Influence of target material on structure of partly defocused laser beam produced plasma outflow

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Abstract

Our recent experimental results have proved that the formation of plasma jets is a fundamental process accompanying the laser produced plasma expansion, if a massive planar target with relatively high atomic number (Z) is irradiated by a defocused laser beam. It is impossible to get the plasma jet from light target material like Al or plastic. Experimental results presented here demonstrate differences in both the plasma configuration and the plasma source geometry between Cu (high-Z material) and plastic (low-Z material) targets. The experiment was carried out at the PALS iodine laser. An attempt of explanation of differences in the plasma configuration was taken by means of numerical simulations using the two-dimensional hydrodynamic code ATLANT-HE.

1. Introduction

Collimated plasma outflows (jets) are a subject of great interest in the study of astrophysical phenomena [1] and are of interest also for a new fast ignition concept [2]. In spite of that a history of the laser produced-plasma jet creation is relatively short. The first attempts to generate jets relevant to astrophysical observation were presented in 1999 and 2000 in Refs. 3 and 4. Conically shaped targets made of different materials were irradiated there by five beams of the Nova laser with a pulse duration of 100 ps and an energy of each beam of 225 J or by six beams of the GEKKO-XII laser with the same pulse duration, but the total energy of 500 J. The jet-like structures were formed by collision of ablated flows at the axis of conically shaped targets. In 2006 we reported about the simple method of the plasma jet generation using a flat massive target with atomic number $Z \geq 29$ ($Z=29$ corresponds to Cu) irradiated by one partly defocused laser beam [5]. Although this plasma jet production method is very simple, explanation of mechanism of the plasma jet forming is not simple. The experimental data, such as a strong gradient of electron density on the axis and a great plasma concentration in the centre, indicate that the plasma jet is produced by collision of a convergent plasma on the axis. However, if the target is made of light materials like plastic or Al, no plasma jet configuration is observed, in spite of the same initial laser intensity distribution for both kinds of target material.

Our experimental investigations and numerical simulations were aimed at to answer the debatable question concerning differences in an interaction of laser beam with plasma with reference to light and heavy target materials.

2. Experimental set-up and results

The experiment was carried out with the use of the PALS iodine laser facility. Plasma was generated by a laser beam of diameter about 160 mm, which was focused by means of an aspherical lens with focal lengths of 600 mm for the third harmonic used ($\lambda=0.438$ μm). The

plastic and Cu planar targets were irradiated by the laser beam under the following conditions: laser energy of 30 J, focal spot radius of 400 μm (whereas the focal point was located inside the targets), and the pulse duration of 250 ps (FWHM). In this case the average laser intensity is $0.24 \cdot 10^{14}$ W/cm^2.

To study the plasma expansion a 3-frame interferometric system with automatic image processing was used. The delay between subsequent frames was set to 3 ns. The diagnostic system included an x-ray streak camera placed in a side view. The streak camera registered radial distribution changes of the plasma radiation in the vicinity of the target surface. The temporal and spatial resolutions of x-ray images were 30 ps and 50 μm, respectively. To avoid registration of visible radiation from plasma, the recording channel of the camera was equipped with 8.5 μm of mylar and 40 nm of aluminium. As a result of that, the transmission was negligible for photons of energy less than 0.8 keV. Because such high temperature has the plasma only during the laser action so a distribution of plasma radiation in this period should correspond exactly to a distribution of laser beam intensity on the target surface.

The interferometric measurements corresponding to the high-Z (Cu) and low-Z (plastic) target materials are presented in Fig. 1 in a form of sequences of interferograms and electron isodensitograms corresponding to them.
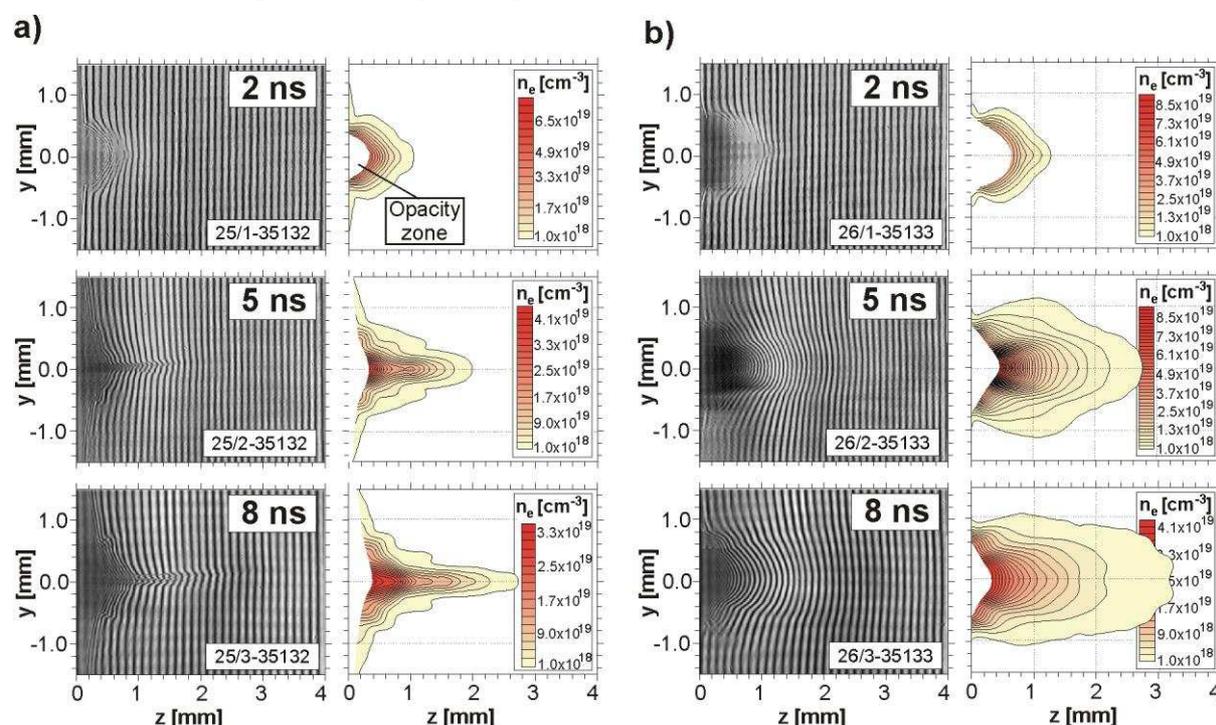

Fig. 1. Sequences of interferograms and electron equidensitograms showing evolution of plasma structure. in the case of: a) Cu and b) plastic target.

In all the diagrams the plasma stream boundary is represented by the electron density contour $n_e=10^{18}$ cm^{-3}. The step of the adjacent equidensity lines is $\Delta n_e=2 \cdot 10^{18}$ cm^{-3}. On the first frame ($\Delta t=2$ ns) the plasma configurations corresponding to both the materials are similar. The only difference concerns the plasma volume resulting from the difference in plasma velocities ($6 \cdot 10^7$ cm/s for plastic and $4 \cdot 10^7$ cm/s for Cu). One can see that in both the cases plasmas have tendency toward the plasma jet creation. The great difference in the plasma outflow structure appears on the second frame ($\Delta t=5$ ns). In the case of Cu target the jet creation process is continued, whereas the plastic plasma expansion changes essentially and assumes a divergent character. This character of plasma outflow is also conserved at later time.

3.   Numerical modeling

Explanation of the initial similarity of the plasma structure for both materials and the later great difference could be found on the basis of measurements of plasma radiation by the streak camera. In Fig. 2 the exemplary results of these measurements are presented. To get radial x-ray radiation intensity distributions the registered streak images were transformed by means of the Abel inversion. Due to the great difference in the maximum plasma radiation intensity between Cu and plastic (greater about 30 times for Cu), the x-ray plasma emission intensity distributions are presented here in the normalized to unit form. All the adjacent equidensity lines are distant by 0.02.

For both the targets the annular form of the x-ray radiation seems to be dominant. However, in the case of the plastic target at a certain instant of the laser action the additional radiation in the center appears. This radiation lasts even long time after the laser pulse end. The change of the annular configuration of the plastic plasma radiation source to a central one corresponds to the change of the initially convergent plasma outflow to a divergent one. At the moment of the central plasma radiation appearance the ablative plasma reaches only a distance of about 100 μm thus making strong deflection of the laser radiation to the axis rather unlikely. Therefore, another phenomenon must be responsible for this process.
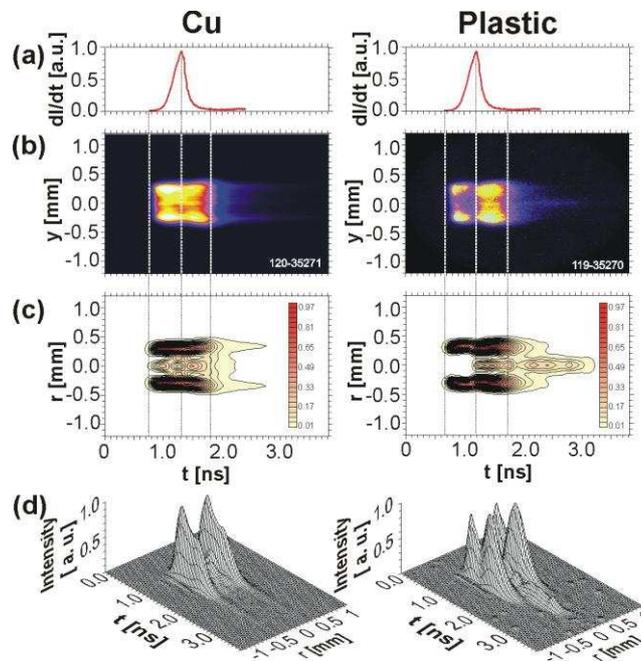

Fig. 2. The laser pulse (a), typical streak image of x-ray emission from Cu and Al plasma (b), and x-ray emission intensity distribution in forms of equidensitograms (c) and spatial distribution (d).

An attempt of explanation of it was taken by means of numerical simulations of the laser beam interactions with the planar Cu and plastic targets using the two-dimensional hydrodynamic code ATLANT-HE [6]. The computations were performed for the PALS radiation conditions. A homogeneous target irradiation was assumed. The calculations were performed using the equation of the perfect gas. Kinetics of ionization and recombination were not included, the average charge of ions for the CH-target (plastic) was taken $Z_{CH}=3.5$ and for the Cu-target $Z_{Cu}=19$. The energy losses caused by the thermal emission and radiation transfer in plasma were not considered.

In Fig. 3a the spatial distributions of the density and the electron temperature of the plastic and Cu plasmas at the instant of the laser pulse end are shown. In these distributions the essential differences in the plasma expansion features between the plastic and Cu targets are clearly visible. Due to much lower plasma expansion velocity in the case of the Cu target (see Fig. 3b) the longitudinal size of the expanded plasma (along the z axis) at the moment of

the laser pulse end is about one half of its transverse dimension. In this case the plasma expansion has a planar geometry. On the contrary, in the case of the plastic target the longitudinal size of the plasma plume is larger than its transverse one and the expansion exhibits the spherical symmetry. The lower velocity of the plasma expansion for Cu target is a result of larger evaporation (ablation) of the mass of this target in comparison to the plastic one. Increase of the evaporated mass of the Cu target in comparison with the plastic target ($\Delta m_{Cu}/\Delta m_{CH} = 5.21$) is a consequence of a deeper heating of the target by electron heat conductivity wave in the case of Cu target compared to the case of the plastic target.
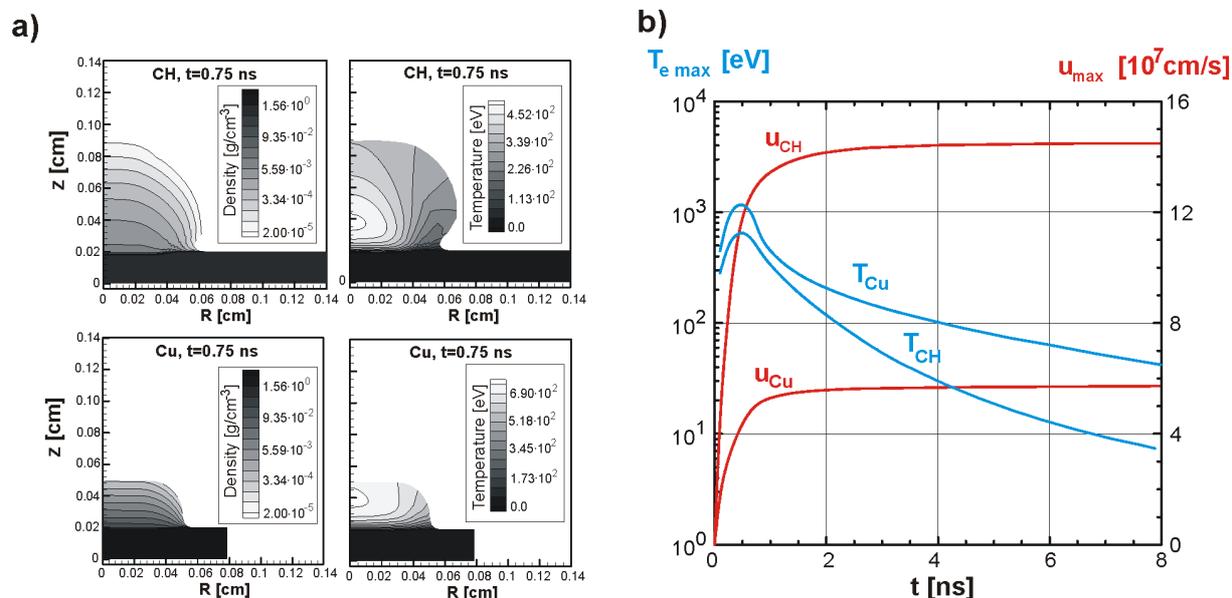
a)

b)

Fig.3. Spatial distributions of plasma density (in g/cm^3) and electron temperature (in eV) at the moment of laser pulse end for plastic and Cu targets (a) and temporal dependence of electron temperature maximum T and plasma boundary velocity u for plastic and Cu targets (b).

4. Conclusions

The numerical modeling presented here allowed us to come to the following conclusions. Due to the increase of evaporated mass of the Cu target in comparison with that of the plastic one and, simultaneously, the decrease of the Cu plasma expansion, the inertial stage of the Cu plasma expansion runs in the planar geometry. Plasma flow at the large distance from the target has the stream form with the diameter corresponding to the interaction spot. Much higher velocity of the plastic plasma expansion during the laser pulse action leads to the inertial plasma expansion in the geometry close to the spherical one. In that case the transversal dimension of the ion beam increases, whereas the density falls rapidly with the increasing distance from the target.

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