Simulation Study of Detached Plasmas by Using Advanced Particle Model and Fluid Model

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Abstract. Fluid simulations and particle simulations are performed to understand the physics of detached plasmas in the tokamak divertor. Two dimensional fluid simulations show that detached divertor plasmas are formed for the high density operation in the W-shaped divertor configuration of JT-60U tokamak. Charge-exchange and recombination processes play important roles to cause the detachment. The asymmetry of inner-and-outer divertor plasmas is studied based on a fluid model, and the bifurcated nature of the asymmetry caused by the SOL current is found. Advanced particle simulations demonstrate that the E×B drift by the radial electric field in a SOL plasma causes the asymmetry of flow pattern and density profile. A detached plasma is formed in the divertor region from which the drift flows out, when the ratio of the E×B drift speed to the sound speed exceeds a threshold. Effects of the radial gradient including diamagnetic drift flow on SOL and divertor plasmas are also studied with the two-dimensional particle simulation.

1. Introduction

The divertor is expected to play key roles in tokamak reactors, such as ITER, for the heat removal, ash exhaust, and impurity shielding. The reduction of the heat load on divertor plates is one of critical issues, and the detached divertor plasma operation is a strong candidate to clear this problem [1]. Such divertor functions have been studied experimentally in many divertor tokamaks. Analyses of experimental results and extrapolation of the results to the divertor performance of future reactors are being carried out by using comprehensive simulation codes with the fluid model [2]. We have developed a fluid simulation code SOLDOR under the NEXT (Numerical EXperiment of Tokamak) project in JAERI. The project aims to investigate numerically the physics of fusion plasmas. The simulation study of divertor plasmas is one of major subjects of the NEXT. The formation of detached plasmas in JT-60U is demonstrated by fluid simulations in this paper. The fluid model for scrape-off layer (SOL) and divertor plasmas, however, adopts various physics models, i.e., boundary conditions at the plasma-wall boundary, heat conductivity, viscosity and so on. Kinetic approach is required to examine the validity of such physics models. One of the most powerful kinetic models is the particle simulation. We have developed a particle simulation code PARASOL (PARticle Advanced simulation for SOL and divertor plasmas) under the NEXT project. Particle simulations in one-dimensional (1D) and two-dimensional (2D) systems are performed to establish physics models required for the study of detached plasmas. Effects of the drift are especially investigated in the present paper.

2. Fluid Simulation of Detached Plasma

The SOLDOR code is a two-dimensional divertor simulation code with a fluid model by adopting the TVD (Total Variation Diminishing) scheme to accurately solve steep profiles [3]. Non-orthogonal meshes can be treated, which are superior for complex divertor geometries. Transport of neutral particles is calculated by a Monte-Carlo method. We have obtained numerical solutions with high convergence speed and high accuracy. Simulation results show that detached divertor plasmas are formed in the W-shaped divertor configuration of JT-60U tokamak. This configuration enhances the particle recycling efficiently, and the cold and dense plasma is easily formed near the inner divertor plate for the high SOL plasma density n(0) (FIG. 1 (a)). When n(0) increases further, the detachment occurs in front of the plate (FIG. 1 (b)). Charge-exchange and recombination processes play important roles to cause the detachment. In the present fluid simulations, however, the drift and the SOL current were not included. Introduction of these effects to the SOLDOR code is the future work by referring to results of particle simulations with the PARASOL code.

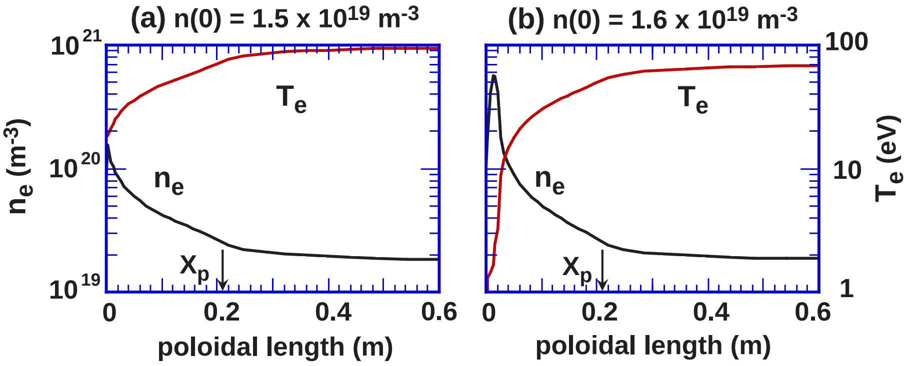

FIG. 1 Profiles of density and temperature of divertor plasma along poloidal direction. Poloidal length is from the inner divertor plate. X_p is the position just outside the X point. Detached divertor plasma is formed for high density case (b) with the power P = 12 MW.

3. Divertor Asymmetry Due to SOL Current

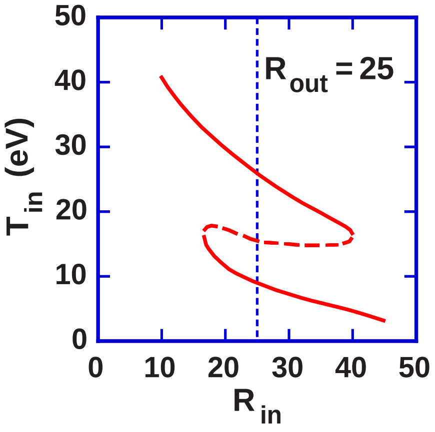

FIG. 2 Bifurcated dependence of T_{in} on R_{in} for asymmetric divertor plasma of JT-60U with P = 10 MW and particle flux $\Phi = 5\times10^{22}$ s^{-1}. Solid lines are stable solutions and broken line is unstable solution.

The asymmetry of inner-and-outer divertor plasmas in a tokamak is caused by the drift flow and difference of recycling rates. The SOL current, I_{SOL}, also influences the generation of the asymmetry. Asymmetric divertor-plasma temperatures ($T_{in} \neq T_{out}$) induce I_{SOL}, and the heat flux brought by I_{SOL} amplifies the asymmetry. When this amplification exceeds the symmetrizing effect of convective/conductive heat flux, a symmetric divertor equilibrium becomes unstable (thermoelectric instability) and an asymmetric equilibrium appears. Onset condition is the divertor plasma temperature lowered below a threshold value in a high-recycling state [4]. Basing on the fluid model, we investigate the characteristics of the asymmetry for the case of particle flux amplification factors R_{in} and R_{out} being different between inner and outer divertors. Due to the effect of I_{SOL}, a symmetric equilibrium is unstable and two asymmetric equilibria exist for $R_{in} = R_{out}$. There can be an equilibrium with $T_{in} > T_{out}$ even for $R_{in} > R_{out}$, and consequently the R dependence of T has a bifurcated structure (FIG. 2) [5]. In a low-temperature divertor side of an asymmetric equilibrium, the detached plasma state is easily formed by the momentum loss of plasma flow due to charge-exchange and recombination processes.

4. Model of Advanced Particle Simulation

The simulation model of the PARASOL code is described briefly in this section. Detailed explanation was given in Ref. [6]. The two-dimensional (2D) system with system lengths L and L_y is employed here. Two divertor plates are located at positions, x = -L/2 and L/2. Both plate surfaces are perpendicular to the x direction. Walls are put at $y = -L_y/2$ and $L_y/2$. The uniform magnetic field $B = (B_x, 0, B_z)$ is given, which intersects the divertor plates obliquely, i.e., the incident pitch of the magnetic field line $\Theta \equiv B_x/B << 1$.

Electron motions are approximated as their guiding-center motions (2D-2V), while ion motions are fully traced (2D-3V). Diamagnetic drift and polarization drift as well as E×B drift are naturally simulated for ions. The SOL current is also simulated except the electron diamagnetic-drift effect. The electrostatic field in the x-y plane is calculated with a usual PIC (Particle in Cell) method. Collisional effects are essential in the SOL plasma, and are simulated by a binary collision model [7]. Major procedures are as follows. (i) 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. (ii) Change in the relative velocity results from a coulomb interaction. Total momentum and total energy are conserved. This model describes the Landau collision integral. The cross-field diffusion is added with the use of a Monte-Carlo method. Hot particle source is put in the central region of the SOL plasma, and cold particle source is put near the divertor plate. Generated particles flow into divertor plates and vanish there.

Simulation parameters are as follows. As for the numerical parameters, the number of ions N_i is 10^6, the number of spatial grids are $M_x = 400$ and $M_y = 64$, the grid size Δx is $\lambda_{D0}/2$ and Δy is $2\lambda_{D0}$ (λ_{D0} : Debye length at hot electron temperature T_{e0} and initial uniform density n_{e0}). When we perform 1D simulations, we use $N_i = 10^5$ and $M_x = 800$. As for the physical parameters, the charge number of ions is unity, the mass ratio mi/me is 400, the temperature ratio of hot source T_{i0}/T_{e0} is 1/2, the incident pitch of magnetic field Θ is 0.2, the collisionarity $L_{//} /l_{mfp0}$ is 2 ($L_{//} \equiv L/\Theta$: system size along the magnetic field, and l_{mfp0} : mean free path at T_{e0} and n_{e0}), and the normalized Larmor radius ρ_{i0}/L is 0.01 (ρ_{i0} : ion Larmor radius at T_{i0}).
A simulation run continues till the plasma becomes almost stationary. The computation time of a run is about 5 hours for 1D simulations and about 20 hours for 2D simulations by a parallel computer Paragon XP/S15-256.

5. Results of PARASOL Simulations

5.1 1D Simulation of Detached Plasma Induced by E×B Drift

The radial electric field Ey in the SOL plasma makes the flow pattern asymmetric due to the E×B drift along the poloidal direction (x direction in the present system). The asymmetry becomes remarkable as the incident angle of the magnetic field to the plates is shallow ($\Theta << 1$), because the poloidal flow velocity is given as $V_x \approx \Theta V_{//} + V_{E\times B}$. At first we study the effect of E×B drift in a 1D system, where the uniform E_y is given artificially. The boundary condition of the flow speed at the entrance of the magnetic presheath in front of a divertor plate is clearly shown from simulation results; $V_x^2 \geq \Theta^2(T_{e//} + \gamma_a T_{i//})/m_i$ [8]. The adiabatic index γ_a is found to be about 3. The flow velocity normal to the divertor plate V_x is larger than a specific sound speed, $C_s \equiv \{(T_{e//} + \gamma_a T_{i//}) /m_i\}^{1/2}$, projected in the normal direction.

The E×B drift makes the SOL and divertor plasmas asymmetric as is shown in FIG. 3(a) for the case of $V_{E\times B}/\Theta C_{s0} = 0.55$ ($C_{s0} \equiv (T_{e0}/m_i)^{1/2}$). The higher density is observed in the divertor region where the $V_{E\times B}$ flows in to the plate, and the lower density is seen in the divertor region where the $V_{E\times B}$ flows out from the plate. Hereafter we use suffixes in and out corresponding to $V_{E\times B}$ flowing in to the plate and flowing out from the plate, respectively. The asymmetry in V_x

between left and right divertor regions is not so large due to the boundary condition described above, while the asymmetry in $V_{//}$ becomes remarkably large in the presence of E×B drift (FIG. 3(b)). The asymmetry in SOL/divertor plasma parameters becomes large with the increase of E×B drift velocity. The ratio of asymmetric densities, n^{out}/n^{in}, is shown in FIG. 3(c) as a function of the normalized drift speed, $V_{E\times B}/\Theta C_s^{in}$. When $V_{E\times B}/\Theta C_s^{in}$ exceeds a threshold, n^{out}/n^{in} becomes very small. This phenomenon is the detachment of the divertor plasma induced by the E×B drift [8].

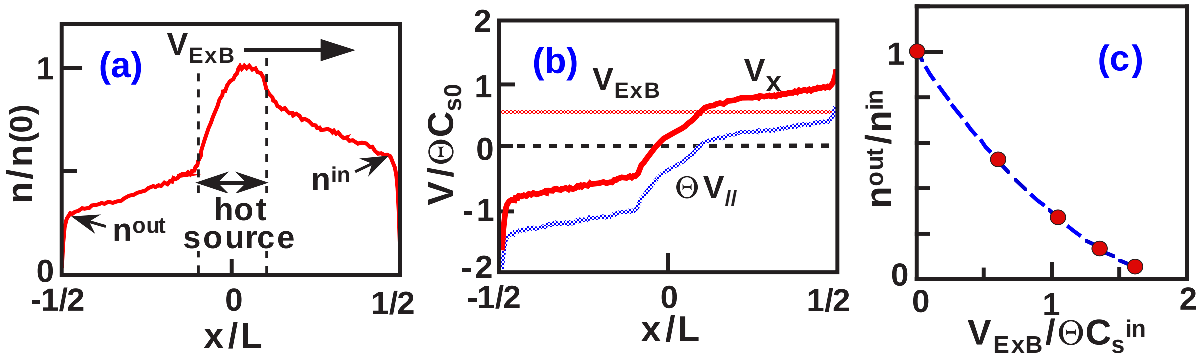

FIG. 3 Profiles of (a) normalized density, n/n(0), and (b) normalized flow velocities, $V/\Theta C_{s0}$, along x direction for $V_{E\times B}/\Theta C_{s0}$ = 0.55. Asymmetry in profiles is induced by E×B drift. Dependence of n^{out}/n^{in} on $V_{E\times B}/\Theta C_s^{in}$ is shown in (c).

5.2 2D Simulation of Radial Gradient and Diamagnetic Drift

In a realistic situation of the SOL and divertor plasmas, there exist radial gradients of plasma density, temperature and so on. These gradients induce the diamagnetic drift flow in addition to the E×B drift flow. The asymmetric flow pattern in a 2D system becomes complex compared with that in a 1D system with the uniform E×B drift. 2D simulations by the PARASOL code are performed to study effects of radial gradient and drift flow.

FIG. 4(a) shows the radial profile of plasma density n. In the simulation, the radial direction corresponds to the y direction and the poloidal direction to the x direction. At the SOL plasma center (x/L = 0), the profile is radially symmetric, while it becomes asymmetric in the off-center region. Inward shift of the plasma in the region where the drift velocity V_D flows to the divertor plate ($x > 0$ and $y > 0$ / $x < 0$ and $y < 0$ for the present situation). FIG. 4(b) shows the poloidal profile of n at $y/L_y = 0.11$, where radial gradient of n is steep. The density profile becomes poloidally asymmetric due to the drift velocity V_D, which is towards the right side divertor plate. Poloidal profiles of velocities at this radial position are shown in FIG. 4(c). The poloidal flow velocity V_x consists of parallel velocity projected in the x direction $\Theta V_{//}$, E×B drift velocity $V_{E\times B}$ and diamagnetic drift velocity V_{dia} (polarization drift is negligible except near the divertor plate). All their speed are comparatively large, $|V| \sim \Theta C_s$, and the asymmetry in SOL/divertor plasmas can be remarkable.

For the case of 1D plasma with the uniform E×B drift, V_x is nearly symmetric though $V_{//}$ is asymmetric. On the other hand, for the 2D case, V_x is also asymmetric as well as $V_{//}$. The $|V_x|$ is larger at the V_D flowing-in region, and smaller at the flowing-out region. Accordingly the density profile asymmetry in the 2D case being opposite to that in the 1D case. This difference is caused by the boundary condition of the flow speed at the divertor plate. The analytic expression of the boundary condition in the presence of diamagnetic drift will be described soon, and simulation results will be compared with the expression [9].

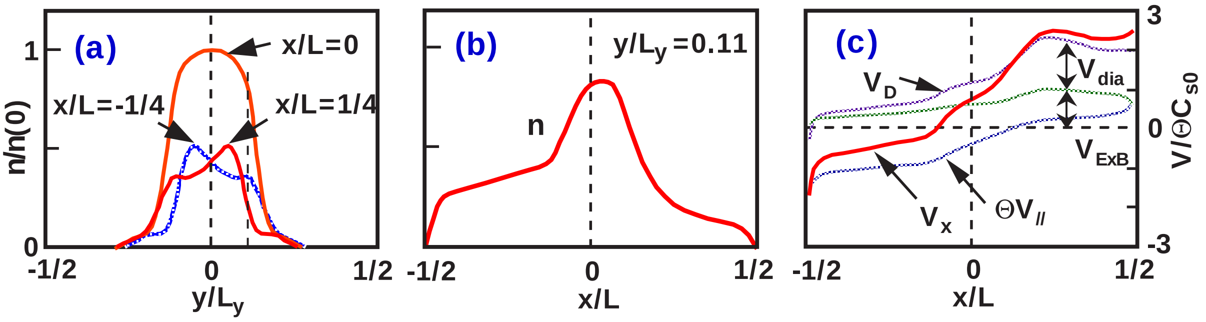

FIG. 4 (a) Radial profiles of normalized density n/n(0) at x/L = -1/4, 0, and 1/4. (b) Poloidal profile of n/n(0) at y/L_y *= 0.11. (c) Poloidal profiles of normalized velocities* $V/\Theta C_{s0}$ *at* y/L_y *= 0.11.*

6. Conclusions

Fluid simulations and particle simulations are performed to understand the physics of detached plasmas in the tokamak divertor. Two dimensional fluid simulations with the SOLDOR code show that detached divertor plasmas are formed for the high density operation in the W-shaped divertor configuration of JT-60U tokamak. Charge-exchange and recombination processes play important roles to cause the detachment. The asymmetry of inner-and-outer divertor plasmas is studied based on a fluid model, and the bifurcated nature of the asymmetry caused by the SOL current is found. Advanced particle simulations with the PARASOL code demonstrate that the E×B drift by the radial electric field in a SOL plasma causes the asymmetry of flow pattern and density profile. A detached plasma is formed in the divertor region from which the drift flows out, when the ratio of the E×B drift speed to the sound speed exceeds a threshold. Effects of the radial gradient including diamagnetic drift flow on SOL and divertor plasmas are also studied with the two-dimensional particle simulation.

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