# Effect of charge exchange on the marfe effect in a tokamak plasma

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The charge exchange of impurities with hydrogen atoms raises the threshold for the onset of a poloidal asymmetry in the emission in the edge plasma of a tokamak (i.e., the threshold for the marfe effect). This circumstance explains the stable poloidal symmetry in the detached-plasma regime.

**1.** As the power radiated by impurities at the plasma edge in a tokamak increases, the emission may acquire a pronounced poloidal asymmetry. This "marfe effect" usually arises in the attached-plasma regime, in which the emitting zone touches the limiter.[1] The occurrence of the marfe effect is usually linked with the onset of a radiation-condensation instability (Refs. 2–4, for example). In the detached-plasma regime, on the other hand, in which the emitting zone detaches from the limiter as a result of gas injection,[1,5–9] it is very difficult for the marfe effect to occur, although all the destabilizing factors seem to be present.

A possible change in the instability threshold due to a change in the temperature dependence of the radiative loss was pointed out in Ref. 10. Below we examine both plasma emission regimes for the actual structure of the radiative loss due to carbon ions. We show that the change in the temperature dependence of this loss due to charge exchange with neutral hydrogen atoms (a change which is characteristic of the detached-plasma regime) stops the instability at a given total emission level in this regime.

**2.** It has been assumed that the radiative loss $L$ for a plasma with a carbon impurity can be calculated from the corona model incorporating the charge exchange of carbon ions with neutron hydrogen atoms:

$$L=n_e \sum_{z=0}^{5} n_c^z L_c^z(T) \,, \qquad (1)$$

$$L_c^z=\sum_k \langle \sigma_{0k} v\rangle \Delta E_k^z \,. \qquad (2)$$

Here $\sigma_{0k}$ is the cross section for electron-impact excitation, $\Delta E_k^z$ is the excitation energy of level $k$, and $n_c^z$ is the density of carbon ions, with a charge $z$. To calculate $n_c^z$ we use the balance equations incorporating charge exchange and dielectronic recombination. We make use of the data of Ref. 11. The results calculated for electron temperatures in the interval 5 eV$\leqslant T \leqslant$50 eV can be approximated by

$$L=10^{-26} n_e n_c A(t-t_1)\exp\{-b(t-t_1)\}\, W/\mathrm{cm}^3. \qquad (3)$$

  

Here $nc=\Sigma_{z=0}^{6} n_c^z$ is the total carbon density, $t=T/T_0$, and $T_0$ is an arbitrary normalization temperature. We chose $T_0=1$ eV. The parameters $A$ and $b$ are functions of the ratio of the density of neutral atoms to the plasma density, $n_H/n$. If $n_H/n\leqslant 5\times 10^{-5}$, the parameters $A$ and $b$ are essentially constant, and we can set $A=3.8$ and $b=0.63$. If $n_H/n\geqslant 2\times 10^{-4}$, we can use the simple expressions

$$A=0.78(n/n_H)^{0.18}, \tag{4}$$

$$b=0.041(n/n_H)^{0.31}. \tag{5}$$

The parameter $t_1$ depends weakly on $n_H/n$, and over the entire range $0\leqslant n_H/n\leqslant 2\times 10^{-1}$ we can assume $t_1=4.4$.

**3.** A thermal equilibrium is reached in the edge plasma as the result of a balance struck by radiative cooling and the heat flux due to thermal conductivity out of the central region. The corresponding balance equation is

$$\frac{d^2t}{dx^2}=L(T_0\kappa_\perp)^{-1} \tag{6}$$

with the boundary conditions $t(0)=t_a$, $\kappa_\perp T_0(dt/dx)(x=\infty)=q_0$. Here $x=a-r$ is the distance to the wall, $a$ is the radius of the wall, and $q_0$ is the heat flux out of the central region.

We can write a solution of Eq. (6) in quadrature form:

$$x=T_0\kappa_\perp q_0^{-1}\int_{t_a}^{t}[1-q_1^2M(t)]^{-1/2}dt, \tag{7}$$

where

$$M(t)=\int_t^\infty Ldt\Big/\int_{t_a}^\infty Ldt;\quad q_1^2=2\kappa_\perp T_0q_0^2\int_{t_a}^\infty Ldt.$$

The parameter $q_1$ is related to the fraction of the power which is reradiated by the impurity as follows:

$$q_{\rm rad}/q_0=1-(1-q_1^2)^{1/2}. \tag{8}$$

The stability with respect to azimuthally asymmetric perturbations is determined by a linearized equation[4] for the perturbed temperature $\tilde{t}$:

$$\kappa_\perp\frac{d^2\tilde{t}}{dx^2}-\left[\frac{5}{2}n\gamma+k_\parallel\kappa_\parallel(T_0)t^{5/2}-\frac{2L}{T_0t}+\frac{1}{T_0}\frac{dL}{dt}\right]\tilde{t}=0. \tag{9}$$

Here $\gamma$ is the instability growth rate. It has been assumed here that the parallel thermal conductivity is described by the Braginskiĭ formula. Going over from the independent variable $x$ to the variable $t$ through the use of expression (7), and introducing the function $\varphi=\tilde{t}(1-q_1^2M)^{-1/4}$, we find the following equation (the prime means the derivative with respect to $t$):

$$\varphi''-q_1^2U_{\rm eff}\varphi=0. \tag{10}$$

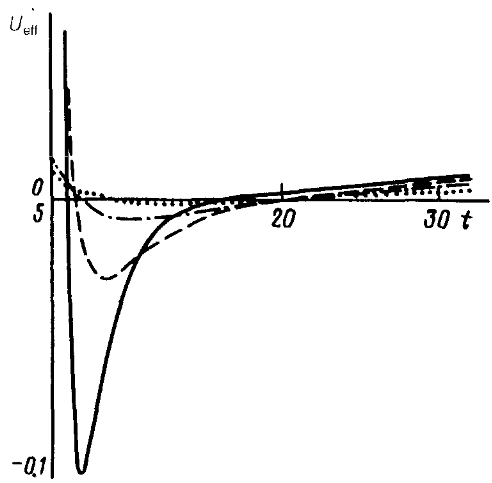


FIG. 1. Shape of the effective potential well for various values of the relative density of neutral atoms, $n_H/n$: Solid line—$10^{-5}$; dashed line—$2\times10^{-3}$; dot-dashed line—$2\times10^{-2}$; dotted line—$2\times10^{-1}$.

Here

$$U_{\rm eff}=(U-E)M_1^{-3/4}+\frac{L_1'}{4M_1}-\frac{3}{16}q_1^2L_1^2M_1^{-2}\,;$$

$$U=\frac{L_1'}{2}-\frac{L_1}{t}+wt^{5/2}q_1^{-2}\,;\quad w=k_{\|}\kappa_{\|}(T_0)\kappa_{\perp}\,T_0q_0^{-2}\,;$$

$$E=-\frac{5}{4}n\gamma T_0\left(\int_{t_a}^{\infty}Ldt\right)^{-1};\quad M_1=1-q_1^2M;\quad L_1L/\int_{t_a}^{\infty}Ldt\,.$$

The case $E=0$ corresponds to the stability boundary. An estimate for a medium-size tokamak yields $w\simeq10^{-6}$. Figure 1 shows $U_{\rm eff}$ versus $t$ for $q_1=0.9$, $w=10^{-6}$, and $E=0$. As the parameter $n_H/n$ increases, the depth of the potential well evidently decreases, while its width increases. This increase, however, is limited because of the rapid growth of $w$ with increasing $t$.

With increasing $n_H/n$, the existence of an $E=0$ level should lead to an increase in the parameter $q_1$. For a given fraction of the power which is reradiated, a plasma with a relatively low density of neutral hydrogen is evidently less stable.

Equation (10) has been solved numerically for the case $E=0$. Figure 2 shows the results of calculations of the critical level of reradiated power, corresponding to the stability boundary, for two values of the parameter $w$. This parameter is determined by the thermal conductivity. With increasing density of neutral hydrogen, the threshold value $q_{\rm rad}/q_0$ increases rapidly at large value of $n_H/n$. At the values of $n_H/n$ characteristic of the detached-plasma regime, the radiation-condensation instability may be completely suppressed. If so, the marfe effect will be prevented. A corresponding effect may occur if there is a rapid transverse diffusion of the impurity near the wall.

In summary, it has been shown that a change in the temperature dependence of the radiative energy loss at impurities as the result of their charge exchange with

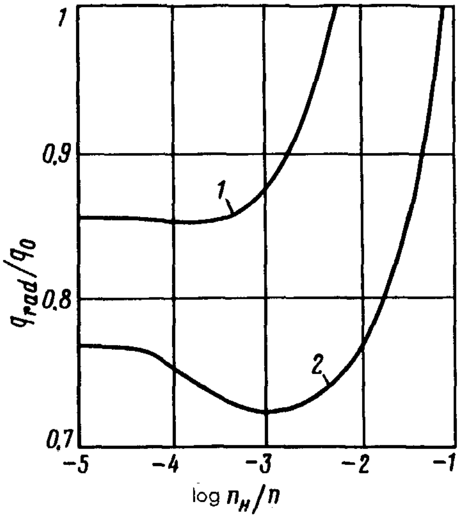


FIG. 2. Critical fraction of the power which is reradiated, $q_{rad}/q_0$, versus the relative density of neutral hydrogen. 1—$w=10^{-6}$; 2—$w=10^{-7}$. The region below the curve is the stability region.

neutral hydrogen atoms in the edge region of the tokamak leads to an increase in the threshold for the growth of the azimuthally asymmetric mode of the radiation-condensation instability.

These results explain the stability of the edge plasma with respect to the occurrence of the marfe effect in detached-plasma regimes.


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