Effect of injected neutrals on radiation from impurities in thermonuclear plasma

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(Submitted 9 February 1979)

Pis'ma Zh. Eksp. Teor. Fiz. **29**, No. 6, 353–357 (20 March 1979)

It is shown that the radiation loss due to impurity ions can be increased by additional heating of thermonuclear plasma by injecting a beam of neutrals. The radiation loss due to iron ions was calculated taking into account the effect of charge exchange on distribution of ions according to the ionization multiplicity.

PACS numbers: 52.50.Gj, 52.40.Mj, 52.20.Hv, 52.55.Pi

1. When an intensive beam of neutrals is introduced into a thermo-nuclear plasma,[1,2] the distribution of the impurity ions according to their multiplicity is greatly influenced by the charge exchange of neutrals in the impurity. Therefore, the presence of neutrals shifts the distribution toward the low multiplicities of impurity ions, which in turn can increase the radiation loss. To estimate the danger of this effect, we must first compare the radiation loss in the impurities in the presence of injected neutrals and in their absence. In this paper, we make the relevant calculations.

2. To determine the distribution of the impurity ions, according to their multiplicity we used the set of equations for the coronal equilibrium,[3] into which terms taking into account the charge exchange were introduced

$$S_k^z y_k^z = (R_{k+1}^z + C_{k+1}^z \xi) y_{k+1}^z, \quad k = 0, 1, 2, \ldots, z-1, \tag{1}$$

where k is the ion charge, z is the nuclear charge of the ion of a given element, y_k^z

$= N_k^z/N^z$ is the relative concentration of the ions of multiplicity k, N^z is the total concentration of the impurity of a given kind, S_k^z is the rate of ionization due to electronic impact, R_k^z is the rate of radiative recombination, C_k^z is the rate of charge exchange, $\xi = N_0/N_e$ is the relative concentration of the neutrals, N_0 in the concentration of the neutrals, and N_e is the concentration of the electrons.

3. On the basis of the distribution y_k^z obtained from the solution of Eq. (1), we determined the radiation loss from a unit volume per unit time

$$Q_{\text{rad}} = Q_{\text{brem}} + Q_{\text{recomb}} + Q_{\text{line}}. \tag{2}$$

In determining the bremsstrahlung loss Q_{beam}, the radiative recombination loss Q_{rec}, and the quantities S_k^z and R_k^z, we use the same formulas as those in Ref. 4. The line radiation

$$Q_{\text{line}} = Q_{\text{excit}} + Q_{\text{d.recomb}} + Q_{\text{c.exch}} \tag{3}$$

is comprised of terms connected with the excitation due to electronic impact as well as dielectron recombination and charge exchange. They are given by

$$\frac{Q_{\text{excit}}}{N_e N^z} = \sum_{k=0}^{z-1} y_k^z \sum_m V_{m1}^k \Delta E_{m1}^k ,$$

$$\frac{Q_{\text{d.recomb}}}{N_e N^z} = \sum_{k=1}^{z-1} y_k^z \left(\sum_m a_{m1}^k \Delta E_{m1}^k + \Delta E_{k-1}^z \sum_m a_{m1}^k \right),$$

$$\frac{Q_{\text{c.exch}}}{N_e N^z} = \xi \sum_{k=1}^{z-1} y_k^z C_k^z \Delta E_{k-1}^z ,$$

where ΔE_{m1}^k is the energy of the transition 1-m, ΔE_k^z is the ionization potential of the given ion, V_{m1}^k is the rate of the collision excitation of an ion by an electron, and α_{m1}^k is the rate of the dielectron recombination of an ion due to a resonance with the level m.

For the excitation rates we used the Van Regemorter approximation[5] with a coefficient proposed by Mewe.[6] We used the rates of dielectron recombination of ions proposed by Burgess[7] with the correction[8] for the transitions $\Delta n = 1$.

4. The concentration of the neutrals was estimated by using the balance equations

$$\frac{dN_0}{dt} = G - (S_{0e} + S_{0i} + C_{0C}) N_e N_0 = 0, \tag{4a}$$

$$\frac{dN_T}{dt} = C_{0C} N_e N_0 - S_{0e} N_e N_T - \frac{N_T}{\tau_T} , \tag{4b}$$

where G is the effective number of fast neutrals per unit volume per unit of time, $N_0 N_T$ is the concentration of the fast and thermal neutrals, respectively, $S_{0e} S_{0i}$ are the rates

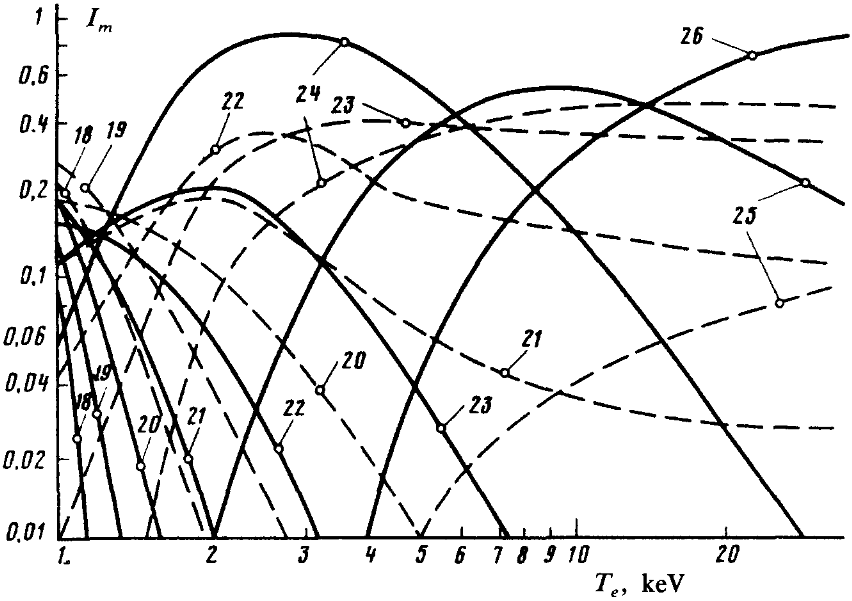

FIG. 1. The curves for ionization equilibrium of iron ions ignoring the charge exchange (solid curves) and taking into account the charge exchange at $\xi = 3\times10^{-6}$ (dashed curves). The numbers above the curves denote the ion charge.

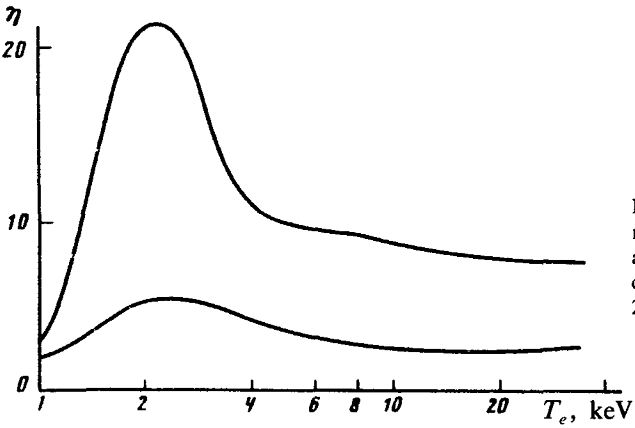

FIG. 2. Coefficient of increase of the radiation losses [Eq. (5)] taking into account the charge exchange. Curve 1 corresponds to $\xi = 3\times10^{-6}$ and curve 2 corresponds to $\xi = 1.5\times10^{-5}$.

of ionization of fast neutrals by electrons and protons, respectively, C_{0c} is the rate of charge exchange of a fast neutral by a proton, and τ_T is the characteristic time of departure of the thermal neutrals from the volume under considerations. The geometry of injection of the neutrals and the possibility of diffusion of fast protons along the magnetic field can be taken into account by choosing an effective value of G. To estimate the effect in question from the bottom, we ignored the contribution to the charge exchange of thermal neutrals. The cross sections for charge exchange of fast neutrals by impurity ions were taken from Ref. 9. At $v \approx 3\times10^8$ cm/sec the cross section for the charge exchange is approximated well by the expression $\sigma_k \approx 0.7 \times 10^{-15} k$ cm^2 ($k \geqslant 10$) (see Ref. 10).

5. In the calculations we used as a guide the neutral beams with 40-keV particles and a beam power $W \approx 1$ MW for a cross section $S \approx 500$ cm^2.[2] This corresponds to a flux density of neutrals $j \approx 3 \times 10^{17}$ cm^{-2}–sec^{-1} for a particle velocity $v_0 \approx 3 \times 10^8$ cm/sec. The quantity ξ can be estimated in terms of (4a) by the relation

$$\xi \approx j/2\pi R(S_{0i} + C_{0C} + S_{0e}) N_e^2 \ .$$

It is assumed here that the neutrals are injected uniformly into the magnetic tube whose radius is approximately equal to that of the beam. Assuming that $j \approx 3 \cdot 10^{17}$ cm^{-2}-sec^{-1}, $S_{0i} + C_{0c} + S_{0e} \approx 10^{-7}$ cm^3-sec^{-1}, and $R \approx 2 \times 10^2$ cm, we obtain $\xi \sim 3 \times 10^{21}/N_e^2$, which for $N_e = 10^{13}$–10^{14} cm^{-3} comprises $\xi \sim 3 \times 10^{-5}$–$3 \times 10^{-7}$.

To illustrate the effect, we conducted calculations for $\xi = 0$, $\xi = 3 \times 10^{-6}$, and $\xi = 1.5 \times 10^{-5}$. Figure 1 shows the realtive concentrations of the more representative iron ions ($z = 26$). It can be seen that already $\xi = 3 \times 10^{-6}$ the charge exchange changes radically the distribution of ions according to their multiplicity. Ions of low multiplicity and stronger radiation are produced. The quantity

$$\eta = Q_{\text{rad}} \ (v_0, T_e \ , \ \xi \neq 0) \ / \ Q_{\text{rad}} \ (v_0 \ , \ T_e, \ \xi = 0) \ , \qquad (5)$$

which represents the ratio of the radiation loss in the presence of neutrals and in their absence, is a measure of the increase of radiation. As can be seen from the results of the calculations (Fig. 2) for the real values of ξ and T_e, the quantity η can be much larger than unity. Of course, the results of calculations of η have approximately the same accuracy as the cross sections that are used.[5,6] The universal constants of approximation, which were proposed by Mewe,[6] may produce an ~100% error in the region $T_e \sim 1$–4 keV.

Thus, the calculations demonstrate that the effect of charge exchange on the radiative energy balance of the impurity is significant. This effect must be taken into account in analyzing the potentialities of the additional methods of heating and the design of thermonuclear installations.

We thank K.A. Razumova and V.I. Gervids for discussions.

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