Investigation of the transfer of impurities in experiments on the injection of macroparticles into FT-1 Tokamak

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A collapse of perturbation of the impurities (Li, C, O, Si, Ti, stainless steel, Cu, Mo, W), which was introduced into the central region of the plasma by a macroparticle, is investigated. It is shown that the impurities are extracted from the discharge with a characteristic time τ that depends weakly on their type. The values of τ are determined according to the prediction of the theory which takes into account the poloidal rotation of the plasma.

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The confinement and transfer of impurities in a tokamak have been analyzed by using different methods.[1–5] The obtained data indicate that there is a mechanism that can remove the impurities from a discharge, where their average lifetime τ depends weakly on the charge and mass of the impurity. The reason for this removal is still unclear. In Refs. 2–4 the removal of impurity was attributed to the presence of a mixing zone with $q < 1$ in the central region. However, the impurities cannot be directly extracted from a discharge as a result of mixing in the central region. On the other hand, a theoretical analysis shows that a flow of impurities to the external region can occur even in a quiescent plasma.[6] A difference in the investigated regimes, an indirect

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nature of some techniques, and a low accuracy of experimental data hinder a quantitative comparison of the obtained results.

We describe below an experimental study of the transfer of impurities in the FT-1 Tokamak using a new macroparticle method[7] which makes it possible to determine τ for different impurities by the same method of direct measurements. A decay of perturbation of the impurity concentration, which was introduced into the central region of the plasma by a macroparticle, was investigated in the experiments. This made it possible to analyze the transfer of impurities to the external region directly under identical conditions. The containment of pure elements was investigated - C, Si, Ti, Cu, Mo, W, LiH and LiOH mixtures, and stainless steel. In contrast with earlier experiments, in which the velocity of poloidal plasma rotation was measured,[8] and which used ~1-mm graphite macroparticles, we introduced into the chamber in our experiments 100-to 200-μm macroparticles containing 10^{17}–10^{18} atoms. As a result of interaction with the plasma, these macroparticles heated up in 1–3 msec to a temperature corresponding to the onset of evaporation. The evaporation stage of a particle took 2–4 msec. A redistribution of the impurity ions along the cross section and establishment of an equilibrium ionization state were accomplished in $\lesssim 5$ msec. The measurements were carried out in the subsequent decay stage in which the impurity concentration decreased almost exponentially and the plasma parameters were unperturbed. The discharge characteristics were as follows: current $J_d = 30$–40 kA, magnetic field $B = 5$–10 kG, average density $\bar{n}_e = (4$–$6) \times 10^{12}$ cm^{-3}, electron temperature at

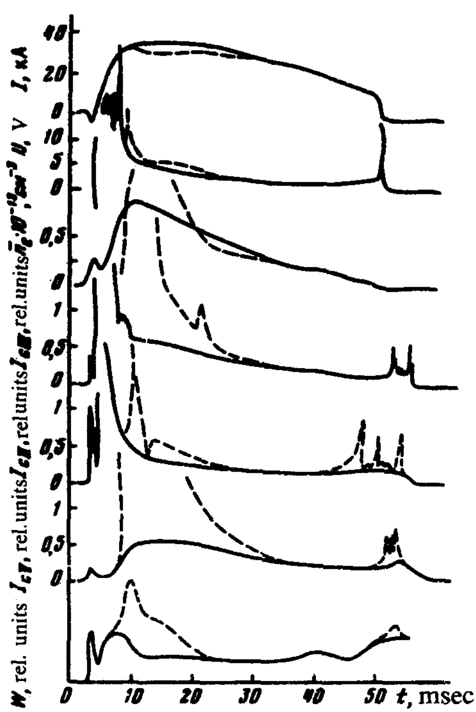

FIG. 1.

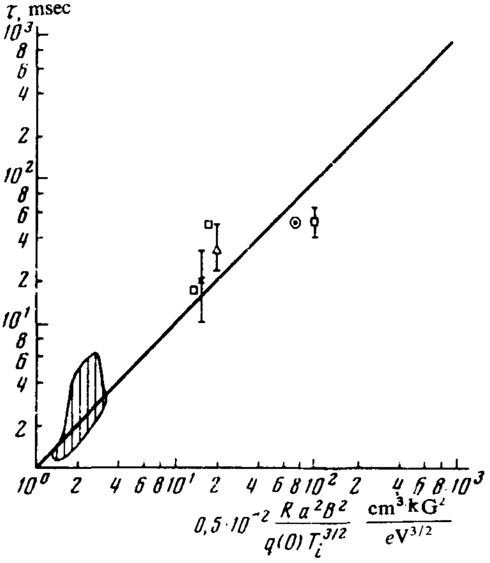

FIG. 2. The shaded area represents the results of our work. ×, *T*-4; □, *T*-10; *Δ*, *TFR*; ⊙, *PLT*.

the center $T_e(0) = 300$ eV, ion temperature $T_i(0) \approx 100$ eV, large radius of the device $R = 62.5$ cm, and the diaphragm radius $a = 15$ cm.

Since the manner in which the macroparticles interacted with the plasma and their evaporation dynamics do not vary greatly when different materials were used, we present below the results for graphite macroparticles. Figure 1 shows typical oscillograms for the current J_d, voltage at the bypass v_b, $\bar{n}_e$, emission of the CII, CIII, CV lines and of the bolometer signal W for discharges in the normal regime (solid curves) and for those with an injected macroparticle (dashed curves). In spite of an increase in density and of a sharp increase of radiation losses and of line radiation of the impurities at the beginning of a discharge, the injection of a macroparticle, on the whole, does not disturb the MHD stability of a discharge. The current and the voltage at the bypass do not differ greatly from the unperturbed values. The difference becomes small after 20 to 25 msec, and we can use the measurement data for the unperturbed discharge.

The lifetime was determined from the constants for the decay of perturbation of the luminescence of the lines or the bolometer, which were approximated by exponential functions. The values of τ, which were determined from the CII, CIII, and CV lines, were equal to 14.7 and 3 msec after injection of a carbon macroparticle. The values of τ for LiOH, which were measured from the OII and OV lines, turned out to be equal to 1.5 and 3 msec. The lifetimes obtained by using the bolometric signal and the decay rate of electron density are shown in Table I. We can see that they are similar for all investigated elements. The larger values of τ for carbon than those for other elements are apparently attributable to the fact that this technique takes into account in the specified lifetime the recycling in the region of the wall and the return

Table I.

	LiH	LiOH	C	Si	Ti	SS	Cu	Mo	W
z^*	3	6	4	12	12	16	18	20	25
m_I	7	–	12	28	48	56	64	96	184
τ_{bol}	2.5	4	10	3.5	2	3	3	3	3
τ_{n_e}	4	–	5	2.5	3	3	2.5	5	3

z^* represents the maximum permissible calculated ion charges: τ_{bol} is the lifetime in the bolometer and τ_{n_e} is the lifetime with respect to density.

flow for carbon is appreciable. An increase of the constants for the decay of luminescence of the lines for carbon ions as a result of transition from CV to CII favors this process. The lifetime *C* increased from 7 to 11 msec as a result of increasing the magnetic field from 7 to 10.5 kG. A reduction of the current from 30 to 20 kA reduced the lifetime τ from 2 to 1.2 msec.

If $T_e \gg T_i$ and $d\ln n_e/dr \gg (1/z)\, d\ln n_I/dr$, which holds in our experiments, and the plasma center has a positive charge relative to the periphery, then the radial velocity of the transfer of impurities in a quiescent plasma will be given by the expression[6]

$$v_{rI} = -\sqrt{\frac{\pi}{2}}\,\frac{q(r)c^2 m_i^{1/2}\, T_i^{3/2}}{Re^2B^2}\left(\frac{d\ln T_i}{dr} + \frac{T_e}{T_i}\,\frac{d\ln n_e}{dr}\right). \tag{1}$$

Thus, the characteristic time for extraction of impurity ions is of the order of magnitude

$$\tau = \left\langle \frac{a}{v_{rI}} \right\rangle = \beta\,\frac{R a^2 B^2 e^2}{T_i^{3/2}(0)\; q(0) m_i^{1/2}\, c^2}\,. \tag{2}$$

The parameter β depends on the temperature profiles and on the concentration. Thus, for example, if we assume that

$$T_i / T_i(0) = n_e / n_e(0) = T_e / T_e(0) = 1 - r^2/a^2,$$

$$q(r) = q(0)\,(1 - r^2/a^2)^{-1/2},$$

in the main volume of the tokamak, then we obtain $v_{rI} = Ar$, where

$$A = 2\sqrt{\frac{\pi}{2}}\left[1 + \frac{T_e(0)}{T_i(0)}\right]\frac{q(0)c^2 m_i^{1/2}\, T_i^{1/2}(0)}{R\, a^2 e^2 B^2}\,.$$

A decrease of concentration of the impurity is described by the equation

$$\frac{\partial n_I}{\partial t} + Ar\frac{\partial n_I}{\partial r} + 2An_I = 0, \tag{3}$$

which corresponds to an exponential decay with a time constant $\tau = (1/2)A$, so that the parameter β in Eq. (2) is $\beta = \{2\sqrt{2\pi}(1 + [T_e(0)/T_i(0)])\}^{-1}$. The parameter β is equal to 0.05 for FT-1 under our experimental conditions. Figure 2 compares the experimental values of the lifetime of impurities in different tokamaks with the calculated values using Eq. (2) for $\beta = 0.05$

$$\tau(\text{msec}) = 0.5\cdot 10^{-2}\frac{Ra^2B^2}{q(0)T_i^{3/2}}\left(\frac{\text{cm}^3\cdot\text{kG}}{\text{eV}^{3/2}}\right). \tag{4}$$

We can see that the calculated values are in fairly good agreement with the experimental data. We should also point out that Eq. (4) coincides with the neoclassical time for thermal conductivity of the main ions with an accuracy to a coefficient of the order of unity.

We have therefore showed that the impurity, which is artificially introduced into a tokamak during the initial discharge stage, is extracted from the plasma. The experimental results confirm Rozhanskiĭ's[6] conclusions that the impurities are ejected to the external region, irrespective of their type. The technique proposed by us, which makes it possible to investigate the behavior of impurities in different elements, may prove to be useful for detailed analyses of the transfer of impurities in tokamaks.

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