Effects of Radial Losses of Particle and Energy on the Stability of Detachment Front in a Divertor Plasma*)

Satoshi TOGO, Makoto NAKAMURA[1)], Yuichi OGAWA, Katsuhiro SHIMIZU[2)], Tomonori TAKIZUKA[2)] and Kazuo HOSHINO[1)]

Graduate School of Frontier Science, 5-1-5 Kashiwanoha, Kashiwa, Chiba 277-8568, Japan
[1)]Japan Atomic Energy Agency, 2-166 Oaza-Obuchi-Aza-Omotedate, Rokkasho, Kamikita, Aomori 039-3212, Japan
[2)]Japan Atomic Energy Agency, 801-1 Mukoyama, Naka, Ibaraki 311-0193, Japan

(Received 9 December 2011 / Accepted 25 April 2012)

Operation under partially detached divertor (PDD) plasmas is a hopeful way in order to reduce the divertor heat load in the next generation tokamaks. The physical mechanism of PDD plasmas, however, has not fully been understood yet. We have studied them with a multi-layer one-dimensional divertor model. The PDD plasmas are successfully reproduced by introducing a neutral gas puffing model. Effect of the cross-field heat transport on the PDD plasmas is investigated. It is found that cross-field heat transport both in the SOL region and in the divertor region prevents detachment fronts from moving upstream in a detached flux tube.

Keywords: divertor heat load, partially detached divertor plasma, detachment front, plasma fluid model, neutral model, cross-field heat transport, thermal stability

DOI: 10.1585/pfr.7.2403087

1. Introduction

Reduction of the divertor heat load is one of the crucial issues in designing the next generation tokamaks such as ITER and DEMO. In order to resolve this issue, detached divertor plasmas are considered to be a promising way [1]. It has been shown by experiments that partially detached divertor (PDD) plasmas are more stable than fully detached divertor plasmas [2]. PDD plasmas will be adopted for ITER operation scenarios [3].

In modeling divertor plasmas, two-dimensional (2D) codes, such as SONIC [4] and SOLPS [5], and point divertor models have been used. It is considered, however, that 2D codes are computationally massive to focus on studying each physical phenomenon in plasmas. On the other hand, the latter models are very easy, but have not reproduced detached divertor plasmas so far. Thus the one-dimensional (1D) codes [6, 7], which are computationally lighter than 2D ones, have been used to gain physical insights of detached divertor plasmas. In spite of their usefulness and comprehensibility, the 1D codes are essentially incapable of modeling PDD plasmas due to their radial variation from detached plasma to attached one.

The 'multi-layer (ML)' 1D model [8, 9] has been developed for the purpose of solving this dimensional problem by treating cross-field transport, which have been proven to significantly affect behaviors of the PDD plasmas [10, 11], as source terms in the 1D plasma transport equation. Detached and attached flux tubes are put adjacent to each other in order to analyze interactions between these tubes.

In this paper, we first show simulation results of high recycling, attached divertor plasmas so as to check consistency of the 1D plasma transport code with the simple two-point model. Second, by introducing the neutral gas puffing to the neutral model and the cross-field heat transport between the detached and attached tubes to the 1D plasma transport model, we investigate the stability of the detachment fronts in the detached flux tube.

2. Model

2.1 Geometry

The 1D divertor model is used to analyze a SOL-divertor plasma along the magnetic field shown in Fig. 1. We introduce x-axis along the magnetic field and set the stagnation point and the divertor plate to be $x = 0$ and

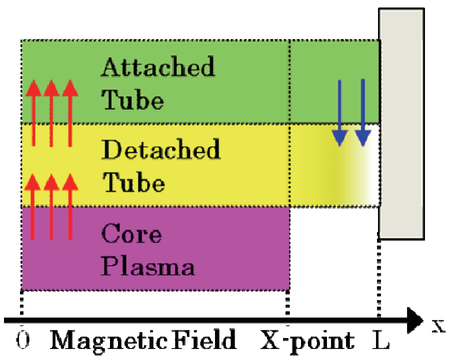

Fig. 1 Schematic picture of multi-layer 1D model.

author's e-mail: togo@ppl.k.u-tokyo.ac.jp

*) This article is based on the presentation at the 21st International Toki Conference (ITC21).

$x = L$, respectively. The particle and heat flux from the core plasma are considered in the SOL region. The cross-field transport across the flux tubes is locally estimated in all region along the field. All the fluxes in the perpendicular direction are described as the source terms in the plasma fluid equations.

2.2 Plasma fluid model

The 1D transport equations are given as follows [12];

$$\frac{\partial (mn)}{\partial t} + \frac{\partial (mnV)}{\partial x} = mS, \tag{1}$$

$$\frac{\partial (mnV)}{\partial t} + \frac{\partial \left(mnV^2 + P\right)}{\partial x} = M, \tag{2}$$

$$\frac{\partial}{\partial t}\left(\frac{1}{2}mnV^2 + 3nT\right) + \frac{\partial}{\partial x}\left\{\left(\frac{1}{2}mnV^2 + 5nT\right)V - \kappa_e \frac{\partial T}{\partial x}\right\} = Q. \tag{3}$$

Here, the density n, the flow velocity V, the temperature T of ions and electrons are assumed to be equal, respectively. $P(= 2nT)$ is the plasma pressure and κ_e is the parallel electron heat conductivity. The particle, momentum and energy source/sink terms are represented by S, M and Q, respectively, in which several kinds of atomic processes are taken into account. For the details of each term, see [8, 9, 12].

2.3 Boundary conditions

At the stagnation point ($x = 0$), we use the following symmetric boundary conditions:

$$\frac{\partial n}{\partial x} = 0, \quad V = 0, \quad \frac{\partial T}{\partial x} = 0. \tag{4}$$

At the divertor target ($x = L$), we use the following boundary conditions:

$$M_s = 1, \tag{5}$$

$$q_{heat} = \gamma n T c_s. \tag{6}$$

Here, M_s is the Mach number, c_s is the sound speed, q_{heat} is the heat flux and γ (≈ 6.5) is the sheath energy transmission factor.

2.4 Neutral model

We have introduced 1D neutral model:

$$n_n v_n = (n_n v_n)_{ref} \exp\left(-\Delta s/\lambda_{ref}\right). \tag{7}$$

Here, the subscript 'n' represents neutral particles. The coordinate s is along the poloidal direction and λ_{ref} is the decay length of the neutral flux at the reference point. We used following two models for λ_{ref}:

$$\lambda = \lambda_{ion}, \tag{8}$$

$$\lambda = \sqrt{\lambda_{cx}\lambda_{ion}}. \tag{9}$$

Here, λ_{ion} and λ_{cx} are the ionization and charge-exchange mean free paths of neutral particles, respectively. The former model is for divertors of existing relatively smaller tokamaks such as ASDEX Upgrade (AUG), while the latter one is for divertors of relatively larger tokamaks such as ITER.

At the divertor plate, we use the following condition:

$$(n_n v_n)_{div} = \eta_{trap} (nV)_{div} \sin\theta + n_{n,div,aux} v_n. \tag{10}$$

Here, η_{trap} is the recycling rate, θ is the pitch of the magnetic field and $n_{n,div,aux}$ is auxiliary neutral density at the divertor plate by neutral gas puffing. Recycling and neutral gas puffing at the divertor plate are considered as neutral sources in this model. In our simulation results below, θ and the neutral temperature T_n are fixed to be 2 degree and 3.2 eV, which is Franck-Condon energy, respectively.

2.5 Cross-field transport

The physical mechanism of the cross-field transport of particles and heat is not understood fully yet. In the ML 1D model, we assume that the cross-field transport is modeled by the diffusion model:

$$S_\perp \Delta_{tube} = -D_\perp \frac{\partial n}{\partial y} = -D_\perp \frac{\Delta n}{\Delta_{SOL}/2}, \tag{11}$$

$$Q_\perp \Delta_{tube} = -\kappa_\perp \frac{\partial T}{\partial y} = -\tilde{n}\chi_\perp \frac{\Delta T}{\Delta_{SOL}/2}. \tag{12}$$

Here, $D_\perp$ and $\chi_\perp$ are the particle and heat diffusion coefficient, respectively. Both of them are input parameters and can be set to be different values between the SOL region and the divertor region while they are set uniformly in space in each region. The coordinate y is in the perpendicular direction to the magnetic flux tube. The thicknesses of the SOL and each flux tube are represented by Δ_{SOL} and Δ_{tube}, respectively. The plasma density with tilde sign means the harmonic average between tubes adjacent to each other.

3. Single-Layer Simulation of High Recycling Divertor Plasmas

Without neutral gas puffing, we have done divertor plasma simulations with a single flux tube for various recycling rates η_{trap}. In these simulations, we set the plasma parameters to be AUG-like [13] as shown in Table 1 (a). Figure 2 shows the densities and temperatures at the stagnation point, X-point and divertor plate, respectively, as functions of the input flux amplification factor $R_{in}(= 1/(1-\eta_{trap}))$. As the value R_{in} becomes larger, the density (the temperature) at the divertor plate becomes higher (lower), while those parameters at the stagnation point and the X-point tend to be saturated. Such a correlation between plasma parameters and R_{in} is consistent with that of the two-point model [14].

The spatial profiles of the plasma density, Mach number and temperature under $R_{in} = 5$ and 25 are shown in Fig. 3. We have been successful in simulating the attached divertor plasma regime. All of the parameters are almost constant in space in the SOL region, especially in the low

Table 1 The plasma parameters assumed. The symbols Γ_{in} and q_{in} mean the particle and heat flux from the core plasma, respectively.

	(a) AUG-like	(b) ITER-like
L	22 m	100 m
X-point	17.6 m	80 m
Γ_{in}	6.0×10^{21} s^{-1}	1.5×10^{23} s^{-1}
q_{in}	4 MW	80 MW
Δ_{SOL}	2 cm	4.7 cm

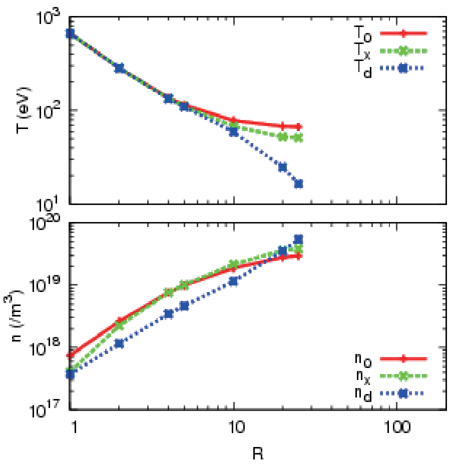

Fig. 2 Correlation between plasma parameters and flux amplification factor R_{in}. The subscript "0", "x" and "d" represent the stagnation point, the X-point, and the divertor plate, respectively.

recycling case (R_{in} = 5). The density becomes higher near the divertor plate and decreases at the divertor plate in the high recycling case (R_{in} = 25) because the velocity reaches the sound speed in the sheath region. The temperature decreases in the divertor region. These results, however, indicate that detached divertor plasma regime cannot be reproduced under reasonable values of R_{in} considering only recycling at the divertor plate as neutral source.

In order to simulate detached divertor plasma regime, we might have to revise the neutral model. First, the model should be replaced with time-dependent one because present neutral model implicitly assumes steady state. Second, volume recombination effect should be considered as neutral source because the ion flux, which is the neutral source, decreases in the detached divertor plasma regime. Third, we should introduce some diffusion effects to the neutral model because the motion of neutrals is not affected by the magnetic field. These revisions are our future works.

4. Multi-Layer Simulation of the Movement of Detachment Fronts

In our previous studies, we introduced the heat source

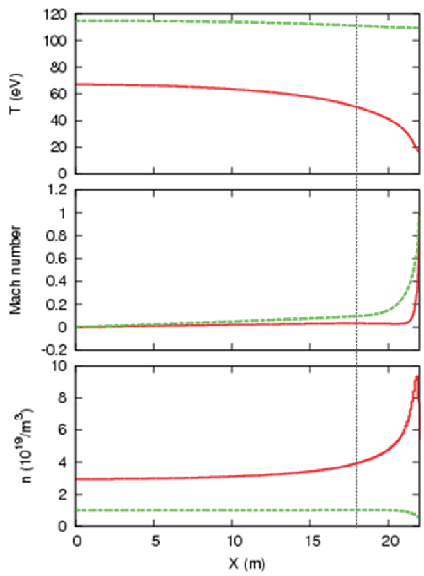

Fig. 3 Spatial profiles of plasma density, Mach number and temperature under in R_{in} = 5 (green line) and 25 (red line). The gray line represents the X-point.

term representing the cross-field heat transport in the 1D SOL-divertor plasma transport model [8], where the heat source terms was an input parameter. In Ref. [9], the more realistic cross-field transport model in the divertor region was introduced in the ML 1D model, and the simulation results similar to those in [8] were obtained. In this paper, we introduced the cross-field transport term in the ML 1D model not only in the divertor region but also in the SOL region, and investigated the mechanism of the stabilizing effect of the perpendicular heat transport on the detachment front.

4.1 Results

To simulate the detached plasma, we introduced a gas-puff neutral source in the detached tube. Hereafter, we set the plasma parameters to be ITER-like [15] as shown in Table 1 (b). The recycling rate η_{trap} is fixed to be 0.8. The thickness of detached tube is 0.8 cm while that of attached one is 3.9 cm. The cross-field transport is considered. The particle diffusion coefficients in the SOL and divertor region are fixed to be 0.5 and 0 m^2/s, respectively. The heat diffusion coefficient in the SOL region is fixed to be 1.0 m^2/s.

The time-dependence of the plasma parameters for two patterns of the heat diffusion coefficient in the divertor region $\chi_{\perp,div}$ and $n_{n,div,aux}$ is shown in Fig. 4. The region of low density and low temperature starts to expand upstream while the profiles in the attached tube do not change as shown in Figs. 4 (a)-(d), for $\chi_{\perp,div}$ = 0 and $n_{n,div,aux}$ = 1.37×10^{20} m^{-3}. The head of this region is called the detachment front characterized by the remarkable decrease of density and temperature. As shown here, we have simulated the PDD plasma regime. These re-

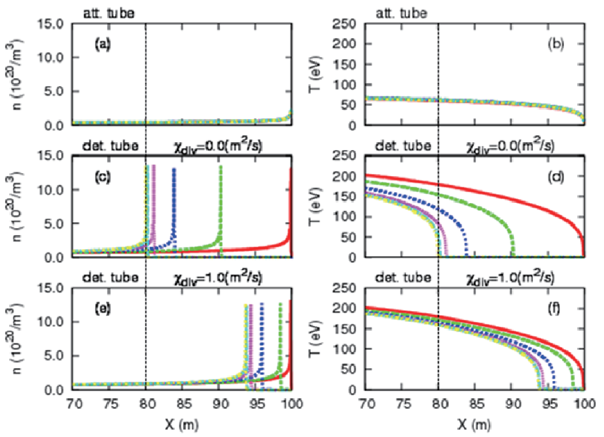

Fig. 4 Snapshots of the spatial profiles of plasma density and temperature in the PDD plasma regime. (a) and (b) are attached tube and (c) and (d) are detached tube for $\chi_{\perp,\mathrm{div}} = 0$. (e) and (f) are detached tube for $\chi_{\perp,\mathrm{div}} = 1.0\,\mathrm{m^2/s}$. The black broken line is the X-point. Each color of curves represents the passage of time from the initial condition (red) to the steady state (yellow).

sults, however, indicate that the detachment front in the detached tube is unstable. Secondly, for $\chi_{\perp,\mathrm{div}} = 1.0\,\mathrm{m^2/s}$ and $n_{\mathrm{n,div,aux}} = 1.26\times 10^{20}\,\mathrm{m^{-3}}$, the detachment front going upstream stops in the divertor region as shown in Figs. 4 (e)-(f) while the profiles in the attached tube do not change from those for $\chi_{\perp,\mathrm{div}} = 0$ and $n_{\mathrm{n,div,aux}} = 1.37\times 10^{20}\,\mathrm{m^{-3}}$. These indicate that the cross-field heat flux in the divertor region stabilizes the detachment front.

4.2 Effects of cross-field heat transport

We investigated the position of the detachment front in the detached flux tube in a steady state for various values of $n_{\mathrm{n,div,aux}}$ and $\chi_{\perp,\mathrm{div}}$. The result is shown in Fig. 5. As $\chi_{\perp,\mathrm{div}}$ becomes higher, the critical value of $n_{\mathrm{n,div,aux}}$ leading the plasma to be detached becomes lower. In the simulation results the cross-field heat flux directs outward, which cools the inner flux tube and makes it easier to change into the detached state. Therefore, less neutral gas puffing is needed for the detachment to occur in the higher $\chi_{\perp,\mathrm{div}}$ simulation cases. In the low temperature and density region downstream of the detachment front in the detached tube, the radial temperature gradient is reversed, i.e., the particle and heat transport from the attached tube to the detached one takes place in the region between the detachment front and the divertor plate.

It is worth noting that even if $\chi_{\perp,\mathrm{div}}$ is zero, the detachment front can be stable due to $\chi_{\perp,\mathrm{SOL}}$. When the detachment front goes upstream, the temperature in the SOL region of detached tube becomes lower due to the fast heat conduction in the direction parallel to the magnetic field, so that the radial temperature gradient becomes smaller and the outward cross-field heat flux is decreased in the SOL region. As a result, the parallel heat flux directing from the SOL to the divertor plate is increased in the detached tube

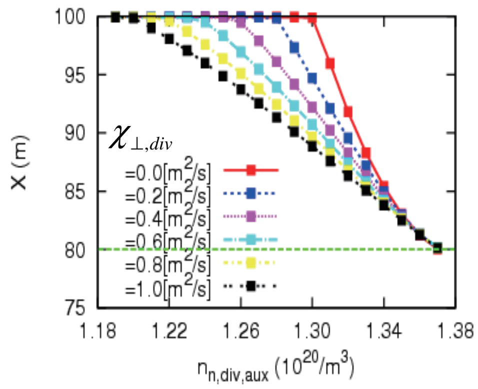

Fig. 5 Correlation between auxiliary neutral density and the position of detachment front in steady state for various values of $\chi_{\perp,\mathrm{div}}$.

because of the energy conservation. This increased heat flux, in turn, 'pushes' the detachment front toward downstream. It indicates that the cross-field heat transport not only in the divertor region but also in the SOL region plays an important role in stabilizing the detachment front in the PDD plasma regime.

5. Conclusion

We have studied the partially detached divertor (PDD) plasmas with the multi-layer 1D model. In the single-layer model, we simulated high recycling plasma up to the flux amplification factor $R_{\mathrm{in}} \sim 25$. The simulation results are consistent with the simple two-point model calculation.

We reproduce PDD plasmas by introducing the gas-puff neutral source into the ML 1D simulation code, where the particle and energy transport across the flux tubes is taken into account. It has been shown that cross-field heat transport both in the SOL region and in the divertor region can stabilize the detachment front.

[1] ITER Physics Expert Group on Divertor, Nucl. Fusion **39**, 2391 (1999).
[2] A.W. Leonard *et al.*, Phys. Rev. Lett. **78**, 4769 (1997).
[3] L. Loarte *et al.*, Nucl. Fusion **47**, S203 (2007).
[4] H. Kawashima *et al.*, Plasma. Fusion. Res. **1**, 031 (2006).
[5] R. Schneider *et al.*, Contrib. Plasma Phys. **46**, 3 (2006).
[6] R. Goswami *et al.*, Phys. Plasmas **8**, 857 (2001).
[7] W. Fundamenski *et al.*, J. Nucl. Mater. **290-293**, 593 (2001).
[8] M. Nakamura *et al.*, J. Nucl. Mater. **415**, S553 (2011).
[9] M. Nakamura *et al.*, Plasma Fusion Res. **6**, 2403098 (2011).
[10] M. Wischmeier *et al.*, J. Nucl. Mater. **390-391**, 250 (2009).
[11] S. Wiesen *et al.*, J. Nucl. Mater. **415**, S535 (2011).
[12] S. Nakazawa *et al.*, Plasma Phys. Control. Fusion **42**, 401 (2000).
[13] A. Kallenbach *et al.*, Nucl. Fusion **48**, 085008 (2008).
[14] K. Shimizu *et al.*, J. Plasma Fusion Res. **80**, 189 (2004).
[15] M. Shimada *et al.*, Nucl. Fusion **47**, S1 (2007).