Gyrokinetic particle simulation of a tokamak Ohmic transport equilibrium

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Recent progress in gyrokinetic full f global particle simulation [1, 2] has made possible a full transport simulation and analysis of tokamak discharges over the energy confinement time. The benefit of such simulations is the incorporation of turbulence and neoclassical physics within the same calculation based on physics of first principles. An important test for the validity of such a scheme is to find the Ohmic transport equilibrium determined by the balance of Ohmic heating and turbulent transport. In tokamaks, the Ohmic equilibrium is reached by feedback controlling a constant current into the plasma. In other words, the transformer drives initially with a huge loop voltage a steady current against the cold plasma which heats the plasma until the electron temperature is so high that the resistive heating (and loop voltage) ceases to the level of heat losses by transport. This process can be illustrated qualitatively by [3]

$$n(r,t)\frac{dT_e(r,t)}{dt} = \eta(r,t)\, j(r,t)^2 - \frac{3n(r,t)\,T_e(r,t)}{\tau_E}, \tag{1}$$

which expresses the evolution of electron temperature, T_e, as a function of radius and time in the presence of the Ohmic heating (ηj^2) and transport losses ($3nT_e/\tau_E$). In the equation, j is the current density, η is the resistivity, n is the density, and τ_E is the energy confinement time. For the equilibrium, the current density in the equation is ramped up and maintained by actively adjusting the loop voltage, V, through $j = E/\eta$ with $E(t) = V(t)/2\pi R$, where R denotes the major radius. The active adjustment requires a balance between the loop voltage and the friction forces as can be seen from the time derivative of the current density parallel to the magnetic field

$$\frac{dj_{||}}{dt} = \frac{ne^2}{m}\left(E_{||} - \eta_{||} j_{||}\right), \tag{2}$$

where e and m are the electron charge and mass, respectively. The equation shows that the loop voltage has to response to the evolution of plasma resistivity in order to maintain a steady current.

In Elmfire [1], a fixed total plasma current is given as an input and used for calculating the static poloidal component of the magnetic field. This current is then created in a simulation by applying a sufficiently large loop voltage until, within the time scale of hundreds of time steps, a current density profile is generated that integrates to the plasma current given in the input. After the correct current level is reached, the loop voltage is adjusted at each time step to sustain the current. This means decreasing loop voltage and increasing electron temperature until the balance with thermal losses and other current drive sources, e.g., bootstrap current, is found. In Elmfire, the thermal losses consist of radial transport and electron radiation losses inside the separatrix and of transport losses to the limiter surface, enhanced electron convection losses and electron radiation losses in the scrape-of-layer (SOL) region. The radiation model in the code is based on an experimentally measured radiation loss profile. Enhanced electron convection losses, including the tail energy effect and the secondary emission effect, are modeled based on the expression found in [3]. Energy losses to the limiter are considered by removing ions and electrons pairwise according to the ion flux to the limiter. The particles hitting the limiter are recycled back into the plasma as ionized low-energy neutrals. The recycling model is based on an experimentally measured neutral density profile.

To test the Ohmic transport equilibrium with Elmfire, a FT-2 tokamak [4] Ohmic discharge is simulated over 0.2 ms with a time step of 30 ns. The default test discharge parameters for hydrogen plasma are for minor radius a = 0.077 m, major radius R = 0.55 m, total current I = 18.9 kA and toroidal magnetic field B_t = 2.2 T. The simulation region includes the SOL plasma region (3 mm), and in addition to the hydrogen ions, oxygen impurity ions (charge state +6) at 7 % concentration are simulated, forming a plasma of the effective charge of Z_{eff} = 3.1. The Ohmic current is driven as described above. The initial density and temperature profiles are nearly the same as measured experimentally from the discharge. In Fig. 1, the initial radial profiles of the particle density and electron temperature are presented together with the simulated evolution of them. The time evolution of the density profile shows minor relaxation within 7000

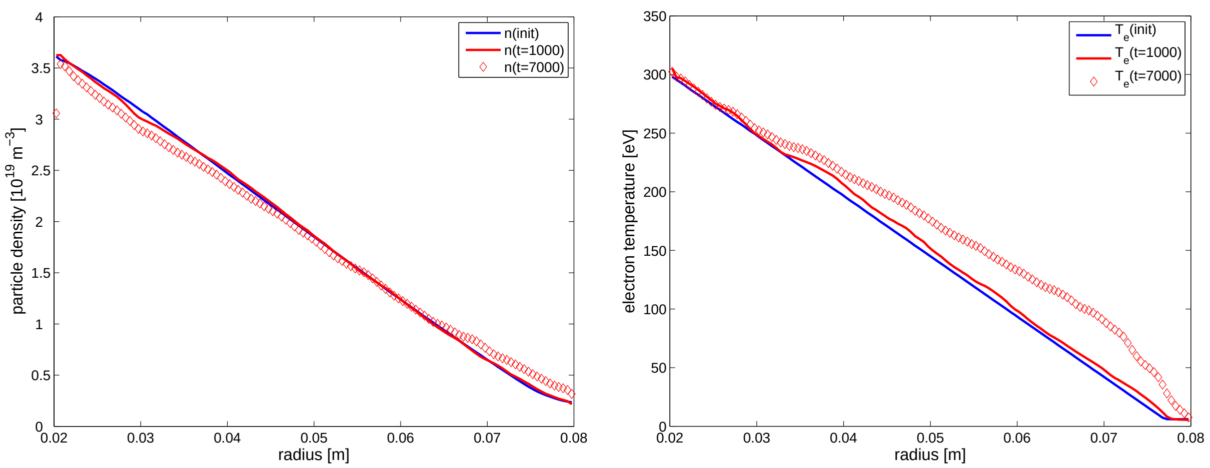

Figure 1: Evolution of density and electron temperature in comparison with the inital profiles

time steps, while the radial profile of the electron temperature is seen to heat up moderately and to build up near the separatrix because of the relaxation of the density profile. In Figs. 2, the Ohmic current generated by the feedback controlled loop voltage is shown. The total plasma current is ramped up fast at the beginning of the simulation and, after that, sustained accurately at the level given as an input through the simulation. The loop voltage, correspondingly, increases from the inputted value at the beginning and, after the correct plasma current is reached, roams downwards slowly as the increasing electron temperature decreases plasma resistivity. In Fig. 3, the toroidal current density profile, used for the evaluation of the poloidal magnetic field, is compared with the simulated profiles. The simulated profile shows rather fair agreement with the input profile at the 1000th time step while at later time steps the simulated profile relaxes, following the evolution of the density and electron temperature profiles. Judging from the decreasing loop voltage, dynamical processes have not ceased and a steady state Ohmic equilibrium is not reached within the simulation time. In addition, a transport plug seems to suppress energy transport in the separatrix region, resulting in the buildup of the temperature profile. Thus, the experimentally measured profiles are not sustained in the simulation.

In Fig. 3, the electrical conductivity calculated from the simulation is compared to the theoretical (neoclassical) estimate. The former is determined simply as a ratio of the parallel current density and the parallel electric field generated by the loop voltage, while the latter is obtained from the Hirshman et al. formulation [5]. The comparison reveals that the conductivity profile from Elfmire equals to the neoclassical profile both at the 1000th and 7000th time step (the evolution of the profiles results from the changes in the electron temperature profile).

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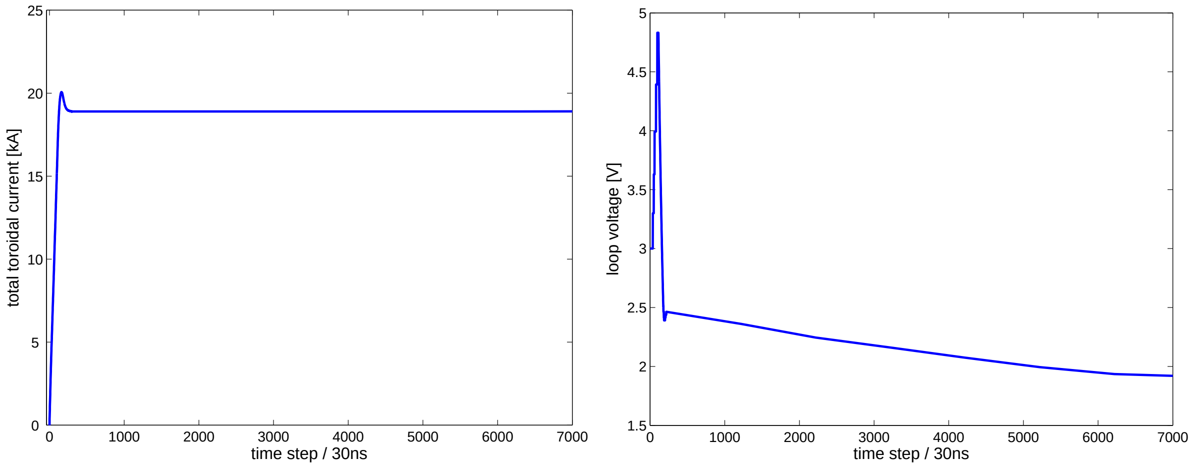

Figure 2: Time evolution of total toroidal current and loop voltage

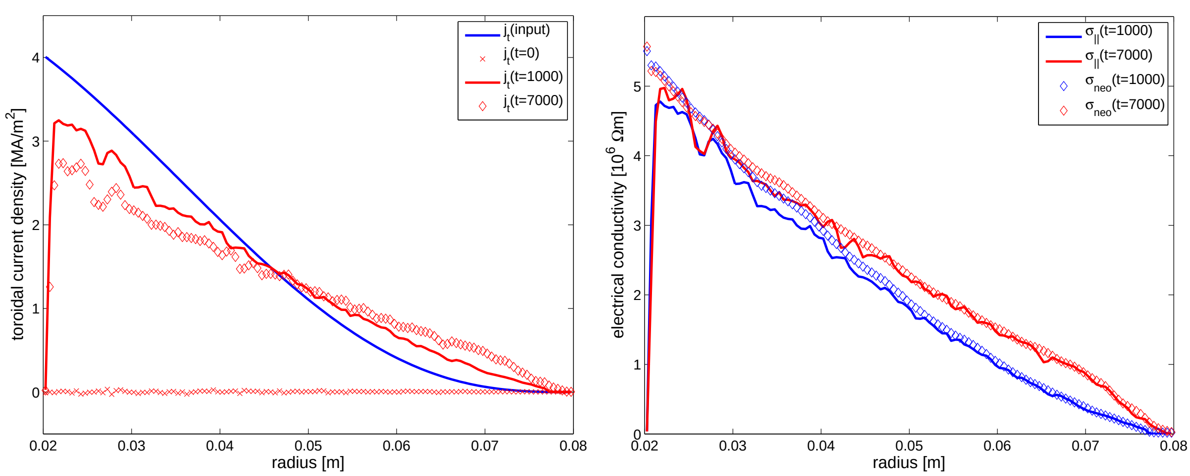

Figure 3: Inputted radial profile of toroidal current density together with simulated profiles (left). Radial profiles of electrical conductivity from the simulation compared with the theoretical estimate (right)