Investigation of energy transfer from PALS iodine laser beam to shock wave generated in solid target relevant to shock ignition

T. Pisarczyk¹, Z. Kalinowska¹, J. Badziak¹, A. Kasperczuk¹, S. Borodziuk¹, M. Rosiński¹, P. Parys¹, T. Chodukowski¹, S. Yu. Gus’kov², N.N. Demchenko², D. Batani³, L. Antonelli³, P. Koester⁴, L. A. Gizzi⁴, L. Labate⁴, G. Cristofoletti⁴, F. Baffig⁴, J. Ullschmied⁵, E. Krousky⁶, M. Pfeifer⁶, O. Renner⁶, M. Smid⁶, J. Skala⁶, and P. Pisarczyk⁷

¹Institute of Plasma Physics and Laser Microfusion, Warsaw, Poland
²P.N. Lebedev Physical Institute of RAS, 53 Leninsky Ave., 119 991 Moscow, Russia
³CEILIA, University Bordeaux-I, Bordeaux, France
⁴Intense Laser Irradiation Laboratory at INO-CNR, Pisa, Italy
⁵Institute of Physics ASCR, v.v.i., Na Slovance 2, 182 21 Prague 8, Czech Republic
⁶Institute of Plasma Physics ASCR, v.v.i., Za Slovankou 3, 182 00 Prague 8, Czech Republic
⁷Warsaw University of Technology, ICS, 15/19 Nowowiejska St., 00-665 Warsaw, Poland

Abstract

The efficiency of the laser energy conversion to a shock wave has been investigated in solid targets irradiated by a single or two consecutive laser beams. The first laser pulse was used to produce the plasma simulating conditions relevant to shock ignition approach. One- and two-layer planar targets (bulk Al and Cu alternatively covered by a thin CH layer) were used. The laser provided a 250 ps pulse within the intensity range of 1-50 PW/cm² at the first and third harmonics with wavelengths of 1.315 and 0.438 μm, respectively. Three-frame interferometry and measurements of crater parameters were used as the main diagnostics. The contribution of fast electrons to ablation and the laser energy conversion into shock wave have been investigated for different conditions of the target irradiation, including the pre-plasma presence. 2D numerical simulations and theoretical analysis were carried out to support explanation of experimental results.

1. Introduction

One of the main research aims related to the shock ignition concept (SI) [1,2] is to investigate the mechanism of ablation pressure production by the laser spike of 1-50 PW/cm² intensity and of several-hundred-ps duration when a main part of the absorbed laser energy is converted in fast electrons under the presence of the pre-plasma. Energy transfer by fast electrons into the plasma with supercritical density can provide an ablation pressure of several hundreds of Mbar which is necessary for igniting shock generation [3,4]. The recent experiments with OMEGA laser [5,6] have demonstrated an increasing efficiency of the energy transfer to both planar and spherical targets resulting from a contribution of fast electrons generated due to stimulated Raman scattering and two-plasmon decay in an extended pre-plasma.

This work extends our previous research [7, 8] on the role of fast electrons in the laser energy conversion to shock waves performed with PALS iodine laser at intensities of 1-50 PW/cm² using the first (1ω) and third (3ω) harmonics radiation. In those experiments massive targets of Al and Cu have been irradiated at various focal spot radii of the laser beam R_L to identify the mechanisms of the laser radiation absorption and to determine their influence on absorbed energy transfer to the target. The mass of the ablated plasma as well as the fraction of the laser energy deposited in solid material have been determined by using the 3-frame-interferometer and by measuring-the-volume of the crater created on the solid surface. The experiments have shown a strong influence of the wavelength and the intensity of the laser beam on the efficiency of the laser energy transfer to the massive target, independent from the kind of the material. The 2D numerical simulations with calculations of fast electrons
transport, as well as theoretical analysis based on the analytical model [9] fully confirmed the experimental results and allow to conclude that in the case of $1\omega$ and intensities of 10-50 PW/cm$^2$ and absence of the pre-plasma on the target surface, the dominant ablation mechanism is heating by fast electrons generated by resonant absorption [8]. For the maximum laser energy 580 J and intensity of 50 PW/cm$^2$, the ablative pressure reaches about 180 Mbar in spite of two-dimensional expansion of target corona. However, for $3\omega$ the ablation pressure originates from thermal electron conductivity heating, and its value of about 50 Mbar is several times lower in comparison with $1\omega$ case.

The results of the next step experiments directed at the study of the pre-plasma influence on the ablation and the energy conversion efficiency to the shock wave are presented below.

2. Experimental results and discussion

In the reported investigation, the planar layered targets consisting of massive Cu and a 25-μm-thick layer of the light CH material were applied. Accordingly to SI concept, the targets were irradiated using two laser pulses. The $1\omega$ laser beam with the energy of ~50 J produced a pre-plasma imitating the corona of the pre-compressed ICF target. The spike-driven shock wave was generated by means of the $1\omega$ or $3\omega$ main pulse with energy of ~ 200 J. The influence of the pre-plasma on the parameters of the shock wave was determined from the crater volume measurements and the electron density distributions obtained for different focal spot radius $R_L$ in the range of 40-160 μm. Interferograms were registered 2 ns after the second laser pulse maximum. The delay $\Delta t=1.2$ ns between the main and auxiliary laser beams was selected. Figure 1 presents a comparison of the crater volumes $V_{cr}$ and the $N_e/V_{cr}$ ratios obtained for two wavelengths in the cases of absence and presence of the pre-plasma ($N_e$-total electron number in plasma torch). Ne Without the pre-plasma, Fig. 1a, the dependences of $V_{cr}$ and $N_e/V_{cr}$ on $R_L$ are similar for both Al and Cu targets. For $3\omega$, i.e., at the predominant inverse bremsstrahlung absorption, the efficiency of the crater creation reduces with the decreasing $R_L$ due to the two-dimensional expansion effect. In contrast, for $1\omega$ the efficiency of the crater creation increases with the decreasing $R_L$ which, according to numerical simulations, directly corresponds to an energy transfer to the target by fast electrons generated due to resonant absorption. The strong influence of the pre-plasma on the crater creation process in the case of $1\omega$ is clearly visible in Fig. 1b. The crater volume decreases by more than one order of magnitude and...
simultaneously, $N_e/V_{cr}$ increases by the same rate. It testifies the weakness of the fast 
electrons role in the energy transport process. In the case of $3\omega$, the pre-plasma influences the 
crater formation process only weakly and both $V_{cr}$ and $N_e/V_{cr}$ values remain at the same level 
as in the case of the pre-plasma absence.

In order to obtain a more detailed information about the ablated plasma state, the 
quantitative analysis of interferograms has been performed to determine a gradient of the 
electron density that is the most important characteristics of the plasma state. The maximal 
axial gradient was derived from the approximation of experimental axial density profiles by 
the exponential function $y=A_0 e^{-z/L}$ (see Fig. 2a). The parameters of this function 
determine the maximal electron density gradient in the opacity zone: $[dy/dz]_{z=0} = A_0/L$, where 
$L$ – scalelength of density gradient and $A_0$ – maximal electron density. The dependences of 
the plasma axial density gradient on $R_L$ for the above-mentioned conditions of the target 
irradiation are shown in Fig. 2. At the pre-plasma absence and $1\omega$, Fig. 2b, the density 
gradient increases strongly with the decreasing $R_L$ even for the radii smaller than 80 $\mu$m. 
When compared with $1\omega$ case, at $3\omega$ the plasma expansion is more extended in the direction 
of $z$ axis in comparison with $1\omega$ and the density gradient increases with the increasing radius of

Fig. 2 The maximum density gradient for $1\omega$ and $3\omega$ in the cases of: b) with and c) without pre-plasma.

the focal spot. In the case of the pre-plasma presence, Fig. 2c, the constraint of the plasma 
radial expansion by the pre-plasma causes an elongation of the plasma stream. In the case of 
$3\omega$, the pre-plasma constraint is stronger due to the axial character of expansion. The 
absorption of the main beam in the long, relatively cold pre-plasma occurs mainly by the 
inverse bremsstrahlung mechanism for both $1\omega$ and $3\omega$ radiation. Under these conditions the 
heating is distributed in the area of a significant longitudinal size (Fig. 2c) that leads to the 
decreasing axial density gradient as compared with the solid target irradiation. Stronger 
refraction in the case of $1\omega$ - in comparison to $3\omega$ - leads to a stronger re-distribution of the 
absorbed energy in the lateral direction that is the reason for an additional decrease of the 
density gradient.

The density gradient was evaluated using a model [9] based on self-similar solutions 
of isothermal expansion of the given mass material at the planar (corresponding to relatively 
large focal spot radius of 160 $\mu$m) and spherical ($R_L=40 \mu$m) geometries. If laser beam 
irradiates directly a surface of the solid target (the pre-plasma is absent), the density gradient 
in planar and spherical geometries is given by the following expressions, respectively:

$$\frac{dn_e}{dz} \approx \frac{Z}{A m_p \pi R_L^2 (2K_a E_{L} t / m)} \quad \text{and} \quad \frac{dn_e}{dz} \approx \frac{Z}{A m_p \pi (2K_a E_{L} t / m)^2}$$

where: $Z$, $A$, $m_p$ are the charge, atomic number and proton mass, $K_a$ is the absorption 
coefficient, $t$ is the current time and $m$ is the mass ablated (evaporated) during the period of 
the laser pulse duration $\tau_L$. The mass for electron-conductivity-driven ablation (valid for $3\omega$ 
and $1\omega$ at $R_L=160 \mu$m) or fast-electron-driven ablation (valid for $1\omega$ at small radii of 40 and 
80 $\mu$m) follows from formulae:
\[ m_c = 1.1 \times 10^2 \left( \frac{A}{Z+1} \right)^{7/6} \frac{(K\alpha L \tau L)^{2/3} R_L^2}{(Z+3.3)^{1/3}} , \]  

and \[ m_e = \pi R_L^2 \mu_e \approx 10^{-5} \frac{A}{Z} R_L^2 (I_L \lambda^2)^{4/3} , \]

where the expressions \( \mu_{e(g/cm^2)} = 5.2 \times 10^{-7} \frac{A}{Z} E_0^{2}(keV) \) and \( E_0(keV) = 8 \left( \frac{I_L(\mu m^2)}{\lambda^2} \right)^{2/3} \) were used for the fast electron range and average energy. The values \( I_L, \tau_L, R_L \) and \( \lambda \) are introduced in units of PW/cm\(^2\), ns, cm and \( \mu m \), respectively. First of all, in the case of small radii the expression for spherical expansion shows that the decreasing radii lead to the strongly increasing density gradients, as \( R_L^{-2} \), at the fast-electron-driven ablation under 1\( \omega \)-beam irradiation and, in contrast, to the strongly decreasing gradients, as \( R_L^{-2} \), at the electron-conductivity-driven ablation under 3\( \omega \) irradiation. Consequently at small radii of the laser beam, the density gradient is larger for 1\( \omega \)-irradiation as compared to 3\( \omega \) case and at large radii, the relation between the values of gradients is reversed. According to numerical simulations, the absorption coefficients of 1\( \omega \) and 3\( \omega \) radiation are about of 0.21 and 0.63 for the beams with the radius of 40 \( \mu m \) and 0.31 and 0.82 for the beams with the radius of 160 \( \mu m \), respectively. When taking into account this data, the above presented expressions give the values of density gradients equal to \( 5 \times 10^{21} \) and \( 1.5 \times 10^{21} \) cm\(^{-3}\) for 1\( \omega \) and 3\( \omega \) radiation at \( R_L=40 \mu m \), and \( 4 \times 10^{21} \) and \( 2 \times 10^{21} \) cm\(^{-3}\) for 3\( \omega \) and 1\( \omega \) radiation at \( R_L=160 \mu m \), respectively.

A presence of the pre-plasma creates poor conditions for resonant absorption and, therefore, for the laser energy conversion to fast electrons. This results in suppression of the fast electrons contribution to the ablation process. The significantly smaller effectiveness of the energy transfer to dense plasma regions under the pre-plasma created by the high-intensity 1\( \omega \) pulse is clearly seen from both the craters volumes and density gradient data.

**Conclusions**

Two-beam experiments directed to imitate the spike-laser interaction with the pre-produced plasma have shown a significantly decreasing efficiency of the laser energy transport to the solid part of the target for the 1\( \omega \) main (spike) beam. Similar phenomenon observed in previous experiments using the 1\( \omega \) single beam was associated with the fast electrons energy transfer to a dense plasma region. Those experiments however have not provided data indicating alteration of the fast electrons generation due to resonant absorption in the relatively short pre-plasma by any other mechanism connected with parametric plasma instabilities.

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