Global Gyrokinetic Simulations of Electromagnetic Instabilities in Tokamak Plasmas

I. Holod, Z. Lin, Y. Xiao, W.J. Deng, H.S. Zhang, Z.X. Wang, L. Chen

Department of Physics and Astronomy, University of California, Irvine

W.L. Zhang

CAS Key Laboratory of Basic Plasma Physics, University of Science and Technology of China, Hefei, Anhui 230026, China

Outline

- Motivation and general approach
- GTC formulation
- Verification and validation of RSAE/TAE simulation using DIII-D dedicated experiment #142111
  - Linear benchmarks of frequency and mode structure
  - RSAE-TAE transition
  - EP drive
- Beta-induced Alfven eigenmode (BAE)
  - Linear benchmark
  - Fast frequency chirping of BAE simulation

Gyrokinetic Electromagnetic Simulation

- Fully self-consistent simulation of turbulence and transport in burning plasmas must incorporate three new physics elements
  - Linear and nonlinear kinetic effects of thermal & energetic particles
  - Nonlinear interaction of *meso*-scale shear Alfven waves with *micro*-scale kinetic effects and wave-particle resonance
  - Cross-scale couplings of *meso-micro* turbulence
- Large dynamical ranges of spatial-temporal processes require global simulation codes efficient in utilizing massively parallel computers at petascale level and beyond
- Therefore, studies of transport physics in ITER burning plasmas call for a new approach of global nonlinear gyrokinetic simulation
- This presentation reports progress in this new approach

- Nonlinear gyrokinetic equation, Poisson equation, Ampere's law

$$\frac{\partial F}{\partial t} + (v_{\parallel}\mathbf{b} + \mathbf{v}_d)\cdot\frac{\partial F}{\partial \mathbf{R}} + \dot{v}_{\parallel}\frac{\partial F}{\partial v_{\parallel}} = 0$$

$$\phi - \tilde{\phi} = -\sum_s 4\pi e Z_s \bar{n}_s$$

$$\nabla^2 A_{\parallel} = -\sum_s \frac{4\pi e}{c} Z_s \bar{n}_s u_s$$

- In fluid limit, gyrokinetic system recover MHD modes including Alfven wave, interchange mode, kink mode, KBM

KBM

SAW

$$\frac{\omega(\omega-\omega_{*P})}{v_A^2}\nabla_\perp^2\delta\phi - i\boldsymbol{B}_0\cdot\nabla\left\{\frac{\boldsymbol{b}_0\cdot\nabla\times[\nabla\times(k_\parallel\delta\phi\boldsymbol{b}_0)]}{B_0}\right\}$$

$$-\frac{i\omega}{c}\delta\boldsymbol{B}\cdot\nabla\left(\frac{\boldsymbol{b}_0\cdot\nabla\times\boldsymbol{B}_0}{B_0}\right)$$

kink drive

$$-i\omega\frac{4\pi}{c}\left[\nabla\times\boldsymbol{b}_0\cdot\nabla\left(\frac{\delta P_\parallel}{B_0}\right) + \boldsymbol{b}_0\times\nabla B_0\cdot\nabla\left(\frac{\delta P_\perp}{B_0^2}\right) + \frac{\nabla\times\boldsymbol{b}_0\cdot\nabla B_0}{B_0^2}\delta P_\perp\right]$$

$=0$

interchange drive

*[W. Deng, et al., Phys. Plasmas **17**, 112504 (2010)]*

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- GTC integration: microturbulence + MHD + EP
  - Non-perturbative (full-f) & perturbative (δf) simulation
  - General geometry using EFIT & TRANSP/ONETWO data
  - Kinetic electrons & electromagnetic fluctuation
  - Neoclassical effects using Fokker-Planck collision operators
  - Equilibrium radial electric field, toroidal rotations; Multiple ion species
  - Efficient parallelization

[Lin, et al, Science 281, 1835 (1998)]

http://phoenix.ps.uci.edu/GTC

- Gyrokinetic description for ions
  - Gyroaveraged equations of motion for ion gyrocenter
- Fluid-kinetic hybrid model for electrons
  - Lowest order: adiabatic response
    - continuity equation for massless electron
- Higher-order: non-adiabatic response
    - drift-kinetic equation for electron guiding center
- Gyrokinetic Poisson's equation
- Ampere's law
- Faraday's law

Ion gyrokinetics remove fast time scales

- Gyrocenter equation of motion

$$\frac{d\mathbf{X}}{dt} = v_{\parallel}\frac{\mathbf{B}}{B_0} + \mathbf{v}_E + \mathbf{v}_d$$

- Parallel acceleration

$$\frac{dv_{\parallel}}{dt} = -\frac{1}{m_\alpha}\frac{\boldsymbol{B}^*}{B_0^*}\cdot\left(\mu\nabla B + Z_\alpha\nabla\phi\right) - \frac{Z_\alpha}{m_\alpha c}\frac{\partial A_{\parallel}}{\partial t}$$

- Gyrocenter drift velocities

$$\mathbf{v}_E = \frac{cB_0\times\nabla\phi}{B_0^2} \qquad v_d = \frac{\mu}{m_\alpha\Omega_\alpha}\frac{\mathbf{B}_0}{B_0}\times\nabla B_0 + \frac{v_{\parallel}^2}{\Omega_\alpha}\nabla\times\frac{\mathbf{B}_0}{B_0}$$

$$\mathbf{B}^* = \mathbf{B}_0^* + \delta\mathbf{B} = \mathbf{B}_0 + \frac{B_0 v_{\parallel}}{\Omega_\alpha}\nabla\times\frac{\mathbf{B}_0}{B_0} + \delta\mathbf{B}$$

Lowest order fluid description for electrons

- Electron continuity equation

$$\frac{\partial \delta n_e}{\partial t} + \mathbf{B}\cdot\nabla\left(\frac{n_0 \delta u_{\parallel}}{B_0}\right) + B_0 \mathbf{v}_E \cdot \nabla\left(\frac{n_0}{B_0}\right) - n_0\left(\mathbf{v}_* + \mathbf{v}_E\right)\cdot\frac{\nabla B_0}{B_0} = 0$$

- Perturbed diamagnetic drift velocity

$$\mathbf{v}_* = \frac{1}{n_0 m_e \Omega_e B_0}\mathbf{B}_0 \times \nabla\left(\delta P_{\parallel} + \delta P_{\perp}\right)$$

- Perturbed pressure

$$\delta P_{\parallel} = \int d\mathbf{v}\,\mu B_0 \delta f \qquad \delta P_{\perp} = \int d\mathbf{v}\, m v_{\parallel}^2 \delta f$$

- Ampere's law

$$n_0 e \delta u_{\parallel e} = \frac{c}{4\pi}\nabla_{\perp}^2 \delta A_{\parallel} + \sum_{\alpha \neq e} n_\alpha Z_\alpha \delta u_{\parallel \alpha}$$

- Gyrokinetic equation for ions

$$\frac{d}{dt}\frac{\delta f_\alpha}{f_{0\alpha}} = -\left(1-\frac{\delta f_\alpha}{f_{0\alpha}}\right)\frac{\delta \hat{L} f_{0\alpha}}{f_{0\alpha}}$$

- Higher order DKE for electrons

$$\frac{d}{dt}\frac{\delta h_e}{f_{0e}} = -\left(1-\frac{\delta f_e^{(0)}}{f_{0e}}-\frac{\delta h_e}{f_{0e}}\right)\left[\frac{\delta \hat{L} f_{0e}}{f_{0e}}+\frac{\hat{L}_0 \delta f_e^{(0)}}{f_{0e}}+\frac{\left\langle \delta \hat{L}\right\rangle f_e^{(0)}}{f_{0e}}\right]$$

- Perturbed densities

$$\delta n_\alpha = \int d\boldsymbol{v}\,\delta f_\alpha \qquad \delta n_e^1 = \int d\boldsymbol{v}\,\delta h_e$$

Field equations

- Gyrokinetic Poisson's equation

$$\sum_{\alpha \neq e} \left(\tilde{\phi}_\alpha - \phi \right) \frac{n_{0\alpha} Z_\alpha^2}{T_\alpha} = -\sum_\alpha n_\alpha Z_\alpha$$

- Ampere's law

$$n_0 e \delta u_{\|e} = \frac{c}{4\pi} \nabla_\perp^2 \delta A_\| + \sum_{\alpha \neq e} n_\alpha Z_\alpha \delta u_{\|\alpha}$$

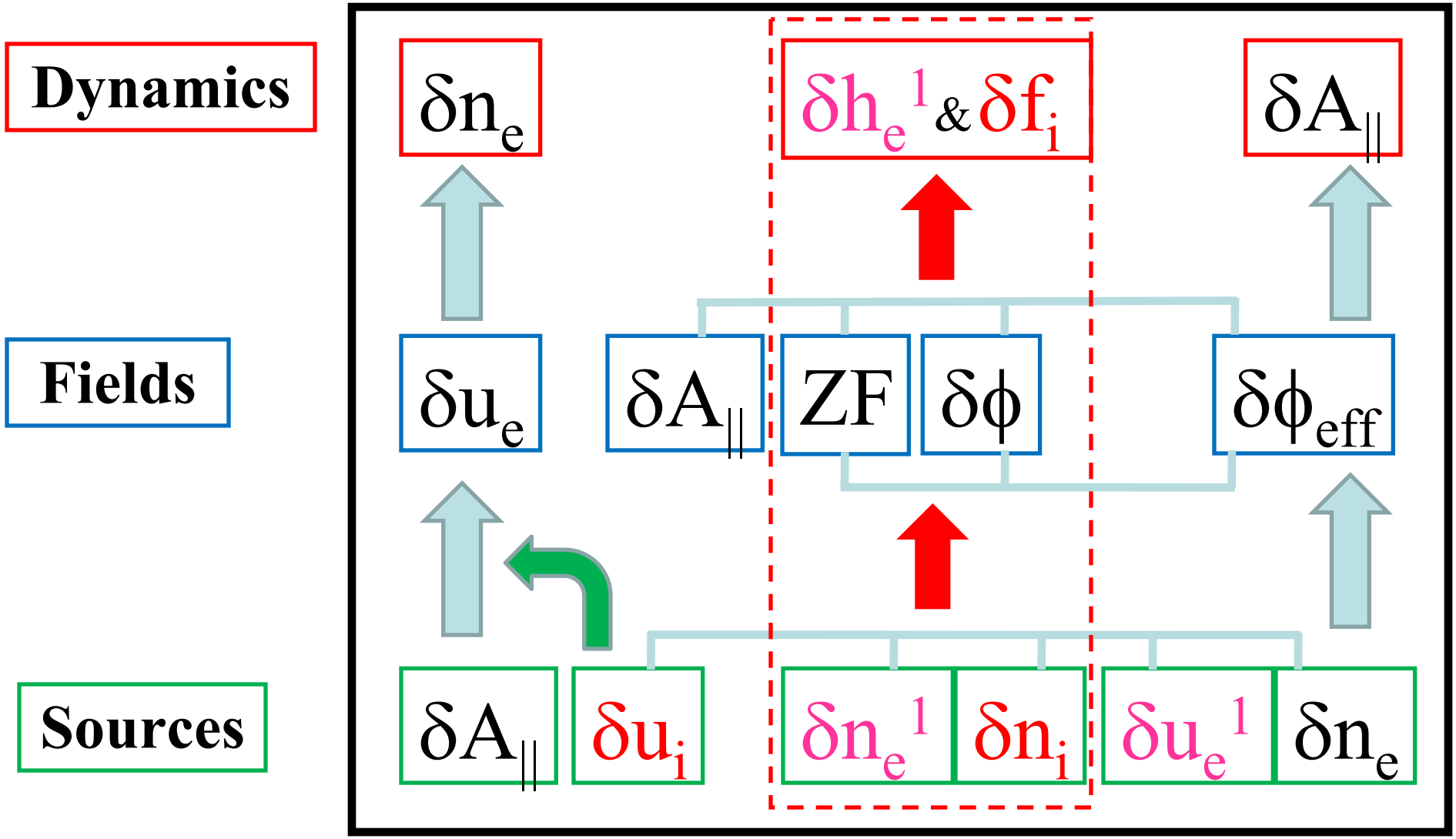
- Faraday's law

$$\frac{\partial A_\|}{\partial t} = -\delta E_\| - \nabla_\| \phi = \nabla_\| \phi_{\text{eff}} - \nabla_\| \phi$$

- Electron adiabatic response

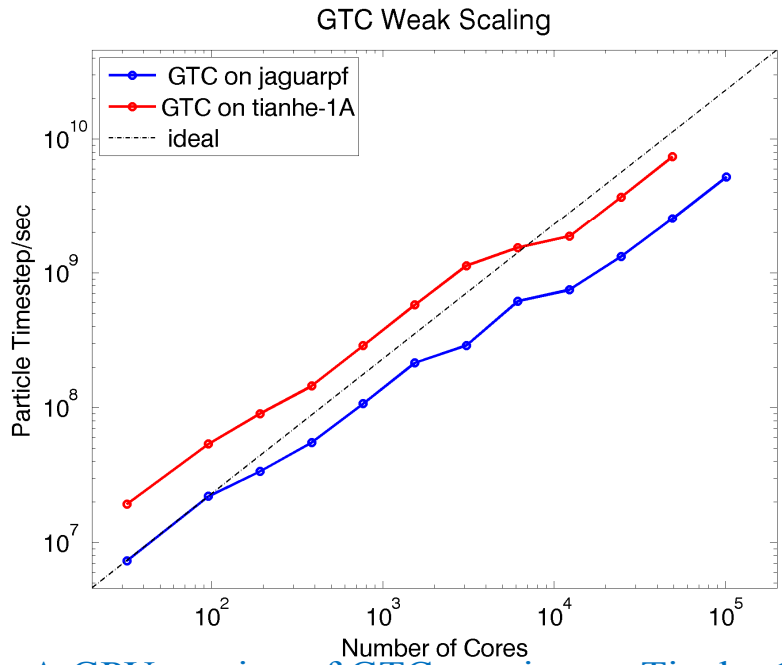
$$\frac{e\phi_{eff}}{T_e} = \frac{\delta n_e}{n_{0e}} - \frac{\delta n_e^1}{n_{0e}} - \left. \frac{\partial \ln f_{0e}}{\partial \psi} \right|_{v_\perp} \delta\psi$$

General algorithm



GTC Multi-level Parallelism

- GTC solves gyrokinetic-Poisson equations in 5D phase space: fields represented on 3D fixed grid; particles move in 5D
- Level 1: 1D particle-field domain-decomposition using MPI
- Level 2: Parallel field solvers
- Level 3: OpenMP loop parallelization
- Current priority: GPU acceleration (4.7PF Tianhe-1A at NSCC-TJ & 20PF Titan at ORNL)



A GPU version of GTC running on Tianhe-1A

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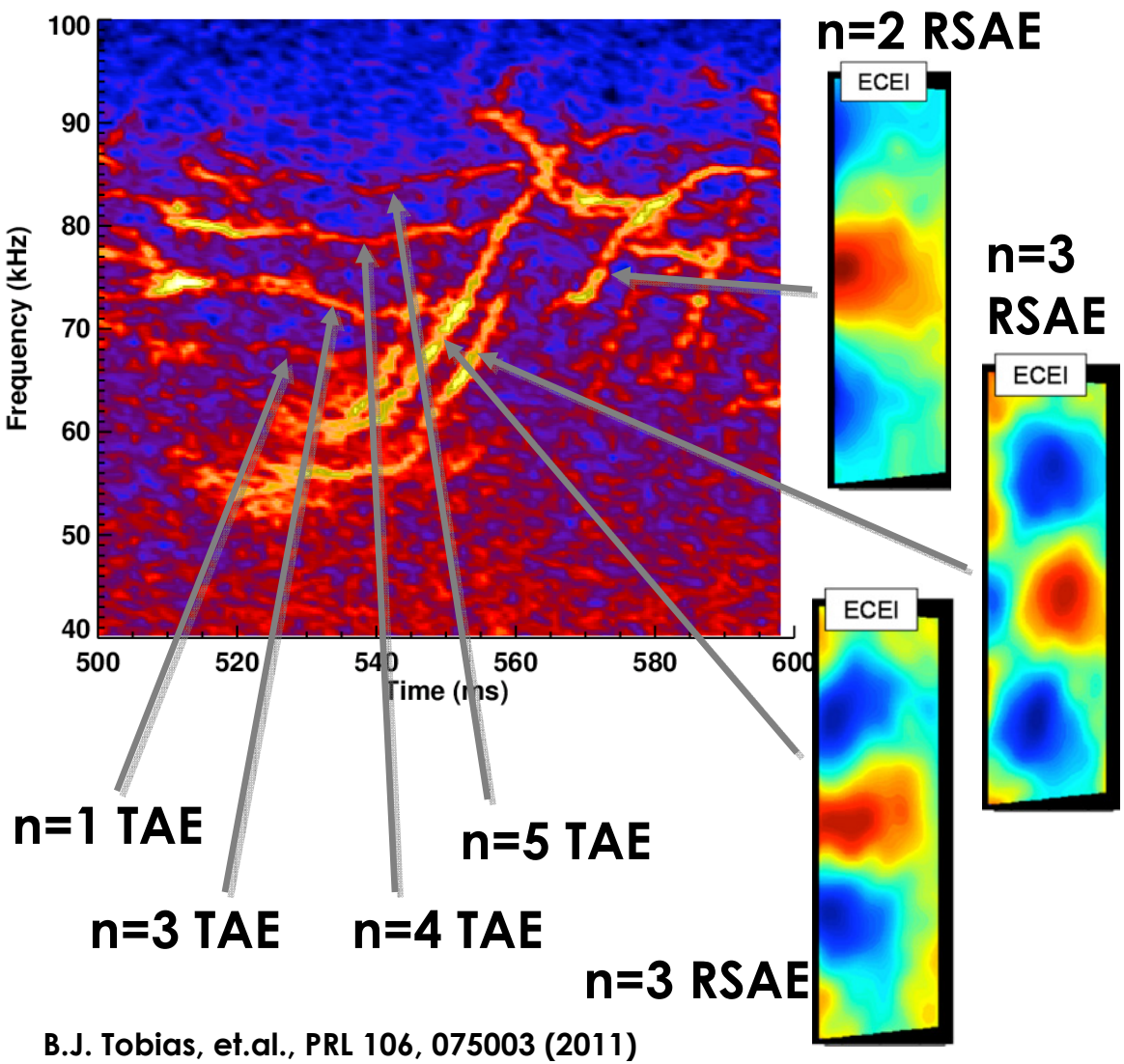
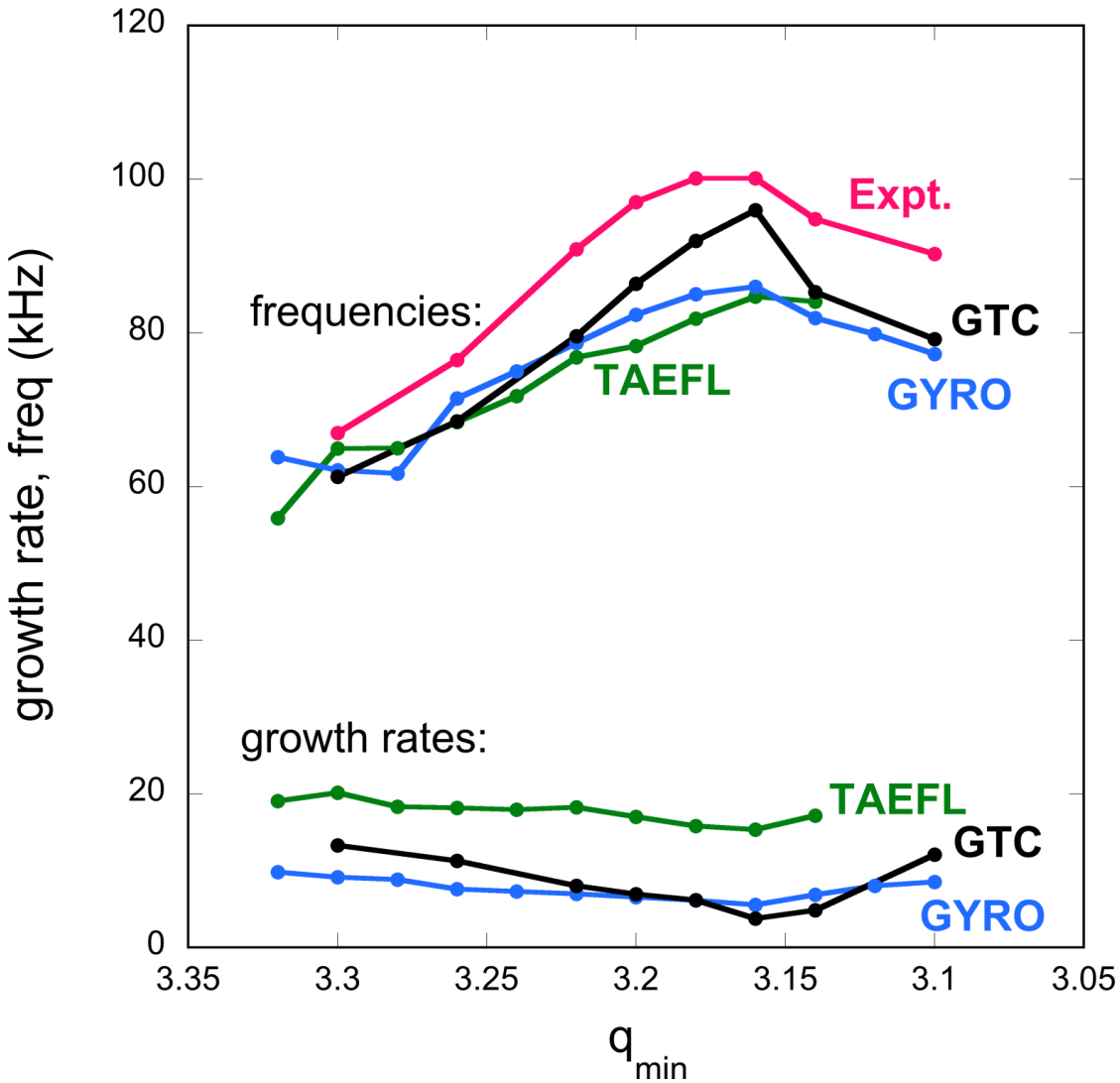
DIII-D Discharges Typically Have a Variety of Alfven Eigenmodes



B.J. Tobias, et.al., PRL 106, 075003 (2011)

- RSAEs and TAEs are present during the current ramp
  - TAEs appear as relatively constant frequency modes
  - RSAEs sweep up in frequency as q_{min} decreases
- Measurements of mode frequency, structure, etc. are used for validation
- Mode structures are obtained using a variety of techniques but ECE radiometry has played the largest role

RSAE linear frequency & growth rate benchmark



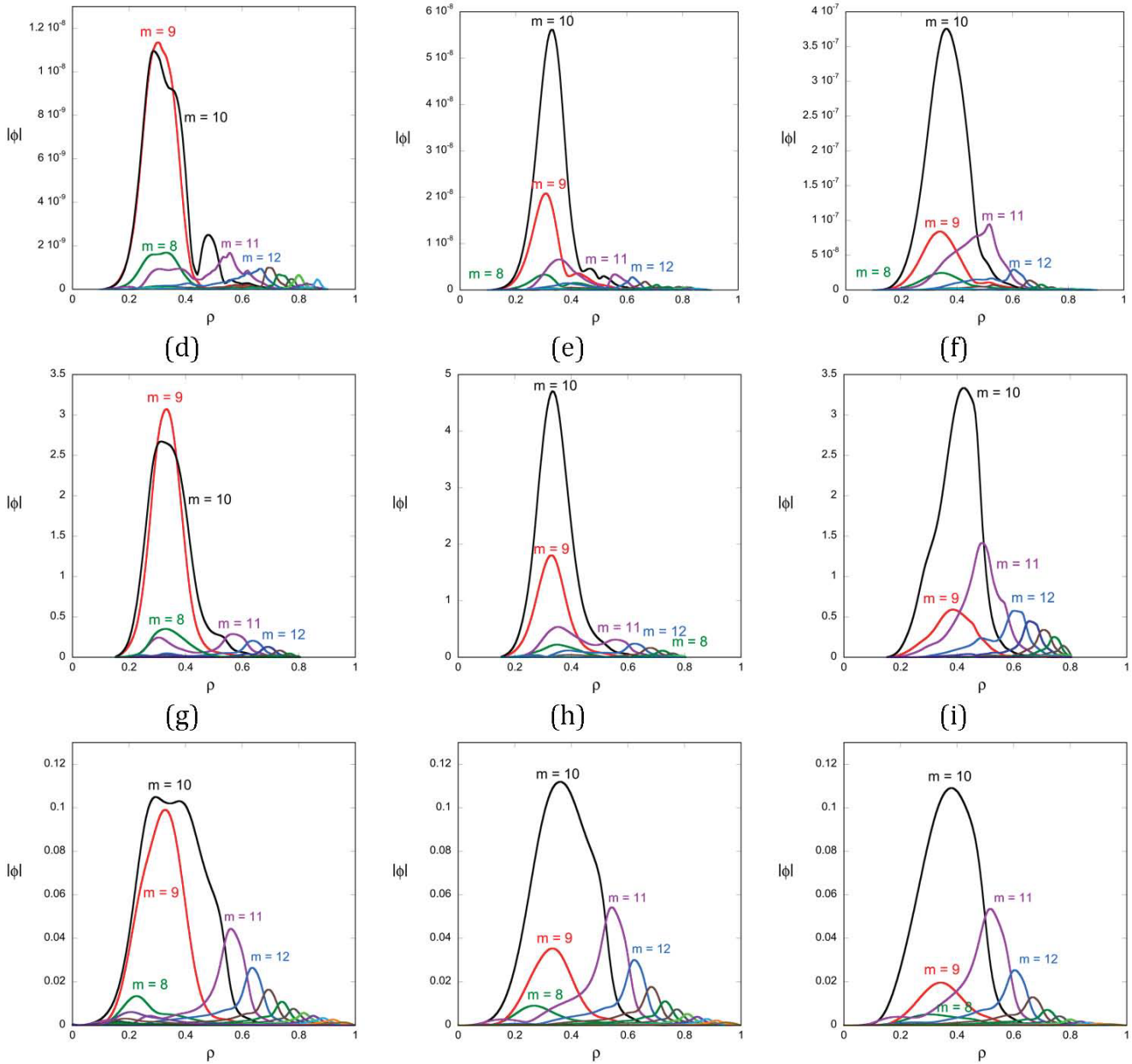
[D. A. Spong, E. M. Bass, W. J. Deng et al, 2011]

RSAE mode structure benchmark

GTC

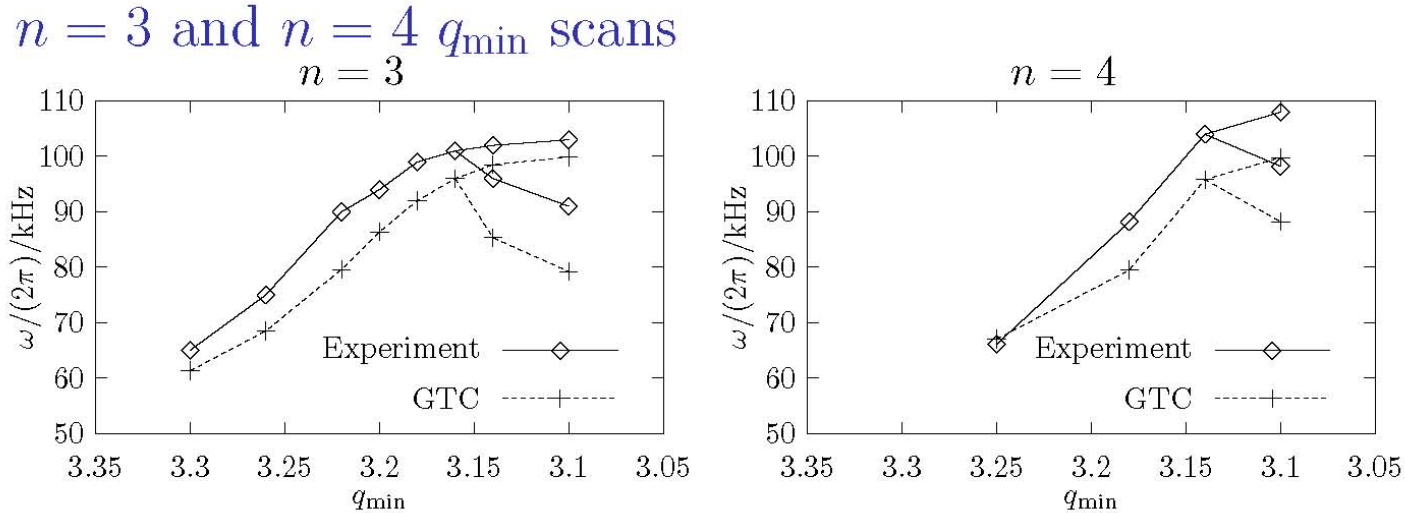
GYRO

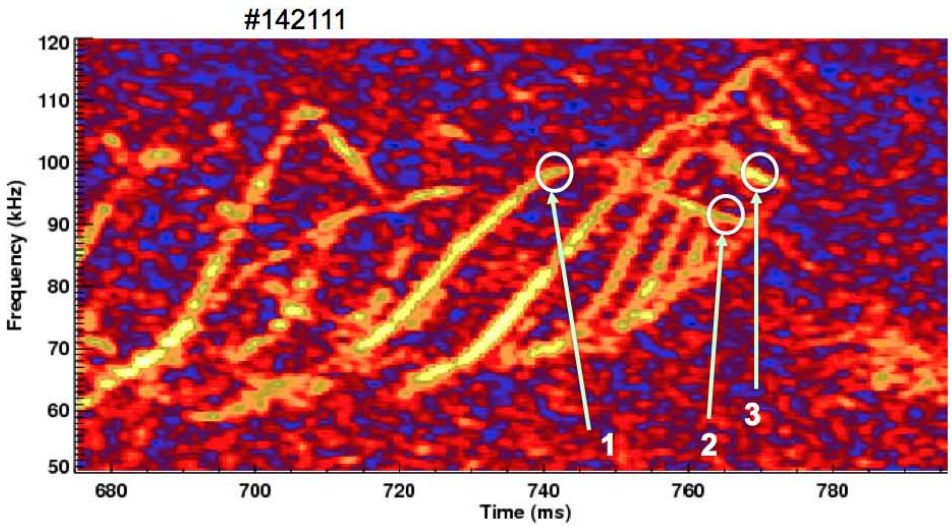
TAEFL



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

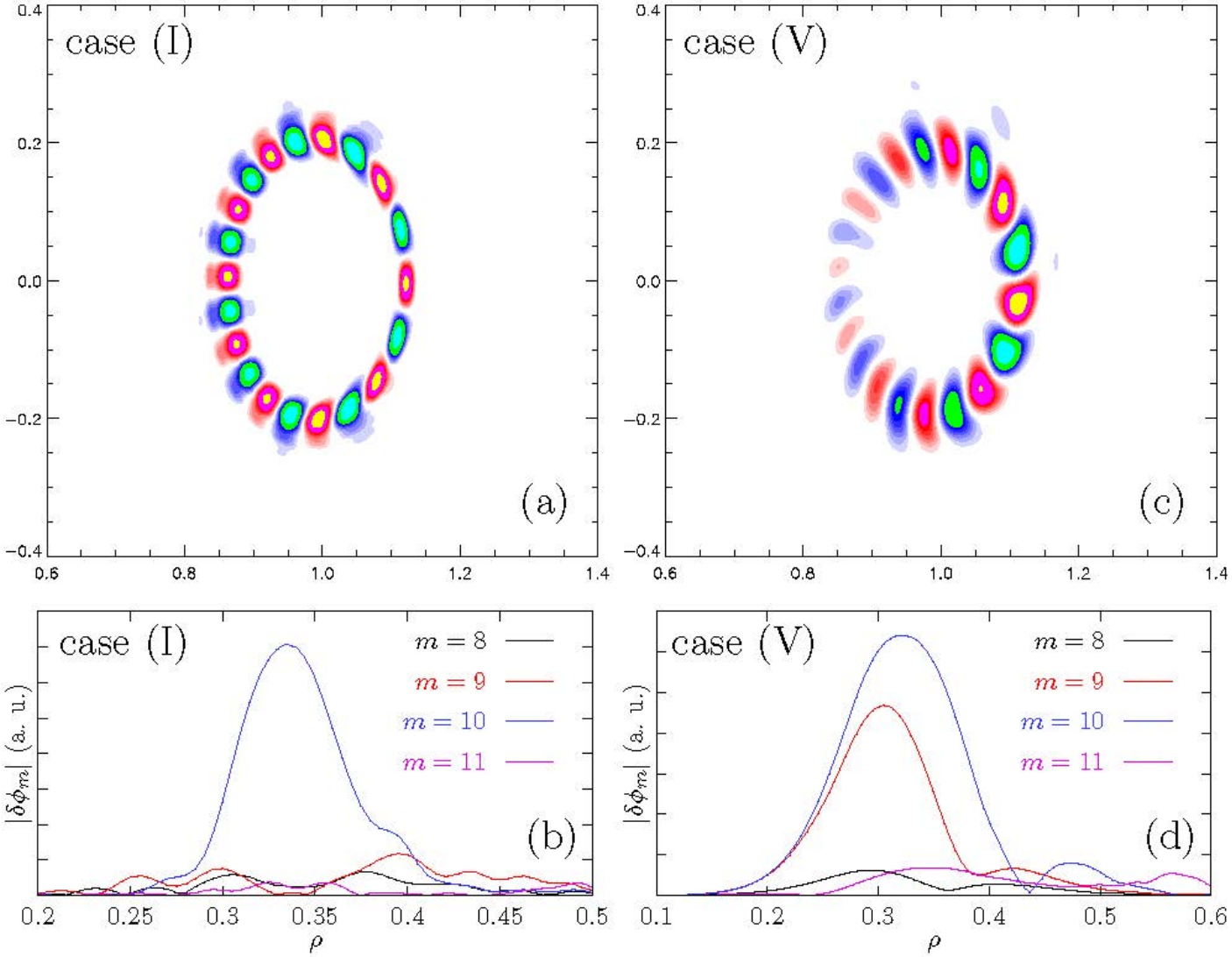
RSAE q_{min} scan reveals frequency sweeping





[Linear properties of reversed shear Alfven eigenmodes in DIII-D tokamak, W. J. Deng Z. Lin, I. Holod, Z. X. Wang, Y. Xiao, and H. S. Zhang, submitted to Nuclear Fusion, 2011]

- EP non-perturbative contribution & toroidal coupling modify RSAE mode structure with respect to ideal MHD



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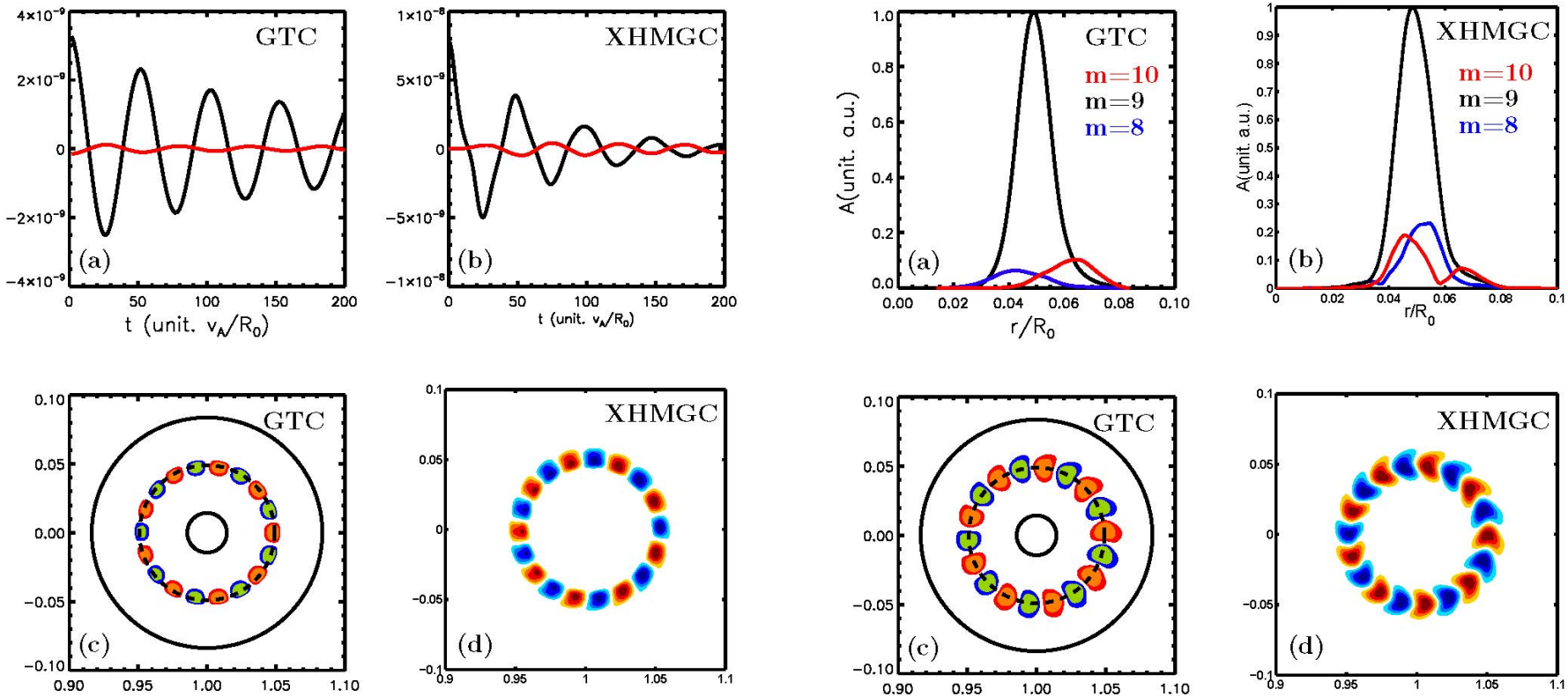
BAE linear benchmark

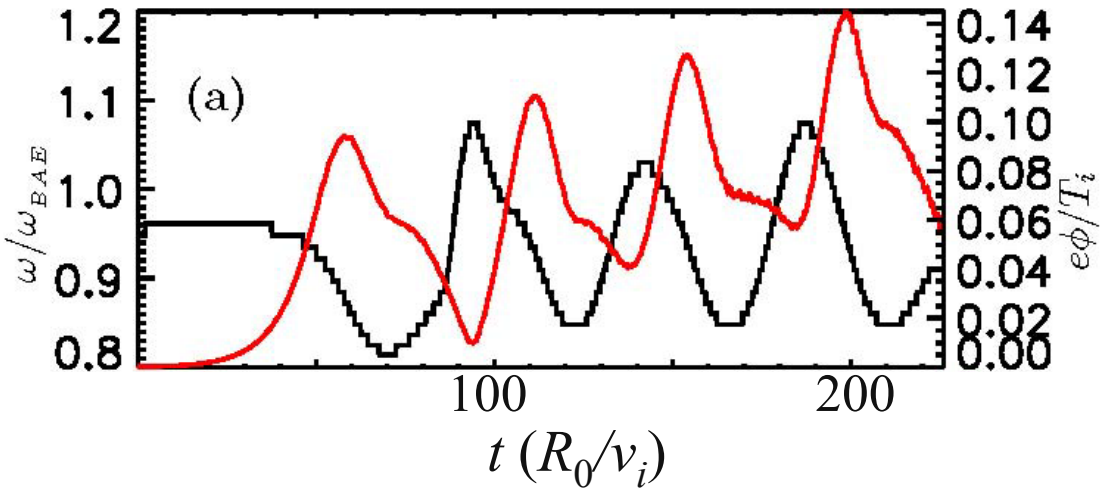


- Damped BAE from initial perturbation (left) and unstable BAE excited by EP (right) in GTC & HMGC simulations

*["Gyrokinetic particle simulation of beta-induced Alfven eigenmode", H. S. Zhang, Z. Lin, I. Holod, X. Wang, Y. Xiao, W. L. Zhang, Phys. Plasmas **17**, 112505, (2010)]*

BAE frequency fast chirping

- GTC Nonlinear simulations find fast chirping of BAE frequency
- 90° phase shift between intensity oscillation (red) and frequency chirping (black)
- Chirping mechanism?

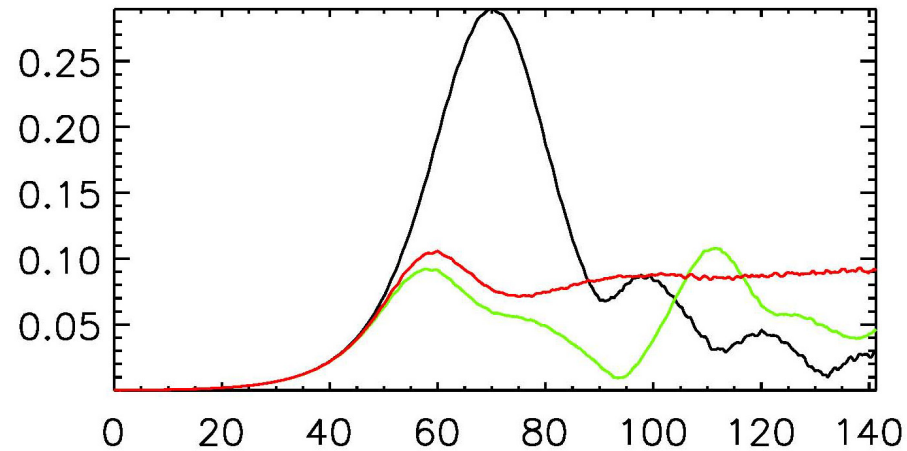


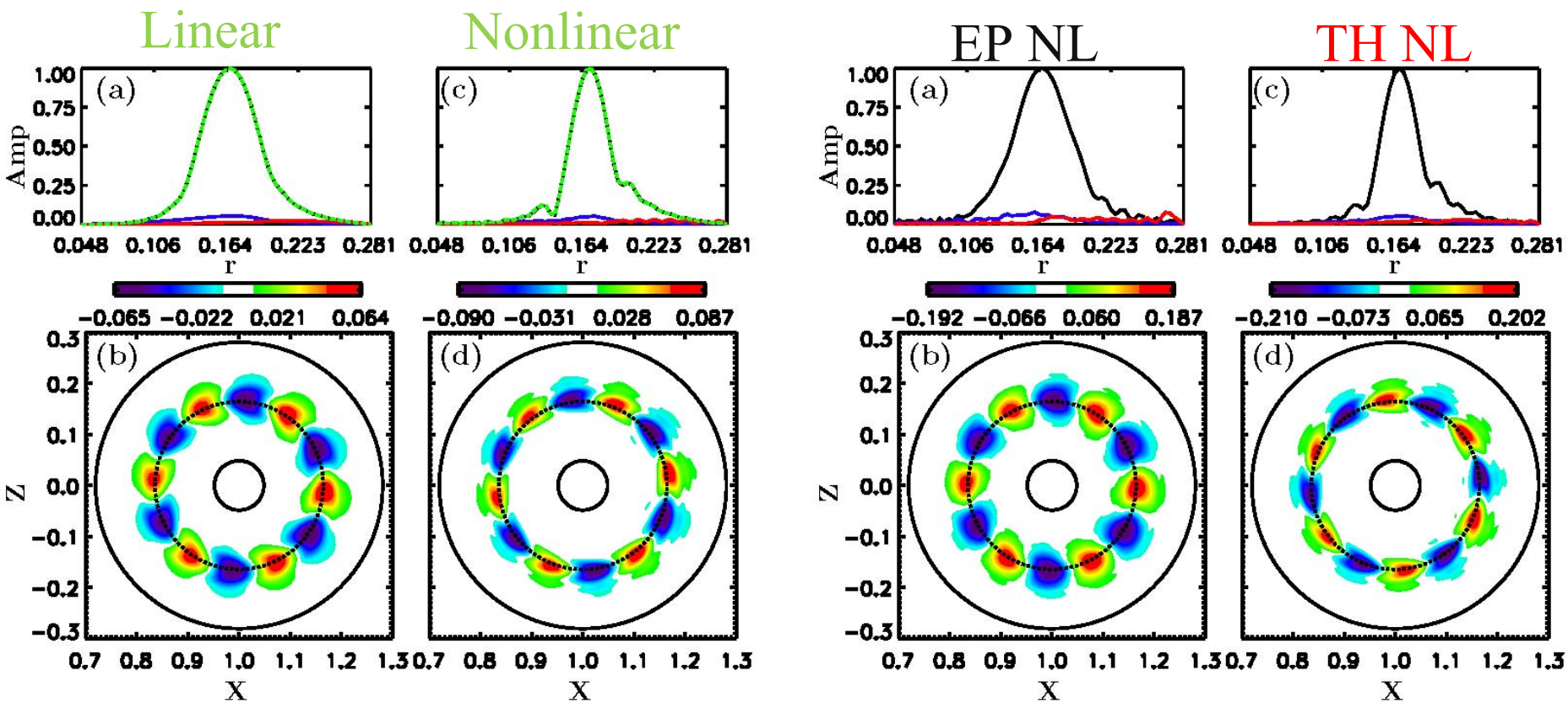
$\gamma/\omega_r \sim 0.1$

["Alfven Wave Frequency Chirping Induced by Nonlinear Dynamics of Charged Particles", H. S. Zhang et al, Manuscript in preparation, 2011]

Nonlinearity of Thermal & Energetic Particles

- Saturation amplitude & mode structure set by thermal ion nonlinearity
- Chirping induced by energetic particle nonlinearity





Summary

- Gyrokinetic turbulence simulation is a powerful tool for studying EP turbulence and transport
- Good agreement between GK codes on RSAE frequency and mode structures
- Frequency sweeping and RSAE-TAE transition
- Linear benchmark of BAE mode
- Nonlinear dynamics of thermal and energetic ions play a key role in saturation and chirping