Gyrokinetic Simulation of Edge Plasma in L-H Transition Conditions

J.A. Heikkinen[1], T.P. Kiviniemi[2], T. Kurki-Suonio[2], and S. Janhunen[2]

[1] *VTT Processes, Euratom-TEKES Association, P.O. Box 1608, FIN-02044 VTT, Finland*
[2] *Helsinki University of Technology, Euratom-TEKES Association, FIN-02015 HUT, Finland*

Introduction

The development of gyrokinetic particle models [1], based on drift orbits of electrons and ions in tokamak geometry and including finite Larmor radius effects and magnetic mirroring forces, has allowed the investigation of self-consistent particle orbits and electrostatic potential fluctuations, together with basic neoclassical properties of such plasmas. Based on 1-D polarization equation valid in the long wavelength limit of the gyrokinetic formalism, formation of radial electric field at L-H transition conditions in the edge plasma of large tokamaks was investigated [2]. There, particle simulation was applied to consistently incorporate the neoclassical and finite orbit effects. Strong shear in the poloidal $E \times B$ flow was found to arise just inside the separatrix from the ion orbit loss through the separatrix which was found to scale most strongly with the ion edge temperature T_i and its profile. However, no bifurcative transition of the sheared flow was obtained for increasing T_i. As the L-H transition in experiments can not always be regarded as soft, it is worth of investigating other mechanisms affecting the flow. Inclusion of the full gyrokinetic electric potential is one step in this direction. Based on so called δf technique, various authors (see e.g., [3]) have investigated the generation of zonal flows by particle-in-cell simulation for annular plasma residing in the gyrokinetic turbulent ITG or TEM dominated inhomogeneous plasma core. However, these conventional gyrokinetic algorithms have so far been accomplished by using (to improve the computing speed) the assumption of adiabatic electron distribution or by neglecting collisions, thus eliminating the neoclassical ambipolar field and rotation. Moreover, no investigation of the edge plasma pertinent to L-H transition with the present method has been made.

In the present paper, we shall dicuss the application of the gyrokinetic formalism to the plasma in L-H transition condition using the newly developed gyrokinetic version of the ASCOT code – ELMFIRE [4]. In this code, a 3-D electrostatic potential solver is applied with full-f technique allowing the concurrent solution of the neoclassical ambipolar electric field and 3-D electrostatic turbulent fields across the separatrix. While electromagnetic effects may prove to be important for the properties of edge plasma turbulence, the electrostatic model is believed to provide a satisfactory paradigm for the generation of Reynolds stress related sheared flow [5].

Particle simulation model

In ASCOT/ELMFIRE, each particle is followed along its guiding-center orbit determined by the $\mathbf{E} \times \mathbf{B}$, gradient and curvature drifts, collisions, polarization and gyro-viscosity drifts. The particle following takes place in a realistic geometry including the region outside the separatrix. The guiding center equations are written in straight magnetic field line coordinates using canonical Hamiltonian variables to avoid numerical drifts. The magnetic background is assumed stationary. In order to properly treat the momentum equation and momentum generation, a binary collision model that conserves momentum and energy in pairwise collisions between the ions has been implemented. For a fixed electric field $\vec{E}$ and for a field obtained from the 1-D (radial) polarization equation, the adopted numerical model has been tested by calculating poloidal rotation relaxation rates for a homogeneous plasma, and by comparing the perpendicular conductivity and parallel viscosity evaluated by the code with the analytical expressions.

In the initial phase of a bounce period, there can transiently exist a finite net radial current even with closed orbits and no collisions. This transient current decays away with oscillations on a few bounce time scale, but may severely perturb the solution for the $\vec{E}$ dynamics. This can be avoided by initializing sub-particles in the invariant space that spans the different particle orbits. In the presence of collisions, however, the particles can not complete the orbits, which makes a proper initialization of the orbits computationally extremely difficult. Because avoiding any unphysical radial current is of primary importance for solving $\vec{E}$, an initialization on collisionless orbits is adopted here. This guarantees that no current arises at the start from the radial inhomogeneity (and related weight factor variation) even in the presence of collisions. It is worth noting that for orbits intersecting the vessel wall or divertor plates/limiter, the distribution of subparticles is nontrivial. In principle, the particles with orbits intersecting the plasma facing components should not re-enter the plasma and, therefore, the subparticles should not be initially distributed on the section of these orbit on which the particles are moving inwards from the separatrix. However, for collisional plasmas such an initialization may overestimate the initial orbit loss current since the particles can not complete the trajectories. Therefore, to ensure a smooth initialization, a full distribution of subparticles on the orbits inside the plasma is applied even on the orbits intersecting the plasma facing components.

The computational effort is reduced enormously by restricting the simulation to a relevant region $\rho_L < \rho < \rho_R$ in minor radius. Whenever there are no special constraints at the boundaries ρ_L and ρ_R posed by the problem, and when the mass flow parallel to the magnetic field is given at the boundaries, $\vec{E}$ can be evaluated in the region $\rho_L < \rho < \rho_R$ by using the well-known neoclassical analytical ambipolar value $E_a(\rho)$ as the boundary condition at $\rho = \rho_L$ and $\rho = \rho_R$. If the outer boundary lies outside the separatrix, $\rho_R > \rho_s$, $E_r(\rho_R) = 0$ is used. On boundaries in contact with metal, zero potential or sheath potential condition is applied. As for the particles at the boundaries, whenever ρ_L and ρ_R lie inside the plasma, the outflowing particles are reflected at these boundaries. This is accomplished by following the orbits for $\rho < \rho_L$ and $\rho > \rho_R$ in the absence of collisions, gyroviscosity drift and polarization drift, and stopping the clock during the time the particles spend in these regions. This is consistent with the

assumption of no toroidal momentum source and zero radial current for $\rho < \rho_L$ and $\rho > \rho_R$. The ions are initialized within $\rho_L < \rho < \rho_R$, and those hitting the divertor or wall outside $\rho > \rho_R$ are promptly reinitialized at $\rho = \rho_R$. The reinitialization is uniform in pitch and poloidal angle, with the local Maxwellian velocity distribution. This reinitialization does not create any physical current in the simulation domain and, being more uniform (in phase space) than the loss process, it simulates well the replacement of charge lost through the separatrix. This method has recently been successfully applied, with the outer boundary at the separatrix, $\rho_R = \rho_s$, to calculate [6] the orbit loss as well as the related source of poloidal rotation and its dynamics for L-H transition conditions in ASDEX Upgrade and JET.

Gyrokinetic field

The polarization term in the gyrokinetic Poisson equation is solved by sampling the ion polarization drift steps as described in Ref.[4]. Thus, no assumption on the ion velocity or configuration space distribution is made here, allowing a full f simulation of the edge. The field solver has been tested against various interpolation and sampling methods to ensure the accuracy and to avoid numerical instabilities arising e.g., from false divergence of $\vec{E} \times \vec{B}$ flows [7]. Also, the polarization term is benchmarked against analytical term based on Maxwellian distribution in both quasi-ballooning and purely toroidal coordinates. The electrons are treated either adiabatically, keeping a fixed electron distribution, or following their orbits in drift-kinetic approximation. Only the last choice is satisfactory for the edge plasma simulation at transition conditions. However, the former methods have been used for diagnostic purposes in checking numerical performance and accuracy. In the present work, no effort has been made to ensure proper heat and particle source on the inner boundary, necessary for longer runs. Thus, a relatively strong profile relaxation for initially steep gradients in density and temperature profile is found on longer runs. Fig. 1a shows the equipotential lines for the electrostatic field in (r, χ) plane, and in Fig. 1b the poloidal electric field structure in (θ, z) -plane (straight field line coordinates) is shown. Here, a case with $a = 0.13$ m, $R = 0.25$ m, $B_T = 2$ T, $I = 0.22$ MA, $n_L = 2 \times 10^{19}$ m^{-3}, $T_L = 400$ eV, $N_\rho = 20$, $N_\chi = 200$, $N_z = 6$ is shown, the latter three parameters indicating the mesh size in radius, quasipoloidal, and toroidal coordinates. 960000 ions were initialized in the calculation domain bounded by the radii $\rho_L = 0.08$ m, $\rho_R = 0.11$ m. Here, a is the plasma minor radius, R the major radius, B_T the toroidal magnetic field, and I the plasma current. The temperature and density have linear profiles with values at $\rho = \rho_R$ being half of those at $\rho = \rho_L$. Circular cross-section with cocentric magnetic surfaces is assumed. In all three quasi-balloning coordinates ρ, χ, and z, the grid cells are equidistant. Initialization is performed with a Maxwellian distributed particles and zero potential. Both at the inner and outer boundary the potential is taken to be zero. No smoothing algorithm is applied. The CIC technique in sampling and force interpolation was selected. The coefficient matrix is accumulated in sampling only over the time step Δt. $\Delta t = 2 \times 10^{-7}$ s was used with 8 points used for gyrophase averaging. The simulation was performed with adiabatic electrons so that the neo-classical non-ambipolar effects were eliminated. The time at the instant of recording in Fig.1 was 40 μs, which is sufficiently long to cover the finite ion orbit effects, but
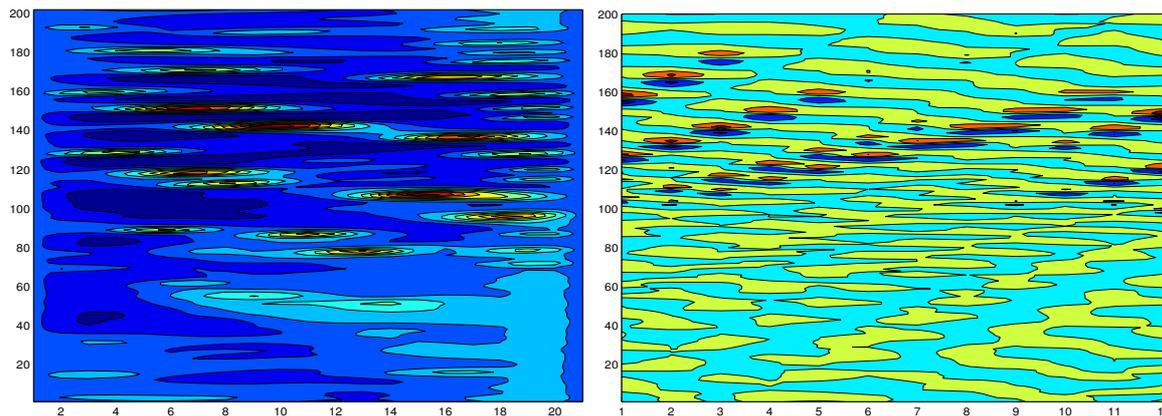
Figure 1: *a) Potential structure in (r, χ) plane and b) Poloidal electric field in (θ, z)-plane*

too short to adapt the collisional effects. The appearance of intense convective cells is apparent from the result, indicating the effect of $\vec{E} \times \vec{B}$ flows. The obtained result with the present parameters showed convergence with respect to the time step, number of the particles, and the grid mesh size. Further work is needed to incorporate the kinetic electron treatment, extension of the simulation time to the collisional time scale, and refining the boundary conditions to extend the simulation domain to the scrape-off layer region. This is expected feasible because of the relatively modest CPU and memory requirements applied for the present work.

Summary

A gyrokinetic electrostatic approach and method have been described for the analysis of $\vec{E} \times \vec{B}$ flows in the tokamak edge plasmas in L-H transition conditions. The method is amenable to include both the neoclassical and electrostatic turbulent mechanisms for the sheared flow generation. With large orbit widths, steep gradients, and large poloidal Mach number, the solutions have been found to become sensitive to the initialization. Although the proper initialization is not possible without knowing the very solution, orbit initialization, i.e., distributing the ensemble particles uniformly on the particle collisionless orbits, has been found important for quiescent start of the simulation.

References

[1] W.W. Lee, Journ. Comp. Phys. 72 (1987) 243.
[2] J.A. Heikkinen et al., Journ. Comp. Phys. 173 (2001) 527.
[3] Z. Lin et al., Science 281 (1998) 1835.
[4] T.P. Kiviniemi et al., "Particle modelling of neoclassical effects and low-frequency turbulence in tokamak plasmas", paper P-5.038, this conference.
[5] P.H. Diamond and Y.B. Kim, Phys. Fluids B3 (1991) 1626.
[6] J.A. Heikkinen, et al., Phys. Rev. Lett. 84 (2000) 487.
[7] J.A. Byers et al., Journ. Comput. Physics 115 (1994) 352.