THE INFLUENCE OF ZONAL EXB FLOWS ON EDGE TURBULENCE IN TOKAMAKS AND STELLARATORS

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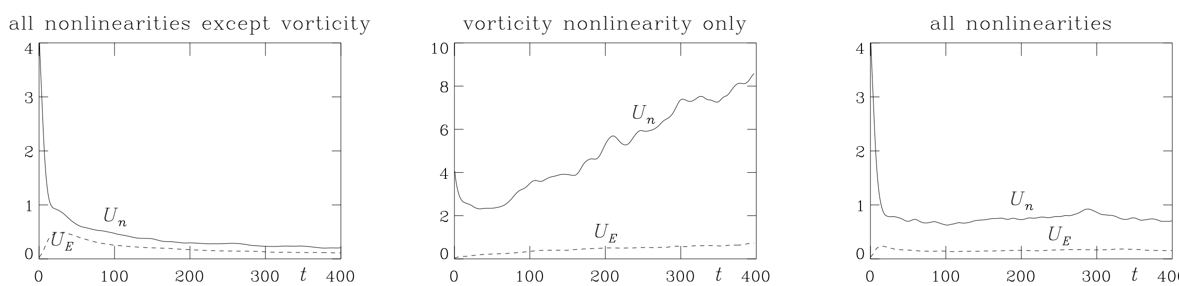
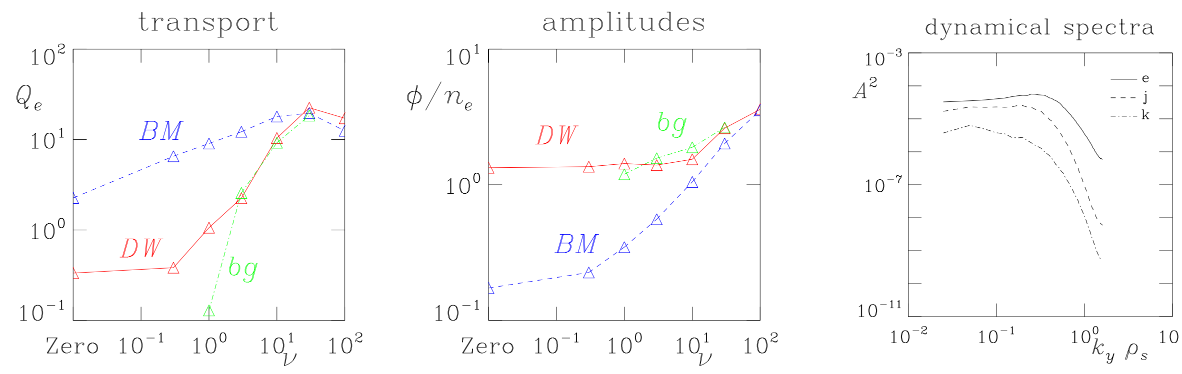
We report on fluid, gyrofluid and gyrokinetic numerical studies of edge turbulence in both tokamak and stellarator geometry, regarding both its physical character and its interaction with the flux surface averaged ("zonal") ExB flows which have proved so important in ion-temperature dominated core turbulence. Zonal ExB flows have a very strong effect in shutting off mechanisms which tend to drive radial flows, and therefore are a part of the overall nonlinear physics which strongly reduces the role of familiar resistive magnetohydrodynamics (MHD) phenomena in edge turbulence. We run several electromagnetic models under drift ordering in globally consistent flux tube geometry [1]: DALF3 (fluid model with dependent variables $\{\widetilde{\phi}, \widetilde{n}_e, \widetilde{J}_\|, \widetilde{u}_\|\}$, treating the basic physics), DALFTE (adding $\{\widetilde{T}_e, \widetilde{q}_{e\|}\}$), DALFTI (further adding $\{\widetilde{T}_i, \widetilde{q}_{i\|}\}$), GYRO (six moment model for both electrons and ions [2,3]), and finally GENE (gyrokinetic phase space continuum model for both electrons and ions [4]). The DALFTE/I models employ a Landau closure for the parallel heat fluxes, which are treated dynamically [5,6]. The fluid models all run at arbitrary collisionality. The numerical scheme, parameter definitions, and computational setup are described elsewhere [3,4].

1. Physical Character of the Turbulence. The drift wave nonlinear instability [7] relies on incoherent scattering in wavenumber space through the ExB vorticity nonlinearity, while the advective ExB nonlinearities involving the thermodynamic variables are always stabilising. This result was found by direct testing using DALF3 in both two- and three-dimensional (2D and 3D) models, which are qualitatively identical.



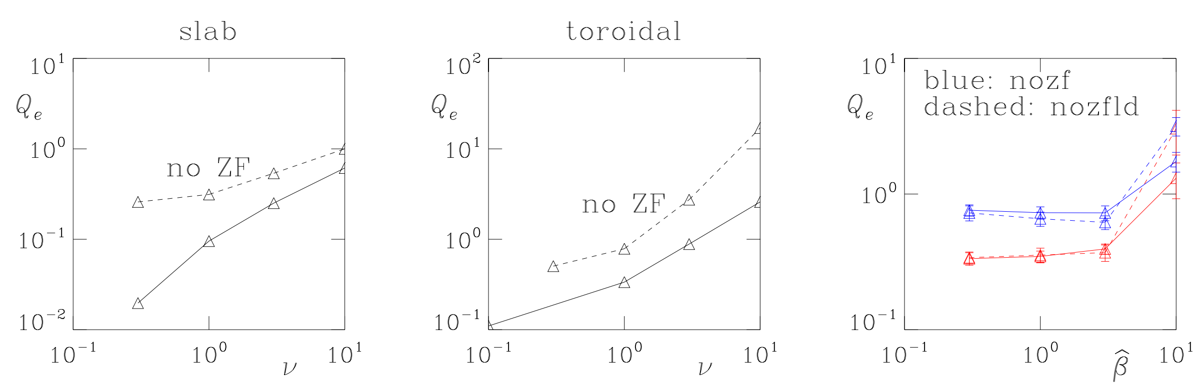
When all nonlinearities except the vorticity one are kept, both the pressure (U_n) and ExB velocity (U_E) contributions to the free energy decay. When only the vorticity nonlinearity is kept, both U_n and U_E grow. When all nonlinearities are kept, the turbulence saturates. While one could treat the pressure nonlinearity with a conventional diffusive mixing model, the ExB vorticity nonlinearity is by contrast nearly dissipation free: its net energy transfer is negligible compared to its randomising effects on the relative phase shifts. It is important to note that this process is statistical and cannot be captured by secondary instability models which by definition rely on coherent nonlinearities.

In the toroidal situation, we test the DALFTE model ('DW' in the figures) against a resistive MHD model ('BM'), constructed by removing the $\nabla_\| p_e$ terms in the Ohm's law and the $\nabla_\| J_\|$ terms in the electron density and pressure equations in DALFTE. The transport scalings versus collisionality (ν, here given by $\nu_*/13.5$) differ, and a Braginskii version ('bg') of the DALFTE model fails to function properly below $\nu_* \approx 40$. The ν-scaling shows no regime breaks for about $3 < \nu_* < 300$.



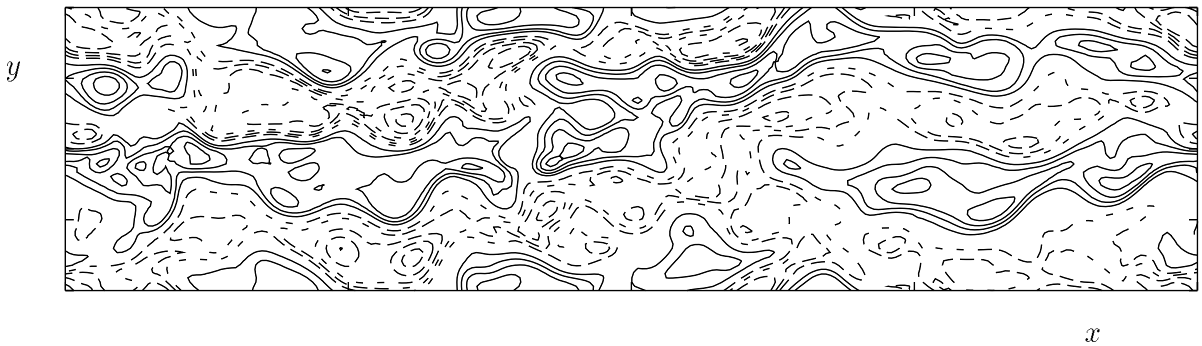
The relative amplitudes ($\widetilde{\phi}/\widetilde{n}_e$) also differ dramatically, showing that resistive MHD is not applicable to tokamak edge turbulence since the MHD regime ($\widetilde{\phi} > \widetilde{n}_e$) is reached only for ν_* above 130. The DALFTE dynamical spectra show that the rms levels of the nonlinear vorticity ('e') and the parallel current gradient ('j') are in relative balance and that the curvature ('k') is subdominant. Fluctuation diagnostics of both drift wave and resistive MHD turbulence show that the principal physical process for electrons is still the nonlinear drift wave dynamics [3]. This change of physics in the nonlinear regime renders the conclusions of linear mode analysis (growth rates, correlation lengths) inapplicable to the study of edge turbulence. We find similar results for DALFTI and GYRO, except for the emergence of ITG turbulence for $\eta_i \gtrsim 2$ (indicated by $\widetilde{T}_i > \widetilde{\phi} \sim \widetilde{p}_e$).

2. The Role of Zonal ExB Flows in the Turbulence. Part of the overall dynamical system including the turbulence is zonal ExB flows, defined in terms of the flux surface averaged component of the radial electric field which nevertheless has radial and temporal scales comparable to those of the turbulence, and which has recently been shown to be of great importance to the tokamak core [8]. Their effect is determined by comparing runs under DALF3 with the full set of dynamics against the same runs repeated with the flux surface averaged vorticity set to zero. Zonal flows always tend towards suppression of the turbulence, and in toroidal geometry have a greater effect if the electrons are more nonadiabatic. These effects were measured in 3D slab and toroidal turbulence at various collisionality. We find a level of transport in relevant cases which is lower by a factor of about $2-5$ than it would be if zonal flows were switched off. It is interesting to note that



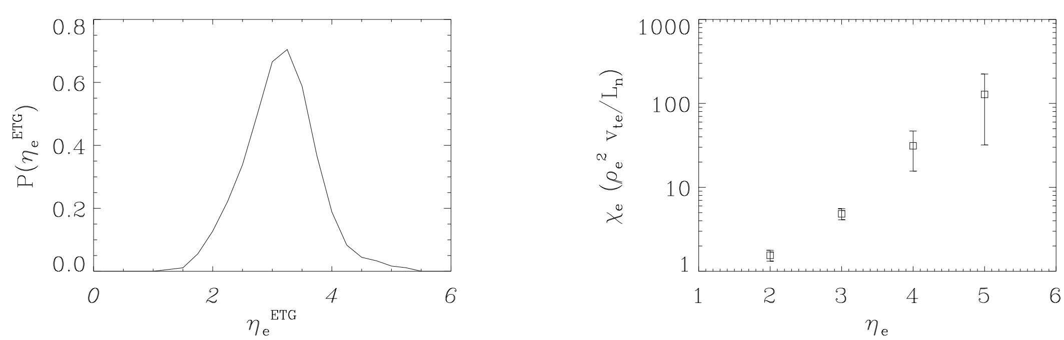
zonal fields (flux surface averaged poloidal magnetic field disturbances) have little effect on drift Alfvén turbulence but emerge as the ideal ballooning limit is approached. The basic β-scaling is flat in gyro-Bohm units below the ideal MHD boundary.

Our gyrokinetic studies show that "hyperfine" ($\Delta_\perp < \rho_i,\ \ \omega > c_s/L_T$) turbulence driven by the electron temperature gradient (ETG) persists and can produce substantial electron heat transport in the presence of strong zonal flows. This is because the ions are adiabatic at these scales, which inhibits vortical flow (Kelvin-Helmholtz) dynamics and hence shear-flow suppression. This leads to radially extended flows and hence the transport.



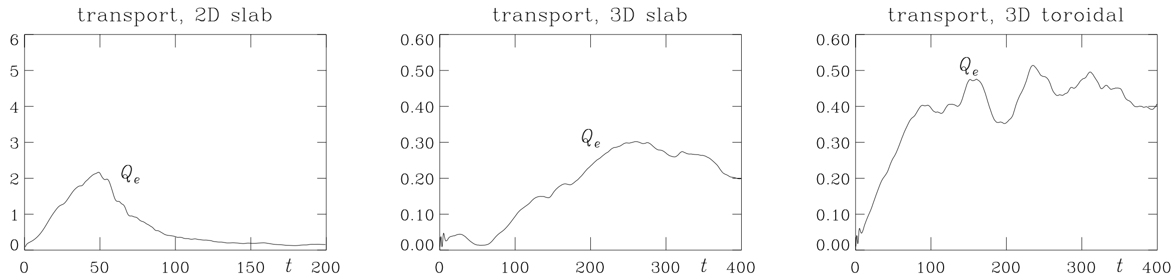
This ETG turbulence may take on a principal role in core transport barriers where the larger scale ion temperature gradient (ITG) turbulence is eliminated by strongly sheared ExB flows [4] (please see also the contributions by W. Dorland and F. Ryter).

Although at scales normally thought to be unimportant, ETG turbulence may be important not only in providing a floor for H-mode edge transport. It may also act as a large background diffusion for ITG turbulence. We find that L-mode edge turbulence has a wide distribution of instantaneous values for $\eta_e = d\log T_e/d\log n$, and at the higher side of this histogram we note that the ETG turbulence corresponds to a diffusion coefficient as large as unity in the usual gyro-Bohm units (multiply the ETG results by a factor of $\sqrt{m_e/M_i}$).



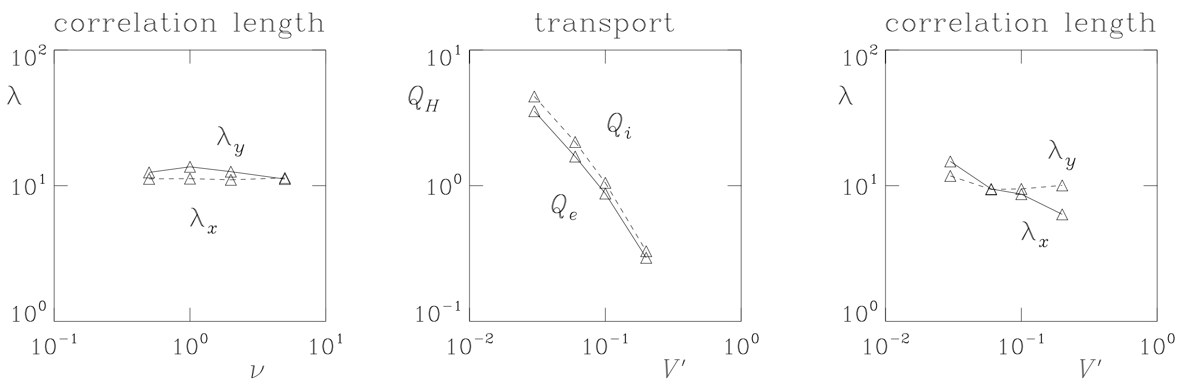
3. The Effect of Mean ExB Flows on the Turbulence. Apart from zonal flows, which are part of the turbulence, a mean ExB flow, which in contrast to zonal flows should be temporally persistent and have a radial scale comparable to that of the profile gradient, is part of the equilibrium. Although 2D homogeneous drift wave turbulence [9] can generate these flows self consistently (to obtain this one must switch off the coupling constant for $k_y = 0$), the DALF3 cases in both slab and toroidal geometry do not show this classic spin-up-and-suppress scenario: In 3D, there is a spectrum of Alfvén modes with $k_y = 0$ but $k_\parallel \neq 0$,

and these prevent significant driving of the zonal flow mode. The resulting self-generated



mean flow vorticity never exceeds "diamagnetic level" (diamagnetic velocity divided by pressure scale length), and therefore is never large enough to suppress the turbulence commensurate with the L-to-H transition.

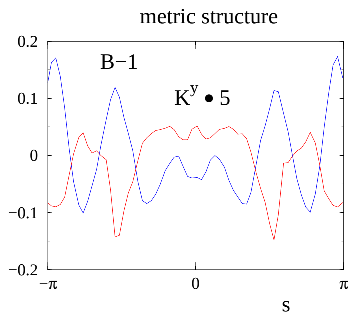
By contrast, we find that a sheared ExB flow imposed by the neoclassical equilibrium does diminish the transport and the radial correlation length for mean vorticity values below those required for total suppression. Since the mean flow vorticity is the parameter to which the radial correlation length (λ_x) is most sensitive, the reflectometry results on ASDEX Upgrade [10] might be indicative of an edge equilibrium ExB shear layer in L-mode which gradually increases with parameters until the L-to-H transition is reached. We can reproduce this by prescribing the mean flow vorticity. We find no dependence of λ_x on ν (DALFTI, left), but a strong one on V' (GYRO, center and right).

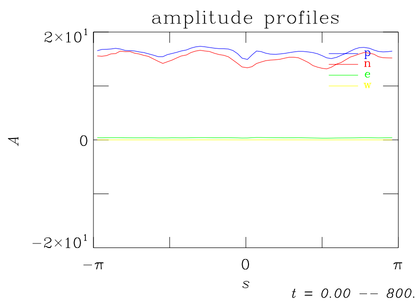


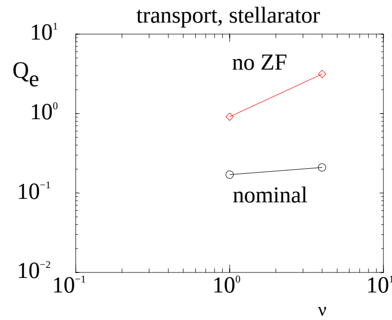
Progress towards a fully self consistent model continues but remains preliminary. However, the classic scenario which is built from an essentially 2D, local turbulence paradigm does not function effectively in 3D local turbulence and hence is not a viable scenario for the bifurcation process behind the L-to-H transition. For that one needs the processes by which the profile physics produces a self consistent edge radial electric field and the corresponding ExB shear layer.

4. Stellarator Geometry. We have extended our globally consistent, flux tube metric geometry to nonaxisymmetric systems. A stellarator equilibrium is computed using the NEMEC code [11], Hamada coordinates are found in the usual manner, and then the flux tube is constructed following Ref. [1]. Although the metric is now 3D, we can assess the turbulence and transport intrinsic to the model geometry of particular field lines. The stellarator metric has dramatic structure parallel to the magnetic field, but since the drift wave dynamics limits itself to long parallel wavelengths, this structure is largely averaged over.

Nevertheless, although the intrinsic physics is the same as for tokamak cases, significant morphology differences can occur.

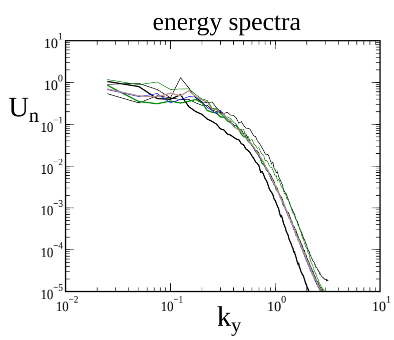


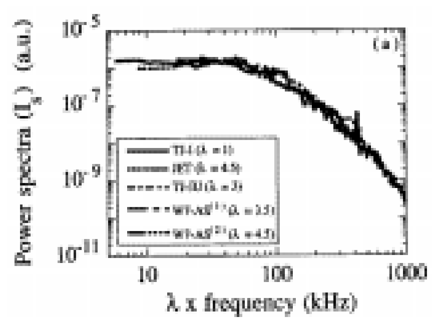




For cases at the same parameters as for tokamak turbulence ($1 < \hat{\beta} < 5$ and $2 < C < 10$) we find a general lack of poloidal asymmetry following the departures of the structure of the normal curvature from the simple sinusoidal form. The difference made by eliminating the zonal flows is found to be about the same as in the tokamak cases.

The underlying similarity of drift wave mode structure in both cases together with the lack of central importance of poloidal "ballooning" to the basic physics is felt in the universality of the turbulence spectra in various model geometries (tokamak to bumpy tokamak to helical stellarator), known from Langmuir probe experiments done on various devices [12].





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