

Improvement of Characteristics of Laser Source of Ions by changing the interaction angle of laser radiation

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Abstract

Using the time-of-flight mass-spectrometer with an electrostatic analyzer we studied the effect of interaction angle of laser radiation θ on the properties of laser-produced plasma ions. We found that both the energy, as well as the charge of the ions are maximum at small angles ($\theta \le 20^\circ$), where the absorption of the laser radiation is maximal. With increasing θ from 20° to 70° the intensity of single charged ions increases while the intensity of highly charged ions are not much affected (slightly decreases). Analysis of energy spectra of ions shows that with increasing θ the shape of energy spectra for ions with charge Z \ge 1 practically does not change, although the maximum of the distribution shifts to lower energies

I. Motivation

It is well known that laser source of ions is capable to provide larger intensity of ions for the injection of ions into different kinds of accelerators [1-4]. For the practical applications one has to be able to increase the intensity and duration of the ions pulse keeping the charge of the ions fixed. There are several methods to increase the duration of the ions' pulse [5-7] by changing either the parameters of the laser (e.g., the intensity, frequency, laser pulse duration etc.) or the properties of the target itself (e.g., target composition, structure, density, etc.). We have recently shown that [6] the intensity of the ions can be increased by smoothly changing the concentration of the light element in two-element PbMg targets. It was found experimentally that the energy spectra of ions broaden for more than 2 times and the duration of the ions' pulse increases for more than 10 times with increasing the concentration of Mg in the target. At the same time the energy spectra of ions of both Mg and Pb is larger than spectra of ions in a single component plasma. These effects were explained by the energy transfer between the light and heavy ions. In Refs. [7,8] the mass-spectrometric method has been used to investigate formation

process of laser-plasma ions depending on the density of porous Ho_2O_3 targets. It was found that at small targets densities highly-charged oxygen ions are formed in the lower energy part of the spectra. With increasing the target density the charge of the oxygen ions decreases and highly-charged Ho ions are registered. The reason for such an effect was shown to be the instabilities in the ionization process due to the change of the volume of the target which absorbs the laser radiation. Ref. [9] was devoted to study the characteristics of multi-charged ions, generated on the surface of the Al target under the action of laser radiation working in the frequency mode. It was shown that with increasing the frequency of the laser (i.e., the repetition of the laser pulses) the focusing condition of the laser radiation changes resulting in nonlinear increase of the intensity and energy of plasma ions.

II. The aim

In this work we conducted systematic studies of the effect of the interaction angle of the laser radiation with the target (θ) on the parameters of the laser-produced plasma ions. This problem has already been addressed by several authors in the past [10-12], however some of the conclusions in those works were contradicting. For example, the optimal angle for the formation of the ions was shown in Ref. [10] to be $\theta = 30^{\circ}$, while the other values of optimal θ was given in Refs. [11, 12]. This difference could be due to the different initial conditions for the experiments. Therefore, we have conducted systematic studies (in the same initial conditions) of the effect of θ on the formation process of multi-charged plasma ions. It is known [13] that for certain parameters of the laser radiation and geometry of the experiment electric field in the plasma region with a critical density sharply increases and oscillation in the electron density takes place. The electrons in this critical region accelerate and collection of high energy electrons are formed [14]. The emission of these electrons is restricted by the self-consisting electric field generated due to electron-ion separation. Taking into account the effect of the increase of the longitudinal component of the electric field in the region of the critical density we expect that for certain values of θ the parameters of the laserproduced plasma can be improved.

III. Experimental setup



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Experiments were carried out on a static mass-spectrometer with mass resolution of dm/m = 100 and time-of-flight distance 362 cm [see Ref. [15] for more details of the experimental setup]. Nd:YAG laser was operated at 1.06 μ m wavelength, 50 ns pulse duration, 5 J pulse energy and in a single shot mode. The laser beam was focused through a convergent lens on a target with diameter 100 μ m placed inside a vacuum chamber pumped down to 10⁻⁶ Torr. The size of the focused beam spot was 10⁻⁴ cm². The power density of the laser radiation on the surface of the target was in the range $q = 10^8 - 10^{12}$ W/cm². The target could be moved vertically with the vacuum feed through, so that each laser shot could hit a fresh surface to avoid the effect of crater formation. The surface of the targets was cleaned by the first pulse of the laser and the results presented here were averaged over the next 4 pulses. The error in measuring the mass-charge spectra of ions is 10%.

IV. Experimental results and discussions

It is known that with decreasing θ (at constant power density of the laser radiation) the part of the absorbed by the plasma energy increases. This leads to the increase of the maximal charge Z_{max} and intensity of ions. Typical examples of the experimentally obtained time-of-flight spectra of Al ions are shown in Fig. 1 for $\theta = 18^{0}$ (a), $\theta = 30^{0}$ (b) and $\theta = 60^{0}$ (c). In this particular case the charge of the ions decreases from 9 to 6 with increasing θ . It is known that [12] at angles $\theta > 60^{0}$ the interacting laser radiation is less absorbed by the expanding plasma. Therefore, parameters of the emitted from the plasma multi-charge ions are only determined by physical properties (optical, thermal) of the target. At angles less than 60^{0} the plasma starts to absorb the laser radiation which leads to increased charge of ions. Sharp increase of the maximal charge of ions close to $\theta = 18^{0}$ ($\pm 5^{0}$) is observed for all studied targets.



Fig. 1: The time-of-flight spectra of Al ions obtained at q=7 10^{11} W/cm² for (a) $\theta = 18^{0}$, (b) $\theta = 30^{0}$ and (c) $\theta = 60^{0}$.

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Experimental results show that the ability of plasma to absorb the laser radiation strongly depends on the angle θ : the plasma becomes more transparent for the radiation with increasing θ . We also found that with increasing θ the threshold intensity of the laser radiation for the formation of plasma increases. For example, it increases from 10^8 W/cm² to 3 10^8 W/cm² with increasing θ from 15^0 to 60^0 . Analysis of the experimental data has shown that regardless of the mass of the target element the threshold intensity of the laser considerably increases at angles $\theta \ge 60^{\circ}$. Dependence of plasma formation efficiency on θ can be seen from the change of the energy spectra of single-charged ions: with decreasing θ the energy of these ions increases and their structure becomes simpler. This change in the structure of energy spectra of single-charged ions suggests that at small angles the efficiency of secondary processes considerably decreases in the system. We can assume that this is due to the decrease of the time of interaction of plasma with the target resulted from the large hydrodynamic acceleration.

Experimental results also show that the decrease in θ leads not only to the increase of the intensity of the present ions, but it also results in the appearance of ions with larger charge. For example, at the laser intensity q=7 10⁻¹¹ W/cm², the maximal charge of Al ions increases from Z_{max} =5 to Z_{max} =9 with decreasing θ from 70⁰ to 15⁰ (see Fig. 1). Such sudden increase of the ions' charge at θ <20⁰ is independent on the

atomic mass of the target element and observed for all the studied samples. Of course, the maximal charge of the plasma ions depend on the intensity of the laser radiation as shown in Fig. 2. In this figure we compared our finding with the analytical results (dashed curve) obtained in Ref. [16, 17, 18] – a good agreement is seen at smaller intensities of the laser radiation. However, at larger laser intensities we observed divergence of these two results. To our understanding, this discrepancy could be due to the fact that theoretical results are based on the assumption that there is a thermodynamic equilibrium in the plasma. However, at present there is no physical model which takes into account all the processes of ionization and recombination and could give good agreement with the experimental results.



Fig. 2. Dependence of the maximal charge of Al ions on the intensity of the laser radiation (solid curve) for the interaction angle of the laser radiation with the target $\theta=18^{\circ}$. Dashed curve presents the analytical estimate [16] of the maximal charge of ions.

We also found that the decrease in θ leads not only to the increase of the charge of the ions but it also influences the formation process of the energy spectra of ions. For example, the energy spectra of ions expand both to larger and smaller energies;

12 IAEA Fusion Energy Conference 8 -13 October 2012, San Diego, USA. smaller the angle θ the larger is the shift of the maximum of the energy distribution. The efficiency of the change of the energy spectra with changing the interaction angle depends on the target material. For example, the maximal energy of ions in the plasma increases with increasing the mass of the target element as shown in Fig. 3. However, the behavior of the E(m) curve strongly depends on the interaction angle – the (quasi-) linear dependence at larger angles is changed to power-low dependence at smaller angles.



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Fig.3. Dependence of the maximal energy of ions on the mass of the target elements for different θ at $q = 10^{12}$ W/cm².



Fig. 4. Dependence of the maximal energy of ions on the laser intensity q for different interaction angles.

Figure 4 shows the effect of θ variation on the dependence of the maximal energy of ions on the laser intensity. It is seen from this figure that E_{max} increases almost linearly with q at larger interaction angles. Sharp increase of E_{max} is observed for

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smaller θ (< 20⁰) for q > 5.10¹¹ W/cm².

Next we study the temporal characteristics of the plasma ions. We found that independent on the mass of the target element with decreasing the angle θ the duration of the ions' current increases. As shown in Fig. 5, at the same energy the duration of ions pulse increases from 50 µs to 100 µs with decreasing the angle from $\theta = 70^{0}$ to $\theta = 18^{0}$. With decreasing θ the time of ions arrival to the detector becomes smaller. For example, Al⁵⁺ ions generated at $\theta=70^{0}$ reaches the detector at 11 µs, while such ions reach the detector at 7 µs for $\theta=18^{0}$. We found that with decreasing θ the time interval between two consecutive ions signals with given charge decreases.



Fig. 5. Temporal characteristics of Al ions generated under the action of the laser radiation of intensity q=7 10¹¹ W/cm² for angles =70⁰ (a), =30⁰ (b) and =18⁰ (c).

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Duration of ions of given charge dt dependence on the charge of the ions, as shown in Fig. 6: larger the charge smaller the dt. This time interval also depends on the interaction angle θ - with decreasing θ the time interval of all charge increases.



Fig. 6. Duration of Al ions packet vs. the ions' charge at different θ .

It is clear that knowing the temporal characteristics of the multi-charged ions, one can easily determine their amount which is detected. Fig. 7 shows the results of such calculations. It is seen from this figure that at $\theta = 30 \div 70^{\circ}$, the amount of ions with ¹⁷ IAEA Fusion Energy Conference 8 -13 October 2012, San Diego, USA. given charge is similar to each other. At $\theta = 18^{\circ}$ the amount of ions is more than at the other angles θ . This figure allows one to determine the total amount of ions if we know that data for given charge.

Thus, with changing θ we can manipulate the time of ions' expansion, duration of the whole ions packet, as well as ions of given charge. The largest amount of ions are obtained at $\theta = 18^{\circ}$.



Fig. 7. The total amount of multi-charge Al ions at different θ .

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Fig. 8. The total amount of Al ions as a function of the laser intensity for different θ .

Mutual analysis of the energy and time characteristics of plasma ions obtained at different θ , shows that ions generated at small angles obtain larger initial and final

velocity during the formation and expansion process. As the recombination loses are proportional to ions speed, it is obvious that decreasing the interaction angle is one of the methods to decrease the efficiency of recombination loses. The proof is the increase of the duration of ions packet with any charge, as well as the increase of the total amount of ions arriving to the detector:

$$N_{z} = \frac{1}{\varepsilon(m, z)} \int_{0}^{\tau} \frac{dN}{dtd\,\Omega} dt \tag{1}$$

Where, ε (m,z) is the efficiency of the detector, which is proportional to the charge of ions $\varepsilon \sim Z$ [13,14], and Ω is aperture of the detector. The total amount of ions obtained at different θ , is shown in Fig. 7. It is seen from this figure that with decreasing θ from 70⁰ to 30⁰ the amount of ions does not increase considerably. However, at smaller angles ($\theta < 20^{0}$) this amount increases suddenly. Taking into account that minimal threshold for the plasma formation and maximal absorption of the laser radiation is obtained at these angles, we can relate the increase of the amount of ions with given charge not only to the larger charge state of the plasma at the initial stage and decrease of the efficiency of the recombination processes, but also to the formation of large amount of ions. We obtained total amount for ions of each charge state for different values of the laser intensity as shown in Fig. 8. We observed considerably increase of the amount of ions with decreasing θ from 30⁰ to 18⁰.

4. Conclusions

Using the static mass-spectrometric method we conducted systematic study of the effect of the interaction angle of the laser radiation on the formation of charge and energy characteristics of multi-charge ions of laser-produced plasma. We found that the interaction angle is one of the main tools to manipulate the efficiency of the physical processes on the stage of absorption of the laser radiation, formation, ionization, acceleration and expansion of the plasma. Sudden increase of the charge, energy and intensity of the plasma ions are observed at the resonant absorption of the laser radiation by the plasma.

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