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 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, so that EP-drive through wave-particle resonance and bulk plasma-damping induced by DAW-continuum interaction can be accurately described [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 covers 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 calculates character frequency for all orbit-types in Constant of Motion (CoM) phase space [3-7]. 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 DAWs with toroidal mode number (n) and frequency (ω) in a broad range of interest, of which physics model, methodology and workflow benefit the community through fast parameter scans, shot-to-shot analysis and the optimization of fusion experiments.

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, and 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 to 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 wavelength 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 improves the computational efficiency without sacrificing leading physics.

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 [3], which covers the normal modes of kinetic Alfvén wave and ion sound wave, the MHD modes of low-n kink and tearing [8], and the drift-wave instabilities of high-n ion temperature gradient mode and kinetic ballooning mode [9]. MAS is successfully applied to model the AE activities in DIII-D discharge #159243, and the EI FOW stabilization effect is found to be important in the regime of $k_\perp \rho_d \geq 1$ being consistent with GTC first-principle gyrokinetic simulations (ρ_d is the magnetic drift orbit size) [5]. 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 indicate the correlation between continuous spectra and AEs as well as their tunneling interaction through bulk plasma kinetic effects [3]. It is also found that the thermal ion FLR effect can induce Alfven continuum shift to the ion direction, which breaks the ion-electron MHD symmetry that can be significant in the edge pedestal [6].

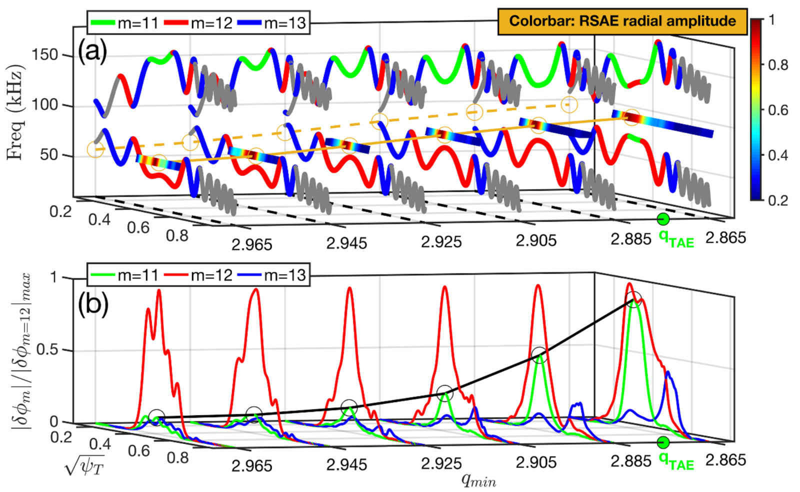

Fig. 1 Evolutions of (a) continuous spectra and (b) RSAE mode structures as q_{min} decreases in DIII-D shot #159243.

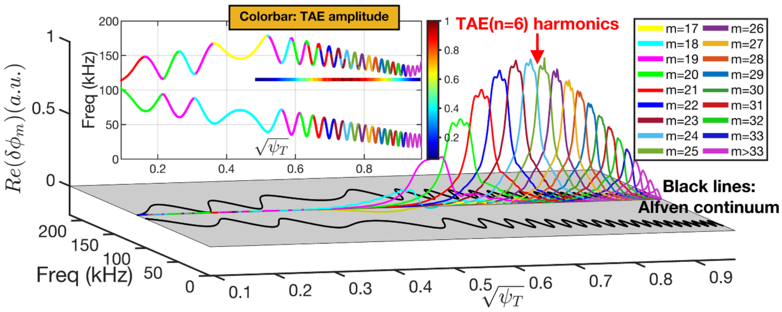

Fig. 2 Tunneling interaction between n=6 TAE and Alfvén continua in DIII-D shot #159243. The TAE energy is dissipated by the kinetic Alfven waves characterized by fine scale structures on top of each m-harmonics.

Practical Applications-- Building on the kinetic physics capability, MAS has been widely applied for AE problems in EAST and HL-2A 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 [10], which attribute to the fact that large poloidal and toroidal frequencies mostly cancel each other and satisfy the EAE resonance condition with primary energy exchange from MAS simulation, and thus provide insights for alpha particle physics in future fusion reactor characterized by small normalized orbit width (normalized by machine size). Besides the experimental applications, MAS has several theoretical applications, including EE-driven BAE (e-BAE) [4,7], RSAE-TAE hybrid mode, synergy effect of EI and EE on BAE stability, and the polarization characters of AE gap modes and continuous spectra in spherical tokamak etc. Regarding to the key contribution 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 cross microscale high-n to macroscale low-n regimes, and processing the self-consistent interactions among continuous spectra, discretized DAWs and EPs through non-perturbatively incorporating various bulk plasma and EP kinetic effects.

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