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Experimental and theoretical investigations of the crater formation process by means of double-target technique

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Abstract. Experimental and theoretical investigations of the crater formation process by means of double-target technique are reported. Experiments were performed at the PALS iodine laser facility by using double planar targets. An ablatively accelerated thin foil (made of Al) may reach high velocity, which cannot be obtained in any other way (for the mass of order of 10^{-6} g). The accelerated foil fragment may be regarded as a projectile and, colliding with the massive part of the double target, it is able to produce a crater. To illustrate the process of crater formation and to interpret the results obtained in our experiment, two-dimensional numerical code was applied. A good mutual agreement between the experimentally measured and numerically calculated fundamental parameters characterising the process of crater formation has been found.

1. Introduction

Craters are natural products of the interaction of high intensity laser beams with solid targets. For the first several years in typical "laser - target" experiments the craters were treated as secondary phenomena. More detailed and directed studies of this problem took place when the international program of Halley's Comet investigation was carried out. The laser simulation method [1] was applied in those works [e.g. 2-4] to analyse the collisions of super fast projectiles (comet dust particles) with massive targets (cosmic probe shields).

The more convenient and natural laser method of investigating the high velocity impact problem is exploiting a double-target technique [5]. This method takes advantage of laser ablative acceleration of a thin foil. The massive part of a double-target is placed at a distance where the accelerated foil fragment has already a high velocity and, simultaneously, its density is still comparable to the initial solid density. The laser method using an ablatively accelerated thin foil colliding with a massive target may be applied at studying many key issues of laser plasma physics (e.g. strong shock waves and high pressures generation, crater formation, equations of state, lateral heat transfer). In the present work we concentrate mainly on the crater formation process. To understand better the nature of the crater formation we performed also two-dimensional numerical simulations of the whole process.

2. Experimental set up

In the experiment, which was carried out with the use of the PALS facility [6], targets were irradiated by the first harmonic of the iodine laser beam ($\lambda = 1.315$ µm) with energy at the level of 130 J and with the pulse duration of 0.4 ns. To compare the results of the direct and indirect laser actions, two types of targets made of Al were employed: a single massive target and a double target consisting of a foil (6 μm thick), placed before a slab at a distance of 200 μm. The focal spot diameter of the laser irradiation on the target surface was equal to 250 μm.

To study both the plasma expansion and the foil acceleration a three frame interferometric system with automated image processing was used [7]. In order to determine exact shapes and dimensions of the craters, crater replicas were made of acetate cellulose. In our experimental and numerical considerations the moment of t = 0 ns corresponds to the maximum of the laser pulse.

3. Experimental results

On the basis of the interferograms registered it was possible to reconstruct the free electron density distributions at different instants of the plasma stream expansion. In Fig. 1 sequences of the electron density distributions in the form of isodensitograms for both target types are presented. The plasma stream boundary is

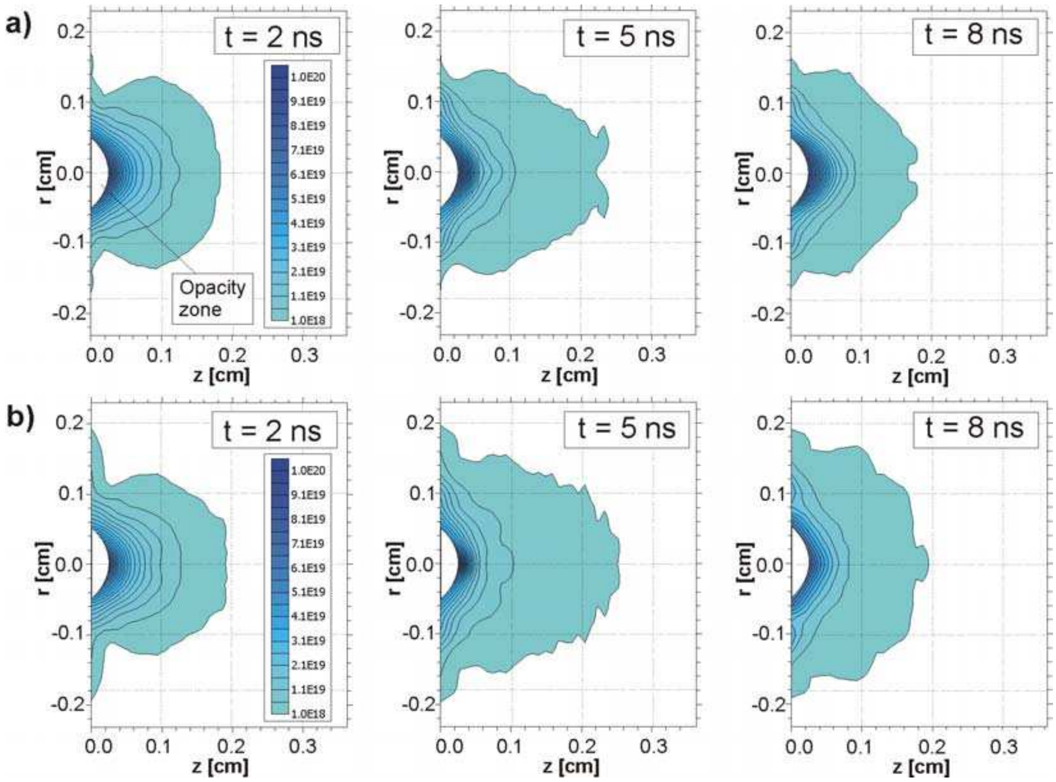

Fig. 1: Sequences of the electron density distributions in the cases of a) double target and b) single target.

represented here by the electron density contour $n_e = 1\cdot10^{18}$ cm^{-3} and all subsequent equidensity lines are integer multiples of $n_e = 5\cdot10^{18}$ cm^{-3}. Taking into account measurement errors, the presented electron density distributions for both target types at the moment of 2 ns are very close one to another. This similarity allows us to assume, that the laser energy absorption and the target heating for the both considered cases are approximately the same. Some differences seen later resulted from the foil dislocation.

In order to determine the velocity of the ablatively accelerated foil, the gap between the foil and the slab was enlarged up to 500 μm. It allowed us to register two frames during the foil flight with a delay of 3 ns. The impact velocity turned out to be equal to (6±0.2) 10^6 cm/s. By using this velocity value, the foil flight time could be determined. It amounts to about 3.3 ns. Because the foil starts from the zero velocity, the foil flight can last a bit longer. Important information about the efficiency of the laser target interaction is accessible from the crater parameters, i.e. from their shape and dimensions. In Fig. 2 the craters obtained by the both methods, indirect (a) and direct (b), are shown. On the basis of these experimental data it can be easily

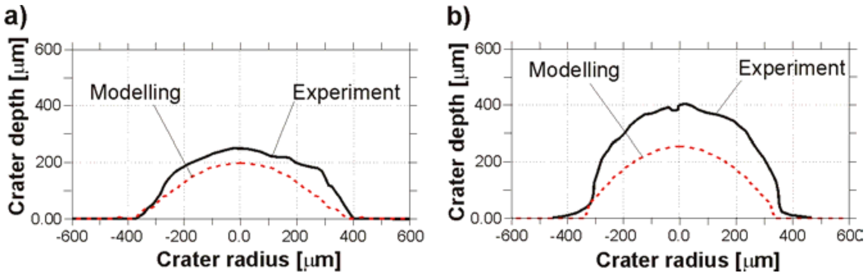

Fig. 2: Comparison of crater shapes and dimensions measured experimentally and calculated numerically in the case of a) double-target and b) massive target.

concluded that the indirect method of the crater creation via an inelastic impact of the ablatively accelerated foil fragment with the massive wall is less effective than the direct one. The efficiency β of the energy transfer from the fast macroparticle to the massive target may be found from the ratio of the crater volume for the double target to that for the single one. The β value in our experiment was equal to about 0.65.

The second difference concerns the crater shape. The craters created by the direct laser action have an almost hemispherical form while those obtained by collision of the foil fragment with the massive slab are clearly shallower. Apart from important data concerning the process of crater creation, our crater investigation served additionally to verification of the numerical modelling of this process.

3. Numerical modelling of the crater formation process

For numerical modelling of the foil acceleration and the crater formation the two-dimensional Lagrangian hydrodynamic code ATLANT-HE [8] was used. This code is based on one-fluid and two-temperatures model of plasma with electron and ion heat conductivity consideration. It includes, among others,

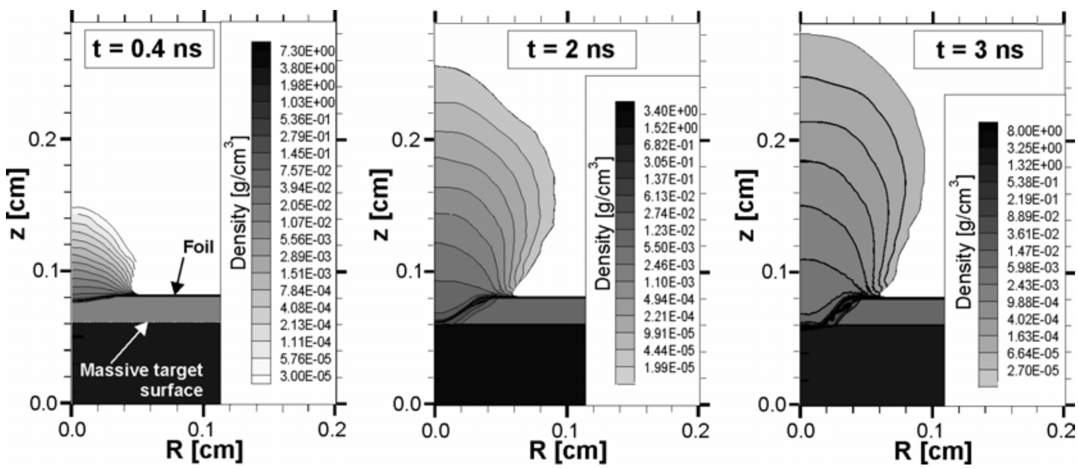

Fig. 3: Simulation of the ablative plasma generation and the foil acceleration.

laser radiation reflection, inverse bremsstrahlung and resonant absorption, as well as fast electron generation and transport. The results of calculation correspond to the experimental data. The process of the foil acceleration is seen in Fig. 3. The sequence of the images shows the ablative plasma stream and the foil motion in the direction opposite to the plasma expansion. The central part of the accelerated foil reaches the massive wall after 2.3 ns. The foil velocity at the impact instant is equal to $9{\cdot}10^6$ cm/s. The next sequence (Fig. 4) corresponds to the crater formation stage. This stage begins when the macroparticle is already completely decomposed. For the crater contour determination we used a simple procedure. If the ion temperature behind the shock wave is higher T_{cr} = 0.4 eV, the contour is moving together with the shock wave front. When the ion temperature becomes less than T_{cr} the contour position is fixed. The final crater shape and dimensions obtained by the numerical modelling are presented in Fig. 2. The efficiency β obtained from this calculation is higher

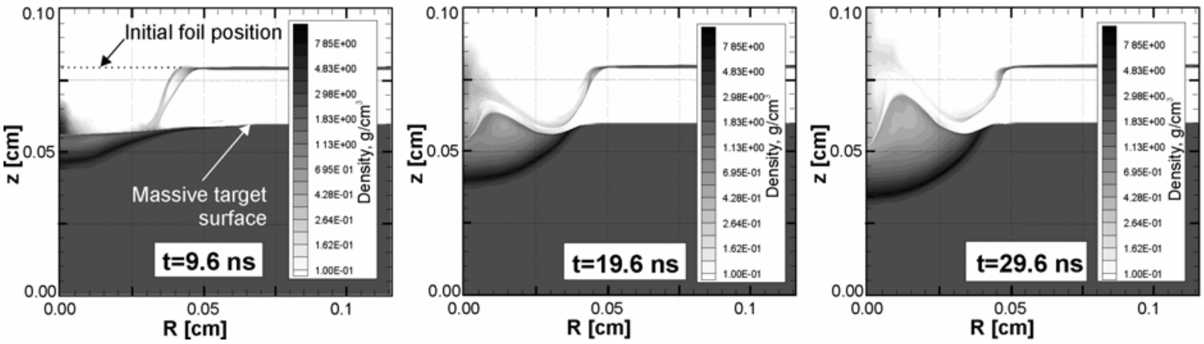

Fig. 4: Simulation of the crater formation process.

and amounts to 0.77. This discrepancy could be attributed to a simple model of the phase transition as well as to the use of a rather simple equation of state (perfect gas). Nevertheless, within the framework of these crude assumptions, the calculated crater contours have turned out to be close enough to those found in the experiment.

5. Conclusion

Our experiments and numerical modelling proved the possibility of the use of the laser accelerated foil and the shock wave in double targets to study many physical problems: cosmic particles impact, strong shock waves in solid body, equation of state, phase transition and crater formation etc.

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