HIGHLY COLLISIONAL TWO-FLUID ANDGYROKINETIC SIMULATIONS OF TOKAMAK EDGE TURBULENCE AND THE TRANSITION BETWEEN KINETIC AND FLUID REGIME

K. HALLATSCHEK

Max-Planck-Institut für Plasmaphysik, Boltzmannstr. 2, 85748 Garching, Germany
Email of corresponding author: Klaus.Hallatschek@ipp.mpg.de

Abstract

Gyrokinetic and non-local fluid codes have complementary limitations in the tokamak edge. To arrive at a common basis, the gyrokinetic code CGYRO and the non-local two-fluid code NLET have both been applied to identical parameters sets ranging from resistive ballooning turbulence - approaching the collisional fluid limit - relevant to the edge of a tokamak, up to high-gradient kinetic ITG modes at higher temperatures in the core-edge transitional regime, yielding comparable results. As a non-trivial, novel result, linear growth rate and nonlinear transport agree between the codes in the fluid limit of high collision numbers, not least, because the kinetic code employs the Sugama collision operator with momentum and energy conservation, Galileian invariance and exact self-adjointness property.

1. INTRODUCTION

Gyrokinetic simulations have come to be the standard of current turbulence modelling in the low gradient, nearly collisionless region in the core of tokamak discharges, since they include nearly all the kinetic effects to be expected for a small ratio of the turbulence to the Larmor frequency [1]. However, they exhibit serious problems upon approaching the notoriously difficult edge region of the plasma. The full nonlinearities that become relevant due to the high fluctuation amplitude there are incompatible with the assumption of small $\delta f$ inherent in the gyrokinetic equation, and at present cannot be implemented in a gyrokinetic framework. In addition the sufficiently accurate modelling of the collisions becomes an issue for the large collision frequencies encountered for certain edge parameters. An example of the problems is the difficulty matching the L-mode transport with the simulations in certain DIII-D discharges [2], a hot topic of current research.

A fluid approach is more robust for the high fluctuation levels in the edge region, since only fundamental conservation laws are used in the derivation of the respective turbulence equations. Moreover, it becomes more reliable at the large collision frequencies at the edge, tends to yield more physical insight than fully kinetic simulations and allows relatively inexpensive high resolution simulations.

On the other hand, for relatively low collision frequencies, in the hotter plasma regions away from the very edge, the fluid equations are deficient in the representation of kinetic phase mixing – they require an empirical rescaling of the dissipation coefficients.

To arrive at a common basis, the gyrokinetic code CGYRO [3] and the non-local two-fluid code NLET [4] have both been applied to identical parameters sets ranging from highly collisional, resistive ballooning turbulence scenarios - which approach the fluid limit - relevant to the edge of a tokamak, up to high-gradient kinetic ITG turbulence at higher temperatures in the core-edge transitional regime. Earlier attempts with a less sophisticated collision operator in the gyrokinetic code were unsuccessful to come close to the expected transport values owing to problems with the momentum conservation and with the numerics of the high collision frequencies. Surprisingly, it has been much easier to match fluid and gyrokinetic results in the lower collisionality ITG regime in the core-edge transitional region. Even in the collisionless core the transport difference between fluid and gyrokinetic results for non-marginal instabilities are $\lesssim 30\%$ [5]. A non-trivial, novel result is that the linear growth rate and nonlinear transport agree between the codes in the fluid limit of high collision numbers and low wavenumbers, not least, because the kinetic code employs the Sugama collision operator with momentum and energy conservation, Galileian invariance and exact self-adjointness property.

All the described simulations are for simplicity in $s-\alpha$ geometry.

2. LINEAR GROWTH RATES

Unfortunately, there are no reasonably simple fluid equations available that could model drift instabilities self-consistently up to second order in the gyro radius (even not [6]). (Note that the plasma response to a given
FIG. 1. Figure a and b, show the growth rate (black) and real frequency (red) of a CGYRO (solid) and NLET (dashed) linear eigen modes as a function of poloidal wave number for ballooning at the outboard midplane and, respectively, parameters $q = 31.8, R/L_n = 25, v_{ei} = 36.6 \sqrt{T_e/m_i}/R, T_i/T_e$ = 0.1 (resistive ballooning, no temperature gradients) and $q = 3.2, R/L_n, v_{ei} = 41.5 \sqrt{T_e/m_i}/R, R/L_n = 25, R/L_{Ti} = 75, R/L_{Te} = 0$ (high gradient ITG in core edge transitional regime) for a very slender tokamak $\epsilon \to 0$.

The electromagnetic field may be described up to second order in gyro radius, but a self-consistent solution requires even higher order due to the near ambipolarity of ion and electron fluxes.) A requirement for the comparison between kinetic and fluid equations is therefore to study non-marginal situations with large scale turbulent modes. For the resistive ballooning regime it turned out that a good starting point consists of low ion temperature ($T_i \sim 0.1T_e$) to reduce Larmor radius effects, low diamagnetic drift frequency compared to the ballooning frequency ($\alpha_d \sim 0.1$ in ballooning units [4]) and relatively high safety factor $q \sim 31$, which reduces the required ion collision number for the given $\alpha_d$ – otherwise the classical perpendicular ion diffusion can become significant in this parameter range. (The effect of the collisions on the ballooning growth rate is proportional to $v_{ei}q^2$.) To rule out trapped particle effects, a slender tokamak with $\epsilon \to 0$ is simulated.

Figure 1a shows a comparison of the growth rate and real frequency of the fastest growing ballooning modes with ballooning angle 0. At small wavenumbers $k\rho_i \lesssim 0.3$ ($\rho_i := \sqrt{T_e/m_i}/(eB)$) a near perfect match between the kinetic and fluid framework is obtained.

Similarly in the high gradient ITG regime relevant to the core-edge transition regime a match is obtained for low wavenumbers, while for higher wave numbers $k\rho_i > 0.3$ a transition to a different mode branch is observed in the kinetic case (fig. 1b).

Even though for high wavenumbers the linear modes are different between the kinetic and the fluid simulations, it is expected that nonlinear runs will show similar behavior, as the high mode numbers should be quenched according to the mixing length argument since their effective diffusion rate of the modes compared to the growth rate $Dk^2/\gamma$ will be smaller than the one of the small wave numbers.

3. NONLINEAR RUNS

As an example for the nonlinear cases, the following figures compare cross-sections for the density perturbations in fully developed turbulence. Also for the fully developed turbulence the amplitude, pattern, time- and length-scales of the turbulence are on the same order, whereby the agreement is clearly better for the ITG case than for the ballooning one (even though the linear agreement is better for the ballooning case). E.g., the gyro-Bohm particle diffusivities in the ballooning case are $\chi_{CGYRO} = 412, \chi_{NLET} = 266$ (in units of $\rho_i^2c_i/R$). The cross ion and electron heat diffusivities approximately 3/2 times that, $\chi_{CGYRO}^Q = 657, \chi_{NLET}^Q = 379, \chi_{CGYRO}^eQ = 574, \chi_{NLET}^eQ = 378$.

For the resistive ballooning simulation run in the edge regime the density fluctuations are shown in figure 2 for CGYRO (a,c) and the NLET code (b,d). In both cases the fluctuations are similarly scaled. Important are the fluid-like Kelvin-Helmholtz plumes visible in both cases, which is very different from the collisionless turbulence, which exhibits a strongly dispersive behaviour and correspondingly much more diffuse and random looking
perturbations. Due to small temperature gradients the temperature fluctuations are unimportant.

For the high gradient ITG core-edge transitional regime (parameters as in fig. 1) the transport coefficients agree within 10%.

The particle transport coefficients $\Gamma/\nabla n$ in gyro-Bohm units ($\rho_i^2 c_s / R$) were $\chi_{CGYRO} = 10.8$, $\chi_{NLET} = 8.8$. The ion heat diffusivities $Q_i/\nabla T_i$ were $D_i^{Q_{CGYRO}} = 23.3$, $D_i^{Q_{NLET}} = 21.5$, and the electron cross heat diffusivity $Q_e/\nabla T_e$ was $D_e^{Q_{CGYRO}} = 4.4$, $D_e^{Q_{NLET}} = 3.6$.

A comparison of instantaneous density and ion temperature fluctuations is shown in fig. 3. In both cases GAMs are excited, which is visible from shearing of the fluctuations. The fluctuations are less fluid like in that they do not show as pronounced Kelvin-Helmholtz-plumes, which is due to the significant drift and dispersion effects. Thirdly, the gyrokinetic dispersion causes a more diffuse look of the gyrokinetic fluctuations, which corresponds to a reduction of the high wavenumbers. However, as mentioned this does not alter the transport strongly.

Several prior results from the fluid code have also been confirmed with the gyrokinetic codes, such as the proper ratio of the excitation of stationary zonal flows to GAMs in the fluid limit, as well as the strong reduction of GAM damping for very high collision numbers.

Certain differences are caused by the collisionless modifications due to trapping. These effects tend to become less
FIG. 3. Figure a and b show the instantaneous density fluctuations for CGYRO and NLET, respectively, at the outboard midplane, figure c and d the ion temperature fluctuations, for a high gradient ITG run with parameters $q = 3.2, R/L_{Te}, v_{ei} = 41.5 \sqrt{T_e/m_i}/R, R/L_{n_i} = 25, R/L_{Ti} = 75, R/L_{Te} = 0$.
important for the high collision numbers often encountered approaching the edge. Lastly, at perpendicular wavelengths of the order of the ion gyroradius there are deviations due to the fluid ion polarizability (if the turbulence saturates by inertial and not other dissipative effects). In principle, this requires correction terms to the fluid ion inertia, but becomes less important in non-marginal situations, where the turbulence is dominated by large scale modes.

All in all, in non-marginal regimes, far from instability thresholds, the results of the fluid code are in a certain agreement with the kinetic results for low and high collision numbers. In the former case, it is because the resonances responsible for fine phase space structures become sufficiently wide to allow a representation by fluid moments of the distribution functions, and in the latter, agreement occurs if the collision operators are accurate enough to reach the proper fluid limit. Surprisingly it is much more difficult to obtain agreement in the latter case.

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