Gyrokinetic Particle Simulation of Microturbulence in Tokamak Plasmas

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Abstract:

Recent progress in gyrokinetic simulations of plasma microturbulence using GTC code is reported. Several topics are covered, including anomalous transport of toroidal angular momentum, simulations in real geometry, validation and verification efforts, and extension of the simulation model to include the magnetic field perturbations. Simulations of momentum transport driven by the ion temperature gradient (ITG) and collisionless trapped electron model (CTEM) turbulence emphasize the important role of particle flux in the momentum convection. Parameter dependence of the momentum pinch is investigated showing strong dependence on the background density gradient. GTC simulations of electromagnetic effects in microturbulence are presented, which include finite- β ITG and kinetic ballooning mode simulation. Initial simulations of plasma edge region are demonstrated as a part of verification efforts. Work is supported by US DOE SciDAC GSEP Center

1 Introduction

Microturbulence plays crucial role in anomalous transport of heat and momentum in tokamak plasmas. The characteristic frequencies of interest are typically much lower than the ion gyrofrequency, which allows us to use gyrokinetic simulations as a powerful tool to study turbulent processes. In this work we report progress in the recent gyrokinetic simulations using GTC code [2]. The following topics are addressed: anomalous transport of toroidal angular momentum, simulations in real geometry and validation and verification efforts, and extension of the simulation model to include the magnetic field perturbations. The gyrokinetic toroidal code (GTC) is a global particle-in-cell code designed to simulate turbulence and transport in burning plasmas with wide range of temporal and spacial time scales. It has successfully demonstrated the ability to simulate both electrostatic (ITG, CTEM, ETG) and electromagnetic (TAE, RSAE, BAE, KBM) modes. To improve the numerical properties the fluid-kinetic hybrid electron model [1] has been adopted which relaxes the electron Courant condition. The model is based on the separation of the electron response into the lowest order adiabatic part treated as a fluid, and higher-order kinetic correction, while the full ion response is treated gyrokinetically.

2 Simulation of toroidal momentum transport

Momentum transport is one of the topics of current interest in fusion research. In general, the radial flux of toroidal angular momentum density (further referred as momentum for simplicity) can be expanded into diffusive, convective and residual components

$$\Gamma_{\phi} = -\chi_{\phi} \partial_r L_{\phi} + V L_{\phi} + S_{\phi}$$

where $L_{\phi} \equiv mRv_{\phi}$, R is the tokamak local major radius, v_{ϕ} is plasma toroidal velocity, and m is the ion mass (m = 1 in our normalization).

Convective and diffusive components of momentum flux are proportional to the momentum and momentum gradient respectively. The convective flux directed inward is often referred to as a pinch. The leftover part of the momentum flux is usually called the residual stress. In our previous studies of the momentum transport using gyrokinetic particle simulation of the toroidal ion temperature gradient (ITG) turbulence with adiabatic [3] and kinetic electrons [4], we have observed the existence of the momentum pinch, and the intrinsic Prandtl number. In this paper we present the comparative studies of the toroidal momentum transport for two electrostatic turbulence regimes: collisionless trapped electron mode (CTEM) and ITG mode with kinetic electrons. All three components of the momentum flux have been studied one-by-one. In order to separate them, first we run simulations of plasma with no background rotation. The momentum flux in this case is purely residual.

The typical radial profiles of the toroidal angular momentum after nonlinear saturation in a plasma with no background rotation are shown in Figs. 1 and 2 for the case of CTEM and ITG turbulence respectively. As we can see, plasma rotation is redistributed within the radial simulation domain, with the volume averaged value staying close to zero. Momentum flux through the boundaries is zero, since all fluctuations are suppressed in the near-boundary region. We observe that rotation direction in corresponding radial locations are opposite in the CTEM and ITG turbulence, leading to the negative (contrcurrent) spinning up of the plasma core in the CTEM case, and positive (co-current) spinning up in the ITG case. It turns out that plasma rotation is well correlated with the self generated radial electric field $-\partial_r \phi_{00}$, shown in dashed line in Figs. 1, 2, where ϕ_{00} is zonal component of the electrostatic potential. Possible explanation could be the partial relaxation to neoclassical state, with turbulence acting as an effective collision operator.

Simulating plasma with rigid rotation provides the convective part, after subtracting the residual flux. The convective flux can be separated into a particle convection and a momentum pinch

$$\Gamma_{\rm conv} = \frac{1}{n} \Gamma_n L_\phi + V_\phi L_\phi,$$

where Γ_n is the particle flux, and V_{ϕ} is the momentum pinch velocity.

Particle convection, mainly determined by the density gradient, is typically outward in our simulations, while the momentum pinch usually has radially inward direction. We observe the particle convective flux to be relatively small in the ITG case (Fig. 3(a)), and much more pronounced in the CTEM cases (Fig. 3(b),(c)). In the case of large density



FIG. 1: Time-averaged radial profiles of toroidal angular momentum (solid line) and self generated radial electric field (dashed line). CTEM case with $R_0/L_{Ti} = 2.2$, $R_0/L_{Te} = 6.9$, $R_0/L_n = 2.2$.



FIG. 2: Time-averaged radial profiles of toroidal angular momentum (solid line) and self generated radial electric field (dashed line). ITG case with $R_0/L_{Ti} = 6.9$, $R_0/L_{Te} = 2.2$, $R_0/L_n = 2.2$.

gradient the particle convection is able to overturn the momentum pinch and switch the direction of the resulting momentum convective flux from inward to outward (Fig. 3(c)).

Finally, considering sheared rotation case allows us to separate the diffusive component. The example of the structure of toroidal momentum flux for the CTEM turbulence is shown in Fig. 4, where we plot the time-averaged radial profiles of the residual (dashed red line), convective (dashed blue line), diffusive (dashed green line), and total (solid black line) toroidal momentum fluxes. For a given rotation profile, $\omega_{\phi} = (0.05 - 0.1r/a)v_i/R_0$, diffusive flux is dominant. The residual flux can be comparable to the total flux locally, but it is generally smaller after volume averaging. Momentum convection is negligible, since the volume averaged angular frequency is chosen to be zero. Similar to CTEM picture is observed in the case of ITG turbulence.



FIG. 3: Time-averaged radial profiles of momentum pinch flux (dashed blue line), momentum convected by particle flux (dashed red line) and total momentum flux (solid black line). Panel (a): ITG case with $R_0/L_{Ti} = 4.5$, $R_0/L_{Te} = 0$, $R_0/L_n = 1$. Panel (b): CTEM case with $R_0/L_{Ti} = 0$, $R_0/L_{Te} = 4.5$, $R_0/L_n = 1$. Panel (c): CTEM case with $R_0/L_{Ti} = 0$, $R_0/L_{Te} = 4.5$, $R_0/L_n = 4.5$. Angular frequency of rigid rotation is $\omega_{\phi} = 0.075v_i/R_0$ for all cases.

3 Electromagnetic gyrokinetic simulation of microturbulence

To verify the electron model used in the GTC we run series of linear simulations using the Cyclone Base Case parameters for the background plasmas. These are $R_0/L_{Ti} = R_0/L_{Te} = 6.9$, $R_0/L_{ni} = R_0/L_{ne} = 2.2$, and $T_e = T_i$. The inverse aspect ratio is $a/R_0 = 0.357$, where R_0 and a are the tokamak major and minor radii respectively. Diagnostic is taken at the radial position r/a = 0.5, where q = 1.4 and $\hat{s} = 0.78$. The simulated system size is $a/\rho_i = 125$. In the simulations all ions are protons. For trapped electrons the higher-order kinetic correction is taken into account using realistic mass ratio $m_e = 5.45 \times 10^{-4} m_p$. We only consider perturbations with fixed toroidal mode number n = 10which corresponds to the fastest growing mode of $k_{\theta}\rho_i = 0.22$.

The verification of the fluid-kinetic hybrid electron model is performed by running simulations with different on-axis electron density, which corresponds to varying β_e . The electrostatic regime represents the limiting case of $\beta_e = 0$. The dependence of the linear growth rate and real frequency is show in Fig. 5. In the left panel of Fig. 5 we can observe the initial reduction of the growth rate as β_e increases, which corresponds to the effect of β -stabilization of the ion temperature gradient (ITG) mode (negative real frequency in the right panel of Fig. 5, corresponding to the ion diamagnetic direction). As β_e approaches zero both real frequency and linear growth rate approach electrostatic limit recovering



FIG. 4: Time-averaged radial profiles of residual momentum flux (dashed red line), convective momentum flux (dashed blue line), diffusive momentum flux (dashed green line), and total momentum flux (solid black line). CTEM case with $R_0/L_{Ti} = 2.2$, $R_0/L_{Te} = 6.9$, $R_0/L_n = 2.2$. Angular frequency of sheared rotation is $\omega_{\phi} = (0.05 - 0.1r/a)v_i/R_0$.

previously published results [6]. The mode has a distinct ballooning structure as shown in Fig. 6. At $\beta_e \sim 1.15\%$ the ITG growth rate becomes equal to the growth rate of the collisionless trapped electron mode (CTEM) which later becomes dominant (switch to the positive real frequency in the Fig. 5). At $\beta_e \sim 1.4\%$ the growth rate of the kinetic ballooning mode (KBM) increases sufficiently to become dominant and another switch in the real frequency sign occurs. The growth rate of the KBM mode continues to increase as β_e further increasing.



FIG. 5: Linear growth rate (left panel) and real frequency (right panel) of $k_{\theta}\rho_s = 0.22$ mode as a function of β_e .

4 GTC simulation of plasma pedestal

GTC simulations in a pedestal region are done using equilibrium parameters of DII-D shot #131997 at time 3011. The original intent is to provide pressure scan for simulation of



FIG. 6: Poloidal snapshot of electrostatic potential (a), and parallel vector potential (b) taken at $\beta_e = 0.5\%$.

kinetic ballooning mode (KBM) onset. Two locations, at the top of a pedestal ($\psi = 0.95$) and in the region of peak gradient ($\psi = 0.98$) are chosen.

GTC "local" simulations (narrow annulus) at the top of the pedestal recovers electrostatic ITG mode (Fig. 7), which is in agreement with local simulations using GEM and GYRO codes.

In the steep gradient region the unidentified electron mode is observed. The mode structure appears to be peaked at $\theta = \pm \pi/2$. Similar mode is observed in GYRO simulations.

For each of two locations multiple cases with varying radial domain size are considered (Fig. 8). It is found that both growth rate and real frequency depend on the domain size, which indicates that nonlocal effects are important.

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FIG. 7: Poloidal mode structure for electrostatic potential at the top of the pedestal



FIG. 8: Real frequency and growth rate as a function of the domain size