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Transition to H-Mode by Energetic Electrons

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Abstract

Effect of the electron loss due to the toroidal ripple on an H-mode transition is studied. When energetic electrons exist in tokamaks, e.g., in the case of the current drive by lower hybrid (LH) waves, the edge electric field can show the bifurcation to the more positive value. In this state, both the electron loss and ion loss (such as loss cone loss) are reduced. The criterion for the transition is derived. Comparison with H-mode in JT-60 LH plasma shows a qualitative agreement.

Keywords: H-mode, Hot Electrons, Radial Electric Field,
Bifurcation, Ripple Loss

After the H-mode was found in ASDEX by the neutral beam injection (NBI) heating$^{1)}$, the H-mode has been found independent of the method of the plasma heating. The operational region in which H-mode can appear has been studied extensively. The research for the criteria of the H-mode region has not been completed, but the H-mode can be more easily realized above a certain density$^{2)}$. The H-mode in JT-60 with lower hybrid wave heating$^{3)}$, has shown a peculiar behaviour. It was realized in the low density plasma. In addition to it, the superposition of the NBI heating easily terminates the H-mode. The many of characteristics of the H-mode, such as the reduction of loss, sharp edge gradient, and so on, are common to all the H-mode, independent of the heating method: However, there is still noticeable differences among various H-mode discharges; one example is the one in JT-60 LH plasma. The analysis of this H-mode will deepen the understanding of the physics of the H-mode which is the generic nature of tokamak plasmas.

To understand the H-mode phenomena, we have proposed a model based on the bifurcation of the radial electric field, $E_r$$^{4)}$. This model provided a picture of the bifurcation of the transport coefficient and establishment of the transport barrier. The establishment of the radial electric field has been confirmed by experiments$^{5,6)}$. Further extensions of this model were made$^{7,8)}$ which explains the sign of the observed radial electric field and reduced anomalous transport. It has later been demonstrated that transition can occur both into more positive E_r and more negative $E_r$$^{9)}$. The nonlinear response of the radial current to the radial electric field has also been confirmed in the probe experiment$^{9)}$. Based on these progresses, it can now be said that the picture of the H-mode physics based on the electric field bifurcation is obtaining a firm basis.

In this article, we apply the electric bifurcation model to the plasma in the presence of the energetic component of electrons. Such electrons can carry radial current due to the toroidal ripple. The impact of this current on the self-consistent solution of E_r is studied. It is shown that this current can induce a transition of the radial electric field. The threshold condition is derived, which shows a qualitative agreement with the experimental result of the LH H-mode in JT-60.

We consider a thin plasma layer near edge. The Poisson equation with equation of motion can be written as

$$\varepsilon_0 \varepsilon_\perp \frac{\partial}{\partial t} E_r = -e(\Gamma_i - \Gamma_e), \qquad (1)$$

where ε_0 is the dielectric constant of the vacuum, $\varepsilon_\perp$ is the perpendicular dielectric coefficient, Γ_i is the bipolar component of ion flux, and Γ_e is the one for electrons.

In the edge regions, model of Γ_i has been proposed such as the ion orbit loss$^{4)}$, ion flux by bulk viscosity$^{7)}$ and that by shear viscosity$^{10)}$. We here neglect the shear viscosity (i. e., we look for the necessary condition for inducing the transition). We also consider the plasma in which the ionic charge is one. The radial current by the ion orbit loss is approximately given as4,7) $[n_i \nu_i \rho_p F/\sqrt{\varepsilon}]\exp(-Y)$ $(Y=\sqrt{\nu_*+X^4})$ and that by the bulk viscosity as7,10) $m_i n_i \nu_i V_p q^2 f(X)/eB_t$, to yield

$$\Gamma_i = n_i \nu_i \rho_p[(F/\sqrt{\varepsilon})\exp(-\sqrt{\nu_*+X^4}) + \varepsilon^2 f(X)X] \qquad (2)$$

where n_i is the ion density, ρ_p is the poloidal ion gyro radius, ε is the inverse aspect ratio, F is a numerical coefficient of the order unity, ν_i is the ion-ion collision frequency, ν_* is the normalized collision frequency, X is the normalized radial electric field

$$X = e\rho_p E_r/T_i \qquad (3\text{-}1)$$

and the function f(X) shall be further approximated as7,10)

$$f(X) = 1/(1+X^2). \qquad (3\text{-}2)$$

The normalized electric field X corresponds to the poloidal mach number $Bu_p/B_p v_{Ti}$ if we evaluate the poloidal velocity u_p by E_r/B, where v_{Ti} is the ion thermal velocity. (Note that we consider the case $|\rho_p n'/n| \ll 1$.)

The energetic electrons can diffuse by the ripple diffusion, which is caused by the toroidal ripple. We consider the case that electrons consist of the bulk component and hot component. (For the simplicity, we assume that $T_i = T_e$ for bulk electrons.) This ripple loss flux is intrinsically bipolar and has been obtained as11)

$$\Gamma_e = C_e\delta^{1.5}\left(\frac{T_h}{eBR}\right)^2 \frac{1}{\nu_{eh}} n_h\left\{\frac{n'_h}{n_h} + \frac{eE_r}{T_h} + 3.45\frac{T'_h}{T_h}\right\} \qquad (4)$$

where $C_e \simeq 5.8$, δ is the toroidal ripple, R is the major radius, ν_e is the electron collision frequency, and the subscript h denotes the hot component. This *flux has strong* temperature *dependence* ($T_h{}^2/\nu_{eh} \propto T_h{}^{3.5}$), and the contribution from the bulk electrons are not important except for very hot plasmas. (Equation (4) is given as the value averaged over the magnetic surface.) The necessary condition for hot electrons to enter the ripple region is given as[1)

$$\nu_{eh} < (\varepsilon\delta)^{3/4} v_{Te}/R. \qquad (5)$$

The charge neutrality equation $\Gamma_e = \Gamma_i$ determines the radial electric field and the net particle flux for given plasma density and temperature profile. For the analytic insight of the problem, we assume that $T'=0$. The electron flux can be written as

$$\Gamma_e = \Gamma_0\{\lambda_h - (T_i/T_h)X\} \qquad (6)$$

where

$$\Gamma_0 = C_e\delta^{1.5}\left(\frac{T_h}{eBR}\right)^2 \frac{1}{\nu_{eh}} \frac{n_h}{\rho_p} \qquad (7\text{-}1)$$

and

$$\lambda_h = \rho_p n_h'/n_h. \tag{7-2}$$

The dependences of Γ_i and Γ_e on the radial electric field X is schematically drawn in Fig.1. It can be seen that when the gradient parameter for the hot electrons is large

$$\lambda_h > T_i/T_h \tag{8}$$

and $\Gamma_e(X=0)$ exceeds some criterion, the solution of X, which is characterized by the small plasma flux, is found. (This situation is the same as in Ref.[4].) For the parameter of our interest [3], the barrier near $X=0$ comes from the contribution of the ion bulk viscosity. The critical conditions to enter the low-flux condition are obtained as Eq.(8) and $\Gamma_0 \lambda_h > \varepsilon^2 n_i \nu_i \rho_p$ or

$$C_e \varepsilon^{3/2} \left(\frac{T_h}{T_i} \right)^{3.5} \frac{n_h}{n_i} \sqrt{\frac{m_e}{m_i}} \; \lambda_h \left(\frac{v_{Ti}}{qR\nu_i} \right)^2 > 1 \tag{9}$$

where we used the relation $\nu_{eh} \sim [(T_i/T_h)^{1.5}\sqrt{m_i/m_e}]\nu_i$ and q is the safety factor.

The result of Eq.(9) indicates that there is a threshold value for $T_h{}^{3.5} n_h$ as

$$T_h^{3.5} n_h > A \equiv \frac{1}{C_e \lambda_h \varepsilon^{1.5}} \sqrt{\frac{m_i}{m_e}} \left(\frac{\nu_i q R}{v_{Ti}} \right)^2 n_i T_i^{3.5}, \qquad (10)$$

at the plasma edge. It should be noted that the critical parameter *A* scales as

$$A \propto \lambda_h^{-1} \varepsilon_t^{-1.5} n_i^{3} T_i^{-0.5}. \qquad (11)$$

This result shows that the criterion has a strong dependence on the edge plasma density, and the transition can take place in the lower density case. On theother hand, the threshold weakly depends on the bulk temperature.

The result can be examined by comparing the continuum of Bremsstrahlung. The frequency spectrum of the continuum $I(\omega)$ from the hot electrons is approximated as[12)]

$$I(\omega) = G n_i n_h T_h^{-0.5} exp(-\hbar\omega/T_h) \qquad (12)$$

where G is a universal constant. If the spectrum is written as $I(\omega)=I_0 exp(-\hbar\omega/T_{ph})$, the condition for the transition Eq.(10) gives

$$I_0 T_{ph}^{4} > G A n_i. \qquad (13)$$

Figure 2 compares the criterion Eq.(12) with experimental result[3)] for given parameter $A n_i$. The line is drawn so that the point ▼ is on the line. We see a qualitative agreement between the prediction Eq.(13) and the observed boundary for the LH H-mode.

We can also evaluate the necessary power P_{hot} of the hot electron loss in order to induce the H-mode. Evaluating the energy flux at $X=0$, we have [energy flux] $\simeq 5T_h\Gamma_e$, which is derived in Ref.[11,13], and $P_{hot} \simeq 20\pi^2 aRT_h\Gamma_e$. Noting the necessary condition $\Gamma_e > \varepsilon^2 n_i \nu_i \rho_p$, we have

$$P_{hot} > 10\varepsilon^2 \frac{T_h\rho_i}{T_i a}\nu_i n_i T_i V \tag{14}$$

where V is the plasma volume, and quantities in the right hand side is evaluated at the plasma surface. The total energy content of the plasma is roughly estimated by $W_p \simeq Vn(0)T(0)$ and the total heating power P_{tot} must satisfy $P_{tot} = W_p/\tau_E$, where τ_E is the energy confinement time (argument 0 indicates the plasma center). Using these relations and $P_{hot}<P_t$, Eq.(14) gives a necessary condition from the energy balance as

$$10\varepsilon^2 \frac{T_h\rho_p}{T_i a}\left(\frac{n_i(a)}{n_i(0)}\right)^2 \tau_E \nu_i(0) < 1. \tag{15}$$

This condition is more easily satisfied for large devices, and is satisfied in experiment on JT-60 3).

In summary, we have analysed the H-mode in the LH heating plasma in JT-60. The electric field bifurcation model is applied by taking into account of the ripple diffusion of the energetic electrons. The critical condition for the energetic electrons is derived. This condition is tested by the experimental results, and qualitative agreement is confirmed. In this case, the radial electric field is predicted to be more positive in the H-mode. This could be tested by future experiments. The criterion is found to be strongly dependent on the plasma density at edge (the critical parameter A is proportional to $n(a)^3$). This result suggests that the careful conditioning is necessary to realize this H-mode in the LH heating plasma. Operational condition to realize the H-mode in LH heated plasma was also discussed in Ref.[3]; It is summarized that the parameter T_{ph} of the hard X-ray spectrum has a criterion rather than the choice of the rf frequency. This result is consistent with this theoretical modelling.

Impact of energetic electrons on H-mode has been discussed based on the bifurcation model. The experiments on JT-60 indicates the important role of energetic electrons in the non-inductive-current-drive plasma. This result also suggests that the H-mode in future high temperature plasma, where the bulk electrons can also be subject to the ripple loss, may change it nature from present experimental observations.

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Figure Captions

Fig.1 Schematic dependence of the bipolar electron flux Γ_e (dashed line) and the bipolar ion flux Γ_i (solid line). Crossing of these two lines gives the self consistent electric field and the plasma flux. When parameters λ_h and Γ_0 is small (a), solution with small $|X|$ and the large flux is obtained. When λ_h and Γ_0 are increased, the transition to the solution of the large X and the small flux is realized (b).

Fig.2 Comparison with the criterion Eq.(12) and the experimental result. The solid line is the prediction, Eq.(12). The open symbols and closed symbols correspond to the cases of H-mode and L-mode, respectively. The solid line is drawn to go through the symbol ▼ for the qualitative comparison.

Fig. 1

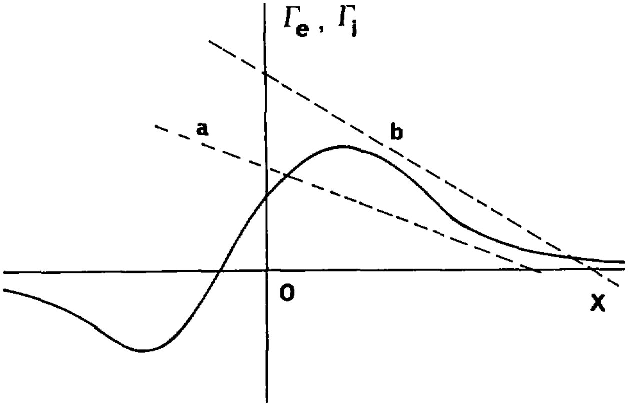
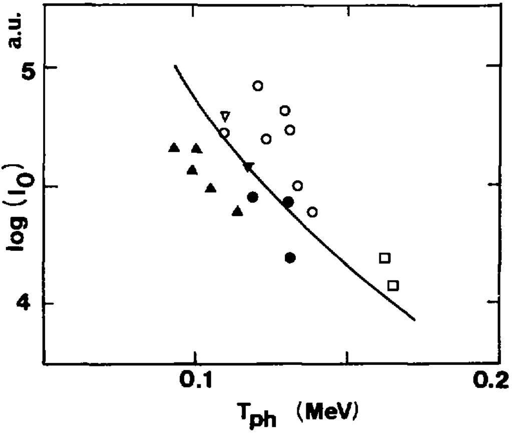


Fig.2



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