

## CONFERENCE PRE-PRINT

## KINETIC MODELING OF INTERACTIONS AMONG DRIFT-ALFVEN INSTABILITY, CONTINUOUS SPECTRUM AND ENERGETIC PARTICLE IN FUSION EXPERIMENTS

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Drift-Alfven wave (DAW) instabilities have been widely observed in tokamak experiments that interact with both thermal and energetic particles and play important roles in plasma anomalous transport processes, of which fluctuation spatial scales cover the range from the thermal ion Larmor radius to the system-size, and the frequency spectra cover the whole range from acoustic frequency up to Alfven frequency. We developed an eigenvalue code MAS that non-perturbatively couples drift-MHD model for bulk plasmas and gyrokinetic model for energetic particles, which captures the important kinetic effects of thermal plasmas beyond MHD and non-perturbative effects of energetic particles beyond traditional perturbative method. Building on the kinetic physics capability and attractive efficiency in computation, MAS has the advantages of fast calculation of dispersion relation and global mode structure for various DAW instabilities in general experimental geometry, which is helpful for understanding the experimental observations.

## 1. INTRODUCTION

Drift-Alfven wave (DAW) instabilities including dissipative- and reactive-type modes are widely observed in fusion experiments, which influence the bulk plasma and energetic particle (EP) transports and attract researchers' attentions [1]. Evaluations of these unstable DAWs require kinetic treatments on both EP and bulk plasma responses in a self-consistent and non-perturbative manner, which are responsible for EP drive through wave-particle resonance and bulk plasma damping induced by DAW-continuum interaction, respectively [2]. In this talk, we shall report our efforts in this aspect, a new plasma stability toolbox MAS (Multi-scale Analysis for plasma Stability) using general geometry is developed from scratch that consists of global kinetic-MHD eigenvalue code, gyrokinetic orbit code and Boozer coordinate mapping code, which integrates the continuous spectra, low- $n$  MHD modes, mediate- $n$  Alfven eigenmodes (AEs) and high- $n$  drift-wave instabilities in an unified physical and numerical framework that supports a hierarchy of kinetic physics levels beyond MHD, and provides the distribution of orbit characteristic frequencies in Constant of Motion (CoM) phase space with calculating corresponding resonance lines [3-8]. MAS balances theoretical and experimental requirements on key physics issues of mode structure and polarization, excitation mechanism, resonance condition etc., and has been successfully applied for DAW problems with wave toroidal mode number ( $n$ ) and frequency ( $\omega$ ) in a broad range of interest, of which physics model, methodology and workflow can benefit the community for fast parameter scans, shot-to-shot analysis and the optimization of fusion experiments.

## 2. KINETIC PHYSICS MODELS FOR EACH SPECIES AND NON-PERTURBATIVE COUPLING SCHEME

In MAS framework, the bulk plasma is described by drift-MHD model using proper closure technique for both electron and ion Landau resonance, as well as keeping other kinetic effects beyond MHD including electron and ion diamagnetic drifts, ion finite Larmor radius (FLR) and finite parallel electric field etc., which faithfully captures the continuum damping, radiative damping and Landau damping [3]. Meanwhile, energetic ion (EI)/electron (EE) based on gyrokinetic/drift kinetic models are implemented in MAS and coupled with bulk

plasma model non-perturbatively through EP moments integrated from distributions, and the contributions of adiabatic fluid convection and non-adiabatic kinetic compression are separated for distinguishing interchange ballooning drive and wave-particle resonance drive, respectively. The dominant wave-particle resonances and finite orbit width (FOW) effects are retained for calculating EP responses to arbitrary wave length electromagnetic fluctuations [4,5], with an efficient numerical scheme that integrates EP distribution function in velocity space using well-circulating and deeply-trapped approximations for high aspect ratio machines, which greatly improve the computational efficiency with keeping leading order physics that can recover theory in the long wavelength limit.

### 3. VERIFICATION & VALIDATION

MAS has been well benchmarked with theory and other gyrokinetic and kinetic-MHD hybrid codes in a manner of adopting the unified physical and numerical framework, which covers the normal modes of kinetic Alfvén wave and ion sound wave, the MHD modes of low- $n$  kink and tearing [9], and the drift-wave instabilities of high- $n$  ion temperature gradient mode and kinetic ballooning mode [10]. Regarding the practical application, MAS is successfully applied to model the AE activities in DIII-D discharge #159243, which exhibits good agreements with other codes on RSAE mode structure and dispersion relation, and the FOW stabilization effect is found to be important in the regime of  $k_{\perp}\rho_d \geq 1$  (where  $\rho_d$  is the magnetic drift orbit size). Two typical physics processes of RSAE and TAE are shown in Fig. 1 and Fig. 2, i.e., RSAE frequency sweeping and TAE radiative damping, which reflect the correlation between continuous spectra and AEs as well as their tunneling interaction through bulk plasma kinetic effects [3]. It is also found that plasma diamagnetic drifts can induce the frequency shift of Alfvén continuum to the ion direction [6], which breaks the ion-electron MHD symmetry that can be significant in the edge pedestal. Several key issues of EE-driven BAE (e-BAE) are analyzed, including the parametric dependences of e-BAE stability on EE mass, temperature and density with corresponding phase space dynamics, EE non-perturbative effects on the symmetry breaking of mode structure, and the EE density and temperature thresholds for e-BAE excitation required to overcome bulk plasma damping [4,7]. The synergy effects of energetic ions and energetic electrons on BAE stability are also investigated [8]. It is found that for the center-peaked EI and EE pressure profiles that effectively drive i-BAE and e-BAE unstable, the synergy effects between EI and EE can lead to the stabilizations for both i-BAE and e-BAE branches, which attribute to the EP fluid convection and kinetic particle compression (KPC) responses, that modify the MHD interchange and wave-particle resonances. As shown in Fig. 3, a stabilizing regime due to EE and EI synergy effects is then demonstrated for BAE, which is helpful for explaining experimental observations and control of Alfvén eigenmode activities through multiple auxiliary heatings.

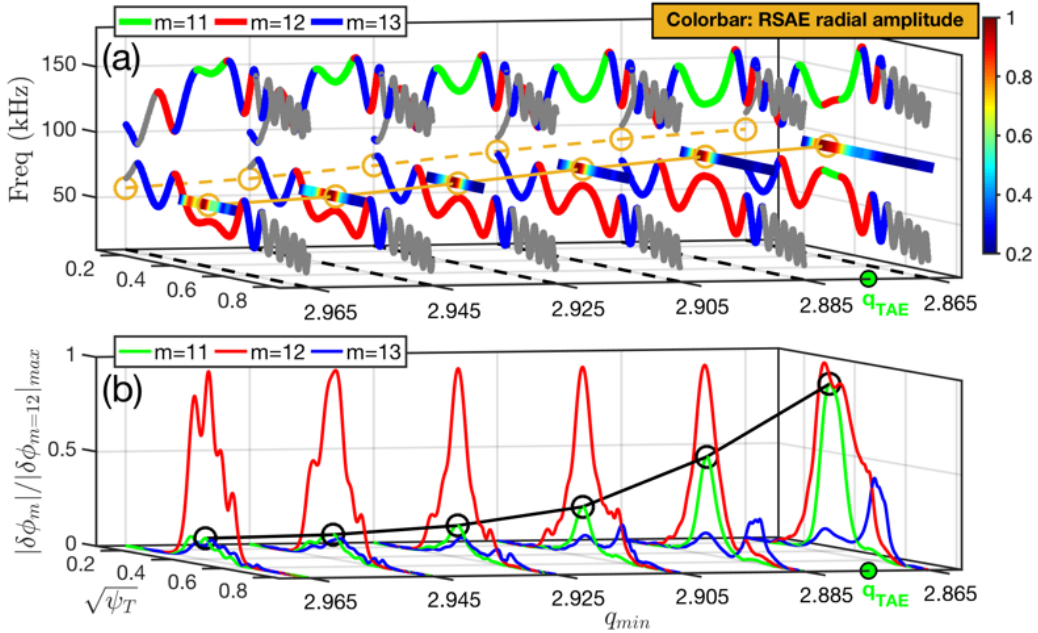


FIG. 1. Evolutions of (a) continuous spectra and (b) RSAE mode structures as  $q_{min}$  decreases in DIII-D shot #159243. (Figure reproduced from Ref. 3)

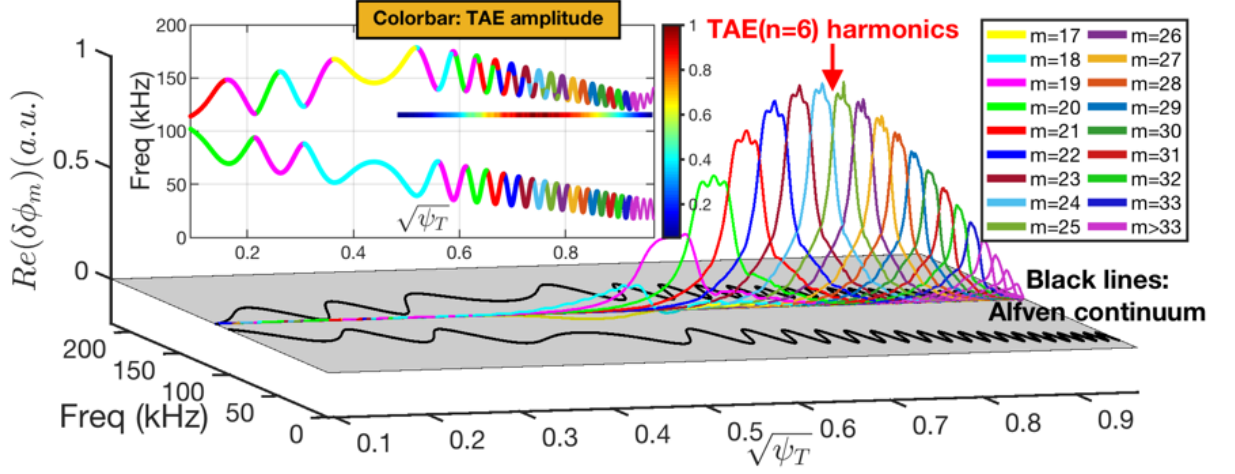


FIG. 2. Tunneling interaction between  $n=6$  TAE and Alfvén continua in DIII-D shot #159243. The TAE energy is dissipated by the kinetic Alfvén waves characterized by fine scale structures on top of each  $m$ -harmonics. (Figure reproduced from Ref. 3)

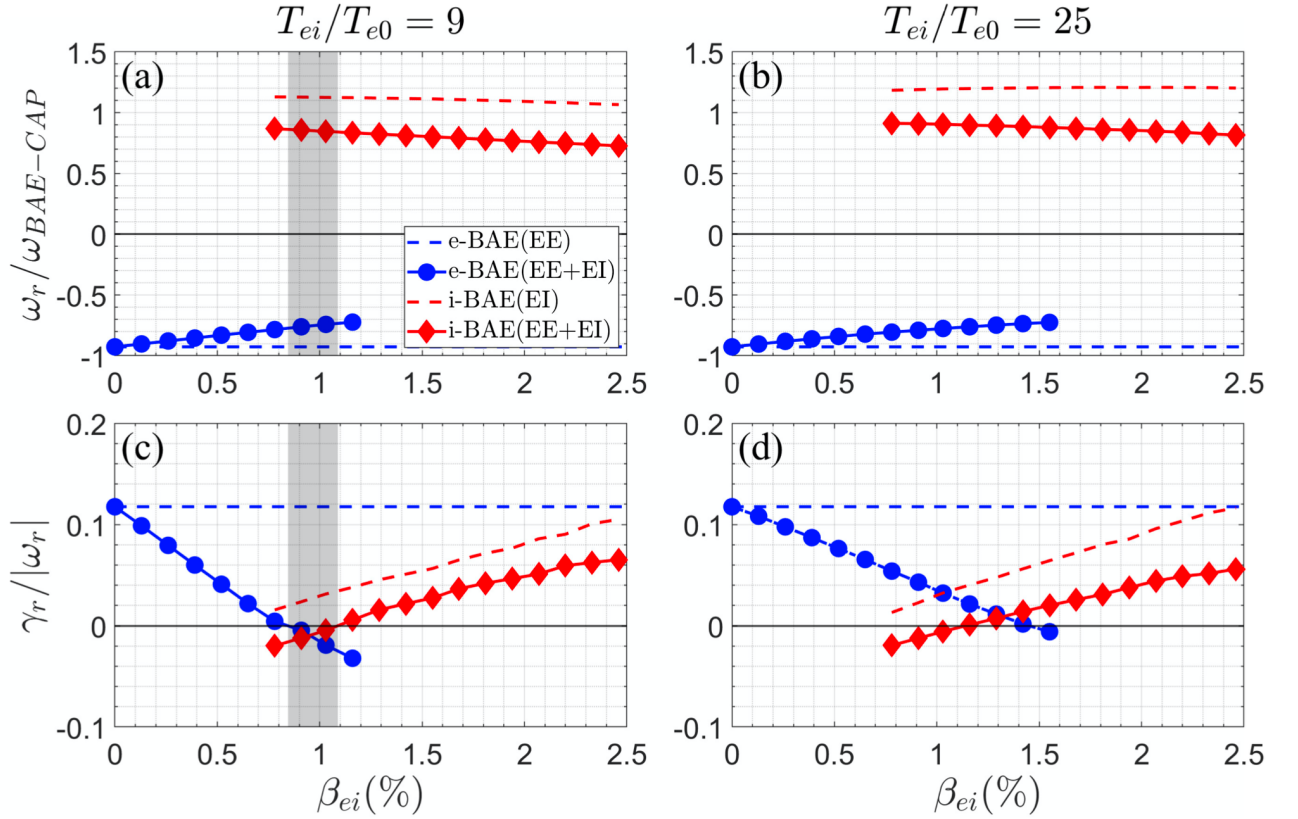


FIG. 3. The dispersion relations of e-BAE and i-BAE with different fractions of energetic ion (EI) and energetic electron (EE). The solid marker lines represent the cases with EI and EE synergy effects, while the dashed lines represent the cases with only EP species for excitation.  $\omega_{BAE-CAP}$  represents the frequency of BAE continuum accumulation point. (Figure reproduced from Ref. 8)

#### 4. PRACTICAL APPLICATIONS

Building on the kinetic physics capability, MAS has been widely applied for analyzing AE problems in EAST [11-16] and HL-2A [17] experiments, such as continuous spectra, AE fluctuation distribution and resonance condition etc. It is worthwhile mentioning that passing EEs that move much faster than Alfvén velocity can be able to destabilize EAEs in EAST discharge, which attribute to the fact that the large poloidal and toroidal frequencies mostly cancel each other and satisfy the EAE resonance condition with primary energy exchange from MAS simulation as shown in Fig. 4 [13], and thus provide insights for alpha particle physics in future fusion reactor characterized by small normalized orbit width (normalized by machine size). Recently, MAS is also applied for the Alfvén continuum analysis in the design of China Fusion Engineering Demo Reactor (CFETR) as shown in Fig. 5 [18]. Besides the experimental applications, MAS has several theoretical applications under reviews, including radial phase variation of RSAE-TAE hybrid mode induced by EI non-perturbative effect in Fig. 6, and the polarization properties of AE gap modes and continuous spectra in spherical tokamak in Fig. 7. Regarding to the key progress to the community, MAS has the advantage of combining rich physical ingredients, realistic global geometry and high computation efficiency together for plasma stability analysis, especially on covering modes with both electrostatic and electromagnetic polarizations from microscale high- $n$  to macroscale low- $n$  regimes, and processing the self-consistent interactions among continuous spectra, discretized eigenmodes and EPs through non-perturbatively incorporating various bulk plasma and EP kinetic effects.

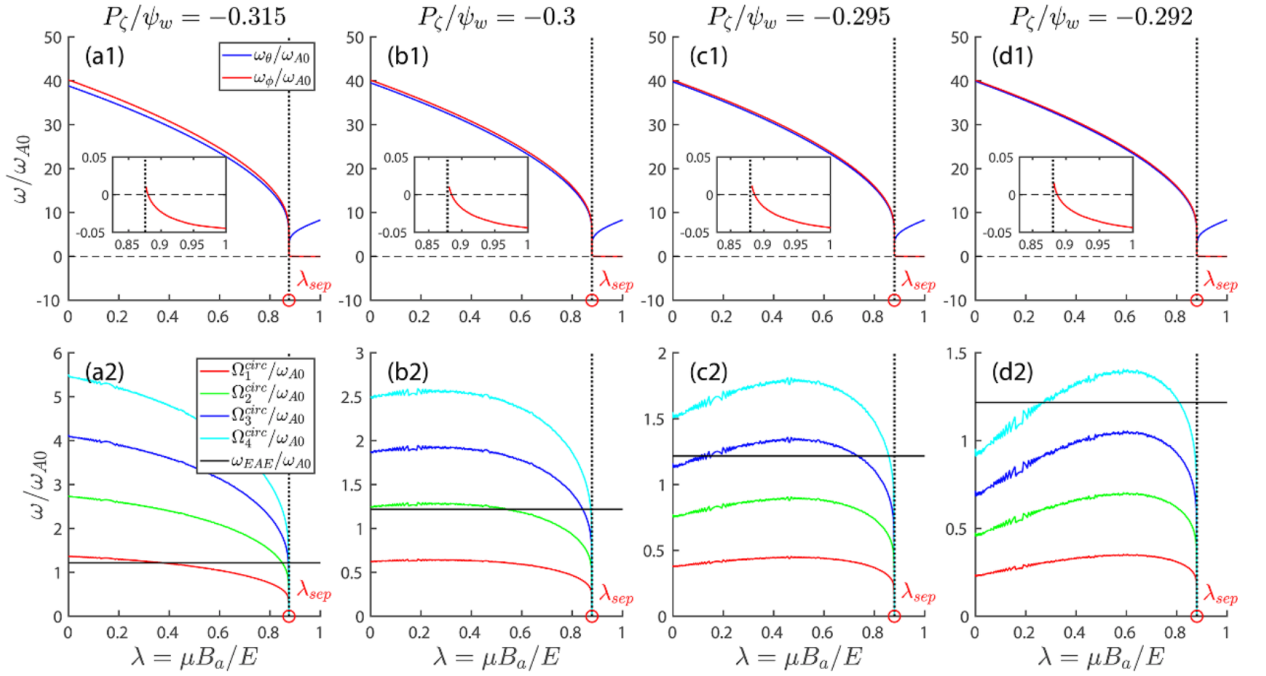


FIG. 4. (a1)-(d1) The pitch angle ( $\lambda = \mu B_a/E$ ) dependences of toroidal and poloidal frequencies of passing EEs at different radial locations in EAST shot #112786. (a2)-(d2) The EAE frequency  $\omega_{EAE}$  and EE characteristic frequency curves with  $n=1-4$ :  $\Omega_1^{circ} = \omega_\phi - \omega_\theta$ ,  $\Omega_2^{circ} = 2\omega_\phi - 2\omega_\theta$ ,  $\Omega_3^{circ} = 3\omega_\phi - 3\omega_\theta$ , and  $\Omega_4^{circ} = 4\omega_\phi - 4\omega_\theta$ . (Figure reproduced from Ref. 13)

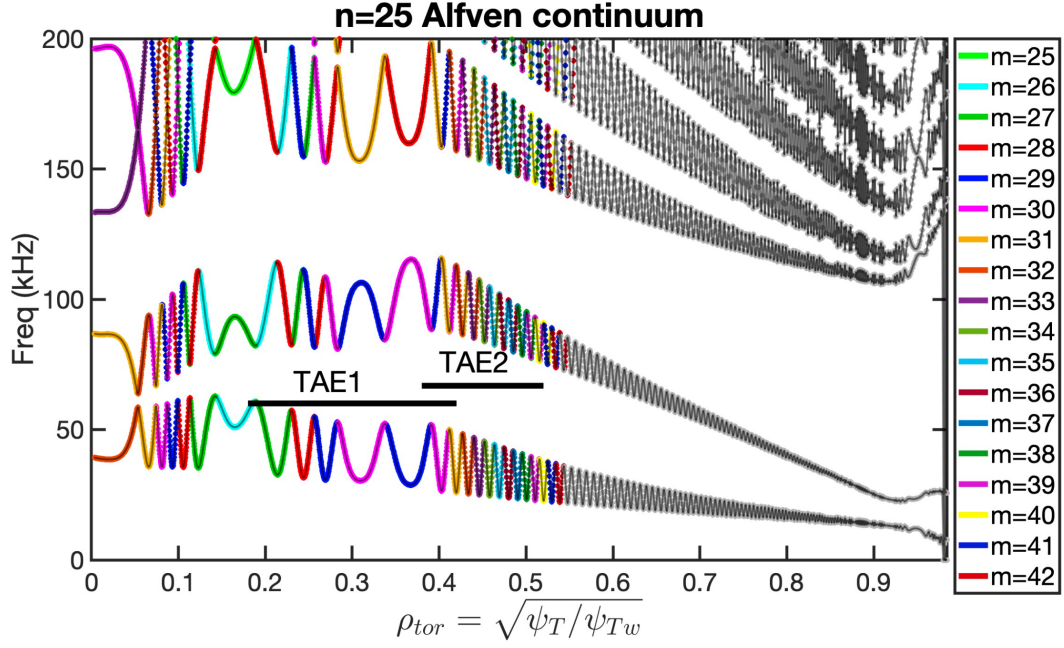


FIG. 5.  $n=25$  Alfvén continuum and two dominant TAEs driven by alpha particles in the core of CFEDR-H mode plasmas. (Figure reproduced from Ref. 18)

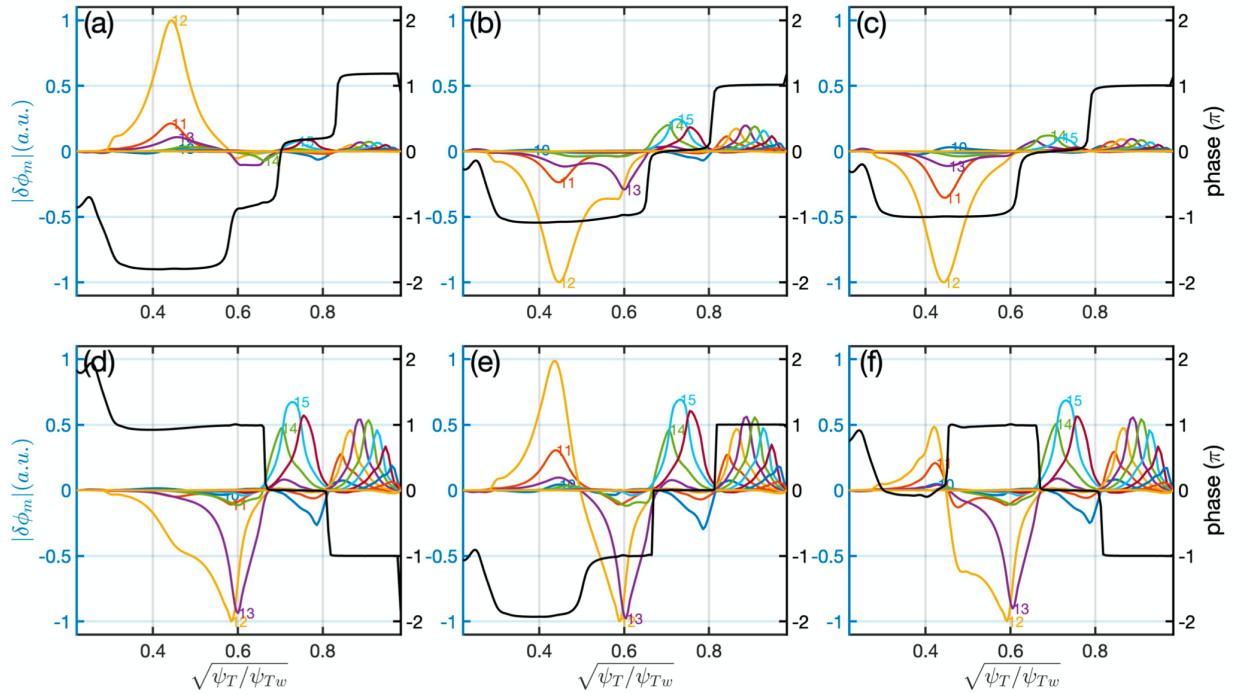


FIG. 6. The radial mode structures of RSAE-TAE hybrid modes in DIII-D shot #159243. The  $q_{min}$  value gradually decreases from (a) to (f) during RSAE frequency up-sweeping.

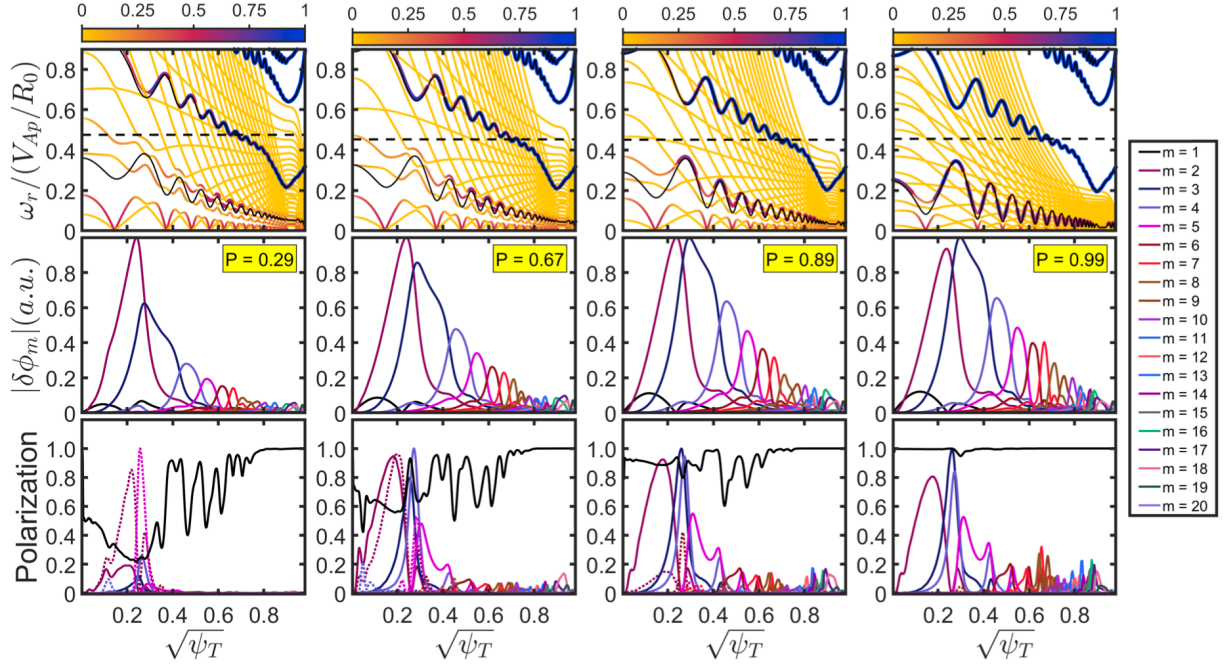


FIG. 7. Continuous spectra and polarization of  $n=3$  TAE in EXL-2 spherical torus. From the left to the right columns:  $\beta_e = 6.91\%$ ,  $\beta_e = 4.84\%$ ,  $\beta_e = 2.76\%$  and  $\beta_e = 0.69\%$  are applied. In the top row of continuous spectra, the color indicates the polarization defined by the Alfvénic component fraction of  $0 \leq P \leq 1$ , and the black solid lines represent the Alfvén continuum using slow sound wave approximation.

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