EXPLORING THE ROLE OF SUBDOMINANT KINETIC BALLOONING MODE IN DRIVING TURBULENT TRANSPORT IN NSTX

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Understanding the mechanisms of turbulent transport driven by plasma instabilities, such as kinetic ballooning modes (KBMs), is essential for improving plasma confinement and advancing the operational goals of spherical-tokamak-based fusion reactors. This work investigates the role of subdominant KBM in driving the turbulent transport in low-collisionality plasmas using the local gyrokinetic simulations with the CGYRO code [1] for NSTX discharge #120982 at r = 0.6 a. Complementary insights from global gyrokinetic simulations with the GTC code [2] provide a broader context, highlighting the critical role of KBMs in NSTX-U [3]. Linear GTC simulations reveal that KBMs become unstable at significantly higher plasma beta values compared to conventional tokamaks, primarily due to plasma shaping effects. Nonlinear GTC simulations further demonstrate that self-generated zonal flow regulates KBM-driven turbulence by reducing the size of turbulent eddies and shortening the radial correlation length. These global trends align with CGYRO results (Figure 1), where compressional magnetic field fluctuations ($\delta B_{\|}$) play a crucial role in KBM destabilization. In the absence of $\delta B_{\|}$ fluctuations, only micro-tearing modes (MTMs) are unstable. A comparison of nonlinear simulations with and without $\delta B_{\|}$ fluctuations show similar electron heat fluxes, while ion heat transport remains negligibly small. This suggests that electron heat transport is anomalous, whereas ion heat transport is neoclassical. Flow shear, with a shearing rate much larger than the growth rate of the modes, has a distinct impact on linear stability—stabilizing KBMs while leaving MTMs unstable. These findings are particularly relevant for high-temperature NSTX-U scenarios, where KBMs are expected to be near the stability threshold [4]. In such cases, large flow shear is desirable to stabilize these modes, which could otherwise limit the set of achievable plasma profiles.

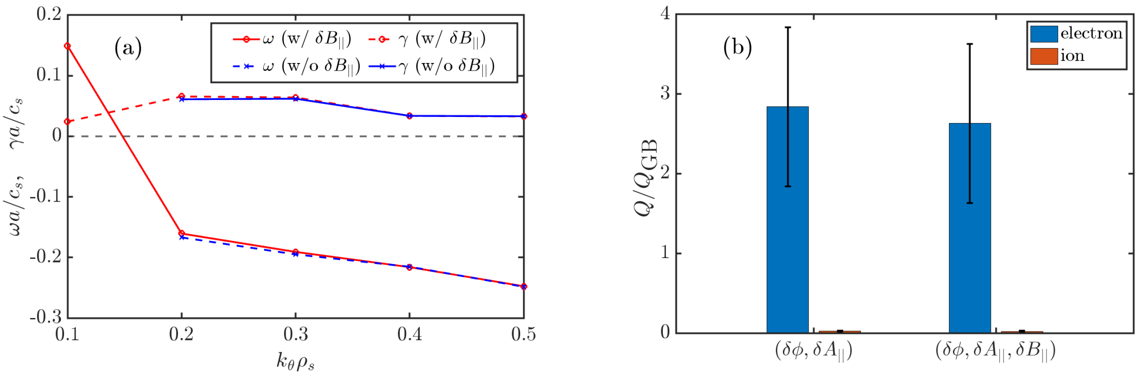

Figure 1. (a) The variation of the linear growth rate and frequency of the plasma instabilities in the absence of flow shear, (b) the nonlinear electron and ion heat fluxes normalized with the gyro-Bohm values with and without compressional magnetic field fluctuations in the presence of flow shear for the low-collisionality NSTX discharge #120982 @620 ms at the radial location r = 0.6 a.

NSTX-U [5] marks a milestone in fusion energy research, demonstrating the potential of spherical tokamaks as sustainable energy sources. Building on NSTX's legacy, NSTX-U aims to bridge the gap between experimental facilities and fusion pilot plants, addressing challenges such as anomalous transport caused by small-scale plasma instabilities, which degrade confinement by driving particle, momentum, and energy fluxes. Gyrokinetic simulations reveal that ion transport in NSTX is largely neoclassical, while electron transport is anomalous [6-8]. Recent simulations for NSTX and NSTX-U highlight a complex interplay of instabilities, with the ion temperature gradient (ITG) modes stable at thresholds far above experimental values and KBMs near instability threshold [4]. Unstable KBMs can deviate ion transport from neoclassical behavior, increasing turbulent fluxes and relaxing plasma profiles, which are critical for limiting plasma profiles. The low-collisionality scenario in NSTX-U provides a platform to investigate these effects, with recent studies showing the impact of electromagnetic effects on turbulence [9]. These insights motivate further exploration of KBMs and their role in optimizing plasma confinement.

CGYRO simulations reveal that $\delta B_{\|}$ plays a critical role in KBM dynamics. The absence of $\delta B_{\|}$ term leads to the stabilization of KBM, while it has an almost negligible effect on the MTM instability. The adopted plasma equilibrium and profile parameters are presented in Table 1 for a low-collisionality discharge (#120982) at 620 ms in NSTX at the radial location r = 0.6 a. This scenario is based on linear gyrokinetic analysis, representing a hybrid case where MTMs are present for wavenumbers $k_\theta\rho_s \geq 0.2$ and KBMs dominate on the low-wavenumber side $k_\theta\rho_s < 0.2$. The case provides a valuable opportunity to examine the effect of KBMs on turbulent transport. Here, k_θ is the poloidal wavenumber and ρ_s is the ion sound gyro-radius. The spectrum of the plasma instabilities is shown in Fig. 1(a). The negative frequency represents the mode propagating in the electron diamagnetic direction. KBM is isolated from the simulations by turning off the $\delta B_{\|}$ term, ensuring that anomalous transport arises solely only from the MTMs. MTM is majorly responsible for the electron turbulent transport and thus drives the electron heat fluxes, while not contributing to the ion turbulent transport. Simulations that retain the $\delta B_{\|}$ term in the gyrokinetic equations yield similar turbulent heat fluxes, highlighting the crucial role of flow shear in stabilizing subdominant KBMs, while MTMs continue to contribute to electron heat transport. These results are presented in Fig. 1(b) and emphasize the importance of flow shear, particularly for projected NSTX-U scenarios where KBMs are predicted to be near the stability threshold. A sufficiently large flow shear is necessary to suppress KBMs, preventing a transition from neoclassical to anomalous ion thermal transport and ensuring the sustainability of plasma profiles.

q	s	κ	δ	T_i/T_e	a/L_{ne}	a/L_{ni}	a/L_{Te}	a/L_{Ti}	Z_{eff}	β_e	α_{MHD}	$\nu^{e/i}$	$\gamma_E a/c_s$
2.97	0.97	2.2	0.24	1.15	-0.93	-0.095	1.59	2.86	1.78	0.012	0.54	0.58	0.3

Table 1. Equilibrium and profile parameters for the low-collisionality discharge #120982 @620 ms at the radial location r = 0.6 a, where q is the safety factor, s is the magnetic shear, κ is elongation, δ is triangularity, T_i/T_e is the ion to electron temperature ratio, a/L is normalized profile gradient, Z_{eff} is the effective charge, β_e is the electron beta, α_{MHD} is the ballooning parameter, $\nu^{e/i}$ is the electron-ion collision frequency, and γ_E is the flow shearing rate.

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