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Roles of Kinetic Ion Dynamics on Electron-Scale Turbulent Transport

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ABSTRACT

- The present gyrokinetic simulation study reveals roles of kinetic ion dynamics on the electron temperature gradient (ETG) turbulence and transport in magnetic fusion plasma, and provides new insights into a fundamental process in cross-scale interactions in plasma turbulence.
- The polarization effect due to finite ion gyroradius turns out to play essential roles not only in enhancement of the linear instabilities of the slab and toroidal ETG modes but also in the nonlinear saturation of the ETG turbulent transport.

BACKGROUND

- The anomalous electron heat transport has long been a key issue in physics of burning plasma confinement. Recent large-scale gyrokinetic simulations have also demonstrated contributions of electron-scale turbulence to the total heat transport through cross-scale interactions of turbulence [Maeyama et al. 2015; ibid 2017; Howard et al., 2016].
- Importance of kinetic ion dynamics on the electron temperature gradient (ETG) turbulence was pointed out by gyrokinetic simulations [Jenko et al., 2000; Candy et al., 2007], while the physical mechanism leading to a lower transport level has long been an open issue.

BASIC EQUATIONS

- Local gyrokinetic equations for ions and electrons with quasi-neutrality and Ampere's law:

$$\left(\frac{\partial}{\partial t}+v_\parallel\nabla_\parallel+i\omega_{sd}-\frac{\mu\nabla_\parallel B}{m_s}\frac{\partial}{\partial v_\parallel}\right)\tilde{f}_{sk}(z,v_\parallel,\mu,t)+N_{sk}$$

$$-\frac{e_sF_{sM}}{T_s}\left[v_\parallel\left(-\nabla_\parallel J_{0sk}\tilde{\phi}_k-\frac{\partial J_{0sk}\tilde{A}_{\parallel k}}{\partial t}\right)-i\omega_{sd}J_{0sk}\tilde{\phi}_k+i\omega_{s*}J_{0sk}\left(\tilde{\phi}_k-v_\parallel\tilde{A}_{\parallel k}\right)\right]=C_{sk}, \qquad (1)$$

$$\sum_{s=i,e}\frac{e_s^2n_s}{T_s}(1-\Gamma_{0sk})\tilde{\phi}_k=\sum_{s=i,e}e_s\int J_{0sk}\tilde{f}_{sk}dv^3, \qquad (2)$$

$$k_\perp^2\tilde{A}_{\parallel k}=\mu_0\sum_{s=i,e}e_s\int v_\parallel J_{0sk}\tilde{f}_{sk}dv^3. \qquad (3)$$

KINETIC ION & FINETE BETA EFFECTS ON SLAB ETG MODES

- **Dispersion relation of slab ETG modes** with gyrokinetic ions & electrons

$$\left[\sum_{s=i,e}\frac{2\alpha_s^2}{k_\perp^2d_s^2}(1-G_{0s})\right]\left[1+\sum_{s=i,e}\frac{2\alpha_s^2}{k_\perp^2d_s^2}G_{1s}\right]+\left[\sum_{s=i,e}\frac{2\alpha_s^2}{k_\perp^2d_s^2}G_{1s}\right]^2=0, \qquad (5)$$

$$G_{0s}=\Gamma_{0sk}\left\{-\alpha_sZ(\alpha_s)\left[1-\frac{\omega_{*n}}{\omega}+\frac{\omega_{*T_s}}{\omega}b_{sk}\left(1-\frac{I_{1sk}}{I_{0sk}}\right)\right]+\frac{\omega_{*T_s}}{\omega}\left[\alpha_s^2-\frac{1}{2}\alpha_sZ(\alpha_s)+\alpha_s^3Z(\alpha_s)\right]\right\}, \quad (6)$$

$$G_{1s}=G_{0s}-\Gamma_{0sk}\left[1-\frac{\omega_{*n}}{\omega}+\frac{\omega_{*T_s}}{\omega}b_{sk}\left(1-\frac{I_{1sk}}{I_{0sk}}\right)\right]. \qquad (7)$$

- **With long-wavelengths and steep T_e-gradient** in a fluid limit, one finds

$$\omega^3+\frac{k_\parallel^2v_{te}^2\omega_{*T_e}}{1-\Gamma_{0ik}}-\frac{\omega_{*T_e}}{k_\perp^2d_e^2}\omega^2=0. \qquad (8)$$

- **The critical beta for stabilization of the slab ETG mode** reduces to

$$\beta>\frac{3k_\perp^2\rho_{te}^2}{(1-\Gamma_{0ik})^{1/3}}\left(\frac{k_\parallel v_{te}}{2\omega_{*T_e}}\right)^{2/3}. \qquad (9)$$

- Equations (8) and (9) well capture destabilization/stabilization effects on the slab ETG modes with low- $k_\perp$.
- Nonlinear gyrokinetic simulations manifest that the low-$k_\perp$ ETG mode results in a high saturation amplitude, making a great impact on the electron turbulent transport [Maeyama et al., 2021].

KINETIC ION EFFECT ON TOROIDAL ETG MODES

- **Polarized ion model** derived from a simple modification of the adiabatic response is

$$\tilde{n}_{ik}=-(1-\Gamma_{0ik})\frac{e\tilde{\phi}_k}{T_i}. \qquad (10)$$

- **Linear stability** of toroidal ETG mode is well reproduced by the polarized ion model.

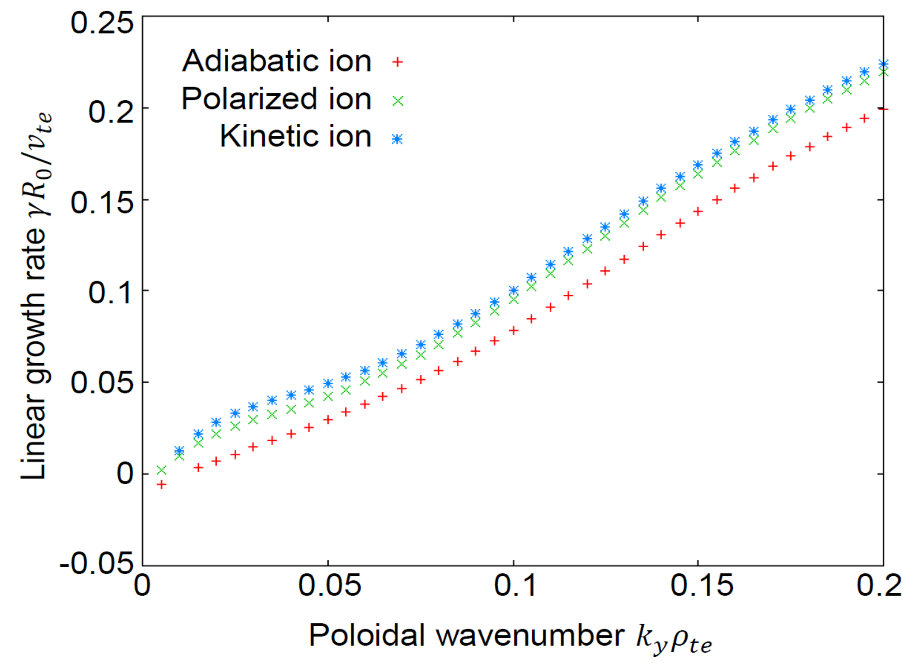

FIG. 1. Linear growth rate γ of toroidal ETG modes

- **Nonlinear turbulence simulations** with adiabatic, polarized, and gyrokinetic ion models demonstarate the role of kinetic ions, where the ion polarization plays a key role in turbulence regulation.

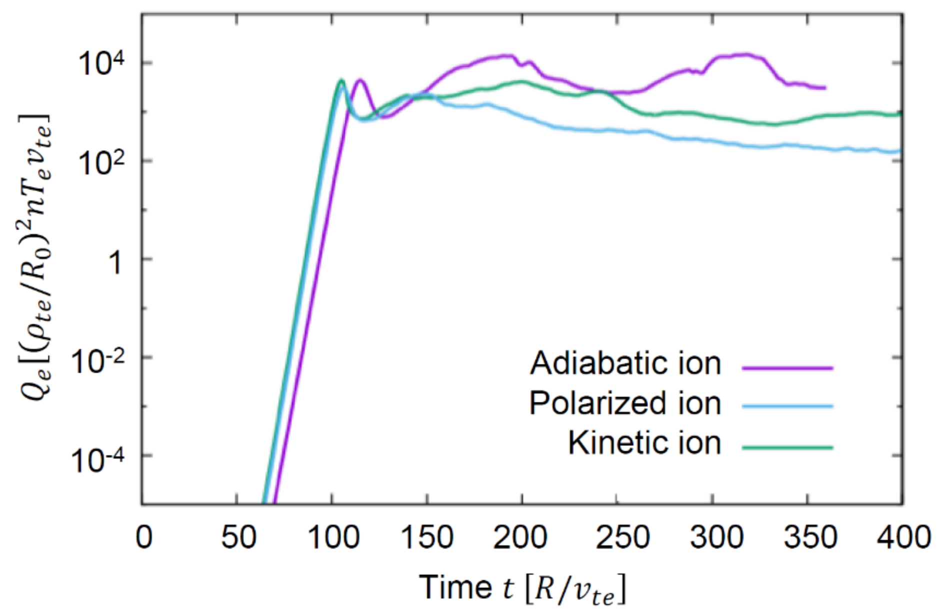

FIG. 2. Time histories of the electron heat flux Q_e obtained by gyrokinetic simulations of toroidal ETG turbulence

- **Vortex structures of the ETG streamers** are deformed by the secondary growth of the Kelvin-Helmholtz type instability enhanced at low $k_\perp$ through the kinetic ion effect [G. Plunk, 2007] , which is consistent with the results of the polarized ion model.

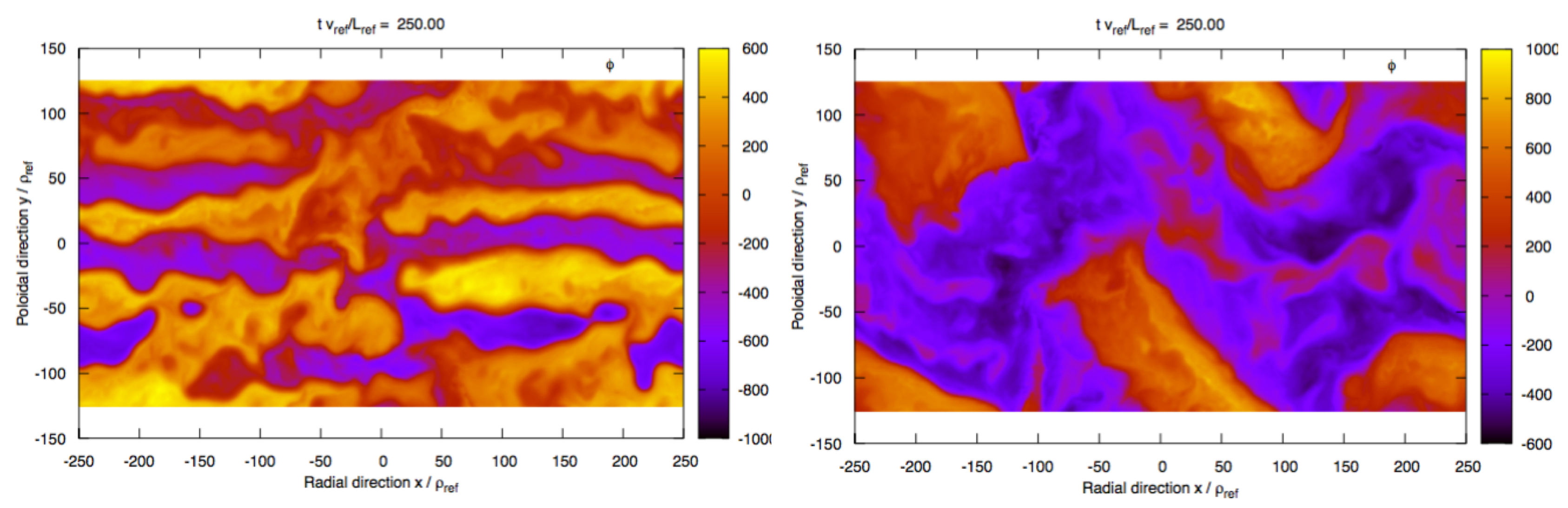

Fig.3 Snapshots of the electrostatic potential $\tilde{\phi}(x,y)$ (two dimensional slices at $z=0$) observed in the nonlinear saturation phase of the toroidal ETG turbulence in cases with the adiabatic (upper) and kinetic (lower) ion models.

SUMMARY

- **Ion polarization effect** enhances the slab and toroidal ETG instability in the low-$k_\perp$ regime.
- **Finite beta effect** works to stabilize the low-$k_\perp$ slab ETG mode.
- **Polarized ion model** mimics the kinetic ion response to the ETG modes both in the linear and turbulent regimes, and makes an impact on the electron heat transport.

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