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MEASUREMENT OF THE CHARGE COMPOSITION OF IONS IN EXPERIMENTS ON INTERACTION OF A LASER PLASMA FLOW WITH A PULSED GAS JET

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The ion composition of a plasma flow obtained by intense irradiation of a solid target is determined by methods of probing diagnostics and measuring the secondary emission rate. As the ions fly through a dense gas jet, C^{5+} *ions are found to recharge to* C^{4+} *ions and then to* C^{3+} *ions. The fraction of high-charge ions in the initial plasma flow and their concentration in the region of interaction with the jet are calculated. The concentration of atoms in the gas jet is estimated on the basis of the integral change in the charge value. Results necessary for analyzing the conditions of experiments on effective charge-transfer pumping and laser generation in the far ultraviolet spectral range are obtained.*

Key words: *charge transfer, laser plasma, gas jet, secondary emission rate.*

Introduction. In addition to impact electron excitation and recombination, charge transfer is one of the fundamental atomic excitation processes. The quasi-resonant character of this process allows inversion of the population of the levels of high-charge ions owing to charge transfer on atoms, molecules, or low-charge ions.

As was estimated in [1, 2], obtaining high gain factors in the spectral range at a wavelength shorter than 10 nm requires interaction to be organized with reagent concentrations being 10^{16} to 10^{17} cm^{-3}. A pulsed nozzle was used for the first time in the series of experiments with the laser plasma [3–5] for creating a compact gas jet, and resonant pumping of O^{2+}, O^{3+}, C^{3+}, and C^{5+} ions with significant enhancement of luminescence in the corresponding lines in the spectral range with wavelengths of 10 to 50 nm was observed. The experiments [3–5] confirmed that interaction of flows with clearly expressed fronts allows the charge-transfer intensity to be substantially increased. A pulsed gas nozzle was also used in the experiments [6]; in contrast to [3–5], however, a laser with a large stock of energy (up to 200 J in the pulse) necessary to generate a large number of high-charge ions was used in [6]. Under these conditions, controlled charge transfer on neural particles with concentrations of reagents greater than 10^{16} cm^{-3} could be realized for the first time. Resonant pumping of the third quantum level of the C^{3+} ion was registered by spectral methods, and plasma photographs were taken, which made it possible to find the structure of the region of intense charge transfer. The results measured by remote electric probes testify that the gas jet exerts a considerable effect on plasma expansion. The observed deceleration of the frontal part of the plasma flow with a loss of approximately 20% of energy shows that the plasma entrains hydrogen ions during the charge-transfer process. As a whole, the effect of the gas jet on the signal of the remote probe becomes more pronounced with increasing pressure and distance between the target and the jet.

It should be noted that direct measurements of changes in the charge composition in experiments on charge-transfer interaction of dense flows have not been performed until now. Such a study of the charge composition of the plasma interacting with a dense gas jet was performed in the present work with the use of the secondary emission

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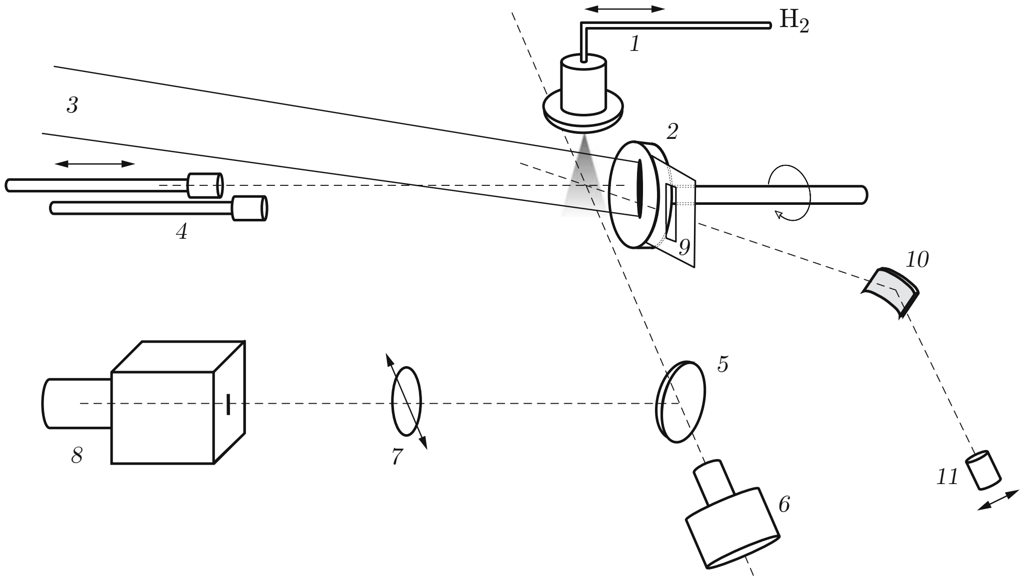

Fig. 1. Arrangement of the experiment: 1) pulsed gas nozzle; 2) target; 3) laser beam; 4) Faraday cup and plane electric probe; 5) mirror; 6) electron-optical converter for taking photographs of the plasma; 7) lens; 8) optical monochromator; 9) slot; 10) parabolic grid; 11) x-ray probe.

rate measured by an electric probe and by a Faraday cup, which allowed us to estimate the mean charge of ions in the plasma flow. Electric probes also make it possible to find the degree of variations of the examined quantities in different spatial regions of the flow (on the front, in the maximum, and in the tail), which are of interest from the viewpoint of studying charge-transfer pumping. Note that it is difficult to use methods of direct separation of ions, for instance, with a mass analyzer, into constituent elements because of the high density of the plasma.

Arrangement of Experiments and Measurement Techniques. The radiation of a CO_2 laser with an energy of 100 J and a half-width pulse duration of 50 nsec was focused on the surface of a flat target at an angle approximately equal to 20° (Fig. 1). The shape of the focused beam was either a spot approximately 0.2 cm in diameter or a line 15.0 mm long and 0.2 mm wide. The radiation intensity reached approximately 10^{15} W/m^2. The target shaped as a disk made of Caprolon ($C_6H_{11}ON$) and pure carbon was rotated after a certain number of shots to take the fractured target surface away from the focal spot. The nozzle of the pulsed gas valve was located parallel to the target plane at a controlled distance from the latter. The gas (molecular hydrogen) was injected from a tank with controlled pressure (ahead of the valve) maintained within 5 bar. Interaction of the laser plasma with the gas jet was arranged in the following sequence: a gating pulse was fed to the valve, and then the laser radiation was supplied after a certain time interval (more than 4 msec) necessary for a quasi-steady gas jet to form.

In addition to probing measurements, the experiment included spectral diagnostics in the visible range and high-speed filming (see [6]). The effect of charge-transfer pumping of the C^{5+} ion was registered on the basis of luminescence of 13.5-nm and 18.2-nm lines in the x-ray spectrum. For this purpose, the Rowland scheme was used with an approximately 20° angle of incidence of radiation onto a parabolic grating with a platinum coating.

The local and integral characteristics of the laser plasma flow were measured by a Faraday cup (FC) and by a plane probe (PP), which were described in [6]. The probes were located at a distance of 72 cm from the target, on a line passing through the gas jet and the focal spot on the target. Simultaneous registration of signals by the ion collector FC and by the plane electric probe PP allowed us to measure the effective secondary emission rate averaged over the charge composition of ions moving with a given velocity. The ion current density is $J = I/S$ (I is the measured current in the probe circuit and S is the area of the collimating orifice). The flow parameters depend on the registered current density as follows:

$$J = eV \sum_i n_i (Z_i + \gamma_i).$$

Here e is the proton charge, V is the instantaneous velocity of the flow, $Z_i \equiv i$ is the ion charge, n_i is the

TABLE 1

Characteristics of Secondary Emission for Carbon and Hydrogen Ions

Ion	V^{j+}, V	ΣV^{j+}, V	γ_i	$\gamma_{zi} = \gamma_i / z_i$
H^+	13.59	13.59	0.0840	0.0840
C^{1+}	11.26	11.26	0.0413	0.0413
C^{2+}	24.37	35.64	0.4870	0.2400
C^{3+}	47.86	83.50	1.3600	0.4540
C^{4+}	64.47	147.90	2.5400	0.6350
C^{5+}	391.90	539.90	9.6990	1.9400
C^{6+}	489.80	1029.80	18.6800	3.1100

concentration, and γ_i is the true secondary ion–electron emission rate for a given type of ions determined by the formula [7]

$$\gamma_i = k\Big(\sum_{j=2}^{i} V^{j+} - 2\varphi\Big),$$

where $k = 0.0183$ eV^{-1}, V^{j+} is the ionization potential, and φ is the electronic work function (taken to be 4.5 eV). The data on the characteristics of the secondary emission for carbon and hydrogen atoms used in the present study are summarized in Table 1.

As $\gamma_i = 0$ for the Faraday cup [8], it is possible to measure the ion flow directly; with the use of the plane probe, it is also possible to measure the mean value of the specific secondary emission rate:

$$\gamma_{\rm exp} \equiv \frac{I_{\rm PP}}{I_{\rm FC}} - 1 = \frac{\sum Z_i n_i + \gamma_i n_i}{\sum Z_i n_i} - 1 = \frac{\sum Z_i n_i \gamma_{zi}}{\sum Z_i n_i}. \tag{1}$$

Using the measured values of the secondary emission rate $\gamma_{\rm exp}$ and known emission rates γ_{zi}, we can determine the mean charge of ions in different flow regions and its changes due to interaction with the gas.

Measurement Results and Model. The results of measurements in the visible and x-ray spectral ranges show that the plasma at a distance $R \approx 1$ cm from the target contains a large number of high-charge ions C^{5+} and C^{6+}, in addition to C^{4+} ions with a low ionization potential. Interaction with the gas jet leads to charge transfer between ions, which is evidenced by intense resonant luminescence in certain lines of the spectrum [6]. The present paper described only the results of probe measurements.

The secondary emission rate was studied with the use of the plasma obtained by means of laser irradiation of a graphite target in high vacuum, which makes the analysis substantially simpler than in the case with a Caprolon target containing a large number of hydrogen atoms. Figure 2 shows the typical oscillograms obtained by the Faraday cup and by the plane probe for the plasma propagating in vacuum and through a jet of molecular hydrogen, which were averaged over several individual measurements providing stable and repeatable results. The attenuation of the ion flow of the laser plasma observed owing to its interaction with the gas jet is also registered outside the expansion axis (Fig. 3), i.e., the interaction process has a non-local character. Figure 4 shows the measured values of the specific secondary emission rate for the cases illustrated in Fig. 2.

It seems of interest to determine the number of high-charge ions and the degree of changing of the plasma charge due to its interaction with the gas. The problem of determining the partial composition of the plasma by Eq. (1) is ill-posed in the general case, but certain physical assumptions make the analysis substantially less complicated. The range of the measured values of the specific secondary emission rate $0.5 < \gamma_{\rm exp} < 2.0$ allows us to conclude that C^{4+} and C^{5+} ions prevail in the flow (see Table 1). It is also seen in Fig. 4 that the change in the charge due to interaction with the gas jet occurs only on the plasma front approximately within the time interval $t < 3.5$ μsec (the maximum of the flow where $\gamma_{\rm exp} > 1$). As the plasma contains high-charge ions in this interval and charge transfer occurs, we consider only the plasma front before the flow maximum.

We further assume that there are no completely ionized carbon ions C^{6+} in the plasma flow under study. The reasons are the high ionization potential of these ions and the higher intensity of their three-part recombination prevailing at the initial stage of expansion, which is almost two times the intensity of recombination of C^{5+} ions. We also assume that there are no C^{3+} ions on the front of the initial flow. As ions with different charges separate in

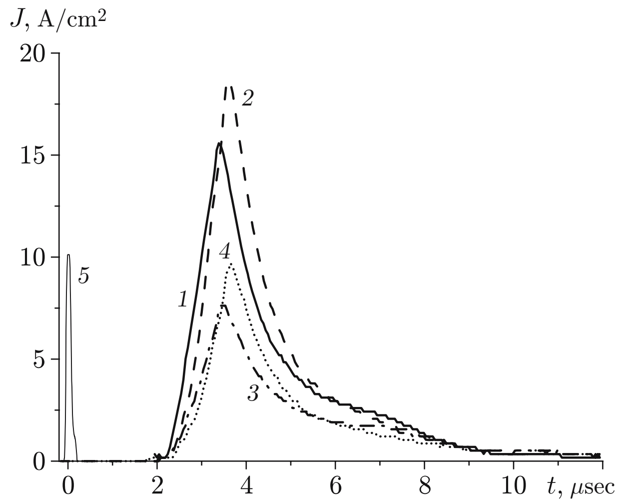

Fig. 2

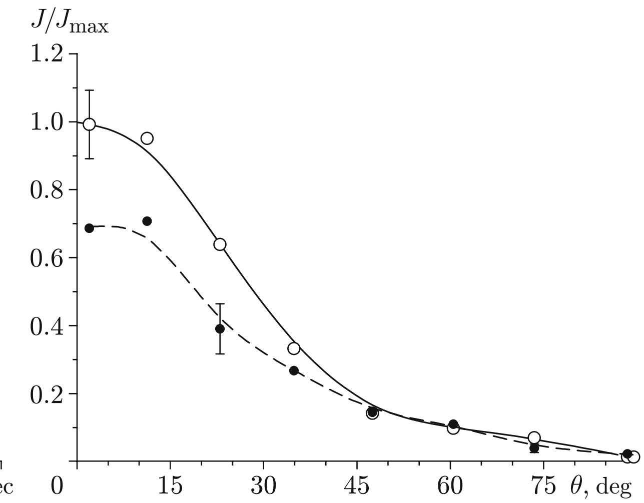

Fig. 3

Fig. 2. Current oscillograms obtained during laser plasma expansion into vacuum and through the gas jet: curves 1 and 2 show the results measured by the Faraday cup in vacuum and in the gas, respectively; curves 3 and 4 show the results measured by the plane probe in vacuum and in the gas, respectively; curve 5 is the laser pulse.

Fig. 3. Normalized ion current density of the leading front of the plasma in vacuum (solid curve) and in the presence of the hydrogen jet (dashed curve) versus the angle of observation with respect to the expansion axis at $R = 27$–37 cm, which was obtained by an isotropic probe consisting of three mutually orthogonal cylindrical Langmuir probes.

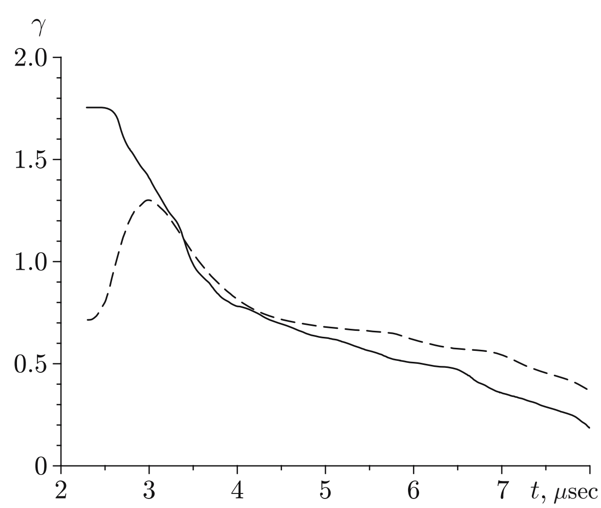

Fig. 4. Experimentally measured specific secondary emission rate of the plasma flow in vacuum (solid curve) and in the presence of the gas jet (dashed curve) versus time.

space in the laser plasma because of different accelerations in the corona near the target, the majority of ions on the plasma front are C^{5+} ions, while C^{3+} ions are located in the tail of the flow and are not considered, as well as C^{2+} ions and ions with lower charges. It is assumed, however, that new C^{3+} ions are formed during charge transfer of C^{4+} ions in the case of interaction with the gas jet.

For convenience, we present the concentration of C^{3+} ions as a certain fraction of the concentration of C^{4+} ions: $n_3 = \alpha_3 n_4$. In this case, the dependence of the partial (normalized) composition of the flow on the measured

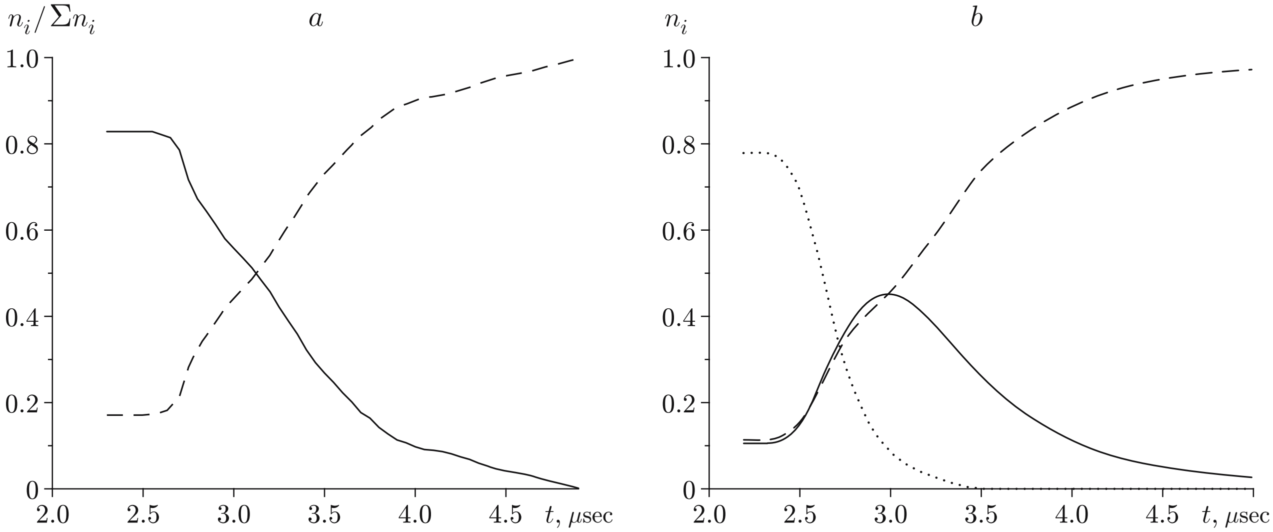

Fig. 5. Normalized fractions of ions in the initial plasma flow in vacuum (a) and after interaction with the gas jet (b) for C^{5+} ions (solid curves), C^{4+} ions (dashed curves), and C^{3+} ions (dotted curve).

emission rate $\gamma_{\rm exp}(t)$ is described by the following relations:

$$\begin{gathered} n_3 + n_4 + n_5 = 1, \\ n_3 = \alpha_3(\gamma_5 - 5\gamma_{\rm exp})/D, \\ n_4 = (\gamma_5 - 5\gamma_{\rm exp})/D, \\ n_5 = (\alpha_3(3\gamma_{\rm exp} - \gamma_3) + 4\gamma_{\rm exp} - \gamma_4)/D, \\ D = \alpha_3(3\gamma_{\rm exp} - \gamma_3) + 4\gamma_{\rm exp} - \gamma_4 + (1+\alpha_3)(\gamma_5 - 5\gamma_{\rm exp}). \end{gathered} \tag{2}$$

Assuming that C^{3+} ions are formed as a result of charge transfer only, we can determine the unknown coefficient α_3. For ions moving with an identical velocity in one element of the plasma, the expression for the charge-transfer effect is [9]

$$\tilde{n}_i = n_i \exp\Big(-\sigma_i \int n_a\, dl\Big),$$

where σ_i is the cross section of charge transfer of the ith ion on neutral atoms of the jet; the tilde indicates the quantities for the case where the plasma flow interacts with the gas jet; the integral describes the total number of atoms that interact with ions flying through the jet. In the general case, the value of $\tilde{n}_i$ depends on time, but it is always identical for ions of the same element of the plasma. Taking this fact into account, we can express the change in the concentrations in the plasma flow via the changes for some ion: $\tilde{n}_i = n_i(\tilde{n}_k/n_k)^{\sigma_i/\sigma_k}$. After simple transformations, we can express the coefficient α_3 for the case of the gas jet via the change in the concentration of C^{5+} ions:

$$\alpha_3 = (n_5/\tilde{n}_5)^{\sigma_4/\sigma_5} - 1. \tag{3}$$

According to experimental measurements, the areas of the corresponding cross sections are approximately identical: $\sigma_4 \approx \sigma_5 \approx 2.5 \cdot 10^{-15}$ cm^2 [10]. Note that the coefficient α_3 is a function of time, like the partial fractions.

Figure 5a shows the fractions of ions in the initial plasma flow in vacuum, which was calculated by Eqs. (2). It is seen that the possible presence of C^{3+} ions, which was neglected, exerts only a minor effect on the fraction of high-charge ions C^{5+}. Figure 5b shows the calculated ion composition of the plasma interacting with the jet. In this case, the fraction of C^{3+} ions was calculated by Eq. (3). We can argue that the number of high-charge ions C^{5+}

on the leading front of the flow substantially decreases owing to interaction with the jet; these ions are converted to C^{4+} ions and then to C^{3+} ions. The mean fraction of ions over the flow is determined by the formula

$$\langle n_k\rangle = \int \frac{J_{\rm FC}}{\langle Z\rangle} n_k\,dt \Big/ \int \frac{J_{\rm FC}}{\langle Z\rangle}\,dt, \qquad \langle Z\rangle = \sum Z_i n_i.$$

For the initial plasma flow in vacuum, the mean fraction of C^{5+} ions is 47% before the maximum current is reached; after interaction with the gas jet, the fraction of these ions decreases to 35%. The maximum concentration of C^{5+} ions at the point of probe location is $n_5 = 1.6\cdot 10^{11}$ cm^{-3}. Recalculation by the model of self-similar expansion to a distance of 1.3 cm from the target yields the value $n_5 = 2.7\cdot 10^{16}$ cm^{-3}. The estimate from below for the integral change in the plasma charge and, hence, the number of hydrogen molecules in the jet can be found by integration over the flow

$$\Delta Q = \int J_{\rm FC}\Big(1 - \frac{\langle\tilde Z\rangle}{\langle Z\rangle}\Big)\,dt,$$

where $\langle\tilde Z\rangle = 3\tilde n_3+4\tilde n_4+5\tilde n_5$ and $\langle Z\rangle = 4n_4+5n_5$. As a result, we obtain $\Delta Q \approx -2.3\cdot 10^{-7}$ C/cm^2. As the probes were located at a distance of 72 cm and the gas jet was at a distance of 1.3 cm and had a width $L = 1$ cm, the concentration of neutral particles due to charge transfer in the jet is greater than $n_0 = (\Delta Q/(eL))(72/1.3)^2 \approx 4.3\cdot 10^{15}$ cm^{-3}.

Additional important information can be obtained from the difference in the probe signals in vacuum and in the case of interaction with the gas jet. It should be borne in mind that interaction with the gas jet involves not only ion charge transfer, but also insignificant deceleration of ions. Hydrogen ions entrained from the jet by the plasma flow appear in the tail of the flow. (A model of acceleration due to interaction of dense flows was proposed in [6].) Under these conditions, objective information can be obtained only by integration over the entire length of the flow [until $t \approx 10$ μsec (see Fig. 2)]. As the total charge of ions remains unchanged during charge transfer, the quantity $\Delta Q = \displaystyle\int (J_{\rm FC} - \tilde J_{\rm FC})\,dt \approx 2.5\cdot 10^{-6}$ C/cm^2 allows us to estimate the minimum number of hydrogen ions formed in the initial neutral jet as a result of ionization processes: $n_+ \approx 4.5\cdot 10^{16}$ cm^{-3}.

Conclusions. The charge composition of the laser plasma is studied by the method of identification of multicharge ions on the basis of electron emission. With a minimum number of additional assumptions, this method allows the ion composition to be reconstructed in each element of the initial plasma flow and in the plasma leaving the interaction region. In the experiment performed, the fraction of high-charge ions C^{5+} on the front of the plasma flow (before its maximum) reaches approximately 50%. In the course of interaction with the gas jet, these ions recharge in a cascade manner to C^{4+} and C^{3+} ions. As the number of atoms in the jet is smaller than the number of ions in the plasma, the ion charge changes only on the front of the flow. In the tail of the flow, the ions fly through an already ionized gas, and no charge transfer occurs. The measured concentration of C^{5+} ions on the gas-jet centerline $n \approx 3\cdot 10^{16}$ cm^{-3} corresponds to the value necessary for experiments on charge-transfer pumping and laser generation in the x-ray spectral range, while the predicted concentration of neutral particles involved into charge transfer turns out to be lower (almost by an order of magnitude) than the initial concentration of hydrogen molecules in the gas jet $n_{\rm H_2} \approx 5\cdot 10^{16}$ cm^{-3}. This value measured previously by an ionization gauge [6] agrees well with the value calculated in the present work on the basis of the change in the total charge arriving on the Faraday cup. The result obtained shows that it is necessary to increase the density of the gas jet and to take into account the effect of ionization of the gas jet by intense radiation and hot electrons coming from the focal spot on the target surface.

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