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Global theory of beta-induced Alfven eigenmode excited by trapped energetic electrons

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Free energy associated with Energetic particle (EP) pressure gradient, can drive collective instabilities, e.g., shear Alfvén waves, via wave-particle resonance, and induce EP anomalous transport due to the breaking of toroidal symmetry. One of such Alfvén wave instabilities, which has received considerable interest, is the beta-induced Alfvén eigenmode (BAE) [1].

BAEs have been recently observed in HL-2A during the Ohmic and ECRF heating [2]. Moreover, gyrokinetic simulations using HL-2A parameters [3] show that the precessional resonance of trapped energetic electrons (EEs) can drive BAE (e-BAE) instabilities and induce the typically observed croissant-like up-down asymmetric mode structures. To our knowledge, detailed theoretical understanding of the e-BAE physics, including the excitation mechanism, the global stability and corresponding radial mode structures, are still lacking. On the other hand, the EE finite orbit width normalized to the minor radius of the present-day tokamaks, could be comparable to that of the alpha particles characterized by small dimensionless orbits in reactors, e.g., ITER. Thus, the in-depth understanding of the e-BAE physics based on first-principle-based theory [4] is needed, and this constitutes the main motivation of the present work.

In this work, employing the WKB-ballooning mode representation along with the generalized fishbone like dispersion relation [5], the two-dimensional (2D) global dispersion relation of the high-n e-BAEs excited by precessional resonance of magnetically trapped EE is derived in large aspect-ratio, low-β and low magnetic shear tokamaks with shifted circular flux surfaces. It has been proved that [6] the contribution of the trapped EEs to the global e-BAE dispersion relation is limited to the ideal MHD structure of the BAE due to the EE bounce averaging dynamic being governed by normal curvature. Moreover, our numerical results show that, (i) for the local properties of e-BAE: the mode can be destabilized by EEs using the typical equilibrium parameters in HL-2A, and the mode frequency is consistent with the experimental observation. Varying the background plasma parameters can lead to transitions between e-BAEs and energetic particle modes. Moreover, the dependence of the e-BAE frequencies and growth rates on energetic electron parameters shows that the growth rates monotonically increase(decrease) with the energetic electron density(the normalized energetic electron density gradient scale length), and the frequencies are not much affected. The frequency and growth rate are sensitive to the energetic electron temperature, and there exists a maximum growth rate. (ii) For the global properties of e-BAE [6], the mode is radially localized in the potential well generated by the pressure gradient of EEs, and for the parameter regime we interested, (i) at the ground radial eigenstate, the mode growth rate has a maximum with increasing energetic electron density; (ii) the ground and excited radial eigenstates can be unstable simultaneously, and the most unstable mode is related not only to the pressure gradient of energetic electrons, but also to the width of the mode itself; (iii) the corresponding two-dimensional mode structures are twisted due to the anti-Hermitian contribution from wave-energetic electron interaction and show an opposite deformation directions compared with that in the presence of energetic ions, shown in Fig. 1, which agrees with that of the existing numerical simulations. Finally, we have also shown that, the radial symmetry breaking of mode structure with respect to parallel wave-number has a potential impact on toroidal momentum transport, which is with, however, relatively weak importance on transport due to the relatively localized e-BAE mode structure.

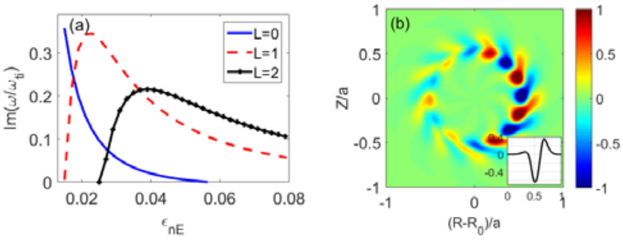

Figure 1 (a) The mode growth rates of e-BAE vs ϵ_{nE} for different radial mode number L; (b) Poloidal contour plots of $\delta\phi(R, Z)$.

References

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