Photographs of laser plume in line radiation of multiply charged ions in the far vacuum ultraviolet

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Plasma photographs are obtained in the radiation of individual spectral lines of multiply charged carbon, calcium iron, and nickel ions in the region $\alpha \sim 100$ Å. A joint analysis of the photographs of the plasma and of the spectra with spatial resolution has made it possible to trace the acceleration of the ions, to determine the electron temperature, the ion kinetic energies, the density variation, and the position of the critical point.

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A definite limitation on the traditional methods of plasma diagnostics using a spectrograph is that a spatial resolution obtains at best only along one coordinate, when radiation from different sections of the source reaches spectral-line sections of different height; integration over the entire cross section is preserved in this case. A modification of a grazing-incidence spectral instrument was proposed in[1] for the registration of photographs of a laser plasma with two-coordinate spatial resolution in the line radiation of the far ultraviolet region of the spectrum ($\lambda < 500$ Å). We report below that photographs of a laser plume were obtained in lines of multiply charged C, Ca, Fe, and Ni ions with the aid of such a dispersive microscope.

The laser plasma was generated by a pulse from a neodymium laser ($\tau_L \approx 2.5$ nsec; $E_L \approx 10$ J). A beam of 45 mm diameter was focused by a spherical lens with $f = 300$ mm on a flat target in vacuum. The target surface was parallel to the Rowland circle, and the laser-beam axis was normal to the target.

Figure 1a shows a photograph of a carbon plume in the radiation of the 3–2 transition of the ion C VI; Fig. 1(b) shows a number of plasma photographs taken in

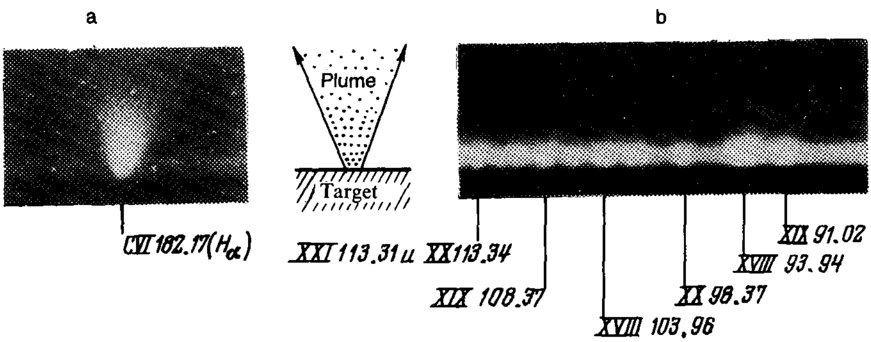

FIG. 1.

the spectral lines of F-, O-, and N-like iron ions. It is seen that the ions of higher multiplicity exist in the narrower regions of the plume. The diameters $d_{0.5}(\mu\mathrm{m})$ of the emission zones of the ions at the target surface (at a level of 0.5 of the maximum exposure) are listed in Table I. The quantities in the parentheses are the ionization

TABLE I.

Element / Ion type	Ca	Fe	Ni
[F], $2s^2 2p^5$	—	145 (1.35)	140 (1.64)
[O], $2s^2 2p^4$	155 (0.73)	110 (1.45)	80 (1.75)
[N], $2s^2 2p^3$	—	85 (1.57)	—

potential (keV) of the corresponding ions. The spatial resolution over the target surface parallel to the dispersion direction was determined by the Doppler width of the spectral lines and amounted to 5–10 μm for a nickel plasma and 10–20 μm for a calcium plasma.

The images of the plume in various spectral lines are shaped like truncated cones that have different base diameters as well as aperture angles. Both characteristics have a tendency to decrease with increasing ionization multiplicity and atomic number of the target material. Thus on the photograph of the plume in the H_α line of the C VI ion the half aperture angle of the cone is $\alpha = 26 \pm 2°$ as against $\alpha = 12$–$14°$ for the oxygenlike Ni XXI ion.

The macroscopic motion of the plasma and the presence of a velocity component in the observation direction give rise to a Doppler broadening of the spectral line. This broadening depends both on the distance l to the target and on the type of the spectral transition and the type of ion. The last circumstance is connected, in particular, with the fact that the ions of higher multiplicity may fly apart at smaller angles. Figure 2 shows the Doppler broadening of the transitions $2s^2\,2p^k - 2s2p^{k+1}$ of the ions Ca XIII

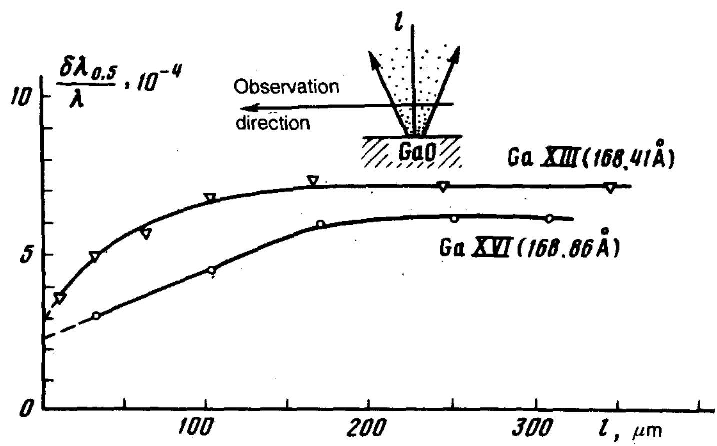

FIG. 2.

and Ca XVI, measured at the 0.5 level, as a function of l. It is seen that at $l \approx 200\,\mu$m the acceleration is already mainly over, and the ions move by inertia. Assuming the emission velocity to be the same over the cross section, we can determine from the Doppler shift (at the 0.1 level) the emission velocity from the relation $v\sin\alpha/c = \delta\lambda_{0.1}/2\lambda$. The generatrix of the emission cone was defined by us as the line that joins together points from different plume sections with exposure 0.1 of the maxi-

TABLE II.

Ion	C V	Ca XIII	Ni XVIII
$v_{as}^{\rm exp}$, 10^7 cm/sec	4.5	4.4	7.6 – 10
E_{as}, keV	13	40	180 – 300
$v_{as}^{\rm theor}$, 10^7 cm/sec	5.1	4.6	4.6

mum in a given section parallel to the target plane. Table II lists the asymptotic emission velocities v_{as} and the corresponding ion kinetic energies. Each set of measured values of α and $\delta\lambda_{0.1}$ pertained to one and the same transition.

Let us compare the measurement results with estimates of the temperature and velocity on the basis of the stationary model of the "corona" of the laser plasma, investigated in[2]. According to[2], the qualitative picture of the state of the corona is determined by the dimensionless parameter $\gamma_0 = \kappa_0^{3/4} q_l/\rho_{\rm cr}^{7/4} R_0^{3/4}(M_i/Z)^{21/8}$ (κ_0 is the coefficient of electronic thermal conductivity), $\rho_{\rm cr} = (M_i/Z)10^{21}\,{\rm cm}^{-3}$ is the critical (for the neodymium-laser emission) density, R_0 is the radius of the spherical target, q_L is the laser-emission flux density at the target, and M_i and Z are the mass and charge of the ions. Assuming in the estimate of γ_0 that the radius R_0 is equal to the distance from the surface of the target to the point of intersection of the emission-cone generatrices, namely $R_0 = r_{\rm foc}/\tan\alpha \sim 200\,\mu$m, we have $\gamma_0 \approx 10$ at $q_L \sim 10^{13}$ W/cm^2. According to[2], at $\gamma_0 \ll \gamma_0^* \approx 10^2$ the coordinates of the critical point and of the Jouguet point coincide, and the values of the velocity at small γ_0 are determined by the formulas

$$v_{\rm cr} \approx (q_L/3\rho_{\rm cr})^{1/3};\; v_{as} \approx \sqrt{6}\,v_{\rm cr};\; T_{\rm cr} = M_i v_{\rm cr}^2/Z;\; E_{as} \approx 3ZT_{\rm cr}.$$

Here $T_{\rm cr}$ and $v_{\rm cr}$ are the electron temperature and velocity at the critical point. The mean value of the ion charge $\bar{Z}$ needed for the estimates was determined by us from experiment[3] and amounted to 5.5, 13, and 20 for the carbon, calcium, and nickel plasma, respectively. Table II gives the calculated values of v_{as}. It is seen that the observed velocities for carbon and calcium plasma are close to the calculated ones.

These velocities correspond to values $T_{\rm cr} \approx E_{as}/3Z \approx 0.8$ keV and ≈ 1.0 keV. The presence of temperatures of the order of 1 keV is attested also by the ionization state of the nickel plasma. Near the target the ratio of the concentrations of the O-like and F-like Ni ions, estimated from the relative intensities of the transitions $2s^2p^k 2s2p^{k+1}$ on the spectrum with spatial resolution turns out to be [O]/[F]$\sim$0.75

(averaged over the cross section). Within the framework of the stationary corona model[4] such an ionization state corresponds to a temperature $T_z \sim 1.0$ keV. The values of T_z on the plume axis, estimated from pictures of the nickel plasma in line radiation, are 1.5 times larger.

Having obtained the $v(l)$ dependence and having determined the value of the electron concentration N_e at some arbitrary section of the plume, we can determine the mean value of N_e at any other section if we confine ourselves to the region $l < l_0$ in which a quasistationary $N_e(l)$ profile manages to become established (at $v \sim 4 \times 10^7$ cm/sec and $\tau_L \approx 2.5$ nsec, $l_0 \approx 1$ mm). The continuity relation must then be satisfied: $N_i vS = \text{const} \times (N_e = \bar{Z} N_i)$. Starting from the value $N_e \approx 4 \times 10^{18}$ cm^{-3} at $l = 400$ μm determined from the spectrum of the O-like Ca XIII ion[5] and recognizing that $\bar{Z}$ varies very little,[3] we obtain the profile of N_e in the region $l < 400$ μm (Fig. 3). At $l \lesssim 15$ μm (the resolution limit at the target) the plot of $N_e(l)$ is no longer reliable, but there is no doubt that a density drop by three orders of magnitude (from $N_e \sim 10^{20}$ cm^{-3} to $N_e \sim 10^{23}$ cm^{-3}) takes place over a length $\sim 10^{-3}$ cm. We note that even at distances

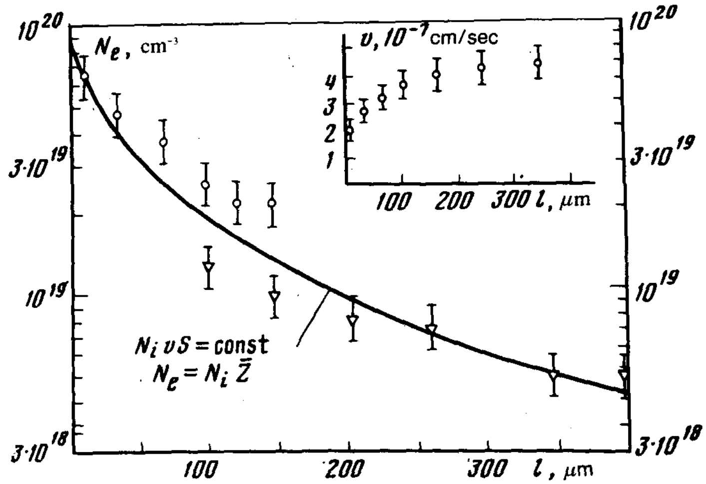

FIG. 3. $N_e(l)$ profile reconstructed with the aid of the continuity relation (solid curve). Figure 3 shows also the values of N_e determined from the spectra of the O-like ions Ca XIII (triangles) and Ni XXI (circles), with an indication of the accuracy of the photometric measurements. The data on the Ni XXI ion pertain to the central region of the plume. Upper right—plot of the dispersal velocity of the calcium plasma.

$l \sim 15$ μm we alrady have $v > 2 \times 10^7$ cm/sec (Fig. 3), i.e., the plasma dispersal becomes supersonic. This alone already attests that the point with critical density is located near the target surface, namely $l_{cr} < 15$ μm.

Using the obtained values of v, N_i, and S we find that the ion kinetic-energy flux directed counter to the laser beam amounts to ~ 15, ~ 8, and (25–50)% of the laser radiation flux for carbon, calcium, and nickel plasma, respectively.

The joint utilization of the spectra and photographs of the plasma in lines of multiply charged ions uncovers a possibility of measuring the ion composition, temperature, and velocity with a spatial resolution with respect to two coordinates.

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[1]A.A. Ilyukhin, G.V. Peregudov, and E.N. Ragozin, Pis'ma Zh. Eksp. Tekh. Fiz. **2**, 681 (1976) [Sov. Tech. Phys. Lett. **2**, 266 (1976)].

[2]Yu. V. Afanas'ev, E.G. Gamaliĭ, O.N. Krokhin, and V.B. Rozanov, Zh. Eksp. Teor. Fiz. **71**, 594 (1976) [Sov. Phys. JETP **44**, 311 (1976)].

[3]A.A. Ilyukhin, G.V. Peregudov, and E.N. Ragozin, Kvantovaya Elektron. (Moscow) **4**, 607 (1977) [Sov. J. Quantum Electron. **7**, 336 (1977)].

[4]C. Jordan, Mon. Not. R. Astr. Soc. **142**, 4 (1969).

[5]A.V. Vinogradov, G.V. Peregudov, E.N. Ragozin, I.Yu. Skobelev, and E.A. Yukov, Kvantovaya Elektron. (Moscow) **5**, 1077 (1978) [Sov. J. Quantum Electron. **8**, 615 (1978)].