Influence of the focal point position of a focusing lens on a character of an ablative plasma expansion

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Abstract: This paper is devoted to explanation, why at a fixed spot diameter of the partly defocused laser beam on the target surface the possibility of creating plasma jets depends strongly on the relative position of the focusing lens focal point to the target surface, i.e. whether it is located inside or in front of the target. We demonstrate how the focal point position can influence properties of the expanding plasma plume and, therefore, substantially change conditions for plasma jet forming. The results of this paper have evidently proved that the plasma strongly modifies the initial distribution of the laser intensity. A change of the laser intensity distribution due to plasma interaction involves also changing the plasma properties, e.g. tendency to the plasma jet forming.

1. Introduction
Collimated plasma outflows and jets are a subject of high interest at studying astrophysical phenomena [1,2], as well as at simulation of the jets generated at contact surfaces of different materials in a multi-shell target geometry [3,4]. Recently, we have demonstrated a simple method of jet production by interaction of a relatively low-energy laser pulse with a massive planar metallic target [5,6]. Numerical simulations of the plasma dynamics related to the experimental data, performed by using the laser-plasma interaction hydrodynamic code FCI2, have shown [7] that the fast radiative cooling of plasma, which starts before the expansion process, plays a crucial role at launching the jet and at its collimation. This paper is aimed at explanation of one important question arising at attempts to generate plasma jets by interaction of defocused laser beams with targets made of metals with atomic numbers equal to and higher than that of Cu. Namely, why at a fixed diameter of the laser beam spot on the target surface the possibility of creating plasma jets depends strongly on the relative position of the focusing lens focal point to the target surface, i.e. whether it is located inside or in front of the target. We demonstrate how the focal point position can influence properties of the expanding plasma plume and, therefore, substantially change conditions for plasma jet forming.
The experiment was carried out with Cu as target material using the Prague Asterix Laser System (PALS) iodine laser. The investigations were performed with the laser energy of 70 J at the third harmonic of laser radiation ($\lambda=0.438$ µm), pulse duration of 250 ps (FWHM), and focal spot radii of 250 µm and 400 µm. The experimental data were obtained by means of a three-frame interferometric system, x-ray streak camera, ion collectors, and measurement of crater parameters.

2. Results of interferometric measurements

The electron density distributions presented in Fig. 1 illustrate the shape of plasma streams for the Cu target material, two different beam spot radii and two (positive and negative) positions of the lens focal point. The plasma stream boundary is represented here by the electron density contour $n_e=10^{18}$ cm$^{-3}$. The step of the adjacent equidensity lines is $\Delta n_e=2\times10^{18}$ cm$^{-3}$.

On the basis of the above electron distributions we can conclude that:

- At the beam spot radius of 250 µm the plasma plume shapes for the positive and negative focal point positions differ considerably. If the focal point is located inside the target ("plus" position) the plasma stream consists of a wide part in the target vicinity (a jet pedestal) and of a narrow structure (a plasma jet) elongated considerably along the axis. If the focal point is set to the "minus" position the jet-like part of the plasma stream is practically absent (Cu) or is fragmentary (Ta).

- The situation changes substantially if the beam spot of radius 400 µm is applied. For the "plus" position of the focal point a characteristic long plasma jet is created, however of much larger diameter and, therefore, of much lower electron density. Evidently, the conditions are not proper for jet forming in the latter case. On the other hand, at the "minus" focal point position nice jets are formed, similar to those observed for the "plus" position at $R_L(\pm)=250$ µm.

![Figure 1](Image)

Figure 1. Electron isodensitograms at the instant of 8 ns after the laser action for Cu target and different target irradiation conditions: $R_L(\pm)=250$ µm and $R_L(\pm)=400$ µm.

3. Characteristics of craters

To obtain information about the shape and dimensions of the laser-produced craters, their replicas were made of cellulose acetate. The typical crater profiles, presented in Fig. 2, allow to come to the following conclusions:

- For $R_L(\pm)=250$ µm, it can be seen that the craters created at "+" and "−" focal point positions differ substantially.

- At the positive focal point position the craters have a semitoroidal shape, while at the negative position they resemble rather a hemisphere. The diameter of the semitoroidal crater is larger in comparison with the hemispherical one.

- In contrast to that, for $R_L(\pm)=400$ µm just semitoroidal craters are produced, independently of the focal point position and target material. They differ, however, substantially in size. The
craters arising at $R_L(+)=400$ µm are considerably larger and shallower than those created at $R_L(-)=400$ µm.

- It is worth noting that the profiles of the craters produced at $R_L(-)=400$ µm and $R_L(+)=250$ µm, i.e. at irradiation conditions under which the best jets were observed, are very similar.

![Figure 2](image1.png)

**Figure 2.** Illustration of the crater shapes and dimensions for Cu target and different target irradiation conditions: (a) $R_L(\pm)=250$ µm, (b) $R_L(\pm)=400$ µm.

4. **Determination of the plasma influence on the laser intensity distribution on the target**

Our investigations of the electron density distributions in the focal area using a gas (He) target (see Fig.3), where the radial profile of the electron density distributions in the focal area is characterized by a minimum on the axis, allow us to suppose that the laser intensity distribution should be characterized in the whole area under observation by a maximum (or a flat top) in the centre.

![Figure 3](image2.png)

**Figure 3.** Electron density distribution in the focal area results from interaction of the laser beam of 72 J energy with the He gas target with pressure of 40 bar at instant of 2 ns after the laser action.

Meanwhile distributions of an x-ray radiation from the solid target (Cu) surface, corresponding to the target irradiation distributions, recorded by an x-ray pinhole camera differ substantially for both positions of the focal point (see Fig.4). In the case of $R_L(+)=250$ µm the x-ray radiation distribution is characterized by depression in the centre, while in the other case a maximum of the radiation in the centre is observed. It testifies that the dense plasma originating from the solid target strongly changes the laser intensity distribution and this change depends on the target position.
5. Final conclusions

The new results reported in this paper have proved that the laser-produced plasma strongly modifies the initial distribution of the laser intensity. The outcome of this modification depends strongly on both the position of the focal point, related to the target surface, and its distance from the target. Even if the focal point lies relatively far off the target (up to 1630 µm in our case), the differences between the laser intensity distributions for the "plus" and "minus" focal point positions, concluded from the measured crater shapes, are very distinct.

The best jets can be formed at the beam spot radius $R_L(+) = 250 \, \mu m$, if the focal point is located inside the target, for the opposite focal point position the optimum conditions for jets occur at $R_L(-) = 400 \, \mu m$. In both these cases the laser-produced craters have similar dimensions and shapes. On the contrary, at $R_L(-) = 250 \, \mu m$ the laser intensity concentration is too strong, and at $R_L(+) = 400 \, \mu m$ the laser radiation scattering too large for the jets to be produced.

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