31st EPS Conference on Plasma Phys. London, 28 June - 2 July 2004 ECA Vol.**28G**, P-5.147 (2004)

Validation of gyrokinetic particle code ELMFIRE for tokamak edge transport analysis

S.J. Janhunen[1], T.P. Kiviniemi[1], J.A. Heikkinen[2],
[1]*Association Euratom-Tekes, Helsinki University of Technology, Department of Engineering Physics and Mathematics, P.O. Box 2200, FIN–02015 HUT, Finland*
[2]*Association Euratom-Tekes, VTT Processes, P.O. Box 1608, FIN–02044, VTT, Finland*

Introduction

Detailed physics of drift instabilities, such as ion temperature gradient modes (ITG) and trapped electron modes (TEM), can be studied numerically either with gyrofluid or gyrokinetic approaches. The gyrokinetic full f particle code ELMFIRE [1] is an electrostatic code where guiding centre orbits of particles are followed in a toroidal geometry and the gyrokinetic approach is chosen to include finite Larmor radius effects. The code is a gyrokinetic version of ASCOT code [2]. A self-consistent nonlinear model includes electrostatic perturbations and a non-Maxwellian distribution function. As real orbits are followed in toroidal geometry with binary collisions, also the neo-classical physics is included in the simulations. Electrons can be either adiabatic or fully kinetic.

Benchmarking the code in the linear regime (i.e., growth rates and frequencies) is performed. There exists many linear gyrokinetic codes available using spectral method and adiabatic (or kinetic) electrons but exluding collisions and assuming circular cross-section (e.g., Kinezero [3]). Here, ITG and TEM modes obtained with full f gyrokinetic particle code ELMFIRE are compared with the results of the Weiland model and KINEZERO. Also, the effect of collisions on the modes is investigated.

Ion thermal diffusivity χ_i is simulated, and the results are contrasted to published results of other codes (as presented in Ref. [4]).

ELMFIRE and the simulation parameters

The ELMFIRE employs a low beta equilibrium with circular cross section, and the simulation region is a toroidal annulus spread between chosen flux surfaces. The current density profile used is given by $j(r) = j_0(1-(r/a)^2)^{\alpha_j} + c_j$ with $\alpha_j = 1$ and $c_j = 0$, and the temperature and density profiles $T_{e,i}(r)$ and $n_{e,i}(r)$ have the same functional dependence on the radius as the current density profile (with $T(0) = 300\,\mathrm{eV}$ and $n(0) = 5\cdot 10^{19}\,1/\mathrm{m}^3$, profile exponents $\alpha_T = 1.3$ and $\alpha_n = 2.5$, and small but finite constants c_n and c_T), for the ions and electrons respectively. The test particles are initialized quiescently on invariant orbits in the beginning of the simulation, irrespective of the simulation grids. Electrons are kinetic in the simulations to allow TEM development as well as ITG modes.

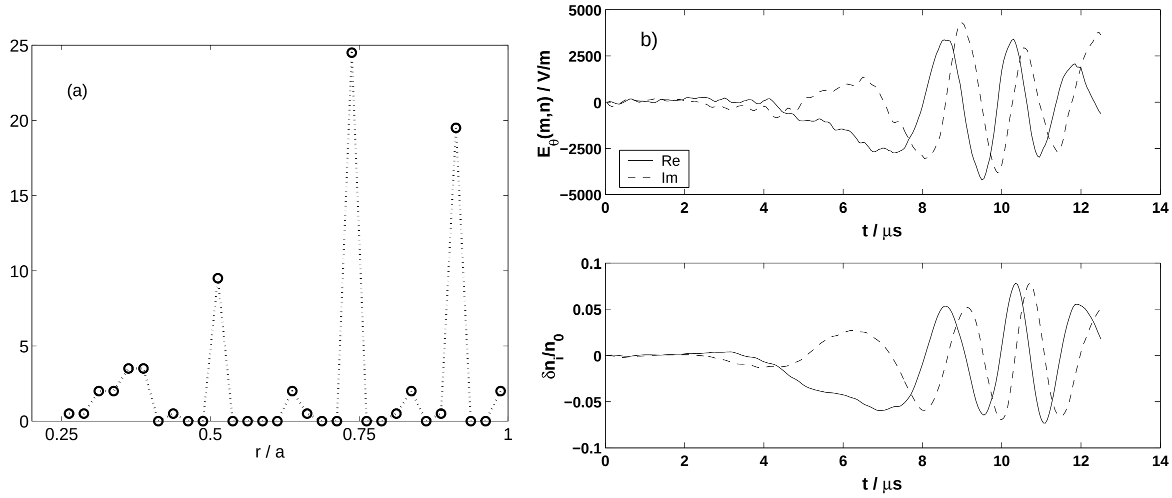

Figure 1: *a) Number of unique resonant modes in the simulation at radius r (normalized to a), b) the time evolution of the (m,n)=(16,4) mode to the end of linear growth at* $12\,\mu s$*, poloidal electric field and density perturbation associated with this mode are shown.*

The toroidal magnetic field on the magnetic axis is set to $B_t = 2.2\,\mathrm{T}$, and the magnetic shear and the safety factor at normalized radius $r = 0.74$ are $s = \frac{r}{q}\frac{\partial q}{\partial r} = 0.75$ and $q = 4$, respectively. The field equations are discretized in the quasi-ballooning coordinates. We study the evolution of modes in the ITB formation regime [1] with the highest number of resonant (or flute) modes, where we have $R/L_T \simeq 6$, $R/L_n \simeq 36$, $T_e/T_i \simeq 0.7$, and the inverse aspect ratio is $\epsilon_a = a/R = 0.145$, with major radius $R = 0.55\,\mathrm{m}$. The number of unique flute modes (with $m/n = q$) in the torus is illustrated in Fig. 1a. The modes are expressed in the ballooning representation [3], where m is the poloidal mode number and n is the toroidal mode number.

As an example of a growing mode, we illustrate the linear growth of the $(16, 4)$ flute mode on radius $r = 0.74$ in Fig.1b up to the start of the non-linear mode cascade.

Benchmarking

A non-linear simulation model, such as ELMFIRE, needs to be benchmarked both in the linear and non-linear regimes. In the linear regime the frequencies ω_r and growth rates γ of the unstable modes are compared to analytic estimates or results given by a linear code. The applied models in the linear regime are the Weiland reactive fluid model (as presented in Ref. [5]) and the KINEZERO code [3], which both are used for calculating the growth rates and frequencies of unstable drift modes relevant to our simulations. Both of these models have been benchmarked against fully toroidal gyrokinetic codes.

KINEZERO is a local linear gyrokinetic code, which allows the actual profiles from ELMFIRE simulations to be used in evaluating the stability of drift modes in the torus. It also includes electron temperature gradient modes and the effect of impurities, which

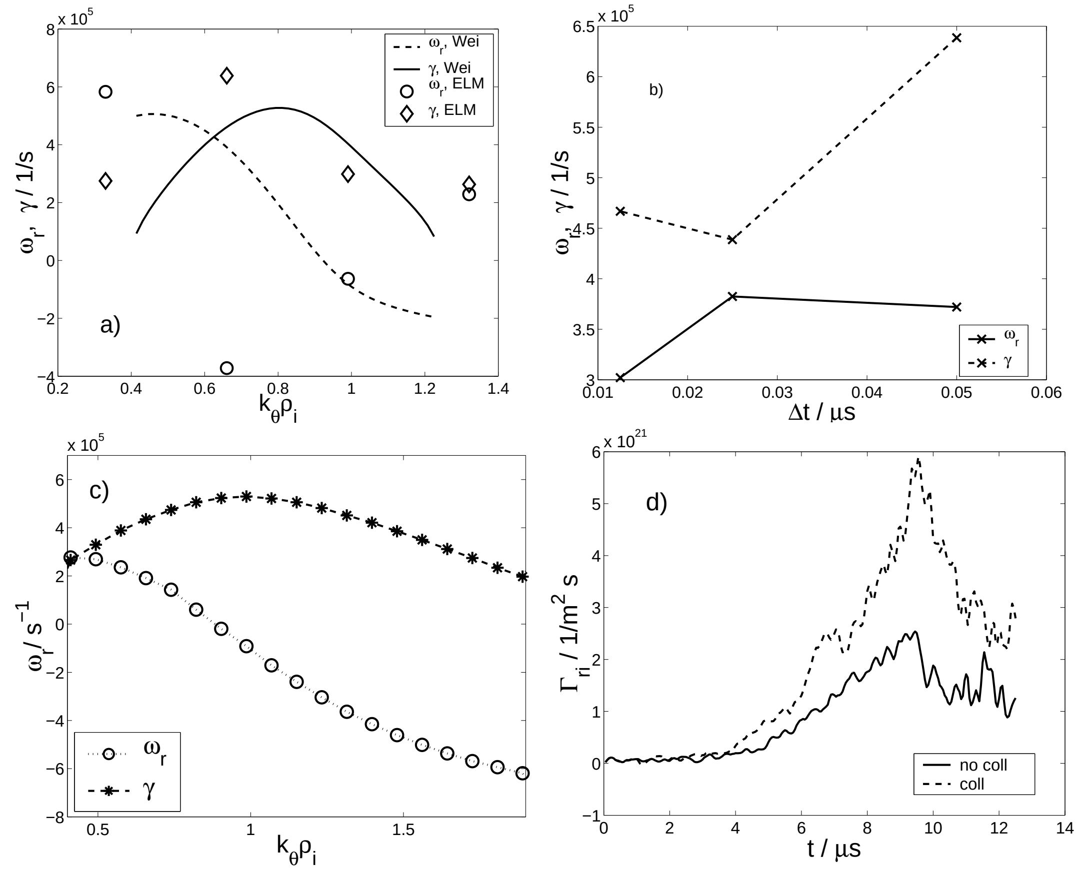

Figure 2: *a) frequency and growth rate of flute modes at* $r = 0.74$ *(Weiland model prediction marked by Wei, ELMFIRE by ELM), b) convergence of the most unstable (32,8) mode while time step* Δt *is varied (negative value of* ω_r *is plotted for clarity), c) frequency and growth rate as obtained from KINEZERO for modes at* $r = 0.74$*, d) effect of collisions on the radial* $E \times B$ *flux in the linear stage.*

are not modelled in ELMFIRE.

The runs with ELMFIRE, the Weiland model and KINEZERO are illustrated in Fig. 2a and 2d. The ELMFIRE reproduces the growth rates given by the Weiland model to reasonable accuracy. KINEZERO produces the most unstable modes in the region of $k_\theta \rho_i > 1$ (k_θ is the poloidal wave number and ρ_i is the Larmor radius for ions), while the maximum growth rates are comparable with those produced by ELMFIRE.

The convergence of ω_r and γ in terms of time step is illustrated in Fig.2b. We observe convergence in the growth rates, but there appears to be slight variation in the frequency.

In the non-linear regime, however, such straightforward tests are not feasible. In Ref. [4] the non-linear behavior is investigated by comparing various non-linear gyrokinetic and gyrofluid codes in terms of critical temperature gradient scale length, as well as scalings for transport in the saturation state for different temperature gradient scale lengths. In the ELMFIRE we observe an ion diffusion coefficient of $\frac{\chi_i L_n}{\rho_i v_{ti}} = 2.8$ at $R/L_T = 6$, which appears to be just slightly larger than the results given for gyrokinetic codes in Ref. [4], but smaller than those given by gyrofluid codes. This may be due to the kinetic electron species or collisions, the effects of which were not present in the reference.

In the comparison between the collisional to the non-collisional case (see Fig. 2d), we observe the flux surface averaged radial $E \times B$ flux rise more rapidly and attain larger values than in the non-collisional case. The mode growth is clearly damped by collisions, as expected.

Discussion

The resonant surfaces have a similar scale length as the density and temperature scale lengths, which complicates the linear analysis of modes. If the resonant surfaces are far apart as in our test cases, the radial structure of modes becomes more important. Also, the modes in the resonant radii where there are only a few modes tend to be high in $k_\theta \rho_i$, so the the role of these modes in terms of transport needs to be investigated. In the current analyses of the gyrokinetic scheme we see proper linear behavior only for modes of $k_\theta \rho_i \lesssim 1$.

The linear growth rates appear to correspond to the linear estimates very closely, except for the slight shift in $k_\theta \rho_i$ with the Weiland model. KINEZERO predicts the maximum growth rate at $k_\theta \rho_i = 1$, which is not observed in ELMFIRE. This requires additional investigation.

The non-linear behavior of ELMFIRE appears to be in order, but more complete comparisons to other non-linear codes are still required.

Acknowledgements

The computing resources of CSC - Scientific Computing Ltd were used in this work.

References

[1] J.A. Heikkinen, S.J. Janhunen, T.P. Kiviniemi, this conference

[2] J.A. Heikkinen, T.P. Kiviniemi, T. Kurki-Suonio, A.G. Peeters, and S.K. Sipilä, Journal of Computational Physics **173** (2001) 527

[3] C. Bourdelle, X. Garbet, G.T. Hoang, J. Ongena and R.V. Budny, Nucl. Fusion **42** (2002) 892

[4] Dimits *et al* Phys. Plasmas **7** (2000) 969

[5] J. Weiland, "Collective Modes in Inhomogeneous Plasma; Kinetic and Advanced Fluid Theory", IOP Publishing Ltd (2000)