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Particles Acceleration Processes in the Laser Plasma

Victor V. Apollonov[1], **Sergei M. Silnov**[2]

[1]*A.M. Prokhorov General Physics Institute, Russian Academy of Sciences, ul. Vavilova, Moscow, Russia*

***Corresponding Author: Victor V. Apollonov,** *A.M. Prokhorov General Physics Institute, Russian Academy of Sciences, ul. Vavilova, Moscow, Russia*

Abstract: *To date, as a result of a large series of experimental and theoretical studies scientists managed to identify the role and nature of the absorption of laser radiation in a plasma, the mechanisms of energy transfer between different components, the main properties of kinetics of the ionization state and dynamics of expansion of the laser-plasma torch. A significant contribution to the experimental research has been made, in particular, due to the development and application of laser mass spectrometry, allowing one to determine the charge composition of the plasma, the properties of the processes of ionization, acceleration, and recombination in laser plasma. Numerous studies have established that the laser plasma is an intense emitter of charged and neutral particles: the electrons, ions, and atoms. The mechanisms of the energy spectra of ions and neutral particles have been studied in detail, and laser sources of particles, which have found application in accelerators, cyclotrons, and mass spectrometers, have been developed and technically implemented. A laser-plasma generator of multiply charged ions produces a large number of heavy ions in the regime of short periodic pulses, which is of interest for ion accelerators operating in the pulse periodic regime. The source of this type is also promising for research in the field of heavy-ion fusion. The laser-plasma generator is based on the physical phenomenon of generation of highly excited states of atoms by a high-power laser pulse focused on the surface of a solid target. With expanding a high-temperature laser plasma into vacuum a high-power flux of charged particles is produced.*

1. INTRODUCTION

Earlier in the experiments on the interaction of laser radiation action with a solid body surface, during the explosion of thin wires in vacuum and in various types of electrical discharges, the ions were observed with a very high energy of directed motion exceeding the thermal energy, which indicates the presence of different acceleration mechanisms in the plasmoids with high temperature and density [1]. The experimental study of the production and acceleration of the particles in the laser torch upon their free expansion into the vacuum is one of the most interesting problems, which are important both from fundamental and purely application-oriented points of view, i.e., the problems of the inertial thermonuclear fusion, film sputtering techniques and fabrication of particle sources. In theoretical and experimental works devoted to the expansion of plasmoids produced, in particular, under laser irradiation, two main mechanisms of acceleration of atoms and ions are considered: due to the existence of a large pressure gradient in the plasma–vacuum system and as a result of collective processes of interaction between electrons and ions.

Many papers are devoted to the expansion of plasmoids indicates three mechanisms and regimes of electromagnetic plasma acceleration: due to the existence of a large pressure gradient, as a result of electron–ions friction, and as a result of the action of an electric field. The energy spectra of the ions are constructed on the recombination heating of the plasma torch. The acceleration of the laser plasma particles was explained within the framework of gas-hydrodynamic effects. The most probable explanation is that the laser plasma particle is accelerated due to the electric forces acting in the torch at early stages of the plasmoid formation. Consider some models of electromagnetic nature. V.P. Silin [2] presented a formula to calculate the ion velocity by using the effect of an increase in the electric field in the region of the plasma critical density due to the existence of an electric field vector component, which is normal to the target surface:

$$v_{max} \sim \frac{E_0}{\sqrt{4\pi n_i M}} \frac{1}{v} \sqrt{\frac{c\omega_0}{2\pi a}}. \tag{1}$$

where ***Eo*** is the amplitude of electric field in the light flux, ω_0 is the effective frequency of electron collisions, ***v*** is the radiation frequency, ***ni*** is the density of the ions in the region of the critical point, ***M*** is the ion mass, and ***a*** is the typical change in the plasma density.

It follows that the plasma is accelerated by an extremely heavy wall having a velocity **V**; that is why the plasma energy is proportional to the ion mass. As was pointed out by V.P. Silin [2], the velocity of the accelerated ions depends on the coordinate axis. Thus, at some instant **V(r)** will be equal to the speed of sound. On this base the conclusion was made about the existence of the acceleration range: from the speed of sound to $\mathbf{V_{max}}$. At the same time, he estimated the total number of the accelerated ions by the formula:

$$\delta n_i \sim n_i \frac{4\pi r_0^2 \alpha}{\sqrt{2\pi\rho}} \left[\frac{E_0^2}{4\pi/(n_e kT_e + n_i kT_i)}\right]^{\frac{1}{2}} \tag{2}$$

The acceleration time is extremely short and is evaluated, depending on the experimental conditions, to be 10^{-9}-10^{-8}s. Numerical calculations based on this model indicate an increase in the ion energy with increasing radiation flux density and ion charge.

Some theoreticians considered the ion acceleration in the case of the expansion of rarefied plasma into vacuum; such acceleration is due to spatial splitting of the charges. The splitting appears because of the presence of the electrons with the velocities higher than the velocities of the ions. Due to this reason the electrons tend to exit from plasma.

As a result, a self-consistent an electrostatic field appears, which transfers high kinetic energy to ions. Such effects were studied, which indicates some features forthcoming in the plasma in the presence of such electrostatic acceleration: ions with a large charge pass the accelerating region at high velocities; low-charged ions (especially singly charged ions) must have a more sophisticated energy spectrum due to a change in the electrostatic field potential during the expansion process; and ions with different atomic weights have different acceleration velocities. By the model of electrostatic self-consistent ion acceleration in the laser plasma is easy to obtain the dependence of the ion energy on the charge:

$$Ei = Z^2 \tag{3}$$

whence it follows that the expansion velocity is proportional to the square of the ion charge. The first mass-spectrometric studies of the laser plasma showed that in the expansion products contain particles with velocities much exceeding thermal velocities. Even at threshold densities of the radiation flux, the torch consists of atoms having a velocity of (3–8)×10^5cm/s.

2. MULTIPLY CHARGED POSITIVE IONS OF THE LASER PLASMA

To illustrate the influence of acceleration processes on multiply charged ions of the laser plasma, Fig.1 presents the energy distribution of the cobalt ions at 10^{13}W/cm^2 [1]. The plasmoid of such plasma contains particles with a maximal energy up to 40keV. Let us describe the most important features of the energy spectra of multiply charged ions:

1. Energy distributions of the ions of each charge have their left low-energy boundary, which is not equal to zero.
2. Most often the right high-energy boundary of the distribution is common for all the ions (if to consider it at the same level of the sensor sensitivity) and differs if to consider it at the level 0.1 or 0.5 in relation to the intensity maximum of the particles.
3. The spectrum contains such an intensity maximum of these particles intensity whose energy position depends on many factors.
4. The entire plasmoid consists of a set of ions whose energy spectra with increasing charge Z are successively located after each other and overlap the region of high energies.

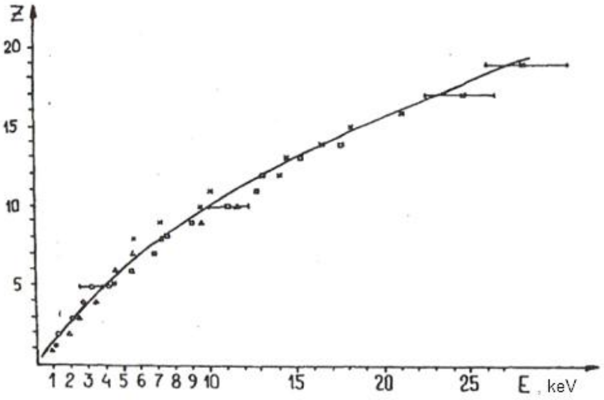

Fig1. *Ions energies as a function of the charge*

The values of multiply charged ion energies leave no doubt about the existence of acceleration processes in the laser plasma. If we consider the plasmoid as a whole, there is a common energy boundary. This boundary depends essentially on the radiation flux density and ion charge: the higher the latter, the higher the ion energy (Fig.2). Besides, this value is a function of a sample element: the higher the sample atomic weight, the larger the value of the energy boundary of the spectrum. In this case, an important characteristic of the value of the energy boundary of the distributions is the appearance of the ions with maximal charge in the plasma.

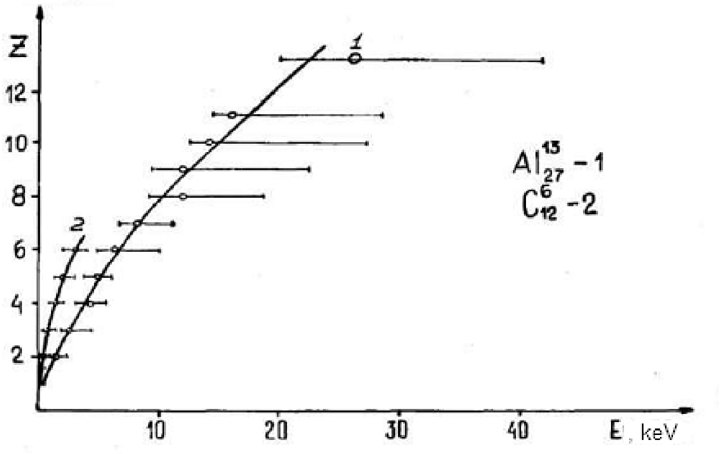

Fig2. *Ions energies as a function of the charge for samples made of (1) aluminum and (2) graphite*

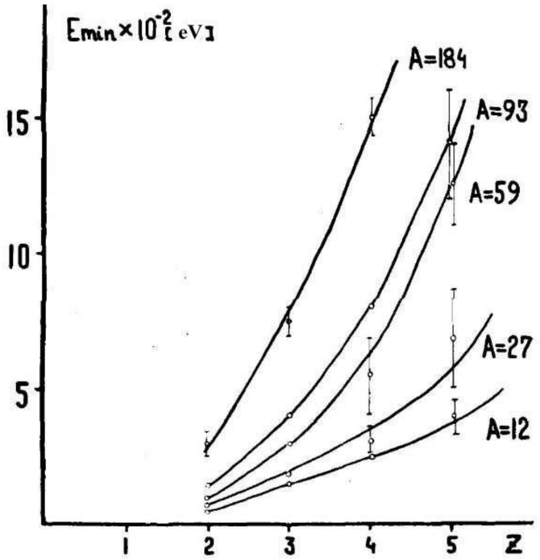

Fig3. *Value of the low-energy boundary of the ion distribution versus ion charge for carbon, aluminum, cobalt, columbium and wolfram at 10^9–10^{10}W/cm^2*

To single out the parameters affecting the acceleration processes, we consider the influence of the initial conditions on the maximum energy of each charge. In this case, the boundary of each distribution was considered at a sensitivity level of one tenth and a half of the particle intensity in the distribution maximum. Fig. 3 presents the dependence of maximum energies of carbon and aluminum ions on the value of the charge. It is seen that with increasing atomic weight, the energy of the ions of the same charge grows. This dependence was obtained at a fixed radiation flux density equal to 5×10^{13}W/cm^2. From above it follows that the formation of the intensity maximum of the particle distribution and its right high-energy boundary occurs mainly as a result of recombination processes from ions with higher values of the charge Z. Hence the characteristics of right high-energy distribution boundaries reflect not only the acceleration of the ions of the considered charge but also make the contribution of many ion distributions into the spectrum. A more exact and unambiguous characteristic of the acceleration processes of the laser plasma ions of this or that charge is the value of the low-energy boundary of the distribution. The ions emerging in the region of the left distribution boundary are due only to ionization and acceleration processes. The ionization process takes place before the acceleration starts; that is why, apparently it is not important so much that before the acceleration starts these ions have had the charge less by unity because these particles have not had the thermal velocity. Thus, the value of the low-energy boundary must not depend on the recombination processes. It is found and confirmed that the value of the left energy boundary of the spectrum is independent of the angle at which the particles leave the torch and is weakly dependent on the radiation flux density. The latter statement is correct at least for the radiation flux densities 10^8–10^{13}W/cm^2 because when the radiation flux density changes by three or four orders of magnitude, the value of the low-energy boundary could change by no more than 2 times. With increasing ion charge, the low-energy boundary of the distribution shifts to the region of high energies. Fig. 4 presents the change in the low-energy boundaries of the ion distribution as a function of the charge for several samples. When the atomic weight is increased, the value of low-energy distribution boundary grows as well. Figure 5 shows the dependence of the change in the low-energy distribution boundary on the ion charge and the element atomic weight at a large range of the radiation flux densities. Within spread of the experimental points we may assert that the velocity of the laser plasma expansion products (judging by the low-energy boundary) does not depend on the sample element and grows proportionally to the ion charge.

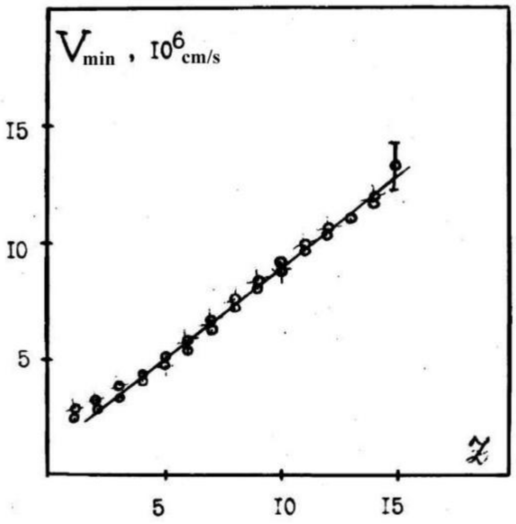

Fig4. *Change in the minimal velocity of the ions as a function of the charge for the 10.6-μm radiation (***o***–cobalt,* ***ϕ*** *–copper)*

3. LASER TORCH ELECTRONS INFLUENCE ON THE ACCELERATION PROCESSES

The electrons of the laser plasma play an essential role in the formation of spectral and charge distributions of the ionic component: they determine the charge composition and the number of the ions of a particular charge. The presence of a large number of high-energy electrons affects also the formation of the energy spectra of the ions despite of a great difference in the particle masses. Even if we suppose that the ion and electron energies are equal (at the stage of the plasmoid heating), the electron velocities will be higher than that of the ions by several orders of magnitude. The electrons are located in the plasma cloud and cannot freely leave the cloud without the violation of the plasmoid neutrality, because separation of the ions and electrons in a dense plasma (10^{19}–10^{21}cm^{-3}) is prevented by electric forces, which leads to mutual influence and the change in the velocities of the directed motion of the electrons and the ions.

For comparison of the electron pulses with the ion characteristics it is convenient to consider the temporal structure of the expansion products obtained at a distance of 450 cm (Fig. 5). The plasmoid fore-body is formed of the ions of all charges from $Z=1$ up to $Z_{\max}$, and their number drastically increases as the plasmoid moves inside into the torch, just as in the case of the electron pulse.

The higher the ions charge, the less the duration of the particle flux. The temporal distribution of ions of different masses is given by the example of the binary compounds of lead dichloride (PbCl2). The temporal distributions of the particle fluxes reflect not only the dynamics of the torch in time but also in the drift space. Despite great differences in atomic weights of all these elements (MPb/MCl=208/35=6), there exists a common front boundary passing through the plasma–vacuum interface. This comparison allows one to come to a conclusion that either a great value of friction exists between ions in the plasmoid or the ions experience collective acceleration up to electron velocities, the values of which (as will be shown below) depend on the radiation flux density, the sample material Mave and other parameters.

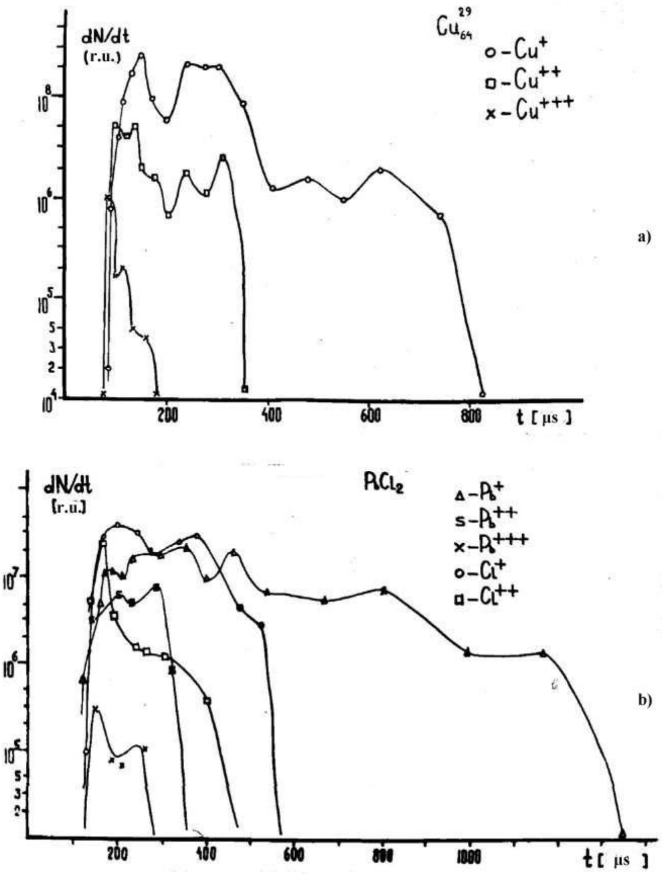

Fig5. *Temporal distribution of ions in the plasmoid for (a) single-components samples and (b) binary samples*

By comparing the temporal electron distributions Fig.5 with the temporal ion distributions, the process of the leading edge steepening of the electron pulses becomes clearer. The increase in the radiation flux density is accompanied by an increase in the number of the higher-energy electrons, which leads to the production of multiply charged ions and their motion to the fore-body of the plasmoid. The heavy ions in turn decelerate the most energetic electrons by creating of a steeper leading edge of the pulse.

The value of the high-energy boundary of the electron component spectrum is a very convenient characteristic of the velocity of the plasmoid expansion and formation. This correspondence is indicated in Fig. 6, where shows the equality of maximal velocities of the electron and ion expansion measured in the range of almost three orders of magnitude with respect to the radiation flux density.

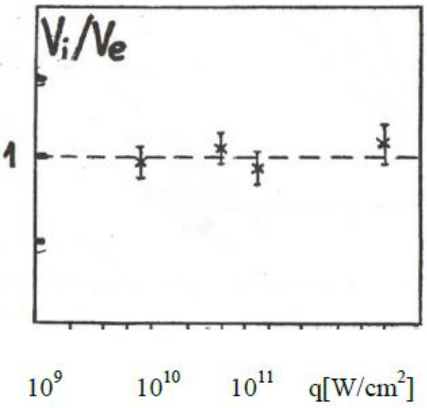

Fig6. *Comparison of the velocities of the directed motion of ions and electrons in the torch*

Consider the influence of the radiation flux density on the maximum velocity of the electrons in the laser plasma expansion (Fig. 7) for several materials. For lighter elements, the particle velocity increases significantly. With increasing atomic weight, the electron component expansion slows down and the velocity of the electrons increases slower with increasing radiation flux density on the targets. The experimental curves in Fig. 7 make it possible to find the relation between the three parameter: velocity (energy) of the particles, atomic weight of the sample ions and radiation flux density:

$$u_e \approx \sqrt{\left(E_i/M_i\right)} \approx \ln q \tag{4}$$

Having obtained this relation and substituted the relevant coefficients into it, one can determine in advance the velocity of the moving plasma front and the maximum energy of the multiply charged ions of a particular element. It follows from this relation that only a small part of the radiation energy is spent to increase the velocity of the directed motion of the particles.

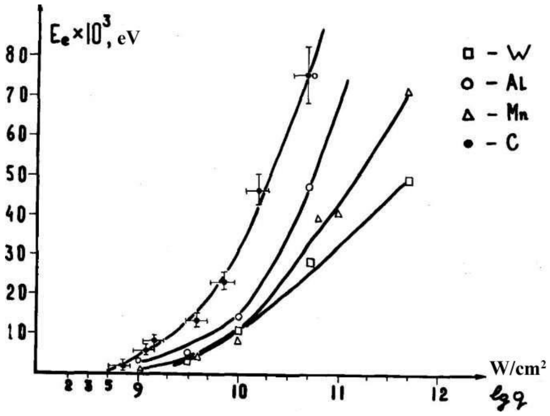

Fig7. *Radiation flux density versus electrons energy for different samples*

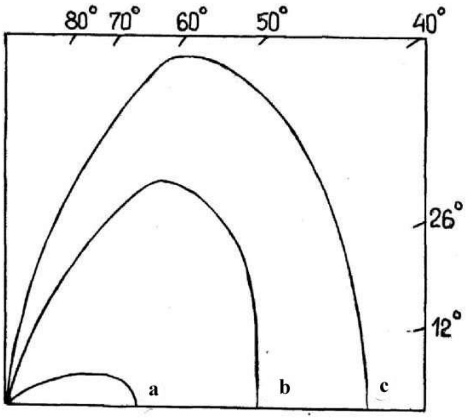

Fig8. *Dynamics of the angular expansion of electrons as a function of q at W/cm^2 (a–4x10^9; b–1,6x10^{10}; c–5x10^{10})*

Besides, in our experiments we found an anisotropy of the dependence of the maximum velocity on the exit angle of the particles (Fig. 9). With increasing radiation flux density, the maximum velocity of the plasmoid becomes constant in the entire range of the exit angles, and the function of the exit angle broadening with increasing radiation flux density can be written as:

$$\varphi^2 \sim \ln q \qquad (5)$$

Using the data obtained we can conclude that faster electrons fly apart in a comparatively narrow angular interval along the normal to the target.

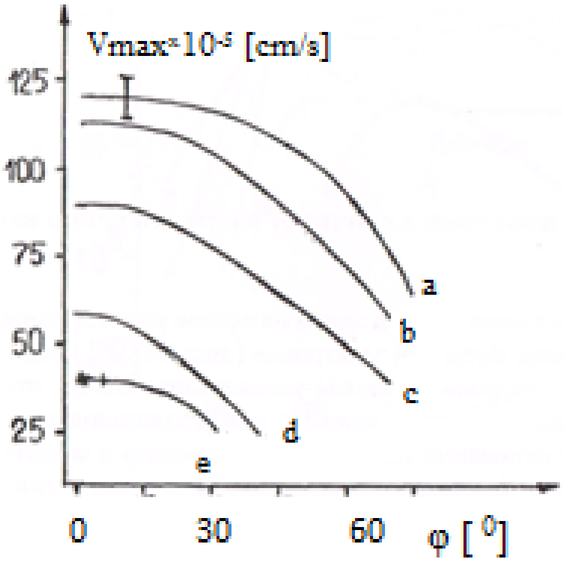

Fig9. *Maximum velocities of the ions and electrons as a function of the exit angle analysis: (a) electrons at* $5x10^{10}$*W/cm*^{2}*, (b) ions at* $3x10^{10}$ *W/cm*^{2}*, (c) electrons at* $1.6x10^{10}$ *W/cm*^{2}*, (d) electrons at* $4x10^9$ *W/cm*^{2}*, (e) ions at* $3x10^9$*W/cm*^{2}*)*

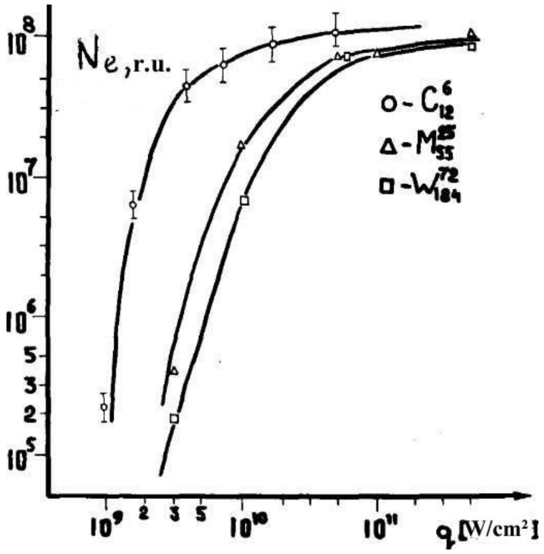

Fig10. *Number of the ions and electrons in the plasma as a function of the radiation flux density for different samples*

Let us continue the comparison of the electron and ion characteristics by using velocity distributions of the ions of all the charges and the electrons (Fig. 11). Within the limits of the error, the coincidence of both distributions is quite satisfactory, which indicates the joined expansion of these two components and the electron neutralization in the laser plasma. Therefore, this makes it possible to conclude that the electrons and the ions experience collective interactions, typical of this type of plasma torch (Fig. 10).

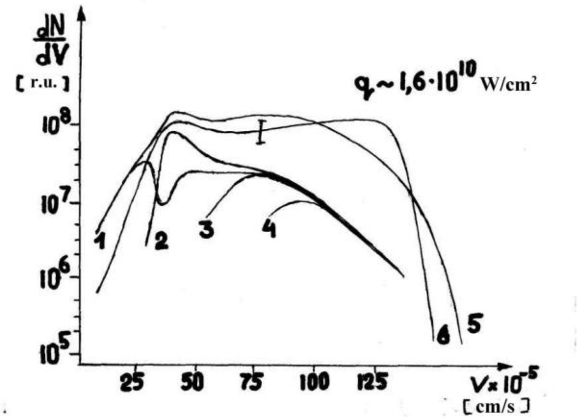

Fig11. *Velocity distributions of the ions and electrons (1, 2, 3, 4 – ion charges; 5 – total charge; 6 – electron distribution)*

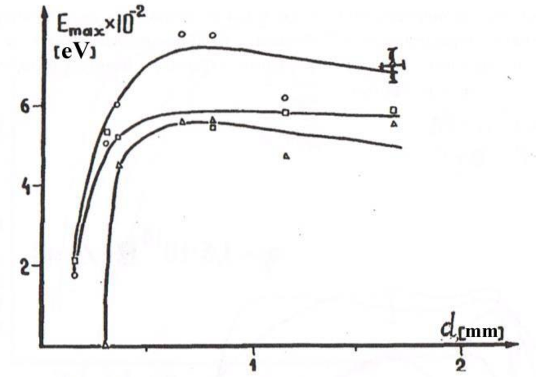

Fig12. *Change in the maximum energy of aluminum ions as a function of the initial size of the torch (o–Z=1, n–Z=2; ^–Z=3)*

4. INITIAL CONDITIONS INFLUENCE ON THE PARTICLE ACCELERATION IN THE TORCH

Let us return to the experiments, in which we changed the initial conditions of the plasmoid formation, namely to the studies, where the influence of the focusing spot diameter on the laser torch characteristics was examined. Changing the initial size of the torch leads not only to a change in the plasma lifetime but also can significantly affect the plasmoid expansion geometry, i.e., with increasing focusing spot diameter, the initial phase of the expansion must approach to a plane case, which is reflected in the change of the geometrical parameters of the torch expansion, namely, the angular and energy expansion spectra. Fig. 12 presents dependence of the change in the maximum energies of the ions of different charges on the focusing spot diameter (taken at maximum possible level of the sensitivity). Initially, when the ratio of the diameter to heated layer depth was increased, we observed a sharp increase (by several times) of the high-energy boundary of the ion spectra. Besides, the shift is observed also for the low-energy boundary of the ion spectra, i.e., the energy distributions move into the regions with higher energies. Table 1 lists the values of the low-energy boundary of chlorine ions obtained on the samples made of lead dichloride.

Table1.

Initial size of the torch (*d*)	0.2	0.25	0.45	0.55	0.65	1.4
Value of the low-energy boundary (eV)						
Z=1	25	30	35	70	70	70
Z=2	60	60	90	150	150	-

If changes in the high-energy boundary can be explained by ionization and recombination processes (by varying the focusing spot) as a result of emergence of ions with higher charges *Z*, the shift of the spectrum as a whole with the displacement of the low-energy distribution boundary indicates the changes in the acceleration processes at different value of the relation *d*/*L* (where *L* is the depth of the heated layer or the plasma torch thickness at the instant of its heating by radiation). It follows from these experimental results that under flatter initial expansion, the acceleration processes are more efficient. To confirm this statement, we performed additional experiments. We measured the angular expansion of the laser plasma for two different cases: tight focusing and large *d/L*. As a result of this experiment (providing that the radiation flux density coincided in both cases) we found that the angular expansion is limited at large *d/L* (Fig. 13)

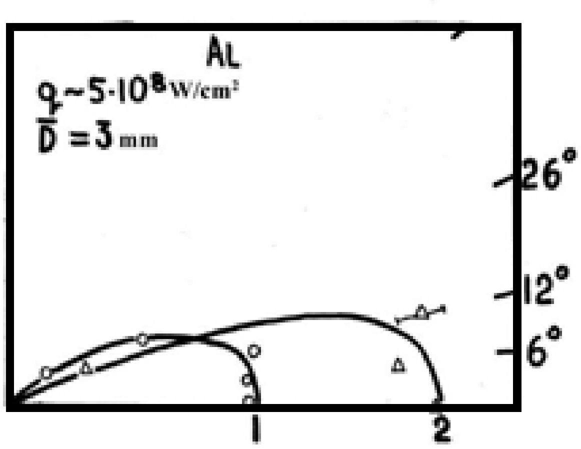

Fig13. *Angular distributions of aluminum ions at* $q=5x10^8 W/cm^2$ *for a defocused beam*

The change in both boundaries of the energy spectrum testifies to the change in the acceleration processes when the initial experiment conditions are varied. Such spectrum changes cannot be explained due to the strengthening of recombination with increasing radiation density. One of possible mechanisms of the particle acceleration in the torch is the collective acceleration of ions by the laser plasma electrons. The energy, which can be transferred to the ions, depends on the number of the electrons and their velocity. Note that the ions can be accelerated up to electron velocities only in the presence of the field constantly acting on electrons that compensate for the energy loss spent on the ion acceleration (or else the electrons will decelerate in the ion field). During the action of the laser pulse on the plasma, the electrons can absorb the energy lost as a result of collisions or deceleration in the ion field (Fig. 14). As was shown above (Fig. 13), when the atomic weight of the plasmoid changes, one can observe a significant change in the energy spectrum of the plasma ions. Fig. 15 presents the change in the maximum and minimum energies of natrium ions as a function of the atomic weight of the second component of the binary compound. With the increase in the atomic weights of the entire plasmoid, the velocity of the entire plasmoid decreases, i.e., the energies of natrium ions fall. The electrons, which have received the energy from laser radiation, transfer it to the ions due to electrostatic acceleration only in certain limits (part of this energy is spent on the plasmoid ionization). Thus, we can note that the higher the average atomic weight of the plasmoid, the less the plasmoid velocity, up to which it can be accelerated (other experimental conditions being equal).

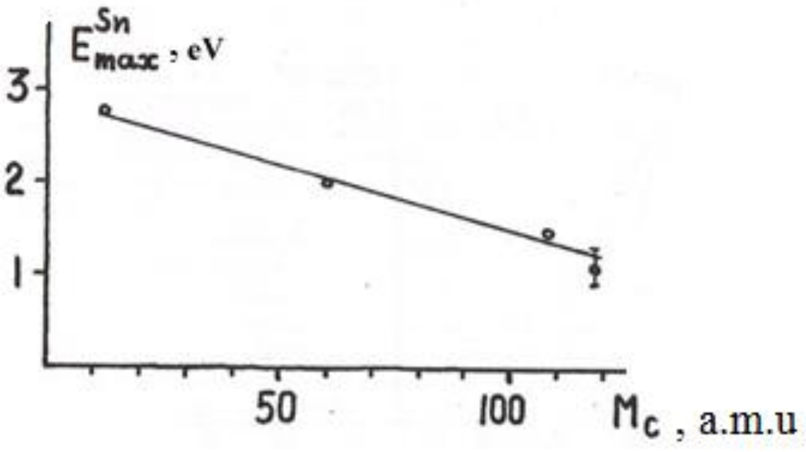

Fig14. *Dependence of the maximum energy of Sn ions on the plasmoid average mass*

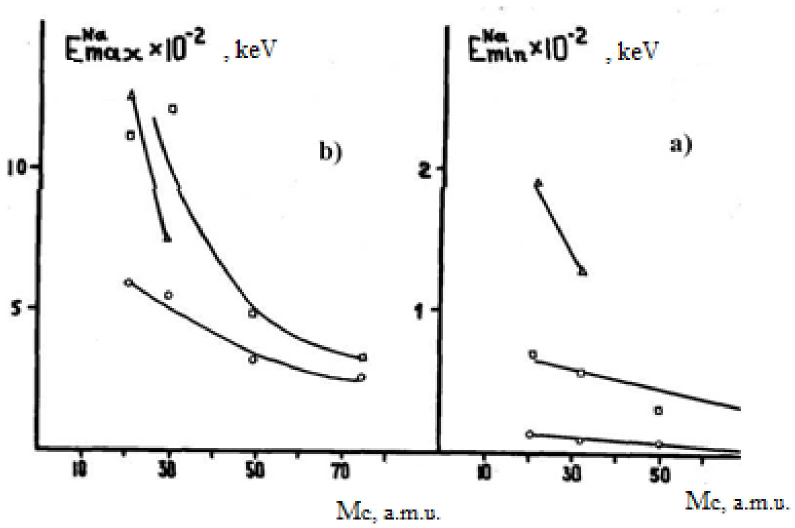

Fig15. *Influence of the average atomic weight of sample on the value of the (a) minimal and (b) maximal ion energies (o –particles with the charge Z=1; n–Z=2; ^– Z=3)*

Thus, when the average atomic weight of the plasmoid is increased, one can observe a proportional decrease in the ion energy (part of the energy is spent on the acceleration of the second component; see Fig. 14. One can observe not only a change in the high-energy boundary of the spectrum (which can be due to different recombination processes), but also a shift of the low-energy part of the spectrum into the region of low energies (Fig. 15), i.e. the shift of the entire ion beam is observed on the energy scale.

5. FOCUSING EFFECT FOR IONS WITH A MAXIMAL CHARGE

In studying the angular spectrum of the torch expansion products we can refine and determine the main mechanisms of the laser plasma formation. In the case of thermal heating of a material, i.e., under conditions of thermodynamic equilibrium, the angular expansion must be isotropic. If in the plasma torch the acceleration processes of the ions or electrons are essential, the angular distribution will be anisotropic with the direction motion determined by the torch expansion geometry.

Fig.16 presents the energy distributions of the aluminum and carbon ions at fixed values of q for different angles of the analysis. The energy distributions for each angle and a charge Z can be used to calculate the number of the particles exiting at the given angle.

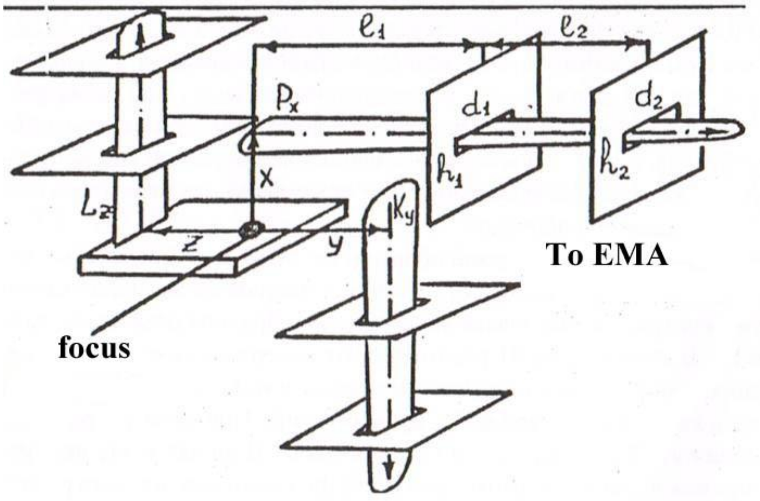

Fig16. *System of apertures to select regions of the laser plasma torch*

The main features of the angular expansion of the laser plasma in the plane Lo are (Figs. 17-20):

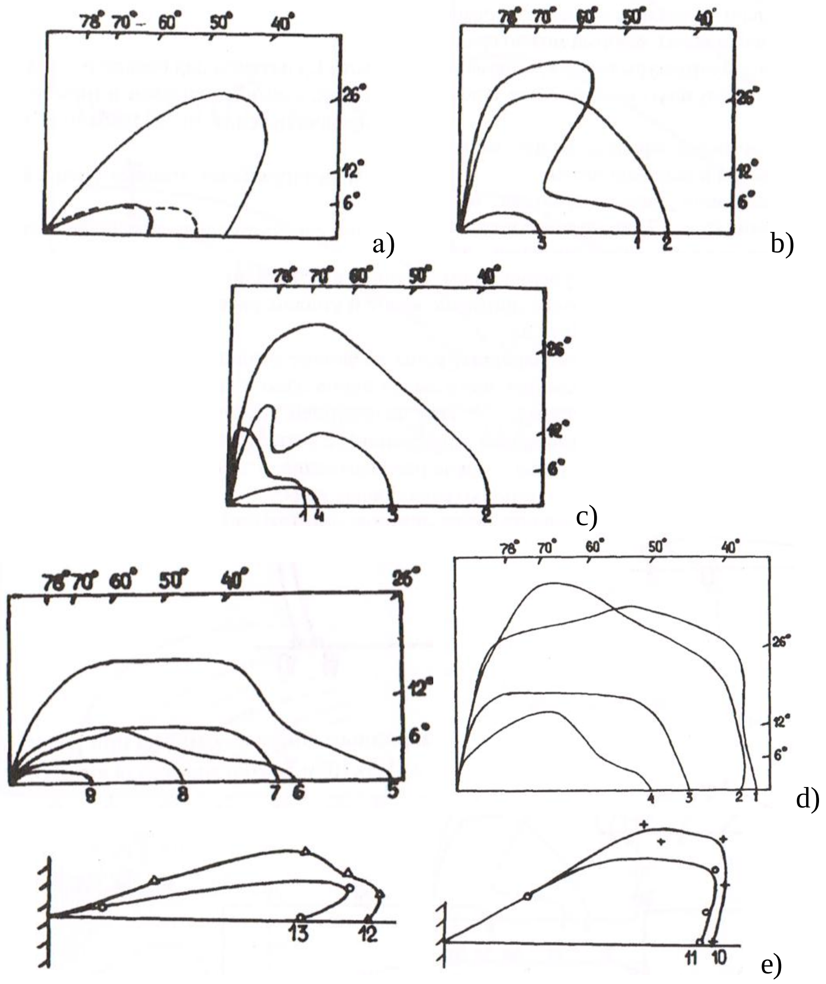

Fig17. *Angular spectra of multiply charged aluminum ions at different radiation flux densities (in W/cm^2): (a) 1.5x10^8 and 5x10^8 (solid line), (b) 1x10^9, (c) 3x10^{10}, (d) 3x10^{11}, (e) 5x10^{13}*

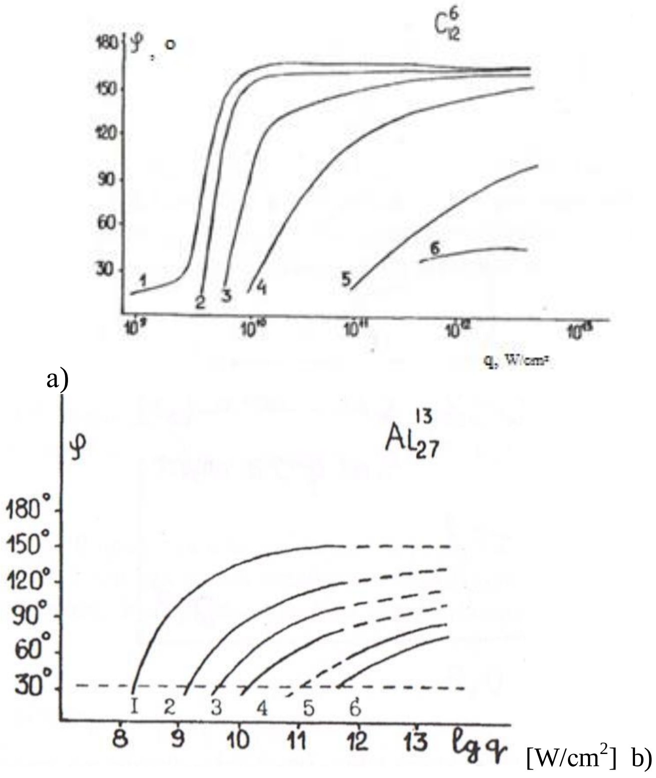

Fig18. *Dependence of the exit angle of (a) carbon and (b) aluminum ions from a laser plasma on the radiation flux density*

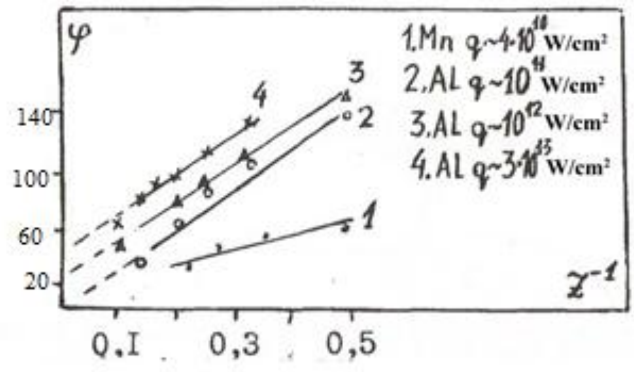

Fig19. *Angular scattering of ion beams of different elements as a function of the charge for fixed q*

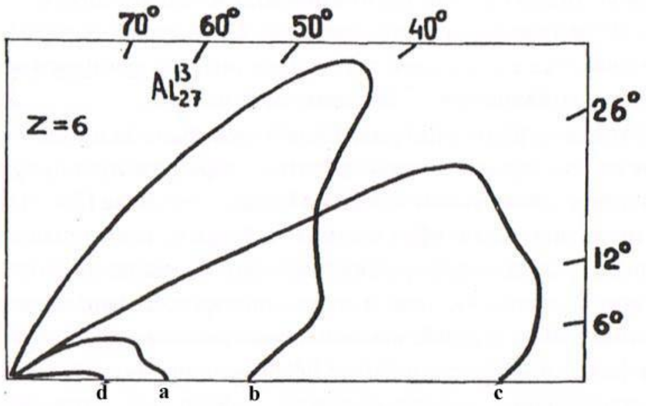

Fig20. *Angular distributions of the hexa-charged aluminum ions at various fixed values of energy: (a) 1300eV, (b) 1950eV, (c) 2880eV, (d) 5200eV*

a) The particle expansion is symmetric with respect to the normal of the target. Either the sample plane or the initially formed plasma layer, which can be represented as a flat disc, plays the major role for the expansion structure; and the normal to this plane is the pivot, around which we obtain the symmetric angular distribution.

b) The angular expansion of the particles narrows with increasing ion charge, which is an indicative of the acceleration effect on the laser plasma ions.

Thus, the laser plasma at any fixed radiation flux density on the sample contains the ions with the charge from Z=1 up to $Z_{\max}$ determined by initial experimental conditions (Fig. 18). The ions having a maximum charge fly apart in a narrow interval, i.e. narrow beams of highly charged ions are formed. The ions having a maximum charge form narrow beams and focus themselves along the normal to the target. This phenomenon first discovered by us in the laser plasma was called the ‘focusing’ effect of the highly charged ions beams (Fig.19). This effect can be used in various fields of science, engineering and technology and characterizes the acceleration processes in the laser plasma.

The verification of the influence of the crater (formed under irradiation of a solid body surface) on the ion focusing along the normal to the target surface was conducted as follows. The laser radiation was defocused in such a way that the interaction area of light with the surface increased by two orders of magnitude in comparison with the common case (100–200 μm). To keep the flux density at the previous level, the radiation energy was increased correspondingly. The crater diameter exceeded its depth by several orders of magnitude. The angular distributions resembled the lobes and were elongated along the normal to the sample surface. These experimental data indicate that the ‘focusing’ effect is not a result of the crater formation process but depends on the acceleration conditions in the laser plasma at early stages of the plasmoid expansion. There exists the dependence of the angular emission of the particles with a given charge on the position of these particles in the energy distribution (Fig. 20). These experiments indicate that the effect of ‘focusing’ of ions having a maximum charge is a consequence of the fact that the ions situated close to the low-energy boundary are intrinsic ions in contrast to the recombination ones, and so they have a very narrow angular distribution. These ions are formed due to non-elastic collisions of atoms and ions having the charge Z–1 with electrons at the initial sizes of the torch (in the form of a disc) with a subsequent acceleration. The second part of the energy spectrum (namely, its middle part including the intensity maximum of the particles) is a result of recombination of ions with higher charges Z. This process occurs later when the torch becomes spherical. Thus, the angular exit of the ions from the middle part of the energy spectrum is wider. The last high-energy part of the distribution is composed of the ions formed also as a result of the recombination process but from ions with the maximal charge Zmax, which have had initially a very narrow angular distribution. The ions with the considered charge in the region of high energies have again a very narrow angular distribution.

Therefore, the location of the ions in different energy intervals reflects the acceleration processes at different stages and with different particles, which can be effectively split and separated in the plasmoid.

6. ENERGY OF MULTIPLY CHARGED IONS AS A FUNCTION OF THE HEATING RADIATION WAVELENGTH

It was shown experimentally that the processes of laser plasma heating and formation depend significantly on the wavelength of incident radiation. Therefore, to understand the acceleration processes in the laser plasma, it is important and necessary to establish dependences of the changes in ions energies on the incident radiation wavelength. While comparing the energy spectra of ions of the laser plasma formed under irradiation at different wavelengths, the following questions arise:

- On what part or on which boundary of the spectra to make comparisons?
- Which flux density range to select for comparison?
- How to compare the energies values arising due to differences in the initial experimental conditions?

The intensity maxima of the particles and the right high-energy boundaries of the spectra are not suitable for such a comparison because plasmoids formed by radiation with a higher wavelength exhibit the ions with a higher charge, which would essentially change the location of these values due to the difference in the course of the recombination processes. Therefore, the most suitable parameter for the comparison is the value of the low-energy boundary of the spectrum. In selecting the low-energy boundary of the spectrum for comparing the results, one can also take into account a weak dependence of the left boundary of the ion distributions on the flux density; hence, one can compare the values of the low-energy boundaries of the spectra in a wide range of radiation densities. Now the third question: How to take into account the dependendence of the parameters compared on the selection of the sample material and the focusing spot diameter? As was shown above, the best parameter for the comparison is the characteristic of the minimum velocity of the ion expansion, which (see Fig. 14) is independent of the atomic weight of the element. Hence, the comparison is possible for various elements. The both conditions can be easily met because information about the minimal expansion velocities is available and measurements a performed for many substances.

The most difficult task to accomplish is the selection of the conditions, which would provide the same focusing spot diameter because in the lasers emitting at 10.6μm, the focusing spot in our experiments could not be less than 1 mm. However, most ion energy spectra of the plasma formed by the radiation at 1.06 and 0.69μm were obtained at the initial torch sizes equal to 0.1–0.2mm. To match these two values we shall use the dependences of the low-energy boundary on the focusing spot diameter.

Fig. 21 presents the change in the minimum energy of the ions as a function the charge for plasmoids consisting of the aluminum ions and formed by radiation at 1.06 and 10.6μm. It follows from the comparison of these dependences that the ion acceleration in the plasmoid formed by the radiation at 1.06μm is more pronounced. If we take into account that the initial size of the plasmoid formed by radiation at 1.06μm is less by an order of magnitude. The ion energy increases with increasing focusing spot diameter. Thus, the ion energy in the plasma produced by radiation at 1.06μm is twice that in the plasma produced by radiation at 10.6μm.

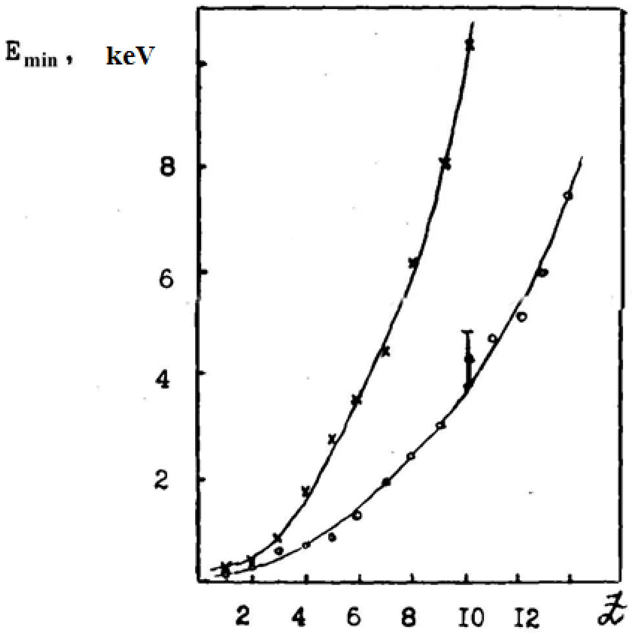

Fig21. *Dependence of the minimum energy of the ions on the charge for plasmoids formed by radiation at 1.06 (x) and 10.6 (o) µm (the sample is aluminum)*

It follows from the work [2] that $V_{max} \sim \lambda^{-1/6}$ (6)

7. CONCLUSIONS

In the literature devoted to the acceleration process of the particles in the laser plasma, it is often assumed that this phenomenon has a threshold nature with respect to the radiation flux density. Using the results of mass-spectrometric studies, we draw the conclusion that acceleration of the particles is a continuous process and starts at the moment of the plasmoid formation. Gas-dynamic (neutral fluxes) and electric (the effect of the charge on the particle energy) fields are involved in the acceleration. Thereby, the laser plasma ion energies reach 50keV for the given radiation flux densities. Distinctive characteristics of these processes are the independence of the low-energy velocity of the ion expansion on the atomic weight of the element as well as the direct proportionality of the low boundary of the particle velocity and the ion charge. The electrons and ions participate in these processes and influence the characteristics of each other.

The characteristics of the angular expansion of the laser plasma ions fit to the common scheme of description of the acceleration processes in the torch, where it is necessary to take into account intrinsic processes in the electrostatic field of electrons emerging at early stages of the plasmoid expansion during the times compared with the radiation pulse duration. All the recombination processes of the ions with a higher charge into the ions with a less charge occur after the acceleration terminates. This fact is experimentally confirmed by the structure of the energy distributions (the energy displacement is absent of the recombination intensity maxima) and by the ‘focusing’ effect as well as with by the presence of many accelerated particles (and not only in the thin layer of the torch, i.e. in a ‘crust’), having very high energies of directed motion. In addition, the presence of the electrostatic field effectively pulling the ions out, which has a positive effect on the process of hardening of the multiply charged ions, allows (among other products of the laser plasma) obtaining the directed beams of ions with a high charge (Z=25) and nuclei of various elements (aluminum, carbon, etc.).

The experimental data make it possible to represent the acceleration process of the laser plasma particles as follows. First, the acceleration process occurs mainly at an early stage of the torch development, following directly the ionization process. Second, initially the laser plasma electrons accelerate in the field of the electromagnetic wave, roughly speaking according to the mechanism pointed out in [2]. Under certain circumstances these superfast electrons have been apparently observed in the experiments on the laser fusion. And third, during the pulse action, there occurs a transfer of the kinetic energy of the electrons in a self-consistent electrostatic field [3].

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