Possibility of observing coronal spectral lines in a laboratory plasma

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The factors that determine the possibility of registration, under laboratory conditions, of forbidden lines observable in the spectrum of the solar corona are discussed. Certain results of spectroscopic measurements in the "Tokamak-4" installations are interpreted as observation of the "green line" of the ion Fe XIV.

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1. Observation of spectral lines belonging to multiply charged ions and produced as a rule as a consequence of magnetic-dipole transitions has served for a long time as an important method of investigating the physical conditions in the solar corona.[1] When attempts are made to measure these lines in a gas-discharge plasma, a number of difficulties are encountered, due primarily to the low probabilities of the radiative transitions ($A \approx 10^2$ sec^{-1}). By now, however, a plasma with particle containment times τ_p estimated at dozens of milliseconds has been obtained in quasistationary plasma system (at an electron temperature T_e amounting to several keV and at a density $n_e \approx 10^{13}$–10^{14} cm^{-3}).[2] It is of interest to analyze the possibility of observing the considered lines for a plasma having such parameters. We confine ourselves to transitions in configurations of the type ns^2np and ns^2np^5. The numerical estimates were made for the 530.3-nm "green line" (Fe **XIV**, $^2P_{3/2}$–$^2P_{1/2}$).

We denote by g_1 and g_2 the statistical weights of the upper and lower levels, and by N_1 and N_2 their populations. We take into account the radiative transition and the excitation and de-excitation by electrons with rates $S_{12}n_e$ and $(g_1/g_2)S_{12}n_e$, respectively. In this model, the line intensity is

$$I = h\nu \frac{A n_e S_{12}}{A + (g_1/g_2) n_e S_{12}} N_1. \qquad (1)$$

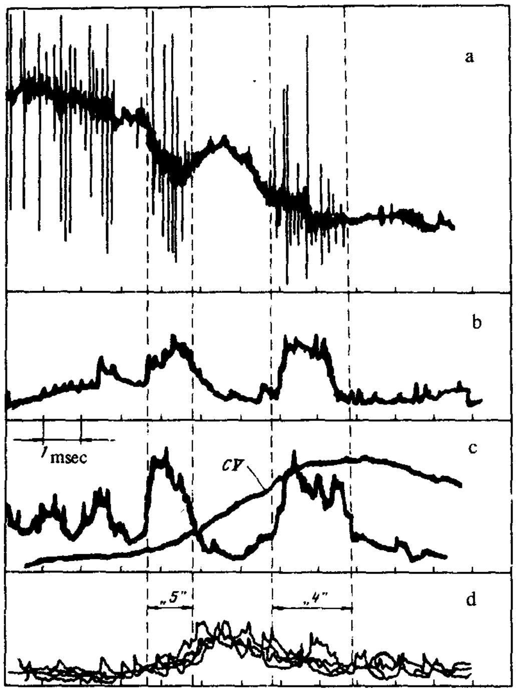
Unlike the solar corona ($n_e \approx 10^8$ cm^{-3}, $A \gg (g_1/g_2)n_c S_{12}$), a laboratory plasma is characterized by densities $n_e \approx 10^{10}$–10^{11} cm^{-3}, and expression (1) goes over into

$$I = h\nu A (g_2/g_1) N_1, \qquad (2)$$

i.e., the case of Boltzmann equilibrium. It follows from (2) that if the ion density n_j is fixed ($n_j \approx N_1 + N_2$), the intensity I does not increase with increasing n_e. When n_j and n_e increase simultaneously, restrictions are imposed by the growth of the intensity I_c of the continuum, since $I \sim n_j$ and $I_c \sim n_e n_j$. Thus, for a plasma consisting of Fe XIV ions, the line and continuum intensities in the interval $\Delta\lambda$, where $\Delta\lambda$ is the line half-width, become comparable at $n_e \approx 2\times 10^{17}$ cm^{-3} (we assume a Doppler broadening mechanism and $(T_e/T)^{1/2} \approx 1$.

In the range of parameters of interest to us, the density amounts to $n_e \approx 10^{13}$–10^{14} cm^{-3}. In accordance with (2), it is necessary to accumulate in the plasma a sufficient number of ions n_j in the required state j. If t_j is the time of ionization of the atom to the state j and τ_j is the time for the ionization $j \to j+1$, then it is desirable, in order to obtain high densities n_j, that the relations $\tau_p > t_j$ and $\tau_j > t_j$ be satisfied. For the considered ions, however, the second condition practically contradicts the first, since it is satisfied only at low values of T_e. As shown by an analysis of the conditions in the plasma of the T-4 setup (for a description of the setup see[3]), a typical case is $\tau_p \geq t_j$ and $\tau_j \approx t_j$; at the usual amounts of impurities in the plasma one should not count on obtaining high intensities of the "coronal" lines, but there are no difficulties in principle in observing these lines during definite stages of the discharge.

2. We used for the spectroscopic measurements a VMS-1 monochromator with an interference filter at



Behavior of a number of spectral lines in the initial stage of the discharge in the T-4 installation: a—derivative of the discharge current; b—intensity of the 229.7-nm C III ion line; c—371.99-nm and 227.1-nm C V lines; d—λ = 530.3 nm.

530.3 nm, as well as an auxiliary ÉMR-3 monochromator.

We investigated the initial stage of the discharge (up to the tenth millisecond). Passage through the resonance values of the stability margin q occurs with increasing current (see[2]), and this is accompanied by the development of instabilities. This is evident from the figure, where the bands "$q=5$" and "$q=4$" were arbitrarily separated, and where the derivative of the current was also plotted (Fig. a). At these instants, the influx of impurities, including iron, into the plasma pinch increases (Figs. b and c), and at the same time there exists an unperturbed hot region of the pinch (see the behavior of the line of the C V ion in Fig. c). The idea of the experiment is to choose a regime in which the values of n_e and T_e (and consequently t_j) between the passage through bands "5" and "4" is such that the concentration of the Fe XIV ions reaches a maximum precisely during that period, and by the same token, the 530.3-nm line turns out to have a time dependence that is different from those of the numerous lines of the low-ionized impurities, which interfere with the measurements. The measurements of T_e were performed by the laser-scattering method, and the electron density was investigated with the aid of a microwave interferometer. The 530.3-nm spectral line was registered in a relatively narrow range of discharge regimes; its time dependence is shown in Fig. d. The observed time required to reach the maximum line intensity agrees well with the calculated value for the Fe XIV ion at plasma-parameter values measured between the bands (average electron density $\bar{n}_e \approx 6\times10^{12}$ cm^{-3}, $T_e = 300$ eV). The absolute line-intensity measurements can be used to estimate, using (2), the percentage of the Fe XIV ions. It turned out that $n_j/\bar{n}_e \approx 0.02\%$.

We note one more possible diagnostic application of coronal lines of this type. One of the most important problems in high-temperature plasma physics is the distribution of the impurity ions over the cross section of the plasma pinch.[4] Expression (2) shows that in this case to calculate $n_j(r)$ from $I(r)$ there is no need for detailed knowledge of either $T_e(r)$ or $n_e(r)$; all we need are rough estimates of n_e and T_e to verify the validity of (2).

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