Active diagnostics of impurity ions in the plasma of a *T*-4 tokamak

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The absolute content of carbon nuclei in a plasma was measured, for the first time ever, by a method based on the registration of the radiation produced in charge exchange of impurity ions with the atoms of the beam injected in the plasma. It is shown that light impurities do not accumulate in the plasma and the effective time of departure of the carbon nuclei from the central region of the pinch (20±10 msec) is estimated.

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At the presently attained discharge parameters in tokamaks, an appreciable fraction of the energy input in the plasma is lost because of radiation by impurities. Yet there are no direct methods of monitoring the content of light impurities in the plasma. The use of traditional spectroscopic methods is hindered by the presence of a large number of processes that lead to emission of the ions, as well as by the fact that the greater part of the light impurities (carbon, oxygen) are in a fully ionized state. A method for local diagnostics of the content of impurity ions in the plasma, including nuclei, is proposed in Ref. 1 and is based on registration of the radiation produced when a beam of fast hydrogen atoms is injected into the plasma. When a hydrogen atom collides with a multiply charged ion I^{z+}, the electron is captured, with a large cross section (10^{-15}–10^{-14} cm^2) by an excited level $I^{(z-1)+}$ of the ion:

$$H + I^{z+} \rightarrow H^{+} + I^{(z-1)+(*)} \rightarrow H^{+} + I^{(z-1)+} + h\nu.$$

By observing, on different sections of the beam path in the plasma, the increase produced in the intensity of the characteristic lines by the decay of the excited states of the ions $I^{(z-1)+}$ formed in the charge exchange, it is possible to measure the absolute local content of the impurity ions I^{z+}. Reliable information is presently available only on the probabilities of the population of the initial excited states with respect to the principal quantum numbers.[2–4] Therefore practically the only possibility of a quantitative diagnostics is offered by observation, in an active experiment, of the intensity burst of the L_α lines of the ions, since the probability of this transition in cascade decay of an excited state produced in charge exchange depends little on the scheme of the initial population with respect to the orbital angular momenta.

The atom injector developed by Dimov and Roslyakov[5] was used with the T-4 installation at the Kurchatov Atomic Energy Institute, where the described method was realized. The energy of the hydrogen atoms was 8 keV, the injection time 180 μsec, and the equivalent beam density in the center of the plasma pinch 10 mA/cm^2. With these parameters, the beam hardly perturbed the plasma. To increase the contrast of the active signal the radiation receiver was place at an angle 7° to the direction of the probing beam. The region from which the signal was registered measured $20\times5\times3$ cm^3. Since the diameter of the diaphragm was 34 cm, this made it possible to separate the central hot region of the discharge. The radiation receiver was a photoelectronic spectrometer developed by us, in which radiation with energy E_γ incident on the sensitive element, was converted into electrons with energy $E_e = E_\gamma - J$ (J is the known ionization potential of the target atom), and the photoelectrons were energy-analyzed. By varying the voltage on the electron-energy analyzer, it is possible to energy-analyze the radiation during the course of the discharge. The employed control system made is possible to obtain in one discharge 15 scans of the energy spectrum of the photons at a discharge duration 150 msec in the installation. This also increased greatly the accuracy and the amount of obtained information in the registration of the plasma radiation proper.

A time scan of the L_α(33.7 Å) of the C VI ion, for a discharge in hydrogen, is shown in Fig. 1. The emission intensity of this line, as well as of other lines of highly ionized states of light impurities, reaches a stationary level at 30 msec after the start of the discharge, thus indicating the absence of accumulation of light impurities in the plasma.

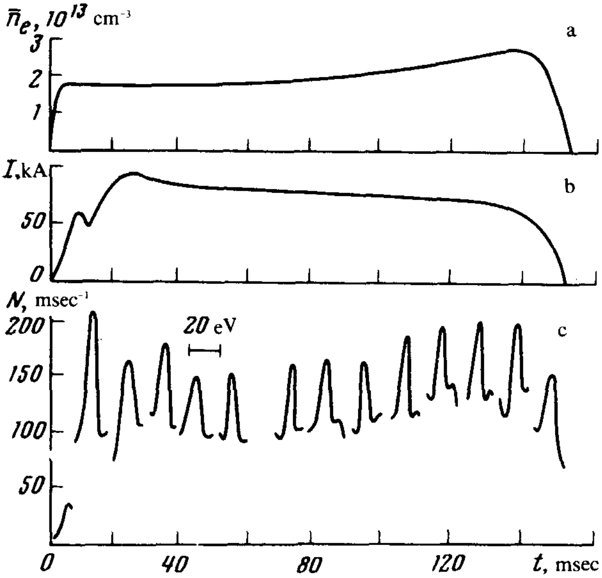

FIG. 1. Change of the emission intensity of the L_α(33.7 Å) line of the C VI ion during a discharge in the tokamak T-4 (c). The figure shows also the time dependences of the average electron density (a) and of the current discharge (b).

The method of active sounding of the plasma was used to study discharges in hydrogen and helium in the presence of a graphite diaphragm in the installation. Typical parameters of the investigated discharge are discharge current $I = 90$ kA, toroidal magnetic field $H_z = 30$ kOe, average electron density $\bar{n}_e = 2\times10^{13}$ cm^{-3}, and electron temperature at the center of the pinch $T_e(0) = 1$ keV. In a hydrogen plasma, as well as in a helium plasma, with the chamber not conditioned beforehand, a noticeable flash of radiation in the region of the L_α line of the C VI ion was observed during the time of injection of the hydrogen-atom beam. The increase of the intensity was

8.6×10^8 and 1.1×10^9 photons/cm^3 per plasma injection pulse in the first and second cases, respectively. In the helium discharge, after prolonged prior conditioning of the chamber, the active signal decreased and corresponded to an intensity increase of 3.6×10^8 photons/cm^3 per plasma injection pulse. The absence of such a signal in the cold plasma of the preconditioning discharge, and also in the case of the departure from the analyzer voltage by an amount equal to the instrumental resolution ($\Delta E/E = 0.1$), confirms that in our experiment we observed an increase, due to the interaction of the hydrogen atom beam with the carbon nuclei, of the intensity of the L_α resonance line of the C VI ion. The concentration of the carbon nuclei at the center of the plasma, determined from the value of the active signal, is $(1.1\pm0.5)\times10^{11}$ cm^{-3} for a discharge in hydrogen and $(0.5\pm0.3)\times10^{11}$ and $(1.3\pm0.5)\times10^{11}$ cm^{-3} for a discharge in helium in a clean and "dirty" chamber, respectively; this constitutes 0.25–0.65% of the average electron density in the plasma. The decrease, by a factor of two, of the content of carbon in the plasma on going from a hydrogen discharge to a helium discharge can indicate that an important role is played by the "chemical" sputtering of the diaphragm in the hydrogen plasma (formation of volatile hydrocarbon compounds).

The active signal in our experiments is due to charge exchange and is proportional to the concentration of the C VII carbon nuclei, while the background signal is due mainly to excitation of hydrogenlike ions by electron impact and is proportional to the C VI concentration. The ratio of these signals can be calculated by using the balance equations for the ions of the corresponding multiplicities. The varied parameter in our calculation was the diffusion term in the balance equation. The necessary distributions of the electron density and of the temperature over the pinch were taken from experiments on laser scattering, while the distributions of the ion temperature and of the hydrogen atoms were taken from experiments on active and passive[8] corpuscular diagnostics, respectively. From a comparison of the calculated ratio with the experimental value we found that the sign of the diffusion term in the balance equation corresponds to a departure of the carbon nuclei from the center of the plasma, and the effective departure time is 20 ± 10 msec.

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