# Spectroscopic measurement of the electron plasma density of the "hot spot" in a low-inductance vacuum spark

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A redistribution of the satellite intensities on the resonance lines of He-like Ca and Ti ions because of transfer of the excitation between the autoionization states due to electron collisions was used to determine the electron density of the "hot spot" in a low-inductance vacuum spark. It is shown that the electron density of the plasma heated to a temperature of $\sim 1$–$1.5$ keV is $\sim 10^{23}$ cm$^{-3}$.

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1. A discharge in a low-inductance vacuum spark (LVS), which was described by Cohen *et al.*[1] for the first time, makes it possible to heat a plasma to the electron temperature $T_e = 5$–$10$ keV.[2] The data for the electron density ($n_e$) of the "hot spot" of a LVS and especially for its dynamics are of obvious interest. The available results ($n_e \sim 10^{21}$–$10^{22}$ cm$^{-3}$), which were obtained on the basis of the integral characteristics of the discharge, do not describe its development with time. The measurements of Datla and Griem[3] based on broadening of the spectral lines of H and He-like Mg and Al ions with the ionization potential $E_i \sim 2$ keV apparently pertain to that heating phase of the micropinch in the LVS when the plasma temperature is sufficiently high for excitation of these ions $T_e \sim 0.5$ keV. The variation of the plasma density as a result of further heating is the basic problem in the formulation of a comprehensive theory of the micropinch effect in the LVS.

2. To measure $n_e$ in the later heating stage, we used the spectra for the resonance transitions $1s^2$–$1s\,2p$ of the He-like Ca ions ($E_i \approx 5.1$ keV) and Ti ions ($E_i \approx 6.3$ keV) and their satellites $1s^2 2l$–$1s2l\,2l'$ in the Li-like ions. This measurement method is based on the fact that the excitation in a sufficiently dense plasma is transferred between the $1s2l\,2l'$ autoionization states due to electron-ion collisions, which effect redistributes the densities of the satellites in the spectrum. An analogous effect for the satellities of the $L_\alpha$ line was discussed in Ref. 4. It seems that the most density-sensitive lines are those which are emitted in the transitions from the levels that have two qualitites: 1) the probability of radiative decay is much greater than that of autoionization $A \gg \Gamma$ and

  

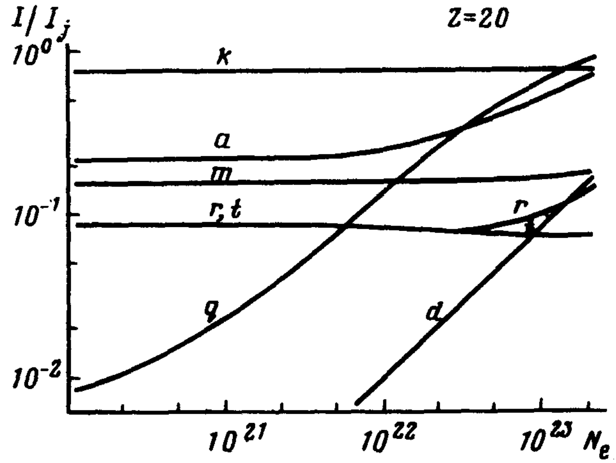


FIG. 1. Dependence of the satellite intensities of the resonance line of a He-like ion on the electron density.

2) there is a coupling by means of collisions with the states for which $\Gamma \gg A$, so that their relatively high population is determined by the Saha-Boltzmann equation.

The $n_e$ dependence of the relative populations of all 16 autoionization levels of the Li-like ions and of the intensities of the satellites was calculated by solving the balance equations with allowance for the collision transitions between the $1s2s^2$, $1s2s2p$, and $1s2p^2$ configurations:

$$N_j \left(A_j + \Gamma_j + n_e \sum_{i=1}^{16}{}' \alpha_{ji}\right) - n_e \sum_{i=1}^{16}{}' N_i \alpha_{ij} = g_j \Gamma_j N_j, \qquad (1)$$

where $j = 1, \ldots 16$ and $\alpha_{kl}$ is the average quasi-classical cross section of the collision transition $k \to l$.[5] To calculate the intensities of the satellites with an intrashell excita-

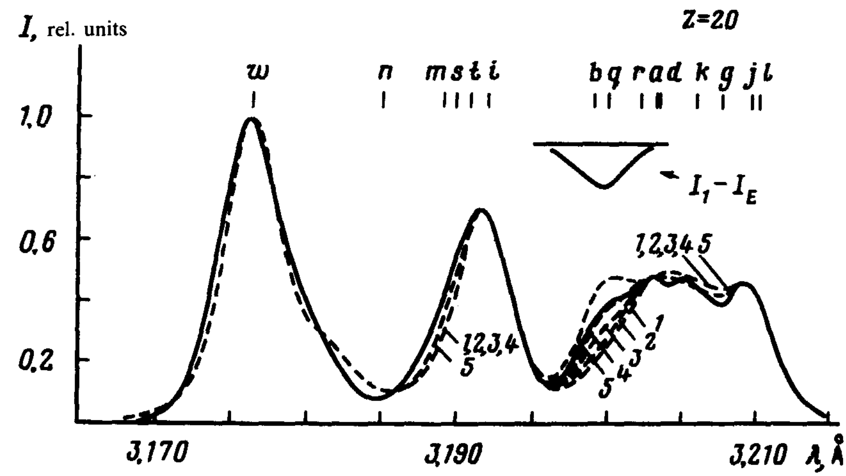


FIG. 2. Spectrum of the satellite of the Ca XIX resonance line: ————, experiment; ------, calculation (1, $n_e \leqslant 10^{20}$ cm$^{-3}$; 2, $10^{22}$ cm$^{-3}$; 3, $3\times10^{22}$ cm$^{-3}$; 4, $10^{23}$ cm$^{-3}$ 5, $3\times10^{23}$ cm$^{-3}$).

tion, the terms on the right-hand side of Eq. (1) were substituted for $\langle V\sigma \rangle_j$ cross section for excitation of the $j$ level from the bound state.[6] The results of calculation for the most intensive satellites are shown in Fig. 1, in which it can be seen that the most density-sensitive satellite is the $q$ satellite-the transition from the level $2s2p\,(^3P)1s^2P_{3/2}$, which was additionally excited by the collision transitions from the $1s2s^2\,{}^2S_{1/2}$ level.

3. The spectra of the H and He-like Ca and Ti ions were recorded by using x-ray quartz crystal spectrograph ($2d = 6.67$ Å) with a spectral resolution of $\sim 5\times 10^{-4}$ Å when the LVS apparatus, which was described elsewhere,[7] was used. The spectrum of Ca XVIII ions and Ca XIX ions in the region of 3.16–3.22 Å is shown in Fig. 2 (solid line) along with the results of selecting the plasma parameters for the purpose of describing in the best possible way the experimental spectrum with the help of the theoretical data (dashed lines). The selection was achieved by optimizing the relative contributions of the dielectron and impact mechanisms of the level excitation for different values of $n_e$. The maximum half-width of a single line used in the calculations, together with the instrumental function, was equal to $2.1\times 10^{-3}$ Å; the result in this case was weakly dependent on the shape of the line (dispersion or Doppler). It can be seen that the largest differences between the maximum theoretical spectrum at low density $n_e \leqslant 10^{20}$ cm$^{-3}$ (curve 1) and the experiment occurs near the $q$ satellite. The corresponding difference in intensities $I_1 - I_E$ is shown in Fig. 2 above the spectrum. The experimental spectrum is best described by the theoretical curve at $n_e = 10^{23}$ cm$^{-3}$ (curve 4); the electron and ionization temperatures, which were calculated from the contributions of the different mechanisms for excitation of autoionization levels; are: $T_e = 1050$ eV and $T_z = 700$ eV. An analogous procedure for the Ti spectrum gives the value $n_e = 2\times 10^{23}$ cm$^{-3}$ at $T_e = 1450$ eV and $T_z = 870$ eV (see, for example, Ref. 8 for determination of $T_e$ and $T_z$). Such high values of $n_e$ apparently will make it possible to explain the anomalously large width of the resonance lines of He-like ions of the heavy elements in the LVS spectra.[9]

Since the obtained result is highly sensitive to the exact calculation of the cross sections for collision transitions $\alpha(1s2s^2\,{}^2S_{1/2}-2s2p(^3P)\times 1s\,{}^2P_{3/2})$, we give the relation for the product $n_e\alpha \approx 5\times 10^{13}$ sec$^{-1}$ in Ca, which allows us to determine the value of $n_e$ more accurately as a result of increasing the accuracy of calculations of the cross sections.

4. To verify our method, we used the densitograms of such spectra in a laser plasma.[4] The estimates show that the intensity of the $q$ satellite in these spectra corresponds to the density $n_e \sim 10^{21}$ cm$^{-3}$, in agreement with the data obtained by using other methods.

Thus, the results of the measurements show that the plasma heating of the "hot spot" in the LVS to temperatures 1,...,1.5 keV is accompanied by an increase of the electron density to values of the order of $10^{23}$ cm$^{-3}$.

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