Gyrokinetic simulation of edge pedestal in a middle-sized tokamak

T. Kiviniemi[1], J.Heikkinen[2], S. Janhunen[1], S. Leerink[1] and T. Korpilo[1]

[1] *Euratom – Tekes Association, Aalto University, Espoo, Finland*

[2] *Euratom – Tekes Association, VTT, Espoo, Finland*

In the present fusion devices, radial transport of particles and heat is mainly determined by plasma turbulence. Due to its complexity, high performance computing, either with particle or Vlasov codes, plays a major role in plasma turbulence research.

While the neoclassical transport is often only a minor part of the total radial transport, the neoclassical physics may indirectly have significant effect on transport level as, at the edge, the neoclassical radial electric field alone can be steep enough to suppress turbulence [1, 2]. As the analytic neoclassical theory is not valid at the edge where the gradients are steep compared to orbit width, particle simulations are required to obtain proper fields. Also, within one orbit width from last closed flux surface the direct ion orbit losses may have important effect on the radial electric field.

In this paper, we use the particle simulation code Elmfire [3], which includes both neoclassical effects and electrostatic turbulence. Such simulations are very CPU consuming which limits the simulations to middle-sized tokamaks. The main code development effort reported here is to include scrape-off-layer (SOL) in order to study edge-core coupling which according to experiments plays an important role in obtaining low-to-high confinement transition which is crucial for future fusion devices such as ITER.

The gyrokinetic full-f code Elmfire

The present code Elmfire [3], solves gyrokinetic equation for full distribution of ions and electrons in the presence of Coulomb collisions between the test particles which allows for simultaneous solution of neoclassical and turbulent physics. Using this technique, simulation of transport phenomena involving wide orbit effects, steep gradients, and rapid dynamic changes in profiles becomes possible. Such multiscale simulation requires resolving gyroradius over several orbit widths in space and kinetic motion of electrons in transport timescale in time. Direct polarization method [4] is used to solve 3D electrostatic perturbations. The mesh of the electric field is in quasi-ballooning (almost straight) coordinates and guiding centre equations in straight field line coordinates. Numerical details are given in [3]. Momentum and energy conserving binary collisions are used but temperature can be maintained or heated up with background collisions.

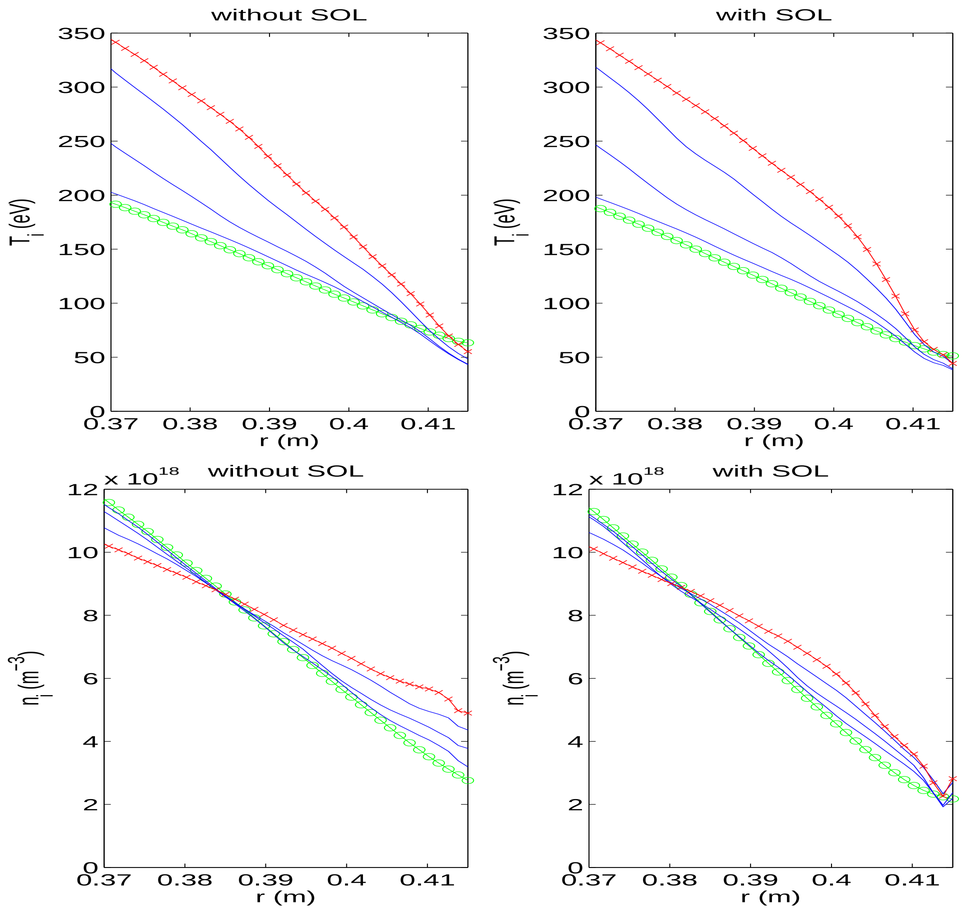

Figure 1: *Temperature profile shows pedestal formation only when SOL is included in the simulation.*

New scrape-off-layer (SOL) model is included in the code. The model is essentially a heat sink as the particles hitting the limiter are recycled back into the plasma as ionized low-energy neutrals according to recycling profile given as an input. This is done pairwise (ion and electron) to maintain quasineutrality.

Results

In this section, the effect of new SOL model is tested in a simulation where plasma is heated up during the simulation. This is compared to the case without SOL model. Parameters similar as in Textor tokamak are used in the simulations ($a = 0.46$ m, $R = 1.75$ m, $B_T = 2.25$ T, $I =$ 350 kA). Here, a is the plasma minor radius, R the major radius, B_T the toroidal magnetic field, and I the plasma current. Pure deuterium plasma is simulated in a 6 cm wide regime ($r = 0.355 - 0.415$ m) where the SOL region is last 0.5 cm in radius and 1.24×10^8 ions and electrons are followed in a $N_r = 50$, $N_\chi = 420$ and $N_\phi = 4$ grid. For thermal $T = 200$ eV particle, Larmor radius is $\rho_L = 1.28$ mm and radial and poloidal resolutions normalized to this

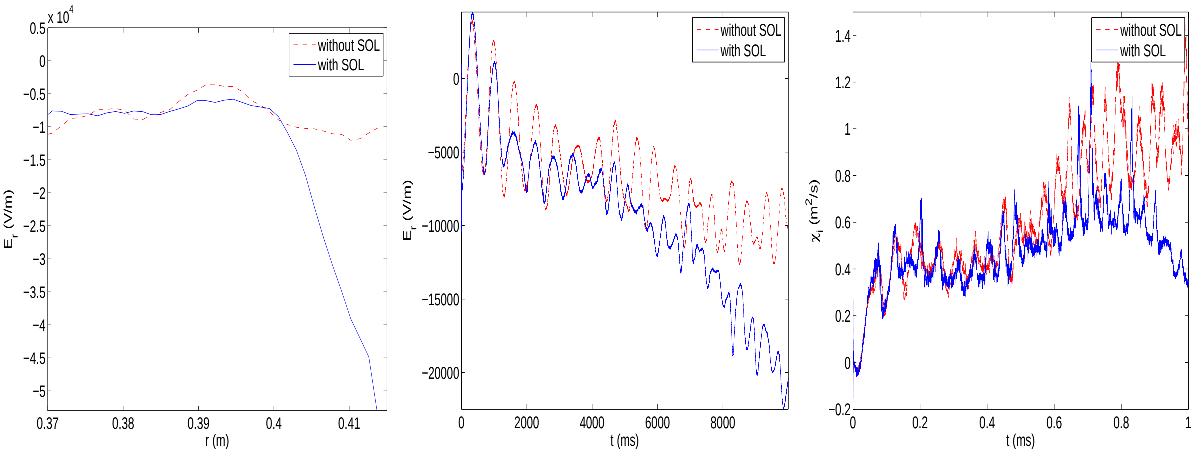

Figure 2: *Radial profile of radial electric field and and time behaviour of E_r and χ_i just inside LCFS for both cases.*

are $\Delta r \approx \rho_L$ and $\Delta\chi \approx 4-5\rho_L$. As only 1500 particles per cell is used, $1/\sqrt{N}$ estimate would give some $\delta n/n = 2.6$ % for noise level. However, the measured density noise level in the beginning of simulation is around $\delta n/n \approx 1.4$ % as gyroaveraging and cloud-in-cell technique used in sampling decrease the noise. This should be compared to density fluctuation at the end of simulation when turbulence has saturated, which is $\delta n/n \approx 3.0$ %. Thus, it is important to note that the contribution of noise is not negligible. One millisecond is simulated with $\Delta t = 0.1\mu$s timestep i.e. taking 10000 timesteps altogether. Both simulations required 17000 CPU hours on Juropa (2.93 GHz, Intel Xeon X5570 quad-core processors).

In Fig. 1, temperature and density profiles with and without heat the SOL model are shown. Initial profiles are shown as green circles and, as shown in time traces, plasma is heated up during the simulation. Heating is done artificially using collisions with fixed background at 1 cm region at the inner edge. These collisions are turned on at $t = 250$ μs and temperature at inner edge is then gradually doubled during next 500 μs after which it is kept constant at this higher level for last 250 μs. In Fig. 2, radial and temporal behaviour of the radial electric field as well as the heat transport coefficient χ_i for the both cases are shown. Here, radial profiles are at the end of the simulations and time plots are averaged over six radial cells around the radial location $r = 0.402$ cm where the E_r gradient is steepest in the SOL case. Main effect seen here is the strong modification of the radial electric field profile within one orbit width from last closed flux surface in the SOL case. This is in qualitative agreement with the results earlier obtained with other particle code, ASCOT, which includes only neoclassical effects [1]. When SOL is not included, E_r and its gradient remain small. High shear in E_r in SOL case is shown to suppress turbulence, which can be seen in heat diffusivity χ_i. In Fig. 1, we can see how this can be seen as steepening of temperature pedestal.

Conclusions

New scrape-off-layer model is tested and shown to strongly modify the electric field profile near the last closed flux surface having also effect on heat diffusivity and temperature profile. As a pedestal type structure and a drop in heat diffusivity is seen, this could be considered as a indication of transport barrier formation and confinement transition. However, in the simulations the noise level was not much below the physical fluctuation so simulations with higher number of test particles are still needed to make final conclusions. Also, the plasma is heated up artificially rapidly compared to experiments and it is difficult to separate the effects of real physics and artificially initiated heat pulse.

Acknowledgements: This work is supported by the grants 122435 and 13134977 of the Academy of Finland and EFDA Topical Group Activities WP10-TRA-01 "Triggering of L-H transition" and WP10-TRA-04 "Theory and modelling of edge turbulence" and is part of the national Tekes work programme. CSC – IT Center for Science Ltd., DEISA and HPC for Fusion are acknowledged for the allocation of computational resources for this work.

References

[1] J.A. Heikkinen, T.P. Kiviniemi and A.G. Peeters, Phys. Rev. Lett. **84**, 487 (2000)

[2] T.P. Kiviniemi, S.K. Sipilä, V.A. Rozhansky, S.P. Voskoboynikov, E.G. Kaveeva, J.A. Heikkinen, D.P. Coster, R. Schneider, X. Bonnin, Physics of Plasmas **10**, 2604 (2003)

[3] J.A. Heikkinen, S.J. Janhunen, T.P. Kiviniemi and F. Ogando, Journal of Computational Physics **227**, 5582 (2008)

[4] J.A.Heikkinen, M.Nora, Physics of Plasmas **18**, 022310 (2011)