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Nonlinear saturation and EP transport by TAE

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ABSTRACT

- Two mode coupling processes for toroidal Alfvén eigenmode (TAE) nonlinear saturation investigated using gyrokinetic theory.
  1. Zonal field structure (ZFS) excitation by TAE self-coupling and scattering TAE to linearly stable short radial wavelength regime
  2. Ion induced scattering cause TAE spectrum downward cascading and saturation due to enhanced coupling to SAW continuum
- Unified model developed accounting both effects on the same footing
- Consequence on EP transport evaluated

BACKGROUND

- Shear Aflvén wave (SAW) instabilities expected to be driven unstable by energetic particles (EPs) and induce EP transport: degrade overall plasma confinement
- TAE excited in toroidicity induced continuum gap: minimized continuum damping + favored resonance condition
- EP transport/redistribution rate depends on SAW instability amplitude & spectrum ⟵ nonlinear saturation
- Two important nonlinear mode coupling processes for TAE saturation: ZFS generation[Chen PRL12] & ion induced scattering[Hahm PRL95, Qiu NF19]
- This work: unified model simultaneously accounting for both effects in burning plasma relevant short wavelength parameter regime

Nonlinear ZFS generation

Zonal field structure

- Typically meso-scale radial corrugation: zonal flow (ZF), zonal current (ZC)
- Nonlinear excitation by DW/DAW + scatter DW/DAW into stable short radial wavelength domain
- ZFS excitation by TAE: breaking of pure Alfvénic state (PAS) due to toroidicity [Chen PRL12]

TAE self-regulation via ZFS generation

$$\nabla_\perp^2\left\{-k_\parallel^2V_A^2+\omega^2-\sum_k\left(\frac{c}{B_0}k_{\theta,k}\right)^2\left[1+\frac{(1-k_\parallel^2V_A^2/\omega_k^2)\omega_k}{\omega_Z\hat{\chi}_{iZ}}\right]\partial_r^2|\delta\phi_k|^2\right\}\delta\phi_k=0. \quad (1)$$

- ZC due from electron nonlinearity
- ZF due to Reynolds/Maxwell stresses noncancellation: breaking PAS ($1-k_\parallel^2V_A^2/\omega_k^2\neq 0$). $\hat{\chi}_{iZ}\simeq 1.6\,q^2/\sqrt{\epsilon}$: neoclassical shielding
- $\sum_k$: multiple TAE-pairs pumping ZFS simultaneously

Equation (1) reveals physics of several level:

1. single-n TAE + separate TAE into fixed-amplitude pump and sidebands with much smaller amplitudes: ZFS generation [Chen PRL12]
2. Single-n TAE: single-n TAE nonlinear evolution and saturation due to ZFS generation ("local"-scattering in n-space)
3. Multi-n TAEs: TAE evolution due to self-generated ZFS + ZFS generated by other TAE pairs ⟶ ZFS act as "mediator" for spectral energy transfer among TAEs

Nonlinear ion induced scattering

Ion induced scattering in low-β_i limit [Hahm PRL95]

- TAE (Ω_0) decay into another counter-propagating TAE (Ω_1) and a low-frequency ion quasi-mode (Ω_S) with finite $k_\parallel$
- Ω_S heavily Landau damped: ion induced/Compton scattering
- Spontaneous decay for $|\omega_0|>|\omega_1|$: downward spectrum cascading
  - ⟶ enhanced coupling to SAW continuum: saturation
  - ⟶ relevant to long-wavelength limit ($k_\perp^2\rho_i^2\ll\omega/\Omega_{ci}$)
- Wave energy $\propto\omega$: bulk ion heating [Hahm PST15]

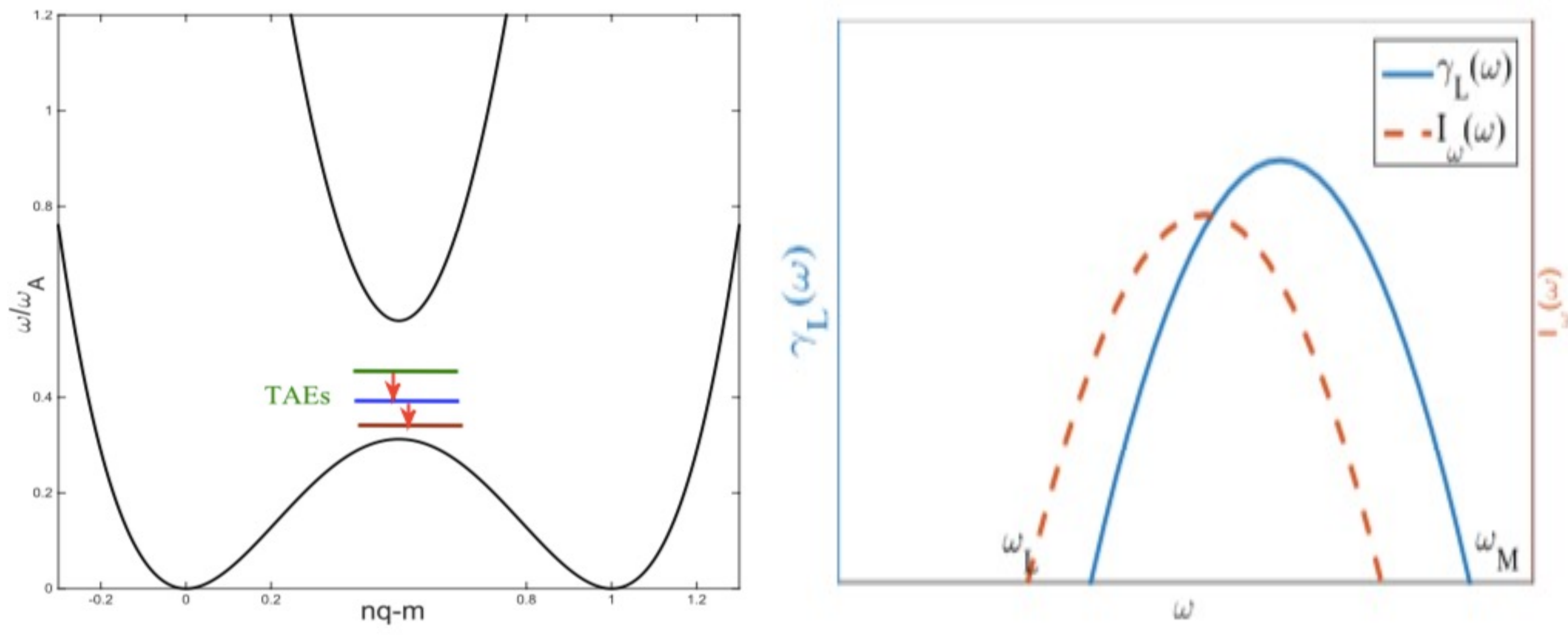

Fig 1: Cartoon for TAE cascading and spectral energy transfer

TAE saturation due to ion induced scattering

- Generalized [Hahm PRL95] to burning plasma relevant short wavelength regime [Qiu NF19]

$$\left[\mathcal{E}_0+\mathcal{E}_0^{\mathcal{NL}}+\sum_{k_1}\frac{\left(\Lambda^S_{0,1^*}\right)^2\beta_1\beta_2}{\hat{b}_0\tau\mathcal{E}_S}|\delta\phi_1|^2\right]\delta\phi_0=0 \quad (2)$$

- "Test" TAE $\delta\phi_0$ evolution due to interaction with background TAEs
- Consider only one background TAE + Ω_S heavily damped for $T_e\sim T_i$:
  ⟶ $\gamma+\gamma_0=|A_1|^2\left(\hat{C}_0/|\mathcal{E}_S|^2+\chi_0\right)\mathcal{E}_{S,i}/\left(\partial_{\omega_0}\hat{\mathcal{E}}_{0,R}\right)$
  1. spontaneous decay for $|\omega_0|>|\omega_1|$: downward cascading
- Many background TAEs within strong interaction region: "continuum limit" ⟶ wave-kinetic equation for spectral energy transfer:

$$\left(\partial_t-2\gamma_L(\omega)\right)I_\omega=\frac{2}{\partial_{\omega}\mathcal{E}_{\omega,\mathcal{R}}}\int_{\omega_L}^{\omega_M}d\omega' V(\omega,\omega')I_{\omega'}I_\omega$$

Saturated spectrum and EP transport derived:

$$|\delta B_r|^2\sim\frac{\epsilon^4\epsilon_{eff}^2}{2\,\tau\,\pi^{3/2}}\frac{\overline{\gamma_L}}{\omega_T}\frac{\omega_T^2/\Omega_{ci}^2}{k_\theta^4\rho_{it}^4}\sim 1.2\times10^{15}A_m q^2N_0^{-1}\epsilon^6R_0^{-2}\frac{T_E^2}{T_i^2}\frac{\overline{\gamma_L}}{\omega_T}$$

$$D_{Res}\sim\frac{1}{4}\frac{V_A}{k_{\parallel,0}}\left|\frac{\delta B_r}{B_0}\right|^2\sim 1.3\times10^{31}A_m^{1/2}\epsilon^6q^3N_0^{-3/2}R_0^{-1}\frac{T_E^2}{T_i^2}\frac{\overline{\gamma_L}}{\omega_T}$$

TAE saturation due to nonlinear mode coupling

- Two processes may have comparable cross-section/threshold condition
  - ✓ expected to play equally important roles in regulating TAE
  - ✓ should be accounted for simultaneously on the same footing
- unified model constructed from equations (1) and (2)

$$\nabla_\perp^2\left[\mathcal{E}_k+\mathcal{E}_k^{\mathcal{NL}}+\sum_{k_1}\frac{\left(\Lambda^S_{k,k_1^{*}{}^*}\right)^2\beta_1\beta_2}{\tau\rho_i^2\mathcal{E}_S}|\delta\phi_{k_1}|^2+\sum_{k_2}\left(\frac{c}{B_0}k_{\theta,k_2}\right)^2\left[1+\frac{(1-k_\parallel^2V_A^2/\omega_{k_2}^2)\omega_{k_2}}{\omega_Z\hat{\chi}_{iZ}}\right]\partial_r^2|\delta\phi_{k_2}|^2\right]\delta\phi_k=0$$

- ✓ Ion induced scattering: nonlocal scattering in n-space
- ✓ ZFS generation: local/nonlocal scattering in n-space
- ✓ TAE saturation due to competitive/synergetic effects

ACKNOWLEDGEMENTS / REFERENCES

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