Radial distribution of the concentration of oxygen nuclei in the plasma of the T-10 Tokamak

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The radial distribution of the concentration of oxygen nuclei was measured for the first time by probing the plasma by a beam of fast hydrogen atoms.[1] It is shown that there is no appreciable buildup of oxygen in the plasma during the steady-state stage of the discharge, and the diffusion lifetime of oxygen nuclei is estimated to be $\tau = 14$ msec.

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A measurement of the concentration of impurity ions and their radial distribution is necessary for analyzing the energy balance of a plasma and for studying diffusion. Since the most important light impurities (carbon and oxygen) exist in the form of nuclei in the central zone of modern tokamaks and are inaccessible for the usual spectroscopic diagnostics, the development of direct, local methods of monitoring the impurity nuclei is very important.

We used in our investigation the corpuscular-spectroscopic-diagnostics method to measure the radial distribution of the concentration of oxygen nuclei. This method, which was proposed in Ref. 1, is based on the injection of a beam of fast hydrogen atoms into the plasma. The capture of an electron

$$H + O^{7+} \rightarrow H^+ + O^{7+*} \rightarrow H^+ + O^{7+} + h\nu \qquad (1)$$

as a result of collision of the hydrogen atoms with the oxygen nuclei resulted in the production of excited, hydrogen-like O^{7+} ions and additional emission of the charac-

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teristic lines of these ions. The absolute increase of the intensity of the L_α line of the O^{7+} ions (19 Å) was measured. Observation was made along the major axis of the torus. The radial distribution of the impurity concentration was measured by rocking the injector. A secondary-electron multiplier with a CsI photocathode, which has a quantum yield of 30% at the $\lambda = 19$ Å wavelength, was used as the radiation detector. The sensitivity bandwidth of the detector (18–19.4 Å) was determined by the filters (Teflon and aluminium films with thicknesses of 5 μm and 1.5 μm, respectively). In addition to the filters, a nickel mirror was placed in front of the photocathode at a 4° angle to the direction of radiation incidence to prevent the hard radiation ($\lambda < 14$ Å) passed by the filters from striking the photocathode.[2] The resulting sensitivity of the bandwidth detector was equal to 8×10^{-4} pulses/photon. The absence of stray lines in the sensitivity bandwidth of the detector was determined by means of a photoelectronic spectrometer,[3] which was also used for absolute calibration of the detector by means of the radiation with a wavelength of 19 Å emitted by the plasma. The calibration of the bandwidth detector was also checked by means of a calibrated, flat-crystal spectrometer and Soller collimator. The intensities of the L_α line of an O^{7+} ion from the plasma, which were measured by a detector and a spectrometer, agreed within the accuracy limits of the calibration.

The investigation was performed using the T-10 Tokamak. We investigated a discharge in deuterium with the parameters: discharge current–230 kA, magnetic field–15 kOe, average electron density in the plasma $\bar{n}_e = 2\times 10^{13}$ cm^{-3}, electron and ion temperatures at the center of the plasma $T_e = 1.1$ keV and $T_i = 550$ eV, and graphite diaphragm radius $a = 29$ cm. We used a hydrogen-atom beam injector[4] with an equivalent beam current density of 3.5 mA/cm^2 in the plasma. The energy of the hydrogen atoms was 12 keV and the injection time was 200 μsec. The radiation was collected from a $8\times 7\times 4$-cm^3 volume.

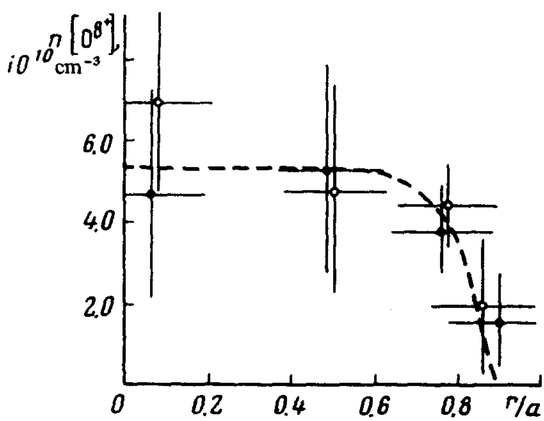

FIG. 1. Radial distribution of the concentration of oxygen nuclei in the plasma of the T-10 Tokamak for the 300th (dark points) and 400th (light points) milliseconds of the discharge. The dashed line represents the calculation in the steady-state, coronal approximation of the relative distribution of nuclei, assuming that the oxygen is uniformly distributed in the plasma column. The curve is normalized to the experimental data at small r/a.

On the basis of the absolute intensity of the additional radiation of the L_α line of an O^{7+} ion, the electron-capture cross section,[5] and the cascade factor $\beta = 0.55$, we have determined the concentration $n[O^{8+}]$ of the nuclei at different locations of the plasma (Fig. 1). The concentration is equal to 0.25% of the average electron density at the center of the column. The large errors (30–50%) indicated in Fig. 1 are due to the large, plasma-oscillation induced modulation of the natural plasma luminescence at the 19-Å wavelength, which makes it difficult to isolate the additional radiation as a result of injecting the beam.

Since no cleaning measures other than the usual heating to 350°C were used to prepare the tokamak chamber, the measured oxygen-concentration in the plasma is unexpectedly small. Additional studies are needed to determine the reasons for this phenomenon.

As seen in Fig. 1, no noticeable buildup of impurity occurs during the steady-state phase of the discharge.

Our investigation made it possible to estimate the diffusion lifetime of oxygen nuclei in the plasma. The method used made it possible to measure the absolute intensity of the natural plasma luminescence of the L_α line of an O^{7+} ion, which is determined primarily by the electron-impact excitation of O^{7+} ions. This intensity can be calculated from the radial distribution of the concentration of nuclei measured by us and from the steady-state, ionization-balance equation for the nuclei

$$\frac{n\,[O^{7+}]}{n\,[O^{8+}]} = \frac{n_e < \sigma_p v_e > + n_H < \sigma_c v_i > + \frac{1}{\tau}}{n_e < \sigma_i v_e >}, \qquad (2)$$

where n_e, n_H, and $n[O^{7+}]$ are the concentrations of the electrons, of hydrogen atoms, and of O^{7+} ions, respectively. The quantities $\langle \sigma_i v_e \rangle$, $\langle \sigma_p v_e \rangle$, and $\langle \sigma_c v_i \rangle$ are, respectively, the ionization rate of O^{7+} by electrons, the photorecombination rate of O^{8+} nuclei, and their capture rate of an electron in the hydrogen atoms. The diffusion term in this equation can be accounted for by introducing the effective lifetime τ of the nuclei. Subsequently, the value of τ is assumed to be independent of r. The luminescence intensity of the line is

$$B = \frac{1}{4\pi} \int_{-a}^{a} < \sigma_b v_e > n_e\, n\,[O^{7+}]\,dr = \frac{1}{4\pi} \int_{-a}^{a} \frac{<\sigma_b v_e>}{<\sigma_i v_e>} \Big(n_e <\sigma_p v_e> + n_H <\sigma_c v_i> + \frac{1}{\tau} \Big)\, n\,[O^{8+}]\,dr, \qquad (3)$$

where $\langle \sigma_b v_e \rangle$ is the rate of excitation of O^{7+} ions by electron impact.

The experimentally determined radial distributions of the electron density and of the electron and ion temperatures,[6] as well as the radial distribution of hydrogen atoms in the plasma, which was calculated by Izvozchikov[7] and normalized in such a

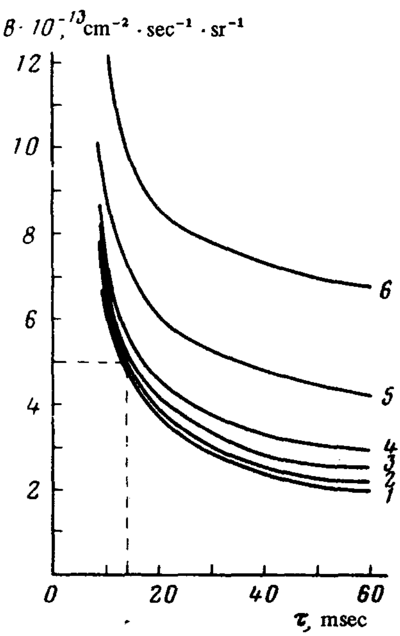

FIG. 2. Dependence of the luminescence intensity of the L_α line of an O^{7+} ion on the diffusion lifetime of nuclei. The curves correspond to different concentrations of the hydrogen atoms at the plasma center $n_H(0)$: 1, 4×10^6 cm^{-3}; 2, 1×10^7 cm^{-3}; 3, 2×10^7 cm^{-3}; 4, 4×10^7 cm^{-3}; 5, 1×10^8 cm^{-3}; 6, 2×10^8 cm^{-3}. The dashed line represents the experimental value of the line intensity.

manner as to explain the observed flow of charge-exchange atoms from the plasma, were used in the calculation of the ionization balance. The concentration of hydrogen atoms at the center of the plasma is $n_H(0) = 1\times 10^7$ cm^{-3}.

The results of the calculation are shown in Fig. 2. As seen in Fig. 2, the luminescence intensity of the line measured by us $B = 5\times 10^{13}$ cm^{-2}·sec^{-1}·sr^{-1} corresponds to a value $\tau = 14$ msec. The obtained result indicates that there is a mechanism capable of effectively removing oxygen from the plasma.

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