Global simulation of drift-Alfvenic instability based on Landau fluid-gyrokinetic hybrid model in general geometry

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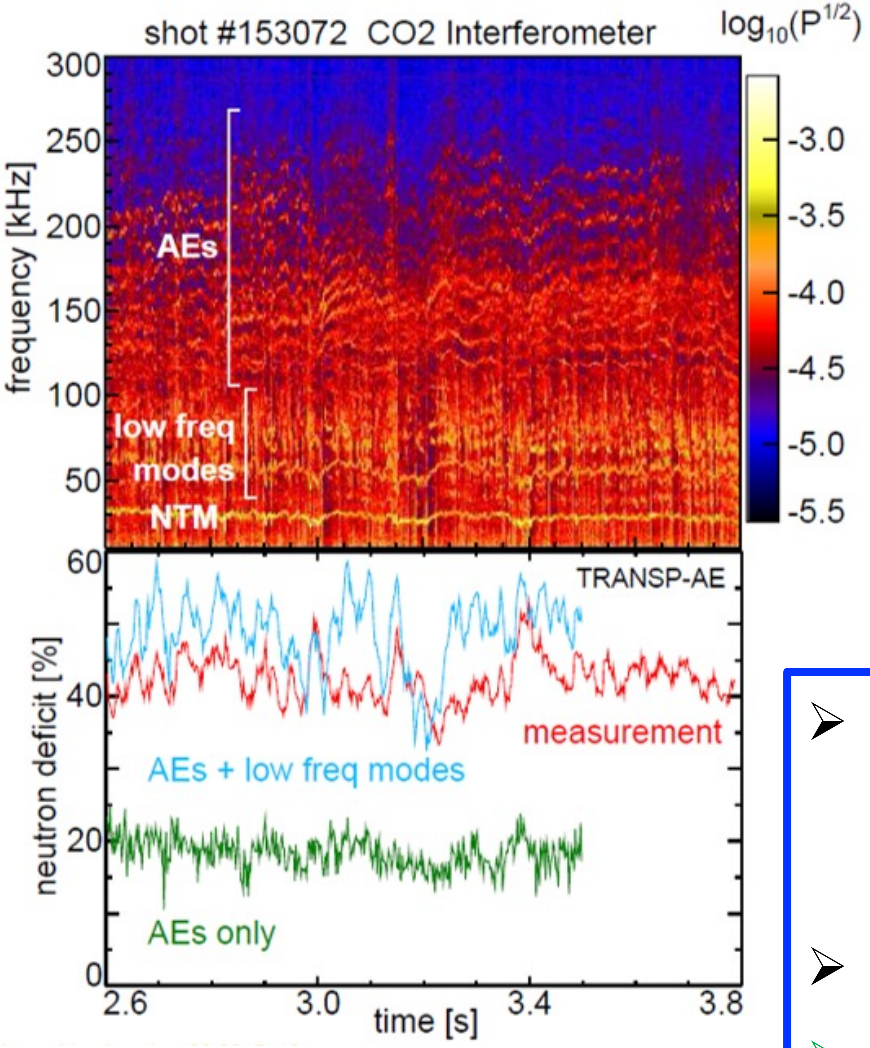
Outlines

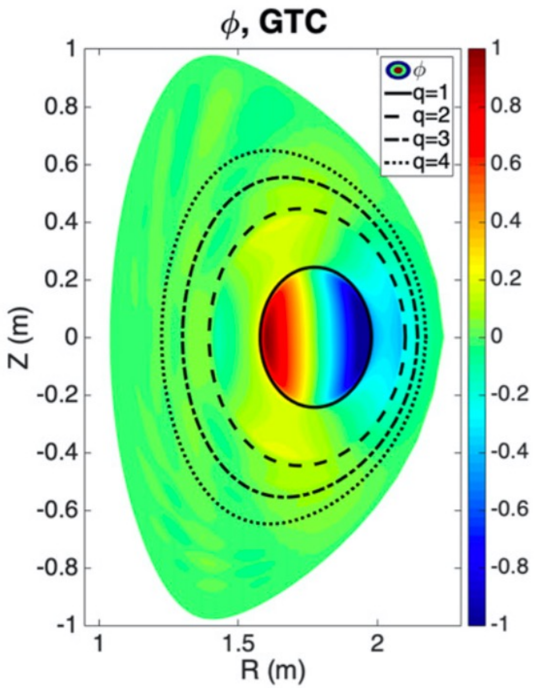
- Background
- Discretized eigenmode
- Continuous spectrum
- Resonance condition in phase space
- Summary

Backgroud



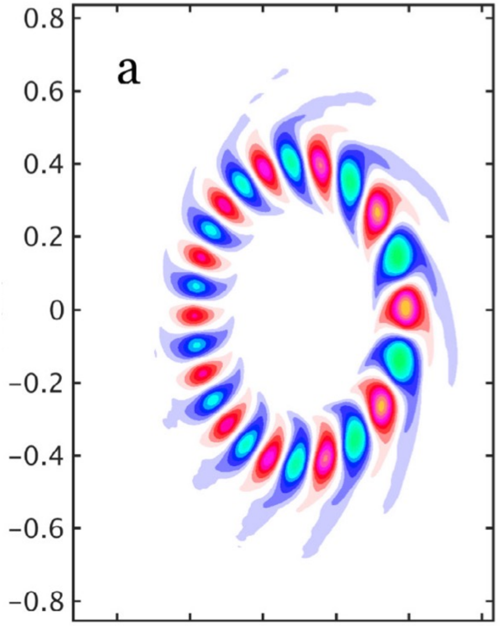
G. Kramer & R. Nazikian

G. Brochard 2022 NF



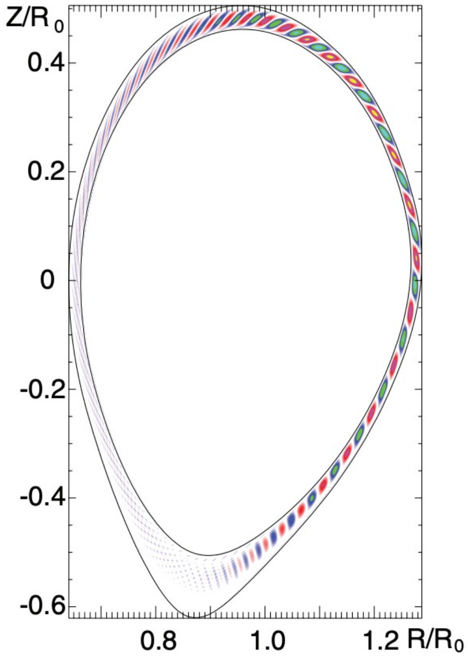
Kink (n=1)

S. Taimourzadeh 2019 NF



RSAE (n=4)

I. Holod 2015 NF



KBM (n=20)

- Drift-Alfvenic instabilities widely exist in burning plasmas: MHD (macro-scale), EP-driven Alfven eigenmode (meso-scale), drift-wave instability (micro-scale).
- Initial value simulation for nonlinear problem (e.g. GTC, M3D-K).
- Eigenvalue simulation for linear stability analysis (e.g. LIGKA, NOVA-K).

Main plasma instabilities

Reactive （fluid-type)
Dissipative （kinetic-type)

Drift-wave instability

- ES: ITG, CTEM
- EM: IBM/KBM

MHD mode

- EM: kink, tearing

Alfven eigenmode

- EM: TAE, RSAE, KBAE
- EM/ES hybrid: BAAE

Modify/Drive

EP kinetic response
(Wave-particle resonance)

Goals of MAS eigenvalue code:
- Cross-scale drift-Alfvenic instabilities
- MHD/kinetic continuous spectrum
- Resonance condition in phase space
- Capability of realistic geometry

Outlines

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- Discretized eigenmode
  - ➢Various bulk plasma instabilities
  - ➢Energetic electron excitation of BAE
  - ➢Energetic ion responses to arbitrary wavelength fluctuations
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Landau fluid model for bulk plasmas

Bao et al, Nucl. Fusion **63** 076021 (2023)

- Vorticity equation

$$\frac{\partial}{\partial t}\frac{c}{V_A^2}\nabla_\perp^2\delta\phi+\underbrace{\frac{\partial}{\partial t}\left(0.75\rho_i^2\nabla_\perp^2\right)\frac{c}{V_A^2}\nabla_\perp^2\delta\phi}_{\{Ion-FLR\}}+\underbrace{i\omega_{p,i}^*\frac{c}{V_A^2}\nabla_\perp^2\delta\phi}_{\{Drift\}}+\mathbf{B_0}\cdot\nabla\left(\frac{1}{B_0}\nabla_\perp^2\delta A_{||}\right)-\frac{4\pi}{c}\boldsymbol{\delta B}\cdot\nabla\left(\frac{J_{||0}}{B_0}\right)$$
$$-8\pi\left(\nabla\delta P_i+\nabla\delta P_e\right)\cdot\frac{\mathbf{b_0}\times\boldsymbol{\kappa}}{B_0}=0$$

- Parallel Ohm's law

$$\frac{\partial\delta A_{||}}{\partial t}=-c\mathbf{b_0}\cdot\nabla\delta\phi+\underbrace{\frac{cT_{e0}}{en_{e0}}\mathbf{b_0}\cdot\nabla\delta n_e+\frac{cT_{e0}}{en_{e0}B_0}\boldsymbol{\delta B}\cdot\nabla n_{e0}}_{\{Drift\}}+\underbrace{\frac{cm_e}{e}\sqrt{\frac{\pi}{2}}v_{the}|k_{||}|\delta u_{||e}}_{\{Electron-Landau\}}+\underbrace{\frac{c^2}{4\pi}\eta_{||}\nabla_\perp^2\delta A_{||}}_{\{Resistivity\}},$$

- Thermal ion pressure Eq.

$$\frac{\partial\delta P_i}{\partial t}+\frac{c\mathbf{b_0}\times\nabla\delta\phi}{B_0}\cdot\nabla P_{i0}+2\Gamma_{i\perp}P_{i0}c\nabla\delta\phi\cdot\frac{\mathbf{b_0}\times\boldsymbol{\kappa}}{B_0}+\Gamma_{i||}P_{i0}\mathbf{B_0}\cdot\nabla\left(\frac{\delta u_{||i}}{B_0}\right)\underbrace{-i\Gamma_{i\perp}\omega_{p,i}^*Z_in_{i0}\rho_i^2\nabla_\perp^2\delta\phi}_{\{Ion-FLR\}}$$
$$\underbrace{+2\Gamma_{i\perp}P_{i0}\frac{c}{Z_i}\nabla\delta T_i\cdot\frac{\mathbf{b_0}\times\boldsymbol{\kappa}}{B_0}+2\Gamma_{i\perp}T_{i0}\frac{c}{Z_i}\nabla\delta P_i\cdot\frac{\mathbf{b_0}\times\boldsymbol{\kappa}}{B_0}}_{\{Drift\}}\underbrace{+n_{i0}\frac{2}{\sqrt{\pi}}\sqrt{2}v_{thi}|k_{||}|\delta T_i}_{\{Ion-Landau\}}=0$$

- Parallel momentum Eq.

$$m_in_{i0}\frac{\partial\delta u_{||i}}{\partial t}=-\mathbf{b_0}\cdot\nabla\delta P_e-\frac{1}{B_0}\boldsymbol{\delta B}\cdot\nabla P_{e0}-\mathbf{b_0}\cdot\nabla\delta P_i-\frac{1}{B_0}\boldsymbol{\delta B}\cdot\nabla P_{i0}$$
$$\underbrace{-Z_in_{i0}\frac{m_e}{e}\sqrt{\frac{\pi}{2}}v_{the}|k_{||}|\delta u_{e||}}_{\{Electron-Landau\}}\underbrace{-Z_in_{i0}\eta_{||}\frac{c}{4\pi}\nabla_\perp^2\delta A_{||}}_{\{Resistivity\}}$$

- Thermal ion density Eq.

$$\frac{\partial\delta n_i}{\partial t}+\frac{c\mathbf{b_0}\times\nabla\delta\phi}{B_0}\cdot\nabla n_{i0}+2cn_{i0}\nabla\delta\phi\cdot\frac{\mathbf{b_0}\times\boldsymbol{\kappa}}{B_0}+n_{i0}\mathbf{B_0}\cdot\nabla\left(\frac{\delta u_{||i}}{B_0}\right)\underbrace{-i\omega_{p,i}^*\frac{Z_in_{i0}}{T_{i0}}\rho_i^2\nabla_\perp^2\delta\phi}_{\{Ion-FLR\}}\underbrace{+\frac{2c}{Z_i}\nabla\delta P_i\cdot\frac{\mathbf{b_0}\times\boldsymbol{\kappa}}{B_0}}_{\{Drift\}}=0$$

Field equations

$$\delta P_e=\delta n_eT_{e0}+n_{e0}\delta T_e$$

$$e\delta n_e=Z_i\delta n_i+\underbrace{\frac{c^2}{4\pi V_A^2}\nabla_\perp^2\delta\phi}_{\{\text{Drift}\}}.$$

$$\mathbf{b}_0\cdot\nabla\delta T_e+\frac{1}{B_0}\delta\mathbf{B}\cdot\nabla T_{e0}=0$$

$$en_{e0}\delta u_{||e}=Z_in_{i0}\delta u_{||i}+\underbrace{\frac{c}{4\pi}\nabla_\perp^2\delta A_{||}}_{\{\text{Drift}\}},$$

$$\delta T_i=\frac{1}{n_{i0}}\left(\delta P_i-\delta n_iT_{i0}\right).$$

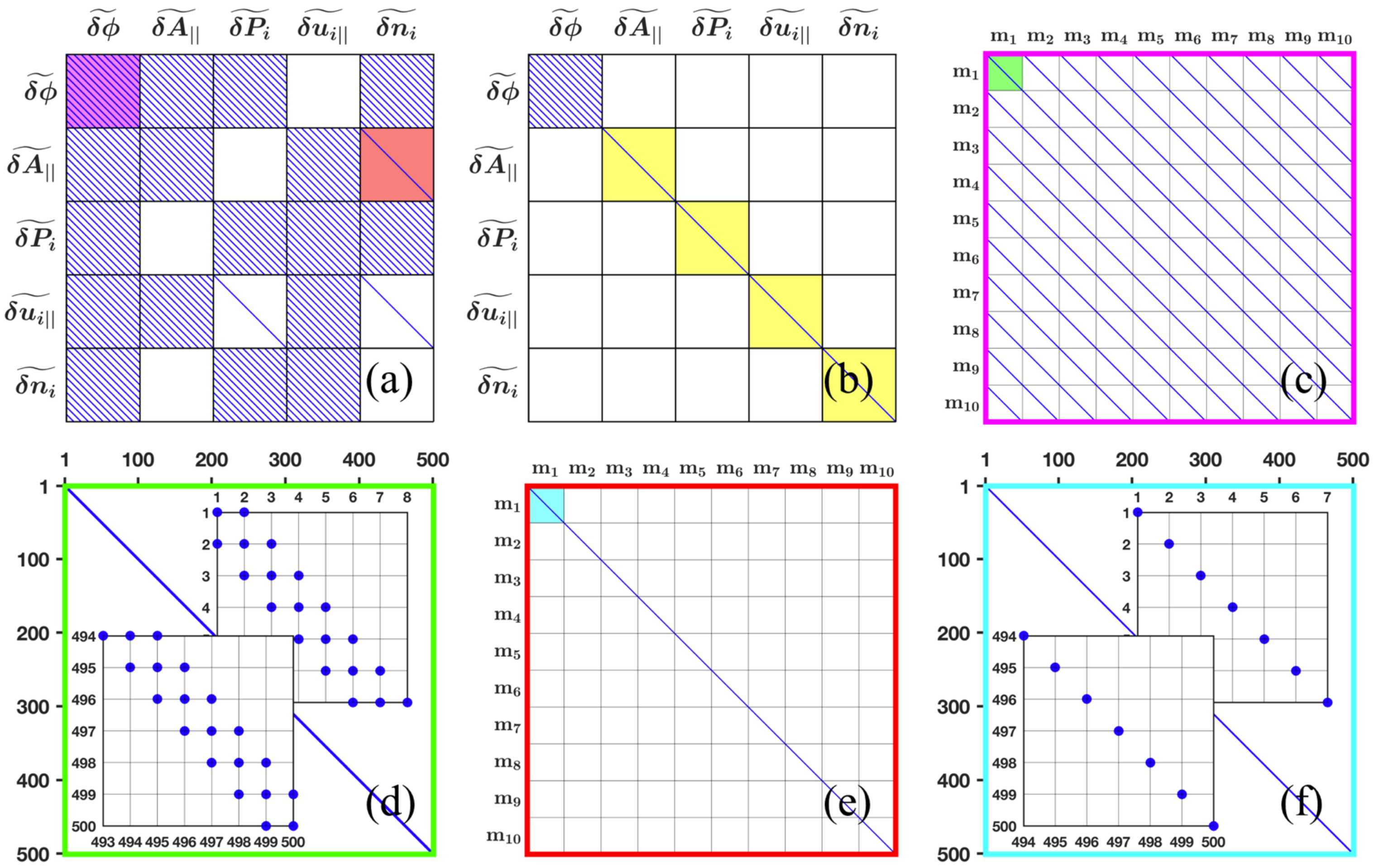
Important features of Landau-fluid model

- Braginskii model using **drift-ordering**
- Kinetic effects on top of full-MHD
  - ✓ Ion/electron diamagnetic drifts
  - ✓ Ion/electron Landau damping (Hammett-Perkins closure)
  - ✓ Ion finite Larmor radius
  - ✓ Parallel electric field
- Reduce to full-MHD by dropping labelled kinetic terms

Algorithm: eigenvalue approach

- Five-field Landau-fluid model can be converted to a generalized eigenvalue problem
  - $AX = \omega BX$
  - $X = (\delta\phi, \delta A_{||}, \delta P_i, \delta u_{i||}, \delta n_i)^T$
- Operator discretization
  - Radial: finite difference
  - Poloidal/toroidal: Fourier expansion
- Language/library
  - matlab/eigs
- Computational speed/cost
  - Less than 1 mins for AE problems on Laptop

Multi-layer block matrices



Normal modes: Alfven wave and acoustic wave

LF:

$$\left[\frac{\omega^2}{k_{||}^2 V_A^2}-1\right]\left[R_e^{\mathrm{LF}}(\xi_e)+\frac{T_{e0}}{T_{i0}}\frac{Z_i^2 n_{i0}}{e^2 n_{e0}}R_i^{\mathrm{LF}}(\xi_i)\right]=\frac{Z_i^2 n_{i0}}{e^2 n_{e0}}k_\perp^2\rho_s^2$$

$$R_e^{\mathrm{LF}}(\xi_e)=\frac{1}{1-i\sqrt{\frac{\pi}{2}}|\xi_e|}$$

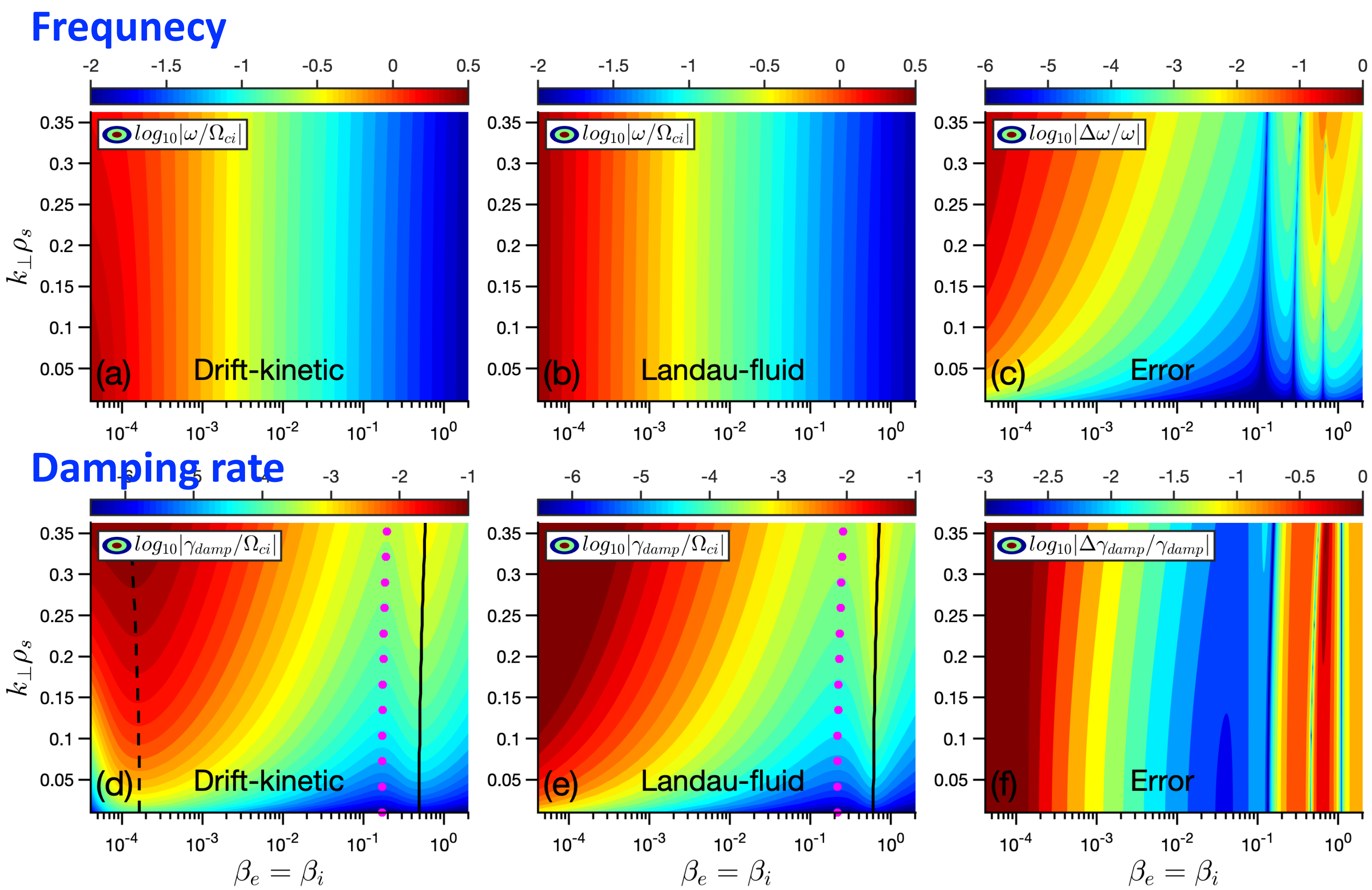
$$R_i^{\mathrm{LF}}(\xi_i)=\frac{|\xi_i|+i\frac{2}{\sqrt{\pi}}}{-2\xi_i^2|\xi_i|-i\frac{4}{\sqrt{\pi}}\xi_i^2+\Gamma_{i||}|\xi_i|+i\frac{2}{\sqrt{\pi}}}$$

DK:

$$\left[\frac{\omega^2}{k_{||}^2 V_A^2}-1\right]\left[R_e^{\mathrm{DK}}(\xi_e)+\frac{T_{e0}}{T_{i0}}\frac{Z_i^2 n_{i0}}{e^2 n_{e0}}R_i^{\mathrm{DK}}(\xi_i)\right]=\frac{Z_i^2 n_{i0}}{e^2 n_{e0}}k_\perp^2\rho_s^2$$

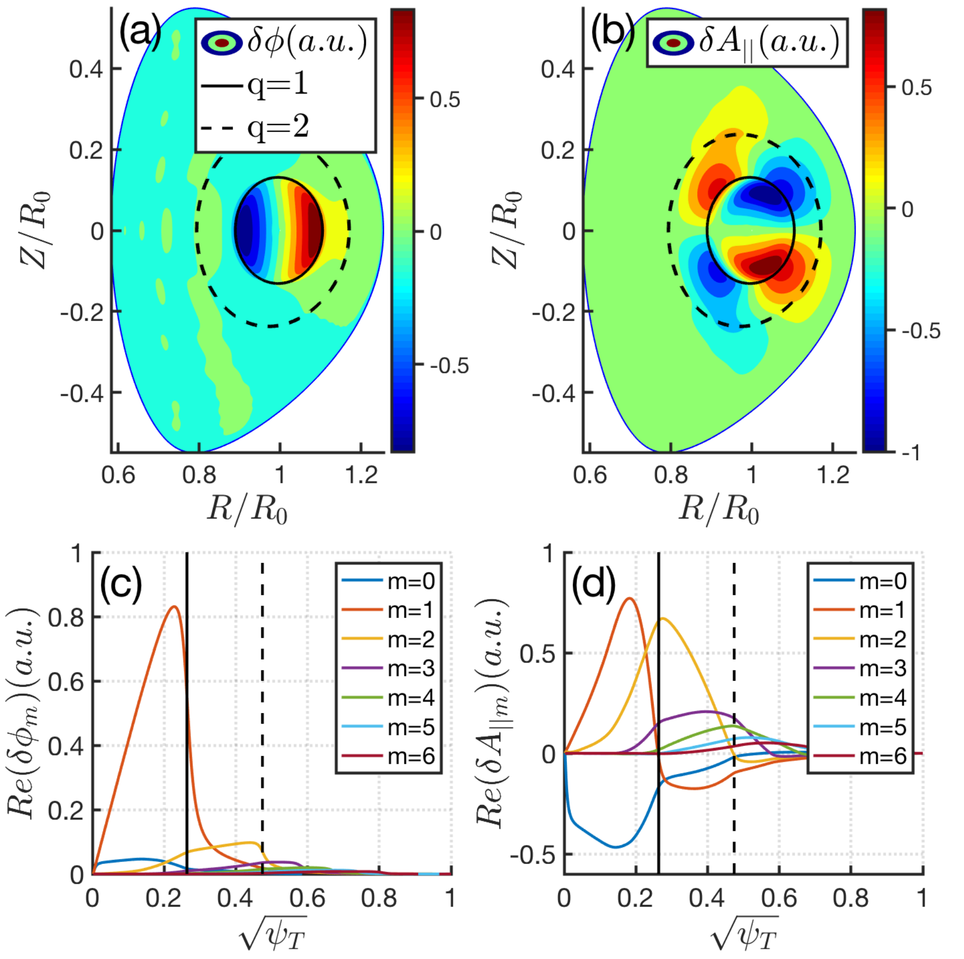
$$R_e^{\mathrm{DK}}(\xi_e)=1+\xi_e Z(\xi_e)$$

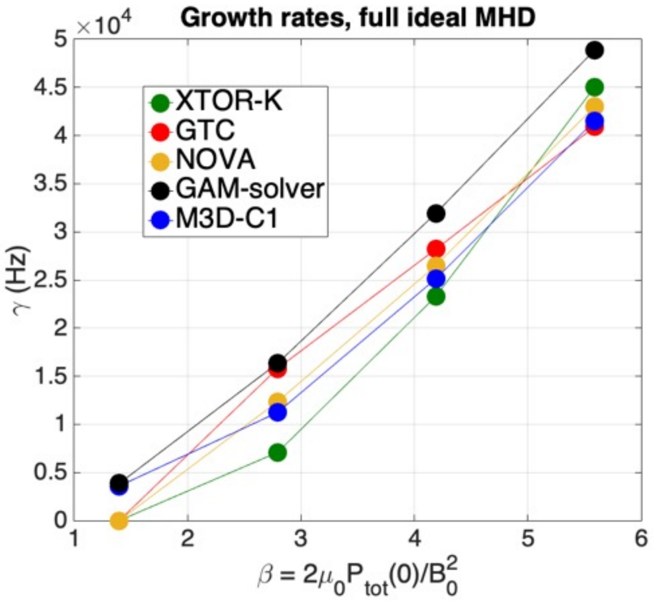
$$R_i^{\mathrm{DK}}(\xi_i)=1+\xi_i Z(\xi_i)$$

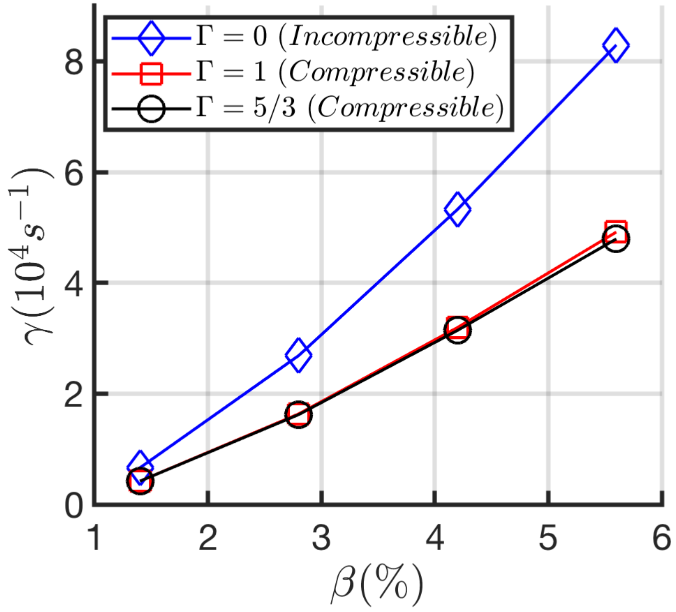


✓ Comparison of coupled KAW-ISW dispersion relation between drift-kinetic model and Landau-fluid model, which show good agreement for typical tokamak plasma beta ($\beta \sim 0.01-0.1$).

MHD mode: internal kink mode





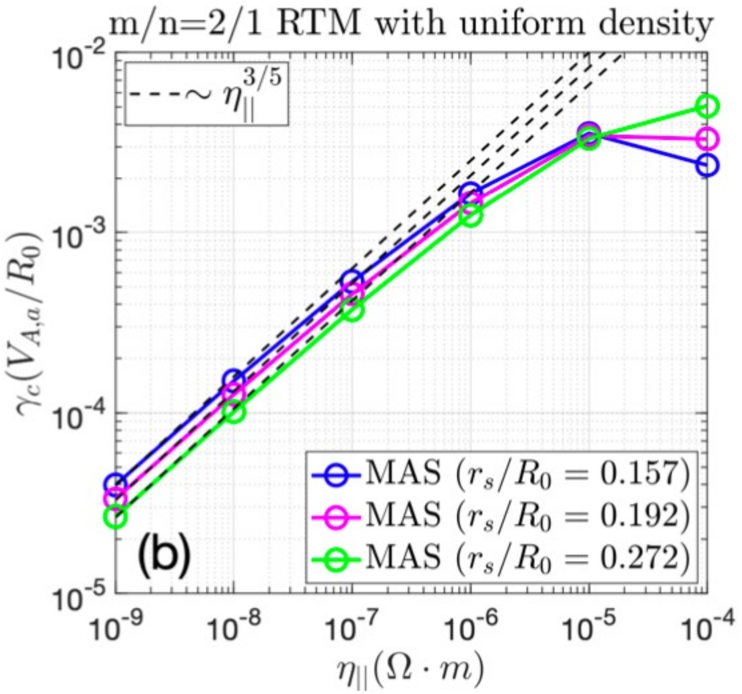


- ➢ Cross-code verification of kink mode (NOVA, XTOR-K, M3D-C1, GTC, MAS)
- ✓ Necessity of full-MHD: finite ion acoustic compression stabilization

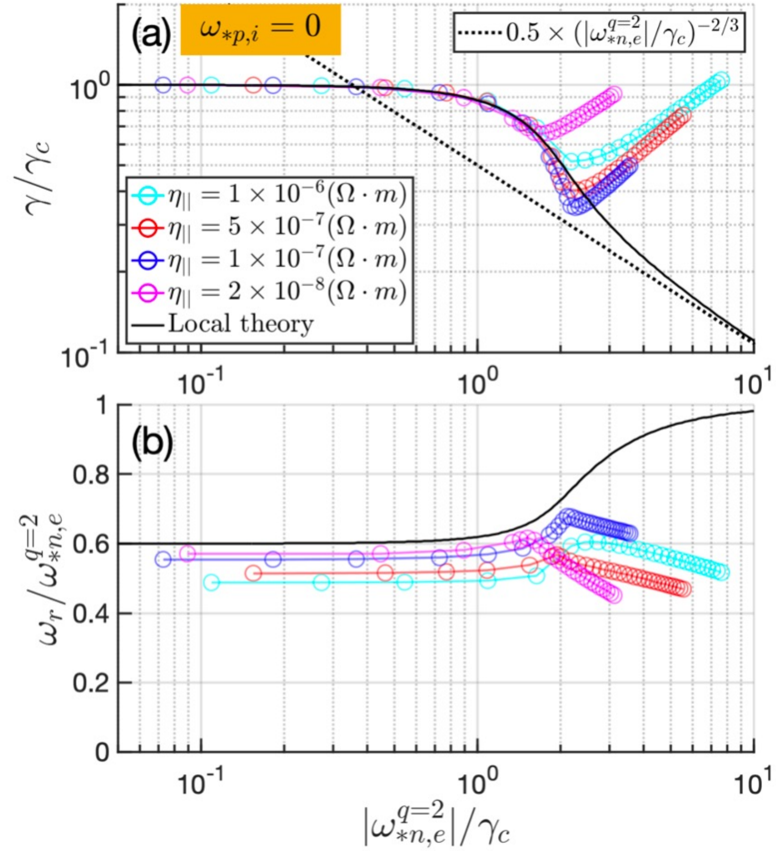
Brochard et al, Nucl. Fusion 62 036021 (2022)

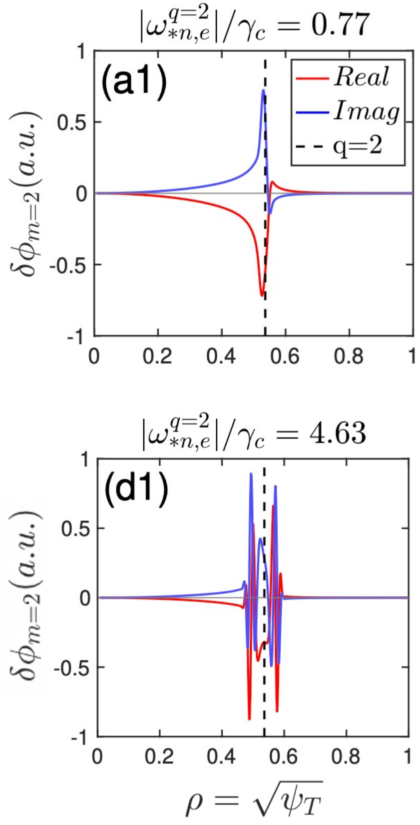
MHD mode: resistive-tearing/drift-tearing modes

$$\gamma_c = \eta_{||}^{3/5} \left(\frac{ns}{r}\right)^{2/5} \left[\Delta' \frac{\Gamma(1/4)}{2\pi\Gamma(3/4)}\right]^{4/5}$$



$$\omega(\omega - \omega_{*p,i})(\omega - \omega_{*n,e})^3 = i\gamma_c^5,$$





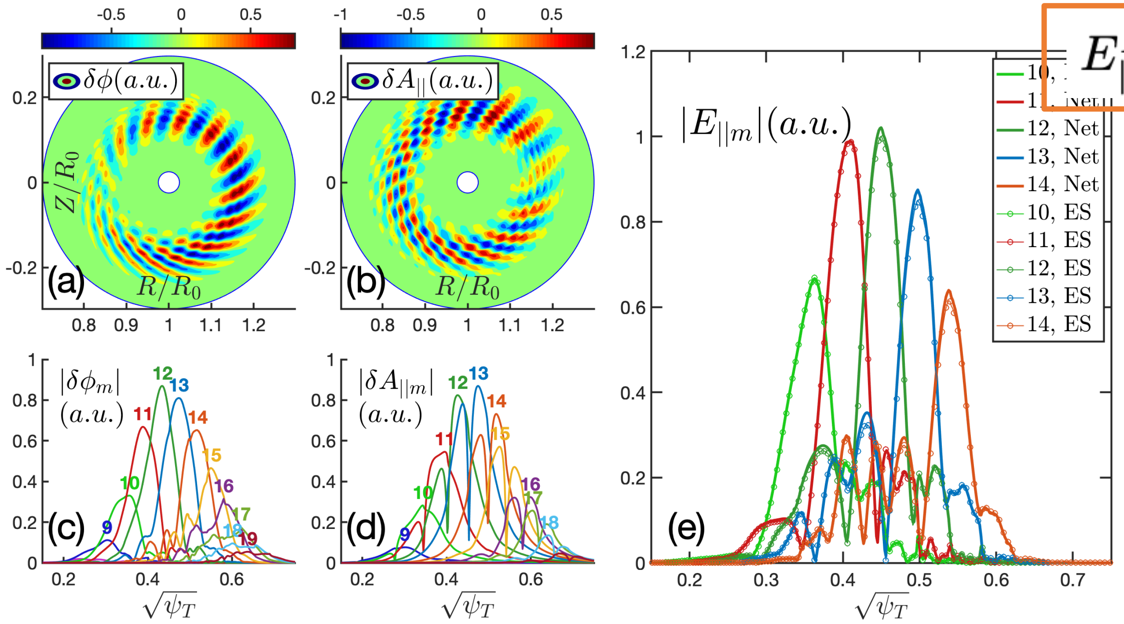
- ✓ The RTM growth rate scaling is close to $\gamma_c \sim \eta_{||}^{5/3}$ in the small $\eta_{||}$ regime.
- ✓ DTM dispersion relation in MAS agrees with local theory in the small ω_e^* regime, while deviates from local theory when $\omega_e^* \sim \gamma_c$ due to the non-local mode structure.

Bao et al, under review in Nucl. Fusion

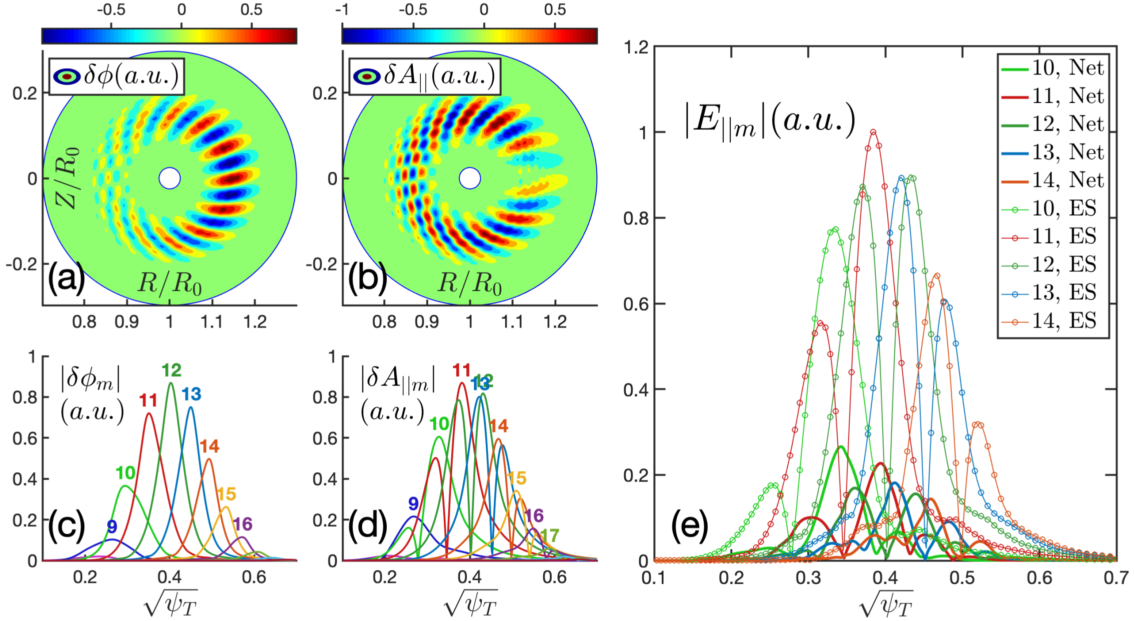
Drift-wave instabilities: ITG/KBM

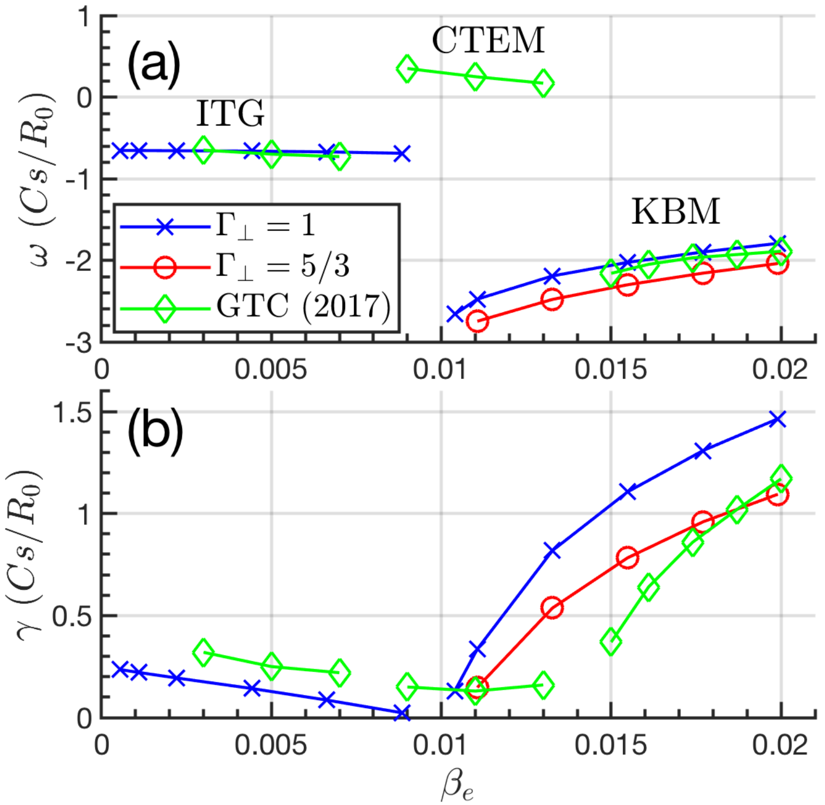
$$E_{||}^{ES} = -\mathbf{b_0} \cdot \nabla \delta\phi \qquad E_{||}^{Net} = -\mathbf{b_0} \cdot \nabla \delta\phi - (1/c)\,\partial_t \delta A_{||}.$$

ITG:



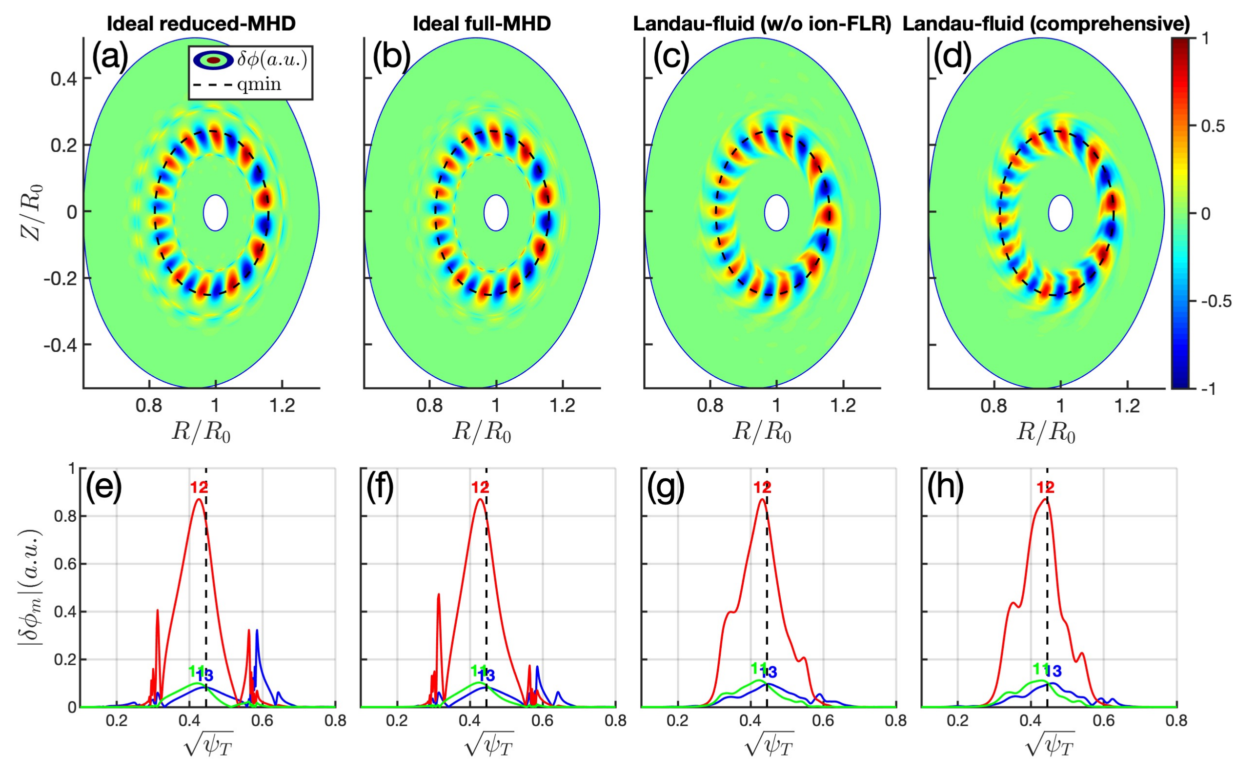
KBM:





- ➢ Cover ITG-KBM transition in CBC case, verify mode polarizations
- ✓ Low beta regime: finite-beta stabilization on ITG
- ✓ High beta regime: KBM onset

RSAE: upward frequency sweeping

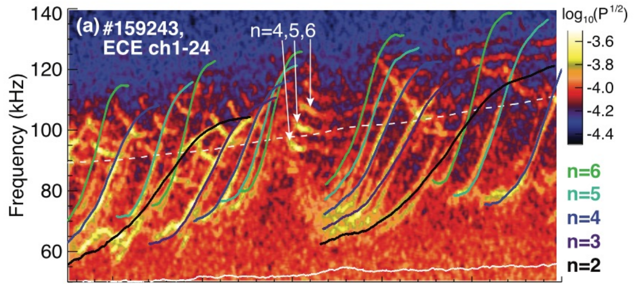


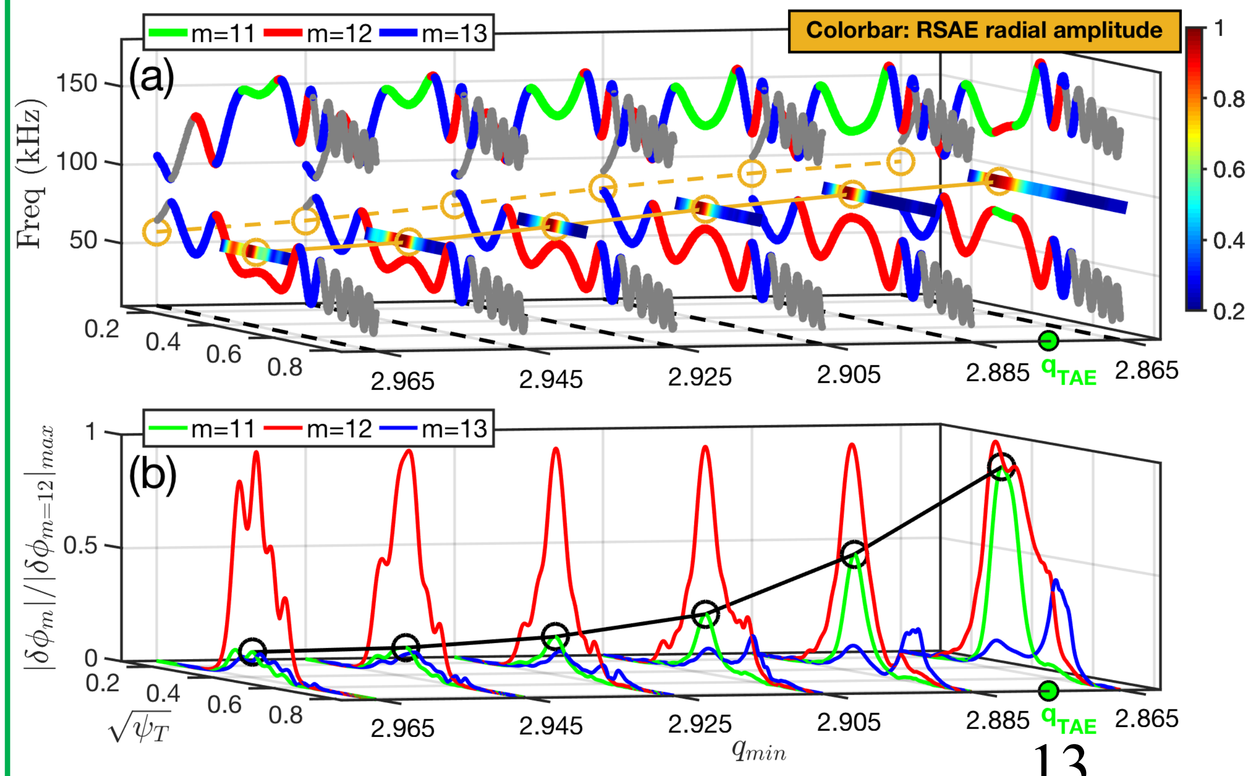
- Comparison of RSAE mode structure between different level physics models

- RSAE frequency increases with decreasing qmin
- RSAE-TAE transition: qmin<qtae=(2m-1)/2n

$$\omega_{\rm RSAE} \approx \left[\left(\frac{m}{q_{\min}} - n\right)^2 \frac{V_A^2}{R_0^2} + \omega_{\rm geod}^2\right]^{1/2} + \delta\omega,$$

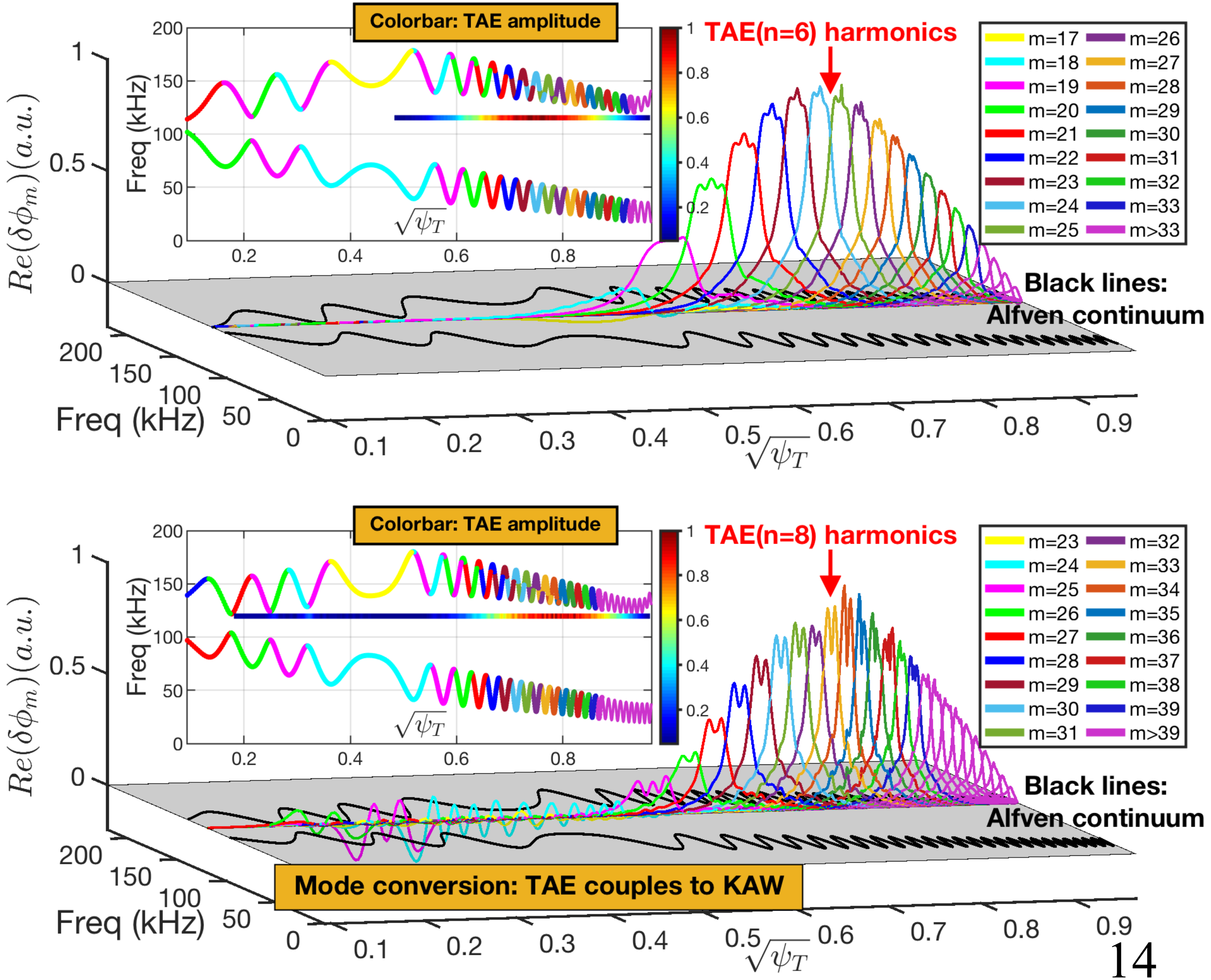
$$m - 0.5 < nq_{\min} < m$$





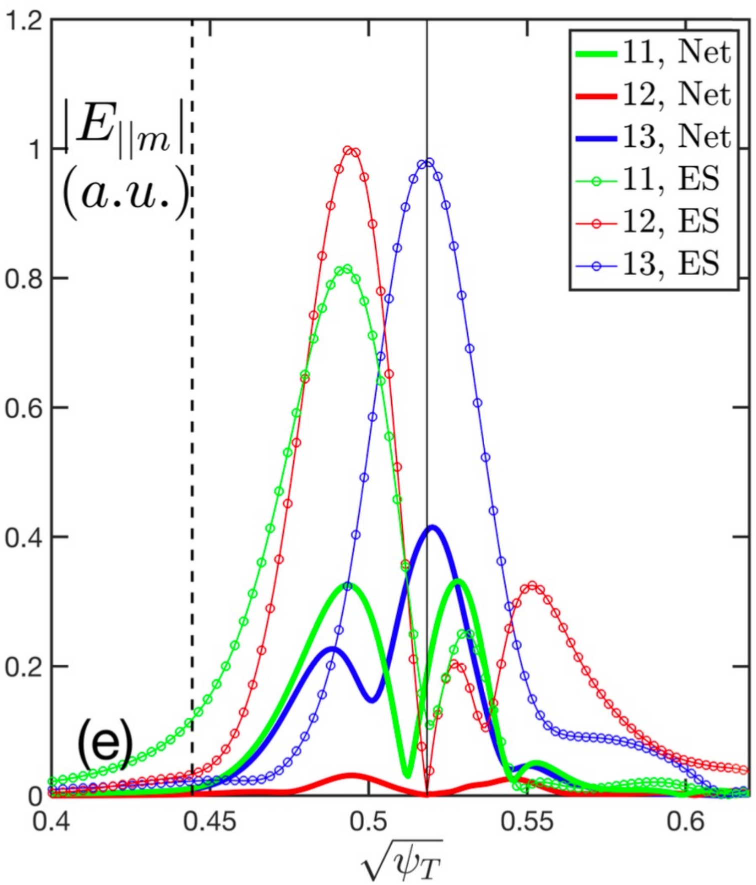
TAE radiative damping

- ➢ Tunneling interaction between TAE and Alfven continua due to kinetic effects (FLR, finite E|| etc)
- ✓ Short-wavelength KAW arises and couples to TAE, enhanced by increasing n number
- ✓ Radiative damping

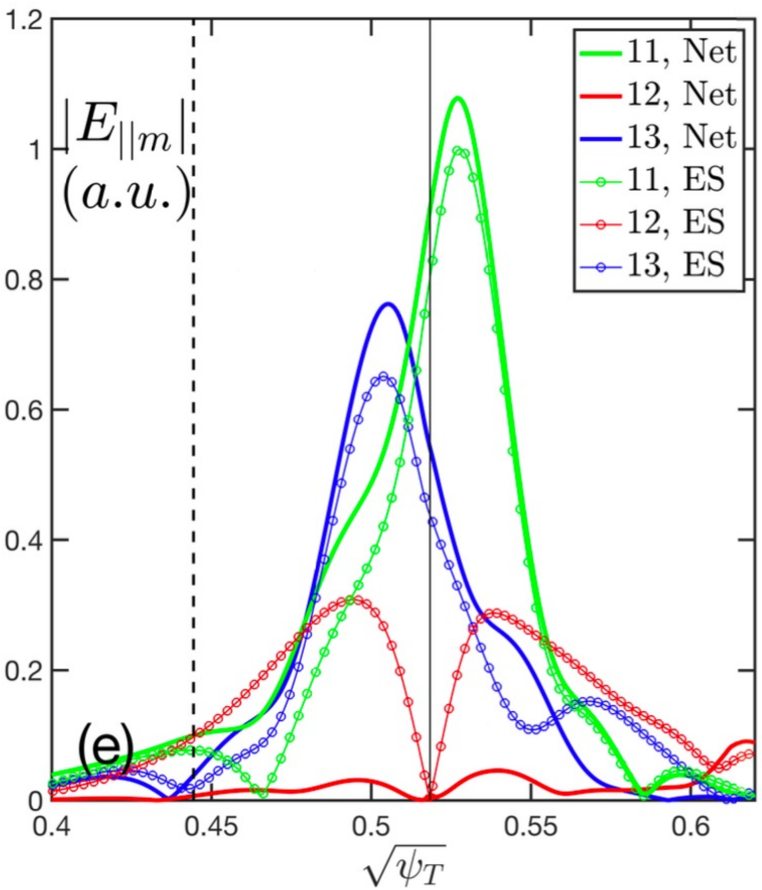


Polarizations of KBAE and BAAE

KBAE:



BAAE:



- KBAE：Alfvenic polarization for all poloidal harmonics ($E_{||}^{Net} \ll E_{||}^{ES}$).
- BAAE：Alfvenic polarization ($E_{||}^{Net} \ll E_{||}^{ES}$) for predominant poloidal harmonics, electrostatic polarization ($E_{||}^{Net} \approx E_{||}^{ES}$) for sidebands $m \pm 1$.

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Drift-kinetic energetic electrons

Linearized drift-kinetic equation

$$L_0\delta f_h + \delta L^L f_{h0} = 0$$

$$L_0 = \frac{\partial}{\partial t} + \left(v_{||}\mathbf{b_0} + \mathbf{v_d}\right)\cdot\nabla - \frac{\mu}{m_e B_0}\mathbf{B_0^*}\cdot\nabla B_0\frac{\partial}{\partial v_{||}}$$

$$\delta L^L = \left(v_{||}\frac{\delta\mathbf{B}}{B_0} + \mathbf{v_E}\right)\cdot\nabla - \left[\frac{\mu}{m_e B_0}\delta\mathbf{B}\cdot\nabla B_0 + \frac{q_e}{m_e}\left(\frac{\mathbf{B_0^*}}{B_0}\cdot\nabla\delta\phi + \frac{1}{c}\frac{\partial\delta A_{||}}{\partial t}\right)\right]\frac{\partial}{\partial v_{||}},$$

- ➢ Adiabatic response
- ✓ convective effect

$$\delta f_h = \delta f^A + \delta K$$

$$\delta f^A = \underbrace{-\frac{q_e}{T_{h0}}\left(\delta\phi - \delta\psi\right)f_{h0}}_{\{I\}} \underbrace{-\frac{q_e}{T_{h0}}\delta\psi\left[\frac{\omega_{*n,h}}{\omega} + \left(\frac{m_e v_{||}^2 + 2\mu B_0}{2T_{h0}} - \frac{3}{2}\right)\frac{\omega_{*T,h}}{\omega}\right]f_{h0}}_{\{II\}}$$

- ➢ Non-adiabatic response
- ✓ Precessional-drift resonance

$$v_{||}\mathbf{b_0}\cdot\nabla\delta K^p = -i\frac{q_e}{T_{h0}}\omega\left(1 - \frac{\omega_{*p,h}}{\omega}\right)\left(\delta\phi - \delta\psi\right)f_{h0} - i\frac{q_e}{T_{h0}}\omega_d\left(1 - \frac{\omega_{*p,h}}{\omega}\right)\delta\psi f_{h0}$$

$$\delta K^t \simeq \delta K_b^t \simeq \underbrace{\frac{\omega}{\omega - \overline{\omega}_d}\frac{q_e}{T_{h0}}\left(1 - \frac{\omega_{*p,h}}{\omega}\right)\left(\overline{\delta\phi} - \overline{\delta\psi}\right)f_{h0}}_{\{I\}} + \underbrace{\frac{1}{\omega - \overline{\omega}_d}\frac{q_e}{T_{h0}}\left(1 - \frac{\omega_{*p,h}}{\omega}\right)\overline{\omega_d\delta\psi}f_{h0}}_{\{II\}}$$

EE moments integrated from kinetic responses

$$\delta n_h^A = \int \delta f^A \mathbf{dv} = -\frac{q_e n_{h0}}{T_{h0}}(\delta\phi - \delta\psi) - \frac{q_e n_{h0}}{T_{h0}}\frac{\omega_{*n,h}}{\omega}\delta\psi$$

$$\delta P_{||h}^A = \int m_e v_{||}^2 \delta f^A \mathbf{dv} = -q_e n_{h0}(\delta\phi - \delta\psi) - q_e n_{h0}\left(\frac{\omega_{*n,h}}{\omega} + \frac{\omega_{*T,h}}{\omega}\right)\delta\psi$$

$$\delta P_{\perp h}^A = \int \mu B_0 \delta f^A \mathbf{dv} = -q_e n_{h0}(\delta\phi - \delta\psi) - q_e n_{h0}\left(\frac{\omega_{*n,h}}{\omega} + \frac{\omega_{*T,h}}{\omega}\right)\delta\psi$$

- Adiabatic response
- ✓ Density
- ✓ Pressure

$$\delta n_h^{NA} = -f_t\frac{q_e n_{h0}}{T_{h0}}\left[\left(1 - \frac{\omega_{*n,h}}{\omega} + \frac{3}{2}\frac{\omega_{*T,h}}{\omega}\right)\zeta R_1\left(\sqrt{\zeta}\right) - \frac{\omega_{*T,h}}{\omega}\zeta R_3\left(\sqrt{\zeta}\right)\right](\delta\phi - \delta\psi)$$
$$- f_t\frac{q_e n_{h0}}{T_{h0}}\left[\left(1 - \frac{\omega_{*n,h}}{\omega} + \frac{3}{2}\frac{\omega_{*T,h}}{\omega}\right)R_3\left(\sqrt{\zeta}\right) - \frac{\omega_{*T,h}}{\omega}R_5\left(\sqrt{\zeta}\right)\right]\delta\psi$$

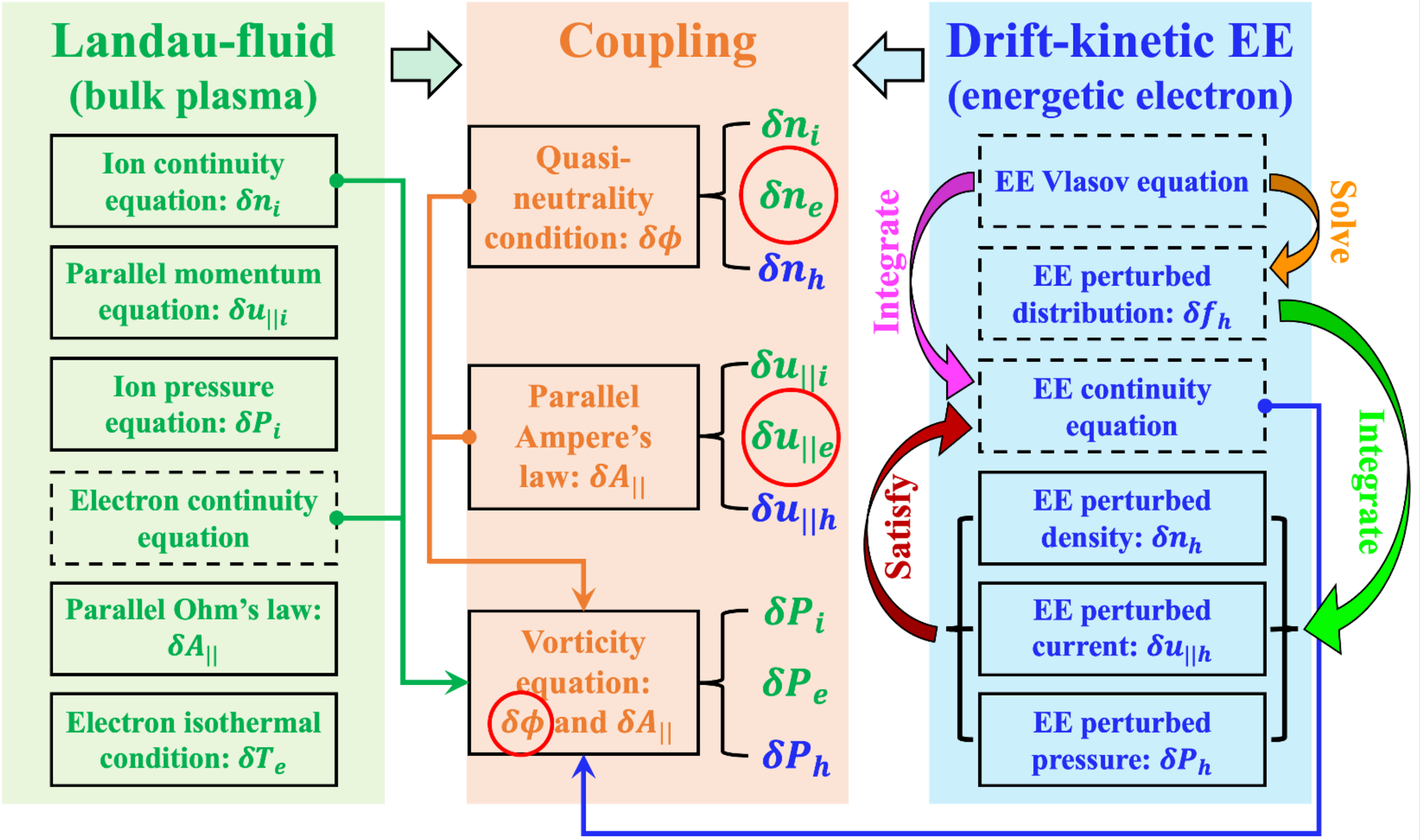
$$\delta P_h^{NA} = -\frac{f_t}{2}q_e n_{h0}\left[\left(1 - \frac{\omega_{*n,h}}{\omega} + \frac{3}{2}\frac{\omega_{*T,h}}{\omega}\right)\zeta R_3\left(\sqrt{\zeta}\right) - \frac{\omega_{*T,h}}{\omega}\zeta R_5\left(\sqrt{\zeta}\right)\right](\delta\phi - \delta\psi)$$
$$-\frac{f_t}{2}q_e n_{h0}\left[\left(1 - \frac{\omega_{*n,h}}{\omega} + \frac{3}{2}\frac{\omega_{*T,h}}{\omega}\right)R_5\left(\sqrt{\zeta}\right) - \frac{\omega_{*T,h}}{\omega}R_7\left(\sqrt{\zeta}\right)\right]\delta\psi$$

- Non-adiabatic response of **trapped electrons**
- ✓ Density
- ✓ Pressure

$$\delta u_{||h} = \frac{e}{T_{h0}}\frac{\omega}{k_{||}}(1 - f_t)\left(1 - \frac{\omega_{*n,h}}{\omega}\right)(\delta\phi - \delta\psi) + 2\frac{e}{T_{h0}}\frac{\omega}{k_{||}}\left(\frac{\omega_d}{\omega} - f_t\frac{3\omega_{D0}}{4\omega}\right)\left(1 - \frac{\omega_{*n,h}}{\omega} - \frac{\omega_{*T,h}}{\omega}\right)\delta\psi$$

- Non-adiabatic response of **passing electrons**
- ✓ Parallel velocity

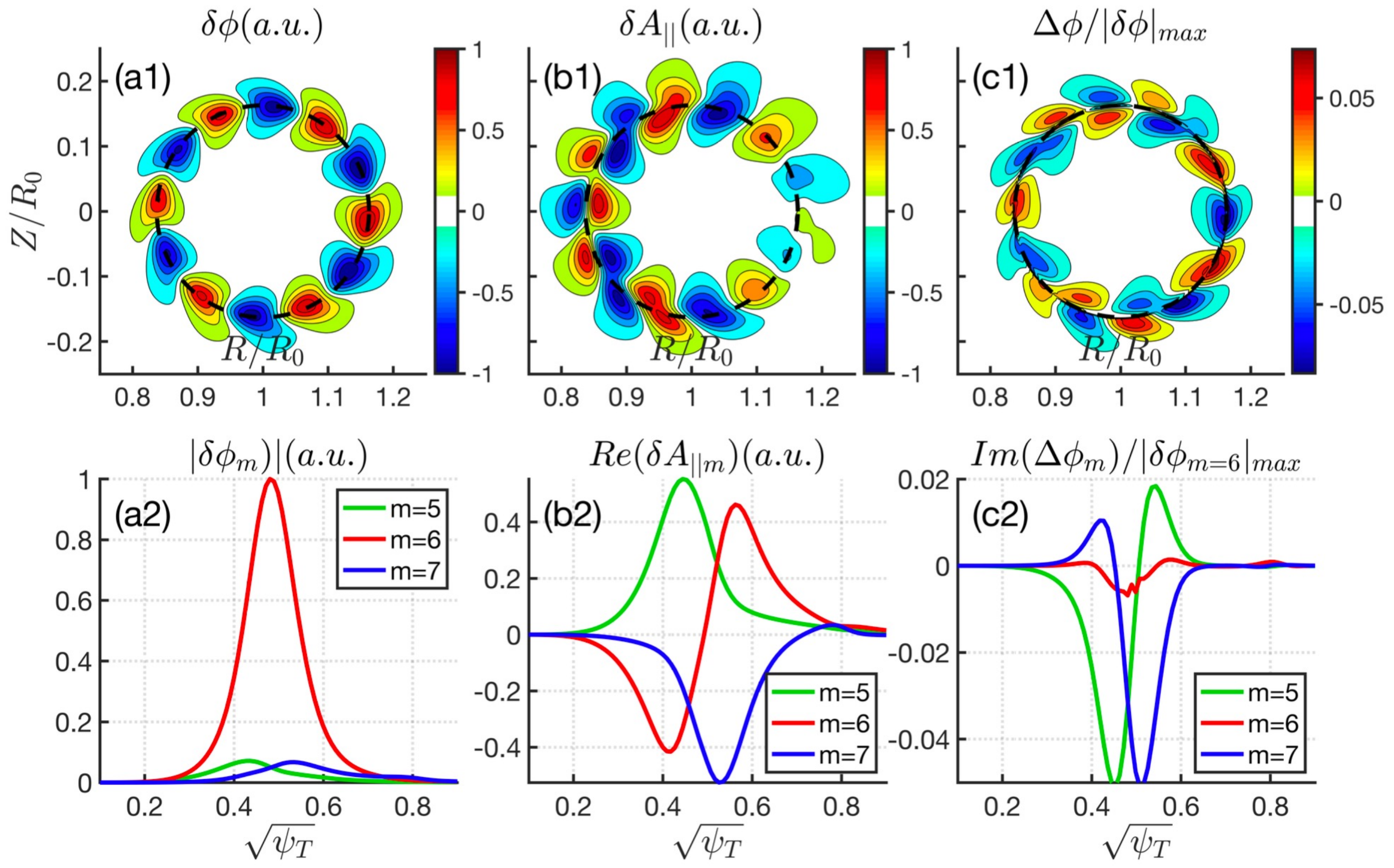
Coupling scheme for EE and bulk plasmas



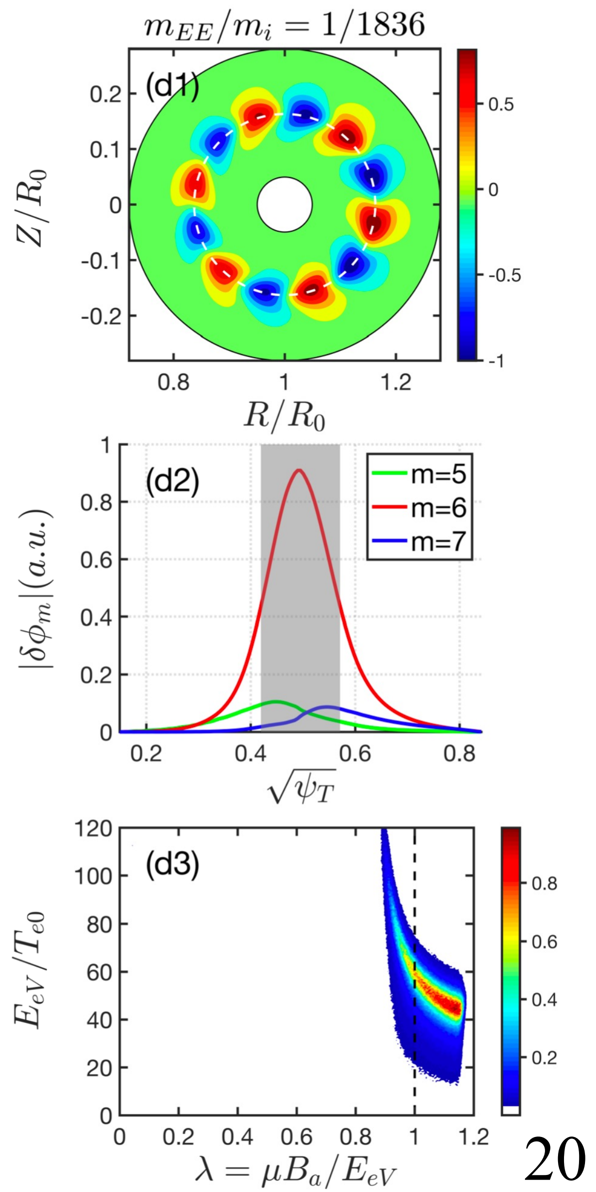
- ✓ δn_h modifies quasi-neutrality condition
- ✓ $\delta u_{||h}$ modifies parallel Ohms law
- ✓ δP_h modifies vorticity equation
- ➢ Enable accuracy for both EM and ES cases **through density and pressure coupling**

Verification of EE-driven BAE (e-BAE)

- **MAS**



- **GTC**

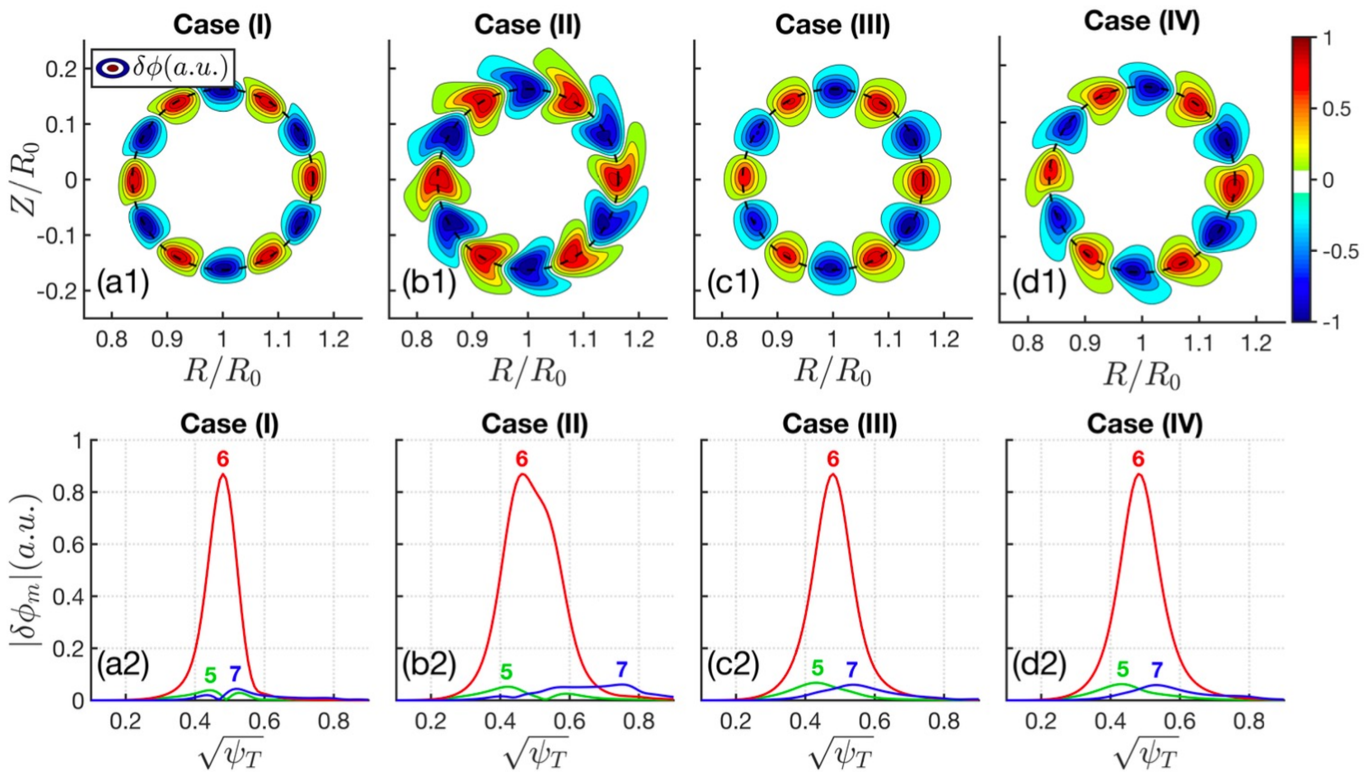


✓ Weakly ballooning mode structure, finite E|| in sidebands, precessional-drift resonance of deeply-trapped EEs.

✓ Good agreements between MAS eigenvalue and GTC initial value results.

Effects of different EE responses on e-BAE

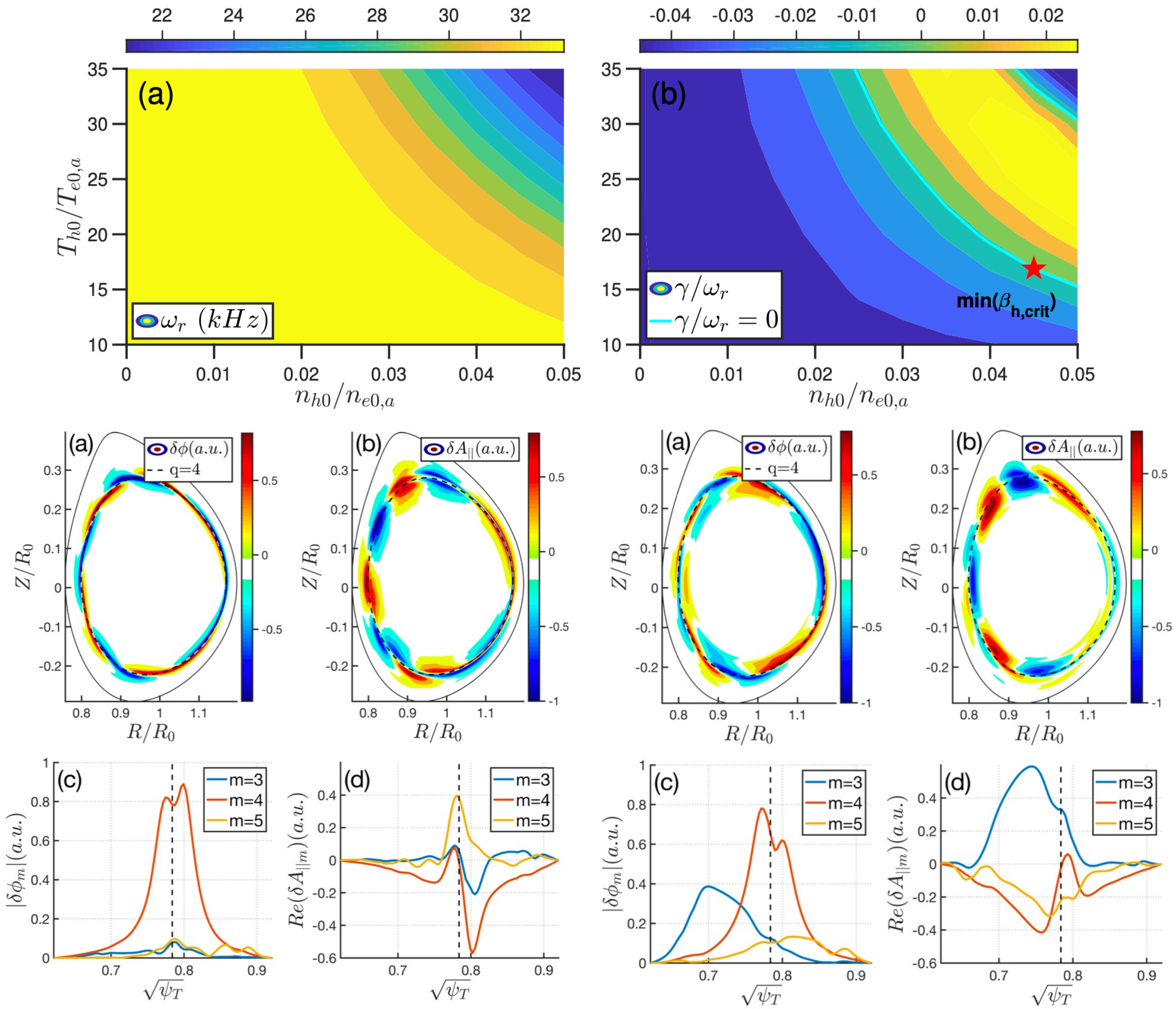
Case	EE-IC	EE-KPC	$\omega_r\,(V_{Ap}/R_0)$	$\gamma\,(V_{Ap}/R_0)$
(I)	No	No	0.160	−0.007 07
(II)	No	Yes	0.175	0.004 96
(III)	Yes	No	0.134	−0.009 09
(IV)	Yes	Yes	0.149	0.009 04



- EE-IC (interchange convective response): **broaden radial width, decrease frequency**
- EE-KPC (kinetic particle compression response): anti-Hermitian contribution to dielectric constant, **induce mode structure poloidal phase variation (triangle shape), increase frequency**

Experimental application in EAST discharges

- Dependences of m/n=4/1 e-BAE ω_r and γ on EE density and temperature in EAST shot #82589.
- EE non-perturbative effects
  - ➢Decrease ω_r
  - ➢Increase e-BAE sideband amplitudes
- Identify the β_h threshold for EE excitation of BAE.



Bao et al, Nucl. Fusion 64 (2024) 016004

Outlines

- Background
- Discretized eigenmode
  - ➢Various bulk plasma instabilities
  - ➢Energetic electron excitation of BAE
  - ➢Energetic ion responses to arbitrary wavelength fluctuations
- Continuous spectrum
- Resonance condition in phase space
- Summary

Gyrokinetic energetic ions

- Numerically integrate EI moments in velocity space from perturbed distributions **with Bessel function coefficients**
- ✓ Transit resonance
- ✓ Precessional drift resonance
- ✓ Finite Larmor radius
- ✓ **Finite orbit width**

Gyrokinetic equation for non-adiabatic response

$$\left(\frac{v_\parallel}{JB}\partial_\theta + i\frac{nqv_\parallel}{JB} - i(w-w_d)\right)\delta K_h = -i\frac{Z_h}{T_h}(\omega-\omega^*_{p,h})J_0 f_{h0}(\Delta\phi + \frac{\omega_d}{\omega}\delta\psi)$$

Solution1:
well-circulating particles

$$J_0\delta K_h = -\frac{Z_h}{T_h}(1-\frac{\omega^*_{p,h}}{\omega})J_0^2 f_{h0}\Sigma_{p,s,m}J_p(\lambda_h)J_s(\lambda_h)i^{p-s}e^{i(p-s)(\theta+\theta_r)}e^{-im\theta}\times$$
$$\left\{\frac{\Delta\phi_m}{R_{N+s}} + \frac{(k_0 v_d/\omega)\delta\psi_m}{R_{N+s}} + \frac{(k_1 v_d/\omega)\delta\psi_m e^{i\theta}}{R_{N+s+1}} + \frac{(k_{-1}v_d/\omega)\delta\psi_m e^{-i\theta}}{R_{N+s-1}}\right\}$$
$$= \mathbb{J}_p \times \mathbb{R} \times \mathbb{J}_s \times (\Delta\phi - i\mathbb{A}\times\delta\psi)$$

where $\lambda_h = k_f\frac{JBv_d}{v_\parallel}$, $k_f = 2\sqrt{k_1 k_{-1}}$ and $R_N = \frac{k_\parallel v_\parallel}{\omega} + \frac{k_0 v_d}{\omega} - 1$, $k_\parallel = \frac{N}{JB} = \frac{nq-m}{JB}$

$$\mathbb{J}_p = \Sigma_p J_p(\lambda_h)i^p e^{ip(\theta+\theta_r)} \quad \mathbb{J}_s = \Sigma_s J_s(\lambda_h)i^{-s}e^{-is(\theta+\theta_r)} = \mathbb{J}_p^\dagger$$

$$\mathbb{R} = -\frac{Z_h}{T_h}(1-\frac{\omega^*_{ph}}{\omega})J_0^2 f_{h0}\frac{v_d}{\omega}\frac{1}{R_N} \qquad \mathbb{A} = \frac{R_0}{JB_0}\{(I\kappa_\zeta - g\kappa_\theta)\partial_\psi - (\delta\kappa_\zeta - g\kappa_\psi)\partial_\theta + (\delta\kappa_\theta - I\kappa_\psi)\partial_\zeta\}$$

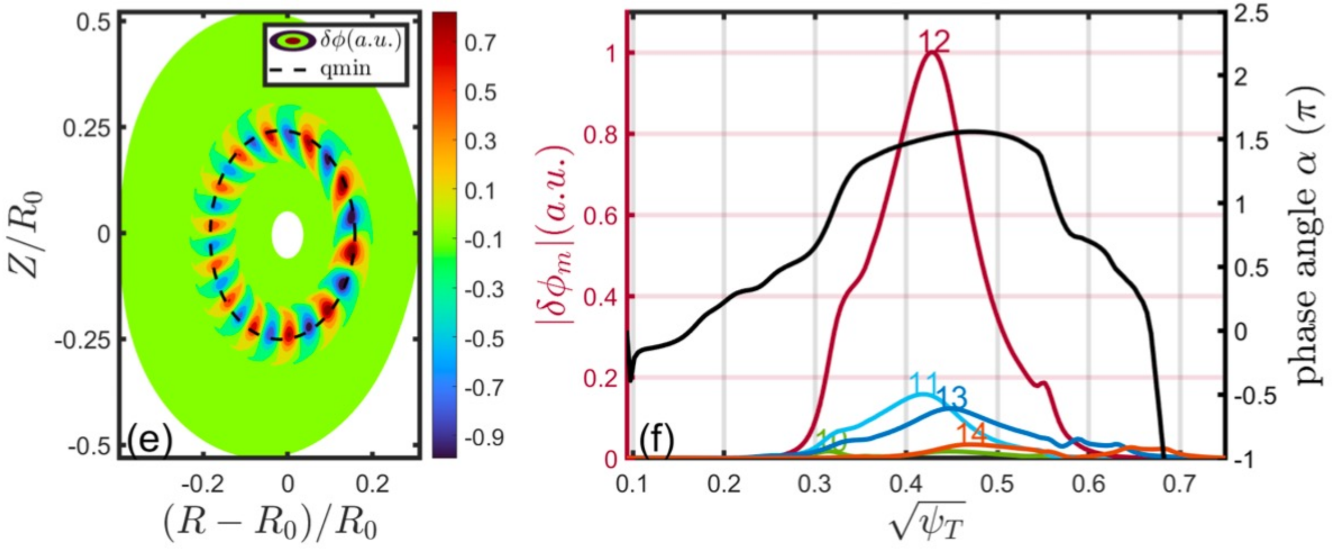
Solution2:
deeply trapped particles

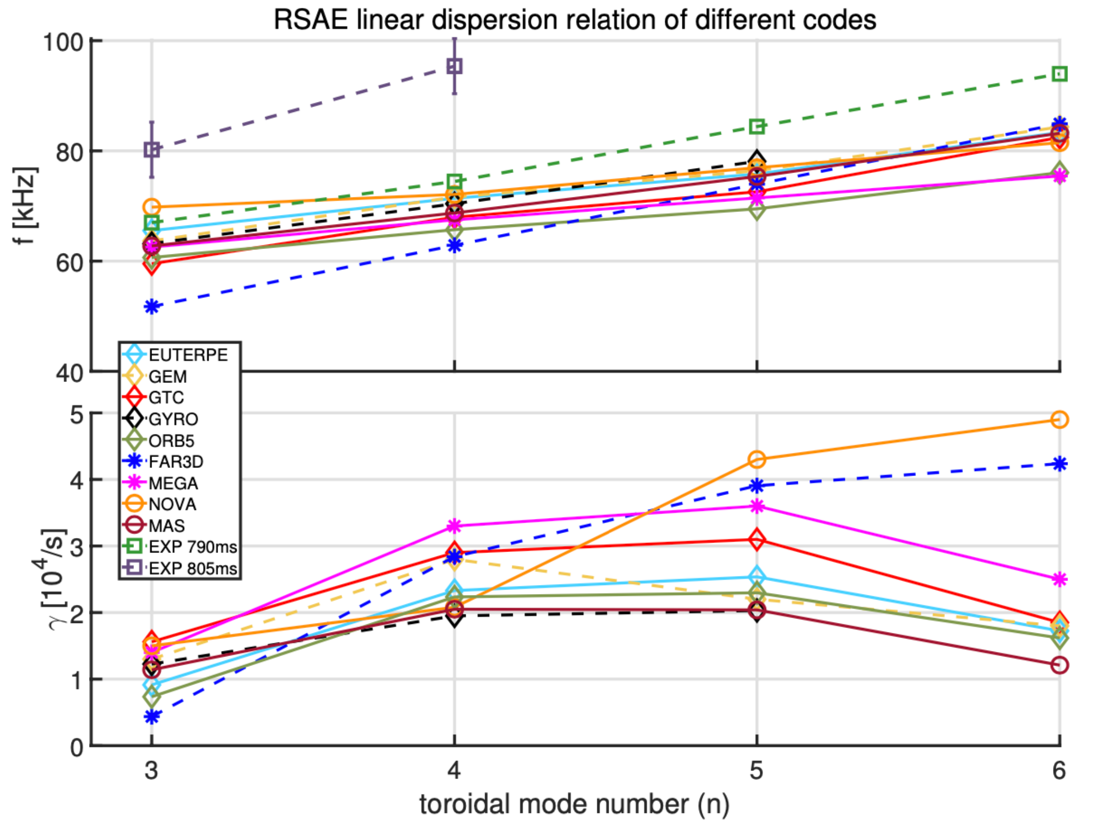
$$J_0\delta K_h = \frac{Z_h}{T_h}(1-\frac{\omega^*_{p,h}}{\omega})J_0^2 f_{h0}\Sigma_{p,s,m}J_p(\lambda_{Bh})J_s(\lambda_{Bh})i^{p-s}e^{i(p-s)\eta}e^{-i(m-nq)\theta}\times$$
$$\left\{\Delta\phi_m T_s + \delta\psi_m\frac{\bar{\omega}_d}{\omega}T_s + \delta\psi_m\frac{-\frac{i}{2}\omega_d^{(1)}e^{i\eta}}{\omega}T_{s-1} + \delta\psi_m\frac{\frac{i}{2}\omega_d^{(1)}e^{-i\eta}}{\omega}T_{s+1}\right\}$$

where $T_s = \frac{\omega}{\omega-\bar{\omega}_d+s\omega_b}$, $\omega_d^{(1)} = \bar{\omega}_d\theta_b\xi$ and $\lambda_{Bh} = \frac{\bar{\omega}_d}{\omega_b}\theta_b\xi$

X. R. Xu et al 2024, submitted to PPCF

Verification of EI-driven RSAE





MAS simulation of EI-driven RSAE in DIII-D shot #159243 equilibrium

- ➢ EI non-perturbatively modifies the RSAE mode structure with radially varied poloidal phase angle (i.e., triangle shape mode structure).
- ✓ **FOW stabilization of RSAE in high-n regime**, good argeements on RSAE dispersion relation with other codes.

Outlines

- Background
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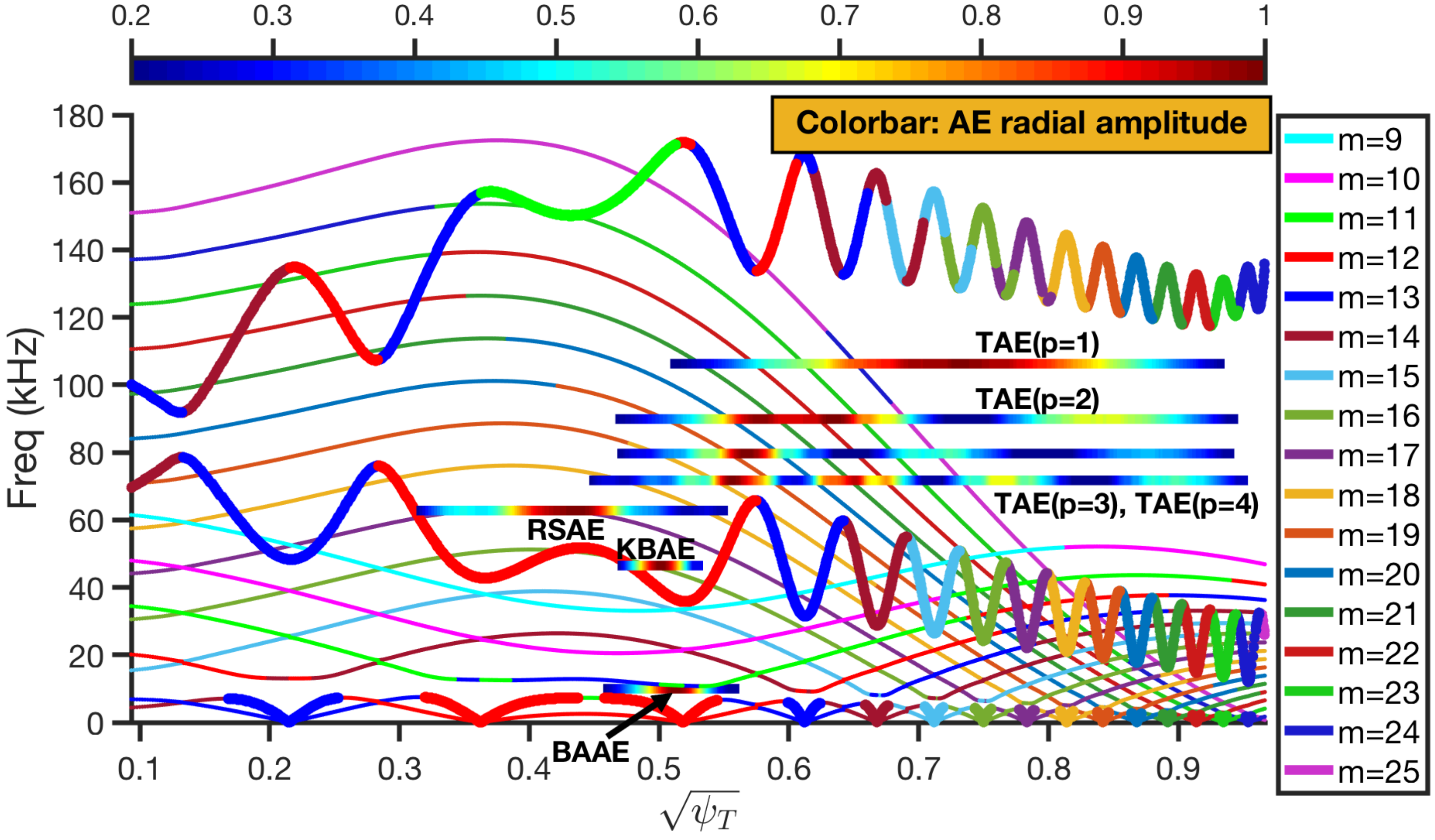
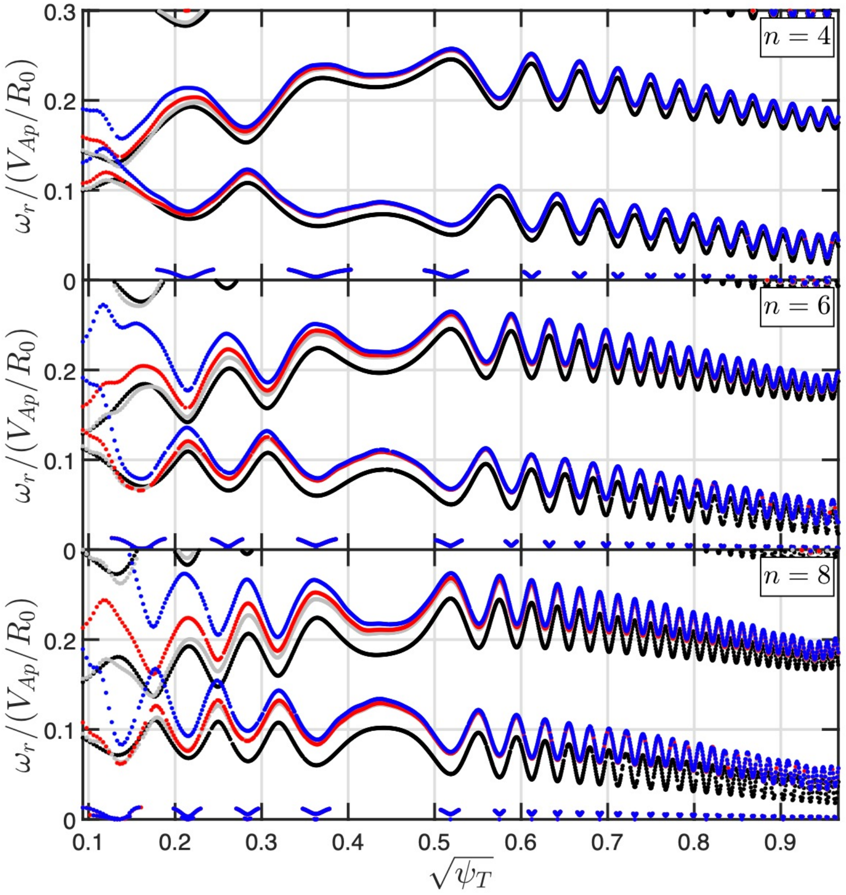
Full-MHD results of n=4 continuum in DIII-D shot #159243

- **Independent continuum module** has been developed in MAS framework.
- ✓ Full-MHD calculations of Alfvenic and acoustic continua, with carefully identifying polarization and poloidal mode numbers.

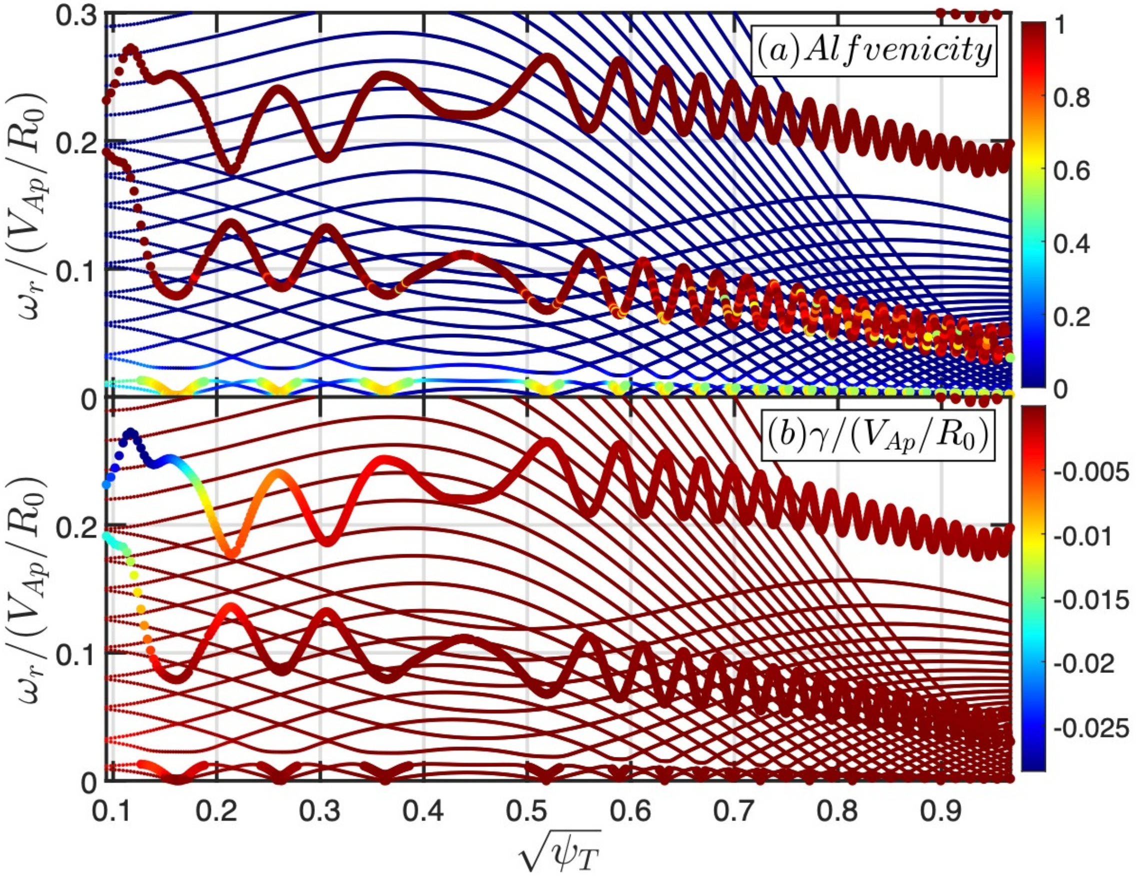


Landau-fluid results with kinetic effects

Ion diamagnetic drift upshifts continuum frequency



Upper panel: polarization indicated by Alfvenicity
Lower panel: damping rate



✓ Effects of ion diamagnetic drifts

✓ Landau damping and radiative damping from thermal plasmas

W. J. Sun, to submit

Outlines

- Background
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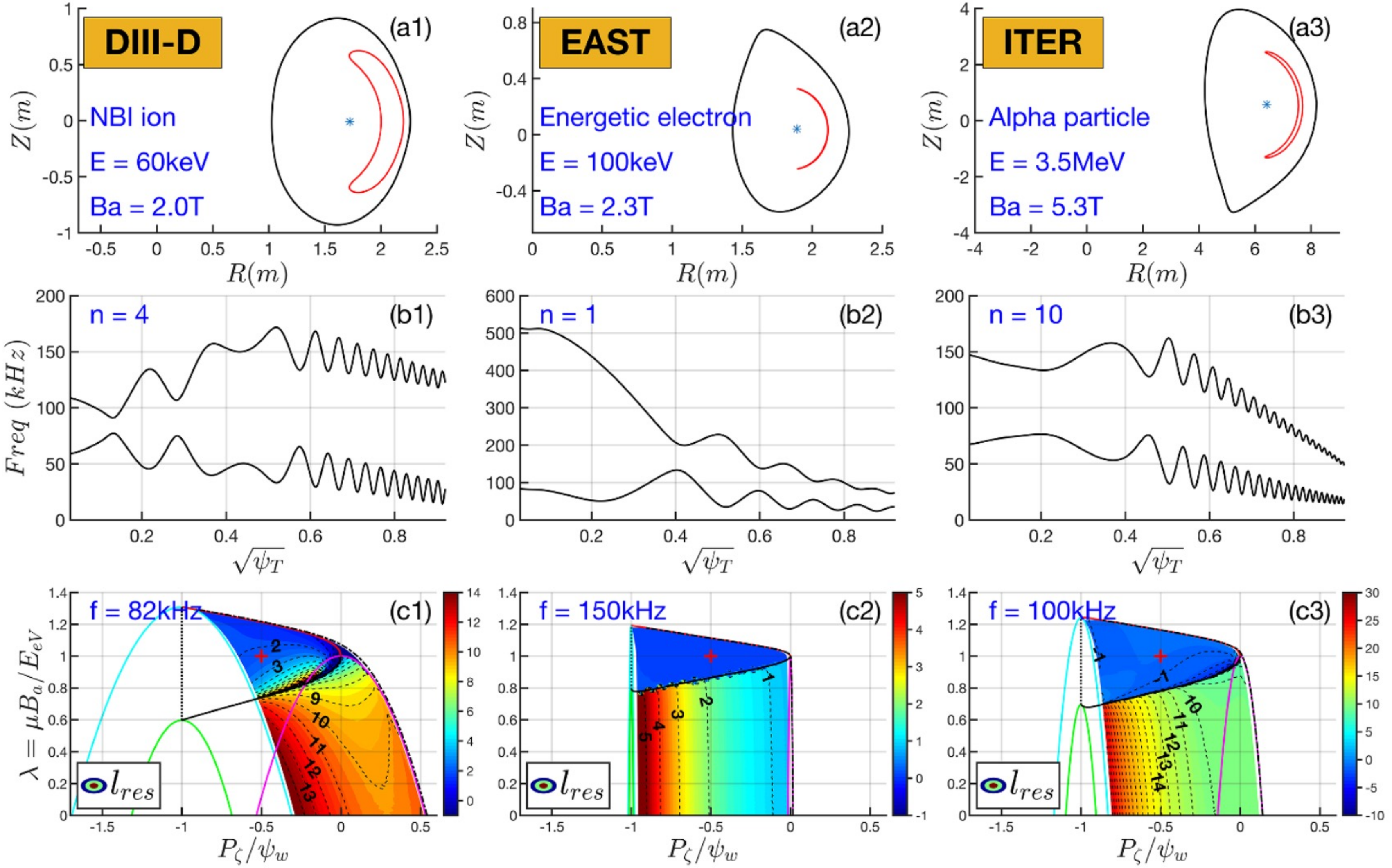
Resonance condition of typical EPs in phase space

$$\Omega(\mathcal{E}, P_\zeta, \mu) = n\langle\omega_\zeta\rangle - l\langle\omega_\theta\rangle - \omega_n = 0,$$

MAS compute poloidal and toroidal frequencies (ω_ζ and ω_θ) by tracing the particle motion.



- **Test particle module** has been developed for calculating EP characteristic frequencies in general geometry.
- The small dimensionless orbit width of EEs in present-day tokamak (i.e., EAST) is close to alpha particles in future fusion reactor (i.e., ITER), which mainly interact with AEs through precessional-drift resonance.

Outlines

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Summary on MAS capability

- ✓ Five-field Landau-fluid model for bulk plasmas
  - Cover cross-scale plasma modes: low-n MHD, mediate-n AE, high-n drift wave instability
  - Diamagnetic drift, Landau damping, FLR, finite parallel electric field $E_{||}$
- ✓ Drift-kinetic EE and gyrokinetic EI
  - Precessional-drift resonance, transit resonance, FOW, FLR
- ✓ Continuous spectra
  - Ideal full-MHD continua: SAW and ISW
  - Landau-fluid continua: KAW and ISW (ion diamagnetic drift, Landau and radiative damping)
- ✓ Resonance condition in phase space
  - Numerical calculation of characteristic frequencies by tracing the particle orbit
  - Resonance line calculation for each harmonics
- ✓ Wide applications for AE stability analysis in EAST, HL-2A/3 and DIII-D experiments.

MAS research activities

- **Code developments and physical applications**

[1] Bao J., Zhang W.L., Li D., Lin Z. et al, MAS: A versatile Landau-fluid eigenvalue code for plasma stability analysis in general geometry Nucl. Fusion 63 076021 (2023)

[2] Bao J., Zhang W.L., Li D., Lin Z. et al, Global simulations of kinetic-magnetohydrodynamic processes with energetic electrons in tokamak plasmas Nucl. Fusion 64 016004 (2024)

[3] Bao J., Zhang W. L., Li D. and Lin Z. Effects of plasma diamagnetic drift on Alfven continua and discrete eigenmodes in tokamaks Journal of Fusion Energy 39 382-389 (2021)

[4] Bao J., Zhang W. L. and Li D. Global simulations of energetic electron excitation of beta-induced Alfven eigenmodes Acta Physica Sinica 72(21) 215216 (2023)

[5] Bao J., Zhang W. L., Lin Z., Cai H. S. et al, Global destabilization of drift-tearing mode with coupling to discretized electron drift wave instability https://arxiv.org/abs/2407.10613, under review in Nucl. Fusion (2024)

[6] Xu X. R., Guo L. Z., Sun W. J., Bao J. et al., Gyrokinetic modelling of energetic ion response to arbitrary wavelength electromagnetic fluctuations in magnetized plasmas under review in Plasma Phys. Control. Fusion (2024)

- **V&V collaboration**

[7] Brochard G., Bao J., Liu C. et al Verification and validation of gyrokinetic and kinetic-MHD simulations for internal kink instability in DIII-D tokamak Nucl. Fusion 62 036021 (2022)

[8] Jiang P. Y., Liu Z. Y., Liu S. Y., Bao J. and Fu G. Y. 2024 Development of a gyrokinetic-MHD energetic particle simulation code. I. MHD version Physics of Plasmas 31 (7) (2024)

- **Experimental collaboration**

[9] Zhao N., Bao J., Chen W. et al Multiple Alfven eigenmodes induced by energetic electrons and nonlinear mode couplings in EAST radio-frequency heated H-mode plasmas Nucl. Fusion 61 046013 (2021)

[10] Su P., Lan H., Zhou C. Bao J. et al, Bursting core-localized ellipticity-induced Alfven eigenmodes driven by energetic electrons during EAST ohmic discharges Nucl. Fusion 64 036019 (2024)

[11] Chen W., Yu L. M., Shi P. W., Hou Y. M., Shi Z. B., Bao J., Qiu Z. et al Nonlinear Dynamics and Effects of Fast-ion Driven Instabilities in HL-2A NBI Heating High-βN H-mode Plasmas Physics Letters A, 129983 (2024)

[12] Zhu X., Qiu Z. Y., Bao J. et al, Toroidal Alfvén eigenmodes excited by energetic electrons in EAST low-density ohmic plasmas Nucl. Fusion 64 126023 (2024)

Thank you for your attention!