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Transport enhancing features of ETG turbulence

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There are regimes in tokamak experiments where the ion thermal transport is reported to be at the neo-classical level while the electron thermal transport is anomalous, such as Internal Transport Barriers (ITBs) and Spherical Tokamaks (STs). Simulations of Electron Temperature Gradient driven (ETG) micro-turbulence have been shown to produce an electron thermal diffusivity relevant to experimental values [1]. Therefore, understanding when ETG turbulence can produce thermal transport that exceeds gyro-Bohm estimates is important for predicting and controlling electron heat losses.

In this paper we employ the gyro-kinetic flux-tube [2] code GS2 [1, 3], to investigate the effects of trapped electrons and charge non-neutrality ($\rho_e \lesssim \lambda_D$) on the thermal transport produced by ETG turbulence. It is found that trapped particles are essential for large thermal transport in the regimes considered here. ETG thermal transport is modestly enhanced by charge non-neutrality at initial saturation, and may give an enhancement of the gyro-Bohm estimate by $2q/\sqrt{\beta_e}$ as predicted by mixing length estimates [4] at late times.

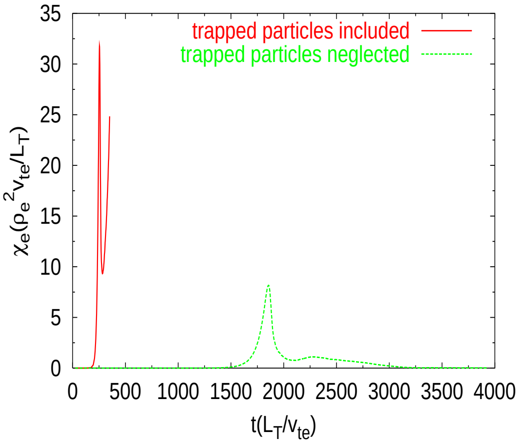

Figure 1: χ_e versus t for two simulations with the cyclone equilibrium parameters and identical flux-tube parameters, with and with out trapped electrons

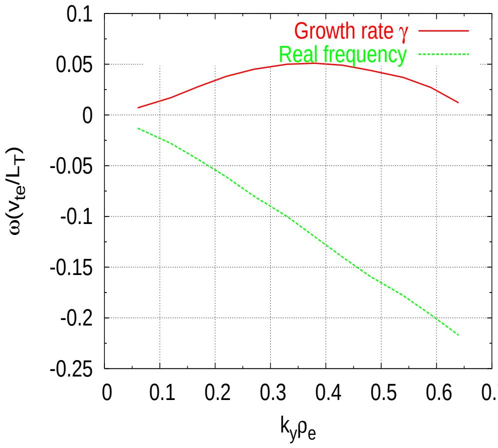

Figure 2: Linear frequency (real and imaginary parts shown) vs. k_y for the cyclone parameters

We begin by reproducing the simulation in reference [1] for the cyclone parameters $q = 1.4$, $\varepsilon = r/R = 0.18$, $R/L_n = 2.2$, $R/L_T = 6.9$, $\hat{s} = 0.8$ and $\alpha = 0.45$ with $\beta_e = 0.013$, using flux-tube parameters[1] $L_x = 250\rho_e$, $L_y = 63\rho_e$, $n_x = 150$ and $n_y = 30$. Repeating the simulation with trapped particles removed (neglecting the trapped particle region of velocity space while retaining finite ε effects on passing particles) causes the transport to saturate at much lower levels and produces strong enough

[1] Flux-tube coordinates are x (radial), y (in surface, perpendicular to magnetic field) and poloidal angle θ (parallel), L_x,L_y,n_x and n_y represent the domain size and number of grid points in x and y respectively.

zonal flow ($k_y = 0$) to almost entirely suppress the heat flux.

The nonlinear $k_y\phi^2(k_y)$ spectra for these two simulations peak at $k_y\rho_e = 0.2$ and $k_y\rho_e = 0.3$ with and with out trapped electrons respectively (figure 3). The real linear frequency of these modes is $\omega \sim 0.05v_{te}/L_T$ and $\omega \sim 0.1v_{te}/L_T$ (figure 2), which are on the order of the bounce frequency $\omega_B \sim (v_{te}/2qR)(\varepsilon/1+\varepsilon)^{1/2} \sim 0.03v_{te}/L_T$ and transit frequency $\omega_T = v_{te}/qR \sim 0.1v_{te}/L_T$.

A scan of ε for the equilibrium and flux-tube parameters $q = 2$, $\varepsilon = r/R = 0.1$, $L_n/R = 0.2$, $\eta_e = 2$, $\hat{s} = 1.0$, $\alpha = 0.6$, $\beta_e = 0.005$, $L_x = 120\rho_e$, $L_y = 63\rho_e$, $n_x = 192$ and $n_y = 24$ with trapped electrons, gives an approximate dependence on the saturated transport of $\chi_e \sim \sqrt{\varepsilon}$ (figure 4), which is proportional to the trapped particle fraction.

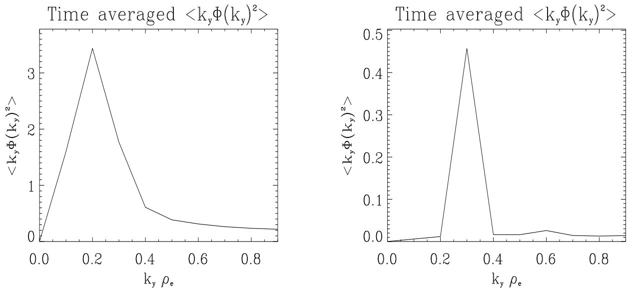

Figure 3: Time averaged $k_y\phi^2$ summed over k_x versus k_y for two simulations with the cyclone equilibrium parameters and identical flux-tube parameters, with (left) and with out (right) trapped electrons

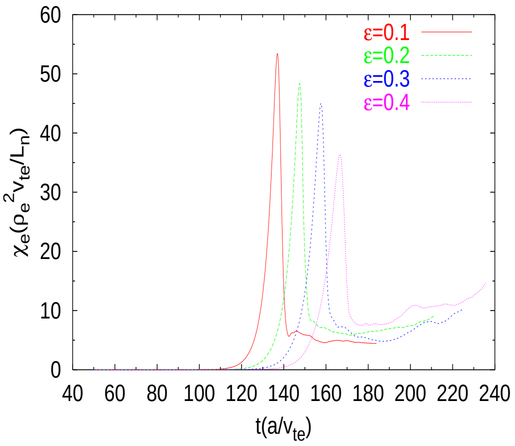

Figure 4: Thermal diffusion coefficient vs. time for four simulations with identical flux-tube parameters ($L_x = 120\rho_e$, $L_y = 63\rho_e$, $n_x = 192$ and $n_y = 24$) and varying ε. The saturated diffusion coefficients increase with ε

The possible increase of electron thermal transport by trapped particles has been documented in the literature in the collisional regime [5, 6]. Here our simulations are collionless and the transport is dominated by electrostatic fluctuations, where as in reference [6] the transport was dominated by stochastic transport.

An explanation of these findings still eludes us. To our knowledge no other calculations have been performed with out trapped particles that retain finite ε effects on passing particles. We have performed convergence tests on both the spatial and velocity grids and tested the effect of removing trapped particles in other equilibria, including a numerical ST equilibrium where ETG transport was observed to be experimentally significant [7], and the transport is either reduced or completely suppressed in all of the cases we have examined.

Many plasma simulations assume the plasma to be quasi-neutral rather than using the full form of Poissons equation. Quasi-neutrality is valid for gyrokinetics if $\lambda_D^2 k_\perp^2 \ll 1$ or for ETG modes $(\lambda_D/\rho_e)^2 = 2v_{te}^2/c^2\beta_e = 1/\beta_* \ll 1$. The significance of charge non-neutrality has been emphasised in previous work [4, 8], and here we calculate the transport in the same parameter regime. Previous work has reported negligible effects from charge non-neutrality [9].

The effect of charge non-neutrality on the linear ETG mode is to stabilise modes with large values of $k_\perp$ leaving the growth rates of the longest wavelength modes (which are quasi-neutral if $(k_\perp \rho_e)^2/\beta_* \ll 1$)) unaltered. Since increasing λ_D/ρ_e will eventually stabilise all ETG modes, then we might only expect an increase in the turbulent heat flux for modest values of $1/\beta_*$, as the linear drive is removed. Figure 5 shows the effect of β_* on linear ETG growth rates.

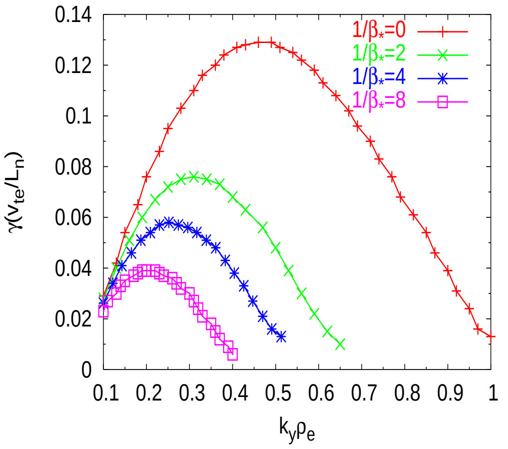

Figure 5: Growth rate γ vs. $k_y \rho_e$ for varying values of β_* with $\varepsilon = 0.1$, $\varepsilon_n = 0.2$, $\eta_e = 2$, $q = 2$, $\hat{s} = 1.0$, $\alpha = 0.6$ and $\beta_e = 0.005$

A scan of β_* (at fixed β_e) for nonlinear ETG simulations with $q = 2$, $\varepsilon = r/R = 0.1$, $L_n/R = 0.2$, $\eta_e = 2$, $\hat{s} = 1.0$, $\alpha = 0.6$ and $\beta_e = 0.005$ shows a slight increase for some values of $1/\beta_*$, although the enhancement is not as large as $2q/\sqrt{\beta_e}$ [4], for the initially saturated state (figure 6). With $1/\beta_* = 2$ and 4 the transport coefficient rises at the end of the simulation to a value which is consistent with an increase of $2q/\sqrt{\beta_e}$. Further work is required to extend the other simulations to see if the flux also increases at later times. Since relatively long wavelengths (which are quasi-neutral) in both the poloidal direction (e.g. figure 3) and radial direction (streamers) dominate the turbulence, the lack of sensitivity to β_* may be expected.

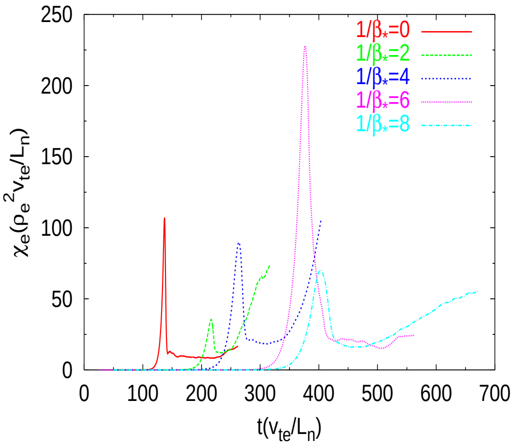

Figure 6: χ_e vs. time for varying values of β_* with $\varepsilon = 0.1$, $\varepsilon_n = 0.2$, $\eta_e = 2$, $q = 2$, $\hat{s} = 1.0$, $\alpha = 0.6$ and $\beta_e = 0.005$

In conclusion, the removal of trapped electrons from the distribution function has the effect of significantly reducing ETG driven transport. It is perhaps wrong to say that the trapped electrons cause large transport, since large transport has been observed with out trapped electrons [1]. The key difference between the simulations in this work and previous work is that here strong orbit modifications due to parallel magnetic field variation are included.

Further work is required to determine whether or not the heat flux is enhanced by charge non-neutrality to the levels predicted theoretically.

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