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Fast Responses of Core Plasma to Dithering ELMs

T. Iwasaki, †S. -I. Itoh, †M. Yagi and ‡K. Itoh

Interdisciplinary Graduate School of Engineering Sciences, Kyushu University 39, Kasuga 816-8580, Japan

†*Research Institute for Applied Mechanics, Kyushu University 87, Kasuga 816-8580, Japan*

‡*National Institute for Fusion Science, 322-6 Oroshi, Toki, Gifu, 509-5292, Japan*

Abstract

A non-local transport model is applied to describe the fast propagations of the pulses induced in the edge by dithering Edge Localized Modes (dithering ELMs). A small fraction of non-local component is found to be very effective in modifying the response of the core electron temperature. A phase reversal of the perturbed electron temperature is predicted in the plasma core based on the non-local transport model.

I. Introduction

The studies of the improved confinement have been developed extensively. Although the ELMy H-mode is one of the improved confinement modes and is considered as a candidate for ITER's operational scenario, the influence of the dithering ELMs on the plasma core confinement has not been fully understood yet.

Transient responses in high temperature plasmas have been studied in a lot of fusion devices [1] to investigate the transport mechanism. Recent experiments on transient transport have shown that the effective heat diffusivity seems to change much faster than the change of the local plasma parameter. The pulses are triggered not only at the plasma core but also plasma edge. They are induced at the plasma center both externally by the heating power switching [2] and heating power modulation [3], and spontaneously by the sawtooth crash [4]. Also, they are induced at the plasma edge both externally by impurity injection [5] and spontaneously through L/H (H/L) transition [6] and ELMs [7].

It has been observed in W7-AS that when the periodic heat pulses are induced at the core plasma by the heating power modulation, the phase of the Fourier-decomposed perturbation of the electron temperature is reversed at the plasma edge [3]. This phenomenon, i.e., the phase reversal, has been explained by the non-local transport model [8], in which it is assumed that the plasma has a long range radial correlation. This model has been also applied to the power switching experiment [8], L/H (H/L) transition [9, 10] and impurity injection [11], and successfully explained the fast responses of the heat flux and electron temperature. If the plasma has a long range radial correlation, the similar phase reversal is expected to appear at the plasma core when the dithering ELMs occur at the plasma edge.

In this paper, we apply the non-local model to the dithering ELMs and study the response of the electron temperature. The fast response in the core plasma is obtained and phase reversal of the perturbed electron temperature is predicted.

II. Non-local Transport Model

In this section, we present our model and explain its properties. To investigate the transient response of the electron temperature, let us start with the transport equation for the electron temperature,

$$\frac{\partial}{\partial t}\left[\frac{3}{2}n_{\mathrm{e}}(r,t)T_{\mathrm{e}}(r,t)\right] = -\nabla\cdot q_{\mathrm{e}}(r,t) + \Sigma Q(r), \tag{1}$$

where n_{e}, T_{e}, q_{e} and ΣQ represent the electron density, temperature, heat flux and sources/sinks, respectively. The boundary conditions are set to be $q_{\mathrm{e}}(0,t) = 0$ and $T_{\mathrm{e}}(a,t) = 0$, where a is the plasma minor radius. We assume that the density is constant and uniform.

A generalized formula of the heat flux is employed as,

$$q_{\rm e}(r,t) \ = \ -\int_0^a n_{\rm e}(r',t)\chi_{\rm e}(r',t)K_l(r,r')\nabla' T_{\rm e}(r',t)dr', \tag{2}$$

where $\chi_{\rm e}$ is the heat diffusivity, K_l is the kernel which includes the non-local effect and $\nabla' \equiv \partial/\partial r'$. We assume that the anomalous transport is caused by turbulent fluctuations, whose property at r is determined by the plasma structure within the radial correlation length [12]. Then the heat flux at r could depend on the parameter at r'. If the relation eq. (2) holds, a very fast change of the heat flux is possible. The interaction of fluctuations with a short radial correlation length and those with a long correlation length ($\sim l$) is modeled into the kernel of integral. The plasma turbulence due to the nonlinear excitation [13] could be a candidate to generate very long correlated structures across the magnetic field. In this study, we choose the following expression for the kernel as an example,

$$K_l(r,r') \equiv \left(\frac{r}{r'}\right)^z \left[C_{\rm local}\delta(r-r') + C_{\rm global}\frac{1}{\sqrt{\pi}l}\exp\left\{-\left(\frac{r-r'}{l}\right)^2\right\}\right], \tag{3}$$

where l is the half width of non-local interactions, $\delta(r-r')$ is a delta function. The parameters $C_{\rm local}$ and $C_{\rm global}$ ($C_{\rm local} + C_{\rm global} = 1$) represent the ratio of the locality and the non-locality included in the transport process. In the limit of $C_{\rm global} = 0$ or of $l \to 0$, the kernel becomes the delta function and the heat flux is reduced to the local transport model, i.e., $q_{\rm e}(r,t) = -n_{\rm e}(r,t)\chi_{\rm e}(r,t)\nabla T_{\rm e}(r,t)$. The weighting function $(r/r')^z$ is introduced to ensure the condition, $q_{\rm e}(0,t) = 0$. z is a parameter that controls the symmetry of the kernel. For the finite value of z, the boundary condition is satisfied although the asymmetry of the kernel is caused. If z is taken to be small ($\ll 1$), the asymmetry of the kernel is reduced in the wide range of r' except for $r' \sim 0$. Here we use $z = 0.1$ in the following analyses. The source term, i.e., the power deposition profile, is modeled as $\Sigma Q(r) \propto P(t)\exp[-(r/r_{\rm power})^2]$, where $P(t)$ is the heating power and $r_{\rm power}$ is the width of the power deposition. In the following calculations, the major radius $R = 2.85$m, the minor radius $a = 0.95$m, the constant electron density $n_{\rm e} = 5\times10^{19}{\rm m}^{-3}$, constant heating power $P = 10$MW and the width of the power deposition $r_{\rm power}/a = 0.3$ are used. The dependences of the transient response on $C_{\rm global}$ and l/a were studied and the comparison study with the experiments were made [8]. From the parameter survey of the model equation, it is considered that $C_{\rm global} = 0.1 \sim 0.2$ and $l/a = 0.3 \sim 0.7$ are the plausible values to reproduce the various experimental results. In the following analysis, we choose $C_{\rm global} = 0.2$ and $l/a = 0.5$. For these parameters, the energy confinement time for the L-mode is 97msec, which is evaluated by the power balance of the energy transport equation.

III. Simulations of Dithering Edge Localized Modes

The response of the plasma temperature perturbation to the dithering ELM is simulated. The dithering ELM is modeled as the repetitive transitions between the L-mode and the H-mode via the periodical change of the diffusivity profile. In this study, the diffusivity profile is modeled as $\chi_{\rm e}(r) = 2q^2(r)$ for the L-mode and $\chi_{\rm e}(r) = 2q^2(r)(0 \le r/a \le 0.8)$, $\chi_{\rm e}(r) = 2q^2(r)[20(r/a-1)^2 + 0.2](0.8 \le r/a \le 1)$ for the H-mode, where the profile of the safety factor is chosen as $q(r) \equiv 1 + 2(r/a)^2$. These diffusivity profiles for the L- and H-mode are shown in Fig. 1(a). The steady state temperature profiles for the L- and H-mode are shown in Fig. 1(b) corresponding to the diffusivity profiles. When the dithering ELMs occur at plasma edge, then modulated pulses of temperature propagate to the plasma center. The frequency of the ELMs, f, is set to 50Hz if it is not specified, where it is assumed that the duration time in H-mode is $0.8f^{-1} = 16$msec and that in L-mode is $0.2f^{-1} = 4$msec. (Dependences of duration time on amplitude and phase are also investigated and it is found that it does not change simulation results qualitatively.)

Responding to the ELMs, the core electron temperature profile is modulated. In this simulation, we choose an initial condition $T_{\rm e}(r,0)$ as the stationary solution of the energy

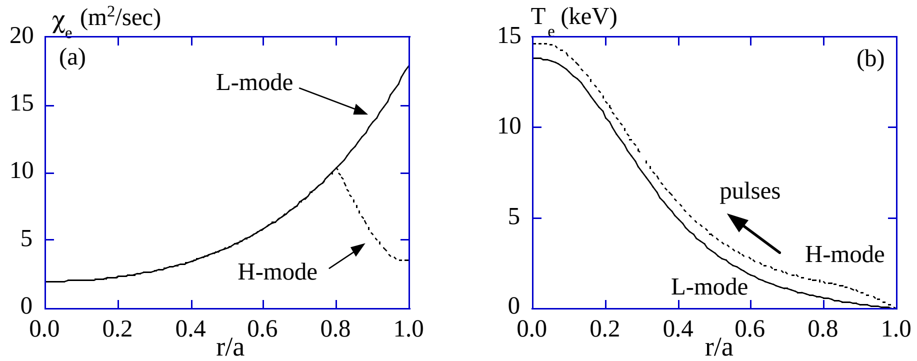

Figure 1: Radial profile of (a) diffusivity and (b) temperature for H- and L-mode.

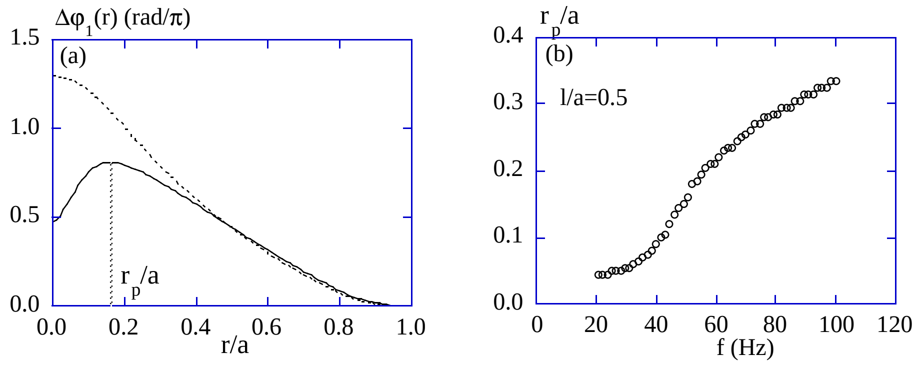

Figure 2: (a) Radial profile of phase difference for $f = 50$Hz. The solid line and dotted line correspond to the non-local model for $l/a = 0.5$ and local model, respectively. r_p/a is the position of the phase reversal. (b) Position of phase reversal as function of ELMs frequency.

transport equation with the L-mode diffusivity and power deposition, and the temporal evolution is calculated until the stationary oscillation is attained. The perturbation of the temperature, $\Delta T_{\rm e}(r,t)$, is Fourier-decomposed as,

$$\Delta T_{\rm e}(r,t) = \sum_{k=0}^{\infty} a_k(r) \sin\left[2\pi k f t - \varphi_k(r)\right], \tag{4}$$

where $a_k(r)$ and $\varphi_k(r)$ are the amplitude and phase of k-th Fourier harmonics at r. The phase difference is defined as, $\Delta\varphi_k(r) = \varphi_k(r) - \varphi_k(a)$ which represents the time delay of the periodical pulsive modulation. Figure 2(a) shows the profile of the phase difference for the fundamental harmonic. The solid line and dotted line correspond to the solution of the non-local model for $l/a = 0.5$ and local model, respectively. The clear difference is seen in Fig. 2(a). In the case of the local model, the phase difference increases monotonically from the edge to the center, which means that the pulse propagates diffusively from the edge to the center. On the other hand, the phase difference is reversed in the plasma center in the case of the non-local model. The electron temperature in the central region is affected by the ELMs faster than that in the middle region. The higher components of the phase difference have the same characteristics as fundamental harmonic although the absolute values vary.

Next, the phase reversed position, r_p/a, defined as the position that the phase difference has the maximum value, is shown in Fig. 2(a). The finite value of r_p/a corresponds to the appearance of the phase reversal, which means that the non-local or nonlinear long range correlation significantly affects the core plasma in the response to the dithering ELMs. Figure. 2(b) shows the dependence of the phase reversed position (r_p/a) on the ELMs frequency (f) for $l/a = 0.5$. The phase reversed position shifts to the plasma edge with an increase of the ELMs frequency. The phase reversal is affected by the non-local correlation length, l/a. If the profile of the phase difference is measured at certain ELMs frequency in an experiment, the non-local correlation length can be estimated within the framework of our non-local model. It is noted that the reversed phase difference has been observed in the plasma edge in the response to the central heating power modulation in W7-AS [3]. The non-local model has been applied and the reversed phase has been explained [8]. Ever for the case with the different physical mechanism and the propagation direction, our non-local model predicts the appearance of reversed phase in the core plasma due to the edge dithering ELM.

IV. Summary and Discussion

In this paper, the non-local transport model was applied and the response of core plasma to the events induced by the dithering ELMs was analyzed.

New feature was found in the simulation of the dithering ELMs. In the Fourier-decomposed perturbation of the temperature, the reversed phase is predicted to occur in the plasma center. The electron temperature in the central region is affected by the ELMs faster than that in the middle region. The possibility of the estimation of the non-local correlation length was discussed. If the profile of the phase difference is measured in an experiment, the non-local correlation length can be estimated by comparing the experimental measurements with the simulation results. It is noted that the reversed phase difference has been observed [3] and explained by our non-local model [8]. For the case with the different physical mechanism and the propagation direction, our non-local model predicts the appearance of reversed phase in core due to the dithering ELM. The reversed phase difference can be the index of the fast response for the periodic perturbation.

The non-local model reproduces the fast transient phenomena independent of the trigger mechanism and diffusivity models [8, 9, 10, 11]. Our method provides a general model, by which various types of transient phenomena could be explained in a unified way.

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