

# The influence of an intense laser beam interaction with preformed plasma on the characteristics of emitted ion streams

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## Abstract

Intense laser-beam interactions with preformed plasma, preceding the laser-target interactions, significantly influence both the ion and X-ray generation. It is due to the laser pulse (its total length, the shape of the front edge, its background, the contrast, the radial homogeneity) as well as plasma (density, temperature) properties. Generation of the super fast (FF) ion groups is connected with a presence of non-linear processes. Saturated maximum of the charge states (independently on the laser intensity) is ascribed to the constant limit radius of the self-focused laser beam. Its longitudinal structure is considered as a possible explanation for the course of some experimental dependencies obtained.

**Keywords:** Fast ions; Laser-produced plasma; Self-focusing

## 1. INTRODUCTION

A laser beam, focused on solid targets, produces laser plasma that is a source of ions with various charge states and of different kinetic energy, as well as a source of X-ray radiation. The laser wavelength, the laser energy, the laser pulse length, the diameter of the focal spot, and the angle of the target irradiation are factors influencing the amount and characteristics of emitted ions (Láska *et al.*, 2007). However, also very important is the focus setting (the position of minimum focus spot with regard to the target surface) that determines the nominal laser intensity, but also the conditions of the laser beam interaction with plasma (created by the laser pulse irradiating a target) (Láska *et al.*, 2004a).

As the plasma is produced from threshold laser intensities of  $\sim 1 \times 10^9$  W/cm<sup>2</sup> (Torrisci *et al.*, 2001; Margarone *et al.*, 2006), all the laser-target interactions are preceded,

primarily, by laser interactions with the preformed plasma of various density. Interactions of the intense laser radiation above  $\sim 1 \times 10^{14}$  W/cm<sup>2</sup> with the preplasma (“optimum” focus position) may significantly increase the charge state, and energy of the produced ions (Láska *et al.*, 2004b, 2005a, 2006a, 2006b) due to the participation of various non-linear effects, including ponderomotive (Hora, 1969; Sun *et al.*, 1987), relativistic (Borisov *et al.*, 1992; Hora, 1975; Hora & Kane, 1977; Häuser *et al.*, 1992; Haseroth & Hora, 1996) and/or magnetic (Pukhov & Meyer-ter-Vehn, 1996; Borghesi *et al.*, 1998; Zverev *et al.*, 2005) self-focusing. Such preplasma can be produced either by using a separate laser prepulse, preceding the main pulse (Borghesi *et al.*, 1998, 2002; Wolowski *et al.*, 2004), or by the main pulse itself. The self-created plasma by the front part of pulses longer than about 100 ps (with which the main part of the laser pulse interacts (Láska *et al.*, 2004b, 2005a, 2006a, 2006b)), or that generated by long lasting (ns) background of very short pulses  $< 1$  ps at a low contrast ratio (Hatchett *et al.*, 2000; Kaluza *et al.*, 2004; Wada *et al.*, 2004), can be regarded as preplasma.

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Recent studies on highly charged heavy-ions generation, using the intense long pulses of the PALS high power iodine laser, operating at different experimental conditions ( $1\omega$ ,  $3\omega$ , various angles of the target irradiation and variable focus positions), are presented in this contribution. Because of the mentioned nonlinear laser-plasma interactions, attention is paid in a more detail also to the properties of the laser pulses themselves.

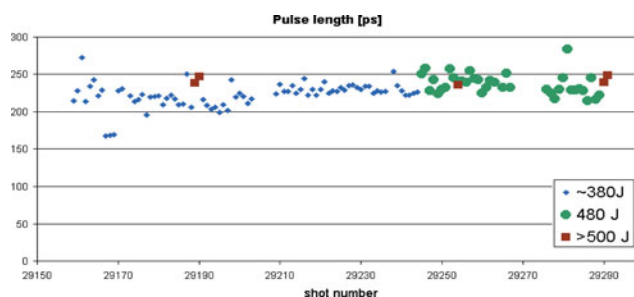
## 2. EXPERIMENTAL ARRANGEMENT

Both fundamental ( $\lambda = 1.315 \mu\text{m}$ ) and the third ( $0.438 \mu\text{m}$ ) harmonic frequencies of the PALS iodine laser system in Prague (Jungwirth *et al.*, 2001; Jungwirth, 2005; Ullschmied, 2006), with the laser pulse energies up to 560 J ( $1\omega$ ) and the pulse length lower than 300 ps, were used in our experiments. The Ta target was irradiated either perpendicularly, or at  $30^\circ$ , while the emitted ion stream was investigated at  $30^\circ$  (in the first case) or perpendicularly to the target (second case). The schematic view of the experimental arrangement is shown, e.g., in Wolowski *et al.* (2003). The minimum focus spot position with regard to the Ta target surface was varied in a broad range to make the changes of the interaction conditions of the laser beam with the self-created plasma significant. The convention used is that  $\text{FP} = 0$  when minimum focal spot coincides with the target surface, while  $\text{FP} < 0$  means that it is located in front of the target surface, and  $\text{FP} > 0$  means that it is inside the target. Usually, the target position was fixed, and the focusing lens was movable.

Characteristics of the ions emitted were investigated by the ion collectors (IC, ICR) and by the electrostatic ion energy analyzer (IEA) in the far expansion zone (Woryna *et al.*, 1996; Krása, 2004). Soft and hard X-ray radiation from the produced plasma was monitored by the diodes with various filters (Ryc *et al.*, 2003). A Kentech low-magnification X-ray streak camera with a sweep range up to 5 ps/mm; placed side-on recorded radiation of energy higher than 0.8 keV, to provide time- and space-resolved information on expanding plasma radiation (Ullschmied, 2006). Two different orientations of its entrance slits (parallel and perpendicular to the laser beam axis) provide spatial resolution of  $20 \mu\text{m}$ , either along the target normal or across the laser beam. Three-frame laser interferometric system with an automatic image processing (Pisarczyk *et al.*, 2002) was used to study the plasma expansion and plasma density, both during the laser pulse and in the post interaction phase. The temporal resolution  $\sim 0.3 \text{ ns}$  was determined and a spatial resolution of  $\sim 20 \mu\text{m}$  was deduced (Kasperczuk *et al.*, 2006; Nikolai *et al.*, 2006).

## 3. LASER PULSE PROPERTIES

Good stability and reproducibility of the PALS laser pulse-length for about 100 shots at  $1\omega$  and laser energy of 380 J, of 480 J, and of  $>500 \text{ J}$  is documented in Figure 1.



**Fig. 1.** (Color online) Statistics of the PALS pulse-length (FWHM) for various laser energy ( $1\omega$ ).

Generally, the pulse length is presented as full width at half maximum (FWHM). However, considering the possible participation of the nonlinear processes, further pulse characteristics are worth mentioning, because of their importance with regard to the possible laser-preformed plasma interactions. Typical shape of the leading edge of the laser pulse (using the logarithmic scale), the reproducibility of which is, however, a little bit worse, is presented in Figure 2a. While the contrast at  $-2 \text{ ns}$  is better than  $10^7$ , it is about  $10^6$  at  $-1 \text{ ns}$ , and only  $10^2$  at  $-0.5 \text{ ns}$ . Thus, at laser intensities higher than  $10^{16} \text{ W/cm}^2$ , the expanding plasma plume appears above the target surface approximately 2 ns before the pulse maximum, moreover, conditions for the appearance of nonlinear processes may be fulfilled approximately 0.5 ns before it. Considering that the measured velocity of various emitted ion-groups range from  $5 \times 10^6$  to  $5 \times 10^8 \text{ cm/s}$  (Láška *et al.*, 2006a), the thickness of plasma layer (of varying plasma density) may attain values from tens of  $\mu\text{m}$ , at least, up to several mm. For the sake of completeness, small peaks above the background plateau were recorded at 6.6 ns, 1.6 ns, and 800 ps before the pulse maximum. The fall time of the pulse is about twice longer than the rising front. Such laser pulse asymmetry may influence the post-pulse plasma dynamics mainly.

The fully flat, homogeneous target irradiation by the PALS laser beam is possible in the case of the first harmonic of the laser radiation, and of the laser energy below 180 J (Kasperczuk *et al.*, 2006). For higher energies, the intensity distribution becomes concave. This is a special feature of iodine laser amplifiers that produce a stronger amplification in the off-axis region. The depth of the cavity in the center increases with increasing laser energy. For the laser energy of  $\sim 600 \text{ J}$ , the ratio of the central intensity to that at the edge may reach the value of 0.9. To obtain the same laser energy in the third harmonics, the energy of the first harmonic before the conversion should be 2–3 time higher. Thus, the intensity distribution of the converted laser beam has usually a minimum in the center. After the conversion, this concave character of the intensity distribution is more pronounced due to the nonlinear wavelength transformation by the DKDP crystal. In addition, the intensity distribution may not be fully symmetric across the beam diameter (Fig. 2b). The comparison of laser beam intensity

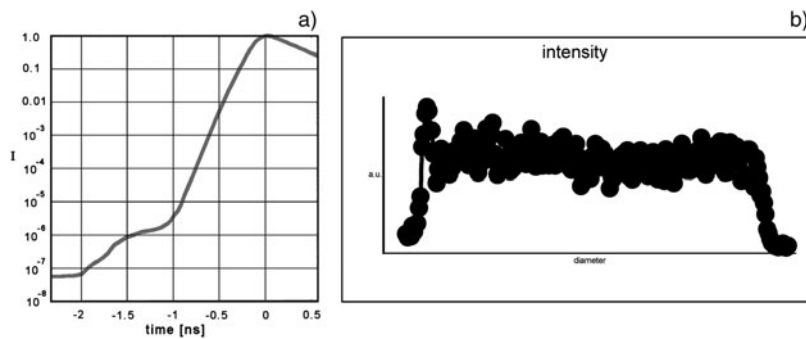


Fig. 2. Front edge (a) and radial homogeneity (b) of the PALS pulse ( $1\omega$ , 380 J).

distributions in the target plane for the first harmonic and the laser energies 100 J and 300 J, recorded by the CCD camera, was published in Nicolai *et al.* (2006).

#### 4. RESULTS AND DISCUSSION

In contrast to the nominal laser pulse length ( $\sim 300$  ps), the lifetime of the expanding plasma attains values of some tens of ns. The expansion of the produced laser plasma is not isotropic with regard to the target surface—its highest velocity is in the direction of the normal to the target surface, independently of the angle of the target irradiation. Interferometric studies of plasma dynamics led even to a discovery of dense ( $n_e > 10^{18} \text{ cm}^{-3}$ ) sharp plasma jets generated at the interaction of defocused laser beam ( $I_L \sim 10^{14} \text{ W/cm}^2$ ) with planar metallic targets (Al, Cu, Ag, Ta, Pb) (Kasperczuk *et al.*, 2006; Nicolai *et al.*, 2006). The jets of diameter less than 1 mm are several mm long and last longer than 17 ns. A typical sequence of electron density distributions for Ta at the third harmonics and at laser energy of 100 J is shown in Figure 3, as an example. Based on dimensional analysis and two-dimensional (2D) hydrodynamic simulation, the prevailing mechanism of jet formation was ascribed to the radiative cooling, while magnetic field should play a minor role (Kasperczuk *et al.*, 2006).

When using the iodine laser, the “optimum” focus position was found to be in front of the target surface ( $FP < 0$ ) (Láska *et al.*, 2003), in which ions with the highest charge states and kinetic energy can be generated (even higher than those produced in the point of the maximum nominal laser intensity). Also, a significant asymmetry of various dependencies (of maximum ion charge states, ion velocities or ion kinetic energy, current of highly charged ions, crater diameters, X-ray radiation, etc.) on the FP, with regard to the position of the nominal laser intensity maximum at  $FP = 0$ , was recorded. This can be understood in terms of various ion-accelerating processes (Láska *et al.*, 2007; Margarone *et al.*, 2006) including nonlinear processes (self-focusing) due to the laser preplasma interactions (Láska *et al.*, 2003, 2004a, 2005b). It is worth noticing that the new point of symmetry of the dependencies is shifted roughly to a distance of  $\sim 200 \mu\text{m}$  in front of the target surface.

In Figure 4a, four possible combinations of laser wavelength and angle of target irradiation, are compared. More asymmetric dependencies of  $z_{\text{max}}$  on FP were recorded for ions emitted perpendicularly to the target surface at both  $1\omega$  and  $3\omega$  (irradiation at  $30^\circ$ ); while these dependencies for perpendicular target irradiation (ions recorded at  $30^\circ$ ) are shifted less. This implicates an anisotropic angular emission of fast ions, which is consistent with the results in Figure 3. The fast ions with the high charge states (around 50+) and of high energy are produced also at the oblique irradiation (lower nominal laser intensity). The group of the fastest ions (with possibly higher charge states) that are emitted into a cone with the angle smaller than  $30^\circ$  (with regard to the target normal), cannot be recorded at the perpendicular irradiation in our experimental arrangement. We can recalculate the dependencies in Figure 4 to those in laser intensity  $I_L$  ( $I_L \lambda^2$ ). Generally—the higher  $I_L$ , the higher charge state and energy of produced ions. Saturation of the values of  $z_{\text{max}}$  in a broad region of laser intensities (see Fig. 4b) implicates that the self-focusing of laser beam to the limiting diameter (of about  $1\lambda$ ) determines the maximum attainable laser beam intensity.

Varying the laser FP with regard to the target surface at a fixed laser beam energy  $E_L$ , it does not mean changes in the laser intensity only, but also changes in the interaction conditions for the laser beam that interacts with an expanding plasma plume. In Figure 5a ( $3\omega$ , 150 J), the dependencies of peak kinetic energy of 14 ion subgroups on FP are presented that have been identified in the IC signals at various focus positions and labeled from 2 to 14. They are distributed, in principle, over three generally accepted ion groups (Wolowski *et al.*, 1995; Rohlena *et al.*, 1996): slow S (Hora & Kane, 1977; Häuser *et al.*, 1992), thermal T (Hora, 1975; Borisov *et al.*, 1992), and fast F (Sun *et al.*, 1987; Láska *et al.*, 2006a) (10, 7). Subgroups (Hora, 1969; Torrisi *et al.*, 2001; Margarone *et al.*, 2006, Láska *et al.*, 2004a, 2004b, 2005a, 2006b), clearly seen in the region of focus positions  $-500 \mu\text{m} < FP < 0$ , represent a super fast (FF) ion group, which is connected with an increased intensity due to self-focusing (Láska *et al.*, 2005c). In the region of the FP printed, the peak ion velocities range from  $5 \times 10^6 \text{ cm/s}$  to  $5 \times 10^8 \text{ cm/s}$ , corresponding to the ion energies from  $\sim 2 \text{ keV}$  to 20 MeV. The limit label 1 may

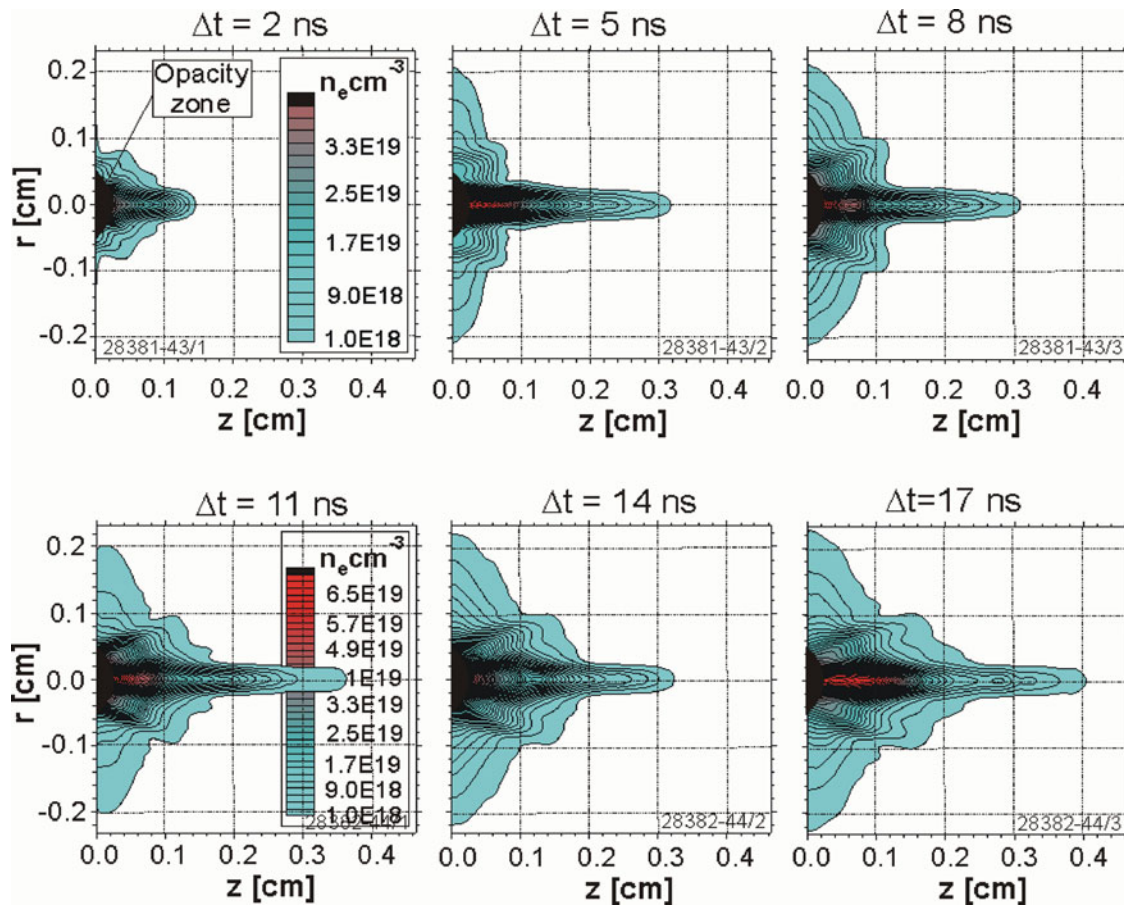


Fig. 3. (Color online) Expanding plasma at 2–17 ns after the target irradiation ( $3\omega$ , 100 J, FP = +300  $\mu\text{m}$ ).

represent impurities (C, O) and missing label 1 fast protons with the energy above 1 MeV. The current density of groups of the fastest ions significantly increases from the threshold value at  $I_L \sim 2 \times 10^{14} \text{ W/cm}^2$  and attains maximum value up to  $\sim 100 \text{ mA/cm}^2$  (1 m from the target). The duplicity of the main ion groups may be

explained by astigmatism of the focusing lens, which produces, in fact, a double focus spot. A similar amount of ion subgroups was recorded at  $1\omega$  with the laser pulse energy  $\sim 380 \text{ J}$ .

A linear increase in the ion energy with increasing charge states characterize the ambipolar acceleration mechanism,

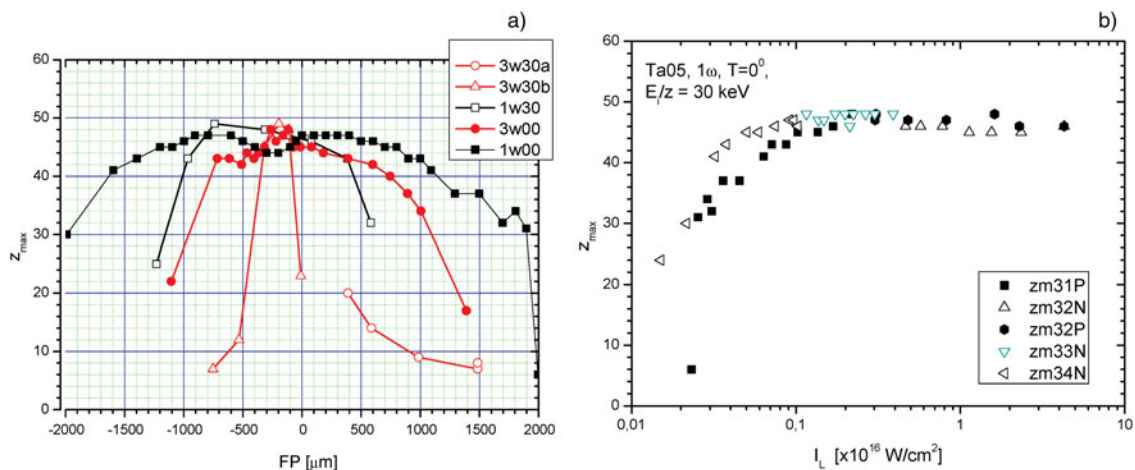
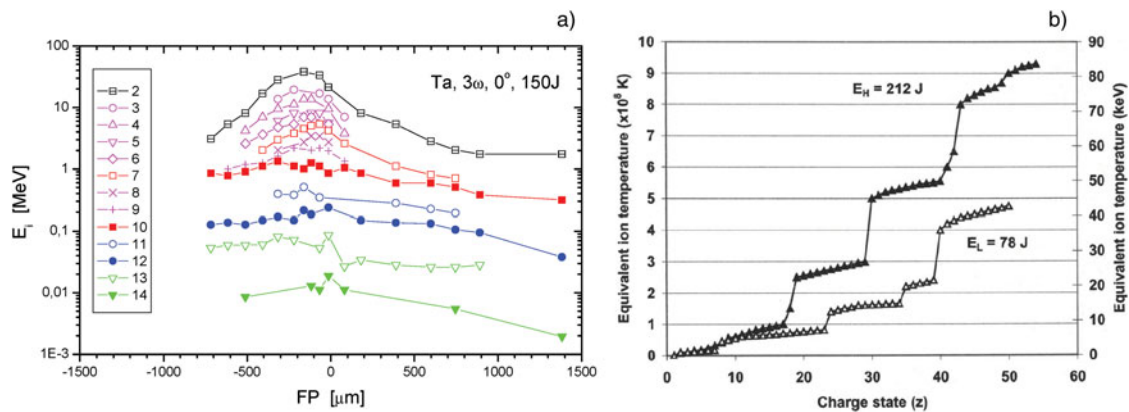


Fig. 4. (Color online) Dependence of the maximum charge state  $z_{\text{max}}$  on the focus position (a) and on the laser intensity (b) for combinations of  $1\omega$ ,  $3\omega$ , and perpendicular ( $0^\circ$ ) and  $30^\circ$  target angle irradiation (P $\equiv$ FP>0, N $\equiv$ FP<0).



**Fig. 5.** (Color online) Peak ion energy  $E_i$  of 14 ion groups, determined from IC signals, in dependence on the focus position FP (a) and four (five) calculated “equivalent” ion temperatures (b).

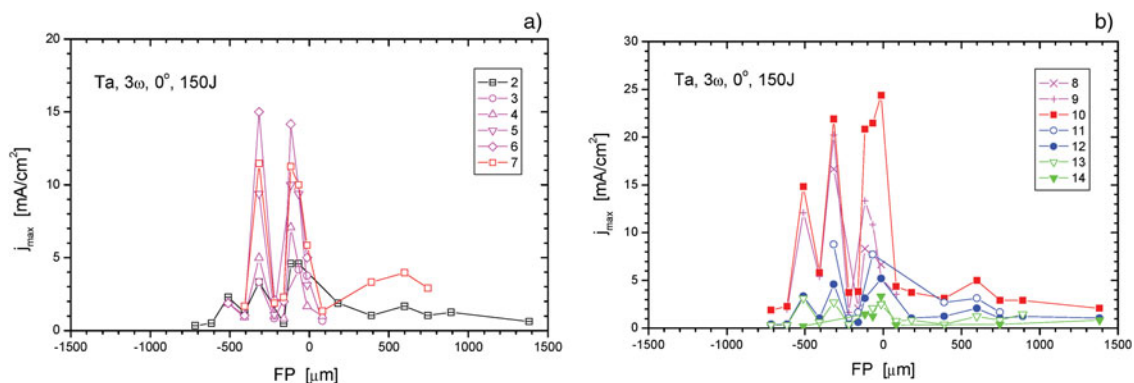
which acts at different (low or high) plasma temperatures. The shifted Maxwell-Boltzmann-Coulomb function was used (Torrìsi *et al.*, 2006a) to fit the measured charge-energy distribution of Ta ions (1–54+), produced in the presence of non-linear processes. Four (five) “equivalent temperatures” with the highest one  $\sim 80 \text{ keV}$  were evaluated (see Fig. 5b) that might be ascribed to four different groups of produced ions. We assume that near LTE conditions, the developed voltage on the distance of the Debye length can be evaluated, knowing the plasma temperature and density. Calculated electric field attains a value of  $6.6 \text{ MV/cm}$  at the laser intensity of  $10^{10} \text{ W/cm}^2$  and  $11 \text{ GV/cm}$  at the laser intensity of  $10^{16} \text{ W/cm}^2$  (Torrìsi *et al.*, 2006b).

By refining the course of experimental step in FP, we obtained a surprising result. Figure 6 shows a current dependence on the basic ion subgroups (8–14) on the laser focus position. Three maxima are clearly visible within the  $\text{FP} < 0$  region in front of the target. Moreover, the maxima and minima of all ion subgroups coincide at the same focus positions FP, approximately, the distance of which is  $\sim 200 \mu\text{m}$ . This is valid also for super fast ion groups (2–7). Similar dependencies were found also for low

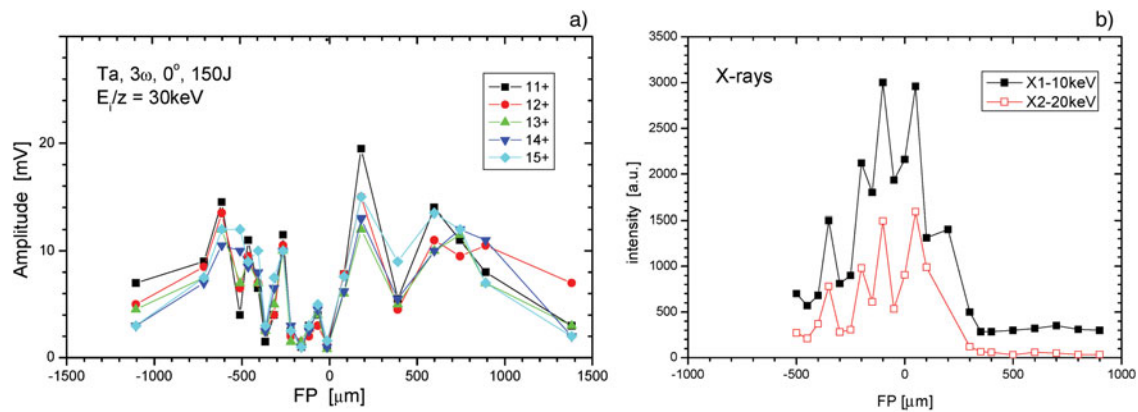
charged ions (see Fig. 7a); the distance of peaks at  $\text{FP} < 0$  is  $\sim 150\text{--}200 \mu\text{m}$  again.

Considering that  $L_{\text{SF}} \sim 200 \mu\text{m}$  is the length necessary for the contraction of the beam, then the position of peak at  $\text{FP} = -500 \mu\text{m}$  indicates, in fact, the place of plasma density, sufficient for self-focusing of the laser beam at the nominal intensity  $\sim 1 \times 10^{16} \text{ W/cm}^2$ . Independent interferometric measurements (Kasperczuk *et al.*, 2006), performed under similar experimental conditions (Ta,  $3\omega$ , 100 J) report the value of  $n_e = 1 \times 10^{18} \text{ cm}^{-3}$  at the distance of 4 mm (normal to the target) even after 17 ns. It should be remembered that in  $\text{FP} < 0$  positions, a front of expanding plume always meets the place of maximum laser intensity, while for  $\text{FP} > 0$  plasma expands against the laser beam with a continuously decreasing intensity than the nominal ( $\sim 5 \times 10^{14} \text{ W/cm}^2$  at  $\text{FP} = +500 \mu\text{m}$ ).

The amount of various kinds of ions depends on the volume of the produced plasma and its temperature. The composition of emitted plasma plume is reflected by the height of the separate ion current peaks in Figure 7a. Two principal side-maxima (modulated) are dominant for ions with the charge states lower than  $\sim 25+$  (similarly as



**Fig. 6.** (Color online) Relative amplitude of the current of the super fast (a) and slow, thermal and fast (b) ion groups (from Fig. 5a) in dependence on the focus position FP.



**Fig. 7.** (Color online) Relative amplitude of the low-charged single ions (a) and hard X-ray radiation (b) dependence on the focus position FP.

for soft X-ray radiation (Tallents *et al.*, 1986)) can be with certainty ascribed to the thermal electrons. For the higher charge states ( $\sim 30+$ ), an independent maximum around  $FP = 0$  appears, which is shifted for the charge states higher than  $30+$  to a  $FP < 0$  position. This maximum (as well as that similar for hard X-rays) is connected with the presence of fast electrons. Substantial amount of ions with the highest charge states (above  $40+$ ) were recorded only at  $FP < 0$ , when conditions for the self-focusing of laser beam were met. Self-focusing lengths  $\sim 100$ – $400$   $\mu\text{m}$  can be estimated from the distances of the superimposed maxima; this spread might be explained by a gradually change of the laser beam intensity and of the electron density during the laser interaction within the expanding plasma plume due to the onset of self-forming.

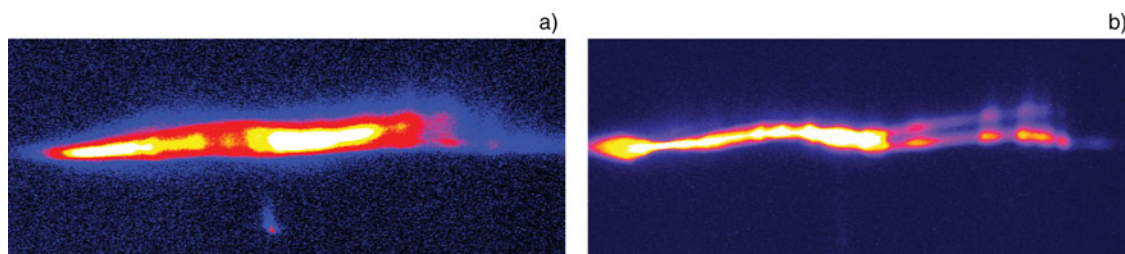
In addition, the same maxima were found on the intensity curves of the emitted hard X-ray radiation ( $< 20$  keV)—see Figure 7b ( $1\omega$ , 380 J,  $0^\circ$ ). The emission of the both soft (0.9–7.1 keV) and hard (5.1–20 keV) X-rays increases with the laser intensity. The position of the hard X-ray maximum and the maximum of the highest charged ions correlate. Both the maxima of soft X-rays are almost symmetrically positioned with regard to the hard X-ray maximum and correspond to the optimum relation of volume and temperature of produced plasma, in agreement with earlier published results (Láška *et al.*, 2005b).

The formation of a longitudinal structure of the self-focused laser beam was theoretically analyzed (Sun *et al.*,

1987; Sharma *et al.*, 2004); the constriction of laser beam may not be equidistant and differs from tens to hundreds of  $\mu\text{m}$ . Borisov *et al.* (1992) gave the first experimental evidence for the formation of a stable mode of spatially confined (channeled) propagation of the beam with a longitudinal structure. They observed the distribution of intensity along the filament: moon-like spots of decreasing intensity with a spatial distance  $\sim 200$   $\mu\text{m}$ .

Using the X-ray streak camera we recorded similar moon-like spots with the time distance of  $\sim 100$  ps and with the changing intensity in the expanding plasma plume (even splitting into two plasma plumes). Examples are presented in Figure 8, in which the size of the black area is about 2 ns (time-axis  $x$ ) times 0.6 mm (space-axis  $y$ ). The plasma produced survives several times the laser pulse length, the total length of which is, in fact, much higher than that presented as FWHM. The measured velocity of majority of emitted fast ions is  $\sim 2 \times 10^8$  cm/s (Láška *et al.*, 2006b); it means that time distance of the bright spots  $\sim 100$  ps could correspond to a space distance of  $\sim 200$   $\mu\text{m}$ .

Various bright spots (moon-like, half-moon-like) can be distinguished on the trace in Figure 8. The structure of the trace for the time above  $\sim 800$  ps is not possible to ascribe to the effect of self-focused laser beam, but likely to a transformation and dissipation of the internal magnetic field. The pinching of very intense ion current beam due to very high ( $\sim \text{MG}$ ) self-created magnetic field (Pukhov &



**Fig. 8.** (Color online) The X-ray streak camera image of an expanding plasma with a longitudinal structure ( $1\omega$ , 380 J,  $FP = +200$   $\mu\text{m}$ ) (a) and even split ( $1\omega$ , 486 J,  $FP = -400$   $\mu\text{m}$ ) (b).

Meyer-ter-Vehn, 1996; Borghesi *et al.*, 1998) may increase the plasma temperature and consequently contribute again to the production of ions with the highest charge states and energy. Since all these phenomena proceed within  $\sim 2$  ns, the detailed processes cannot be distinguished from each other (are integrated) in the far expansion zone ( $\sim 2$  m), of course.

## 5. CONCLUSION

It is evident that the laser target interactions are mostly accompanied (preceded) by interactions of laser beam with the preplasma. The preplasma is self-created by the main pulse—either by the front part of long pulse ( $>100$  ps) or by the background of the short pulse ( $<1$  ps). The lifetime of expanding plasma was proved to be about  $\sim 20$  ns, at least. Above the intensity  $\sim 1 \times 10^{14}$  W/cm<sup>2</sup> ( $I\lambda^2 \sim 1 \times 10^{14}$  W/cm<sup>2</sup>  $\mu\text{m}^2$ ) nonlinear processes may start to increase the charge and the energy of the produced ions. The self-focusing increases the highest attainable laser intensities—which may be even about  $\sim 10^{20}$  W/cm<sup>2</sup>, however, across a very small irradiated area.

About 14 different ion groups (subgroups) were observed in the expanding plasma generated by the high power iodine laser PALS. These can be separated into four main ion groups, where the fastest one (FF) that consists of larger number of subgroups, are connected with the presence of non-linear processes. Surprisingly, oscillating dependencies of the current of single ion-groups, as well as of single (differently charged) ions and/or of X-rays on the focus position FP, were observed (maxima are separated about  $\sim 100$   $\mu\text{m}$ ). These results suggest that the idea of longitudinal structure of the self-focused laser beam could be accepted, similarly, as that of pinching of very intense current beam due to a high ( $\sim$ MG) self-created magnetic field in the post irradiation phase.

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