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Self-focusing in processes of laser generation of highly-charged and high-energy heavy ions

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Abstract

Laser-beam interaction with expanding plasma was investigated using the PALS high-power iodine-laser system. The interaction conditions are significantly changing with the laser focus spot position. The decisive role of the laser-beam self-focusing, participating in the production of ions with the highest charge states, was proved.

Keywords: Laser-plasma interactions; Non-linear processes; Self-focusing

INTRODUCTION

Laser ion sources (LIS) are the most efficient sources of heavy ions with charge states above 50+ and of ions with MeV kinetic energy (without external acceleration). Highly charged heavy ions are considered to be used for the second generation pre-injectors for large accelerators, while high-energy ions can be used for the ion implantation to modify the surface properties of solids. The fairly broad energy distribution of ions from LIS, not too convenient for pre-injectors, may be, on the contrary, an advantage for the implantation technologies. Beside a high dose of implanted ions per single shot (of the order of 10^{14} ions/cm^2), a "non-monoenergetic ion beam" makes it possible to implant ions into different depths of the substrate simultaneously, without any instrumental manipulation (Haseroth & Hora, 1996; Láska *et al.*, 2003).

The higher the intensity of the laser pulse interacting with the target, the higher the plasma temperature, and thus charge states and energies of the ions produced. Experiments on generation of highly charged ions are, in fact, currently accompanied by the laser interaction with pre-formed plasma. Pre-formed plasma can be produced by a separate laser pre-pulse preceding the main pulse (Borghesi *et al.*, 1998; Wolowski *et al.*, 2004*a*). However, even the main pulse itself significantly participates in the pre-plasma formation, in fact. Self-created pre-plasma is formed from the front part of the long pulses >100 ps (Láska *et al.*, 2003, 2004*a*), or due to the long lasting intensity background of the short pulses < 1 ps (low contrast ratio (Hatchett *et al.*, 2000; Wada *et al.*, 2004)). The interaction of the laser radiation above some threshold intensity with plasma of defined properties (plasma density and temperature, expanding plasma length) may significantly increase the charge state and energy of the produced ions. This is due to the appearance of various nonlinear effects, including self-focusing (ponderomotive, relativistic, magnetic) (Haseroth & Hora, 1996; Borghesi *et al.*, 1998; Hora, 1969, 1975; Hora & Kane 1977; Häuser *et al.*, 1992). It can reduce the irradiation channel diameter down to about one wave length, λ. In that case the laser intensity may increase by several orders of magnitude (Haseroth & Hora 1996; Hora & Kane 1977; Láska *et al.*, 2004*b*). Several views on the mechanism(s) of the fast ion acceleration exist up to now, in addition, if the short laser pulses are considered (Osman *et al.*,2004; Badziak *et al.*2005*a*, 2005*b*).

In this contribution, the laser generation of Ta ions with the highest charge states and the highest energy was studied, using long pulse of the PALS iodine laser at both the fundamental (1 ω) and the third harmonic (3 ω) frequencies, and changing the laser focus positions (laser intensities,

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laser-plasma interaction length). The results are compared and discussed.

2. EXPERIMENTAL ARRANGEMENT AND ION DIAGNOSTICS

Experiments were performed with the high-power iodine laser system at the PALS Research Center ASCR in Prague ($\lambda = 1.315$ μm, $E_L \leq 1$ kJ, $\tau \sim 400$ ps; $\lambda/3 = 0.438$ μm, $E_L \leq 0.25$ kJ; minimum focus spot diameter $\sim$70 μm) (Jungwirth *et al.*, 2001; Jungwirth, 2005). The ion diagnostics was based on a ring ion collector (ICR) and/or on a cylindrical electrostatic ion energy analyzer (IEA) (Woryna *et al.*, 1996). Both ICR and IEA were situated in the far expansion zone, perpendicularly to the target surface (L_{ICR} = 182 cm, L_{IEA} = 251 cm). Recorded ion charge states does not mean the maximum ion charge states produced, but those, which survived mainly the three body recombination losses during the process of expansion at our experimental conditions (charge states freezing) (Láska *et al.*, 2003). It is also worth mentioning that there is a larger potential step between Ta^{45+} and Ta^{46+} ions.

Two kinds of experiments can be performed, in principle. The ions are either generated using varying laser pulse energy E_L at a fixed focus position (FP), or at fixed E_L and FP varied. Changes in FP (with a fixed target) result not only in the varied nominal laser intensity due to the shape of laser beam caustic, but also in continuous changes of laser-plasma interaction conditions within the 400 ps pulse duration (see Fig. 1a). Laser pulses with energy of $E_L \sim 220$ J (1 ω, 3 ω) and $E_L \sim 80$ J (3ω), were used to irradiate solid Ta targets at 30° with respect to the target normal. A schematic view of the experimental arrangement is, for example, in (Wolowski *et al.*, 2003). The nominal laser intensity I_L in dependence on the focus position FP for various E_L is shown in Figure 1b. The convention used is that FP = 0 when the minimum focal spot is located at the target surface, while FP < 0 when it is located in front of the target surface and FP > 0 when it is inside the target.

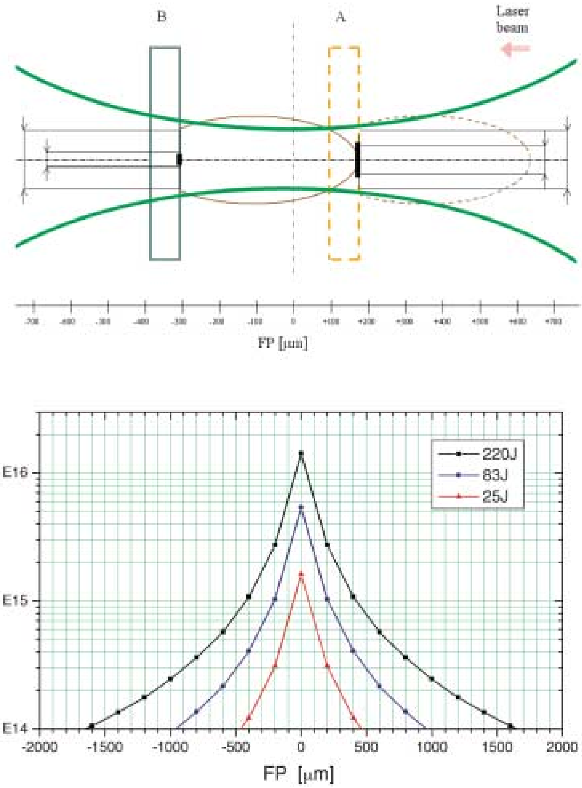

Fig. 1. Different positions (A, B) of the minimum laser focus spot with regard to the target surface and dependence of the nominal laser intensity I_L on the on the focus position FP for various laser energy E_L.

3. RESULTS

Maximum ion charge states z_{max} in dependence on FP for both 1 ω and 3 ω harmonic frequencies are presented in Figure 2. A narrow ($\sim$200 μm), bell-like dependence, was recorded for E_L = 83 J and 3 ω with the peak value z_{max} $\sim$50+ at FP ~ -200 μm. Similar values of z_{max} were recorded for E_L = 220 J and 3 ω. The dependence for E_L = 215 J and 1 ω shows a flat maximum over a broad range of 800 μm, again with peak values $\sim$50+. Significant asymmetries with respect to FP = 0, where the laser intensity on the target has its maximum, are observed in both the cases. Knowing the measured laser beam caustic (Láska *et al.*, 2004*a*) we transformed this dependencies (for $F < 0$ only) to the laser intensity ones in Figure 3. Almost stepwise increase of z_{max} was recorded above $I_L \sim 2 \times 10^{14}$ W/cm^2 for both 1 ω and 3 ω, respectively. After this dramatic increase, the value of z_{max} remains to be saturated (1 ω) or it even decreases (much significantly for 3 ω), in spite of the fact that I_L still increases. The value of z_{max} is thus influenced more strongly by the minimum focus position FP than by the nominal laser intensity itself.

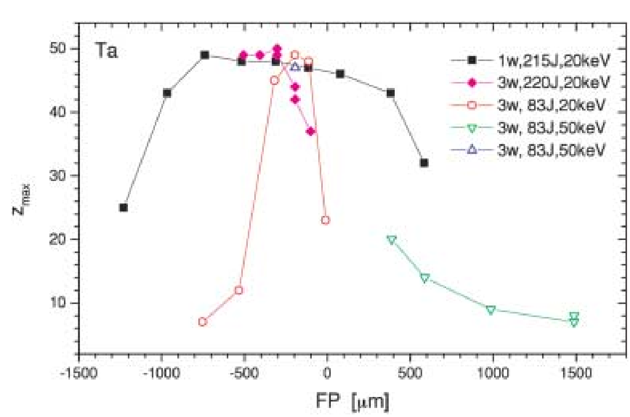

Fig. 2. Dependence of the maximum charge state of ions, z_{max}, on the focus spot position FP for various laser energy E_L and various laser frequencies (1 ω, 3 ω).

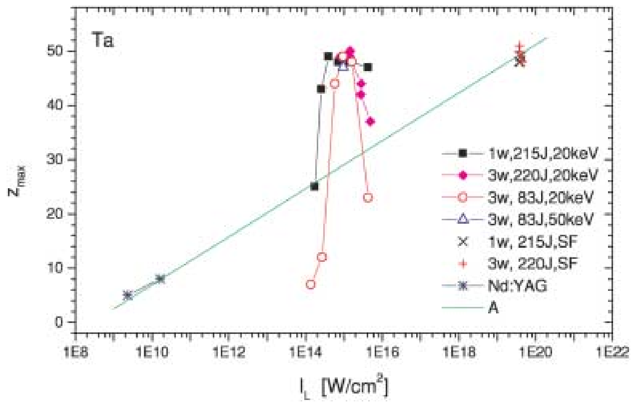

Fig. 3. Dependence of the maximum charge state of ions, z_{max}, on the laser intensity I_L at different focus spot positions FP for various laser energy E_L and various laser frequencies (1 ω, 3 ω)

Supposing the conditions for some kind of self-focusing are fulfilled in the region of the highest charge states recorded, the diameter of the irradiation channel was reduced to about one wavelength, λ (Hora & Kane, 1977). Then the laser intensity could increase up to values of $\sim 1 \times 10^{19}$ W/cm^2 for the respective focus positions. These fictive points were included in Figure 3 (as if the recalculated highest laser intensities only would be responsible for the highest charge states production). Also, the maximum charge states, produced at very low intensities, that is, at conditions with no non-linear processes present, were included in it (Torrisi *et al*., 2001; Láska *et al*., 2002). A solid straight-line (A), connecting z_{max} at the lowest and the highest (recalculated) intensities, means the estimated border of laser-target interactions with significant participation of non-linear processes in pre-formed plasma plume (above the line A) and without them (or with limited importance of them—below it). For laser intensities $I_L > 10^{14}$ W/cm^2 (in our case), this line indicates roughly the appearance of new additional mechanism(s), responsible for the generation (acceleration) of further fast ion group(s), for which a focus position (laser interaction with preformed plasma, in fact) is more important than the nominal laser intensity.

Even up to 13 peaks (ion subgroups) on IC signals for 1 ω, and 11 for 3 ω, more or less pronounced, was distinguished in the performed experiments. Besides the three generally accepted main ion groups (fast (F), thermal (T), and slow (S)) (Wolowski *et al*., 1995; Rohlena *et al*., 1996), a second fast (super-fast) FF group was proved, the existence of which coincides with the region of the maximum recorded z_{max}. The velocities of the single ion groups range from $v \sim 4 \times 10^6$ cm/s for the slowest Ta ions to $\sim 4 \times 10^8$ cm/s for the fastest ones (Figs. 4a and 4b). The corresponding Ta ion energy E_{ip} ranged from about 1.5 keV to $\sim$15 MeV. Humps on v_p and E_{ip} dependencies (much broader for 1ω) confirm again some irregularities with regards to the FP = 0. In another experiment, similar average velocities 1.2×10^8 cm/s of fast ions of different Z elements (C, Cu, Ag, Ta) were determined for 3 ω and E_L = 220 J for given experimental conditions (Wolowski *et al*., 2004*b*).

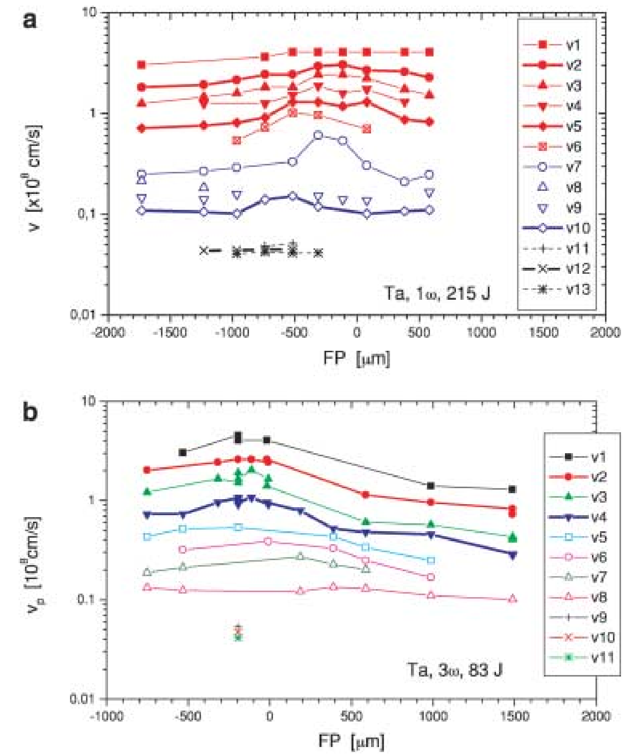

Fig. 4. Dependence of peak velocities, v, of different ion groups on the focus spot position FP for 1 ω and E_L = 215 J (**a**) and for 3ω and E_L = 83 J (**b**).

4. DISCUSSION

The existence of "optimum" laser focus position for generation of the fastest ions with the highest charge states in front of the target surface is consistent with our old observations (Láska *et al*., 2003), as well as with investigations of other authors (Hatchett *et al*., 2000; Wada *et al*., 2004). The course of dependencies and similar values of the highest z_{max}, recorded for both the wave lengths (1 ω, 3 ω) and for the laser energies (E_L = 83 to 220 J) used, indicate a threshold for the appearance of (relativistic) self-focusing of laser beam and a principal limitation of the maximum attainable laser intensity. Differences for 1 ω and 3 ω could be ascribed to a different absorption of laser radiation, in accordance with the scaling relation $I_L \lambda^2$.

A threshold laser power for ponderomotive self-focusing in plasma, based on non-linear force producing a plasma density minimum along the beam axis followed by focusing up to $\sim \mu$m diameter, is about 1 MW (Haseroth & Hora, 1996; Hora, 1969). Relativistic self-focusing (Haseroth & Hora, 1996; Hora, 1975; Hora & Kane, 1977; Häuser *et al*., 1992) is another relevant focusing mechanism expected at higher laser intensities, where the oscillatory quiver motion of the electrons in the laser field reaches energies in the range of mc^2. The relativistic change of the electron mass causes a modification of the optical constants due to the relativistic intensity dependence of the absolute value of the refractive index $\tilde{n}$,

$$\tilde{n}^2 = 1 \times \omega_p^2/(\omega^2\,(1 \times i\nu/\omega)),$$

where ω_p is the plasma frequency, given by $\omega_p^2 = 4\pi e^2 n_e/m_e$, ω is the laser frequency, and e the charge, m_e the mass, n_e the density, and ν the collision frequency of the electrons in the plasma (Haseroth & Hora, 1996). An initially plane wave front is thus bent into a concave wave front, which tend to shrink down to a diffraction-limited beam diameter. The self-focusing length L_{SF} was calculated for a Nd:glass laser: it can be very long at low plasma density ($N \ll 1$, $N = n_e/n_{cr}$) (Hora & Kane, 1977), it is expected to be about 500 μm in (Hora, 1975), and it is very short (as low as two times the beam focus diameter) at the cut-off density, if the laser intensity is above 3×10^{16} W/cm^2 (Haseroth & Hora, 1996). It was accepted that relativistic self-focusing may occur even at the laser intensities much lower than the calculated relativistic threshold $I_{rel} = 3.66 \times 10^{18}/\lambda^2$ W/cm^2 (10^{-3} I_{rel}) (Haseroth & Hora, 1996; Hora & Kane, 1977) and even 10^{-4} I_{rel} in (Häuser *et al.*, 1992).

With the help of Figures 1a, 1b, and Figure 2, it is possible to estimate very roughly the laser pulse-target (plasma) interactions for various FP and E_L. The front part of the 400 ps laser pulse interacts with the target and creates an expanding plasma plume. Considering for simplicity, the expansion velocity $v = 1 \times 10^8$ cm/s, the plasma plume attains the distance of 100 μm within the first 100 ps. For the laser beam diameter of $\sim$ 70 μm, the self-focusing length L_{SF} should be $\sim$100 to 200 μm, at least. For FP > 0, the more the plasma plume expands, the longer the interaction length, but the lower the laser intensity with which the front of the plasma interacts. In contrast, starting from FP $<$ -400 μm, the plasma plume faces during the expansion, increasing laser intensity only. For the laser beam diameter $\sim$ 70 μm, the self-focusing length L_{SF} should be $\sim$100 to 200 μm, at least. The more the plasma plume expands, the longer the interaction length, but the lower the laser intensity with which the front of plasma interacts at FP > 0 positions. In contrary, starting from FP < -400 μm, expanding plasma plume interacts with the increasing laser intensity only. The analysis for $E_L = 215$ J at 1 ω estimates the threshold $I_L \sim 5 \times 10^{14}$ W/cm^2 for the charge state 44+ generation, considering a broad range of acceptable focus positions between FP $= -900$ μm and FP $= +400$ μm and $L_{SF} \sim 200$ μm. The same analysis for $E_L = 83$ J at 3 ω gives the threshold laser intensity $I_L \sim 5 \times 10^{15}$ W/cm^2. The analysis for the maximum charge state generation (50+) estimates the threshold values $I_L \sim 7 \times 10^{14}$ W/cm^2 for 1 ω and $I_L \sim 7 \times 10^{15}$ W/cm^2 for 3 ω. Considering the uncertainties involved, the scaling relation $I_L \lambda^2 =$ constant (Haseroth & Hora, 1996; Gitomer *et al.*, 1986) might be fulfilled.

5. CONCLUSIONS

The following conclusions can be made:

(1) Self-focusing processes influence significantly the generation of ions with the highest charge states, using high power iodine laser with the pulse length of 400 ps.
(2) The threshold laser intensity I_L for the appearance of the non-linear processes with the expanding plasma plume was estimated to be $\sim 2 \times 10^{14}$ W/cm^2 for 1 ω and it is higher for 3 ω.
(3) Considering the self-focusing length $\sim$200 μm, the necessary I_L for production of maximum-ion charge states ($\sim$50+) was estimated to be $\sim 7 \times 10^{14}$ W/cm^2 for 1 ω and $\sim 7 \times 10^{15}$ W/cm^2 for 3 ω.
(4) The step (spread of experimental points) in plots of experimental data on ion energy per nucleon versus $I_L \lambda^2$ compiled by Gitomer *et al.* (1986) most likely reflects a significant participation of non-liner processes due to high-intensity laser interactions with a pre-formed plasma (Láska *et al.*, 2005).

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