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# The impact of laser radiation frequency on the formation of the main characteristics of ions in a mono-element laser plasma

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**Abstract.** The purpose of these studies is to study the patterns of development of the characteristics of multiply charged ions in the plasma generated during the interaction of laser radiation with a target operating in the frequency mode. The characteristics of multiply charged ions in mono-element aluminum plasma were studied using laser time of flight mass spectrometers. By changing the laser radiation power in the range from 0.1 to 100 GW/sm² and different pulse repetition frequencies (1, 3, 5, 10, and 12 Hz), spectra of charged ions of the plasma formed in each case were obtained.

## 1 Introduction

It is known that the problem of studying the properties of multiply charged ions has always attracted the attention of scientists, although, naturally, at different periods of time, the main interest lay in different aspects of this problem. An analysis of scientific publications on the study of multiply charged ions in laser plasma has shown that most research is focused on the creation of laser thermonuclear fusion, while the properties of multiply charged ions in laser plasma, depending on the parameters of laser radiation and the properties of the target, remain insufficiently studied. There is also no systematization of the available data. Consequently, the problem of studying the properties of multiply charged laser plasma ions and their practical application remains very relevant [1].

All studies carried out on the problem of interaction of laser radiation with matter can be divided into two parts: the early stage of the action of radiation during a time comparable to the pulse duration, characterized by small distances from the place of formation of the laser plasma, and the far zone, i.e., research in the later stages of laser plasma development. In both cases, their own methods for studying laser plasma have been developed. In the near zone, the density of particles in a plasma bunch is in the range of $10^{22}$–$10^{15}$ sm$^{3}$, and the electron temperature is Te ~ 1 eV÷1000 eV, and therefore it is effective to use photographic

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methods of plasma analysis, which make it possible to measure changes in temperature and plasma density at different time intervals, and also obtain estimates of the average speed of movement of the plasma clot. Measuring such plasma characteristics is very important for constructing theoretical models of plasma absorption and heating processes [2-4].

It is known that the problem of studying the properties of multiply charged ions has always attracted the attention of scientists, although, naturally, at different periods of time, the main interest lay on different aspects of this problem. An analysis of scientific publications on the study of multiply charged ions in laser plasma has shown that most research is focused on the creation of laser thermonuclear fusion, while the properties of multiply charged ions in laser plasma, depending on the parameters of laser radiation and the properties of the target, remain insufficiently studied. There is also no systematization of available data. Consequently, the difficulty of studying the properties of the charge to be multiplied laser plasma ions and their practical application remains very relevant [5-8].

Issues related to the study of physical processes leading to the formation of the spectrum of multiply charged ions, as well as elucidation of the mechanism for increasing recombination losses on multiply charged ions during the transition from a single-element laser plasma generated near the threshold laser power, are the main aspects considered in this study [9-11].

## 2 Experimental arrangements

To study the properties of multiplicity charged ions of monatomic aluminum plasma were carried out using laser time of flight mass spectrometers.

To obtain reliable experimental results, the parameters of the laser system are critical. It is necessary to strictly control such characteristics of laser radiation as angular divergence (not exceeding $10^{-4}$ radians), uniform distribution of the light flux in the cross-section of the beam, minimal fluctuations in energy (0.2÷0.3 J) and pulse duration. In this study, a solid-state Nd:YAG laser was used with the following technical characteristics: laser wavelength 1064 nm, laser pulse energy 0.8÷1 J, laser pulse repetition rate 1÷50 Hz, the diameter of the laser beam at level 0.9 does not exceed 8 mm, the duration of the laser pulse is at 15 ns, the angular divergence of laser radiation at level 0.5 does not exceed 6 millimeters per radian, the coefficient of symmetry of the laser radiation energy density distribution, measured in two mutually perpendicular planes within the beam diameter at the level of 0.9%, does not exceed 20.

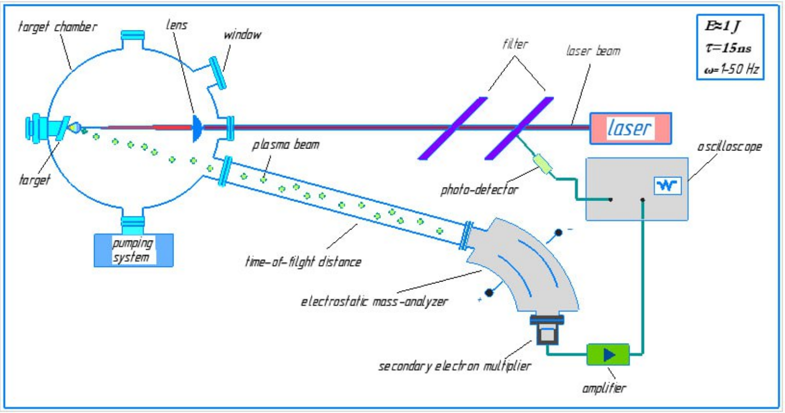

**Fig. 1.** Experimental setup.

The advantage of this laser device is the high stability of the radiation, while the energy spread does not exceed 8%. This is achieved by optimizing the laser operating mode and experimental conditions. The targets must be located in a vacuum chamber at the same initial vacuum (vacuum up to $10^{-6}$ Torr) and under conditions that allow the location of the laser radiation to change from pulse to pulse. The laser radiation parameters are as follows: power density $q = 10^{11}\ W/sm^2$; the radiation focusing area is about $10^{-4}$ $sm^2$ (Figure 1).

The laser time of flight mass spectrometer, combined with a cylindrical electrostatic energy analyzer, had a mass resolution of $m/\Delta m=100$ and a particle flight distance of 100 cm. Its aperture ratio and time resolution were sufficient to study the physical processes of heating and plasma formation depending on the parameters and angle of incidence of laser radiation on the target, its density and the operating mode of the solid-state laser. The targets were made of aluminum in the form of a thick cylinder with a thickness of d=2 mm and a radius of R=0.5 cm.

## 3 Results and discussion

Ions emitted from the surface of solids were detected by a laser beam at a distance of 100 cm from the target, and the dimensions of the entrance and exit slit were approximately 0.4 mm. The experiments used a Nd:YAG laser operating at a frequency of *v=1, 3, 10,and 12 Hz*. Its radiation was directed at the target perpendicular to its surface, that is, the impact angle was u=0°. The laser radiation duration was 15 ns, the radiation power density on the target surface varied in the range $q=0.1–100\ GW/sm^2$. Note that in the frequency mode of laser operation, each experimental value is averaged over five series. When the laser operates in a single-pulse mode, there are five acts of laser radiation impact on the target. In both operating modes of the laser, the experiments were carried out under the same initial conditions: the vacuum in the ion source chamber and throughout the entire drift space was maintained at a level of $10^{-6}$ torr; the location of the target, conditions for focusing radiation, parameters of the mass spectrometer, recording equipment for plasma ions, etc. were completely preserved. The laser radiation, operating with a pulse repetition frequency *v =1–12 Hz*, interacted with the target surface also with the same (series) number of laser “shots”. The power density of the laser radiation on the surface was varied using light filters and monitored using a photoelectric detector. At different levels of laser radiation power density $q=0.1–100\ GW/sm^2$ and different pulse repetition frequencies (*1, 3, 5, 10, and 12 Hz*), the charge spectra of plasma ions, which are formed in each of these scenarios, were recorded. It should be noted that in the obtained mass-charge spectra of the plasma created under the influence of laser radiation on this target, regardless of the repetition frequency, a weak signal of a singly charged oxygen ion, present as a contaminant on the *Al* surface, is observed. The signals of oxygen ions are easily distinguishable because they do not overlap with the signals of *Al* ions, regardless of their charge.

Based on the mass-charge spectra of the plasma obtained at different laser v, the dependencies of the ion intensity (that is, the number of ions) on the charge multiplicity Z were constructed. It was experimentally established that in the plasma formed when *Al* is exposed to laser radiation with $q = 100\ GW/sm^2$, regardless of v of the laser, the maximum charge factor of *Al* ions is $Z_{max}=+4$. However, with increasing v of the laser, the intensities of singly charged $Al^{1+}$ ions change nonlinearly, and the intensities of ions with Z>1 increase. The dependence of the number of *Al* ions on their charge Z, characteristic for each laser *v*, is shown in Figure 2.

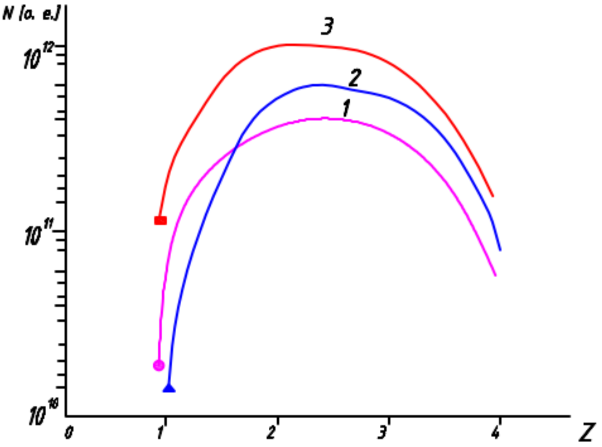

**Fig. 2.** Dependence of the number of *Al* ions on Z, formed u=0°' $q=10^{11}$ $W/sm^2$ at $v$=1, 3, 5 Hz.

From the above figures it is clear that with an increase in v from *1* to *12 Hz* there is a noticeable increase in the yield of ions with Z>+1, and the yield of $Al^{1+}$ ions, registered in the case of $v$ = *1–10 Hz* decreases by an order of magnitude, but at $v$ 12 Hz its significant increase is observed. Based on the charge spectra obtained at $v$ = *1, 3, 5, 10, and 12 Hz,* the energy spectra of plasma ions formed when the laser radiation power density changes in the range $q=0.1–100$ $GW/sm^2$ are constructed. Typical energy spectra of multiply charged *Al* Z=+1–+4 ions recorded in the case when $q=100$ $GW/sm^2$, and $v$ =5 and $v$ =*12 Hz*, are shown in Figure 3.

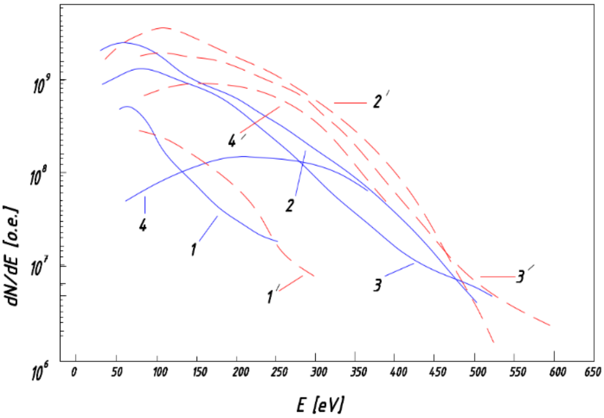

**Fig. 3.** Typical energy spectra of *Al* ions with Z=+l–+4, obtained at $v$ =5 Hz (dashed line), $v$ =12 Hz (solid line), u=0°; $q=l0^{11}$ $W/sm^2$. Where 1–4 and 1'-4' are the charge of Z ions.

From Figure 3 it can be seen that the energy spectra of singly charged *Al* ions have a narrower range of energy distribution and a lower yield relative to more highly charged ions (with Z>+1). It was determined that at high frequencies of laser radiation ($v$ = 12 Hz) the maximum yield of high-energy ions occurs. Furthermore, it should be noted that when laser radiation is incident on the aluminum surface perpendicular to the target surface, the ion yield is greater. Also, it has been shown that the spectra of aluminum with charges from one to four (*Al* with Z=+1–+4) have a maximum energy distribution. At the same time, as Z increases, the tendency for the spectrum maximum to shift remains.

It has been determined that the pattern of formation of the spectra of aluminum ions with charges from one to four (*Al* with Z=+l–+4) changes depending on the frequency (*ν*) of laser radiation: the intensity of aluminum ions with Z>+1 increases significantly with increasing frequency of laser radiation (*ν*=1 Hz to 12 Hz), and the distribution range of the energy spectra not only expands, but also shifts towards higher energies. Changes in the yield patterns and energy spectra of ions with a certain charge that occur with increasing *ν* of laser radiation indicate changes in the efficiency of ionization processes occurring on the target surface. Apparently, this is due not only to the fact that when pulsed - periodic action of laser radiation on the same point of the target changes not only the conditions of its focusing on the surface, but also the conditions of heating and evaporation of the target substance, as well as the formation and heating of a plasma clot.

The intensity and high energy output of multiply charged aluminum ions emitted under the action of perpendicular incidence of radiation on the target, and their emission from the ionized medium, increase with increasing laser radiation power density. This is due to a decrease in the number of low-charge ions and an increase in the degree of “hardening” processes of multiply charge ions in the ionized medium.

This explanation is supported by results where the influence of laser radiation focusing conditions on the charge and energy spectra of ions emitted from the surface of solids was studied. The design of the ion source chamber made it possible to smoothly change the location of the focal spot of laser radiation up to *4 mm* in both directions relative to the original focusing point located on the target surface. This was done by moving the lens. However, at the same time, the power density of the laser radiation at the interaction point was adjusted so that it did not change. It was revealed that the $Z_{max}$ of ions is obtained not with precise focusing but with some removal of the focal spot, both into the volume and from the surface of the target. In this case, it is necessary to change the position of the focal spot; the higher the ion charge.

## 4 Conclusion

At different laser radiation power densities (from *0.1* to *100 GW/sm²)* and pulse repetition rates (*1, 3, 5, 10, and 12 Hz*), charge spectra of plasma ions formed in each case were obtained. It is important to note that in these spectra, regardless of the repetition rate, there is a weak signal from the singly charged oxygen ion present as a contaminant on the *Al* surface. The highest release of high-energy ions was found to occur at higher pulse repetition rates of *12 Hz* during intermittent laser exposure. The signals of oxygen ions are clearly distinguishable and do not overlap with the signals of *Al* ions of any charge.

## References

1. M.R. Bedilov, K.B. Beisembaeva, I.Y. Davletov, Phys. Solid State **44**, 1093 (2002).
2. J. Krása, L. Láska, K. Rohlena, M. Pfeifer, J. Skála, B. Králiková, P. Straka, E. Woryna, J. Wolowski, Appl. Phys. Lett. **75**, 2539 (1999).
3. M.H.A. Shaim, H.E. Elsayed-Ali, Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and Atoms **356–357,** 75-80 (2015).
4. M. Hanif, M. Salik, M.A. Baig, Opt. Lasers Eng. **49**, 1456 (2011).
5. O. Balki, H.E. Elsayed-Ali, Rev. Sci. Instrum **87,** 113304 (2016).
6. J.S. Lash, R.M. Gilgenbach, H.L. Spindler, Plasma Sources Sci. Technol **4**, 511 (1995).
7. S. Mehrabian, M. Aghaei, S.H. Tavassoli, Phys. Plasmas **17,** 043301 (2010).

8. Q.A. Abbas, Iraqi J. Sci. **60(6),** 1251-1258 (2019).
9. V. Apollonov, S. Silnov, Int. J. Phys. Study Res. **1**, 11 (2018).
10. H. Hegazy, E. AlAshkar, H.H. Abou-Gabal, M.N. Aly, N. Hamed, IEEE Trans. Plasma Sci. **42**, 1674 (2014).
11. S. Hafeez, N.M. Shaikh, B. Rashid, M.A. Baig, J. Appl. Phys. **103** (2008).