第15回若手科学者によるプラズマ研究会

Analysis of Partially Detached Divertor Plasmas with Multi-Layer 1D Model

多層型一次元モデルを用いた部分非接触ダイバータプラズマ解析

[a]Satoshi Togo, [b]Makoto Nakamura, [c]Katsuhiro Shimizu, [c]Tomonori Takizuka, [b]Kazuo Hoshino, [a]Yuichi Ogawa

[a]Department of Advanced Energy, Graduate School of Frontier Science, the University of Tokyo 5-1-5, Kashiwanoha, Kashiwa, Chiba 277-8568

[b]Japan Atomic Energy Agency, Rokkasho, Kamikita, Aomori 039-3212

[c]Japan Atomic Energy Agency, Naka, Ibaraki 311-0193

Motivation

Background

・**Detached divertor plasmas are considered to be a promising way to reduce the divertor heat load.**

・**Partially detached divertor (PDD) plasmas are observed in many experiments and have been adopted for ITER operation scenarios.**

We want to know…

・**The condition under which PDD plasmas occur**

- **Elementary steps** i.e. ionization, recombination, charge exchange…
- **Physics in the parallel direction** i.e. conduction, convection…
- **Physics in the perpendicular direction** i.e. $D_{\perp}, \chi_{\perp}$…

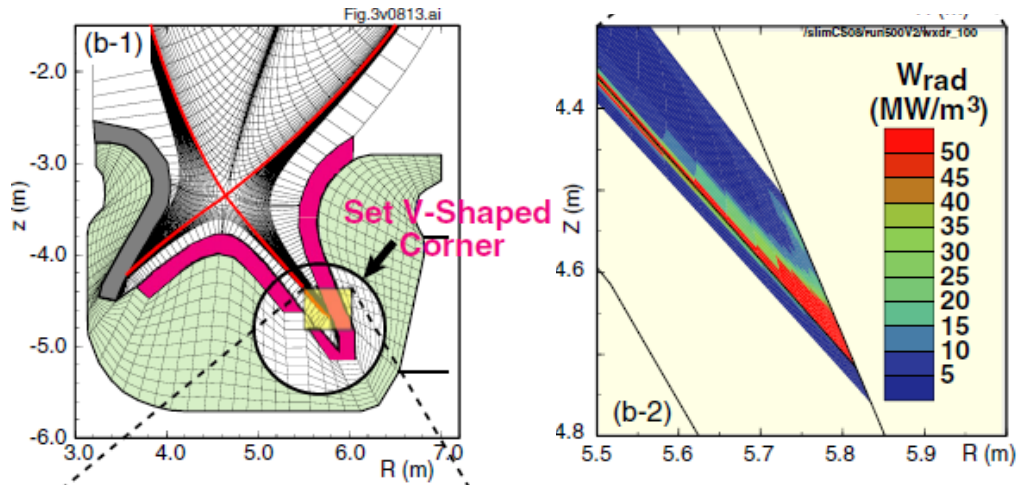
・**The way PDD plasmas are actively stabilized**

The Significance of the 1D Code

▪**2D codes**, **such as SONIC and SOLPS, have been used to simulate SOL-divertor plasmas rigorously and design a future DEMO fusion reactor. They, however, are computationally heavy in order to acquire qualitative insights for detached divertor plasmas.**

▪**Point divertor models** **are computationally light and easy to deduce physical insights. They, however, are unable to model detached divertor plasmas.**

▪**1D codes** **are computationally lighter than 2D codes and able to temporally model detached divertor plasmas. Therefore, they are considered to be adequate to grasp physics of detached divertor plasmas.**



Example of PDD modeling by the SONIC code
(left：the divertor geometry analyzed; right：radiation distribution）
H.Kawashima et al, Nucl. Fusion 49, 065007 (2009).

1D Model -Basic Equations-

Particle conservation:

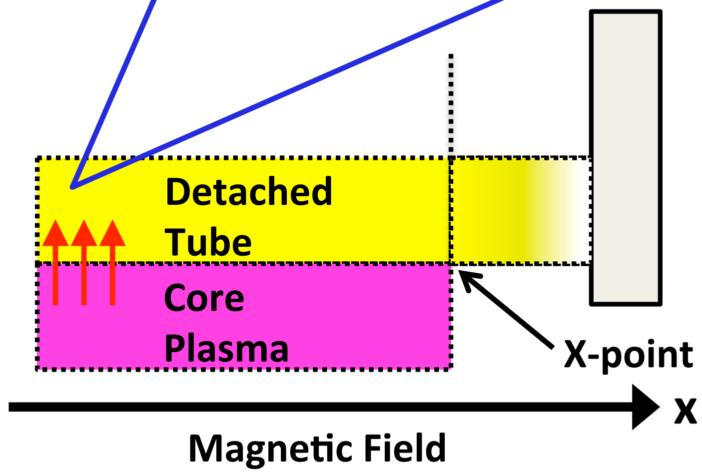
$$\frac{\partial \rho}{\partial t} + \frac{\partial l}{\partial x} = mS$$

Momentum conservation:

$$\frac{\partial l}{\partial t} + \frac{\partial}{\partial x}\left(lv + P\right) = M$$

Energy conservation:

$$\frac{\partial K}{\partial t} + \frac{\partial}{\partial x}\left\{\left(K + P\right)v - \kappa_e \frac{\partial T}{\partial x}\right\} = Q$$

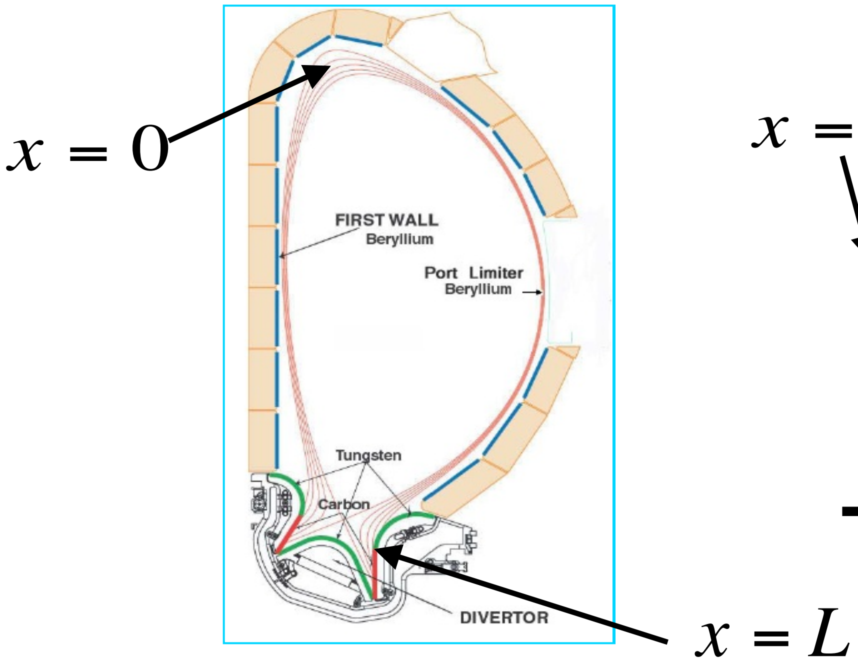


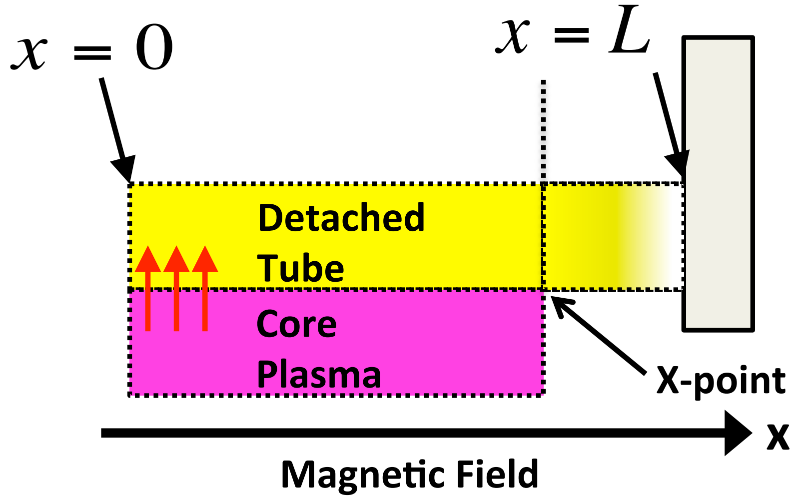
1D Model -Boundary Conditions-

Boundary conditions:

At $x = 0$ $\qquad \dfrac{\partial \rho}{\partial x} = 0 \qquad v = 0 \qquad \dfrac{\partial T}{\partial x} = 0$

At $x = L$ $\qquad v = c_s \qquad q = (K + P)v - \kappa_{\parallel e}\dfrac{\partial T}{\partial x} = \gamma_t nTc_s$





1D Model -Source Terms-

Particle source/loss terms:

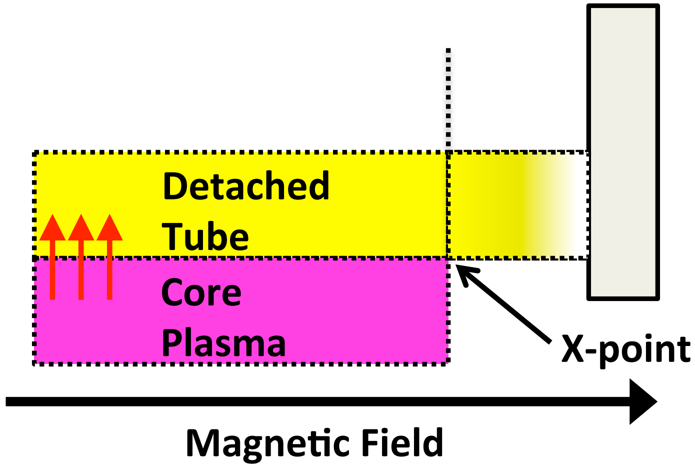
$$S = S_{core} + S_{ion} + S_{rec}$$

Momentum source/loss terms:

$$M = M_{cx} + M_{rec}$$

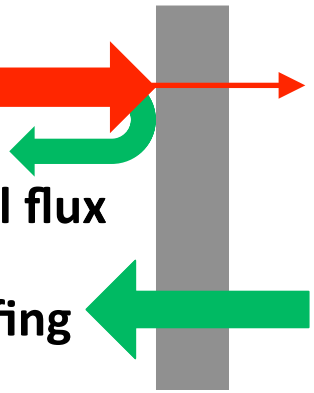
Energy source/loss terms:

$$Q = Q_{core} + Q_{ion} + Q_{cx} + Q_{rec} + Q_{rad}$$



Radial transport is described as source terms in the framework of the ML 1D model.

1D Model -Neutral Model-



Boundary condition at the divertor plate:

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

Decay of neutral flux:

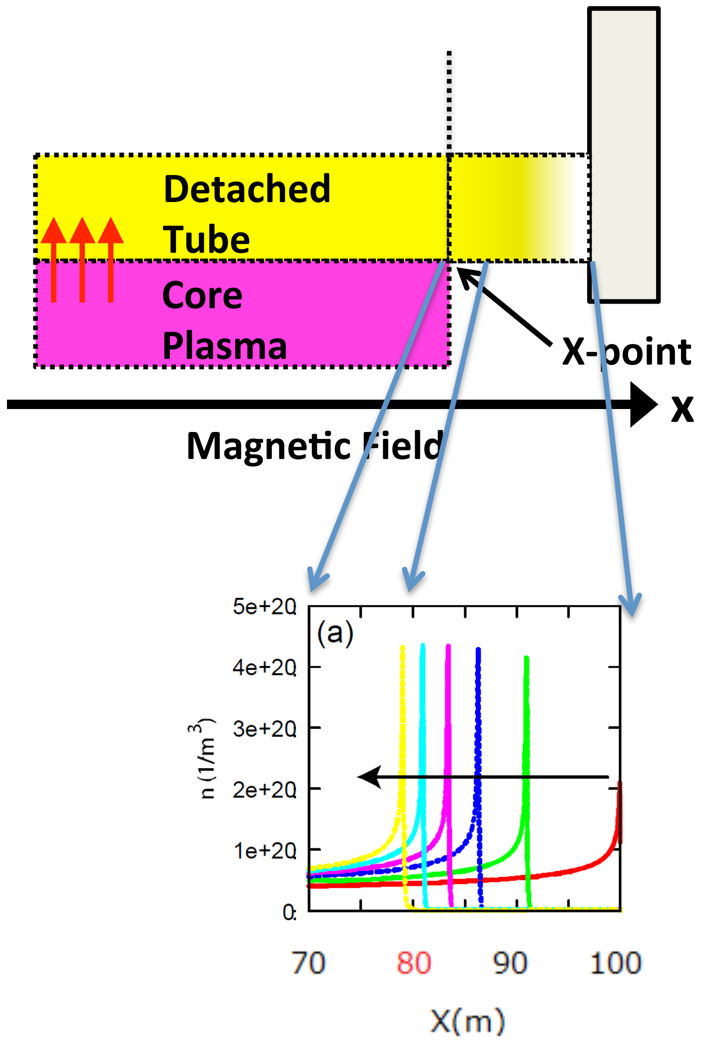
$$n_n v_n = (n_n v_n)_{ref} \exp\left(-s/\lambda_{ion,ref}\right)$$

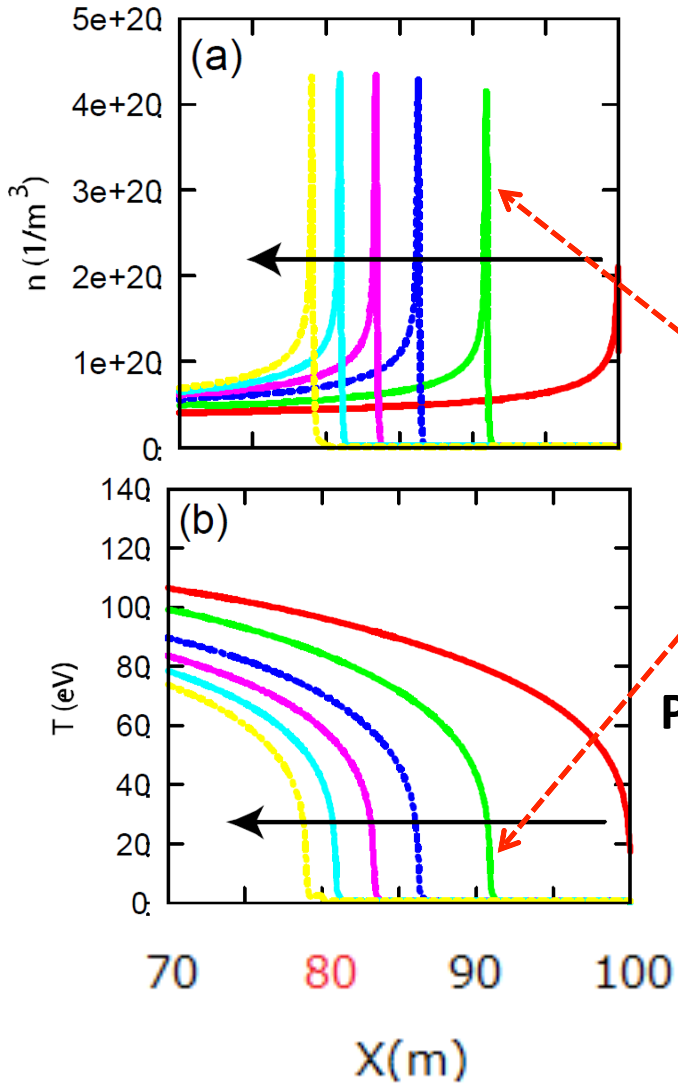
$$\lambda_{ion} = \frac{v_n}{n\langle\sigma v\rangle_{ion}}$$ ≡ **Mean free path of ionization**

"s" is the coordinate along the poloidal direction.

"θ" is the pitch of the magnetic field.

Results -Single Tube Detachment-





Plasma density

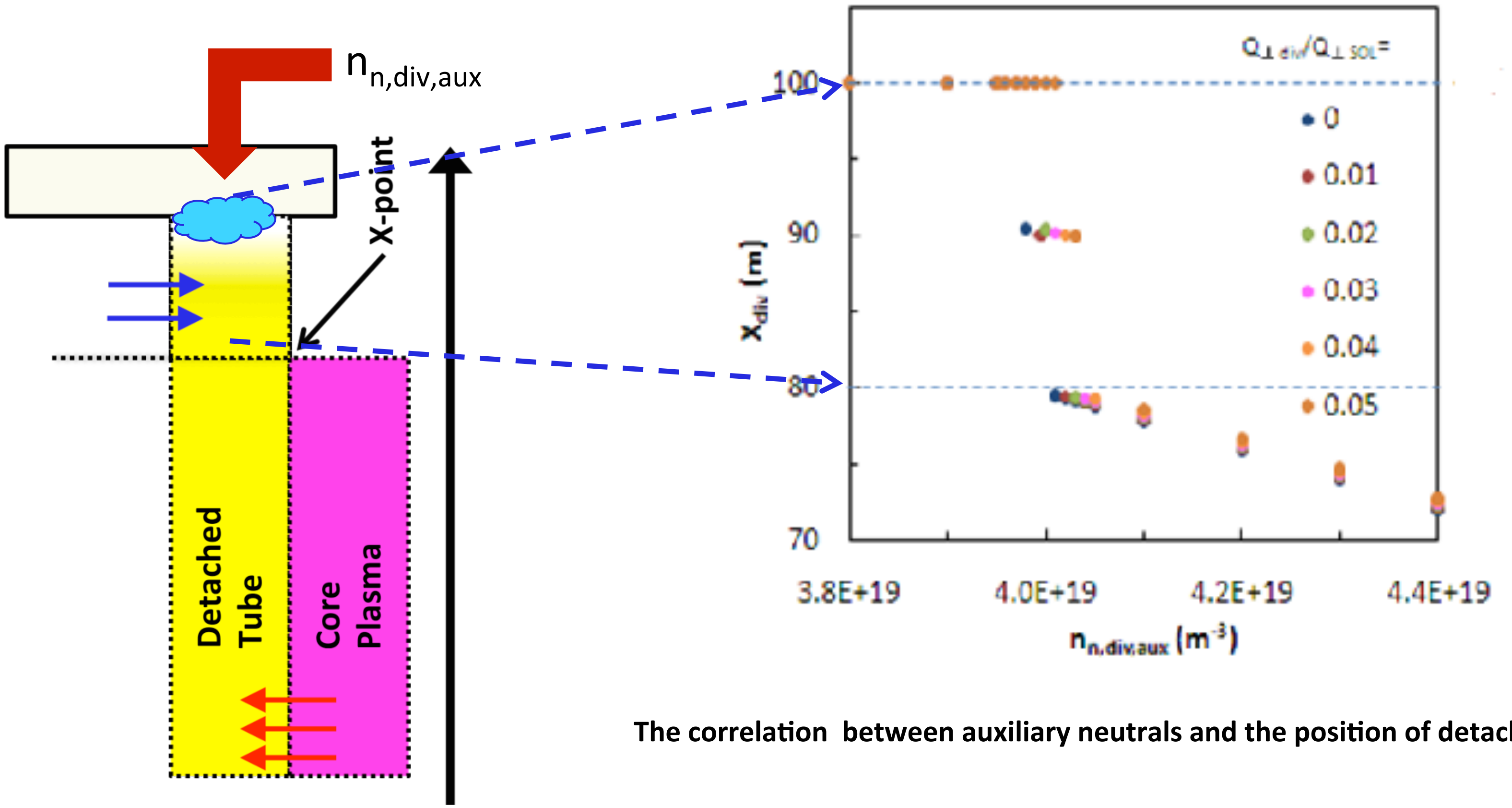
Detachment front

Plasma temperature

Hereafter, we assumed ITER-like plasma.

M. Nakamura *et al.*, J. Nucl. Mater. 415, S553 (2011).

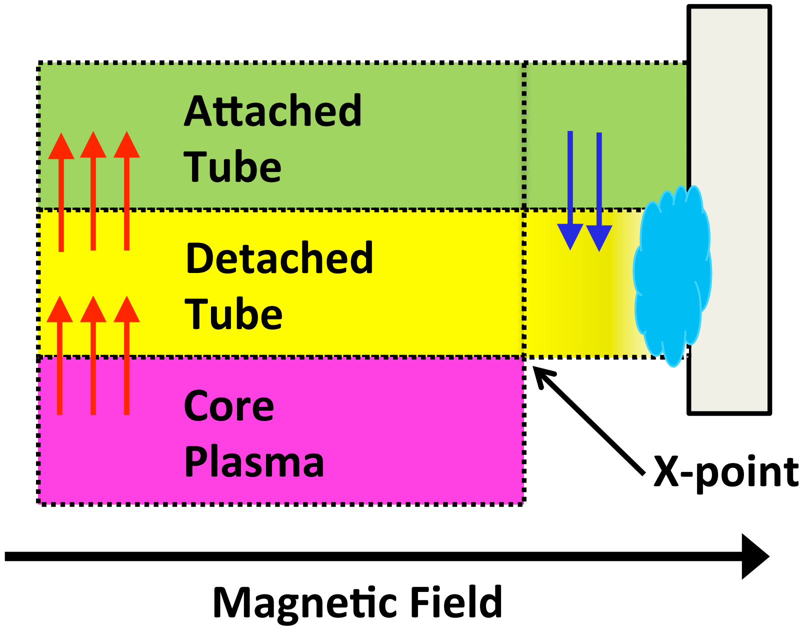
Stability of Detachment Front

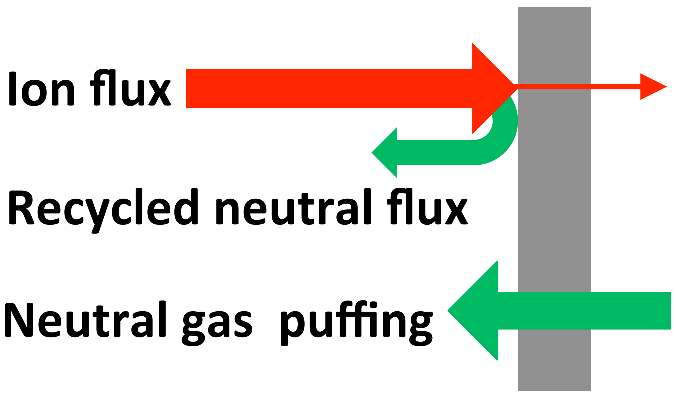


The correlation between auxiliary neutrals and the position of detachment front.

・**Analyzed with single tube, the detachment front was unstable against auxiliary neutrals ending in X-point MARFE.**

Simple ML 1D Model -Features-





- Auxiliary neutrals can be added at the divertor plate, so that detached divertor plasmas can occur.
- The inner (detached) and outer (attached) tubes are put adjacent each other.
- The cross-field particle and energy transport are considered in not only the SOL region but also the divertor region.

Simple ML 1D Model -Source Terms-

Particle source/loss terms:

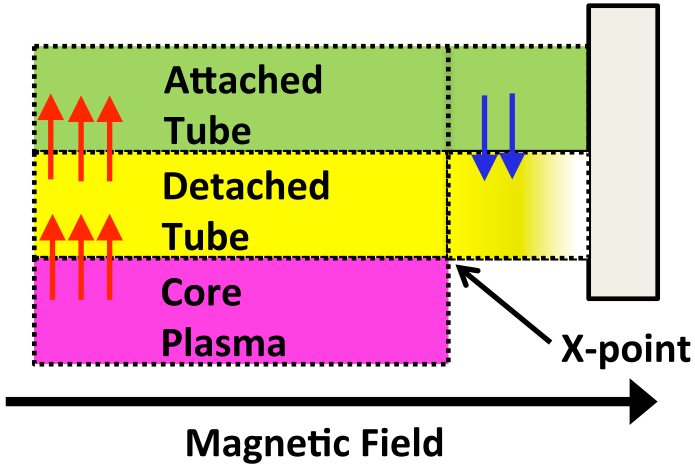
$$S = S_{core} + S_{\perp} + S_{ion} + S_{rec}$$

Momentum source/loss terms:

$$M = M_{cx} + M_{rec}$$

Energy source/loss terms:

$$Q = Q_{core} + Q_{\perp} + Q_{ion} + Q_{cx} + Q_{rec} + Q_{rad}$$



Radial transport is treated as source terms in 1D models.

Cross-field terms are assumed to be estimated by diffusion model.

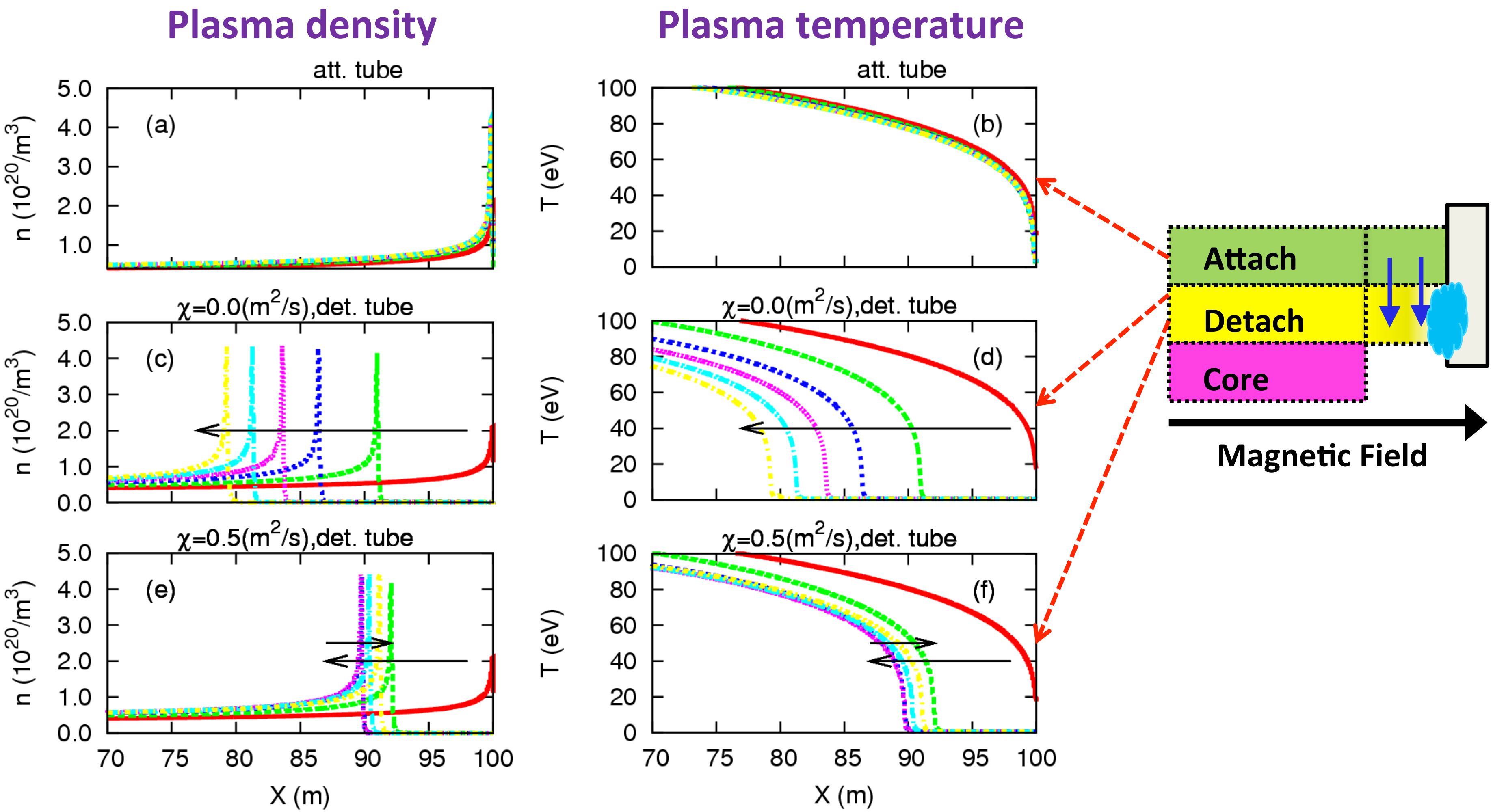
$$\Gamma_{\perp} = -D_{\perp} \frac{\partial n}{\partial y} \qquad q_{\perp} = -n\chi_{\perp} \frac{\partial T}{\partial y}$$

$$S_{\perp} = \frac{\Gamma_{\perp}}{\Delta_{SOL}/2} \qquad Q_{\perp} = \frac{q_{\perp}}{\Delta_{SOL}/2}$$

The particle and heat diffusion coefficients are both input parameters given constantly in SOL region and divertor region, respectively.

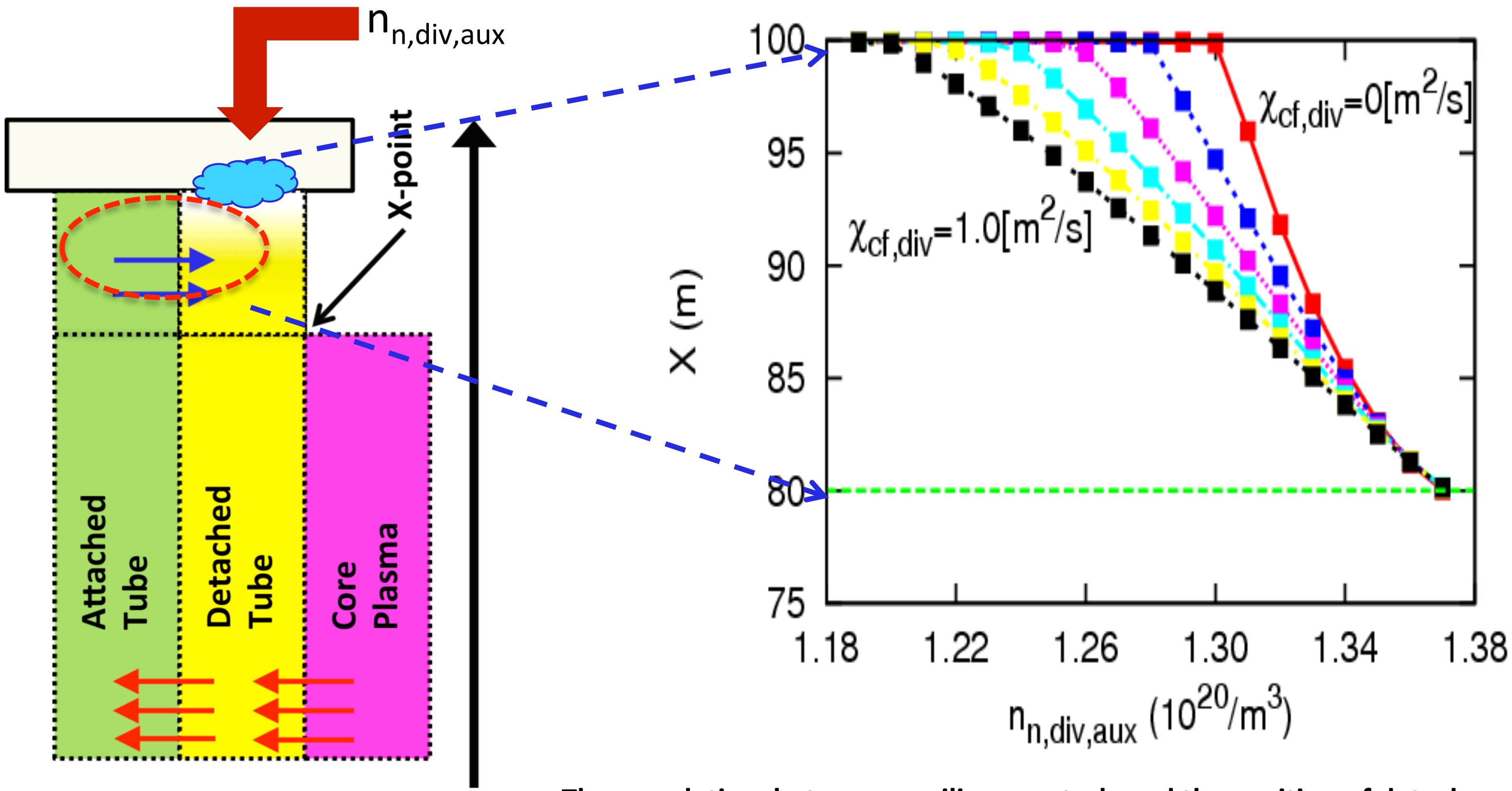
Results -reproduction of PDD plasma-

Red curves: t = 0, green: 0.59, blue: 1.2, pink: 1.8, turquoise: 2.5, yellow: 3.1 ms



Parallel plasma density and temperature profile in each tube.

Results -stability of detachment front-



The correlation between auxiliary neutrals and the position of detachment front.

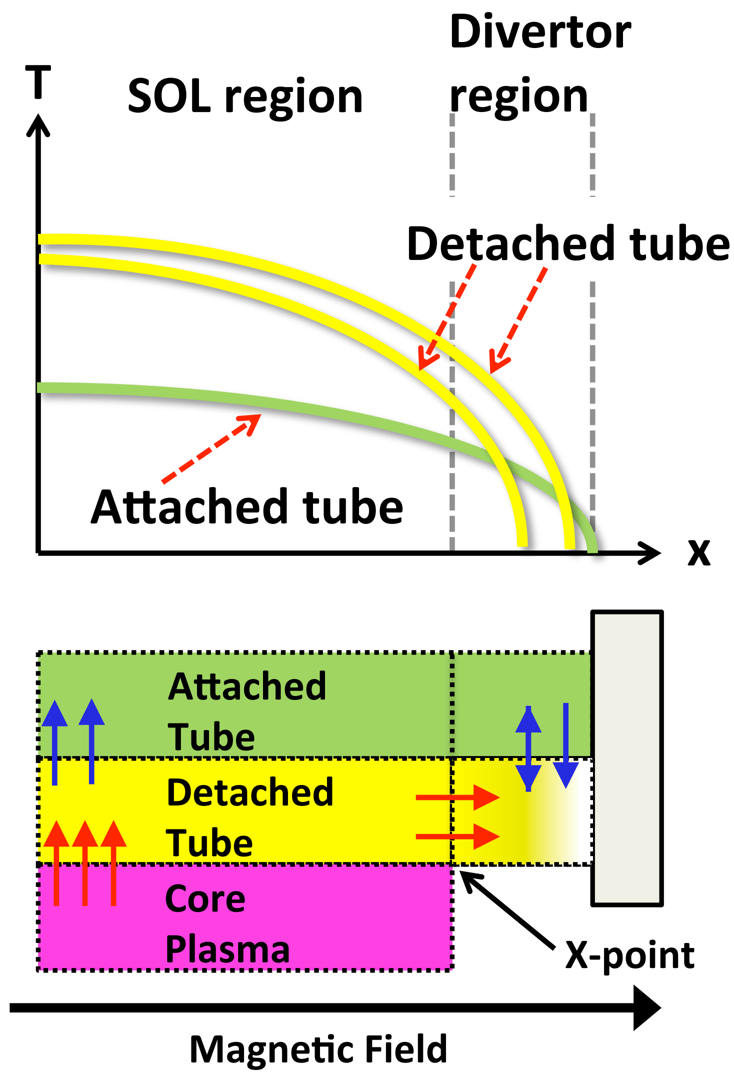
・**Analyzed with two tubes and introducing perpendicular diffusion model, the detachment front came to be stable against auxiliary neutrals.**

Discussion -Effect of Radial Transport-

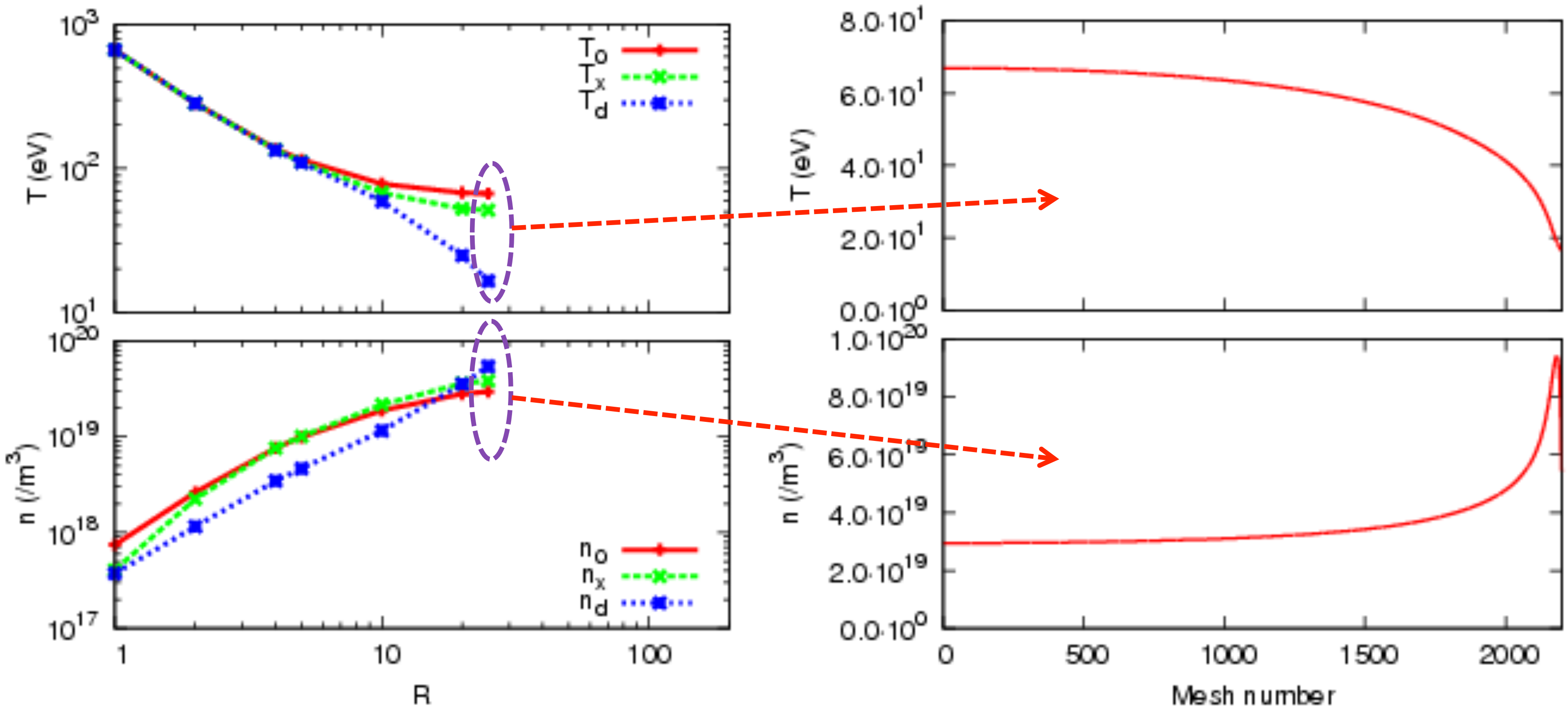
When the detachment front moves toward the X-point, the temperature of the divertor region in the detached tube gets lower.

The temperature gradient in the SOL region gets lower, so that relatively parallel heat flux in the detached tube gets larger.

The region where the temperature in the detached tube is lower than that in the attached tube increases, so that perpendicular heat flux in the divertor region gets larger.



Results

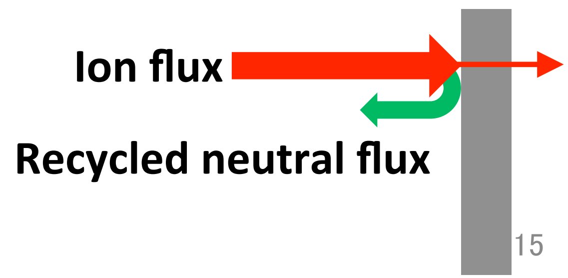


Plasma parameters calculated using the ML 1D model.

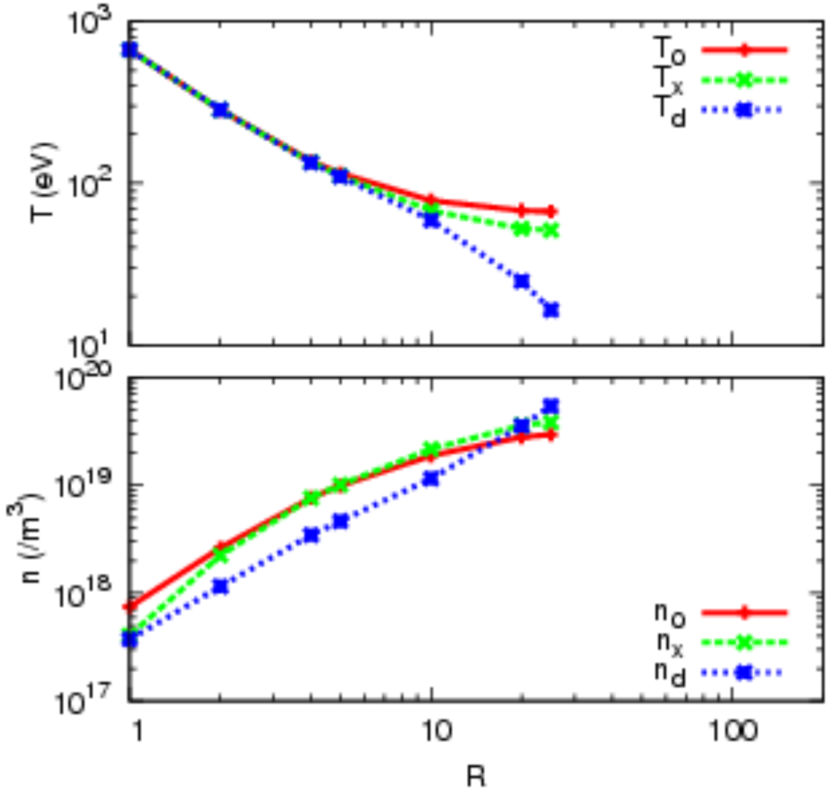
Plasma density and temperature profile under R=25.

$$R = \frac{1}{1-\eta_{trap}}$$

Here, we assumed ASDEX-like plasma.

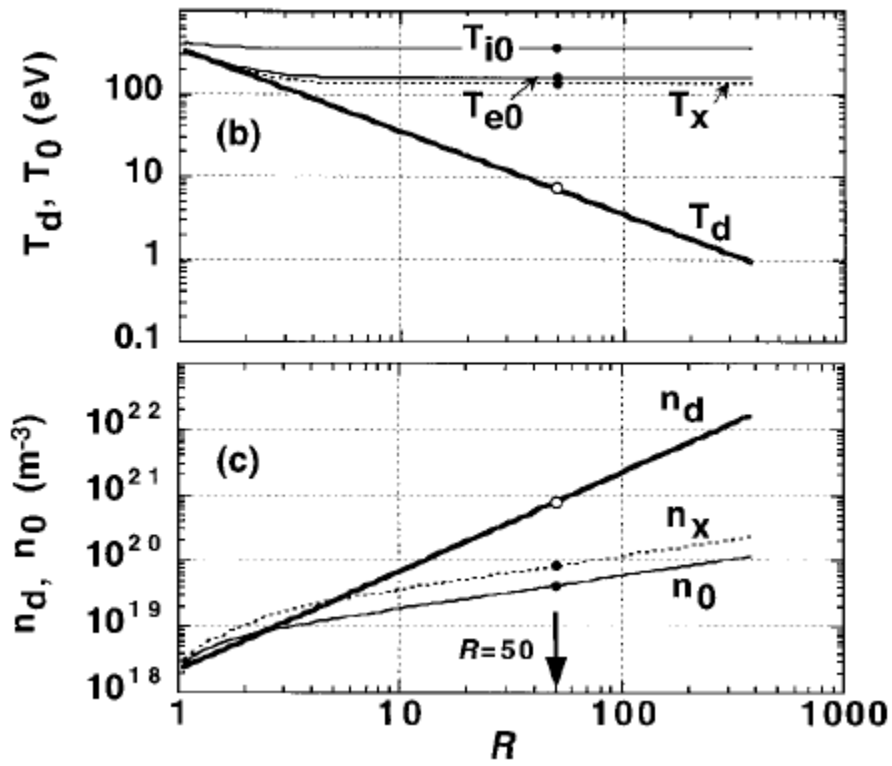


Comparison with Two Point Model



Plasma parameters calculated using the ML 1D model.

$$R = \frac{1}{1-\eta_{trap}}$$



Plasma parameters calculated using the two point divertor model.
K. Shimizu and T. Takizuka, J. Plasma and Fusion Res. 80 No.3 (2004) 187.

Next Step

Present situation

Divertor plasma detachment cannot be reproduced with reasonable flux amplitude factor R.

Presumed causes

・The plasma temperature in the divertor region have to be cooler by considering the energy loss by charge exchange.

・Present neutral model does not consider the volume recombination effect. The only neutral source now is the recycling at the divertor plate.

・Present neutral model assumes static state, that is, the time derivative term is set to be zero. Analysis of detached divertor plasmas might require the time-dependent neutral model. In addition, the diffusion term may have to be introduced.

$$\frac{\partial n_n}{\partial t} + \frac{\partial}{\partial s}\left(n_n v_n\right) + diff = S_n$$

Conclusion

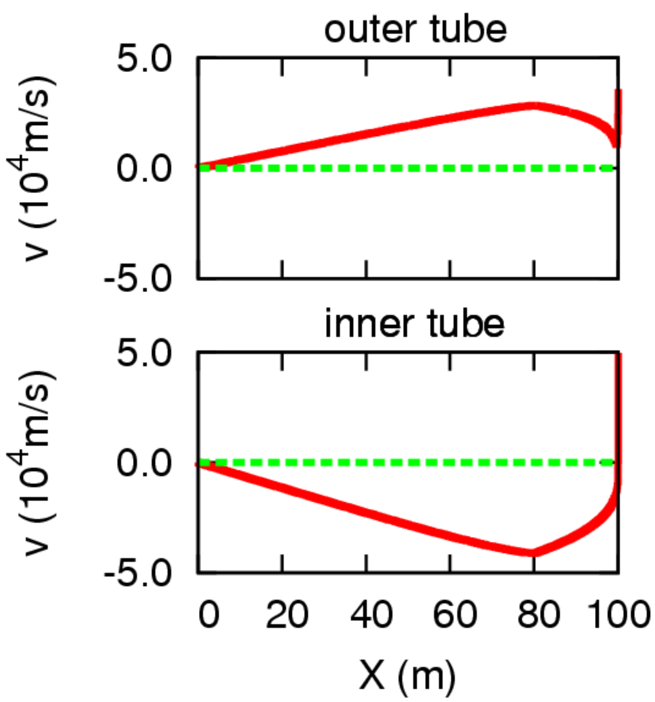
・Partial detached divertor (PDD) plasmas are expected to be a promising way to reduce the divertor heat load. The physical mechanism of them, however, has not been known adequately yet.

・With a simple neutral model, which assumes auxiliary neutrals at the divertor, we could have reproduced PDD plasmas.

・It was shown that radial heat flux both in the SOL region and the divertor region contributes the stability of detachment fronts.

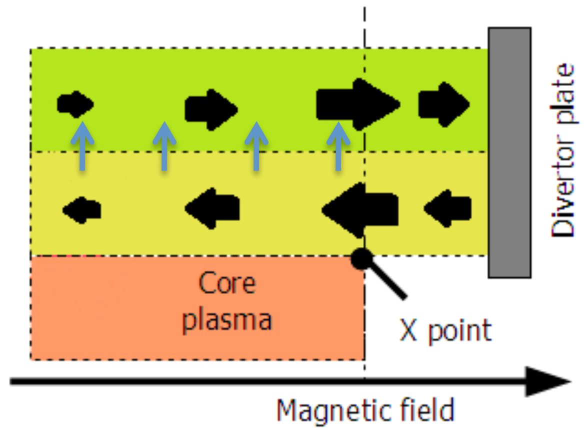
Support documentation

Flow Reversal



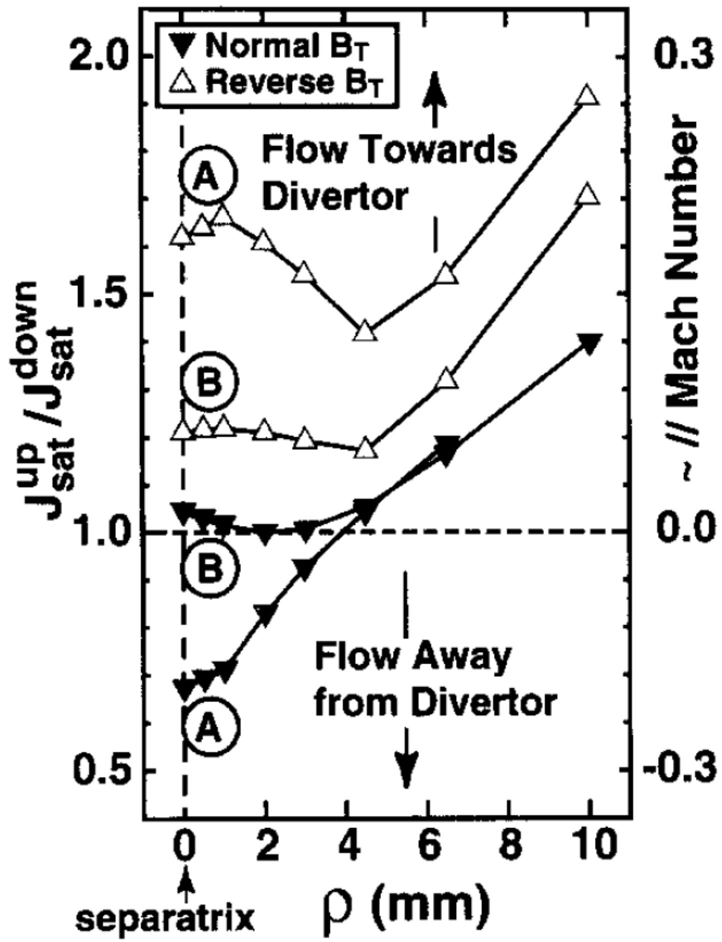
The flow velocity in attached tube (top) and detached tube (bottom) in the steady state of attached plasmas

The flow reversal of particles happens in the detached tube to supply the defection of particles.



The flow direction and velocity

Flow reversal -Experiment-



LaBombard B, Goetz J A, Hutchinson I *et al* 1997 J. Nucl. Mater. 241-243 149

Issues

・Reduction of the divertor heat load

・Detached divertor plasma regime decreases the temperature and the particle flux near the divertor plate.

・Partially detached divertor (PDD) plasmas are thermally more stable than perfectly detached ones and have been adopted for ITER operation scenarios.

・Instability of the detachment front

・The detachment front sometimes reaches the X-point (MARFE) and makes cooler region in the core plasma.

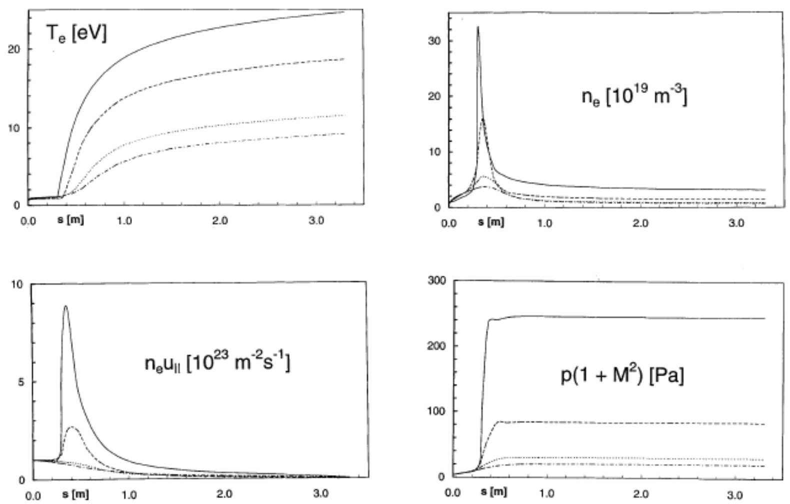
・Therefore we need to control the motion of the detachment front in order to make it stay in divertor region.

Issues

・Modeling of the PDD plasmas

・Some 2D codes have been used but sometimes do not reproduce experimental results of the detached divertor plasmas.

・Somewhat simpler codes such as 1D ones have been expected to be useful in order to get insights for PDD plasmas.



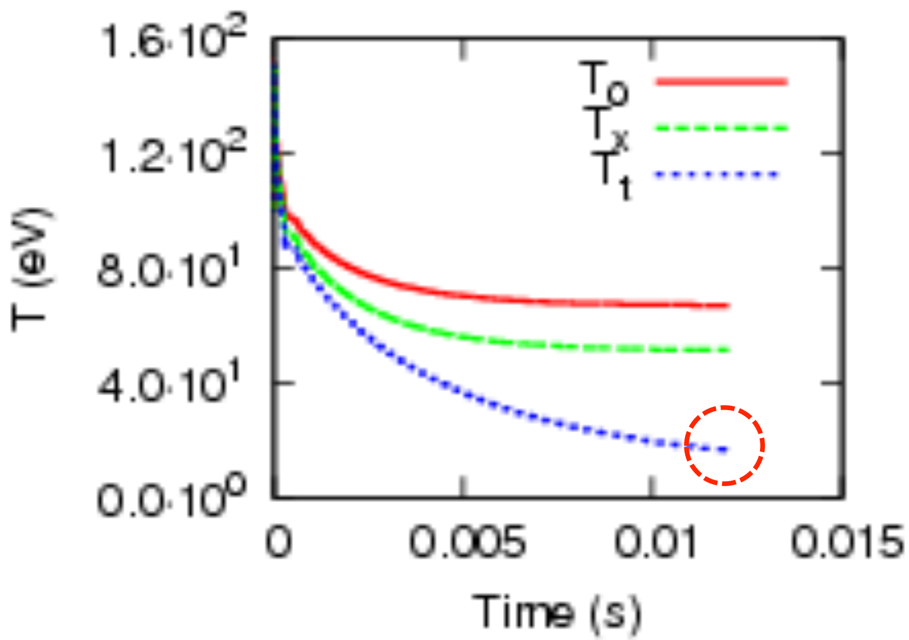
Results of strong detachment with O-SM
J. Nucl. Mater. 266-269 (1999) 1049.

・The multi-dimensionality of PDD plasmas

・1D models, such as Onion-Skin model (O-SM), have been used.

・However, such simpler models cannot reproduce the PDD plasmas because they are multi-dimensional phenomena.

Discussion -Problem of Neutral Model-



The time dependence of temperature under R=25

As the flux amplitude factor R gets larger, the temperature of the target cell gets lower.

When R comes to be around 50, the temperature of the target cell shows negative value, which is ruled out by the laws of physics.

Without auxiliary neutral, detached plasmas could not be reproduced under reasonable recycling rates.

Requirement

・In order to analyze detached divertor plasmas, we first have to solve time-dependent neutral conservation equation.

・Consequently, we will have to solve four conservation equations. The mending of the code will take very much time, so it is our future work.

Plasma particle conservation: $$\frac{\partial \rho}{\partial t} + \frac{\partial l}{\partial x} = mS$$

Momentum conservation: $$\frac{\partial l}{\partial t} + \frac{\partial}{\partial x}\left(lv + P\right) = M$$

Energy conservation: $$\frac{\partial K}{\partial t} + \frac{\partial}{\partial x}\left\{(K + P)v - \kappa_e \frac{\partial T}{\partial x}\right\} = Q$$

Neutral particle conservation: $$\frac{\partial n_n}{\partial t} + \frac{\partial}{\partial s}\left(n_n v_n\right) + diff = S_n$$

Repaired model

▪ **The neutral balance**

The neutral flux decay has become consistent with plasma particle source by ionization in each control volume.

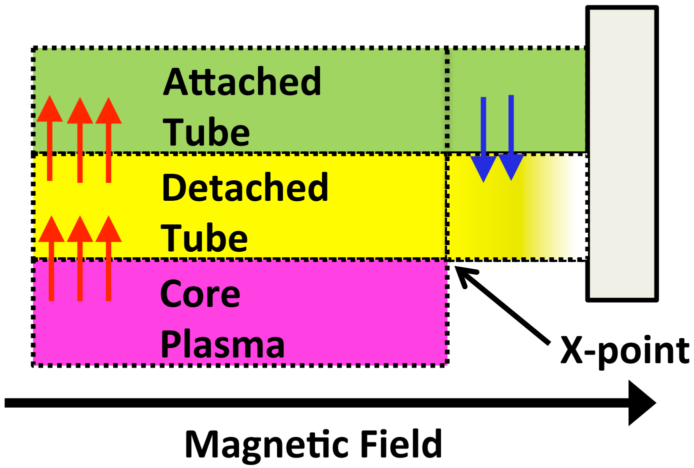
▪ **Boundary condition equation**

The treat of divertor boundary condition has become more sophisticated by solving boundary condition equation below separately from conservation law.

$$n_{div} = \Gamma_{div} / c_{s,div}$$

$$v_{div} = c_{s,div}$$

$$-\kappa_e \frac{\partial T}{\partial x}\bigg|_{div} = (\gamma - 5)\Gamma_{div} T_{div}$$



Solving Method

System equation

$$\frac{\partial \mathbf{U}}{\partial t} = -\frac{\partial \mathbf{F}}{\partial x} + \frac{\partial \mathbf{D}}{\partial x} + \mathbf{S}$$

$$\mathbf{U} = \begin{bmatrix} \rho \\ l \\ K \end{bmatrix} \qquad \mathbf{F} = \begin{bmatrix} l \\ lv + P \\ (K + P)v \end{bmatrix}$$

$$\mathbf{D} = \begin{bmatrix} 0 \\ 0 \\ \kappa_{\|e} \dfrac{\partial T}{\partial x} \end{bmatrix} \qquad \mathbf{S} = \begin{bmatrix} m_p S \\ M \\ Q \end{bmatrix}$$

System equation is devided into convection equation and diffusion equation.

Convection equation:

$$\frac{\mathbf{U}^* - \mathbf{U}^n}{\Delta t} = -\frac{\partial \mathbf{F}^n}{\partial x} + \mathbf{S}^{(conv)n}$$

Conduction equation:

$$\frac{\mathbf{U}^{n+1} - \mathbf{U}^*}{\Delta t} = \frac{\partial \mathbf{D}^{n+1}}{\partial x} + \mathbf{S}^{(cond)n}$$

The time step width is calculated with the equation below.

$$\Delta t = \frac{\Delta x}{\max_j \left| v_j + c_{\gamma,j} \right|} \times CFL$$

Physics near the detachment front