ダイバータプラズマの高速流に対するドリフトの影響

Effect of Drifts on High Mach Flows in Divertor Plasmas

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Background

High parallel flows associated with plasma detachment have been observed in several experiments[1][2] and simulations[3]. Large Mach flows up to Mach 1 or even larger have been measured near the X-point away from the target plate.

[1] ASDEX-Upgrade :

Tsois, N. *et al.*, J. Nucl. Mater. 266-269(1999)1230.

[2] JT-60U W-shaped Geometry :

Asakura, N. *et al.*, Nucl. Fusion 39(1999)1983.

[3]Simulation :

Hatayama,A. *et al*., Nucl.Fusion 40(2000)2009.

We compared numerical analysis by two dimensional transport code(B2-EIRENE) with experimental result.

Numerical result by B2-EIRENE *

(a) Numerical Result **(b) Experimetal Result**

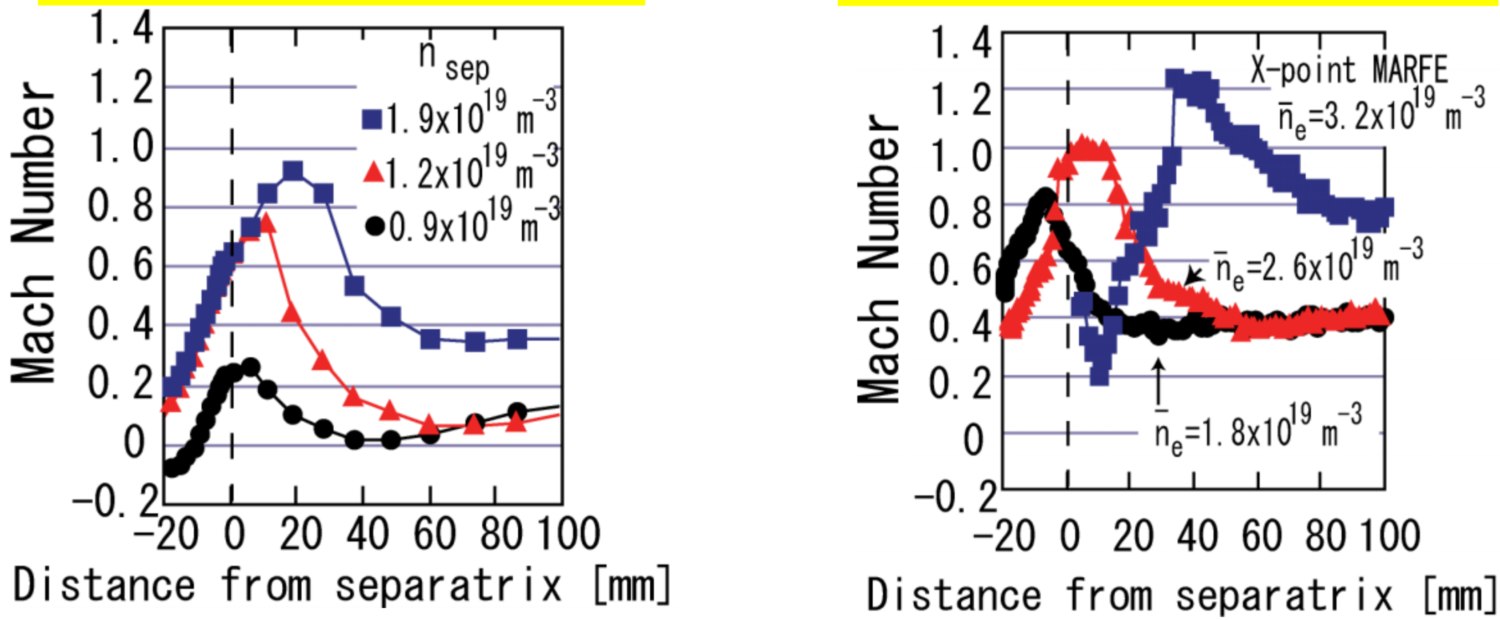


Fig.1 comparison of numerical result(B2-EIRENE) and experimental result.

As the electron density at outer mid-plane increases, the peak of the *M*-profile moves further outward and the peak value becomes larger.

Numerical results qualitatively agree well with the experimental result .

＊ K.HOSHINO,*et.al*.,プラズマ核融合学会19回年会

Formation mechanism of high Mach flow associated with detachment

Appearance of the ionization front associated with plasma detachment.

↓

Separation of the ionization region from the momentum loss region.

↓

Static pressure drops in the ionization region due to temperature decrease, while total pressure is kept almost constant.

↓

Increase in dynamic pressure

Purpose

Several differences are observed between numerical result and experimental result,

1)Mach number tends to be smaller than that of experiment.

2)In experiment, relatively large Mach flows are observed in attachment state.

Effect of various kind of drifts and current is one of the possible causes.

Clarify the effect of various drifts and current on high Mach flows in JT-60U.

↓

Initial numerical results by B2.5-EIRENE are presented to clarify effects on high Mach flows associated with detachment.

Simulation code

B2.5-EIRENE* (SOLPS5.0)

B2.5 : two dimensional transport code

Basic Eq. Ion continuity Eq.

Ion and electron momentum Eq.

Ion and electron energy balance Eq.

current continuity Eq.

EIRENE : natural Mont Carlo code

Basic Eq. Boltzmann Eq.

* **B.J.Braams** *et al*:Fusion Technol.**9**(1986)320.

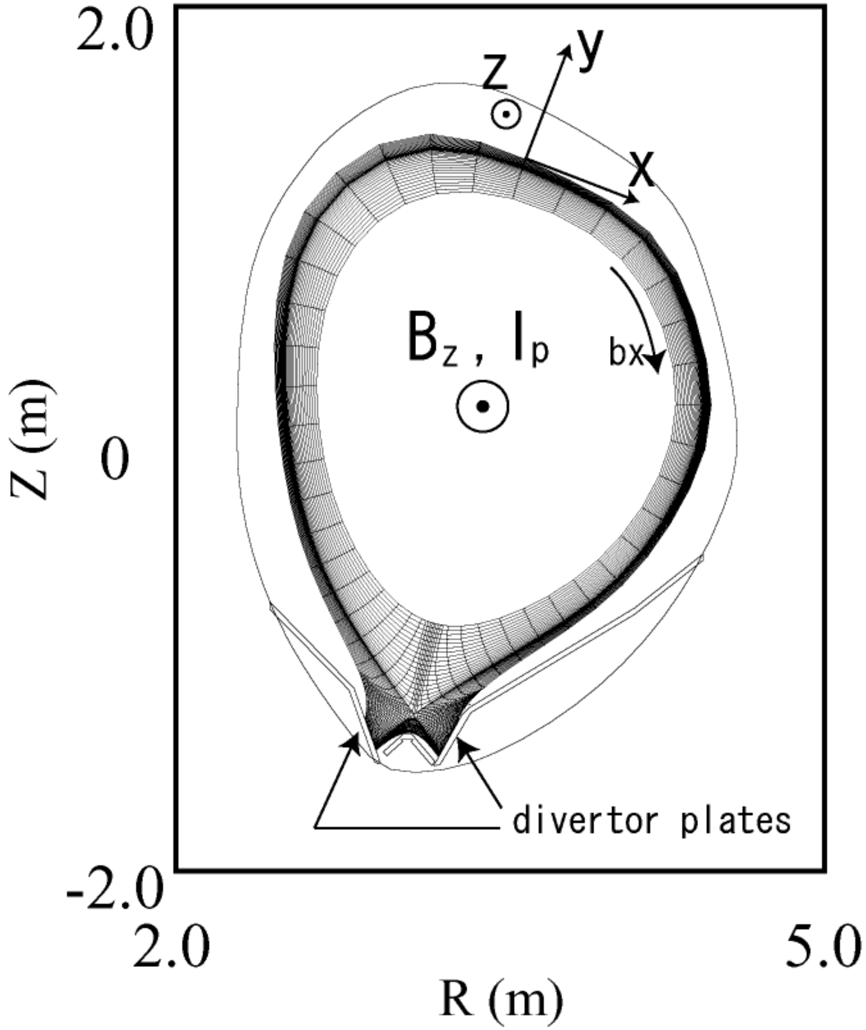
V.A.Rozansky, *et.al*.:Nucl. Fusion **41**(2001)387.

D.Reiter *et al*:J.Nucl.Mater.**196-198**(1992)80.

D.Reiter *et al*:Plasma Physics and Controlled Fusion **33**,**1579**(1991)

R.Schneider *et al*:J.Nucl.Mater.**196-198**(1992)810.

Basic equations (1)



Local curvilinear coordinate system

Metric coefficient

$$h_x = \frac{1}{\|\nabla x\|}, h_y = \frac{1}{\|\nabla y\|}, h_z = \frac{1}{\|\nabla x\|}$$

$$\sqrt{g} = h_x h_y h_z$$

Magnetic field $\boldsymbol{B}$

$$b_x = B_x / B$$

$$b_z = B_z / B$$

Basic equations (2)

Continuity equation for ions

$$\frac{\partial n}{\partial t}+\frac{1}{\sqrt{g}}\frac{\partial}{\partial x}\left[\frac{\sqrt{g}}{h_x}n(b_x V_{//}+b_z V_{\perp})\right]+\frac{1}{\sqrt{g}}\frac{\partial}{\partial y}\left[\frac{\sqrt{g}}{h_y}nV_y\right]=S_p$$

Parallel velocity $V_{//}$

Parallel ion momentum equation

Perpendicular and radial velocity $V_{\perp}, V_y$

Perpendicular and radial ion momentum equation

$$V_{\perp}=V_{\perp}^{E\times B}+V_{\perp}^{DF}+V_{\perp}^{DIA}+V_{\perp}^{IN}+V_{\perp}^{VIS}+V_{\perp}^{S}$$

$$V_{y}=V_{y}^{E\times B}+V_{y}^{DF}+V_{y}^{DIA}+V_{y}^{IN}+V_{y}^{VIS}+V_{y}^{S}$$

$V_{\perp,y}^{E\times B}$: ExB drift

$V_{\perp,y}^{DIA}$: diamagnetic drift

$V_{\perp,y}^{DF}$: diffusion(classical/anomalous)

$V_{\perp,y}^{IN}, V_{\perp,y}^{VIS}, V_{\perp,y}^{S}$:velocity component caused by inertia, viscosity, and collision with neutral

Basic equations (3)

parallel ion momentum equation

$$m_i \frac{\partial (nV_{//})}{\partial t} + \frac{1}{h_z\sqrt{g}}\frac{\partial}{\partial x}\left[\frac{h_z\sqrt{g}}{h_x} n(b_x V_{//} + b_z V_{\perp})V_{//}\right] + \frac{1}{h_z\sqrt{g}}\frac{\partial}{\partial y}\left[\frac{h_z\sqrt{g}}{h_y}(nV_y)V_{//}\right]$$

$$-\frac{1}{h_z\sqrt{g}}\frac{\partial}{\partial y}\left[\frac{h_z\sqrt{g}}{h_y}\eta_2\frac{\partial V_{//}}{\partial y}\right] - \frac{1}{h_z\sqrt{g}}\frac{\partial}{\partial y}\left[\frac{h_z\sqrt{g}}{h_y}\eta_2\frac{\partial V_{//}}{\partial y}\right]$$

$$= -\frac{b_x}{h_x}\frac{\partial (nT_i)}{\partial x}$$ pressure gradient force

$$-b_x \frac{en}{h_x}\frac{\partial \phi}{\partial x}$$ electric force → ϕ is obtained by current continuity eq.

$$+F_k + F_{v//} + F_{v//q} + R_{ie//} + S_{i//}^m$$

$F_k, F_{v//}, F_{v//q}, R_{ie//}, S_{i//}^m$ Parallel component of force caused by 1)Coriolis force, 2)parallel viscosity, 3)parallel viscosity by ion heat flux, 4)collision with electron, and 5)collision with neutral.

Basic equations (4)

Current continuity equation

$$\frac{1}{\sqrt{g}}\frac{\partial}{\partial x}\left[\frac{\sqrt{g}}{h_x}n(b_x J_{//}+b_z J_{\perp})\right]+\frac{1}{\sqrt{g}}\frac{\partial}{\partial y}\left[\frac{\sqrt{g}}{h_y}nJ_y\right]=0$$

Parallel current $J_{//}$

From parallel electron momentum equation

$$J_{//}=\sigma_{//}[\frac{b_x}{e}\frac{1}{h_x}\{\frac{1}{n}\frac{\partial(nT_e)}{\partial x}+0.71\frac{\partial T_e}{\partial x}\}-\frac{b_x}{h_x}\frac{\partial\phi}{\partial x}]$$

Perpendicular and radial current $J_{\perp}, J_y$

We can calculate from sum of vertical ion and electron momentum equation

$$J_{\perp,y}=J_{\perp,y}^{DIA}+J_{\perp,y}^{IN}+J_{\perp,y}^{VIS}+J_{\perp,y}^{S}$$

For 5 Unknowns, $n, V_{//}, \phi, T_e, T_i$,

the system of basic equations is closed by following 5 equations:
1)continuity equation, 2)parallel momentum equation, 3)current continuity equation, 4)ion and 5)electron energy balance equation.

Basic equations (5)

Boundary conditions

core：

$$n = const.: given$$

$$\Gamma^{(m)} = (m_i V_{//} \Gamma_y - \eta_2 \frac{1}{h_y} \frac{\partial V_{//}}{\partial y})\Big|_{C.B.} = 0 \quad \text{or} \quad V_{//}\Big|_{CB} : given$$

$$\tilde{j}_y = 0 \quad Q_{in} : given$$

divertor：

$$b_x V_{//} - \frac{1}{B}\frac{\partial \phi}{\partial y} = \pm b_x C_s$$ C_s Ion sound speed

$$J_x = en[b_x C_s - b_x \frac{1}{\sqrt{2\pi}} \sqrt{\frac{T_e}{m_e}} \exp(-\frac{e\phi}{T_e})]$$

$$q_{ex} = b_x \frac{n}{\sqrt{2\pi}} \sqrt{\frac{T_e}{m_e}} \exp(-\frac{e\phi}{T_e})(T_e + \varepsilon_i)$$ Electron energy flux density

$$q_{ix} = \frac{3}{2} n T_i C_s b_x$$ Ion energy flux density

SOL：

$$\Gamma_y = 0 \quad \Gamma_{//}^{(m)} = 0 \quad \tilde{j}_y = 0 \quad \partial T_i / \partial y, \partial T_e / \partial y : given$$

numerical model

- JT-60U W-shaped geometry
- L-mode discharge
- Ions,neutrals
  D^+ , $C^{+\sim6+}$, D , D_2 , C
- core boundary conditions
  Q_{in}= 2.5 MW (Q_i=Q) ,
  D^+ density n_D= 2.1x10^{19} m^{-3}

Shot #	#029623
I_p	1.2 MA
B_T	3.5 T
q_{eff}	4.4
Q_{in}	5MW

Table1 main plasma parameters

- Transport model :
  Parallel direction : classical transport
  Radial direction : $D = 0.3$ m²/s , $h = mnD$, $\chi_i = \chi_e = 2.0$ m²/s

$$\Gamma_r = -D\frac{\partial n}{\partial r} + nv_p, \quad v_p > 0$$ **(outward radial flow)**

Numerical mesh

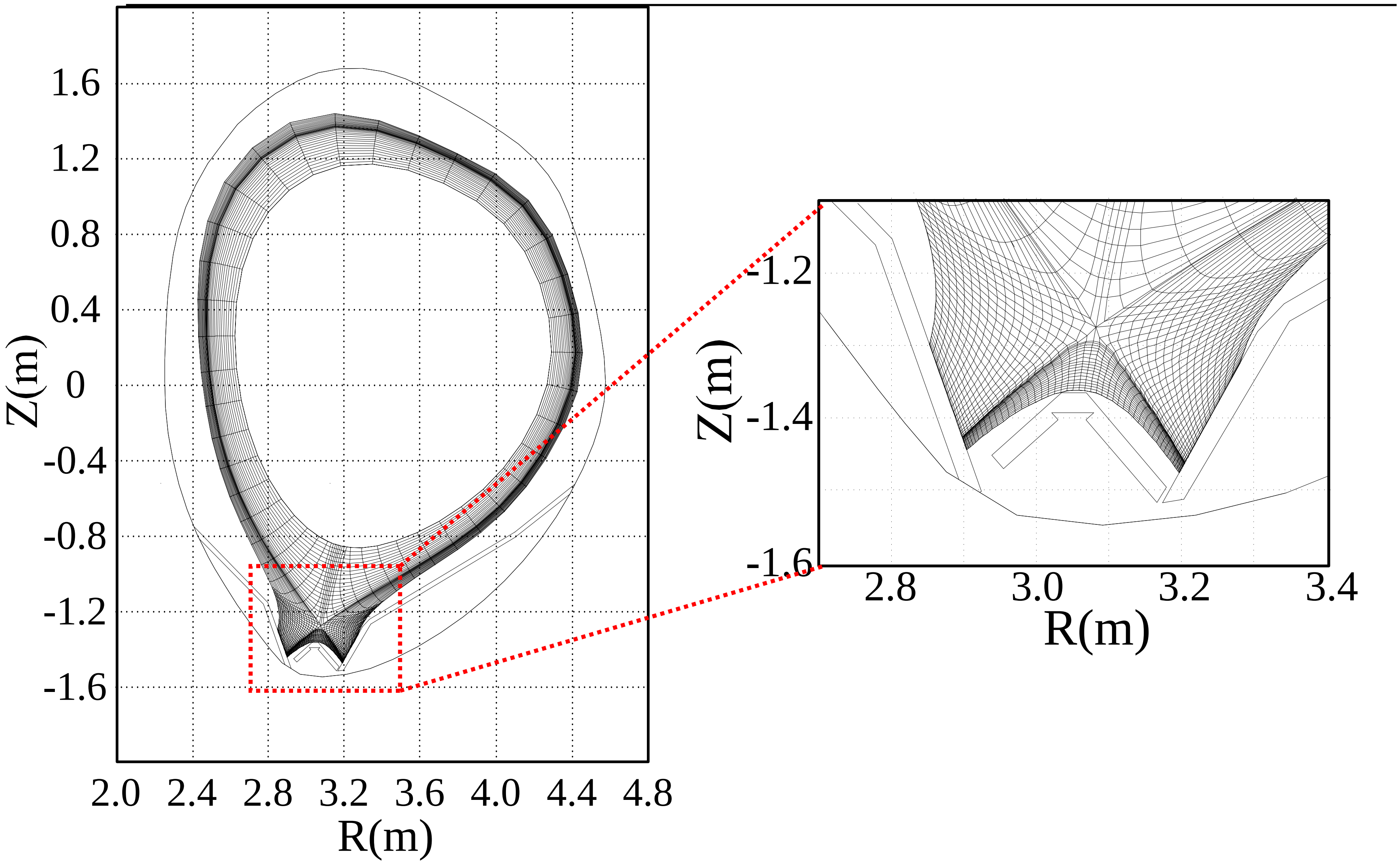


Fig.2a numerical mesh

Numerical results (with ExB drift)

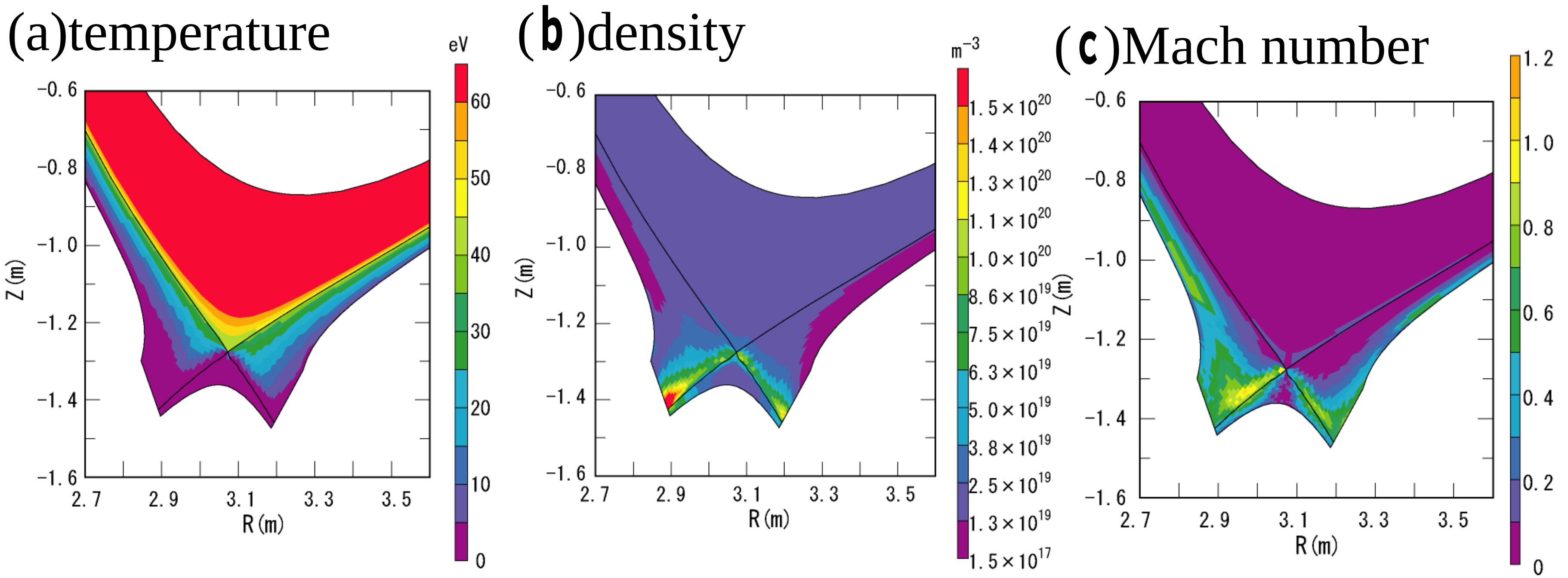


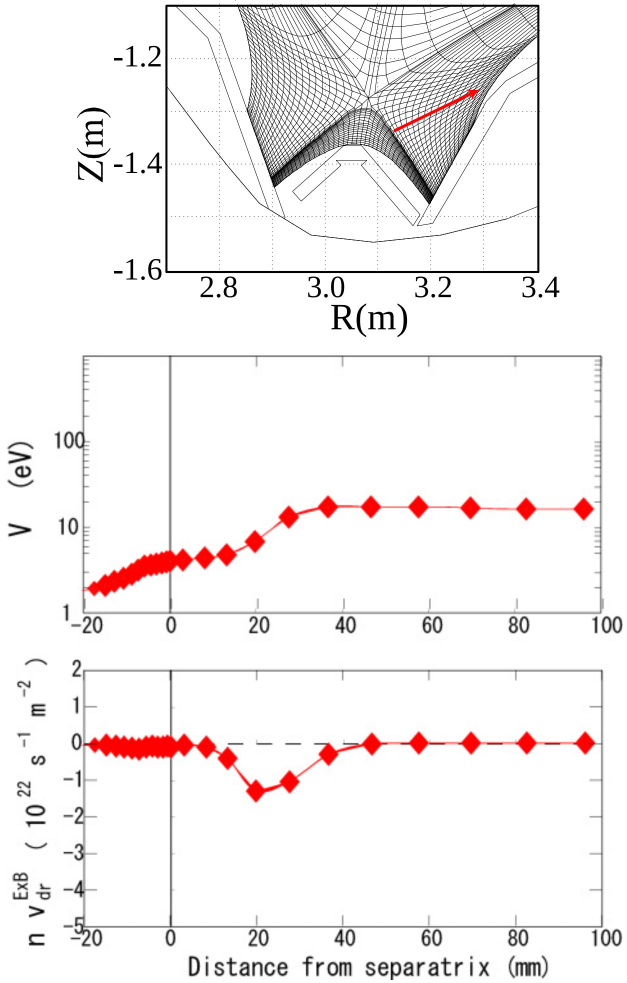
Fig.3 numerical results

Inner divertor $T_e \leq 1eV$ ⇨ detachment

Outer divertor $T_e \leq 10eV$ ⇨ Partial detachment

Comparison with experimental result
(poroidal ExB drift associated with partial detachment)

(a)numerical result **(b)experimental result**



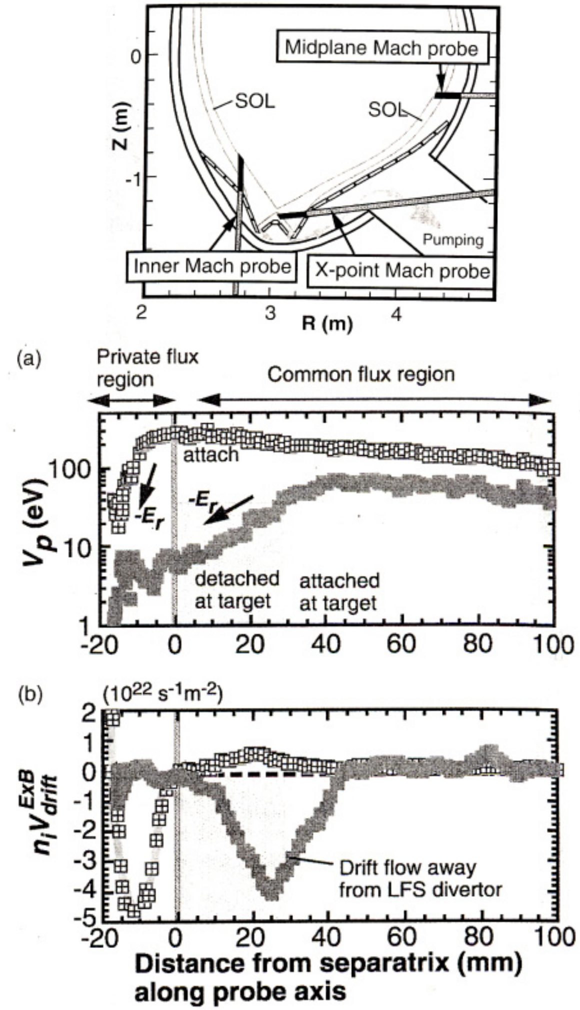
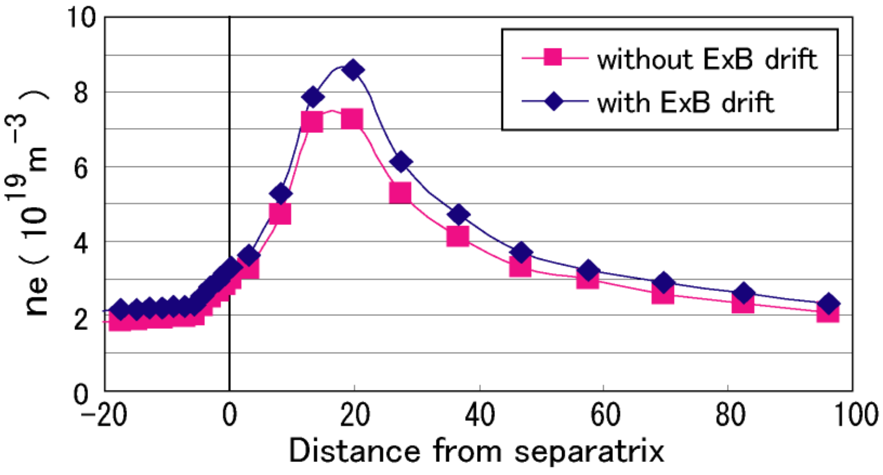
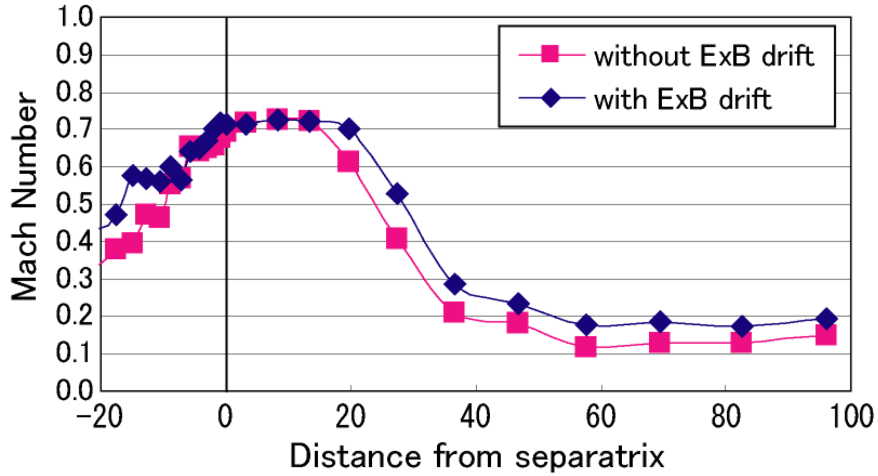


Fig.4 comparison of V, nv_{dr}^{ExB} **N.Asakura, *et.al.*, J.Nucl.Mater,313(2003)820**

Effects of ExB drift





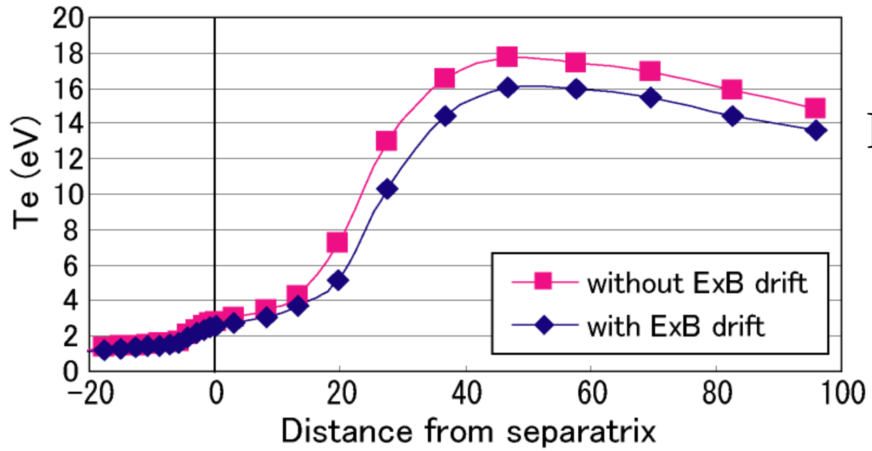


Fig.5 comparison of radial profile
with and without ExB drift
(outer divertor region near the X-point)

Consideration by simple model

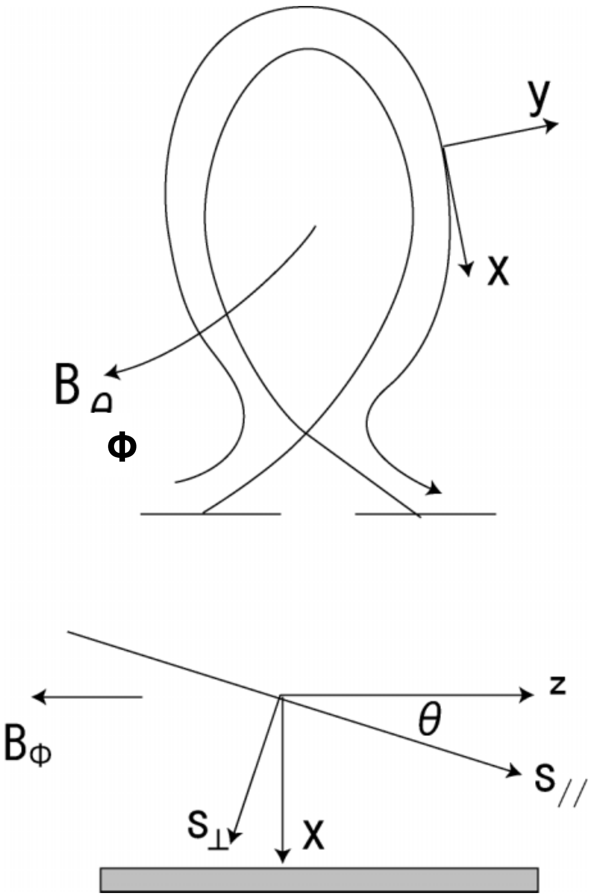


Fig.6 coordinate of simple model

$$\frac{\partial}{\partial x}(\sin\theta n v_{//} + \cos\theta n v_p^{dr}) + \frac{\partial}{\partial y}(n v_r^{dr}) = S_p$$

$$m_i n_i \left[v_r^{dr} \frac{\partial v_{//}}{\partial y} + \left(\sin\theta \cdot v_{//} + \cos\theta \cdot v_p^{dr}\right) \frac{\partial v_{//}}{\partial s_{//}} \right]$$

$$= -\frac{\partial P_i}{\partial s_{//}} + neE_{//} - m v_{//} S_p$$

$$0 \simeq -\frac{\partial P_e}{\partial s_{//}} - neE_{//}$$

$$v_r^{dr} = \frac{E_\theta}{B}, \quad v_p^{dr} = \frac{E_r}{B}$$

$$\frac{\partial}{\partial x}\left[m n v_{//}^2 + P\right] = -\frac{\partial}{\partial y}\left(\frac{m n v_{//} v_r^{dr}}{\sin\theta}\right) - \frac{\partial}{\partial x}\left(\frac{m n v_{//} v_p^{dr}}{\tan\theta}\right)$$

Effect of v_r^{dr}

$$v_r^{dr} = \frac{E_\theta}{B} = -\frac{1}{neB}\frac{\partial P_e}{\partial x}$$

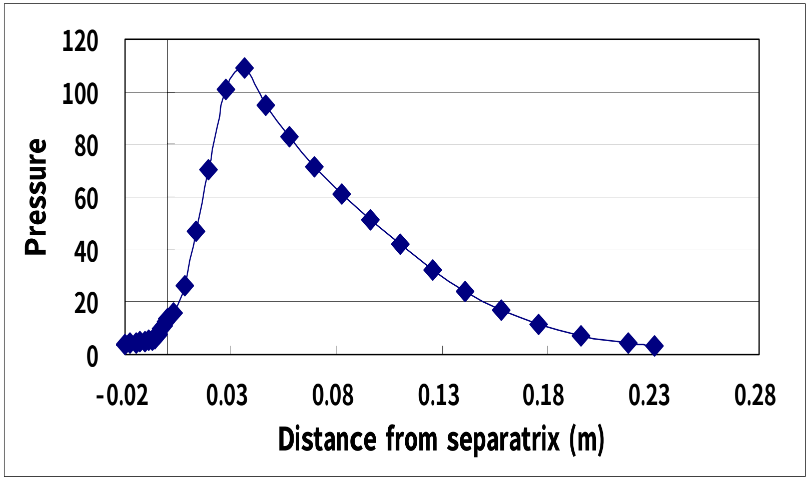
$$-\frac{\partial}{\partial y}\left(\frac{mnv_{//}v_r^{dr}}{\sin\theta}\right) = \frac{\partial}{\partial y}\left(\frac{mv_{//}}{eB\sin\theta}\frac{\partial P_e}{\partial x}\right) = \frac{1}{eB\sin\theta}\left[\frac{\partial}{\partial y}(mv_{//})\frac{\partial P_e}{\partial x} + mv_{//}\frac{\partial}{\partial x}\left(\frac{\partial P_e}{\partial y}\right)\right]$$

$$\frac{1}{eB\sin\theta}mv_{//}\frac{\partial}{\partial y}\left(\frac{\partial P_e}{\partial y}\right) \sim \frac{mv_{//}}{eB\sin\theta}\frac{\partial}{\partial x}\left(\frac{P_e}{\lambda}\right)$$

$$\lambda \simeq \begin{cases} 0.02m(x < 0.04m) \\ 0.18m(x \geq 0.04m) \end{cases}$$

$$\frac{\dfrac{mv_{//}}{eB\sin\theta}\dfrac{\partial}{\partial x}\left(\dfrac{P_e}{\lambda}\right)}{\dfrac{\partial P}{\partial x}} \sim \frac{mv_{//}}{eB\sin\theta}\frac{P_e}{P\lambda}$$

$$\sim \begin{cases} 0.1(y < 0.04) \\ -0.01(y \geq 0.04) \end{cases}$$



Effect of v_p^{dr}

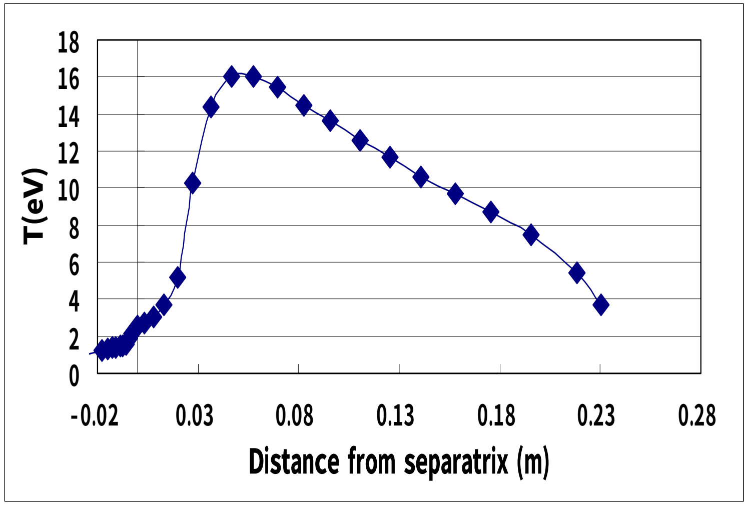
$$v_p^{dr} = \frac{E_r}{B} \sim \frac{1}{B}\frac{3kT_e}{e\lambda}$$

$$-\frac{\partial}{\partial x}\left(\frac{mnv_{//}v_p^{dr}}{B\tan\theta}\right) = -\frac{\partial}{\partial x}\left(\frac{mnv_{//}}{B\tan\theta}\frac{3kT_e}{e\lambda}\right) = -\frac{\partial}{\partial x}\left(\frac{mv_{//}}{B\tan\theta}\frac{3P_e}{e\lambda}\right)$$

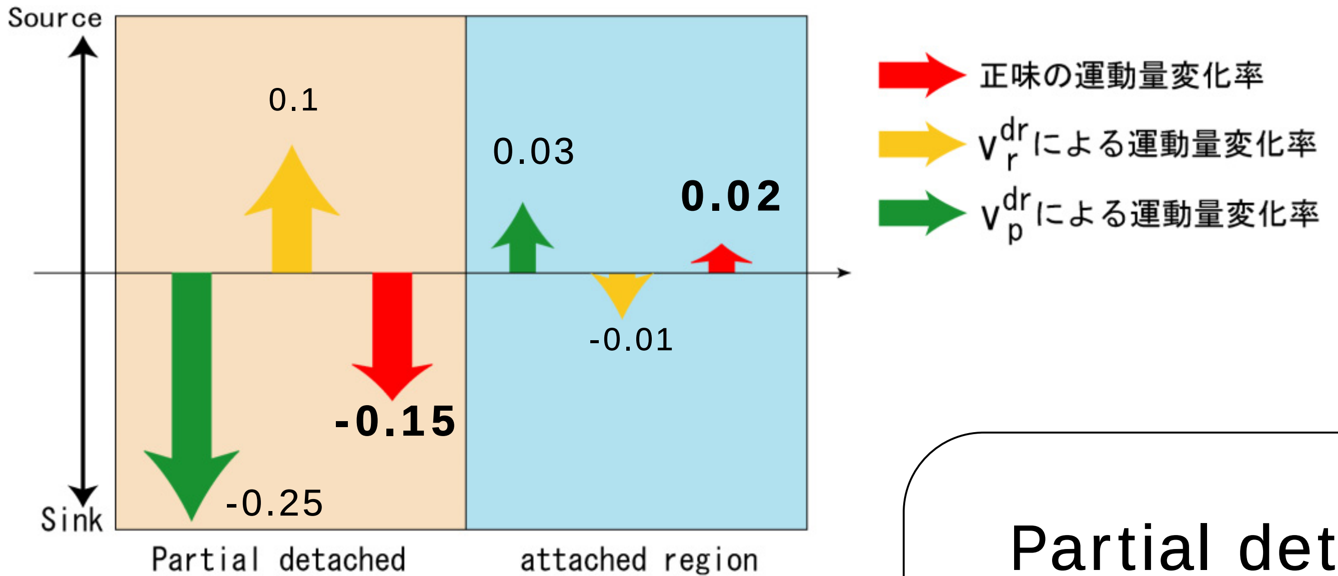
$$\lambda \simeq \begin{cases} 0.02m(y < 0.04m) \\ 0.21m(y \geq 0.04m) \end{cases}$$

$$\frac{-\frac{\partial}{\partial x}\left(\frac{mv_{//}}{B\tan\theta}\frac{3P_e}{e\lambda}\right)}{\frac{\partial P}{\partial x}} \sim -\frac{mv_{//}}{B\tan\theta}\frac{3P_e}{e\lambda P}$$

$$\sim \begin{cases} -0.25(y < 0.04) \\ 0.03(y \geq 0.04) \end{cases}$$



Effect of ExB drift on momentum



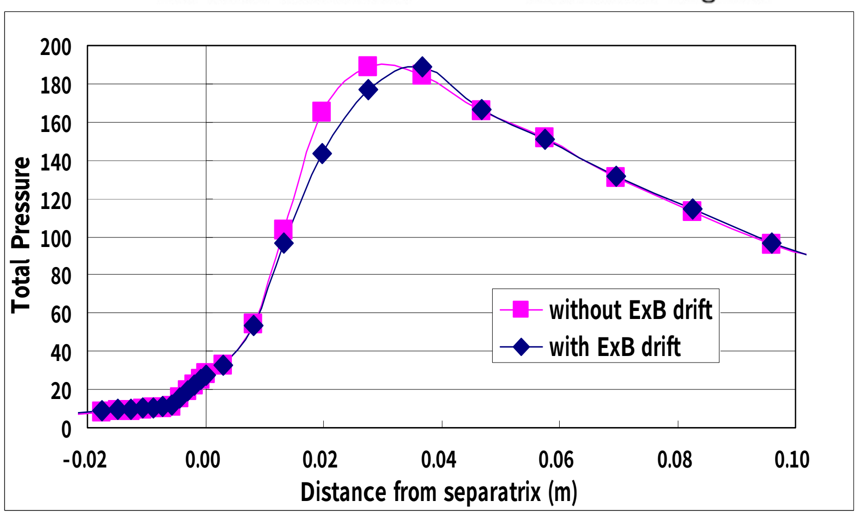


Fig.7 radial profile of total momentum

Partial detached region
about **15%**

Attached region
about **2%**

Summary of estimate by simple model

(1) ExB drift becomes source/sink of parallel momentum $mv_{//}$.

(2) These source/sink by ExB drift is estimated by simple model.

(3) ・**detachment region near the separatrix**：

poloidal ExB drift becomes parallel momentum sink,

and radial ExB drift becomes parallel momentum source.

In total, ExB drift becomes net parallel momentum sink.

・**attachment region**：

Effect of ExB drift is smaller than that in detachment region.

Summary Ⅰ

(1) We investigate the effect of ExB drift on high Mach flow associated with detachment.

(2) In detachment state, relatively large poroidal ExB drift is observed in the simulation. The direction is toward upstream from target plate.

(3) ExB drift is caused by local decrease of electron temperature associated with partial detachment, and the resultant radial electric field.

(4) The tendency of (2)(3) agrees well to experimental results.

(5) Radial ExB drift is observed, but the effect is smaller than the poloidal drift.

Summary II

(6) Relatively large ExB drifts are observed, but their effects on high Mach flows are small

(7) To understand the simulation result, the effect of ExB drift on parallel momentum balance is estimated by simple model.

- ExB drift acts as net parallel momentum sink in partial detachment region near the separatrix, and the effect on parallel momentum balance is about 15%.
- ExB drift does not affect on parallel momentum balance in attachment region far from separatrix.

By considering other drifts , we will investigate overall effects of drifts on detachment characteristics and in-out asymmetry.