Characteristics of Turbulence Driven Multiple-Channel Transport in Tokamaks, and Comparison with Experiments

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While plasma transports of energy, momentum and particles in tokamaks are usually all anomalous, there exist considerable differences in the underlying turbulence dynamics which drives them. New features of toroidal momentum and energy transport found from our gyrokinetic simulations are reported in this paper with emphasis on non-diffusive characteristics.

An optimized plasma flow is believed to play a critical role in both controlling macroscopic plasma stability, and in reducing energy loss due to plasma microturbulence. Understanding the non-diffusive momentum transport mechanisms and the intrinsic rotation phenomenon is a key to predicting plasma flow, particularly in ITER. Our global gyrokinetic simulations using the GTS code [1] have identified an important nonlinear flow generation process due to the residual stress (a non-diffusive element of the momentum flux which is different from a pinch) produced by electrostatic turbulence of ion temperature gradient (ITG) modes and trapped electron modes (TEM). The residual stress is shown to drive intrinsic rotation as a type of wave-driven flow phenomenon which operates via wave-particle momentum exchange. Symmetry breaking in the parallel wave number spectrum induced by turbulence self-generated low frequency zonal flow shear has been identified to be a key, universal mechanism for driving residual stress [2]. For typical tokamak parameters, the nonlinearly generated residual stress is shown to contribute up to more than 50% of the total momentum flux. More importantly, the "intrinsic" torque associated with residual stress is shown to increase close to linearly with the plasma pressure gradient, as is seen in Fig. 2 from ITG simulations. (Note that, to elucidate critical role of zonal flows in the nonlinear flow generation, equilibrium $\mathbf{E}\times\mathbf{B}$ flows are excluded in Fig. 2, which may correspond to typical core turbulence apart from internal transport barriers, where equilibrium shear is not dominant). The dominant underlying physics governing this scaling is that both the residual stress and the zonal flow shear are increased with the turbulence intensity which, in turn, is increased with the strength of the ITG drive R_0/L_{T_i}. This result is consistent with experimental trends observed in various devices [3], including C-MOD where the central flow velocity scales linearly with the edge pressure gradient. Highlighted key results also include the finding, for the first time, of the nonlinear residual stress generation by the fluctuation intensity in the presence of broken $k_\parallel$ symmetry due to zonal flow shear in collisionless TEM turbulence, as is illustrated in Fig. 1. The turbulence-intensity-gradient-driven residual stress [4] is also identified in TEM turbulence by our simulations. On the other hand, simulations, particularly with kinetic electron physics included, also clearly indicate the existence of other mechanisms beyond $\mathbf{E}\times\mathbf{B}$ shear for $k_\parallel$ symmetry breaking. These include the effects of magnetic shear, nonlinear mode couplings, and turbulent radial current. Moreover, the momentum pinch, another non-diffusive element, is also identified in the simulation of TEM turbulence. For typical plasma parameters of fusion experiments, collisionless TEM turbulence can be a major source to drive multiple-channel transport. One of the key results to report is the finding of non-diffusive, inward ion and electron heat fluxes driven by CTEM turbulence with typical DIII-D parameters. As observed in Fig. 3, CTEM driven inward ion heat flux is shown to contribute a significant portion of the ion energy flux. Similar to the residual stress in momentum transport, the non-diffusive heat flux can come from energy exchange between wave and particles. Moreover, the particle flux is shown to carry a large portion of the outward, convective flux for both electron and ion energy and toroidal momentum, as is seen in Fig. 3. Further, remarkably, ∇T_e-driven CTEM turbulence in specific, experimentally relevant parameter regime is found to generate large fluctuation structures with toroidal mode number $n \lesssim 10$ via dramatic inverse energy cascades, as shown in Fig. 4. This phenomenon may have a natural connection to the generation of blobs widely observed at the tokamak edge region. Finally, in the ITG marginality regime, trapped electron physics is shown to play a critical role in determining plasma transport for the parameters of DIII-D plasmas, not only producing the proper ion heat flux in experiments but also substantially enhancing the residual stress generation.

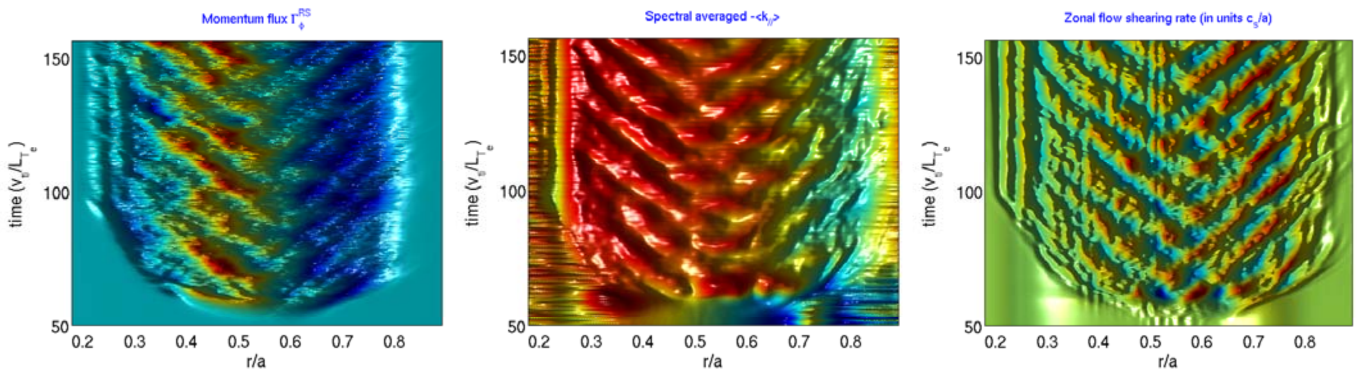

Figure 1: Spatio-temporal evolution of TEM-turbulence-driven residual stress (left), spectrum-averaged $\langle k_\parallel \rangle$ (middle) and zonal flow $\omega_{E\times B}$ (right). Close spatio-temporal correlations among these quantities show nonlinear residual stress driven by turbulence intensity acting with zonal flow shear which induces nonvanishing $\langle k_\parallel \rangle$. An equilibrium $\mathbf{E} \times \mathbf{B}$ flow, included via the radial force balance relation, is shown to have a minor effect on $k_\parallel$-symmetry breaking in this case.

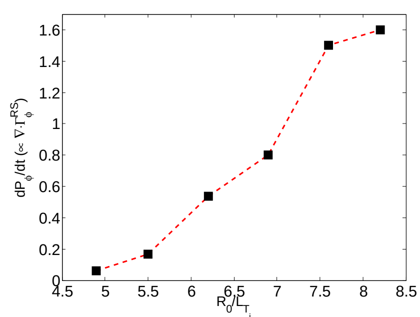

Figure 2: Total intrinsic torque driven by ITG turbulence versus ion temperature gradient R_0/L_{T_i}.

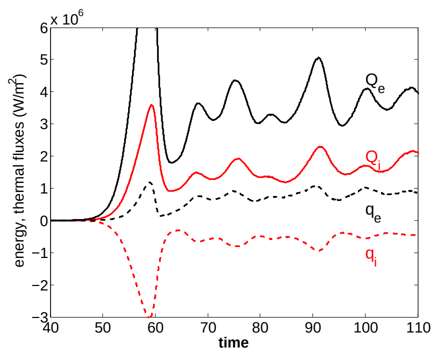

Figure 3: Time histories of electron, ion heat $q_{e,i}$ and energy fluxes $Q_{e,i}$ driven by CTEM turbulence with $R_0/L_{T_e} = R_0/L_{n_e} = 6$, $R_0/L_{T_i} = 2.4$ in DIII-D geometry.

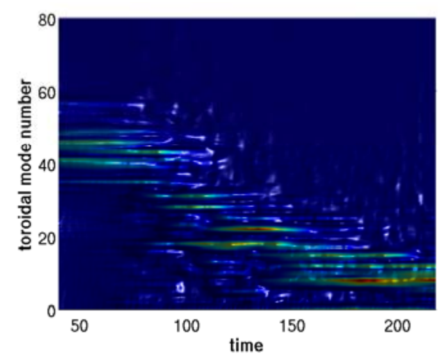

Figure 4: Time evolution of toroidal spectrum of density fluctuations $|\delta n_n|^2$ in ∇T_e-driven CTEM turbulence, showing the generation of low-n, blob-like, large fluctuation structures.

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