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Modelling of ELMs and Dynamic Responses of the H-mode

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Abstract

Based on the electric bifurcation model of the H-L transition, models of the Edge Localized Modes (ELMs) are developed and the dynamic responses of the H-mode are analyzed. The spatial-temporal evolution of the H-L transition is formulated in a form of the time-dependent Ginzburg-Landau equation which includes transport processes. The equation governs the development of the density and radial electric field.

By solving this equation for the given boundary condition, we identify three classes of solutions which attribute to the H-state, L-state and ELMy-H state. The ELMy-H state is characterized by the self-generating oscillations under the condition of constant source. The parameter region of these states are identified. The radial extent of transport barrier during H- and ELMy-H states is characterized by the diffusion Prandtl number.

Transient responses of the H-states to the external perturbations are also analyzed. Sudden change of the flux from the core causes transient ELMy oscillations. When the sinusoidal oscillations are imposed(simulation of sawtoothing), the ELMy oscillations with mode locking to the external oscillation frequency (or the sub-harmonics) appear. This suggests a possible scenario for the ELM control. We also develop the model for the Giant ELMs. Ballooning instability triggers the pulsive loss flux to the edge region. If its magnitude exceeds the threshold, the transport barrier is destroyed for a short period and the large solitary pulse in the outflux is generated.

1. Introduction

Edge localized Modes (ELMs) usually follow the L- to H-mode transition and show a variety of appearances in the magnitude and frequency of the bursts, and occur in a restricted parameter space of the H-phase [1]. The H-mode with small and frequent ELMs is a candidate for the standard operation in the experimental tokamak reactor, because, at present, the improved confinement compatible with the efficient ash exhaust is only found in this operation mode. The giant ELMs are associated with the large heat pulse and cause an unfavourable influence on the plasma facing components. The characterization of ELMs has just been begun, and the research to understand the ELMs and to control them is an urgent task. Extending the bifurcation model of the H-mode[2], we discuss the model of small and frequent ELMs and its parameter range. The dynamic responses of the H-mode to the external perturbation and the model of giant ELM are presented.

2. Model

The slab region near the plasma edge, $-L<x<0$, is of our interest($x=r-a$, r being the minor radius). The radial structures of the density and the radial electric field (or poloidal rotation) are studied where the poloidal and toroidal variations are neglected. The Poisson equation combined with the equation of ion motion is written as $\varepsilon_\perp \varepsilon_0 \partial E_r/\partial t=e(\Gamma_e-\Gamma_i)$, where $\varepsilon_\perp$ is the perpendicular dielectric constant. The effective diffusivity is used to write $\Gamma\equiv -D[E_r]\nabla n$. The model equations consist of the radial transport equations for the density and the normalized radial electric field Z with the viscous diffusivity μ. The equations are given in the dimensionless form as [3]

$$\partial n/\partial t = \partial/\partial x D(Z) \partial n/\partial x \tag{1}$$

$$\varepsilon \partial Z/\partial t = -N(Z,g) + \mu \partial^2 Z/\partial x^2. \tag{2}$$

The parameter ε is a small coefficient ($O(\rho_p/\rho)$, ρ_p and ρ are the poloidal and toroidal ion gyroradius, respectively) showing that Eq.(2) has faster time scale than Eq.(1) when μ and D have similar magnitude. The nonlinear term N corresponds to the local part of $\Gamma_i - \Gamma_e$, which arises from the ion orbit loss, drift wave convection, ripple loss and ion parallel viscosity[2,4]. The variable g corresponds to λd, where $\lambda = \rho_p n'/n$, $d = D_0/\nu \rho_p{}^2$, ν is the ion collisionality, and D_0 is a typical electron diffusivity at L-phase. Length and time are normalized to ρ_p and $\rho_p{}^2/D_0$, D and μ to D_0, and Γ to $D_0 n_0/\rho_p$, respectively. To have an analytic insight, we use of the model S-figure curve for N as $N(Z,g) = g - g_0 + [\beta Z^3 - \alpha Z]$, and D is assumed as $D(Z) = D_+ + D_- \tanh Z$, where $D_\pm = (D_{max} \pm D_{min})/2$. n_0 is chosen so as to satisfy $g_0 = 1$. The parameters α, β, g_0, $D_\pm$ and μ/D_0 are treated as constants. An example of D(Z(g)) for N(Z,g)=0 is shown in Fig.1(a).

The boundary conditions at x=-L and x=0 are chosen as, 1) the particle flux Γ_{in} is given at x=-L and 2) n'/n is constant at x=0 following the result of the transport simulation in the scrape-off layer[5].

3. H-, L- and ELMy-H States

For the case of constant influx Γ_{in}, three classes of solutions of Eqs.(1) and (2) are found. Two of them are constant in time, and attributed to the H- and L-states. The former has the layer near the edge (x=0) in which the effective diffusivity is low even though the steep gradient near edge is formed. This is the tranport barrier of the H-mode. The thickness of which, Δ, is given as $\Delta \simeq \sqrt{2\beta\mu/\alpha}$. In this barrier, D takes the medium value between D_{max} and D_{min}; This layer we call as the mesophase.

Nonlinear solutions of self-generated oscillations of n and Γ_{out} are found for the constant supply of Γ_{in}. This oscillation appears near the L and H phase boundary. Figures 1(b),(c) illustrate the temporal revolution of the pulsive outflux and the spatial variation of D. The thickness of the transport barrier is also given by $\Delta \simeq \sqrt{2\beta\mu/\alpha}$. This oscillatory solution is found in the parameter region of $D_m/g_m < \Gamma_{in}\lambda(0)^2 < D_M/g_M$. The interpretation in the physical parameters depends on the model of the ion flux $\Gamma[E_r]$. An extension of Ref.[2] gives $\alpha = 3\beta \simeq 3\sigma_-/2\sigma_+$ ($\sigma_\pm = 1 \pm d/\sqrt{\ell n(2e/d)}$), $D_M \simeq d$, $D_m \simeq d/2(\ell n 2e/d)$. Figure 2 shows the regions of L, ELMy-H and H states in $(d, \lambda(0)/\sqrt{\Gamma_{in}})$ plane. The dashed lines denote the contours of the oscillation frequency normalized to $\rho_p{}^2/D_0$. The shaded area indicates the bistable region where both the H- and L-solutions are possible and the stationary solution depends on the initial condition.

The gain of the confinement time by the pedestal formation depends strongly on the thickness Δ. The result shows the importance of the Prandtl number, μ/D_0.

4. Transient Response

Variety of the dynamic responses of these states to external perturbations are found. The case near the ELMy-H region in d-λ plane is studied. The density pulses, which are caused by the sawtoothing or MHD Mirnov oscillations, are simulated by the temporal change of Γ_{in}. The sinusoidal oscillation is added to give $\Gamma_{in} = \Gamma_{in,0}+\tilde{\Gamma}\sin(\Omega t)$. Depending on the amplitude $\tilde{\Gamma}$, the mode locking to the applied frequency Ω and to its subharmonics are found (Fig.3). By this perturbation, the region of the periodic oscillation solution is widened in (d,λ) plane. This suggests the possibility to enlarge the operational region for the mode with small and frequent ELMs.

A step-like change in Γ_{in} can induce the transition from L to H-phase, if Γ_{in} in the initial and final states are those in the L and H-states, and vice versa. A few oscillations in Γ_{out}, which precede the transition, are seen in Fig.4. This illustrates that the L to H-mode transition takes place, passing through the ELMy-H state.

5. Giant ELMs

As the transient response of H-states, the model of the giant ELM is developed. This giant ELM is owing to the pulsive change in Γ_{in} caused by the ballooning instability. The magnetic shear is strong near the edge and mode can become unstable inside of the transport barrier($x \lesssim -\Delta$). The dynamics of the ballooning mode near the critical beta is studied, and the pulsive growth and decay of the perturbation is shown[6]. This enhanced loss process within the finite radial extent is modeled by the superposition of an additional diffusivity, D_{add}, to D in the region $x_1<x<x_2\lesssim-\Delta$ for the time interval of $t_1<t<t_2$. $x_{1,2}$ and t_2-t_1 are treated as parameters in this article.

When the magnitude of D_{add} exceeds a certain threshold for given x_1 and x_2, the flux impulse caused by the local flattening of the density in $x_1<x<x_2$ region destroys the edge H-states for a short period, and generates the large pulse in Γ_{out}.(Fig.5) The delay of the burst in Γ_{out} is some fraction of the period of ELMy-H oscillation. The existence of the threshold in D_{add} may explain the experimental observation that the MHD perturbation must exceed a certain magnitude to cause the giant ELM.[7].

6. Summary

The theoretical model of ELMs are developed as the extension of the bifurcation model of the H-mode. A self-generated oscillation of the density n and the loss flux Γ_{out} is found. We identify the parameter ranges for three states and attribute them to L-, H- and ELMy-H modes. The dynamic responses of the states to external perturbations in the influx from the core are investigated. The occurrences of the mode locking to an applied frequency and of the transition triggered by the impulse are shown. The model of the giant ELM is also presented. These analyses provide the basis to explore the method to control the ELMs in future experiments.

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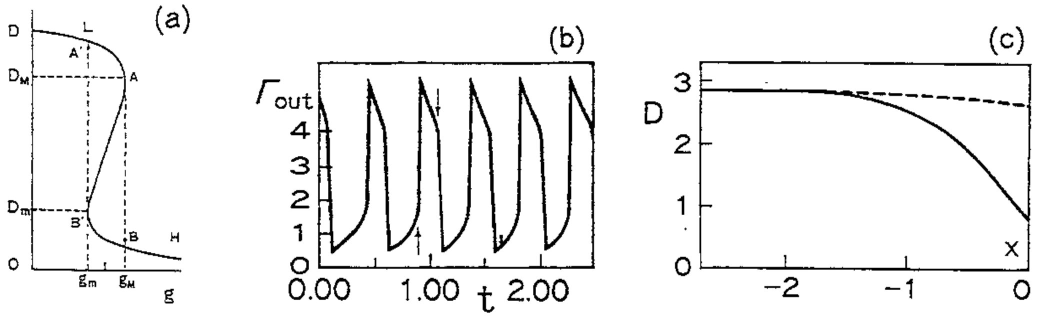

Fig.1 Model of effective diffusivity D as a function of the gradient parameter g (a). ($\alpha=\beta=1$, $D_{max}=3$, $D_{min}=.01$, $g_0=1.$) See text for definitions. Temporal evolution of the outflux from the plasma surface (b). ($\alpha=\beta=0.2$, $\mu=1$, $\Gamma_{in}=3$, $\lambda(0)=4/5.$) Spatial profile of D is shown at the high-confinement (solid line) and low-confinement (dashed line) phases (c). Δ is $\sqrt{2}$ in this case. (See arrows in (b) for specification of the time.)

Fig.2

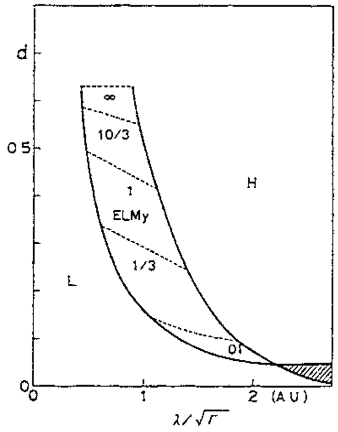

Fig.3

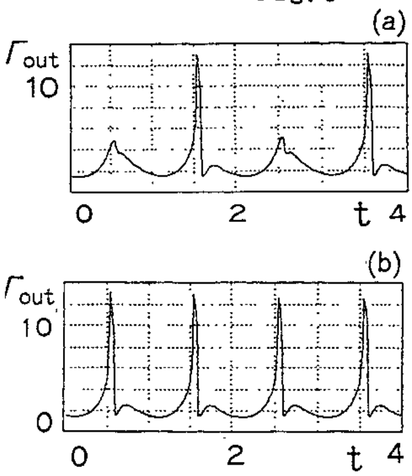

Fig.2 The regions of L-, ELMy H-, and H- modes are shown in the d-$\lambda(0)/\sqrt{\Gamma_{in}}$ plane. Bistable region where both H- and L-mode can appear is shown by the shaded area. Dotted lines indicates the normalized frequency of ELMy oscillation.

Fig.3 Driven oscillation in $\underset{\sim}{\Gamma}_{out}$ by the external oscillation in Γ_{in} ($\Omega=2\pi$). $\lambda(0)=1$, $\Gamma_{in,0}=3$, $\tilde{\Gamma}=5.5$ (a) and 6.0 (b). Period doubling (a) and mode-locking (b) are observed.

Fig.4

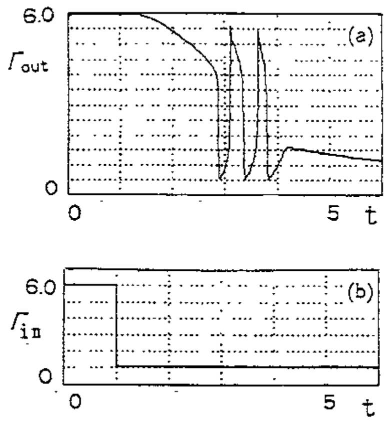

Fig.5

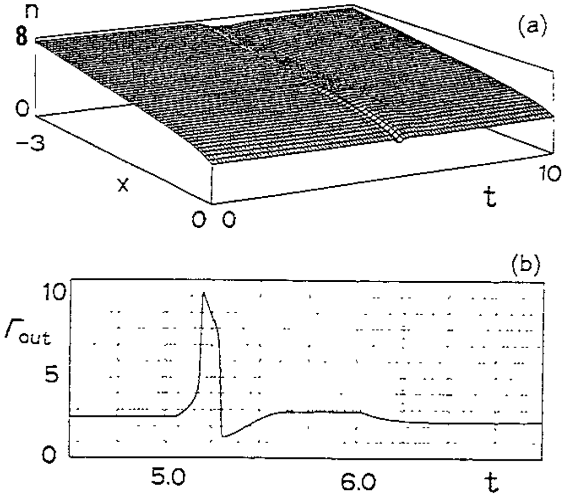

Fig.4 Transition from L to H-states are induced (a) by the sudden change of the flux Γ_{in} (b). A few ELMy oscillation precedes the H-phase.

Fig.5 Giant ELM is generated by the pulsive increase of D_{add}. ($x_1=-2$, $x_2=-1$, $t_1=5$, $t_2=6$, $D_{add}=3.0$) $\Delta=\sqrt{2}$. Local flattening of n causes the pulsive out flux.

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