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Coupled ITG/TEM-ETG Gyrokinetic Simulations[*] TH-C

J. Candy and R.E. Waltz

General Atomics, P.O. Box 85608, San Diego, CA 92186-5608
email: candy@fusion.gat.com

This work reports on the first realistic numerical studies of small-scale electron-temperature-gradient (ETG) turbulence embedded in large-scale ion-temperature-gradient *plus* trapped-electron-mode (ITG/TEM) turbulence. Results are derived from simulations with the global Eulerian (continuum) gyrokinetic code GYRO [1]. GYRO contains all the physics needed for a physically realistic description of tokamak core transport. Previous GYRO simulations of low-$k_\perp$ ITG/TEM turbulence have reproduced core transport levels in DIII-D L-mode discharges [2] (in the absence of transport barriers) roughly within experimental error. Previous GYRO simulations have also shown that neoclassical ion transport ($k_\perp \sim 0$) is additive to turbulent transport with no significant interaction [3].

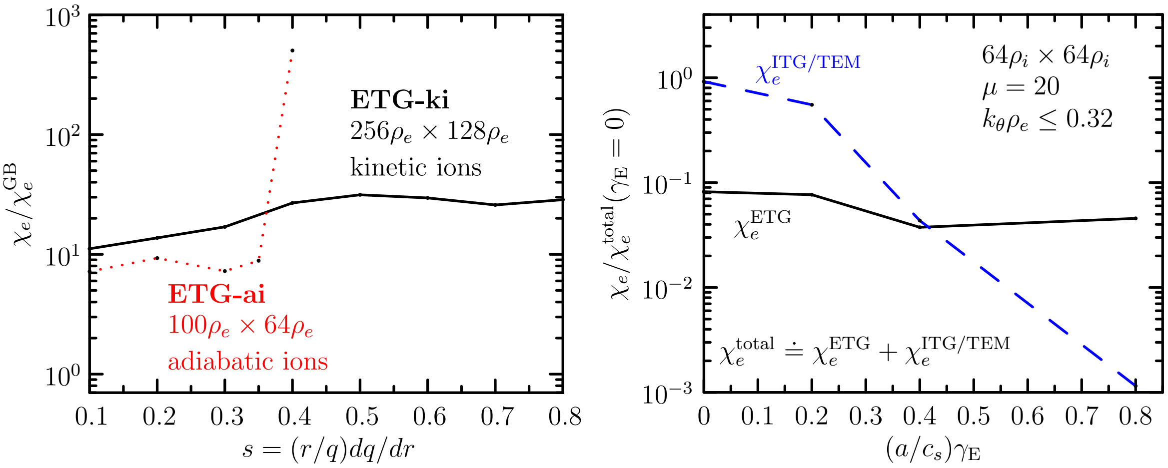

Fig. 1. (a) Small electron-scale-box simulations of the *Cyclone base case*, comparing χ_e computed with the ETG-ai model (dotted red curve) with χ_e computed with the ETG-ki model (black curve) as a function of magnetic shear, s. The diffusivities are total χ_e in electron gyroBohm units. (b) Large ion-scale-box simulations of the *GA standard case* comparing the ITG/TEM (blue dashed curve) and ETG (solid curve) components of the electron energy diffusivity, χ_e, as a function of the equilibrium **E**×**B** shearing rate $\gamma_{\rm E}$. The curves are normalized to the total χ_e at $\gamma_{\rm E} = 0$.

In prior studies, in order to keep the problem numerically tractable, the simulation community has assumed that ions are exactly adiabatic (the so-called **ETG-ai** model) so that high-$k_\perp$ electron transport from ETG effectively decouples from low-$k_\perp$ ITG/TEM transport. However, there has been considerable speculation on the need for nonlinear coupling between ITG/TEM and ETG turbulence [4]. To this end, we have made the necessary modifications and optimizations in GYRO in order to rigorously simulate the ITG/TEM-ETG coupling. Hereafter, we define ETG transport as that which arises from $k_\theta\rho_i > 1$; namely, $\chi_i^{\rm ETG}$, $\chi_e^{\rm ETG}$ and $D^{\rm ETG}$. Analogously, we define ITG/TEM transport as that which arises from $k_\theta\rho_i \leq 1$; namely, $\chi_i^{\rm ITG/TEM}$, $\chi_e^{\rm ITG/TEM}$ and $D^{\rm ITG/TEM}$. In the ETG range, ions are almost exactly adiabatic. To get finite $\chi_i^{\rm ETG}$ or $D^{\rm ETG}$, or to describe ITG/TEM-to-ETG coupling, we require kinetic (nonadiabatic) ions. There are two basic approaches we use to study ITG/TEM-ETG coupling, both employing *fully gyrokinetic ions*: (1) short-scale **ETG-ki** simulations, as in Fig. 1a, reaching up to

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$k_\theta\rho_e \sim 0.75$ but having small electron-scale boxes (e.g. $L_x \times L_y = 256\rho_e \times 128\rho_e$); and (2) long-scale simulations, as in Fig. 1b, reaching only up to $k_\theta\rho_e \sim 0.3$ but having boxes large enough to capture the full ITG/TEM physics (e.g. $L_x \times L_y = 64\rho_i \times 64\rho_i$). Here, ρ_i and ρ_e are the electron and ion thermal gyroradii, where $\rho_i = \mu\rho_e$ and $\mu = (m_i/m_e)^{1/2}$. In a deuterium plasma, $\mu = 60$, whereas for the simulations in this paper we have used $\mu = 20$ (reduced electron mass) to limit the computational cost, which increases slightly more rapidly than μ^3. Our results, briefly summarized, indicate that

1. the ETG-ai model does not always saturate nonlinearly;
2. nonadiabatic (gyrokinetic) ions are required for robust saturated states of χ_e;
3. $\chi_e^{\rm ETG}$ does not significantly add to $\chi_e^{\rm ITG/TEM}$ except when the latter is reduced due to equilibrium $\mathbf{E}\times\mathbf{B}$ shear;
4. ITG can affect ETG (turning on the ITG drive can partially reduce $\chi_e^{\rm ETG}$);
5. there appears to be minimal downward ETG cascade (adding successively higher $k_\perp$ ETG drive does not affect the low-$k_\perp$ ITG/TEM transport).

We now discuss some specific simulation details. Figure 1a shows a magnetic shear scan comparing ETG-ai GYRO simulations (dotted red curve) to ETG-ki simulations (solid black curve) for Cyclone base case parameters. We emphasize that previous simulations of ETG scales (covering $k_\theta\rho_e > 0.3$) have used the ETG-ai model [5]. We also remark that the ETG-ai $s = 0.1$ case has been the subject of a 4-way benchmark comparison [6], for which excellent agreement amongst Eulerian codes (GYRO, GS2, GENE) and a PIC code (PGEQ3) was obtained. Remarkably, GYRO simulations show that saturated states using the ETG-ai model do not exist beyond $s \sim 0.35$. Although PIC simulations have previously found finite saturated values for χ_e at $s = 0.8$, this was shown to be a result of error due to discrete particle noise [7-8]. In contrast to the ETG-ai model, $\chi_e^{\rm ETG}$ obtained using kinetic ions (ETG-ki) does saturate (i.e., when kinetic ion dynamics and correct ion zonal flow physics at $k_\theta\rho_i = 0$ are included). We have defined $c_s = v_i = (T/m_i)^{1/2}$ and $\chi_e^{\rm GB} = \rho_e^2 v_e/a$.

Switching now to large ion-scale boxes, Fig. 1b shows simulations spanning both ETG and ITG/TEM scales. In the absence of $\mathbf{E}\times\mathbf{B}$ shearing ($\gamma_{\rm E} = 0$), $\chi_e^{\rm ETG}$ is less than 20% of $\chi_e^{\rm ITG/TEM}$, and $\chi_i^{\rm ETG} \sim D^{\rm ETG} \sim 0$. However, as shown in Fig. 1b, high-$k_\perp$ ETG transport can still be significant when $\mathbf{E}\times\mathbf{B}$ shear stabilizes the low-$k_\perp$ ITG/TEM transport. At a shearing rate of $(a/c_s)\gamma_{\rm E} > 0.4$, the ETG transport is slightly reduced but can exceed ITG/TEM transport. This result supports the hypothesis that ETG transport is the key electron transport mechanism within an ion transport barrier (ITB). We expect that these conclusions are qualitatively preserved at $\mu > 20$. Simulations to test this are underway.

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