NON-GYROKINETIC HIGH-FREQUENCY MODE INSTABILITY FOR TOKAMAK EDGE LIKE GRADIENTS - TH

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Missing understanding of turbulence in the tokamak edge and H-mode transition necessitates going beyond gyrokinetics. Since the discovery of the high confinement mode (H-mode) [1] it has been evident that an understanding of turbulence in the plasma edge is indispensable, as even the confinement of the plasma core is tightly linked to the transport in the plasma edge [2]. Five-dimensional gyrokinetic turbulence simulations have become the gold standard for theoretical transport studies in the core of magnetic confinement systems [3]. Yet, their descriptive power still falls short of the tokamak edge-plasma and particularly the H-mode transition, likely due to the presence of high gradients (where gradient lengths can become of similar order as the ion Larmor radius $\rho_i = \sqrt{m_i T}/(eB)$) and elevated fluctuation levels. On the other hand, the fundamental assumptions of gyrokinetics, that the distribution function is nearly constant on a Larmor circle and the turbulence time scales long compared to the Larmor period, are ultimately just assumptions.
In recent work [4], we have demonstrated that highly "nongyrokinetic" behavior, i.e., the excitation of IBWs with frequency above the Larmor frequency, even for small parameters. This could be confirmed by nonlinear simulations of saturated IBW turbulence at realistic parameters. These findings suggest that a more comprehensive study of the plasma edge turbulence beyond the gyrokinetic approximation is warranted for a better understanding of the H-mode transition and edge transport.

The IBW instability is unstable for tokamak edge like gradients. We have derived a threshold criterion for the IBW instability, which is takes the form of a simple extension of the one for the ITG criterion. However, unlike gyrokinetic ITGs, the non-gyrokinetic modes require only the presence of a temperature gradient and not a particularly high ratio of temperature to density gradients. In contrast, gyrokinetic ITGs are suppressed when the density gradient is too large relative to the temperature gradient (the η_i criterion). Interestingly, the IBW growth rate tends to increase with the density gradient. Figure 1 shows the growth rate of the various modes as a function of the ratio of temperature and density gradient for fixed temperature gradient. The ITG mode ($p = 0$) is stabilized for $1/\eta = \kappa_T/\kappa_n > 0.9$ and thus is suppressed for typical tokamak parameters. In contrast, the IBWs ($p \neq 0$) are unstable for larger gradient ratios, i.e. the $p = 1$ harmonic of the IBW has its peak growth rate at $1/\eta \gtrapprox 1$. The IBW instability is to dominant slab instability in a wide range of parameters, as shown in figure 2, which displays the mode with maximum growth rate as a function of k_y and $\eta = \kappa_T/\kappa_n$. The grey area indicates typical tokamak parameters [5].

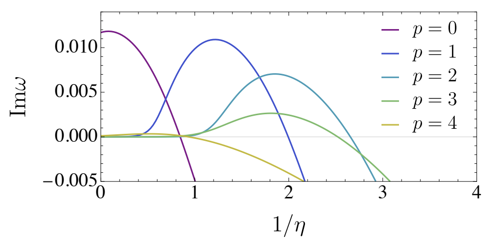

FIG. 1. Growth rate of ITG ($p = 0$) and IBW ($p \neq 0$) instability as a function of $\frac{1}{\eta} = \frac{\kappa_n}{\kappa_T}$ for fixed temperature gradient $\kappa_T = 0.36$ and $k_y = k_\perp = 2$, $k_z = 0.025$.

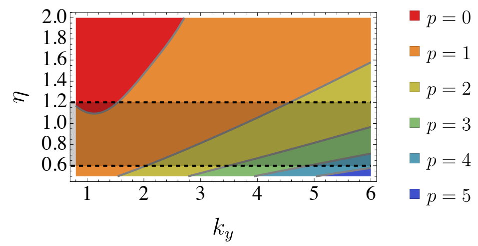

FIG. 2. Mode with maximum growth rate as a function of k_y and $\eta = \frac{\kappa_T}{\kappa_n}$ for fixed temperature gradient $\kappa_T = 0.36$ and $k_y = k_\perp = 2$, $k_z = 0.025$. Grey area indicates typical tokamak parameter [5].

Fist of a kind 6D-Vlasov simulations of saturated IBW turbulence. For the study of turbulence in extreme plasma scenarios, we have developed a novel 6D-Vlasov code BSL6D [6], which is specifically optimized to resolve the Larmor orbits of ions in a strong magnetic field. The analytical predictions of the linear stability analysis are confirmed by 6D-Vlasov simulations of the IBW instability. Figure 3 shows snapshots of the electrostatic potential ϕ for $p = 0$ (left column) and $p = 1$ (right column). The simulation reproduced the predicted growth rates and mode structures. The nonlinear saturation of the turbulence is compared in figure 4, which shows the time series of the spatially averaged potential amplitude $|\phi|$ (top) and internal ion energy flux q_x (bottom). While the potential amplitude is significantly lower for the IBW turbulence, the ion heat flux is of similar magnitude as for the ITG turbulence. The simulations show the presence of a significant non-gyrokinetic instability for steep, but typical tokamak edge gradients. The IBW turbulence saturates nonlinearly and leads to transport comparable to gyrokinetic turbulence.

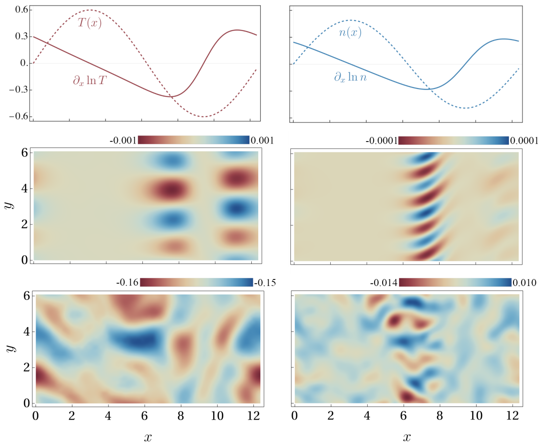

FIG. 3. Profiles of density and temperature (top row) and cross sections of potential fluctuations ϕ for $p = 0$ (left column) and $p = 1$ (right column) at fixed z and $t = 1500, 5500$ (rows).

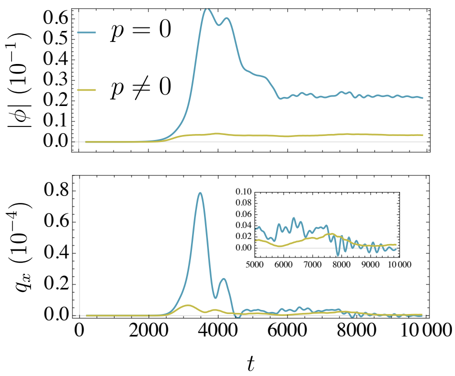

FIG. 4. Comparison between low frequency modes $p = 0$ and IBWs ($p \neq 1$) for potential amplitude $|\phi|$ (top) and internal ion energy flux q_x (bottom), spatially averaged over gradient domain $x = [\pi, 3\pi]$ and box-car averaged over 380 time units.

Significance for our understanding of turbulence in the tokamak edge The demonstrated instability is a first example of a non-gyrokinetic instability for tokamak like parameters. While the study is limited to a simplified slab geometry, the results indicate that the customary restriction of magnetized plasma turbulence studies to the gyrokinetic approximation may not be based on physics but only a practical constraint due to computational cost. It is likely that including additional physics (e.g., magnetic curvature or interactions with kinetic electrons) will significantly amplify the drive of similar non-gyrokinetic instabilities, potentially leading to an expansion of the field of strongly magnetized plasma turbulence.

References

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