Formation of the x-ray line emission spectrum of superdense *X*-pinch plasma

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Experimental and theoretical investigations have been made into the formation of the line emission spectrum of an aluminum *X* pinch. The emission spectra were measured by means of a focusing spectrograph with spatial resolution that uses a spherically concave mica crystal. The characteristics of the emission spectra, including the intensities and profiles of the spectral lines due to transitions from highly excited levels of the He-like Al XII ion and the $3p-1s$ transition of the H-like Al XIII ion, were used to determine the plasma parameters of the *X* pinch at different stages of its evolution. © *1995 American Institute of Physics.*

1. INTRODUCTION

For the solution of many fundamental and applied scientific and technical problems, it is necessary to create laboratory sources of superdense (i.e., with density close to or exceeding the solid-state density) hot plasma. Characteristic examples here are the problem of inertial thermonuclear synthesis and the investigation of superdense astrophysical objects. The methods of creating such plasma have been developed over several decades, and at the present time there are three types of laboratory source of superdense high-temperature plasma. First, there is plasma formed by the laser compression of spherical targets (see, for example, Refs. 1–4), second, the plasma produced by electric discharges (vacuum spark, *Z* and *X* pinches[5–11]) and, finally, plasma formed by the interaction of subpicosecond laser pulses with solid-state targets.[12–16] The creation of these new plasma objects poses the problem of the experimental and theoretical investigation of their radiative characteristics, since these are often the only source of information about the parameters of the superdense plasma and physical processes taking place in them.

The difficulties in the theoretical description of the process of formation of the emission spectrum of superdense plasma are associated, on the one hand, with the need to take into account a large number of elementary radiation and collision processes, the probabilities of which can be modified by screening of the nuclear field of the ions by free plasma electrons (in particular, this can lead to the shift or nonrealization of excited ionic states[17,18]) and, on the other, with the insufficient amount (and quality) of the existing experimental material. Such material could greatly simplify the choice and testing of the adequacy of the employed theoretical models.

In this paper, an attempt is made to describe the emission spectrum of an aluminum plasma formed in *X* pinches. The use of high-luminosity x-ray spectrographs that permit measurement of plasma radiation with spatial resolution has made it possible to obtain a picture of the time evolution of the *X*-pinch plasma parameters even on the basis of time-integrated spectrograms.

2. DESCRIPTION OF THE EXPERIMENT

The experiments were made using the high-current pulsed current generator BIN ($I=270$ kA, $t=100$ ns) at the P. N. Lebedev Physics Institute of the Russian Academy of Sciences. The plasma of *X* pinches formed in the diode of the generator when crossed aluminum wires of diameter 35 μm were used as load was investigated.[10] The x-ray emission of the plasma was measured by spectrographs of various types and by pinhole cameras. The profiles of the spectral lines were investigated by means of a high-luminosity focusing spectrograph with spatial resolution (FSPR-1) using a 100-mm radius concave spherical mica crystal.[19,20] The schematic arrangement of the experiment is shown in Fig. 1a. In the region of crossing of the wires, a hot plasma with complicated structure was formed, and this plasma was observed both in the spectrograms with spatial resolution (Figs. 1b and 1c) as well as in the images obtained by means of the pinholes cameras (Fig. 1d). Our earlier investigations based on analysis of the relative intensities of different spectral lines[9,10] showed that, as a rule, there are formed in the *X* pinch regions of hot plasma ($T_e>300$ eV) with moderate density ($N_e\sim10^{20}-10^{21}$ cm^{-3}) and diameters of order 100–300 μm together with a region of extremely high density ($N_e>10^{22}$ cm^{-3}) and a diameter less than 30 μm. This last region has the greatest interest from the point of view of the investigation of the broadening of the spectral lines.

3. DETERMINATION OF THE PLASMA PARAMETERS

In a sufficiently narrow interval $\Delta\lambda_R$ of wavelengths corresponding to the spectral resolution of the spectrograph, the time-integrated energy flux density of the plasma radiation at the point **R** of a film with normal to the surface *n* is given by the expression

$$I(\mathbf{R},\mathbf{n})=\int\int Q_{\lambda_R}(\mathbf{r},t)g(\mathbf{r},\lambda_R,\mathbf{R},\mathbf{n})d\mathbf{r}dt, \qquad (1)$$

where λ_R is the wavelength, $Q_\lambda(\mathbf{r},t)$ is the spectral energy density of the plasma radiation at the point **r** at the time *t*, or

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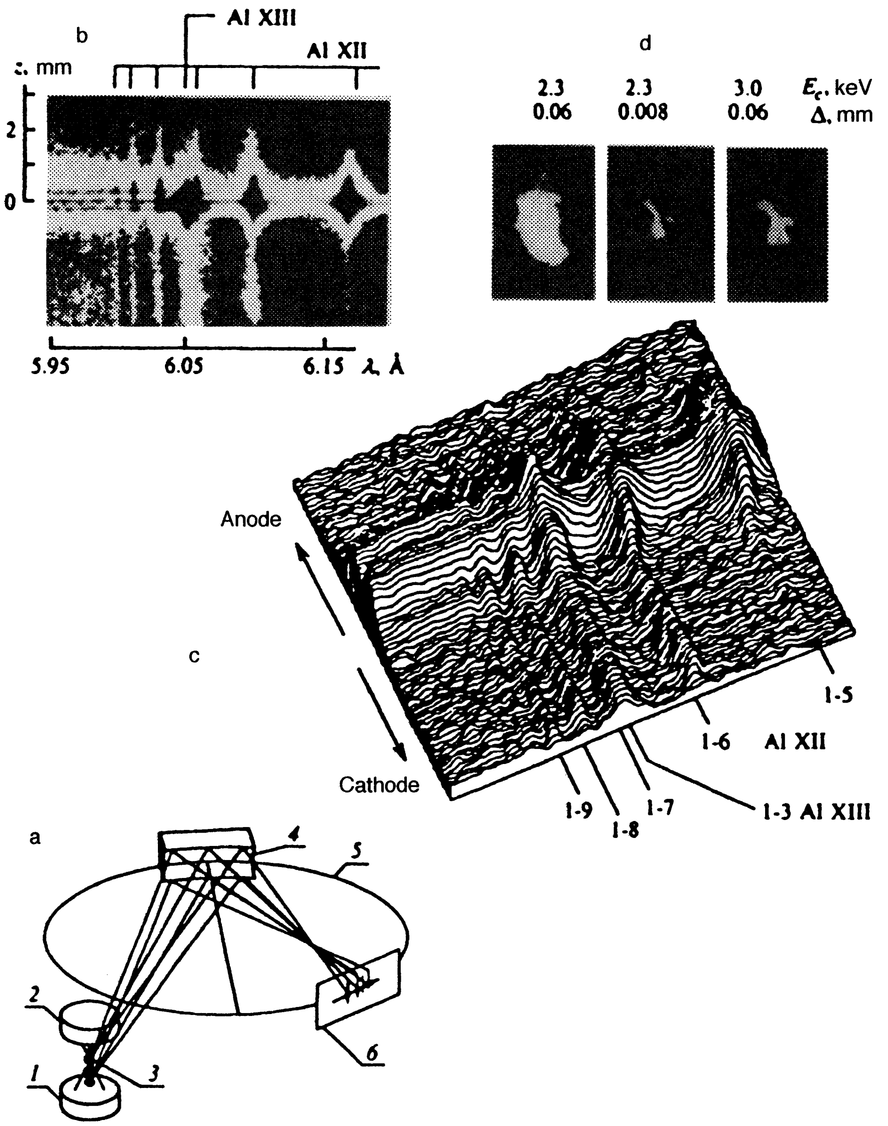

FIG. 1. a) Arrangement for detecting radiation by means of the spectrograph FSPR-1: 1), 2) anode and cathode of diode current generator; 3) X-pinch plasma; 4) spherically concave mica crystal; 5) Rowland circle; 6) photographic film; b) spectrograms obtained by the FSPR-1 spectrograph; c) distribution of the radiation intensity along the axis of the X pinch; d) X-pinch pinhole picture; E_c is the cutoff energy of the filters; Δ is the diameter of the opening.

the emissivity, and $g(\mathbf{r},\lambda,\mathbf{R},\mathbf{n})$ is a weight function. In the general case, the actual form of g is determined by the parameters of the spectrograph and, for an optically dense plasma, also by a nonlocal dependence on its parameters. For an optically thin plasma, g is determined by the spatial resolution of the spectrograph. In this paper, we shall not determine more accurately the form of the weight function, since it will occur only in the fitting parameters used to model the observed spectrum.

Since the emissivity depends only on the local values of the electron temperature $T_e(\mathbf{r},t)$ and the density $N_e(\mathbf{r},t)$ of the plasma and on the expansion geometry, the expression (1) can be represented in the form

$$I(\mathbf{R},\mathbf{n})=\int\int\langle Q_{\lambda_R}(N_e,T_e)\rangle w(N_e,T_e,\lambda_R,\mathbf{R},\mathbf{n})dN_e dT_e, \tag{2}$$

where the angular brackets denote averaging over the characteristics of the macroscopic motion of the plasma, and the function w has the form

$$w(N_e,T_e,\lambda_R,\mathbf{R},\mathbf{n})=\int\int\delta(N_e-N_e(\mathbf{r},t))\times\delta(T_e-T_e(\mathbf{r},t))g(\mathbf{r},\lambda_R,\mathbf{R},\mathbf{n})d\mathbf{r}dt.$$

The plasma emissivity in the spectral range of the lines of the resonance $1snp\ ^1P_1-1s^2\ ^1S_0$ transitions from the $n\geqslant 5$ levels of the He-like Al XII ion is determined by the expression

$$Q_\lambda(N_e,T_e)=(hc/\lambda)\left(\sum_{n\geqslant 5}A_{n1}S_{n1}(\lambda-\lambda_{n1},N_e,T_e)\times N_n(N_e,T_e)+A_{31}S_{31}(\lambda-\lambda_{31},N_e,T_e)\times N_3(N_e,T_e)\right)+Q_\lambda^{\mathrm{H}}(N_e,T_e), \tag{3}$$

where A_{n1} is the rate of the radiative transition, $S_{n1}(\lambda-\lambda_{n1},N_e,T_e)$ is a spectral function determined by the local mechanisms of line broadening and the Doppler shift, and N_n is the level occupancy. The term with $n=3$ corresponds to transition in the H-like ion; $Q_\lambda^{\mathrm{H}}(\lambda,N_e,T_e)$ is determined by the photorecombination and bremsstrahlung radiation.

In a wide range of plasma parameters, the relaxation times of the level occupancies are short compared with the characteristic times of the macroscopic motion of the plasma, so that the occupancies of the excited levels in the quasisteady approximation have the form

$$N_n(N_e,T_e)=\beta_n(N_e,T_e)N_e\,N_1^+(N_e,T_e)+s_n(N_e,T_e)N_1(N_e,T_e), \tag{4}$$

where $\beta_n(N_e,T_e)$ and $s_n(N_e,T_e)$ are occupancy coefficients determined by solving a system of kinetic equations[21,22] and do not depend on the charge composition, and $N_1^+(N_e,T_e)$ is the occupancy of the ground state of the ion of the following multiplicity. At high densities, the recombination channel of occupation [the first term in (4)] is dominant.

To calculate the spectral functions of the lines of resonance transitions from the $n\geqslant 5$ levels of the He-like Al, the Coulomb approximation can be used, since the relativistic effects and interelectron interaction are small compared with the perturbation by the ionic microscopic field of the plasma, which is the main broadening factor of these lines in the dense plasma.[23] Less important is the broadening due to electron–ion elastic collisions and the thermal motion of the ions. With allowance for these broadening mechanisms, the spectral function of the resonance lines can be represented in the form

$$S_{n1}(\lambda-\lambda_{n1})=\sum_\alpha \gamma_{n\alpha}\int_0^\infty W\left(\frac{\lambda-\lambda_{n1}-\Delta\lambda_{n\alpha}^s\beta}{\Delta\lambda_n^D},\frac{\Delta\lambda_{n\alpha}^c}{\Delta\lambda_n^D}\right)P_a(Z_i,\beta)d\beta, \tag{5}$$

where λ_{n1} is the wavelength of the transition, $\gamma_{n\alpha}=A_{n\alpha 1}/\Sigma_{\alpha'}A_{n\alpha'1}$ is the relative transition rate for the sublevel with parabolic quantum numbers $\alpha\equiv(n_1,n_2,m)$; $W(x,y)$ is the Voigt function, which describes the Lorentz collisional and Gaussian Doppler broadening with corresponding widths $\Delta\lambda_{n\alpha}^c(N_e,T_e)$ (Ref. 24) and $\Delta\lambda_n^D(T_e)$; $\Delta\lambda_{n\alpha}^s$ is the linear Stark shift of the sublevel in the field $F_0=2.6Z_ieN_i^{2/3}$; Z_i and N_i are the mean charge and density of the ions; $P_a(Z_i,\beta)$ is the distribution function of the strength of the ionic microscopic field $F=\beta F_0$ with allowance for the Debye screening and the ion–ion correlation (Ref. 25); $a=\sqrt{e/F_0}/r_D$ is a parameter of the distribution function; $r_D=\sqrt{kT_e/4\pi N_e}$ is the electron Debye radius. Detailed expressions for the quantities in (5) are given in Ref. 26.

The macroscopic motion of the plasma can be taken into account in the spectral function by an additional averaging with a certain distribution function, for example, of Gaussian form, this merely requiring the addition to the Doppler width of an effective temperature T_p corresponding to the mean expansion velocity, i.e.,

$$\langle S_{n1}(\lambda-\lambda_{n1})\rangle=S_{n1}(\lambda-\lambda_{n1},\Delta\lambda_n^D(T_e+T_p)).$$

In a dense plasma, the observed line profile is determined by the optical thickness and effects quadratic in the ionic field,[27] and for high n also by the influence of barrier effects,[28] but this region is of less interest for spectroscopy on account of the effective overlap of neighboring lines. The plasma emission spectra in the region of the resonance transitions of the H- and He-like ions can be used to determine the electron density in the range

$$10^{19}T_D^{3/4}Z^{13/4}n^{-3}\leqslant N_e\leqslant 8\cdot 10^{23}Z^4n^{-15/2}\ \mathrm{cm}^{-3},$$

where $T_D=T_e+T_p$ (measured in kilo-electron-volts) determines a lower limit of the density. The maximum value is determined by the overlapping of neighboring lines of the series.[29]

For the line Ly_β, the effect of the optical thickness can be taken into account in the approximation of a homogeneous layer. For this, it is necessary to make in (3) the substitution

$$S_{31}(\Delta\lambda,N_e,T_e)\rightarrow\frac{S_{31}(0,N_e,T_e)}{\tau_{31}(0,N_e,T_e)}\times\left(1-\exp\left[-\tau_{31}\frac{S_{31}(\Delta\lambda,N_e,T_e)}{S_{31}(0,N_e,T_e)}\right]\right), \tag{6}$$

where τ_{31} is the optical thickness at the center of the line. The occupancy must also be calculated with allowance for reabsorption of the radiation, for example, in the Biberman–Holstein approximation.[30]

4. RESULTS AND DISCUSSION

The parameters of the X-pinch plasma were determined by comparing the calculated spectra of the resonance emission of the H- and He-like Al ions with experimental densitograms corresponding to the different stages of the expansion of the "hot point" along the anode–cathode direction. The results of the measurements give a picture that is averaged over the lifetime of the plasma and a certain spatial region of expansion in the transverse direction.

The change in the characteristic features of the spectra for different electron densities can be traced by means of the results of the calculations given in Fig. 2. A change of the local temperature T_e at fixed density changes the relative intensities of the lines of the series without affecting their widths. The effective expansion temperature was chosen to make the sum T_e+T_p correspond to the ionization potential of the H-like ion. In the sum over n in (3), the terms up to $n=15$ took into account the contribution of the quasicontinuum. For the line Ly_β when $N_e>10^{21}$, the profile was corrected with allowance for (6). It should be noted that despite the smallness of the escape coefficient θ_{31} reabsorption has a weak effect on the occupancy of the $n=3$ level, since at these densities the collisional clearing channel is dominant.

Figure 3 gives the measured spectrum of the plasma emission corresponding to the region of the "hot point." Among all the lines in this region, the line Ly_β of Al XIII and also the $1s5p-1s^2$ and $1s6p-1s^2$ lines of Al XII are observed. The observed widths of these lines and the results of the calculations given in Fig. 2 show that the spatial region containing the "hot point" is characterized by changes

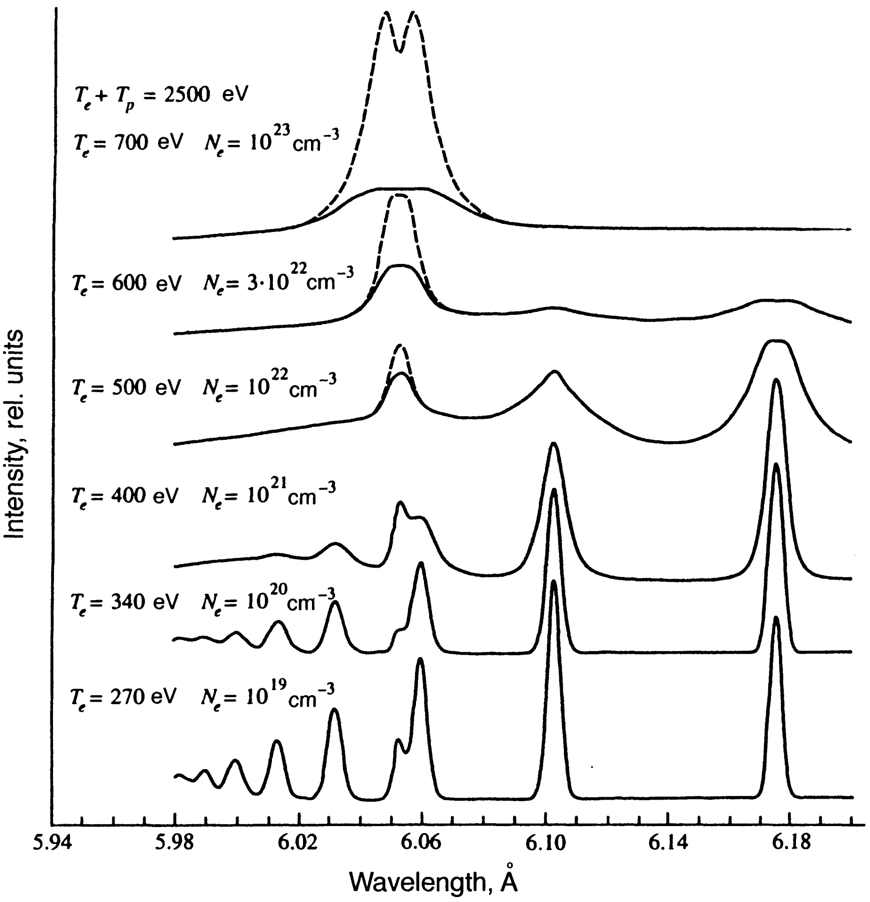

FIG. 2. Results of calculation of the spectrum for different values of the electron density and temperature ($T_e + T_p = 2500$ eV). The dashed curves correspond to an optically thin plasma.

of the electron density in the range from 10^{23} to 10^{21} cm^{-3}. The figure also gives the result of approximating the measured spectrum obtained by varying in (2) the values of w and the ratio N_{nucl}/N_1^H corresponding to the indicated intervals of N_e. It follows from these results that the radiation in the line Ly_β is mainly formed at electron densities $N_e > 3 \cdot 10^{22}$ cm^{-3}, at which the lines of Al XII with $n \geqslant 5$ effectively overlap. At densities greater than 10^{23} cm^{-3}, the possibility of observing the line Ly_β is restricted above all by the large optical thickness of the plasma. The calculation shows that for $N_e = 10^{23}$ cm^{-3} and for the charge composition $N_{\text{nucl}}: N_{\text{H}}: N_{\text{He}} = 38:22:1$ obtained in the steady model the absorption coefficient at the line center is $\kappa_{31} = 4 \cdot 10^3$ cm^{-1}, which corresponds to an optical thickness $\tau_{31} \simeq 4$ for diameter ~ 20 μm of the dense region. The presence in the spectrum of Al XII lines is due to the contribution of regions

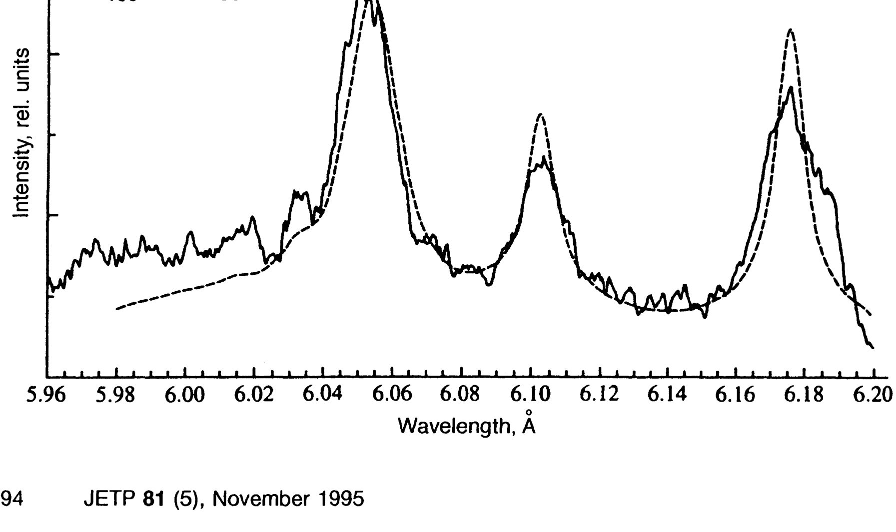

FIG. 3. Densitogram of the emission spectrum of the plasma in the hot region in the range of resonance transitions $1snp\ {}^1P_1 \rightarrow 1s^2\ {}^1S$ ($n \geqslant 5$) of Al XII (solid continuous spectrum) and the results of calculation (dashed curve). The intervals of parameter values are given.

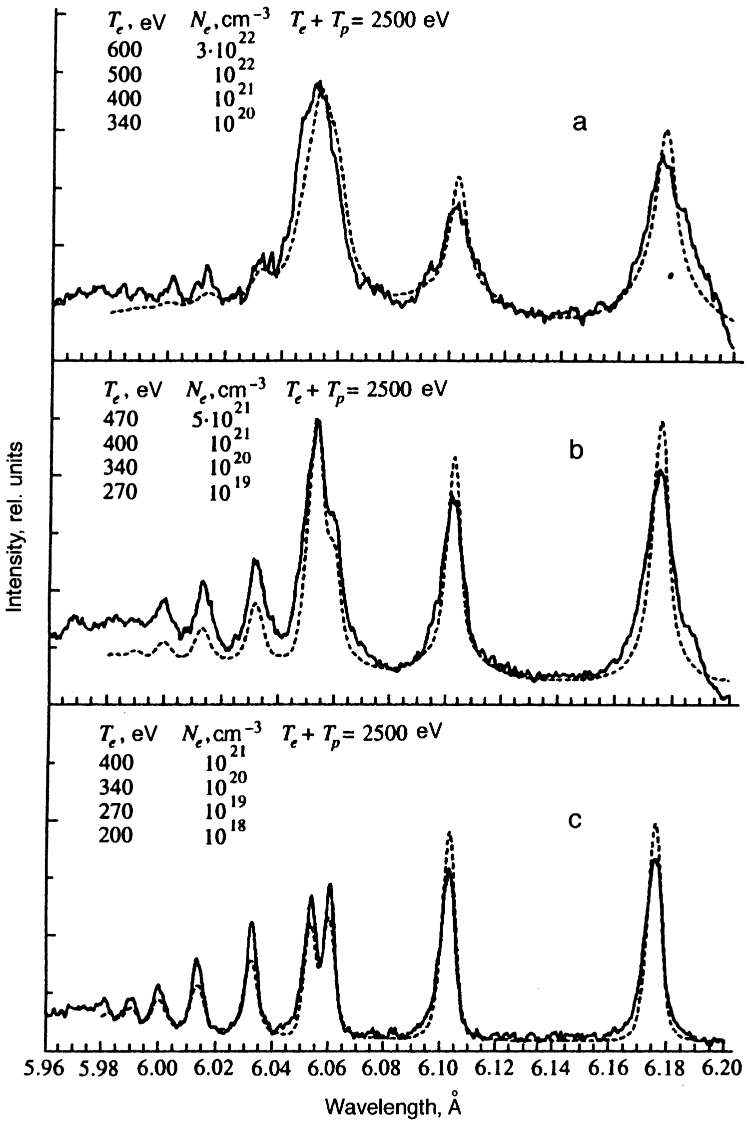

FIG. 4. The same as in Fig. 3 for different distances from the "hot point" along the anode–cathode direction: $z=0.15$ (a), 0.4 (b), 0.8 (c) mm.

of the plasma with density $10^{21} < N_e < 3\cdot10^{22}$ cm^{-3} in the expansion stage. Densities $N_e < 10^{21}$ cm^{-3} are not manifested in lines with $n \geq 7$ because of their low intensity.

The nature of the variation of the plasma parameters in the anode–cathode direction can be deduced from the spectra given in Fig. 4, which correspond to regions of the plasma at different distances from the "hot point." The results of the modeling of the corresponding spectrograms reveal a significant inhomogeneity of the plasma parameters in the different regions. High densities $N_e \simeq 10^{21}$ cm^{-3} are maintained at appreciable distances from the "hot point" and are manifested in the broadening of the lines with $n=5$ and 6, which exceeds the Doppler broadening. With increasing distance from the "hot point," lines with $n \geq 7$ begin to appear. To these lines there correspond densities $N_e \leq 10^{20}$ cm^{-3}, at which the widths of the $3p-1s$ and $1s5p-2s^2$ lines are close to the Doppler widths, while at $N_e \leq 10^{18}$ cm^{-3} the line profiles take the Doppler form right up to $n=11$. It is this range of densities that is most favorable for exact determination of the transition wavelengths and level energies of the corresponding highly excited levels.[31]

5. CONCLUSIONS

The results given here of the investigation of the emission spectra of X-pinch plasma show that the use of the methods of x-ray focusing spectroscopy with high spectral and spatial resolution and modeling of the spectra of H- and He-like ions at different electron densities and temperatures make it possible to determine the nature of the variation of the plasma parameters in the process of expansion of the hot region. The ratios of the contributions to the spectra corresponding to different values of the plasma parameters reflect their time dependences and can be used to test hydrodynamic models of the plasma evolution.

For the "hot point," the observed width of the line Ly_β gives a lower bound $N_e \geq 3\cdot10^{22}$ cm^{-3} for the electron density; this confirms the previously obtained estimates of Ref. 10. At higher densities, the Stark line profile is significantly distorted due to the large optical thickness of the plasma.

The description of the observed relative intensities of the $1snp-1s^2$ series in the late stages of the expansion in the anode–cathode direction obtained in the framework of the steady kinetic model gives higher electron temperatures than are found, for example, in a laser plasma[32] at the same densities.

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