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Transport analyses of the "Cyclone base" case on ELMFIRE

S. Janhunen[1], J.A. Heikkinen[2], T.P. Kiviniemi[1], T. Korpilo[1],
S. Leerink[1], M. Nora[1], F. Ogando[3]

[1] *Helsinki University of Technology, Espoo, Finland*

[2] *VTT Technical Research Centre, Espoo, Finland*

[3] *Universidad Nacional de Educación a Distancia, Madrid, Spain*

The "Cyclone Base case" [1] has become a standard benchmark case for tokamak plasma turbulence simulations. The case has also been adopted as the standard transport benchmark for the EFDA task-force ITM turbulence project [3]. While this choice of tokamak shot parameters may be viewed as somewhat controversial, it never the less has been widely discussed in the literature by a large group of authors in several variations (e.g., [2]). The case prescribes (as given by Ref. [3]) density and temperature profiles, current profiles and adiabatic electrons, due to availability of more material in the literature to compare results to.

The ELMFIRE is a global particle following gyrokinetic full-f code, on which several Cyclone Base benchmarks (e.g., linear growth rates) have been obtained [4]. The main differences in respect to other particle in cell (PIC) gyrokinetic simulations in the field is the application of the numerically linearized non-linear polarization model, and particle discretisation of the full distribution.

Finite gyrocentre precession orbit width effects are rarely investigated by gyro-kinetic codes, because in δf codes the curvature and gradient terms do not act on the background, which acts as a transport source. In gyro-fluid codes such neo-classical effects are introduced through additional conductivities, and while possible to implement, finite orbit width effects are neglegted generally. The full-f calculation models are unique in this regard, as such background distribution dependent terms are naturally included, but this dynamics causes also additional problems near the boundaries due to combination of orbit losses and boundary conditions, as well as complications in initialisation.

In this work we discuss differences in transport evolution of the non-linear benchmark cases with standard initialisation and boundary conditions, and discuss the possible orbit dynamics picture of some of the cases.

Heat transport naturally leads to temperature relaxation, and if the distribution function is assumed to remain isotropic in this process, we may infer a density change due to finite orbit width effects even if orbit centre. In the adiabatic electron model the electron density change is ignored, which will lead to a difference between electron and ion density, which results in a

polarisation response and $E \times B$ flows. This is best illustrated by the following analysis.

If, for simplicity, one takes the perturbation $c\cos(r/b)$ of the ion orbit half width w due to the ion temperature relaxation along the radial direction r, the related shrinking and widening of orbits causes an ion density perturbation $-(cw/3b^2)n_0\cos(r/b)$, where n_0 is the unperturbed density at $r/b = \pi/2$. Taking into account of the ion polarization, quasineutrality condition gives the potential perturbation $-\Omega cB(w/3)\cos(r/b)$, where Ω is the ion cyclotron frequency and B is the magnetic field.

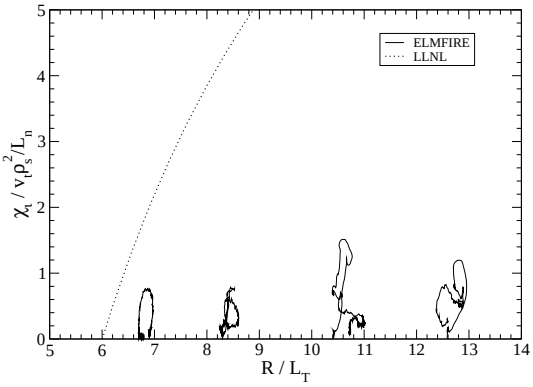

Figure 1: Transport evolution for several R/L_T.

We calculate the amplitude $-\Omega cBw/3$ for the ELMFIRE cyclone base case simulation in figure 1. Here, $B = 1.91\,\mathrm{T}$, $\Omega = 10^8\,\mathrm{s}^{-1}$, and $w = 2.5\,\mathrm{cm}$ for thermal bananas at radius $r/a = 0.5$ (the node of bipolarity $r/b = \pi/2$). The relative ion orbit width perturbation c/w can be, directly read from the data e.g., at the end of calculation. From the picture of T_i profile, we read for the perturbation T_i about $-250\,\mathrm{eV}$ at the inner relaxation maximum implying $a/w = 0.035$. If these numbers, and the fraction of trapped ions 0.3, now are put into our expression of potential perturbation amplitude, we get $500\,\mathrm{V}$ at the inner relaxation maximum for the potential perturbation at the end of calculation.

Note that we have a negative a at the radius index 10 (negative maximum of perturbation) which means a positive potential maximum at that point. Both the direction and amplitude of the resulting bipolar potential perturbation from ELMFIRE simulation are in fair agreement with this theory. What matters here is the magnitude of T_i and its relaxation. The larger T_i or its relaxation, the larger is the effect. In our Cyclone base simulations, we have taken $T_i \approx 4000\,\mathrm{eV}$ at the inner edge. T_i relaxation is also enhanced by the (unphysical) initial transient in ion heat diffusivity in simulations. Thus, for comparison of results from different codes, we have to look at whether the T_i relaxation is equally strong and T_i is at the same level (ion orbits wide enough to clearly see the effect). E.g., any effort to keep the inner edge in thermal bath with T_i fixed may mask this effect.

When electrons are kinetic and collisions are taken into account, the above effect can affect transport, but due to electron dynamics saturates. Collisions take care of the return ion current which neutralizes the charge separation from ion orbit modification sooner or later. Also, T_i relaxation is now also partially controlled by ambipolar electron/ion radial convection. Convective

heat losses do not cause orbit modifications between ions and electrons. In kinetic ELMFIRE simulations with collisions, this effect has not been clearly identified. However, background collisions have been applied as a form of heating, introducing a source heat flux which the code dissipates, as occurs in delta-f codes.

The result means that it is not possible to calculate saturation in the adiabatic limit in the full f code unless electron adiabaticity is redefined to prevent charge separation through the ion orbit shrinking/widening (but this may cause other problems) or unless T_i profile is kept unrelaxed (by some thermal bath or similar ways). In the kinetic case, collisions and electron/ion convection ultimately cancel this charge separation thus preventing any steady potential bipolarity (the latter may appear only transiently for weak collisions).

Strong curvature in the electric potential induces an orbit squeezing (or, widening) effect [5], which also changes density profile. In figure 2 we present the squeezing parameter

$$S = 1 - \frac{q_e}{m_d \Omega_p} \frac{\partial^2 \phi}{\partial r^2}, \tag{1}$$

where $\Omega_p = q_e B_p / m_d$ is the bounce frequency. The particle orbits are proportional to the squeezing parameter by $S^{-1/2}$, so if $S < 1$ we obtain widened orbits. This appears to be most important near the inner border of the simulation, where the orbit loss dynamics caused by the widening may influence radial electric field dynamics due to boundary treatments.

The growth of electric field shear stresses turbulence, and beyond some limit, suppresses it. This results in a decaying of the saturation state in adiabatic cases.

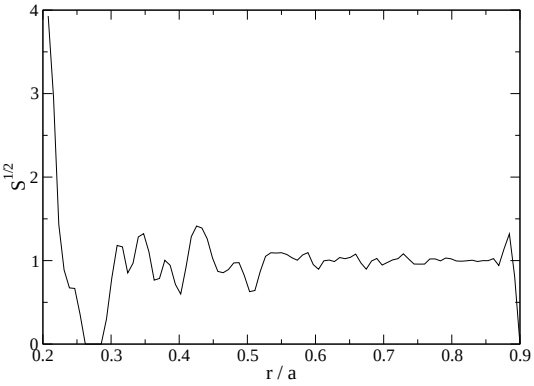

Figure 2: Orbit squeezing parameter.

In full-f global nonlinear simulation of the "Cyclone Base case" with adiabatic electrons we find that the adiabatic condition has to be evaluated carefully to correctly evaluate finite ion orbit effects on electrostatic potential in the presence of temperature and density profile variations of the plasma. Adiabatic simulations may be sustained by mitigation of temperature profile changes by injecting heat flux into the system, which sustains the profiles and therefore, the turbulence.

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