Theory of Dynamics in Long Pulse Helical Plasmas

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Abstract: Self-organized dynamics of toroidal helical plasma, which is induced by the nonlinear transport property, is discussed. Neoclassical ripple diffusion is a dominant mechanism that drives the radial electric field. The bifurcation nature of the electric field generation gives rise to the electric field domain interface, across which the electric field changes strongly. This domain interface is an origin of internal transport barrier in helical systems. This nonlinearity gives rise to the self-organized oscillations; the electric field pulsation is one of the examples. Based on the model of density limit, in which the competition between the transport loss and radiation loss is analyzed, dynamics near the density limit of helical systems is also discussed.

1. Introduction

In "steady-state" plasmas, plasma parameters evolve into self-regulated dynamical states, often being associated with self-organized oscillations [1]. In long plasma discharges, plasmas exhibit the features which are controlled by the nonlinear transport property, being free from the initial conditions. Such a property is the central issue of the physics of steady state plasmas. An example is the self-organized dynamics of the internal transport barrier of high-β_p tokamaks, in which the toroidal current is almost completely sustained by the Bootstrap current [2]. The nonlinear transport drives, in one hand, the transition causing the spatial interface between two different radial domains. On the other hand, it induces the temporal evolution, i.e., the self-organized dynamics. The bifurcation of transport property, which generates the transport barrier like H-mode, gives rise to the self-organized dynamics like dithering ELMs [3]. In this article, physics of domain interface, barrier and self-organized dynamics is discussed for toroidal helical plasmas, from the generic view point of theory and modelling.

2. Model

A simple set of transport equations is taken in order to study the dynamics of helical plasmas. The electron density n , temperature T , and radial electric field E_r are chosen as parameters that characterize the plasma state. The dynamical model consists of the particle balance equation, the equation of momentum or radial electric field, and the equation for temperature, as

$$dn/dt = -\nabla\Gamma_r + S_p, \qquad (1)$$

$$dE_r/dt = \nabla_\perp\mu_v\nabla_\perp E_r - \hat{J}_r, \qquad (2)$$

$$d(nT)/dt = -\nabla q_r - P_{rad}/(3V) + P_{abs}/(3V). \qquad (3)$$

Transport relations between plasma parameters and fluxes Γ_r , q_r , and $\mu_\perp\nabla_\perp E_r$ are nonlinear function of plasma gradient as shown in, e.g., [1]. The particle sources S_p, radial current $\hat{J}_r$, energy input source P_{abs}, and radiation loss P_{rad} play the role of source terms in this dynamical system. The magnetic field is assumed to be constant in time. This simplification excludes the self-organized dynamics like the one of ref.[2] in improved confinement state, but is relevant for low-β helical plasmas. The system of these equations allows a variety of dynamical solutions being associated with transport barrier.

In helical systems, the neoclassical ripple transport could play a dominant role in the term $\hat{J}_r\left[E_r\right]$. Bifurcations of electric field and transport have been studied. The electric field interface, across which radial domains with different electric field polarity touch, has been predicted as a possibility for the internal transport barrier.

The particle flux associated with the helical-ripple trapped particles is employed after [4] in order to have an analytic insight as

$$\Gamma^{NC} = n\,D_j \left\{1 + C_j a^2 e^2 E_r^2 T_e^{-2}\right\}^{-1} \left(-n'\,n^{-1} + eE_r\,T^{-1}\right) \tag{4}$$

with $D_j = 24\varepsilon^2 \varepsilon_h^{1/2} \nu_j^{-1} v_D^2$ and $C_j = 36\,\varepsilon^{1/2} \varepsilon_h^{-1/2} T_e^2 \left(\nu_j r B e a\right)^{-2}$. Notation is as follows: $\varepsilon = r / R$ is the inverse aspect ratio, ε_h is the helical ripple, $v_D = T/eRB$ is the toroidal drift velocity, ν is the pitch-angle collision frequency, r is the minor radius, R is the major radius, a is the plasma minor radius, and the prime $'$ denotes the radial derivative d/dr, and suffix j denotes species (e, i). The coefficient C_e is small and is neglected. Hence the neoclassical electron energy flux is expressed in the regime of ripple diffusion as

$$q_a^{NC} = -\,a^{-1} n T_e\,D_e \gamma_e \left(an'\,n^{-1} + aeE_r\,T_e^{-1} + \eta_{22}\,aT_e'\,T_e^{-1}\right) \tag{5}$$

where coefficients $\gamma_e \simeq 5$, $\eta_{22} \simeq 4.5$ and $\eta_{12} \simeq 3.5$ are numerical constants. The total flux is given as a sum of the neoclassical flux and anomalous flux. The particle and electron energy fluxes are put as

$$\Gamma_{tot} = \Gamma^{NC} - D_{anom}\,n' \tag{6}$$

$$q_{e,\,tot} = q_e^{NC} - \chi n T_e' \tag{7}$$

3. Domain Interface

The bifurcation is studied by solving the stationary solution of Eqs.(1)-(3) for the circumstance of the ECH plasmas. Figure 1(a) illustrates the normalized radial electric field $X = \sqrt{C_i}\;eaE_r/T_e$ and normalized temperature gradient $Y = \pm\sqrt{C_i}\eta_{22}\,aT_e'/T_e$ as a function of the normalized radial energy flux $Q_t = \sqrt{C_i}\,\left(\frac{n}{a} D_e \gamma_e T_e\right)^{-1} q_{e,\,tot}$. (In the case of ECH plasma, density gradient is much weaker than the temperature gradient, and we employ the simplification of $Y >> \left| an'/n \right|$.) At critical energy flux, the electric field jumps to a higher branch on which the neoclassical energy diffusion is much smaller. The transition between two branches takes place at the critical heat flux Q_t^* , at which the Maxwell's construction rule is satisfied,

$$\int_{X_1}^{X_2} \left\{\Gamma_i^{NC} - \Gamma_e^{NC}\right\} dX = 0 \tag{8}$$

where X_1 and X_2 are two stable solutions of the equation $\Gamma_i^{NC}\left(X\right) - \Gamma_e^{NC}\left(X\right) = 0$.

Depending on the magnitude of anomalous transport and the electron-to-ion temperature ratio, the transition could be a soft transition. Figure 1(b) illustrates a soft bifurcation. Figure 2 illustrates the parameter region where the hard transition is possible to occur.

Analyses of Figs.1 and 2 are applied to understand the radial structure.

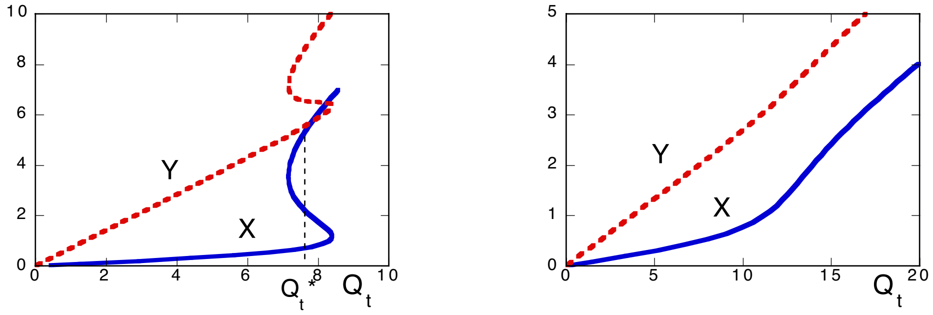

Fig.1 Radial electric field X (solid line) and temperature gradient Y (dashed line) as a function of the heat flux. ($T_e/T_i = 2$, $D_e/D_i = 0.26$, $b = 7/9$, $\chi_a = \chi/\eta_{22}D_e\gamma_e = 0.5$; case (a)) and that for soft transition ($T_e/T_i = 3$, $D_e/D_i = 1.09$, $b = 7/9$, $\chi_a = 3$; case (b)).

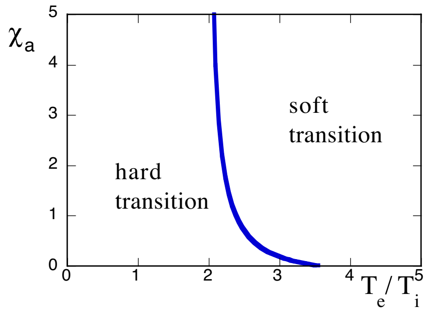

Fig.2 Region of hard transition is illustrated. ($\chi_a = \chi/\eta_{22}D_e\gamma_e$ denotes the normalized anomalous thermal transport coefficient.) Mass ratio is chosen as $m_i/m_e = 1836$. Below this critical line, hard transition can take place.

For a fixed central heating power, the normalized heat flux Q_t is a function of radius. The higher Q_t denotes the inner region and the lower Q_t indicates the outer region. On the magnetic surface where

$$Q_t = Q_t^* \tag{9}$$

is satisfied, the domain interface for radial electric field exists. (Inside of this radius, the electric field is on the 'electron branch' and outside is on the 'ion branch'.) Across this domain interface, the radial electric field changes noticeably, so as to induce a large electric field inhomogeneity. The internal transport barrier (ITB) is established if the inhomogeneity is strong. This models the ITB formation in CHS [5]. Application to LHD plasma is discussed in [6].

4. Dynamics of Barrier

The normalized electron energy flux has a dependence $Q_t \propto q_{e,\,tot} T_e^{-4.5}$. Therefore, the normalized heat flux is perturbed in the presence of temperature modulation $\delta\hat{T}$ as

$$Q_t \simeq \left(1 - 4.5\,\delta\hat{T}\right) Q_{t0} \tag{10}$$

Change of temperature $\delta\hat{T}$ and that of electric field δX are related as $\delta\hat{T} \simeq \delta X$ through

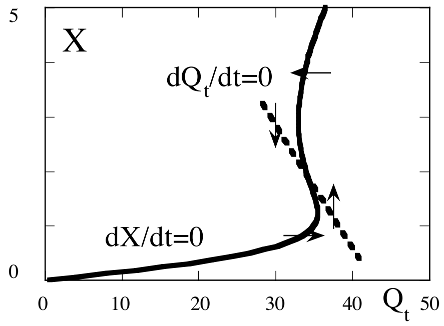

Fig.3 Radial electric field X as a function of the heat flux. Solid and dashed lines indicate $\partial X/\partial t = 0$ and $\partial Q_t/\partial t = 0$, respectively. Self-generated oscillation is possible.

the relation of $Y = \left(1 + \chi_{anom}\right)^{-1}\left(Q_t + X\right)$. Substitution of the approximation $\delta\hat{T} \simeq \delta X$ into Eq.(9) gives an estimate

$$Q_t \simeq \left(1 - 4.5\,\delta X\right) Q_{t0} \qquad (11)$$

where Q_{t0} is the unperturbed value. Figure 3 illustrates the flow diagram in the $\left(X, Q_t\right)$ space. The solid line shows the condition $dX/dt = 0$ and the dashed line indicates $dQ_t/dt = 0$. The cross-point is a fixed point. If the heating power is chosen as appropriate value, the fixed point could be an unstable fixed point. The limit cycle oscillation is possible to occur. This is a model of electric field pulsation which has been found in CHS [5].

The edge transport barrier is also studied. The self-organized oscillation takes place for the edge transport barrier for helical plasmas [7]. The 1-D transport equations (2) and (3) are solved for edge plasma (fixed density). A simple model of transport coefficient is employed as $\chi = \chi_0/\left(1 + X^2\right)$, in order to model the influence of strong localized electric field. An edge transport barrier is established if the heat flux exceeds a critical value. In the vicinity of the critical heat flux, the repetitive establishment and decay of the barrier occur, as is illustrated in Fig.4. This is attributed to the dithering ELMs of helical systems.

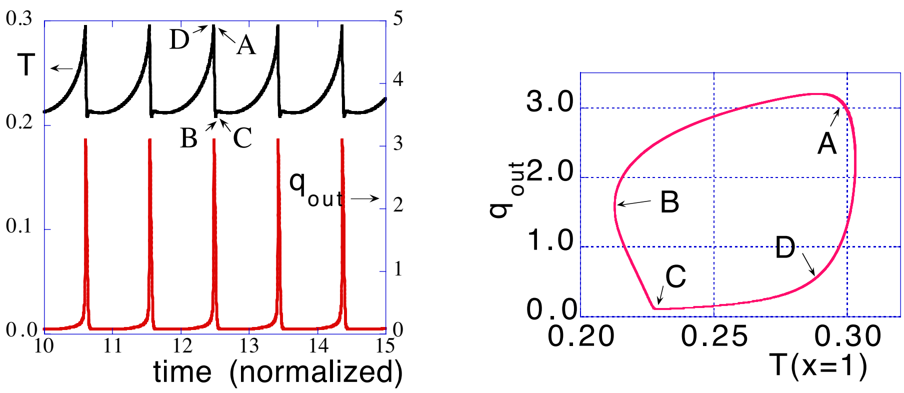

Fig.4 Temporal evolutions of edge temperature and heat flux across the edge q_{out} (left). Trajectory on the $T \pm q_{out}$ is also illustrated (right).

5. Density Limit Oscillation

In impure plasmas, the radiation loss plays an important role in the long time evolution of confined plasmas. The dependence of the radiation loss on the temperature and density, $P_{rad} = n_e n_I \left\langle L_Z(T) \right\rangle V$ with $\left\langle L_Z(T) \right\rangle = \xi\, T^{-\gamma}$, is known to cause the radiation instability, which would bound the operational density of toroidal plasmas. Combinations of transport equations also predict the self-organized dynamics near the density limit. By the growth of the symmetry-breaking perturbations, the rapid loss takes place. The critical condition for this instability is given in terms of the density and temperature as

$$Tn^{-y} \le \left(\xi q^2 R^2 n_I / 3 \chi_{\parallel 0} n_e \right)^{1/(\gamma + 3.5)}, \qquad (12)$$

where $y = 2/(\gamma + 3.5)$ and the parallel transport coefficient is assumed to have a form $\chi_{\parallel} = \chi_{\parallel 0}\, n^{-1} T^{2.5}$. When this instability occurs, the rapid plasma loss happens. By the onset of the reduction of density, the radiation collapse stops to continue, and the high temperature plasma can be recovered. This process repeats itself. This self-generated oscillation of density and radiation loss is a model of density limit oscillation in W7-AS stellarator [8].

Other possible self-organized dynamics in helical plasmas is the thermoelectric oscillation. Under the constant external heating, the absorbed power depends on the plasma parameter and electromagnetic field. This dependence causes another self-organized dynamics in helical plasmas.[9].

6. Summary

'Steady state' plasmas are often considered to be realized in confinement devices, in which the confining magnetic field is constant in time. In such plasmas, however, the nonlinear property of transport is the key for the spatio-temporal structure. The spatial domain interface is predicted to appear, being associated with the transport barrier. This mechanism, at the same time, induces the self-organized dynamics. This self-sustained dynamics is the key issue of the long-time asymptotic nature of the confined plasmas. Helical plasmas could be associated with the variety of dynamical phenomena in the absence of violent MHD activities.

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