Change of Transport at L- and H-mode Transition

S.-I. Itoh and K. Itoh

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Sanae-Inoue Itoh and Kimitaka Itoh

National Institute for Fusion Science, Furocho, Chikusa-ku,
Nagoya 464-01, Japan

Abstract

A new refined model of the L-mode and H-mode transition in tokamaks is presented based on the bifurcation of the radial electric field, E_r, near edge. The radial gradient of E_r is newly introduced to explain the sudden change of fluctuations as well as plasma fluxes at the onset of transition. This model predicts that the L-to H-mode transition is associated with the decrease of dE_r/dr causing reduction of particle and energy fluxes at critical gradient.

Keywords: H-mode Transition, Tokamaks, Anomalous Transport, Reduced Fluctuations, Radial Electric Field, Microinstability

Recently, the knowledge on H-mode[1-9] in tokamaks has strongly incresed. The research on H-mode is motivated by the requirement of the improvement of the energy confinement time. The transition phenomena, which are the key to understand the basic physics of the H-mode, however, still remain unresolved.

In previous articles[10-11], we have presented a model of the L- to H-mode and H- to L-mode transitions, in which the bifurcation of the radial electric field plays the key role. In an old model, the electron particle flux and ion particle flux can be bipolar near edge so that the radial electric field piles up to keep the charge neutrality. The electron flux is assumed to be anomalous and we have assumed that the anomaly is not affected by the change of the radial electric field, E_r. By this simplification, the model has predicted the transition of flux, but the explanation of the reduced fluctuations are left unanswered. The effect of the radial derivative of E_r, E_r', is neglected in the framework of zero-dimensional analysis. The model has been examined by experiments. D-III-D experiments have confirmed the sudden change of E_r at the transition, but the sign of the change of E_r is opposite to the prediction.[12] JFT-2M has also observed the change of the plasma rotation due to E_r, but the direction is not conclusive.[13] The extension and refinement of the model are necessary to cope with these experimental progresses.

Actually, the radial derivative of E_r is not negligiblly small, because E_r is generated within a narrow region near the edge, in which the loss cone loss of ions exist. The characteristic thickness of the transition layer was predicted to be the banana width. Therefore the effects of E_r' on the ion orbit and electron flux can be larger than those of E_r itself. In this article, we extend the previous theory of H-mode transition taking into account the effect of E_r'. By this extension, not only the bifurcation of convective flux but also that of conductive flux are predicted at the critical gradient near edge. Simultaneously, the reduction of microscopic fluctuation near the edge is also explained. The sudden change of E_r takes place so as to reduce E_r'.

We consider the edge plasma (inside of the surface) of a circular tokamak, which is defined by the limiter located at $\theta=\theta_m$. Toroidal coordinates (r, θ, ϕ) are introduced and axial symmetry, $\partial/\partial\phi=0$, is employed. For the poloidal divertor configuration, the poloidal angle of X-point corresponds to θ_m. The particle loss of j-th species (j=i,e) is written as $\Gamma_j= \Gamma^A_j +\Gamma^{NA}_j$, where the superscripts A and NA stand for the ambipolar and nonambipolar parts, respectively. As is discussed in Refs.(10-11), particle flux can be bipolar near edge, so that the relation $\Gamma^{NA}_e=\Gamma^{NA}_i$ determines the ambipolar electric field, E_r. This field also affects the ambipolar part. For simplicity, we in this article treat a single-ion-species plasma and neutral particle effects are discussed in other article.

The bipolar flux of ions comes from the loss cone loss. In the presence of E_r, the minimum energy to enter the loss cone is given as $W_m=W_{m0}\equiv\sigma m_i(E_r/B_p)^2/2$, where $\sigma=2\varepsilon(1-\cos\theta_m)$, ε is the inverse aspect ratio, B_p is the poloidal magnetic field.[11] The energy is evaluated in the rotating frame with the rotation frequency $\omega_E = E_r / RB_p$. R is the major radius of the torus. This shift of minimum energy is due to the centrifugal force. In the presence of E_r', the banana width changes by the factor $1/\sqrt{|1-u_g|+C\epsilon}$ (u_g is defined as $\rho_p E_r' / v_{Ti} B_p$, ρ_p is the poloidal gyroradius. The correction of the order of ϵ dominates in the limit of $u_g \to 1$, and the banana width is limited to a certain value. The numerical coefficient C represents this correction.)[11,14,15]. The minimum energy W_M is given as $|1-u_g| W_{m0}$ including the u_g correction. Taking these u_g corrections to the formula of Γ^{NA}_i in Ref.(11), we have

$$\Gamma_i^{NA} = \frac{F}{\sqrt{\epsilon}} \frac{n_i \nu_i \rho_p}{\sqrt{|1-u_g|+C\epsilon}} \exp\{-\sigma |1-u_g| \left(\frac{\rho_p e E_r}{T_i} \right)^2 \} \tag{1}$$

where F is a numerical coefficient of the order of unity.

The radial gradient of E_r affects the microscopic mode stability. This has been studied and shown for the fluid turbulence due to the Kelvin-Helmholtz instability of the edge plasma[16]. This is also true for the collisionless cases. For example, we study the collisionless limit of trapped particle drift instability. This instability is driven by the toroidal drift of trapped particles[17]. In the presence of E_r', the toroidal precession frequency changes as $\omega_M = \omega_{M0} / (|1-u_g|+C\epsilon)$ (ω_{M0} [illegible]) associated with the change of banana width. For [illegible] of u_g [illegible](1), the toroidal drift of trapped ions [illegible] (u_g [illegible]) or incresed ($u_g>0$). Effect is not seen for electrons. The local dispersion relation is given as

$$2 = \sqrt{2\varepsilon}\left(\frac{\tilde{\omega}-\omega_*}{\tilde{\omega}-\omega_{M0}} + \frac{\sqrt{|1-u_g|+C\varepsilon}\,(\tilde{\omega}+\omega_*)}{\tilde{\omega}+\omega_M}\right) \quad (2)$$

where ω_* is the drift frequency, $\tilde{\omega}=\omega-N\omega_E$, ω is the angular frequency of the mode, N is the toroidal mode number, the ionic charge is unity and $T_e=T_i$ is assumed. The change of the population of trapped ions and the real frequency shift by the rigid rotation due to E_r are also included in Eq.(2). By this effect, the mode is stabilized if E_r' is negative and the condition $u_g<-u_c$ is satisfied. The critical parameter u_c satisfies the relation $u_c^2=8\sqrt{2\varepsilon}(4-u_c)$ and is around 3 for standard parameters. We employ the model growth rate, $\gamma=\mathrm{Im}(\omega)$, such that $\gamma \sim \gamma_0\sqrt{1+u_g/u_c}$, where γ_0 is the growth rate in the absence of E_r'. The anomalous transport coefficient, which is evaluated by the relation $D_e=\gamma/k^2$ from the mixing length theory, is written as $D_e=\sqrt{1+u_g/u_c}D_{e0}$. D_{e0} is the coefficient that is given in the absence of E_r'. The bipoloar flux of electrons near edge, which is originated from the convection of excited waves[10,11,18], is

$$\Gamma_e = -D_{e0}\sqrt{1+u_g/u_c}\; n\left(\frac{n'}{n} - \frac{eE_r}{T_e} + \frac{eBr\omega}{MT_e} + \alpha\frac{T_e'}{T_e}\right). \quad (3)$$

In Eq.(3), the third term of right hand side comes from the uniform rotation effect on the mode and M is the poloidal modenumber. The coefficient α depends on the variety of fluctuation mode, but stays of the order unity.

Equating Eqs.(1) and (3), we have the refined equation to determine the ambipolar electric field as

$$d\sqrt{1+u_g/u_c}\ \lambda = \frac{1}{\sqrt{|1-u_g|+C\varepsilon}} \exp\{-\sigma|1-u_g|X^2\} \qquad (4)$$

where $d=\sqrt{\varepsilon} D_e/\nu_i F \rho_p{}^2$, $X=\rho_p e E_r/T_i$, $\lambda=-(T_e/T_i)\rho_p(n_e'/n_e+\alpha T_e'/T_e)$. This flux is given in the frame rotating with frequency ω_E. The solution of (X,u_g) is calculated for various values of the gradient parameter, λ. Figure 1 shows the solution on u_g-X plane for various values of λ. In Fig. 2, the solutions of of E_r', relative growth rate of instability, and resultant flux are shown. In obtaining the results in Fig.2, we assume the linear relation between E_r and $E_e'\rho_p$ as $X=\eta u_g$. It is shown that at the threshold value of λ, λ_{c1}, the radial derivative E_r' changes from positive to negative. Associated with this, the anomalous transport coefficient and the cross field flux shows transition. The quantities u_g, D_e and Γ have multiple values simultaneously. The state with large flux is to be attributed to L-mode and that with low flux is interpreted as H-mode. It should be noted that the qualitative nature of the solution is not affected by the choice of η. Depending on the sign of η, the jump of E_r associated with transition changes the direction, while the change of E_r' is always negative for L to H transition. In the case of Fig.2, E_r changes from the positive value to the negative one. The reduction of instability growth rate and those of fluxes are obtained independent of the sign of η. By this extention, we recover the critical value of λ, λ_c, for the transition. The absulute value of λ_c is close to that obtained in the previous model.

This model predicts that the improvement of microscopic stability just inside of the plasma surface occurs at the onset of transition. The change of γ takes place at the same time as that of Γ does. Intrinsic ambipolar component of particle flux also reduces due to the reduction of D. By this change of γ, the conductive energy loss of <u>electrons</u> also jumps to the lower state at the onset of L to H transition. The background profile, which is characterized by the parameter λ, starts to change as a result of the bifurcation of conductive and convective fluxes. With respect to the ion conductive loss, we need more analysis.

In summary, we proposed a new refined model for the L to H-mode transition. In this new model, the effect of radial gradient of E_r is taken into account. When E_r' is more negative, the banana width of ions is squeezed, and the electron anomalous flux is also reduced by the improved micro-stability. Due to this mechanism, the state with negative E_r' is characterized by the small fluctuations and reduced edge loss. On the contrary, the state with positive E_r' has larger loss and worse stability. This model attributes the states of negative and positive E_r' to H- and L-phase, respectively, and predicts that the transition between them can takes place at particlular values of gradient, λ_c. As in the old model, the phase curve of λ-Γ has the form of Riemann-Hugoniot catastrophe. The critical value λ_c for L to H transition, λ_{c1}, is larger than that for H- to L transition, λ_{c2}. New model also explains the sudden reduction of fluctuation inside the plasma surface, which is consistent with observations in D-III-D tokamak.[19] On the direction of the radial electric field, this model concludes that jump of E_r depends on the sign of η which relates to the boundary condition. The relation between E_r and E_r' must be determined through the edge condition, which depends on the machine conditions. The existence of E_r' is associated with the shear of rotational velocity. In this regard, model of η needs further theoretical and experimental analyses.

This new model gives the critical value of λ which is close to that in the previous model. This leads to that the evaluation of the critical heating power[20] is not affected much. The location of the limiter/X-point has effect on the transition through σ. The smaller value of σ, i.e., loss point located in the lower field side, gives the larger critical value. In the present model, however, the transition is possible even for the case of $\theta_m=0$. This result is consistent with that the H-mode transition has been observed in JT-60 with outside divertor[21]. The role of neutral particles is to prevent the transition from L to H-mode. The effect of neutral particles can be introduced by straight-forward extension as is discussed in Refs.(11,22,23). Also required is the more thorough calculation on u_g-dependence of γ for the realistic parameter of experiments. The quantitative estimation of the threshold condition will be given by using the explicit form of $\gamma(u_g)$.

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Figure Captions

Figure 1 The solution of Eq.(4) on u_g-X plane is drawn for various values of λ. The dashed line corresponds to $E_r = \eta E_r' \rho_p$. Depending on the coefficient η, the appearance of the transition slightly changes. Parameters are $d=1.0$, $\sigma=0.5$, $u_c=3.0$, $C=2.0$ and $\varepsilon=0.3$.

Figure 2 Gradient of E_r, instability growth rate γ, and particle flux as a function of the gradient parameter λ. Multiple solutions simultaneously exist for λ, and transition takes place at particular value of λ. $\eta=0.25$ and other parameters are the same as in Fig.1. Normalized value Γ_0 is given as $F n_i \nu_i \rho_p / \sqrt{\varepsilon}$.

Fig. 1

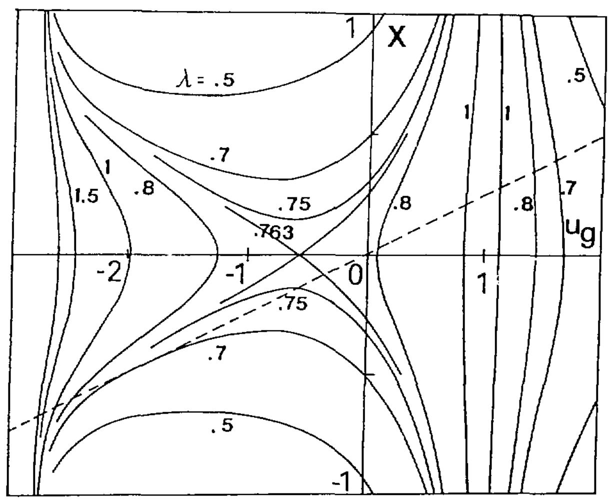
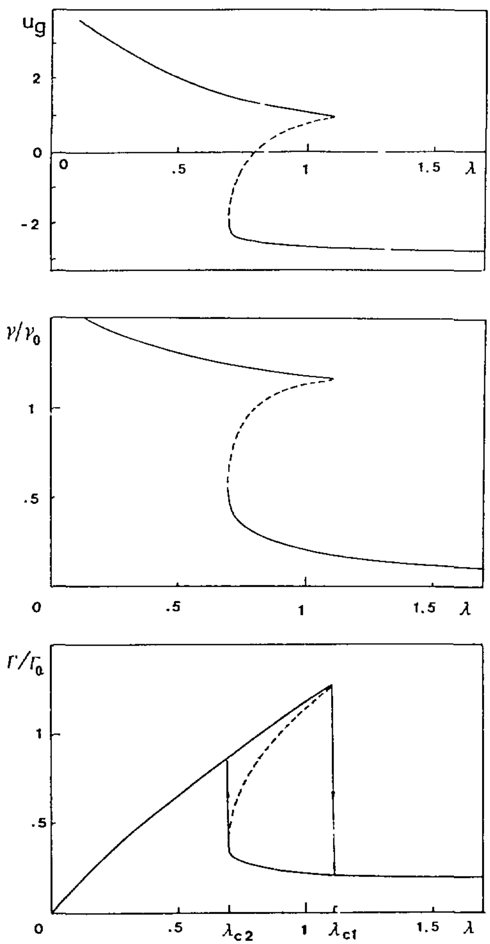


Fig. 2



u_g
2
0
-2
0
.5
1
1.5
λ
γ/γ_0
1
.5
0
.5
1
1.5
λ
Γ/Γ_0
1
.5
0
.5
λ_{c2}
1
λ_{c1}
1.5
λ