合同会合＠筑波大学　2014/08/01

非等方イオン温度と仮想ダイバータモデルを導入したSOL-ダイバータプラズマシミュレーション

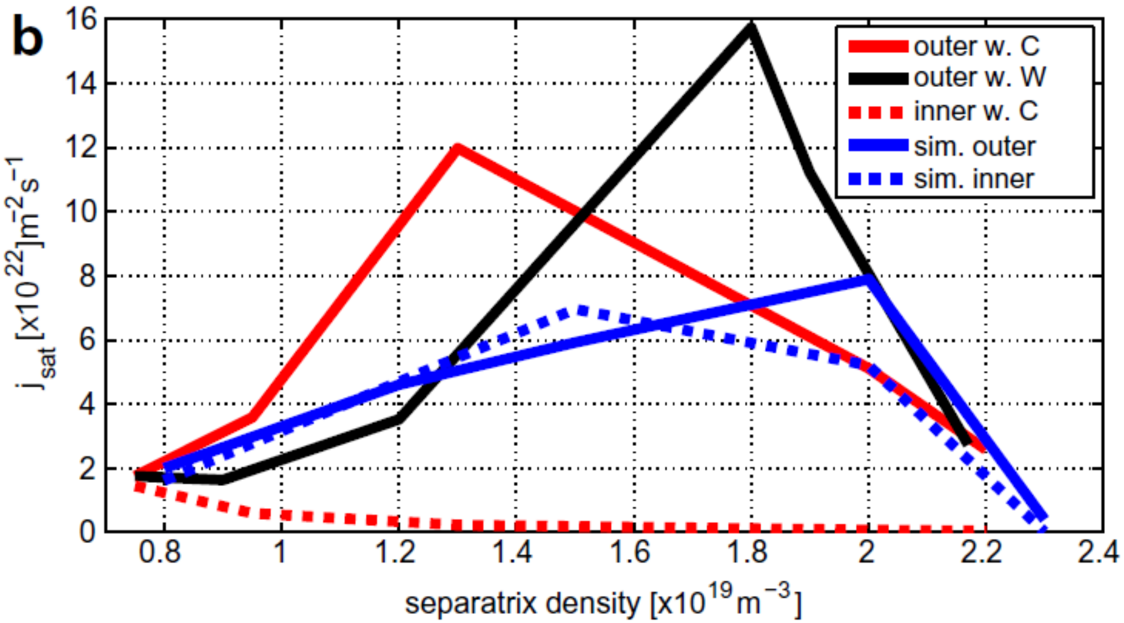
Satoshi Togo, Tomonori Takizuka[a], Makoto Nakamura[b], Kazuo Hoshino[b], Yuichi Ogawa

Graduate School of Frontier Sciences, University of Tokyo, 5-1-5 Kashiwanoha, Kashiwa 277-8568, Japan
[a]Graduate school of Engineering, Osaka University, 2-1 Yamadaoka, Suita 565-0871, Japan
[b]Japan Atomic Energy Agency, 2-166 Omotedate, Obuchi, Rokkasho, Aomori 039-3212, Japan

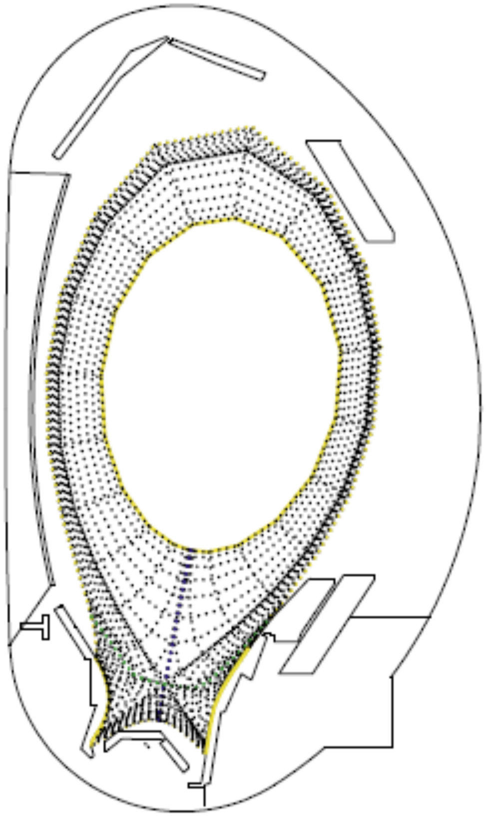
Introduction

Edge transport code packages, such as SOLPS and SONIC, are widely used to predict performance of the scrape-off layer (SOL) and divertor of ITER and DEMO. Simulation results, however, have not satisfactorily agreed with experimental ones.

Comparison of results (EXP vs SIM)



M. Wischmeier *et al.*, J. Nucl. Mater. **390-391**, 250 (2009).



Introduction

The parallel ion viscosity term in the momentum transport equation is an approximated form of the ion pressure anisotropy which is derived under the assumption that the temperature anisotropy is small enough.

$$\frac{\partial m_i nV}{\partial t} + \frac{\partial}{\partial x}\left(m_i nV^2 + nT_{i,//} + nT_e\right) = M$$

rigorous equation with **anisotropic** T_i and **no viscosity term**

$$nT_i = n\left(T_{i,//} + 2T_{i,\perp}\right)/3 \qquad nT_{i,//} = nT_i + \pi_i$$

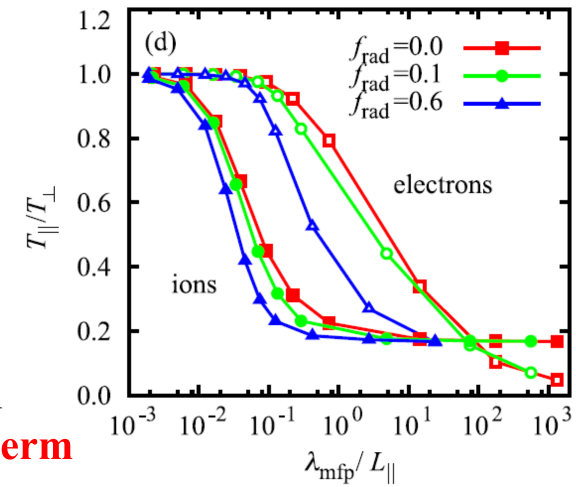
$$\pi_i = 2n\left(T_{i,//} - T_{i,\perp}\right)/3 \qquad nT_{i,\perp} = nT_i - \pi_i/2$$

variable transformation

$$\frac{\partial m_i nV}{\partial t} + \frac{\partial}{\partial x}\left(m_i nV^2 + nT_i + nT_e\right) + \frac{\partial \pi_i}{\partial x} = M$$

$$\frac{\partial m_i nV}{\partial t} + \frac{\partial}{\partial x}\left(m_i nV^2 + nT_i + nT_e\right) + \frac{\partial}{\partial x}\left(-\eta_{i,//}\frac{\partial V}{\partial x}\right) = M$$

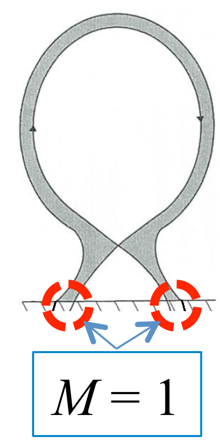
conventional equation with **isotropic** T_i and **viscosity term**



A. Froese *et al.*, Plasma Fusion Res. **5** (2010) 026.

Kinetic simulations showed **remarkable anisotropy in the ion temperature even for the medium collisional regime.**

Boundary condition at the divertor plate is necessary to solve this Eq. and the Bohm condition $M = 1$ is usually adopted, while **rigorous Bohm condition only imposes the lower limit of $M \geq 1$.**



Method (plasma fluid equations)

Eq. of continuity

$$\frac{\partial m_i n}{\partial t} + \frac{\partial m_i n V}{\partial x} = S$$

Eq. of momentum transport

$$\frac{\partial m_i n V}{\partial t} + \frac{\partial}{\partial x}\left(m_i n V^2 + nT_{i,//} + nT_e\right) = M$$

Eq. of parallel (//) ion energy transport

$$\frac{\partial}{\partial t}\left(\frac{1}{2}m_i n V^2 + \frac{1}{2}nT_{i,//}\right) + \frac{\partial}{\partial x}\left(\frac{1}{2}m_i n V^2 + \frac{3}{2}nT_{i,//}\right)V + c\frac{\partial q_{i,//}^{\mathrm{eff}}}{\partial x} = Q_{i,//} + \frac{n\left(T_{i,\perp} - T_{i,//}\right)}{\tau_{\mathrm{rlx}}} + \frac{m_e}{m_i}\frac{n\left(T_e - T_{i,//}\right)}{\tau_e} - V\frac{\partial nT_e}{\partial x}$$

Eq. of perpendicular (⊥) ion energy transport

$$\frac{\partial nT_{i,\perp}}{\partial t} + \frac{\partial nT_{i,\perp}V}{\partial x} + (1-c)\frac{\partial q_{i,\perp}^{\mathrm{eff}}}{\partial x} = Q_{i,\perp} - \frac{n\left(T_{i,\perp} - T_{i,//}\right)}{\tau_{\mathrm{rlx}}} + \frac{2m_e}{m_i}\frac{n\left(T_e - T_{i,\perp}\right)}{\tau_e}$$

Eq. of electron energy transport

$$\frac{\partial}{\partial t}\left(\frac{3}{2}nT_e\right) + \frac{\partial}{\partial x}\left(\frac{5}{2}nT_e\right)V + \frac{\partial q_e^{\mathrm{eff}}}{\partial x} = Q_e + \frac{3m_e}{m_i}\frac{n\left(T_i - T_e\right)}{\tau_e} + V\frac{\partial nT_e}{\partial x}$$

By introducing the anisotropic ion temperature directly into the fluid modeling, **the second-derivative parallel ion viscosity term can be excluded because the ion pressure term can be written by its parallel component $nT_{i,//}$.**

Momentum transport equation becomes **1st order differential equation**. Therefore the boundary condition at the sheath entrance becomes **unnecessary**.

$c = 0.5$

Flux limiting coefficient:

$\alpha_{i,//} = \alpha_{i,\perp} = 0.5$, $\alpha_e = 0.2$

ion temperature anisotropy relaxation time: $\tau_{\mathrm{rlx}} = 2.5\tau_i$

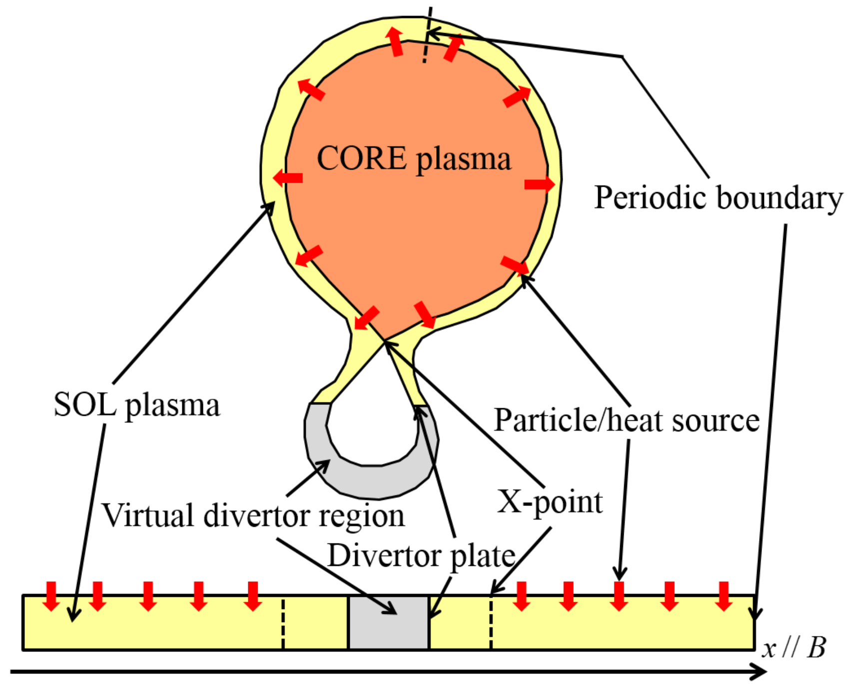
(E. Zawaideh *et al.*, Phys. Fluids **29** (1986) 463)

are used in the present study.

Method (1D system with Virtual Divertor Model)

In order to express the effect of the divertor plate, a "**virtual divertor (VD)" model** is introduced which has an **artificial sinks of particle, momentum and energy**.

This VD model makes **the periodic boundary condition available**.



The model of sink in the VD region:

$$S^{\mathrm{VD}} = -\frac{m_i n}{\tau_{\mathrm{VD}}} \qquad M^{\mathrm{VD}} = -\frac{m_i n V}{\tau_{\mathrm{VD}}} + \frac{\partial}{\partial x}\left(\eta_{\mathrm{VD}} \frac{\partial V}{\partial x}\right)$$

$$Q_{\mathrm{i},//}^{\mathrm{VD}} = -\frac{1}{\tau_{\mathrm{VD}}}\left(\frac{1}{2} m_{\mathrm{i}} n V^2 + g_{\mathrm{i},//} \frac{1}{2} n T_{\mathrm{i},//}\right)$$

$$Q_{\mathrm{i},\perp}^{\mathrm{VD}} = -\frac{g_{\mathrm{i},\perp} n T_{\mathrm{i},\perp}}{\tau_{\mathrm{VD}}} \qquad Q_{\mathrm{e}}^{\mathrm{VD}} = -\frac{1}{\tau_{\mathrm{VD}}}\left(g_{\mathrm{e}} \frac{3}{2} n T_{\mathrm{e}}\right)$$

Artificial viscosity is necessary for the velocity profile to analytically connect in the divertor region.

decay time $\tau_{\mathrm{VD}} = 5\times10^{-6}$ s
artificial viscosity coefficient $\eta_{\mathrm{VD}} = 1\times10^{-5}$ Pa·s
VD cooling coefficient:
$g_{\mathrm{i},//} = 1$, $g_{\mathrm{i},\perp} = 1.2$, $g_{\mathrm{e}} = 2.5$
(in center of VD, $g_{\mathrm{i},//} >> 3$)
are used in the present study.

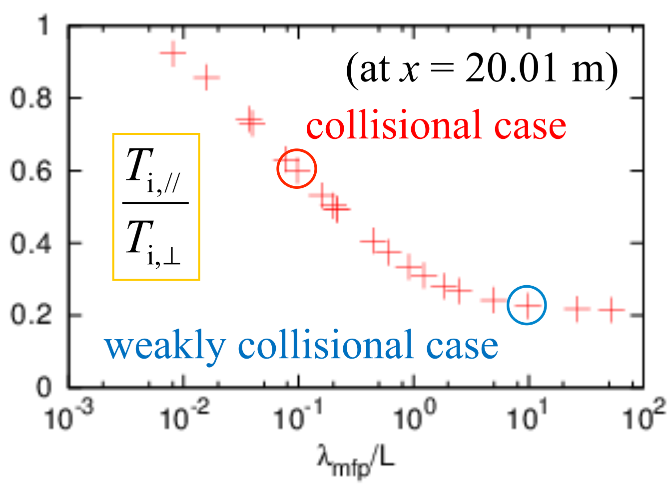
Results (Bohm condition and T_i anisotropy)

Parameters of a symmetric SOL-divertor system
Length of plasma region, VD region, divertor region $L = 44$ m, $L_{VD} = 6$ m, $L_{div} = 4.4$ m (X-point ~ plate)
SOL width, Surface area of the separatrix $d_{SOL} = 2$ cm , $S_{sep} = 40$ m^2
Mesh size, Time step, Calculation time (quasi-stationary) $\Delta x = 2$ cm, $\Delta t = 2\times10^{-8}$ s, $t = 2\times10^{-3}$ s
Γ_{sep} (particle flux) and P_{sep} (heat flux) are given in a wide range

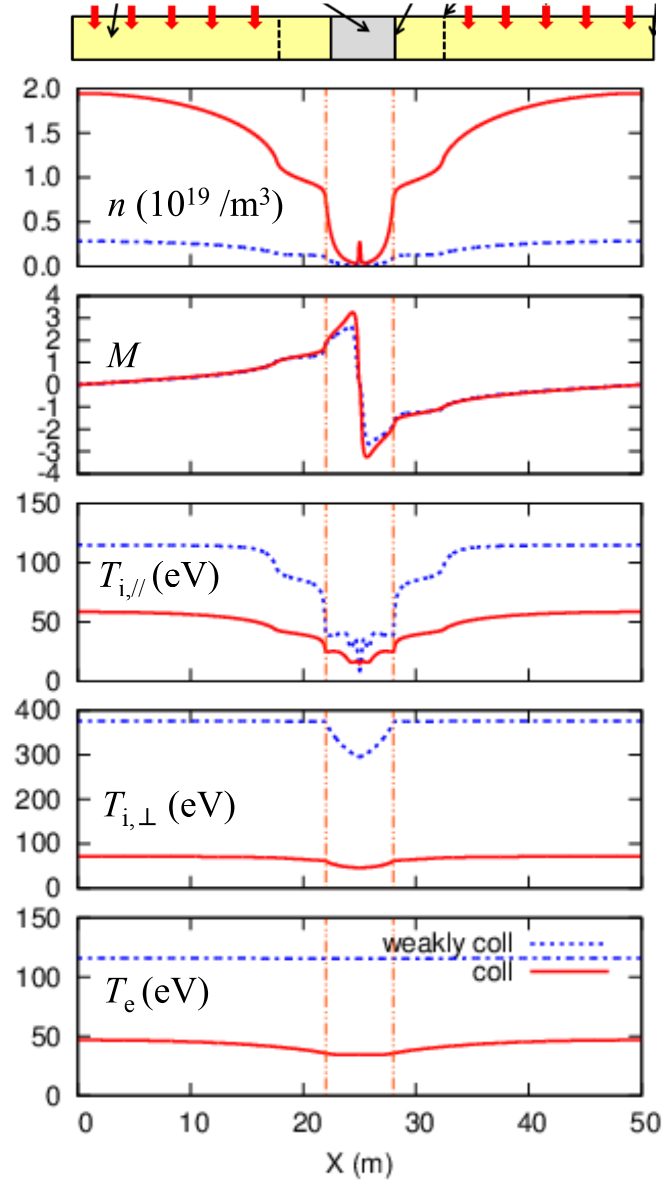
Bohm condition is satisfied automatically.

Ion temperature quickly shifts to anisotropic even for $\lambda_{mfp}/L > 0.01$.

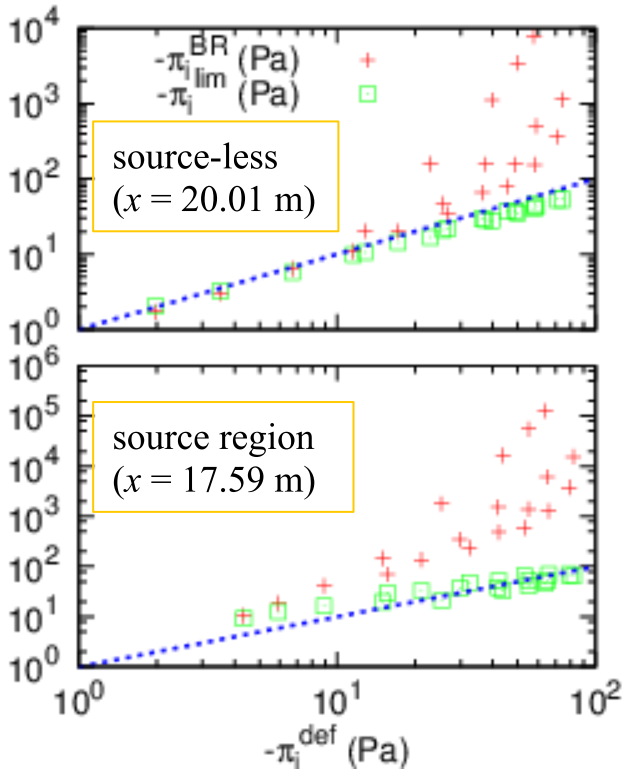
$$\lambda_{mfp} = v_{th,i,//}\tau_i$$



Profiles of SOL-div. plasmas



Results (validity of the approximated ion viscosity)



Two kinds of approximated parallel ion viscosity,

$$\pi_i^{BR} = -\eta_{i,//}\frac{\partial V}{\partial x} \qquad \left(\eta_{i,//} = 0.96nT_i\tau_i\right)$$

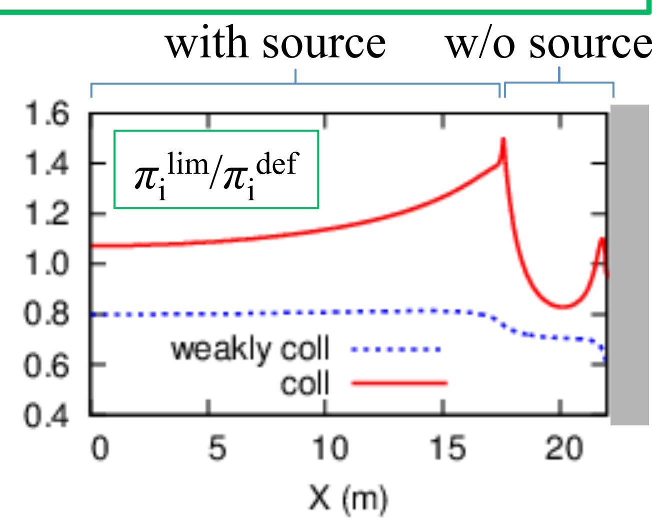
$$\pi_i^{lim} = \left(\frac{1}{\pi_i^{BR}} + \frac{1}{\beta n T_i}\right)^{-1}$$

$\beta = 0.5$:viscosity limiting factor

are compared to the ion pressure anisotropy, $\pi_i^{def} = 2n(T_{i,//}\text{-}T_{i,\perp})/3$, in the **source-less** (x = 20.01 m) and **source region** (x = 17.59 m).

In the source region, **the correlation between π_i^{lim} and π_i^{def} becomes worse.**

In the collisional regime, the limited viscosity π_i^{lim} is dominated by the Braginskii expression π_i^{BR} and much affected by the gradient of V which is brought by the particle source.



Conclusions

・A one-dimensional SOL-divertor plasma simulation code has been developed by introducing the **anisotropic ion temperature** and a **virtual divertor (VD) model** and **we have been successfully obtained the SOL-divertor plasmas satisfying the rigorous Bohm condition, $M \geq 1$**.

・Simulations for various normalized ion MFPs, λ_{mfp}/L, have been conducted and show that **the ion temperature shifts quickly from isotropic to anisotropic even for $\lambda_{mfp}/L \sim 0.01$**.

・The validity of the approximated parallel ion viscosity has also been investigated. The limited parallel ion viscosity shows a good proportional relation to the definition of the parallel ion viscosity in the source-less region, but **the correlation becomes worse in the source region**.

There remain some issues which are not treated with in the present study.

★Introduction of the plasma current, which does not flow in the symmetric system, to study the general asymmetric system

★Introduction of the radiation model and neutral model to investigate the high-recycling cold-and-dense plasmas and detached plasmas.

These issues will be discussed in the future papers.