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Hydrodynamics of metal foil isochorically heated by protons in the warm dense regime

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Introduction

Warm dense matter (WDM) is defined by mild ion ion correlation and partial degeneracy. The physics associated with this particular state of matter can be viewed as the limit where adjacent classical theory fails. It is thus at the periphery of well know state of matter: classical plasma, high density chemistry, dense matter and hot solids. At LULI, laser-target experiments are currently performed in order to generate with high fidelity large amount of well characterized WDM [1]. This is done by exploiting the particular features of laser-generated proton sources produced during the interaction of an ultra high intensity laser pulse with a metallic foil. In our scheme, this proton beam interacts subsequently with a second target and induces fast heating up to a few ten eV of the metal foil along an isochoric thermodynamic path. The resulting state of matter falls into the warm dense regime. In this contribution, we present 1-D hydrodynamic simulation of aluminium foil expansion heated according to this scheme and comparison with experimental data.

Experimental set up

Experiment are performed at LULI on the 100 TW facility. 30 Joules are delivered to the primary target in 400 fs on a spot of radius 10 micrometers; this generates a pulsed (few picoseconds) laminar beam containing about 1E11 protons and multi-MeV energies up to 20 MeV. A second target is located 200 micrometers away from the primary one. The protons irradiate the second target over an area of diameter equal to 200 micrometers. Due to isochoric heating induced by the protons stopping in the second target, hydrodynamic expansion takes place and a chirped laser probe is launched on the rear side of this target in order to measure phase shift due to the displacement of the critical density layer and the reflectivity drop due to transition from the cold solid state to warm and dense state.

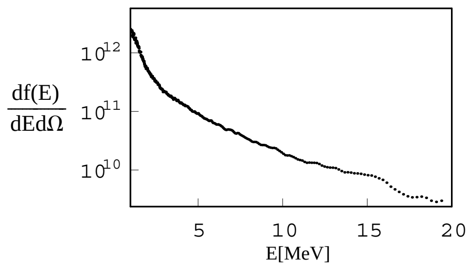

Figure 1: Ion energy distribution function measured in the experiment.

Modeling and Simulation

We have performed the simulation of the heating and expansion of an aluminium thin foil irradiated by a laminar high energy proton source using a one dimensional hydrodynamics code (Esther see Ref [2]). This code solves, according to a Lagrangian scheme, the fluid equation for the conservation of mass, momentum and energy. The target material is described by the Bushman-Lomonosov-Fortov multiphase equation of state spanning a large range of density and temperature from hot plasma to cold condensed. Energy in the target can be deposited by different ways: X ray, laser field or ion beam. The measured ion energy distribution function as generated by the interaction of the 100 TW laser and the first target (10 micrometers width) is showed on figure (1) and we observe that maximum ion energy reaches several MeV. We sample this ion distribution function and use it as input parameter in the simulation. This ion source is taken as a laminar source of duration equal to 5 picosecond and is emited 200 micrometers away from the secondary target. Ion deposit their energy into the secondary target mainly through coulomb collisions with the electrons being free or bounded. For the ion stopping power, we used the value given by the SRIM database. We expect an isochoric heating by energetic ions as for ion energies above 1 MeV, the stopping power is almost constant across the 10 micrometers thin aluminium foil (the Bragg peak is virtually outside the target) whereas below 1 MeV, the variation in the stopping power is compensated by the decrease in the ion distribution function. A laser probe diagnostic is implemented in the code in order to obtain phase and reflectivity after reflecting off the heated target surface and to compare with experimental results. The interaction between the laser field and the target is given by the solution of the Helmholtz wave equation. This requires accurate values for the conductivity; we used the values from Eberling [3], Palik [4] in the solid phase and the Spitzer formula in the plasma phase. Parameters of the simulation were as follows: ion fluence 5e7 J/m2 (during 5 ps), simulation time=100 ps, cells number=101, 201 time steps and probe incidence angle=45 degree. Figure (2) shows the ion-

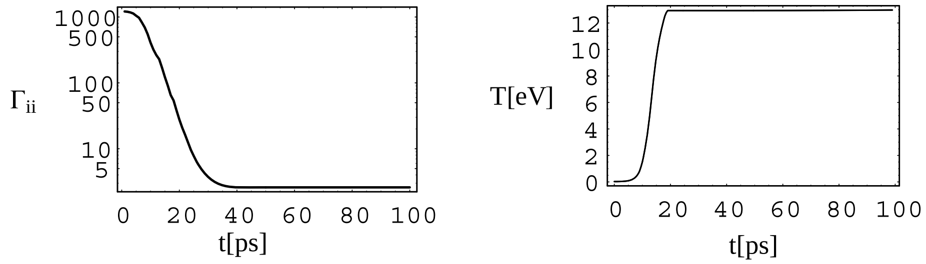

Figure 2: Ion-ion correlation and temperature at the center of the target versus time

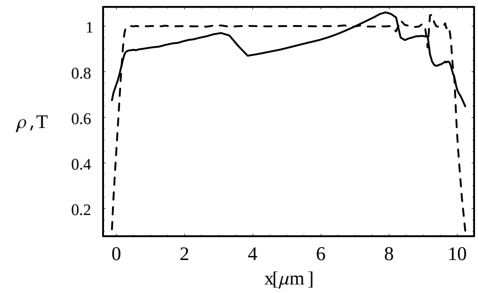

Figure 3: Temperature (full line) and density (dashed line) normalized to their top value after 35 ps

ion correlation factor and the target temperature at its center as a function of time. Warm dense matter conditions, i.e degeneracy parameters equal to one half and ion-ion correlation parameter of the order of two, are obtained after 35 ps. For this simulation, temperature is about 14 eV and the uniformity of the temperature is of the order of 10 percent as shown on figure (3) where both density and temperature are plotted normalized to their maximum (2.7 g/cc and 14 eV). However, irregularities in the temperature profile is due to the sampling of the ion distribution function: low energy ion have their Bragg peak localized inside the target and we expect during the forthcoming development of our study to obtain a smoother profile by refining the sampling of the ion spectrum. The reflectivity of the sample at wavelength=1.06 micrometers is show on figure 4 (a) and clearly show a rapid transition around 10 ps of the target state whose meaning is not currently found. We also found good agreement between the measure phase shift and the computed phase shift (figure 4 (b)).

Conclusion

We have demonstrated that we can produce large amount (about 300 000 microcubics) of WDM. The next step will consist in the study of the ion stopping power (SP) in WDM. As electron structure is known to play an important role in SP, we expect to observe variation in

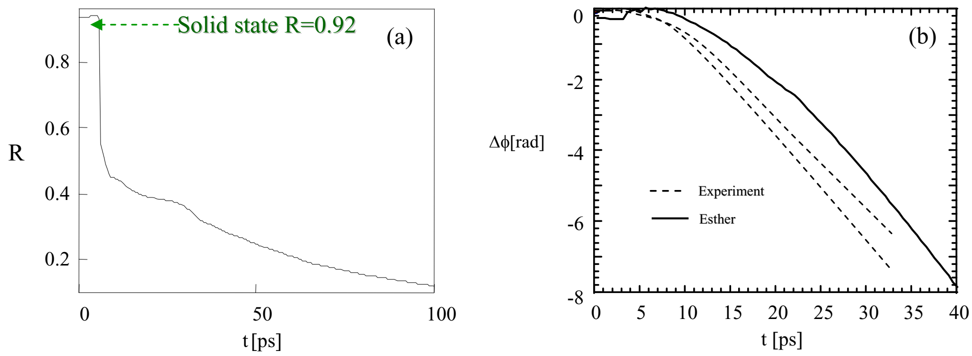

Figure 4: Reflectivity (a) and phase shift (b) as a function of time of the proton heated target.

the stopping power. We also plan to probe WDM in X-UV range by using high order harmonics of a Ti-Saphir laser facility at CEA Saclay. This will generate data relevant for the validation of the conductivity in UV range at solid density and few eV temperature where complex effects in electron ion scattering modify the scaling of the conductivity with respect to frequency. As electron velocity becomes of the order of orbital velocity, inverse stimulated bremsstrahlung in warm dense matter can not be treated in the Born approximation. More over at Nd-Yag wavelength, the laser pulsation is of the order of the duration of a collision (ionic Wigner Seitz radius divided by the Fermi velocity); WDM regime probed in the X-UV range corresponds to this case where little is known on the scaling of the electron-ion frequency with respect to the laser pulsation [5].

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