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ELMy-H mode as Limit Cycle and Chaotic Oscillations in Tokamak Plasmas

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abstract

A model of Edge Localized Modes (ELMs) in tokamak plasams is presented. A limit cycle solution is found in the transport equation (time-dependent Ginzburg-Landau type), which a has hysteresis curve between the gradient and flux. Periodic oscillation of the particle outflux and L/H intermediate state are predicted near the L/H transition boundary. A mesophase in spatial structure appears near edge. Chaotic oscillation is also predicted.

Edge Localized Modes (ELMs) are a regularly observed phenomena characterized by the sudden drop of the edge density/temperature with a burst of particle/heat during the H-phase in tokamak plasmas[1]. When the density/temperature near the plasma edge exceeds a certain threshold value, an L- to H- mode transition takes place.[2] The ELMs have shown a variety of appearances and appear in a some restricted parameter space of the H phase. They are the single ELM[1,3,4], big/small ELMs or grassy ELMs associated with a quasi-periodic oscillation of H_α bursts[5], and their mixtures.[1,3-7] Their phenomenological characterization has recently been begun in experiments[3,5]. Among them, the H-mode with small and frequent ELMs is a candidate for standard operation in future experimental tokamak reactor. Research to obtain the ELMy-H mode by an external control (e.g., EML in JFT-2M tokamak[7]) is an urgent task. However, key physical mechanisms for discriminating various kinds of ELMs are not yet known.

Regarding the periodic oscillations of ELMs, giant-ELMs and small-ELMs have a similar ratio between the period of the ELM and the duration of each burst, which is of the order of 10, and the associated energy loss ratio is also of the order of 10[4,8]. In grassy-ELMs[5,6], a different type of oscillation has been observed. The period and duration of the burst have similar values as is shown in Fig.1. The grassy ELMs, which we analyse here, only appear near the L/H transition boundary[7].

A comparison with critical-β analysis due to the MHD ballooning mode[3,5] has been applied to explain the ELMs. The analyses have shown that the onset of some ELMs occurs far below the critical pressure gradient. Resistive MHD analysis[3] of a surface peeling mode may partly explain ELMs, however the assumed current/pressure profiles are not yet experimentally identified. Futhermore, there remains a question for MHD models why the structure of associated fluctuation/transport is insensitive to the surface q value and current profile. The period and duration of the grassy ELMs are left unsolved in MHD analysis.

A model of ELM as a cyclic oscillation between L and H phases due to impurity accumulation has been proposed[9]. Up to now, however, the impurity accumulation is considered to be the associated phenomena[3,10]. Characterization and classification of ELMs based on the theory have not been done.

In this paper we propose a more complete model of grassy-ELMs (see Fig.1). The L/H transition has been observed to have a hysteresis curve between the thermodynamic forces,(e.g., the density/temperature gradients) and associated flows.[2,3] Previous theories[11,12] have predicted the sudden L/H transition associated with the radial electric field change. Experimental observations[13-15] during the L/H transition confirmed the structural changes in poloidal rotation and radial electric field. The theories of Ref(11,12) are extended to include the temporal evolution and the spatial diffusion. The newly obtained equations for the edge density and the radial electric field are of the time-dependent Ginzburg-Landau type, which contains the solution of a limit cycle oscillation. This oscillation is attributed to be one class of grassy-ELMs. A model S-curve is employed in the phase diagram of the density gradient and the particle flux. The internal structure is obtained and shows the existence of an intermediate state (mesophase) of L and H phases near the edge region. We assume a uniform temperature, since the ELMs discussed in this paper are experimentally insensitive to the heating power.

Model equations consist of the radial transport equations for the density n with the effective diffusivity D, and for the normalized radial electric field (or poloidal rotation) Z with the viscous diffusivity μ. The value of D can be multi-valued and is a function of Z. The equations contain a force, which is a nonlinear function of the density gradient and are given by

$$\frac{\partial n}{\partial t} = \frac{\partial}{\partial x} D(Z) \frac{\partial n}{\partial x} \qquad (1)$$

$$\varepsilon \frac{\partial Z}{\partial t} = -N(Z;g) + \mu \frac{\partial^2 Z}{\partial x^2} \qquad (2)$$

The nonlinear operator N is proportional to the radial current $\Gamma_e - \Gamma_i$, which arises from ion orbit loss, drift wave convection and ion parallel viscous damping. Solutions Z(g) in L and H phases are given by N(Z;g) =0 ($g \propto \rho_p n'/\nu n$; ρ_p is the ion poloidal gyroradius and ν is the ion collisionality.)[11,12], which show the transition between multiple states. The parameter ε indicates a small coefficient showing that Eq.(2) has a faster time scale than Eq.(1) when μ and D have similar magnitude. The curve of N(Z,g)=0 for the given value of g_0 is shown in Fig.2. The large D and the small D branches correspond to the L and the H states, respectively. In the zero-dimensional analysis, the transition from L to H or H to L occurs at certain values of g ($A \to B$ [$L \to H$] or $B' \to A'$ [$H \to L$]). The radial and temporal structure $Z(x,t)$ is obtained here.

To model the dynamics of the L/H transition, we use the simple S-curve of N and D as

$$N(Z,g) = g - g_0 + [\beta Z^3 - \alpha Z]$$

$$D(Z) = (D_{max} + D_{min})/2 + [(D_{max} - D_{min})/2] \cdot \tanh Z$$

In writing explicit forms of N and D, we normalize x in ρ_p, D and μ in D_0 (which are typical values in the L-phase), t in $\rho_p{}^2/D_0$, and flux Γ in $D_0 n_0/\rho_p$. The normalizing density n_0 is chosen so as to satisfy $g_0=1$. $\varepsilon \simeq (\rho/\rho_p)^2$ (ρ is the ion gyroradius)[16]. In the following, we use the normalized variables. μ/D_0 is the diffusion Prandtl number P_D. Parameters g_0, α, β, D_{max}, D_{min} and μ/D_0 are treated as constant.

We numerically solve Eqs.(1) and (2) assuming that $\varepsilon \ll 1$. Actually, we here take a simple condition that $\partial Z/\partial t = 0$ ($\varepsilon = 0$) to solve the temporal evolution of the density. Equation (2) is a kind of time dependent Ginzburg-Landau equation or the one which is used to analyse the reaction diffusion system in chemical reactions. The system contains so-called slow manifold structure due to the assumption with respect to the time scales.

The slab region near the plasma edge, $-L<x<0$, is our interest. As the boundary conditions, at the plasma edge (x=0), we impose the constraint that $(n'/n)^a n^b$ is fixed. We discuss the case of a=1 and b=0. At the core side (x=-L), we give the particle flux Γ_{in}.

Solving Eqs.(1) and (2) with $\varepsilon=0$ we find the state with the periodic oscillations of the edge density n_s and the loss flux Γ_{out} in the restricted parameter space near the boundary of the L and H phases. The flux Γ_{out} is defined at x=0. In Fig.3, the temporal evolutions of Γ_{out} (a), which corresponds to the H_α burst, and the Lissajous figure of n_s and Γ_{out} (b) are shown. The parameters are; $g_0=1$, $\alpha=0.2$, $\beta=0.2$, $D_{max}=3$, $D_{min}=0.1$, $\mu=1$, $\Gamma_{in}=1.25$ and $\lambda_s(\equiv -n/n'$ at the edge$)=1$.

These oscillating solutions are possible in the intermediate regime between L and H phases, and are attributed to ELMy-H mode. The time averaged density is between that in L phase and that in H phase. The parameter space where the ELMy-H mode appears is found to be

$$D_m/(g_m \lambda_s) < \Gamma_{in} \lambda_s < D_M/(g_M \lambda_s), \qquad (3)$$

where $g_m = g_0 - 2\beta(\alpha/3\beta)^{3/2}$, $g_M = g_0 + 2\beta(\alpha/3\beta)^{3/2}$, $D_m = D(Z=\sqrt{\alpha/3\beta})$ and $D_M = D(Z=-\sqrt{\alpha/3\beta})$ and $\lambda_s \propto g^{-1}$, as shown in Fig.2. In this parameter regime, the cross-over point of the hysteresis curve and the g value at the edge becomes unstable and the limit cycle solution on the g and D plane (see Fig.2) appears. When Γ_{in} is large so as to satisfy $\Gamma_{in}\lambda_s^2 > D_M/g_M$ we find the stationary L state ; and the H state with steep density gradient is found in the region

$\Gamma_{in}\lambda_s^2 < D_m/g_m$. Therefore the ELMy-H state found here is the mesophase of L and H phases. If the condition $D_m/g_m > D_M/g_M$ holds, no oscillation is allowed.

The existence of the mesophase of the L and H phases is seen in the radial structure of the density and the effective diffusion coefficient D. In Fig.3 (c) and (d), their radial structures are shown at the times of high and the low confinement. A transport barrier is formed in a phase of rising density. A smooth curve of D is formed due to the finite viscosity μ[17]. The thickness of the barrier, Δ, is estimated as $\Delta \simeq \sqrt{2\beta\mu/\alpha}$ in the small μ limit. Numerical calculation gives $\Delta \propto \mu^{0.44}$, confirming this analysis. (L satisfies $L \gg \Delta$, so that Δ is not limited by the computation region.) In this region, there exists the poloidal rotation. The radial width Δ is different from the width of the density inversion region.

We study the parameter dependence of the period τ of the oscillation. The numerical computation gives $\tau \simeq C\alpha\lambda_s\Delta D_M^{-1}$ where C is a numerical coefficient of the order of unity. As is shown in Eq.(3), λ_s is bounded in a narrow region to realize the oscillation. If the ratio λ_s^2/D_M and other parameters are fixed, we have $\tau \propto D_M^{-0.5}$ over a wide range. On the other hand, if the value of $\Gamma_{in}\lambda_s^2$ and other parameters are fixed, we have $\tau \propto \Gamma_{in}^{-0.5}$.

The ratio of the time interval of good confinement (τ_H) to τ, $\eta = \tau_H/\tau$, represents how close the intermediate state is to the H-mode. (In the H-mode, $\eta=1$; $\eta=0$ for the L-mode). In the parameter space predicted by Eq.(3), η takes intermediate values between one and zero. η is a decreasing function of $\Gamma_{in}\lambda_s^2$, and is discontinuous at the boundaries D_m/g_m and D_M/g_M. For oscillating solutions, η takes its largest value η_{max} at $\Gamma_{in}\lambda_s{}^2 = D_m/g_m$. η_{max} increases and approaches unity if D_m becomes close to D_{min}. This is confirmed by reducing D_m to D_{min} by fixing g_m. For instance, by taking $\alpha=0.2$ and $\beta=\alpha^3$, η can be greater than 0.95, i.e., the period is 20 times longer than the pulse width. In other words, the H-ness depends on the transition structure.

This model with $\varepsilon=0$ produces the periodic birth and decay of the transport barrier and associated bursts of the outflux from the plasma surface. For the case of $\varepsilon\neq0$, another time scale is introduced in the solutions of Eq.(1) and (2). Chaotic as well as intermittent appearances of the bursts are predicted. When we introduce the neutral particle effect to Eq.(1) as a random noise, we also observe the intermittent state and the chaotic appearances depending on its noise level. Details of these effects will be discussed in a separate article.

In summary, the theoretical model of ELMs are developed by extending the bifurcation model to the time-dependent diffusive media. A time-dependent Ginzburg-Landau model equation with the spatial diffusion is applied. A periodic solution of the plasma density and outflux is found revealing a sequence of bursts of plasma loss. The mesophase is found near the plasma boundary. The width of the transport barrier was found to be proportional to $\sqrt{P_D}$. This model reproduces the oscillations in which the decay time of the loss and period are comparable. The region of this nonlinear oscillation is identified in the parameter space; oscillations appear near the H/L mode boundary. These features are consistent with experimental observations of the grassy-ELMs. The parameter dependences of the period and "H-ness" η are studied to identify the intermediate state. The finite diffusion time of the electric field leads to chaotic oscillations. Fluctuations in the source flux or external oscillations also cause additional chaotic oscillations of n, Γ_{out} and E_r.

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Figure Captions

Fig.1 Time trace of the H_α intensity of the grassy H-mode in the JFT-2M tokamak. H_α is given in arbitrary units. For details of the discharge conditions, see Ref.[7].

Fig.2 Model of effective diffusivity D (i.e., ratio of the particle flux to the density gradient) as a function of gradient parameter g. See text for the definition and normalization. (α=1, β=1, D_{max}=3, D_{min}=0.1, g_0=1).

Fig.3 Temporal evolution of the outflux(a) and the Lissajous figure between the edge density and the outflux(b). Parameters are μ=1, Γ_{in}=1, λ_s=1.25, and others are the same as in Fig.2. Spatial profiles of density (c) and diffusivity (d). Time slice is denoted by arrows in (a). Solid and dashed lines show before the burst and end of the burst, respectively.

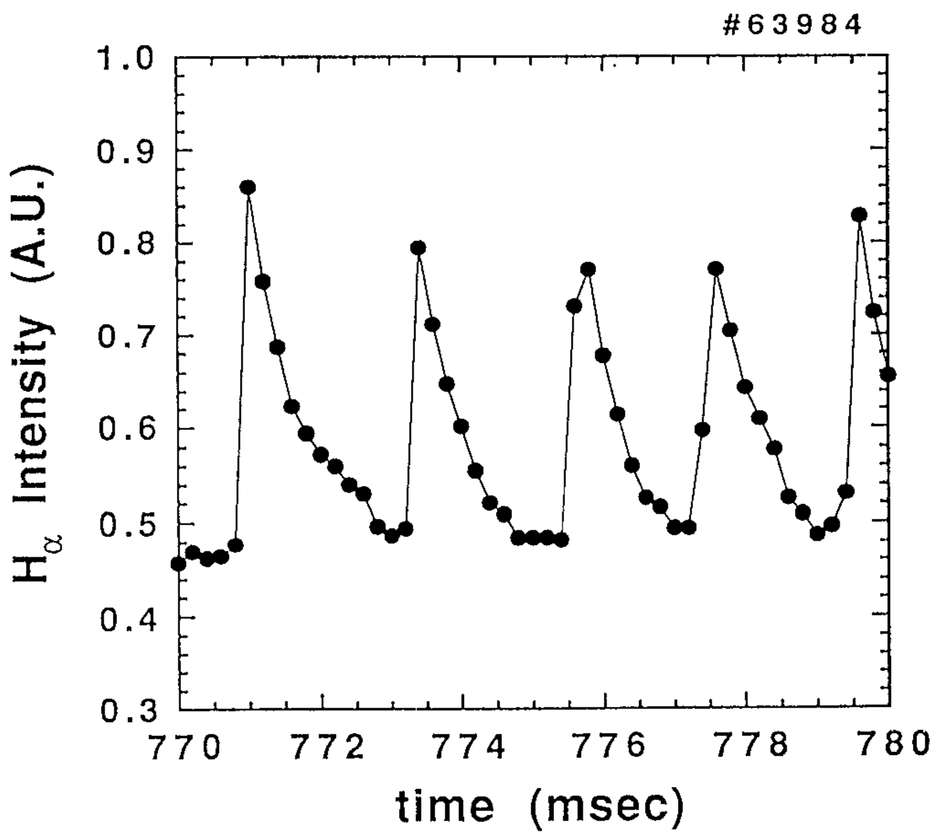

#63984
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
H_α Intensity (A.U.)
770
772
774
776
778
780
time (msec)

Fig. 1

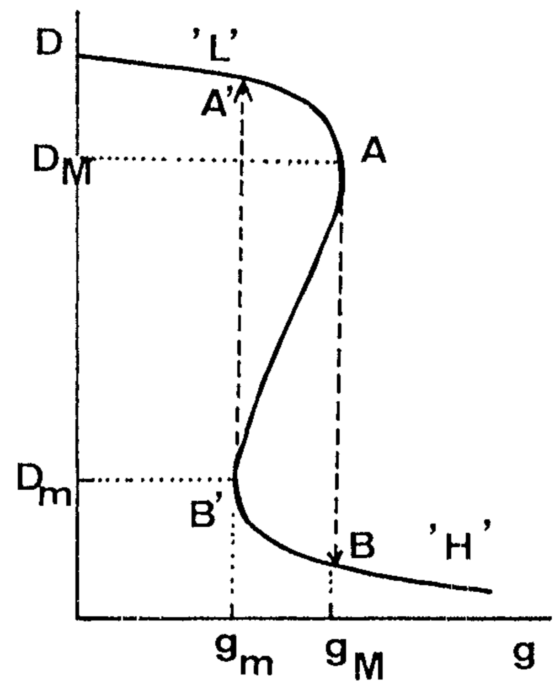
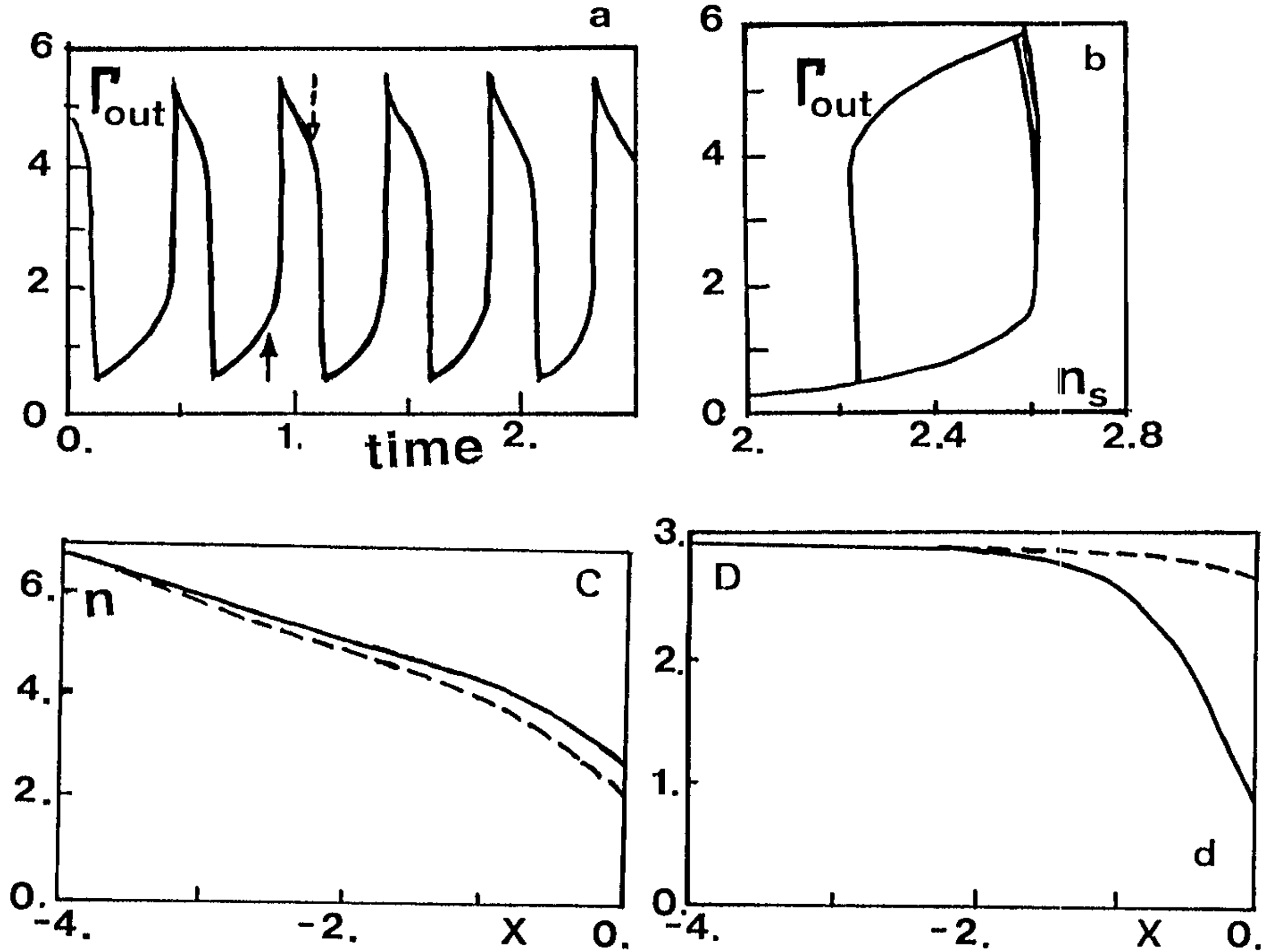

D
'L'
A'
D_M
A
D_m
B'
B
'H'
g_m
g_M
g

Fig.2


a
6
4
2
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0.
1.
time
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b
6
4
2
0
Γ_{out}
n_s
2.
2.4
2.8
C
n
6.
4.
2.
0.
-4.
-2.
X
0.
D
d
3.
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1.
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Fig.3

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