for gold. We start computation at very low temperature $T = 0.00027\,\mathrm{eV} \doteq 3\,\mathrm{K}$ needed for liquid/frozen hydrogen. Computation has been ended after $60\,$ns when hydrogen layer starts to expand after the compression. On the hydrogen boundary which is not adjacent to gold layer we use reflecting boundary conditions. Fig. 1 (a) shows the time evolution of density in hydrogen layer for this configuration. Several shock waves compressing hydrogen are clearly seen.

In the second configuration we assume $100\,\mu$m thick hydrogen layer adjacent to

200 μm thick gold layer which is not moving at the initial time however velocity of the outer gold boundary is prescribed to 1.66 km/s. Initial densities and temperature are the same as in the previous configuration and we perform the computation till time 80 ns. Material density versus time and space is presented in Fig. 1 (b). Moving boundary initiates a shock wave in gold which hits hydrogen layer around time 35 ns an propagates into hydrogen where it reflects several times from boundary $x = 0$ and from the interface with gold. Shortly before maximal compression around time 64 ns a reflected shock wave is formed in the gold layer.

Our results in Fig. 1 compare reasonably well with those of [7] which used different equation of state, namely SESAME [8]. Simulation of planar hydrogen target based on our code agrees reasonably well with the results of comparative, fully independent calculations.



(a) (b)

Fig. 1. (a) Density evolution of 100 μm thick hydrogen layer compressed by 100 μm thick gold flyer having initial speed 2.5 km/s. Gold flyer neighbors the cell no. 50, initially at $x = 100\,\mu$m, i.e. gold is on the right (not displayed). (b) Spatio–temporal plot of material density. Hydrogen layer of thickness 100 μm is compressed by 200 μm gold layer. The speed of upper boundary of the gold layer was set to 1.66 km/s. Different color maps are used for hydrogen on the bottom and gold on the top as seen on color bar on the left which has density tick marks in g/cm^3.

4.2 Simulation of real experiment compressing hydrogen to metallic state

Experiments dealing with compressing hydrogen to metallic state have been performed in the LLNL [9]. We present here simulation of one of these experiments.

The target with impactor is schematically depicted in Fig. 2 (a). The hydrogen layer of thickness $t_1 = 0.5$ mm is covered from both sides by two sapphire anvils of thickness $t_2 = 2$ mm and again both sapphire plates are covered by two aluminum layers of thickness $t_3 = 2$ mm. So the target is formed from five layers. Initially the whole target is cooled to the temperature $T = 0.0018\,\text{eV} \doteq 20\,\text{K}$ necessary for

liquid hydrogen. The target is hit by copper impactor of thickness $t_4 = 3\,\mathrm{mm}$ with initial velocity $v = 5.58\,\mathrm{km/s}$. The initial densities are 0.071, 3.99, 2.7, $8.92\,\mathrm{g/cm^3}$ for hydrogen, sapphire, aluminum and copper respectively. The impact forms the shock wave propagating through aluminum, sapphire and hydrogen layers. This shock wave reflects from the other sapphire anvil and starts a series of reverberating shocks inside the hydrogen layer, which gradually compress the hydrogen. The time evolution of density in all six layers is presented in Fig. 2 (b). Shock waves are clearly visible. Fig. 2 (d) is the zoom of Fig. 2 (b) into the region of hydrogen compression and besides hydrogen layer in the middle includes only two sapphire plates on top and bottom. Fig. 2 (c) presents time evolution of pressure in the center of hydrogen layer. The maximum hydrogen pressure in our simulation is 153 GPa, while 140 GPa was measured in experiment [9] for the same setup. Using the measured pressure and numerical simulation, the maximum hydrogen density of 0.684 $\mathrm{g/cm^3}$ was found in [9], while it is 0.667 $\mathrm{g/cm^3}$ in our simulation. Hydrogen temperature 3860 K at maximum hydrogen density is higher than 2560 K in [9] due to underestimation of thermal conductivity in our model at low temperatures.

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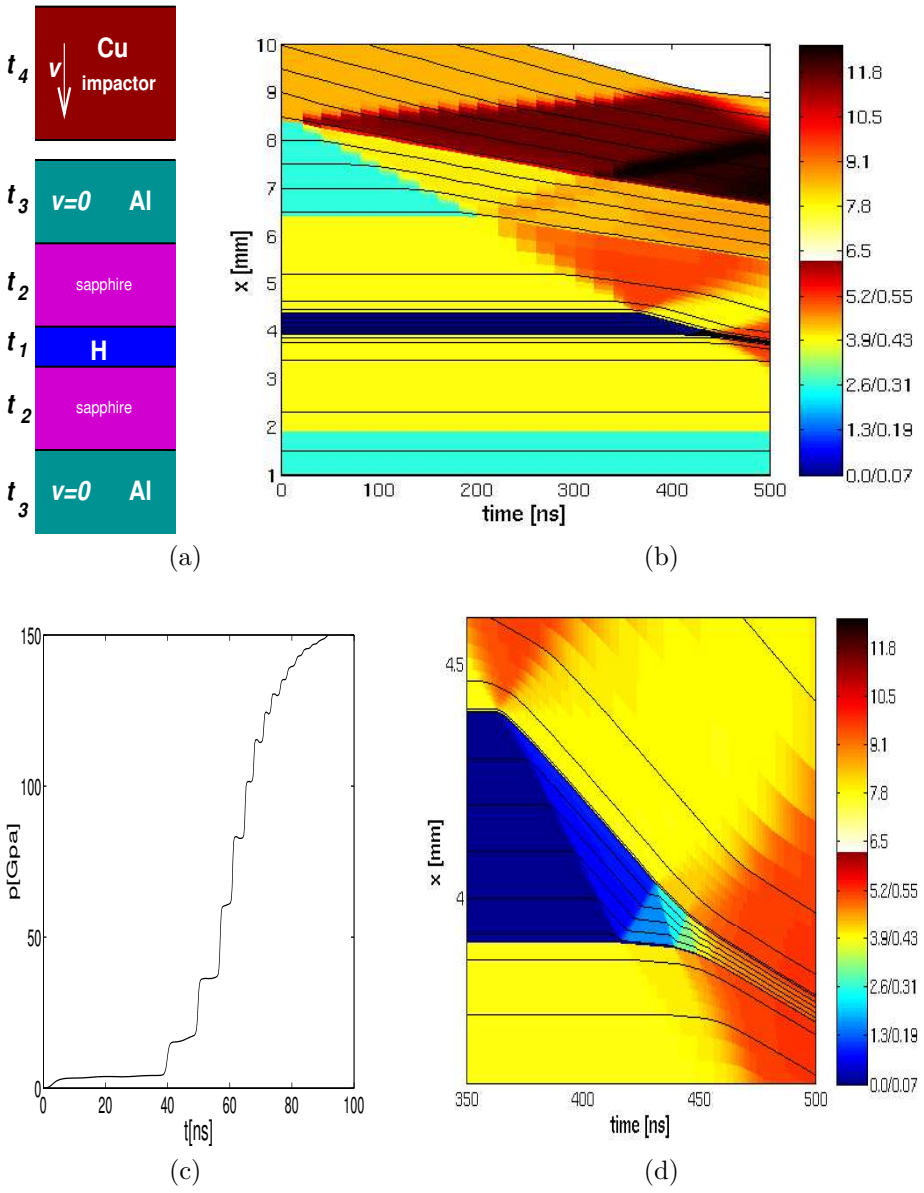

Fig. 2. (a) Scheme of experimental target. (b) Spatio–temporal plot of density in all six layers. (c) Evolution of pressure in the center of hydrogen layer. (d) Spatio–temporal plot of density zoomed to hydrogen compression area. The second (after the slash) value of tick labels at (b) and (d) gives the density value in hydrogen layer while the first (before the slash) one gives the density value in the other five layers.