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Interplay between particle transport, zonal flows and zonal density in Dissipative Trapped-Electron Mode turbulence

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The H-Mode is the main regime of operation for present and future fusion devices like ITER. The transition from L-mode to H-mode (LH transition) has been studied for more than 20 years [1]. One important aspect of the LH transition is the abrupt suppression of the turbulent particle transport at the plasma edge [2]. Turbulence driven flows, i.e. zonal flows are believed to play a major role in the transition by providing the initial quench of turbulence [3]. Analytical models of zonal flow nonlinear generation can be classified into two categories: the parametric interaction approach [4], and the wave-kinetic approach [5]. Recently, Ref. [6] proposed a new quantum-mechanical-like framework to systematically derive the wave-kinetic equation (WKE) from the drift-wave model with adiabatic electrons, i.e. from the Charney-Hasegawa-Mima equation [7], and also to account for dissipation and/or growth. In this work, we extend the wave-kinetic equation to account for non-adiabatic electrons. Starting from the Dissipative-trapped-electron mode (DTEM) fluid model [8,9], a basic representative model for edge turbulence describing a collisional drift-wave instability due to trapped electrons, we apply the wave-kinetic formalism of Ref. [6]. We include both the zonal flows and the zonal density, i.e. the time-dependent corrugation of the density profile. In previous work [9], we showed using the parametric formalism that zonal flows can affect the transport crossphase between density and potential fluctuations. Here, we consider a similar mechanism: using the wave-kinetic formalism, we show that the transport crossphase is modulated by zonal density corrugations. In turn, this modulation nonlinearly drives the zonal density corrugations. This is the analog of ETG growth-rate modulation by ion-scale turbulence [10], altough here, we find that the effect is always stabilizing. In turn, this modulation nonlinearly drives the zonal density corrugations.
The extended predator-prey model is derived for the turbulence energy ε, zonal flow energy $U^2 = \int V_{\rm zon}^2 dr$ and zonal density energy $N^2 = \int n_{\rm zon}^2 dr$:

$\frac{d\epsilon}{dt} = \gamma\epsilon - a_1\epsilon U^2 - a_2\epsilon N^2 - \gamma_{NL}\epsilon^2,$

$\frac{dU^2}{dt} = b_1\epsilon U^2 - \mu U^2,$

$\frac{dN^2}{dt} = c_1\epsilon N^2 - c_2 N^2,$

Here, the terms a_1 and b_1 represent nonlinear coupling between drift-waves and zonal flows, while the terms a_2 and c_1 represent nonlinear coupling between drift-waves and zonal density. Zonal flow damping occurs via neoclassical friction (μ). The coefficients a_2 and c_1 associated to zonal density dynamics are proportional to the inverse of the de-trapping rate ν, i.e. inversely proportional to electron-ion collision frequency.
For different values of the de-trapping rate, the predator-prey model exhibits different saturation mechanisms. In particular, for ν=1, the system shows a saturate state dominated by zonal density, while for larger values of ν, zonal flows are dominant and zonal density is subdominant.

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