Study of EP driven Alfvén eigenmode using theoretical tools and ORB5

Z.X. Lu, thanks for input from A. Bottino, T. Hayward-Schneider, Ph. Lauber, X. Wang , F. Zonca, A. Koenis, A. Mishchenko

Acknoledge: A. Biancalani, F. Palermo

NAT project meeting

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Motivation

- Benchmark of ORB5 and other codes (GTC, TAEFL…) using DIIID parameters
  - RSAE benchmark (with input from A. Koenis, GTC group)
- Use modified experiment parameters, e.g., DIIID or AUG, for various studies, e.g., nonlinear physics (work with LIGKA, XHMGC)
- Extend previous symmetry breaking studies [1,2] from linear, global to nonlinear, with momentum transport & EP considered, by using theory and ORB5

[1] Z. X. Lu, E. Fable, W. A. Hornsby, C. Angioni, A. Bottino, Ph. Lauber, and F. Zonca, Phys. Plasmas, 24, 042502 (2017)
[2] Z.X. Lu, X. Wang, Ph. Lauber, F. Zonca, Kinetic eects of thermal ions and energetic particles on discrete kinetic BAE mode generation and symmetry breaking, Nucl. Fusion, accepted

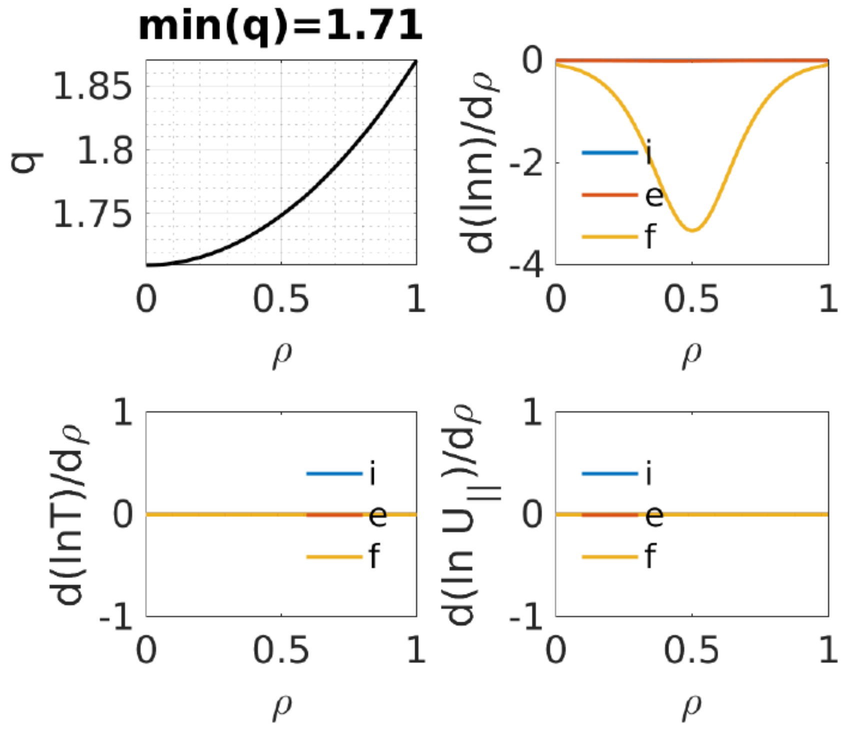
Progress using theory and ORB5

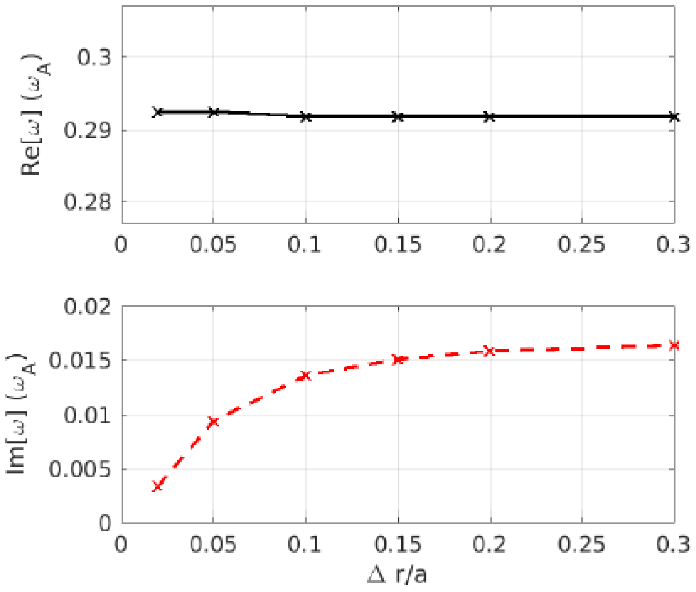
- Produce TAE, RSAE, BAE (BAAE) using computing friendly parameters
  - Eigenvalue scan
  - Mode structure studies (mode width, symmetry breaking)
- RSAE benchmark using DIIID 159243_00805 case
  - Ad hoc (circular) 2D equilibrium + 1D exp. profiles
  - 2D exp. equilibrium + 1D analytical profiles
  - 2D exp. equilibrium + 1D exp. profiles (in progress)
- Extension of symmetry breaking studies
  - GAM/EGAM symmetry breaking

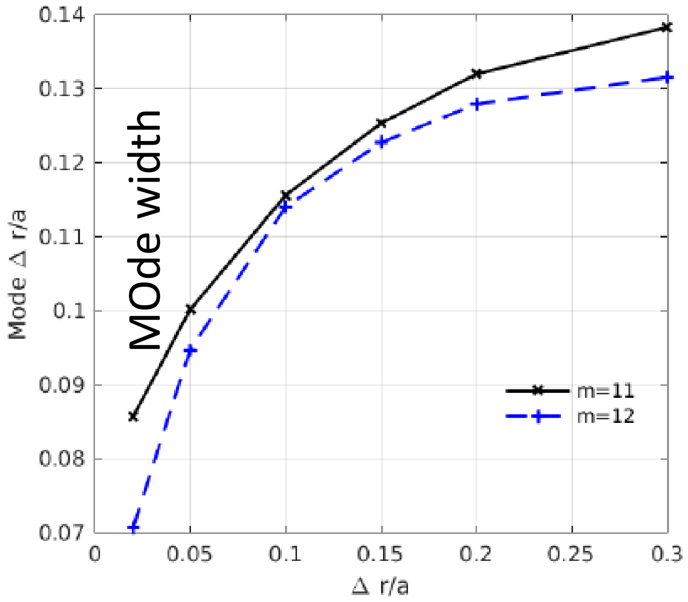
Part I General studies of TAE, RSAE, BAE eigenvalue and mode structure

TAE: EPs’ non perturbative effect on mode width

- EP’s non perturbative effect has been identified using GTC [Wang 13]
- Mode width increases as EP drive width increases







EP drive width

ITPA parameters [A. Biancalina POP 2016]

TAE mode width: effects of FOW/FLR, bad curvature, ω_*

- EPs' non perturbative effects included in vorticity equation:

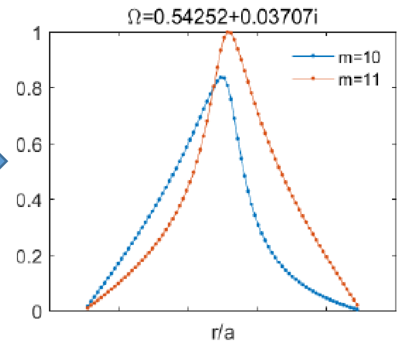
Z.X. Lu, X. Wang, Ph. Lauber, F. Zonca, 2018, Nucl. Fusion, accepted

$$B\partial_\parallel\left[\frac{1}{B}\nabla_\perp^2\partial_\parallel\delta\psi\right]+\nabla_\perp\cdot\frac{\omega^2}{v_A^2}\left[(1-\frac{\omega_{*pi}}{\omega})-\frac{3}{4}b_{i,eff}\right]\nabla\delta\psi-\frac{\alpha g k_\theta^2}{q^2R^2}\delta\psi$$
$$-3qg\delta\psi\left(\frac{b_i}{2}\right)^{1/2}k_\perp k_\theta\frac{\omega\omega_{ti}}{v_A^2}\left(1-\frac{\omega_{*pi}}{\omega}-\frac{\omega_{*Ti}}{\omega}\right)$$
$$=-\sum_{s=i,f}KPC_s\equiv\sum_{s=i,f}\frac{k_\perp^2\omega_{ti}^2q^2\bar{n}_s\tau_s}{v_A^2}\delta\psi_m e^{im\theta}\times\left\{\frac{1}{2}\sum_{\sigma=\pm1}\bar{H}_{m-nq+\sigma,s}\right.$$
$$\left.+\rho_{ti}^2k_\perp^2\left[\frac{\tau_s^2}{8}\left(\frac{q}{\Omega_{(i)}}\right)^2\sum_{\sigma=\pm1,\pm2}(-)^\sigma(m-nq+\sigma)^2\bar{W}_{m-nq+\sigma}-\frac{\tau_s}{4}\sum_{\sigma=\pm1}\bar{O}_{m-nq+\sigma}\right]\right\}$$

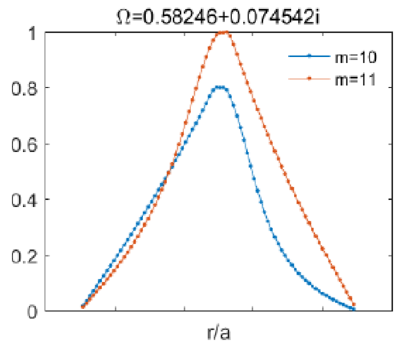
- Or concise form:

$$B\partial_\parallel\left[\frac{1}{B}\nabla_\perp^2\partial_\parallel\delta\psi\right]+\nabla_\perp\cdot\frac{\omega^2}{v_A^2}\left[\left(1-\frac{\omega_{*p}}{\omega}-\frac{\omega_{BAE}^2}{\omega^2}\right)\nabla\delta\psi\right]-\boxed{\frac{\alpha k_\theta^2 g}{q^2R^2}\delta\psi}$$
$$=\sum_m\left(C_{FOW,m}+C_{FLR,m}-\frac{3}{8}\frac{\omega^2}{v_A^2}\right)\rho_{ti}^2k_\perp^4\delta\psi_m\ ,$$

w/ g



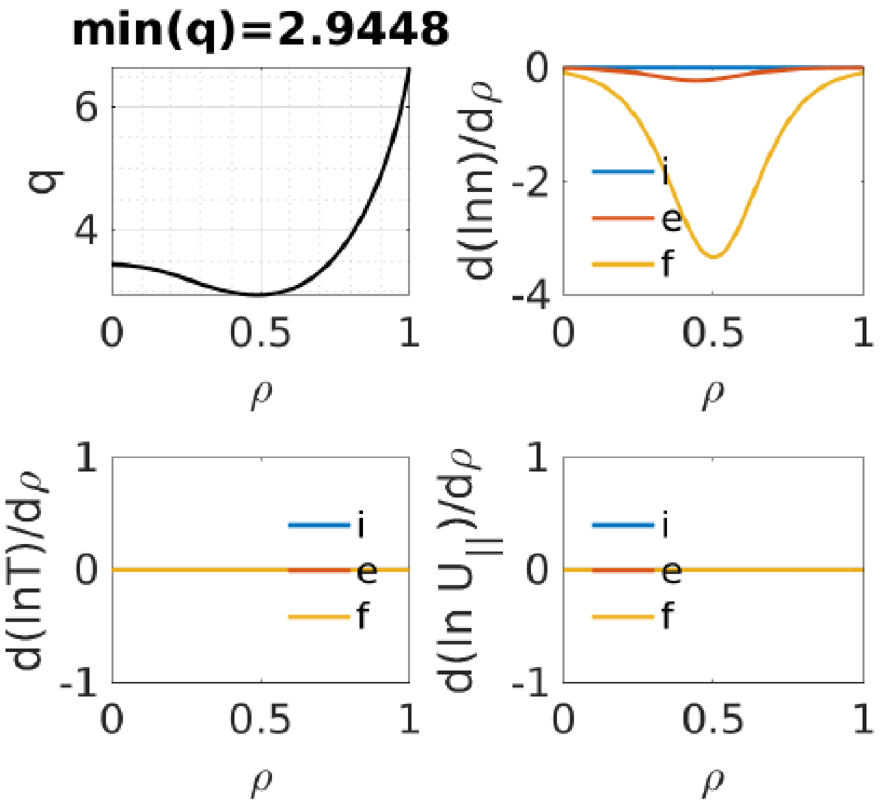
w/o g

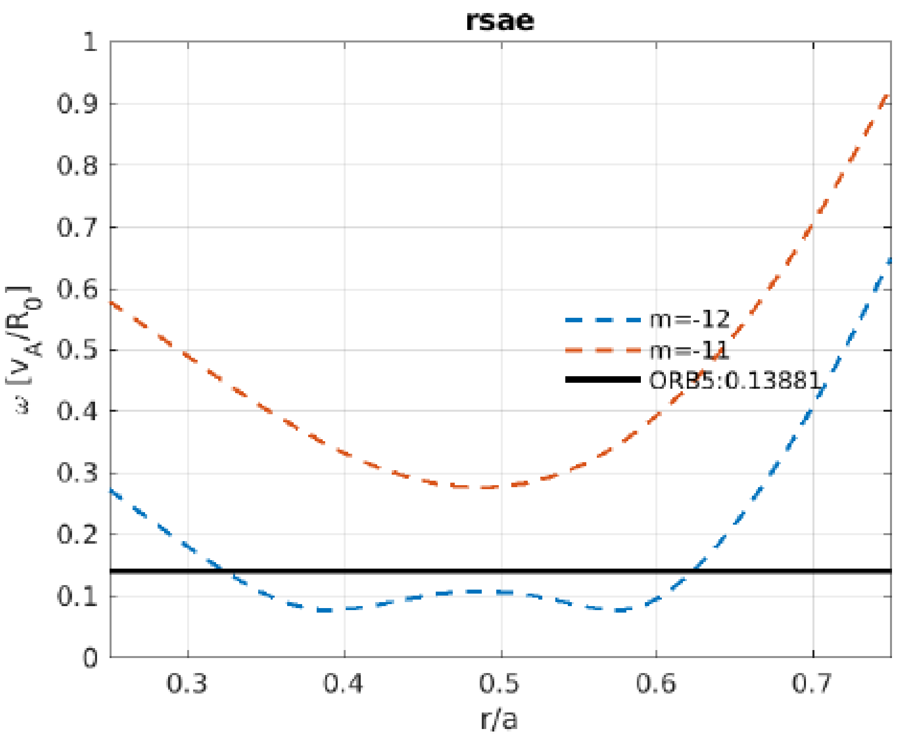


- Comprehensive analysis in progress

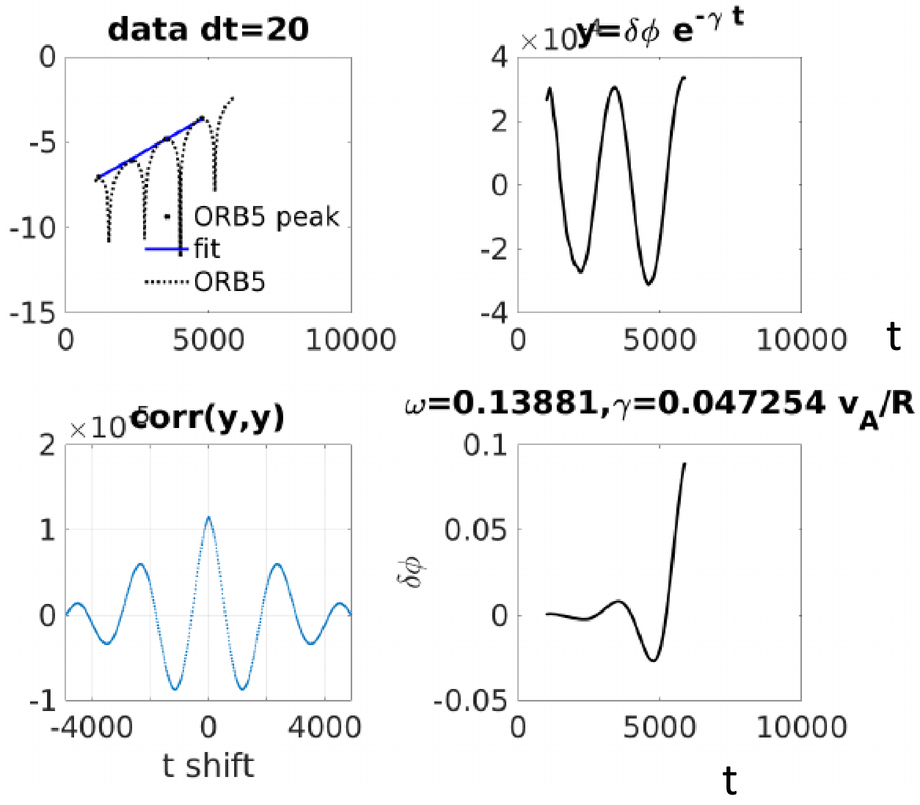
Acknowledge: Ph. Lauber

RSAE: parameters and eigenvalue

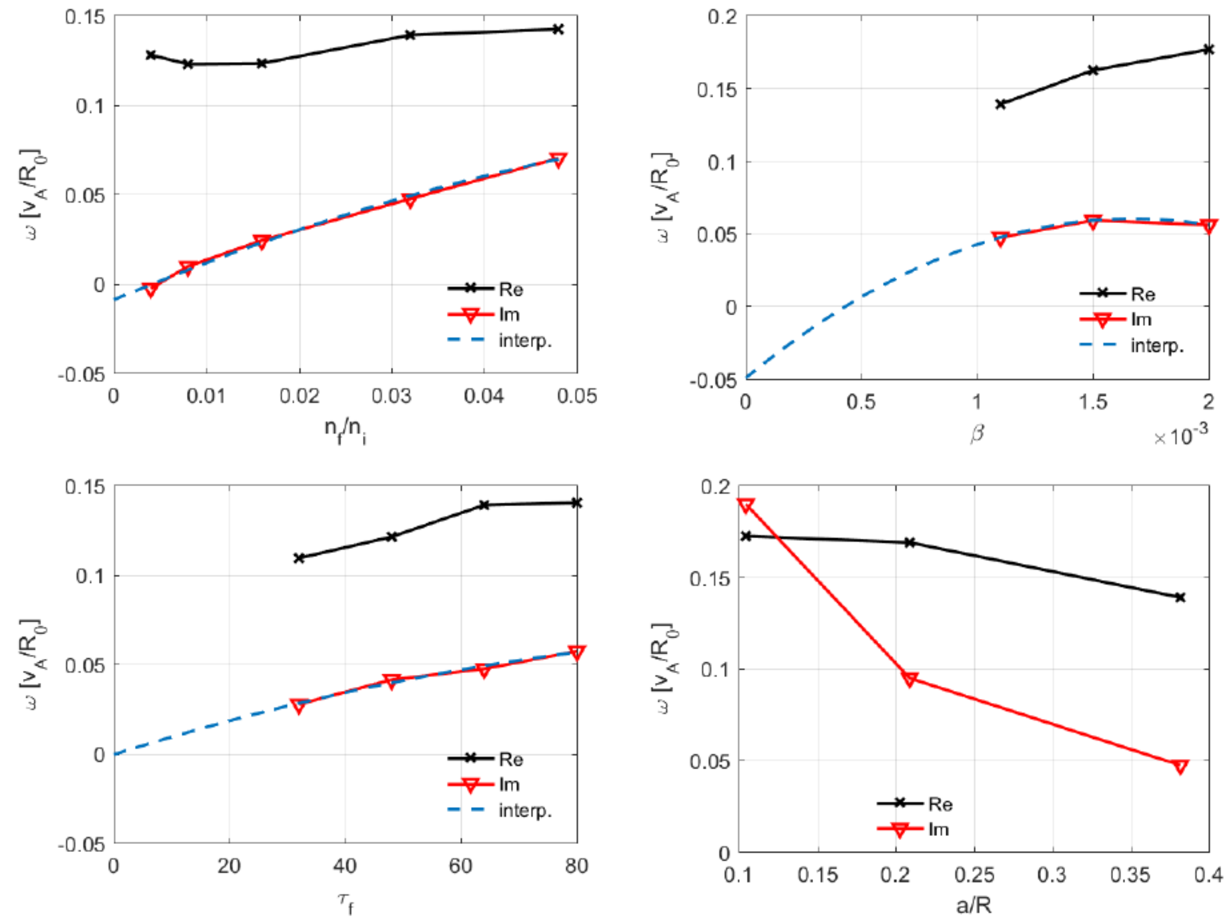




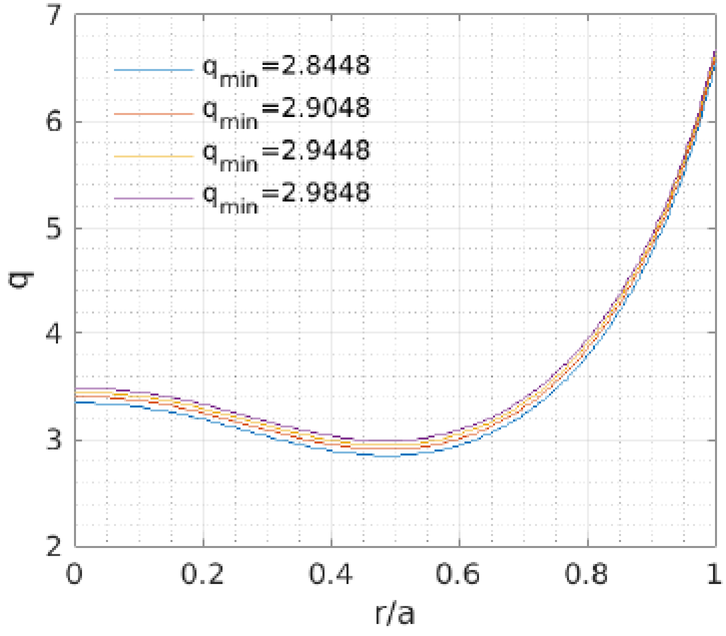
RSAE: parametric studies

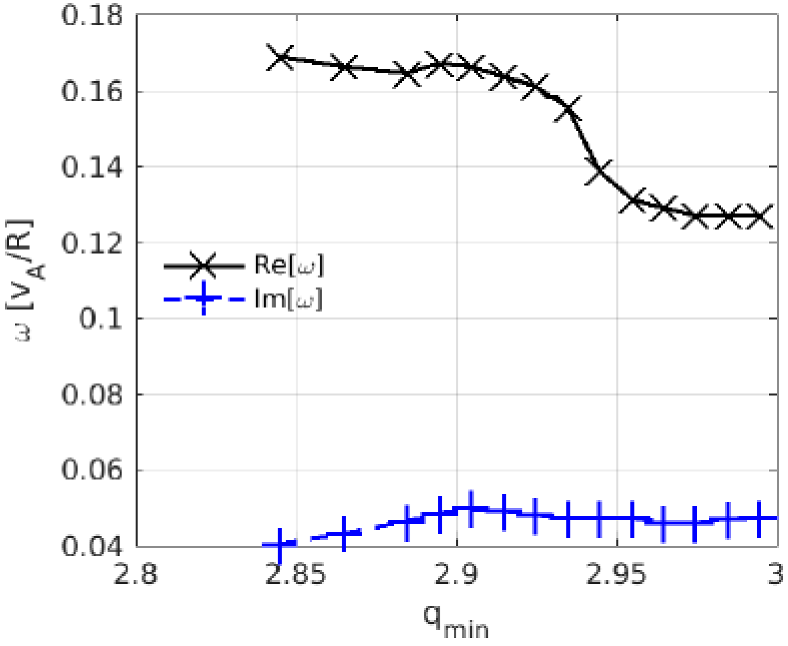


Eigenvalue is fitted using probe data



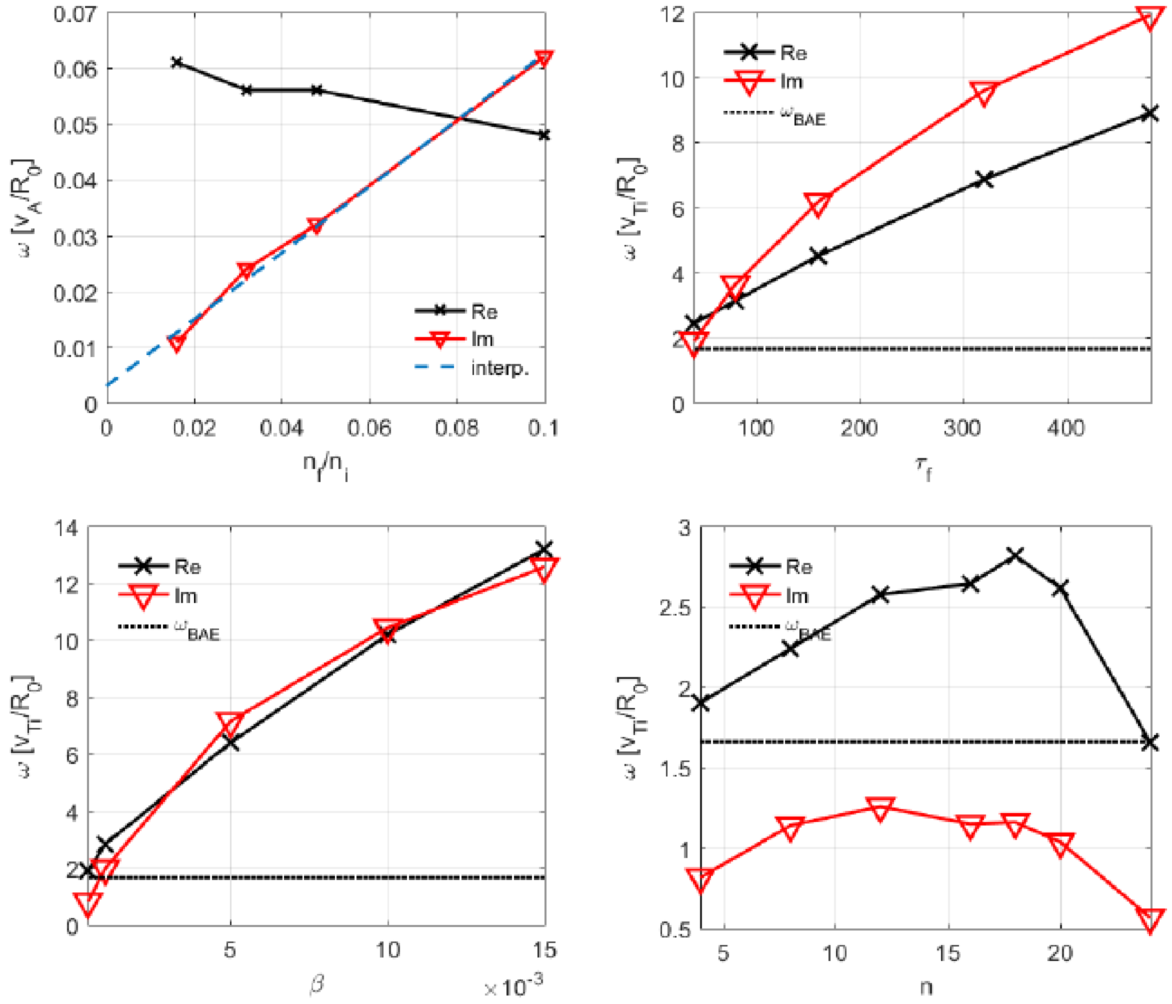
RSAE: frequency cascading





BAE: preliminary scan of eigenvalues

- Scan of EP density, temperature, beta and toroidal mode # n
  - reasonable trend
  - quantitative benchmark need to be done

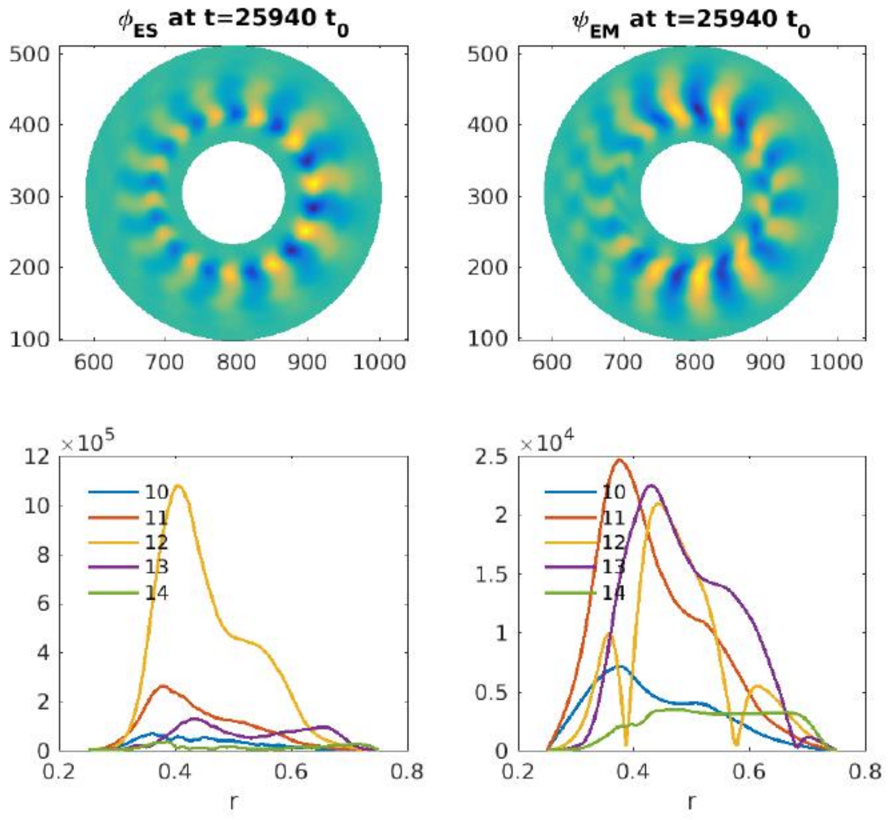


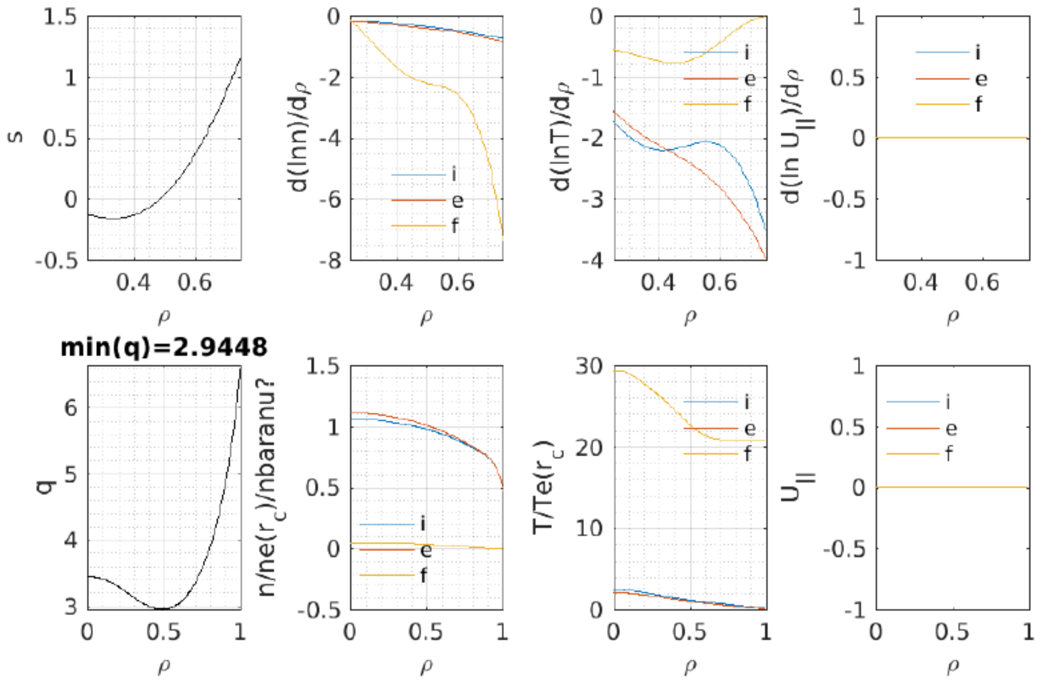
Part II RSAE simulation using DIIID 159243_00805 case

I. Ad hoc 2D equilibrium + 1D exp. profiles
II. 2D exp. equilibrium + 1D analytical profiles
III. 2D exp. equilibrium + 1D exp. profiles (in progress)

Ad hoc equilibrium and numerical equilibrium are implemented in coordinates with r and ψ_p as radial coordinate respectively

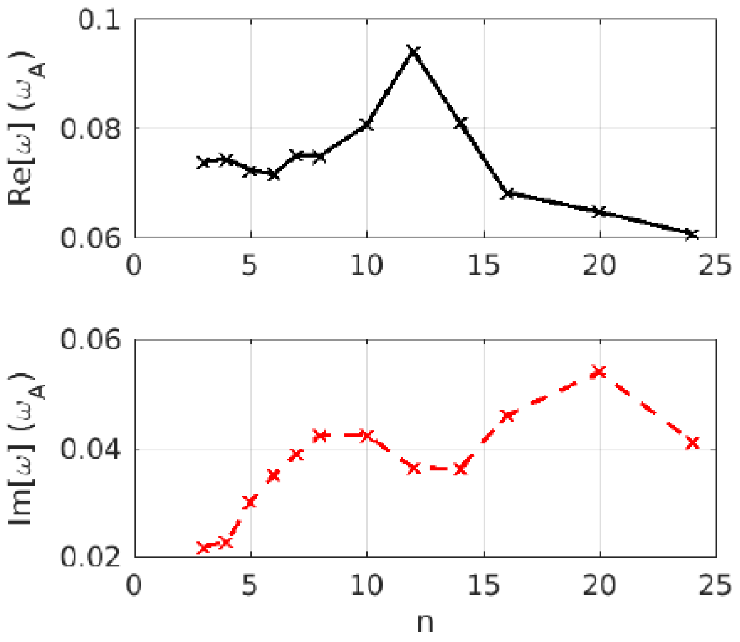
I. Ad hoc 2D equilibrium + 1D exp. profiles



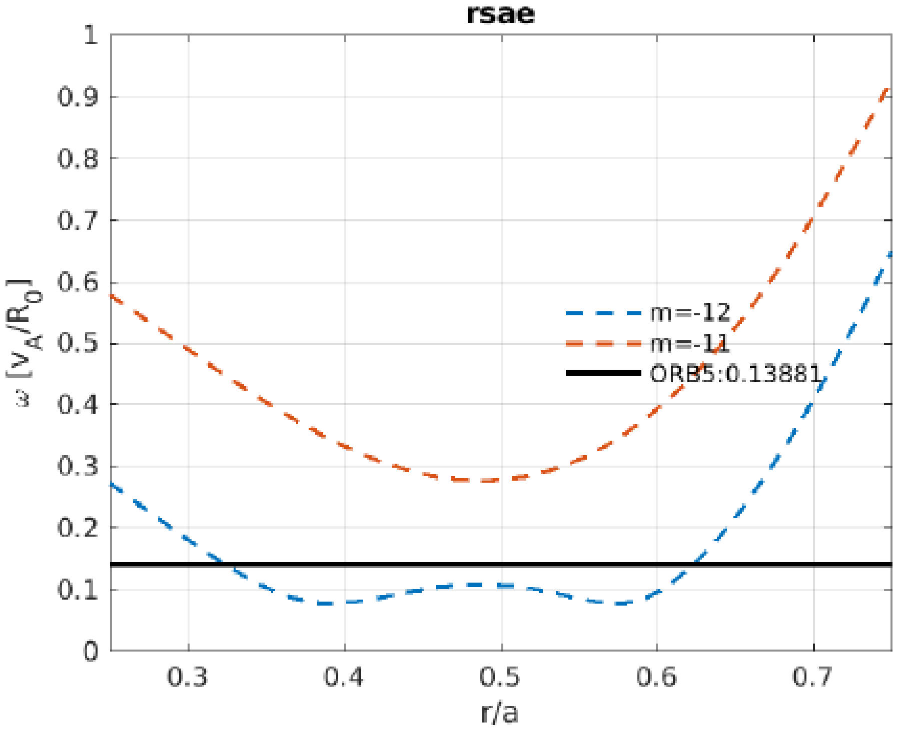


I. Ad hoc 2D equilibrium + 1D exp. profiles

- Beta, Lx (or ρ_*) and EP mass biased from exp. value (need corrected later)

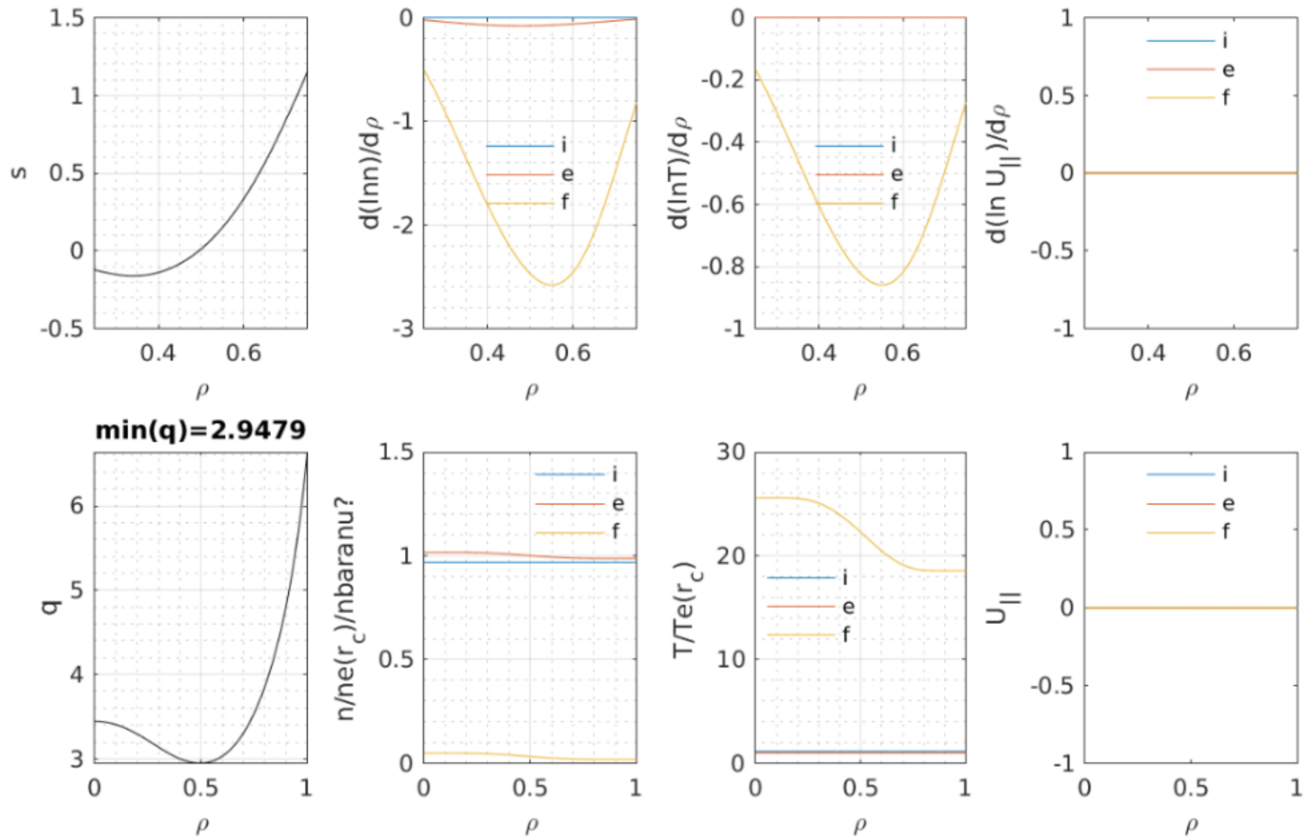


Note: different EP drive compared with exp.



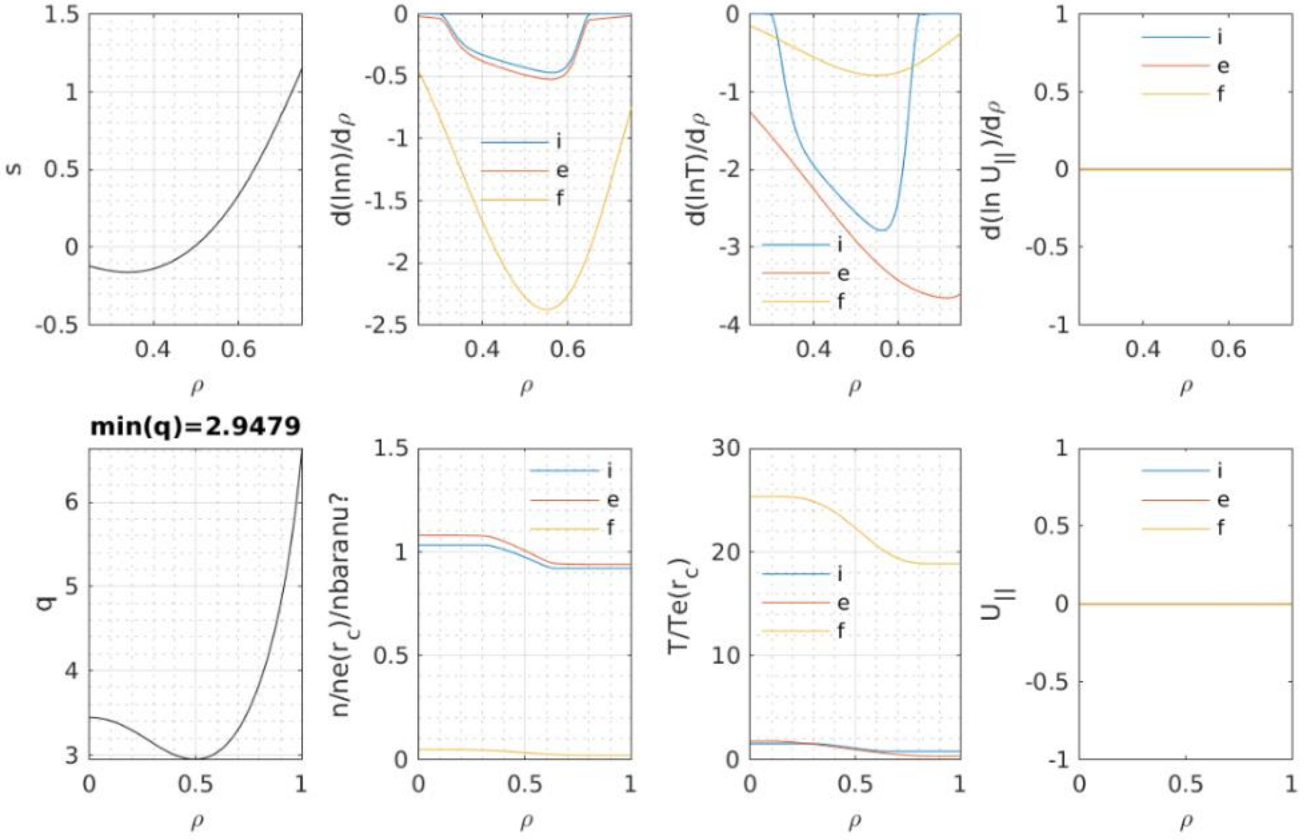
II. Exp. 2D equilibrium + 1D analytical profiles

- Bell shape EP drive



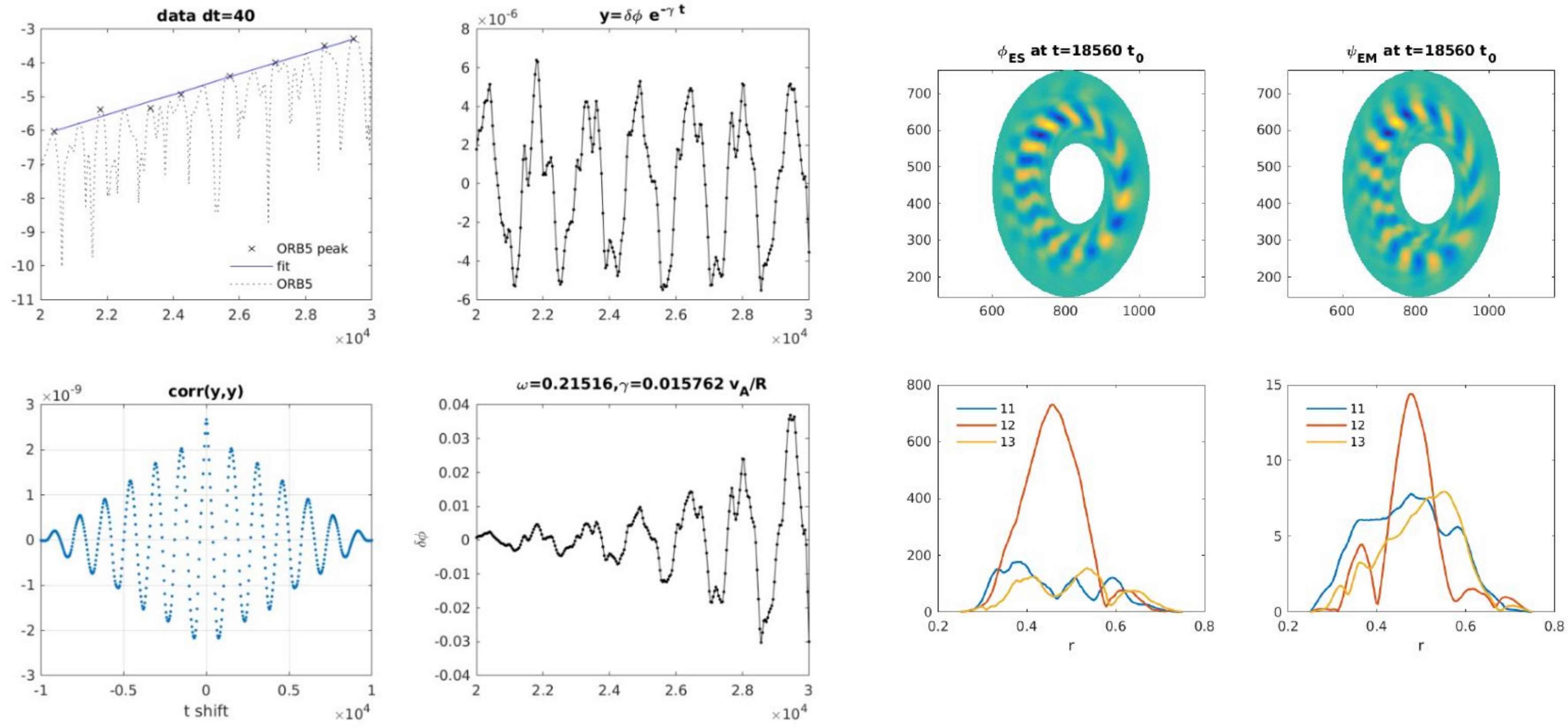
II. Exp. 2D equilibrium + 1D analytical profiles

- Fitted analytic profiles using reference value of exp. profiles



II. Exp. 2D equilibrium + 1D analytical profiles

- Bell shape EP drive

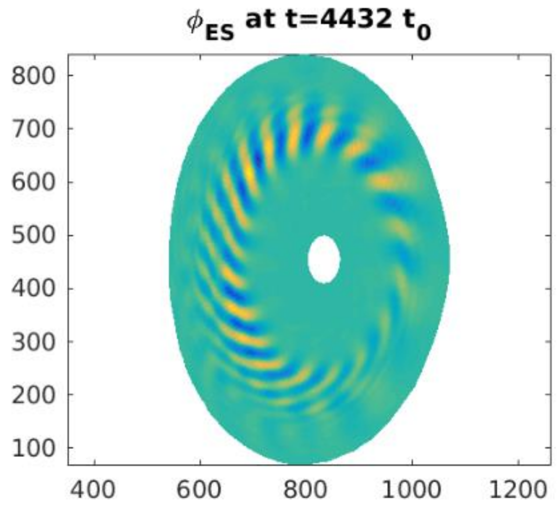


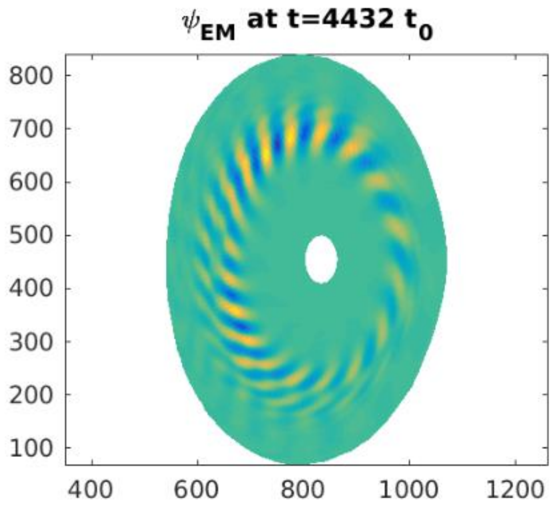
III. Exp. 2D equilibrium + 1D exp. Profiles (in progress)

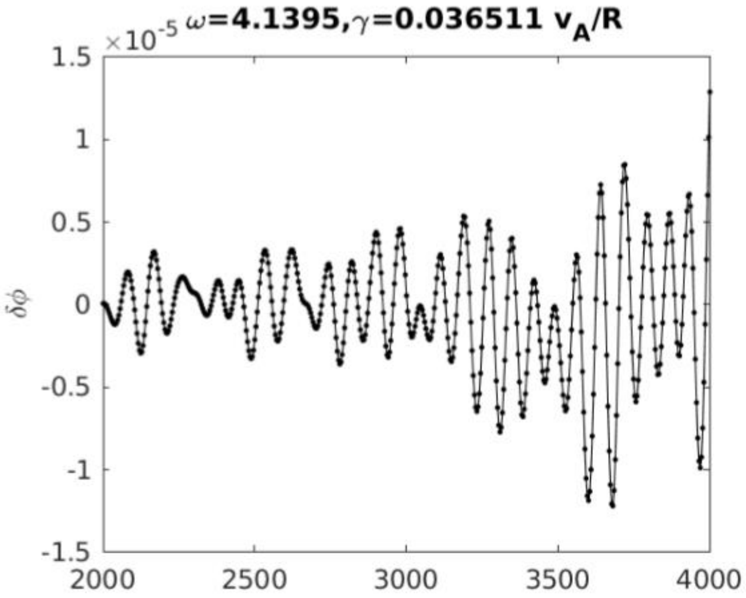
- Numerical 1D profiles: might need check the parameters of input and the code (beta, Lx)
- 1D profiles using polynomial fitting: implemented and being tested
  - Edge numerical instability better understood (filter; thanks to Thomas, Alberto)
  - High m (17,18) mode appears instead of m=12 for n=4 (qmin=2.9479)

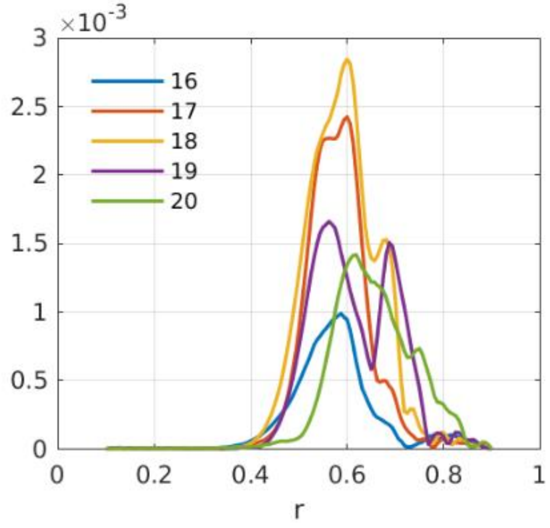
III. Exp. 2D equilibrium + 1D exp. Profiles (in progress)

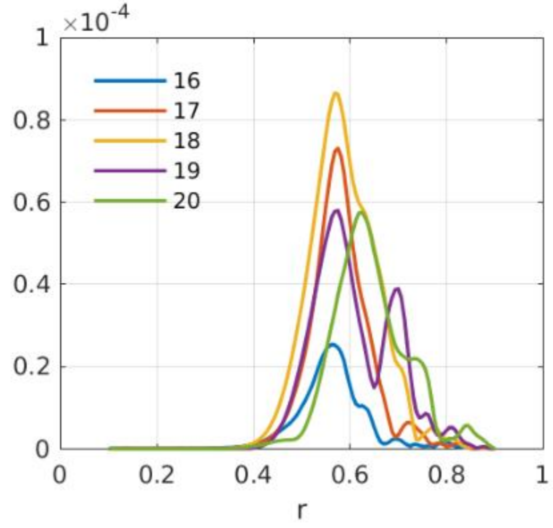
- Filter from m=11~20; expected dominant m=12
- Particle #, dt similar to EUTERPE (thanks for Axiel)











Part III Extension of symmetry breaking studies

GAM/EGAM symmetry breaking

GAM/EGAM equation in local limit

- Equation for $\delta\phi_0$ with multiple species
  - Global effect can be included [Fu 08, Zonca 08, Qiu 10]; here in Fourier space [Lu 18, BAE]

$$D_{ln} \equiv \sum_{s=i,f} \frac{e_s n_s}{T_s} \left[-\frac{k_\perp^2 \rho_{ts}^2}{2} - \frac{\omega_{dts}^2}{4\omega^2} \sum_{\sigma=\pm 1} H_{\sigma,s} \right] + \sum_{\sigma=\pm 1} \frac{1}{4\bar{D}_\sigma} \left(\sum_{s=i,f} \frac{e_s n_s}{T_s} \frac{\omega_{dts}}{\omega} N_{\sigma,s} \right)^2 .$$

- Mode structure $\delta\phi_{\pm 1}$

$$\bar{D}_1 \delta\phi_1 = -\frac{ie^{-i\theta_r}}{2} \left(\sum_{s=i,f} \frac{e_s n_s}{T_s} \frac{\omega_{dts}}{\omega} N_{1,s} \right) \delta\phi_0 ,$$

$$\bar{D}_{-1} \delta\phi_{-1} = \frac{ie^{i\theta_r}}{2} \left(\sum_{s=i,f} \frac{e_s n_s}{T_s} \frac{\omega_{dts}}{\omega} N_{-1,s} \right) \delta\phi_0 ,$$

- For GAM w/o EPs: $\delta\phi_1 + \delta\phi_{-1} \propto \sin\theta$
- EPs → mode structure symmetry breaking

D, H, N: non-adiabatic response function; thanks for GFLDR (Fulvio), LIGKA (Philipp)

Linear solution of GAM/EGAM

- GAM/EGAM pair (A&B) and mode structure symmetry breaking
  - Shifted Maxwellian for EPs
  - As EP density increases, one mode becomes destabilized; similar to results using double shifted Maxwellian EPs [D. Zarzoso, NF14]
  - Analytical continuation: from plasma Z function to D, N, H

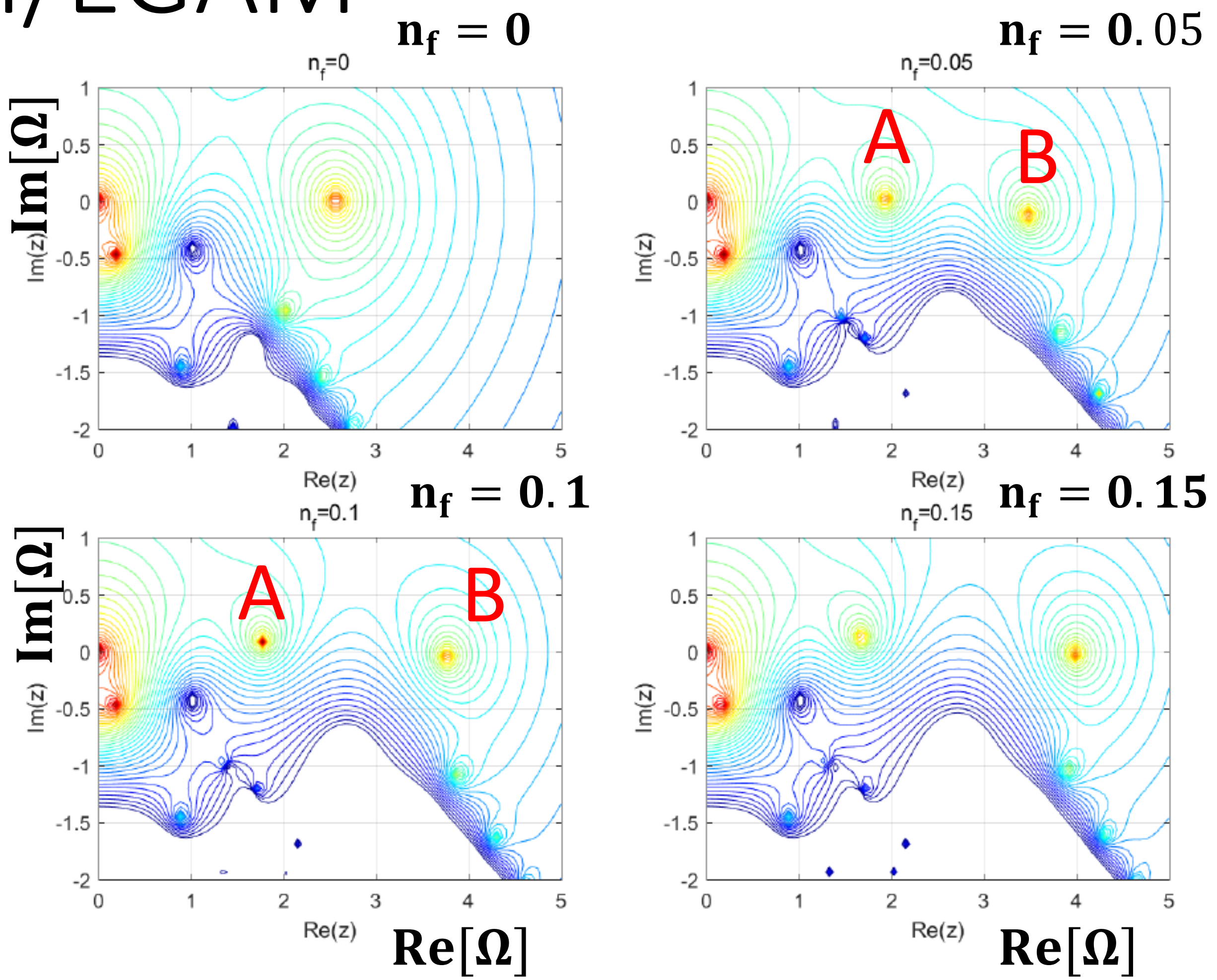
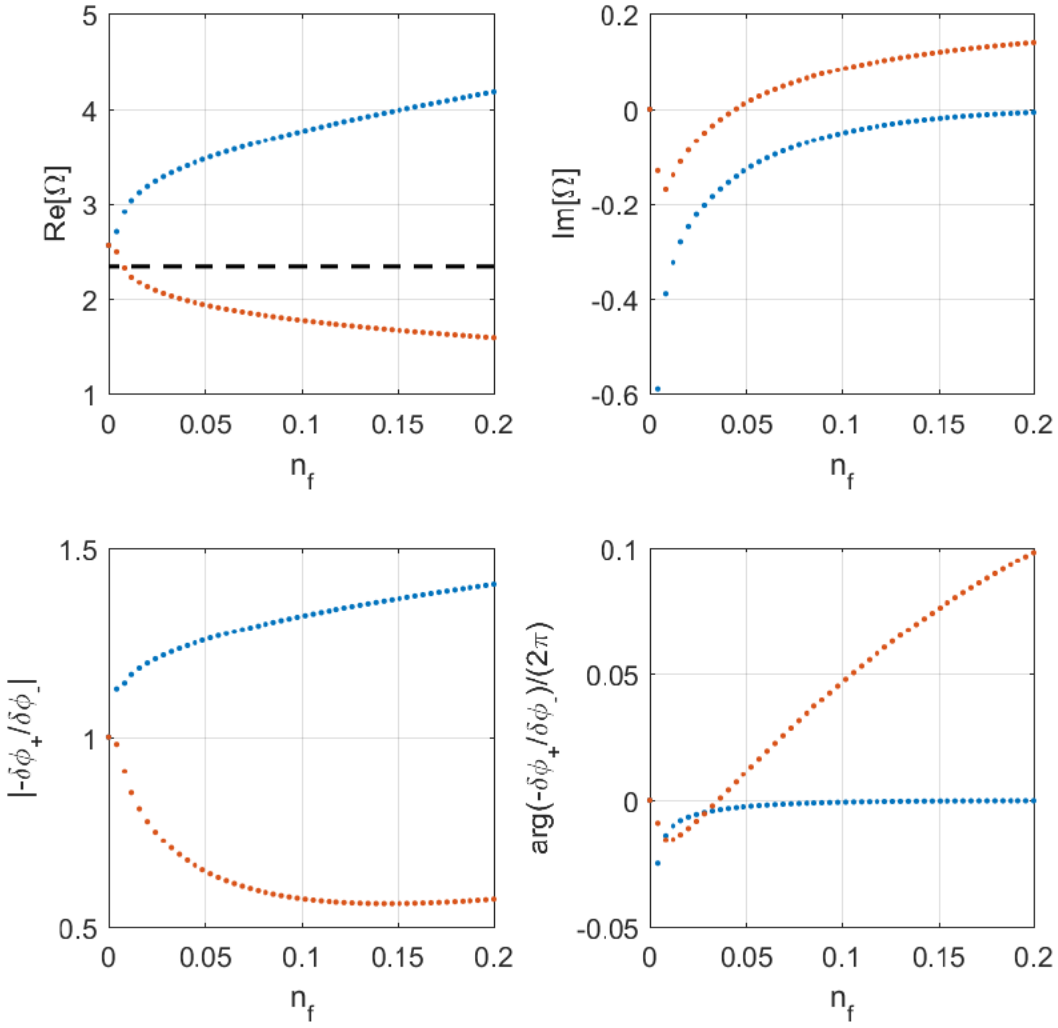


Figure 1. GAM and EGAM for different values of n_f.

Symmetry breaking of GAM/EGAM

- GAM/EGAM pair and mode structure symmetry breaking
- $|\delta\phi_1/\delta\phi_{-1}|$ deviates from 1 as EP density increases
  - EP's non-perturbative effect
  - What's the consequent momentum transport [Sasaki]?



Outlook

- Basic AE studies using ORB5: need re-run some cases for wide radial range and better convergence
- ORB5 run with experimental profile (w EP) & numerical equilibrium of DIIID benchmark case in progress; need fix numerical problem
- BAAE simulation: from analytical profiles to DIIID profiles
- Symmetry breaking studies: GAM/EGAM; electrostatic-electromagnetic coupling

- I appreciate your instructive suggestions.