Global theory of BAE excited by trapped energetic electrons

ID: 1154

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ABSTRACT

- The global dispersion relation of high-*n* beta-induced Alfvén eigenmodes (BAEs) excited by trapped energetic electrons (EEs) in tokamaks are investigated using gyrokinetic theory.
- The contribution of the trapped EEs to the global e-BAE dispersion relation is limited to the ideal MHD structure of the BAE.
- The different radial eigenstates can be unstable simultaneously; the radial mode structure is twisted by EEs and shows opposite deformation directions compared with that in the presence of EIs; the radial symmetry breaking mode structure w.r.t. $k_{||}$ has a potential impact on toroidal momentum transport.

BACKGROUND

- BAE, arising from the combined effects of the ion compressibility and the geodesic curvature of the magnetic field [M. Chu 1992PFB], can be affected by both EPs and thermal ions [F. Zonca et al 1999POP, X. Wang et al 2010PPCF] and has received considerable interest recently.
- BAEs excited by EEs (e-BAEs), have been observed on the low magnetic field side in HL-2A during the Ohmic and ECRH heating [W. Chen et al 2011NF] experiments.
- Gyrokinetic simulations [J. Cheng et al 2016POP, Y. Chen et al 2019POP] show that the EE precessional resonance is responsible for the e-BAE linear excitation and the opposite direction of the triangle mode structure w.r.t. that in the energetic ion (EI) driven BAE case.
- This work is to offer some ideas for multi-mode coexistence of e-BAE in the HL-2A [X.T. Ding et al 2013, 2018NF]; to explain the twisted mode structures; to illustrate the effect of radial symmetry breaking of mode structure on toroidal momentum transport.

GLOBAL DISPERSION RELATION OF e-BAE

THEORETICS MODEL AND DISPERSION RELATION

- The wavelength and frequency orderings: $k_\theta \rho_{Li} \approx \delta$, $k_\theta \rho_{Le} \approx \delta^{5/2}$, $k_\theta \rho_{Li} \approx \delta^2$, and $\varpi_{dEe} \approx \omega_{*i} \approx \omega_{ti} \approx \omega \approx O(\delta^{1/2})\omega_A$;
- The scalar potential $\delta\varphi$ and the parallel (to $\mathbf{b} = \mathbf{B}/B$) vector potential $\delta A_{||} \equiv -(c/\omega)\mathbf{b}\cdot\nabla\delta\psi$: to describe the electromagnetic fluctuations;
- Vorticity equation + gyrokinetic equation + quasi-neutrality condition: to investigate e-BAEs.

Methods: two spatial scales + asymptotic matching [L. Chen et al 1984PRL, L. Chen 1994POP].

$$D(\omega; r, \eta_k) \equiv i\Lambda(\omega) - \delta W_f(r, \eta_k) - \delta W_k(\omega, r, \eta_k) = 0 \qquad (1)$$

The deeply trapped EEs are dominant in the ideal MHD region of e-BAE dispersion relation [R. Ma et al 2020NF].

- δW_f and δW_k correspond to the generalized potential energy due to fluid-like plasma response and the kinetic EE behavior. $\Lambda(\omega)$ accounts for the generalized inertia response, including both thermal ion transit resonances and diamagnetic effects [F. Zonca et al 1996PPCF].
- Assumption: the radial dependence of $D(\omega; r, \eta_k)$ is mainly due to the profile of the energetic electrons via α_{Ee}, i.e., $\alpha_{Ee} = \alpha_{Ee0}\exp\left[-\frac{(r-r_0)^2}{L_{PE}^2}\right]$.

THE GLOBAL EIGENMODE ANALYSIS

The solution of Eq. (1) yields the condition of the most unstable e-BAE. The local equilibrium parameters: $r_0 = 0.5$, $q = 2.0$, $s = 1$, $\epsilon = 0.2$, $\tau = 1.0$, $\beta_i = 0.01$, $\frac{\omega_{*ni}}{\omega} = 1$, $\eta_i = 0.25$, $\frac{L_{ni}}{R_0} = 0.171$, $\eta_E = 0$, $k_\theta \rho_{LE} = 0.01$, $T_{Ei} \equiv \frac{T_{Ee}}{T_i} = 9$, $and\ n = 4$.

Figure 1 shows that the mode growth rate is maximum at $\eta_k = 0$ and $r = r_0$ and decreases as $|\eta_k|$ and $|r - r_0|$ increase. Taylor expanding $D(\omega; r, \eta_k)$ for (r, η_k) around $(r_0, 0)$, respectively.

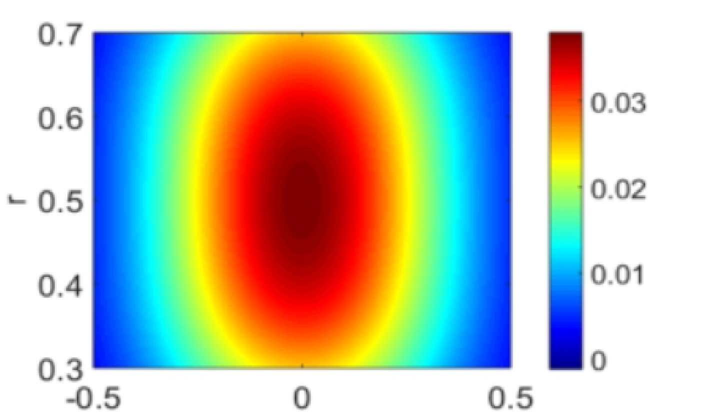

Fig.1 The contour plot of the growth rate of Eq. (1).

Keeping the leading-order contributions, Eq. (1) becomes [R. Ma et al 2021NF]

$$\left[\frac{\partial^2}{\partial z^2} + Q(\omega; z)\right] A(z) = 0 \qquad (2)$$

$z \equiv (nq - m_0) \simeq |nq'(r_0)|(r - r_0)$ and $q'(r_0) = dq/dr$ at $r = r_0$; $Q(\omega; z) = a + bz^2$ with $a \equiv 2(i\Lambda - \delta W_{f0} - \delta W_{k0})/(\delta W^{(2)}_{f\eta_k} + \delta W^{(2)}_{k\eta_k})$ and $b \equiv 2\delta W_{k0}/[L_{PE}^2 k_\theta^2 s^2 \left(\delta W^{(2)}_{f\eta_k} + \delta W^{(2)}_{k\eta_k}\right)]$. The two turning points $z_{T\pm}$ are given by $Q(\omega; z) = 0$. The matching of solutions yields the global dispersion relation for e-BAE, i.e.,

$$\int_{zT-}^{zT+} \sqrt{Q(\omega; z)}\, dz = (L + 1/2)\pi,\ L = 0,\ 1,\ 2, \ldots \qquad (3)$$

The integer L: the radial eigen-mode number labeling the different resonance states.

NUMERICAL RESULTS

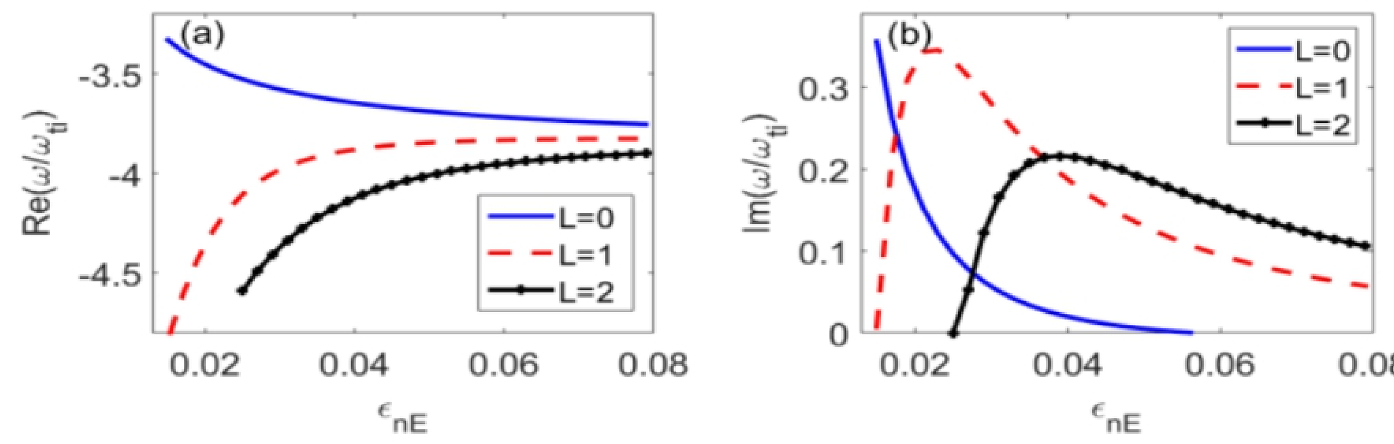

Fig.2 The dependence of the mode frequencies & the growth rates on ϵ_{nE}.

Figure 2 shows that the ground (L=0) and excited radial eigenstates (L=1,2) can be unstable simultaneously.

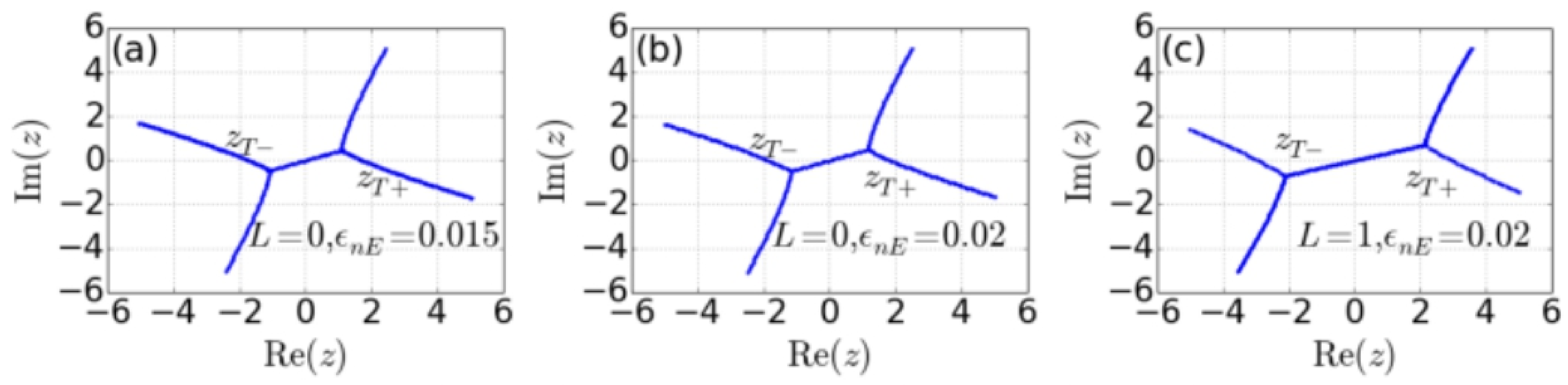

Fig.3 The Stokes structures in the complex-z plane.

Figure 3 shows that the most unstable mode is determined by the pressure gradient of EEs and the width of the mode itself.

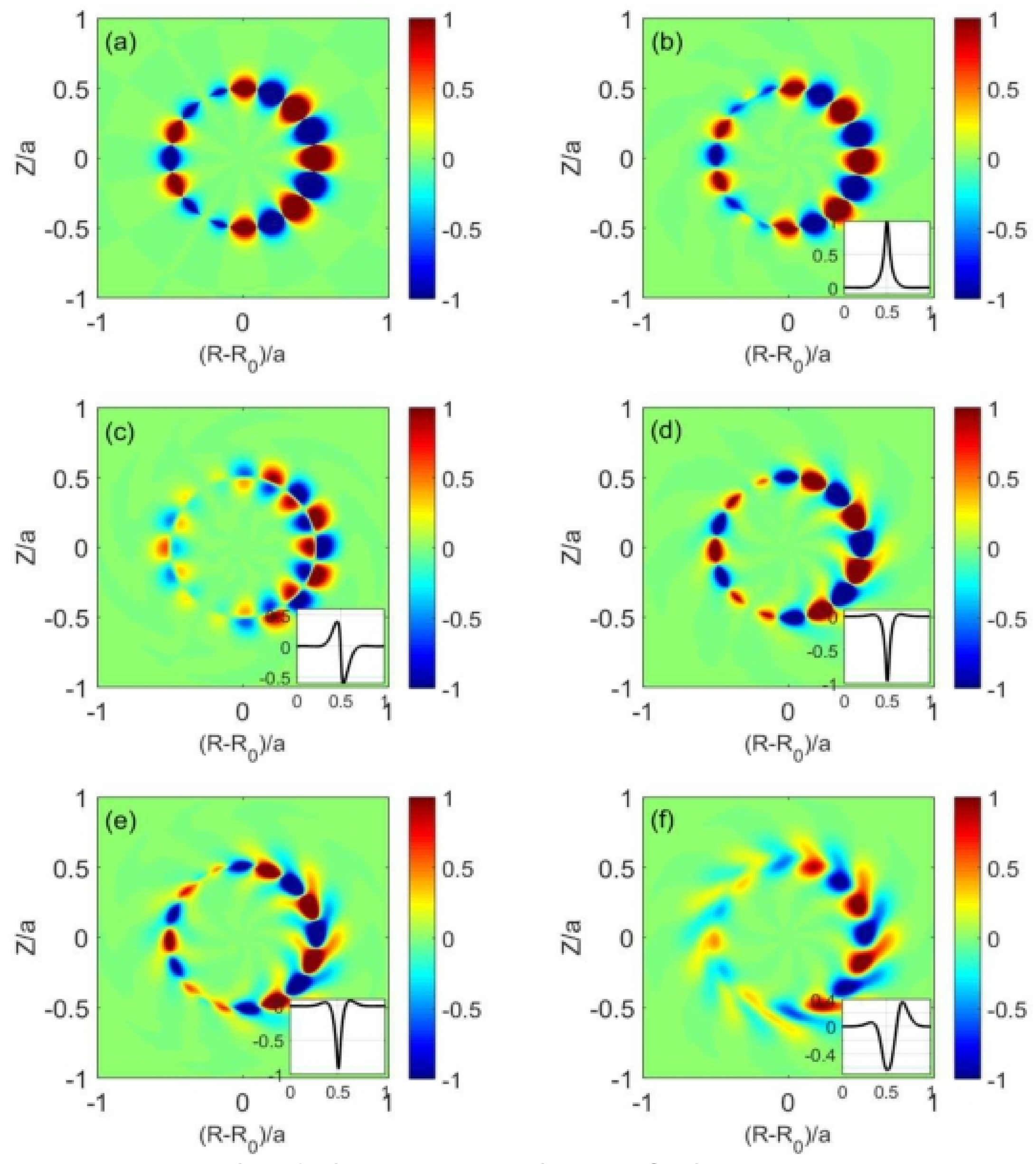

Figure 4 shows that the 2D poloidal mode structures are twisted by EEs.
The L affects the parity of mode structures.
The magnetic shear and EE density affect the mode structures.

Fig.4 Poloidal contour plots of electrostatic potential $\delta\phi_n(r, \theta)$ in (R, Z) plane.

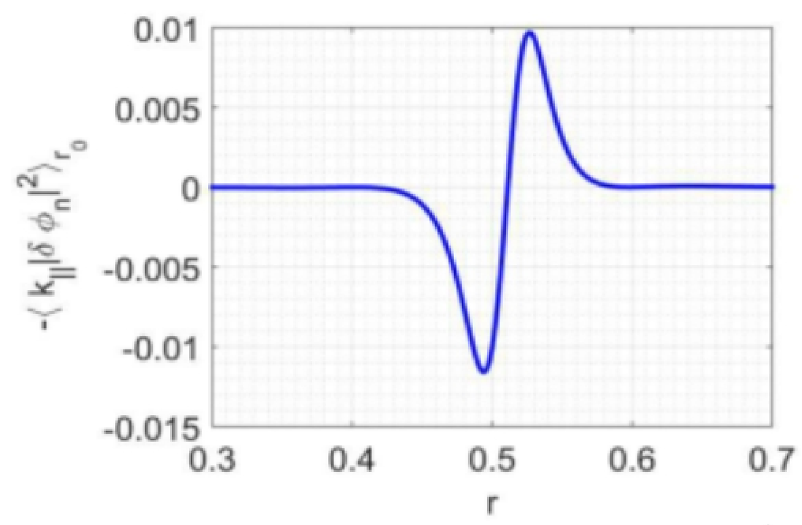

Figure 5 shows that $<k_{||}|\delta\phi_n|^2>_{r_0}$ is asymmetric w.r.t. $r = r_0$. By summing up the contribution from all rational surface, which will generate the residual parallel Reynolds stress.

Fig.5 The dependence of $-<k_{||}|\delta\phi_n|^2>_{r_0}$ on r in the presence of EEs.

ACKNOWLEDGEMENTS

- The work is supported in part by the ITER-CN under Grant No. 2018YFE0304103 and NNSF of China under Grant Nos. 11705050, and the ITER-CN under Grant No. 2017YFE0301900.