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2002 J. Phys.: Condens. Matter 14 10917

(http://iopscience.iop.org/0953-8984/14/44/401)

INSTITUTE OF PHYSICS PUBLISHING JOURNAL OF PHYSICS: CONDENSED MATTER

J. Phys.: Condens. Matter **14** (2002) 10917–10920 PII: S0953-8984(02)37967-0

Numerical simulation study of laser-driven shock wave propagation in planar aluminium foils

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Received 11 June 2002
Published 25 October 2002
Online at stacks.iop.org/JPhysCM/14/10917

Abstract

A comprehensive numerical simulation study of laser-driven shock wave propagation in planar aluminium foils, 20–50 μm, is performed using the one-dimensional radiation hydrodynamic code MULTI. The effect of the spatial mesh size on the shock velocity and peak shock pressure is found to be significant and the optimum mesh size is obtained. Shock velocities and maximum pressure are calculated through simulations for two sets of laser intensities used in an experiment (Fu S, Gu Y, Wu J and Wang S 1995 *Phys. Plasmas* **2** 3461). By using different sets of laser absorption coefficient values we determine the appropriate values reproducing the experimental results. We demonstrate that the simulations can be used as an effective tool for benchmark calculation of laser absorption coefficients.

1. Introduction

Study of matter under high-pressure conditions is of great interest in the fields of astrophysics, materials science, and inertial confinement fusion (ICF) research [1, 2]. Several laser-driven shock wave experiments have been conducted in the past to achieve an accurate equation-of-state (EOS) measurement for Al material that is being used as a standard reference material for determining the EOSs of other materials using the impedance matching technique [3, 4]. We performed a comprehensive numerical simulation study of laser-driven shock wave propagation in a planar aluminium foil target, 20–50 μm, using the one-dimensional radiation hydrodynamic code MULTI [5]. In simulations, selection of the spatial mesh size plays a crucial role. It was first reported by Benuzzi *et al* [6] while studying the preheat effect on the rear-face expansion of foil targets. We noticed that the effect of the mesh size on the shock velocity and peak shock pressure is significant and tried to obtain the optimum mesh size. This mesh size gives very stable pressure and density profiles. It was shown by Schmaltz *et al* [7] using the MINIRA code that a simple grey opacity model works quite well for low-Z materials; his results were compared with the exhaustive work of Duston *et al* [8] for Al material and the

results matched remarkably well. Honrubia *et al* [9] showed that for Al foils the average-atom non-local thermodynamic equilibrium (AA-NLTE) model and the SNOP model give greater preheating temperatures compared to the average-atom local thermodynamic equilibrium (AA-LTE) model. Benuzzi *et al* [6] have also found that the SNOP model overestimates the preheat temperature of the Al target by 1 eV compared to the model used by Honrubia *et al*, giving 0.4 eV as the preheating temperature. In view of the above observations we decided to use grey opacity for the Al target.

2. Numerical simulations

The numerical simulations of the laser-ablation-driven shock wave propagation in planar aluminium foils were performed taking into account the effect of radiation diffusion through the ablated plasma to properly account for the changes in the hydrodynamic properties of the plasma. The numerical simulations are based on the 1D radiation hydrodynamic code MULTI. It is a fully implicit code that solves the Lagrangian hydrodynamics together with multi-group radiation diffusion. However, for the present work, the frequency-averaged (one-group or grey) opacity diffusion approximation assuming LTE conditions was used. MULTI 1D has also been used to cross-check the calculations carried out by the MINIRA code [7] and it was found that the results agree quite well within an infinitesimal error of 1% [5]. We calculate the shock velocity by precisely measuring the relative shift in the position of the shocked density and temperature fronts inside the Al plasma at different time steps. We select only those time steps where the laser peak intensity is reduced and the shock wavefront has attained stability during its propagation through the radiation heat-ablated plasma to the cold dense rear side of the solid material. We further show that it is important to consider the mesh cell boundary space coordinates defined in Eulerian coordinates corresponding to a particular time step.

It is very important to select a proper spatial mesh size when numerical simulations are aimed at:

(i) shock wave propagation studies for compressed matter,
(ii) radiation preheat studies for the rear side of the target and
(iii) studies related to shock pressure and compression enhancements in a layered target due to impedance matching.

In recent work [6], where the authors tried to study the effect of preheating on Al–Au layered targets using one-dimensional code simulations, the sensitivity of the cell size to the density profiles obtained at the rearmost cell of the target was clearly shown. The effect of the fine mesh size has a clearly demonstrated effect on shock emergence. The present study clearly suggests that 500 Å seems to be the optimum cell size for ensuring steady shock wave propagation and correspondingly proper shock pressure values being reached at appropriate time steps. With a coarse mesh (large cell size), the peak shock pressure value shows about 20% increase along with a shift in its position by 200 ps. On the other hand, the use of very fine mesh (small cell size) shows about 6% increase in the shock pressure value but, importantly, the appearance of the peak pressure is 400 ps after the peak of the laser pulse. This can certainly affect the temperature value of the rearmost cell of the target from which shock breakout and a luminous signal are produced. This can also lead to totally different simulation results, which can be used for the study of reflection measurements for preheating studies [6].

3. Results and discussion

Shock velocities and peak shock pressures are calculated using simulations for two sets of laser intensities used in an experiment by the Shanghai group [10, 11]. By using different sets of laser

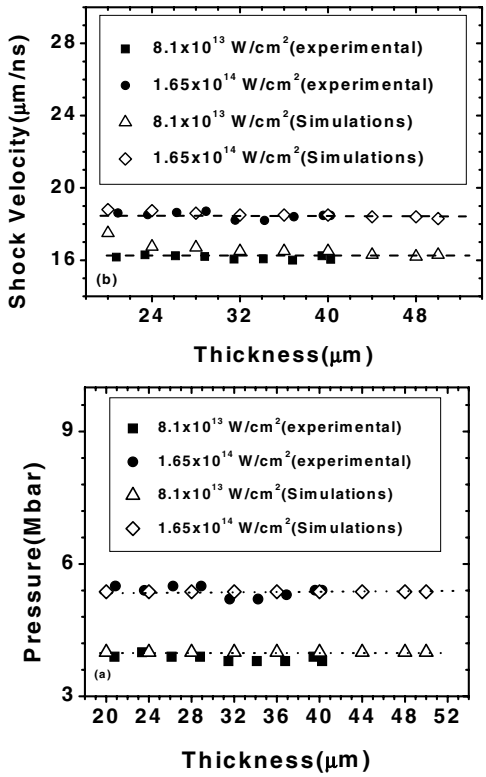

Figure 1. (a) Peak shock pressure values obtained through simulations are shown as a function of target thickness; constant shock pressure values of 4 Mbar and (b) average shock velocities calculated through simulations are plotted against the target thickness. Results for two laser intensity values as shown in (a) are compared with experimental results. The simulation results show good agreement with the experimental values.

absorption coefficient values we obtain the appropriate value of the laser absorption coefficient that reproduces the experimental results. Figure 1 shows plots of shock velocities and peak shock pressures calculated through simulations and their comparison with the experimental values for 20–50 μm thickness of the Al target.

In figure 2, we have plotted the shock wavefront positions versus the time in order to compare our results with the experimental values. Linear fits to the data points shown for both the intensity values were obtained and the slope of the fit gives averages of the shock velocity of 16.5 and 18.5 μm ns^{-1} for the intensity values of 8.1×10^{13} and 1.65×10^{14} W cm^{-2} respectively. When compared with the experimentally obtained values of 16.15 and 18.47 μm ns^{-1}, the results show excellent agreement within the estimated errors of 3.2% given by experiments, and thereby lend further support to our benchmarking simulations of the above experiments.

4. Conclusions

We have carried out a detailed numerical simulation study of shock propagation in planar Al foil targets of different thicknesses irradiated by a fundamental (1.053 μm) laser beam of 8.1×10^{13} and 1.65×10^{14} W cm^{-2} intensity with a Gaussian 1 ns duration (FWHM)

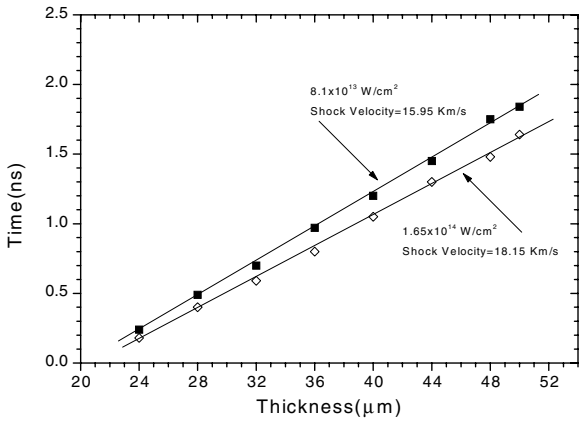

Figure 2. Shock wave propagation time obtained by simulations is shown as a function of target thickness for two laser intensities. The start time is taken from the shock breakout time for 20 μm thickness. Shock breakout times for other thicknesses are measured with respect to this time.

pulse. We have shown, for the first time, that by ensuring nearly constant shock velocity and shock pressure values for 20–50 μm target thicknesses using simulation calculations with optimum cell size and matching results with the experimental values, it is feasible to use this technique for a proper estimation of the laser energy absorption coefficients. The lower values of the laser absorption coefficient obtained through the simulation also suggest that for Al foil targets, highly smoothed surfaces and the increased laser spot diameter used to obtain uniform illumination on the target surface can lead to reduced laser absorption: nearly a factor of 2 lower than that reported from experiments [12].

Acknowledgments

VKS would like to express his sincere thanks to Dr D D Bhawalkar for his keen interest in and support of this work. Special thanks go to Dr Q L Dong and Dr Y Cang for their help in the preparation of this paper. This work was partly supported by TWAS, Trieste, Italy, under the south–south fellowship and partly by the Chinese Academy of Sciences, Beijing, China.

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