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Zonal Flow Measurements Concept I.

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Abstract

We study the characteristics of self-generated zonal flows as observed in nonlinear global gyrokinetic simulations of toroidal ITG turbulence for typical parameters of DIII-D core plasmas, and discuss various possibilities for experimental measurements and the development of new diagnostics.

I. Introduction

$\mathbf{E} \times \mathbf{B}$ shear suppression of turbulence is well known to be responsible for various forms of enhanced confinement regimes[1]. Previous nonlinear decorrelation theory[2], and its generalization to toroidal geometry[3, 4] considered the macroscopic radial electric field shear which varies much slower than turbulent eddy turn-over time as observed in the experiments.

On the other hand, recent global gyrokinetic simulations of ITG turbulence with accurate description of flow damping[5, 6] observe that fluctuating small scale $\mathbf{E} \times \mathbf{B}$ shear flows can be generated by turbulence and regulate turbulence in return, affecting the transport level significantly. This is qualitatively similar to previous simulation results in flux-tube domain including early gyrofluid simulations[7]. Experimental measurements of zonal flows will, therefore, contribute to our progress in finding ways to control transport. In Sec. II.,we summarize the characteristics of zonal flows observed in gyrokinetic simulations of toroidal ITG turbulence. Possibilities of measuring features of turbulent fluctuation which are induced by zonal flows are discussed in Sec. III.

II. Properties of Zonal Flows in ITG Turbulence

Zonal flows are radially localized ($k_r a >> 1$), axisymmetric ($k_\phi = 0$), and mainly poloidal $\mathbf{E} \times \mathbf{B}$ flows, $\mathbf{u_E}$. Since k_θ of the electrostatic potential associated with zonal flows is also zero, there is no radial motion associated with them and zonal flow cannot tap the expansion free energy associated with radial gradient of pressure. Therefore, they are linearly stable, and can only be excited through nonlinear process such as Reynolds' stress[8] associated with inverse cascade of the turbulence[9]. Fig. 1. shows a time history of the radial shear of the turbulence driven zonal flows from gyrokinetic simulations. The flow spectrum is broad and contains components with radial scale and frequency comparable to those of the turbulence. If we take a snap shot at one time of this plot, we obtain the radial structure of the instantaneous $\mathbf{E} \times \mathbf{B}$ shearing rate associated with the zonal flow. By integrating once radially, we obtain the radial structure of $\mathbf{E} \times \mathbf{B}$ flow plotted in Fig 2(a). We can observe that small scale (around several ion gyro-radii) structures are super-imposed on larger scale (fraction of system size) radial variations. Fig 2(b) shows that the instantaneous $\mathbf{E} \times \mathbf{B}$ shearing rate is dominated by the high k_r components which also have high frequency. The peak value of the instantaneous shearing rate which varies in radius and time is much higher than the maximum linear growth rate shown by horizontal lines. Previous gyrokinetic simulations[5] have shown that inclusion of such turbulence-driven small scale zonal flows lead to substantial reduction of ion thermal diffusivity. However, turbulence is not totally suppressed, and ion thermal transport is still anomalous.

This may appear somewhat puzzling since many tokamak groups[1, 10–16] have continued reporting that their plasmas make transition to enhanced confinement regimes when the equilibrium $\mathbf{E} \times \mathbf{B}$ shearing rate[4] exceeds the linear growth rate of microinstabilities. To understand this qualitative difference between the nonlinear simulation results with fluctuating zonal flows and the experimental results regarding the equilibrium $\mathbf{E}\times\mathbf{B}$ flows, we have considered a model problem[17] in which we assumed that the potential for zonal flow is a flux function, but varies sinusoidally in time with a characteristic frequency ω_f. We have shown that fast time varying components of zonal flows are less effective in shearing turbulence eddies. The fundamental reason for this is that the zonal flow shear pattern changes (recall Fig. 1) before the eddies can be completely torn apart. The turbulent eddies can then recover some of their original shape, and the shearing effect is reduced. An effective shearing rate including this effect has been derived analytically and compared favorably with gyrofluid simulations[17].

Our gyrokinetic simulations show significant broadening of the k_r spectrum due to zonal flows[17] as can be deduced from turbulence eddy shape in nonlinearly saturated state[5]. These are in qualitative agreements with our analytical prediction which involves the effective shearing rate. This analysis shows that for typical core plasma parameters, zonal flows associated with high frequency ($\sim v_{Ti}/R$) Geodesic Acoustic Mode (GAM) oscillations is not a dominant contributor to the shearing effect. A statistical theory based on drift wave kinetics in random media consisting of an ensemble of zonal flows[18] also predicts broadening of k_r spectrum by random refraction.

In summary, gyrokinetic simulations of toroidal ITG turbulence for typical core plasmas of DIII-D tokamak exhibit the following characteristics of self-generated zonal flows:

i) $u_E/v_{T_i} \simeq u_\theta/v_{T_i} \leq 10^{-2}$ such that u_E could be as large as diamagnetic velocity due to the equilibrium pressure gradient although there has been no systematic studies on parameter dependences. Turbulence does not generate significant parallel flows $u_{||}$. In simulations, toroidal flows u_ϕ are conserved in time. Therefore, $u_{||} \simeq \frac{B_\theta}{B} u_E$. In the short term zonal flow autocorrelation time scales (explained shortly), we expect the impurity poloidal velocities induced by zonal flow to be the same as the main ion poloidal velocities. In the absence of turbulence drive, the poloidal flow will be eventually damped on the neoclassical time scales[19].

ii) $u_E(k_r)$ peaks at $k_r\rho_i \simeq 0.1$ with a broad width $\Delta k_r \rho_i \simeq 0.5$ as shown in Fig. 3a. Radial scales of zonal flows range from a fraction of system size to several ion gyroradii.

iii) $u_E(\omega)$ at fixed k_r peaks at $\omega = 0$ with a width $\Delta\omega^{ZF}/2\pi \sim 5kHz$ which is the autocorrelation frequency of zonal flows as shown in Fig.3b. Another peak at higher frequency corresponds to GAM. However, the shearing effect due to GAM is expected to be small for typical tokamak core plasma parameters[17]. We note that $\delta n_e^{ZF} = 0$ for ITG models with proper adiabatic electrons[20, 21].

Since $\delta n_e^{ZF}/n_0 << e\Phi^{ZF}/T_e$ is expected for typical core plasmas, it would be advantageous to directly measure either the flows (e.g., with Charge Exchange Recombination Spectroscopy) or the associated radial electric field (e.g., using the Motional Stark Effect). However, achieving the time resolution needed to distinguish the fluctuating component from the equilibrium $\mathbf{E}\times\mathbf{B}$ flows is a challenge.

III. Effects of Zonal Flows on Ambient Turbulence and Transport

Since it may not be feasible to measure the zonal flows directly in the core plasma using present diagnostics capabilities, it will be useful to look for signatures of zonal flows on the ambient turbulence. One idea is to identify the fluctuating component of the zonal flow from the modulated Doppler shift of short scale fluctuation measurements. This method can be applied to any diagnostic measurement. It is important to remember that at least three different time scales are involved in the zonal flow-ambient ITG turbulence system. As stated in the preceding section, zonal flow amplitude could reach up to $10^{-2}v_{Ti}$, inducing significant Doppler-shift of the ambient turbulence frequency spectrum. For instance, we expect $\mathbf{k}\cdot\mathbf{u_E} \leq 100kHz$ for $k_\theta \simeq 2cm^{-1}$, $u_E \simeq 3.10^5 cm/sec$. This is typically larger than the intrinsic decorrelation rate of the ambient turbulence in the plasma frame, $\Delta\omega_T$. Taking $\Delta\omega_T$ to be of the order of the toroidal ITG linear growth rate, $\Delta\omega_T \sim k_\theta\rho_i v_{Ti}/\sqrt{RL_{Ti}}$, we expect the zonal flow induced Doppler-shift $\mathbf{k}\cdot\mathbf{u_E}$ to be larger than the frequency broadening of the ambient turbulence $\Delta\omega_T$ when $u_E/v_{Ti} > \rho_i/\sqrt{RL_{Ti}}$. Finally, since the zonal flow amplitude changes with the autocorrelation rate $\Delta\omega^{ZF}$, it will slowly modulate the ambient turbulence spectrum with $\Delta\omega^{ZF}$ which is typically lower than $\Delta\omega_T$. In summary, for typical tokamak core plasma parameters, we expect

$$\Delta\omega^{ZF} < \Delta\omega_T < \mathbf{k}\cdot\mathbf{u_E}.$$

Since $k_\theta = k_\phi = 0$ for the potential associated with zonal flows, one would expect that the zonal flows will affect turbulence on the same flux surface in the same way regardless of its poloidal or toroidal location[22]. From poloidally or toroidally displaced (much greater than the ambient turbulence correlation length in each direction) density fluctuation measurements, one could look for the correlation properties which are induced by zonal flows. Possibilities include the correlation in the shift of turbulence frequency spectrum mean from tangential imaging of D_α light[23], or in the fluctuation phase velocity from reflectometry[24]. These ideas will be tested first in the gyrokinetic simulations, also addressing required radial resolution and the effects of advection due to mean $\mathbf{E} \times \mathbf{B}$ flow.

Another way to systematically demonstrate the effects of zonal flows is to change plasma parameters in such a way as to change the zonal flow intensity without introducing changes in the instability drive, and show the agreement between experiments (from Beam Emission Spectroscopy) and theory (from gyrokinetic simulations with collisions) of ambient turbulence spectra of k_r and k_θ. This seems feasible with existing diagnostics and simulation capabilities. It is desirable to have data from systematic nondimensional scans of plasmas, especially a ν_* scan, since a realistic level of ion-ion collisions at core plasma will affect only the zonal flow damping, not the ITG or Trapped Ion Mode linear growth rate[6]. As the ion-ion collsions are increased with other parameters fixed in gyrokinetic simulations, the decrease in zonal flow amplitude and increase in ion thermal transport have been observed. Increase in ion thermal transport is in qualitative agreements with trends from ν_* scan of DIII-D H-mode plasmas[25]. Collisional damping of zonal flows seems responsible for this trend. It is also useful to note that bursty behavior of density fluctuations with a period close to collisional damping time of flows has been also observed in simulations near ITG marginality[6]. The observed bursting period ($\sim 3ms$) in TFTR Reversed Shear plasmas[10] is also close to the collisional damping time of zonal flows. Bursting behavior in the experiments[10, 16] could be used for zonal flows studies since it naturally exhibits both the high zonal flow-low ambient turbulence state and the low zonal flow-high ambient turbulence state, and thus facilitates the scalings studies in simulations without a need for changing the equilibrium profiles.

It is sometimes convenient to consider a turbulence plasma as a self-regulating two component system consisting of the usual ambient ITG turbulence and $(k_\phi, k_\theta) = (0, 0)$ component which is zonal flow. Since zonal flow cannot tap the expansion free energy directly, the energy lost by turbulence by random shearing is gained by zonal flows. Although we usually discuss each process independently, duality of random shearing and flow generation is just a statement on the nonlinear mode coupling, specifically a distant interaction between finite k_θ and zero k_θ modes[18]. Therefore, a bi-spectral analysis of fluctuation data[26] could be useful in demonstrating the existence of zonal flows[27].

IV. Zonal Flows in Edge Turbulence

While we have discussed zonal flows in the context of ITG drift turbulence in core plasmas in the preceding sections, ITG may not be a relevant turbulence paradigm for the edge plasmas (at most a few centimeters inside the last closed flux surface) of present day tokamaks. At the edge, sharp pressure gradients make the diamagnetic drift frequency at the relevant long wavelength closer to the GAM frequency[28]. Therefore, the GAM could possibly affect the ambient turbulence. However, many generic qualitative properties of zonal flows which we have discussed should remain valid for the edge turbulence. In the last few years, there have been considerable advances in edge turbulence simulations using Braginskii equations[29, 28]. More emphasis on zonal flow dynamics (including dependence on the flow damping) would provide useful information on possible measurements of zonal flows at the edge. The line-integrated density fluctuations measurements at DIII-D edge via Phase Contrast Imaging[30] seem to be related to zonal flows, although it remains to be demonstrated that $k_\theta = k_\phi = 0$ for the fluctuations. For this, from poloidally or toroidally displaced (much greater than the ambient turbulence correlation length in each direction)potential measurements via langmuir probes[31, 23], one could look for strong correlations.

Acknowledgments

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[22] To be more precise, the potential $\Phi(\psi)$ is a flux function. Flux expansion due to finite aspect ratio, or Shafranov shift, or plasma shaping makes $\mathbf{E}\times\mathbf{B}$ flow and the shearing rate vary on the same flux surface. As discussed in Ref.4, if $k_\theta \simeq k_r$ for ambient turbulence, the equilibrium $\mathbf{E}\times\mathbf{B}$ shearing rate becomes larger at the large major radius side compared to the small major radius side at the same flux surface. This leads to a plausible explanation of an in-out asymmetry in fluctuation suppression behavior in DIII-D as discussed in Ref. 16.

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Figure Captions

1. $\mathbf{E} \times \mathbf{B}$ shearing rate, $\frac{du_E}{dr}$ of turbulence generated zonal flow from gyrokinetic simulation is plotted. Note significant components with spatio-temporal scales comparable to those of the turbulence.

2. Instantaneous zonal flow amplitude (a), and instantaneous $\mathbf{E} \times \mathbf{B}$ shearing rate (b), associated with zonal flow from gyrokinetic simulation are plotted. In (b), instantaneous shearing rate is dominated by high k_r components. maximum linear growth rate is drwan in horizontal lines.

3(a). k_r spectrum of zonal flow intensity $S \propto |u_E|^2$ from gyrokinetic simulation is plotted.

3(b). Frequency spectrum of zonal flow intensity S at fixed $k_r \rho_i$ from gyrokinetic simulation is plotted. Note peaks at zero frequency and at GAM frequency $\sim v_{Ti}/R$.

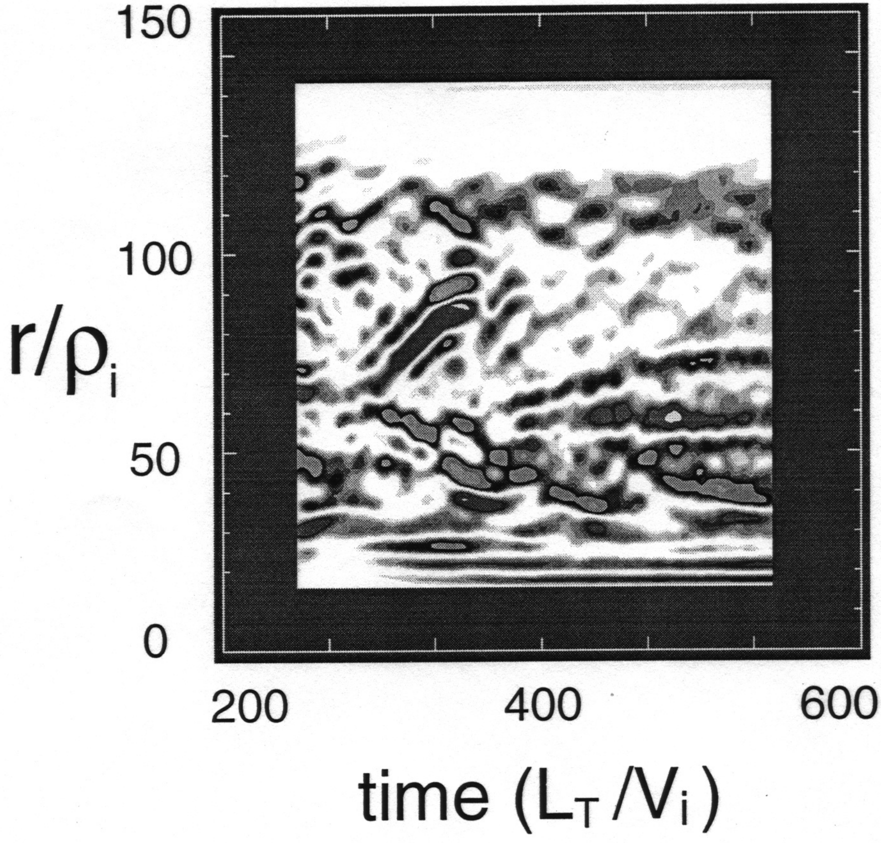

Figure 1: Hahm

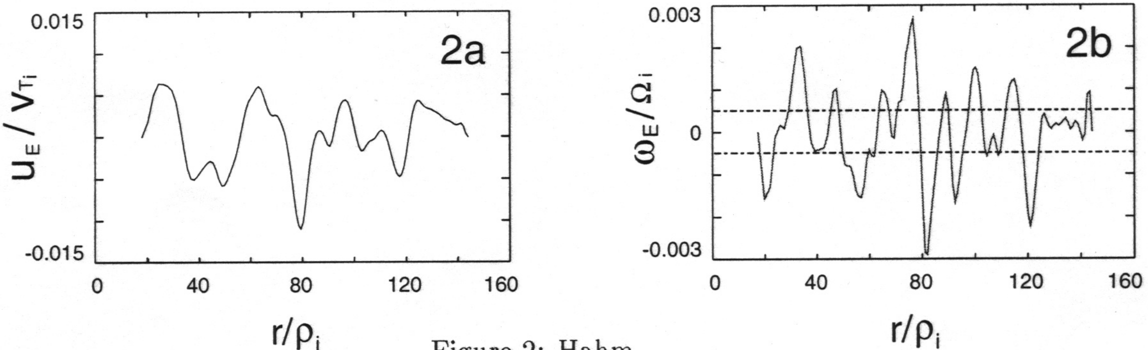

Figure 2: Hahm

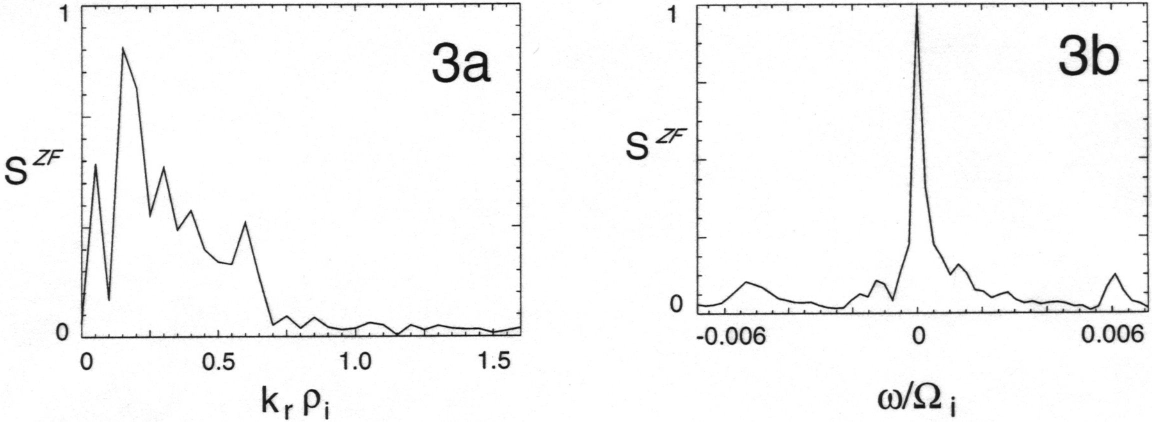

Figure 3: Hahm