Methods for improving characteristics of laser source of ions

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Abstract. In this work we discuss three methods to improve characteristics of laser source of ions, namely: i) effect of the angle of interaction of laser radiation with targets on the plasma ions characteristics, ii) the use of targets of different densities to improve the parameters of plasma ions, and iii) influence of laser frequency on the plasma parameters. Our study will be based on the analysis of mass-charge spectrum of laser-produced plasma ions for different intensity of laser radiation.

1. Introduction

At present there are number of works devoted to the study of laser-produced plasma as a source of ions for the inertial confinement fusion [1-5] together with heavy ion accelerators and the systems on the base of powerful impulse of electrical charge, i.e. Z-pinches. Laser ion source (LIS) have been recently designed [2-3] to load the Heidelberg electron beam ion trap with a pulsed beam of lowly charged ions from solid elements. Due to many characteristics of laser-produced plasmas LIS takes advantages over e.g. a common metal vapor vacuum arc method [5] as a source of ions. Many theoretical [5,6] and experimental [6,7] works have been carried out in order to optimize the performance of the laser ion source and to determine important operating parameters such as the velocity, mass and charge-state distribution of the generated ion beam and plasma temperature. In this work we discuss three methods to improve the characteristics of the LIS, namely, we study i) the effect of interaction angle of laser radiation with solid targets, ii) the influence of target density and iii) frequency of the laser on the parameters of the plasma ions. Our study is based on the analysis of mass-charge spectra (i.e. time-of-flight spectra) of laser-produced plasma ions. Experiments are carried out on a static laser mass-spectrometer with mass resolution of $m/\Delta m$ ~100 and time-of-flight distance L=100 cm. The duration of the Nd:YAG laser impulse was 15 ns and the power density of the maximal laser radiation at the target surface is $q=10^{11}$ W/cm^2.

2. Effect of interaction angle of laser radiation with Al targets

First, we discuss the effect of the interaction angle α of laser radiation with solid targets (made of Al) on the parameters of laser-produced plasma ions. We conducted experiments on the velocity and energy distribution of ions for large energy range for $\alpha=0^0$ and $\alpha=18^0$ with respect to the normal of the target. Figs. 1 (a,b) show the energy spectra of Al ions obtained at these two angles for $q=5x10^{10}$ W/cm^2. When the laser radiation acts perpendicular to the target surface (i.e. $\alpha=0^0$) ions with maximal charge $Z_{max}=4$ are formed (Fig. 1 (a)). Energy distribution of ions has a maximum and it shifts to higher energies with increasing Z. Single charged ions have rather narrow energy range and intensity compared to multi-charged ions. With increase α to 18^0 the maximal charge of the ions remains unchanged (Fig. 1 (b)). The effect of the interaction angle is seen in the intensity and the maximal energy of the ions. The maximal energy for almost all charge multiplicity decreases with increasing α, which is due to the decrease of effective cross-section of the interaction. With increasing α the intensity of ions decreases (see Fig. 1 (c)). We relate this effect to the change in the recombination process during the plasma expansion, which is supported by the shift of the recombination maxima in the energy spectra. Thus, with changing α we can control the current of small-charge ions without applying and additional equipments.

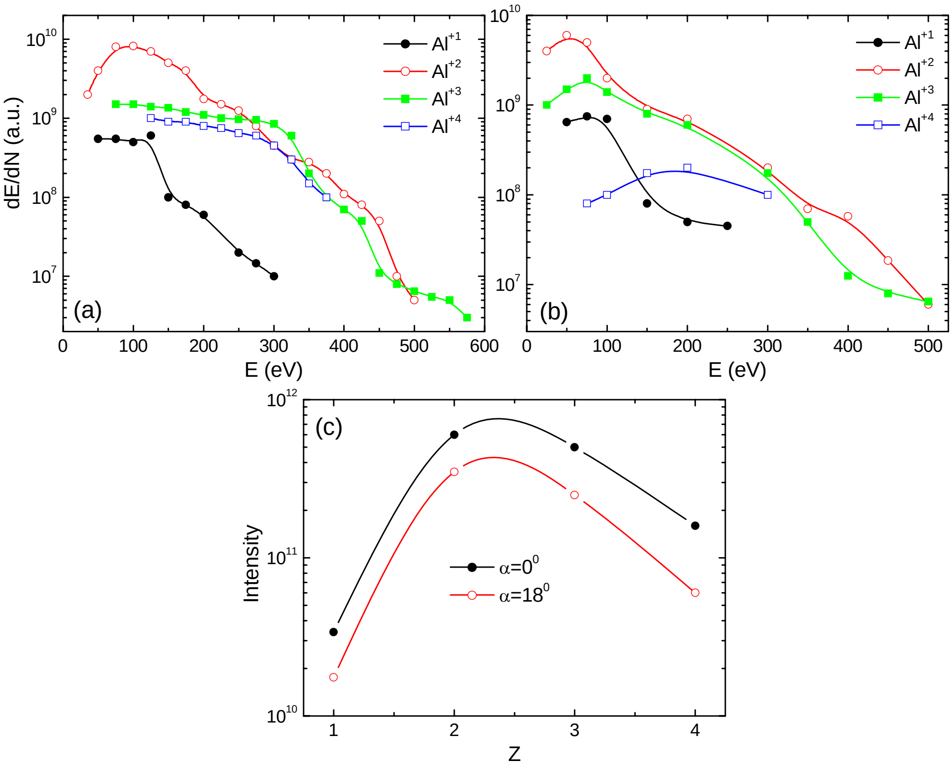

Fig. 1. Energy spectra of Al ions of charge Z=1-4 obtained under the action of laser radiation with $q=5x10^{10}$ W/cm2 for $\alpha=0^0$ (a) and $\alpha=18^0$ (b). (c) shows the intensity of the ions as a function of ions charge Z.

3. Interaction of laser radiation with porous targets

Next, we study the effect of target density on the parameters of laser-produced plasma ions. Targets, made of Ho_2O_3, have densities ρ_0=1.2 g/cm^3 (initial condition-powder), ρ_1=1.4 g/cm^3, ρ_2=2.8 g/cm^3, ρ_3=3.2 g/cm^3, ρ_4=3.5 g/cm^3, ρ_5=3.7 g/cm^3. Plasma is formed on the surface of these targets under the action of laser radiation normal to the target surface and the intensity of the laser was within $q=10^8$-10^{11} W/cm^2. Fig. 2 shows the maximal charge Z_{max} of Ho (solid curves) and O (dashed curves) ions as a function of intensity of laser radiation q for two different values of target density ρ. Regardless on the ions mass, Z_{max} changes non-linear with increasing q. However, Z_{max} strongly depends on ρ – maximal charge of heavy (Ho) ions increases and the one of light (O) ions decreases with increasing ρ.

Fig. 3 shows the energy spectra of ions in Ho_2O_3 plasma obtained at $q=10^{11}$ W/cm^2 for four different values of the target density. For any density of the target, two groups of ions with different spectral range and charge are clearly seen, but the structure and width of energy spectra and intensity and charge of different kind of ions strongly depend on ρ. At low density of the target [Fig. 3(a)] oxygen ions with charge *Z*=1-4 have energies in the range of 25 – 370 *eV*. The maximum charge of *Ho* ions in this case equals to Z_{max}=3 and they have wider energy spectra (50 – 800 *eV*). With increasing target density *O* ions with larger charge (*Z*>2) disappear from the spectra and the energy range of oxygen ions considerably decreases (see Fig. 2(b)). For example, the maximal energy of double charged O^{+2} ions decreases three times for larger $\rho=\rho_2$ compared to the reference sample ($\rho=\rho_0$). *Ho* ions with charge *Z*=4 are detected for ρ=ρ_2 and there is slight increase of energy diapason of *Ho* ions. With further increase of ρ (see Fig. 2 (c)) energy spectra of *O* ions remain unchanged and energy range of *Ho* ions increases. The maximal charge of both kinds of ions remains the same.

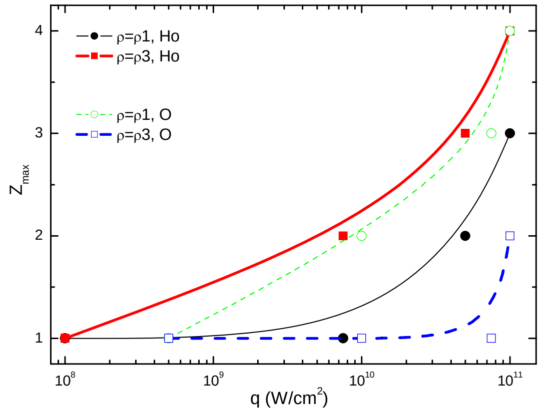

Fig. 2. Dependence of maximal charge Z_{max} of Ho (solid curves) and O (dashed curves) ions in Ho_2O_3 plasma as a function of intensity of laser radiation for the target density ρ_1=1.4 g/cm^3 (thin curves) and ρ_3=3.2 g/cm^3 (thick curves).

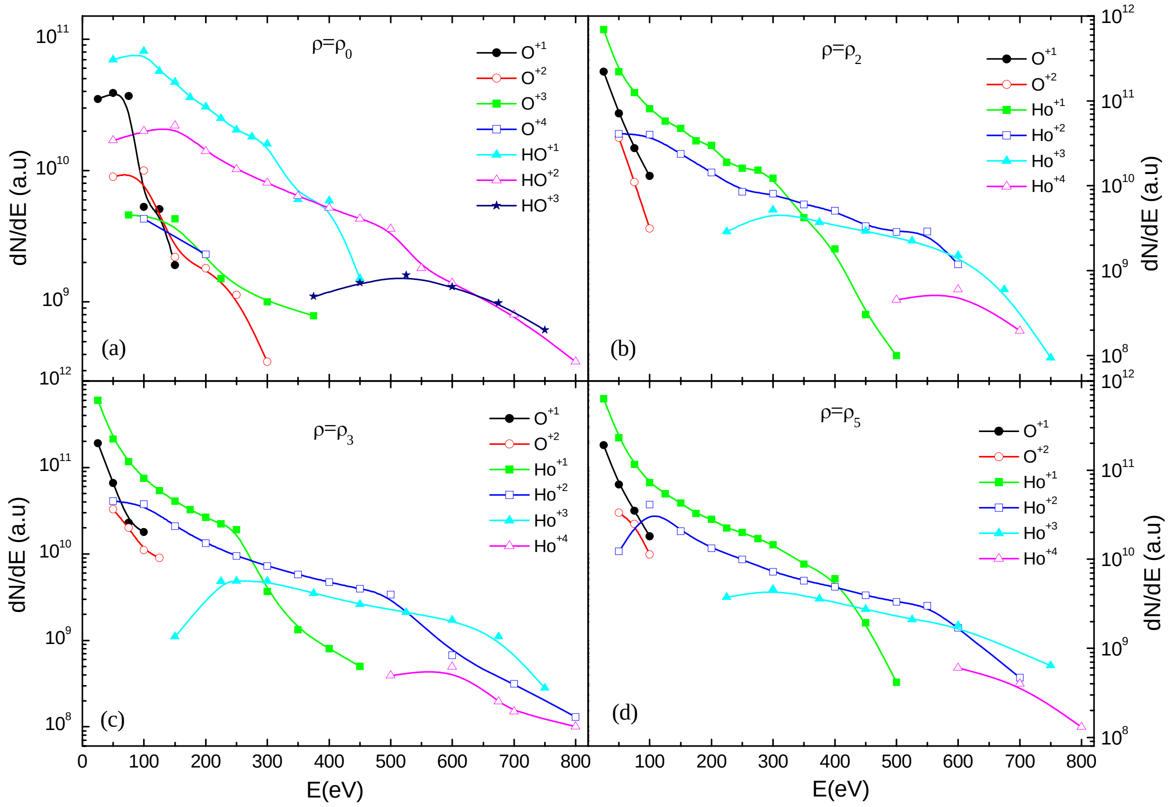

Fig. 3. The energy spectra of ions from two-element Ho_2O_3 plasma for different values of target density: ρ=ρ_0 (a), ρ=ρ_2 (b), ρ=ρ_3 (c) and ρ=ρ_5 (d).

These experimental results can be explained by the nature of the targets. The structure of such porous materials consists of solid particles with different shape alternating with empty spaces. Therefore, the properties of such materials are determined with mass composition, sizes and density of those granules. For small ρ, most of the laser radiation enter deep inside the sample and the radiation is absorbed “volumetrically” due to the “internal evaporation”. In this case decrease of selective recombination losses takes place for multi-charged *O* ions, compared to

Ho ions. Therefore, in this interval of the density ρ maximal charge of *O* ions is higher than the one of *Ho* ions. For larger target density ρ the laser radiation mostly interacts with the surface of the sample. In this case the ionization processes of *Ho* ions predominate and the recombination losses of multi-charge *Ho* ions decrease compared to the one of *O* ions. Therefore, the maximal charge of *Ho* ions is higher than the charge of *O* ions. We have to mention that the characteristics of laser-produced plasma, like maximal charge, energy and intensity of ions does not change with further increasing $\rho>\rho_3$. This indicates that starting from $\rho=\rho_3$ characteristics of our samples become close to the one of solid targets.

3. Effect of laser frequency on the parameters of plasma ions

In this section we investigate the effect of laser frequency, i.e. the frequency of repetition of 15 ns laser impulses, on the formation of plasma ions on the surface of porous Y_2O_3 targets with densities ρ_0=1.2 g/cm^3, ρ_1=1.4 g/cm^3, ρ_2=2.8 g/cm^3, ρ_3=3.2 g/cm^3, ρ_4=3.6 g/cm^3 and ρ_5=3.7 g/cm^3. Here we present our results obtained for the intensity of the laser radiation q= 10^{11} W/cm^2. From the experimental time-of-flight spectra of ions we constructed energy distribution of ions depending both on the target density and the laser frequency. Fig.4. shows the energy spectra of laser-produced plasma ions for $\rho=\rho_0$ (a) and $\rho=\rho_3$ (b) obtained in the mono impulse regime ν=1 Hz. As we have mentioned in the previous section, for $\rho=\rho_0$ O ions has largest charge multiplicity (Z_{max}=4) and they are mostly located in the low energy part of the spectrum (Fig. 4 (a)). Y ions occupy large region in the spectra, due to their heavier mass, and the maximal charge of these ions equals to 3. With increasing the target density O ions with larger charge disappear from the spectra and the energy range of these ions considerably decreases (see Fig. 4 (b)).

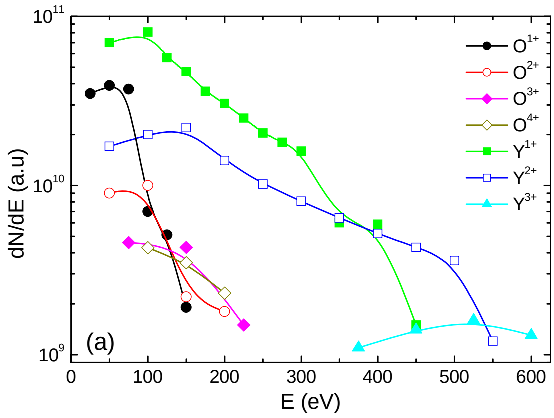

Fig. 4. *The energy spectra of ions from two-element Y_2O_3 plasma obtained for $\rho=\rho_0$ and ν=1Hz.*

Let us now consider the effect of the laser frequency on the energy distribution of the plasma ions. Here we give our results for larger density of the target, so that we neglect the influence of ρ. Fig. 5. shows the energy spectra of ions in Y_2O_3 plasma obtained for the laser frequency ν=3 Hz for two different values of ρ. As we showed above, for $\rho=\rho_3$ (Fig. 5 (a)) O ions are located in a narrow range of the energy (20-200 eV) and their maximal charge is unchanged compare to lower density case (see Fig. 5 (b)). Y ions are located in the energy interval 20-800 eV with Z_{max}=3. This small increase of the laser frequency affects only on the intensity of the ions: O ions of both charge increases, while the intensity of heavy ions considerably decreases with increasing ν.

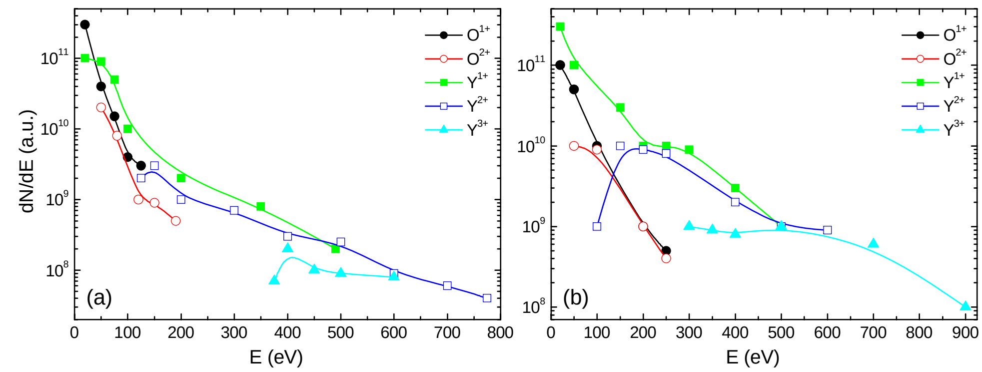

Fig. 5. *The energy distribution of ions in two-element Y_2O_3 plasma obtained at ν=3 Hz and for two different target density: $\rho=\rho_3$ (a) and $\rho=\rho_5$ (b).*

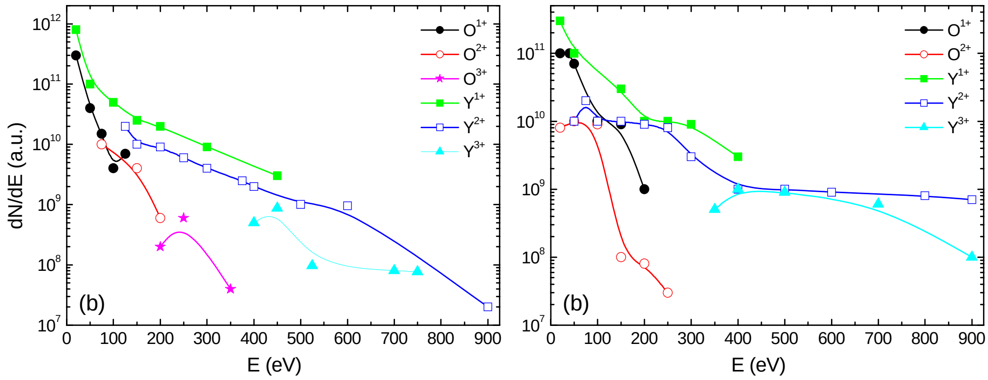

Fig. 6. *The same as Fig. 5, but for ν=10 Hz.*

Fig. 6 (a) shows the energy spectra of ions obtained for larger frequency of the laser (ν=10 Hz). The effect of the laser frequency is quite evident from this figure. First, O ions with charge Z=3 appears in the spectra. Second, the energy spectra of both light (O) and heavy (Y) ions expand to higher energies. Now O ions can be detected in the energy interval 20-350 eV and Y ions in the energy range 20-900 eV. Fig. 7 (a) shows how the maximal energy E_{max} of ions of different charge changes with ν for $\rho=\rho_5$. Interesting to note that with increasing ν E_{max} of oxygen ions and single charged Y ions increases first and for larger ν it decreases again. Whereas E_{max} of highly charged Y ions increases with ν. The same dependence on the laser frequency is obtained for the intensity of the ions (see Fig. 7 (b)).

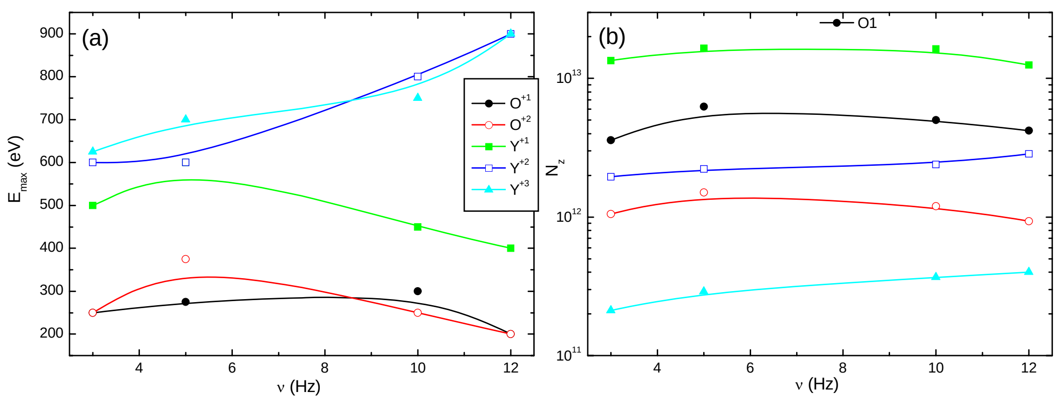

Fig. 7. *The maximal energy (a) and the intensity (b) of Y_2O_3 plasma ions as a function of ν for $\rho=\rho_5$.*

We also studied the dependence of the impulse of the ions beam on the laser frequency. Tabs. I and II presents the duration of ions impulse *t* for different density of the target and laser frequency. From these data we see a nonlinear dependence of *t* on ν. For both kind of ions and for all charge multiplicity the largest impulse duration corresponds to the frequency ν=5 Hz.

Tab. I. Impulse duration of Y ions for different target density and laser frequency.

Y	1.4(gm/cm^3)				2.8(gm/cm^3)				3.7(gm/cm^3)			
	3 Hz	5 Hz	10Hz	12 Hz	3 Hz	5 Hz	10 Hz	12 Hz	3 Hz	5 Hz	10 Hz	12 Hz
1	21.9	30.3	18.2	21.5	17.9	27.1	17.1	21.3	12	18.8	17.7	14.5
2	18.9	21.4	14.6	17.8	12.7	17.4	15.4	17.7	13.5	11.6	11.1	10.7
3	8.4	8.2	13.6	5.5	4.9	9	5.2	4.2	15	10	11.7	12.2
4						1.3						

Tab. II. The same as Tab. I but for O ions.

O	1.4(gm/cm^3)				2.8(gm/cm^3)				3.7(gm/cm^3)			
	3 Hz	5 Hz	10Hz	12 Hz	3 Hz	5 Hz	10 Hz	12 Hz	3 Hz	5 Hz	10 Hz	12 Hz
1	31	34.7	33.5	23.8	34.9	36.3	28.7	30.8	39	39.9	32.5	27.2
2	24.5	29.8	24.9	29.1		24.6	19.2	21.7	26.5		22.1	36.3

We have found that the charge composition and the total current of the ions are strongly affected by the frequency of the laser. This is, to our understanding, due to the change of the focusing condition of the laser radiation on the surface of the targets. The radiation of the laser working in the frequency mode does not only heats the surface of the target but it also forms craters with noticeable sizes, which can strongly change the focusing condition of the laser radiation during the interaction process [2]. The later is due to the fact that the ionization process and the expansion of multi-charge ions take place at small time interval than the time between the impulses and additional thermal processes take place on the surface of the target. Therefore, by the change in the focusing condition – the place of the focal spot or formation of craters, as well as using laser in frequency mode, one can control charge and energy spectra of ions obtained from the surface of two-element targets under the action of laser radiation.

Conclusions

We have studied the effect of target density, the interaction angle α of laser radiation, as well as the effect of laser frequency on the parameters of plasma ions. For small angles (α=0-18^0) the effect of α is clearly seen in the maximal energy and the intensity of plasma ions – the maximal energy of ions decreases, the intensity of small charge ions decreases and the intensity of highly charged ions increases with increases with increasing α. We relate this effect to the change in the recombination process during the plasma expansion, which is supported by the shift of the recombination maxima in the energy spectra to higher energies. Experimental results show the strong dependence of plasma parameters of the density of the target – the maximal charge for light ions is reached at low densities, while maximal charge of heavy ions is obtained at higher target densities. This effect is the results of non-equilibrium ionization processes in the plasma due to the changing of the volume, which absorbs laser radiation. We have shown that with increasing the frequency of the laser the charge, energy and intensity of ions increase for a given parameters of the target. Although, this effect is more pronounced for small densities of the target, significant influence of the laser radiation is observed for larger values of the target density. We related this effect to the change in the focusing condition of the laser radiation due the formation of clusters on the surface of the target.

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