History of PARASOL

T. Takizuka

Graduate School of Engineering, Osaka University

PARASOL was developed at Japan Atomic Energy Agency

OSAKA UNIVERSITY

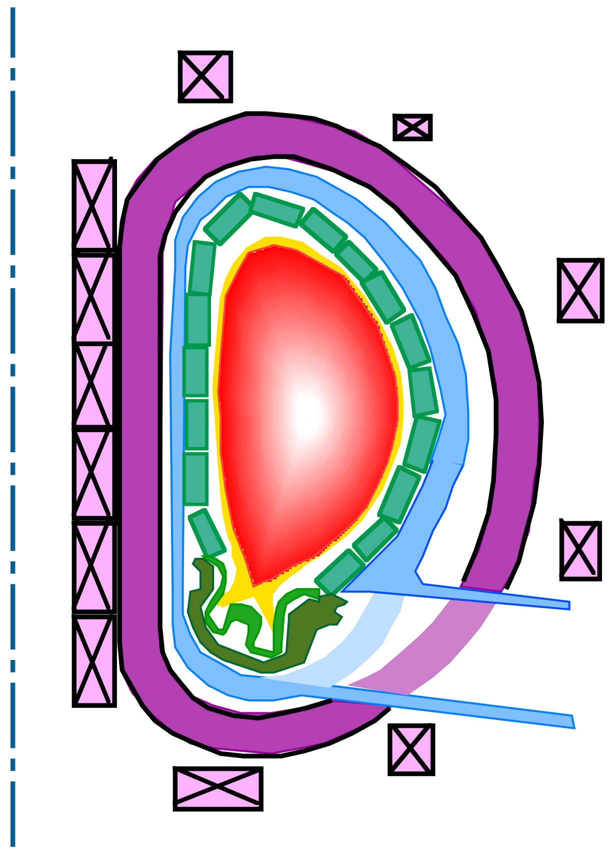
20th NEXT Meeting, Kyoto Terrsa, Kyoto, 13-14 Jan 2015

Edge Plasma Research for Fusion

Hot plasma in the core region is transported across magnetic field lines to the peripheral region (closed field), and brought out to the scrape-off-layer region.

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

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



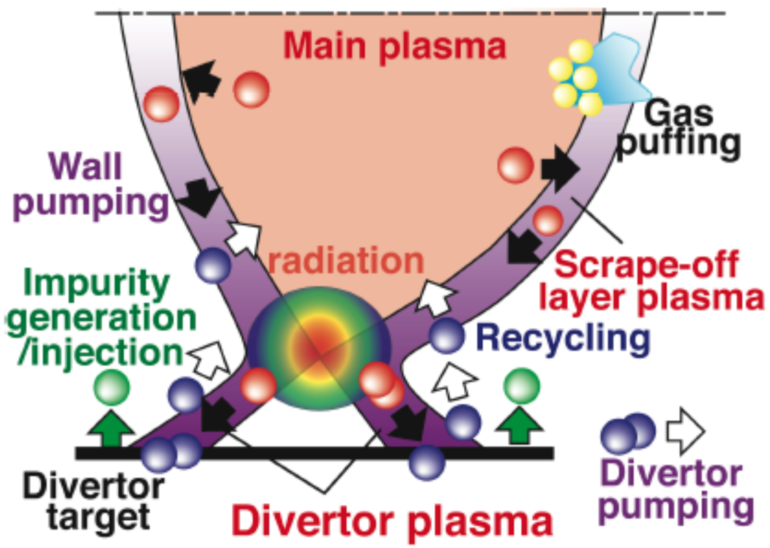
Importance of Edge Plasma Simulation

To understand the complex system of plasma edge in fusion devices, numerical simulations are indispensable.

various non-dimensional parameters $\rho^*, \beta, \nu^* + l_{A\&M\text{-}mfp}, \mathbf{L}_{rad}(\mathbf{T}_e)$
complex geometries of magnetic configuration and wall

Multi-element Integrated Simulation for SOL-divertor plasmas

SOLPS, **EDGE2D/NIMBUS**, **UEDGE**, **SONIC**, **EMC3/EIRENE** etc



Integrated SOL-divertor code developed in JAEA

- Charged particle
- Impurity
- Recycling neutral
- Fuelled particle

fluid model

Monte Carlo model

H. Kawashima, K. Shimizu, T. Takizuka, et al., *Plasma Fusion Res.* **1** (2006) 031.
H. Kawashima, K. Shimizu, T. Takizuka, *Plasma Phys. Control. Fusion* **49** (2007) S77.

Particle Modeling

Various physics models (e.g., boundary condition at the divertor plate $V_{//} = C_s$, parallel heat conduction $q_{//} = -\kappa_{//} \nabla_{//} T$ etc.) are employed in the **fluid modeling** for SOL-divertor plasmas.

Kinetic approach is necessary to validate such physics models.

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

R. Cohen, X.Q. Xu, *Contrib. Plasma Phys.* **48** (2008) 212.
C.K. Birdsall, *IEEE Trans. Plasma Sci.* **19** (1991) 65.
J.P. Verboncoeur, *Plasma Phys. Control. Fusion* **47** (2005) A231.

PARASOL code has been developed for studying the physics of SOL and divertor plasmas.

(PARticle Advanced simulation for SOL and divertor plasmas)

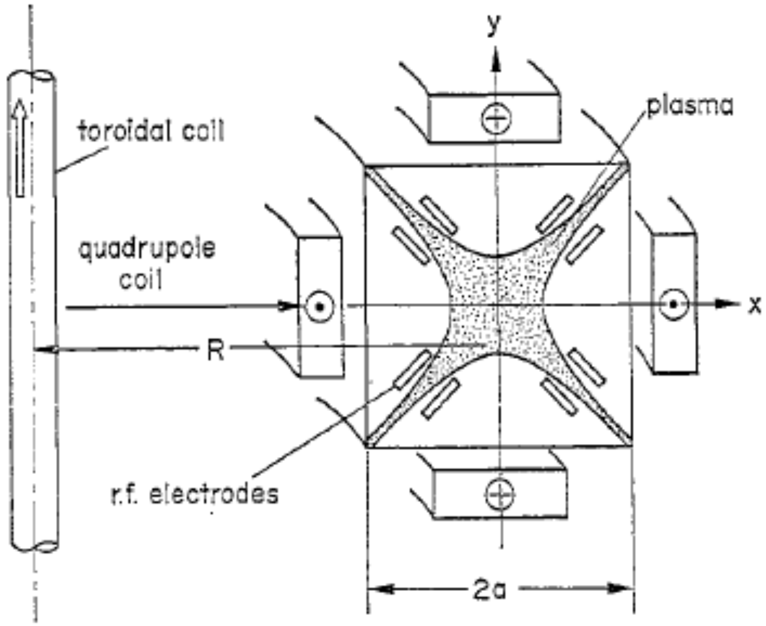
T. Takizuka et al., *proc. 8th IAEA Conf.,* Brussels 1980, **Vol. 1** (1981) p.679.
R. Chodura, *Phys. Fluids* **25** (1982) 1628.
T. Takizuka et al., *J. Nucl. Mater.* **128-129** (1984) 104.
T. Takizuka, M. Hosokawa, *Contrib. Plasma Phys.* **40** (2000) 471.
T. Takizuka, *Plasma Sci. Technol.* **13** (2011) 316.

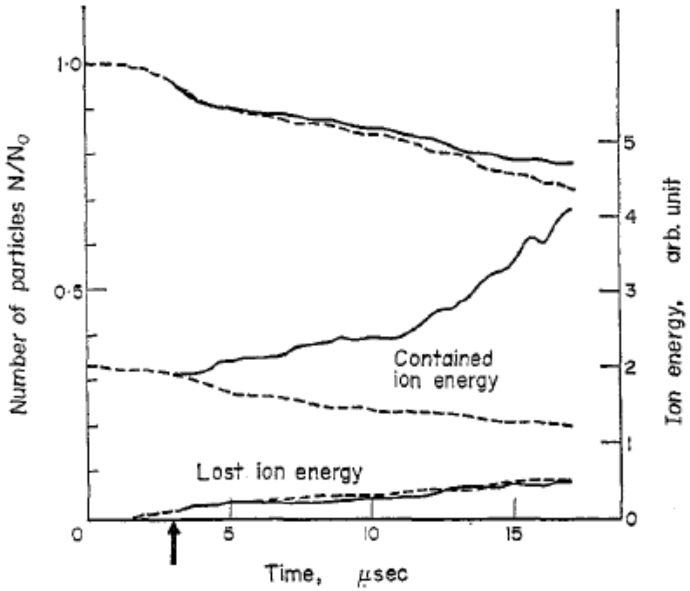
Toroidal Quadrupole

open system => large end loss : improvement by r.f. ?

T. Takizuka et al.,. *Plasma Phys.* **17** (1975) 887.

PIC simulation ($N_{i0} = N_{e0} = 2500$, $m_i/m_e = 25$)





Collisions are essential for the end loss

$$\tau = \tau_{ic} \ln(R_m) + 2R_m \tau_{it}$$

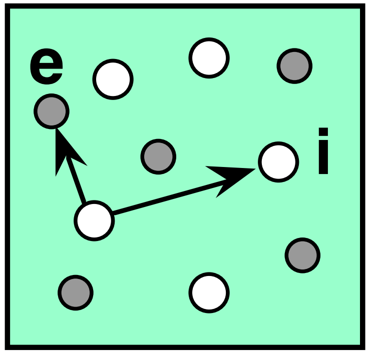
Collision model using modified Langevin's equation, $d\mathbf{v}/dt = \Sigma [-\nu (\mathbf{v} - \mathbf{V}) + \mathbf{A}]$

Small angle scattring, Conservation of momentum and energy in the system

T. Takizuka, Master thesis, 1972 (Kyoto University).

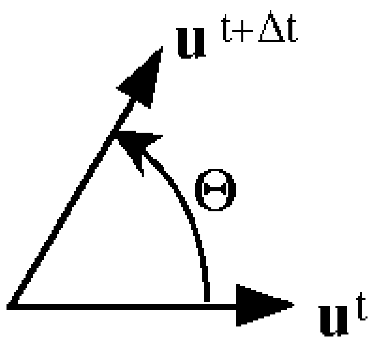
Binary collision model (Takizuka-Abe model)

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



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

Total momentum and total energy are conserved intrinsically.

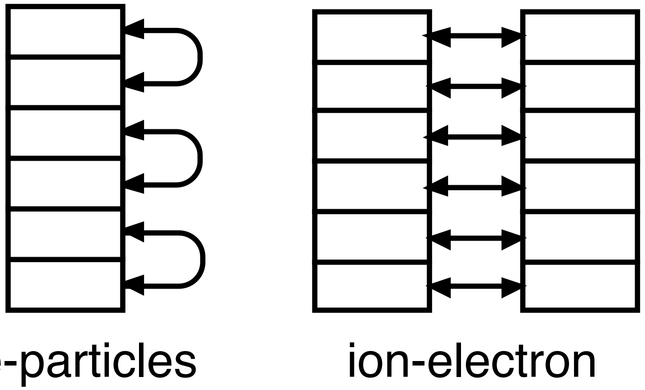


$$<\Theta^2> \sim \nu_d \Delta t$$

Random selection of collision pairs

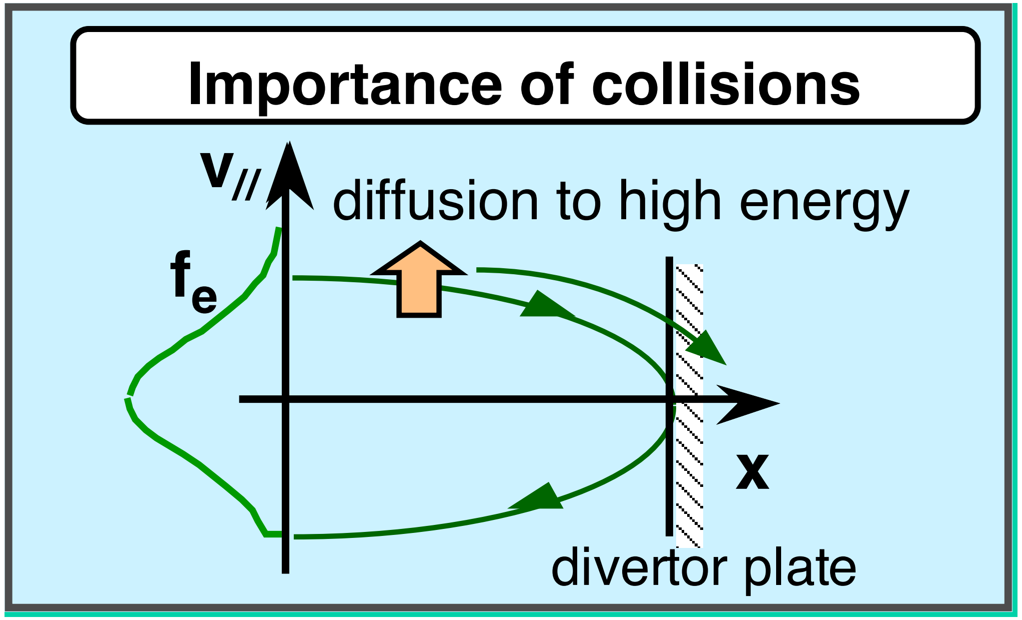
At first; random rearrangement of addresses in every cell at every time step.

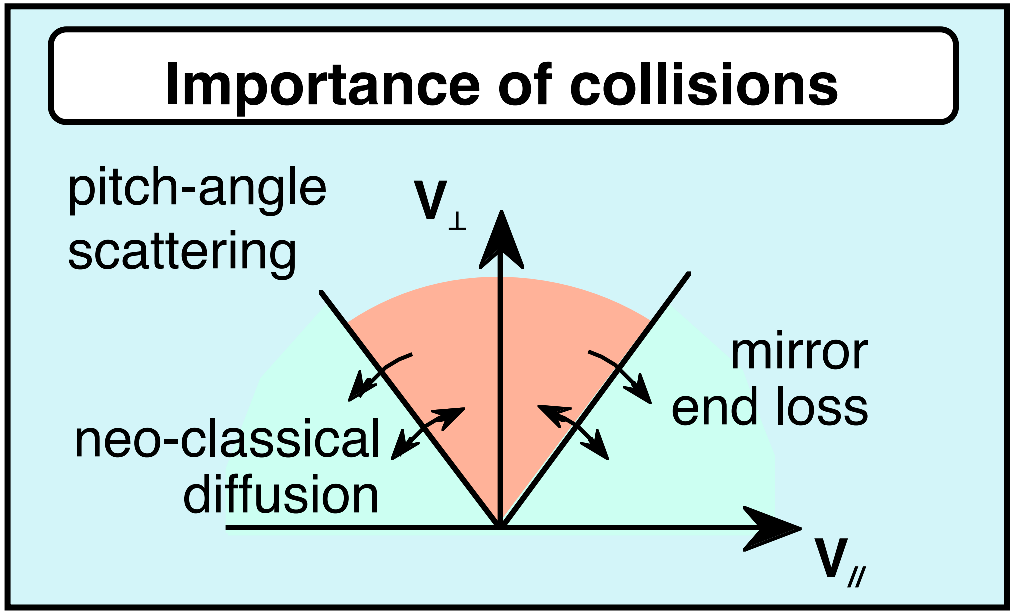
Next ;



Landau collision integral

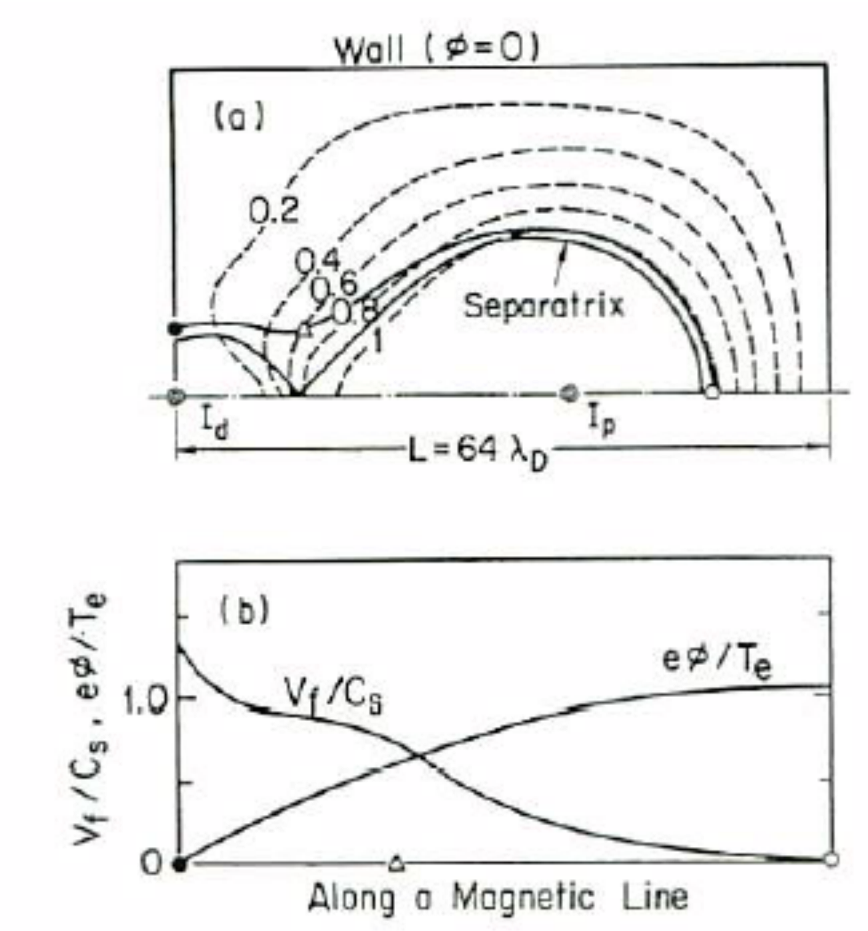
T. Takizuka, H. Abe, *J. Comput. Phys.* **25** (1977) 205.


Importance of collisions
v//
diffusion to high energy
fe
x
divertor plate


Importance of collisions
pitch-angle
scattering
v⊥
mirror
end loss
neo-classical
diffusion
v//

Poloidal Divertor in a Tokamak

T. Takizuka et al., *Plasma Phys. Control. Nucl. Fusion Res. 1980 (proc. 8th Int. Conf., Brussels)* Vol. **1** (IAEA, Vienna, 1981) 679.



Particles are lost from the core to the SOL region by the anomalous diffusion:

$$<\delta_\perp^2> = D_\perp \Delta t$$

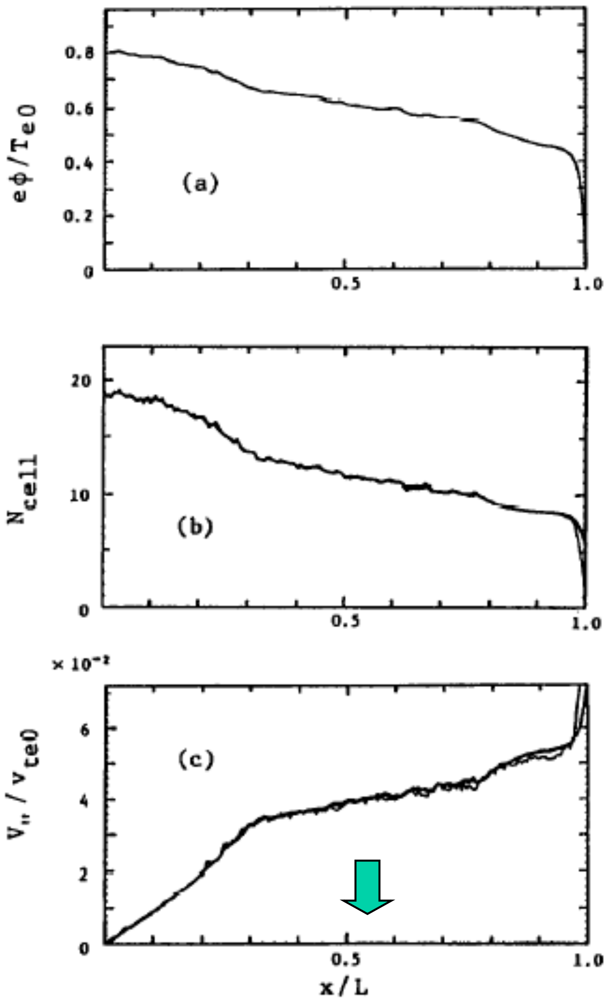
Pre-sheath and sheath are formed in the SOL.

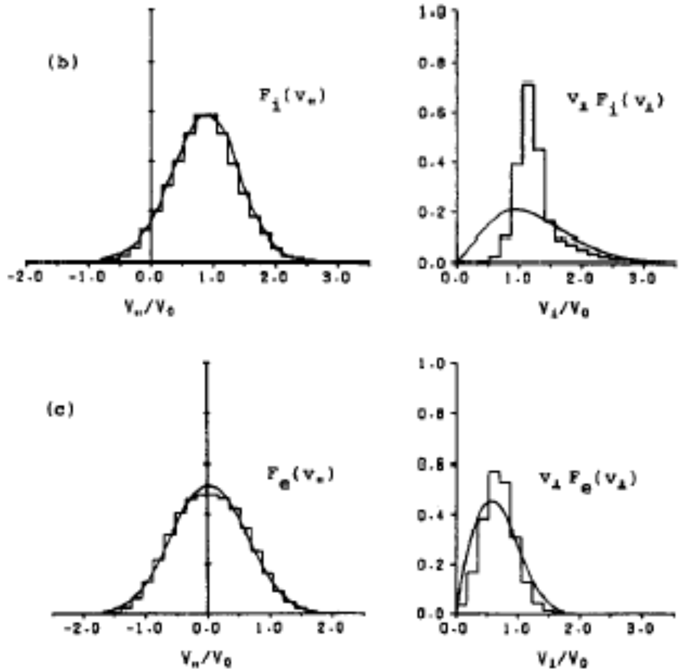
Collision is absent in this work.

Particle Simulation of Divertor Plasma

Combination of PIC Code and Binary Colision Model

T. Takizuka et al., *J. Nucl. Mater.* **128&129** (1984) 104.





Reference: 1D collisionless PIC

R. Chodura, *Phys. Fluids* **25** (1982) 1628.

History of the PARASOL code

Prehistory (1975~1985)

Binary collision model
PIC code of **2D poloidal divertor**
PIC+BiC code of **1D divertor**

Single CPU with ~ 10 MFLOPS
FACOM 230-75, M200, M380
N_i ~ 2500, K_t ~ 10^4

A period of rest (1985~1995)

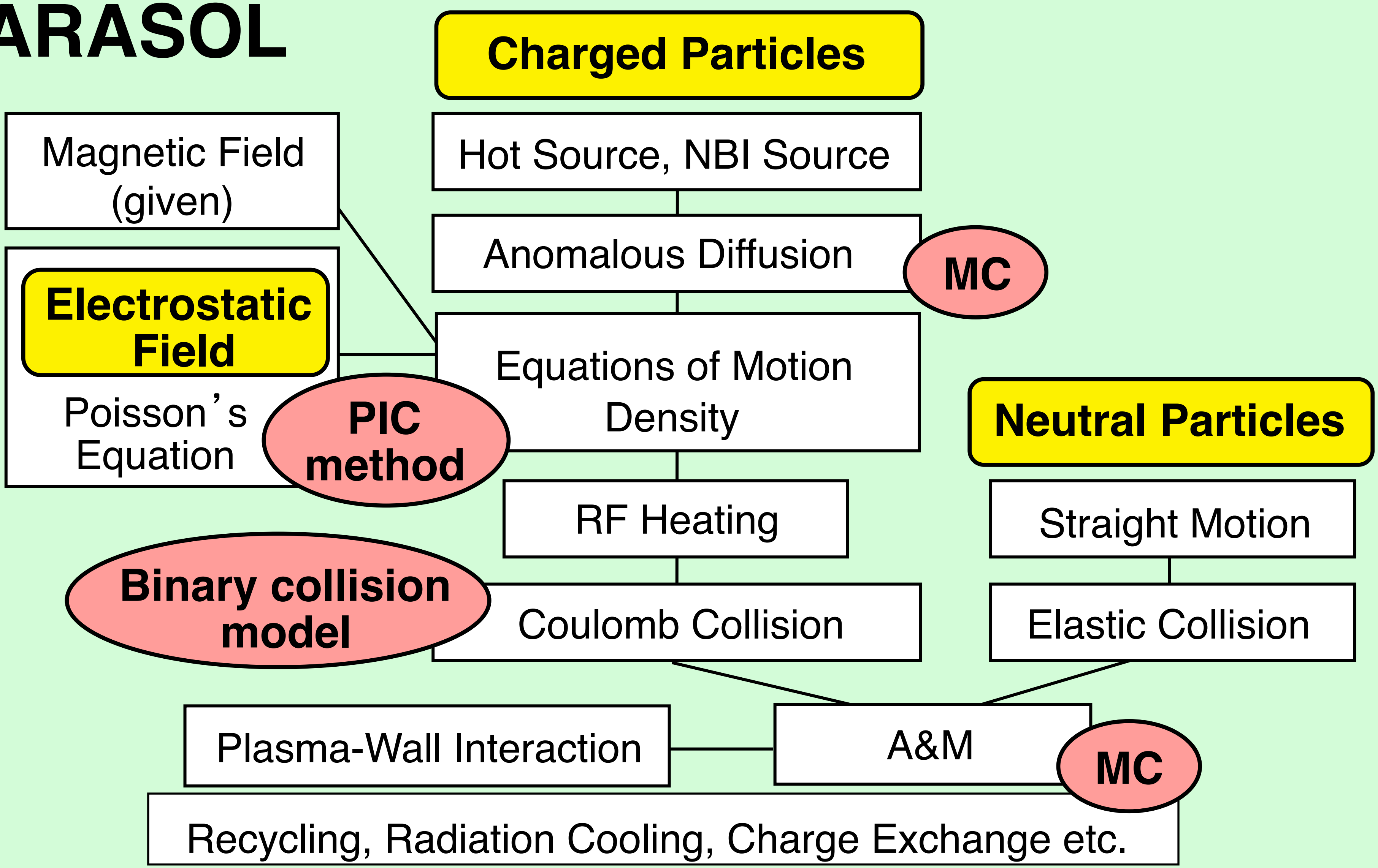
NEXT (Numerical EXperiment of Tokamak) project (1995~)

Integrated modeling project (2000~)

1D PARASOL
1D-dynamic PARASOL
2D-slab PARASOL
2D-separatrix PARASOL
2D-toroidal PARASOL

Massively parallel computer
Intel Paragon XP/S (75 MFLOPS)
64 PEs N_i ~ 10^5, K_t ~ 10^5
SGI Origin 3800 (1 GFLOPS/PE)
Altix 3700Bx2 (6 GFLOPS/PE)
128 PEs N_i ~ 10^6, K_t ~ 10^6
HELIOS (2013 by Azuma)

PARASOL



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

T. Takizuka, Plasma Interaction in Controlled Fusion Devices: 3rd ITER International Summer School, AIP Conference Proceedings **1237** (2010) 138.

T. Takizuka, *Plasma Sci. Technol.* **13** (2011) 316.

System size

Fusion plasma $L/\lambda_D > 10^4$ / PARASOL plasma $L/\lambda_D < 10^3$

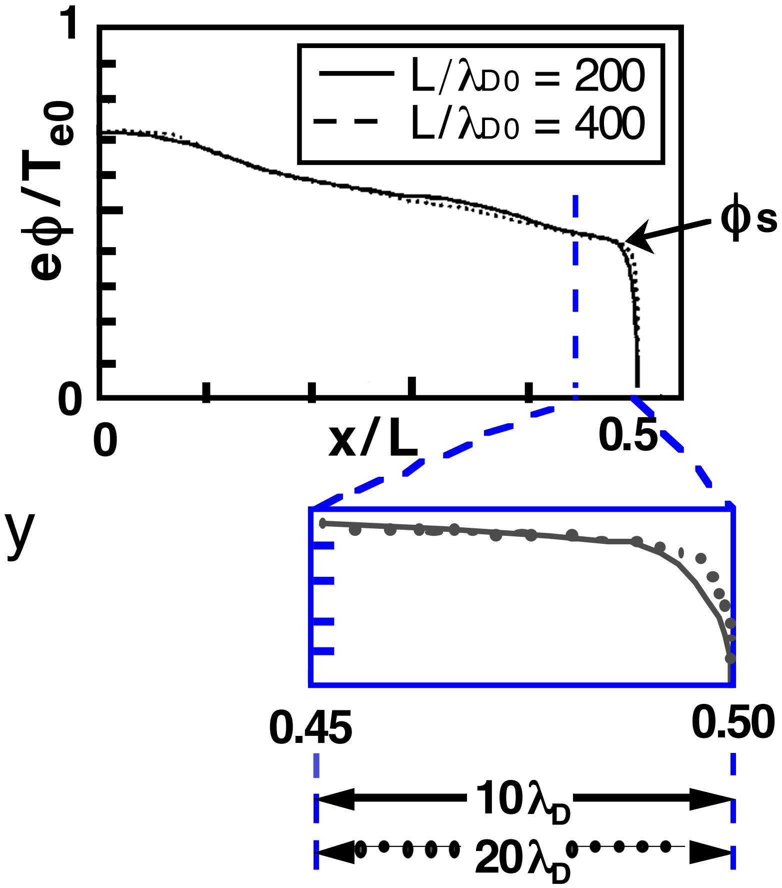
System size L , Mesh size $\Delta \sim \lambda_D$

Particle number $N \propto (L/\lambda_D)^{1,2,3}$ ← dimension

Characteristic time for equilibrium L/C_s

Time steps $K_t \propto (m_i/m_e)^{1/2} (L/\lambda_D)$

Computation time $t_c \propto (m_i/m_e)^{1/2} (L/\lambda_D)^{2,3,4}$



PARASOL simulations are available to study open-field plasmas with smaller values of $L/\lambda_D \sim 10^{2\text{-}3}$, because characteristics are almost unchanged by changing L/λ_D value except the sheath region.

By introducing the binary collision model, we can flexibly perform **PARASOL** simulations at any **arbitrary collisionality** $L_{//}/l_{mfp}$

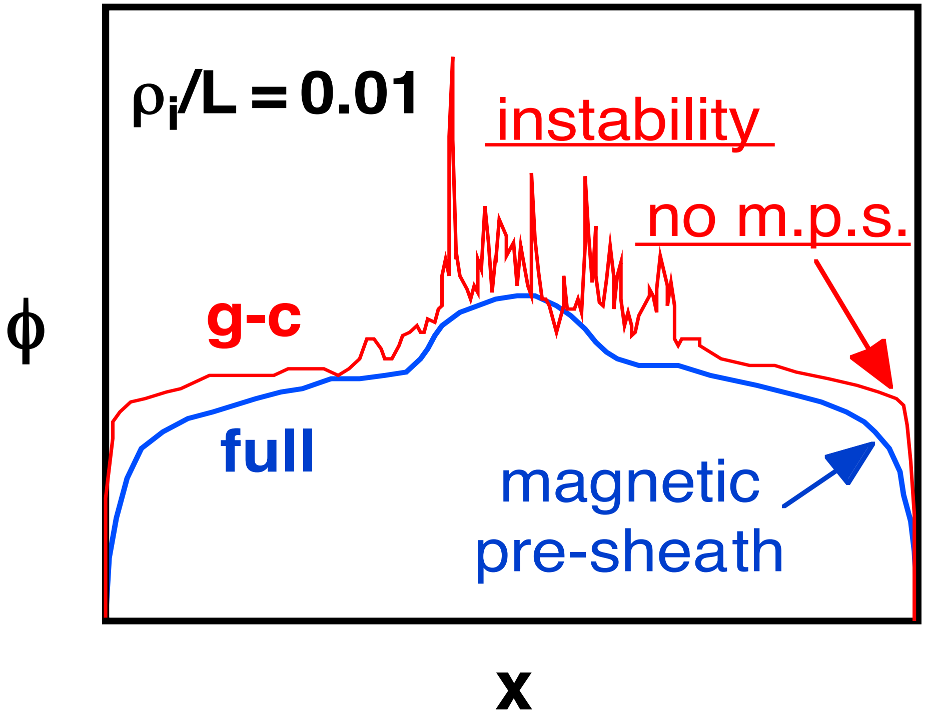
Adopt "collision cut-off" technique near the wall to keep collisionless sheath

Full particle model of PARASOL simulates correctly the edge plasma

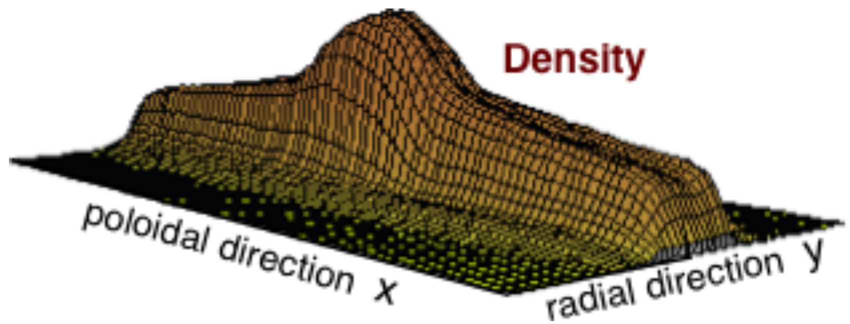
$$m_i \, d\boldsymbol{v}_i/dt = e\,(\boldsymbol{E} + \boldsymbol{v}_i \times \boldsymbol{B})\,, \quad d\boldsymbol{r}_i/dt = \boldsymbol{v}_i$$

Ion polarization drift is essential

$$V_x^{polar} \sim (\Omega_i B)^{-1} dE_x/dt \sim (\Omega_i B)^{-1} v_x \, \partial E_x/\partial x \quad (\, v_x \approx \Theta v_{//} \,)$$



PARASOL 2D-slab code

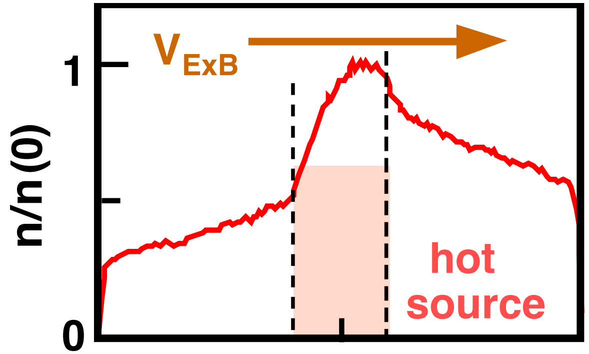


PARASOL Simulation for Physics Modeling

Verification of the Bohm criterion

1D PARASOL simulation

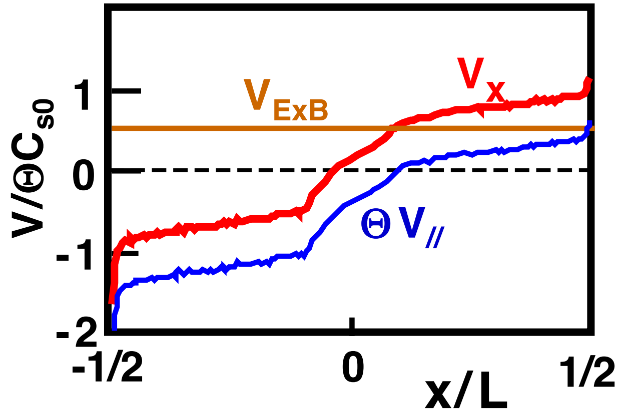
Oblique $\boldsymbol{B}$ ($\Theta = B_x/B \ll 1$), $E_y \times B_z$ drift

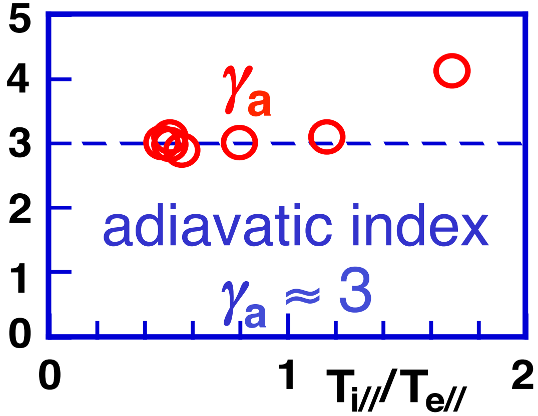


$$m_i V_x^{\,2} \geq \Theta^2\, T_{\mathrm{eff}//}$$

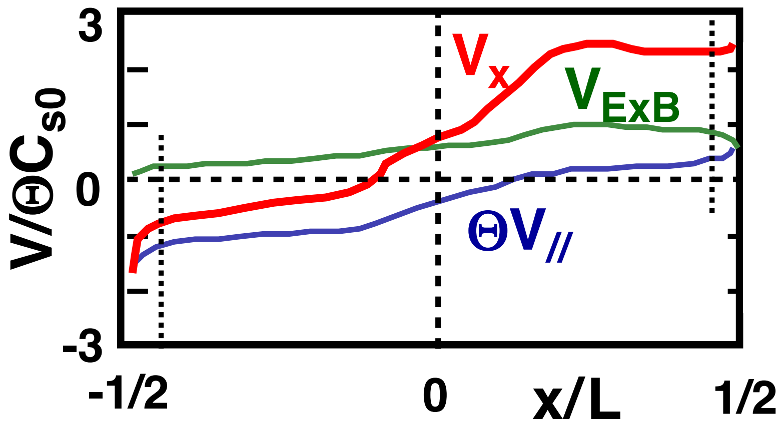
$$V_x = \Theta V_{//} + V_{ExB}$$

$$T_{\mathrm{eff}//} = T_{e//} + \gamma_a T_{i//}$$





2D PARASOL simulation



$$m_i V_{x0} V_x^{*} \geq \Theta^2\, T_{\mathrm{eff}}$$

$$V_{x0} = \Theta V_{//} + V_{ExB}$$

$$V_x^{*} = V_{x0} + n' T_{e//}/nB$$

$$T_{\mathrm{eff}} = T_{\mathrm{eff}//} + (V_{//}'/\Theta\Omega)\, T_{\mathrm{eff}\perp}$$

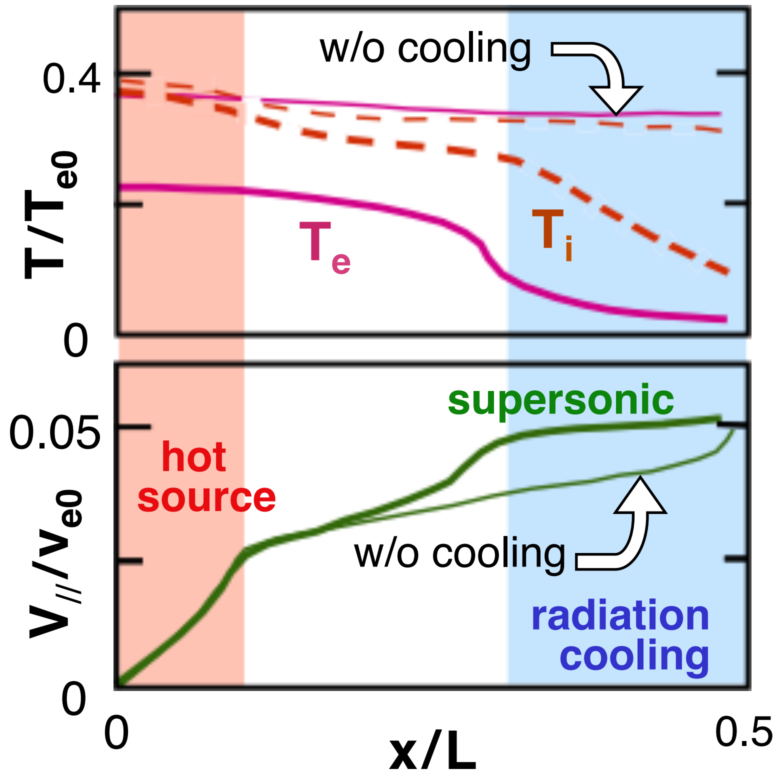
1D : T. Takizuka, M. Hosokawa, *Contrib. Plasma Phys.* **40** (2000) 471.

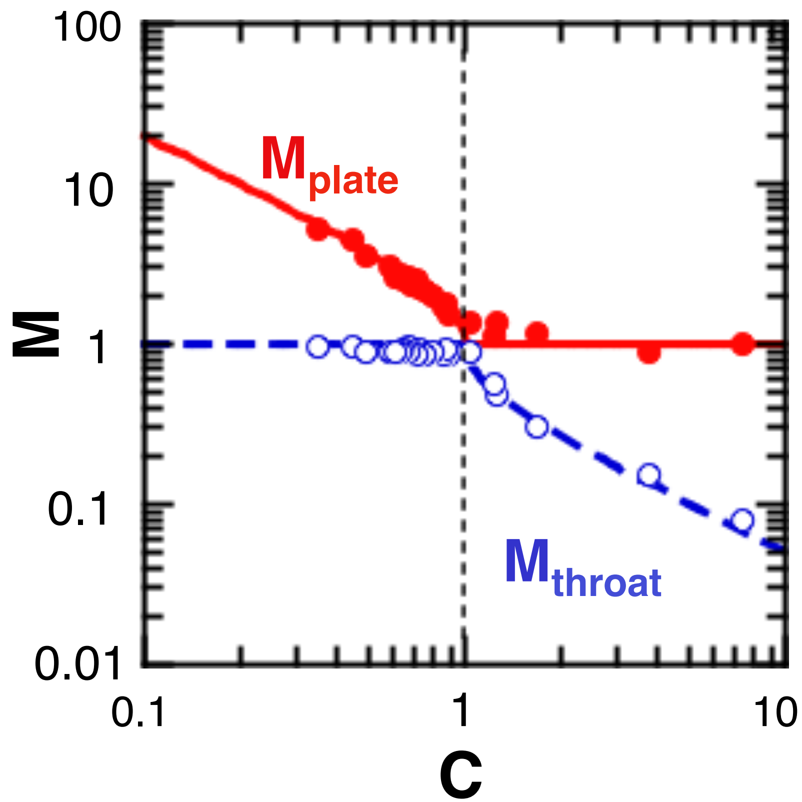
2D : T. Takizuka, M. Hosokawa, K. Shimizu, *J. Nucl. Mater.* **313-316** (2003) 1331.

Supersonic flow in the cold divertor

Supersonic $M_{plate} > 1$ **for** $C \equiv (R_{\Gamma}/R_p)(T_{plate}/T_{throat})^{1/2} < 1$

R_{Γ} : particle flux amplification, R_p : momentum flux loss, T_{plate}/T_{throat} : cooling ratio





PARASOL simulation results agree very well with analytical formula

T. Takizuka, M. Hosokawa, K. Shimizu, *J. Nucl. Mater.* **290-293** (2001) 753.

Kinetic effect on the parallel heat transport in SOL

Collisional $l_{mfp} \ll L$

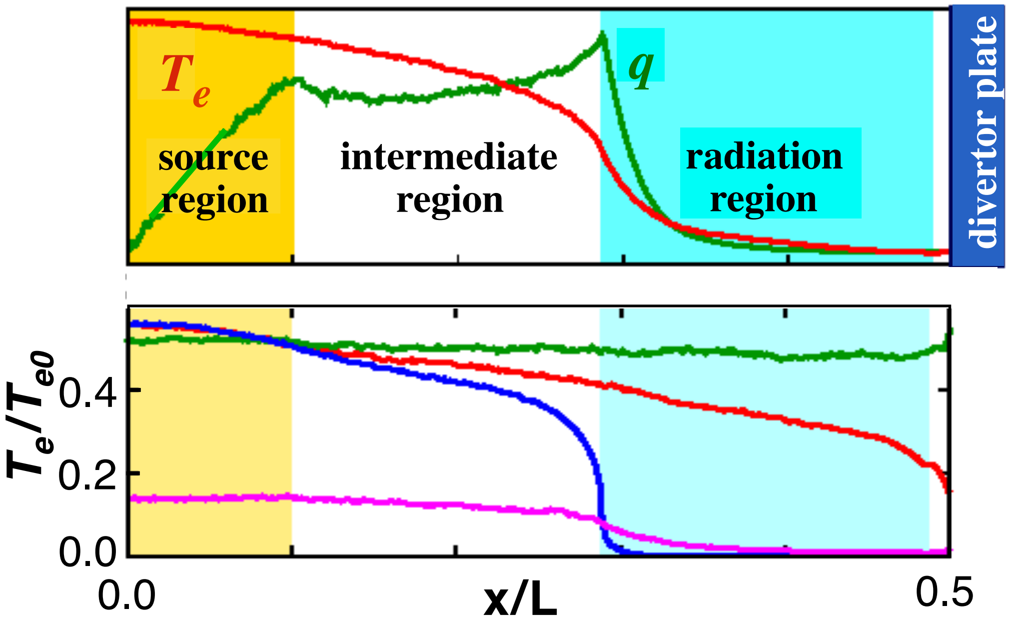
$$q_{e//} = q_{SH} = -\kappa_{e//}\, dT_e/ds$$

Collisionless $l_{mfp} \gg L$

$$q_{e//} = \alpha_e q_{FS} = \alpha_e n T_e v_{eth}$$

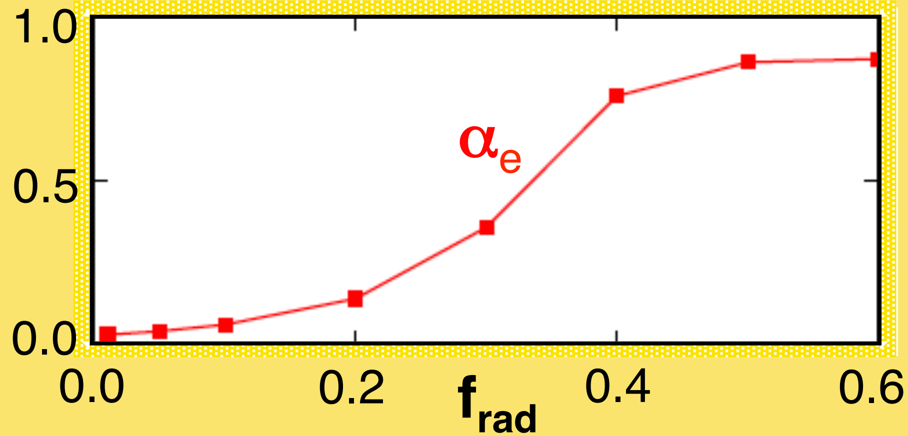
Harmonic average model

$$q_{eff}^{-1} = q_{SH}^{-1} + (\alpha_e q_{FS})^{-1}$$



f_{rad}	l_{mfp}/L		f_{rad}	l_{mfp}/L	
0.1	10^2	green	0.5	10^3	magenta
	10^{-2}	red		10^{-1}	blue

Various values of flux-limiting factor α_e have been reported from small ~0.01 to large ~1 [3].



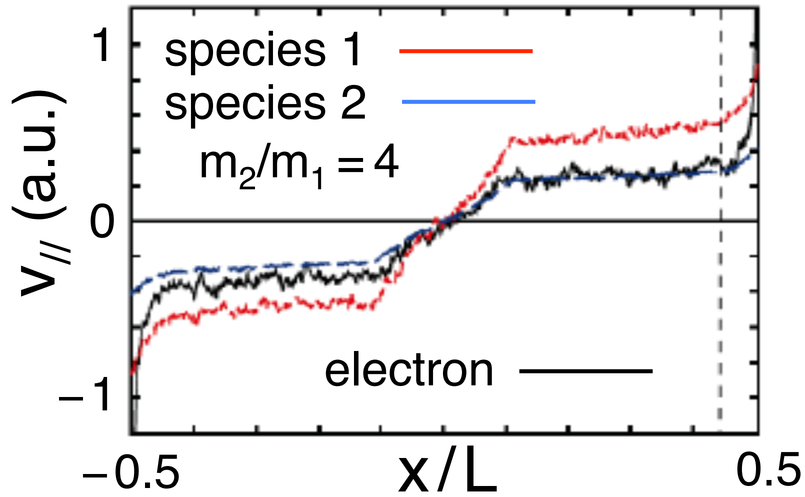
PARASOL simulation shows that α_e value is changed by situations; α_e increases with f_{rad} [1,2].

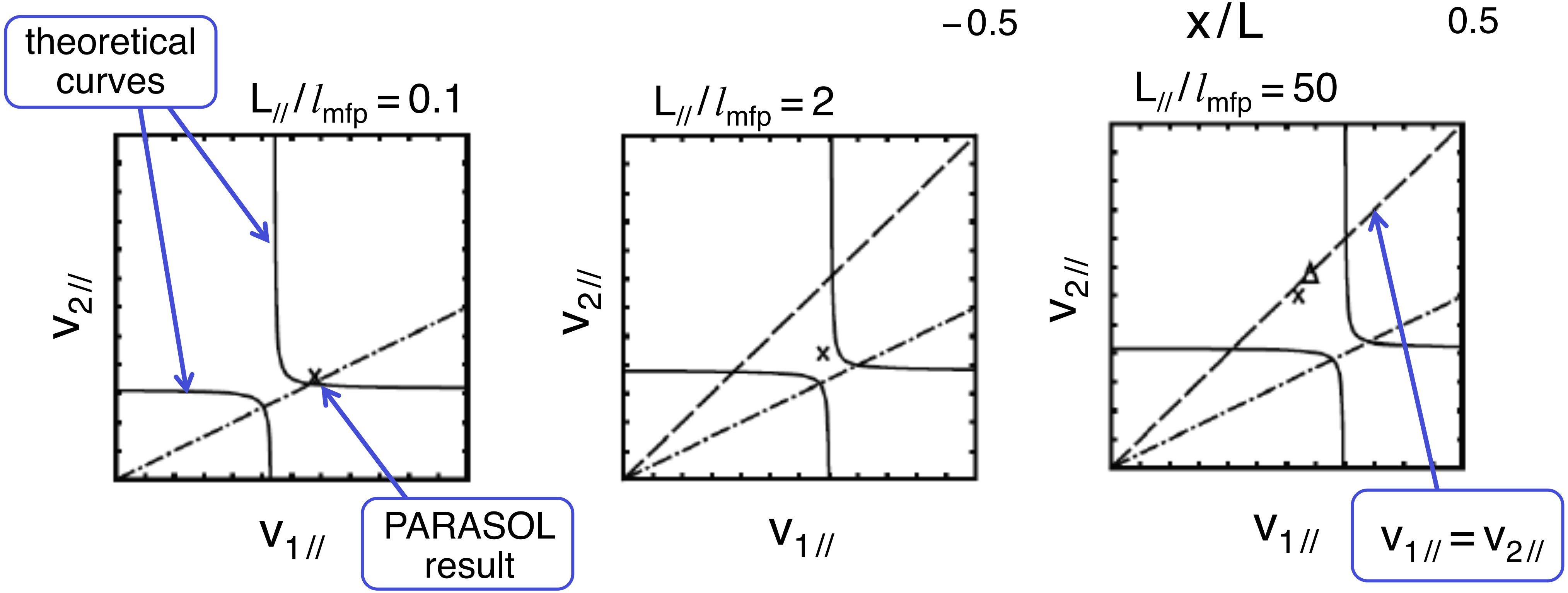
[1] A. Froese, T. Takizuka, M. Yagi, *Plasma Fusion Res.* **5** (2010) S1017.
[2] A. Froese, T. Takizuka, M. Yagi, *Plasma Fusion Res.* **5** (2010) 26.
[3] W. Fundamenski, *Plasma Phys. Control. Fusion* **47** (2005) R163.

Bohm criterion for two-ion-species plasmas

$$(v_{1\|}^2 - C_{s1\|}^2)(v_{2\|}^2 - C_{s2\|}^2) = U_\|^4,$$

$$C_{si\|} = \sqrt{(n_i^* T_{e\|} + \gamma_i T_{i\|})/m_i}, \;\; U_\|^2 = \sqrt{n_1^* n_2^* T_{e\|}^2 / m_1 m_2}$$

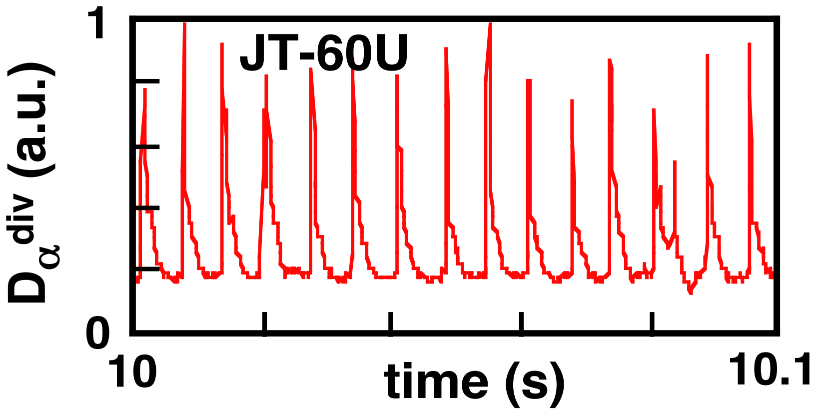


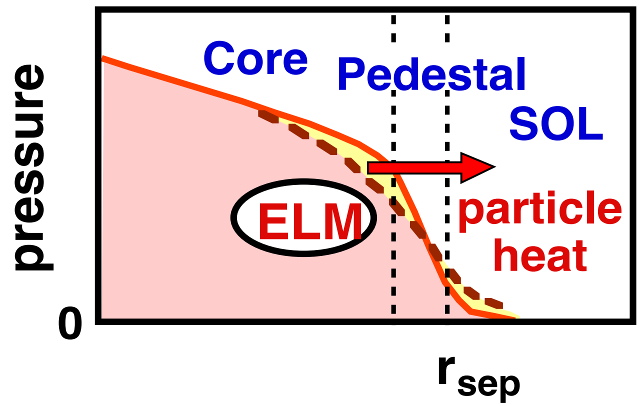


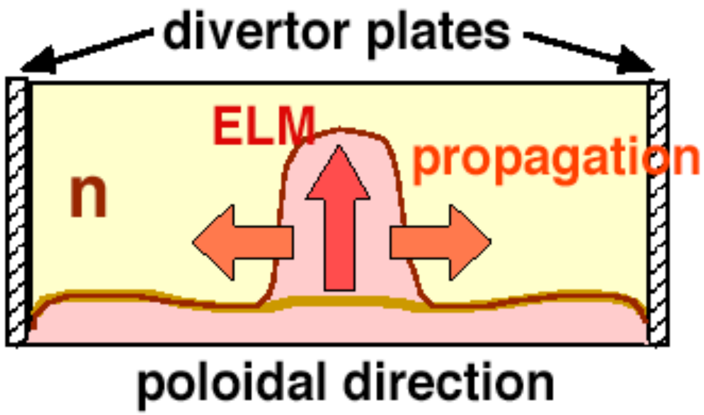
S. Azuma, A. Fukuyama, T. Takizuka, *Contrib. Plasma Phys.* **52** (2012) 512.

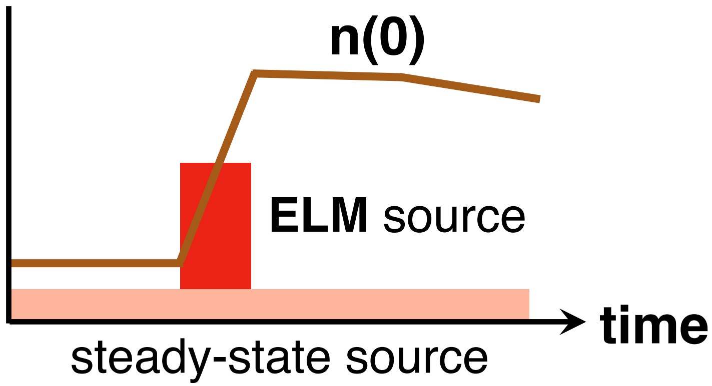
ELM Heat Propagation in 1D SOL-Divertor Plasmas

Enhanced heat and particle fluxes to divertor plates due to **ELMs** in **H-mode** are crucial issues (erosion and lifetime of the plates)



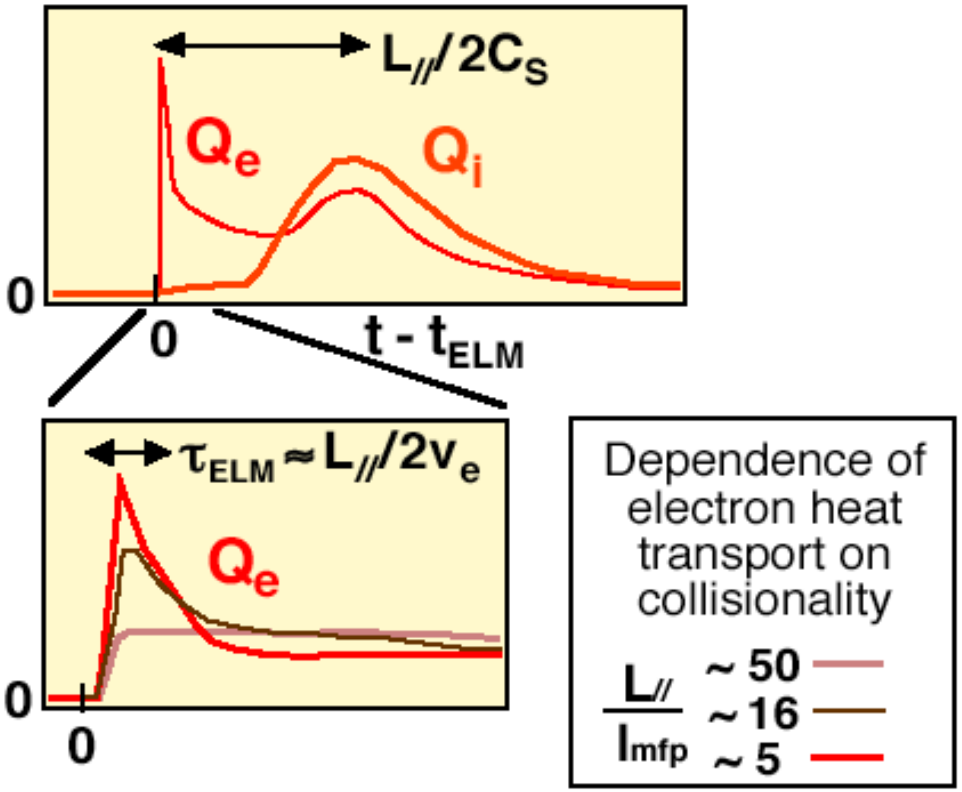


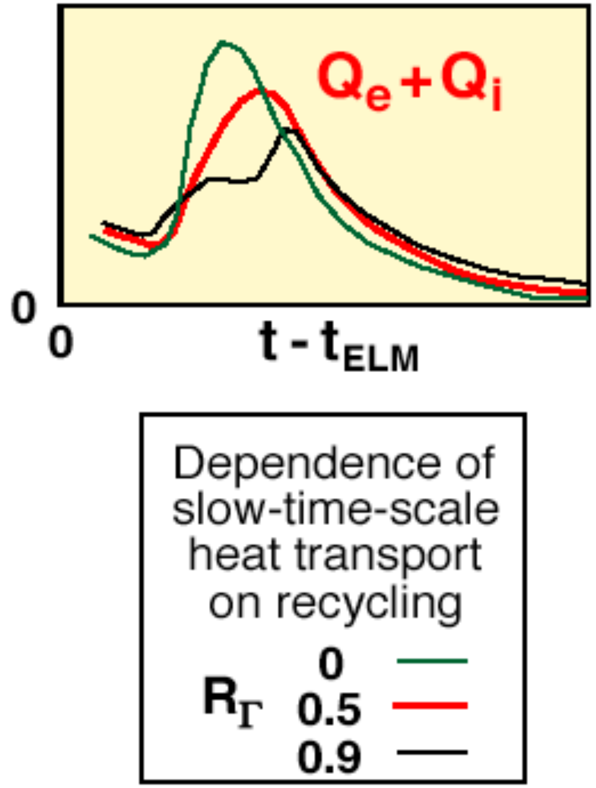




Propagation time of ELM heat flux, a key factor to influence the plates, is studied using **1D-dynamic PARASOL**

Time evolution of the ELM heat flux to a divertor plate





Fast-time-scale behaviors (electron response) are affected by collisions.

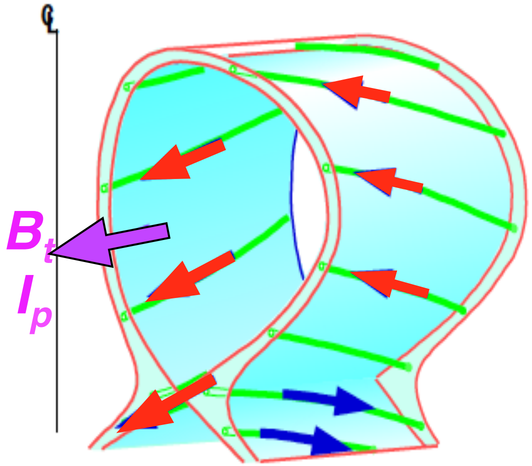
Slow-time-scale behaviors are affected by recycling.

T. Takizuka, M. Hosokawa, *Contrib. Plasma Phys.* **46** (2006) 698.
T. Takizuka, N. Oyama, M. Hosokawa, *Contrib. Plasma Phys.* **48** (2008) 207.

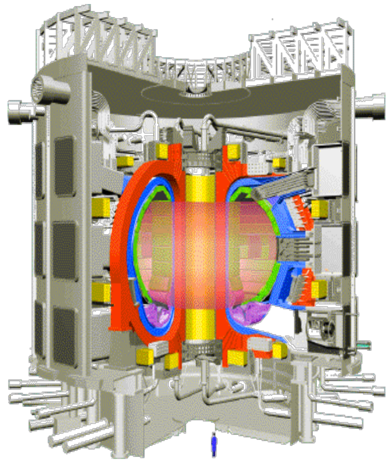
SOL Flow Pattern in Tokamaks

SOL flow important for the particle control in fusion reactors.

The flow works to expel He ashes and to retain impurities in the divertor region, if it is directed towards the plate.



In tokamak experiments, however, the flow direction is sometimes opposite; from the plate side to the SOL middle side in the outer SOL.
This backward flow is seen when the single null point is located in the ion ∇B drift direction.

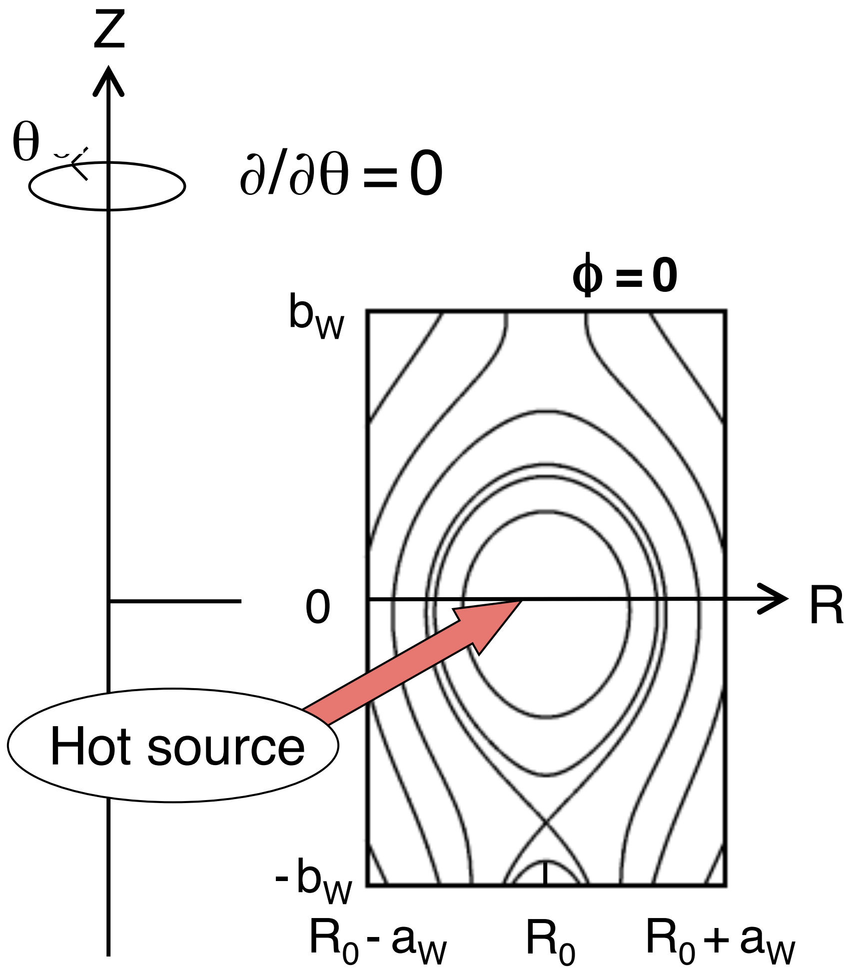


N. Asakura, ITPA SOL and Divertor Topical Group, *J. Nucl. Mater.* **363-365** (2007) 41.

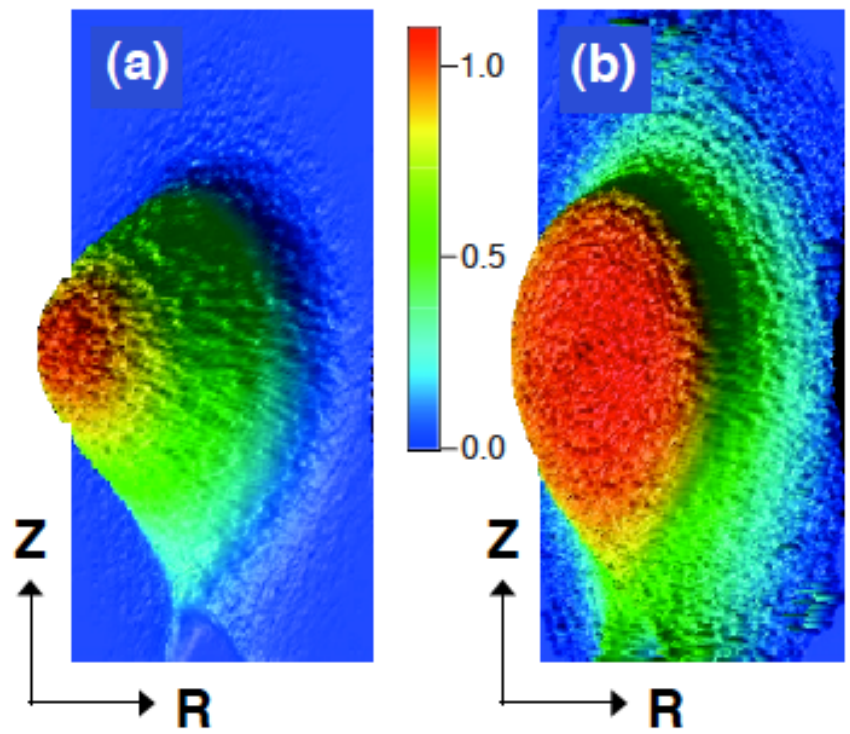
Physics mechanisms of the backward flow have not fully been known, though many simulation studies have been carried out with the fluid model.

Kinetic simulations are considered to bring a breakthrough on this subject. Effects of drifts, banana particles, self-consistent electric fields including sheath etc. important for SOL flow formation are all taken into account.

Full particle simulation with 2D-toroidal PARASOL code



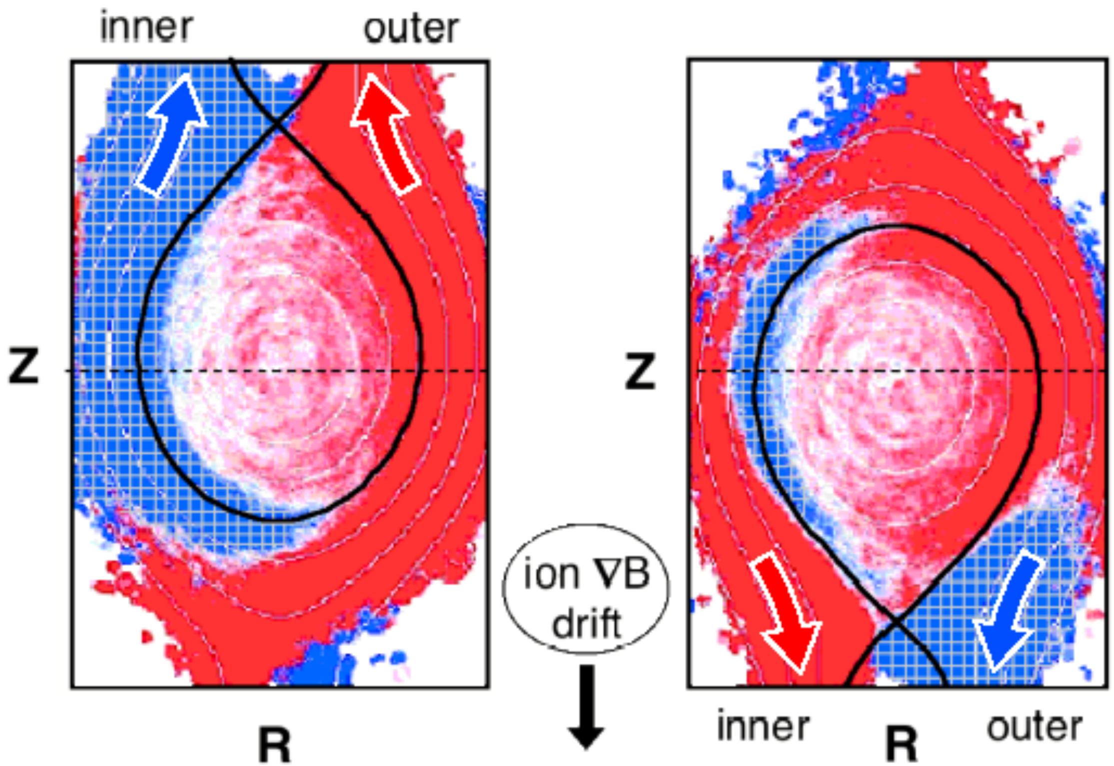
Stationary profiles of n_e and T_e



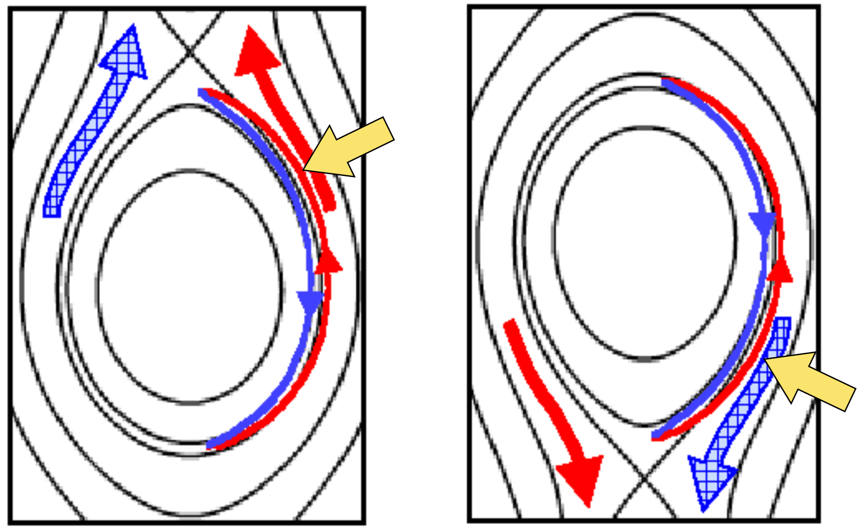
$N_{i0} = 10^6$, $M_R \times M_Z = 320 \times 512$, $m_i/m_e = 400$, $\rho_i/a \approx 0.02$, $D \approx 10^{-5} aC_s$,
$l_{mpf}/L_{//} \approx 1$, $\Theta = 0.2$ (q is not constant for the change of $A = R_0/a$)

SOL Flow ($V_{//}$) Pattern (red : co-flow to I_p , blue : counter-flow)

Upper-null point **Lower-null point**



T. Takizuka, K. Shimizu, N. Hayashi, M. Hosokawa, M. Yagi, Nucl. Fusion **49** (2009) 075038.



Additive or **Subtractive** between original SOL flow and **orbit-induced flow**

On this physics finding from PARASOL simulation, a **new model** of “**ion-orbit-induced flow**” was developed.

T. Takizuka, K. Hoshino, K. Shimizu, M. Yagi, *Contrib. Plasma Phys.* **50** (2010) 267.

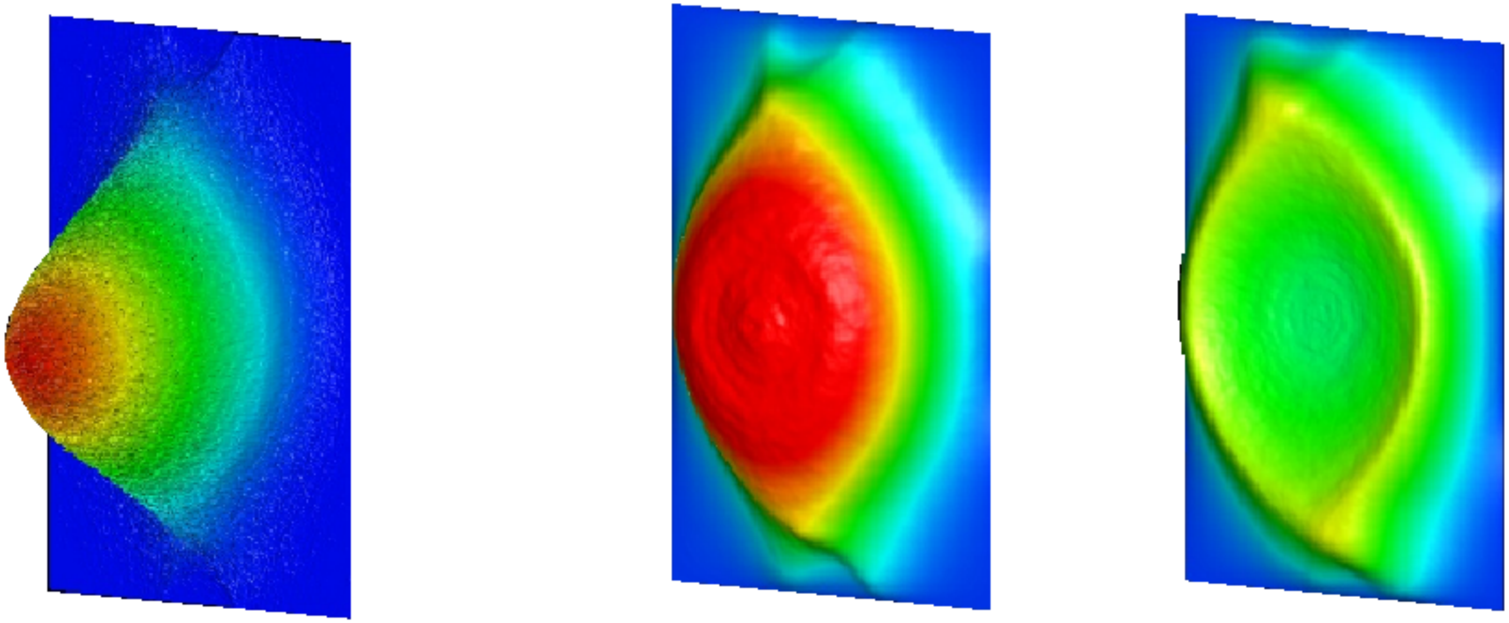
Formation of Electric Field in a Tokamak Plasma

Electric field (or ***E*x*B*** drift flow shear) important for confinement performance.

In open-field SOL/divertor plasmas, electrons flow out faster to the wall, and plasma potential becomes positive against the wall.

How is the potential profile in closed-field core plasmas?

Even in a straight tokamak, potential profile is varied by the FLR effect.



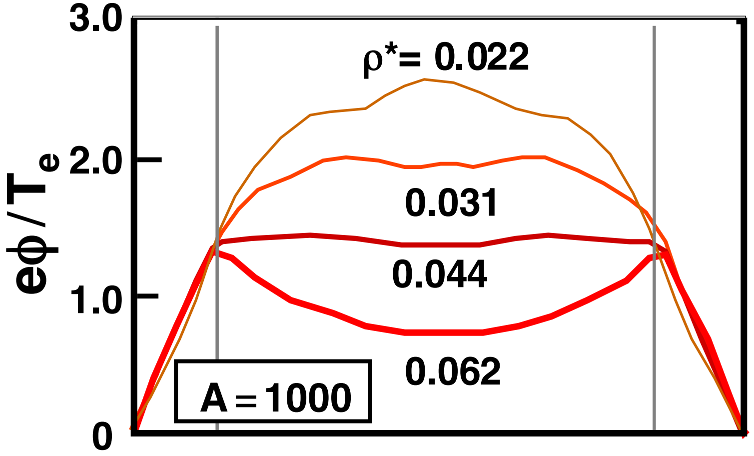
n profile unchanged

convex ϕ profile for small ρ^*

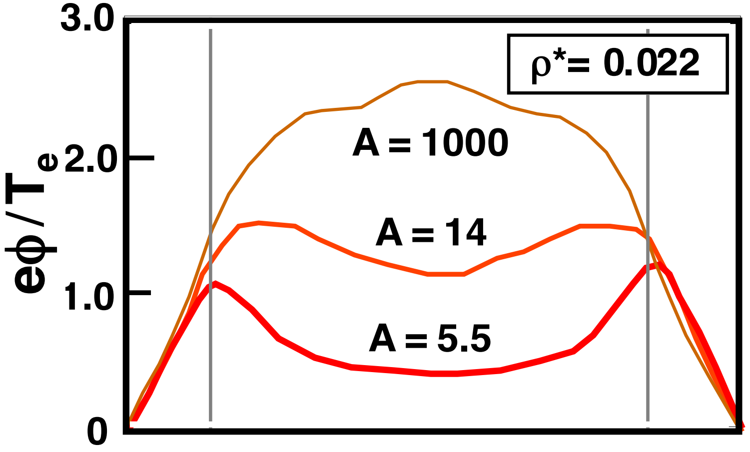
Hollow ϕ profile for large ρ^*

In toroidal plasmas, hollow ϕ profiles are easily formed.

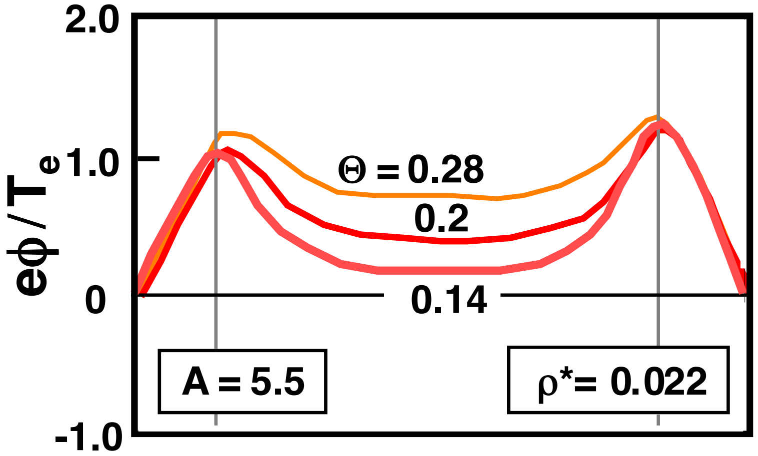
ρ^* dependence for **$A = 1000$**

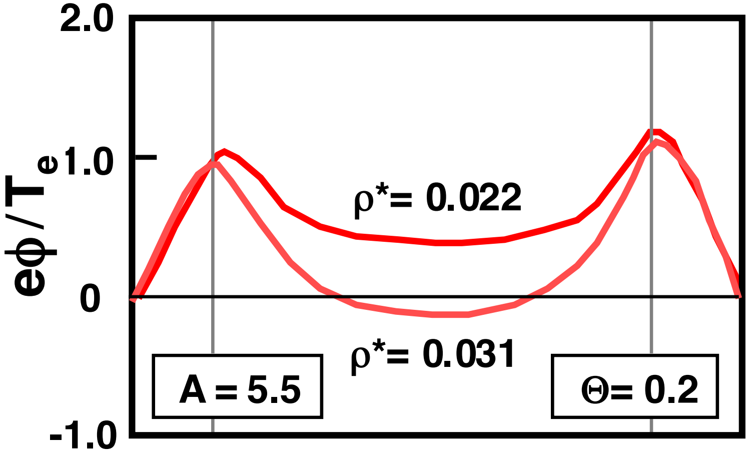


A dependence for **small ρ^***



Dependence on $\rho^*_{\text{banana}} \propto \rho^*/\Theta\sqrt{A}$





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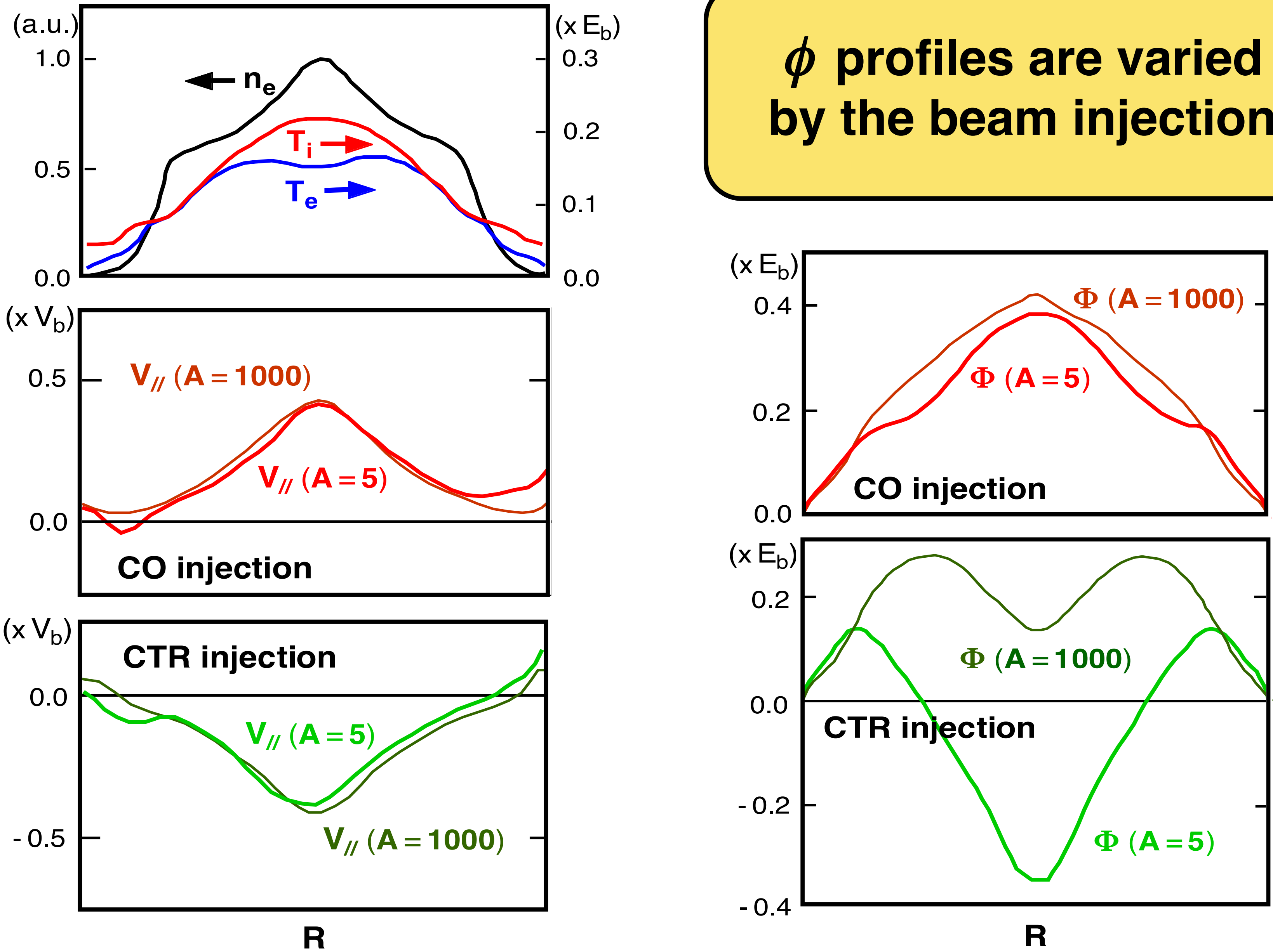
ϕ profiles are varied by the beam injection



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Presentations at NEXT meetings

2nd (1997) "Divertor Simulation Modeling"
4th (1999) "Damping Model for Divertor Particle Simulation"
5th (2000) "Progress of Divertor Simulation in NEXT Project"
6th (2001) "Divertor Simulation – Physics Study and Prediction –"
7th (2002) "Development of Divertor Simulation Code PARASOL" by M. Hosokawa
"Two Dimensional Structure of Divertor Plasma – 2D PARASOL Simulation –"
8th (2003) "Recent Results of PARASOL Simulations"
10th (2005) "ELM Simulation with PARASOL"
11th (2006) "Structure and Dynamics of Divertor Plasmas"
12th (2007) "Present Status of PARASOL Simulation"

19th (2013) "Bohm criterion for two-ion-species plasmas in a wide range of
of mass ratio and collisionality" by S. Azuma
20th (2015) "History of PARASOL"

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