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Edge Plasma Modeling Using PARASOL Code

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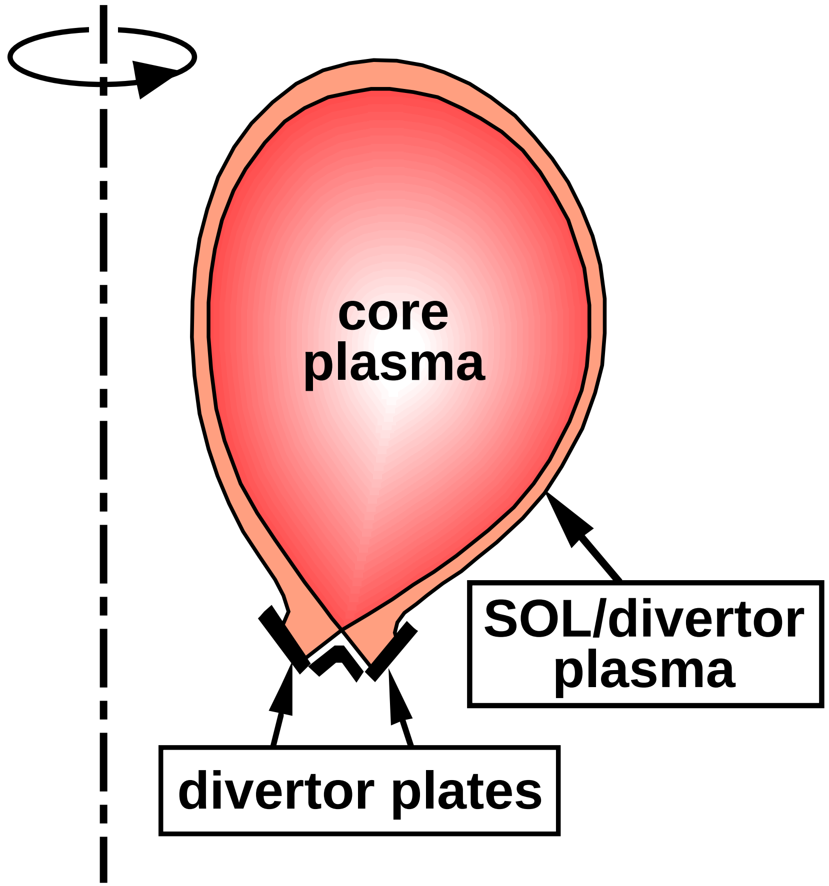
Power and Particle Control by SOL/Divertor Plasmas

Since the SOL/divertor plasmas attach walls directly, plasma particles and heat escape to the walls mainly along magnetic field lines.

Utilizing this nature, we expect divertor functions for the **heat removal**, **ash exhaust**, and **impurity shielding** in fusion reactors, such as ITER.



Simulations for Divertor Study

Experimental analyses and prediction studies for divertor functions have been performed by using comprehensive simulation codes with the **fluid model**.

In the fluid model for open-field plasmas, various **physics models** are introduced, i.e., boundary conditions at the plasma-wall boundary, heat conductivity etc.

$$\mathbf{V_{//} = C_s} \quad \text{(Bohm condition)}$$

$$\mathbf{q_{cond} = -\kappa_{//} \nabla_{//} T}$$

Kinetic approach is required to examine the validity of such physics models.

PARASOL Code

One of the most powerful kinetic models
is the **particle simulation**.

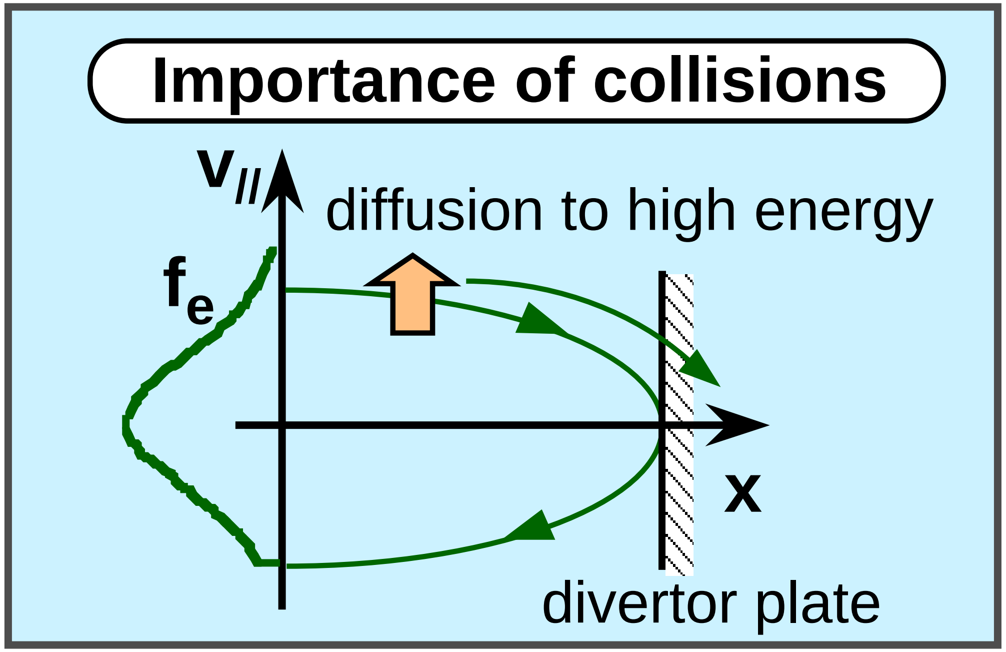
An advanced particle simulation code **PARASOL**

PARticle Advanced simulation for SOL and divertor plasmas

was developed.

PIC method
Binary collision model

Neutral particles
Source, Sink, Heating, Cooling etc.



Motion of Charged Particles

Collisionless motion of ion

$$m_i\, d\mathbf{v}/dt = e\,(\mathbf{E} + \mathbf{v}\times\mathbf{B})\ , \quad d\mathbf{r}/dt = \mathbf{v}$$

Motion of a guiding center of electron

$$m_e\, dv_{//}/dt = -\, e\,\mathbf{E}\cdot\mathbf{B}/B\ -\ \mu\,\nabla_{//}B + m_e\, v_{//}\,\mathbf{v}_{E\times B}\cdot\boldsymbol{\nabla}B/B$$

$$d\mathbf{r}/dt = v_{//}\,\mathbf{B}/B + \mathbf{v}_{E\times B} + \mathbf{v}_{\nabla B}$$

Monte-Carlo cross-field diffusion

$$<\Delta\mathbf{r}^2{}_{anom}> = 2\, D_{anom}\,\Delta t$$

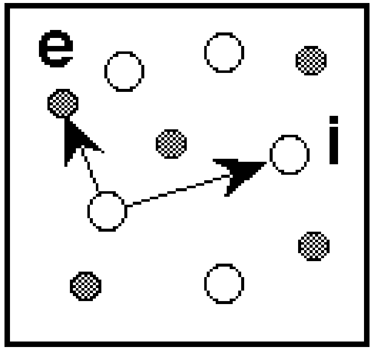
Poisson's equation

$$-\,\nabla^2\phi = (e/\varepsilon_0)\,(n_i - n_e)\ , \quad -\,\boldsymbol{\nabla}\phi = \mathbf{E}_s$$

PIC method $\Delta x \sim \lambda_D$, **Leap-Frog method** $\Delta t \sim \omega_p{}^{-1}$

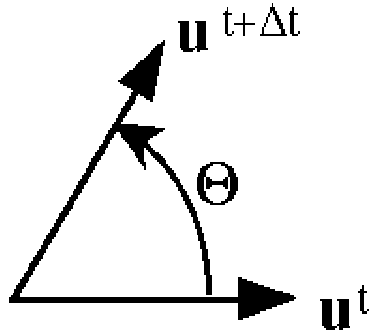
Coulomb Collisions - Binary collision model -

(1) In a time interval, a particle in a cell suffers binary collisions with an ion and an electron which are chosen randomely in the same cell.



(2) Change in the relative velocity results from a coulomb interaction.

Total momentum and total energy are conserved intrinsically.

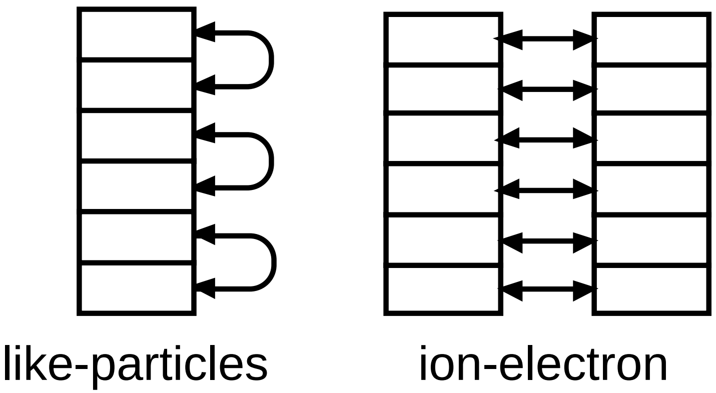


$$<\Theta^2> \sim \nu_d \Delta t$$

Random selection of collision pairs

At first; random rearrangement of addresses in every cell at every time step.

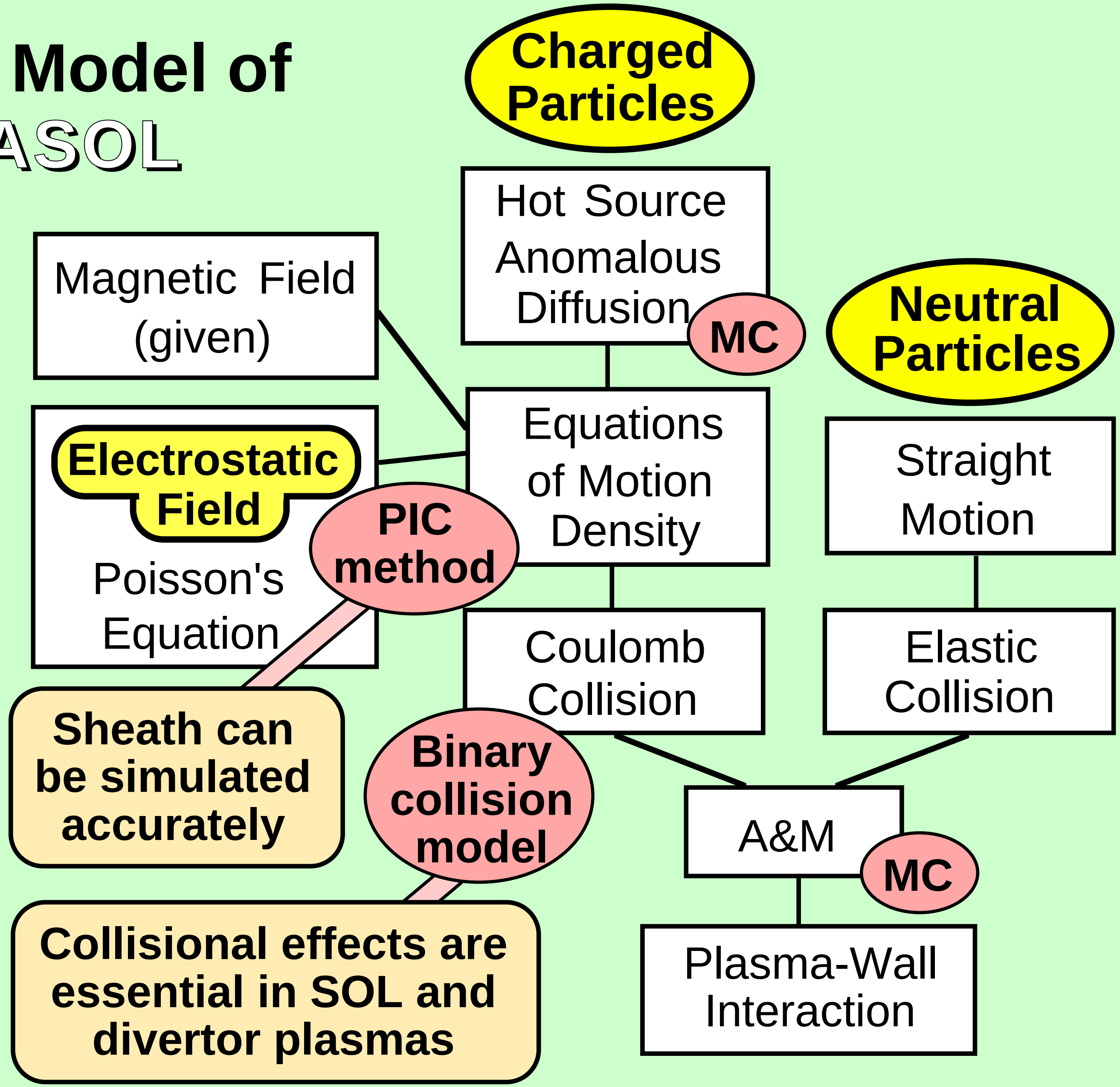
Next ;



Landau collision integral

T. Takizuka, H. Abe, J. Comput. Phys. **25**, 205 (1977).

Physics Model of PARASOL

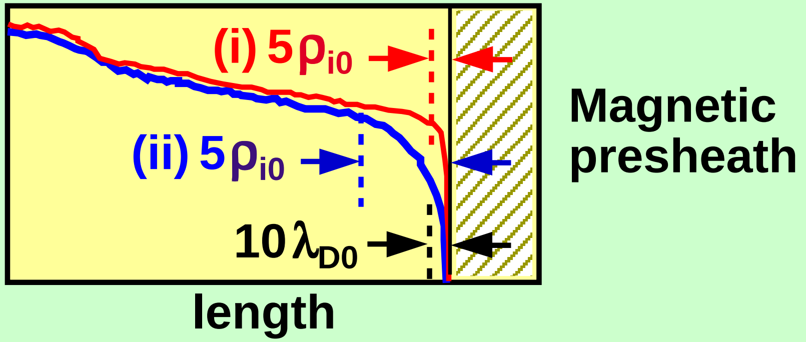


T. Takizuka, M. Hosokawa, K. Shimizu, Trans. Fusion Tech. **39**, 111 (2001).

Various versions of PARASOL

1D Stationary code

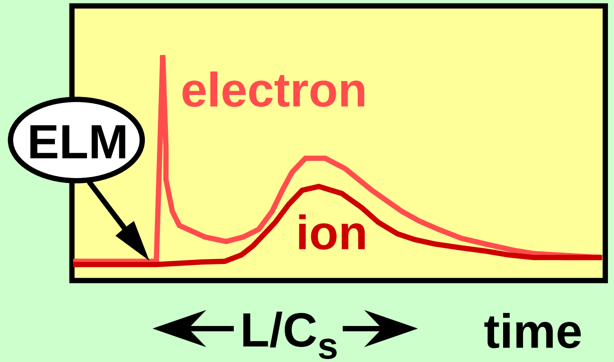
Sheath formation
Parallel transport



1D Dynamic code

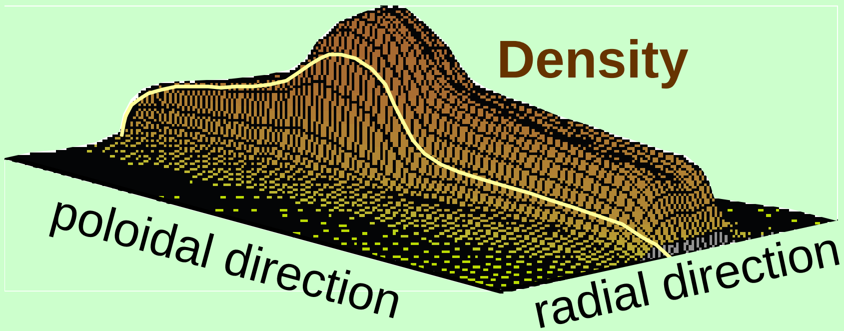
Response to ELM

Heat flux at divertor plate



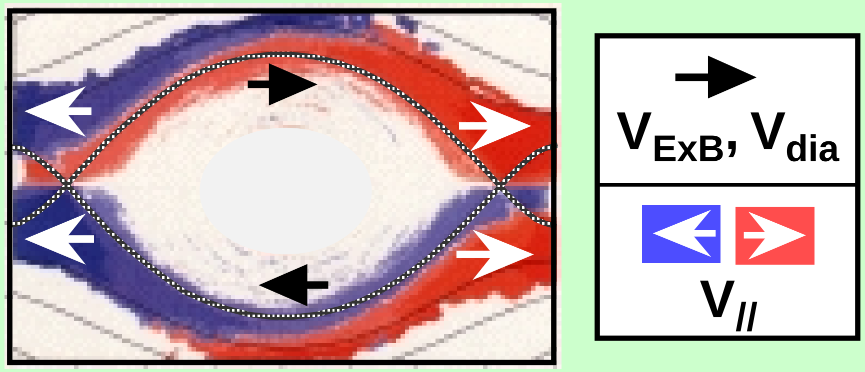
2D Slab code

Divertor asymmetry,
Drift effect



2D Separatrix code

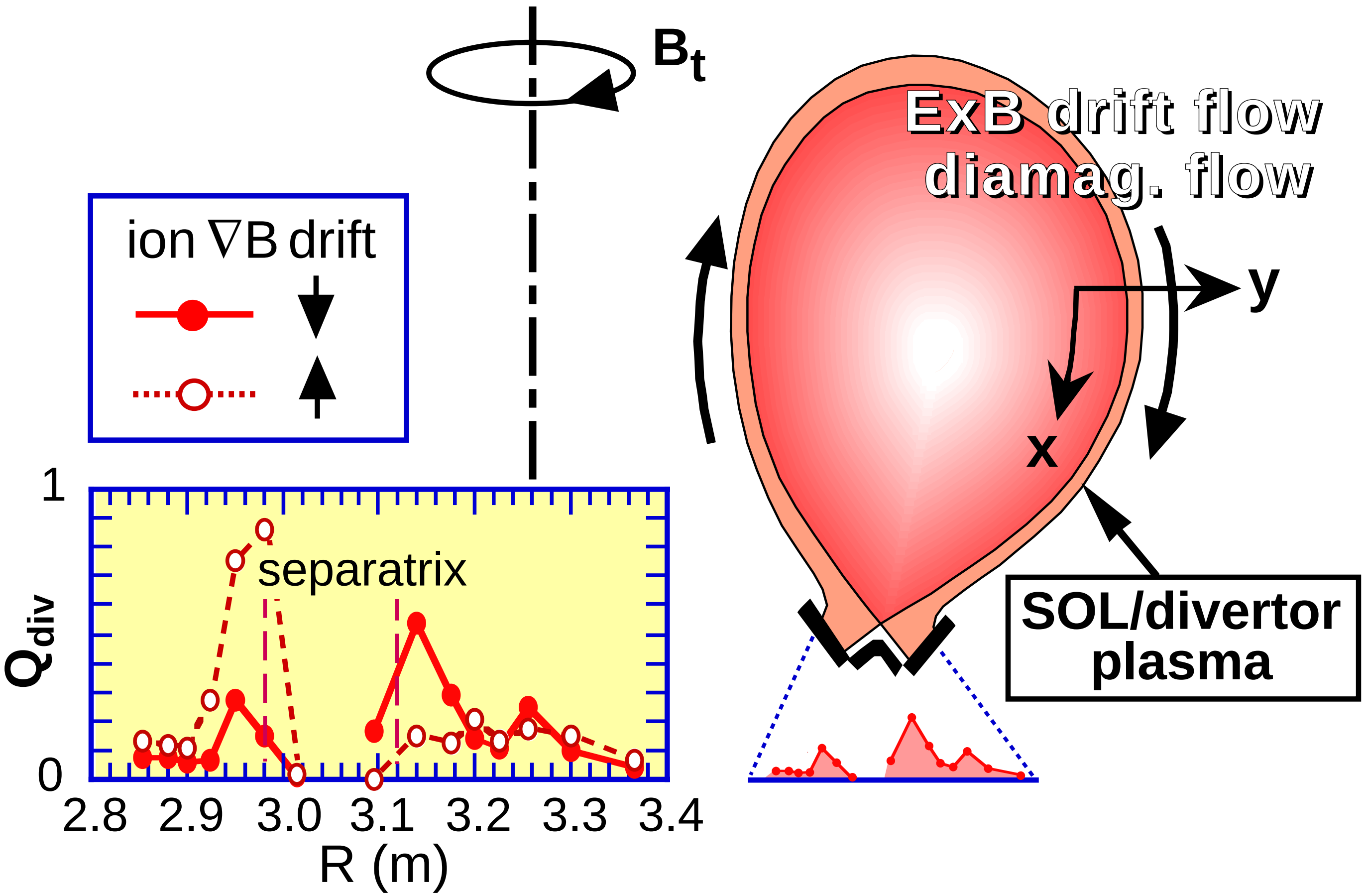
Flow control



Asymmetry between inner and outer divertor plasmas

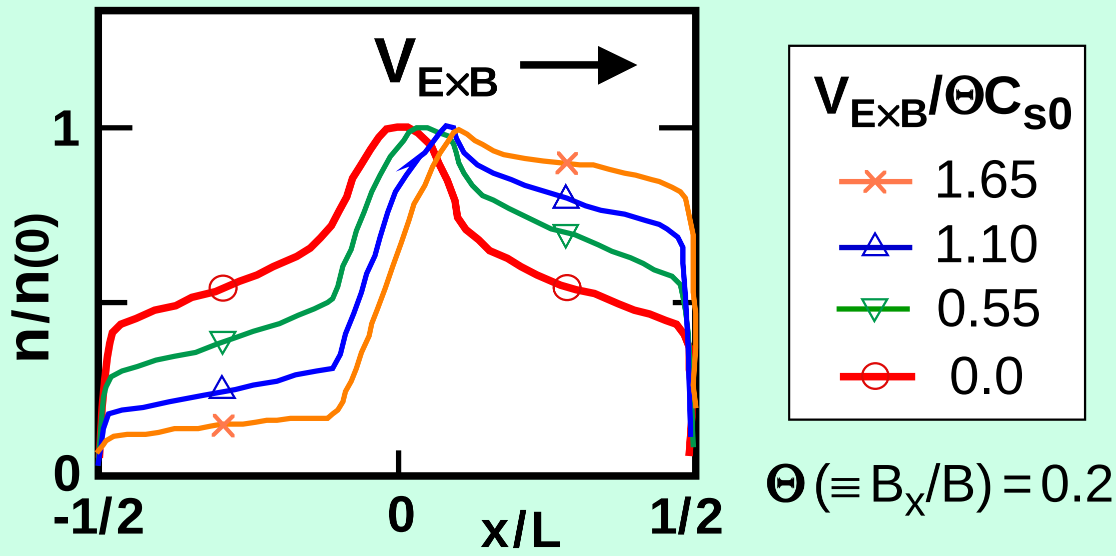
Recycling asymmetry due to configurations and

Effect of Drift flow
(reversal of asymmetry with B_t direction)



Physical mechanism of asymmetry has been investigated by using PARASOL code

1D PARASOL Simulation - Asymmetry due to E×B drift -

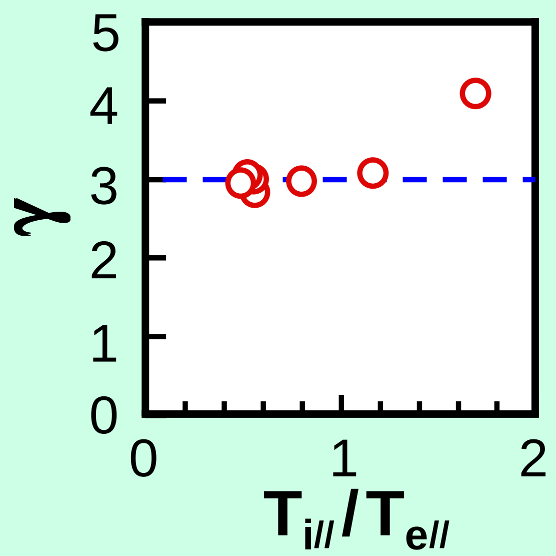


$\Theta (\equiv B_x/B) = 0.2$

$$V_x = V_{E\times B} + \Theta V_{//}$$

$$m_i V_x^2 \geq \Theta^2 (T_{e//} + \gamma T_{i//})$$

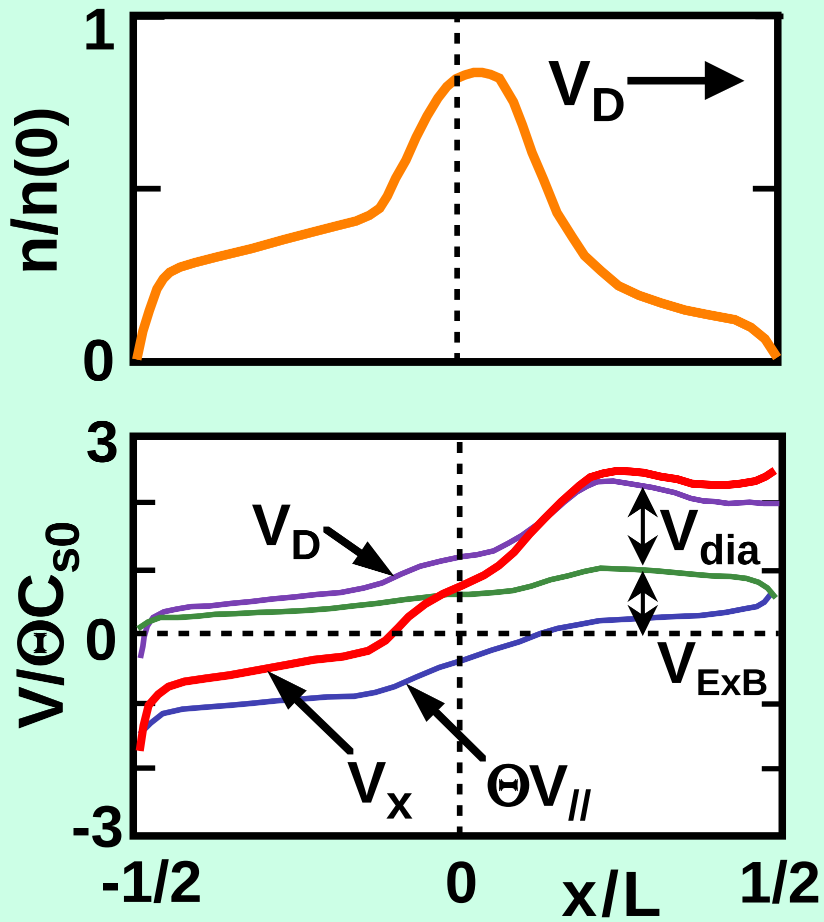
(γ: adiavatic index)

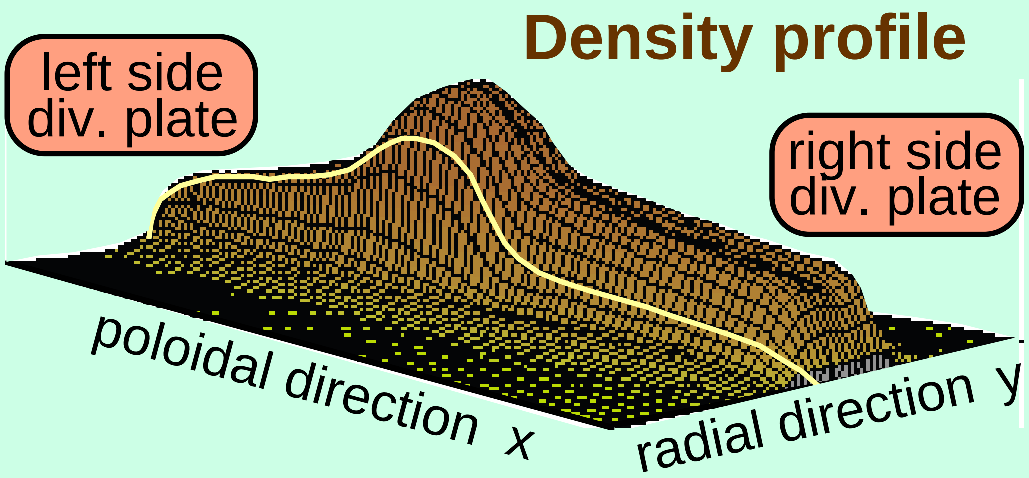


Asymmetry is brought by the boundary condition

T. Takizuka, M. Hosokawa, Contrib.Plasma Phys. **40**, 471 (2000).

2D PARASOL Simulation

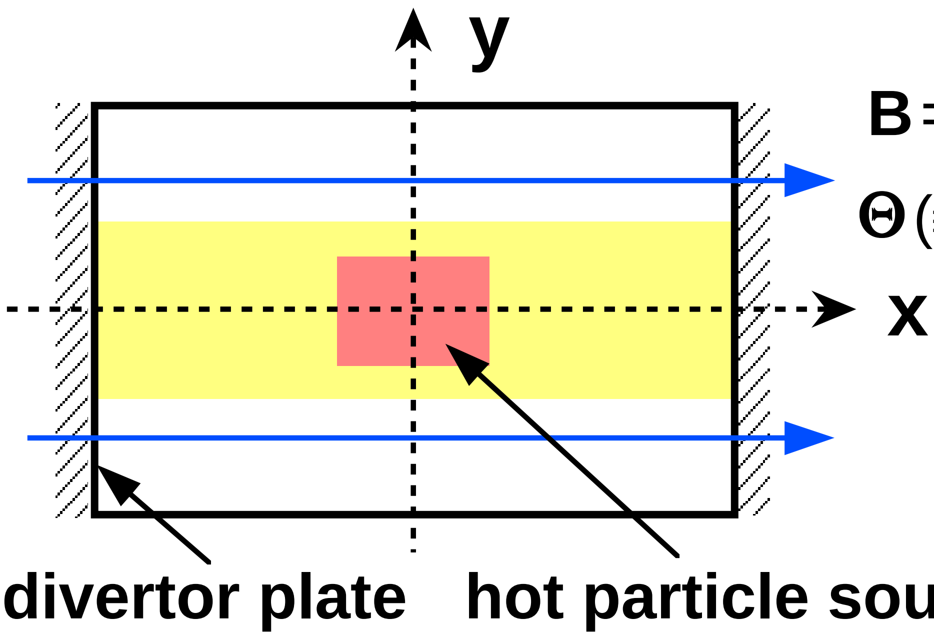




Opposite asymmetry to 1D case

T. Takizuka et al., 18th IAEA Fusion Energy Conf., 2000, Sorento, IAEA-CN-77/THP1/22 (2000).

2D PARASOL Simulation

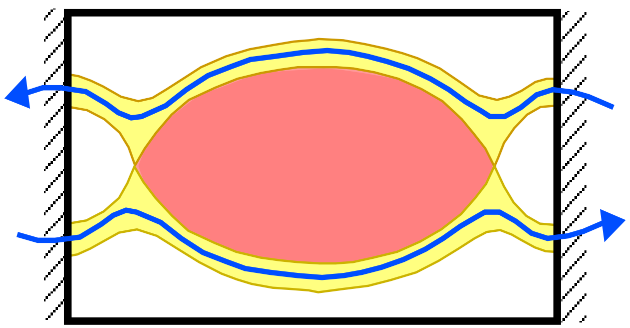


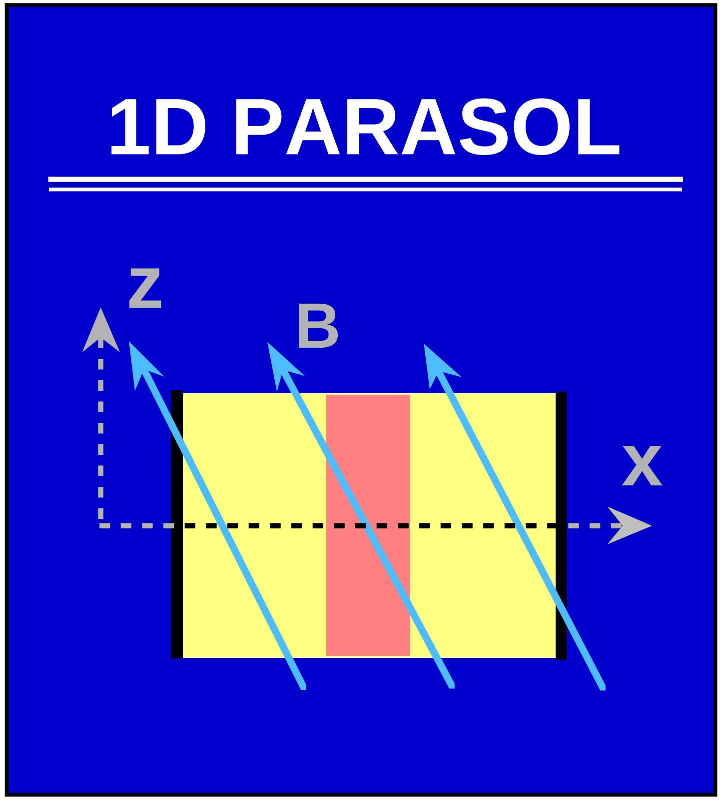
$\mathbf{B} = (B_x, 0, B_z)$

$\Theta (\equiv B_x/B_z) = 0.2$

$M_x \times M_y = 400 \times 256\,, \quad N_i = 10^6$

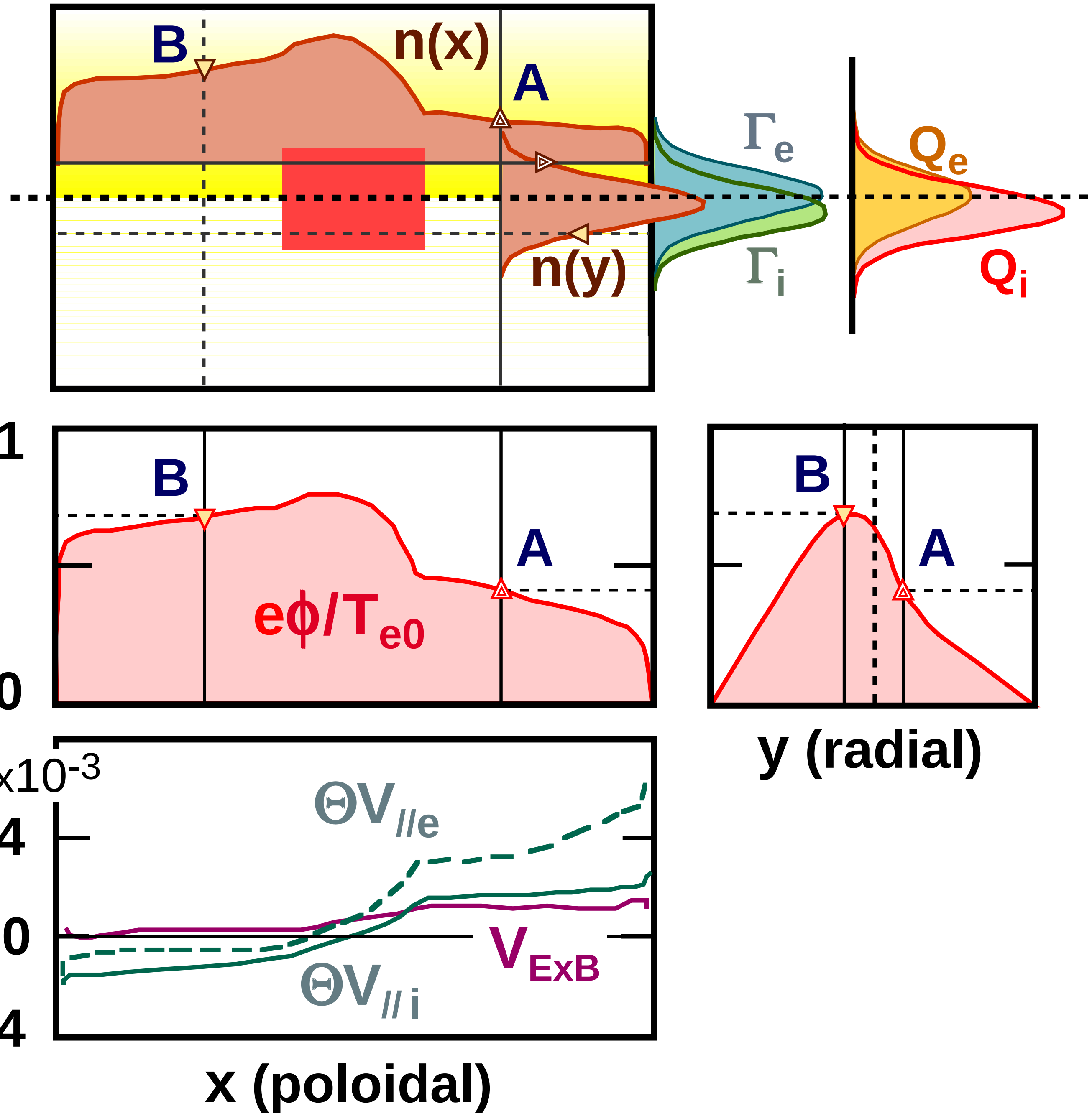
x : poloidal
y : radial
z : toroidal



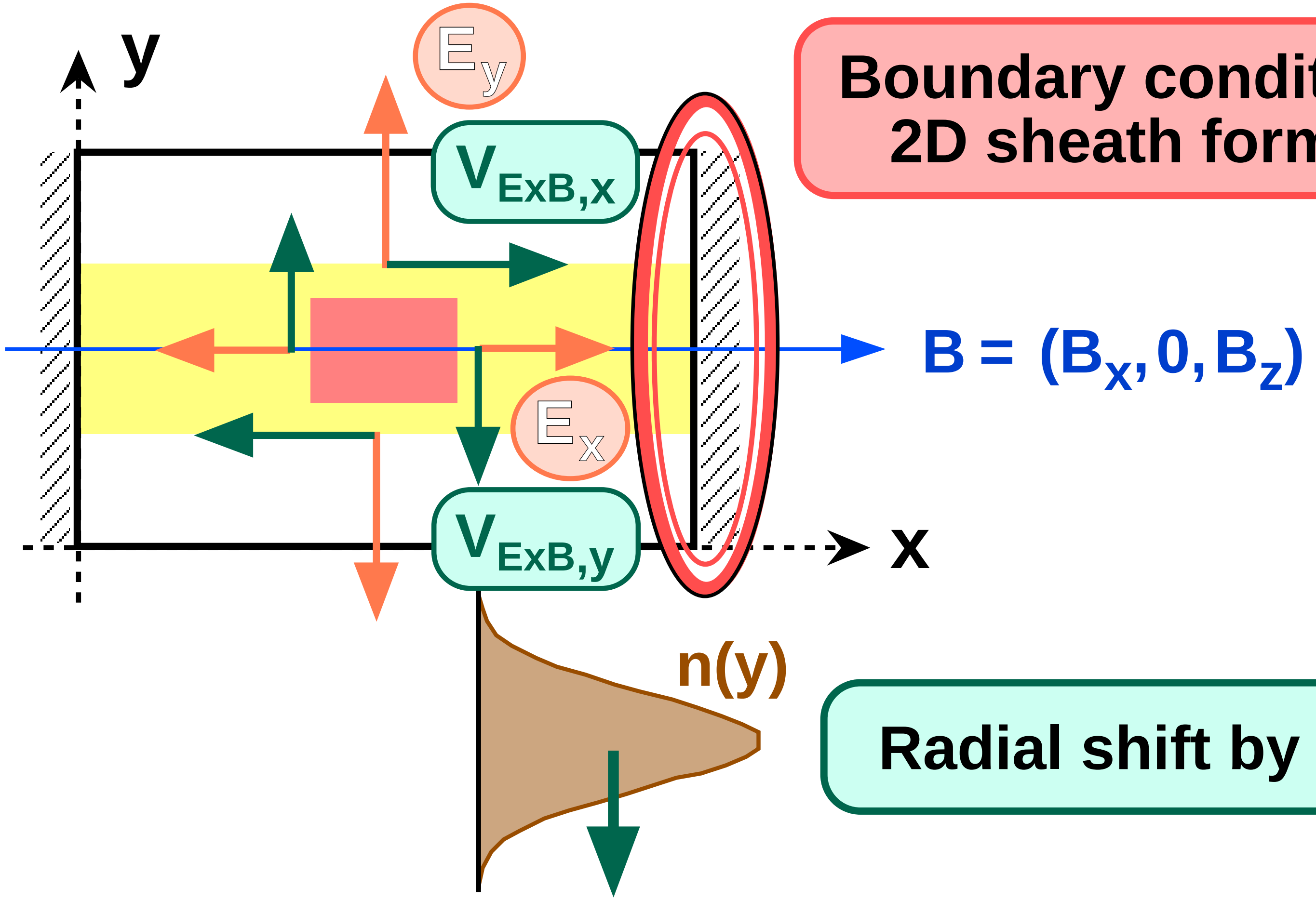


Asymmetric 2D Profiles

Opposite asymmetry to 1D case



Which drift is essential for the asymmetry ?

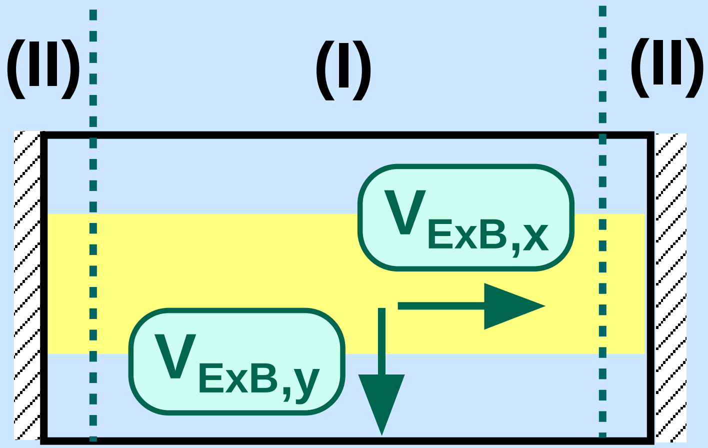


Boundary condition for 2D sheath formation

Radial shift by $V_{ExB,y}$

Artificial elimination of ExB drift to find what is essential

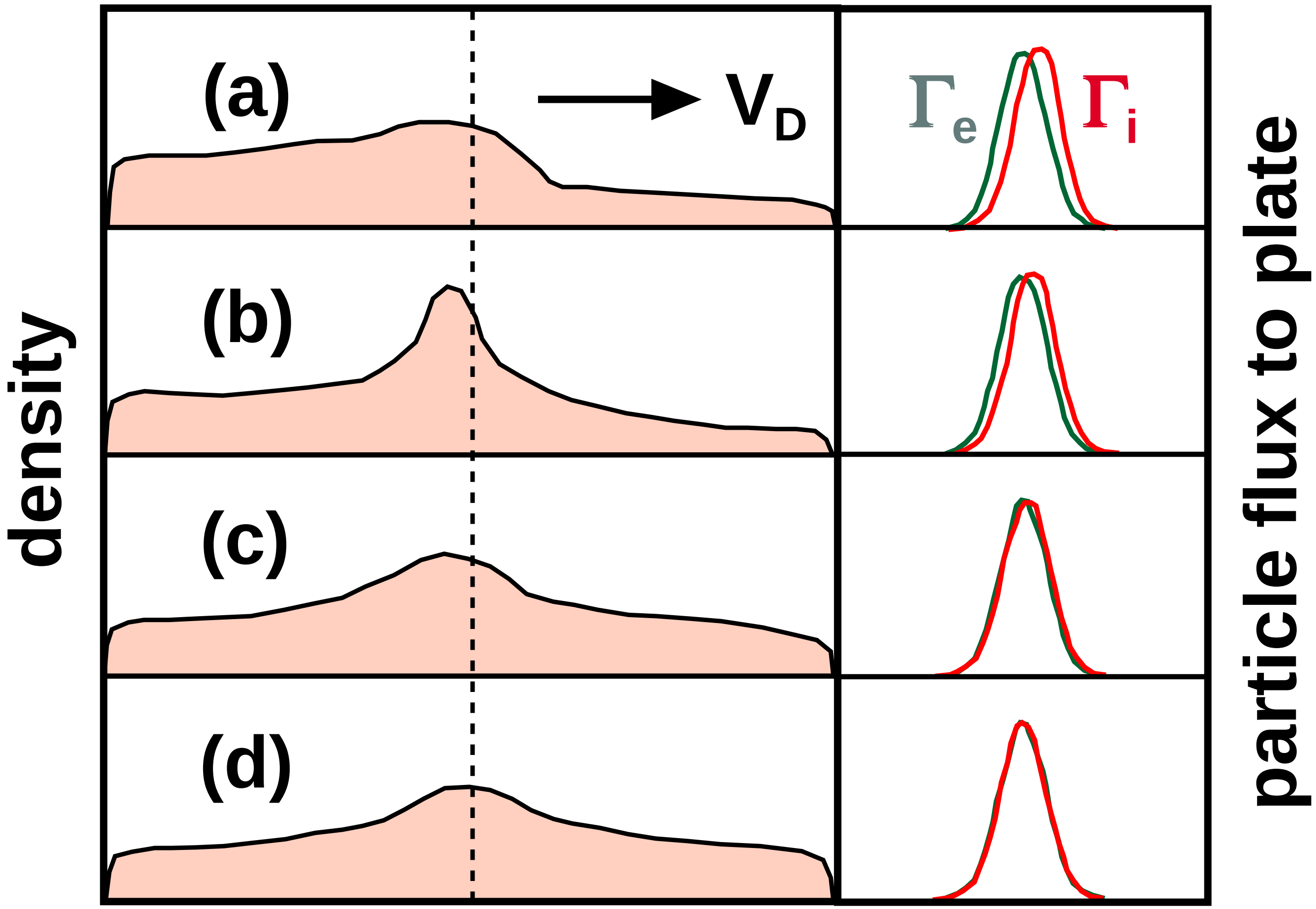
Dividing into (I) central region and (II) boundary region

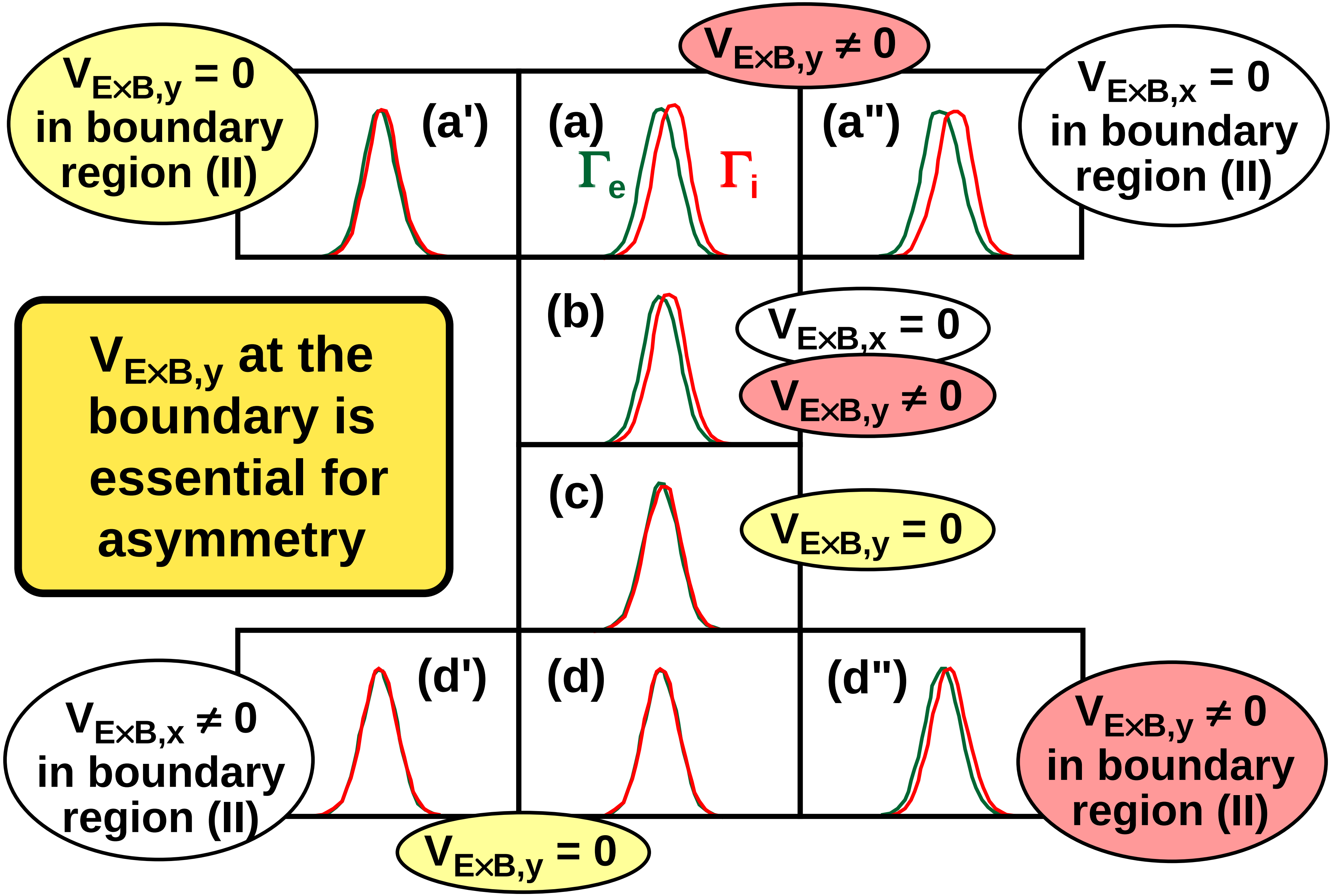


	(I)	(II)
$V_{ExB,x}$	ON/OFF	ON/OFF
$V_{ExB,y}$	ON/OFF	ON/OFF

Asymmetry is mitigated by eliminating $V_{E\times B,y}$

	$V_{E\times B,x}$	$V_{E\times B,y}$
a	○	○
b	—	○
c	○	—
d	—	—





$V_{E\times B,y} = 0$ in boundary region (II)
(a')
(a)
Γ_e
Γ_i
$V_{E\times B,y} \neq 0$
(a'')
$V_{E\times B,x} = 0$ in boundary region (II)
$V_{E\times B,y}$ at the boundary is essential for asymmetry
(b)
$V_{E\times B,x} = 0$
$V_{E\times B,y} \neq 0$
(c)
$V_{E\times B,y} = 0$
$V_{E\times B,x} \neq 0$ in boundary region (II)
(d')
(d)
(d'')
$V_{E\times B,y} \neq 0$ in boundary region (II)
$V_{E\times B,y} = 0$

Condition of sheath formation in a 2D plasma

$$MV_{x0}V_x^* \geq \Theta^2\{T_{eff//} + (V_{//}'/\Theta\Omega)T_{eff\perp}\}$$

$$V_{x0} \equiv \Theta V_{//} + V_{E\times B} + V_{dia}$$

$$V_x^* \equiv \Theta V_{//} + V_{E\times B} - V_{dia}^*$$

$$V_{E\times B} \equiv E_y/B,\ V_{dia} \equiv -P_{i\perp}'/n_e eB,$$

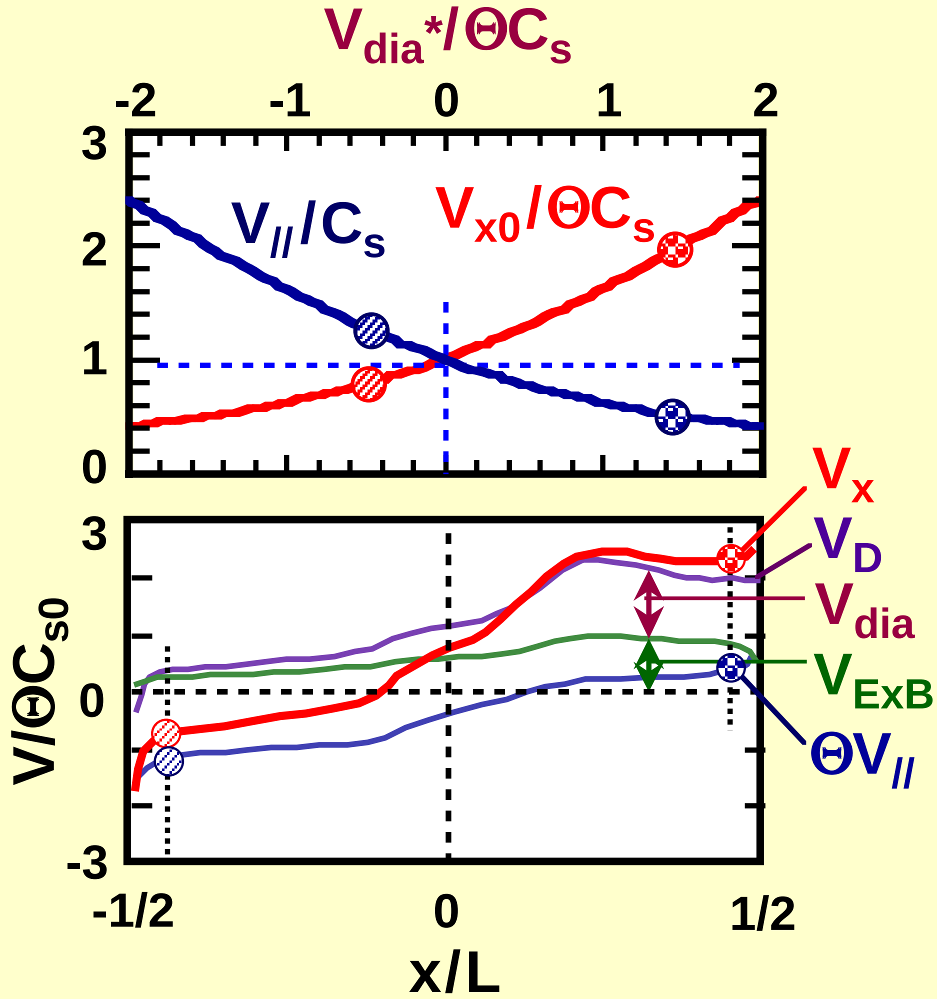
$$V_{dia}^* \equiv -n'T_{e//}/n_e eB$$

$$T_{eff//} \equiv T_{e//} + \gamma T_{i//}$$

$$T_{eff\perp} \equiv T_{e//} + \gamma T_{i\perp}$$

(' denotes d/dy)

originate from the $V_{E\times B,y}$ drift at the boundary



T. Takizuka, M. Hosokawa, K. Shimizu, J. Nucl. Mater. **313-316**, 1331 (2003).

Magnetic presheath formation

Assumption $\partial Q_0/\partial x = 0\,,\quad \partial\delta\Phi/\partial y = 0$

Charge neutrality & Electron responce $\delta n_e = \delta n_i \equiv \delta n\,,\quad \delta n/n_0 = e\,\delta\phi/T_{e0//} \equiv \delta\Phi$

Ion responce

Pressure $\delta P_i/P_{i0} = \gamma\delta n/n_0 = \gamma\delta\Phi$

Flow $\mathbf{V} = (\mathbf{B}/B)\,V_{//} + \mathbf{V}_{E\times B} + \mathbf{V}_{dia} + \mathbf{V}_{pol}$

Polarization drift $\delta V_{pol,x} = -\,V_{x0}\,\rho_{eff}^2\,\partial^2\delta\Phi/\partial x^2 \quad [\,\rho_{eff}^2 \equiv T_{eff\perp}/eB\Omega\,]$

Parallel-momentum equation $M\,V_{x0}\,\partial\delta V_{//}/\partial x = -\left(\Theta\,T_{eff//} + (V_{//0}'/\Omega)\,T_{eff\perp}\right)\partial\delta\Phi/\partial x$

Ion continuity equation $\partial nV_x/\partial x + \partial nV_y/\partial y = 0$

E×B drift by ($\partial\delta\Phi/\partial x$) is important $(\partial n_0/\partial y)\,dV_{E\times B,y} = (\partial n_0/\partial y)\,(T_{eff//}/eB)\,\partial\delta\Phi/\partial x$

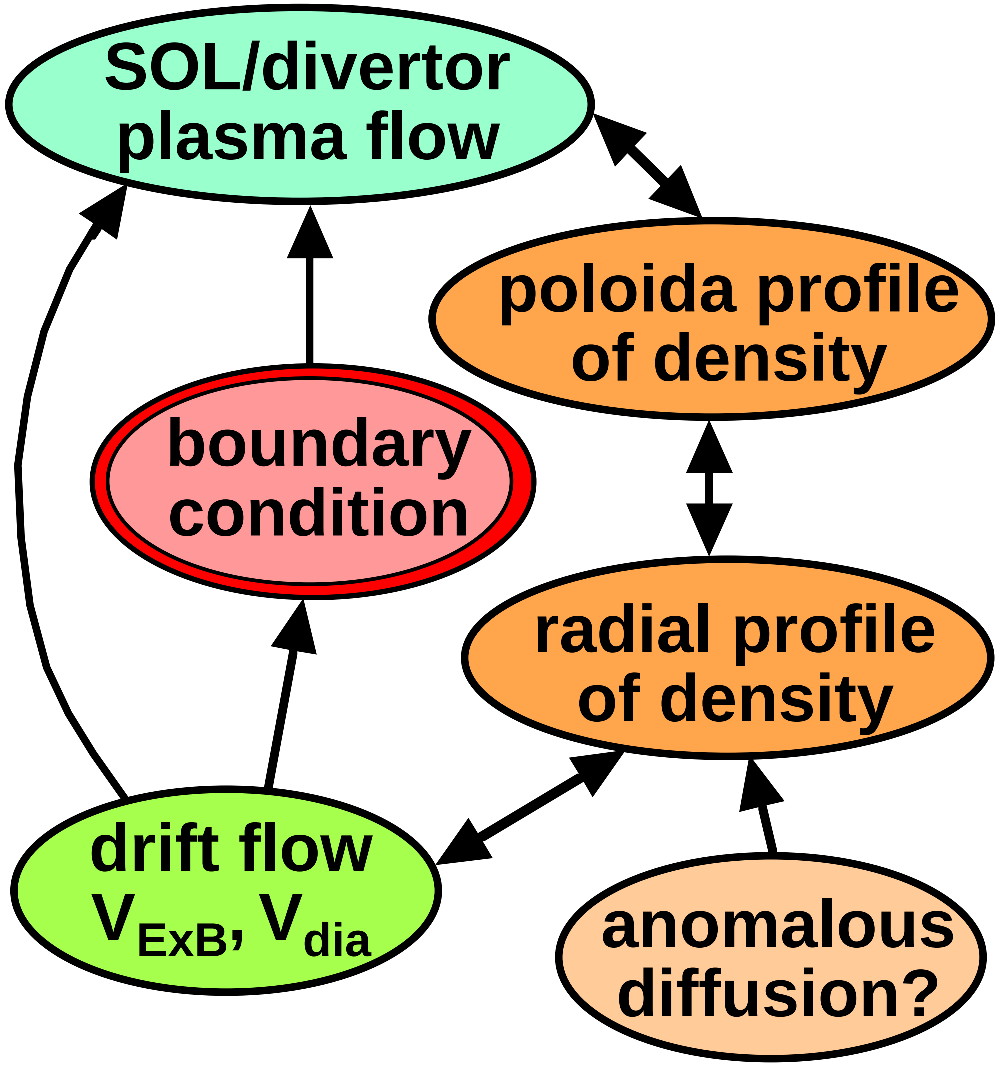
$$M\,V_{x0}^2\,\rho_{eff}^2\,\partial^2\delta\Phi/\partial x^2 = \left\{\underline{M\,V_{x0}V_x^* - \Theta^2\left(T_{eff//} + (V_{//0}'/\Theta\Omega)\,T_{eff\perp}\right)}\right\}\delta\Phi$$

Polarization drift term

≥ 0

Condition of sheath formation
(exponential growing)

Self-organized 2D structure of SOL/divertor plasma

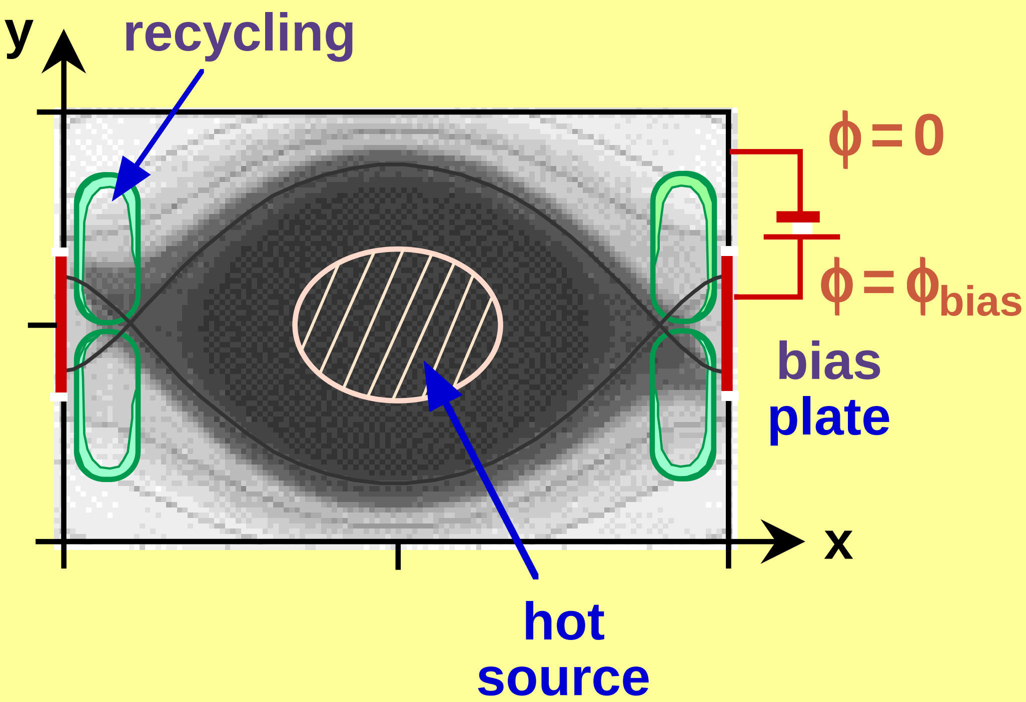


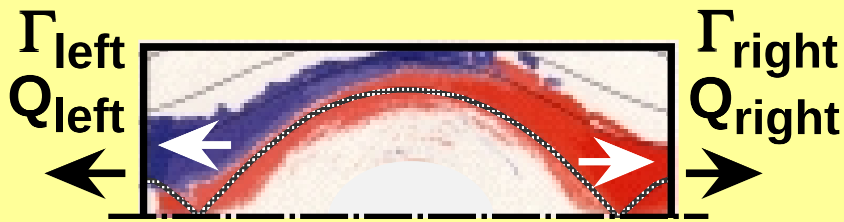
Boundary condition is the key for the 2D structure formation

SOL/divertor plasma is naturally asymmetric

2D Particle Simulation of the Flow Control in SOL and Divertor Plasmas

T. Takizuka, M. Hosokawa, K. Shimizu, J. Nucl. Mater. **313-316**, 1331 (2003).





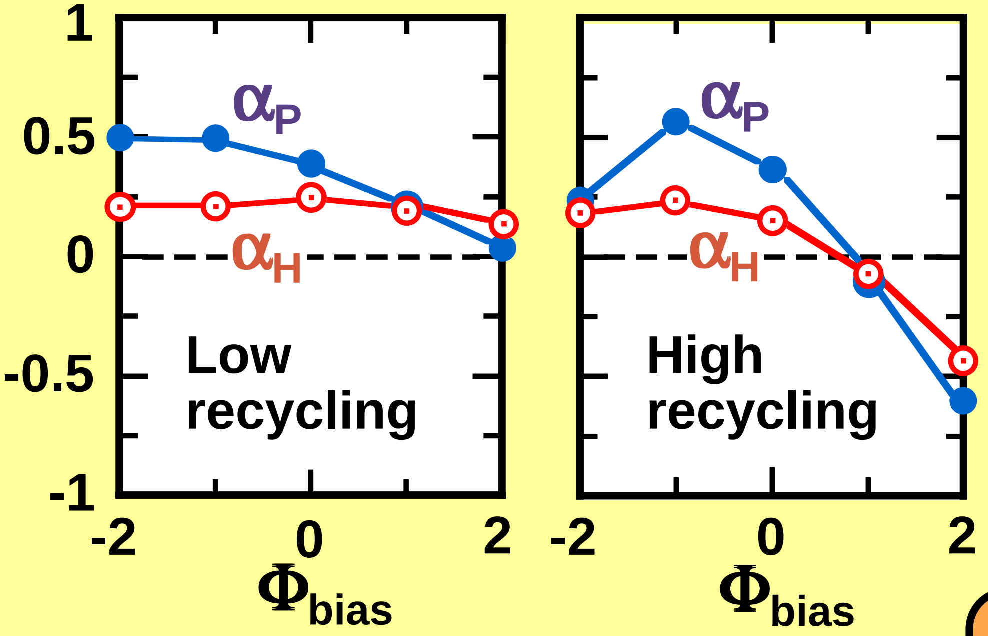
Particle-flux asymmetry

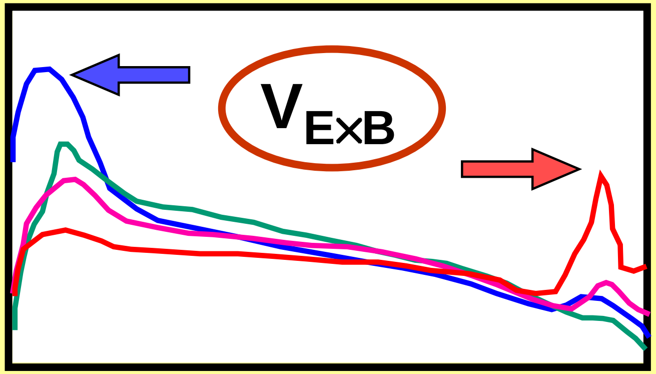
$$\alpha_P = (\Gamma_{left} - \Gamma_{right}) / (\Gamma_{left} + \Gamma_{right})$$

Heat-flux asymmetry

$$\alpha_H = (Q_{left} - Q_{right}) / (Q_{left} + Q_{right})$$

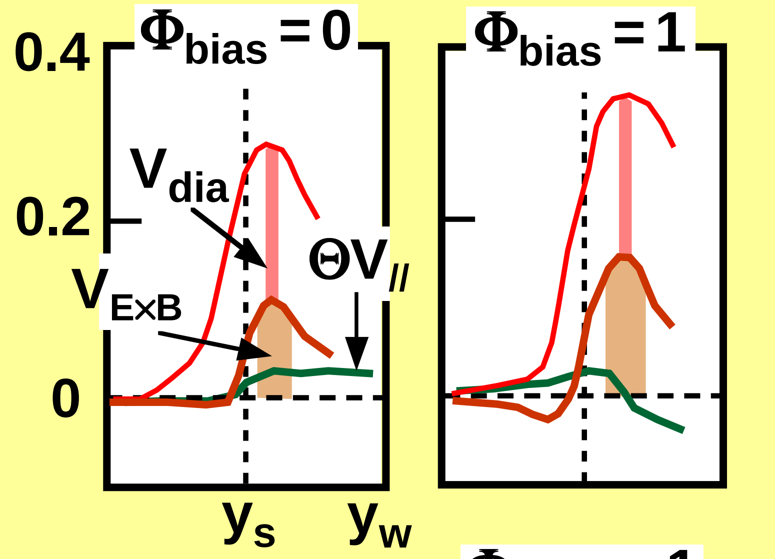
Biasing Controls the Asymmetry

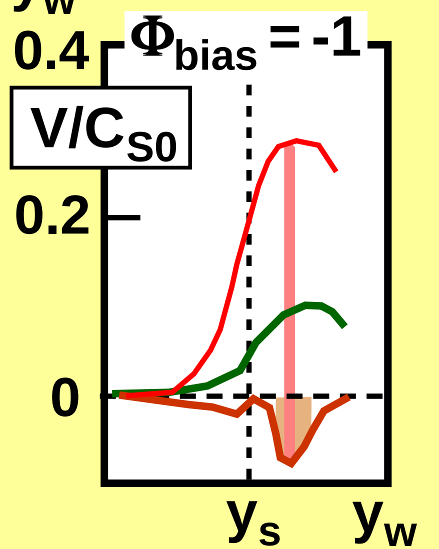




Poloidal profile of density

Biasing changes directly the E×B Drift





Radial profile of flow speed
(at the middle of SOL x = 0)

Summary

- An advanced particle simulation code PARASOL has been developed, to validate various physics models introduced to fluid simulations of SOL/divertor plasmas.

  A binary collision model is incorporated to an electrostatic PIC method.

- Condition for the 2D sheath formation is derived analytically, and confirmed by 2D PARASOL simulation.

- Boundary condition is a key factor for the self-organization of 2D structure of SOL/divertor plasmas.

  Divertor asymmetry is the intrinsic feature.

- Control of the asymmetry by the divertor biasing is demonstrated with 2D PARASOL simulation.