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SPECTRA OF MULTIPLY CHARGED IONS IN LASER PLASMA FORMED FROM GAS-CONTAINING TARGETS[†]

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The paper presents the results of a study of the charge and energy characteristics of multiply charged ions excited on the surface of a single-element and hydrogen-containing multi-component element targets under the influence of laser radiation with a power density *($q=10^8$-10^{12} W/cm^2)*. It has been experimentally shown that, for all used values of *q* laser radiation, laser-induced plasma from gas-containing targets is characterized by a lower relative yield (dN/dE) of multi-charged ions with a charge number of Z>+3, compared to the plasma produced on the surface of the single element target. Moreover, the tendency to reduce dN/dE of multi-charged ions of the multi-element target, in comparison with the relative yield of ions from the plasma of the single-element target, is more significant and it depends on the charge of the excited ions. The increase in the charge and energy state, duration, and yield of ions of the heavy component, which occurs with an increase in the content of the light component in the target, has been established. This is explained by a decrease in the efficiency of recombination processes caused by an increase in the expansion velocity of a plasma plume due to a decrease in its average mass.
Keywords: *Laser-induced plasma, Multiply charged ions, Mass spectrometer, Energy spectrum, Hydrogen-containing two-element plasma, Recombination processes*
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1. INTRODUCTION

The need for a highly efficient source of multiply charged ions has increased significantly due to the emergence of a new direction in the controlled thermonuclear fusion - inertial fusion on heavy ions. Heavy ions are attractive because of the charge features of their interaction with the target material. First of all, this is a strong deceleration of ions in a substance, which makes it possible to provide a high level of heating. In addition, the ion's high energy makes it possible to get by with relatively small currents. The laser ion source is considered one of the leading contenders for participation in the international program on controlled thermonuclear fusion [1–3].

At present, three types of ion sources are considered contenders for participation in the controlled inertial thermonuclear fusion (ITS) program: electron-beam, electron-cyclotron-resonance, and laser. An analysis of their comparative characteristics allows us to conclude that the most promising is the laser source of ions.

A laser-plasma generator (LPG) is a system of a high-power frequency laser, a chamber for interaction with a target, and a device for extracting a high-current ion beam. The system makes it possible to generate intense streams of highly ionized atoms and nuclei of various elements, including radioactive isotopes, and to inject them into electrophysical devices. The experiments showed that to match the ion source with various accelerators fully. It is necessary to reduce the current of low-charged ions and increase the current of highly-charged ions. Controlling the laser power density and selecting various single-element targets to increase the yield and charge of ions did not give the expected outcome [4]. In order to increase the efficiency of ionization processes in a plasma plume and reduce the efficiency of recombination processes, intensive studies are being carried out on the charge and energy state of mono- and multi-element laser plasma. As well as the release of ions from them, depending on the incident angle [5] and the laser wavelength, the conditions for its focusing on the target surface [6,7], the composition of a multi-component target [8,9] and the percentage (or weight) ratio of its constituent components of the target [10], its density, the state of the structure after various types of treatments [11], the presence of certain impurities, the frequency mode of exposure [12].

The formation of multiply charged ions is associated with the absorption of most of the laser radiation energy in the plasma and gradual ionization due to a decrease in the ablation rate with an increase in the laser radiation power density [13]. Creating multiply charged high-order ions is possible using ultrashort fs-pulsed laser radiation, which has a low light flux compared to short *ns*-pulsed laser radiation [14, 15]. The time evolution of the formation of multiply charged ions under the action of *ns* and *fs* pulsed laser radiation on carbon was studied [16, 17].

The term "monoelement target" can be used conditionally since, in real conditions, arbitrary solid material contains light adsorbed gases, such as H and N, which, at a certain content, can not only change the physical properties

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of the object under consideration but, in a certain degree, also affect the efficiency of the processes of its interaction with intense laser radiation, the formation and expansion of the resulting plasma plume.

Detailed and systematic studies are required to obtain a complete physical picture of the formation processes and multi-component plasma expansion depending on the composition of the target in the presence of various impurities. Here, attention must be paid to the factors like charge impurities, energy, angular and dynamic distributions, and the yield of multiply charged ions. Eventually, one can estimate the effectiveness of the kinetic processes of ionization, acceleration and recombination, the prevalence, under certain conditions, of one or another process, and the presence of other processes that affect the characteristics of multiply charged ions.

This work is a step forward to establishing the physical processes of formation and expansion of a two-component laser plasma, which determines the yield, charge, energy and spatial distribution of multiply charged ions. The relevance of this study lies in the fact that the experimental results will complement the physical picture of the formation and expansion of multiply charged ions in a multi-component laser plasma, and, in practice, they will allow not only increase the efficiency of sources of multiply charged ions but also to create a new method for analyzing solids for light injected gas.

This paper presents the results of a study of the charge and energy characteristics of multiply charged ions of a hydrogen-containing two-element plasma formed under the influence of laser radiation with a power density ($q=10^8$-10^{12} W/cm^2) depending on the atomic mass, the main component of the target. An essential advantage of the proposed work is obtaining complete information about the processes occurring in a two-element laser plasma formed under various initial conditions.

2. EXPERIMENTAL PART

The experiments were carried out on an electrostatic mass spectrometer with a mass resolution of *dm/m=100* and a TOF distance of *100 cm* [6]. The Nd:YAG laser beam was directed perpendicular to the target surface. The laser operated at a wavelength of *1.06 μm*, a pulse duration of *50 ns*, an energy per pulse of *5 J*, and in a single-pulse mode. The laser beam was focused through a converging lens onto a target (with focal length *f = 10-30 cm*) placed inside a vacuum chamber evacuated to $133.3\cdot 10^{-6}$ *Pa*. Creation and maintenance of vacuum at the level of 10^{-3}-$5\cdot 10^{-6}$ *Pa* both in the ion source chamber and throughout the entire drift space of ions (with the help of NORD-250 magneto discharge pumps). The spot size of the focused beam was 10^{-4} cm^2. The intensity of the neodymium glass laser operating in the single pulse mode was calibrated in the range $q=10^8$-10^{11} W/cm^2 using light filters. Note that the considered laser intensity exceeds the laser plasma formation threshold ($\sim 10^8$ W/cm^2). The parameters (energy and duration, laser pulse shape) of the laser are controlled separately by calorimeters and photoelectric methods [*Fig. 1*].

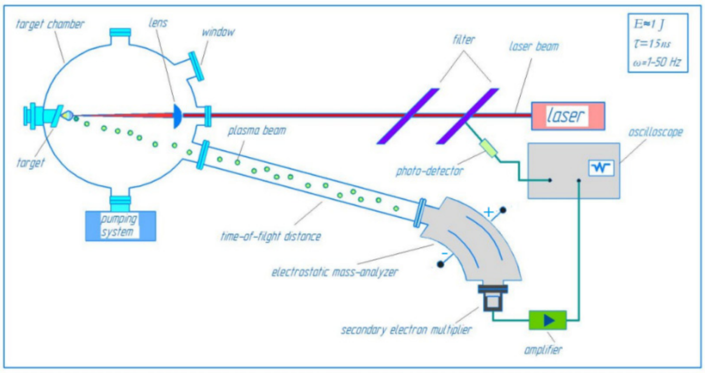

Figure 1. Experimental setup

The potential was applied to the plates of the electrostatic analyzer from a stabilized universal power supply (UPS-1). The ions inside the analyzer move all the time perpendicular to the direction of the electric field, there is no need for additional suggestions about the smallness of the deflection angle. It should be noted that a cylindrical electrostatic energy analyzer ensures the selection of a group of ions with the same ratio of kinetic energy to charge *(E/Z)*. Therefore, simple estimates show that the achieved sensitivity ($\Sigma_c \approx 10^{-3}$ *wt %* and $\Sigma_a \approx 10^{-12}$ *G*) and resolution ($R_m=100$) of the laser mass spectrometer, consisting of a time-of-flight mass analyzer and an electrostatic energy analyzer, close to the limit for this class of devices.

The recording equipment of the mass spectrometer consists of the following elements. A block of laser plasma ion detectors was made, which is connected to the output of an electrostatic analyzer. This block consists of a Secondary electron multiplier (SEM-1A) type detector. The wind turbine gain is $\sim 10^5$.

The targets were made from pure C (i.e. graphite), Cu, polyethylene $(CH_2)_n$ (consisting of bound hydrogen (H) atoms), Cu[H] (with H atoms embedded) and Ti[H,N], Zr[H,N] (consisting of hydrogen atoms (H) and (N)) in the form of a thick cylinder with a thickness of *d=2 mm* and a radius of *R=0.5 cm*. The target could be moved vertically using a vacuum feed, so that each laser shot could hit a fresh surface to avoid the cratering effect. The target surface was cleaned with the first laser pulse, and the results presented here were averaged over the next four pulses. The error in measuring the mass-charge spectrum of ions is 10%.

3. RESULT AND DISCUSSION

In most experiments on laser-induced plasma ions, little attention is paid to the influence of light gas atoms (for example, H, N, Ar), which are present in most solid targets in either specially introduced bound atoms or uncontrolled impurities. However, the presence of such impurities not only changes the physical properties of the target, but also affects the formation of plasma ions under the action of laser radiation. Therefore, the main purpose of this work is to study the effect of such bound or embedded gas atoms on the charge and energy states, duration, and yield of ions in a multi-component plasma.

The time-of-flight spectra of plasma ions generated from the surface of polyethylene, copper, titanium, and zirconium with embedded hydrogen atoms with a concentration of 10^{-4} wt % are experimentally obtained for a mono- and multi-element target depending on different laser radiation intensity *q*.

Investigating the charge spectra of Ti, Cu, and Zr ions obtained by exposure to intense laser radiation and a scanning electron microscope on Cu[H] containing 10^{-4} *wt.%* H, Ti[H,N] and Zr[H,N], in which the concentration of intercalated H and N atoms was 10^{-3}-10^{-1} *wt.%,* their comparison with similar characteristics of ions of these elements in plasma of a mono-element composition showed:

1) Cu ions registered in laser plasma, formed from the copper rod, at $q = 3 \cdot 10^{10}$ W/cm^2 and $q = 10^{11}$ W/cm^2, have Z_{max}=+ 4 and Z_{max}=+6, respectively. Recall that in the plasma formed at the specified *q* laser radiation from C, not containing H, Cu ions with Z_{max} = +5 and +7, respectively, were registered;

2) for Ti and Zr ions formed from Ti[H,N] and Zr[H,N], Z_{max} of ions of these elements at the above values of *q* of laser radiation was +4 and +5, respectively. In plasma produced by the interaction of laser radiation with $q = 3 \cdot 10^{10}$ and 10^{11} W/cm^2 with mono-element Ti, Z_{max} of ions of these elements was +7 and +10, respectively, and Z_{max} of Zr ions was +5 and +7, respectively;

3) it should be especially noted that for all used values of *q* laser radiation for plasma obtained from gas-containing samples, a lower relative yield (*dN/dE*) of ions of the heavy component with Z > +3 is characteristic, in comparison with the plasma of a mono-element composition (see Fig.2). Moreover, the tendency to reduce dN/dE of ions of the heavy component, in comparison with the relative yield of ions from the plasma of a mono-element composition, is the more significant, the greater the charge of the ion. However, the total yield of ions with a given Z in the case of a multi-component plasma is always greater. This regularity is also characteristic of H ions formed from copper rods. However, in this case, it is less pronounced. Undoubtedly, this is due to a lower concentration of intercalated H in it and, secondly, to the presence of two light interstitial gases (H,N) in gas-containing Ti and Zr.

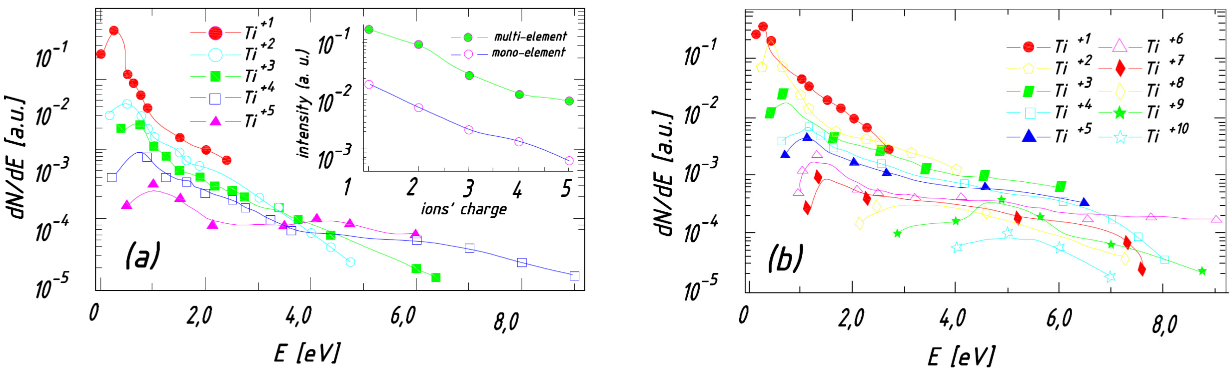

Figure 2. Energy spectrum of TiNH ions formed from multi-element (a) and mono (b) Ti targets at $q \sim 10^{11}$ W/cm^2

As an example, consider the energy spectra of titanium, which consists of hydrogen atoms (H and N) in a bound state. On fig. *Figure 2* shows the energy spectrum of Ti ions formed from mono (b) and multi-element (a) TiNH targets at $q \sim 10^{11} W/cm^2$. It can be seen from this figure that the charge and intensity of multiply charged ions in plasma (Ti) are greater than in plasma (TiNH) for all values of laser radiation intensity *q*. This is due to the higher concentration of H and N atoms in the target (TiNH). Another interesting result we found is that the intensity of H^+ and N^+ ions in plasma (TiNH) decreases with increasing laser intensity *q*, starting from a certain critical intensity.

The study of the energy spectra of Ti and Zr ions expanding in plasma together with H and N ions and comparing the results obtained with the identical characteristics of these ions in a single-element plasma showed that in a plasma obtained from Ti and Zr containing embedded light gases, the range of energy distributions of Ti and Zr ions with Z = 1-5 for all values of *q* laser radiation is greater than the width of the energy spectra of Ti and Zr ions given Z in mono-element plasma.

As shown above, a similar regularity in the charge and energy spectra change is also characteristic of $(CH_2)_n$ and Cu ions flying apart in a two-component laser plasma formed from a copper rod. Based on the analysis of the results of studies of the charge and energy distributions of ions of the heavy component of the plasma formed under the action of laser radiation on a solid body containing embedded light gases, and comparing them with similar characteristics, in the case of single-element targets, it can be argued that the absence of ions in this multi-component plasma with Z_{max} > +5 is due to the fact that ions with Z > +6, for some reason, have lowered their initial charge. The absence of ions with a high charge multiplicity (Z > 4) in $(CH_2)_n$ plasma is associated not with an increase in the efficiency of the recombination process but with a decrease in the lifetime of such a dense plasma in the ionization zone. As a consequence, C ions leave the plasma with a lower charge. The similar energy spectra of C and H ions generated from the $(CH_2)_n$ plasma and the similar spatial distribution of these ions also indicate that ionization processes play an important role in plasma formation and outflow.

A joint analysis of the patterns of change in the charge and energy spectra of the ions of the heavy component of the laser plasma formed from $(CH_2)_n$, Ti[H,N] and Zr[H,N] and Cu[H] shows that, if for all the studied samples identical in nature to the pattern of change in charge states, then the opposite picture is observed for the energy spectra (*Table 1*). Taking into account that the gases under consideration are in different states in the studied complex targets, it can be argued that the mechanism for reducing the maximum charge multiplicity of heavy ions obtained from $(CH_2)_n$ is not adequate to the mechanism for reducing Z_{max} of these ions formed from gas-containing samples.

Table 1. Patterns of changes in the charge and energy spectra of ions of the heavy component of laser plasma

Element	*Target*	Z_{max} *at* $q=3\cdot10^{10}$ *W/cm²* *(a)*	Z_{max} *at* $q=10^{11}$ *W/cm²* *(b)*	E_{max}*, keV (a)*	E_{max}*, keV (b)*
C	*$(CH_2)_n$*	4	4	2,0	3,0
C	*Monoelement*	4	6	2,5	3,5
Ti	*Ti [H,N]*	4	5	6,8	8,0
Ti	*Monoelement*	7	10	7,0	9,0
Cu	*Cu [H]*	4	6	5,0	6,0
Cu	*Monoelement*	5	7	5,0	5,5
Zr	*Monoelement*	5	7	5,0	7,0
Zr	*Zr[H,N]*	4	5	4,0	5,5

It is known that at low laser radiation intensities ($q<10^8$ *W/cm²*) only evaporation of the target material occurs, and plasma is formed only at high laser radiation intensities [18]. Although the intensity of laser radiation in our experiments is high enough to form a plasma, evaporation of the target material occurs due to the long duration of the laser beam (*50 ns*). Neutral atoms and ions with low charge and energy receive additional energy from highly charged ions.

Thus, an analysis of the experimental results shows that the mechanisms of formation of light gas ions in a multi-component plasma and the charge and energy distribution of these ions strongly depend on the conditions for the entry of these gas atoms into the target. When they are introduced into a target in implanted forms, the formation of gas ions in a multi-component plasma occurs mainly due to energy transfer from heavy plasma components to light atoms, while ionization processes dominate.

4. CONCLUSIONS

The effect of the presence of light gas atoms in a target on the formation of the charge and energy spectra of multiply charged plasma ions formed under the action of laser radiation has been studied by mass spectrometry. It has been experimentally shown that the mechanisms of formation of light gas ions in a multi-component plasma and the charge and energy distribution of these ions strongly depend on the conditions for the entry of these gas atoms into the target. When they are introduced into a target in implanted forms, the formation of gas ions in a multi-component plasma occurs mainly due to energy transfer from heavy plasma components to light atoms, while ionization processes dominate. An increase in the charge and energy state, duration and yield of ions of the heavy component, which occurs with an increase in the content of the light component in the target, has been established. This is explained by a decrease in the efficiency of recombination processes caused by an increase in the expansion velocity of a plasma bunch due to a decrease in its average mass.

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REFERENCES

[1] M. Tulej, R. Wiesendanger, A. Riedo, G. Knopp, and P. Wurz, "Mass spectrometric analysis of the Mg plasma produced by double-pulse femtosecond laser irradiation," J. Anal. At. Spectrom. **33**, 1292-1303 (2018). https://doi.org/10.1039/c8ja00036k
[2] B. Ilyas, A.H. Dogar, S. Ullah, N. Mahmood, and A. Qayyum, "Multiply charged ion emission from laser produced tungsten plasma," Laser Part. Beams, **30**(4), 651-657 (2012). https://doi.org/10.1017/S0263034612000687
[3] Yu.A. Bykovskii, Yu.P. Kozyrev, S.M. Sil'nov, and B.Yu. Sharkov, "Spatial structure of an expanding laser plasma consisting of aluminum ions and nuclei, " Sov. J. Quantum Electron. **4**(3), 405-406 (1974). https://doi.org/10.1070/QE1974v004n03ABEH006762
[4] R.T. Khaydarov, H.B. Beisinbaeva, M.M. Sabitov, M. Kalal, and G.R. Berdiyorov, "Conditions defining the mechanisms of the formation of light gas ions in multi-component laser-produced plasmas," Nucl. Fusion, **50**(10), 105007 (2010). https://doi.org/10.1088/0029-5515/50/10/105007
[5] M.R. Bedilov, I.Y. Davletov, M.S. Sabitov, G.R. Berdierov, and T.G. Tsoi, "Multiply charged ion spectra of a laser plasma produced on both sides of the target," Quantum Electron. **31**(5), 453-455 (2001). https://doi.org/10.1070/QE2001v031n05ABEH001977

[6] A. Matnazarov, I. Davletov, and A. Japakov, "Upgraded Experimental Apparatus for the Detection and Investigation of Multiply Charged Ions of a Laser Plasma," Bull. Sci. Pract. **6**(9), 198-203 (2020). https://doi.org/10.33619/2414-2948/58/19
[7] M.R. Bedilov, E.N. Tozhikhonov, I.Yu. Davletov, et al. "Emission of multicharged ions in the dependence of the focusing condition of laser radiation on W target surface," Poverkhnost. Renthenovskye, synkhrotronnye i neitronnye issledovanyia, 8, 35-39 (2003). (in Russian)
[8] M.R Bedilov, R.T. Khaidarov, and I.Yu. Davletov, "Spectra of ions in a four-element laser plasma," Quantum Electronics, **25**(6), 567 (1995). https://doi.org/10.1070/QE1995v025n06ABEH000415
[9] M.R. Bedilov, R.T. Khaidarov, B.Kh. Yakubov, and U.S. Kunishev, "Charge and energy spectra of multiply charged ions of a two-element laser plasma formed from targets of different densities," Quantum Electronics, **26**(9), 814 (1996). https://doi.org/10.1070/QE1996v026n09ABEH000788
[10] I.Y. Davletov. R.M. Bedilov, M.S. Sabitov, "An Installation for Obtaining Intense Flows of Multiply Charged Laser-Plasma Ions Using a Second Laser Beam," Instruments Exp. Tech. **45**(5), 708-710 (2002). https://doi.org/10.1023/A:1020478723480
[11] M.R. Bedilov, K.B. Beisembaeva, and I.Y. Davletov, "Effect of γ-radiation-induced defects in glass on laser destruction," Phys. Solid State, **44**(6), 1093-1097 (2002). https://doi.org/10.1134/1.1485013
[12] A. Matnazarov, M. Latipova, and A. Kodirov, "Formation and Heating of Plasma by Laser Radiation," Bull. Sci. Pract. **8**(5), 32-40 (2022). https://doi.org/10.33619/2414-2948/78/03
[13] D. Wu, X. Mao, G.C.-Y. Chan, R.E. Russo, V. Zorba, and H. Ding, "Dynamic characteristics of multi-charged ions emitted from nanosecond laser produced molybdenum plasmas," J. Anal. At. Spectrom. **35**(4), 767-775 (2020). https://doi.org/10.1039/C9JA00411D
[14] M.H.A. Shaim, F.G. Wilson, and H.E. Elsayed-Ali, "Aluminum multicharged ion generation from femtosecond laser plasma," J. Appl. Phys. **121**(18), 185901 (2017). https://doi.org/10.1063/1.4983008
[15] G.S. Boltaev, M. Iqbal, S.R. Kamalov, M. Vapaev, I.Y. Davletov, and A.S. Alnaser, "Impact of plasma conditions on the shape of femtosecond laser-induced surface structures of Ti and Ni," Appl. Phys. A, **128**(6), 488 (2022). https://doi.org/10.1007/s00339-022-05614-w
[16] O. Balki, M.M. Rahman, M.H. Abdel-Fattah, and H.E. Elsayed-Ali, "Carbon multicharged ions emission from femtosecond laser plume," Opt. Laser Technol. **120**, 105694 (2019). https://doi.org/10.1016/j.optlastec.2019.105694
[17] M.M. Rahman, O. Balki, and H.E. Elsayed-Ali, "Carbon multicharged ion generation from laser-spark ion source," Rev. Sci. Instrum. **90**(9), 093303 (2019). https://doi.org/10.1063/1.5110402
[18] J. Krása, L. Láska, V. Nassisi, and L. Velardi, "Fe and Fe+2%Si targets as ion sources via UV laser ablation plasma," Eur. Phys. J. D, **54**, 473-476 (2009). https://doi.org/10.1140/epjd/e2009-00023-y

СПЕКТРИ БАГАТОЗАРЯДНИХ ІОНІВ У ЛАЗЕРНІЙ ПЛАЗМІ, СФОРМОВАНІЙ ІЗ ГАЗОВМІСНИХ МІШЕНЕЙ

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У статті наведено результати дослідження зарядово-енергетичних характеристик багатозарядних іонів, що збуджуються на поверхні одноелементних і водневмісних багатокомпонентних елементних мішеней під дією лазерного випромінювання з густиною потужності ($q = 10^8$-10^{12} Вт/см^2). Експериментально показано, що для всіх використовуваних значень q лазерного випромінювання лазероіндукована плазма газовмісних мішеней характеризується меншим відносним виходом (dN/dE) багатозарядних іонів із зарядовим числом $Z > +3$, порівняно з плазмою, утвореною на поверхні одноелементної мішені. Більше того, тенденція до зменшення dN/dE багатозарядних іонів багатоелементної мішені, порівняно з відносним виходом іонів із плазми одноелементної мішені, більш значна і залежить від заряду збуджених іонів. Встановлено збільшення зарядового та енергетичного стану, тривалості та виходу іонів важкої компоненти, яке відбувається із збільшенням вмісту легкої компоненти в мішені. Це пояснюється зниженням ефективності процесів рекомбінації, викликаним збільшенням швидкості розширення плазмового факелу внаслідок зменшення його середньої маси.

Ключові слова: *лазерно-індукована плазма; багатозарядні іони; мас-спектрометр; енергетичний спектр; водневмісна двоелементна плазма; процеси рекомбінації*