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# Laser production of ions at different pre-formed plasma conditions

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## 1. Introduction

Generation of highly charged ions with MeV or even GeV energies requires laser pulses of very high intensities [1-3]. At intensities above $\sim 1\text{x}10^{14}$ W/cm$^2$, if the laser radiation interacts with a plasma plume of defined properties (plasma density and temperature, expanding plasma length), conditions for occurrence of various nonlinear processes, including ponderomotive and/or relativistic self-focusing, can be met [4-9]. Thus ions with much higher charge states and energy are generated than those produced in absence of pre-plasma interactions.

The necessary pre-formed plasma can be produced either by a suitable pre-pulse, preceding the main laser pulse, or due to the interaction of the front part of a sufficiently long main pulse (> 100 ps), the rest of which interacts with the self-created plasma. Considering that ion production starts at laser intensity of $10^9$ W/cm$^2$, short (ps and sub ps) laser pulses also interact with pre-formed plasma, because the intensity contrast with regard to the much longer background is usually not sufficiently high. In this contribution the results of studies, based on laser generation of ions with charge states about 50+ and with energies of tens of MeV, using the PALS iodine laser, are presented and compared with published results obtained using other types of lasers.

## 2. Experimental results

The PALS high-power photodissociation iodine laser system ($\lambda$=1.315 μm, $E_L \leq 1$ kJ, $\tau \sim 400$ ps, $I_L \leq 6 \times 10^{16}$ W/cm$^2$) at the PALS Research Center in Prague [10] was used for our experiments. A Ta target was irradiated by the focused laser beam (minimum focal spot diameter 70 μm) at 30$^\circ$ with respect to the target normal. A schematic view of the experimental arrangement is shown e.g. in [11]. The ion diagnostic techniques were based on the time-of-flight method (ion collectors, IC) and a cylindrical electrostatic ion energy analyzer (IEA) [12].

We performed, in principle, two kinds of experiments. In the first case, Ta ions were generated using laser pulse energies that varied from about 40 J to 750 J at a fixed focal position *FP*. In the second, ions were generated at a fixed laser pulse energy ($E_L$ = 215 J ± 15 J) and the focal position *FP* was varied from - 1730 μm to + 580 μm (changing *FP* results in a simultaneous change of both laser intensity as well as of laser-plasma interaction length). The convention used is that *FP* = 0 when the minimum focal spot is located on the target surface, while *FP* < 0 means that it is located in front of the target and *FP* > 0 means that it is inside the target [12].

At fixed *FP* both maximum charge state $z_{max}$ and energy $E_i$ of produced ions increase with increasing $I_L$. Conversely, the variation of $z_{max}$ with *FP* shows a flat maximum over a broad range of about 600 μm, but asymmetric with respect to *FP* = 0, where the laser intensity should have a maximum [3]. Knowing the shape of laser caustic [3] it is possible to transform the variation with position into a dependence on intensity. A dramatic increase of $z_{max}$ was recorded at a laser intensity of $I_L \sim 2 \times 10^{14}$ W/cm$^2$, if *FP* < 0. Above this threshold, the value of $z_{max}$ seems to be saturated with increasing $I_L$ (or it even decreases). As $I_L$ decreases for *FP* > 0 again, $z_{max}$ also decreases. The steep increase of $z_{max}$ indicates the appearance of a different ion production (acceleration) mechanism.

Up to ten ion subgroups (ten peaks on the IC signals) have been distinguished, which are distributed, in principle, into three, generally accepted, main ion groups (fast F, thermal T, slow S). Changing *FP*, the position of maxima of single ion subgroups and their amplitude change significantly; in addition, the ion groups may overlap. The peak ion velocity ranged from v = $4 \times 10^6$ cm/s for the slowest Ta ions to $4 \times 10^8$ cm/s for the fastest ones or impurities. Corresponding Ta ion energy $E_i$ ranged from 1.5 keV to 15 MeV (the maximum values of $6 \times 10^8$ cm/s and 34 MeV were estimated from the first minimum after the photopeak in IC signal). The shape of the variation of $E_i$ on *FP* (with the hump at *FP*< 0) confirms again some irregularity with regards to the corresponding nominal $I_L$. This is seen much more clearly in the variation of maximum ion current $j_{max}$ with *FP*.

In Fig.1 systematically recorded peak ion energies per nucleon $E_i/A$ are compared with our earlier measurements [12] and with some published results [1,13-15]. The straight-line A in it represents laser interactions with the target without (or with very weak) nonlinear processes in the pre-formed plasma plume. It is based on measurements performed at

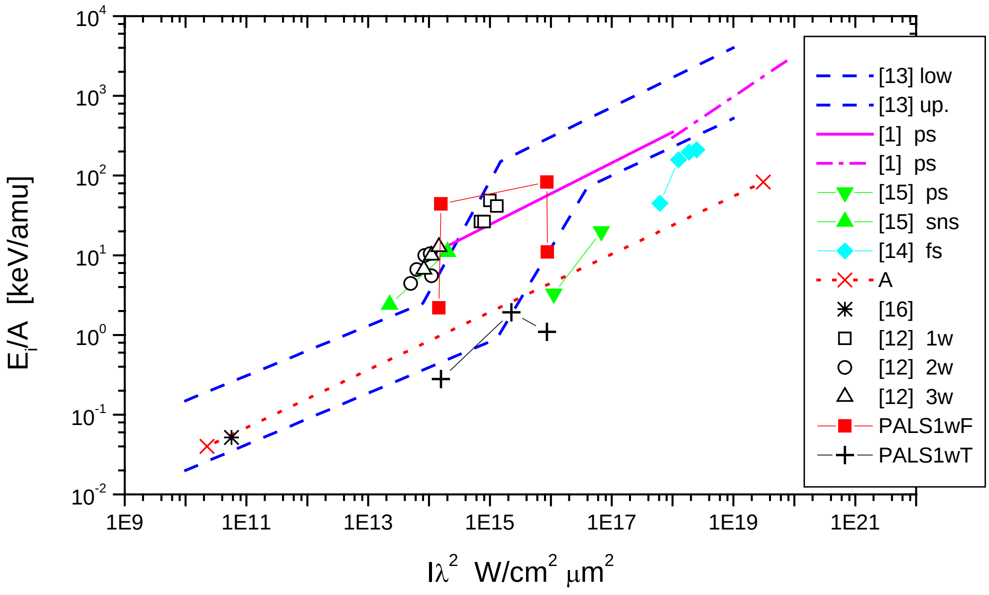


Fig.1. Ion energy per nucleon $E_i/A$ in dependence on the laser intensity parameter $I\lambda^2$.

threshold Nd:YAG laser intensities [16] and on the calculated intensities after consideration of self-focusing of the laser beam, assuming the diameter of the irradiation channel was reduced to one wavelength λ [17]. Above $I_L \sim 1 \times 10^{14}$ W/cm² significantly different values of $E_i$ and $z_{max}$ were recorded at the same values of $I_L$, depending on the interaction length with pre-formed plasma. This seems to be a natural explanation of "a greater vertical spread" of experimental points (step at ~ 1 x $10^{14}$ $Wcm^{-2}$-$\mu m^2$) in Fig. 4 of Gitomer [13].

3. Discussion and conclusions

All our laser shots onto the Ta target represent laser interactions with pre-formed plasma. After 400 ps irradiation, the front edge of an expanding plasma plume (of low density) may attain a maximum distance of 2.4 mm from the target surface. Both the laser intensity, interacting with the expanding plasma, as well as the length of the laser-plasma interaction, change continuously within this interaction. The complexity of the mechanisms of laser interaction with solid targets is due to the nonlinearity of the processes occurring in the plasma generated and of the plasma optical properties, when these depend on the laser intensity [7]. Nonlinear laser-plasma interaction processes – forces of direct electrodynamic interaction - can dominate gas-dynamic forces if the laser intensity (equivalent intensity $I\lambda^2$) is sufficiently high (> $10^{14}$ W/cm²). Different opinions exist on the ion acceleration mechanisms (ambipolar, ponderomotive, skin layer, self-created magnetic field [1,2,6-9,18]), all of which are connected with generation and acceleration of fast electrons.

The following conclusions can be deduced from our experiments: 1) Above $I_L$ ~ 1 x $10^{14}$ W/cm$^2$ there exist focus positions (FP < 0) in which nonlinear processes in pre-formed plasma influence the ion generation significantly and ions with higher charge states and energy can be produced with respect to the experimental conditions without pre-plasma interactions. 2) The increase of the laser beam intensity after self-focusing (estimated up to about $I_L$ ~ 1 x $10^{20}$ W/cm$^2$) depends on its initial intensity, and on the duration (length) of laser interaction with (pre-formed) plasma. 3) A spread of experimental points (step) in Fig. 4 of Gitomer et al. [13] reflects laser interactions with and without a pre-formed plasma.

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