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大域プラズマの静電的および電磁的粒子シミュレーションのための自己無撞着電子挙動を含むインジニアスモデル

Ingenious Models of Electrostatic and Electromagnetic Particle Simulations for Large-scale Plasmas with Self-consistent Electron Dynamics

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An ingenious model for large-scale plasma simulations is proposed here. In PARASOL simulation for SOL-divertor plasmas, an artificial permittivity ε_* much greater than ε_0 (permittivity of free space) has been introduced to the Poisson equation, $\nabla\cdot(\varepsilon_*\nabla\phi) = -\rho$ (ϕ: electrostatic potential, ρ: charge density), and the Debye length λ_D is artificially elongated to λ_{D*} of the order of mesh size Δ [1]. A large-scale system with a reasonable number of spatial grids can be treated stably even for including self-consistent electron dynamics. One-dimensional (1D) PARASOL simulations of ITER SOL-divertor plasma, for instance, were successfully performed, where the system length $L \sim$ 30m, number of grids $N \sim 10^4$, and $\Delta \sim$ 3mm $\gg \lambda_D \sim$ 0.01mm [1, 2]. 2D PARASOL simulations for a small tokamak like COMPASS were also carried out, where $L_R \times L_Z \sim$ 0.6m × 1m, $N_R \times N_Z \sim 600 \times 1000$, and $\Delta \sim$ 1mm $\gg \lambda_D \sim$ 0.01mm [3]. If a conventional PIC simulation is executed under the condition $\Delta \gg \lambda_D$, numerical instability called grid instability occurs and decent results are never obtained.

This artificial elongation of λ_D is allowable because characteristics of SOL-divertor plasma under the quasi-neutral condition are similar to the core plasma, and are governed mainly by collisionality and normalized ion Larmor radius but insensitive to the L/λ_D ratio.

In a SOL-divertor plasma, particles are lost to the divertor plates mainly along $\boldsymbol{B}$. The hot plasma is supplied at the central source region in a 1D system. For a 2D system, the hot plasma is diffused out from the core region to the SOL through a random-walk diffusion model. In order to study tokamak edge plasmas including consistently the turbulence-driven transport nature, reliable 3D simulations are indispensable. Although the introduction of elongated λ_{D*} enables us to handle a large-scale 2D tokamak system within a reasonable number of grids, it is still difficult to try a 3D PIC simulation.

It was proposed that ε_* is further modified to a dielectric tensor $\vec{\varepsilon}$ for the 3D global simulation of tokamak plasmas in cylindrical coordinates (R, θ, Z) [4]. A diagonal element for toroidal axis, $\varepsilon_{\theta\theta} = \alpha^2\varepsilon_*$ ($\alpha \gg 1$), is set much larger than those for poloidal plane, $\varepsilon_{RR} = \varepsilon_{ZZ} = \varepsilon_*$, and Δ_θ can be α times larger than Δ_R and Δ_Z. It becomes possible to carry out 3D simulations with small number of N_θ, e.g., $N_\theta \sim 200 < N_R, N_Z \sim 10^3$ by setting $\alpha \sim 20$, where the turbulence modes can be treated up to $n \sim 30$ and $m \sim 150$.

Electromagnetic (EM) response becomes important when a plasma pressure gradient is large, e.g., ELM in the edge region of H-mode plasma. The above ingenious model is extended to the EM simulation including self-consistent electron dynamics. To eliminate the light-speed EM waves, a Darwin model [5] is applied for Ampere's law, $-\nabla^2\boldsymbol{A} = \mu_0(\boldsymbol{J} - \vec{\varepsilon}\,\partial\nabla\phi/\partial t)$ ($\boldsymbol{A}$: magnetic vector potential, $\boldsymbol{J}$: current density), which is modified to be consistent with the use of $\vec{\varepsilon}$ in the Poisson equation.

Individual particle motions are traced in the EM fields calculated consistently by the PIC method. Gyro motion of ions is followed to simulate polarization effects completely, while guiding-center orbit is followed for electrons. Coulomb collisions are very important to determine the plasma properties especially in edge plasmas, and they are simulated by using a binary collision model.

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