Shear Alfvén fluctuation spectrum in Divertor Tokamak Test facility plasmas

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Outline

- Introduction
- Simulation model and parameters
- Linear stability analyses
  - Central core linear stability analyses
  - Outer core linear stability analyses
- Summary and discussion

Introduction

- The Divertor Tokamak Test (DTT) facility mainly focuses on investigating power exhaust solutions for DEMO.
- There exists substantial integrated core and edge plasma physics in DTT plasmas, which is reflected in terms of a set of dimensionless parameters.
- The key physics aspects considered in this work are the properties of the Alfvénic fluctuation spectra in DTT and the related EP dynamics.

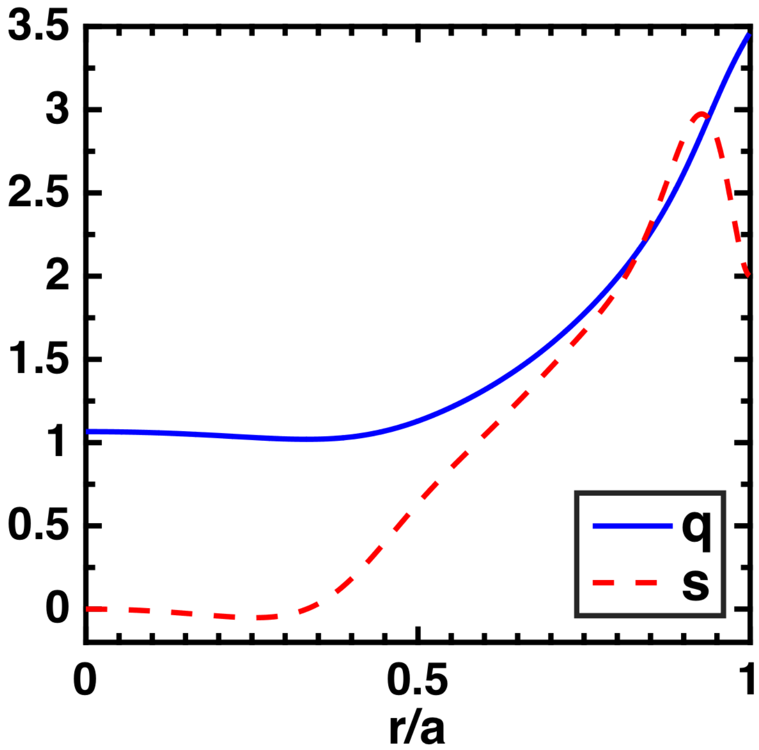
Introduction

- Simulations by HMGC to investigate the meso-scale features of Alfvénic fluctuation spectrum. We assume a typical DTT (FAST) reference scenario, based on a FAST-reference equilibrium and ITER-like EP parameters. FAST carries similar core plasma profiles and dimensionless parameters with respect to DTT. The equilibrium is also similar to ITER.
- Therefore, this work could also provide insights into relevant physics for next generation Tokamaks (e.g. ITER and CFETR).
- We perform single n simulations with $n = 2 \sim 10$, which is consistent with the DTT target design and relevant spatiotemporal scales.

Simulation model and parameters

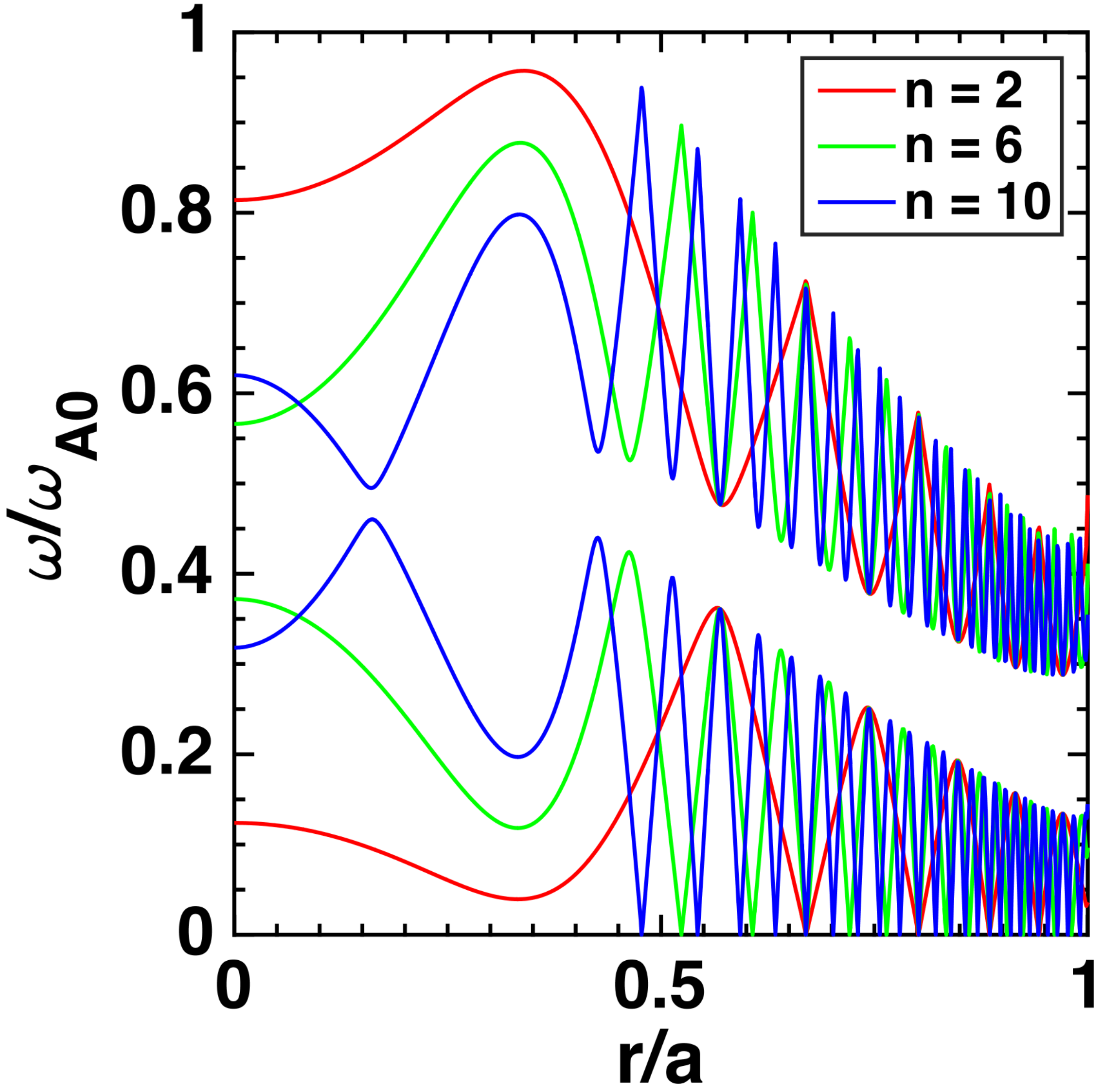
HMGC physics model

- Hybrid model, non-perturbative EP treatment.
- Core plasma are assumed to be cold.
- High aspect ratio equilibrium with shifted circular magnetic surfaces.



- $\varepsilon = 0.18$ allows us to extend the approach to moderate or high n.

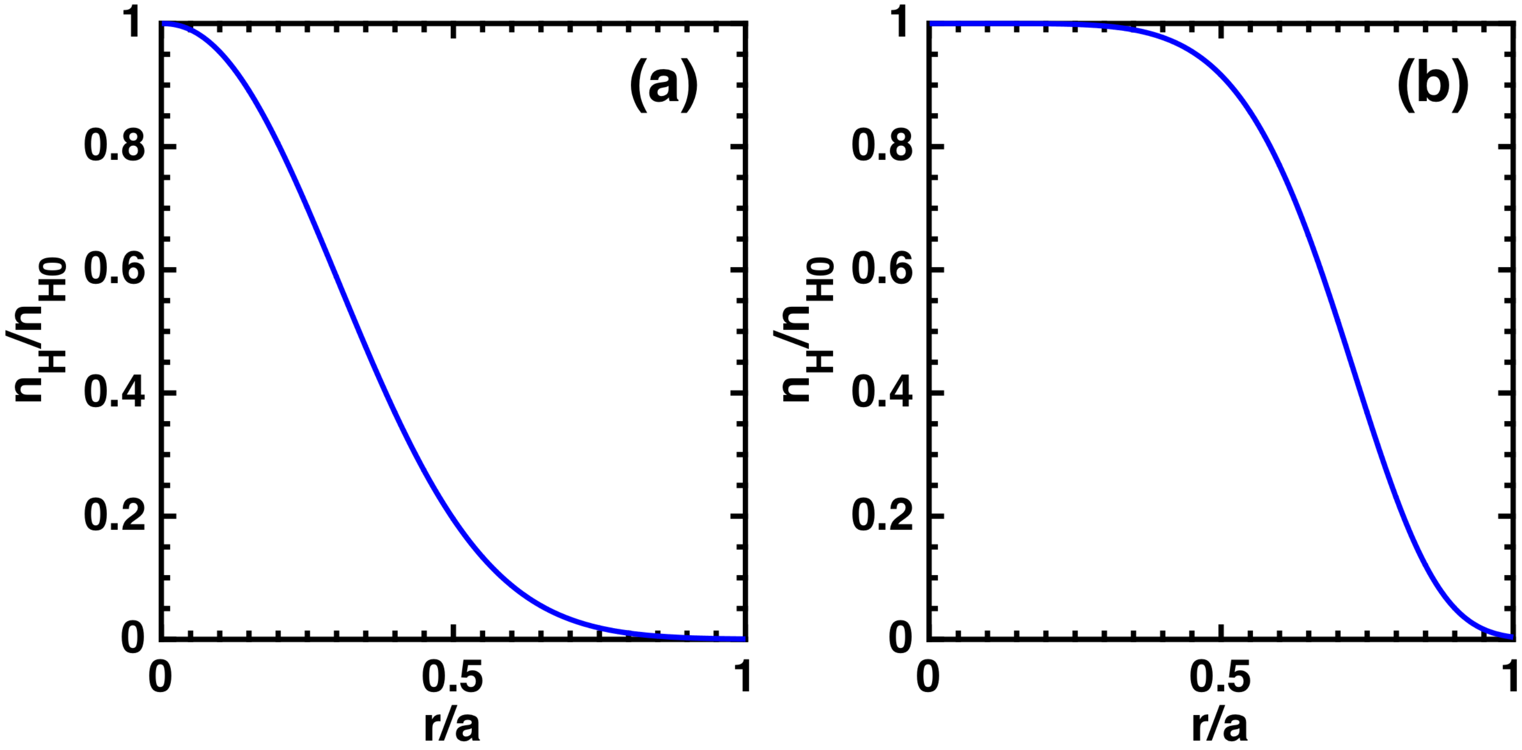
Simulation model and parameters



- Two regions can be identified from q profile and the features of shear Alfvén continua.
- Central core region with nearly flat q and reverse shear, and outer core region with larger q and finite shear.
- Existence of frequency gaps can also be noted.

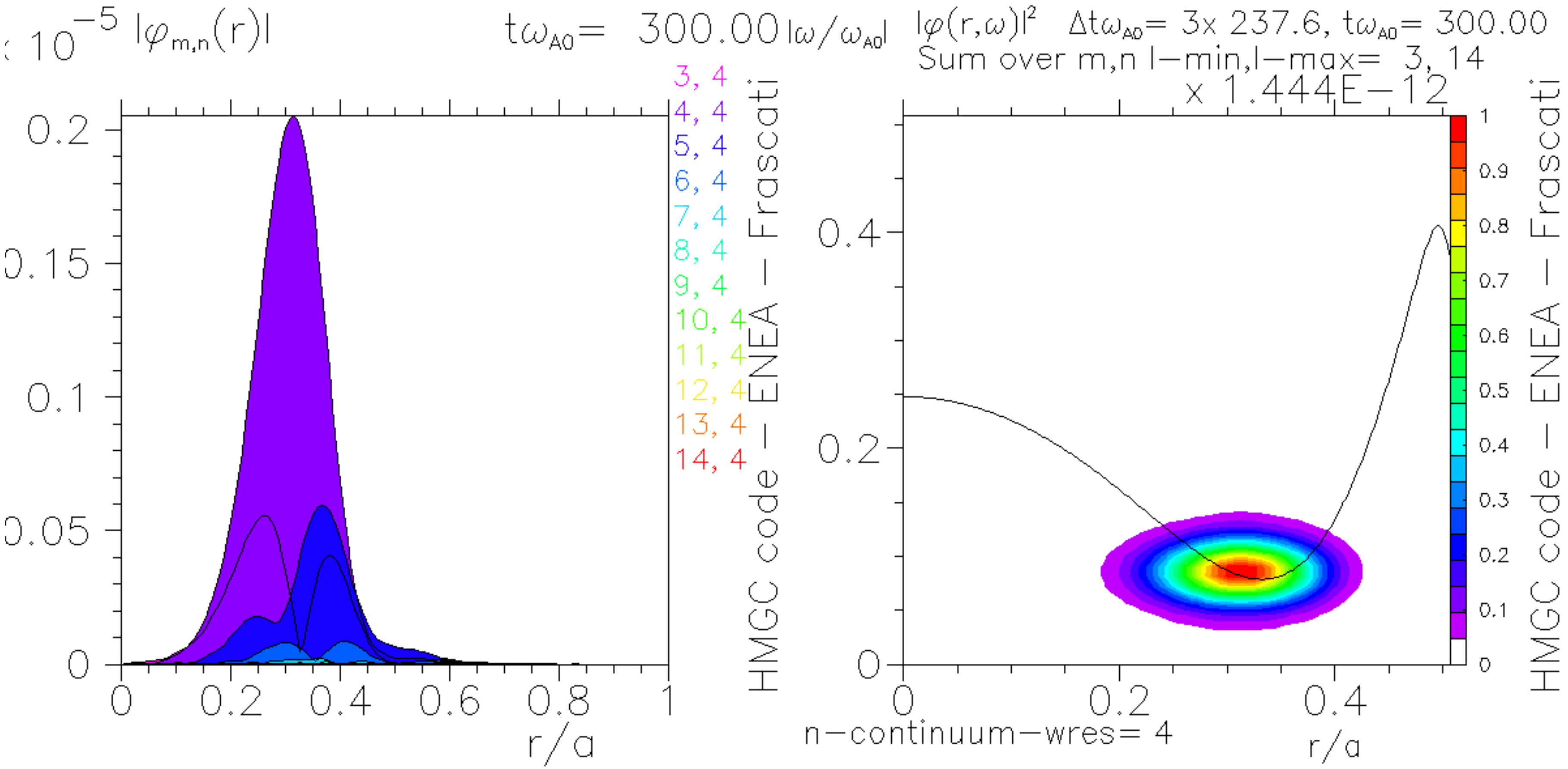
EP parameters

- EPs are assumed to be characterized by an isotropic slowing-down initial distribution function.
- $\rho_H/a = 0.01$, $v_H/v_{A0} = 1.80$, $n_{H0}/n_{i0} = 3.0\times10^{-3} \rightarrow \beta_{H0} \cong 1.08\times10^{-2}$ (typical)



- (a): ITER reference scenario SC2
- (b): Outward shifted from (a)
- (a) and (b) with different gradient peaks, will be used for studying central and outer core regions.

Central core linear stability analyses



- $n = 4$ reference case. $\omega_r/\omega_{A0} \cong 0.08630$, $\gamma_L/\omega_{A0} \cong 0.02946$.

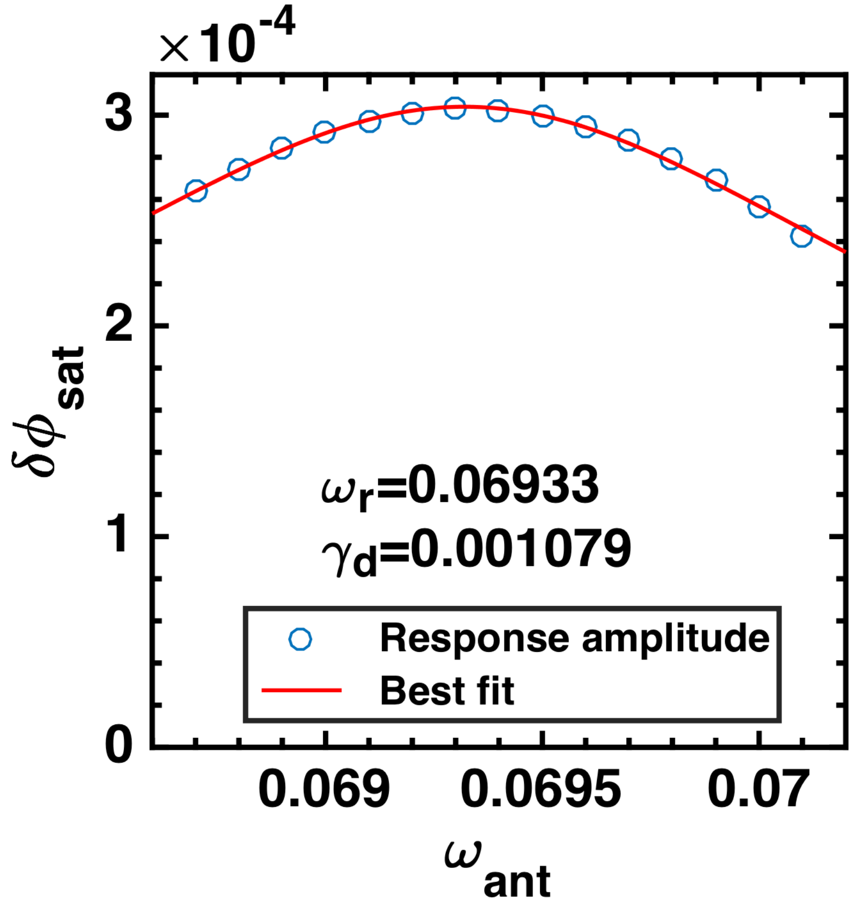
Antenna excitation

- Antenna can verify eigenmode structures, real frequency and damping rate in the MHD limit.

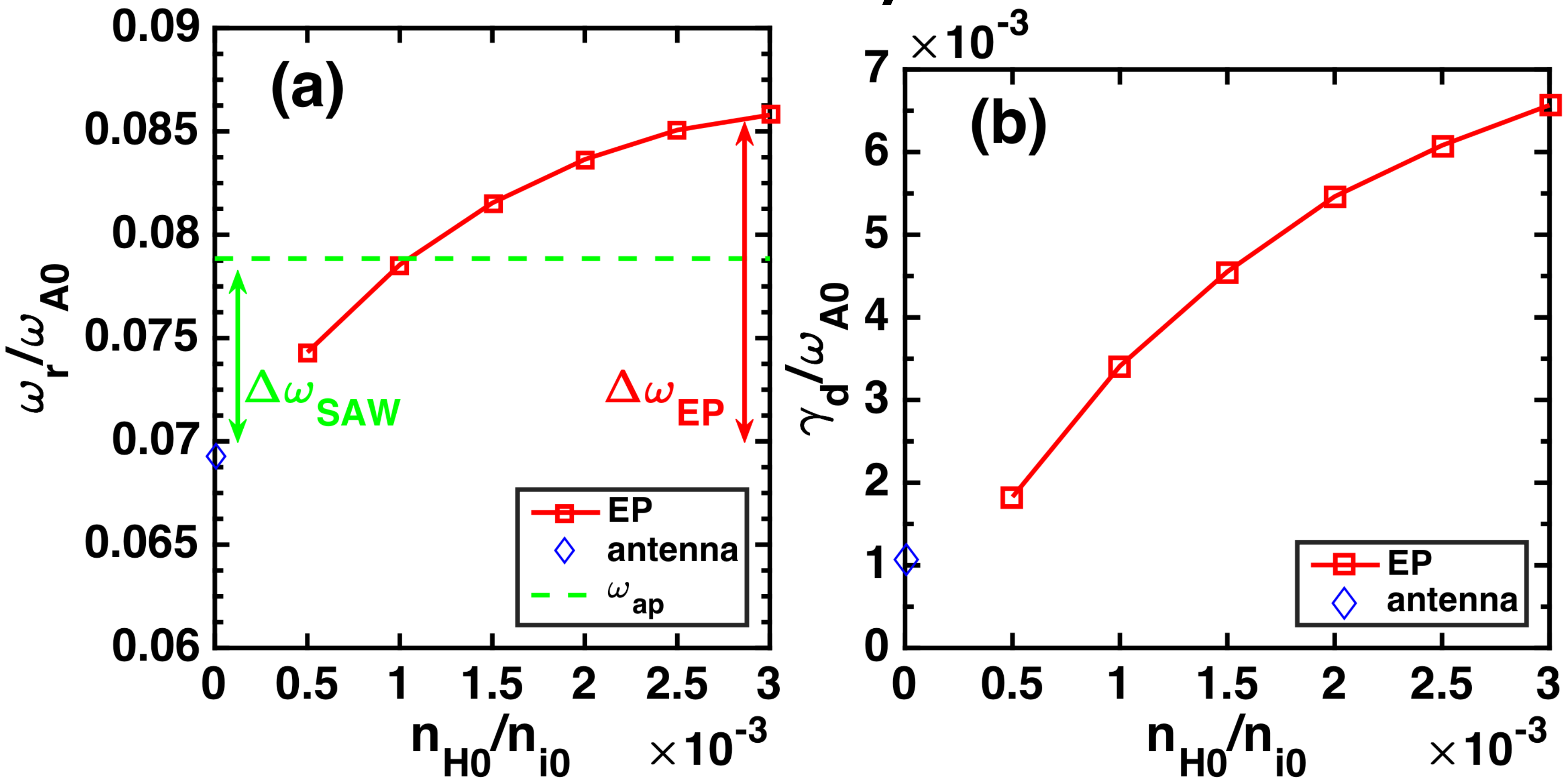
- Saturated response amplitudes are related with antenna frequencies as:

$$\delta\phi_{sat} \propto \frac{1}{\sqrt{(\omega_0^2-\omega_{ant}^2)^2+4\gamma_d^2\omega_{ant}^2}},\ \omega_0^2=\omega_r^2+\gamma_d^2$$

- Frequency scan and fitting:



EP density scan



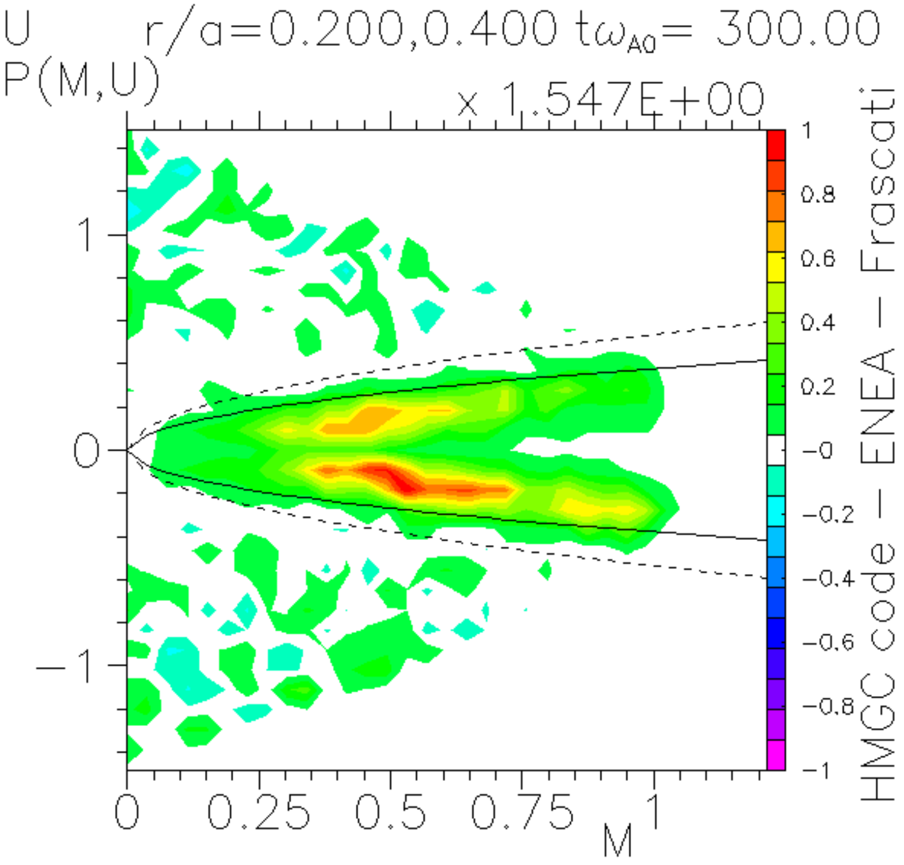
(a): ω_r for EP-driven and antenna cases. ω_{ap} is the RSAE accumulation point.

(b): $\gamma_d = \gamma_{drive} - \gamma_L$ for EP-driven cases, and MHD limit measured by antenna;

The EP effects are clearly non-perturbative as $\Delta\omega_{EP} > \Delta\omega_{SAW}$

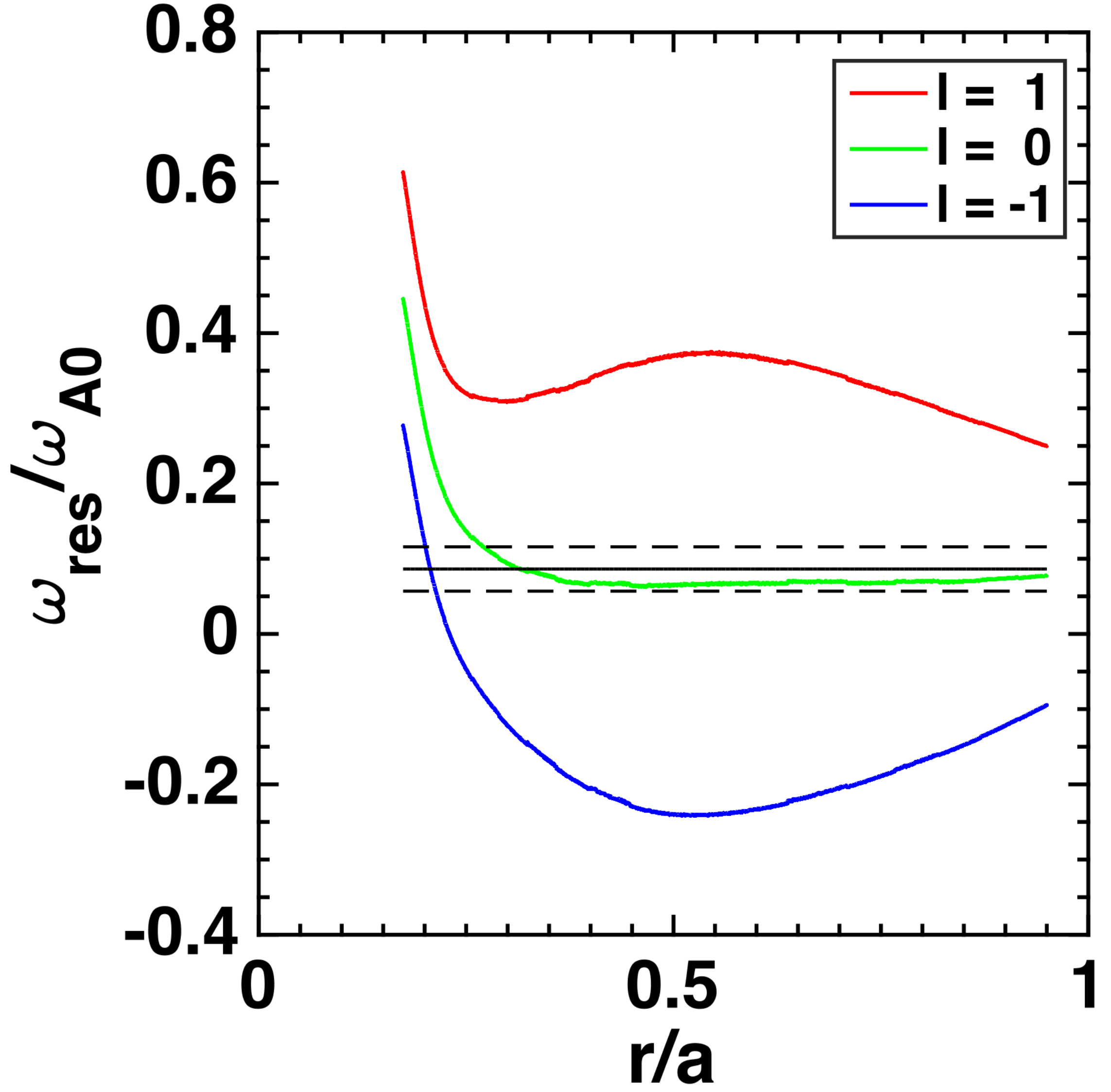
Resonance analyses

- $P(M, U)$ integrated around mode radial location



- From the wave-particle power exchange, we can select test particles from phase space where the power transfer is significant, as representatives of resonant particles.
- Test particles are characterized by two constants of motion (M, C), $C = \omega P_{\phi} - nE$
- Following test particle orbits allows us to calculate the characteristic frequencies.

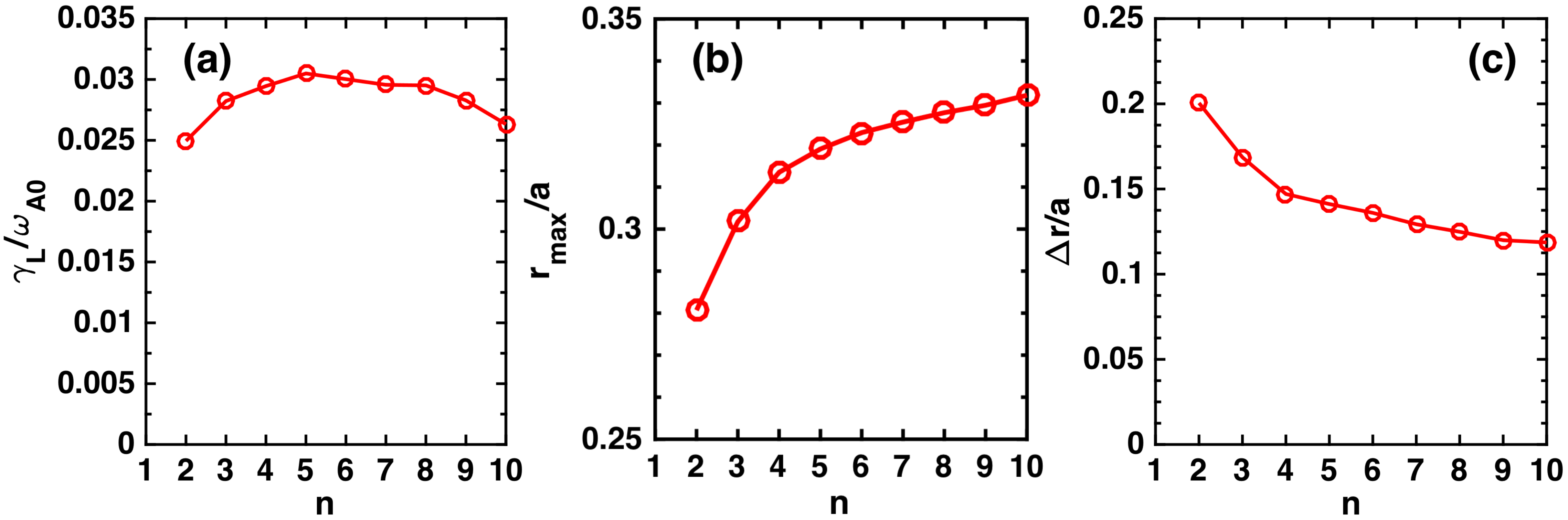
Resonance analyses



- $\omega_{res} = n\omega_d + l\omega_b$ (trapped)
- Resonance condition:

  $|\omega - \omega_{res}| \lesssim \gamma_L$
- The relevant bounce harmonic is $l = 0$, which is the precession resonance of the trapped particles.

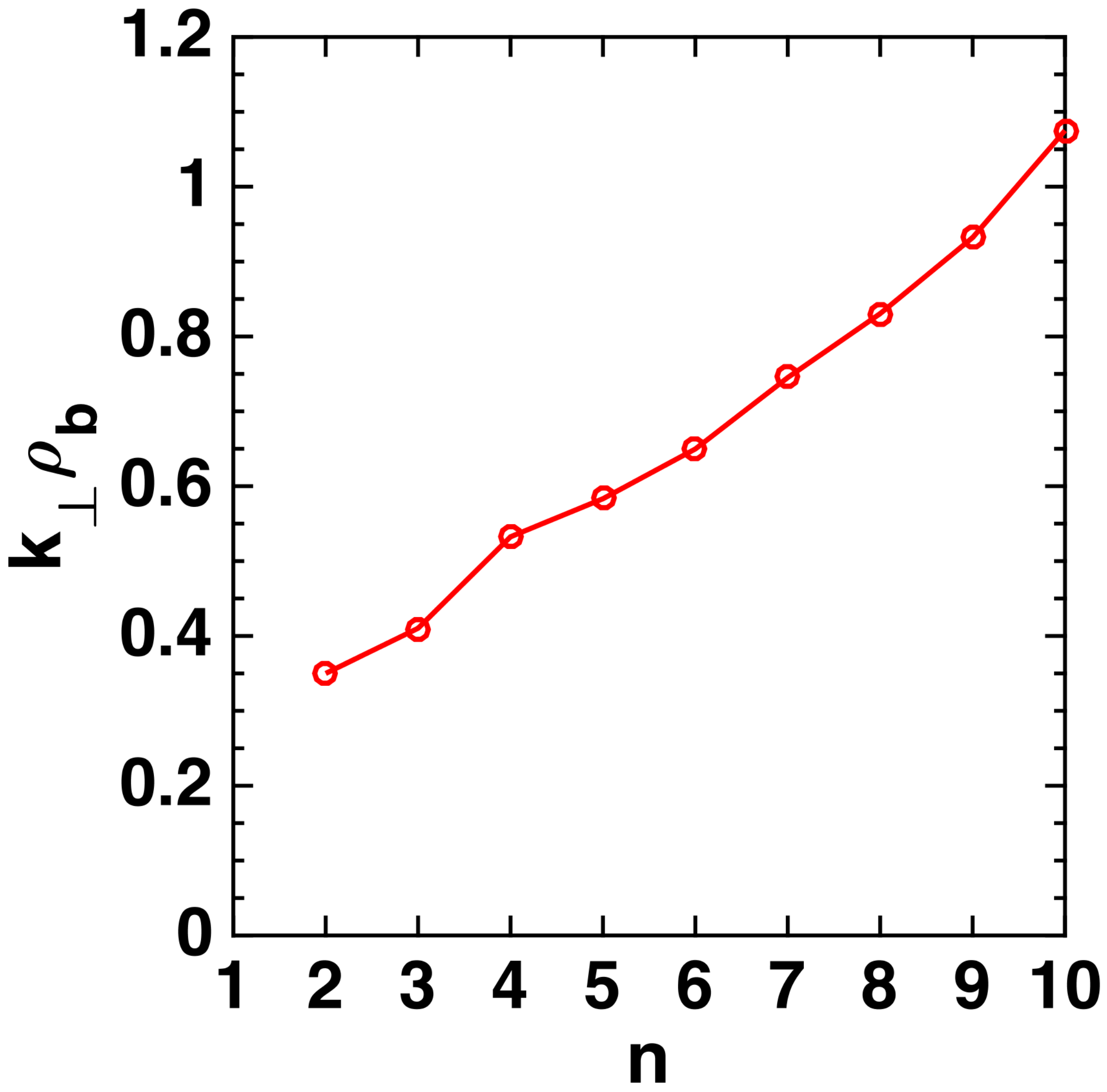
Central core linear stability analyses



(a): Linear stability properties with $n_{H0}/n_{i0} = 3.0\times10^{-3}$.
(b): r_{max} is the radial location of maximum mode amplitude;
(c): Δr is the characteristic radial width of the mode structure envelope;

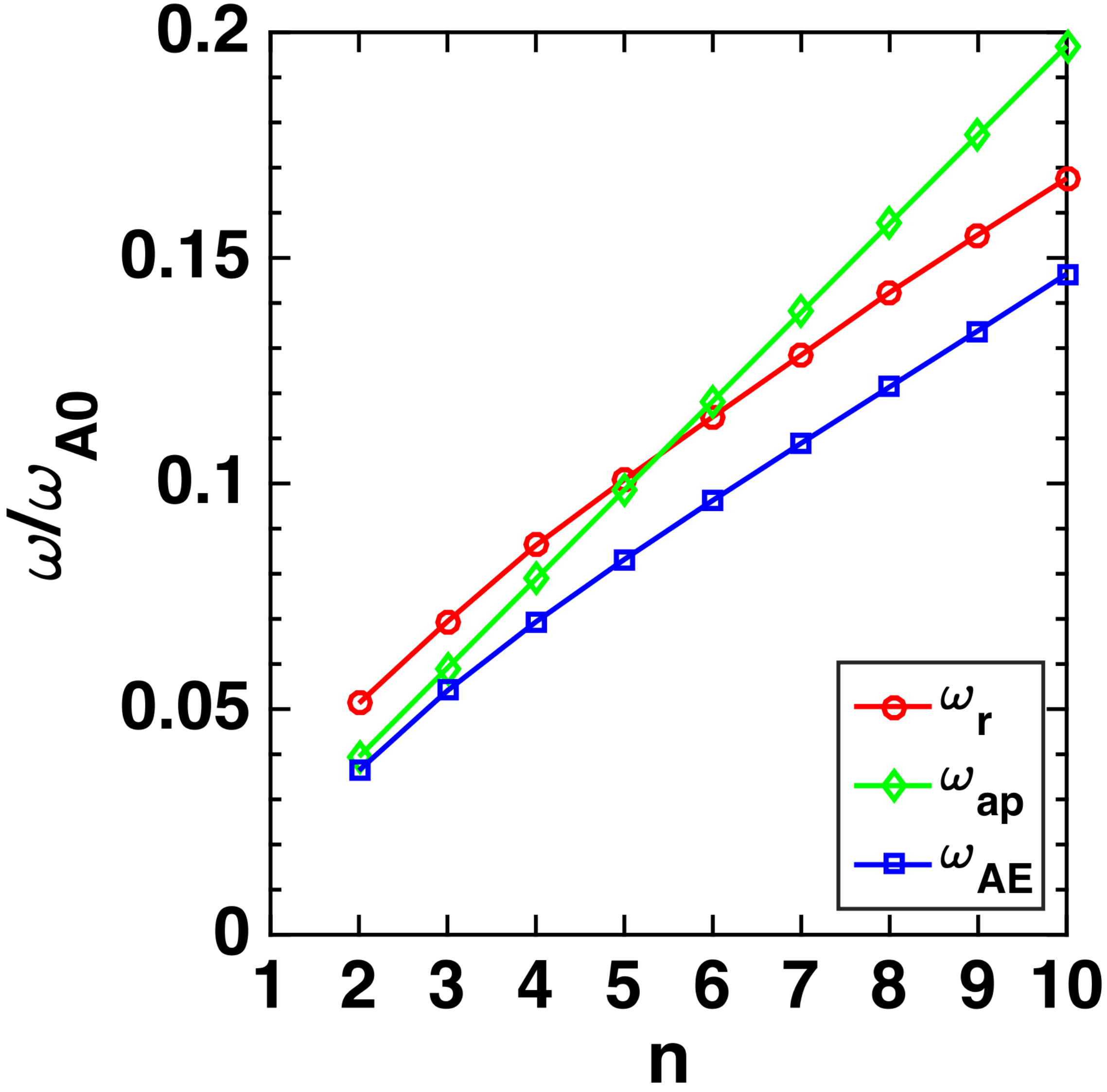
The most unstable mode number is in the order of $n = O(10)$

Central core linear stability analyses



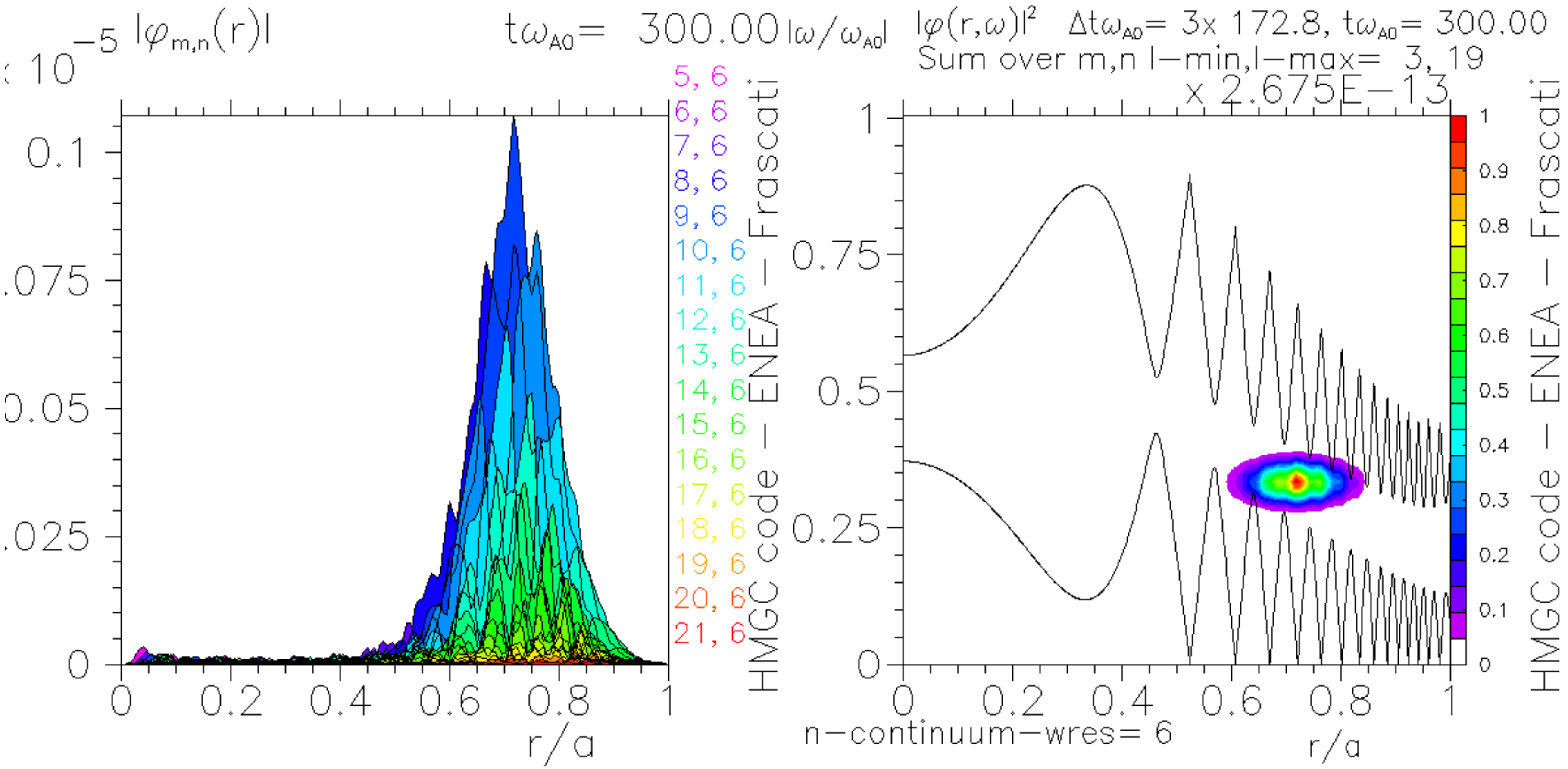
- $k_\perp^2 = k_r^2 + k_\theta^2$, k_r and k_θ are calculated from mode structures.
- ρ_b are measured from respective resonance test particle orbits.
- $k_\perp \rho_b = O(1)$ for the most unstable mode number in our simulations.

Central core Alfvénic fluctuation spectrum



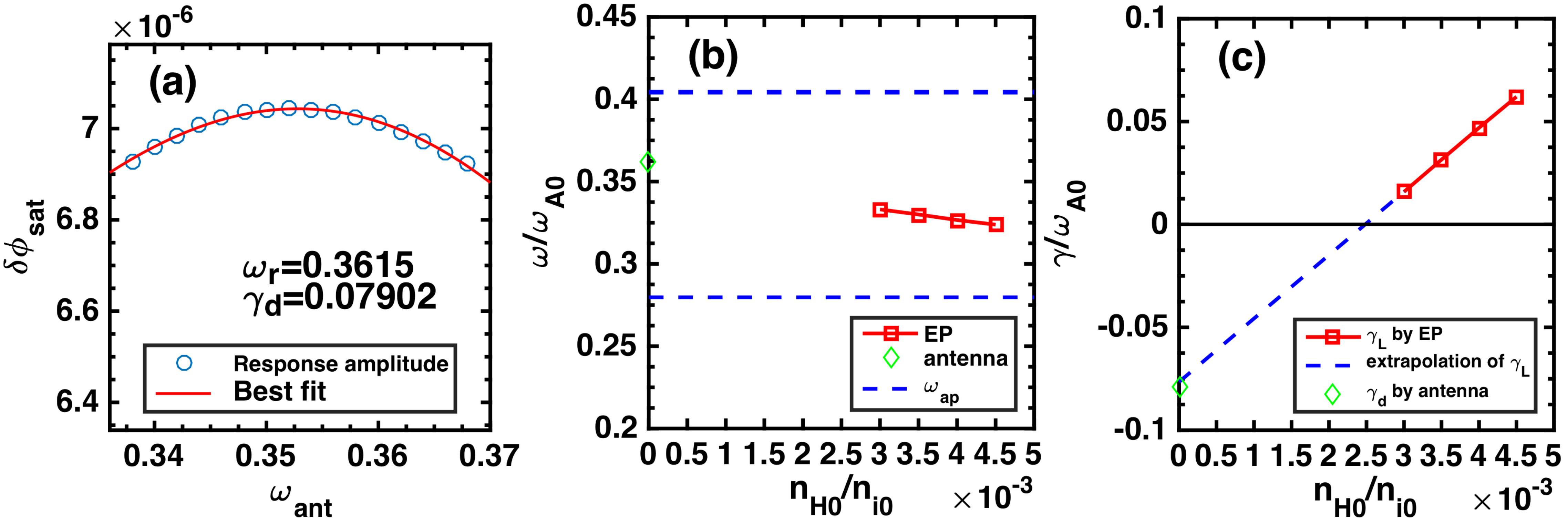
- ω_{AE} is measured by antenna.
- The change of frequencies with respect to the accumulation points shows that the EP effects are non-perturbative in the lower mode number cases, and could be perturbative in the higher mode number cases.

Outer core linear stability analyses



- $n = 6$ reference case. $\omega_r/\omega_{A0} \cong 0.3331$, $\gamma_L/\omega_{A0} \cong 0.01585$.

Antenna excitation and EP density scan



(a): Antenna frequency scan and fitting;

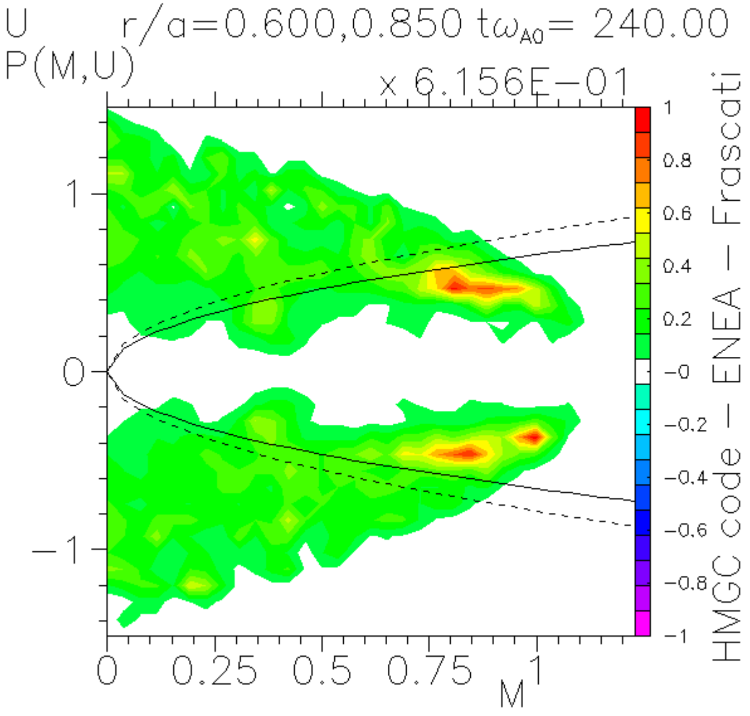
(b): ω_r for EP-driven and antenna cases. ω_{ap} is the upper and lower accumulation points.

(c): γ_L for EP-driven cases, and γ_d in the MHD limit measured by antenna;

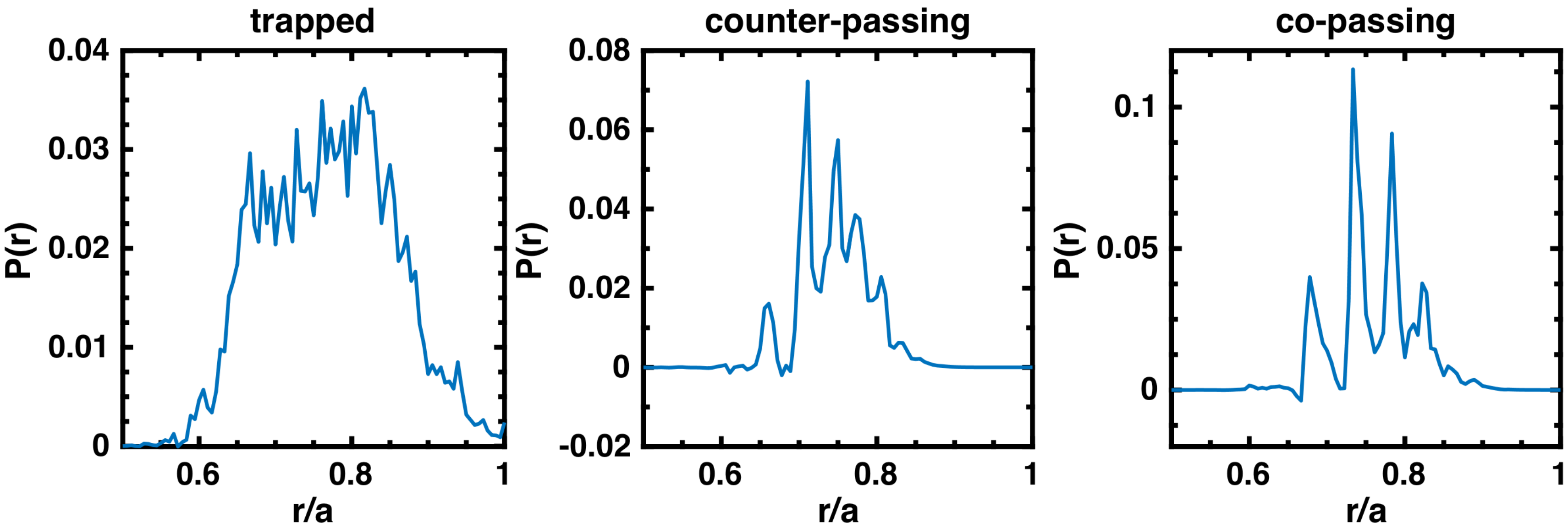
EP effects could be perturbative. There is a threshold for TAE destabilization.

Resonance analyses

- $P(M, U)$ integrated around mode location

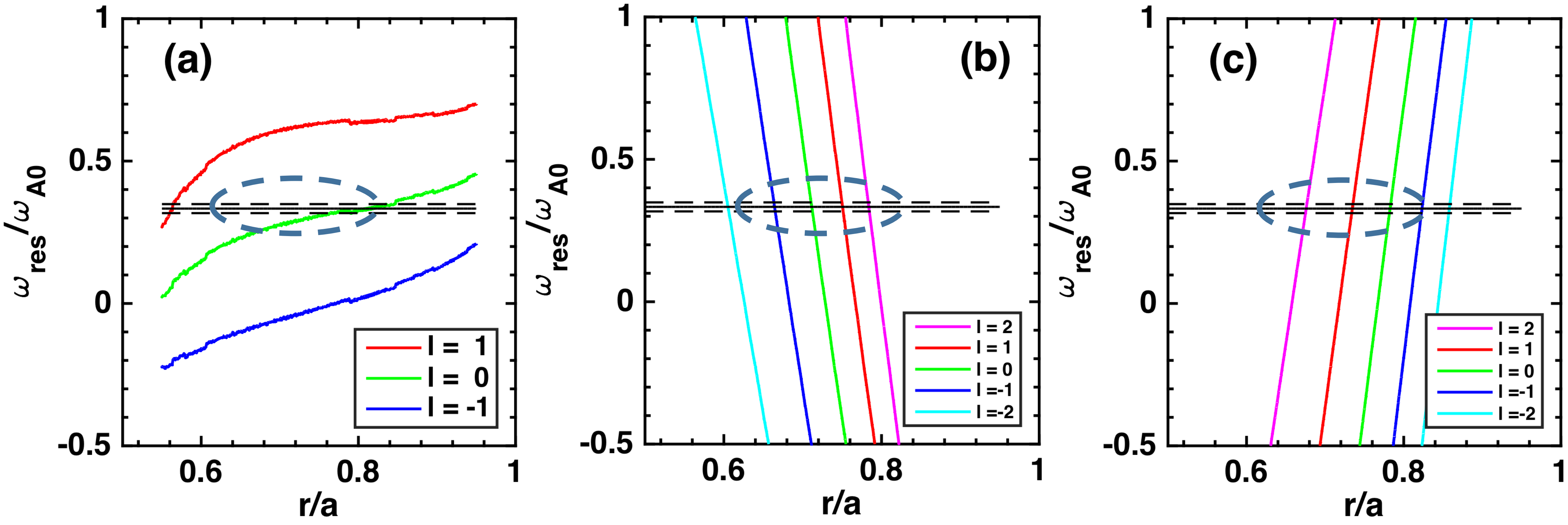


- $P(r)$ integrated over M and U



- Trapped and passing particles play comparable roles in the mode destabilization.

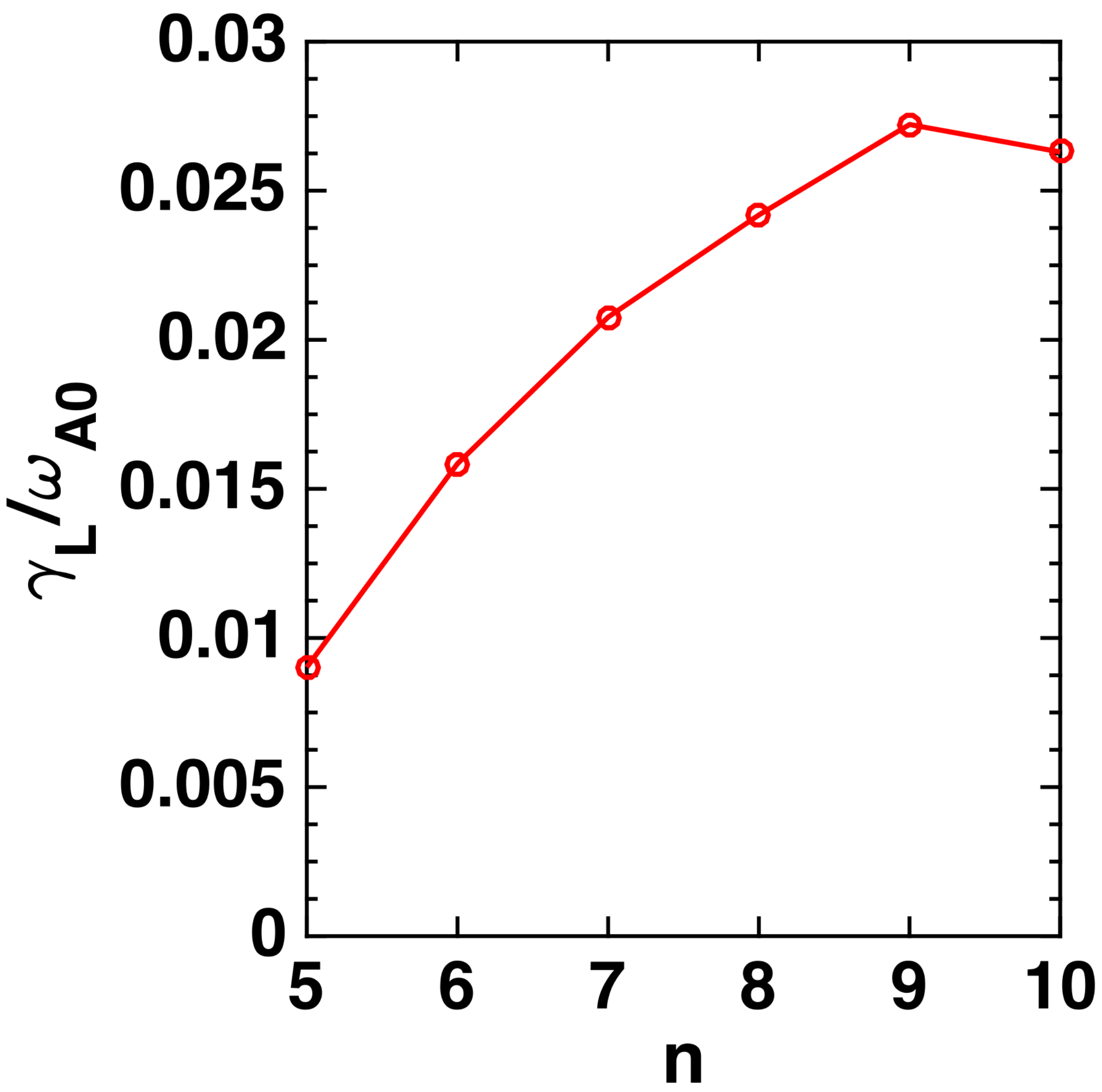
Resonance analyses



(a): trapped test particles; (b): counter-passing test particles; (c): co-passing test particles.

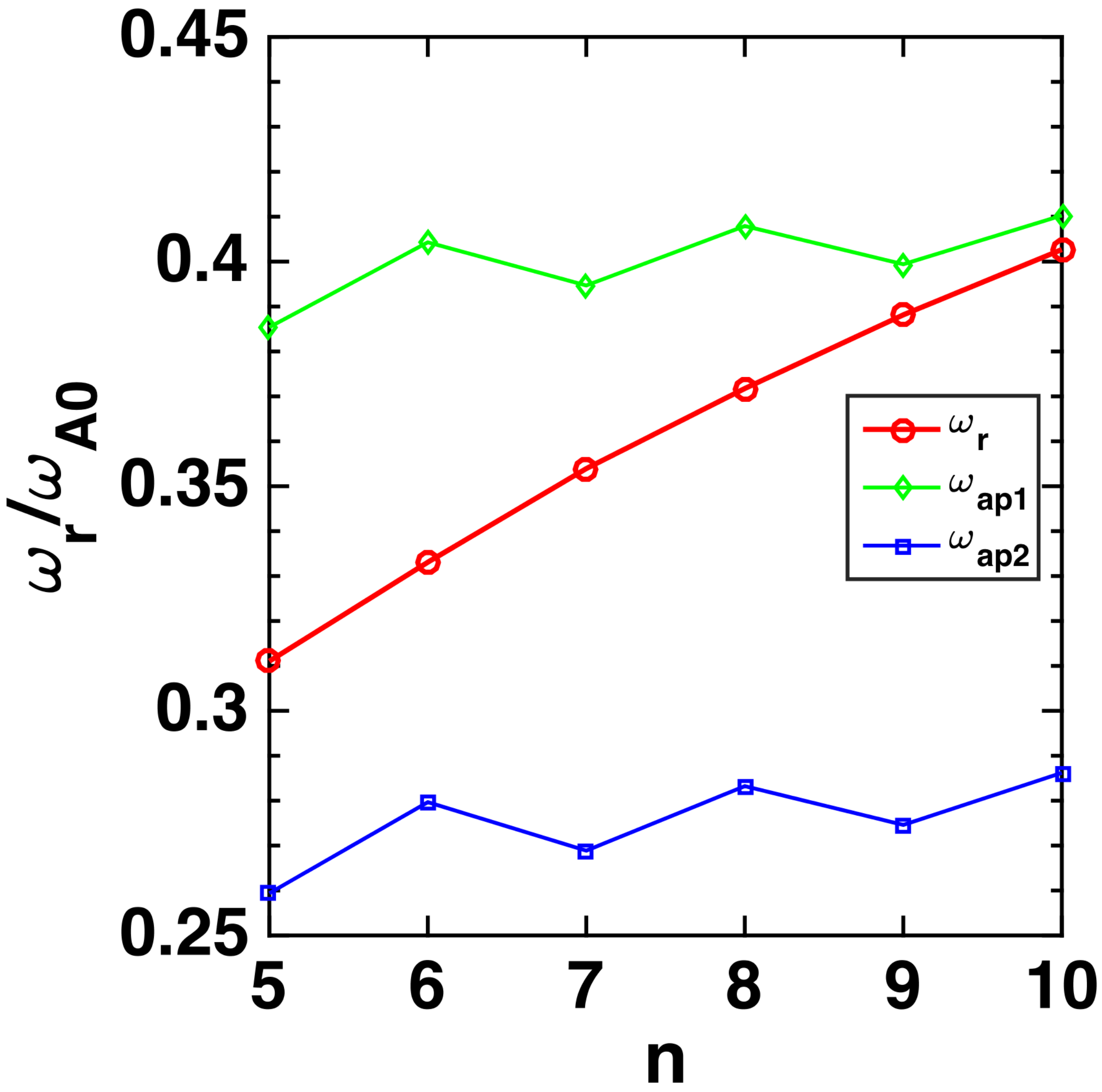
- $\omega_{res} = n\omega_d + l\omega_b + (n\bar{q} - m)\omega_b$ (passing). Steep profiles of ω_{res} are because of large ω_b (transit frequency) and steep q profile in the outer core region.
- The resonance frequency for trapped particles is precession resonance.
- Transit resonances of passing particles show narrower resonance widths.

Outer core linear stability analyses



- Part of the analyses is on-going.
- The mode is stable for $n = 2 - 4$.
- The results suggest the most unstable mode number is likely higher than $n = 10$. As $\rho_d < \rho_b$ in the outer core region, we anticipate the most unstable mode number yielded by trapped particles is also smaller than the one by passing particles.

Outer core Alfvénic fluctuation spectrum



- As n increases, the mode frequency increases. KTAE could be driven unstable instead of TAE. The EP effects then become non-perturbative.

Summary and discussion

- We have investigated the shear Alfvén fluctuation spectrum of the DTT reference scenario. The simulation results can be essentially divided into a central core region and an outer core region, with very distinctive behaviors.
- The simulations show the importance of shear Alfvén continuum, resonance conditions and EP non-perturbative effects in determining the fluctuation dynamics.
- The simulations also suggested the important role played by meso-scale dynamics in the nonlinear regime. They will be investigated in a future work.