

# GENERATION OF HIGHLY CHARGED IONS USING ND-GLASS LASER

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## Abstract

The parameters of ions (charge state distributions, currents and pulse durations) were measured in laser plasma generated by 3 J/30 ns Nd-glass laser for wide range of elements from  $^{12}\text{C}$  to  $^{181}\text{Ta}$  and for different laser power densities at the target surface. It is shown that such a laser can effectively generate highly charged ions for elements from  $^{12}\text{C}$  to  $^{56}\text{Fe}$ . Registered ion charge states significantly drops for heavier elements because of recombination losses of highly charged ions during laser produced plasma expansion into vacuum. Absolute currents and numbers of ions with different charge states were obtained by normalization of charge state distributions summary on total ion currents measured by Faraday cup for  $10^{11}\text{ W/cm}^2$  and  $10^{12}\text{ W/cm}^2$  laser power densities at the target surface. The results obtained are useful for Laser Ion Source (LIS) development, in particular, for Direct Plasma Injection Scheme (DPIS) study<sup>1</sup>.

and  $10^{12}\text{ W/cm}^2$  for 300 mm and 100 mm focal length lenses respectively. A moveable Faraday cup (FC) with an input aperture of 10 mm for measuring ion current and an electrostatic ion analyzer (EIA) for measuring charge state distribution were placed normal to the target surface at distances of 2.4 m and 3.7 m from the target respectively. Vacuum conditions during measurements were better than  $10^{-6}$  Torr in all parts of the installation.

## EXPERIMENTAL RESULTS

At first, the target was moved along the direction normal to the surface in steps of 0.5 mm and total ion current was measured by FC to find target focal position for all elements. The target position with the maximum measured current and fastest arrival of ions to the FC was chosen as the best one to get the highest yield of highly charged ions. This fact was later confirmed by the results of EIA measurements.

## EXPERIMENTAL SET-UP

The experimental set-up is presented in Fig. 1. A moveable planar target was placed inside vacuum chamber with residual gas pressure below  $10^{-6}$  Torr.  $^{12}\text{C}$ ,  $^{27}\text{Al}$ ,  $^{48}\text{Ti}$ ,  $^{56}\text{Fe}$ ,  $^{74}\text{Ge}$ ,  $^{93}\text{Nb}$  and  $^{181}\text{Ta}$  were used as target elements (with purity better than 99.99%). A 3D manipulator allowed moving the target with minimal step of about 10  $\mu\text{m}$  in three perpendicular directions.

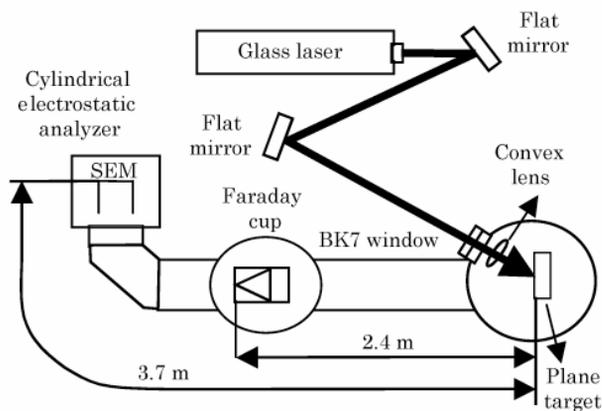


Figure 1: Experimental set-up.

Lenses with focal lengths of 100 mm and 300 mm were used to focus the laser beam onto a target surface at an incident angle of 30 degrees. Taking into account the typical value of beam divergence for Nd-glass lasers of about of  $5 \cdot 10^{-4}$  rad, the maximal laser power densities at the target surface can be estimated as about  $10^{11}\text{ W/cm}^2$

Table I: Ion charge state with the highest yield and the maximum registered ion charge state for different laser power densities and for different elements of periodic table together with corresponding ionization potentials (in brackets).

Element	Laser Power Density $10^{12}\text{ W/cm}^2$		Laser Power Density $10^{11}\text{ W/cm}^2$	
	Highest Yield Charge State	Highest Charge State Measured	Highest Yield Charge State	Highest Charge State Measured
$^{12}\text{C}$	6+ (476 eV)	6+ (476 eV)	4+ (67.6 eV)	6+ (476 eV)
$^{27}\text{Al}$	10+ (427 eV)	11+ (471 eV)	6+ (207 eV)	9+ (207 eV)
$^{48}\text{Ti}$	10+ (227 eV)	13+ (738 eV)	-	
$^{56}\text{Fe}$	14+ (404 eV)	17+ (1168 eV)		
$^{74}\text{Ge}$	5+ (87 eV)	8+ (200 eV)		
$^{93}\text{Nb}$	4+ (39.6 eV)	7+ (120 eV)	4+ (39.6 eV)	7+ (120 eV)
$^{181}\text{Ta}$	4+ (36.3 eV)	6+ (92.7 eV)	2+ (14.5 eV)	6+ (93 eV)

It was observed that the amplitude of the current drops with number of shots at the same target spot (especially strongly for the smaller focal spot size). For all further

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measurements target was always shifted between laser shots to provide a fresh surface to keep ion yield as high and stable as possible.

The ion charge state with the highest yield and the maximum registered ion charge state are summarized in Table I for different elements and laser power densities together with corresponding ionization potentials<sup>2</sup>. From Table I, one can clearly separate two groups of elements: highly charged ions with ionization potentials in the range 500 - 1000 eV were registered for all elements between <sup>12</sup>C and <sup>56</sup>Fe; ions with about-one-order-less ionization potentials were registered for elements between <sup>74</sup>Ge and <sup>181</sup>Ta. The most probable reason for such a big difference is recombination losses of highly charged ions during laser-produced plasma expansion into vacuum<sup>3</sup>.

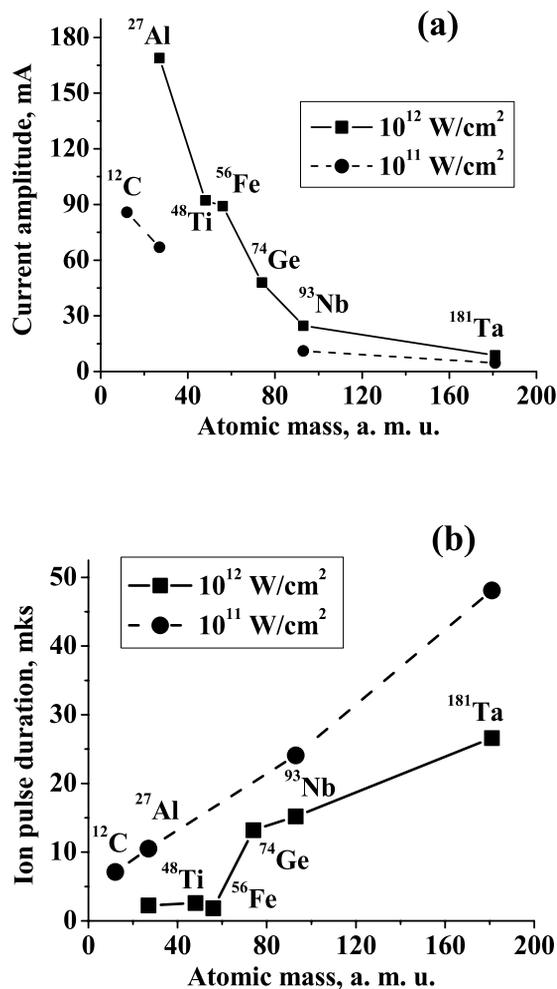


Figure 2: (a, b): Dependences of current amplitude (a) and ion pulse duration (at 0.1 level of current amplitude) (b) on target element atomic mass for different laser power densities. All parameters scaled to 1 m distance from target into aperture with  $1 \text{ cm}^2$  square.

Special measurements were performed to verify recombination losses in the case of the <sup>181</sup>Ta target. The FC was placed at three different distances from the target:

32.5 cm, 142 cm and 242 cm. Time structures of FC current recorded at these distances from the target were scaled to the same distance according to relations<sup>4</sup>:

$$t \propto L, I(t) \propto d^2/L^3. \quad (1), (2)$$

In these relations,  $I(t)$  is ion current measured at the time  $t$ ,  $d$  is diameter of FC aperture,  $L$  is distance from the target. As an increase of ion current with decreasing FC - target distance was not observed, one can conclude that there are no recombination losses of ions in Ta plasma at distances longer than 32.5 cm from the target and any recombination processes should take place at shorter distances.

Dependences of current amplitude, ion pulse duration (at 0.1 level of current amplitude) on target element atomic mass are presented in Fig. 2 (a, b) for different laser power densities. Ion parameters were obtained by scaling of values measured by the FC at 2.4 m distance from the target to 1 m distance into a  $1 \text{ cm}^2$  aperture according to relations (1) and (2).

Table II. Ion parameters for <sup>48</sup>Ti target and laser power density of  $10^{12} \text{ W/cm}^2$ , scaled to 1 m distance from the target into a  $1 \text{ cm}^2$  aperture ( $z$  – ion charge state,  $E_{1,2}^{\max}$  and  $J_{1,2}^{\max}$  – ion energy and current density corresponding to the maximum ion current (1 – for the first peak of ion current, 2 – for the second peak of ion current),  $\Delta t^{0.1}$  and  $N^{0.1}$  – ion pulse duration and number of ions defined at the levels of 0.1 times the maximum current).

$z$	$E_{1,2}^{\max}$ , keV	$J_{1,2}^{\max}$ , mA/cm <sup>2</sup>	$E_{1,2}^{\max}$ , keV	$J_{1,2}^{\max}$ , mA/cm <sup>2</sup>	$\Delta t^{0.1}$ , $\mu\text{s}$	$N^{0.1}$ , $10^{10}/\text{cm}^2$
1	-	-	0.42	0.025	5.5	0.05
2	-	-	0.98	0.21	13.7	0.54
3	-	-	1.48	0.54	11.8	0.61
4	3.11	0.43	1.96	0.95	11.8	0.48
5	3.44	1.23	2.46	0.57	6.39	0.43
6	8.25	1.82	-	-	5.31	0.63
7	9.63	4.57	-	-	4.1	0.89
8	9.63	7.14	-	-	3.02	0.98
9	10.8	14.6	-	-	2.43	1.25
10	10.4	16.6	-	-	2.23	1.09
11	9.48	16.2	-	-	3.02	0.76
12	9.3	10.1	-	-	2.37	0.36
13	8.92	0.95	-	-	0.48	0.013

Having an entire set of FC and EIA data, the absolute values of ion currents, ion pulse durations, energy ranges and numbers of ions with different charge states were calculated for all the elements and laser power densities used in the experiments. Such a specification was done in the following way and under the following assumptions: the dependence of secondary electron emission coefficient (SEEC) on the energy and charge state of registered ions was neglected; time distributions of ion yield were summed for all charge states to give total ion yield; current measured by the FC was scaled to EIA distance according to relations (1) and (2); and the

amplitude of the total ion yield was normalized to the amplitude of scaled ion current measured by the FC giving absolute values of ion current for each charge state. After that, the time dependences of the ion currents for different charge states were scaled to 1 m distance from the target into an aperture 1 cm<sup>2</sup> area and all ion parameters were specified under such conditions. As an example, Table II gives the result for <sup>48</sup>Ti with laser power density of 10<sup>12</sup> W/cm<sup>2</sup>, where the main ion parameters important for LIS application are summarized. The same parameters have been specified for all elements and laser power densities used in experiments. Ion parameters for charge state which corresponds to maximum current density in the distributions are presented in Fig. 3 for different target elements and 10<sup>12</sup> W/cm<sup>2</sup> laser power density.

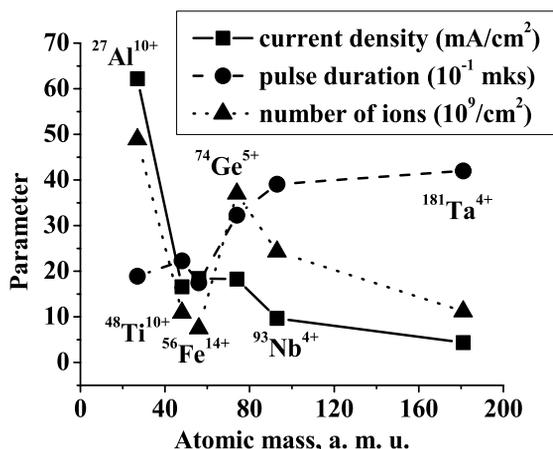


Figure 3: Ion parameters for charge states corresponding to maximal current density in the distribution for different elements and 10<sup>12</sup> W/cm<sup>2</sup> laser power density (1 m distance from the target into aperture of 1 cm<sup>2</sup> square).

Charge state distributions show a double peak structure of ion current dependence on time for the most charge states of all elements and for both laser power densities. Energies corresponding to maximum current of these two ion groups are presented in Fig. 4 for <sup>93</sup>Nb target and laser power density of 10<sup>11</sup> W/cm<sup>2</sup>. Errors in energy definition are caused by steps of voltage applied to IEA and half of the time difference between neighbouring points was taken as a possible error in definition of time corresponding to the peak amplitude of each group. The faster group has weak dependence of energy on ion charge state, and the energy of slower ion group very well follows the simple relation:

$$E_z (keV) \cong 0.5keV \times z, \quad (3)$$

where z is the charge state and E<sub>z</sub> is the energy of ions with charge state z corresponding to maximum ion current of this group. Similar behaviour was observed for all elements and laser power densities used in experiments. Quite surprising is that the slower ion groups with energies defined by relation (3) were found for all elements and laser power densities. Further

investigations are required to understand this phenomenon.

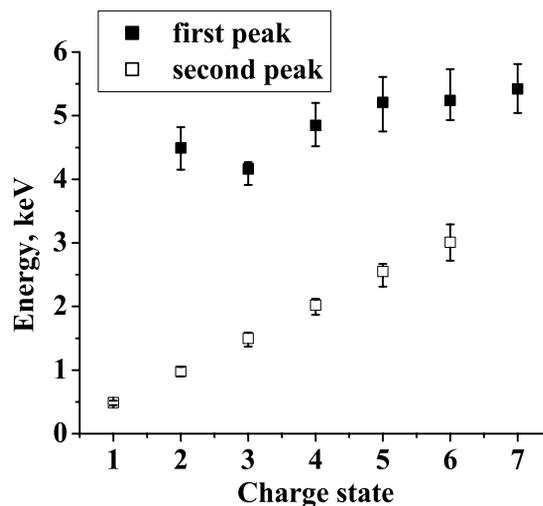


Figure 4: First and second peak ion energies of different charge states for <sup>93</sup>Nb target and laser power density of 10<sup>11</sup> W/cm<sup>2</sup>.

### CONCLUSIONS

The main results of this work are:

- Principal limitation of highly charged ion yield for heavier elements, caused by recombination losses in laser-produced plasma, has been found
- The main parameters of ion yield are summarized and compared for different elements and laser power densities
- Very interesting phenomena was found: energy of slower ion group of double peak ion current structure always follow a very simple relation (3) with very high accuracy independently on element atomic mass and laser power density.

### ACKNOWLEDGMENT

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