Gyrokinetic calculation of plasma transport with a material boundary

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Abstract

Both the radially outer wall and the limiter are investigated as material boundary conditions for electrostatic gyrokinetic full particle distribution simulation for axisymmetric tokamaks. Emphasis is put on conditions keeping the simulation stable with least effect on the plasma turbulent structures.

Introduction

While the gyrokinetic formalism and its implementation in numerical procedures are presently well studied up to widely accepted accuracy and ordering, even in so called full *f* distribution calculation, progress is still required in adapting such tools to the plasma-wall interface. The latter introduces the complexity by neutrals, atomic physics, sheaths, and recycling among others, which recently have been dealt with some success with a higher dimensional particle-in-cell approach for the scrape-off plasma region [1]. In numerical gyrokinetic implementation, numerical stability issues arise due to the imposed boundary conditions on the distribution function and electrostatic potential. In the present work, the introduction of the plasma-material interface in the tokamak scrape-off-layer region to the gyrokinetic solution is investigated both by the physics and numerical viewpoint. The full *f* global electrostatic gyrokinetic code Elmfire [2] for tokamaks is applied in such studies, and physical and numerical issues relevant for the interface implementation are discussed and formulated. A metallic wall in its simplest geometry is set as the outer boundary of the calculation region and the solutions are investigated with respect to the plasma density and electrostatic potential from the plasma to the wall. As a further complication, a toroidal limiter as an extension of the wall and defining the separatrix is set as the boundary. Numerical stability issues of the solution are investigated as well as the effect of the limiter configuration on the Bohm condition of the plasma along the open field lines.

Model

The simulations are performed with the global electrostatic particle-in-cell code Elmfire [2,3]. This code simulates the full distribution function (full *f*) of drift kinetic electrons and an arbitrary selection of gyrokinetic plasma ions (here, deuterium is considered) in an axisymmetric tokamak plasma up to the material wall radius $r = a_w$. Neumann and Dirichlet boundary conditions for the potential are used at the inner and outer radial boundary, respectively. Collisions are modeled by a momentum and energy conserving binary collision model between all particle species [4] and a toroidal angular momentum conserving interpolation scheme for the electric field is applied [5]. Elmfire exploits quasineutral condition for each grid cell in order to solve for the electrostatic potential, as usual in gyrokinetic codes. This means that charge separation, as would arise, e.g., at sheath boundaries from the non-zero Laplacian in the Poisson equation, will not appear in the solution. This can be considered as a powerful simplification, because locally high grid resolution is not required to resolve this charge separation in a regime close to the wall, the spatial extent of which in the case of a Debye sheath can be either of the order of Debye length or ion Larmor radius along the magnetic field. What remains to be shown is that proper long-scale variation of plasma variables further from the wall or along the open magnetic field lines intersecting the limiter are observed in spite of this omission of fast changes of plasma variables in the sheath.

The wall boundary is well known about its numerical drift instability in magnetized plasma in particle simulations [6]. Related instabilities are also observed in gyrokinetic simulations where usually the stabilization is ensured by suppression of the potential by artificial tools near the boundary. In the Elmfire code, to stabilize the boundary plasma, an artificial smoothening of the poloidal variations of the potential on the grid cells next to the wall has been earlier applied [1]. In the present work, this is avoided by letting the ion gyro-orbits to intrude into the wall. Whenever, the whole gyro-circle is found inside the wall, the ion is recycled together with an electron back to the plasma according to the probabilistic radial distribution of neutral density as measured. The electrons are recycled as soon as their guiding-centre enters the wall. In this way, a stable wall boundary plasma has been observed.

In introduction of the limiter, a configuration shown in Fig.1 is numerically resolved in Elmfire. Here, all the ions whose gyro-centre or electrons whose guiding-centre crosses the limiter surface are recycled back to the plasma as an ion-electron pair, as with recycling from the wall. Excess charge (ion or electron charge) is repositioned on that front of the limiter

from which poloidal side this particular charge originally crossed the limiter. The finite size clouds of the particles are not allowed to be sampled through the limiter. Whenever any part of the cloud intersects the limiter surface, the cloud is sampled fully back to the poloidal angle side where the particle resides with respect to the limiter. The sampling means here both the deposition of the charge onto the grid as well as interpolation of the electric force from the potential values on the grid cells. These techniques are observed to keep the plasma numerically stable next to the limiter.

Results

A simulation region of $r/a_w =$ [0.25 − 1] with a grid of $50\times200\times16$ in radial(r)/poloidal(θ)/toroidal(φ) direction and a time step of Δt = 30 ns are employed. The limiter is as described in Fig. 1 with the limiter position at $4\pi/5$ (poloidal angle running anti clockwise and zero angle defined on the outboard equator). The wall radius is at 0.08 m and the limiter tip is positioned at r = 0.074 m. The magnetic field is 2.2 T, the plasma current is 55 kA with a parabolic current density profile. The initial density profile is take as linear ramping down from $4.5\cdot10^{19}$ m^{-3} at $r = a_w/4$ to $2.5\cdot10^{18}$ m^{-3} at the limiter tip. Inside the scrape-off-layer the density is taken to be constant initially. Total number of the simulation particles is 221 million for both electrons and deuterons.

The evolution of the flux surface averaged electron temperature (ion temperature was initially alike) and electrostatic potential are shown as a function of radius in Fig.2 for the first 1000 time steps. Electron temperature is found at the limiter tip to be about 5 eV, and sheath potential about 15 V. We find all the time this ratio of about 3 between sheath potential and T_e/e. This ratio holds also radially, as T_e radially decreases from the limiter tip to the wall. The results show suppression of the potential towards the limiter as one would expect from the assumed zero potential boundary condition there. We get a suppression of both electron and ion densities, too, towards the limiter. A run with T_e = 24 eV initially in the SOL (previously T_e = 2.5 eV initially) at the limiter tip produces a flux surface averaged potential raised at 75 V after the first 1000 time steps. These results are close to the theoretical Bohm estimate for the ratio of the sheath potential and T_e/e which is 2.8. This is expected in spite of the simplifications made in simulation for the plasma behavior close to the limiter material, as the Bohm condition can be shown to arise from the balance of electron and ion currents towards the limiter along the magnetic field lines.

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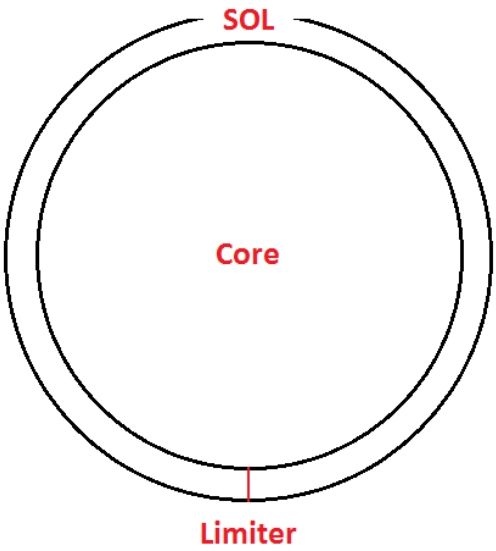

Fig. 1. Sketch of the limiter model in the Elmfire code.

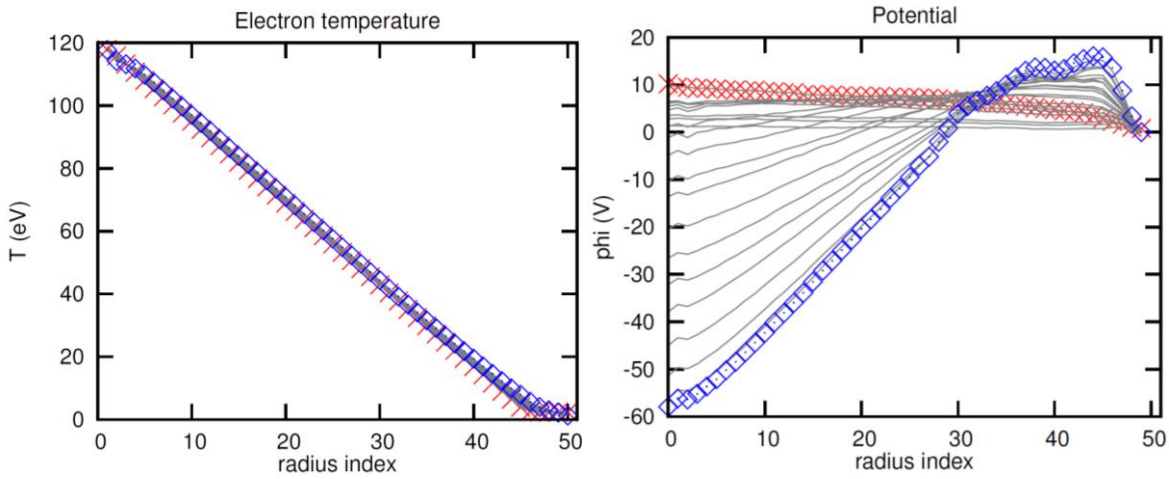

Fig. 2. The time evolution of electron temperature and electrostatic potential as a function of radius during the first 1000 time steps. The initial state is plotted with X, and the final state is denoted by diamonds.