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Full f gyrokinetic simulation of transport in tokamak plasmas

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Introduction: The electromagnetic gyrokinetic (GK) plasma simulation [1] for toroidal magnetic fusion devices has become a standard tool for turbulence analysis. Recently, it has been recognized that transport involving dynamic changes in profiles requires modelling with full f GK methods [2]. In the present work, we report on transport simulations for the FT-2 tokamak plasma with a full f nonlinear 5D gyrokinetic electrostatic (ES) particle-in-cell code ELMFIRE using an implicit solution method for the full f plasma quasi-neutrality.

The description of the ELMFIRE code and its validation for the linear mode growth and turbulence saturation in Cyclone Base case as well as for neoclassical (NC) effects are described in Refs [2-4]. The NC effects were studied for the radial electric field and its evolution in heated and relaxing pressure profiles for a small FT-2 tokamak configuration, and are further discussed in [5]. For transport simulations, the stochastic lower hybrid (LH) wave ion heating and Ohmic heating are used to support the otherwise relaxing temperature. To obtain a stable evolution of the pressure profile, the proper treatment of the plasma boundaries becomes important. Here, the scrape-off-layer (SOL) plasma is not simulated, but is used as a boundary. Various recycling conditions for the out flowing particles are considered, and the flux surface averaged transport coefficients were evaluated for LH heated FT-2 experimental conditions [6]. The turbulence was characterized with the global analysis of Fourier spectra, cross-correlation function and PDF as well as visually [7,8]. The effects of ion impurities on turbulent transport were addressed in Ref [3].

FT-2 configuration and simulation parameters: In the following, an FT-2 configuration with a=0.08 m, R=0.55 m, B=2.2 T, and I=55 kA for the minor radius, major radius, toroidal magnetic field, and plasma current, respectively, is considered. The simulations are performed between the plasma radii r_l=0.02 m and r_r=0.08 m in a quasi-toroidal magnetic configuration of circular magnetic surfaces with no Shafranov shift. The particles are initialized on their collisionless finite orbits. Outflowing ions and electrons are recycled by ionization of neutral atoms from the SOL region. The radial electric field is zero at r_l and the potential zero at r_r. The collisions are modelled by binary collisions between all species.

The simulation is performed in a quasi-ballooning grid with 30 radial, 200 poloidal and 4 toroidal cells. This grid allows resolving modes up to $k\rho_i$~1, where k is either the radial or poloidal wave number and ρ_i is the ion Larmor radius. 28 million ions and 28 million electrons are used providing more than 1000 particles per cell. The time step for updating the ES potential from the GK Poisson equation is 50 ns. The electrons are treated kinetically using an implicit method. The simulation was started with the flux surface averaged density (n) and temperature (T) profiles depicted in Fig.1. No heat source was on.

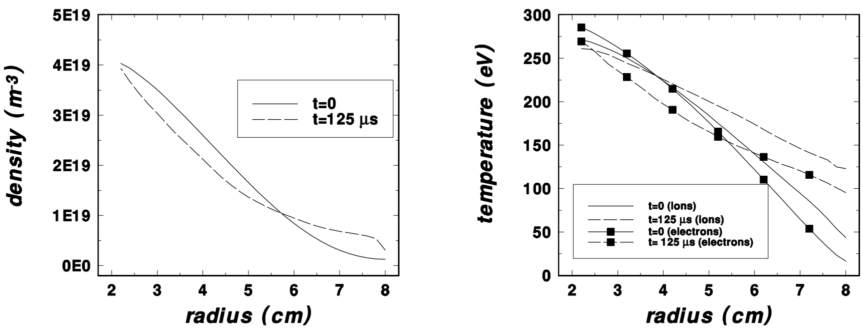

Fig. 1 Flux surface averaged density and temperature radial profiles at the start of simulation and after 150 µs.

Results: In the absence of heat sources, the radial n and T profiles relax by turbulent transport within 150 µs as shown in Fig.1. Although the recycled ions and electrons are introduced at the low 15 eV temperature after the neutral ionization, and ionization energy losses take energy from electrons within the neutral ionization exponentiation range of 1 cm from the outer edge $r=r_r$, the edge T rises for both electrons and ions. This is in contrast to experimental observations (at I=22 kA and 32 kA) at FT-2 [9], and may indicate underestimation of the edge transport with the present model. The flux surface averaged radial transport fluxes of particles and heat are shown in Fig.2 as obtained after 150 µs simulation. The declining of fluxes towards the outer edge is partially explained by the continuing rise of density and temperature in the periphery and partially by recycling of particles from the outer boundary. The energy content of the plasma is found to decrease at an almost constant rate of 55 kW in the present simulation after the onset of turbulence after a few μs. This gives us an energy confinement time τ_E of 1.6 ms which should be compared to the post-LH measurements of $\tau_E \sim$ 1.7-3 ms and pre-LH measurements of $\tau_E \sim$ 0.8-0.9 ms in FT-2 experiments [9].

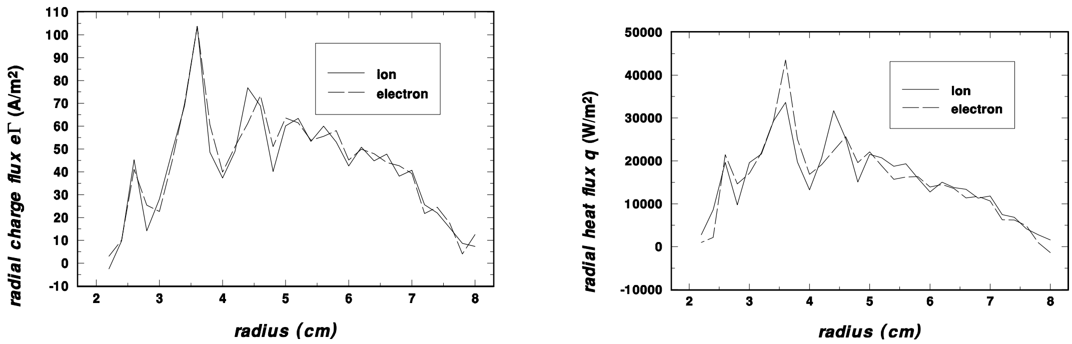

Fig.2 Flux surface averaged radial charge flux profiles of ions and electrons and corresponding heat flux profiles after 150 μs simulation taken at one time step.

The time evolution of transport fluxes is discussed in the separate paper [5]. The contribution of noise to the transport fluxes was measured to be small. Well before the onset of turbulence, the flux surface averaged electron radial charge flux is about -20 A/m^2 at r=5 cm. Due to the FLR correction $1+(k^2\rho_i^2/4)$ to the electric drift, this flux is smaller for the ions. From the radial ion polarization current density $(n_i e/\Omega B)d\langle E_r\rangle/dt$ obtained at the start of the simulation, we deduce the radial current density of j~ -8 A/m^2 and the ion radial charge flux about 12 A/m^2. Other sources of non-ambipolarity were here non-existent, e.g., by precise initialization of particles for ambipolarity. The origin of this noise flux was further confirmed by the convergence analysis of the number of simulation particles. About 1000 simulation particles (for both electrons and ions) per cell are generally required for fair convergence both in transport fluxes and in the NC behaviour in the FT-2 configuration. From NC balance $j_{NC}=nD(e\langle E_r\rangle/k_BT - n'/n - \gamma T'/T)\exp(-E_r^2/B_p^2 v_T^2)$ between the radial current density j_{NC} and electric drive with $D=(\sqrt{\pi}/2)\varepsilon^2(k_BT/\Omega B_p)v_T/r$ and $\varepsilon=r/R$, $v_T=\sqrt{k_BT/m}$ and $\Omega=eB/m$ for plateau collisional regime, we deduce a noise generated positive radial electric field of $\langle E_r\rangle \sim 1500$ V/m in response to $j_{NC}= -j \sim 8$ A/m^2. This estimate is used as a correction for the NC benchmarking in the separate paper [5].

The turbulence at t=150 μs is further characterized by the PDF of density fluctuations as measured at r= 6 cm. Fig.3 shows that relative fluctuations less than 10% appear on that radius and fair agreement with a Gaussian distribution is found for positive fluctuations while density depletions seem to have non-Gaussian tails.

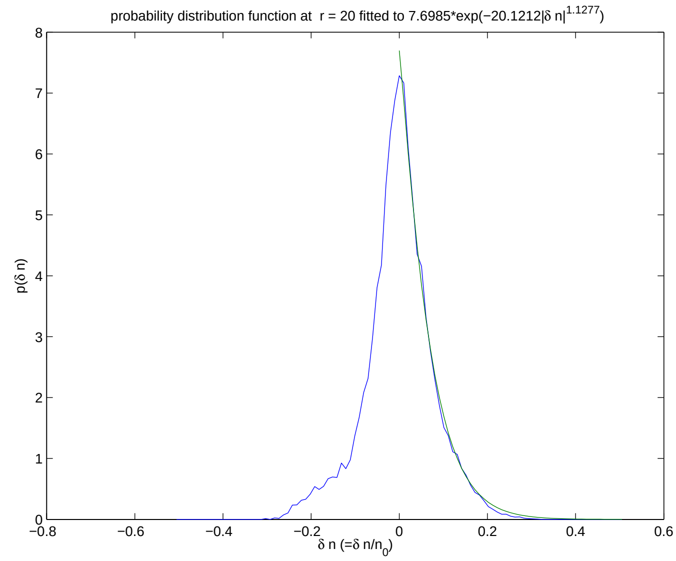

Fig.3. The PDF of density fluctuations taken at r=6 cm on t=150 μs.

The obtained heat diffusivities of 1-4 m^2/s for the radii r=0.03-0.07 cm are close to those modelled with the interpretative fluid transport codes for the FT-2 discharges [9] under similar pressure profiles. However, as strong tendency of the diffusivities to grow towards the outer radial boundary as in [9] is not observed in simulations. This may indicate the need to include the scrape-off-layer plasma into the simulation. This work is in progress.

The computations have been made with CSC's computing environment. CSC is the Finnish IT centre for science and is owned by the Ministry of Education.

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