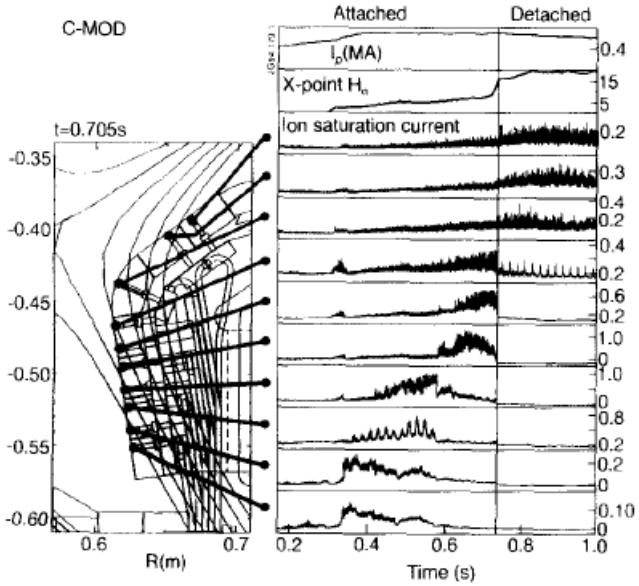
Simulation Study on behaviors of a detachment front in a divertor plasma: roles of the cross-field transport

Makoto Nakamura
Prof. Y. Ogawa, S. Togo, M. Ito

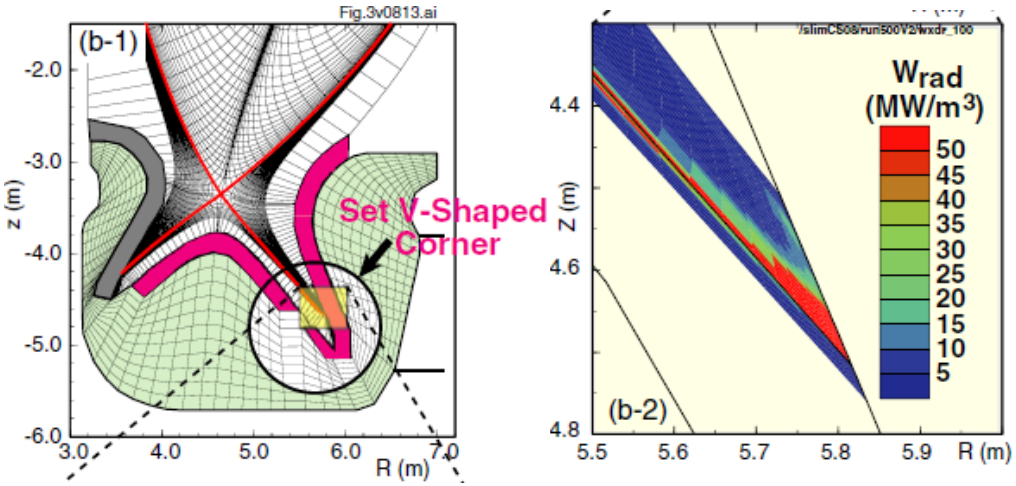
Department of Frontier Sciences,
the University of Tokyo

Introduction

- **Reduction of the divertor heat load**
  - **Partially detached divertor (PDD) regime**
    - ITER operation senario, the design of Slim-CS
- **Modeling of the PDD plasma**
  - 2D plasma-neutral coupling codes, e.g. SONIC and SOLPS, have been used.
    - The 2D codes sometimes do not reproduce experimental results of the detached plasmas.
    - They take too much time per a simulation.
      - which could be a serious problem to integrate core and SOL-divertor plasma transport codes.
    - **It is still unclear** how the detachment front is "captured" in a divertor region.



Typical experimental results of the PDD plasma
G.F. Matthews, J Nucl Mater 220-222 (1995) 104.

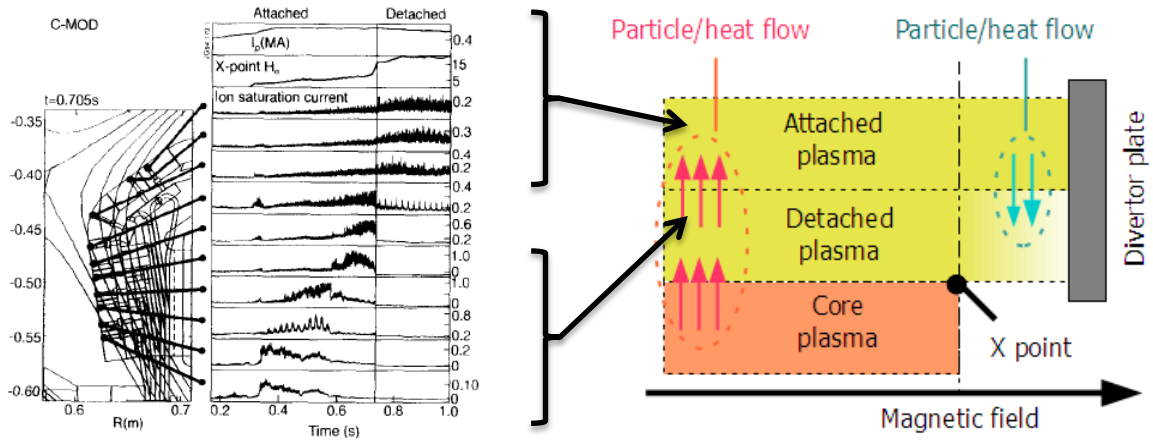


Example of PDD modelling by the SONIC code
(left：the divertor geometry analyzed; right：radiation distribution)
H.Kawashima etal, Nucl Fusion 49, 065007 (2009).

Introduction

- **Motivation**
  - Can the PDD plasma be analyzed by a model that is simpler than the 2D models ?
    - However, a 1-dimensional model, which is simpler than the 2D models, cannot reproduce the PDD plasmas, because the **PDD is a multi-dimensional phenomenon.**

- **Multi-Layer (ML) 1D model**
  - Intended to examine characteristics of the PDD plasma **one-dimensionally**



M. Nakamura et al, to be published in J Nucl Mater (2011)

  - Features:
    - the 1D axis is along the magnetic field, and the inner and outer tubes are **put adjacent each other**.
      - The **inner** tube should be **detached**, while the **outer** one should be **attached**.
    - The cross-field energy and particle transport terms are **approximated as source or loss terms** in the 1D transport equations of each tube.

- **Purposes of this work**
  - to analyze the PDD plasma by using a simple model like the ML1D model
  - to understand mechanisms to stabilize the detachment front in the divertor region

Model equations

- **1D plasma transport equation（for each tube）**

Particle conservation: $\frac{\partial n}{\partial t}+\frac{\partial}{\partial x}(nv)=S$

Momentum conservation: $\frac{\partial}{\partial t}(mnv)+\frac{\partial}{\partial x}\left(mnv^2+P\right)=M$

Energy conservation: $\frac{\partial}{\partial t}\left(3P+\frac{1}{2}mnv^2\right)+\frac{\partial}{\partial x}\left\{\left(5nT+\frac{1}{2}mnv^2\right)v-\kappa_{\|e}\frac{\partial T}{\partial x}\right\}=Q$

Particle source/loss terms:

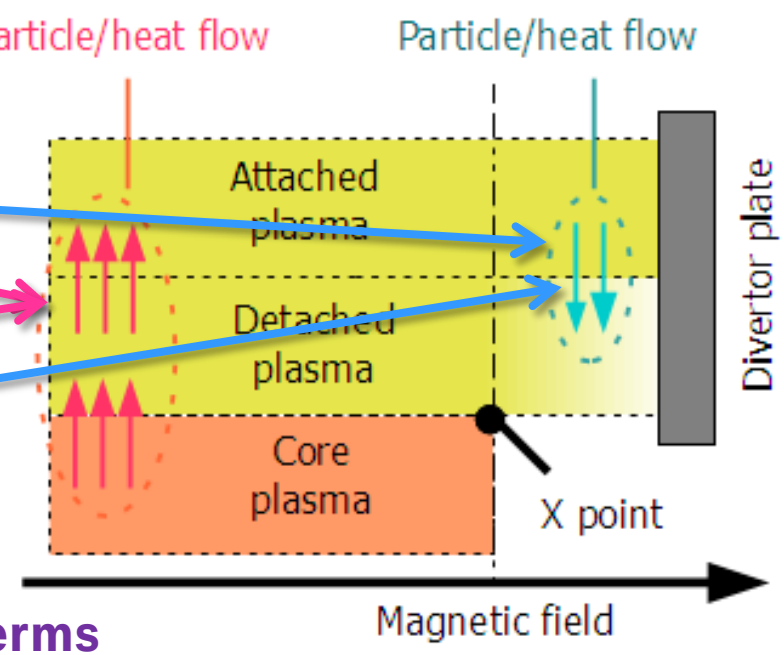
$$S=S_{\perp SOL}+S_{\perp div}+S_{ion}-S_{rec}$$

Momentum source/loss terms :

$$M=-M_{ion}-M_{cx}-M_{rec}$$

Energy source/loss terms :

$$Q=Q_{\perp SOL}+Q_{\perp div}-Q_{rad}-Q_{ion}-Q_{cx}-Q_{rec}$$

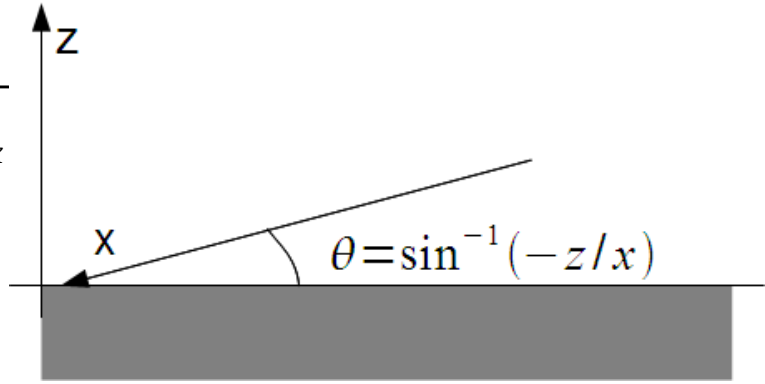


Cross-field transport is described as **source terms** in the framework of the ML1D model

Model equations

- **1D diffusion equation for neutrals**

$$\frac{\partial}{\partial z}\left(-D_n \frac{\partial n_n}{\partial z}\right) = S_{rec} - S_{ion} \qquad D_n = \frac{T}{mnS_{cx}}$$



Analytical solution:

$$n_n = n_{n,ref} \exp\left(-\frac{\xi}{\lambda_{n,ref}}\right)$$

$$\lambda_{n,ref} = \frac{v_n}{n\sqrt{\langle \sigma v \rangle_{cx} \langle \sigma v \rangle_{ion}}\,\sin\theta} \qquad \xi = \int_0^{\xi} \frac{n(\xi')}{n_{ref}} d\xi'$$

R. Schneider et al., Contrib Plasma Phys 46 (2006) 3.

Boundary condition for n_n @ the divertor plate:

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

Neutral outflux

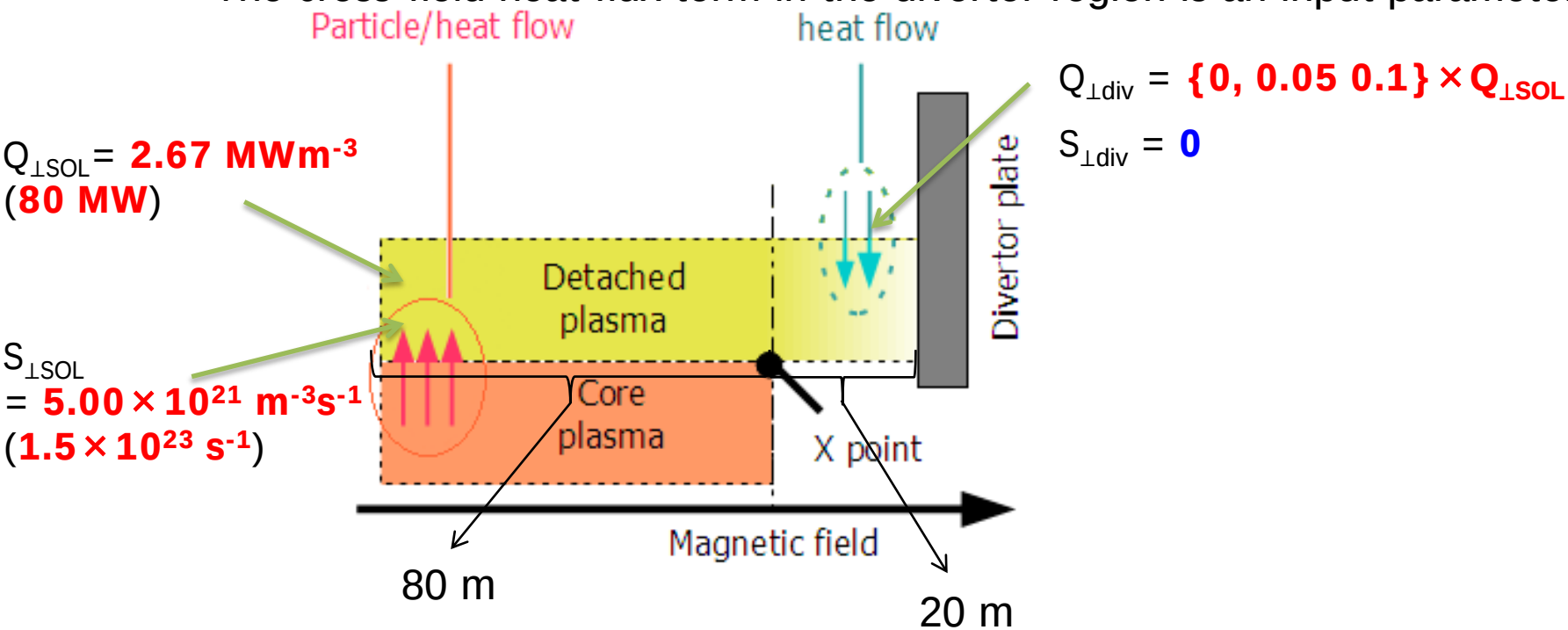
Plasma particle flux

Auxiliary neutral outflux at the divertor target (scan parameter)

Preliminary results : simulation *only* of the inner tube

M.Nakamura etal, to be published in J. Nucl. Mater. (2011).

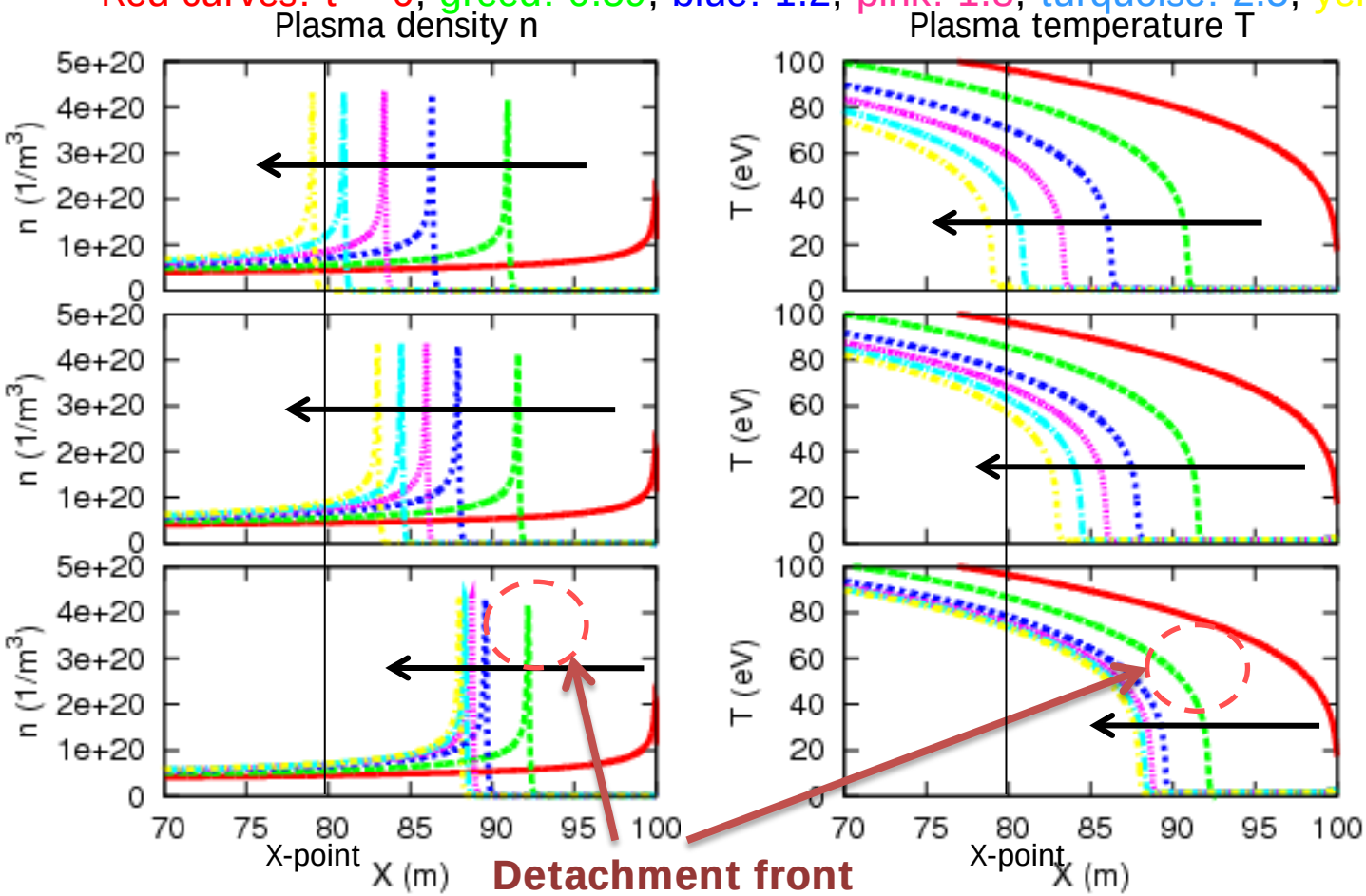
- **Movement of a detachment front in the inner flux tube**
  - Conditions : ITER-like SOL-divertor plasma
    - The cross-field heat flux term in the divertor region is an input parameter



Under these assumptions, we performed 1D plasma simulations *only* for the *inner* flux tube.

- **Simulation results: time evolution of n & T**

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



(reference)
$Q_{\perp div}$ = **0**
(w/o the cross-field heat flux)

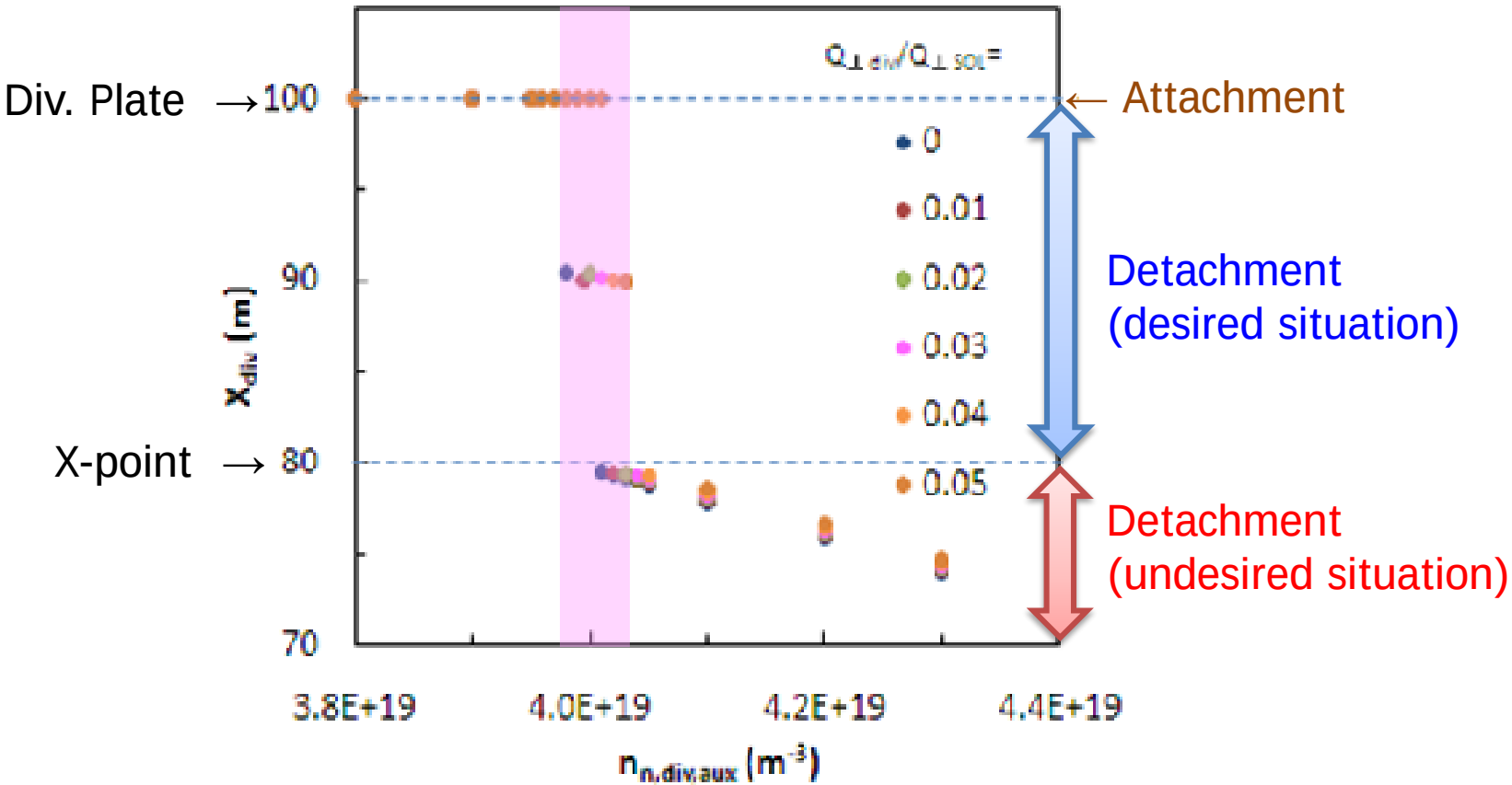
$Q_{\perp div}$
= **0.05 × $Q_{\perp SOL}$**
(w/ the cross-field heat flux)

$Q_{\perp div}$
= **0.1 × $Q_{\perp SOL}$**
(w/ the cross-field heat flux)

- **The cross-field heat flux in the divertor region can prevent the detachment front from moving upstream.**

M.Nakamura etal, to be published in J. Nucl. Mater (2011).

- **Position of the detachment front in a steady state**
  - as a function of the auxiliary neutral density at the divertor plate

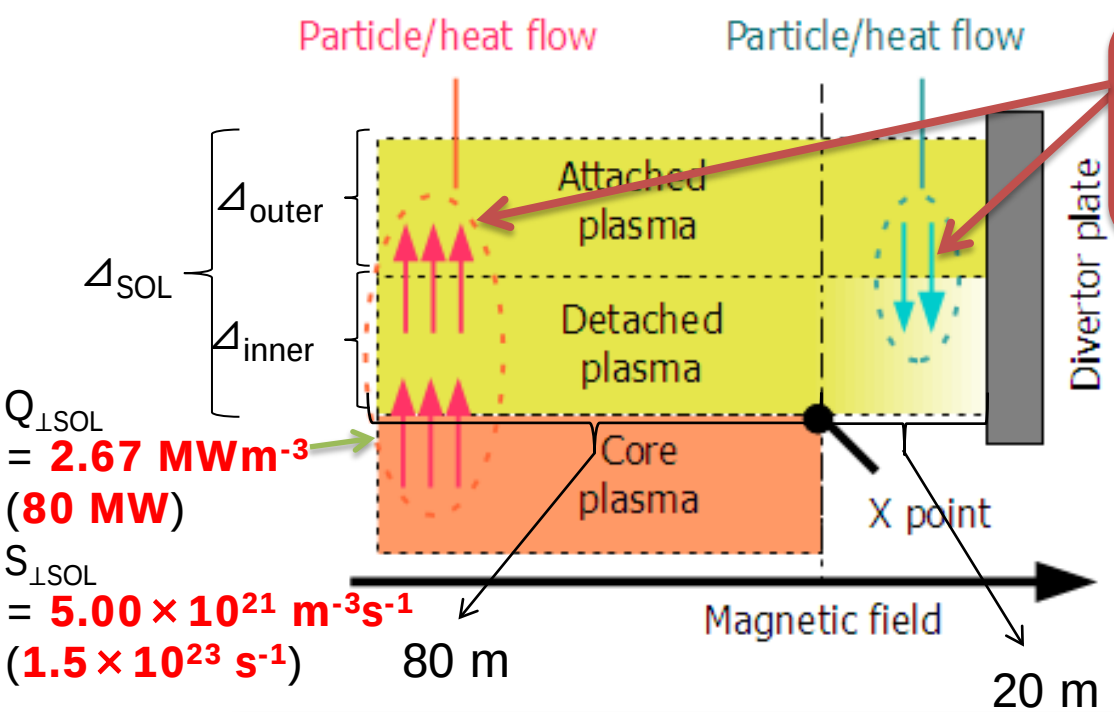


● The operation range of the neutral density at divertor plate such that the the detachment front in the divertor region is so narrow.

✓ The detachment front in the divertor region is **thermally unstable**.

Simulation by the ML1D model

- **Simultaneous simulation of the inner/outer tubes 1:**
  Effects of the cross-field heat flux
  - Conditions: ITER-like SOL-divertor plasma
    - We used the model cross-field heat flux



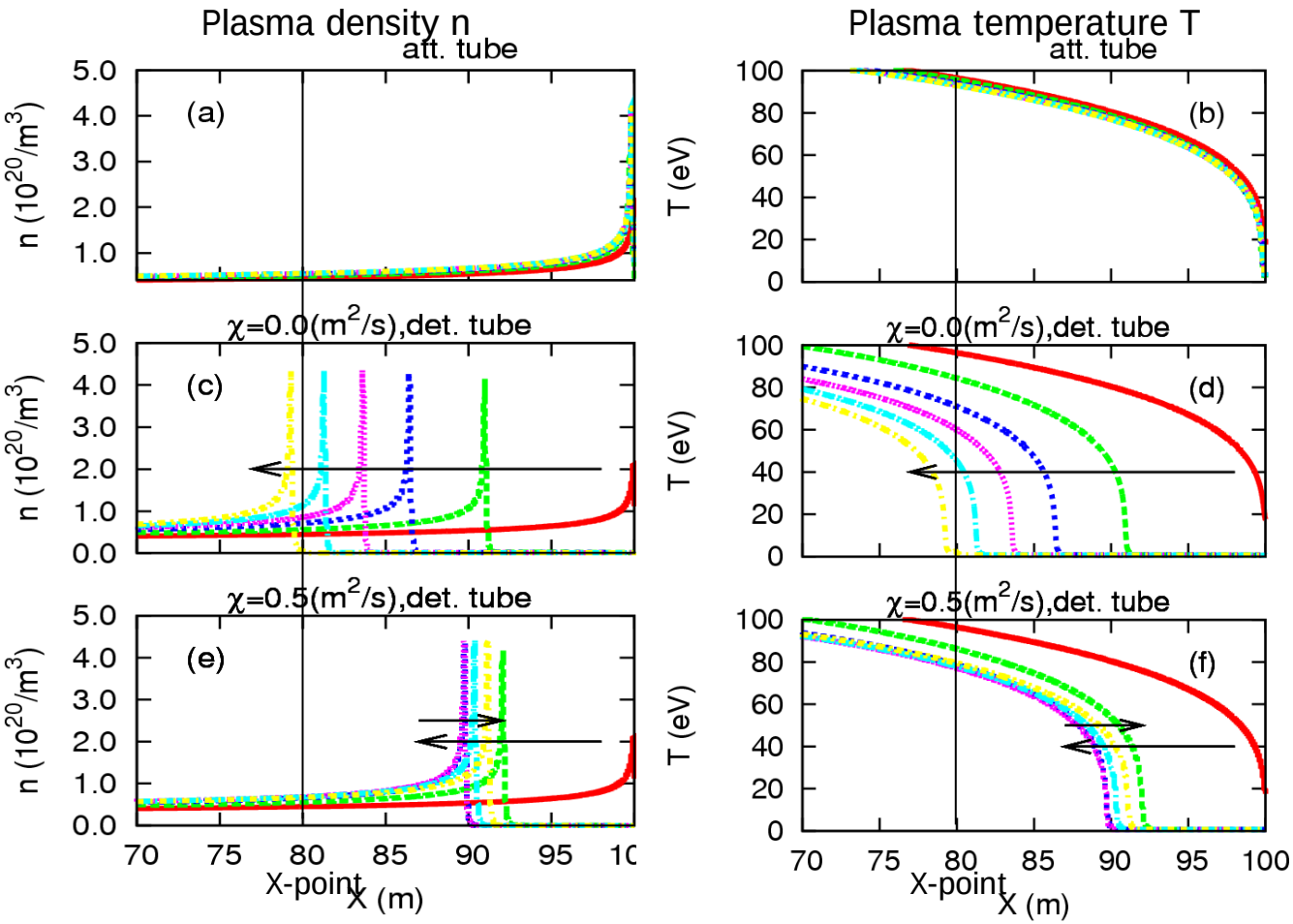
Cross-field heat flux:

$$q_{\perp div} = -\chi_{\perp} n (T_{det} - T_{att}) / (\Delta_{SOL}/2)$$

Under these assumptions, we performed 1D plasma simulations *both* for the *inner and outer* flux tubes

- **Simulation results: time evolutions of n & T**

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



Outer (attached) tube

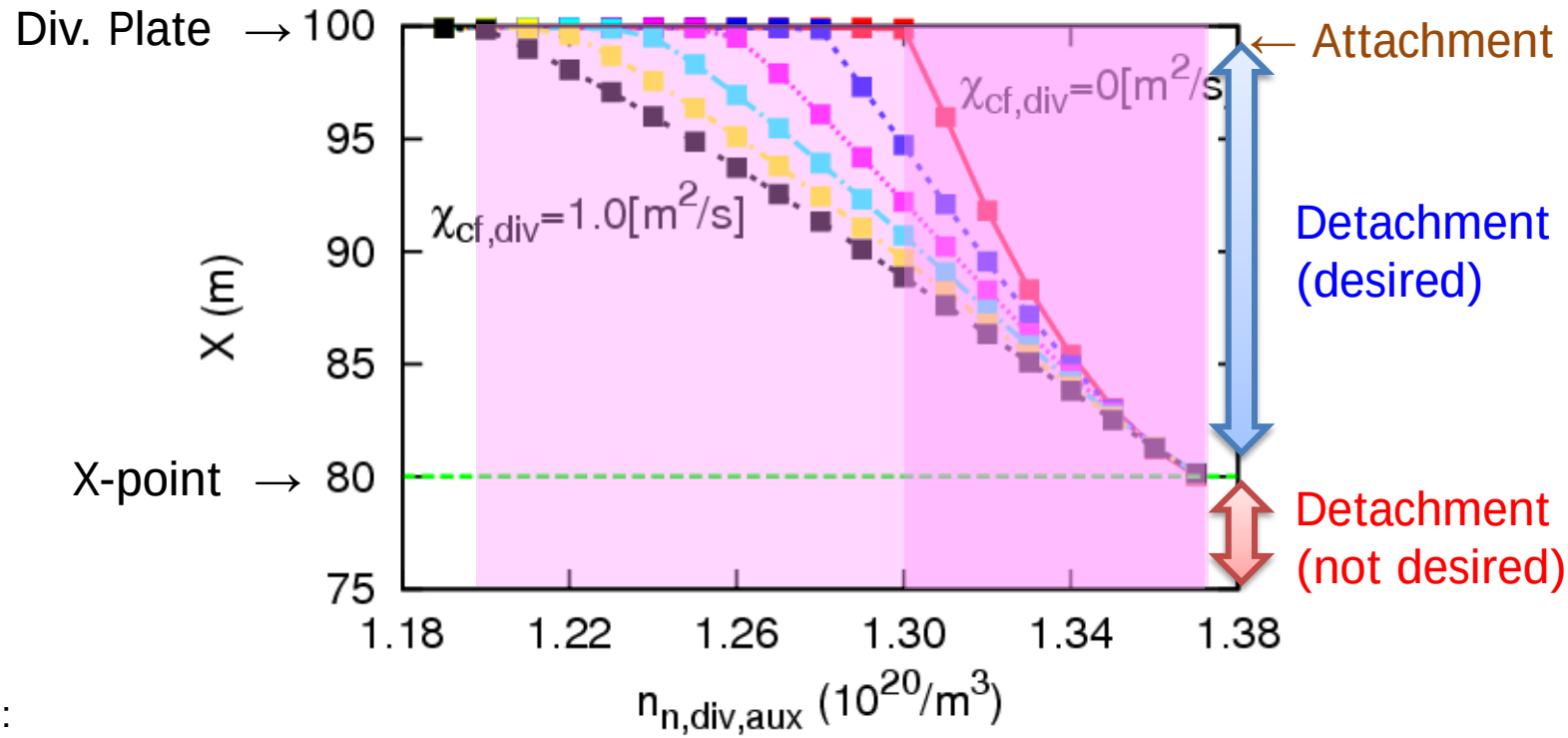
Inner (detached) tube (**w/o the cross-field heat flux in the divertor region**)

Inner (detached) tube (**w/ the cross-field heat flux in the divertor region**)

$\chi_\perp$ = 1.0 m^2/s

- **In the case with the cross-field heat flux in the divertor region, it prevents the detachment front moving upstream.**
  - ✓ agreeing with the previous simulation study only of the inner tube.

• Position of the detachment front in a steady state



NOTE:
- $D_\perp$=0 is assumed at the divertor region.
- The non-zero $\chi_\perp$ and $D_\perp$ are given in the SOL region.

● In the framework of the ML1D model, even in the case without the cross-field heat flux in the divertor region, **the neutral particle operation range** in which the detachment front is stagnated in the divertor region is **broadened**.

● When **the cross-field heat flux** is introduced in the divertor region, such neutral operation range is **extended further**.

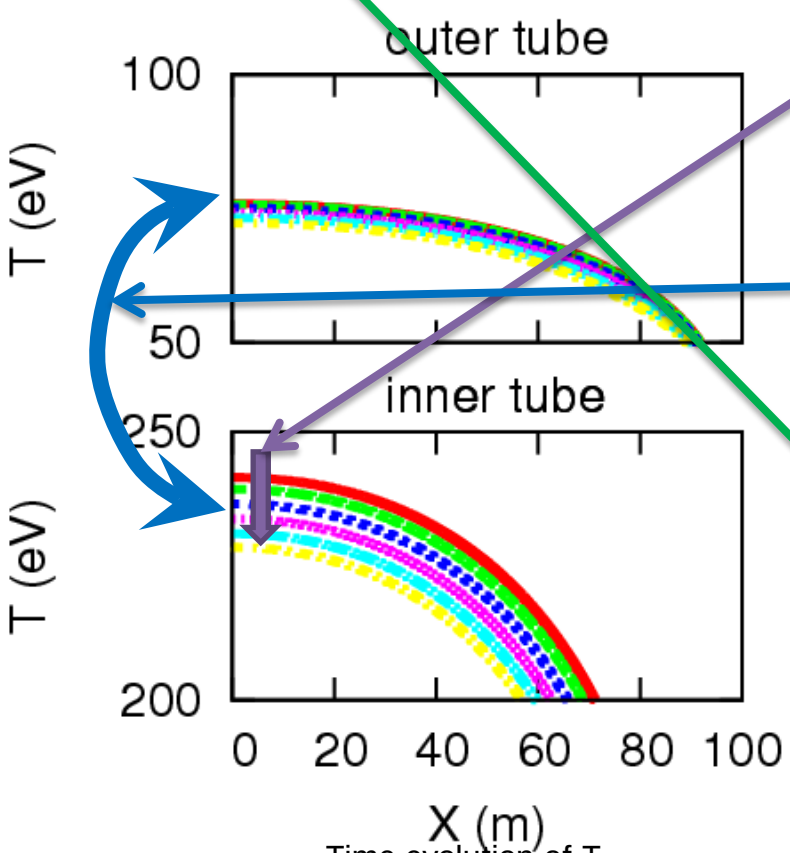
• Discussion 1: effect of the cross-field transport in the SOL region

The energy balance of the control volume around the detachment front (DF)

$$\frac{dK}{dt} = \int q_{\parallel} dS + \int q_{\perp} dS - \int |Q_{loss}| dV$$

increased

dK/dt < 0 : the DF moving upstream
dK/dt > 0 : the DF moving downstream



Time evolution of T
in the outer (top) and inner (bottom) tubes

1. Because of the detachment near the divertor plate in the inner tube and the parallel heat conductivity, the upstream SOL temperature is decreased rapidly.
2. The difference in the upstream temperatures between the inner and outer tubes is decreased.
3. The outward cross-field heat flux from the inner tube to the outer tube is decreased in the SOL region.
4. The parallel heat flux from upstream into the DF region is increased because of the energy conservation in the SOL region.
5. **dK/dt becomes zero or positive, and the DF stops moving upstream.**

The heat transport in the upstream SOL region affects the stability of the DF in the divertor region.

- **Discussion 2: effect of the cross-field transport in the div. region**

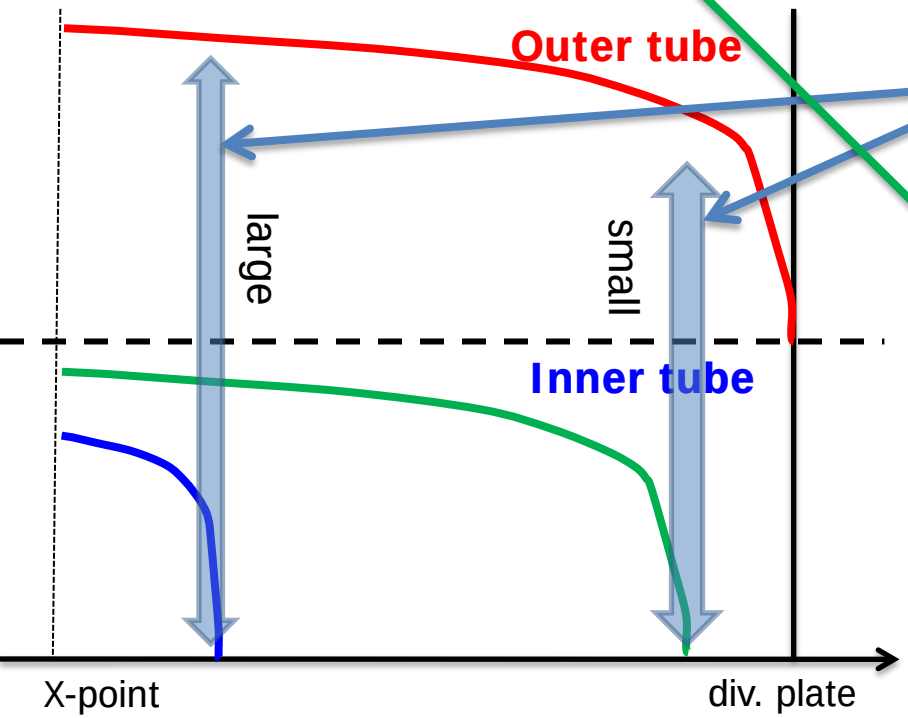
The energy balance of the control volume around the detachment front (DF)

$$\frac{dK}{dt} = \int q_{\parallel} dS + \int q_{\perp} dS - \int |Q_{loss}| dV$$

increased

dK/dt < 0 : the DF moving upstream
dK/dt > 0 : the DF moving downstream

Schematic picture of T in the inner/outer tubes



1. As the DF moves upstream, difference in the temperature between the inner and outer flux tubes is increased in the divertor region.
2. The inward cross-field heat flux into the control volume around the DF in the inner tube is increased.
3. **dK/dt becomes zero or positive, and the DF stops moving upstream.**

The cross-field heat transport in the downstream divertor region also affects the stability of the DF in the divertor region.

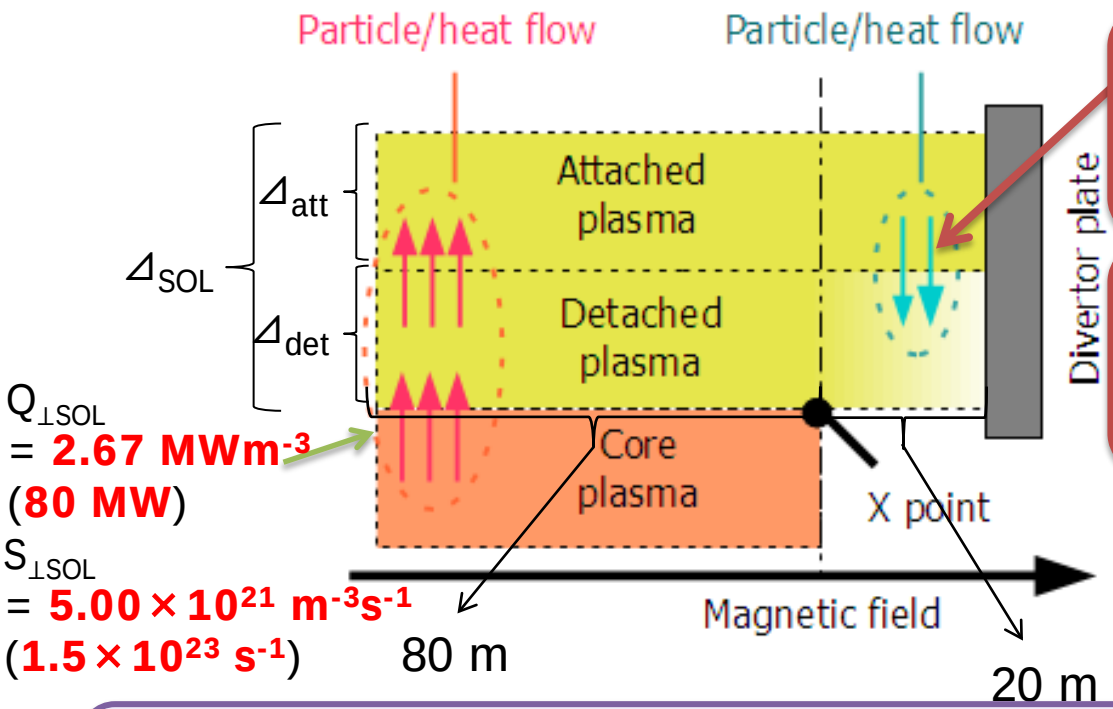
Simulation by the ML1D model

- **Simultaneous simulation of the inner/outer tubes 2:**

  Effects of the cross-field heat & particle flux

  – Conditions: ITER-like SOL-divertor plasma

    - Not only the model cross-field heat flux but also the model particle flux in the divertor region



Cross-field heat flux:

$$q_{\perp div} = -\chi_{\perp} n (T_{det} - T_{att}) / (\Delta_{SOL}/2)$$

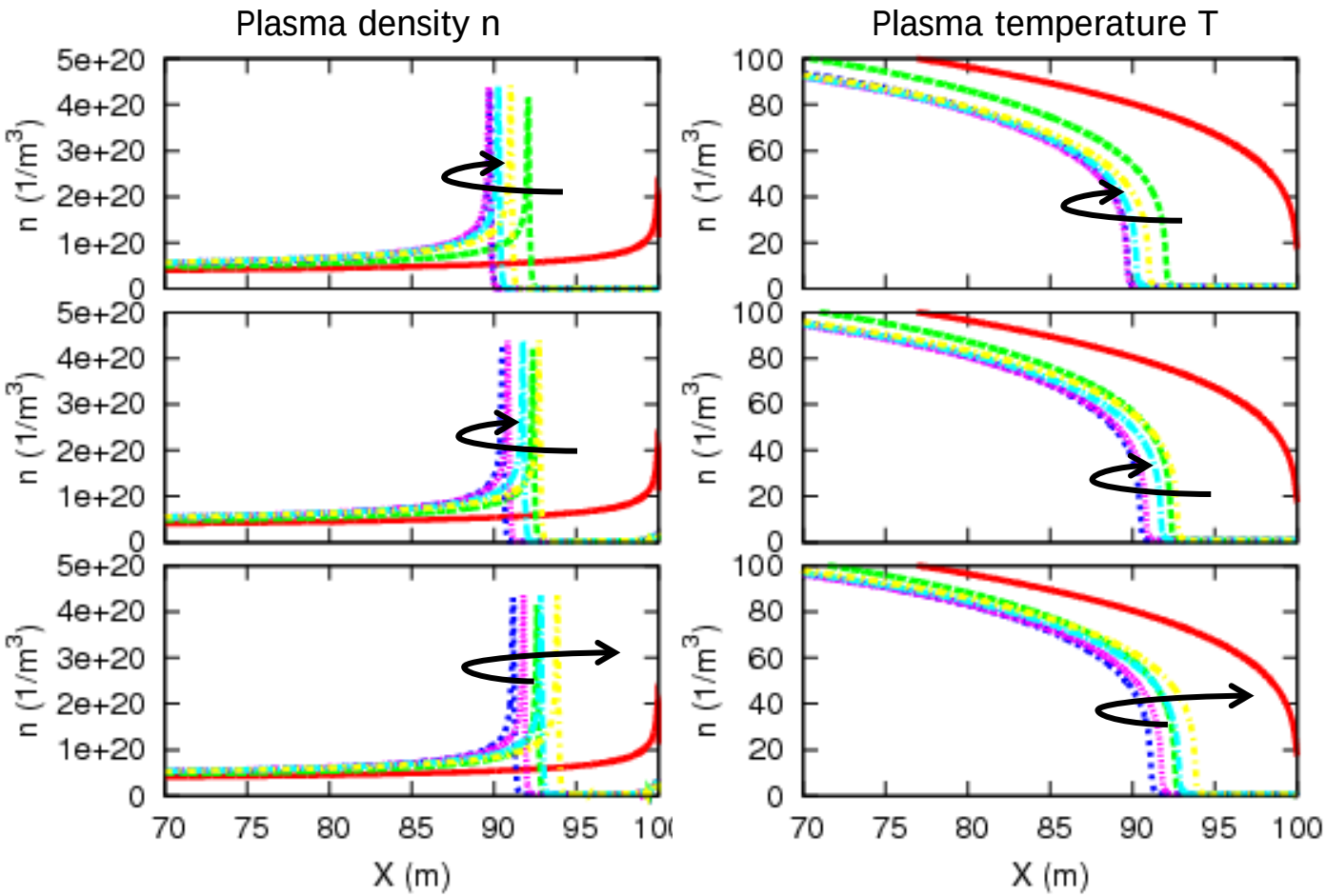
Cross-field particle flux:

$$\Gamma_{\perp div} = -D_{\perp} (n_{det} - n_{att}) / (\Delta_{SOL}/2)$$

Under these assumptions, we performed 1D plasma simulations ***both*** for the ***inner and outer*** flux tubes.

- **Simulation results: time evolutions of n & T**

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



(reference)
$\chi_\perp$ = 1.0 m^2/s
$D_\perp$ = 0
(**w/o the cross-field particle transport in the divertor region**)

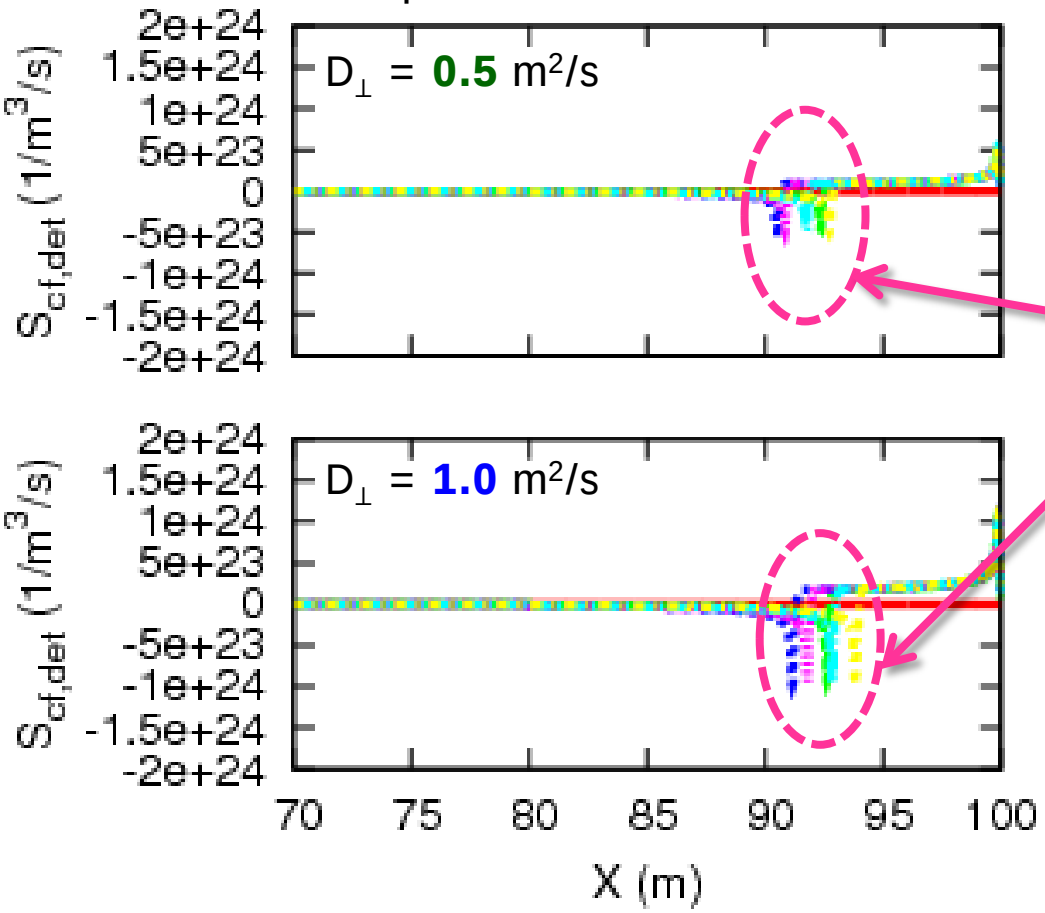
$\chi_\perp$ = 1.0 m^2/s
$D_\perp$ = **0.5** m^2/s
(**w/ the cross-field particle transport in the divertor region**)

$\chi_\perp$ = 1.0 m^2/s
$D_\perp$ = **1.0** m^2/s
(**w/ the cross-field particle transport in the divertor region**)

- **The cross-field particle flux in the divertor region, as well as the cross-field heat flux, prevents the detachment front from moving upstream.**

- **Discussion 3:**
  effects of the cross-field particle transport in the divertor region

The cross-field particle source term in the inner tube



<u>Around the detachment front</u>

$S_\perp < 0$:

- The cross-field particle transport is **outward**.
  - ➢ Because of the density peaking due to ionizations
  - ➢ Decrease in the density peaking and energy loss due to recombinations.

- **The cross-field particle transport in the divertor region prevent the detachment front from moving upstream.**

Summary

Simulation study on behaviors of the detachment front in a divertor plasma

- We proposed **the multi-layer 1D model** to analyze the PDD plasma one-dimensionally.
- By using this model we found that
  - **the cross-field heat transport** in both of the **upstream SOL** and **downstream divertor** regions affects the stability of the detachment front in the divertor region, and that
  - **the cross-field particle transport** in the divertor region also affects the stability of the detachment front.

Our simulation results show that
in order to establish operation conditions of the detached plasma regime, it is crucially important to **measure and model the cross-field transport coefficients in the SOL-divertor plasma.**