Global gyrokinetic particle simulation of kinetic ballooning modes with energetic ions

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In fusion reactors that feature a substantial population of alpha particles and high β plasmas ($\beta = 2\mu_0 p/B_0^2$), the interactions between energetic ions (EIs) and kinetic ballooning modes (KBMs) [1] are inherently unavoidable. This study investigates the effect of EIs on KBM using first-principles gyrokinetic simulations in Gyrokinetic Toroidal Code (GTC), which encompass comprehensive physics including MHD ballooning interchange, kinetic wave-particle resonance, finite Larmor radius (FLR) and finite orbit width (FOW) etc. To investigate different natures of EI responses to KBM electromagnetic fluctuations, a new gyrokinetic EI model is implemented and verified in GTC following Chen-Hasegawa theory [1], which separates the contributions of adiabatic fluid convection and non-adiabatic kinetic particle compression (KPC) responses to EI perturbed distribution function. As the EI temperature (T_h) increases, the real frequency ω_r exhibits a slight increase, while the growth rate γ is more sensitive and exhibits non-monotonic phenomena. In regime of $T_h/T_e \sim 1$, the KBM become more unstable with increasing T_h, which attributes to enhancement on MHD ballooning interchange drive and strong trapped particle precessional drift resonance drive [2] with $\omega_r \sim \overline{\omega}_{d,h}$ ($\overline{\omega}_{d,h}$ is the EI precession frequency), which arise from the EI adiabatic fluid and non-adiabatic kinetic responses. However, as the T_h continues to increases, the EI effects transit from destabilization into stabilization [3] and gradually converge toward dilution limit in regime of $T_h/T_e \gg 1$. The main reason for EI has minimal destabilization effects includes: (i) the trapped particle precessional drift resonance becomes ignorable since $\omega \ll \overline{\omega}_{d,h}$. (ii) the significant orbit averaging effect of FOW screens the KBM electromagnetic fluctuations to EI dynamics and weaken the EI response, results in the MHD ballooning interchange drive is also weakened due to the cancellation by KPC with opposite sign. (iii) The FLR effect further weakens EI fluid contribution to MHD ballooning interchange. Additional, single-n nonlinear simulations were conducted to investigate the EI effects on saturation and transport of KBM with the inclusion of zonal flow and zonal current. The simulations reveal that the EI with $T_h/T_e \gg 1$ reduce the saturation level, while EI enhance it slightly in regime of $T_h/T_e \sim 1$, consistent with the linear EI effect on KBM. Furthermore, it is found that the EI slightly reduce the transport level of thermal ion, but the effective diffusivity D_h for EI in regime of $T_h/T_e \gg 1$ is significantly suppressed compared to D_h at in regime of $T_h/T_e \sim 1$. These temperature-dependent linear and nonlinear EI effects hold significant implications for fusion plasma performance and support the view that high energy alpha particles can stabilize KBM and thus improve the burning plasma confinements, while the low energy alpha particles can destabilize and resonate with KBM which might benefit for helium ash removal.

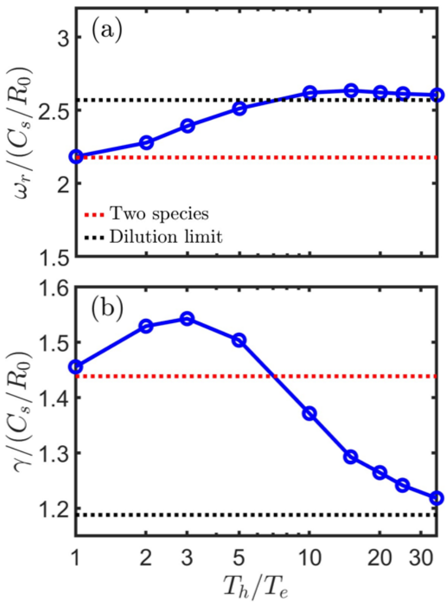

Figure: The (a) real frequency ω_r and (b) growth rate γ using CBC equilibrium with varying EI temperatures T_h/T_e. The EI density is fixed with $n_h/n_e = 0.03$ at $r = 0.5a$. The red dotted line corresponds to the simulation of two species and the black dotted line represent the dilution limit.

References

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