Simulations of Alfvén Eigenmode Destabilized by Energetic Electrons and Energetic Electron Effects on Energetic-Ion Driven Alfvén Eigenmode

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— Theory of Plasma Instabilities

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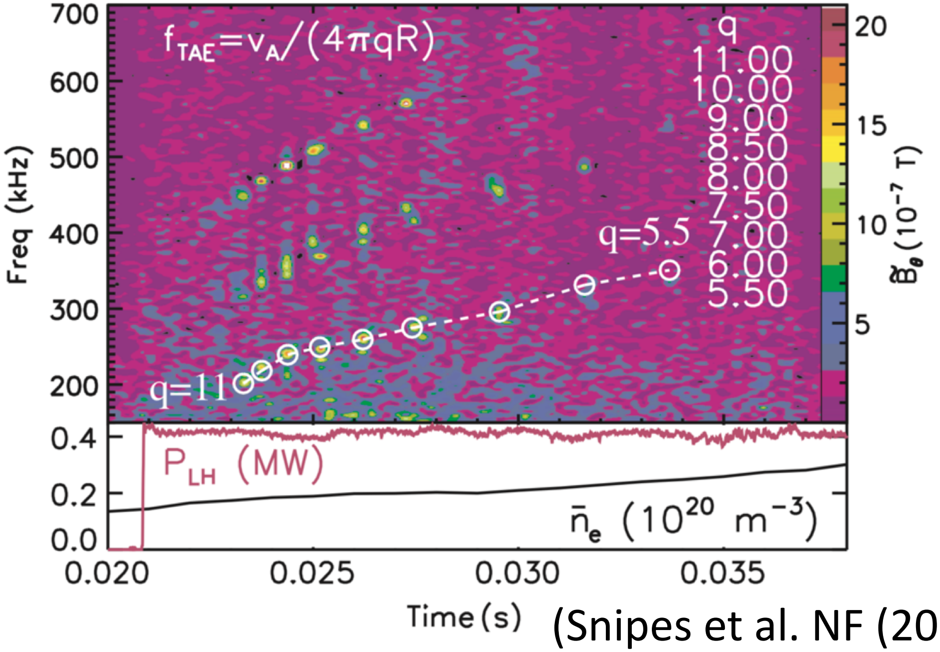
Outline

- **Introduction**
- **Simulation model (MEGA code)**
- **Numerical results**
  - Destabilization mechanism of Alfvén eigenmodes (AEs) by energetic electrons
  - Energetic electron effects on energetic ion driven TAE
- **Summary**

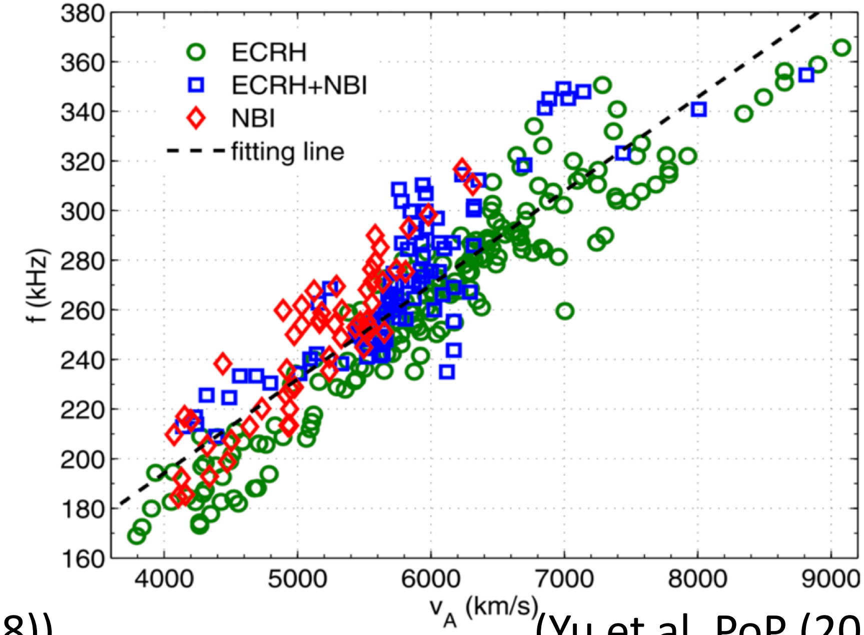
AEs driven by energetic electrons in experiments

TAE during LHW in C-mod



(Snipes et al. NF (2008))

TAE during ECRH in HL-2A



(Yu et al. PoP (2018))

- Energetic electron (EE) driven AE, like TAE, BAE, were observed in many devices during high power LHW and ECW experiments.
- The destabilized mode can propagate in both ion and electron diamagnetic directions.
- Considering interactions between EEs and AEs, could EEs also affect TAE driven by energetic ions?

Physical model

Bulk plasma (Fluid)

$$\frac{\partial \rho}{\partial t} = -\nabla \cdot (\rho \mathbf{v}) + \nu_n \triangle(\rho - \rho_{eq}),$$

$$\rho \frac{\partial}{\partial t}\mathbf{v} = -\rho \boldsymbol{\omega} \times \mathbf{v} - \rho \nabla(\frac{v^2}{2}) - \nabla p + (\mathbf{j} - \mathbf{j}_h') \times \mathbf{B}$$

$$- \nabla \times (\nu \rho \boldsymbol{\omega}) + \frac{4}{3}\nabla(\nu \rho \nabla \cdot \mathbf{v}),$$

EP effects

$$\frac{\partial \mathbf{B}}{\partial t} = -\nabla \times \mathbf{E},$$

$$\frac{\partial p}{\partial t} = - \nabla \cdot (p\mathbf{v}) - (\gamma - 1)p\nabla \cdot \mathbf{v} + (\gamma - 1)$$

$$\times [\nu \rho \omega^2 + \frac{4}{3}\nu \rho (\nabla \cdot \mathbf{v})^2 + \eta \mathbf{j} \cdot (\mathbf{j} - \mathbf{j}_{eq})] + \nu_n \triangle(p - p_{eq}),$$

$$\mathbf{E} = -\mathbf{v} \times \mathbf{B} + \eta(\mathbf{j} - \mathbf{j}_{eq}),$$

$$\boldsymbol{\omega} = \boldsymbol{\nabla} \times \mathbf{v},$$

$$\mathbf{j} = \frac{1}{\mu_0}\nabla \times \mathbf{B},$$

Energetic particle (drift kinetic)

$$\mathbf{u} = \mathbf{v}_\parallel^* + \mathbf{v}_E + \mathbf{v}_B,$$

$$\mathbf{v}_\parallel^* = \frac{v_\parallel}{B^*}(\mathbf{B} + \rho_\parallel B \nabla \times \mathbf{b}),$$

$$\mathbf{v}_E = \frac{1}{B^*}(\mathbf{E} \times \mathbf{B}),$$

$$\mathbf{v}_B = \frac{1}{Z_h e B^*}(-\mu \nabla B \times \mathbf{b}),$$

$$\rho_\parallel = \frac{m_h v_\parallel}{Z_h e B},$$

$$\mathbf{b} = \mathbf{B}/B,$$

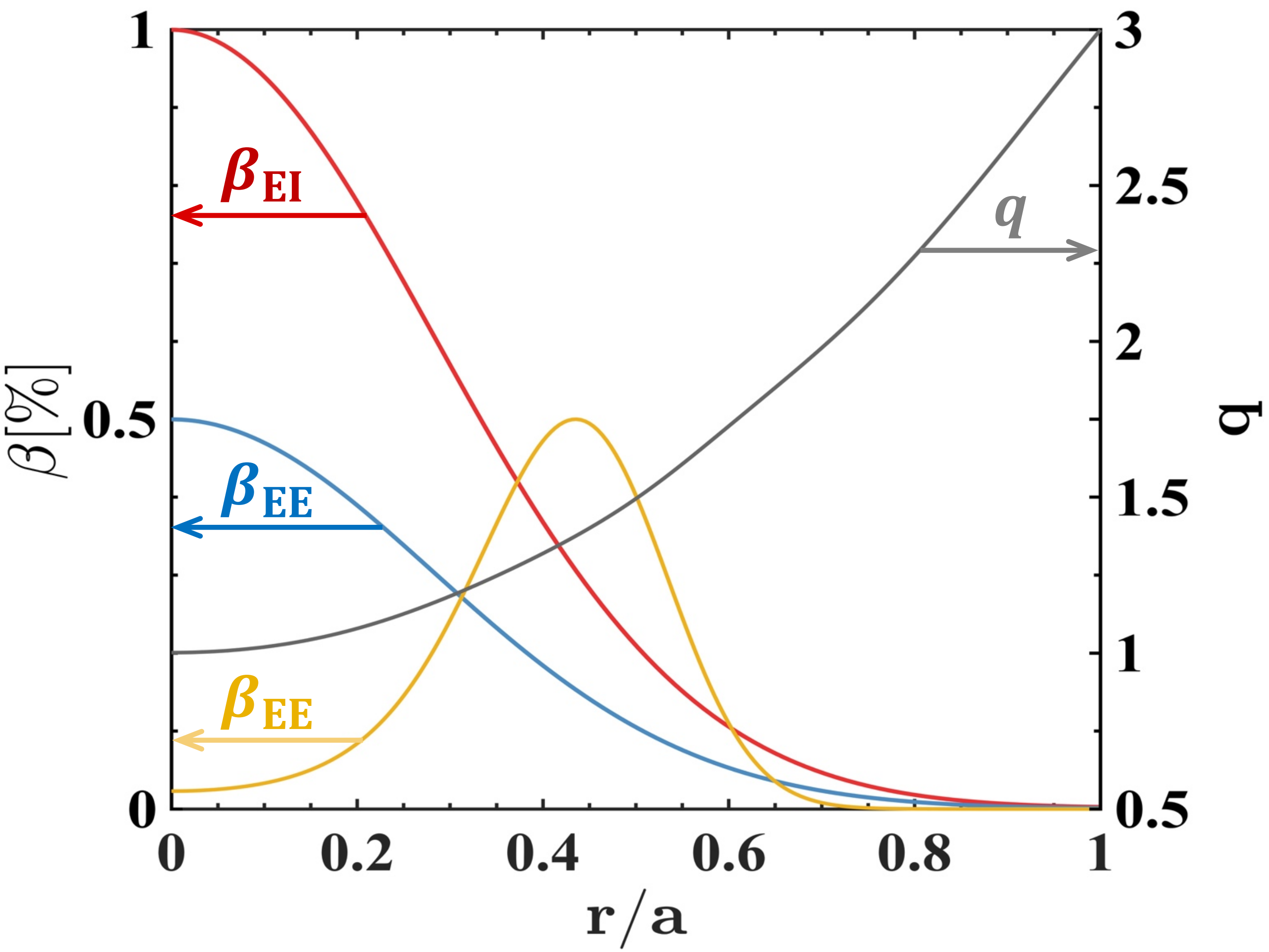
$$B^* = B(1 + \rho_\parallel \mathbf{b} \cdot \nabla \times \mathbf{b}),$$

$$m_h v_\parallel \frac{dv_\parallel}{dt} = \mathbf{v}_\parallel^* \cdot (Z_h e \mathbf{E} - \mu \nabla B),$$

$$\mathbf{j}_h' = \int (\mathbf{v}_\parallel^* + \mathbf{v}_B) Z_h e f d^3 v - \nabla \times \int \mu \mathbf{b} f d^3 v,$$

- Only n = 4 harmonic of the hot particle current is retained in simulations.
- Maxwellian distributions are used for both EEs and EIs.
- The of grid points is (128×16×128) in cylindrical coordinates (R, ϕ, Z).
- The number of marker particles is $2.1\text{x}10^6$.

Equilibrium profiles



- A central-peaked profile (blue curve), which is similar to EI beta profile (red curve), and an off-axis peaked profile (yellow curve) were adopted as EE beta profiles.

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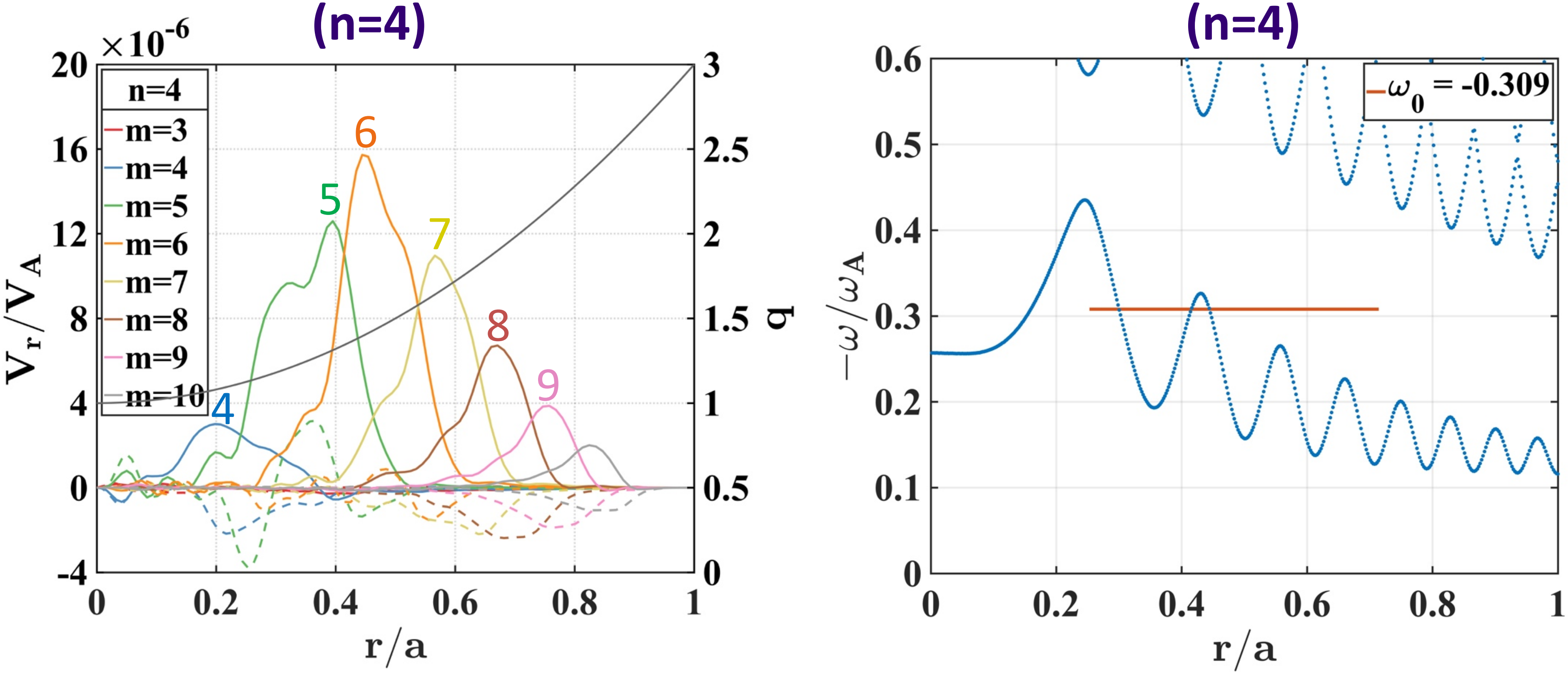
TAE driven by EEs with central-peaked profile

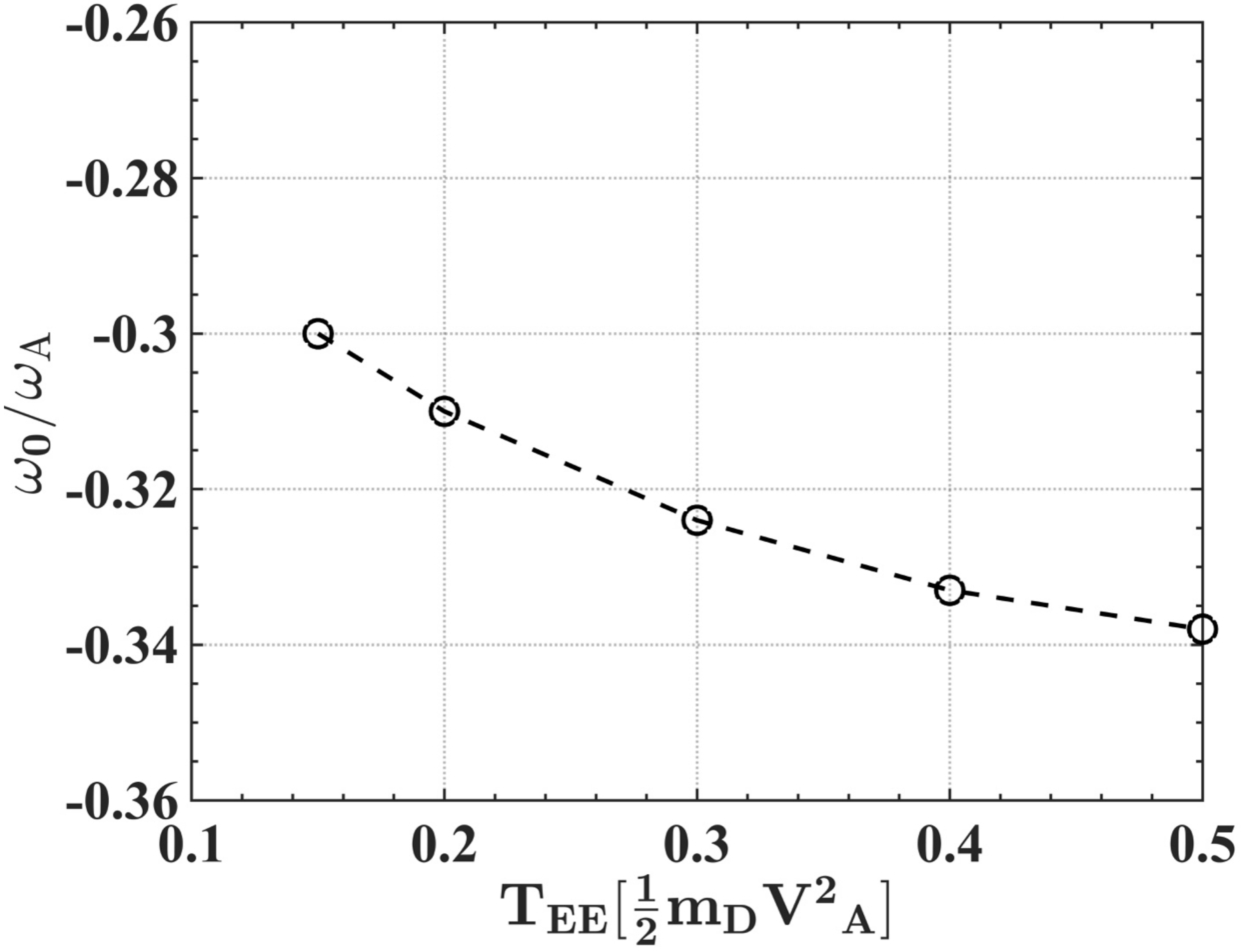
TAE spatial profiles (n=4)

Alfvén continuous spectra (n=4)



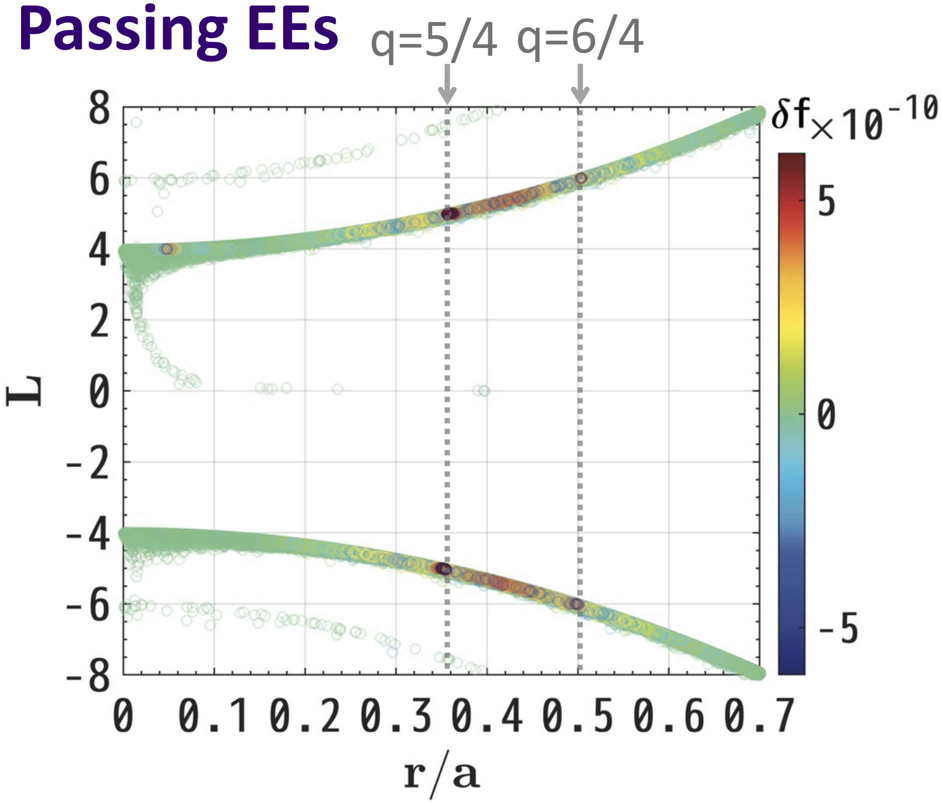
- TAE can be destabilized by energetic electrons (EEs).
- TAE propagates in the electron diamagnetic drift direction with a central peaked EE beta profile.

Mode frequency dependence on EE energy

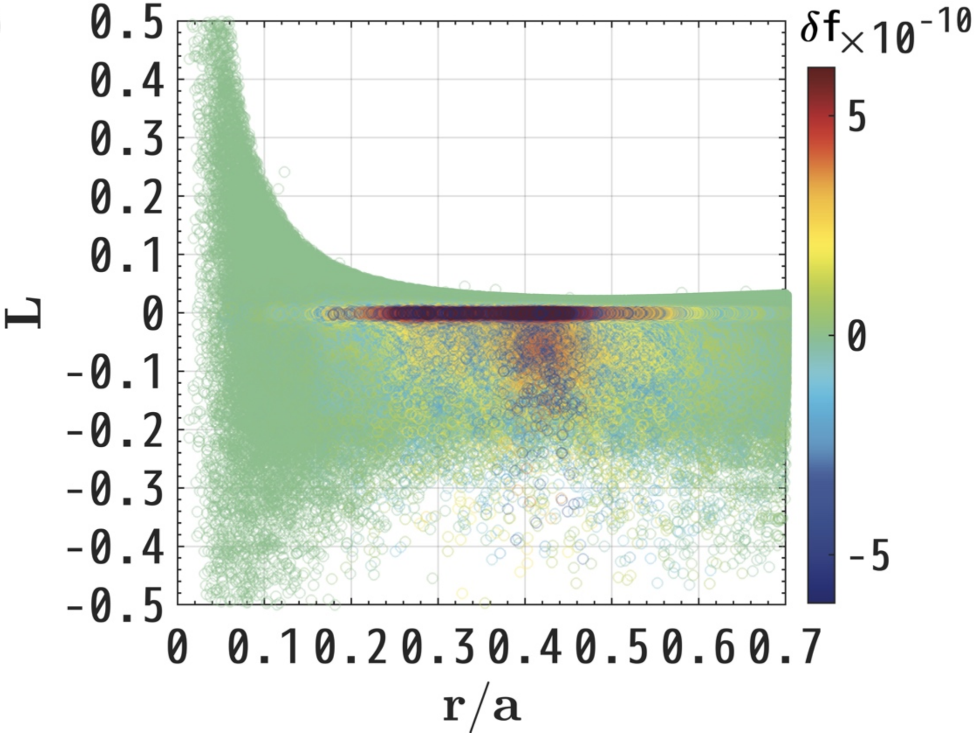


- Mode frequency increases with the increase of EE energy.
- The mode is stable at T_{EE}=0.1 due to the strong continuum damping.

Resonance condition: $\omega - \mathbf{L} * \omega_\theta(\mu, E, P_\varphi) - n * \omega_\phi(\mu, E, P_\varphi) = 0$



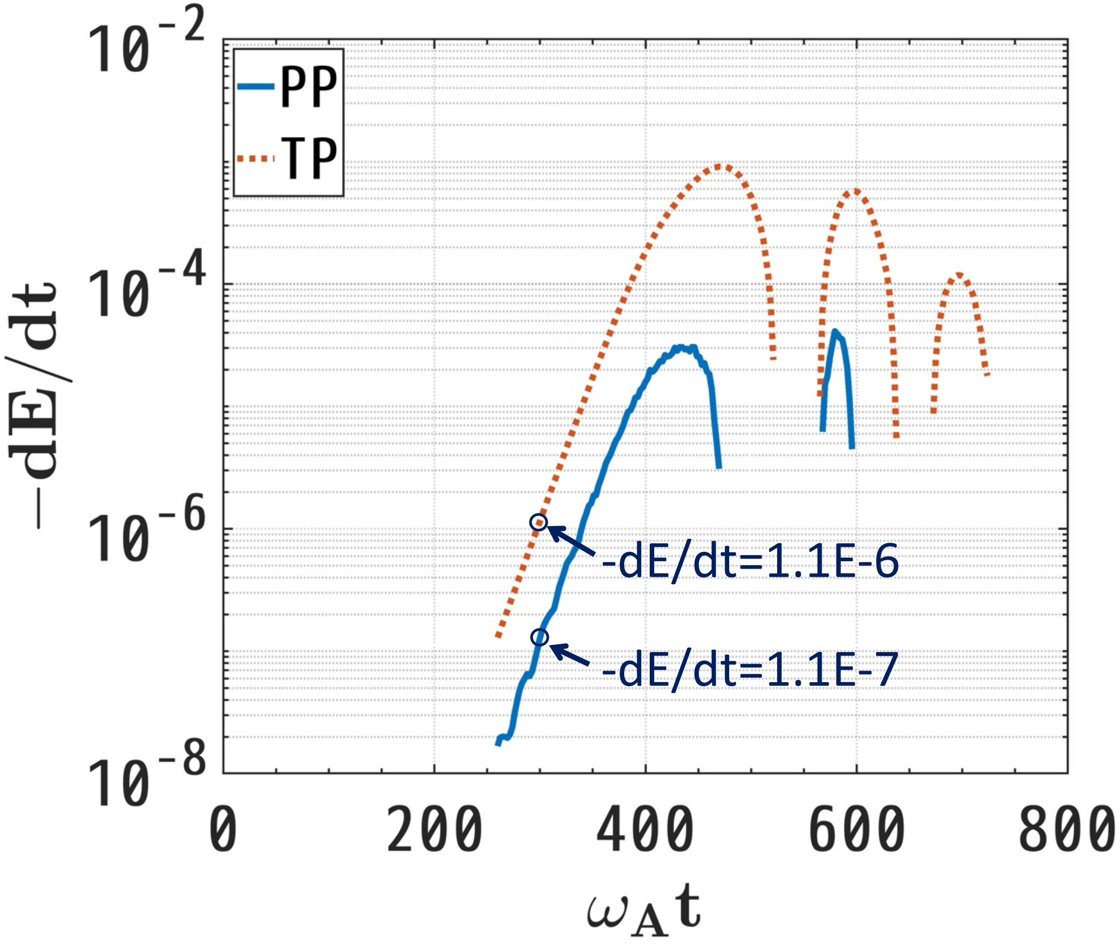
Passing EEs



Trapped EEs

- A few Passing EEs located around rational surfaces with $\mathrm{L} = \pm 5$ and $\mathrm{L} = \pm 6$ are resonating with TAE.
- Deeply trapped EEs at a wide range of minor radius are resonating with TAE through precessional resonance with L=0.

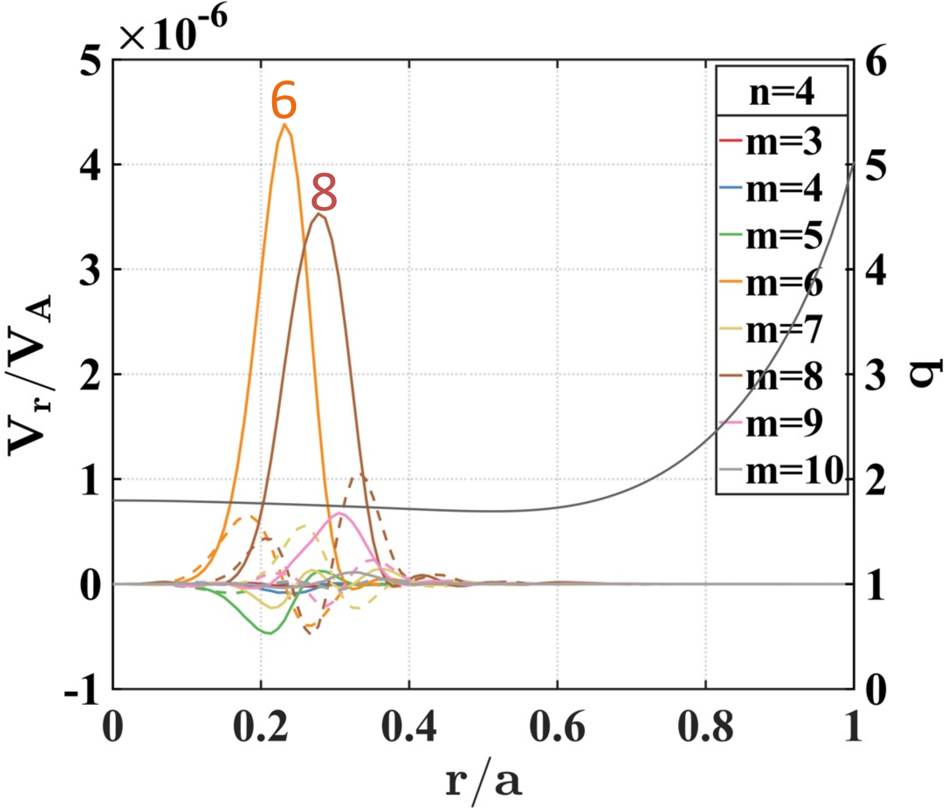
Energy transfer from EEs to wave mainly from trapped EEs



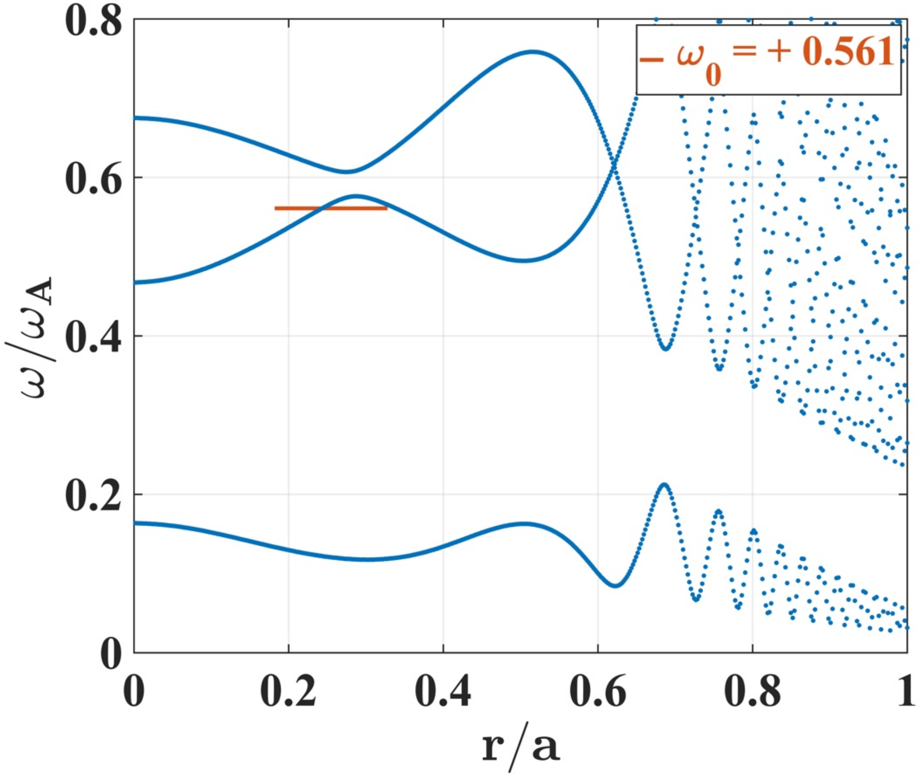
- Trapped EEs dominate the mode destabilization.
- Resonance of passing EEs mainly occurs around rational surfaces, but the net energy transfer from these resonant particles is very small.
- Passing EEs will be more important in a weak shear case.

Positive frequency AE driven by EEs with off-axis EE profile

EAE spatial profiles (n=4)

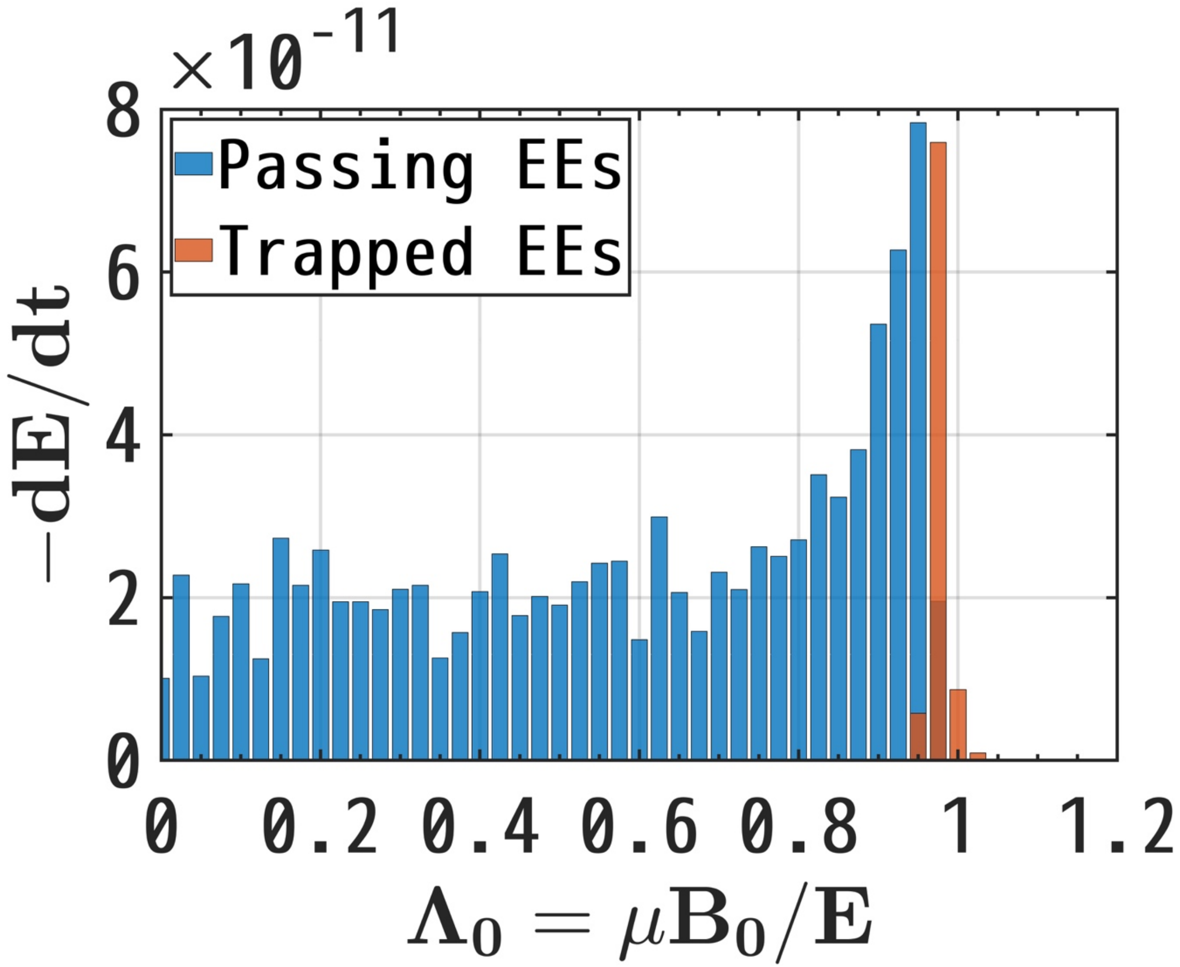


Alfvén continuous spectra (n=4)



- ➢ The AE (EAE) destabilized by EEs with positive frequency is observed at positive spatial gradient of EE distribution function in a weak shear configuration.

Energy transfer from EEs to EAE



- The EAE with positive frequency is driven by passing and barely trapped EEs.
- Particles around passing-trapped boundary transfers more energy.

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    - **EE with central-peaked profiles**
    - EE with off-axis peaked profiles
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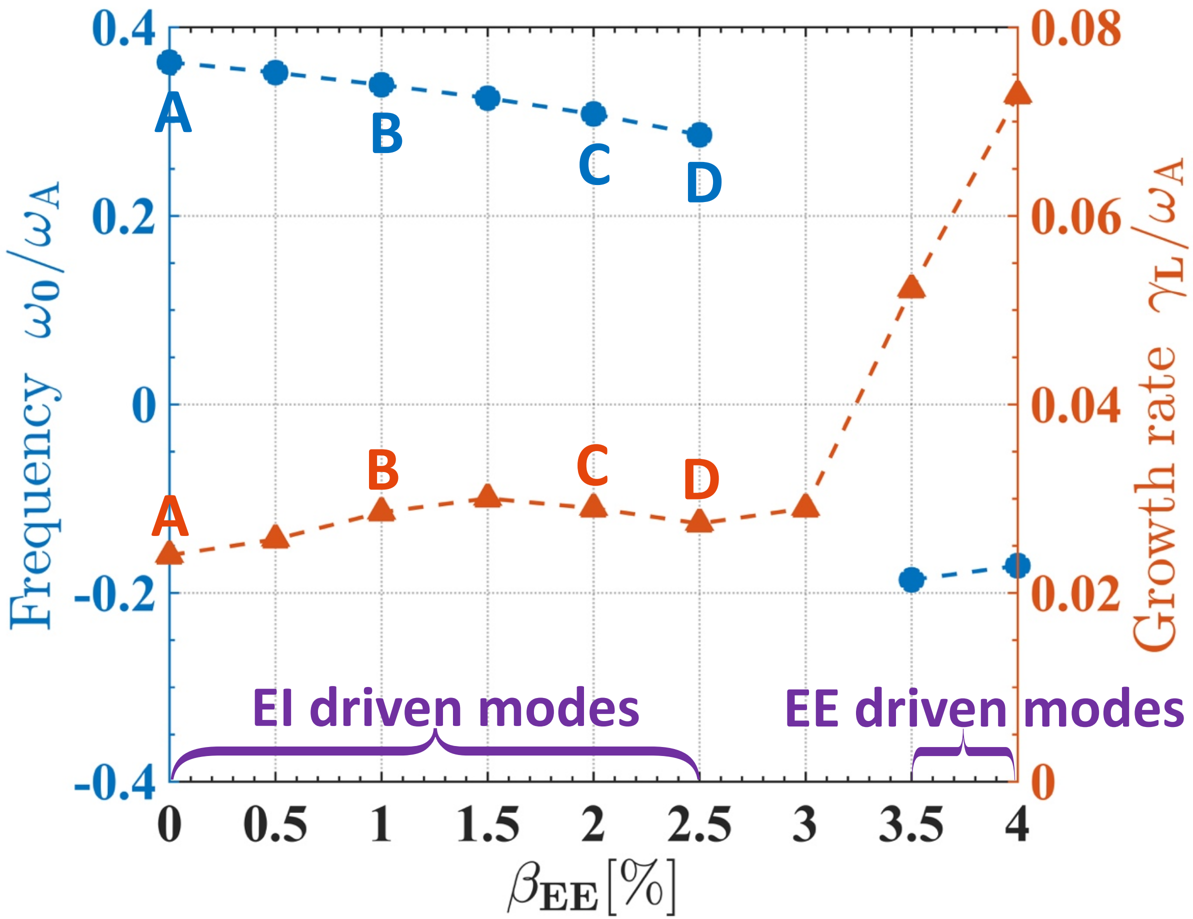
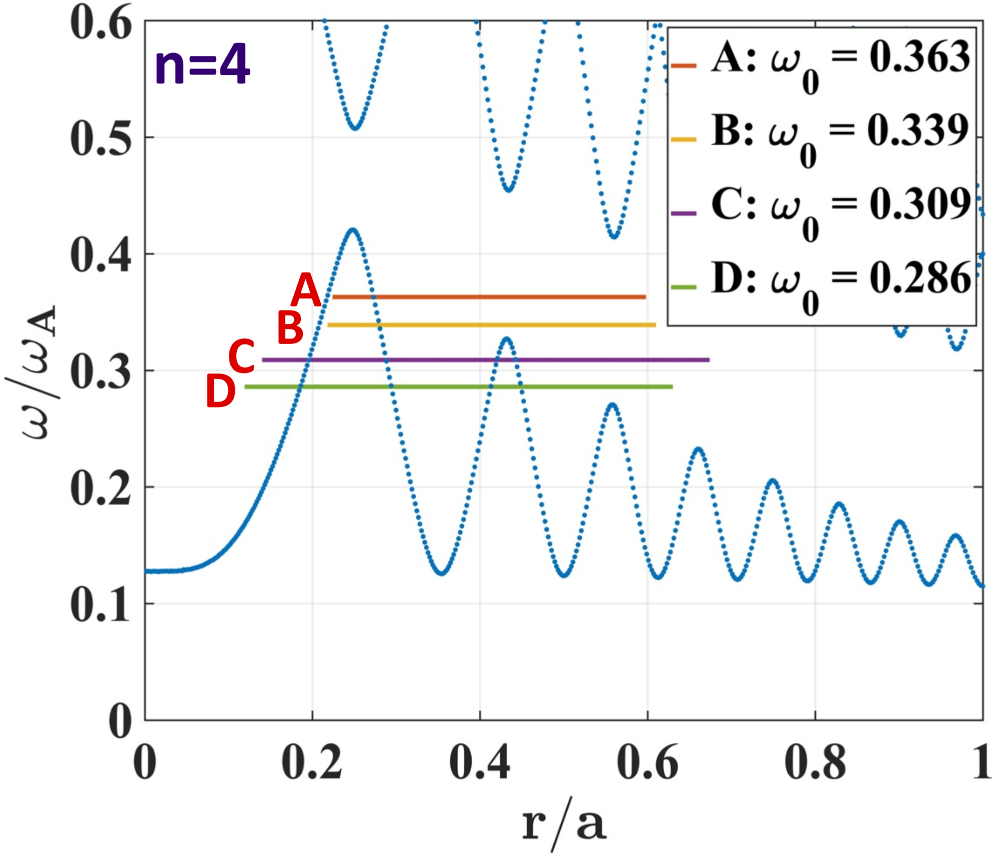
EE with central-peaked profile affect TAE frequency and growth rate

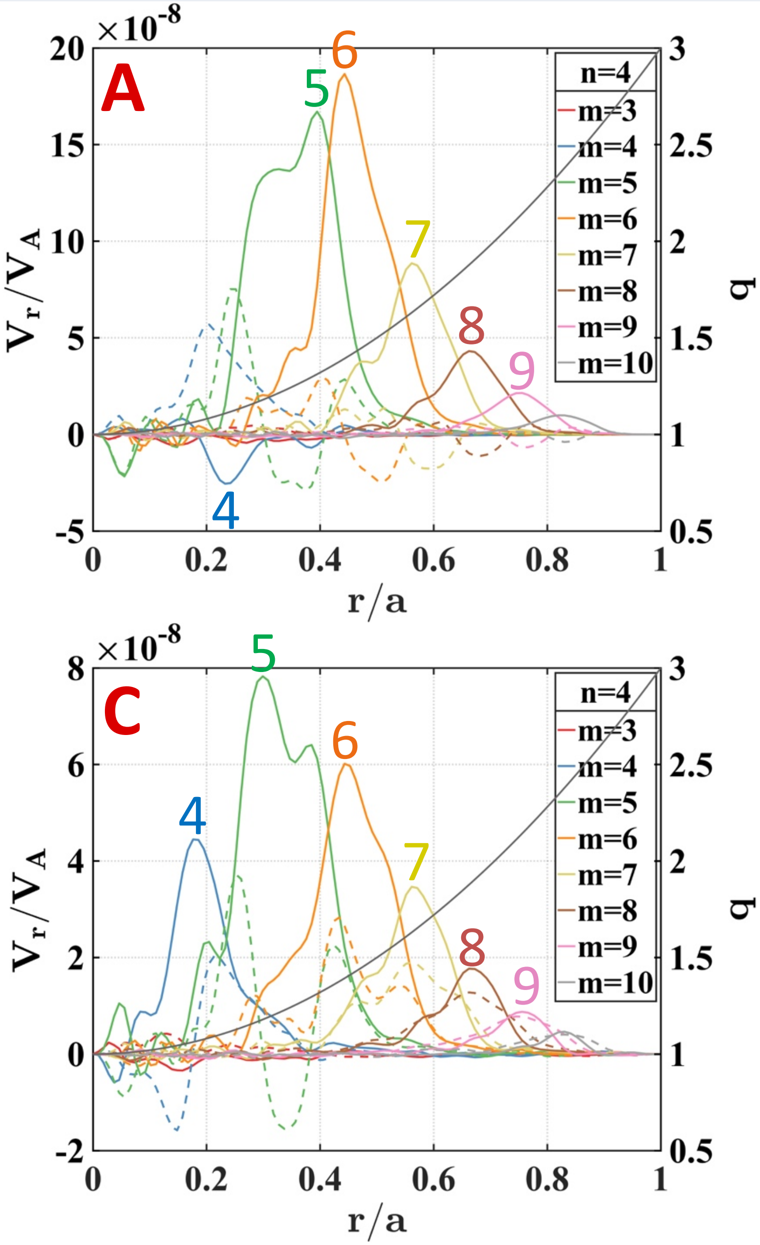


- No significant stabilization is observed.
- Increasing EE beta will decrease TAE frequency.
- Further increasing EE beta will change to an EE driven mode with negative mode frequency and a larger growth rate.

Change of resonance condition may lead to a larger γ_L

EE beta : β_{EE}(A) < β_{EE}(B) < β_{EE}(C)





- A broader spatial profiles may lead to a larger linear growth rate due to the change of mode frequency.

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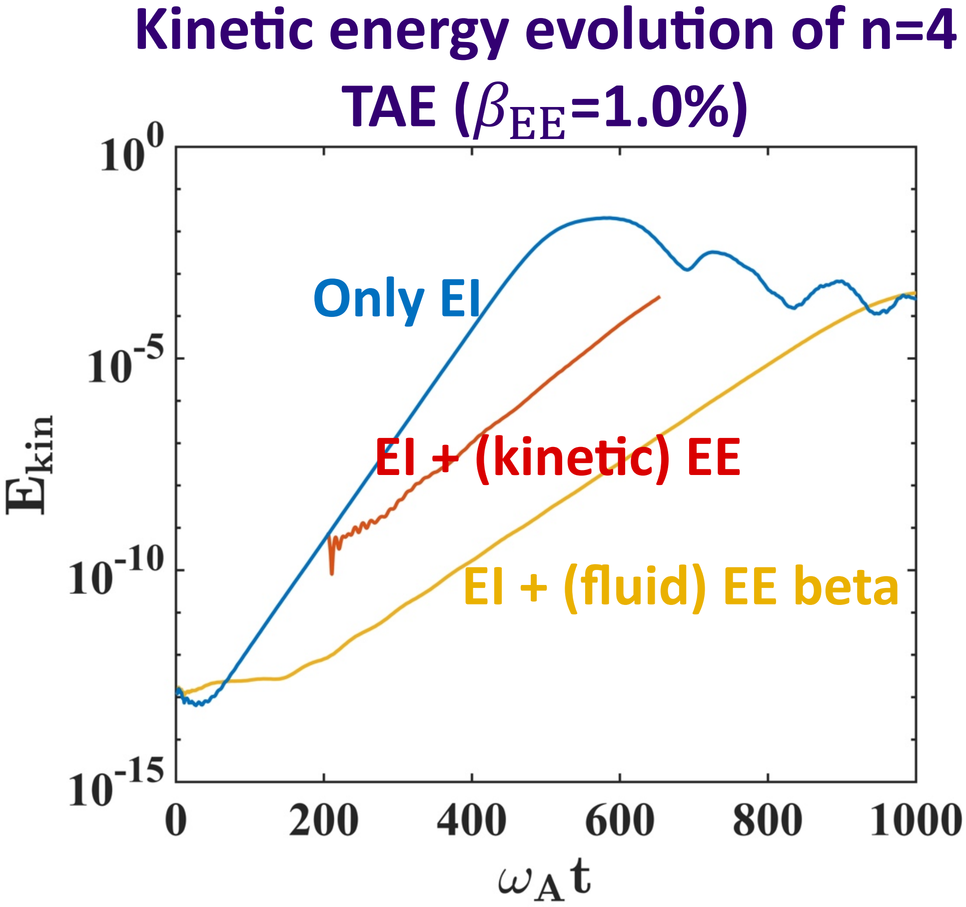
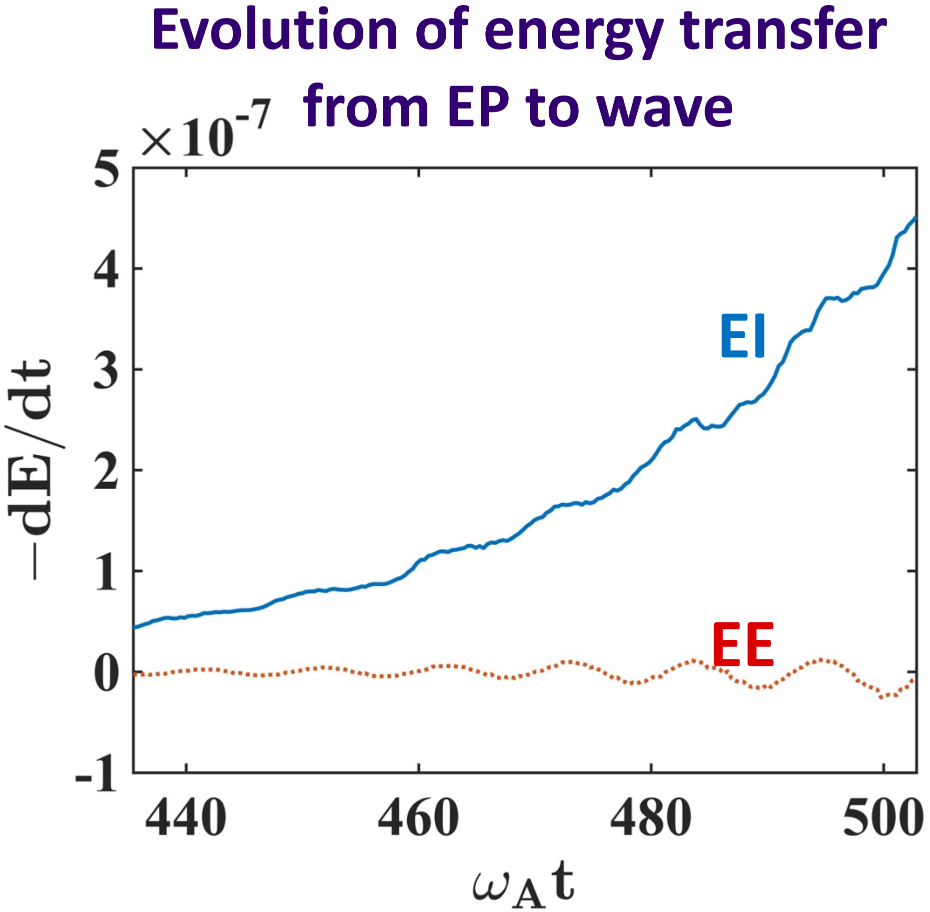
EE with off-axis peaked profile stabilizing EI driven TAE

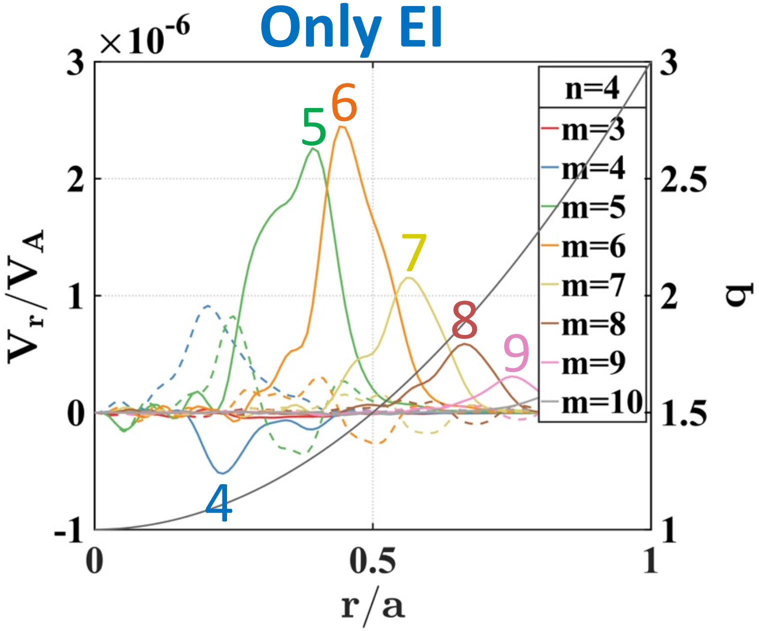




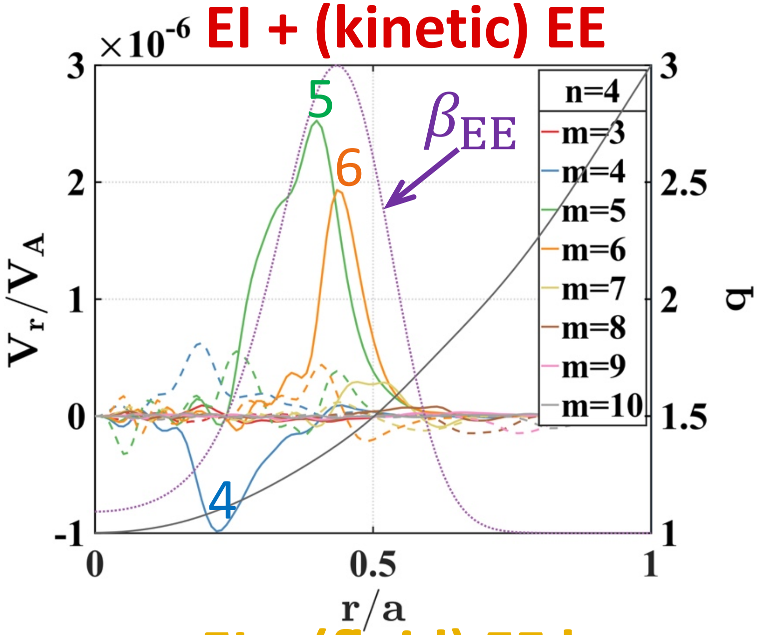
- EEs with off-axis peaked profile can significantly stabilize EI driven TAE.
- Kinetic effect of EEs contributes little to the mode stabilization.
- The stabilization mainly comes from the pressure gradient of EE profile.

Spatial profiles of n=4 TAE

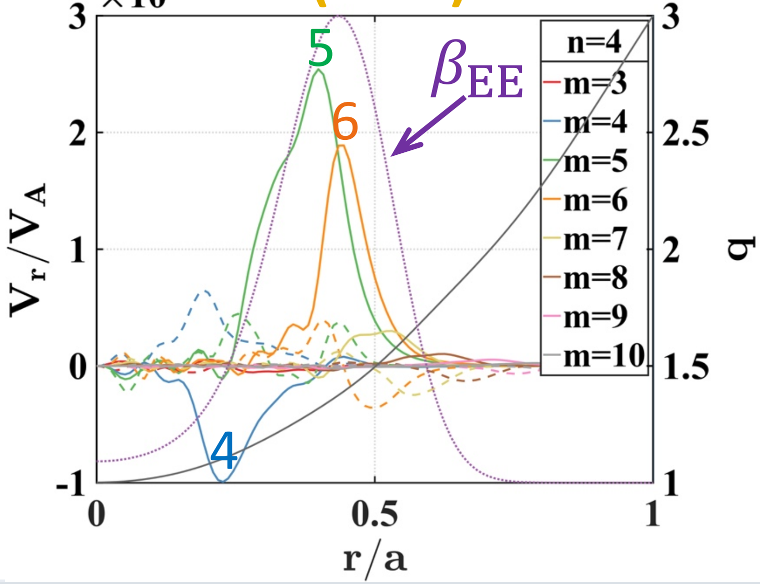
Only EI



EI + (kinetic) EE



EI + (fluid) EE beta



- Inclusion of kinetic EEs or fluid EE beta profile shows almost the same mode structures.
- m=6 harmonic is significantly damped, while m≥7 harmonics are almost fully suppressed.

Decrease of driving rate lead to stabilization (r_h =0.43)

I. β_{EE}=0.0%; $\omega_o/\omega_A = 0.359$

growth rate: γ_L/ω_A=0.0288

driving rate: γ_h/ω_A=0.0403

damping rate: γ_d/ω_A=0.0128

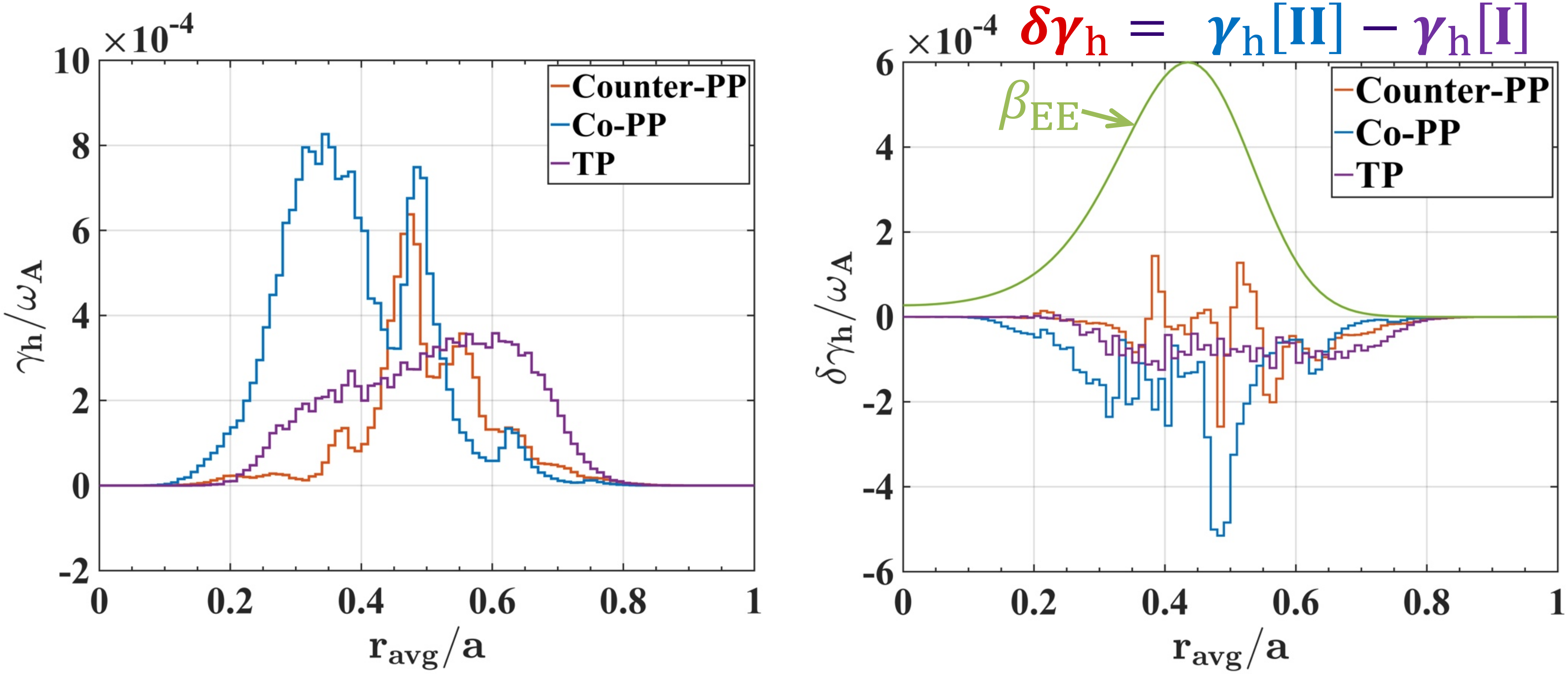
II. β_{EE}=1.0%; $\omega_o/\omega_A = 0.362$

γ_L/ω_A=0.0133 ($\delta\gamma_L$: - 0.0155)

γ_h/ω_A=0.0271 ($\delta\gamma_h$: - 0.0132)

γ_d/ω_A=0.0143 ($\delta\gamma_d$: +0.0015)

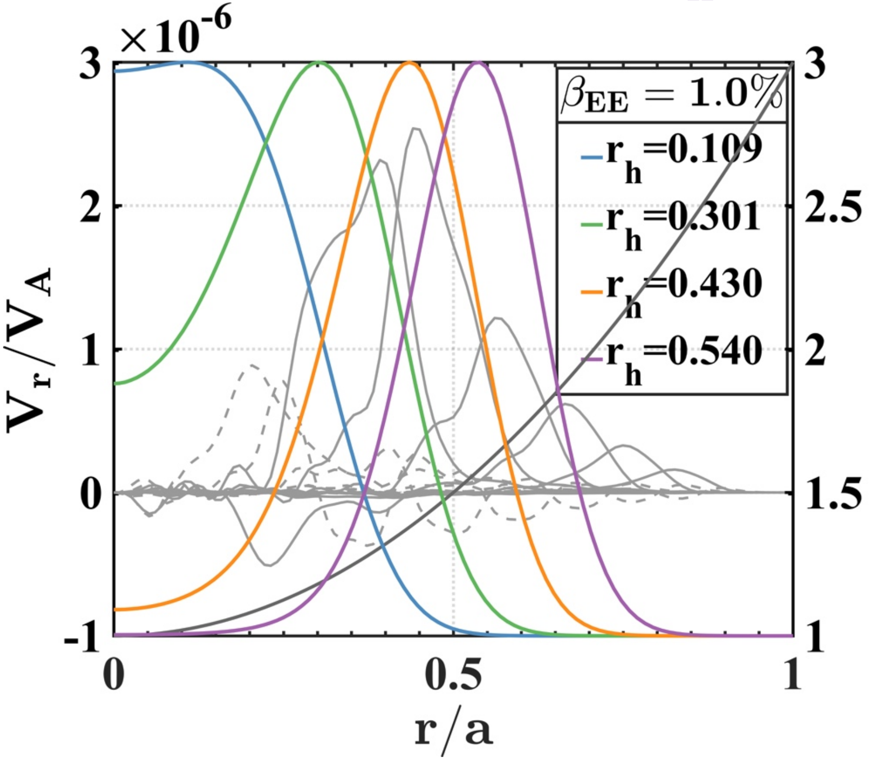
$\delta\gamma_h = \gamma_h[II] - \gamma_h[I]$

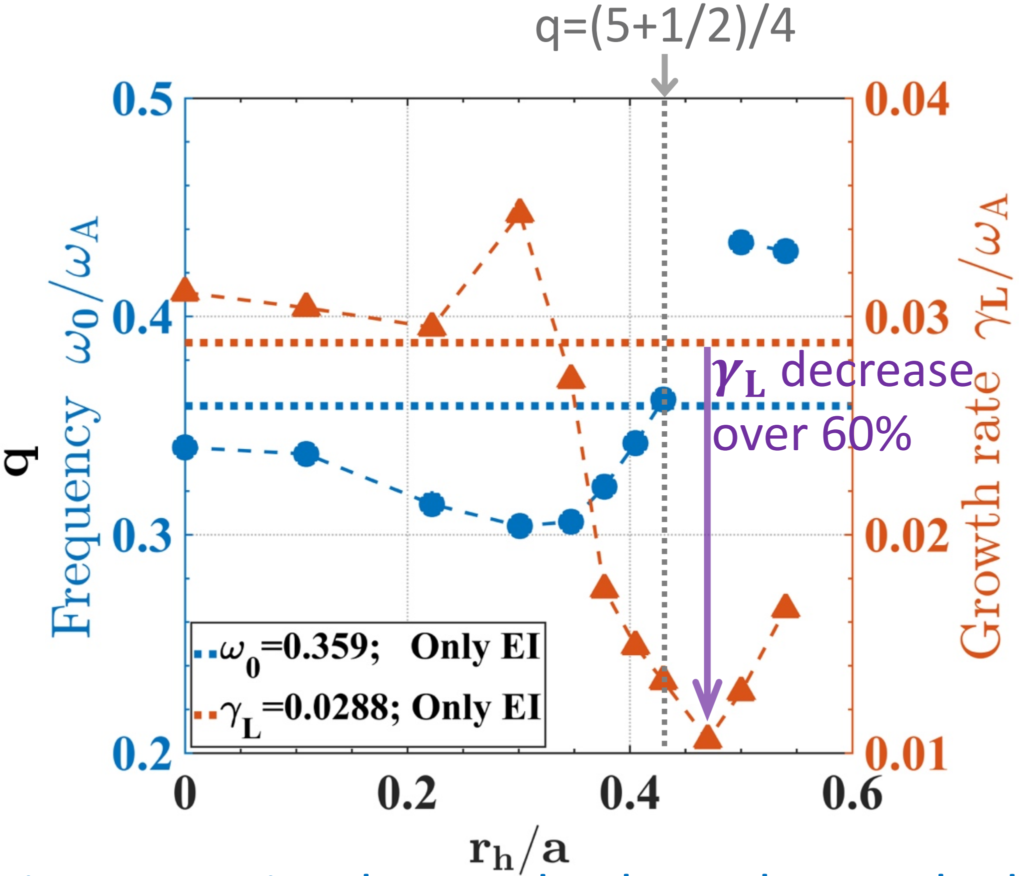


- The dominant stabilizing effect of TAE is from the decrease of EP driving rate, rather than the significant increase of damping rate.
- Both positive and negative pressure gradient have a stabilizing effect on TAE.

Effects of different EE beta profile locations on EI driven TAE

EE beta profiles with different peaked locations r_h

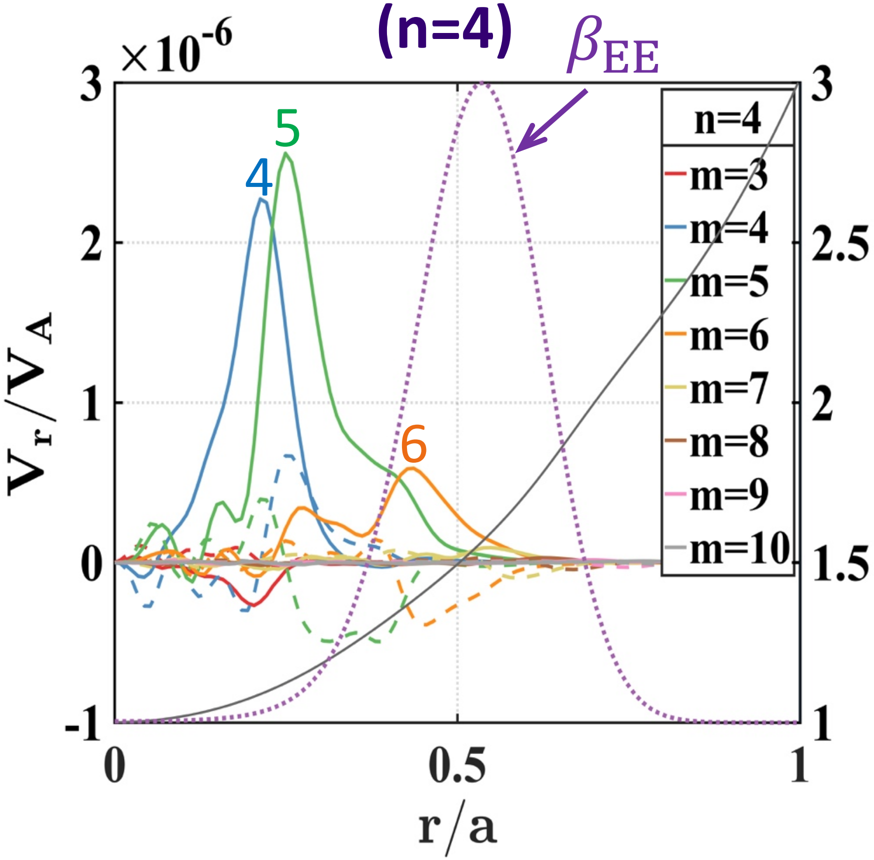




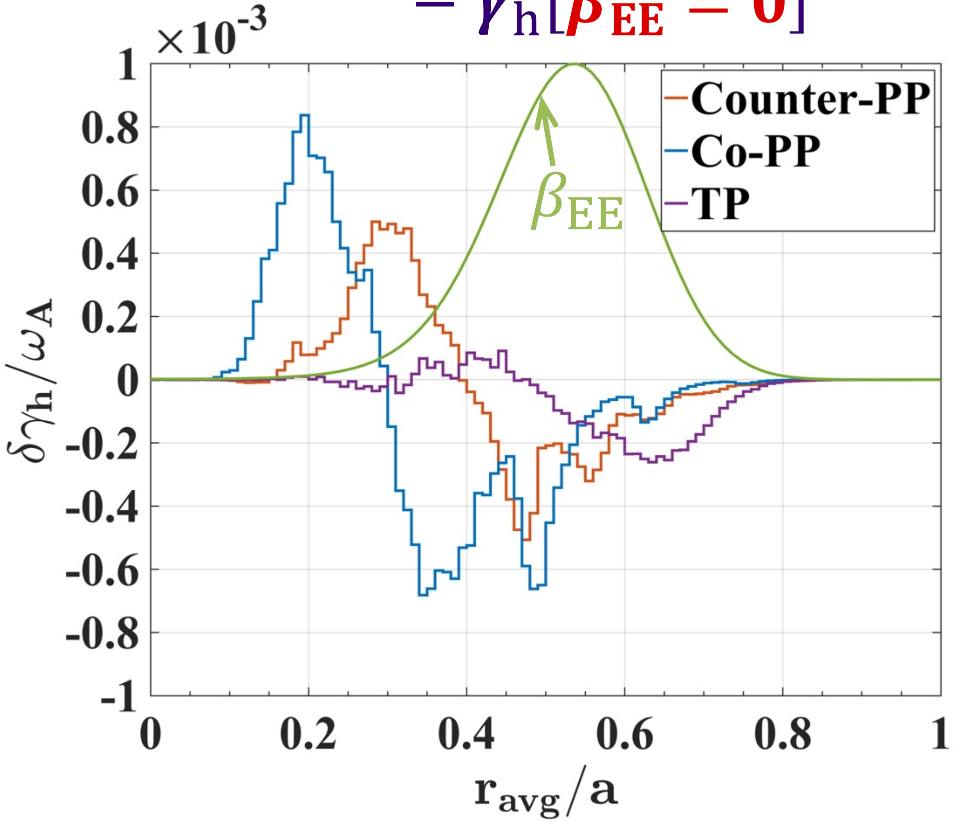
- ➢ An obvious suppression of EI driven TAE is observed when the peaked location of EE beta profile r_h is inside the mode region.
- ➢ The strongest suppression will be achieved with a slight shift of r_h from the mode center.
- ➢ TAE frequency decreases firstly and then increases, when r_h moves outward.

Sub-dominant poloidal harmonics appears for $\mathbf{r_h = 0.54}$

TAE spatial profiles (n=4)



$$\delta\gamma_h = \gamma_h[\mathbf{r_h} = 0.54] - \gamma_h[\beta_{EE} = 0]$$



- ➢ When r_h further moves outward from the mode center, m=6 harmonic will be strongly damped.
- ➢ A mode with dominant harmonics m=4 and m=5 appears in the core region, which is out of strong EE pressure gradient region.

Summary

- **Interactions between EEs and AEs were investigated using a hybrid code MEGA.**

- **We clarified the destabilization mechanism of AEs by EEs:**
  - Trapped EEs dominate the TAE destabilization through precession drift resonance with L=0. A few passing EEs located closely to the rational surface can resonate with the mode.
  - In a weak shear configuration, passing EEs will be important and can destabilize some AEs.

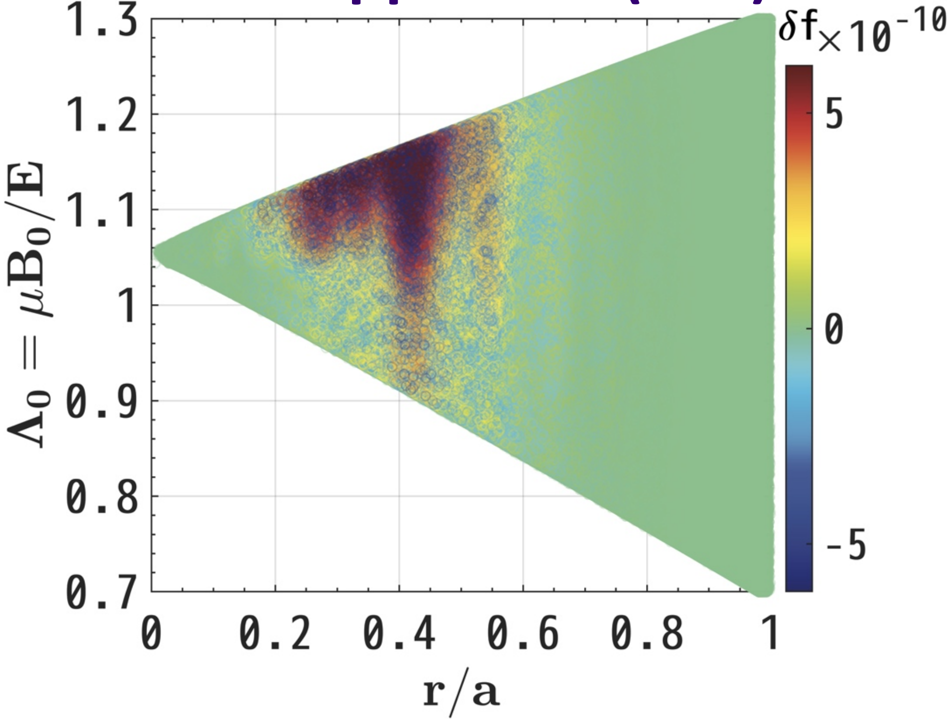
- **EE effects on EI driven TAE were also presented:**
  - An obvious stabilizing effect was found when an off-axis peaked EE beta profile was applied inside the mode region.
  - The stabilization mainly comes from the EE pressure gradient, rather than kinetic effects of EEs.
  - A positive (negative) ∇P_{EE} at the mode center will increase (decrease) the TAE frequency for a monotonic q-profile.

Thank you for your attention!

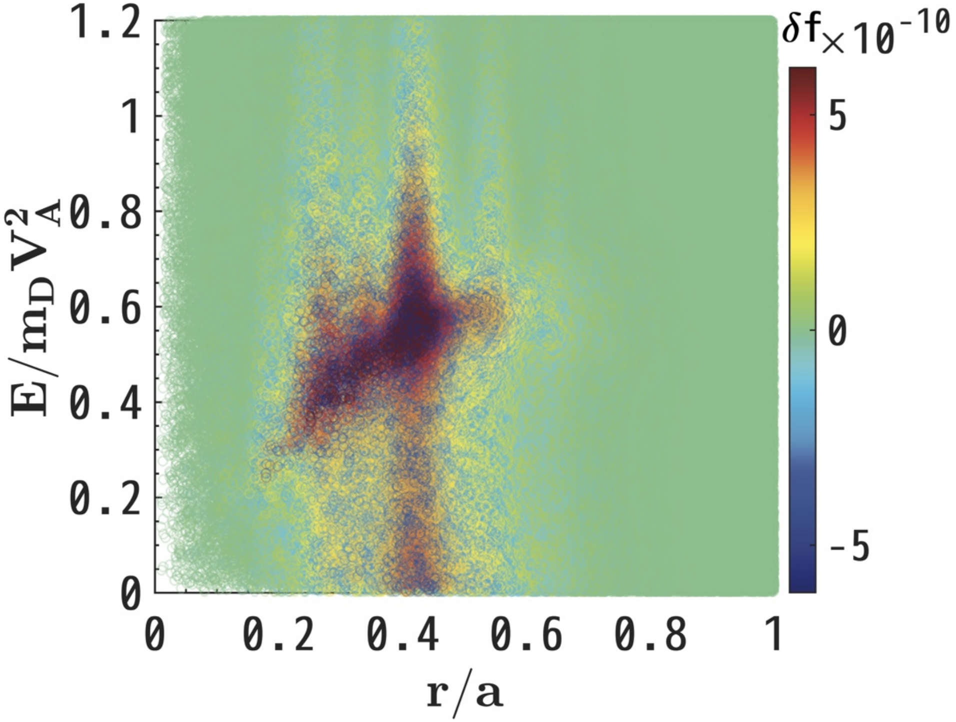
BACKUP SLIDES

Properties of trapped EEs in driving negative frequency TAE

Pitch angle dependence for trapped EEs (n=4)

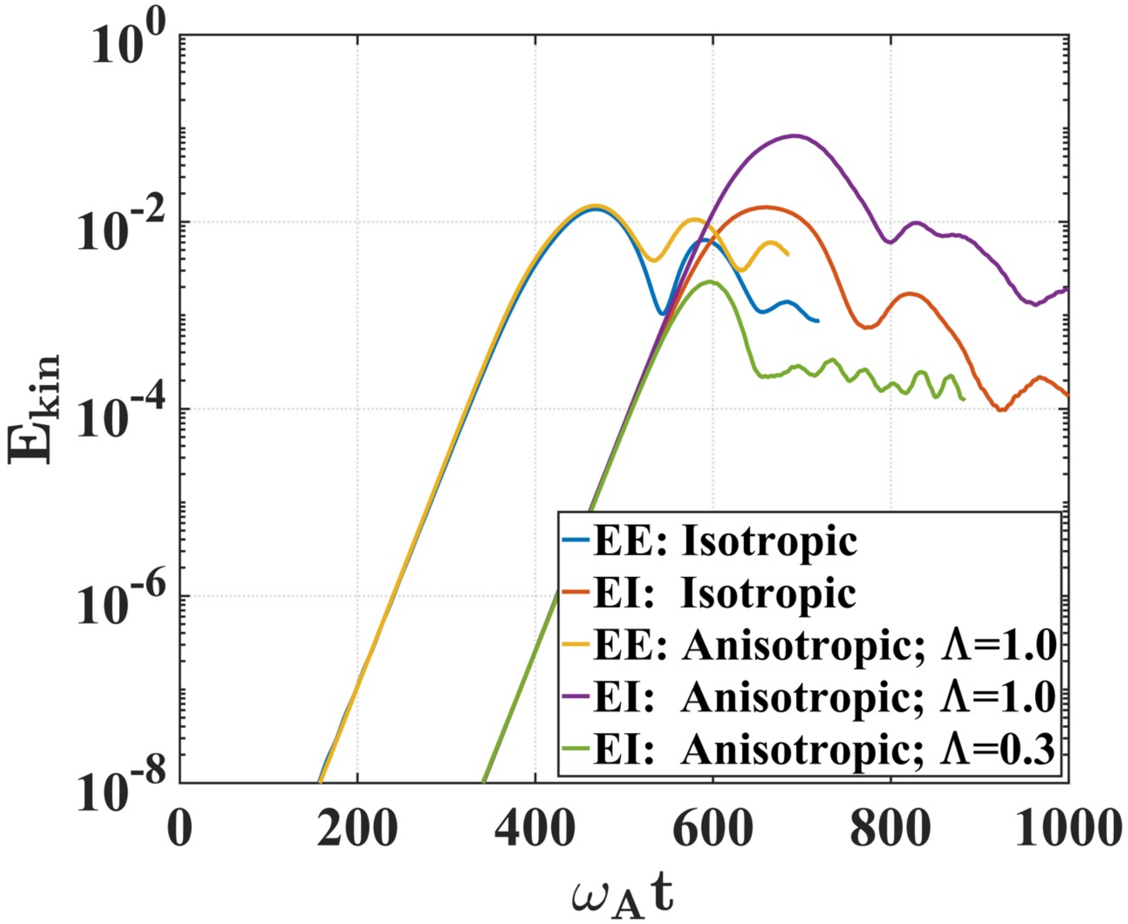


Particle energy dependence for trapped EEs (n=4)



- Deeply trapped EEs are most important resonant particles.
- Kinetic energy of these resonant particles is 0.4~0.6 $[m_D V_A^2]$, or an equivalent speed from $54 \sim 66\ [V_A]$.

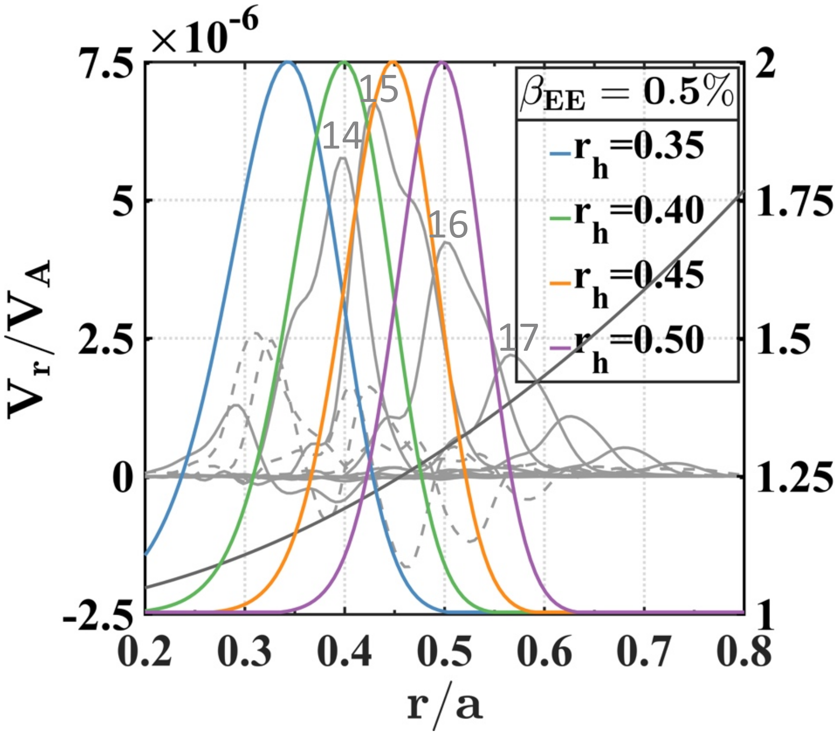
Saturation level of EE driven TAE

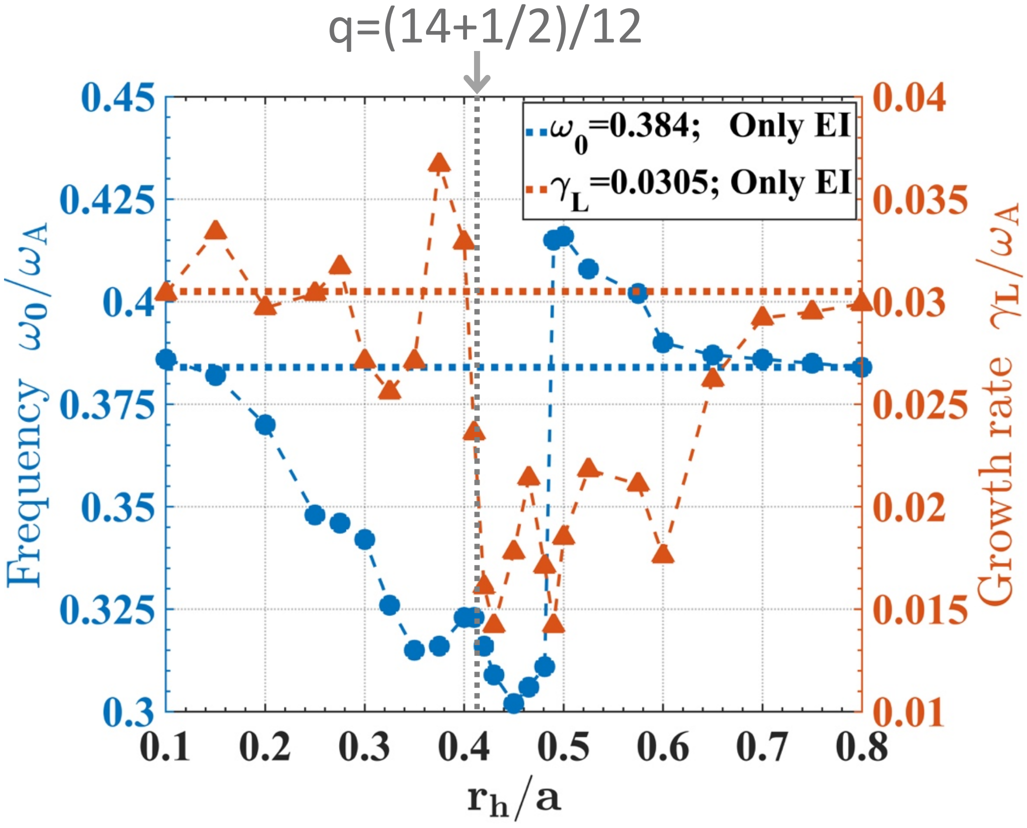


- Saturation levels are similar for EE and EI driven TAE with the same isotropic Maxwellian distributions.
- Bounce frequencies of trapped EI, passing EI and trapped EE are different for the same mode amplitude: $\omega_b(EI_{TP}) < \omega_b(EE_{TP}) < \omega_b(EI_{PP})$

EE effects on n=12 TAE driven by EIs

EE beta profiles with different peaked locations r_h





- The dominant poloidal harmonics of n=12 EI driven TAE are m=14 and 16.
- Conclusions are similar to EE effects on n=4 EI driven TAE.