Global Gyrokinetic Simulation of Electron Temperature Gradient Turbulence and Transport in NSTX Plasmas

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Plasmas in various magnetic fusion experiments universally exhibit anomalous electron energy transport whose origin, however, remains unknown under most circumstances. As such a candidate for driving the electron transport, short scale fluctuations driven by the electron temperature gradient (ETG) modes have been a subject of high interest to experiment, simulation and theory. The role of ETG turbulence is also an important issue for ITER, for which energy losses are expected to be dominated by electron transport. Using the GTS code [1], global, nonlinear simulations of ETG turbulence for experimental discharges have been carried out with emphasis on direct validation against high-k scattering measurements of electron gyroradius scale fluctuations in NSTX, and quantitatively testing the role of ETG for driving anomalous electron energy transport in experiments. This unique simulation study offers interesting new insight into the characteristics of ETG turbulence in experimental conditions and underlying nonlinear spectral dynamics. The key results of our simulations also include the prediction of significant ETG-induced contributions to anomalous electron heat transport in NSTX, and predicted frequency and wavenumber spectra that are in general agreement with experimental observations.

Global kinetic simulation of electron scale turbulence in a real fusion device is a truly grand challenge. Thanks to strong equilibrium $\mathbf{E}\times\mathbf{B}$ flows which may largely suppress ion temperature gradient modes and trapped electron modes in NSTX, couplings between ETG and low-k turbulence are limited. This allows us to assume adiabatic ions in our ETG simulations. First, our nonlinear ETG simulations of NSTX reveal highly remarkable new features with regard to nonlinear spectral dynamics in 2D perpendicular wavenumber space. Specifically, there exists direct, strong energy coupling between high-k ETG modes and electron geodesic acoustic modes (e-GAMs with high frequency and poloidal mode number $m = 1$), as illustrated in Fig. 1. At the same time, zonal flows with fine radial scale are generated and continuously grow. This direct energy coupling may represent a new insight into the underlying mechanism for nonlinear ETG saturation. It also implies that the collisional damping of zonal flows and e-GAMs may have considerable impact on the formation of the steady state spectrum and saturation level. Moreover, the ETG fluctuations are characterized by strong anisotropy in the perpendicular wave number space with $k_r \ll k_\theta$ (Fig. 1), corresponding to radially elongated streamers emerging even in the well developed turbulence regime. The simulation predicted $k_\perp$ spectrum of density fluctuations is in general agreement with the experimental measurement using coherent scattering of electromagnetic waves [2] in the range of $k_\perp\rho_s \sim 5 - 15$, which is the range that the high-k scattering diagnostic covers. The existence of ETG streamers may be a unique characteristic of NSTX plasmas where low-k fluctuations are largely suppressed, presumably by strong mean $\mathbf{E}\times\mathbf{B}$ shear flow. The identification of streamers offers a good opportunity for the high-k diagnostic to validate nonlinear ETG simulation models and to clarify the effects of turbulence coupling between different scales. Further, our global simulations reveal a remarkable effect of self-consistent relaxation of the electron temperature profile due to the effect of ETG driven transport on simulated turbulence and transport levels, particularly in the marginal ETG regime. Eliminating the influence of the profile relaxation is shown to be crucial in achieving a stationary turbulence steady state, and in determining the value of the electron heat flux, as seen in Fig. 2. Given that plasma profiles and parameters are subject to significant experimental errors, sensitivity studies of simulated ETG-driven electron thermal transport with respect to the local profiles of electron temperature, safety factor and effective charge number $Z_{\rm eff}$ have been carried out. As shown in Fig. 2, both the ETG growth rate and saturated flux are increased by a factor of two as the electron temperature gradient is increased by 20%. More critically sensitive dependence of threshold, growth rate and saturation level of ETG modes on the parameter $Z_{\rm eff}$ is obtained from our nonlinear simulations, which raises an important issue for the experimental measurement of the $Z_{\rm eff}$ profile. Taking all these effects into account, we conclude that, within experimental uncertainties in plasma profiles, the ETG turbulence may drive experimentally relevant transport for electron heat in NSTX (see Fig. 2). ETG turbulence spreading and its effects are also identified in our global simulations. As illustrated in Fig. 3, ballistic spreading of fluctuations is observed mainly towards the positive magnetic shear region (outward) for a distance of a few tens of ρ_e, with a front propagation velocity $V_s \sim 10^{-3} c_s$. Also discussed is the interesting phase space structure of the electron heat flux, elucidating the roles of resonant and nonresonant electrons. Finally, a newly developed synthetic diagnostic, which reproduces the experimental conditions of high-k scattering, is shown to yield frequency spectra for simulated fluctuations, which are in reasonable agreement with experimental observations. This includes the maximum spectral amplitude detected at frequencies below 0.5 MHz and the feature of the broadening in frequency for increasing wavenumber values.

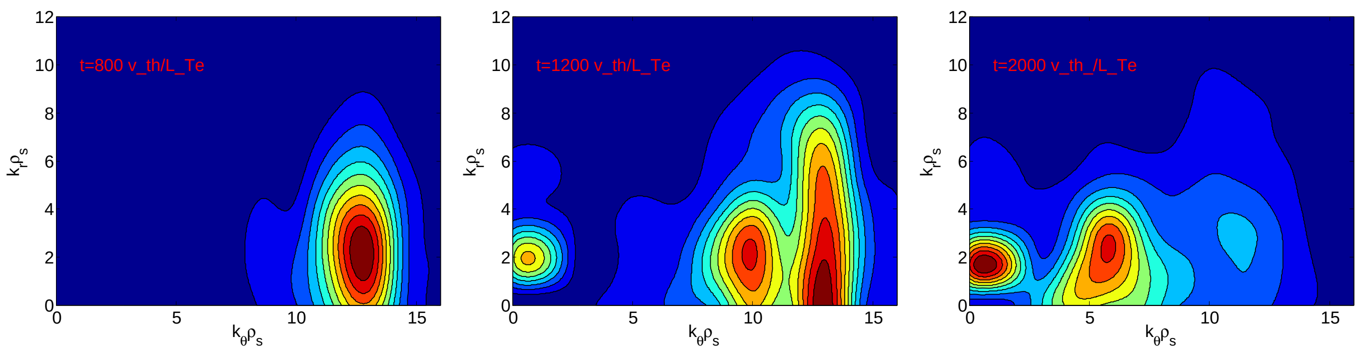

Figure 1: Time evolution of 2D spectra of density fluctuations from an ETG simulation of NSTX.

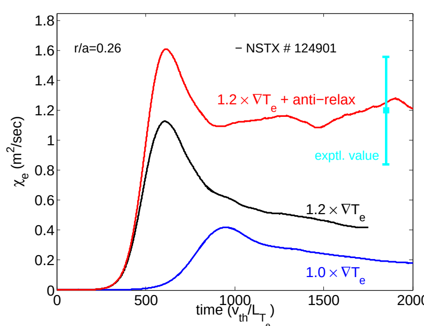

Figure 2: Time histories of χ_e from global ETG simulations of an NSTX discharge and comparison with experimental estimate. The ∇T_e is boosted by 20% for red and black curves, and an “anti-relax” technique is used to maintain a constant ∇T_e drive for red curve.

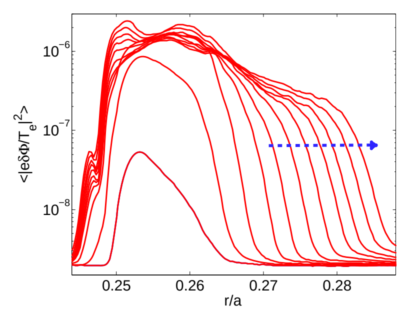

Figure 3: Spatio-temporal evolution of ETG-driven potential fluctuation intensity, showing an outward spreading.

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[1] W. X. Wang *et al.*, Phys. Plasmas **13**, 092505 (2006).

[2] E. Mazzucato *et al.*, Nucl. Fusion, **49**, 055001 (2009).