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# PALS laser energy transfer into solid targets and its dependence on the lens focal point position with respect to the target surface

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**Abstract**

This paper is devoted to investigations of laser energy transfer into solid targets with respect to the focusing lens focal point position relative to the solid target surface as obtained at the PALS laser facility. The third harmonic of the PALS laser beam with energy ~90 J and pulse duration ~250 ps (FWHM) was used for irradiation of two kinds of targets made of Cu: a slab and a 3.6 μm thick foil. The focal point of the beam was located either inside or in front of the target surface, and care was taken to ensure the same laser spot radii in both cases (250 μm). It was demonstrated that these two opposite focal point positions give rise to significantly different laser-plasma interactions: with either depression or maximum of the laser intensity distribution in the center of the beam, respectively. It was also verified that the focal point position inside of the target is favorable for plasma jets creation, whereas the opposite case is more effective for acceleration of flyers.

**Keywords:** Crater creation; Electron density distribution; Focal point; Foil acceleration; Interferometric measurement; Plasma jet; Target irradiation; X-ray radiation

## INTRODUCTION

The goal of this paper is to demonstrate the significant differences in laser energy deposition into targets related to two opposite positions of the focal point of a focusing lens with respect to the target surface: either *in front* (negative position) or *inside* (positive position). Influence of these two different interaction geometries on plasma jets formation and acceleration of thin Cu foils will be presented.

Certain differences in plasma properties were noticed by us for the first time during the experiment devoted to plasma jets generation, where the position of the focal point influenced strongly the main characteristics of these plasma jets. On the basis of the collected experimental data (Kasperczuk *et al.*, 2006, 2007*a*, 2007*c*; Sizyuk *et al.*, 2007; Schaumann *et al.*, 2005), we have concluded that plasma jets formation is a *fundamental process*, which accompanies expansion of the laser plasma produced by a partly defocused laser beam during irradiation of massive planar targets made from relatively high atomic number materials. That conclusion, however, concerned only the case in which the focal point of the focusing lens is located inside the target. If the focal point is situated in front of the target, conditions for creating plasma jets are much less favorable. Recently, we have shown that the plasma properties related to these focal point positions, located even relatively far from the target surface (1–1.5 mm), differ drastically. These differences concern not only the plasma jet formation, but also emission of X-ray radiation, and ions (Kasperczuk *et al.*, 2007*b*; Badziak *et al.*, 2007).

Some important information could be obtained from comparison of shapes of craters for both focal point positions produced by the direct laser action on the solid planar targets made of Cu or Ta (Kasperczuk *et al.*, 2007*b*). At the same focal spot radius on the target surface for both the focal point positions, equal to 250 μm, the crater shapes differ

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substantially. At the positive focal point position, the craters have a semitoroidal shape, while at the negative position they resemble a hemisphere. Since the crater shape depends predominantly on the laser intensity distribution in the interaction region adjacent to the target surface, the observed dissimilarities should result from diverse target irradiation conditions. Our investigations with the use of He gas as the only target have shown that the laser beam intensity distributions have quite similar forms at both sides of the focal point (Kasperczuk *et al.*, 2007*b*). However, in the case of irradiating solid targets, the resulting laser intensity distribution varies significantly between both focal point positions. Explanation of these features is one of the aims of this paper.

Since the target irradiation geometry is clearly connected with efficiency of laser energy transfer into the target, the position of the focal point seems to be of great importance also in the case of *acceleration of flyer targets*. It is a well established fact that high power lasers can be used to efficiently accelerate thin targets (flyers) to very high velocities—reaching $10^7$ cm/s and more. During a subsequent impact of the accelerated flyer on a massive target, the flyer's kinetic energy is rapidly transferred into a massive target in the form of thermal energy. It leads to generation of an extremely high pressure in a planar shock. Consequently, this process is a subject of great interest for areas of modern physics, such as determination of the equation of state (EOS) in materials under extreme conditions, modifications of physical properties of materials, etc. (Lomonosov, 2007; Desai *et al.*, 2007; Eliezer *et al.*, 2007; Batani *et al.*, 2000; Cauble *et al.*, 1993; Tanaka *et al.*, 2000; Ozaki *et al.*, 2001; Verker *et al.*, 2004; Cottet *et al.*, 1985). The flyer-impact configuration could also play an important role in the field of inertial confinement fusion. Recently, the so called *impact ignition* scheme was proposed (Caruso & Pais, 1996; Murakami *et al.*, 2005; Velarde *et al.*, 2005), where the flyer impact energy is used to ignite a relatively cold fuel precompressed by the main laser driver.

Our earlier investigations of the flyers (Limpouch *et al.*, 2004; Kasperczuk *et al.*, 2004; Pisarczyk *et al.*, 2004; Borodziuk *et al.*, 2005) were aimed at determination of macro-particles acceleration and craters creation efficiency with respect to: (1) the macro-particle type (the extracted foil fragment or prefabricated disk) and (2) the laser beam wavelength (the first or third harmonic of the iodine laser). Attention was also paid to the delay in the flyer's getting under way with respect to the laser pulse timing, final velocity achieved for different target thickness, and wavelength employed. Our paper later (Borodziuk *et al.*, 2007) has demonstrated that the acceleration and subsequent collision of the flyer with the massive target are very complex processes due to plethora physical phenomena involved. Maximum achievable velocity of the flyer represents a crucial factor. When a thin foil accelerated by means of a laser beam to velocities exceeding $10^7$ cm/s collides with a target at rest, a very strong shock wave and pressure of the order of 100 Mbar can be generated. So, this paper is also partly aimed at determination of influence of the focal point position on an acceleration of the thin foil.

In the first part of this paper, we show the above mentioned differences in the laser intensity distributions corresponding to two opposite positions of the focal point, and corresponding implications for the plasma jets creation. The second part is devoted to presentation of differences in acceleration of a 3.6 μm thick Cu foil using two opposite focal point positions for the third harmonic of laser radiation at nominally the same laser irradiance. In both cases, the beam spot radii on the target surface ($R_L$) are the same and equal to 250 μm.

## EXPERIMENTAL SET-UP AND CONDITIONS

The experiment was carried out with the Prague Asterix Laser System (PALS) (Jungwirth, 2005; Laska, 2006*a*, 2006*b*; Batani *et al.*, 2007) iodine laser. A schematic drawing of the experimental arrangement is depicted in Figure 1a.

The laser beam with a diameter of 290 mm was focused by means of an aspherical lens with a focal length of 600 mm. Two types of the target, i.e., a slab and a 3.6 μm thick foil made of Cu were irradiated by the third harmonic of laser radiation ($\lambda = 0.438$ μm) with energy of about 90 J, and pulse duration of 250 ps (FWHM).

To test the influence of the focal point position on the plasma properties, two placements of the focal point with respect to the target surface were chosen: +960 and −960 μm, where the *positive* sign means the focal point position is *inside* the target, and vice versa (see Fig. 1b). They correspond to the beam spot radii on the target surface ~250 μm.

The time evolution of the plasma configuration and process of the foil acceleration were studied by means of a three-frame interferometric system with automatic image processing. Each of its optical channels was equipped with an independent interferometer of the folding wave type, illuminated by a split-off part from the main laser beam. The delay between subsequent interferometric frames was set to 3 ns.

To determine a form of an X-ray radiation from the target surface, a Photonic Science PE7051 X-ray pinhole camera was used. The diagnostic system included also streaked-slit imaging of the plasma X-ray radiation by KENTECH low magnification X-ray streak camera mounted on a side view. The temporal and spatial resolutions of X-ray images were 30 ps and 50 μm, respectively. The transmission of the cameras was negligible for photons of energy less than 0.8 keV, and amounted to about 20% for 1.3-keV photons.

In order to obtain information about the shape and dimensions of the laser-produced craters, their replicas were made of cellulose acetate.

## INFLUENCE OF THE FOCAL POINT POSITION ON AN ACTUAL DISTRIBUTION OF THE TARGET IRRADIATION

The experimental results presented in Figure 2 illustrate the two typical plasma configurations, which result from an

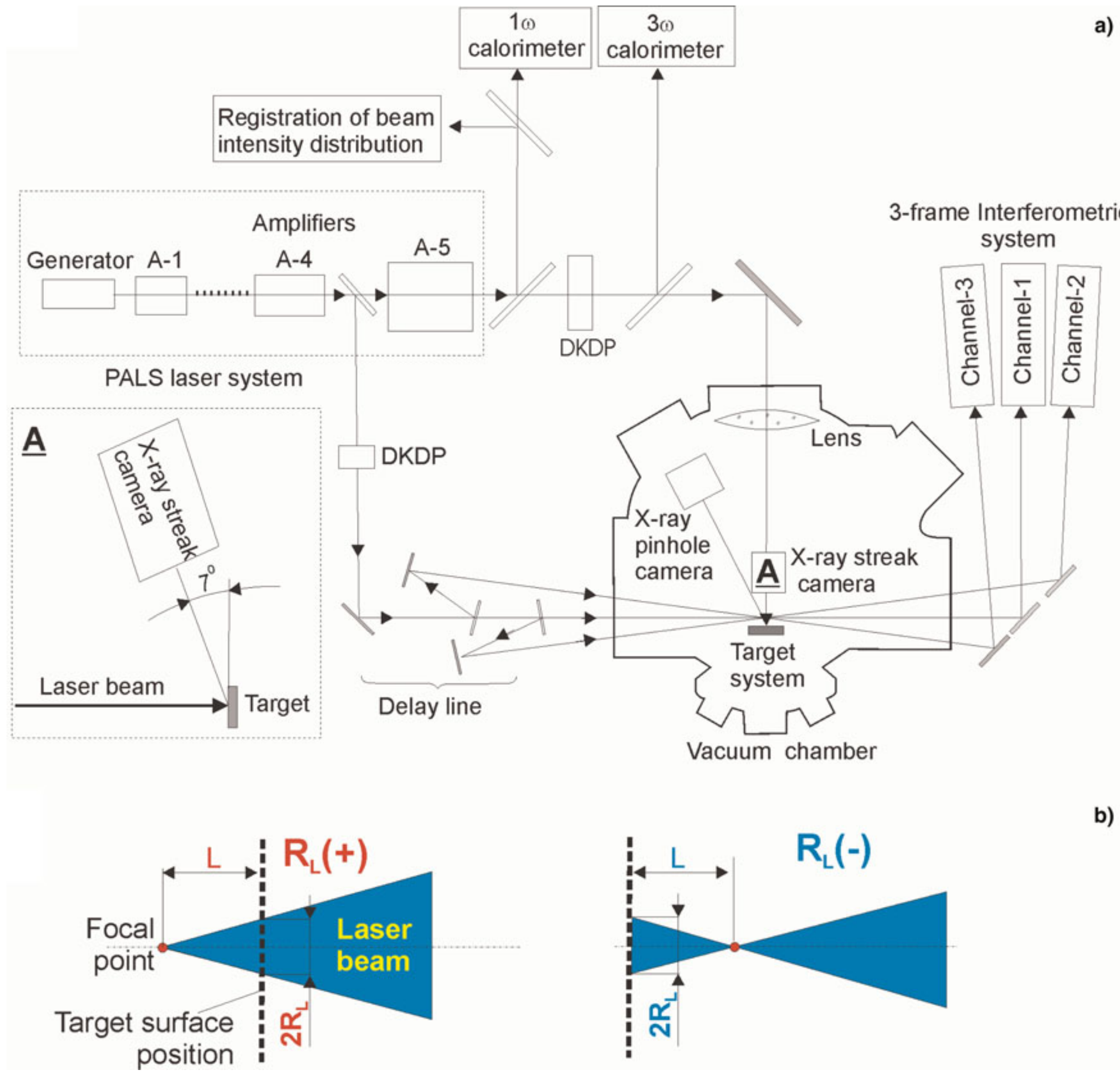


**Fig. 1.** (Color online) Experimental setup (**a**) and geometries of target irradiation (**b**), where: $\mathbf{R}_L(+)$ corresponds to the positive focal point position, and $R_L(-)$ to the negative one.

action of the laser beam on the massive Cu target, corresponding to the two opposite positions of the focal point at the instant of 8 ns. If the focal point is located inside the target (positive position), the plasma stream has a form of the jet. If the focal point is set to the negative position, the jet-like plasma stream is practically absent. The differences in the plasma stream structure are accompanied by the differences in both the form of X-ray radiation from the target surface and the shape of laser-produced craters (see Fig. 3). Although the X-ray radiation form corresponds to the initial stage of plasma expansion, whereas the crater form corresponds to the final one, both forms related to the same

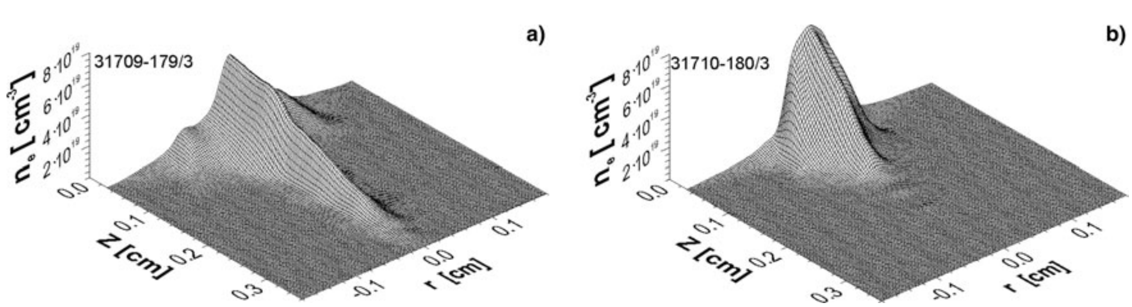


**Fig. 2.** Plasma configurations for the massive target at 8 ns corresponding to two opposite positions of the focal point: (**a**) inside the target, and (**b**) in front of the target.

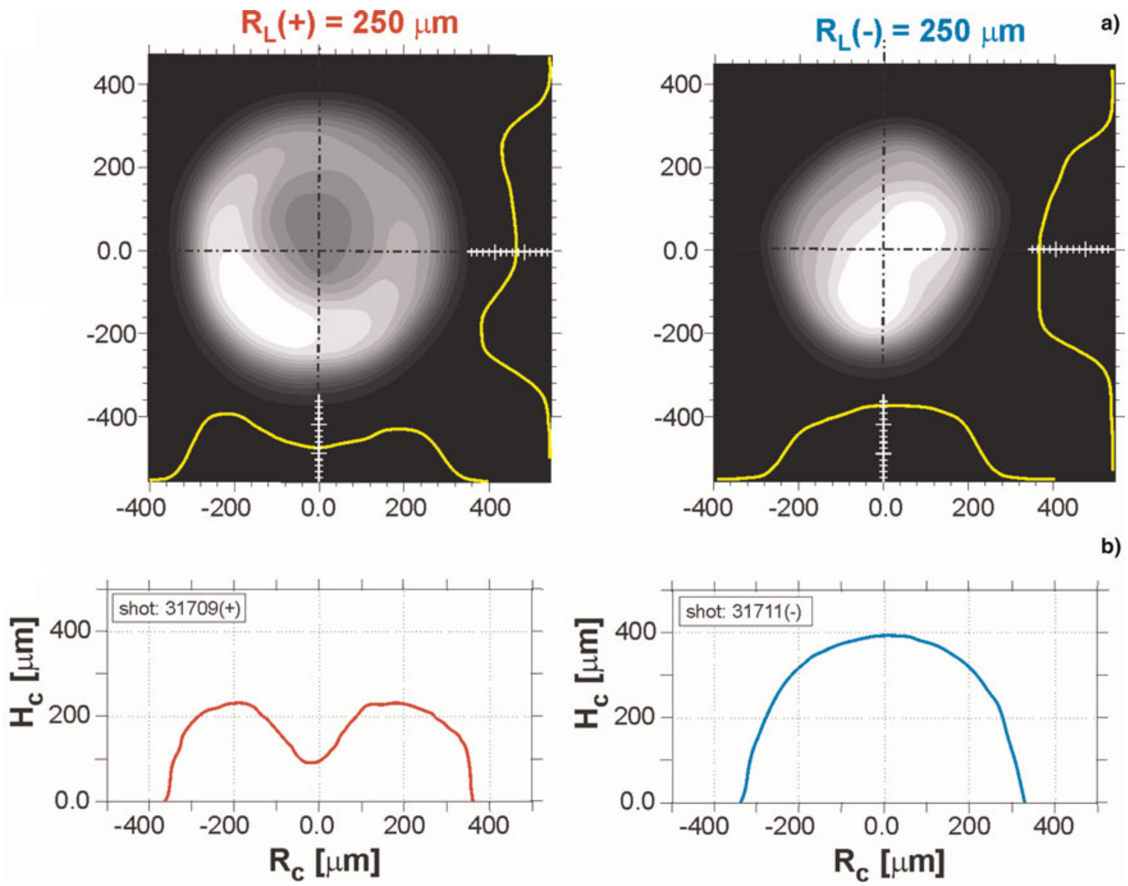


**Fig. 3.** (Color online) The X-ray radiations from the target surface (**a**) and the crater profiles (**b**) for two opposite focal point positions: positive $\mathbf{R}_L(+)$ and negative $R_L(-)$.

focal point position are similar to each other. It should be pointed out that the *annular* target irradiation is *gradually* created during the laser beam—plasma interaction from initially *flat* laser radiation distribution provided the focal point of a focusing lens is situated inside the target. The opposite case with the focal point location in front of the target leads to concentration of the laser energy around the axis of symmetry and no plasma jets are observed.

The above mentioned observations allow us to conclude that the *radiative cooling* mechanism so far considered as the *only* mechanism responsible for the plasma jet formation (Nicolai *et al.*, 2006) should be complemented by *convergence* of supersonic plasma flow due to the *annular* irradiation of the target.

Assumption about the irradiation geometry influence on the plasma jet creation makes possible to explain some characteristic jet parameters, namely its lifetime (longer than 20 ns) and its maximum length (about 4 mm—reached after ~8 ns). The *lifetime* of the jet is connected with the time of plasma emission from the crater (which lasts for a few tens of ns), whereas the jet *length* is likely determined by a diameter of the spontaneously generated annular distribution of the laser intensity at the interaction region adjacent to the target surface. Certain confirmation of these conclusions can be found elsewhere (Kasperczuk *et al.*, 2007*a*), where it was shown that the final jet length grows with the increasing focal spot radius. The jet length grows initially with the velocity up to $7 \times 10^7$ cm/s in the period of the first 5 ns. Subsequently, the axial motion of the jet is slowing down and after 8 ns it takes its final form (appearing to be at rest). According to our opinion, the radiative cooling plays an essential role at the initial stage of the plasma jet formation, when the plasma is very hot. However, its role decreases in time.

Protection of the laser beam against the side-scattering seemed to be of importance from the point of view of an efficiency of the laser energy transfer into the target. As our interest is also devoted to acceleration of flyers, finding optimum conditions for their irradiation should provide some improvement in this process. On the basis of the above experimental results, we concluded that the negative configuration of the target irradiation should be more effective for acceleration of the flyers. To verify such conclusion, the foil acceleration experiment with the use of the two opposite positions of the focal point was carried out.

## INVESTIGATION OF THE FOIL ACCELERATION

This part of our investigation was mainly devoted to measurements of the foil velocities with the use of the two opposite

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positions of the focal point. In Figure 4, some examples of such foil velocity measurement are presented. The shadowgrams show the temporary positions of the accelerated foils. It is clearly seen that the velocity of the foil corresponding to the negative focal point position is higher. This velocity is equal to $(6.7 \pm 0.2) \times 10^6$ cm/s. In the case of the positive position of the focal point, the velocity amounts to $(5.2 \pm 0.2) \times 10^6$ cm/s and is lower by about 25%.

The differences concern also the shape of the foil deformation. In the case of the focal point located in front of the target, for which the energy concentration takes place, the accelerated foil at later time (8 ns) has a rounded top and its diameter is a bit smaller.

The electron density distributions in Figure 4 inserted together with the shadowgrams illustrate the connection between the plasma stream form and the efficiency of the foil acceleration. The results of the interferometric measurements are presented here in a form of electron isodensitograms, in which 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 $\Delta n_e = 2 \times 10^{18}$ cm$^{-3}$.

Some differences of these plasma configurations in comparison with those in the case of the massive target (compare Fig. 5 with Fig. 2) result from the foil deformation. A concave shape of the deformed foil corresponding to the negative focal point position creates additional favorable

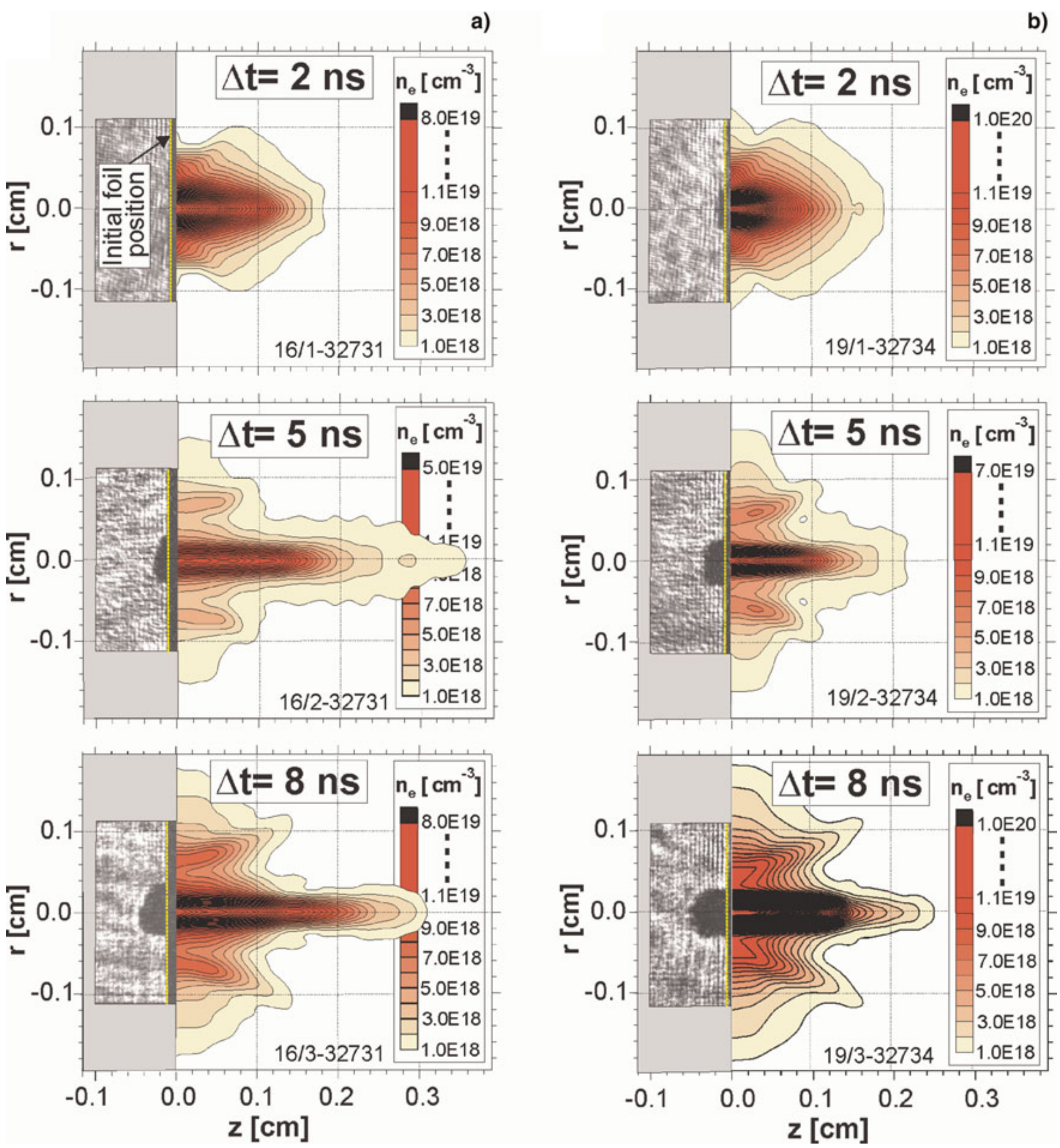


**Fig. 4.** (Color online) Illustration of the process of the foil acceleration for two opposite positions of the focal point: (**a**) inside the target, and (**b**) in front of the target.

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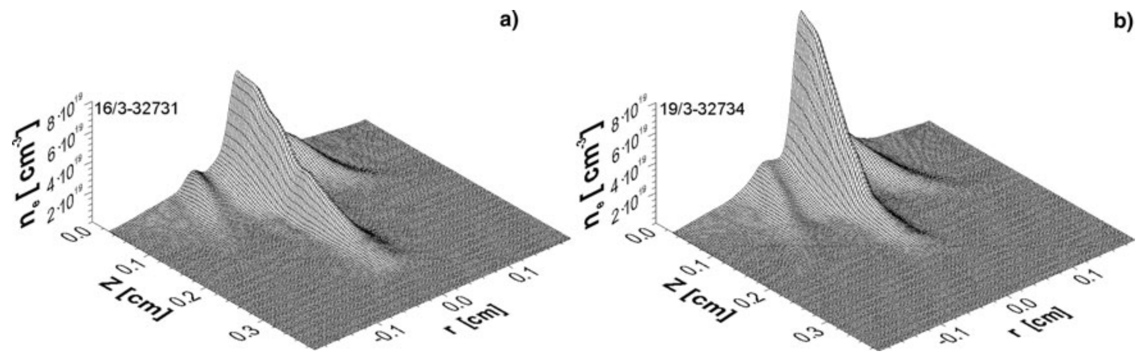


**Fig. 5.** Plasma configurations for the foil target at 8 ns corresponding to two opposite positions of the focal point: (**a**) inside the target, and (**b**) in front of the target.

terms for the plasma jet production. Therefore in the case of the foil, we observe also the jets for the focal point location in front of the target, but its quality is worse. Therefore, the good plasma jet structure can provide the evidence for the side-scattering of the laser beam and lower efficiency of the laser energy transfer into the target.

## DISCUSSION OF EXPERIMENTAL RESULTS

Our considerations will be devoted to an explanation of the differences between both the shapes of the X-ray radiation from the target surface and the craters created directly by the laser action at the two opposite positions of the focal point.

In case of laser energies used in these experiments, the intensity distribution in the cross-section of the laser beam in front of the focus has approximately a flat form. The same form of the laser intensity is expected at the same distance behind the focus. On the basis of our earlier experiment (Kasperczuk *et al.*, 2007*b*), we suppose that in the absence of plasma, the laser beam intensity distribution on the target surface, similar in the form for both sides of the focal point, should be characterized by a flat top in the center. However, the situation changes quickly during the beam interaction with the plasma originating from a solid target. Large gradients of electron density in this plasma deflect laser rays from their initial trajectories, thus deforming substantially the laser intensity distribution on the target. The observed differences in the crater shapes and in the forms of X-ray radiation confirm that for particular irradiation conditions, the intensity distribution can be modified in a different way. In order to get the laser intensity distribution with a depression in the center, a gradient of the electron density should be directed toward the axis, whereas the intensity distribution with a maximum in the centre can be only induced by the electron density distribution with a hole in the center. The purely illustrative schemes of these cases are presented in Figure 6.

There is the fundamental question: what is the reason for such a different electron density distributions? The certain information could be obtained by means of the X-ray streak camera. Streaked images of X-ray emission from the plasma for both positions of the focal point are presented in Figure 7. The basis of the streaks has a form of a wavy line, the thickness of which decreases in time. After about 400 ps an additional, very intensive, plasma radiation above that line appears, coming from a distant and more rapidly expanding plasma regions. One can suppose that it is induced by a very fast increase of plasma temperature in the center of the plasma plume at the period corresponding probably to the maximum of the laser pulse. The intensity of this additional radiation is considerably higher in the case of the focal point position in front of the target, for which the laser intensity from the geometrical point of view should be considerably higher.

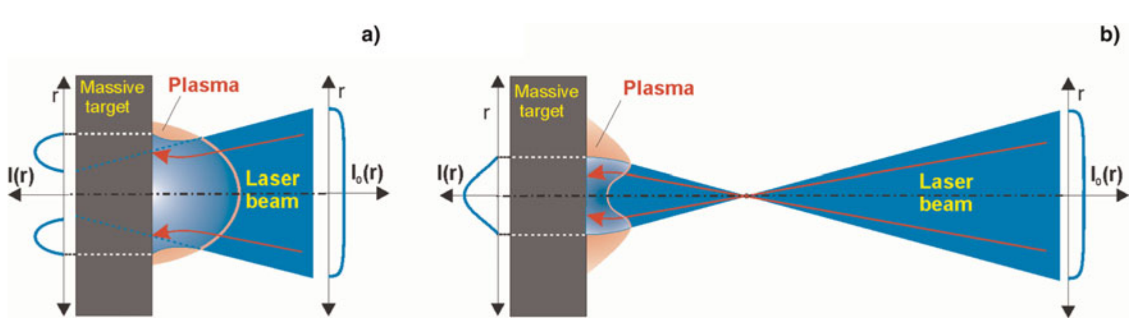


**Fig. 6.** (Color online) Schematic pictures showing transformation of the initial laser beam intensity distribution for two opposite positions of the focal point: (**a**) inside the target, and (**b**) in front of the target. Denotations: $I_0(r)$ initial laser intensity distribution and $I$(r) laser intensity distribution after transformation.

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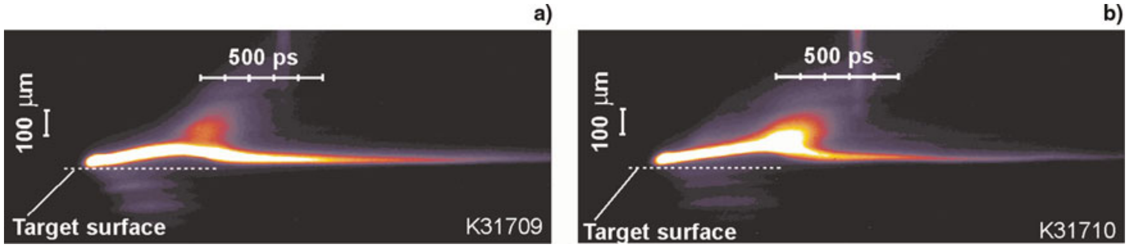


**Fig. 7.** (Color online) X-ray streak images for two opposite positions of the focusing lens focal point: (**a**) – inside the target, and (**b**) in front of the target.

The experimental studies of interaction of intense laser beam with a laser-created plasma (Laska *et al.*, 2005, 2006*a*, 2006*b*) carried out at the PALS facility proved that at laser intensities above ~$10^{14}$ W/cm$^2$ various non-linear interactions, such as self-focusing and filamentation, may significantly influence the plasma properties. Under our experimental conditions such high intensities are reached already at the beam spot radius of 300 μm. In the case of the negative focal point position, the high-intensity region is spread along the whole plasma plume. At interaction of a relatively long-pulse laser beam with the target, the beam rays coming later interact with the plasma preformed by the pulse front. Due to nonlinear mechanisms, the interaction becomes stronger in the vicinity of the axis, so that the axial plasma is heated to a temperature higher than the peripheral one. For that reason the central part of the plasma plume expands faster, which is results in the plasma configuration with a cavity at the axis, which leading to the laser intensity concentration in the axis vicinity.

## CONCLUSIONS

Our investigations have shown that the target irradiation method influences strongly the character of ablative plasma expansion and can induce various very interesting effects from the point of view of their potential applications. The focal point located inside the target causes the plasma jet creation, which can have application in astrophysical and ICF experiments (Pisarczyk *et al.*, 2007). Meanwhile, the focal point position in front of the target leads to the laser energy concentration in the center, which can be useful from point of view of flyer acceleration.

The finding about the transformation of the initial laser intensity distribution due to the interaction of the laser beam with the plasma seems to be very important in the context of acceleration of flyers with limited area, like disks. Because in the case of the focal point location inside the target, the plasma plays the role of a defocusing lens, too small diameter of the flyer, although a bit larger than diameter of the undisturbed beam, can result in the loss of laser energy due to deflection of a part of the laser beam outside the target.

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