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Study of Symmetry Breaking and Momentum Transport in Tokamaks

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We present gyrokinetic simulation studies of symmetry breaking in electrostatic turbulence and intrinsic rotation generation in tokamak plasmas. By analyzing fluctuation spectrums obtained from ITG and TEM turbulence simulations, we investigate the spatio-temporal patterns of fluctuation energy transport and zonal flow generation. Due to the drift velocity appearing in the relation for zonal flow generation, it is shown that ITG and TEM have different global zonal flow shearing profiles, which results in the intrinsic torque reversal at the TEM → ITG transition.

1. Introduction

The observation of spontaneous toroidal plasma rotation reversals in recent experiments [1,2] poses an interesting challenge to the theory of intrinsic rotation generation by plasma turbulence. The abrupt sign change occurs during the plasma density ramp-up experiments. The density values at the reversal show linear correlation with the critical density at the linear Ohmic (LOC) to saturated Ohmic (SOC) confinement transition, which suggests the connection of the reversal phenomena to the TEM → ITG transition.

In this work, we critically examine the theory of residual stress generation by fluctuation symmetry breaking as a key mechanism for the intrinsic torque [3] and the torque reversal at the TEM → ITG transition. The global δf gyrokinetic code *gKPSP* is used for the study, which employs a bounced averaged kinetic model for efficient simulation of the relevant non-adiabatic electron responses [4].

2. Fluctuation Symmetry Breaking

We analysed the fluctuation spectrums of ITG and TEM turbulence in ω and k_r space to study the radial propagation of fluctuation energy. It was found that the propagation shows similar pattern in both cases, i.e. the same direction of the radial group velocity of the fluctuations in the same radial region. However, due to the drift velocity V_* appearing in the relation for the non-linear correlator $\langle k_r k_\theta \rangle$ and the radial propagation of the fluctuation energy, which can be readily seen by taking the k_r derivative of the simple drift wave dispersion relation,

$$\frac{\partial \omega}{\partial k_r} = -\frac{2V_* k_r k_\theta \rho_s^2}{\left(1+k_\perp^2 \rho_s^2\right)^2},$$

we found that opposite trends of fluctuation asymmetry appear in k_r and k_θ space for ITG and TEM turbulence spectrum as can be seen in Fig.1.

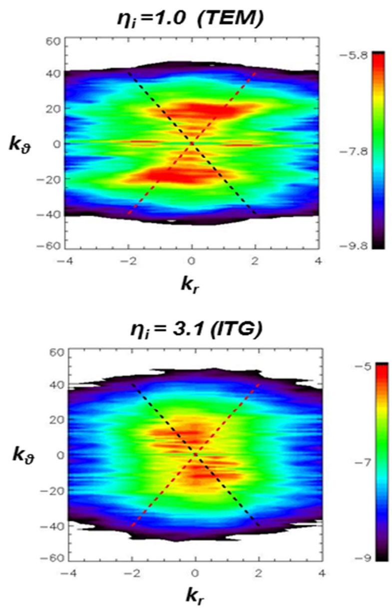

Fig. 1. Fluctuation spectrum in $\boldsymbol{k_r}$ and $\boldsymbol{k_\theta}$ for TEM (upper) and ITG (lower) turbulence. Different asymmetry appears due to the opposite drift velocity $\boldsymbol{V_*}$.

In Fig.1, we can see that the TEM case shows spectrum peaks at higher $|\boldsymbol{k_\theta}|$ compared to the ITG because of the higher mode numbers. It is important to note that the spectrum peaks are shifted toward $k_r k_\theta > 0$ for the TEM and $k_r k_\theta < 0$ for the ITG case, respectively.

The relation for zonal flow $\langle V_\theta \rangle$ generation by turbulence driven Reynolds stress can be written as

$$\frac{\partial}{\partial t}\langle V_\theta \rangle = -\frac{\partial}{\partial r}\langle \tilde{V}_r \tilde{V}_\theta \rangle = \frac{\partial}{\partial r}\frac{c^2}{B^2}\sum_k k_r k_\theta |\phi_k|^2$$

Here, we note that the key non-linear correlation of fluctuating potential ϕ_k for zonal flow generation is $\langle k_r k_\theta \rangle$, which suggests different zonal flow shearing profiles from TEM and ITG turbulence. From the simulations, we found that global zonal flow shearing profiles show roughly opposite pattern for the TEM and ITG case.

This is significant because the ExB shearing by zonal flow is one of the well-known mechanisms for the $k_{||}$ fluctuation symmetry breaking [5], which is necessary for the residual stress generation [3]. We confirmed the opposite $k_{||}$ symmetry breaking trend by evaluating fluctuation weighted wave vector $\langle k_{||} \rangle$ defined as

$$\langle k_{||} \rangle \equiv \sum_{m,n} \frac{1}{qR_0}(m - nq)\left|\phi_{m,n}\right|^2,$$

where m, n denote poloidal and toroidal mode number, respectively.

3. Intrinsic Torque Reversal at TEM → ITG Transition

The residual stress formula is given by [3],

$$\Pi_{r||}^W = \sum_k \left[-\tau_{c,k} k_{||} V_{gr}^2 \frac{\partial}{\partial r}\langle N_k \rangle + \tau_{c,k} V_{gr} k_\theta k_{||} \langle V_E \rangle' \frac{\partial}{\partial k_r}\langle N_k \rangle \right]$$

The first and second term in the right hand side represent the symmetry breaking effect by fluctuation intensity gradient and ExB shearing, respectively. Since there are no sign flip in $k_{||} k_\theta$ and V_{gr}, the results in the previous section imply the sign reversals in both the intensity gradient and ExB shearing term, which can result in the sign reversal of the residual stress and therefore the intrinsic torque.

Indeed, we found that the intrinsic torque and rotation from TEM and ITG show roughly opposite radial profiles as shown in Fig.2.

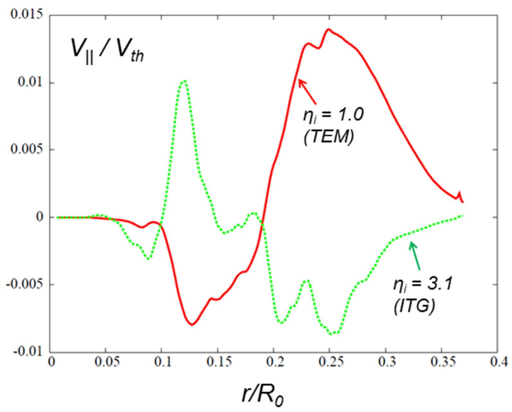

Fig. 2. Intrinsic rotation profiles generated by TEM(red) and ITG(green dotted) turbulence. They show spatially opposite structure.

The radial profiles show the so called zonal pattern i.e. dipolar structure. We note that the net sign of toroidal momentum inside plasma will be ultimately determined by the action of boundary condition, which is a subject of on-going study.

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