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Study of preheating effects in laser driven shock wave EOS experiments

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In the last two decades, a large number of applications including condensed matter physics, astrophysics, material science etc. provide impetus for studying Equation of State (EOS) of matter at pressures of few tens of Megabars. In fact all most all the elements and some compounds are theoretically studied and well tabulated in Sesame[1]/MPQeos which have similar values. Nevertheless, very few experimental results are available to validate the theoretical predictions at high pressures above 10 Mega bars.

In this report we present an analysis on one of the measurements relevant to the recent experimental results[2] on carbon Hugoniot data. Experimental results are systematically lower in pressure and fluid velocity (P-U) plane than the theoretical Hugoniot obtained from Sesame/MPQeos. There can be several reasons for the deviation from the theoretical curve including target preheating caused due to the generation of X-rays and hot electrons. Considering the experimental range of the laser intensity, hot electron generation is negligible and hence it is out of the scope of the present report. We simulate the conditions using the experimental target configuration (two steps - two material) and the laser parameters to study the shock transit time in the step target which is one of the experimentally measured quantity for the study of EOS of carbon. Evolution of the preheat in the base and step targets and its impact on the shock propagation time is the theme of this paper and the simulations reveal the behaviour of shock wave propagation in a preheated medium.

When a laser radiation is focused on the surface of a target (aluminium), an intense shock is generated and propagates inwards. In experiments, the appearance of shock luminosity is the signature of the shock arrival at the rear surface. To bring the simulation closer to the experimental conditions, we perform one-dimensional simulations using SARA[3] code with 48 opacity groups and adopt MPQeos. We assume a target configuration (single/two layers as per the requirement) having a finite thickness with uniform density and a given initial temperature. To investigate the effect of preheating on the shock propagation, it is necessary to study its behaviour in comparison with a colder medium. Therefore we have two cases; case-1, aluminium base target is subjected to generate X-radiation and the subsequent absorption allows the preheating of the base target and step targets, and case-2, X-rays are not generated but the system retains all other processes as in the first case. To study the shock transit time in the carbon step target, we generate the data but adopt two different approaches; 1.Experimental approach 2.Simulation approach.

1. Experimental approach: In the recent experiments[2], EOS of carbon is studied using two steps - two material targets configuration where aluminium with known EOS acts as a reference material along with a step of the test material. Thickness of the base aluminium target is 8 µm and carbon step thickness is 9.5 µm. Characteristics of the PALS laser system are λ=0.44 µm and τ(FWHM) = 0.45 ns. Experimental set up shown in fig.1 have usual meaning. Experimentally, the shock transit time in the carbon step is measured as $\{t_c\}_{Ex} = \{t_s - t_b\}_{Ex}$ where t_s is shock exit time from the rear of the carbon step target and t_b is shock exit time from the rear of the Al-base target.

Similar to the above experimental method, we also obtain from simulation, the shock exit time from base and rear of the carbon step. Shock transit time is calculated as $\{t_c\}_{Si\text{-}Ex} = \{t_s - t_b\}_{Si\text{-}Ex}$. These results are compared with $\{t_c\}_{Si}$ discussed below. The nomenclatures $_{EX}$ - represent experiment, $_{Si\text{-}EX}$ - simulations for corroborating experimental results and $_{Si}$ for independent simulations discussed in the following text.

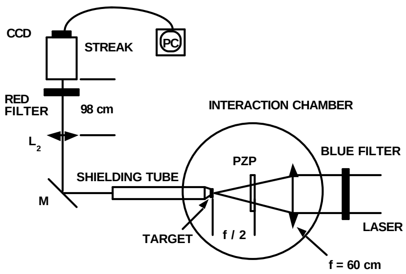

Fig.1. Experimental set up at PALS.

2. Simulation approach: Here we are presenting the simulation data to predict the shock transit time in the step target. We consider two layered targets, aluminium (thickness ~8 µm, ρ=2.7 g/cc) as a base and carbon (thickness ~ 9.5 µm, ρ=1.6 g/cc) as a step. The shock transit time in the step is calculated as $\{t_c\}_{Si} = \{t_s - t_a\}_{Si}$ where t_s is shock exit time from the rear of the step target and t_a is shock arrival time at the beginning of the carbon layer. The concept of the shock transit time described here is slightly different than the experimental

approach. We record the times for radiative (implies X-ray generation and the corresponding preheat in the step target) aluminium base target and also for non-radiative target. In the present simulation we adopt the opacity for carbon given by Palik.

Results and discussion: Fig.2 shows the evolution of preheat at the rear for a) base target b) aluminium step target and c) carbon step target as a function of time. Laser is incident on the aluminium base target at t = 0. It is clearly seen from fig. 2 that preheating develops in the entire target assembly and is higher in al-step as compared to carbon step. This is due to efficient absorption of aluminium X-rays generated in the base target and their subsequent absorption in aluminium step whereas aluminium X-rays are poorly absorbed in carbon step. This fact was verified in the simulation by the X-ray transmission spectra from aluminium and carbon steps. X-ray generation in the aluminium base target and subsequent preheating causes the rear side expansion of the base target. An efficient absorption of X-rays in the step targets also result in the rear side expansion of the step targets. For PALS parameters at $I=10^{14}$ W/cm^2, Al-step expands by 0.45 μm and the C-step by 1.40 μm. Although preheating is less in carbon, the lower density (1.6 g/cc) allows higher expansion.

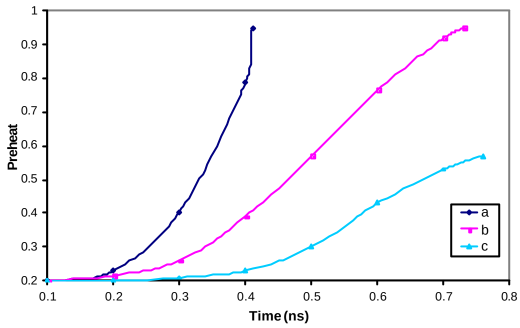

Fig.2. Preheat evolution in eV at the rear surfaces Vs. time in ns.

It is observed that the shock transit times are longer when shock travels in a preheated medium as compared to the cold medium. For PALS experimental parameters at $I=10^{14}$ W/cm^2, shock transit time according to $\{t_c\}_{Si\text{-}Ex}$ ~ 321 ps in preheated target and ~ 293 ps in cold target implies an increase of ~9.55 %. According to the simulation carried out in the step target alone, the shock transit time $\{t_c\}_{Si}$ in a pre-heated carbon is 320 ps where as under identical conditions, with no pre-heating, it is 288 ps, implies an increase of ~ 11 % in the shock transit time. Fig. 3 represents the propagation of the shock in the aluminium base and carbon step target configuration. Laser is incident from the top. The rear carbon surface corresponding to the initial position (at 0 μm) shows expansion before the arrival of the shock. Red colour corresponds to aluminium target and green for carbon step.

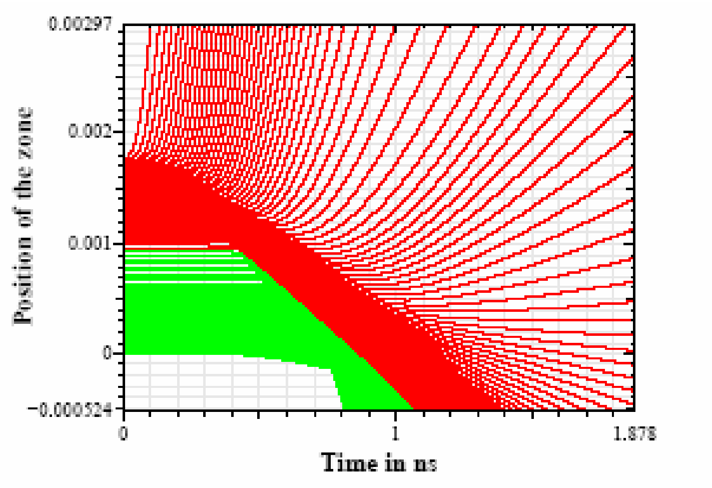

Fig.3. Shock propagation in the aluminium base and carbon step target configuration.

Similarly, for Luli experimental[2] parameters (λ=0.53 μm, τ=1ns), simulations predict longer shock transit times in preheated carbon target compared to the respective cold target and this enhances with increasing value of the preheat.

It is clear from the simulations that in a preheated carbon medium shock transit times are longer than the respective cold medium. The topic needs further analysis on the behavior of carbon, perhaps many processes which are strongly temperature based can provide explanation.

In conclusion, the preliminary simulation results show that EOS of a carbon is affected due to preheating of the target by X-radiation. Shock transit time in the heated carbon material is enhanced compared to the cold material. In the case of non-heated carbon, simulation results agree (as expected) with theoretical carbon Hugoniot. Details of the work will be published elsewhere.

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