Radiative losses due to impurities and the $n_e\tau$ parameter of a thermonuclear plasma with fast neutral particle injection

V. A. Abramov, V. I. Gervids, V. A. Krupin, and V. S. Lisitsa
I. V. Kurchatov Institute of Atomic Energy

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At present, one of the most promising and developed methods of generation of a plasma with thermonuclear parameters is injection of high-power fast neutral particle beams into a plasma.[1] Beam injection (with a specific power P_B) leads, however, to occurrence of two contradictory effects: 1) plasma heating and generation of additional power P_{BF} as a result of a fusion reaction involving the beam atoms and 2) plasma cooling due to increased rate of radiative losses (RL) R which is determined by the rapid change in the ionization equilibrium of impurity ions in the course of a charge transfer between the beam atoms. In this paper values of the $n_e\tau$ parameter are calculated for a thermonuclear plasma with both effects taken into consideration.

The equation of power equilibrium in a plasma with a beam is as follows[1]:

$$\frac{3}{2\tau}\left[n_e T_e + \sum_i n_i T_i\right] + R(j, T) = 0.2\,(P_F + P_{BF}) + P_B, \tag{1}$$

where $T_e = T_i = T$, n_e, n_i are the plasma temperature and electron and ion density, τ is the confinement time, and $R(j,T) = \Sigma_z\ n_z\, n_e\ L_z(j,T)$ is rate of RL due to impurity ions with concentration $n_z = 2n_D f = n_e f/(1 + \langle z\rangle f)$; $L_z(j,T)$ is the specific rate of losses per impurity electron and ion which depends in particular on the density of equivalent current j of neutral particles in the beam, $P_F = n_D{}^2\langle vG_F\rangle E_F$ is the magnitude of thermonuclear energy yield in the plasma; here and below we refer to a D-T reaction rate in the case of deuterium injection into a tritium plasma; the coefficient 0.2 in Eq. (1) takes into consideration a portion of the energy transferred by alpha-particles in the D-T reaction with an energy yield $E_F = 17.6$ MeV.

By introducing standard designations[1,2]: $Q = (P_F + P_{BF})/P_B$ and $A = (1 + 0.2Q)/[Q - (P_{BF}/P_B),]$, we get the following from Eq. (1):

$$n_e\tau\,(f) = \frac{\frac{3}{2}\,T[2 + f\ + f < Z >,]}{A < \sigma v > E_f\ /4(1 + f < Z >) - f\,L_Z}, \tag{2}$$

where $\langle Z(j,T)\rangle$ is the mean impurity ion charge.

We shall assign typical parameters to the thermonuclear plasma: $T = 10$ keV, injected deuterium energy $E = 200$ keV (100 keV/amu). In modern tokamaks the typical heavy impurities are Fe(*PLT*, *T*-10) and Mo (*T*-11, *TFP*). The neutral particle current density j depends strongly on the type of reactor and, therefore, we shall consider several values of j: 0.02, 0.05 and 0.1 A/cm², see Ref. 1. The value of Q lies in the range $1 \lesssim Q \leqslant 10$; below, we use $Q = 5$. Under the above conditions we get[1]: $P_{BF}/P_B = 2$, such that $A = 0.67$.

Calculations of $L_z(j,T)$ and $\langle Z(j,T)\rangle$ were carried out by means of the stationary corona model[2-5] which takes into account ionization and excitation of photo- and dielectron recombination by the electron shock, and also charge transfer between the beam atoms. Charge transfer cross sections were assumed to be equal to the mean value obtained by the decay model[6] and bare nuclei model,[7,8] which satisfactorily agrees with the experiment.[8] Evidently, allowance for charge transfer is equivalent to effective enhancement of the recombination processes which leads to a displacement of the ionization equilibrium in the direction of smaller z.

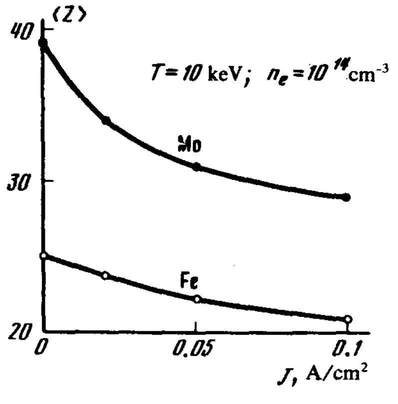

FIG. 1. Dependence of mean ion charge $\langle z\rangle$ on the equivalent neutral particle current j.

Figure 1 shows the dependence of the mean charge $Z(j,T)$ of Fe and Mo ions on current density j at $T = 10$ keV. Evidently, the value of $\langle Z \rangle$ decreases considerably in comparison with its value at $j = 0$. This leads to a sharp increase in the linear RL compared to the case for $j = 0$. Thus, in the case of Fe ions the linear losses at $j = 0.05$ exceed the value at $j = 0$ almost by an order of magnitude. Similarly, in the case of Mo increase in the losses at $j = 0.1$ A/cm^2 is 4.3 times the value at $j = 0$. The effect in question in typical for heavy impurities and also manifests itself in the normal coronal equilibrium at $j = 0$ for which a decrease in $\langle z \rangle$ depends on the temperature decrease.[2-5] It is clearly associated, with a transition to Li-, Be- and other-like ion shell which has a large number of intensive transitions that are easily excited by electron shock.

Alongside conventional types of RL at $j = 0$ (linear, bremsstrahlung, in the case of photo- and dielectron recombination), considerable contribution is made in the given case by radiative losses during charge transfer. Actually, in the case of charge transfer involving an ion with a charge Z an electron remains in a state characterized by the principal quantum number $n \sim Z^{3/4} \gg 1$[7]; as a result of a subsequent transition into the ground state the energy emitted is of the order of the ionization energy I_{z-1} of an ion with a charge $(Z - 1)$. We shall show that this emission at $j = 0.02$ involving Fe and Mo constitutes 90 and 56% of the linear losses, respectively.

The effect of increased RL is particularly well-defined in the case of light impurities (C,O). This may be explained in terms of a more rapid decrease with Z of the recombination rate ($\sim Z^2$) compared to the charge transfer rate ($\sim Z$). Thus, at $j = 0.1$ RL increase approximately 30-fold in the case of carbon (C). The occurrence of charge transfer leaves $\langle Z \rangle$ practically unchanged, but it causes a significant increase (by two–three orders) in the relative concentration of H-like C^{5+} ions which leads to a corre-

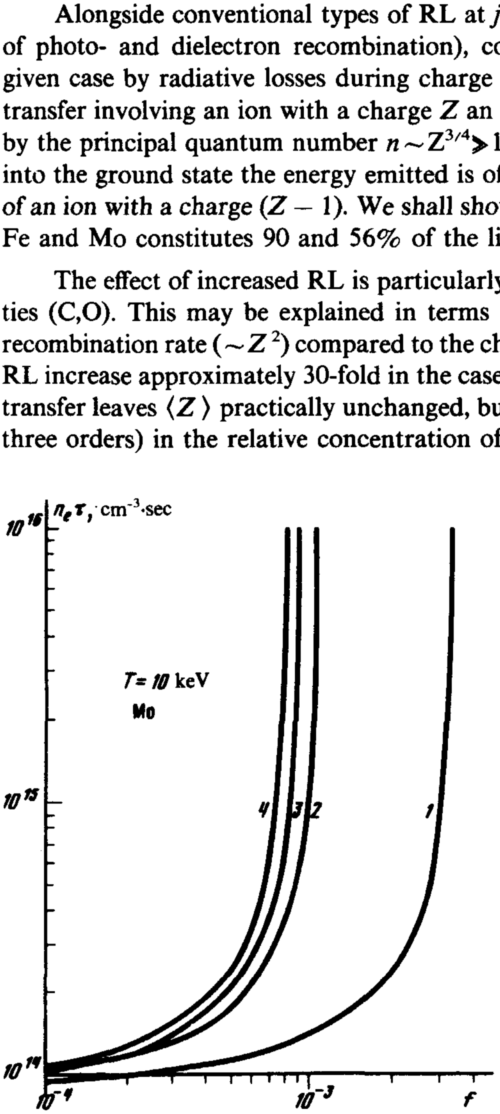

FIG. 2. Dependence of parameter $n_e\tau$ on the relative impurity concentration f: 1 —$j = 0$; 2—$j = 0.02$ A/cm^2; 3—$j = 0.05$ A/cm; 4—$j = 0.1$ A/cm^2.

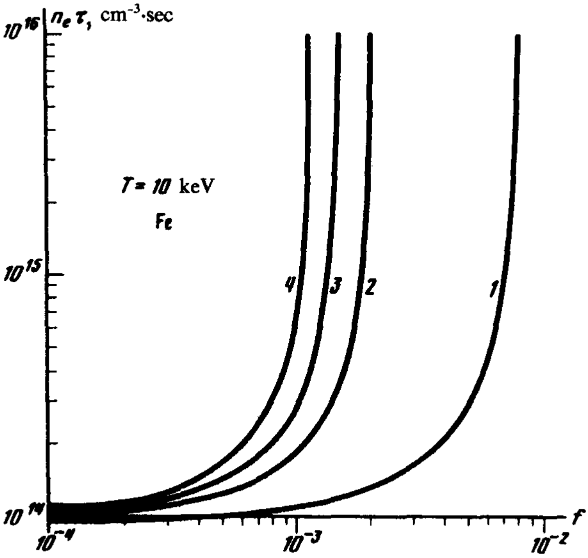

FIG. 3.

corresponding sharp increase in the linear losses. Emission losses in the case of charge transfer are of the same order of magnitude.

It may be concluded from the foregoing that the RL L_z in a thermonuclear plasma constitute a sensitive function of current density j.

Figure 2 shows the dependence of parameter $n_e\tau$ on the concentration f of impurities Fe and Mo for different values of j. A sharp dependence of $n_e\tau$ on j is seen which leads to, for example, concentration of the iron impurity being already more unsafe at $j = 0.02$ (from the standpoint of increased $n_e\tau$) than the same concentration of Mo at $j = 0$. The magnitude of the effect is easily characterized by means of the impurity concentrations f_∞ [3] that correspond to $n_e\tau = \infty$ in Eq. (2) and the corresponding value $(n_z/n_e)_\infty$.

In conclusion we should note that it was assumed above that beams fill a large portion of the hot region of the plasma bunch. If injection is aimed only at a portion of the bunch, strong longitudinal diffusion of impurities takes place in the torus due to occurrence of inhomogeneities in $\langle Z\rangle$. Allowance for the diffusion leads to noticeable lowering of the $\langle Z\rangle$ value, as it undergoes additional averaging over the long torus path which, in turn, increases the integral losses in the plasma.

TABLE I. Value of $(n_z/n_e)_\infty$ at different values of $j(Q = 5)$.

j, A/cm^2	0	0.02	0.05	0.1
Fe, %	0.65	0.19	0.145	0.11
Mo, %	0.29	0.11	0.090	0.08
C, %	10.0	4.90	2.900	1.80

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