Impurity Accumulation and Edge Localized Mode (ELM)

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Abstract

The effect of the impurity ions on the L/H and H/L transitions in tokamaks is discussed. It is found that the impurity accumulation can trigger the transition from the H-mode to the L-mode. The relation with ELM is also discussed.

Keywords :

Edge Localized Mode, H-mode, Impurities, Tokamak,

A model based on neoclassical behavior of ions has been proposed^{1), 2)} to explain the H-mode of tokamak plasmas. The model was extended to include the effect of the radial electric field E_r ³⁾. The ions in one banana orbit encounter the electrostatic potential difference of $E_r \rho_b$ where ρ_b is the banana size. As a result, the loss cone may be closed for some ions ($E_r > 0$) or the trapped population may be reduced ($E_r < 0$). Consequently the ion loss flux depends on E_r^2 . On the other hand, the electron loss flux depends on E_r . By equating the ion and electron fluxes, it is found that the plasma edge is a bistable one with high electron temperature and the other with low electron temperature.

The experimental data show that the impurity concentration near the edge increases between the ELM's. Also it has been known that the neoclassical effects transport the impurity ions inward. The accumulation of the impurity ions may produce radial electric field and acts as a trigger for the transition from the H-mode to the L-mode. The presence of impurities may also affect the critical condition for the L to H transition.

After the establishment of the transport barrier due to the L to H transition, the steep pressure gradient of ions is formed. Owing to this steep gradient, impurity transport takes place in ion-ion collision time. The inward motion of the impurity ions due to the frictional drag force from the bulk ions can be

derived in the Pfirsch-Schlüter regime ⁴⁾ or in the banana regime ⁵⁾. The impurity ions drift inward because of the collisional drag in the direction parallel to the magnetic field. The radial drift velocity u^* is given by

$$u^* = \frac{\sqrt{\epsilon} \nu_{ii} Z m_i}{e^2 B_\theta^2} \left(\frac{1}{n_i} \frac{\partial p_i}{\partial r} - \frac{1}{Z n^*} \frac{\partial p^*}{\partial r} \right) C, \quad (1)$$

where $C=1$ for the banana regime and $C=\epsilon^{3/2}$ for the Pfirsch-Schlüter regime, p is the pressure, n is the density, Ze is the charge of impurity ions, ν_{ii} is the proton-proton collision frequency, ϵ is the inverse aspect ratio, B_θ is the poloidal magnetic field and the circular cross-section plasma is assumed. Subscript i and superscript $*$ denote protons and impurity ions, respectively. We consider the regime of the impurity concentration which satisfies the relation $Z^2 n^*/n_e \sim 0(1)$ and $Z n^*/n_e \ll 1$. The inward drift of the impurity ions has the relation to the outward velocity u_i of protons as $n_i u_i^A = -Z n^* u^{*A}$; in order that there is no net current (the superscript A stands for the ambipolar component). Note that the drift velocities are independent of the radial electric field. The accumulation of the impurity ions continues until the pressure gradient of the impurity ions reaches the value given by

$$\frac{dp^*}{n^* dr} \simeq \frac{Z}{n_i} \frac{dp_i}{dr}. \quad (2)$$

This impurity accumulation affects the radial electric field and the condition for the L/H and H/L transitions. Let us examine this effect. According to Ref. (3), we simply extend the forms of losses of ions and electron loss as

$$\Gamma_i = \Gamma_i^N (\text{loss cone}) + n_i u_i^A + \Gamma_i^A, \quad (3-1)$$

$$\Gamma^* = \Gamma^{*N} (\text{loss cone}) + n^* u^{*A} + \Gamma^{*A}, \quad (3-2)$$

$$\Gamma_e = -D_e n_e (n'_e / n_e + e E_r / T_e + \alpha T'_e / T_e) + \Gamma_e^A \equiv \Gamma_e^N + \Gamma_e^A, \quad (3-3)$$

where D_e is the coefficient of the anomalous electron transport, α is a numerical coefficient of the order of unity (which is characterized by the mechanism of the anomalous transport) and the superscript N stands for the nonambipolar part. The third term in the ion/impurity loss is the other ambipolar component.

The radial electric field is determined by the zero-net-current condition, i.e. $\sum_j Z_j \Gamma_j^N = 0$, or

$$\Gamma_e^N = \Gamma_i^N (\text{loss cone}) + Z \Gamma^{*N} (\text{loss cone}). \quad (4)$$

For a given electron transport coefficient, we see from Eq. (3-3) that the positive electric field reduces the convective loss (i.e., H-phase) and that the negative electric field enhances the loss (L-phase). Increment of either Γ_i^N or Γ^{*N} reduces the radial electric field and may cause the H to L transition.

When we consider the impurity accumulation phase, we have two possible mechanisms which can enhance the ion losses. One is the enhancement of the pitch angle scattering of bulk ions due to the presence of impurities as $Z_{\text{eff}} \nu_{ii}$. This enhances the loss cone loss of protons. The other is the increment of banana orbit size of impurity due to the rotation caused by the steep edge gradients. This enhances the impurity loss cone loss.

The impurity accumulation occurs because the collisions tend to equalize the diamagnetic flow of the impurities and protons. When $(\nabla p^*/p^*)$ becomes comparable with $|Z \nabla p_i/p_i|$, the impurity rotates in the toroidal direction with the same speed as protons. The toroidal rotation velocity U_ϕ can reach of the order of v_{Ti} , if E_r is of the order of $T_i/e\rho_b$. Since impurities have the same speed as protons, the impurity velocity can reach the value of $\sqrt{m^*/m_i} v_{Ti}^*$ (assuming that $T^*=T_i$). Under this rapid rotation, the centrifugal force determines the banana size of impurities and can purge them⁶⁾. In Ref. (6), ρ_b^* is estimated to be ($T_e=T_i$)

$$\rho_b^* \simeq \frac{(m^*/m)^2}{Z(m^*/m - Z/2)} \frac{U_\phi}{v_{Ti}} \rho_b \simeq \frac{m^*}{mZ} \rho_b. \quad (5)$$

Owing to the enhanced banana orbit, the loss through the loss cone arises. Γ^{*N} (loss cone) may be estimated as $\Gamma^{*N} = \nu^* n^* \rho_b^{*2} F^*/\sqrt{\epsilon} \rho_b$ (where F^* is a coefficient of order unity). This positive flux tends to reduce the radial electric field.

In order to obtain the consistent electric field with these effects, the analyses of the velocity distributions and that of the location of the loss cone are necessary. We therefore give a crude estimation of the critical impurity concentration for the H to L transition. The loss due to the loss cone may be written as

$$\Gamma_i^N = \left(1 + \frac{n^*}{n_i} Z^2\right) n_i \nu_{ii} \rho_b F/\sqrt{\epsilon}, \quad (6)$$

$$\Gamma^{*N} = \frac{m^* n^*}{m_i n_i} n_i \nu_{ii} \rho_b F^*/\sqrt{\epsilon}, \quad (7)$$

where $F(E_r, \dots)$ and $F^*(E_r, \dots)$ are the relative numbers in the loss cone in the velocity space and $0 \leq F, F^* \leq 1$ holds. In the dimensionless form, Eq. (4) reduces to

$$d(\lambda - X) = \left(1 + \frac{n^*}{n_i} Z^2\right) F + \frac{m^* n^*}{m_i n_i} Z F^* \quad (8)$$

where $d = D_e T_i \sqrt{\varepsilon} / T_e \rho_b^2 \nu_{ii}$, $\lambda = -T_e \rho_b (n'/n + \alpha T_e'/T_e/T_i)$, $X = e E_r \rho_b / T_i$. The H-phase has the positive electric field, $X > 0$. The increment of the ion losses either by $(1 + n^* Z^2 / n_i)$ or $m^* n^* Z / n_i m_i$ reduces the value of X , provided that the other parameters are unchanged.

Let us estimate the order of the critical density of impurities. As is discussed in Ref. [3], the ion fluxes (the right hand side of Eq. (8)) becomes smaller for increasing $|E_r|$. The electron loss (the left hand side of Eq. (8)) is a decreasing function of X . The necessary condition for the positive E_r is that LHS is larger than RHD in Eq. (8) at $X = 0$. Substituting $X = 0$ in Eq. (8), we find that the plasma is brought back to the negative E_r solution (L-mode) if the inequality holds;

$$d \lambda < Z_{eff} \hat{F} + \frac{m^* n^* Z}{m_i n_i} \hat{F}^*, \quad (9)$$

where $\hat{F}$ and $\hat{F}^*$ are values of F and F^* at $X = 0$, respectively. The critical value of $d \lambda$ is obtained in the case of $n^*/n_i = 0$ in Ref. [3], and the estimation by the condition $\Gamma_e(X=0) < \Gamma_i(X=0)$ (i.e., $d \lambda < \hat{F}$) for L-mode was found to be a good approximation. From Eq. (9), we find that the impurities enhance the critical values of λ by the factor of $Z_{eff} + m^* n^* Z \hat{F}^* / m_i n_i \hat{F}$. The critical value depends on the effective charge and species of the impurity. In the case of the light impurities, such as carbon and oxygen, $m^* Z / m_i$ can be close to $2Z^2$ (for hydrogen plasma). On the other hand, in the case of metal impurities, $m^* Z / m_i$ is larger than $2Z^2$, and the effect to reduce E_r is larger for the given Z_{eff} . The value λ is several times larger than L-phase after the H-mode establishes. Therefore the doubling of Z_{eff} after entering the H-phase is a measure of the H to L transition. Furthermore, the deuteron plasma is less affected by impurities than hydrogen plasma, provided that the other parameters (such as Z_{eff} , d ...) are unchanged, because of the larger m_i value.

In Fig. 1, we show a schematic trajectory of the plasma parameters on the $(\lambda, n^*/n_i)$ plane associated with $L \rightarrow H \rightarrow L \dots$ transitions. After the first $L \rightarrow H$ transition, the pedestal is formed (i.e., λ goes up) (I) and the inward drift of impurities occurs. The impurities start to accumulate (II). When the impurity concentration becomes sufficiently large the $H \rightarrow L$ transition may occur. This $H \rightarrow L$ transition which is caused by the edge impurity may be observed as a periodic burst, i.e., ELM. After the disappearance of the transport barrier, the edge plasma will disappear in a time of ρ_b^2 / D_e (III) which is less than 1 ms for $D_e = 1 \text{ m}^2/\text{s}$ and $\rho_b = 3 \text{ cm}$. The impurities in the pedestal region are also purged. As a result, λ and Z_{eff} reduces rapidly. The reduction continues until the parameters $(\lambda, n^*/n_i)$ hit the condition of the $L \rightarrow H$ transition (at C in Fig. 1). Then the process repeats anew. The parameter $(\lambda, n^*/n_i)$ moves on a cycle in Fig. 1 in a counterclockwise direction. Because the increasing time of n^*/n_i is much longer than the time of Z_{eff} decay, the state III may be observed as a burst of the plasma across the surface.

Fig. 1. Schematic drawing of the bistable solution $E_r(\lambda, n^*/n_i)$ and the trajectory of $(\lambda, n^*/n_i, E_r)$ (a). Transitions occur at A, B, C and D (a). The projection on the $(\lambda, n^*/n_i)$ plane is given in (b).

The parameter (λ, Z_{eff}, E_r) changes with a slow time scale in L and H phases. Because the steep gradient and positive E_r is generated in a narrow region near the edge, $|a-r|/\rho_b \approx 0(1)$, the toroidal rotation U_ϕ is also localized near the edge and has a large shear, i.e., $|(dU_\phi/dr)/U_\phi| \approx 0(\rho_b^{-1})$. The viscosity tends to reduce the rotation. The time scale of the reduction is typically $\tau_v = \rho_b^2/\mu_i$ (μ_i being the ion viscosity and is approximately given by $\rho_b^2 v_{ii} \epsilon^2/10^7$). The viscosity damping, which is also enhanced by Z_{eff} , has an effect to reduce the radial electric field. For typical values of $n \approx 5 \times 10^{13}/\text{cm}^3$ and $T_i \approx 500$ eV, we have $\tau_v \approx 20$ ms. The actual accumulation time of impurities in relatively clean plasma is probably limited by the supply of the impurity atoms. The experimental data of D-III-D show that the edge impurity concentration increases linearly in time between ELM's⁸⁾. The doubling time is typically 100 ms in this case. According to this model, dirty wall conditions lead to frequent small ELM's and clean conditions to infrequent large ELM's. Since the limiter discharges are more likely to have a large impurity recycling, it is more difficult to obtain H-mode discharge.

There is another source of the radial electric field, namely the plasma rotation in the toroidal direction induced by neutral beam injection. The co-injection of the beam produces the positive radial electric field and should help in inducing the H-mode. The toroidal rotation should strongly affect the loss rate of ions due to the loss cone. Future work is necessary to obtain the quantitatively correct threshold.

There are several different phenomena which may affect the radial electric field, the mirror loss of ions at the edge, the impurity transport and the toroidal rotation. It may be that the H-mode is produced when the combined effects result in the positive radial electric field.

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