

# Gyrokinetic simulations of ETG and ITG turbulence

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**Abstract:** We report on the resolution of a significant discrepancy between published continuum-code simulations and subsequent global particle-in-cell (PIC) simulations of electron-temperature-gradient (ETG) turbulence. Our investigations, using gyrokinetic  $\delta f$ -PIC- and continuum-code simulations and analytical theory, strongly support the conclusion from the earlier continuum-code simulations that ETG turbulence can drive the electron thermal conductivity  $\chi_e$  large enough to be significant in some tokamaks. A successful ETG-turbulence benchmark between  $\delta f$ -PIC and continuum codes for ETG turbulence has also been completed. Scans in the magnetic shear show an abrupt transition to a high- $\chi_e$  state as the shear is increased from the benchmark value of  $s=0.1$  to above  $s=0.4$ . When nonadiabatic ions are used, this abrupt transition is absent, and  $\chi_e$  reaches values consistent with transport analyses of DIII-D, JET, JT60-U, and NSTX discharges. The balances of zonal-flow driving and damping terms in late-time quasi-steady phase of ITG turbulence have been unfolded using a new run-time gyrokinetic-simulation diagnostic. The zonal flow level is set by a balance of large driving and damping terms which almost cancel each other. The driving is found to be mostly by the Reynolds' stress, while the dissipation is mostly by the linear (transit-time) damping terms. It is also shown that useful zonal-flow-balance information can be obtained with spatially localized samples at as few as four poloidal locations. Real-geometry simulations have been undertaken, using the nonlinear  $\delta f$ -PIC gyrokinetic code SUMMIT/PG3EQ\_NC, of the DIII-D ‘‘Cyclone’’ shot #81499 and of shot #118561, which had broad-wavenumber-range density fluctuation measurements. Real geometry is found to have a significant effect on the transport rates, even though the effect on the linear growth rates is often modest.

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## 1. Introduction

We report on 1) the resolution of disparities between published continuum [1,2] and particle-in-cell (PIC) [3,4] nonlinear gyrokinetic simulations of toroidal electron-temperature-gradient (ETG) turbulence, 2) analysis of sources and sinks of zonal flow in ion-temperature-gradient (ITG) turbulence, and 3) real-geometry simulation of ITG turbulence.

Gyrokinetic continuum-code simulations of ETG turbulence have indicated a sufficiently large value of the electron thermal conductivity  $\chi_e$  to be potentially significant in tokamaks [1,2]. This was cast into doubt by more recent PIC simulations [3,4] which, using similar plasma parameters, gave significantly lower values of  $\chi_e$ . The differences between [1,2] and [3,4] were attributed to insufficient phase-space resolution and novel physics associated with global geometry [3,4]. Refs. [1] and [2] also differ from [3] and [4] in that magnetically trapped particles are eliminated in [1] and [2]

( $r/R = 0$ , where  $r$  and  $R$  are respectively the minor and major radii), but retained in [3] and [4] ( $r/R = 0.18$ ). In section 2, we summarize investigations of the above discrepancy that we have carried out [5,6] using gyrokinetic simulations complemented by analytical theory, of the proposed explanations, and of the more general question of whether ETG turbulence can be important in tokamaks.

Anomalous ion thermal transport in some tokamak discharges [7] is believed to be caused by toroidal ITG and related turbulence. There is now widespread evidence from simulations (see e.g., Refs. [8], [9], and [10]) that zonal flows are a key component in the dynamics of such turbulence. For example, differences in zonal-flow dynamics account for the large difference in normalized transport values between ITG and ETG turbulence [1,2]. (Here, the normalization is to the respective ‘‘gyroBohm’’ level  $\chi_{iGB} = v_{ti} \rho_i^2 / L_{Ti}$  for ITG turbulence, and  $\chi_{eGB} = v_{te} \rho_e^2 / L_{Te}$  for ETG turbulence, where  $v_{ti}$  and  $v_{te}$  are the ion and electron thermal velocities,  $\rho_i$  and  $\rho_e$  are the ion and electron thermal gyroradii, and  $L_{Ti}$  and  $L_{Te}$  are the ion and electron temperature scale lengths.) Several studies to date have addressed the initial generation of zonal flows [11] and the stability of idealized zonal-flow states [12] in ITG turbulence. However, information on the relative importance of different driving and damping mechanisms in the late-time quasi-steady state would greatly add to the understanding the turbulence-zonal-flow system, and is directly accessible in simulations. We have therefore developed a run-time gyrokinetic-simulation diagnostic to extract this information and which has enabled us to unfold the balances of zonal-flow driving and damping terms in late-time quasi-steady ITG turbulence. This diagnostic and its application are discussed in section 3.

Our zonal-flow-balance diagnostic is similar in approach to work by B. Scott [13] and by K. Hallatschek *et al.* [14]. Scott [13] addressed zonal flows in electromagnetic drift turbulence using with a decomposition of the sources and sinks of zonal flow both by physical term and wavenumber. Our diagnostic is integral in wavenumber. A wavenumber decomposition of the sources and sinks in our ITG and ETG simulations will be presented in future work. Hallatschek *et al.* [14] examined zonal flow sources and sinks in drift wave turbulence with a real-space diagnostic which is similar in spirit to ours, but further decomposes the zonal-field sources into a zero-frequency modal component and a geodesic-acoustic-mode (GAM) component. An approximate analogue of this diagnostic may be possible for our kinetic simulations, but is less straightforward than for the fluid system considered in [14]. Reference [14] also focused on terms that were useful for the identification of a  $V_{ii}$  instability as the mechanism for tertiary instability of the zonal flows in the tokamak-edge-relevant regime considered there.

Real tokamak discharge cross sections have significant departures from circularity due to intentional distortions (e.g., elongation and triangularity), and the proximity of divertor X points. This has motivated the development of SUMMIT/PG3EQ\_NC, a real-geometry version of the gyrokinetic code PG3EQ [10]. Some results of applications of SUMMIT/PG3EQ\_NC are presented in section 4.

The simulations shown and discussed in this work are collisionless. While collisions have been shown to be potentially important for ITG turbulence, especially in regimes where collisions damp otherwise undamped zonal flows which strongly limit the transport [15], the effect of collisions is much more modest in cases such as those presented here, where there is robust transport in the absence of collisions.

Conclusions and discussion of the results of this work are presented in section 5.

## 2. ETG turbulence

Simulations were carried out using the flux-tube gyrokinetic  $\delta f$ -PIC code, PG3EQ [10], using the same physical parameters as in [3], [4], and [18], as well as with  $r/R = 0$ . (We refer to these parameters as ‘‘Cyclone-like,’’ since they match those used in the ‘‘Cyclone’’ study reported in [18]). Both sets of

simulations reproduce the key features of the results reported in [3,4] including (1) the first nonlinear-saturation peak in  $\chi_e$ , (2) the rise after this peak shown in Fig. 4 of Ref. [4], (3) the low late-time value of  $\chi_e$  ( $\chi_e \approx 3\chi_{eGB}$  for  $r/R = 0.18$  and  $\chi_e \approx 1.5\chi_{eGB}$  for  $r/R = 0$ ), and (4) the downshift in wave number of the nonlinear spectrum relative to the linear spectrum [4]. Thus, global effects and the parallel nonlinearity [16,17] are eliminated as the cause of the discrepancy between [1] and [2]. The removal of trapped particles (setting  $r/R=0$ ) does not significantly change the time dependence of  $\chi_e$  nor its value in the late-time low- $\chi_e$  state.

We have shown [5], however, that in this low- $\chi_e$  state in both these PG3EQ simulations and those reported in [3,4], discrete particle noise has become large enough to suppress the physical ETG turbulence. Since discrete particle noise is a numerical artifact, it cannot be inferred on the basis of the PIC simulations of Refs. [3,4] that the higher  $\chi_e$  values given by the continuum-code simulations of Refs. [1,2] are incorrect. Other simulation studies [19,20] have shown that global PIC gyrokinetic codes can reproduce the higher  $\chi_e$  values of Refs. [1,2], provided that care is taken to monitor and manage the simulation noise.

The demonstration that the late-time low- $\chi_e$  state in the  $\delta f$ -PIC Cyclone-like ETG simulations is a result of discrete particle noise was facilitated by the development of a theoretical model of the interaction of  $\delta f$ -PIC simulation noise and physical turbulence [5]. This model reproduces the behavior of noise-affected gyrokinetic  $\delta f$ -PIC simulations of both ETG turbulence, in which the noise suppresses the turbulence, and ITG turbulence, where the noise and turbulence coexist and both contribute to the net transport. A key component of this model is a detailed theoretical result for the spectrum of electrostatic potential noise fluctuations in a  $\delta f$  gyrokinetic particle simulation. This result is based on Krommes' calculation of the gyrokinetic noise spectrum [22], extended to include the effects of numerical filtering and finite-size, weighted particles. Spectra from the late-time, low- $\chi_e$  phase of the Cyclone-like  $\delta f$ -PIC ETG simulations show excellent agreement with this noise-based result, indicating that at that time, these simulations are dominated by noise.

We have also shown directly [5] that simulation noise can reduce the linear growth of or completely stabilize the physically unstable ETG modes. Furthermore, the time of maximum amplitude of each mode in our nonlinear  $\delta f$ -PIC Cyclone-like ETG simulations coincides with the time at which its linear growth rate, as modified by the noise diffusion, goes from positive to negative. This strongly suggests that this stabilization is the cause of suppression of the turbulent transport in these simulations.

Gyrokinetic simulation codes are subject to various discretization errors in addition to the simulation noise exhibited by PIC codes. In continuum codes discretization errors in the numerical advection scheme may result in dispersion errors or dissipation that could result in errors in real frequencies or growth rates of modes, and errors in the balances in the nonlinear phase. Careful choices of the phase space meshing can minimize advection related errors by ensuring as much as possible that the mesh is aligned with the directions of advection (e.g., by using coordinates based on constants of the motion or adiabatic invariants [23]). In contrast to the noise in the  $\delta f$ -PIC simulations of Refs. [1], [2], and [5], these errors are not expected to have a secularly growing impact on the dynamical balances in the nonlinear states. The effects of these discretization errors on the linear growth rates in continuum codes have been checked (see [1,2] and references therein, and [23,24]). The need to check that the simulations have successfully reduced these errors to acceptable levels in the nonlinear states motivates nonlinear benchmarks. We therefore undertook a successful inter-code benchmark [6] involving the continuum gyrokinetic codes GYRO [23], GS2 [1,2], and GENE [1,2], and the  $\delta f$ -PIC code PG3EQ [10]. Because all of these codes show strong sensitivity of the results to numerical parameters at the physical plasma parameters used in [3,4], this benchmark was undertaken at an alternate reference point, magnetic shear  $s=0.1$  instead of  $s=0.796$ . This change produces a large (two

orders of magnitude) drop in the heat transport even though the change in the linear growth spectrum is modest. Good agreement was achieved by several measures, with the time-interval weighted standard deviation in  $\langle \chi_e \rangle$  between codes less than that achieved in the Cyclone ITG benchmarking exercise [18].

Scans in the magnetic shear [6] show that as the magnetic shear is increased over the range  $0.1 \leq s \leq 0.35$  average of  $\chi_e$  undergoes only a modest change, from 2.7 to 3.8  $\chi_{eGB}$ . When the magnetic shear is increased further to  $s=0.4$  the electron thermal conductivity takes a dramatic jump to  $\langle \chi_e \rangle = O(100) \times \chi_{eGB}$ . In simulations with PG3EQ at  $s=0.4$  the heat flux rises to track the results from GYRO and GENE before simulation noise suppresses the turbulence.

The magnetic shear scan was repeated, employing GYRO, with the adiabatic ions replaced by full gyro-kinetic ions at a mass ratios of  $m_i/m_e=400$  and 600, with a somewhat larger flux-tube cross-section,  $256\rho_e \times 128\rho_e$ . With kinetic ions the electron heat flux settles down to a modest late-time average value, in the range of 10-14  $\chi_{eGB}$ .

Transport analyses of DIII-D [26], JET [27], JT-60U [28], and NSTX [29] discharges yield  $\chi_e/\chi_{eGB}$  values in the range of 1 to (usually somewhat less than) 25. This is consistent with our ETG simulation results and suggests that ETG turbulence may be responsible for the electron heat transport across thermal barriers and in the L-mode edge of discharges with internal transport barriers.

### 3. ITG turbulence: sources and sinks of zonal flow

The development of the zonal-flow-balance diagnostic for gyrokinetic simulations (of ITG turbulence) proceeds by writing an equation for the rate of change of the zonal-flow  $\mathbf{ExB}$  shear  $V'_{EB}$ :

$$\frac{\partial V'_{EB}}{\partial t} \propto \frac{\partial \langle n_{gi} \rangle_{fs}}{\partial t} = \left\langle \int B d\mu dv_{\parallel} d\theta \frac{\partial \delta f_g(x - \rho \hat{\rho}_x)}{\partial t} \right\rangle_{fs}. \quad (1)$$

Here,  $n_{gi}$  is the gyrocenter density  $\delta f_g$  is the perturbed ion gyrocenter distribution,  $t$  is the time,  $B$  is the magnetic field,  $\mu$  is the magnetic moment,  $v_{\parallel}$  is the parallel velocity,  $\theta$  is the gyrophase angle,  $x$  is the real-space radial position,  $\rho$  is the gyroradius, and  $\hat{\rho}_x$  is the radial component of the gyroradius unit vector, and  $\langle \rangle_{fs}$  denotes a flux surface average. Note that this relationship is accurate to second order in the gyroradius, as are typical finite-Larmor-radius fluid models (e.g., that of Ref. [30]). Higher order terms could be kept if desired either by the insertion of a suitable Pade-based operator (which can be implemented using tridiagonal matrix inversions, as is already done in the zonal field-solver in the PG3EQ code [10]), or simply by viewing  $\langle n_{gi} \rangle_{fs}$  as a useful generalized vorticity quantity given by a positive self-adjoint integral operator acting on  $\langle \phi \rangle_{fs}$ . Upon replacement of  $\partial \delta f_g / \partial t$  using the nonlinear gyrokinetic equation [31,10], each term therein yields a contribution to  $\partial V'_{EB} / \partial t$  that can be identified as a source or sink of zonal flow or zonal flow shear.

The terms associated with the radial gyroaveraged ExB drift flow  $\bar{V}_{EBx}$  can be further decomposed. Thus,

$$\frac{\partial}{\partial x} \left\langle \int B d\mu dv_{\parallel} d\theta V_{EBgx} \delta f_g(x - \rho \hat{\rho}_x) \right\rangle_{fs}, \quad (2)$$

where  $V_{EBgx}$  is the radial ExB drift at the gyrocenter, can be identified as the Reynolds stress. The related term

$$\frac{\partial}{\partial x} \langle \int B d\mu dv_{\parallel} d\theta (\bar{V}_{EBx} - V_{EBgx}) \delta f_g(x - \rho \hat{\rho}_x) \rangle_{fs}, \quad (3)$$

where  $\bar{V}_{EBx}$  is the gyroaveraged radial ExB drift, can be identified with the diamagnetic Reynolds stress [32, 33]. There are several linear terms. One class of terms can be viewed as the divergences of the perturbed  $\nabla B$  and curvature-drift flows (magnetic pumping) or (with the addition of appropriate magnetization currents) the perturbed diamagnetic and neoclassical fluid flows

$$\frac{\partial}{\partial x} \langle \int B d\mu dv_{\parallel} d\theta (V_{\nabla Bx} + V_{cx}) \delta f_g(x - \rho \hat{\rho}_x) \rangle_{fs}. \quad (4)$$

Here,  $V_{\nabla Bx}$  and  $V_{cx}$  are the radial components of the  $\nabla B$  and curvature drifts. Additionally, there are terms for which the gyrocenter density change can be thought of as due the compression of the ExB drift.

$$\frac{\partial}{\partial x} \langle \int B d\mu dv_{\parallel} d\theta (V_{\nabla B} + V_c) \cdot \nabla \phi(x - \rho \hat{\rho}_x) F_M \rangle_{fs}. \quad (5)$$

In the case of the  $\nabla B$ -drift term, this compression is in the direction of  $\nabla B$  due to the decrease of the ExB drift as  $B$  increases. In the case of the curvature drift, this compression is due to the convergence of an ExB drift across a curved magnetic field. Here  $\phi$  is the electrostatic potential, and  $F_M$  is the equilibrium distribution. These terms are nonzero as a result of the velocity dependences of the  $\nabla B$  and curvature drift flows. The above decomposition results in an equation of the form

$$\frac{\partial V'_{EB}}{\partial t} \simeq \sum_i R_i. \quad (6)$$

To facilitate analysis, it is helpful to recast this as an equation for a positive definite scalar quantity. One choice is  $\langle |V'_{EB}|^2 \rangle_x$ , where  $\langle \rangle_x$  represents a radial average, which is the enstrophy associated with the zonal ExB flow. The resulting equation is

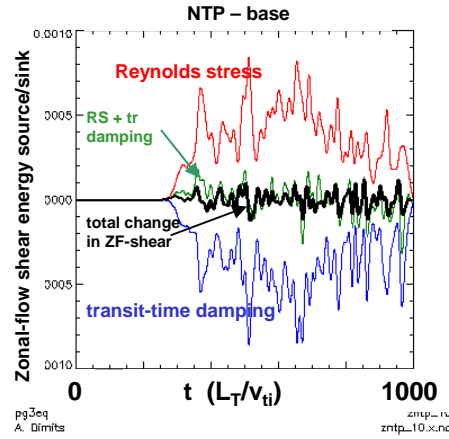
$$\frac{\partial \langle |V'_{EB}|^2 \rangle_x}{\partial t} \simeq 2 \sum_i \langle R_i V'_{EB} \rangle_x. \quad (7)$$

Alternatively, the zonal-flow energy  $\langle |V_{EB}|^2 \rangle_x$  can be used. It can be shown that (e.g., it follows rigorously from the exact form of the gyrokinetic Poisson equation or from the Pade approximation used in PG3EQ [10]) that  $\langle \phi n_{gi} \rangle_x$  is positive definite. This leads to a useful approximate equation for the zonal-flow energy:

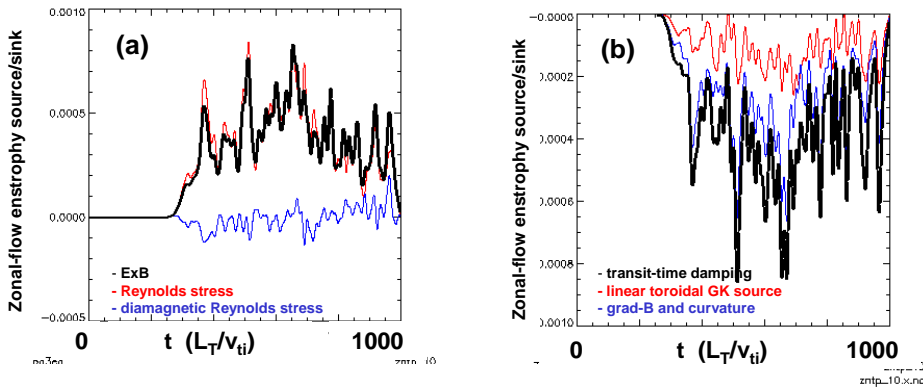
$$\frac{\partial \langle |V_{EB}|^2 \rangle_x}{\partial t} \simeq 2 \sum_i \langle \phi R_i \rangle_x. \quad (8)$$

Each of the  $R_i$ 's contributes a term in Eq. (7) or (8), and is calculated as a profile on the radial mesh in PG3EQ through suitable ‘‘particle deposition’’ operations. The resulting contributions to  $\langle |V'_{EB}|^2 \rangle_x$  in Eq. (7) or  $\langle |V_{EB}|^2 \rangle_x$  in Eq. (8) are then calculated as a postprocess using the GKV analysis package [5] (and the profile of  $\delta n_{gi}$  or  $\phi$ .) It has been carefully verified that the resulting terms do indeed satisfy Eq. (6) to good accuracy (i.e., that the accumulated  $R_i$  terms add to the directly calculated values of  $\partial V'_{EB}/\partial t$ ), and consequently also satisfy Eqs. (7) and (8).

Figure 1 shows the results of applying this diagnostic to the calculation of the terms in Eq. (7) for a PG3EQ simulation using the parameters of [34], with the adiabatic-electron model of Ref. [35] (also used in [8] and [9]). [The terms of Eq. (8) have also been examined and yield qualitatively similar conclusions to those for Eq. (7).] The Reynolds stress contribution [Eq. (2)] is seen to be positive definite and is the main source of zonal flow shear. The linear terms ([Eqs. (4) and (5)], the sum of which is the blue curve) act as sinks. The total rate of change of  $\langle |V'_{EB}|^2 \rangle_x$  is shown as the black curve, while the green curve is the sum of just the Reynolds stress of Eq.(2) and linear terms of Eqs.(4) and (5). That the green curve tracks the black curve well indicates that that the Reynolds stress and linear terms capture most of the contribution. The net imbalance in the early time ( $t=200-300$ ) variation is associated with the initial buildup of the zonal flow. It is clear from the figure that the Reynolds stress and linear damping terms are each much larger than the net rate of change of  $\langle |V'_{EB}|^2 \rangle_x$ , which is the small residual difference between these two terms.



**Figure 1.** Relative contributions to  $\partial \langle |V'_{EB}|^2 \rangle_x / \partial t$  from a PG3EQ simulation using the NTP base case parameters. The red curve is the Reynolds stress term, the blue curve is sum of linear terms, the green curve is the sum of the Reynolds stress and linear terms, and the black curve is the total rate of change of  $\langle |V'_{EB}|^2 \rangle_x$ .



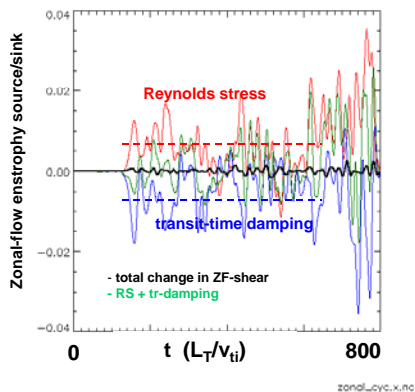
**Figure 2.** Further decomposition of the sources (a) and sinks (b) of zonal-flow enstrophy  $\langle |V'_{EB}|^2 \rangle_x$  from the simulation shown in figure 1.

The sources and sinks are further decomposed in figure 2. The diamagnetic-Reynolds-stress contribution [Eq. (3)] is found to be small, and acts as a weak sink. The linear damping terms have

comparable contributions from the magnetic pumping terms [Eq. (4)] and the ExB-compression terms [Eq. (5)]. This diagnostic has been applied to and the same conclusions reached for a variety of PG3EQ simulation cases, including several points in temperature-gradient scans about the Cyclone parameter set [18] and the “NTP” parameter set [34].

We note that the present diagnostic does not distinguish between the zero-frequency zonal-flow and geodesic-acoustic-mode (GAM) contributions (see, e.g., Ref. [14]). In the future, we plan to extend these calculations to the first sinusoidal components (in poloidal angle) of relevant fields and flows. It is seen from Figs. 1 and 2 that the Reynolds stress source has a significant steady mean squared value in addition to the fluctuating component. The linear collisionless damping present in these simulations [represented by Eqs.(4) and (5)] acts through the GAM’s only. The zero-frequency component is undamped (as was verified e.g., in Ref [18]). The decay of the zonal flows likely has a nonlinear component associated with tertiary instabilities. The present diagnostic does not extract this effect, but lumps it in with the Reynolds-stress sources of Eqs.(2) and (3).

We have also extended this analysis to provide guidance for experimental fluctuation diagnostics, which are typically able to measure fluctuations in a spatially localized region rather than an entire flux surface or even a flux-surface ring (spanning a poloidal circuit and a small range of toroidal angle). It is found that 4 poloidally localized samples are sufficient, and appear to be necessary, to provide a resolution of the zonal-flow shear sources and sinks. An example of this is shown in figure 3. Using 8 poloidal samples improves the quality of the time traces of the sources and sinks over 4 samples. Attempts have been made with 2 poloidally localized samples at various poloidal locations. These give traces for the either the net linear or nonlinear contribution, or both, that do not have a measurably nonzero average.



**Figure 3.** Relative contributions to  $\partial(|V'_{EB}|^2)_x / \partial t$  from a simulation using the same parameters as for that shown in figure 1, but with the quantities calculated by sampling at four poloidal locations (outer and inner midplane and top and bottom).

Some interesting results have been obtained from investigations of zonal-flow dynamics and the application of the above diagnostic to ETG turbulence simulations (carried out with PG3EQ): (1) In the Cyclone-like  $s=0.8$  cases in which the transport rises to large values, it has been found that this tendency for  $\chi_e$  to rise to large values goes away if the zonal potential ( $\mathbf{ExB}$  flow) is removed. The cause for this counterintuitive result is under investigation. (2) Restarts during the  $\chi_e$  rise phase with the zonal potential set to zero result in a cessation of the rise. (3) For the  $s=0.1$  benchmark case, which does reach a reasonably robust steady state, the zonal-flow balance dynamics differs significantly from that in ITG simulations. The Reynolds’s stress is still found to be a source, but it is compensated by the diamagnetic Reynolds’ stress so that the net contribution of the gyroaveraged ExB drift

$$\frac{\partial}{\partial x} \left\langle \int B d\mu dv_{\parallel} d\theta \bar{V}_{EBx} \delta f_g(x - \rho \hat{\rho}_x) \right\rangle_{fs}$$

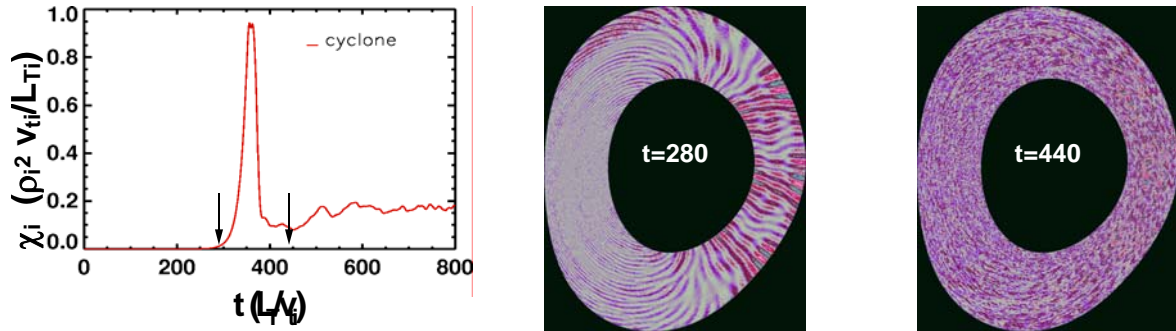
is small. Additionally, the compression of the radial  $\nabla B$  and curvature-drift fluxes [Eq.(4)] acts as a source, while the linear toroidal compression term [Eq.(5)] acts as a sink of zonal flow energy and enstrophy. The linear terms negate each other as do the nonlinear terms.

#### 4. ITG turbulence: real-geometry-tokamak gyrokinetic simulations

SUMMIT/PG3EQ\_NC is a nonlinear  $\mathcal{J}^2$ -PIC gyrokinetic code which implements real geometry using the quasi-ballooning representation [10] of the field quantities. It has been interfaced to DIII-D equilibrium analyses from the EFIT [36], ONETWO [37], and PLOTEQ [38] codes.

Verification of PG3EQ\_NC has been carried out by comparing it in detail to the earlier circular-cross-section gyrokinetic code PG3EQ [10]. Agreement to roundoff for many time steps, and across different parallel domain decompositions has been obtained when the initial loading and equilibrium are identical.

Real-geometry PG3EQ\_NC simulations have been undertaken of toroidal ITG instability growth and turbulence using equilibria from several DIII-D shots including shots #81499 and #118561. The electrons were treated with the adiabatic-electron model [8,9,35]. Simulations using “circularized” equilibria with parameters set to the radially local poloidally averaged values or appropriate sinusoidal approximations from the actual equilibria are also shown below and discussed for comparison. This circular-equilibrium approximation is discussed in Ref. [18], in which a circularized version of DIII-D shot #81499 was used as the basis for the “Cyclone” ITG turbulence simulation comparison. Shot #118561 was part of a recent DIII-D campaign in which broad wavenumber range density fluctuation measurements were performed. This range includes wavenumbers from  $\sim 0.7 \text{ cm}^{-1}$  to  $35 \text{ cm}^{-1}$  ( $k\rho_s \approx 0.2 - 10$ ), covering the range of ITG, and ETG instabilities. Plasma instabilities were excited by using short duration neutral beam blips to modify the plasma parameters from a low-transport ohmic state. These perturbations modified the background temperature and density as well as the density fluctuation behavior. The measured response to these perturbations varied with wavenumber, supporting the need for broad wavenumber comparisons including both the ITG and ETG range of wavenumbers.



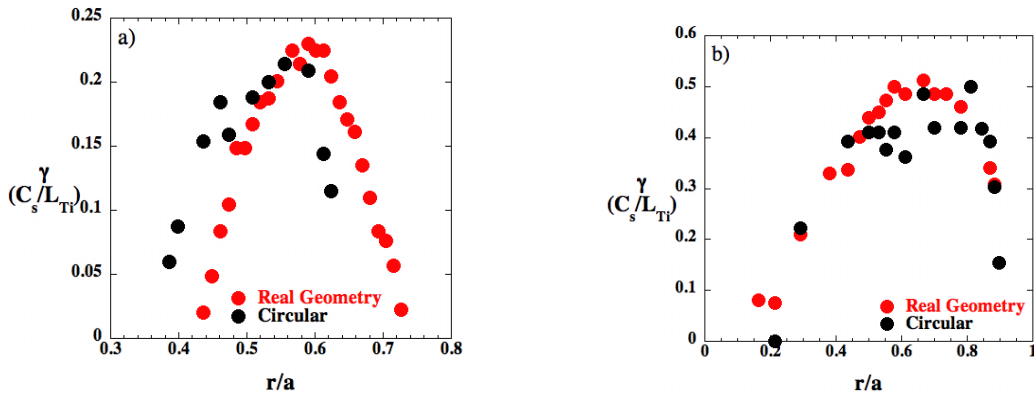
**Figure 4.** Time history of  $\chi_i$  and images of the electrostatic potential in a poloidal section from a PG3EQ\_NC simulation using a real DIII-D equilibrium from EFIT and ONETWO analyses of shot #81499 at  $t=4000\text{ms}$ , and  $r/a=0.509$ . The simulation times for the electrostatic potential plots in the simulation are  $t=280$  and  $440 L_{Ti}/c_s$ .

Figure 4 shows the time history of the ion thermal transport and images of the electrostatic potential  $\phi$  on a poloidal section from the ITG simulations using PG3EQ\_NC and equilibria from EFIT and ONETWO analyses for shot #81488 at  $t=4000\text{ms}$ . These simulations show the expected linear ITG instability growth and saturation. The maximum linear growth rate for the case shown in figure 4 is very close to that for the corresponding circularized case [figure 5(a) at  $r/a=0.5$ ], while the late-time ion thermal transport level is reduced to less than half of that for the circularized case. This case was



run with a 128x128 (perpendicular) x 64 mesh, with an outboard-midplane perpendicular grid cell size of  $0.9817\rho_i$ , and 16 particles per cell. Convergence tests indicated that higher parallel resolution is needed for the noncircular case than for the corresponding circularized cases, primarily because of the somewhat sharper poloidal variation of the local magnetic shear and the curvature components as a function of poloidal angle. This sharper variation leads to stronger poloidal localization of the turbulence, which may be a key factor in the reduction of  $\chi_i$ . The zonal-flow intensity and mean shearing rate undergo a modest reduction (a factor of 0.6-0.8), so it appears unlikely that the change in the zonal flow properties is a cause of the reduction in  $\chi_i$ .

Figure 5 shows profiles of maximum ITG growth rates vs. minor radius from PG3EQ\_NC simulations using real DIII-D equilibria and circularized equilibria from shot #81499 and shot #118561. There is some jumpiness in the growth-rate profiles for the circular-geometry cases, which is present because the box size was not optimized for every case to capture the most unstable mode exactly. Despite this variability in the circular cases, some conclusions can be drawn. The shot-#81499 cases show a modest systematic effect of shaping, with the real-geometry growth-rate profile  $\gamma(r)$  shifted slightly outwards relative to the circular case. The shot #118561 cases show very little effect of shaping on the maximum growth rates. Examination of the local equilibrium parameters indicates that the toroidal ITG modes become stable at large minor radius primarily because the magnetic shear becomes large. At small minor radius, the growth rates become small because the temperature gradient becomes small causing the dimensionless parameters  $R/L_{Ti}$  and  $\eta_i=L_{ni}/L_{Ti}$ , where  $L_{ni}$  is the ion density gradient scale length, to fall below marginal values.



**Figure 5.** Maximum ITG growth rates (in units of  $c_s/L_{Ti}$ ) vs. minor radius from PG3EQ\_NC simulations using real DIII-D equilibria (red) and circularized equilibria (black) from (a) shot #81499 at  $t=4000\text{ms}$  and (b) shot #118561 at  $t=1450\text{ms}$ .

Presently being undertaken are (a) a comparison of these  $\gamma(r)$  profiles with results from the GKS code [31], and (b) larger nonlinear simulation runs for that will yield  $\chi_i$  profiles for both of the discharges studied here.

## 5. Summary and conclusions

We have reported progress on understanding three aspects of ETG and ITG turbulence obtained using nonlinear gyrokinetic simulations.

We have carried out an investigation, using both PIC and continuum simulations as well as analytical theory, of the discrepancy between previous continuum-code [1,2] and global-PIC [3,4] gyrokinetic simulations of ETG turbulence. This investigation strongly supports the conclusions of the earlier

continuum-code simulations, that levels of the electron thermal conductivity  $\chi_e$  are large enough to be significant in some tokamaks.

A successful benchmark between PIC and continuum codes for ETG turbulence has been completed. Because both PIC- and continuum-code ETG simulations at the plasma parameters used in [1,2] and [3,4] produce very large intermittent transport and strong sensitivity of the results to numerical parameters, this benchmark was undertaken at an alternate reference point, magnetic shear  $s=0.1$  instead of  $s=0.796$ . At this more tractable benchmark point, good agreement was achieved, with the time-interval weighted standard deviation in  $\langle\chi_e\rangle$  between codes yielding an error in our estimate of the mean of less than 10%. This is better than was achieved in the Cyclone ITG benchmarking exercise [18]. Scans in the magnetic shear show an abrupt transition to a high- $\chi_e$  state as the shear is increased above  $s=0.4$ , and good agreement between codes in tracking this trend. When nonadiabatic ions are used, this abrupt transition is absent, and  $\chi_e$  increases gradually reaching values consistent with transport analyses of DIII-D, JET, JT60-U and NSTX discharges.

The balances of zonal-flow driving and damping terms in late-time quasi-steady phase have been unfolded using a new run-time gyrokinetic-simulation diagnostic. This investigation contrasts with most previous zonal-flow generation and damping studies, which mostly addressed either the early-time onset of the zonal flows or otherwise transient behavior evolving from a simplified initial state, and is important because zonal flows play a key role in regulating toroidal ITG turbulence and transport in the nonlinear phase of the simulations. The zonal flow level is set by a balance of large driving and damping terms which almost cancel each other. The driving of the zonal flows was found to be mostly by the Reynolds' stress, while the dissipation is mostly by the linear (transit-time) damping terms. An issue affecting the viability of applying such a diagnostic directly to experimental data has been addressed by showing that in the simulations, useful zonal-flow-balance information can be obtained with spatially localized samples at as few as four poloidal locations.

Finally, studies of the effect of real geometry on ITG turbulence using SUMMIT/PG3EQ\_NC, a real-geometry version of our nonlinear  $\delta f$ -PIC gyrokinetic code PG3EQ, were reported. Real DIII-D equilibrium reconstruction data from EFIT, ONETWO, and PLOTEQ-code analyses are used. The simulations completed so far show modest effects of real geometry on the maximum linear growth rate profiles, but some reduction in the thermal transport levels in the late-time nonlinear state compared with the circularized cases.

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