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Factors influencing parameters of laser ion sources

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Abstract

Various applications demand various kinds of ions. Charge state, energy and the amount of laser produced ions depend, primary, on the wavelength, the energy, the pulse duration, and the focusing ability of the laser used. Angle of the target irradiation, angle of the ion extraction (recording), and mainly the focus setting may significantly influence especially the portion of ions with the highest charge states. The participation of non-linear processes on the generation of ions with extremely high parameters is demonstrated. The observed effects support the idea of a longitudinal structure of the self-focused laser beam with a space period of ~200 μm.

Keywords: Highly charged ions; Laser-plasma; Self-focusing

1. INTRODUCTION

Laser ion sources (LIS) are the most efficient sources for highly charged ions. The ion current density, j, more than 10^{10} A/cm^2 in the vicinity of a target (Badziak *et al.*, 2004), which exceeds hundreds of mA/cm^2 at a distance of ~1 m from the target. Depending on the experimental conditions, the laser plasma emits ions with a charge state from 1+ to above 50+ (any material can be evaporated and ionized), and with the ion energy ranging from hundreds of eV up to hundreds of MeV (without external electrostatic acceleration) (Clark *et al.*, 2000; Wolowski *et al.*, 2002; Láska *et al.*, 2003). Highly charged heavy ions are considered for a second generation of preinjector for large accelerators (Sharkov *et al.*, 1998). Promising results have been reported recently for a direct injection of charged ions from laser plasma into a radio frequency quadrupole (RFQ) accelerator without an intermediate low energy beam transport (LEBT) system. A current of tens of mA of C^{6+} ions (important for medical therapy) and of Al ions with a charge from 9+ to 11+ has been reported (Kashiwagi *et al.*, 2006; Sakakibara *et al.*, 2006). High-energy ions can be used for various technological purposes, like ion implantation, solid surface modification, etc. (Boody *et al.*, 1996; Torrisi *et al.*, 2003). In contrast, low charge state ions with energy of only hundreds of eV are necessary for the hybrid ion source, which combines the best properties of both the electron cyclotron resonance (ECR) ion source and the LIS (Gammino *et al.*, 2004). Other demands are connected with the laser-driven inertial fusion, considering both the direct and the indirect driven laser-beam interaction with the target (Roth *et al.*, 2001).

Various factors influence the characteristics and the amount of laser produced (or extracted) ions. Some earlier results for documentation and quite new experimental results are presented, and the influence of various factors on characteristics of the ion streams produced (on LIS) are summarized, and the ion generation (acceleration) mechanisms, are discussed.

2. LASER ION SOURCES (EXPERIMENTAL ARRANGEMENT)

LIS consists of a laser (of various wavelength, pulse energy, and pulse length), a vacuum target chamber equipped with a target holder (usually movable in x, y, z, and φ directions), and targets of various Z elements (foils, slabs, or solid

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materials). Lenses (spherical or aspherical) or mirrors (parabolic, ellipsoidal, or off-axis) can be used to focus the laser beam onto the target with the focus spot of required area (diameter). The irradiation of the target may be normal or oblique, with regard to the target surface. Ions can be extracted (recorded) either from the front or rear side of the target (against or in the direction of the laser beam). Ions can be utilized without an external acceleration or they can be transformed into an ion beam. Lasers with a high repetition frequency are preferred for applications.

The prague asterix laser system (PALS) high-power photo dissociation iodine laser ($\lambda = 1.315\ \mu m$, $E_L \leq 1$ kJ, $\tau \leq 300$ ps, $I_L \leq 6 \times 10^{16}\ W/cm^2$, possible conversion to 2ω and 3ω) at the PALS Research Center in Prague (Jungwirth *et al.*, 2001; Jungwirth, 2005) was used for generation of highly charged and high-energy ions of various medium- and high-Z elements (PERUN laser in the first experiments; Láska *et al.*, 1996). The laser beam is focused with aspherical lens onto the targets with a minimum focal spot diameter of $\sim 70\ \mu m$. The schematic view of the experimental arrangement is presented e.g., by Wolowski *et al.* (2003).

Diagnostics of the ions (Woryna *et al.*, 1996; Krása, 2004) which are usually recorded in the far expansion zone (~ 1 m), is mostly based on the time-of-flight methods (Faraday cups, ion collectors-IC), which may be combined with a superimposed electric and/or magnetic field (electrostatic or magnetic ion energy analyzers, Thomson parabola spectrometer). The accompanying soft and hard X-ray radiation from the plasma produced was detected by the photodiodes with filters (Ryć *et al.*, 2003), and the expanding plasma monitored by using an X-ray streak camera.

3. RESULTS AND DISCUSSION

The plasma electron density, n_e, the plasma temperature, T_e, and the interaction time (pulse length) τ_L are the parameters which control the ionization state of the plasma. The laser pulse energy, absorbed in the vicinity of the critical surface due to the inverse bremsstrahlung process, determines the temperature of the thermal electrons in the laser plasma ($\sim$hundreds of eV). At higher laser intensities, a certain part of the laser energy absorbed due to a resonance absorption or parametric instabilities can be transferred into a smaller number of suprathermal (fast, hot) electrons accelerated by the Langmuir electrostatic wave. These electrons have the energy distribution, characterized by a higher "hot tail" temperature, T_h, which increases with the increasing laser intensity. T_h from keV to tens of keV in the range of $I_L \sim 10^{14} - 10^{17}\ W/cm^2$ was reported by Gitomer *et al.* (1986). At $I_L > 3 \times 10^{17}\ W/cm^2$ about 10% of the absorbed energy is carried by the hot electrons with $T_h \sim 80$ keV (Tallents *et al.*, 1986). Conversion efficiency reaching 40–50% of laser radiation at $I_L \sim 3 \times 10^{20}\ W/cm^2$ and the electrons with T_h in the MeV range were presented by Hatchett *et al.* (2000). The following factors influence the ion generation from the laser produced plasmas:

3.1. Laser wavelength and intensity

Absorption of incident laser radiation depends (among others) on the laser wavelength and the laser intensity. The laser radiation is reflected in the hot dense plasma from the surface where the critical density, $n_{cr} = (\omega_p^2 \varepsilon_0 m)/e^2 \sim 1/\lambda^2$, makes the plasma frequency equal to the laser frequency, $\omega_p = \omega_L$ (e and m are the charge and mass of electrons, ε_0 is the vacuum permitivity). The interaction conditions are similar if the product of the laser intensity I_L and λ^2 is approximately the same (Hora *et al.*, 1992). Thus, a number of fast electrons generated, which is proportional to $I_L\lambda^2$ are reduced when using the same laser intensity, but a shorter wavelength. It can vary in a broad range from 193 nm (excimer lasers) to 1.06 μm (Nd), 1.315 μm (iodine), and 10.6 μm (CO_2) of infrared lasers. Various theoretical scaling laws for the hot electron temperature are in the form T_h [keV] $= A\ (I_L\lambda^2)^\alpha$ [W/cm^2 μm^2], where A is a constant and the value of α varies from $\alpha \sim 1/3$ to $\alpha \sim 2/3$ (Ehler, 1975; Amiranoff *et al.*, 1982; Gitomer *et al.*, 1986).

The laser power density (intensity) depends on the area (diameter) of the spot, on which the laser power is focused. The material of the target is evaporated starting at I_L of $\sim 10^3\ W/cm^2$. Between $I_L \sim 10^7\ W/cm^2 – 10^9\ W/cm^2$ (depending on λ and τ_L), the vapor becomes partially ionized. At intensities above $10^{10}\ W/cm^2$ hot and highly ionized plasma starts to be formed. Generally, the higher the laser intensity, the higher the plasma temperature, and the higher charge states and energy of ions generated (Láska *et al.*, 2004*a*). A linear increase in the ion energy with increasing charge states represents the main ambipolar acceleration mechanism, which acts at different (low or high) plasma temperatures (Láska *et al.*, 2004*b*). The demands for high laser intensity needs high laser energy, or for the highest intensities, a significant shortening of the laser pulse length. Pulse length may be of tens of ns (CO_2 laser), of ns (Nd laser), of hundreds of ps (iodine laser), but it can be shortened down to ps or even fs range. It is worth remembering that in most cases, the pulse length is defined as a full length in the half maximum (FWHM). It was proven (see Section 3.3) that full length of the laser pulse, especially the shape of its raising part, is even more important. For example, the amplitude of the rising edge of 300 ps pulse from the PALS iodine laser at the distance of 0.5 ns in front of the pulse maximum represents about 1% of the pulse maximum value. The value of the decreasing edge at the same distance is even higher.

The intense pulse interaction with pre-plasma produced by the front edge may be a source of various non-linear processes, supporting the extreme characteristics of the produced ions. This is the reason for a well documented appearance of more or less significant self-focusing of intense laser beams (present in almost all of such interaction experiments), even with a possible longitudinal structure (Lei *et al.*, 2006; Láska *et al.*, 2006*a*, 2006*b*), as well as of generation of a large number of superfast ion subgroups (Láska *et al.*,

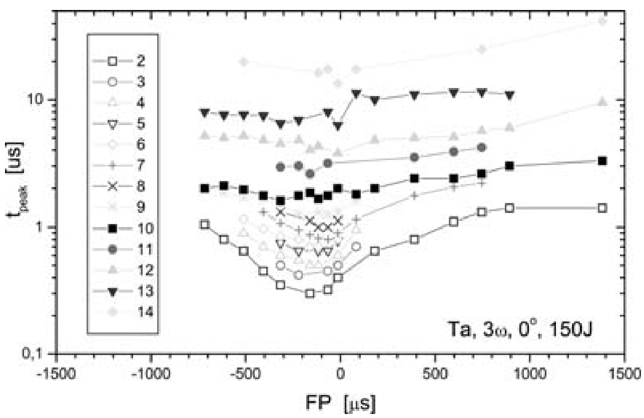

Fig. 1. Time of flight t_{peak} of single ion groups (2–14) vs. focus position.

2005*a*, 2005*b*, 2005*c*). In Figure 1, up to 14 more or less pronounced peaks on the IC signals (14 ion subgroups) have been distinguished, numbered from 2 to 14, which are distributed, in principle, over three generally accepted ion groups: slow S (13,14), thermal T (12,11), and fast F (10,7). Subgroups (9, 8, 6, 5, 4, and 3) mean a superfast (SF) ion group, which is connected with the presence of nonlinear processes. Label 2 represents impurities (C, O) and label 1 represents fast protons with energy above 1 MeV (not included here). The duplicity of the main ion groups may be explained, most likely, by astigmatisms of focusing lens, which produces, in fact, a double focus spots. Long total length of the laser pulse may also be the reason for appearance of moon-like structure of long lasting (>2 ns) expansion of the plasma plume, recorded with an X-ray streak camera (Láska, 2006*b*), as well as of long lasting intense plasma jets (~20 ns) as recorded by Kasperczuk *et al.* (2006).

3.2. Angle of the target irradiation and of ion emission

The absorption of laser radiation does not change over a range of irradiation angles between 0° and 30° (Tallents *et al.*, 1986). The maximum of ion charge-state generated, z_{max}, as a function of focus position (FP) for similar experimental conditions (iodine laser, 3ω), but differing in the angle of target irradiation (with regard to the target normal), is presented in Figure 3. Ions with the kinetic energy of $E_i/z = 20–50$ keV (selected by ion energy analyzer) are included. Similar highest charge states were recorded, but the dependence for 30° irradiation is much narrower than that for a perpendicular irradiation. The step in the charge state from 10+ to 40+ at about FP = −500 μm and within a FP change of about 100 μm indicates a threshold for a change in the mechanism of the generation of ions with the highest charge states (Láska *et al.*, 2004*a*, 2005*a*).

As for the angular distribution of ion emission, experiments confirmed that ions with velocities up to 1×10^8 cm/s (energies up to about 1 MeV) are preferentially emitted along the target normal, independently of the angle of irradiation. The experimental data are fitted by the $\cos^P(\alpha - \alpha_0) + y_0$ function. The narrowest distribution at low laser intensities ($<10^{11}$ W/cm^2) was recorded for W, while the widest shape belonged to Al and Ni. We obtained the angular distributions with the following sequence of FWHM: W (19.9°), Nb (23.7°), Cu (24.9°), Au (31.9°), Pb (34.9°), Ta (37.4°), Sn (37.2°), Ni (47.2°), and Al (51.1°). The value of the exponent p used in the $\cos^p$ function was as follows: Al – 4, Ni – 5, Sn – 7, Ta – 7, Pb – 8, Au – 10, Cu – 21, Nb – 23, and W – 33 (Láska *et al.*, 2003). However, at higher intensities ($>10^{14}$ W/cm^2) an additional maximum at about 30° appeared for ions with higher velocities, depending on the FP for different target materials (see Woryna *et al.*, 1999; Wolowski *et al.*, 2003). Such superfast ion groups, forming secondary maxima at an angle to the target normal, are ascribed to a relativistic self-focusing of laser beam (Häuser *et al.*, 1992).

3.3. Interaction with pre-formed plasma

Above a threshold of $\sim 1 \times 10^{14}$ W/cm^2, interaction with a pre-formed plasma significantly affects the generation of ions with the highest charge states, and energies due to

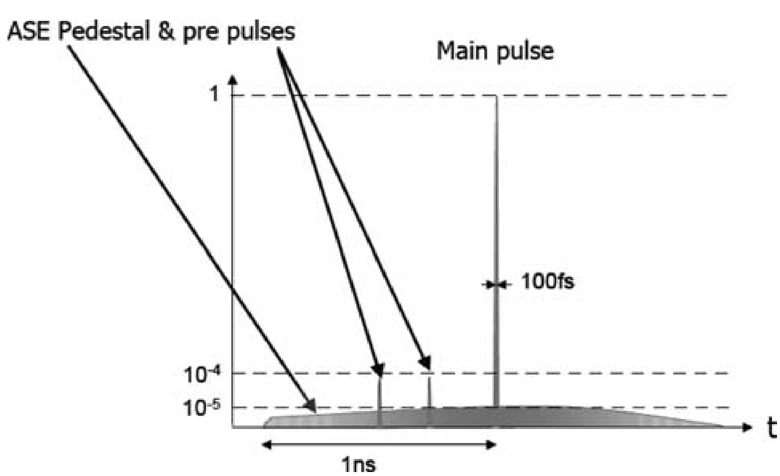

Fig. 2. Typical shape of the short laser pulse (Oksenhendler, 2006).

various non-linear effects. The pre-plasma can be produced using a separate laser pre-pulse (Wolowski *et al.*, 2004; Lei *et al.*, 2006). However, the pulse (longer than $\sim$100 ps) itself also forms by its front part a self-created pre-plasma, with which the main part of the laser pulse then interacts. This may be an advantage of the appropriate shape and pulse length in the case of the iodine laser. Similarly, a pre-plasma is created in the case of short pulses ($<$1 ps) due to a long term ($\sim$ns) background, and a low contrast ratio. A typical (standard) example of such pulse with the amplified stimulated emission pedestal contrast of $\sim 10^{-5}$ and of separate pre-pulses contrast $\sim 10^{-4}$ at a ns scale was presented by Oksenhendler (2006) (see Fig. 2).

Depending on the laser pulse and plasma parameters, various forms of laser beam self-focusing, filamentation or channeling may occur, leading to an increase in the local laser beam intensity by orders of magnitude. These effects may be ascribed to the ponderomotive force expulsion of electrons from the laser pulse channel, in the presence of relativistic electrons, but also to the self-created magnetic field, and a subsequent pinching at high current densities. The relativistic self-focusing is an immediate fast process, whereas the ponderomotive self-focusing rises in time as the electrons are pushed out of the laser beam (Häuser *et al.*, 1992). It occurs as a result of an increase in the wave refractive index $n = n_0 + n_2E^2 + \ldots$ Various theories presented so far (Hora, 1975) are all based, in principle, on a modification of the optical constants (plasma heating by absorption of laser radiation, a combined Brillouin scattering and nonlinear forces, presence of magnetic field).

Experimental studies (Borisov *et al.*, 1992) gave evidence for the formation of a stable mode of spatially confined (channeled) propagation of the beam with a longitudinal structure. The distribution of intensity along the filament was observed as moon-like spots of decreasing intensity with a spatial distribution of $\sim$200 μm; conditions for their appearance were derived from theoretical modeling. Similar moon-like spots in the expanding plasma plume with the time distance around 100 ps and with the changing intensity (even splitting into two plasma plumes) was recorded by an X-ray streak camera (Láska *et al.*, 2006*b*). Considering the measured velocity of the majority of emitted fast ions $\sim 2 \times 10^8$ cm/s (Láska *et al.*, 2006*b*), we obtain a similar space scale around $\sim$200 μm. Formation of a longitudinal structure of the self-focused laser beam was considered also elsewhere (Sun *et al.*, 1987; Sharma *et al.*, 2004). The constriction of laser beam may not be equidistant and differs from tens to hundreds of μm.

3.4. Focus setting and multiple shots to the same focal spot

It was observed that using the iodine laser, an “optimum” FP exists in front of the target surface (Láska *et al.*, 2003). Ions with higher ion charge states and kinetic energy can be generated in this position (with the presence of pre-plasma

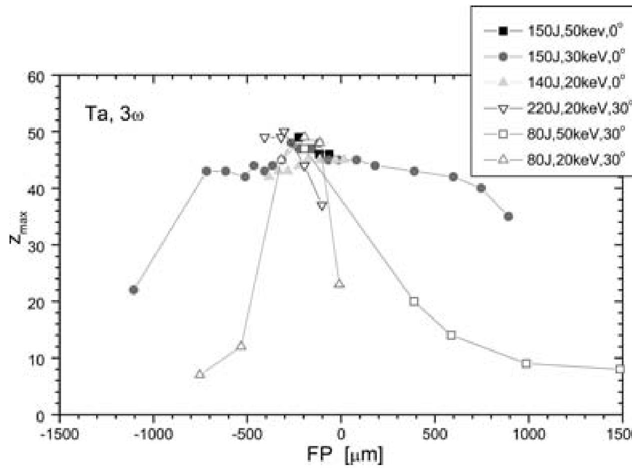

Fig. 3. Maximum ion charge state $z_{\max}$ vs. focus position.

interactions) than when produced with higher nominal laser intensity, but in the absence of non-linear processes. Significant asymmetry of various dependencies (of maximum ion charge states (Fig. 3), of minimum crater diameters, X-ray radiation, etc.) on the FP was found, considering the nominal laser intensity maximum is at FP $= 0$ (Láska *et al.*, 2003, 2004*b*, 2005*c*; Margarone *et al.*, 2006). The convention used is that FP $= 0$ when minimum focal spot coincides with the target surface, while FP < 0 means that it is located in front of the target surface, and FP > 0 means that it is inside the target.

Changing the laser FP with regard to the target surface at a fixed laser beam energy E_L does not mean a change in the laser intensity only, but also continuously changing interaction conditions for the laser beam, interacting with an expanding plasma plume. Fourteen different subgroups of ions were identified in the laser plasma (Fig. 1, also see Section 3.1) when using the PALS high power iodine laser at 3ω with pulse energy of 150 J. In the region of the FP recorded, peak ion velocities range from 5×10^6 cm/s to 5×10^8 cm/s, corresponding to the ion energies from $\sim$2 keV to 20 MeV. In addition to generally accepted thermal fast and slow ion groups, the appearance of the superfast ion groups (3–9) is clearly seen in the region of focus positions -500 μm $<$ FP $<$ 0. Outside this mentioned region, a smaller amount of ion groups is observed. Figure 4 shows a surprising dependence of the ion current of basic ion subgroups on the laser FP. Three maxima are clearly visible within the FP region mentioned above. Their distances are $\sim$200 μm. It is worth noticing that the peak values of all the ion subgroups are around the same FP. The relative amount of various kinds of ions in dependence on the FP is presented in Figure 5. Two modulated side-maxima are dominant for the ions with the charge states lower than 30+. The distance of superimposed peaks is $\sim$150–200 μm again at FP < 0. For higher charge states, a maximum around FP $=$ 0 appears, which is shifted for charge states higher than 31+ to a FP < 0 position.

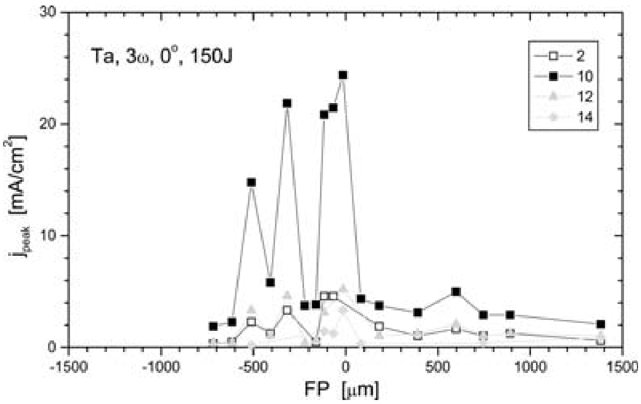

Fig. 4. Maximum ion current density j_{max} of single main ion groups (2, 10, 12, 14) vs. focus position.

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 5. Supposing $v = 5 \times 10^8$ cm/s is the velocity of the front of the expanding plasma plume—it will attain a distance of 1500 μm before the end of laser pulse (300 ps). The laser pulse interacts, therefore, primarily with the expanding plasma, where it diverges or focuses, dependent on the interaction conditions (I_L, n_e). If it is focused, the laser intensity increases, higher charge states are generated, but the volume of plasma with higher temperature decreases —therefore just a limited amount of these ions will be produced. Any change of $FP = 0$ (either to $FP < 0$ or to $FP > 0$) means a decrease in the nominal laser intensity, an increase in the plasma volume, but a decrease in the plasma temperature, which means a generation of ions with lower charge state. Let us suppose that the interaction of laser beam would occur in the absence of the pre-formed plasma. In that case, monotonic decreasing (or monotonic increasing) dependencies should be obtained, if only a single mechanism is responsible for the ion generation. Two principal side-maxima in the dependencies for the ions with charge states lower than 30+ in Figure 5 (similarly as for soft X-ray radiation, Tallents *et al.*, 1986) can be with certainty ascribed to thermal electrons. The maximum for ions with the higher charge states (as well as for hard X-rays) is connected with the presence of fast electrons. Substantial amounts of ions with the highest charge states (above 40+) were recorded only at $FP < 0$, it means that the conditions for the self-focusing of laser beam were met. Self-focusing lengths ~100–400 μm can be estimated from the distances of the superimposed maxima, this spread is due to a continuously changing laser beam intensity and electron density during the laser interaction within the expanding plasma plume. These experiments proved that the group of superfast ions is connected with the presence of nonlinear processes.

In the dependence on the focus diameter and the target material, only a spot is left on the target surface at low laser intensities, but large and deep craters of various shapes, and dimensions may be created at high laser intensities (Torrisi *et al.*, 2003; Margarone *et al.*, 2006). Since the depth of the crater after a single shot only may attain values in the order of hundred μm, a number of intense laser shots to the same place may influence significantly the focus setting (moreover using high repetition rate lasers), which is important especially at highly charged ions generation, as it was documented above.

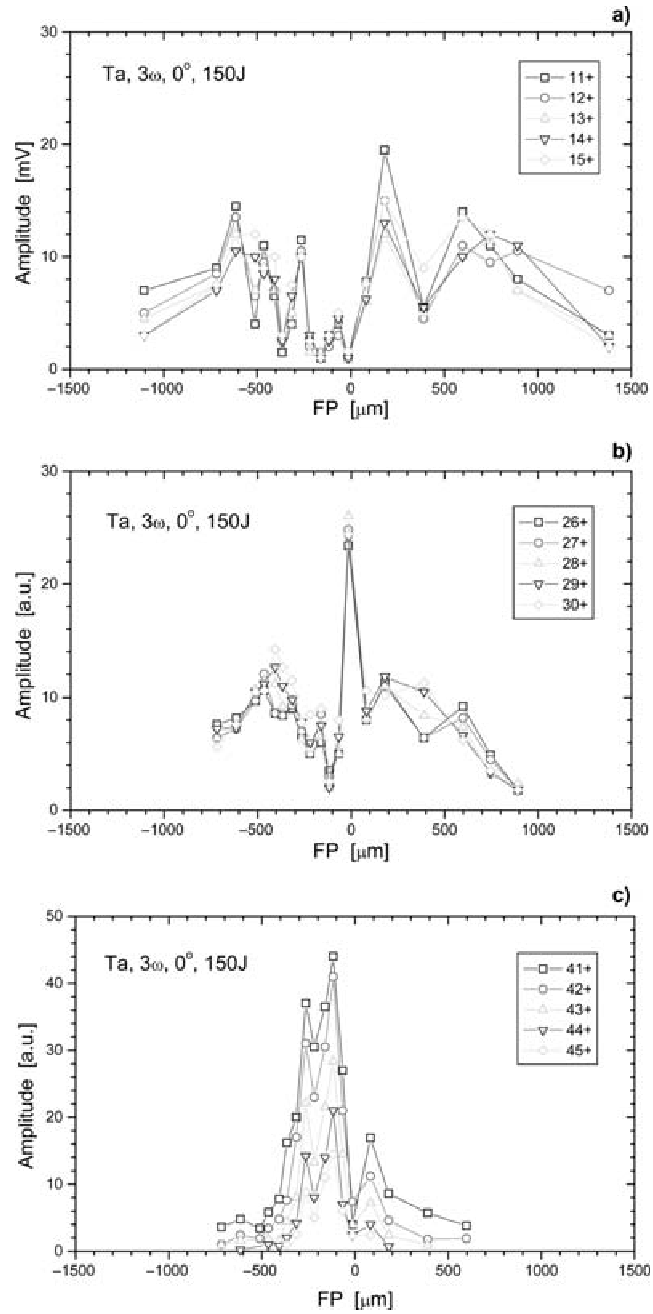

Fig. 5. Relative amount of single ions vs. focus position FP: 11+ − 15+ (**a**), 26+ − 30+ (**b**), 41+ − 45+ (**c**).

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