Gyrokinetic particle simulations of reversed shear Alfvén eigenmodes (RSAEs) in DIII-D tokamak

W. Deng[1,2]

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Other codes: E. Bass[4] (GYRO), D. Spong[5] (TAEFL)

Experimental data: W. Heidbrink[1], B. Tobias[2], M. Van Zeeland[4]

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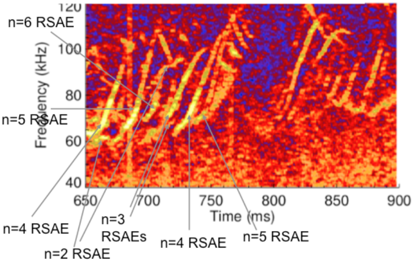
Introduction

- Gyrokinetic simulation is a powerful tool to study energetic particle transport by Alfvén eigenmodes.
  - Self-consistent inclusion of global effects, kinetic effects, nonlinear effects, etc.
  - Capability of separating different levels of physics: linear and nonlinear physics; driving and damping mechanisms.
- Simulations of TAE [W Zhang *et al.*, PoP 2012], RSAE [Deng *et al.*, PoP 2010 & NF 2012a], BAE [H Zhang *et al.*, PoP 2010] by GTC have been verified against analytic theory and reliable hybrid MHD-gyrokinetic code.
- Now we push this forward to the validation of RSAE simulation against a well-diagnosed DIII-D experiment #142111. [Deng *et al.*, NF 2012b]

$$\uparrow \omega_{\mathrm{RSAE}}(t) \approx \frac{v_{\mathrm{A}}}{R_0}\left|\frac{m}{\downarrow q_{\min}(t)} - n\right|$$



Spectrogram of DIII-D #142111 showing frequency up-sweeping of RSAEs driven by NBI energetic particles [Van Zeeland *et al.*, PoP 2011; Tobias *et al.*, PRL 2011]

Outline

1. GTC gyrokinetic model for kinetic-MHD modes
2. Simulations of RSAEs in DIII-D discharge #142111
   - Good agreements among GTC, GYRO, TAEFL, & experiment
   - RSAE frequency up-sweeping and RSAE to TAE transition
   - Damping and driving mechanisms
   - Mode structures
3. Simulations of TAEs in DIII-D discharge #142111 (Z. Wang)
   - Frequency and mode structure agreement with experiment

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Kinetic-MHD via gyrokinetic simulation

- Nonlinear gyrokinetic equation, Poisson's equation and Ampère's law

$$\frac{\partial f}{\partial t} + (v_\parallel \boldsymbol{b} + \boldsymbol{v}_\mathrm{d}) \cdot \frac{\partial f}{\partial \boldsymbol{X}} + \dot{v}_\parallel \frac{\partial f}{\partial v_\parallel} = 0$$

$$\begin{aligned} \frac{Z_\mathrm{i} n_\mathrm{i}}{T_\mathrm{i}}(\phi - \tilde{\phi}) &= \sum_\alpha Z_\alpha \bar{n}_\alpha \\ -\frac{c}{4\pi}\nabla_\perp^2 A_\parallel &= \sum_\alpha Z_\alpha \bar{n}_\alpha u_\alpha \end{aligned}$$

- In fluid limit, gyrokinetic system recovers MHD modes including Alfvén wave, interchange mode, kink mode, KBM

$$\begin{aligned} &\underbrace{\frac{\omega(\omega - \overbrace{\omega_{*\mathrm{P}}}^{\text{KBM}})}{v_\mathrm{A}^2}\nabla_\perp^2\,\delta\phi + \overbrace{i\boldsymbol{B}_0 \cdot \nabla \left[\frac{\nabla_\perp^2 (k_\parallel\,\delta\phi)}{B_0}\right]}^{\text{SAW}}} \\ &-i\nabla(k_\parallel\,\delta\phi) \times \boldsymbol{b}_0 \cdot \nabla \left(\frac{\boldsymbol{b}_0 \cdot \nabla \times \boldsymbol{B}_0}{B_0}\right) \qquad \longleftarrow \text{kink drive} \\ &\underbrace{-i\omega\frac{4\pi}{c}\left[\nabla \times \boldsymbol{b}_0 \cdot \nabla \left(\frac{\delta P_\parallel}{B_0}\right) + \boldsymbol{b}_0 \times \nabla B_0 \cdot \nabla \left(\frac{\delta P_\perp}{B_0^2}\right) + \frac{\nabla \times \boldsymbol{b}_0 \cdot \nabla B_0}{B_0^2}\,\delta P_\perp\right]}_{\text{interchange drive}} \\ &= 0 \end{aligned}$$

[

, W. Deng, Z. Lin and I. Holod, **52**, 023005 (2012)]

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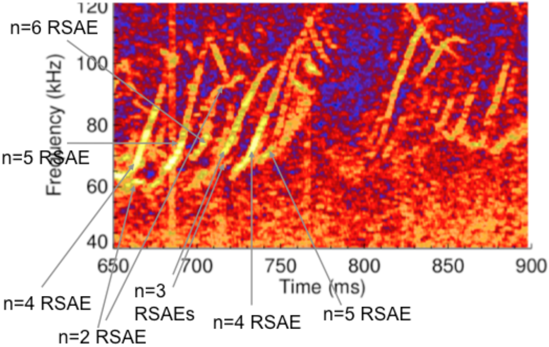
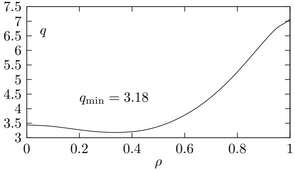
DIII-D #142111 spectrogram and 745ms profiles from EFIT/ONETWO

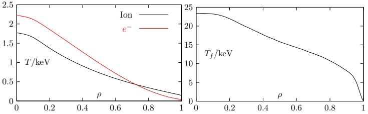


[Van Zeeland , PoP 2011; Tobias , PRL 2011]

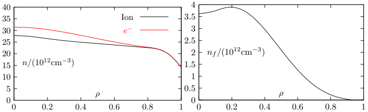
q-profile:

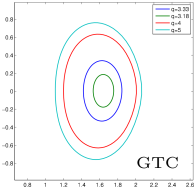


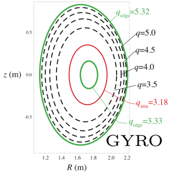
Temperature:

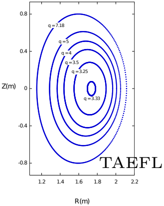


Density:



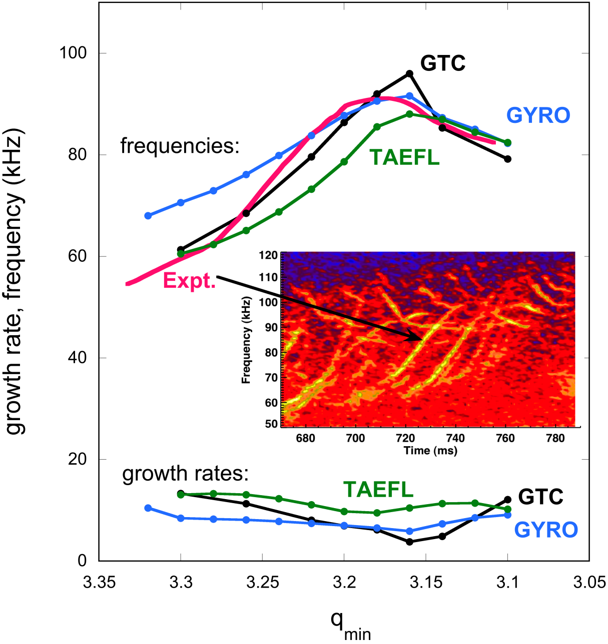






- GTC, GYRO and TAEFL use the same geometry from EFIT and the same plasma profiles from ONETWO for rigorous benchmark.

Freq./growth rate agreement among GTC, GYRO and TAEFL



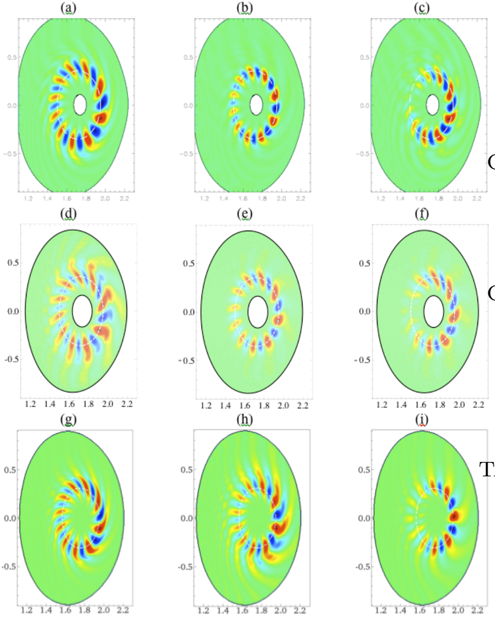
Experimental frequency shown here has Doppler shift by plasma rotation (8kHz) subtracted.

GTC: gyrokinetic particle-in-cell (PIC) code

GYRO: gyrokinetic continuum code

TAEFL: MHD-gyrofluid code

Mode structure agreement among GTC, GYRO and TAEFL

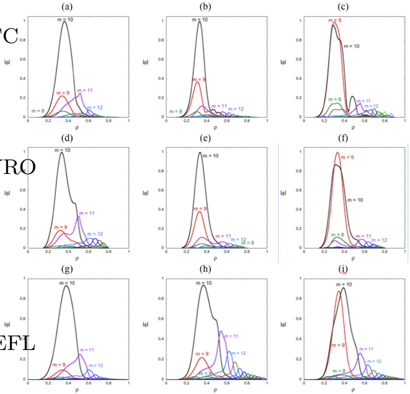


$q_{\min} = 3.30$ $q_{\min} = 3.22$ $q_{\min} = 3.16$

GTC

GYRO

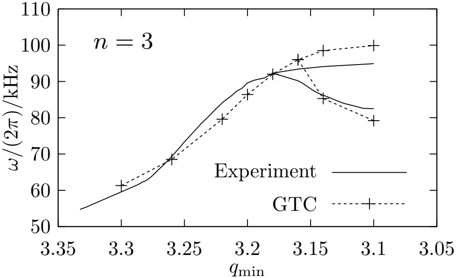
TAEFL



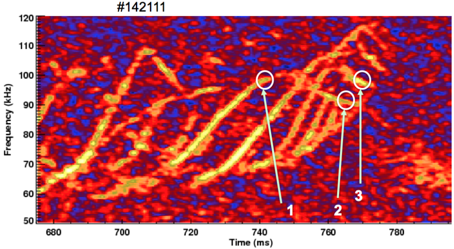
$q_{\min} = 3.30$ $q_{\min} = 3.22$ $q_{\min} = 3.16$

[D. Spong *et al.*, in preparation 2012]

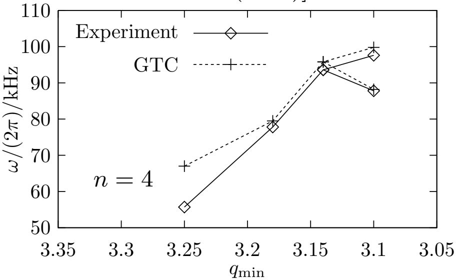
RSAE freq. up-sweeping and RSAE to TAE transition

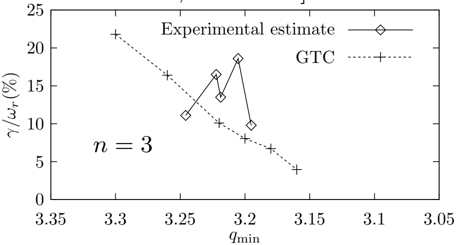


[W. Deng *et al.*, *Nuclear Fusion* **52**, 043006 (2012)]



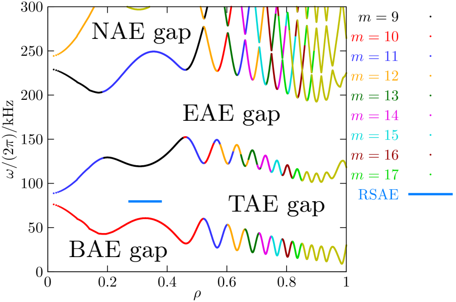
[Van Zeeland *et al.*, PoP 2011; Tobias *et al.*, PRL 2011]

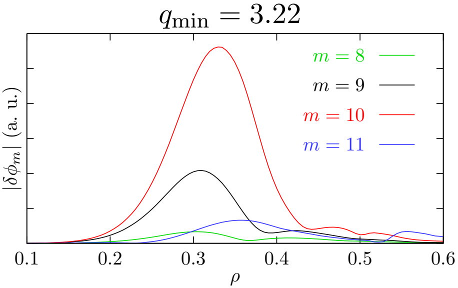




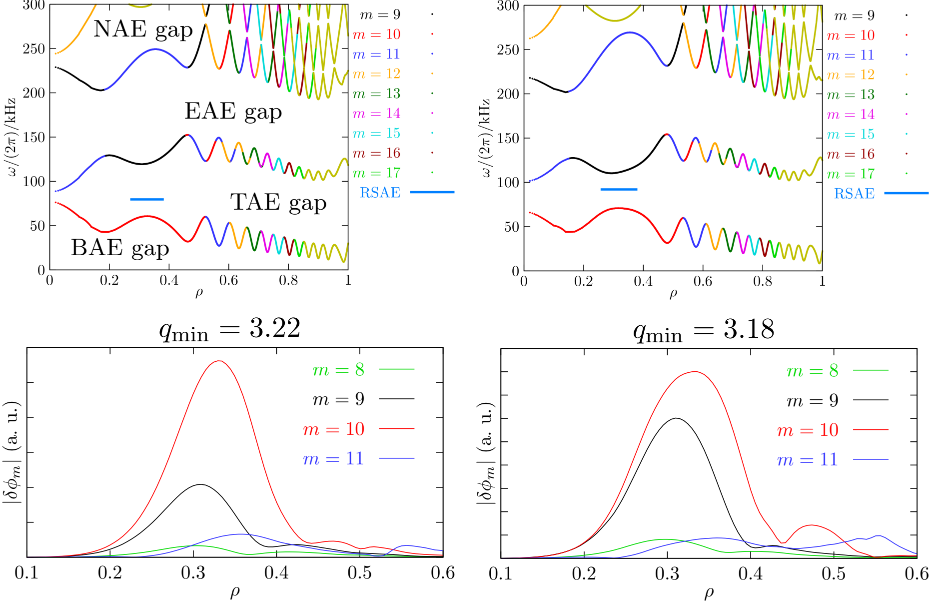
Expt. data provided by B. Tobias

Closer look at transition from RSAE to TAE (1)



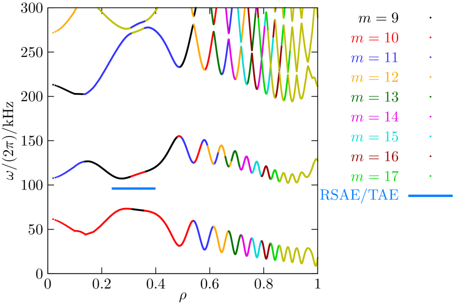


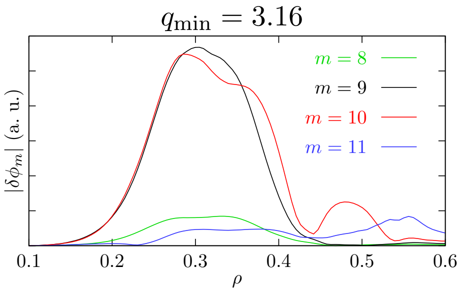
Closer look at transition from RSAE to TAE (1)



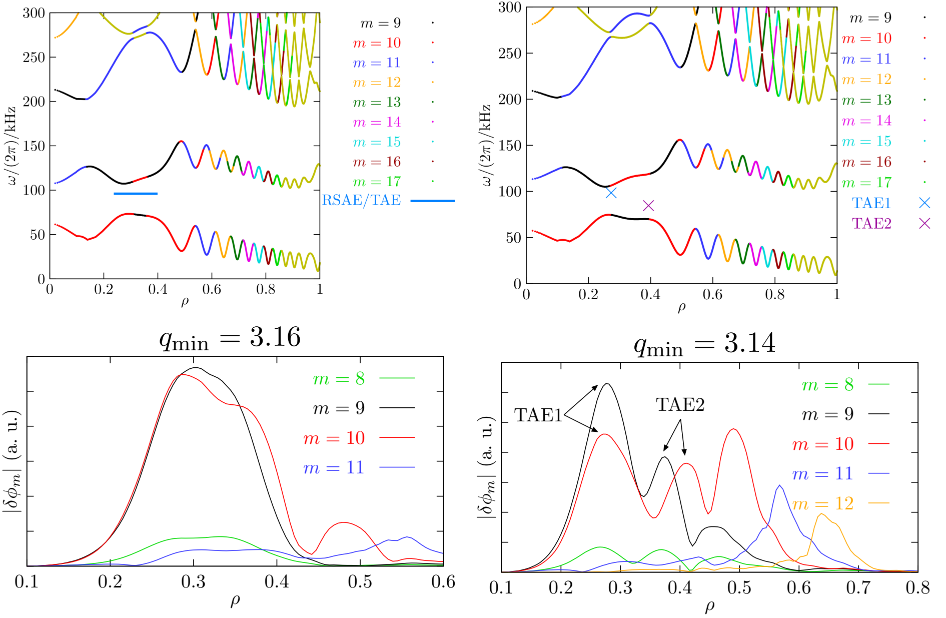
Alfvén continua plotted by ALCON code [Deng *et al.*, NF **52**, 043006 (2012)]

Closer look at transition from RSAE to TAE (2)





Closer look at transition from RSAE to TAE (2)



Damping and driving mechanisms identified & measured

$q_{\min} = 3.18$

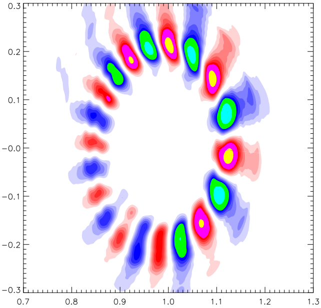
Case	Description	$(\omega_r, \gamma)/(2\pi)/\mathrm{kHz}$	γ/ω_r and damping or driving mechanism
(I)	Zero temperature ideal MHD	$(73.8, \sim 0)$	Continuum damping
(II)	Finite $\delta E_\parallel$, adiabatic e^- with $T_e \to T_e + 7T_i/4$, kinetic ion with $T_i \to 0.01T_i$	$(87.3, -3.12)$	Radiative damping added on top of case (I)
(III)	Same as case (II) except for real T_e & T_i profiles recovered	$(85.1, -0.499)$	Ion Landau damping & pressure gradient driving added on top of case (II)
(IV)	Drift-kinetic e^- added on top of case (III)	$(85.1, -1.61)$	e^- kinetic damping added on top of case (III)
(V)	Same as case (III) except that fast ions are added in	$(92.6, 6.79)$	Fast ion gradient driving added on top of case (III)
(VI)	Drift-kinetic e^- added on top of case (V)	$(92.0, 6.17)$	e^- kinetic damping added on top of case (V)

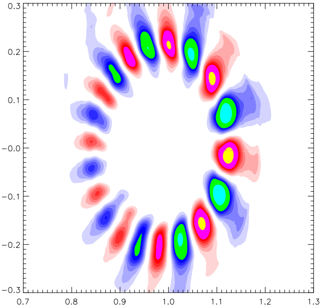
- Damping rate calculation requires non-perturbative, fully self-consistent mode structure, which will be clearly seen in the next two slides.

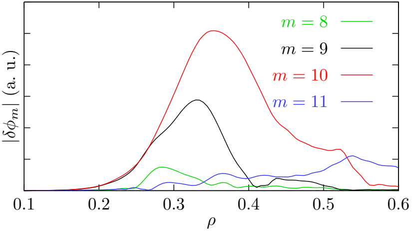
[W. Deng *et al.*, *Nuclear Fusion* **52**, 043006 (2012)]

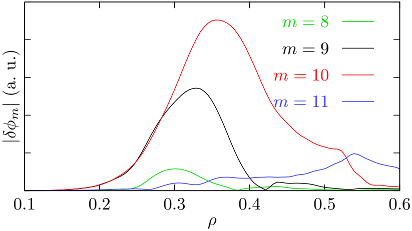
Mode structures of cases (III) and (IV)

(III) GK bg ion, no fast ion, ad. e^- (IV) GK bg ion, no fast ion, DK e^-







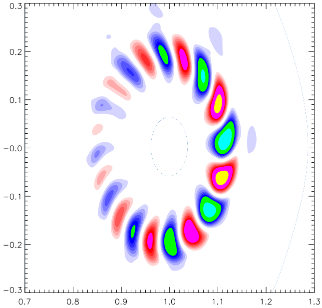


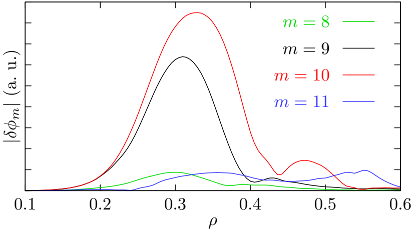
$\gamma = -0.499\text{kHz}$ $\gamma = -1.61\text{kHz}$

e^- kinetic damping contribution: $-1.61 - (-0.499) = -1.11\text{kHz}$

Mode structures of cases (V) and (VI)

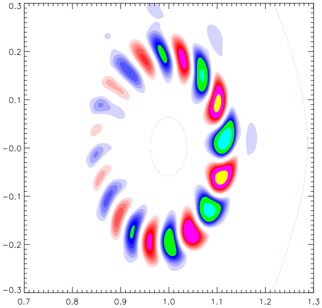
(V) GK bg & fast ion, adiabatic e^-

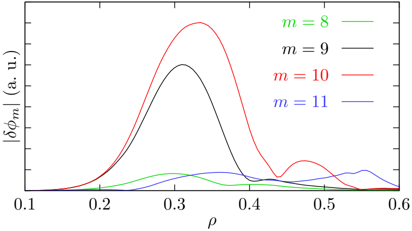




$\gamma = 6.79\text{kHz}$

(VI) GK thermal & fast ion, DK e^-

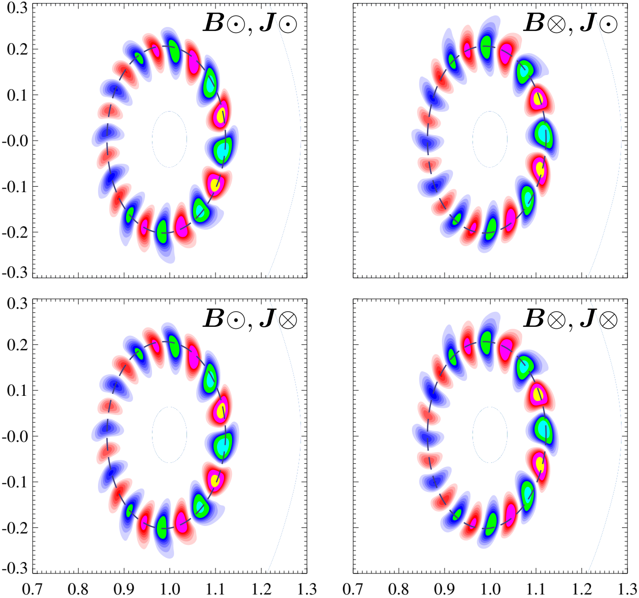




$\gamma = 6.17\text{kHz}$

e^- kinetic damping contribution: $6.17 - 6.79 = -0.62\text{kHz}$

$\boldsymbol{B}_{\text{tor}}$ and $\boldsymbol{J}$ direction effect ($q_{\min} = 3.22$)



[W. Deng *et al.*, *Nuclear Fusion* **52**, 043006 (2012)]

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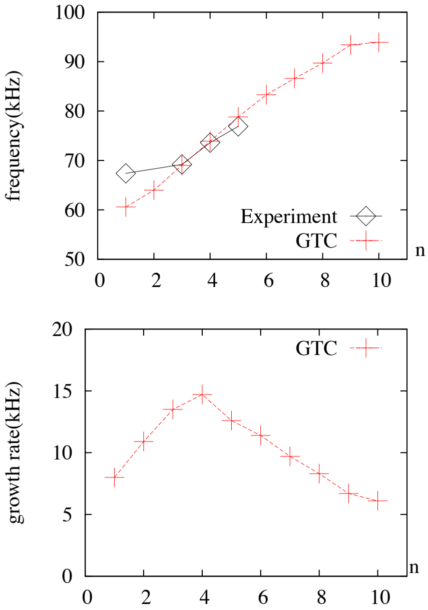
n-scan of TAEs at t=522ms ($q_{min} = 4.025$)



- The frequencies of $n = 3, 4, 5$ agrees well with experimental results.
- In experiment, the signals from $n = 3, 4, 5$ are the strongest. So are the growth rates in our simulation.
- The reason why $n = 2$ TAE is missing in experiment is unknown.

$n = 4$ TAE mode structure comparison with DIII-D

The mode structure agrees quite well with the ECEI data from DIII-D (data provided by Benjamin Tobias)

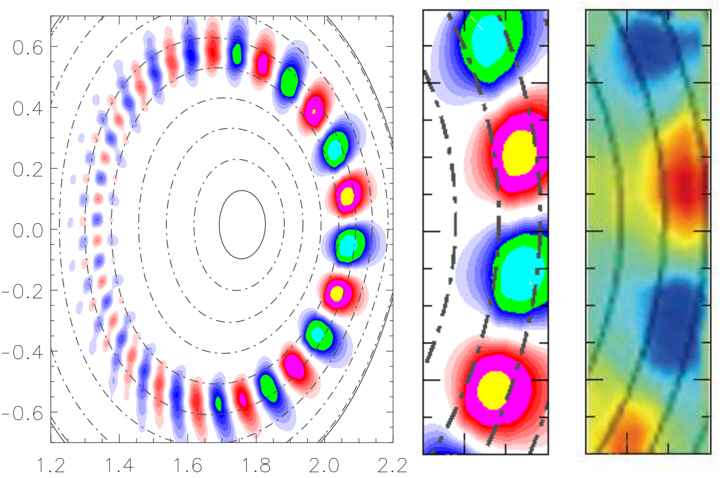


Figure: **Left:**snapshot of TAE mode structure on a poloidal cross section. **Right:** Comparison of TAE structure in GTC with that in DIII-D discharge # 142111 from ECEI image

Summary

- Electromagnetic gyrokinetic simulation model used in GTC can be shown to reduce to ideal MHD theory in the linear and long wave-length limit.
- Validation of simulations of RSAEs in DIII-D discharge #142111
  - Good agreements in frequency, growth rate and mode structure in comparisons among GTC, GYRO and TAEFL.
  - Simulation frequencies close to experiment in both up-sweeping RSAE and RSAE to TAE transition regions. Simulation growth rates close to experimental estimate.
  - Damping and driving mechanisms of RSAE identified and measured.
  - Nonlinear simulations for studies of RSAE saturation mechanism and fast ion transport are in progress.
- Validation of simulations of TAEs in the same DIII-D shot also gives good agreements in frequency and mode structure.