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Study of symmetrising action of laser prepulse on inhomogeneity of thin foil heating

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Abstract. **The results of theoretical and experimental studies of plasma heating by laser radiation having an inhomogeneous spatial structure are presented as well as the results of investigation of the symmetrising action of a laser prepulse on the inhomogeneity of heating of thin foils modelling thin-walled laser fusion targets. The high efficiency of the method of ablation pressure symmetrisation by a laser prepulse is demonstrated.**

Keywords: *laser heating of plasma, inhomogeneous irradiation, symmetrisation by a laser prepulse.*

1. Introduction

In order to achieve high gains in laser fusion targets, it is necessary to compress DT fuel to a density exceeding $10^4 - 10^5$ times its initial value. For this purpose, spherical targets are exposed to a large number of laser beams in order to ensure a uniform heating of outer layers on the target surface. It is virtually impossible to attain a 100 % uniformity of target exposure because of a nonuniform overlapping of beams, interference phenomena in high-coherence laser beams, a nonuniform gain in the laser channel, and defects in the amplification channels of the laser. These nonuniformities of irradiation lead to a perturbation of the ablation pressure at the boundary of evaporation of the substance. The development of hydrodynamic instabilities in the compression process leads to an increase in the initially small perturbations of density and pressure, which may result in symmetry violation of the thermonuclear target shell being accelerated, mixing of the inertial layers of the shell with the DT fuel, and a sharp decrease in the thermonuclear energy release (see, for example, [1, 2]).

It was proposed in [3] to use a symmetrising laser prepulse to reduce the effect of nonuniform heating of spherical targets. The two-dimensional numerical computations carried out in [4] using the ATLANT software package show that a symmetrising laser prepulse with an energy about one-tenth of the energy of the basic heating pulse causes a two- or threefold decrease in the perturbation build-up rate upon compression of a glass shell filled with DD gas. The use of a symmetrising laser prepulse of wavelength longer than that corresponding to the basic heating pulse was suggested in [5]. A cycle of investigations of symmetrisation of radiation nonuniformity using a prepulse of wavelength two or three times longer than that of the basic pulse was carried out at the Institute of Physics, Czech Academy of Sciences in collaboration with the Lebedev Institute of Physics, Russian Academy of Sciences and the Institute of Mathematical Modelling, Russian Academy of Sciences. A comparison of the experimental data with the results of two-dimensional numerical computations shows that the uniformity of target heating can be enhanced significantly for an appropriate choice of the parameters of the basic heating pulse and the prepulse [6, 7].

Studies of heating and acceleration in thin foils with the help of high-power laser pulses have been carried out for several years on the Pico setup in the Laser Plasma Laboratory of the Lebedev Institute of Physics, Russian Academy of Sciences [8, 9]. A strong dependence of the fraction of laser energy passing through the foil on the foil thickness, as well as a decrease in the transmitted laser pulse duration, was observed in the experiments. A comparison with the results of numerical calculations shows that such a ‘bleaching of the target’ for thin Al foils of thickness not exceeding 3 μm is due to evaporation of the material. However, a certain fraction of laser energy passes through quite thick aluminium foils also, which can be explained simply by an evaporation of outer layers [8]. A similar effect of anomalously high transmission of laser radiation through thick foils was also observed on the Gekko facility in Japan [10]. Such an anomalously high penetration of laser radiation through thick layers can be due to the effect of microindentation [11], when dense layers move apart due to large transverse pressure gradients associated with the presence of speckles in the cross section of laser beams and allow the radiation to pass through. It was proposed in [8] to symmetrise the ablation pressure with the help of a laser prepulse with a wavelength equal to the wavelength of the main pulse used for heating the plasma.

In this work, we present the results of preliminary two-dimensional computations demonstrating the possibility of microindentation. Measurements on the Pico setup have confirmed experimentally the high efficiency of the proposed

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method of symmetrisation of the ablation pressure nonuniformity caused by the presence of speckles in the laser radiation focusing region.

2. Numerical simulation of symmetrisation using a laser prepulse

The NATSI software was used in Euler cylindrical coordinates (r, z) in order to simulate nonuniform heating and micorindentation of condensed target layers [12]. The system of equations of gas-dynamics, nonlinear thermal conductivity and transport of laser radiation along the laser beam axis OZ was solved numerically. For convenience of calculations, a nonuniform (in both directions) mesh with the smallest pitch along the OZ axis near the initial position of the aluminium foil ($z \approx 0$) was used, and the mesh pitch was then increased in both directions in geometrical progression. The smallest pitch along the radius was used in the vicinity of the axis and increased in the direction of R. The selected parameters of the problem were close to those realised in the experiment.

The problem was formulated as follows. An aluminium target of thickness $d = 3$ μm was irradiated by two laser pulses. Both pulses had a triangular time profile with time points $t_i = t_0$, $t_i = t_0 +$ 1.5 ns, $t_i = t_0 + 3$ ns, where t_0 is a parameter equal to zero in the first pulse ($i = 0$) and equal to the time delay Δt between pulses in the second pulse ($i = 2$). The highest pulse intensities are denoted by Q_1 and Q_2. The first pulse had a constant radial intensity distribution ($0 \leqslant r \leqslant R$), while the second pulse had a Gaussian distribution ($\propto \exp[-(r/r_{\text{eff}})^2]$, where r_{eff} is the effective beam radius). The first pulse models the laser prepulse, while the second models a speckle. In the course of calculations, the values of Q_1, Q_2, r_{eff} and Δt were varied while the target parameters were fixed.

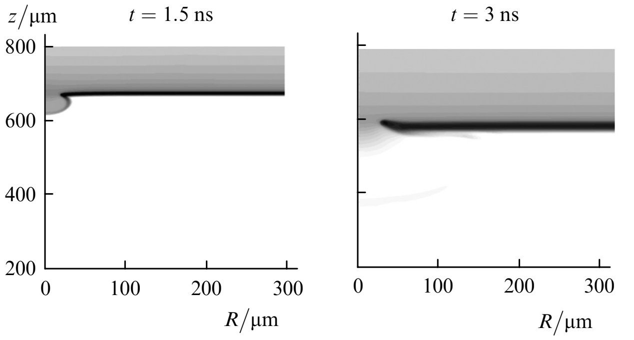

Figure 1. Formation of a hole in the target at the instants 1.5 and 3 ns for the intensity ratio $Q_2/Q_1 = n = 36$ and a delay $\Delta t = 0$ of the heating pulse relative to the prepulse; $Q_1 = 2.358 \times 10^{13}$ W cm^{-2}, $Q_2 = 8.48 \times 10^{14}$ W cm^{-2}, $r = 5$ μm, $R = 300$ μm.

In the first series of calculations, we studied the symmetrising action of the prepulse for $\Delta t = 0$, 0.5 and 1.5 ns and a fixed ratio of the laser pulse intensities. The first case corresponds to the absence of a prepulse ($\Delta t = 0$) for $Q_1 = 2.358 \times 10^{13}$ W cm^{-2}, $Q_2 = 8.48 \times 10^{14}$ W cm^{-2} (the ratio n of laser pulse intensities is equal to 36), $r_{\text{eff}} = 5$ μm, and the calculation domain size $0 \leqslant z \leqslant 1200$ μm, $0 \leqslant r \leqslant R = 300$ μm. A plasma region of density of the order of critical density and lower was formed in the target near the beam axis at a time t approximately equal to 1.5 ns, and was preserved till the end of the pulse (Fig. 1). A complete symmetrisation of the target was observed for delay times $\Delta t = 0.5$, 1.5 ns and for a ratio n of laser pulse intensities equal to 36.

In the second series of calculations, we studied the dependence of symmetrisation on the ratio of intensities. Calculations were made for $n = 90$, 200 and 360 for a fixed value of $Q_2 = 8.48 \times 10^{14}$ W cm^{-2} and $\Delta t = 1.5$ and 0.5 ns. The ablation pressure was completely symmetrised for a time delay $\Delta t = 0.5$ ns right up to $n = 200$. Complete symmetrisation for a time delay $\Delta t = 1.5$ ns occurs for $n \leqslant 250$.

A curious flow effect was observed during calculations when the hole formed during target indentation is filled by plasma from the peripheral layers. Figure 2 shows the results of calculations for the case $n = 90$ and $\Delta t = 0$. One can see that a hole is formed in the dense plasma near the axis by the time $t = 1.5$ ns while, on the contrary, a compaction emerges near the axis by the time $t = 3$ ns

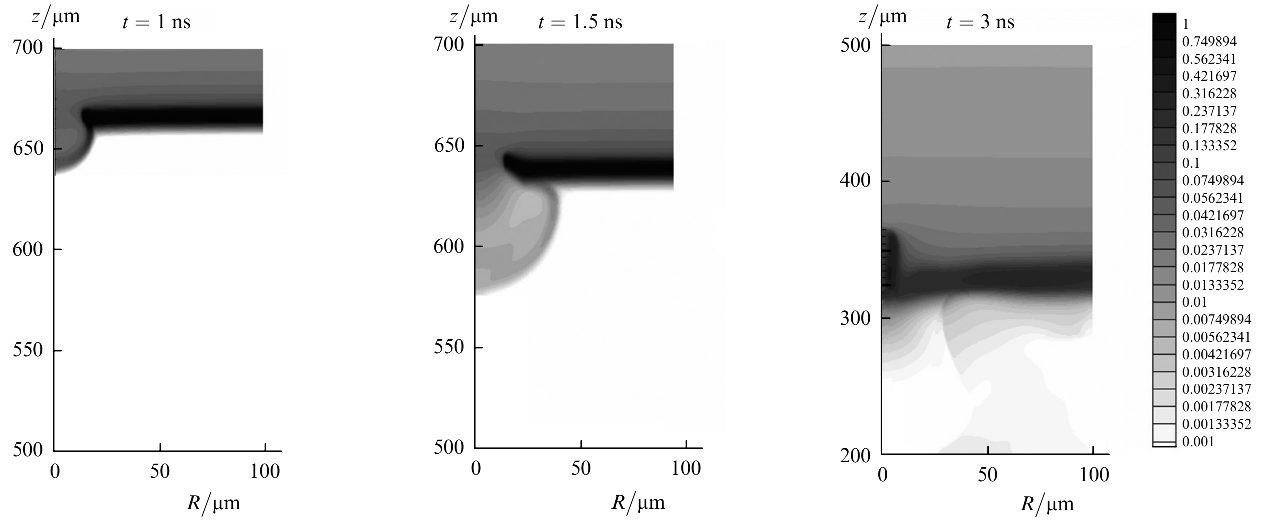

Figure 2. Formation of a hole in the target for the intensity ratio $n = 90$ and a delay $\Delta t = 0$. The figure shows the hole formation by the instant 1.5 ns followed by the plasma flow; $Q_1 = 9.5 \times 10^{12}$ W cm^{-2}, $Q_2 = 8.48 \times 10^{14}$ W cm^{-2}, $r = 5$ μm, $R = 100$ μm.

because of collisions of plasma bunches flowing from the peripheral layers. Since speckles may change their position during target heating in the course of the actual experiment, it can be expected that blinking patterns may be formed due to the flow effect during photography of the target luminescence from the backside with an appropriate time resolution.

Thus, our numerical calculations show that a symmetrising prepulse with an intensity $\sim 1\,\%$ of the heating pulse intensity can suppress small-scale inhomogeneities in target heating caused by the speckle structure in the radiation distribution for the main heating pulse.

3. Experimental results

Aluminium foils of thickness $3-10$ μm were used as laser targets. The target was exposed to 1.06-μm, 2-ns Nd-glass laser pulses. The output laser energy was varied in the range $10-30$ J, providing a flux density of $10^{13}-10^{14}$ W cm^{-2} on the target surface. The beam divergence was $2\alpha = (5-8)\times 10^{-4}$ rad, the energy contrast was $K_{\rm E} = 10^4 - 10^5$, and the FWHM of the Gaussian radiation spectrum was $\delta\lambda = 30$ Å. Figure 3 shows a typical experimental speckle structure of laser radiation at the target surface recorded by a CCD camera [13, 14].

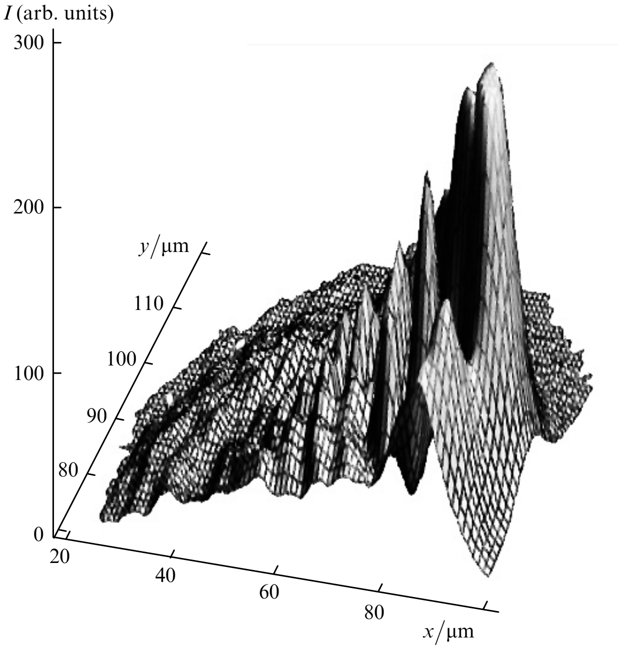

Figure 3. Characteristic transverse intensity structure for a nonuniform irradiation of the target. The size of the minimum spike is $5-10$ μm, which is close to the diffraction size. The peak intensity exceeds the beam-averaged value by a factor of up to 10.

The time profile of the prepulse almost repeats the shape of the main pulse heating the target. The main pulse could be delayed by $0.5-5.0$ ns relative to the prepulse in a controlled manner. The prepulse energy could be varied in the interval $10^{-3}-10^{-1}$ of the main pulse energy. Uniformity of the spatial structure of the prepulse was ensured by using a special phase plate.

To simulate the processes occurring in laser thermonuclear synthesis targets in the Pico setup, we developed a technique for studying laser plasma in experiments on heating of foil targets. This technique includes the system of data collection and automatic processing of the experimental data on the energy and time characteristics of laser radiation in the interaction zone using a calorimetric complex and coaxial photoelectric cells, as well as an automated system for monitoring the structure of laser radiation being focused on the target, in the same way as in the case of nonuniform irradiation of foils on the Pico setup as described in Ref. [8].

The experimentally observed smoothing effect of the prepulse is illustrated graphically in Fig. 4. The results of burning through the foil with and without a prepulse have the form of the plots showing the ratio of laser radiation energy passing through the hole burnt in the foil to the energy of radiation incident on the target as a function of the energy of the heating radiation incident on the target.

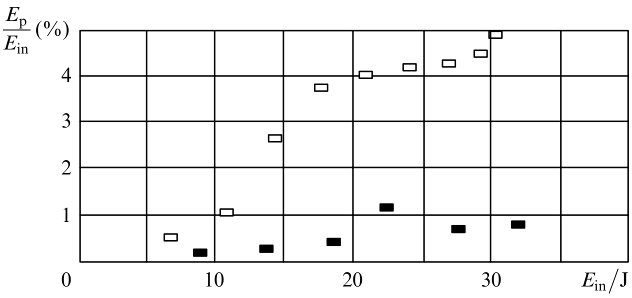

Figure 4. Experimental dependence of the ratio of the energy $E_{\rm p}$ of the radiation passing through the foil and the energy $E_{\rm in}$ of the incident radiation without (light rectangles) and with (dark rectangles) the prepulse. The size of the symbols corresponds to the error in calorimetric measurements.

The energy $E_{\rm in}$ of radiation incident on the target varied from 10 to 30 J, while the prepulse energy was $0.1E_{\rm in} \approx 1-3$ J. The prepulse preceded the main pulse by 1.5 ns. Less than 2 % of radiation was reflected into the lens aperture. A 3-μm thick aluminium foil was used as the target.

4. Conclusions

Our experimental studies reveal a considerable effect of the prepulse on the nature of target burning by radiation having a speckle structure (the fraction of the transmitted energy decreases by almost an order of magnitude), as well as a good agreement between the experimental results and theoretical calculations. As far as the thermonuclear applications are concerned, the obtained results show that an effective symmetrised ablation is possible by using a prepulse in addition to other possible methods like a lowering of the laser beam coherence, an improvement of the structure of a large number of laser beams in multichannel devices and, finally, by using special thermonuclear targets (with low-density ablators, X-ray converters, etc.).

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