History of PARASOL

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PARASOL was developed at Japan Atomic Energy Agency
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 $\rho^*, \beta, \nu^* + l_{A&M-mfp}, L_{rad(T_e)}$

complex geometries of magnetic configuration and wall

Multi-element Integrated Simulation for SOL-divertor plasmas

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

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.


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

( PARticle Advanced simulation for SOL and divertor plasmas )

Collisions are essential for the end loss:

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

Collision model using modified Langevin’s equation, \( \frac{dv}{dt} = \sum \left[ -v (v-V) + A \right] \)

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

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.

Random selection of collision pairs

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

Next;

-like-particles
-ion-electron

Landau collision integral

\[ <\Theta^2> \sim \nu_d \Delta t \]

Importance of collisions

- diffusion to high energy
- divertor plate

Importance of collisions

- pitch-angle scattering
- neo-classical diffusion
- mirror end loss
Particles are lost from the core to the SOL region by the anomalous diffusion:

\[ <\delta^2_\perp> = D_\perp \Delta t \]

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 Collision Model


Reference: 1D collisionless PIC

History of the PARASOL code

Prehistory (1975~1985)

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

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)
- SGI Origin 3800 (1 GFLOPS/PE)
- Altix 3700Bx2 (6 GFLOPS/PE)
- HELIOS (2013 by Azuma)
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 \( N \propto (L/\lambda_D)^{1,2,3} \)

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 \( L/\lambda_D \sim 10^{2-3} \), because characteristics are almost unchanged by changing \( L/\lambda_D \) 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

\[ m_i \frac{dv_i}{dt} = e (E + v_i \times B), \quad dr_i/dt = v_i \]

Ion polarization drift is essential

\[ V_{x}^{\text{polar}} \sim (\Omega_i B)^{-1} \frac{dE_x}{dt} \sim (\Omega_i B)^{-1} v_x \frac{\partial E_x}{\partial x} \quad (v_x \approx \Theta v_{//}) \]

PARASOL 2D-slab code
PARASOL Simulation for Physics Modeling

Verification of the Bohm criterion

1D PARASOL simulation

Oblique \( B \) (\( \Theta = B_x/B << 1 \)), \( E_y \times B_z \) drift

\[
\frac{m_i V_x^2}{\Theta^2} \geq T_{\text{eff} / /}
\]

\[
V_x = \Theta V_{/ /} + V_{\text{ExB}}
\]

\[
T_{\text{eff} / /} = T_{e / /} + \gamma_a T_{i / /}
\]

2D PARASOL simulation

\[
\frac{m_i V_{x0} V_x^*}{\Theta^2} \geq T_{\text{eff}}
\]

\[
V_{x0} = \Theta V_{/ /} + V_{\text{ExB}}
\]

\[
V_x^* = V_{x0} + n' T_{e / /} / n B
\]

\[
T_{\text{eff}} = T_{\text{eff} / /} + (V_{/ /}' / \Theta \Omega) T_{\text{eff} \perp}
\]


Supersonic flow in the cold divertor

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

$R_\Gamma$: particle flux amplification, $R_p$: momentum flux loss, $T_{\text{plate}} / T_{\text{throat}}$: cooling ratio

PARASOL simulation results agree very well with analytical formula

Kinetic effect on the parallel heat transport in SOL

Collisional \( l_{\text{mfp}} << L \)
\[
q_{e//} = q_{\text{SH}} = -\kappa_{e//} \frac{dT_e}{ds}
\]

Collisionless \( l_{\text{mfp}} >> L \)
\[
q_{e//} = \alpha_e q_{\text{FS}} = \alpha_e nT_e v_{\text{eth}}
\]

Harmonic average model
\[
q_{\text{eff}}^{-1} = q_{\text{SH}}^{-1} + (\alpha_e q_{\text{FS}})^{-1}
\]

Various values of flux-limiting factor \( \alpha_e \) have been reported from small \( \sim 0.01 \) to large \( \sim 1 \) [3].

PARASOL simulation shows that \( \alpha_e \) value is changed by situations; \( \alpha_e \) increases with \( f_{\text{rad}} \) [1,2].

Bohm criterion for two-ion-species plasmas

\[
(v_{1\parallel}^2 - C_{s1\parallel}^2)(v_{2\parallel}^2 - C_{s2\parallel}^2) = U_{\parallel}^4,
\]

\[
C_{s\parallel} = \sqrt{(n_i^* T_{e\parallel} + \gamma_i T_{i\parallel})/m_i}, \quad U_{\parallel}^2 = \sqrt{n_1^* n_2^* T_{e\parallel}^2 / m_1 m_2}
\]

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.


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 $\nabla B$ drift direction.


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 $T_e$

\[ \frac{\partial}{\partial \theta} = 0 \]

\[ \phi = 0 \]

Hot source

\[ N_{i0} = 10^6, M_R \times M_Z = 320 \times 512, \frac{m_i}{m_e} = 400, \frac{\rho_i}{a} \approx 0.02, D \approx 10^{-5} a C_s, l_{mpf}/L_\parallel \approx 1, \Theta = 0.2 (q \text{ is not constant for the change of } A = R_0/a) \]
On this physics finding from PARASOL simulation, a new model of “ion-orbit-induced flow” was developed.

Electric field (or $E \times B$ 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 $\phi$ profile for small $\rho^*$
- Hollow $\phi$ profile for large $\rho^*$
In toroidal plasmas, hollow $\phi$ profiles are easily formed.

φ profiles are varied by the beam injection

Presentations at NEXT meetings

4th (1999) “Damping Model for Divertor Particle Simulation”
5th (2000) “Progress of Divertor Simulation in NEXT Project”
   “Two Dimensional Structure of Divertor Plasma – 2D PARASOL Simulation –”
8th (2003) “Recent Results of PARASOL Simulations”
10th (2005) “ELM Simulation with PARASOL”

19th (2013) “Bohm criterion for two-ion-species plasmas in a wide range of mass ratio and collisionality” by S. Azuma
References