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One-dimensional dynamical analysis of detached divertor plasmas
非接触ダイバータプラズマの1次元動的解析

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Plasma operation with detached divertors is considered to be a promising way to resolve this issue of divertor heat load reduction. However, transient characteristics of the detached divertor plasma have not been studied yet. The edge localized mode can cause temporally changing cross-field heat and particle inputs from the core to the scrape-off-layer. Even in such a situation the plasma should be kept detached and re-attachment onto the divertor should be avoided. In this presentation we report extensions of our recent one-dimensional analysis of detached divertor plasmas. We investigate response of the detachment fronts propagating upstream to the temporally changing heat and particle inputs.

1. Introduction

Reduction of divertor heat load is a crucial issue for next generation fusion devices such as ITER and DEMO. Plasma operation with detached divertors is considered to be a promising way to resolve this issue. For example, a partially detached divertor regime will be one of the ITER operation senarios [1] and has been used for the design of the DEMO reactor Slim-CS [2]. However, the plasma operation with divertor detachment involves an issue that should be resolved; detachment fronts of plasma parameters, e.g. density, temperature and particle and heat fluxes, should be ”captured” in a divertor region. Otherwise, cold neutrals and impurities would be transported upstream and cool a core plasma region. It is, therefore, crucial for divertor heat handling to elucidate characteristics of the detachment fronts.

Stability and propagation of the detachment fronts have been studied by some researchers so far. For example, Krasheninnikov et al. have found that the detachment front is thermally destabilized when $Q_{\mathrm{H}} < Q_{\mathrm{rec}}$ where Q_{H} is the total power input which can reach a recombination region of a divertor plasma and Q_{rec} is the power sink due to recombination [3]. A similar power balance condition was found independently by one-dimensional (1D) plasma fluid simulations by Nakazawa et al [4]. They also analyzed time-dependent behavior of the detachment fronts. They successfully simulated propagation of the fronts of the plasma density and temperature toward upstream. In these studies, the cross-field particle and heat inputs from the core to the scrape-off layer (SOL) region were assumed to be spatially uniform and temporally constant. Recently, Havlickova et al. studied some transient behaviors of a SOL-divertor plasma when the cross-field inputs are changed temporally [5]. It is due to the edge localized mode (ELM) that such transient behaviors can occur. However, transient characteristics of the detached divertor plasma have not been clarified yet. In order to keep the heat load onto divertor plates small, the plasma should remain detached and re-attachment of the plasma should be avoided even if the cross-field inputs are temporally changed. Therefore, it is important to study the transient characteristics of the detached divertor plasma.

In this presentation we report extensions of our recent 1D analysis of detached divertor plasmas [6]. In our previous work we analyzed propagation of the detachment fronts toward upstream and showed that the cross-field particle and heat transport can affect the front propagation. As a next step, we discuss transient response of the detachment fronts to the cross-field inputs that are temporally changing.

2. Model

Behaviors of the detached divertor plasma is described by the 1D transport equations [4-6]:

$$\frac{\partial n}{\partial t}+\frac{\partial (nv)}{\partial x}=S \tag{1}$$

$$\frac{\partial (mnv)}{\partial t}+\frac{\partial (mnv^2+P)}{\partial x}=M \tag{2}$$

$$\frac{\partial}{\partial t}\left(3nT+\frac{1}{2}mnv^2\right) +\frac{\partial}{\partial x}\left\{\left(5nT+\frac{1}{2}mnv^2\right)v-\kappa_{\parallel e}\frac{\partial T}{\partial x}\right\}=Q \tag{3}$$

Here, P (=2nT) is the plasma pressure, $\kappa_{\parallel e}$ is the parallel electron heat conductivity, and the viscosity and heat conductivity of ions are neglected. Here, n, v and T are the plasma density, velocity and temperature, respectively. In the transport equations above, it is assumed that $n = n_e = n_i$, $v = v_e = v_i$ and $T = T_e = T_i$, where the subscripts e and i represent electrons and ions, respectively. The arc length x is along the magnetic field lines from the stagnation point (x = 0) to the divertor target (x = L).

The source/loss terms in the particle, momentum and energy equations are represented by S, M and Q, respectively. The terms S and Q involve the cross-field particle and energy inputs $S_{\perp\mathrm{SOL}}$ and $Q_{\perp\mathrm{SOL}}$, respectively. The terms S and Q also involve several kinds of atomic processes, such as ionizations, charge exchanges and recombinations. For more detailed see [4-6].

For the spatial profile of the neutral particle flux Γ_n, we use the following simple exponential-like decay form:

$$\Gamma_n=\Gamma_{n,d}\exp\left(-\frac{\Delta s}{\lambda_{n,ion}}\right),\quad \lambda_{n,ion}=\frac{v_n}{n\langle\sigma v\rangle_{ion}}. \tag{4}$$

Here, it is assumed that the neutral particle flux decays only due to ionization, and v_n corresponds to the Franck-Condon energy, $\langle\sigma v\rangle_{\mathrm{ion}}$ is the rate parameter of the ionizations. Effects of cross-field transport of the neutrals on divertor plasmas will be discussed in [7].

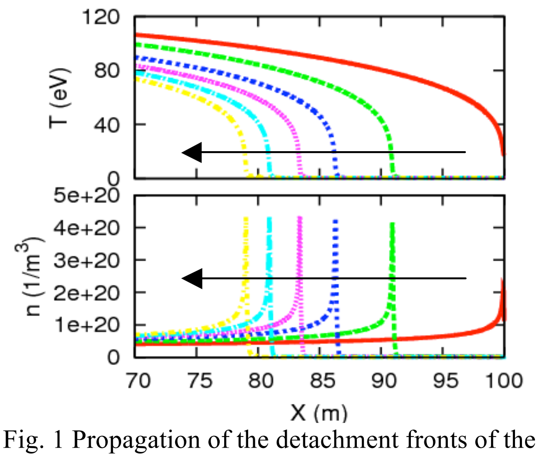

Fig. 1 Propagation of the detachment fronts of the plasma temperature (a) and density (b). The direction of the front propagation is represented by an arrow in each panel. The X-point is located at x = 80 m.

3. Simulation result and further works

An example of propagation of the detachment fronts of the plasma temperature and density obtained by the 1D transport simulation is shown in Fig. 1 [6]. Here the ITER-like plasma condition was assumed. The connection length L is 100 m. The power and particle inputs from the core to the SOL are 80 MW and 1.5×10^{23} 1/s, respectively. The surface area A_{SOL} is ~640 m^2 and the SOL width λ_{SOL} is 4.7 cm; therefore, the cross-field energy and particle source terms in the SOL region, $Q_{\perp\mathrm{SOL}}$ and $S_{\perp\mathrm{SOL}}$, are estimated to be 2.67 MW/m^3 and 5.0×10^{21} 1/m^{3}s, respectively. As for computational methods, the semi-implicit numerical scheme is employed to perform the simulations. The diffusion terms are discretized by the conventional central implicit scheme; the convection terms are discretized by the first order explicit flux vector splitting method developed by Steger and Warming [8].

As shown in Fig. 1, the detachment fronts propagating beyond the X-point are well simulated, which is an unfavorable situation since the neutral particles are transported upstream together with the front propagation. Similar simulation results were reported in [4].

In the presentation we will discuss effects of a temporary changes in $S_{\perp\mathrm{SOL}}$ and $Q_{\perp\mathrm{SOL}}$, to the detached divertor plasma. Particularly, we simulate response of the detachment fronts propagating upstream to the pulsed-like change in $S_{\perp\mathrm{SOL}}$ and $Q_{\perp\mathrm{SOL}}$ like ELM. We evaluate to what extent of the change in $S_{\perp\mathrm{SOL}}$ and $Q_{\perp\mathrm{SOL}}$ the detached plasma is re-attached onto the divertor.

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