SciDAC ISEP
Integrated Simulation of Energetic Particles

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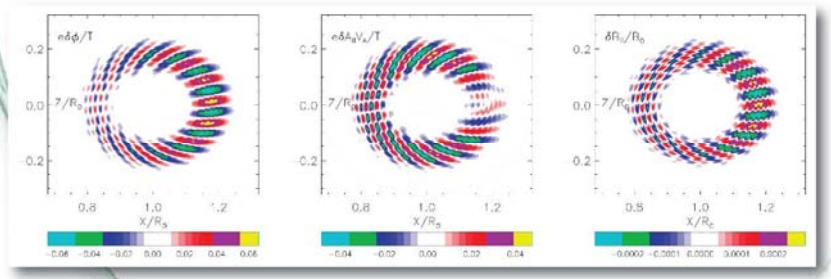
AIP | Physics of Plasmas



SPECIAL TOPIC:

Gyrokinetic Particle Simulation: A Symposium in Honor of Wei-li Lee

Gyrokinetic particle simulations of the effects of compressional magnetic perturbations on drift-Alfvenic instabilities in tokamaks
by G. Dong, J. Bao, A. Bhattacharjee, A. Brizard, Z. Lin, and P. Porazik

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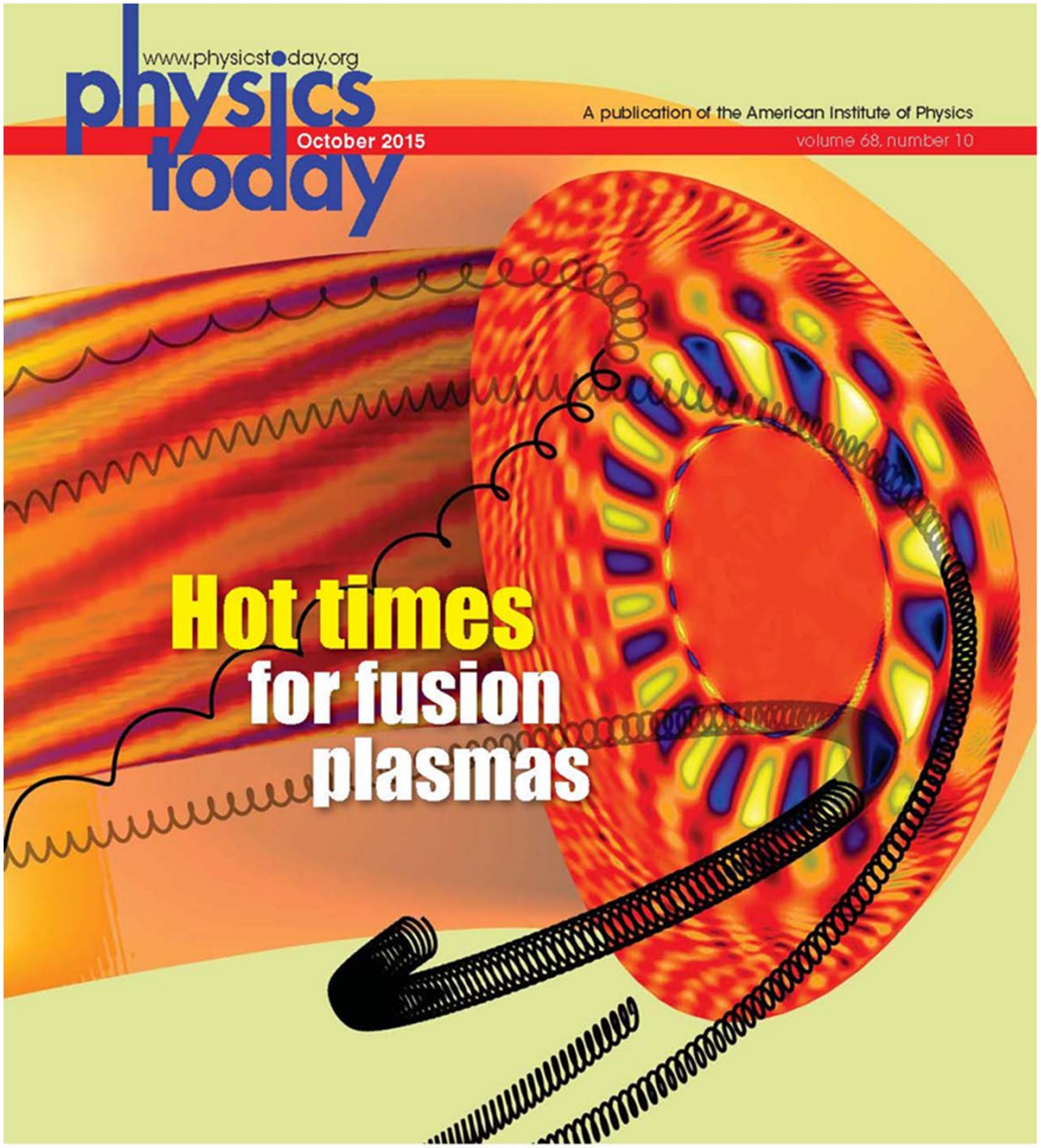
Outlines

- SciDAC ISEP
- ISEP V&V
- Integrated EP simulation
- TAE saturation via zonal fields
- Excitation of BAAE



Confinement of Energetic Particle in Burning Plasmas

- The confinement of energetic particles (EP) is a critical issue for burning plasma experiments since the ignition in ITER relies on the self-heating by energetic fusion products (α-particles)
- Plasma confinement properties in the *new* ignition regime of self-heating by α-particles is one of the most uncertain issues when extrapolating from existing fusion devices to ITER
- **Energetic particles turbulence and transport**: EP excite meso-scale instabilities and drive large EP transport, which can degrade overall plasma confinement and threaten the machine integrity
- **Interaction between energetic particles and thermal plasmas**: since EP constitute a significant fraction of plasma energy density in ITER, EP will strongly influence microturbulence responsible for turbulent transport and macroscopic magnetohydrodynamic (MHD) instabilities potentially leading to disruptions

SciDAC ISEP: Integrated Simulation of Energetic Particles in Burning Plasmas

- SciDAC GSEP (2008-2017): established the new paradigm of nonlinear kinetic simulations of energetic particle turbulence by treating relevant physical processes from micro to macro scales on the same footing
- In 2017, GSEP & CSEP (2011-2017) jointly established ISEP, one of 9 SciDAC-4 centers funded by OFES & ASCR with the goal of validated whole device modeling (WDM)
- SciDAC ISEP (2017-2022) goals
  - To improve physics understanding of EP confinement and EP interactions with burning thermal plasmas through exascale simulations
  - To develop a multiscale and multiphysics ISEP framework with predictive capability as an EP module in future WDM project

ISEP Objectives

- Study EP physics needed for predictive capability
  - EP transport by mesoscale EP turbulence
  - EP coupling with microturbulence and macroscopic MHD modes
  - First-principles simulations: GTC, GYRO, FAR3D, M3D-K
- Develop integrated simulation capability for EP physics
  - ISEP framework based on GTC
- Develop EP module with predictive capability for WDM
  - Reduced EP transport models (CGM, RBQ)
  - First-principles ISEP framework
- EP module verification and validation (V&V via kick model)
- Computational partnership
  - Workflow/data management
  - Solvers
  - Optimization & portability

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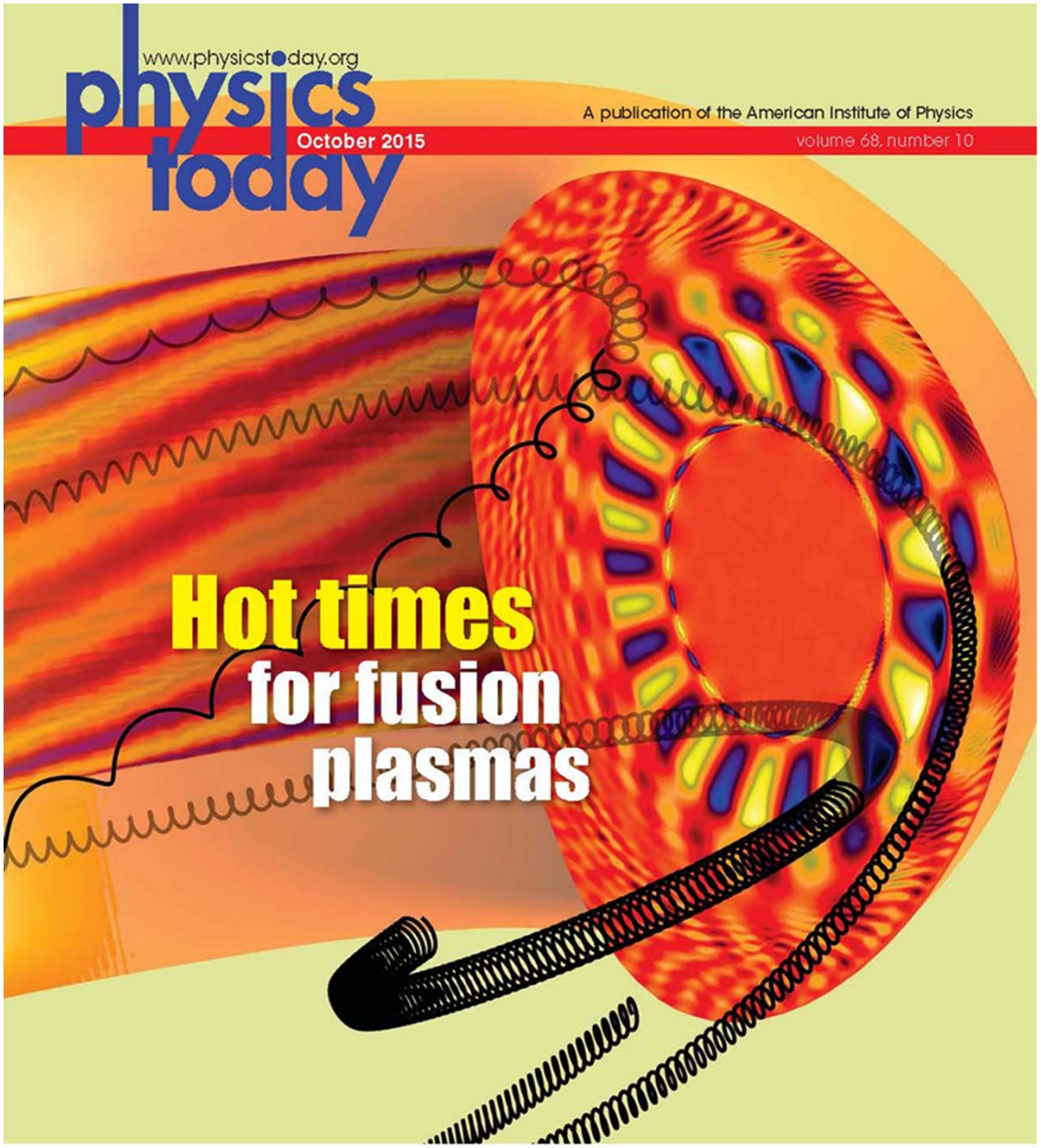
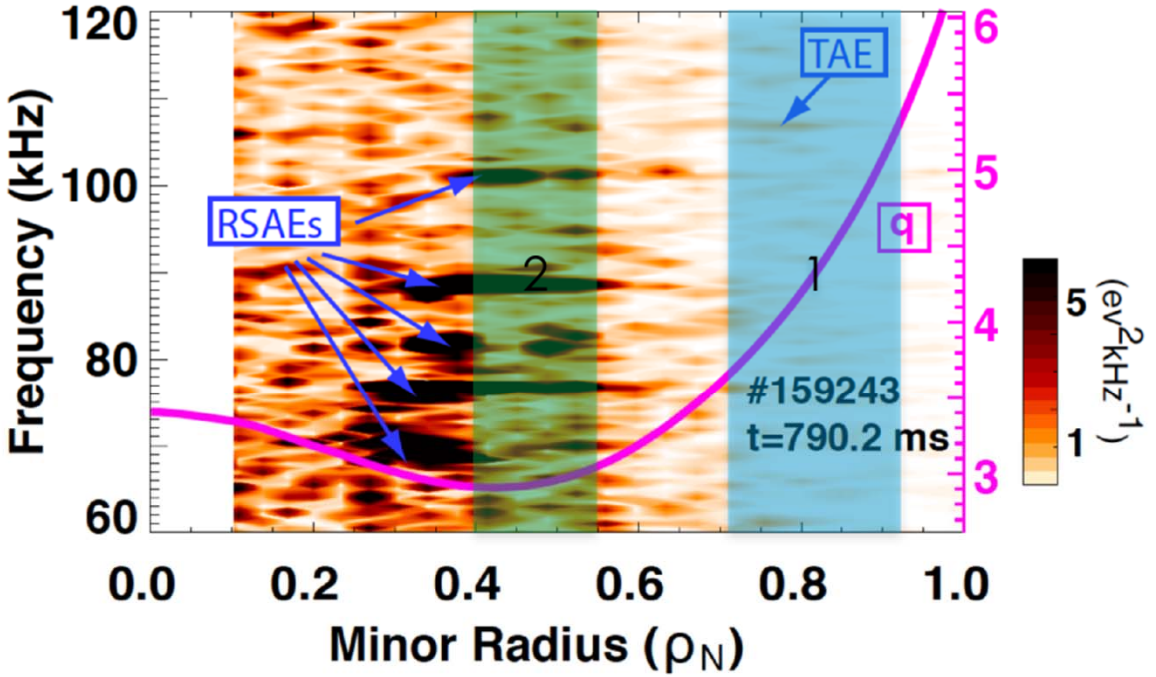


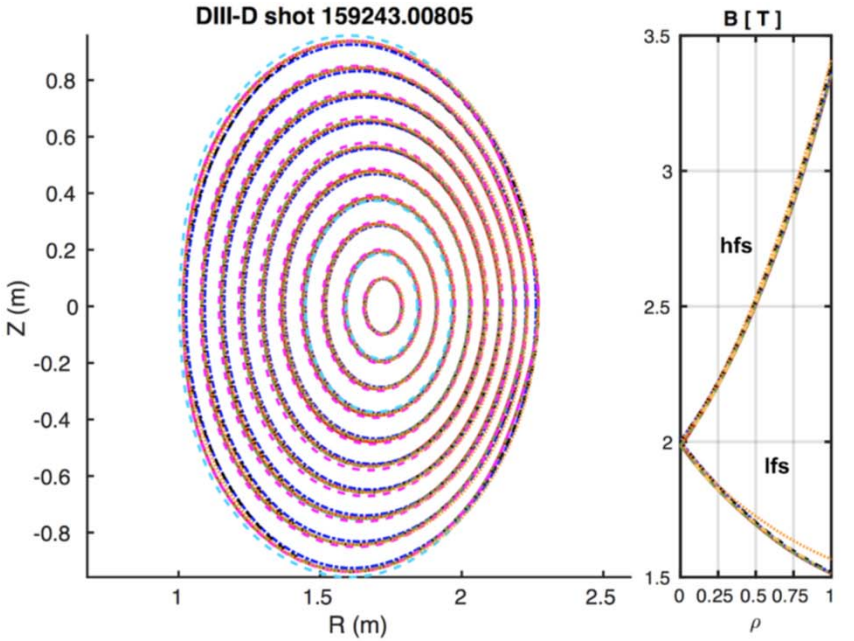
159243, Mode structure in ECE (From Cami), ECEI volume overlay

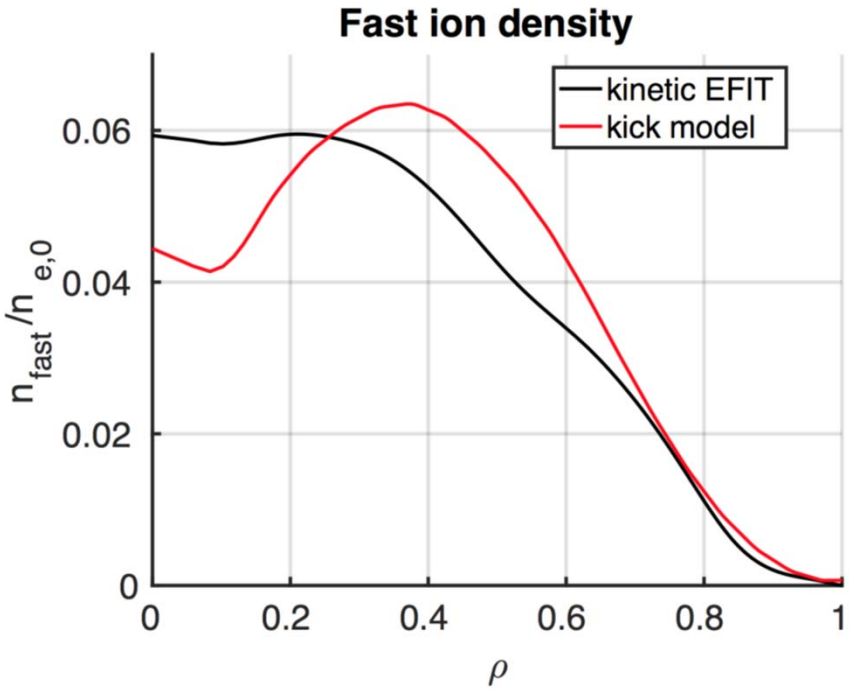
- **RSAEs near rho~0.4**
- **TAEs > rho~0.7**
- **ECEI Dual Array**
  - 2 rho: 0.4~0.56, match RSAE location
  - 1 rho: 0.72~0.94, match TAE location

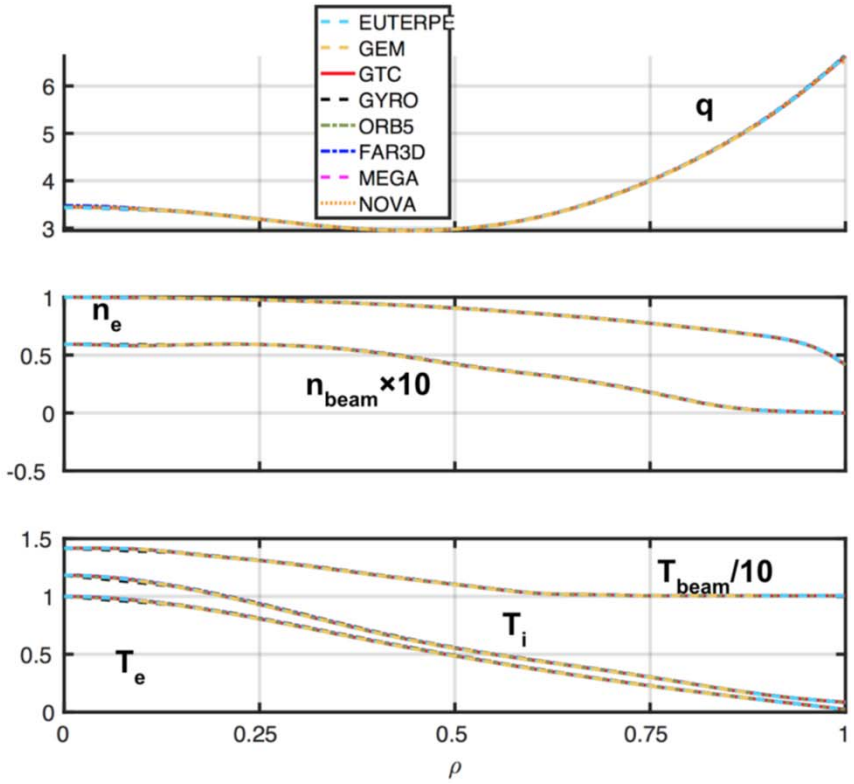


- RSAE, RSAE, microturbulence co-exist
- What is saturation & transport mechanisms?
- Linear & nonlinear V&V of 8 GK & MHD simulation of RSAE/TAE
- V&V of 3 reduced EP transport models
- Linear benchmark nearly done. Nonlinear simulation in progress

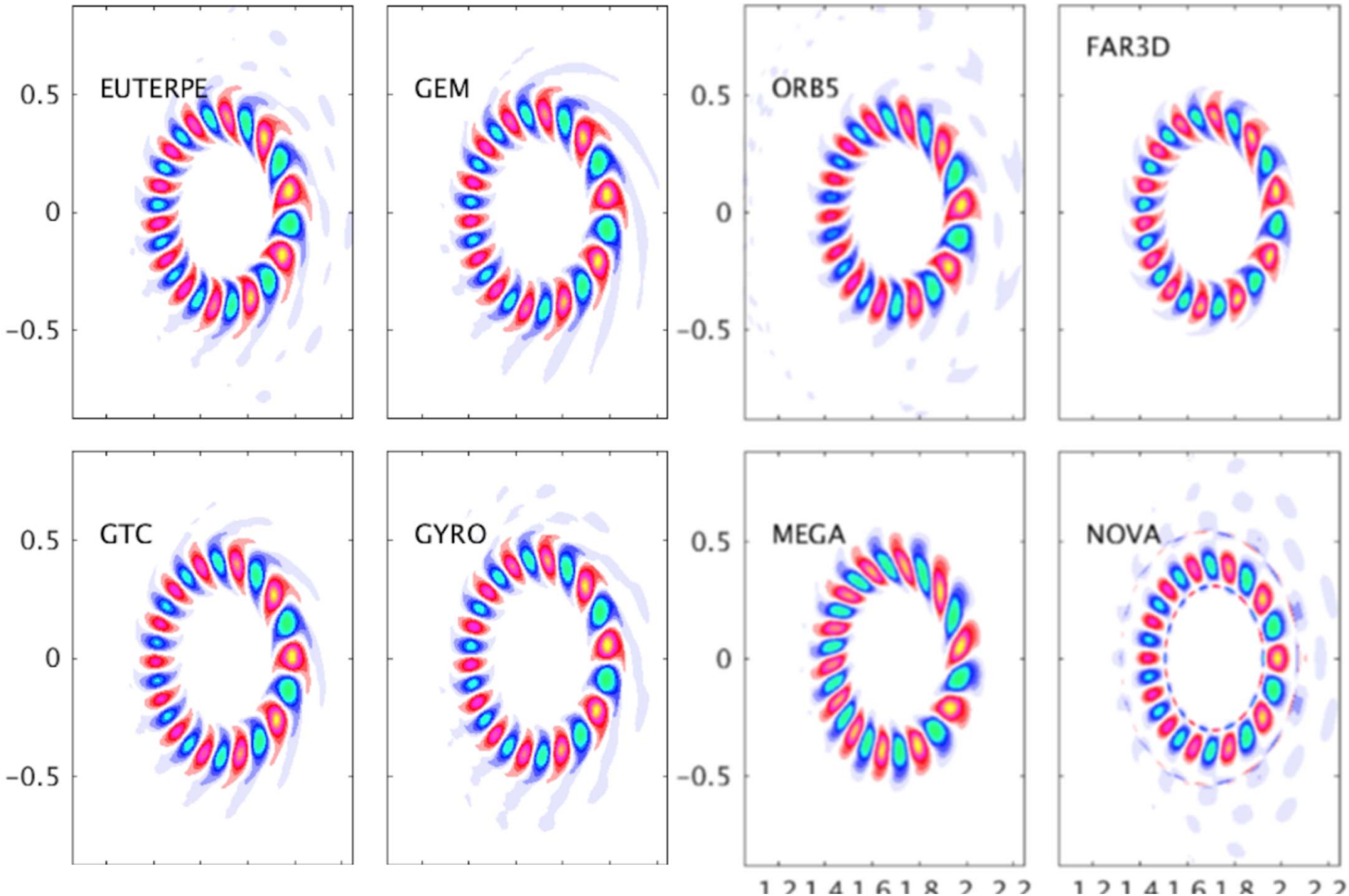
DIII-D shot 158243 at 805ms for ISEP V & V of AE Saturation & EP Transport





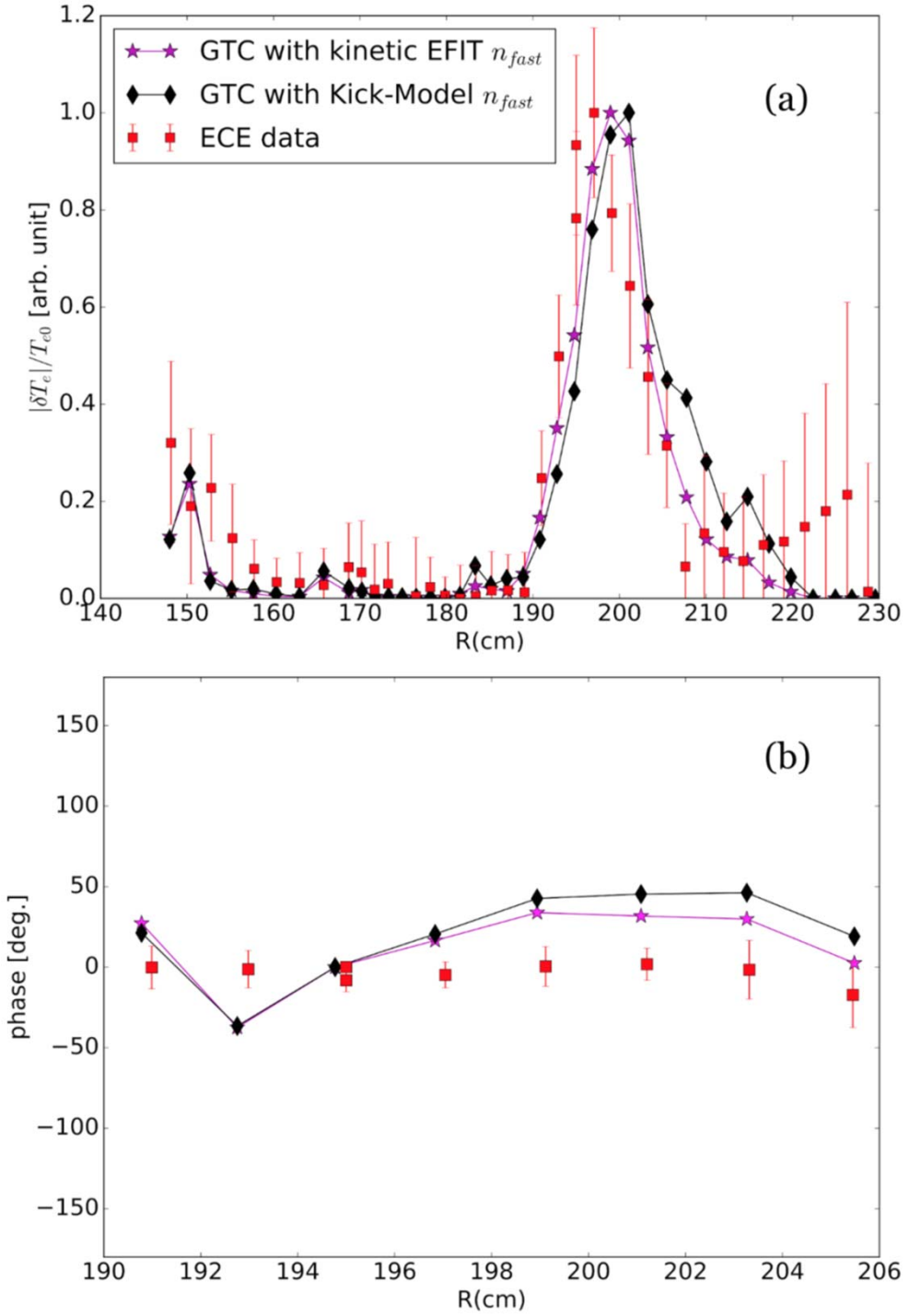


n=4 RSAE in DIII-D shot 158243 at 805ms



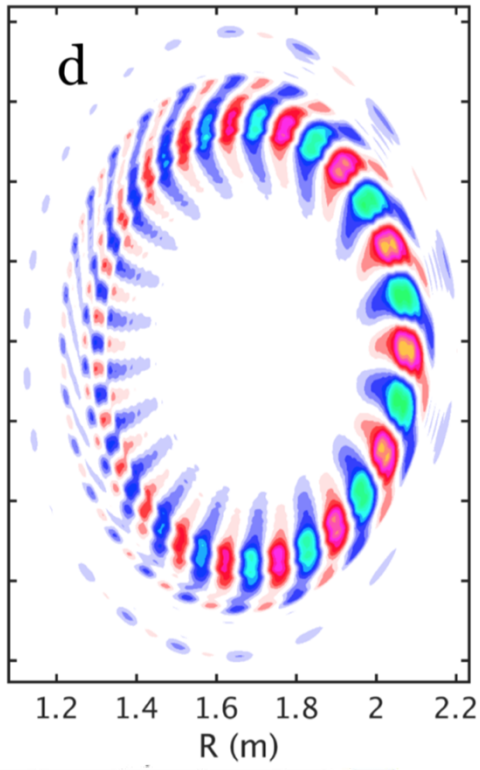
Validation via Synthetic Diagnostics

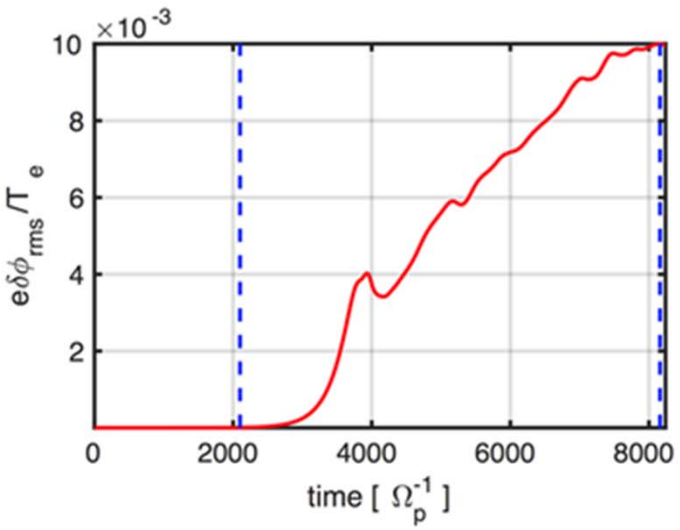
Comparison of GTC simulation with experimental ECE data using Synthetic Diagnostic Platform *[Shi, 2017]*. (a) Radial structure of δT_e. (b) The n = 4 mode's phase with respect to R = 195.0 cm

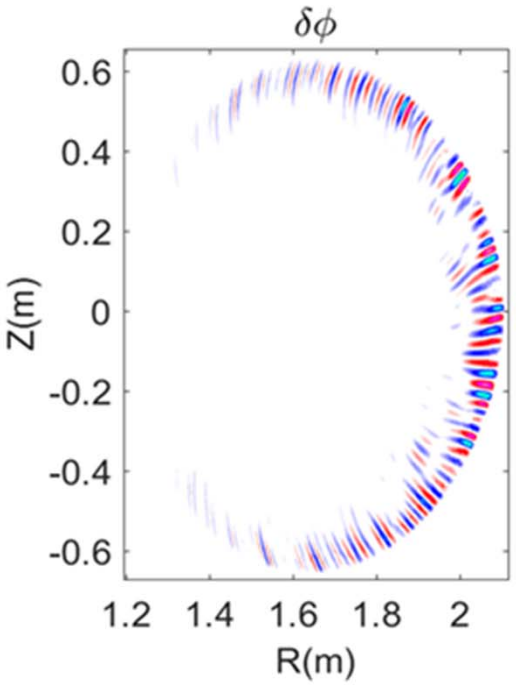


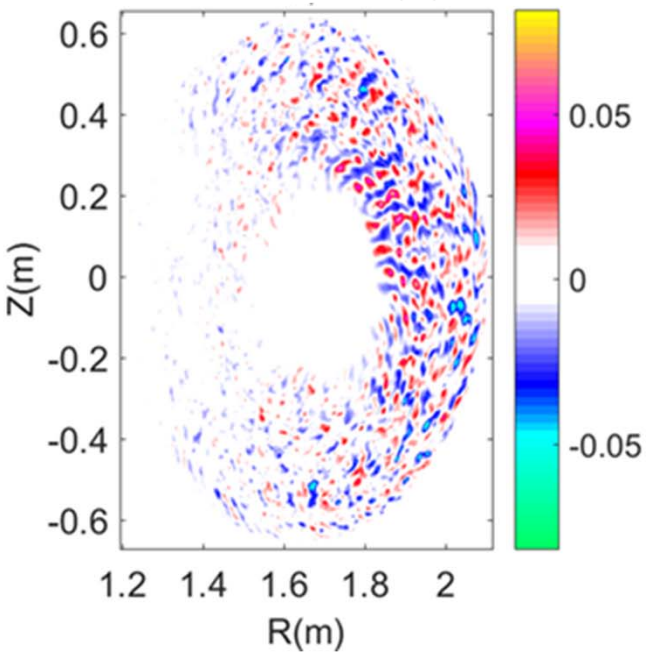
Nonlinear Interaction of RSAE, TAE, ITG

- Using EP profile from kick model, GTC finds n=6 TAE weakly unstable in the outer edge, good agreement with DIII-D
- GTC finds strong ITG instability in the outer edge, nonlinearly spreading to core









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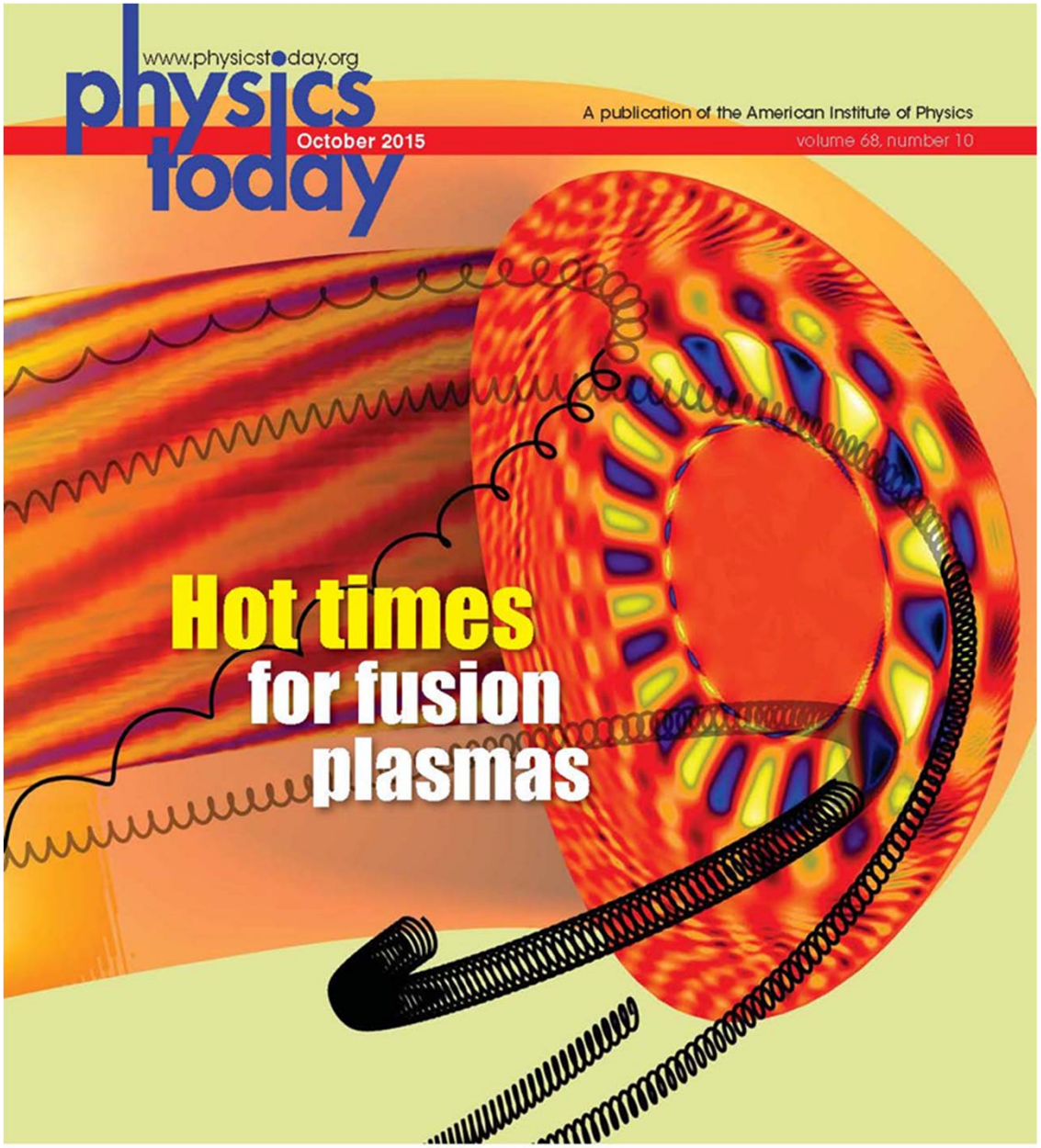


Kinetic-MHD via Gyrokinetic Simulation

- 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 linear 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, Z. Lin, and I. Holod, Nuclear Fusion ***52****, 023005 (2012)*

Difficulty in Gyrokinetic Simulation of MHD Modes: $E_{||}$

- Parallel electric field $\boldsymbol{E}_{||} = -\nabla_{||}\phi - \frac{\partial A_{||}}{\partial t}$ *[Lin, SciDAC PMP meeting, GA, 2001]*
- Need to calculate accurately scalar ϕ and vector potentials $A_{||}$

$$\phi - \tilde{\phi} = -\sum_s 4\pi e Z_s \bar{n}_s \qquad \nabla_\perp^2 A_{||} = -\sum_s \frac{4\pi e}{c} Z_s \bar{n}_s u_s$$

- Ideal MHD $E_{||} \sim 0$. $|E_{||}|/|\nabla_{||}\phi| \sim |E_{||}|/|\frac{\partial A_{||}}{\partial t}| \sim (k_\perp \rho_s)^2 \ll 1$
- Physics: cancellation between electrostatic and inductive $E_{||}$

*A conservative scheme for electromagnetic simulation of magnetized plasmas with kinetic electrons, J. Bao, Z. Lin, and Z. X. Lu, Phys. Plasmas **25**, 022515 (2018)*

- Canonical momentum used as independent velocity variable

$$\left(\nabla_\perp^2 - \frac{\omega_{pe}^2}{c^2} - \frac{\omega_{pi}^2}{c^2}\right)\delta A_{||} = \frac{4\pi}{c}\left(e n_{e0}\delta u_{||ec} - Z_i n_{i0}\delta u_{||ic}\right), \qquad (5)$$

- LHS: $|1^{st}\ term|/|2^{nd}\ term| \sim (k_\perp d_e)^2 \ll 1$. Small numerical error of RHS leads to large error of $A_{||}$
- Infamous "cancellation problem": calculate 2nd-order $\mathcal{O}(k_\perp^2 \rho_s d_e)^2$ term from 0th–order $\mathcal{O}(1)$ equation!

Solution: $E_{||}$ from Electron Parallel Force Balance

- For $\omega/k_{||} << v_e$, electron response mostly adiabatic (isothermal)
  Adiabatic $E_{||} = -\nabla_{||}(\phi + \phi_{ind})$ from massless electron *[Holod, PoP2009]*

$$\frac{e\phi_{ind}}{T_e} = -\frac{e\phi}{T_e} + \frac{\delta n_e}{n_0} - \frac{\delta\psi^A}{n_0}\frac{\partial n_0}{\partial\psi}$$

Alfven wave, IAW, drift wave

  - ✓ Vector potential $A_{||}$ calculated from $E_{||}$ $\quad \frac{\partial A_{||}}{\partial t} = \nabla_{||}\phi_{ind}$
  - ✓ Perturbed current δu_e from Ampere's law $\quad n_0 e\delta u_e = -\nabla_\perp^2 A_{||}$
  - ✓ Perturbed density δn_e from continuity equation $\quad \frac{\partial \delta n_e}{\partial t} = -\nabla_{||} n_0 \delta u_e$
  - ✓ Electrostatic potential ϕ from Poisson equation using perturbed density δn_e

- No cancellation problem or electron particle noise

  *A Fluid-Kinetic Hybrid Electron Model for Electromagnetic Simulations, Lin and Chen, Phys. Plasmas **8**, 1447 (2001)*

- Mixed-variable gyrokinetics [*Mishchenko et al, PoP (2014)*] separates $A_{||}$ into "symplectic" and "Hamiltonian"; ideal MHD as "symplectic" ϕ_{ind}=-ϕ : Alfven wave. However, IAW, drfit wave have cancellation problem and electron particle noise

Fluid-Kinetic Hybrid Electron Model *[Lin & Chen, PoP2001]*

- Total $\boldsymbol{E}_{\|}$ corrected by non-adiabatic $\boldsymbol{E}_{\|}$ from kinetic electron response using split-weigh scheme *[Manuilskiy and Lee, PoP2000]* to reduce noise

$$f_e = f_0 e^{e(\phi+\phi_{ind})/T_e} + \delta g_e$$

- Collisionless tearing mode removed in this expansion based on small electron mass; Resistive tearing mode kept via Ohm's law
- Electrostatic version *[Lin et al, PPCF2007]* removes numerical ω_h mode, enabling simulation of trapped electron mode
- Electron model extensively utilized by GSEP for simulating microturbulence, Alfven eigenmodes, kink & resistive tearing modes

$$\left[\frac{\partial}{\partial t} + \left(v_{\|}\boldsymbol{b} + \boldsymbol{v}_{\mathrm{d}} + \boldsymbol{v}_E\right)\cdot\frac{\partial}{\partial \boldsymbol{x}} - \boldsymbol{b}^*\cdot\nabla(\mu B - e\phi)\frac{\partial}{m_{\mathrm{e}}\partial v_{\|}} - C_{\mathrm{e}}\right]\delta g_{\mathrm{e}}^{(1)}$$

$$= -f_{\mathrm{e}0}\mathrm{e}^{e\delta\phi/T_{\mathrm{e}}}\left[\frac{\partial}{\partial t}\left(\frac{e\delta\phi^{(0)}}{T_{\mathrm{e}}}\right) + \delta\boldsymbol{v}_E\cdot\nabla\left(\ln f_{\mathrm{e}0}\right)_{|v_{\|},v_{\perp}}\right.$$

$$\left. -\left(\boldsymbol{v}_{\mathrm{d}} + \delta\boldsymbol{v}_E\right)\cdot\nabla\left(\frac{e\langle\phi\rangle}{T_{\mathrm{e}}}\right)\right],$$

*Global gyrokinetic particle simulations with kinetic electrons, Z. Lin, et al, Plasma Phys. Contr. Fusion **49**, B163 (2007)*

A Conservative Scheme Solving Exact DKE

- Calculate total $\boldsymbol{E}_{||}$ as sum of adiabatic and non-adiabatic parts

$$A_{||} = A_{||}^{A} + A_{||}^{NA}$$

Alfven wave, IAW, drift wave

$$\frac{\partial A_{||}^{A}}{\partial t} = \nabla_{||}\phi_{ind} \qquad \frac{e\phi_{ind}}{T_e} = -\frac{e\phi}{T_e} + \frac{\delta n_e}{n_0} - \frac{\delta\psi^{A}}{n_0}\frac{\partial n_0}{\partial\psi}$$

- Define electron adiabatic responses using adiabatic $\boldsymbol{E}_{||}$

$$f_0 + \delta f_A = f_0 e^{e(\phi+\phi_{ind})/T_e} + \delta\psi^{A}\frac{\partial f_0}{\partial\psi}$$

- Solve exact DKE by calculating kinetic electron non-adiabatic responses δh_e

$$f_e = f_0 + \delta f_A + \delta h_e$$

- Non-adiabatic part of $\boldsymbol{E}_{||}$ calculated via electron parallel momentum equation (generalized Ohm's law) using non-adiabatic response

A conservative scheme of drift kinetic electrons for gyrokinetic simulation of kinetic-MHD processes in toroidal plasmas, J. Bao, D. Liu, Z. Lin, *Phys. Plasmas* **24**, 102516 (2017)

A Conservative Scheme Solving Exact DKE

- Recover collisionless tearing mode with current sheet at d_e scale
- Non-tearing current screened by d_e, no "cancellation problem"
- Recover nonlinear MHD dynamo term, "nonlinear polarization term", "ponderomotive force": $\delta\mathbf{j}_{pol} \times \delta\mathbf{B}_{\perp}$

$$\left(\nabla_{\perp}^2 - \frac{1}{d_e^2}\right)\frac{\partial A_{||}^{NA}}{\partial t} = \frac{1}{d_e^2}\chi_{||} - c\nabla_{\perp}^2\left(\nabla_{||}\delta\phi_{ind}\right)$$

$$\chi_{||} = \underbrace{-\frac{c}{en_0}\mathbf{b_0}\cdot\nabla\delta P_{||}^{NA}}_{\{III\}} \underbrace{-\frac{c}{en_0B_0}\delta\mathbf{B}^{NA}\cdot\nabla P_{||0}}_{\{IV\}} \underbrace{-\frac{c}{en_0B_0}\delta\mathbf{B}\cdot\nabla\delta P_{||}^{NA}}_{\{V\}} \underbrace{-\frac{c}{B_0}\delta\mathbf{B}\cdot\nabla\delta\phi_{ind}}_{\{VI\}}$$

$$\underbrace{+\frac{c}{B_0}\delta\mathbf{B}\cdot\nabla\langle\phi\rangle}_{\{VII\}} \underbrace{-\frac{cm_e}{en_0}\nabla\cdot\left[n_0\delta u_{||e}\left(3\mathbf{V}_c+\mathbf{V}_g\right)+n_0u_{||0}\mathbf{V}_E\right]}_{\{VIII\}} \underbrace{-\frac{cm_e}{en_0}\nabla\cdot\left(n_0\delta u_{||e}\mathbf{V}_E\right)}_{\{IX\}}$$

$$\underbrace{+\frac{c}{en_0}\frac{P_{||0}-P_{\perp 0}}{B_0^2}\delta\mathbf{B}\cdot\nabla B_0+\frac{c}{en_0}\frac{\delta P_{||}^{NA}-\delta P_{\perp}^{NA}}{B_0^2}\mathbf{B_0}\cdot\nabla B_0}_{\{X\}}$$

Compressible Magnetic Perturbations via Perpendicular Force Balance for Slow Modes

$$\frac{\delta B_{\parallel} B_0 \{1+\beta_e+\beta_i [I_0(k_\perp^2\rho_i^2)-I_1(k_\perp^2\rho_i^2)]\exp(-k_\perp^2\rho_i^2)\}}{8\pi}$$

$$+\frac{\beta_i B_0^2 e\delta\phi}{16\pi T_i}\{[I_0(k_\perp^2\rho_i^2)-I_1(k_\perp^2\rho_i^2)]\exp(-k_\perp^2\rho_i^2)-1\}$$

$$=-\pi\Omega_e^2\int d\mu dv_{\parallel} B_0\int_0^{\rho_e} F_e^{gyro} r dr-\pi\Omega_i^2$$

$$\times\int d\mu dv_{\parallel} B_0\left\langle\int_0^{\rho_i} F_i^{gyro} r dr\right\rangle. \qquad (13)$$

When $k_\perp\rho_i \ll 1$, Eq. (13) reduces to

$$\frac{\delta B_{\parallel} B_0(1+\beta_e+\beta_i)}{4\pi}=-\delta P_{e\perp}-\delta P_{i\perp}, \qquad (14)$$

Gyrokinetic particle simulations of the effects of compressional magnetic perturbations on drift-Alfvenic instabilities in tokamaks, Dong *et al*, *Phys. Plasmas* **24**, 081205 (2017)

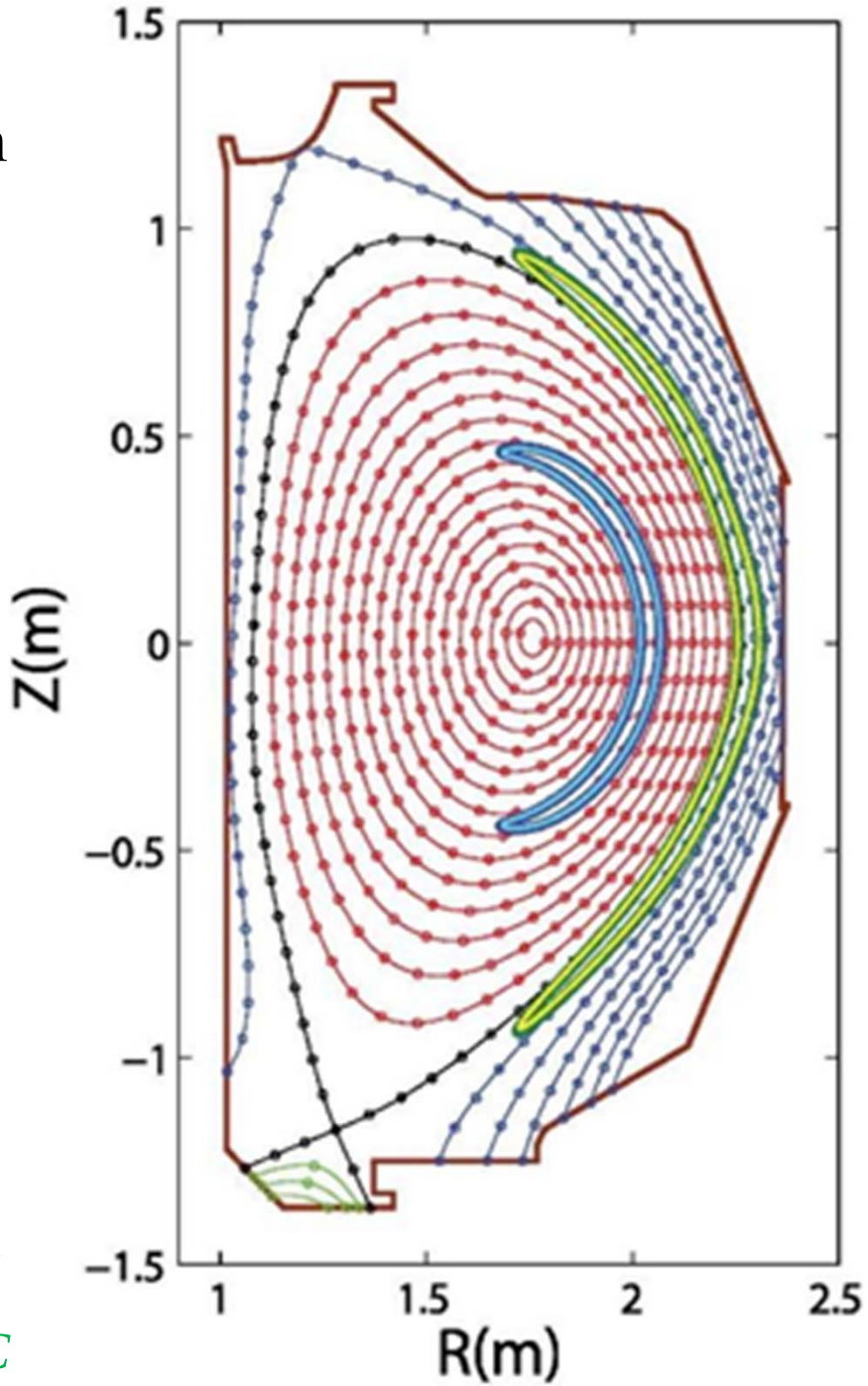
- Significant effects of $\delta B_{||}$ on KBM
- Effects of $\delta B_{||}$ on TAE linear dispersion very small

Gyrokinetic Toroidal Code

- First-principles, integrated simulation capability for nonlinear interactions of multiple kinetic-MHD processes
- Current capability in a single version
  - ✓ Global 3D toroidal geometry & experimental profiles
  - ✓ Microturbulence: 5D gyrokinetic ions & electrons, electromagnetic fluctuations (including compressional perturbations, tearing & non-tearing parity)
  - ✓ MHD and energetic particle: Alfven eigenmodes, kink, tearing modes
  - ✓ Neoclassical transport: Fokker-Planck operators
  - ✓ Radio frequency waves: 6D Vlasov ions

[Lin et al, Science1998]

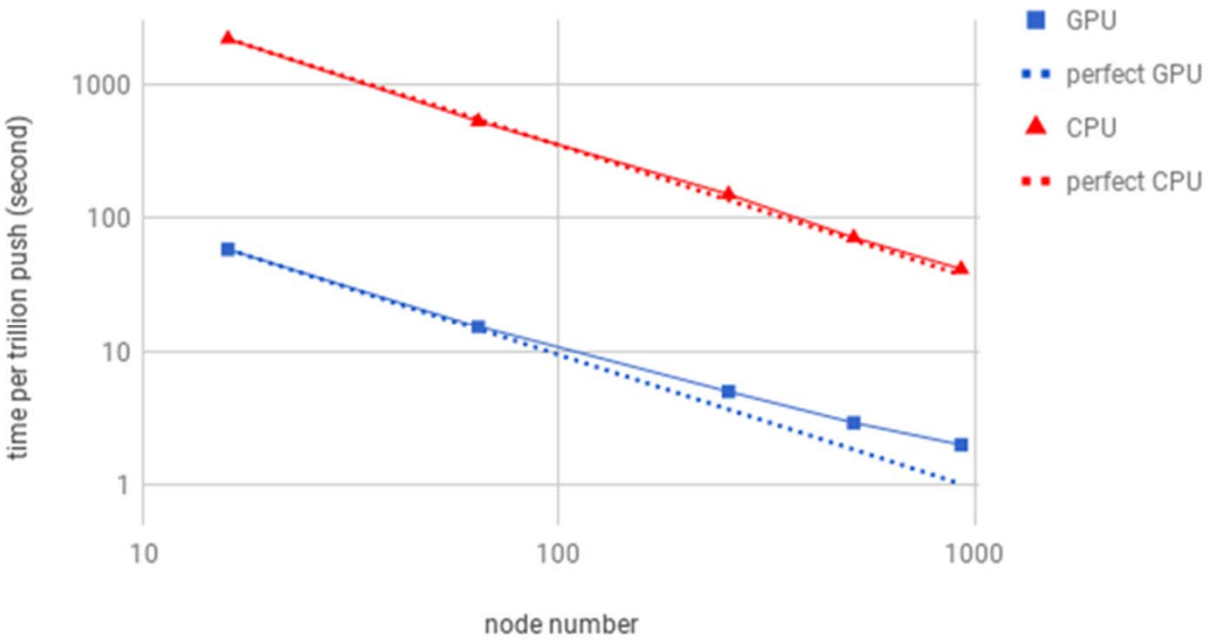
Phoenix.ps.uci.edu/GTC



Optimizing GTC for Exascale Computing

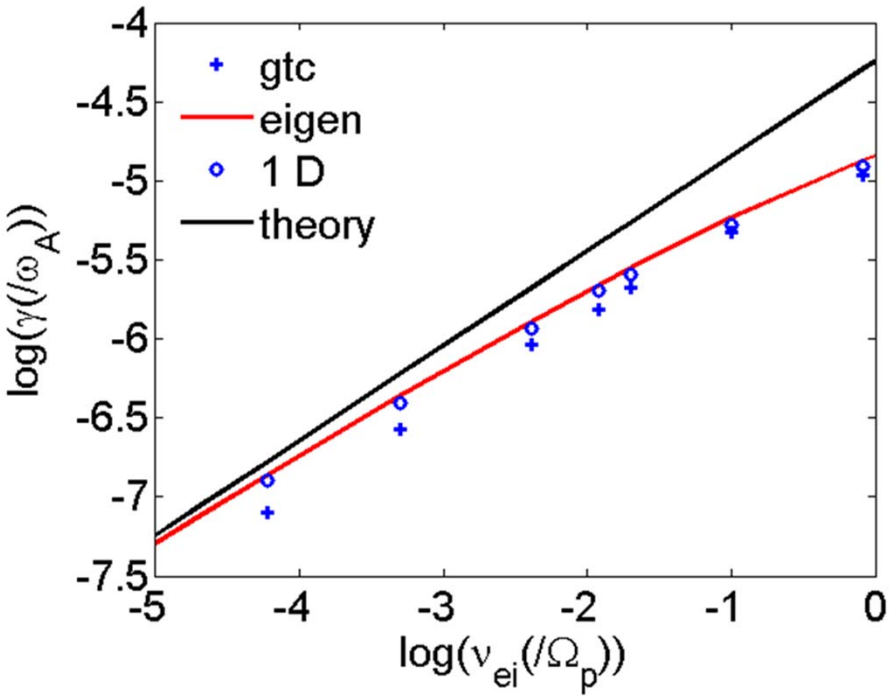
- GTC being developed as energetic particle module in fusion WDM by SciDAC ISEP collaborations: UCI, GA, PPPL, ORNL, LBNL, LLNL
- GTC speeds up 20X from CPU to GPU on SUMMIT (world's fastest computer) by CAAR (Center for Accelerated Application Readiness) project: UCI, PU, ORNL, NVIDIA, IBM
- GTC recently selected by NVIDIA as one of Top 15 App Worldwide

Wall-clock time for one trillion particle pushes in GTC weak scaling test on Summit

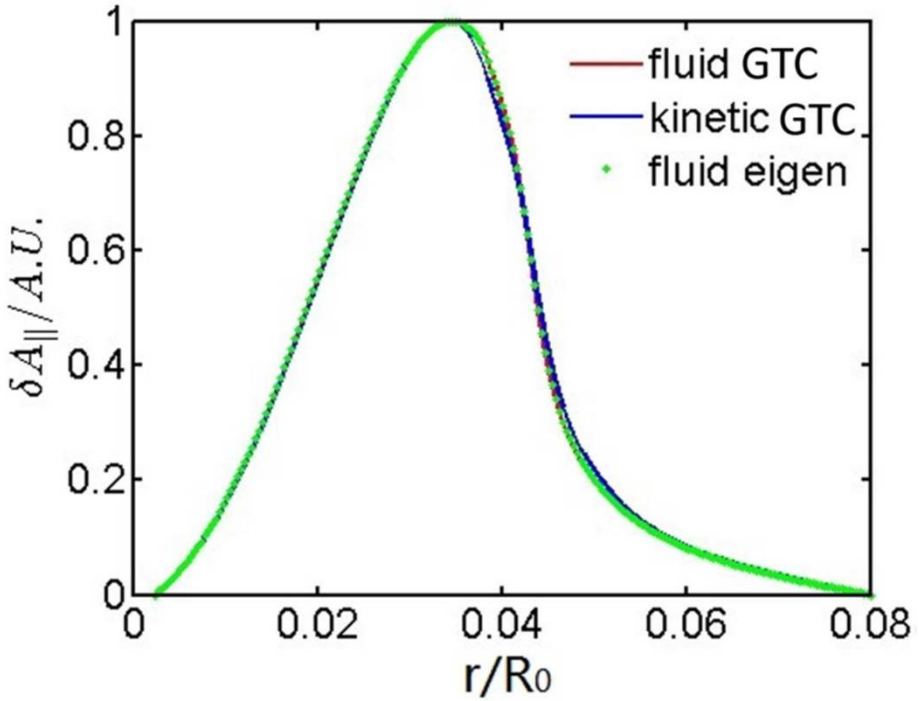


GTC Simulation of Current Driven Instabilities: Kink, Resistive & Collisionless Tearing Modes

- GTC finds ion kinetic effects and toroidicity reduce growth rate of kink *[McClenaghan, PoP2014]* and resistive tearing mode *[Liu, PoP2014]*
- GTC simulations of collisionless tearing mode *[Bao, 2017]*
  - ✓ GTC kinetic $\gamma=0.0031C_s/R_0$, *[Drake & Lee, PF1977]* kinetic theory $\gamma=0.0027$
  - ✓ GTC fluid $\gamma=0.0014C_s/R_0$, *[Liu & Chen, PPCF1977]* fluid theory $\gamma=0.0015$



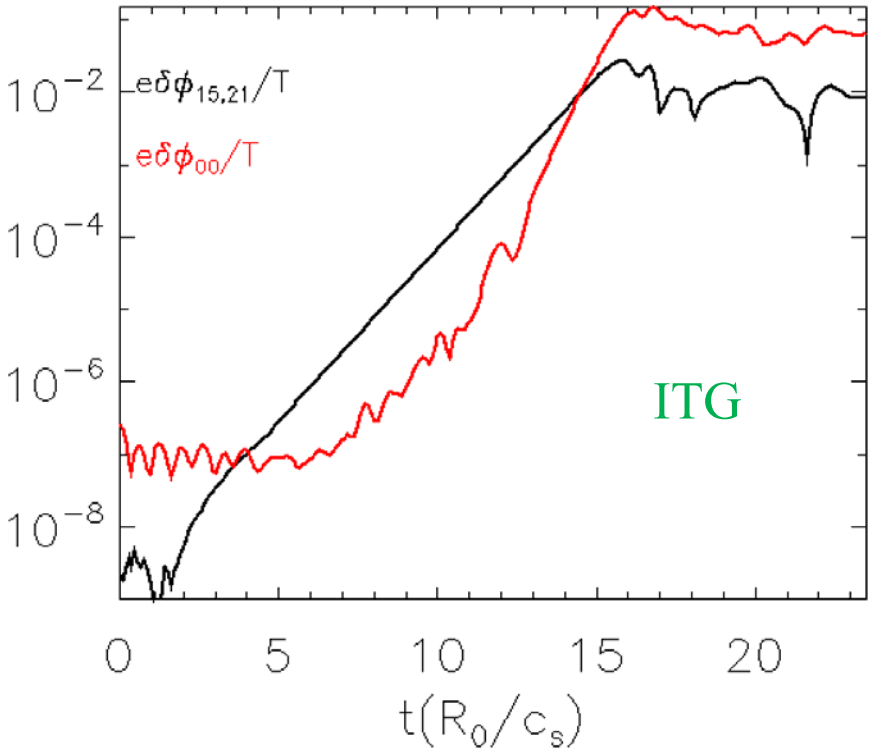
GTC simulation of resistive tearing mode in cylinder *[Liu, PoP2014]*

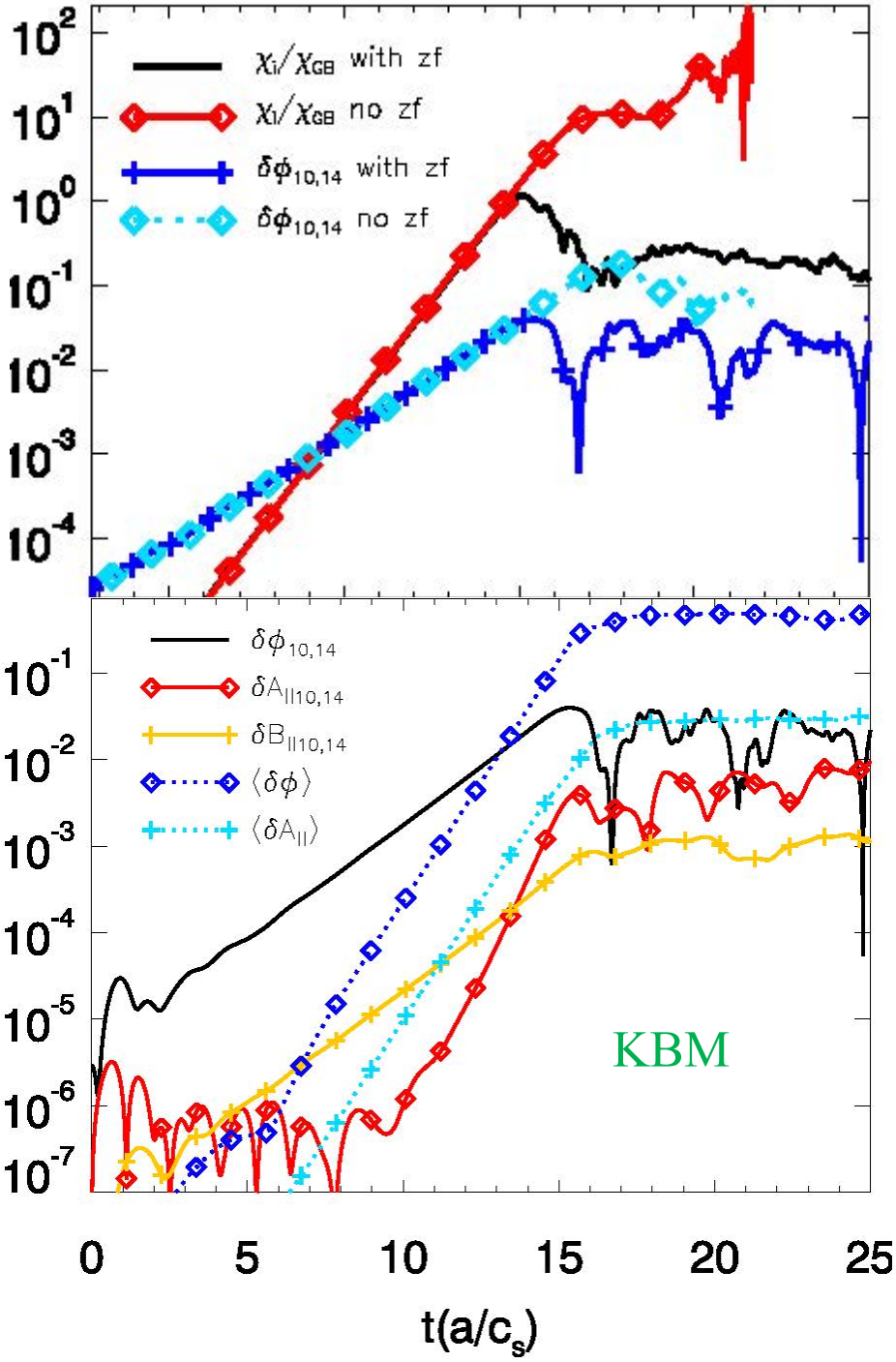


GTC simulation of collisionless tearing mode in cylinder *[Bao, PoP2017]*

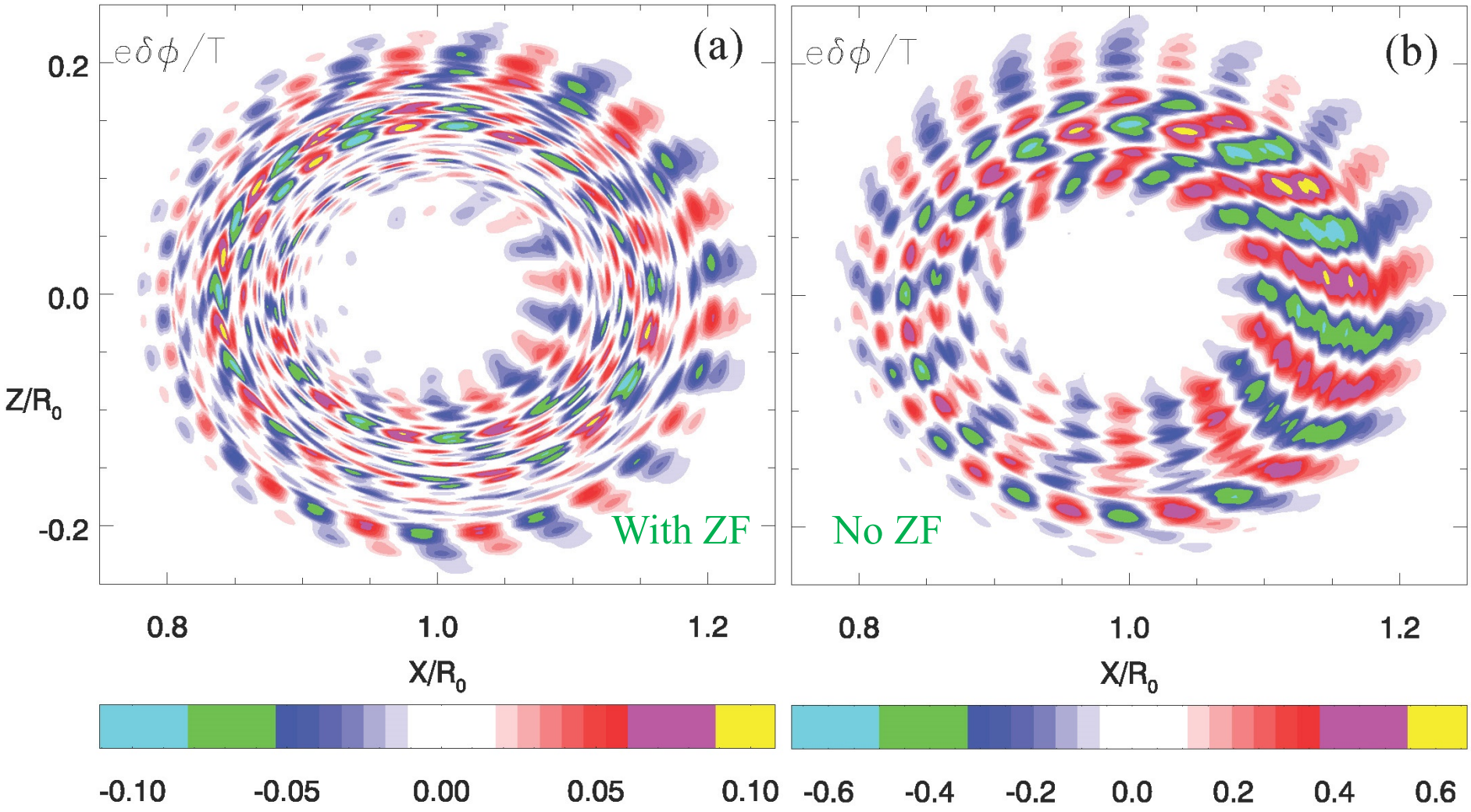
KBM Saturation via Zonal Fields (ZF)

- ZF generated ($2\gamma^{lin}$) via KBM 3-wave coupling, in contrast to ITG modulational instability
- Localized current sheet generated ($3\gamma^{lin}$) by ponderomotive force





KBM Mode Structure Broken by Zonal Fields



Nonlinear Saturation of Kinetic Ballooning Modes by Zonal Fields in Toroidal Plasmas, G. Dong, J. Bao, A. Bhattacharjee, and Z. Lin, submitted to PRL, 2018

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- TAE saturation via zonal fields
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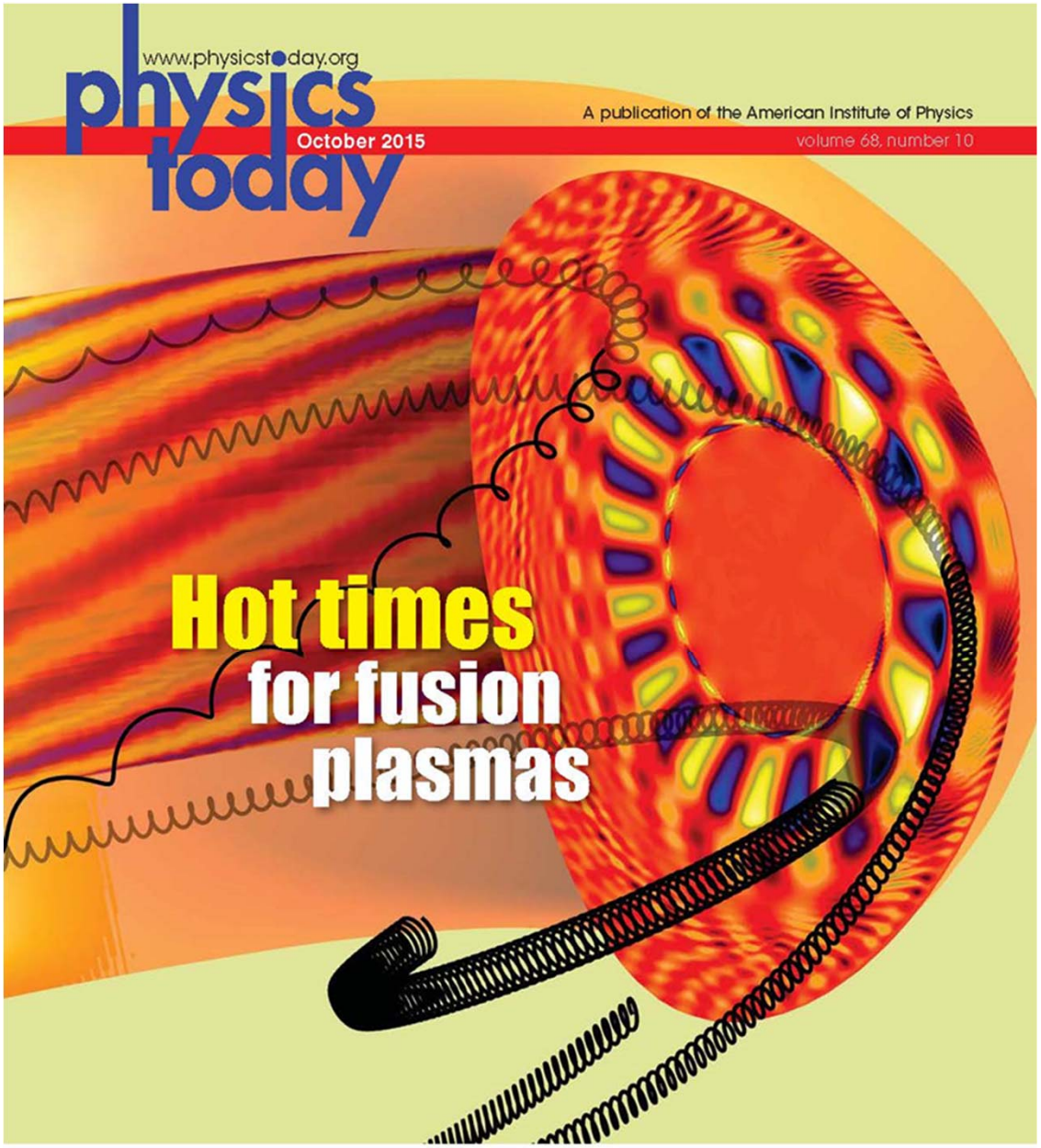
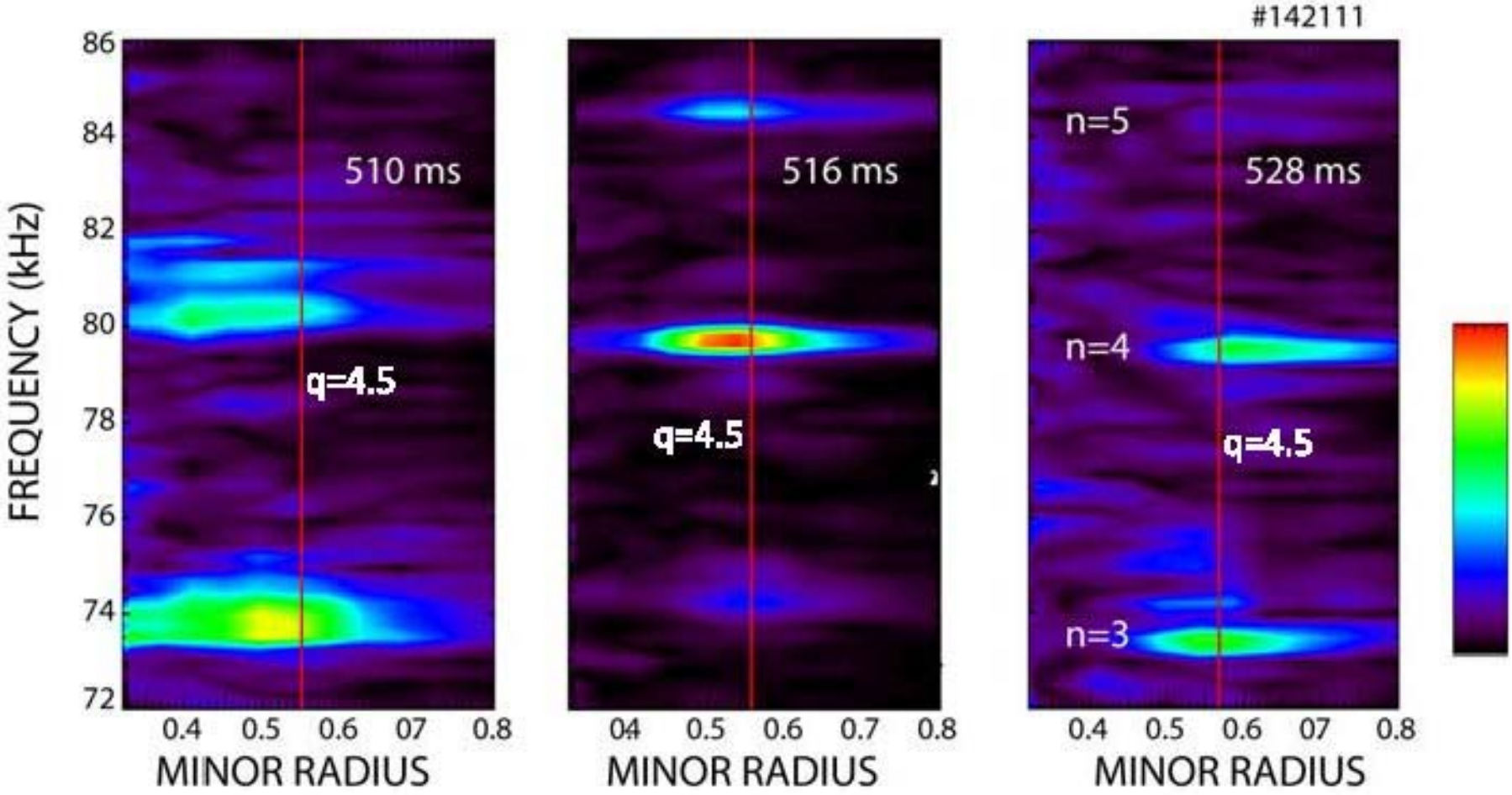


ZL9

Measurement Shows Fast Radial Drift of TAE in DIII-D

- TAE moves rapidly while thermal plasma profiles barely change
- Cannot be explained by perturbative theory: thermal plasma profiles set MHD mode structure, EP only drives growth rate



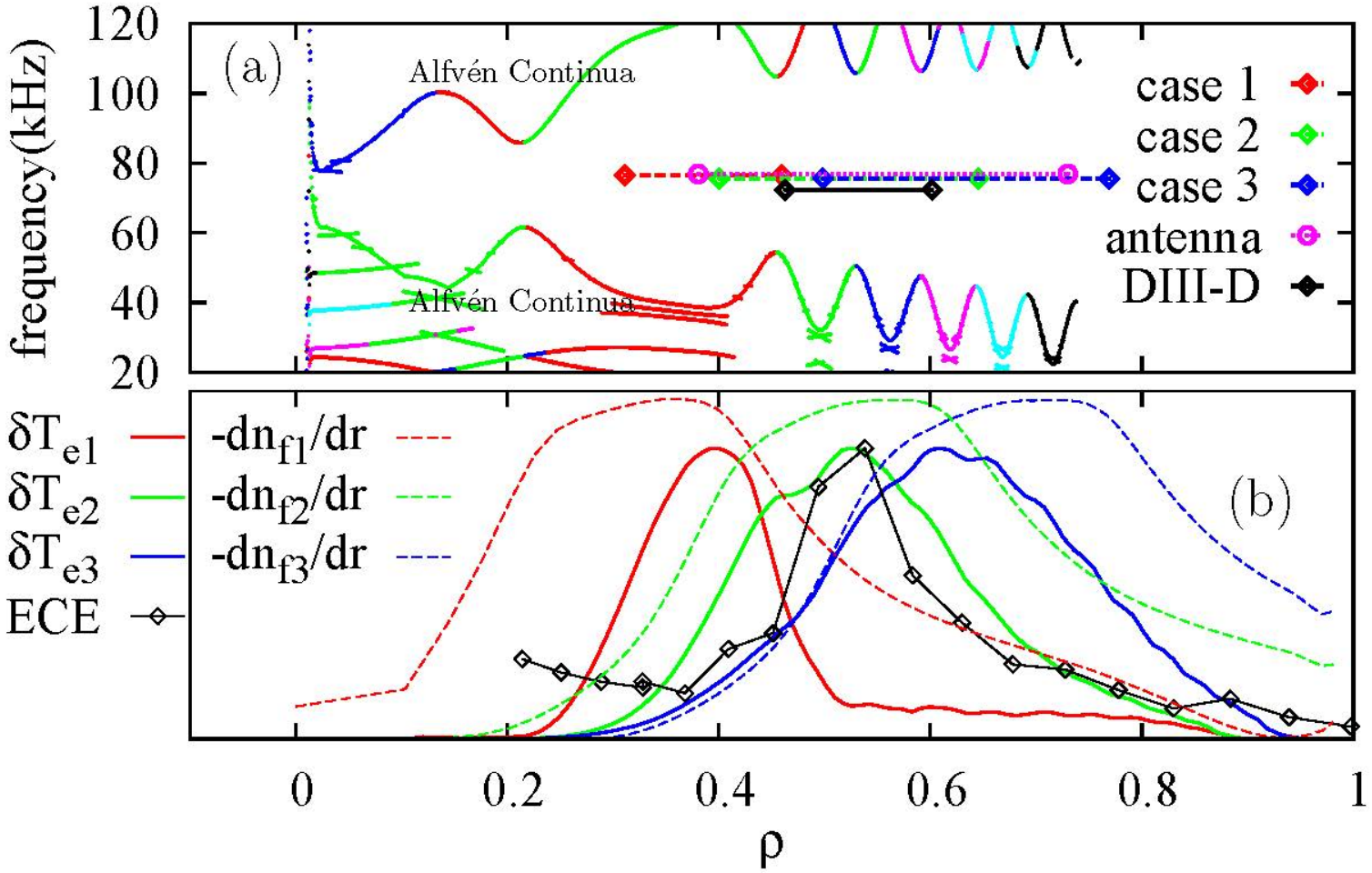
TAE in DIII-D shot # 142111 around 525ms

ZL10

GTC Simulations Find TAE Radial Localization

- Simulations scan EP profiles within experimental uncertainty
- Unstable TAE radial structures move with EP density gradient
- In contrast, stable TAE excited by antenna has larger radial width
- EP non-perturbative contribution induces TAE radial localization

TAE in DIII-D shot # 142111 at 525ms

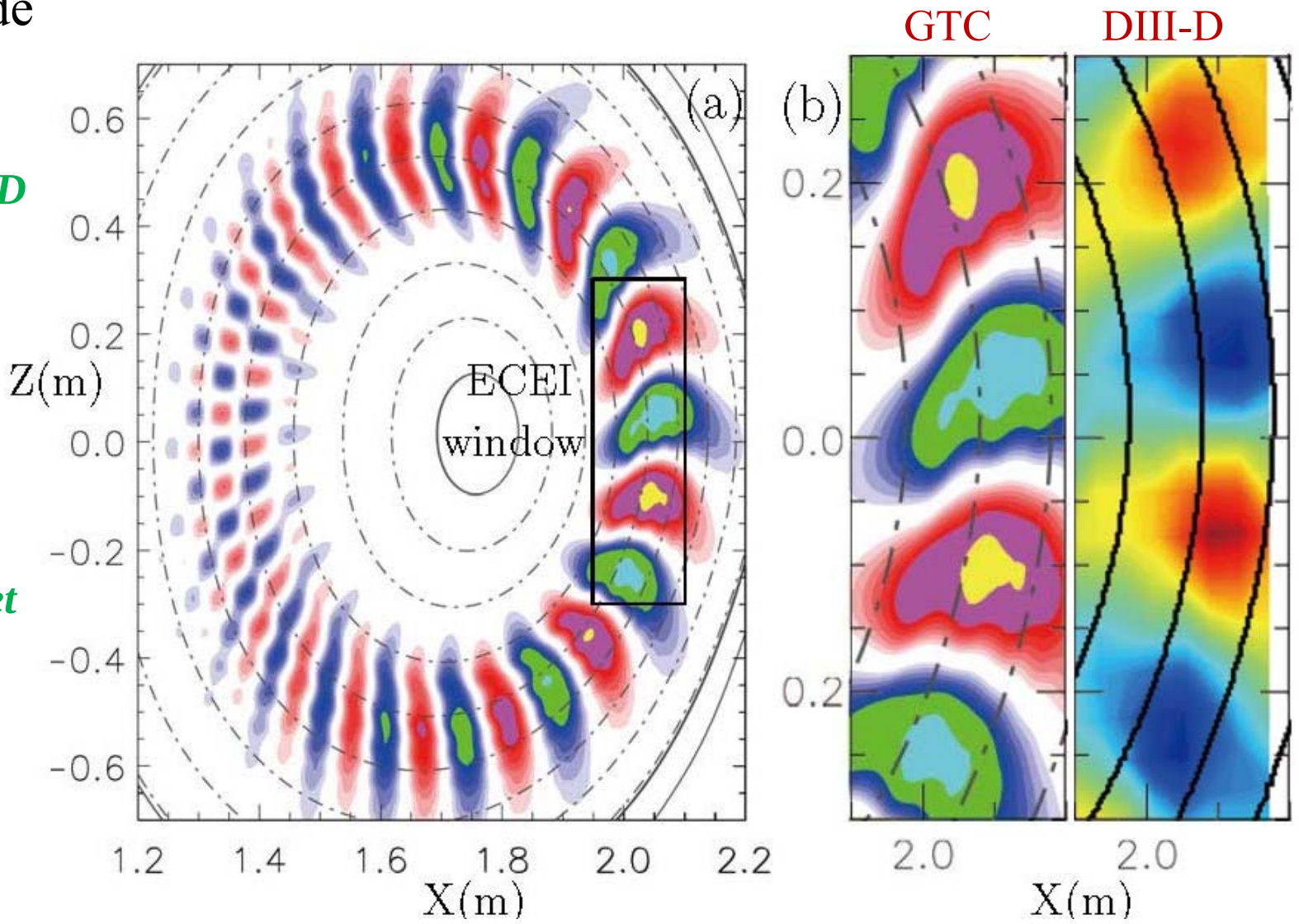


Comparison of TAE Mode Structures between Simulation & Experiment

- EP non-perturbative contribution breaks radial symmetry of TAE eigenmode

TAE in DIII-D shot # 142111 at 525ms

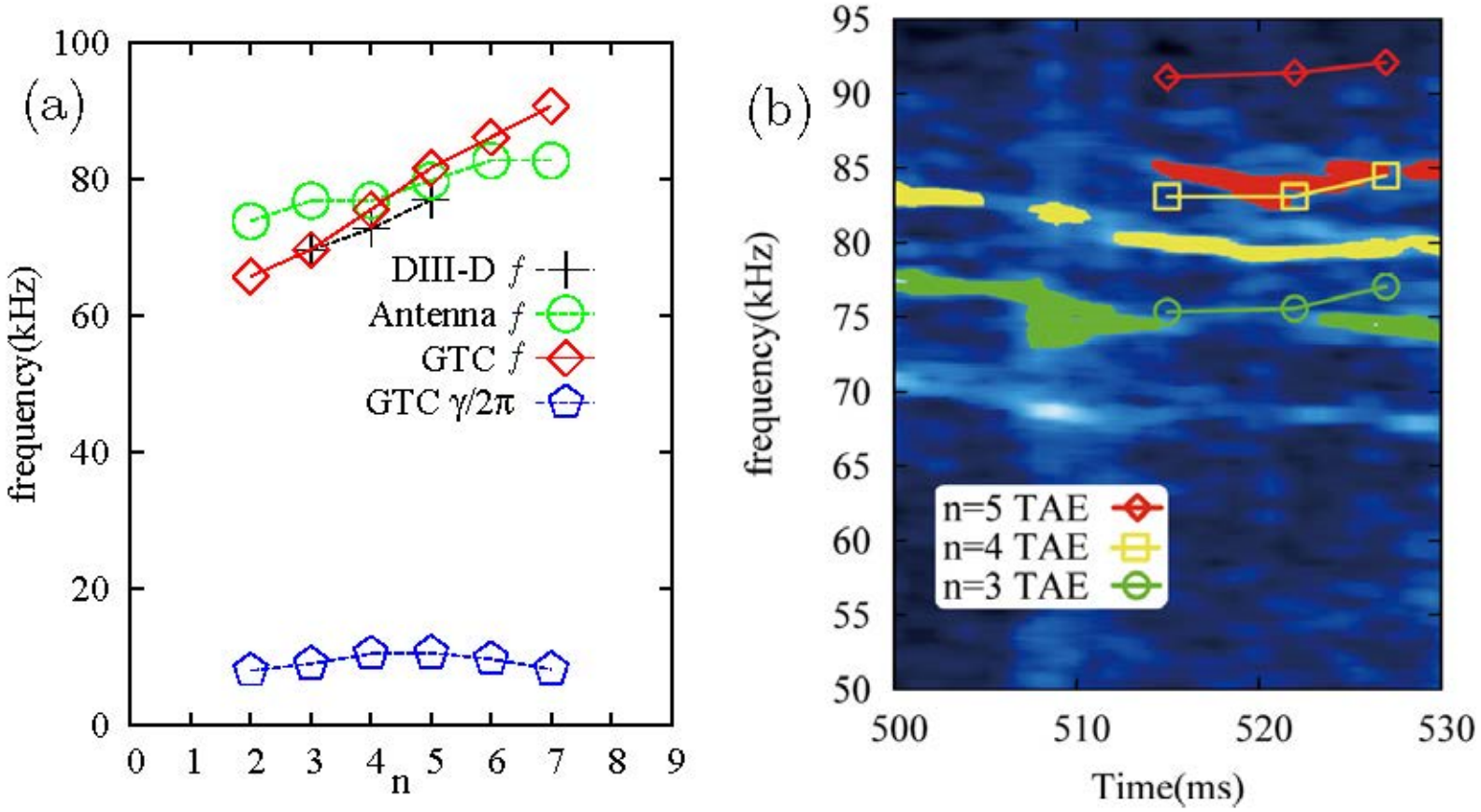
[Z. X. Wang et al, PRL2013]



ZL13

Comparison of TAE Frequency between Simulation & Experiment

- EP non-perturbative contribution and trapped electron effects induce TAE frequency dependence on toroidal mode number n

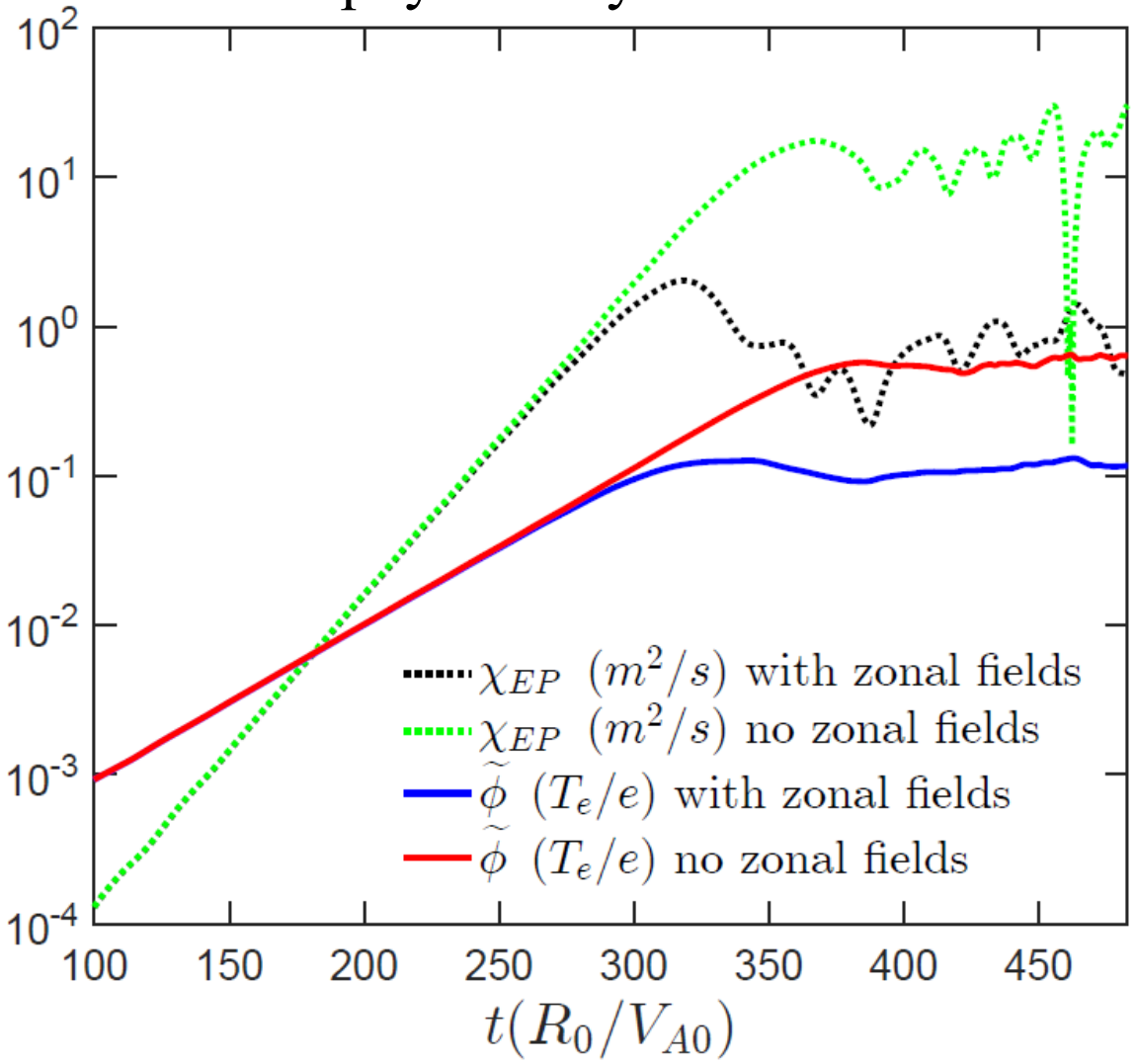


TAE in DIII-D shot # 142111 at 525ms

TAE Saturation via Zonal Fields

- Conventional model: Perturbative theory and reduction from 3D to 1D, i.e., single toroidal mode, radially local
- Non-perturbative simulation: Nonlinear physics beyond 1D model
  - ✓ Zonal fields (flow & current)
  - ✓ Fast chirping induced by radial variations of amplitude & guiding center dynamics

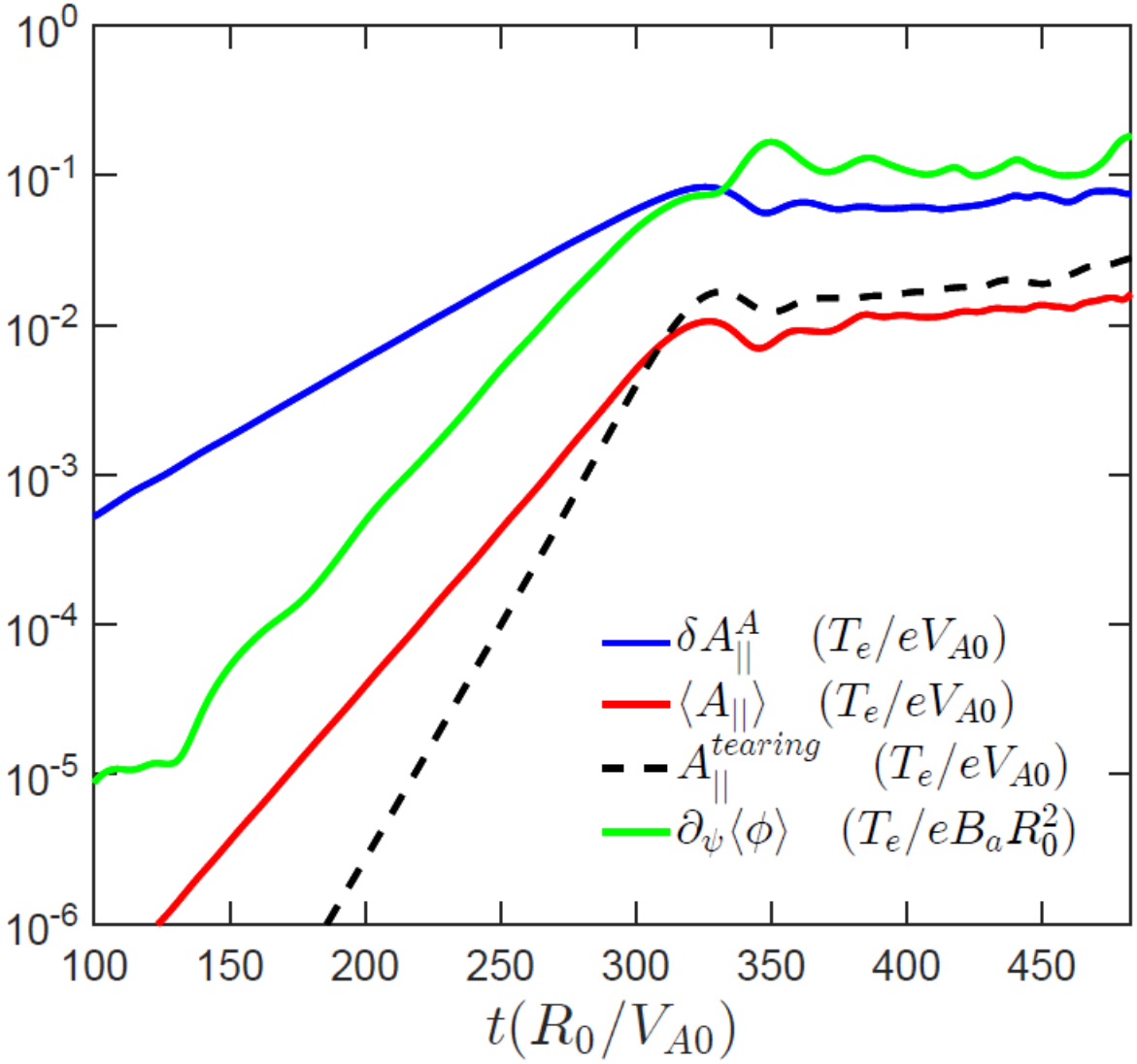
  [Zhang et al, PRL2012]



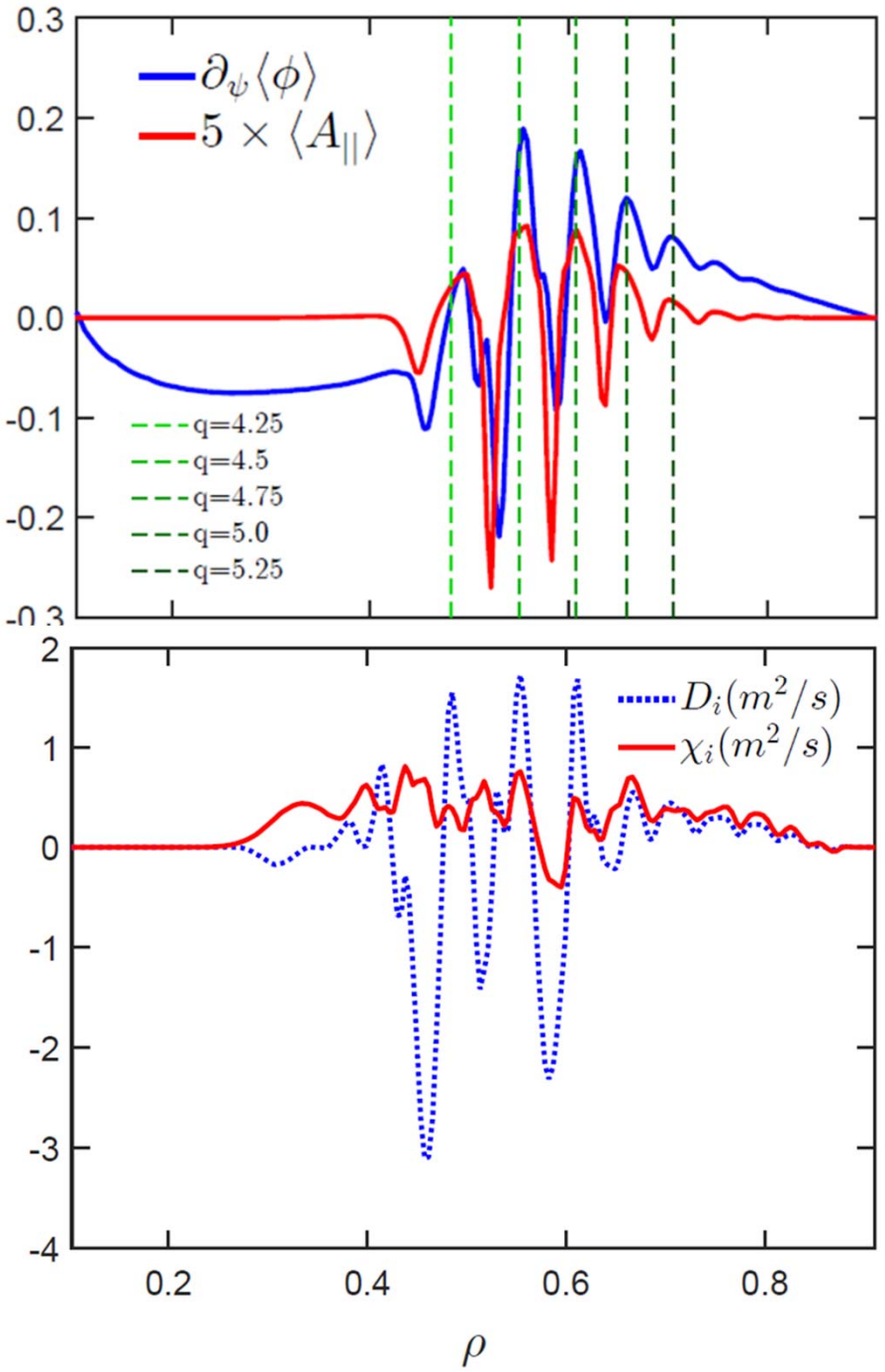
- TAE saturates by zonal flow
- Zonal current has little effects on TAE saturation

TAE Saturation via Zonal Fields

- ZF generated via 3-wave coupling, $\gamma_{ZF} = 2\gamma_{lin}$
- Generation of localized current sheet $\gamma_{CS} = 3\gamma_{lin}$

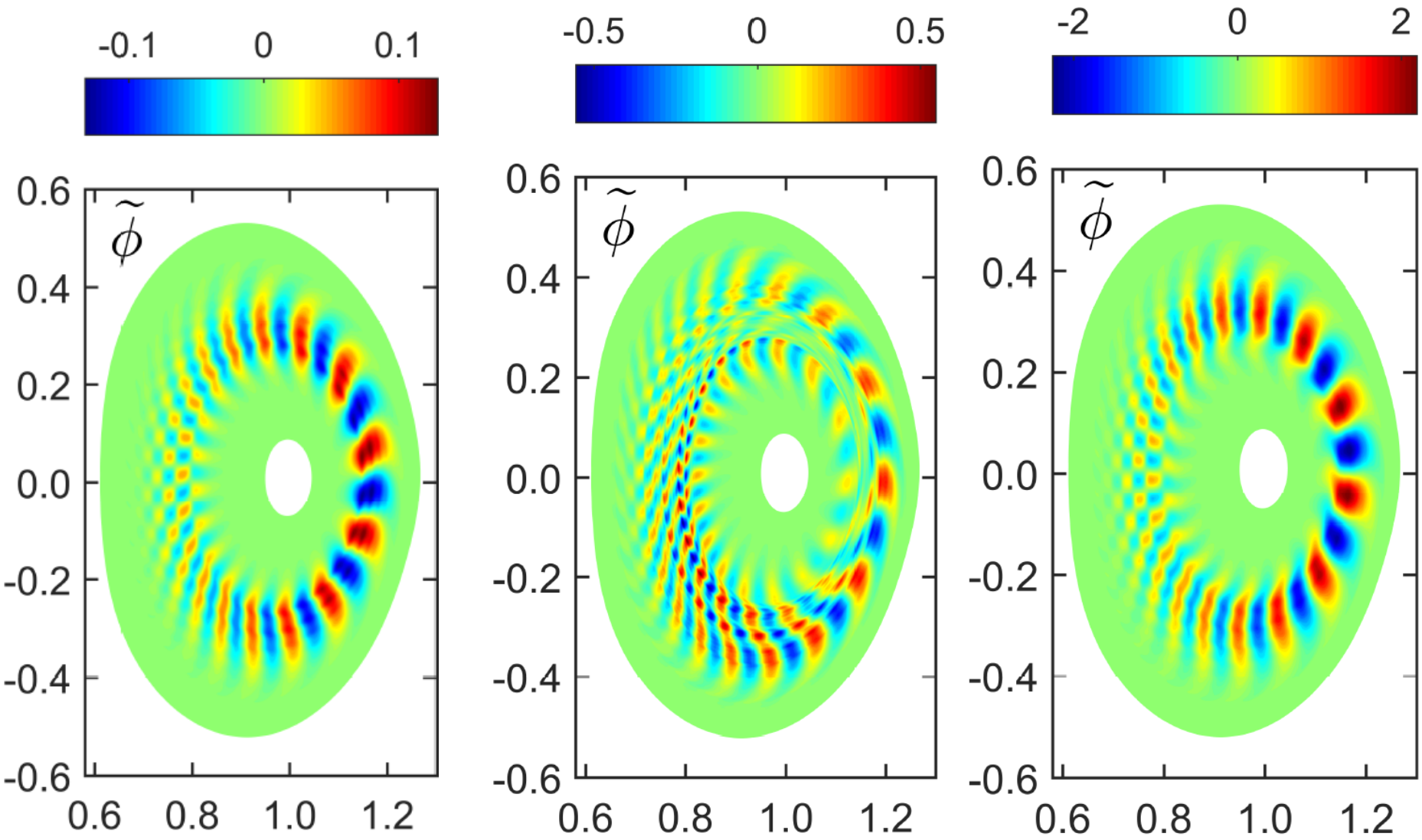


Radial profiles of zonal flows and zonal currents, thermal ion particle diffusivity and heat conductivity



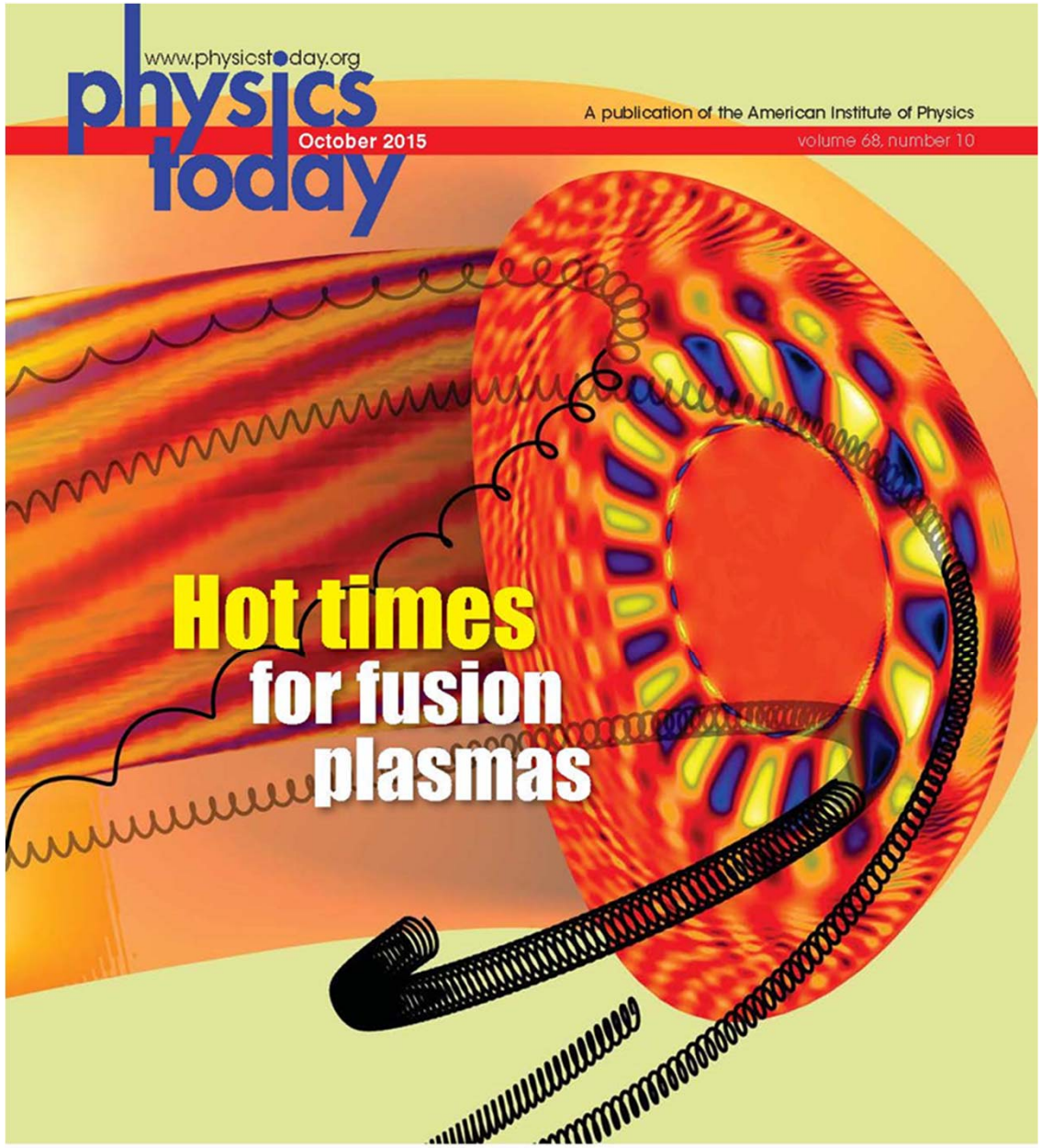
TAE Saturation via Zonal Fields

- TAE linear mode structure broken by ZF



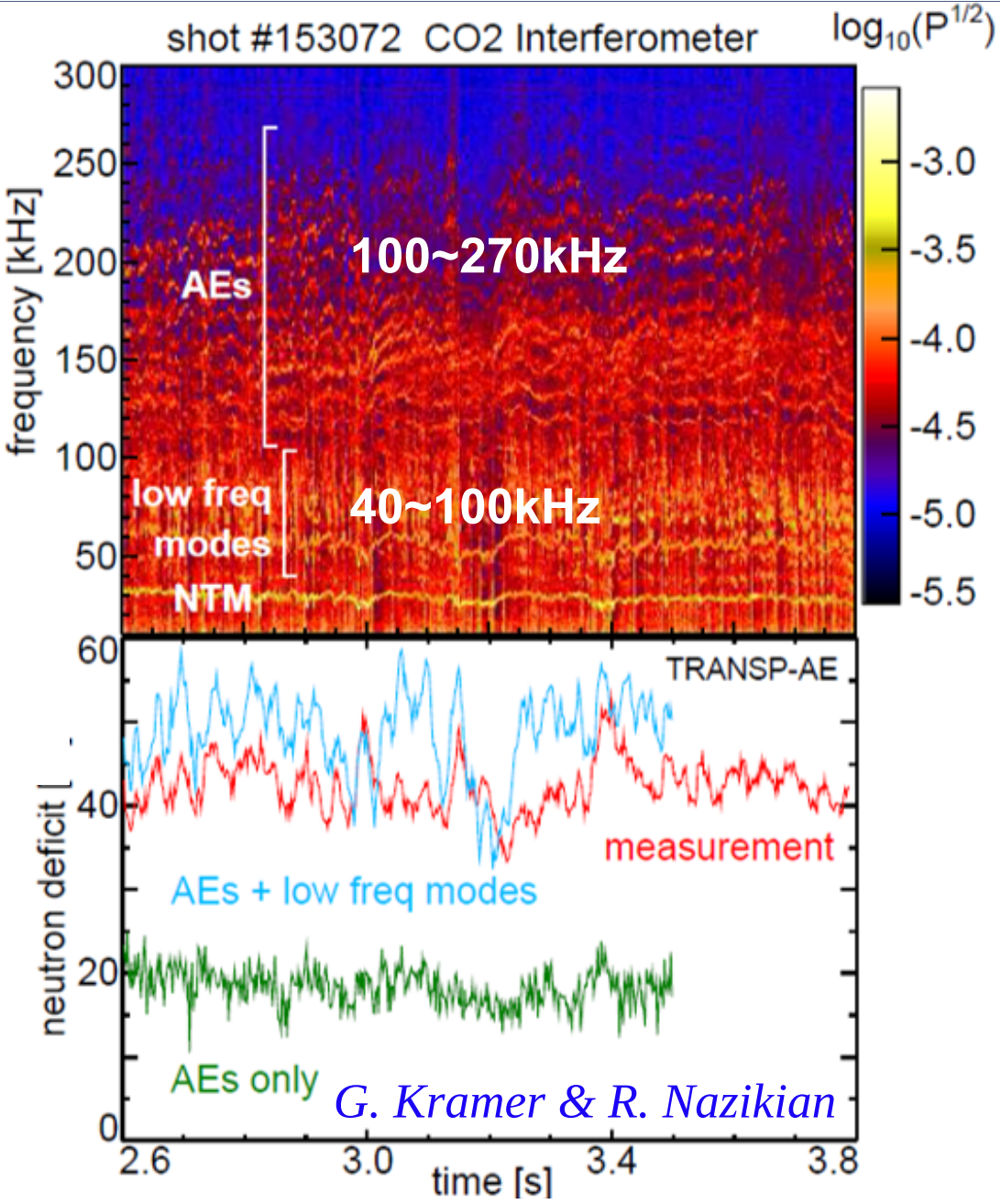
Outlines

- SciDAC ISEP
- ISEP V&V
- Integrated EP simulation
- TAE saturation via zonal fields
- Excitation of BAAE



Low Frequency Modes Induced Fast Ion Loss in DIII-D

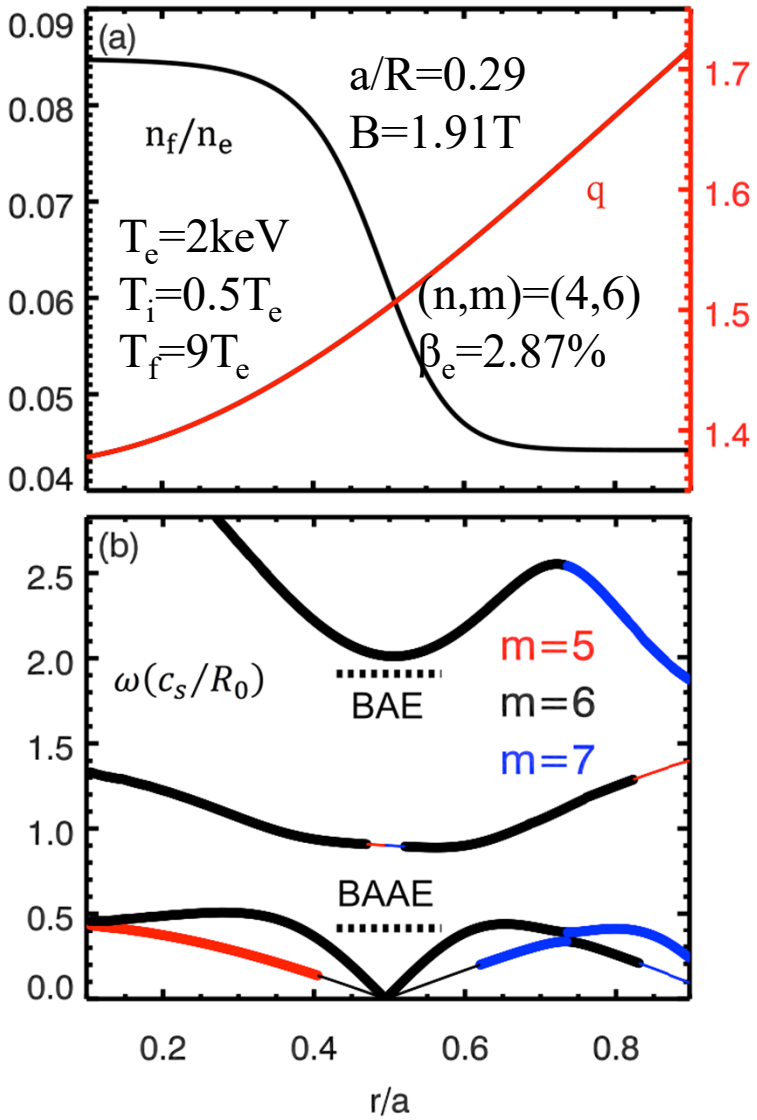
- Both high frequency Alfvén eigenmodes (AE) and low frequency modes (LF)
- Up to 45% neutron deficit observed; Half induced by AE; The other half caused by LF modes
- LF: Beta-induced Alfven eigenmode (BAE)? beta-induced Alfven-acoustic eigenmode (BAAE)?

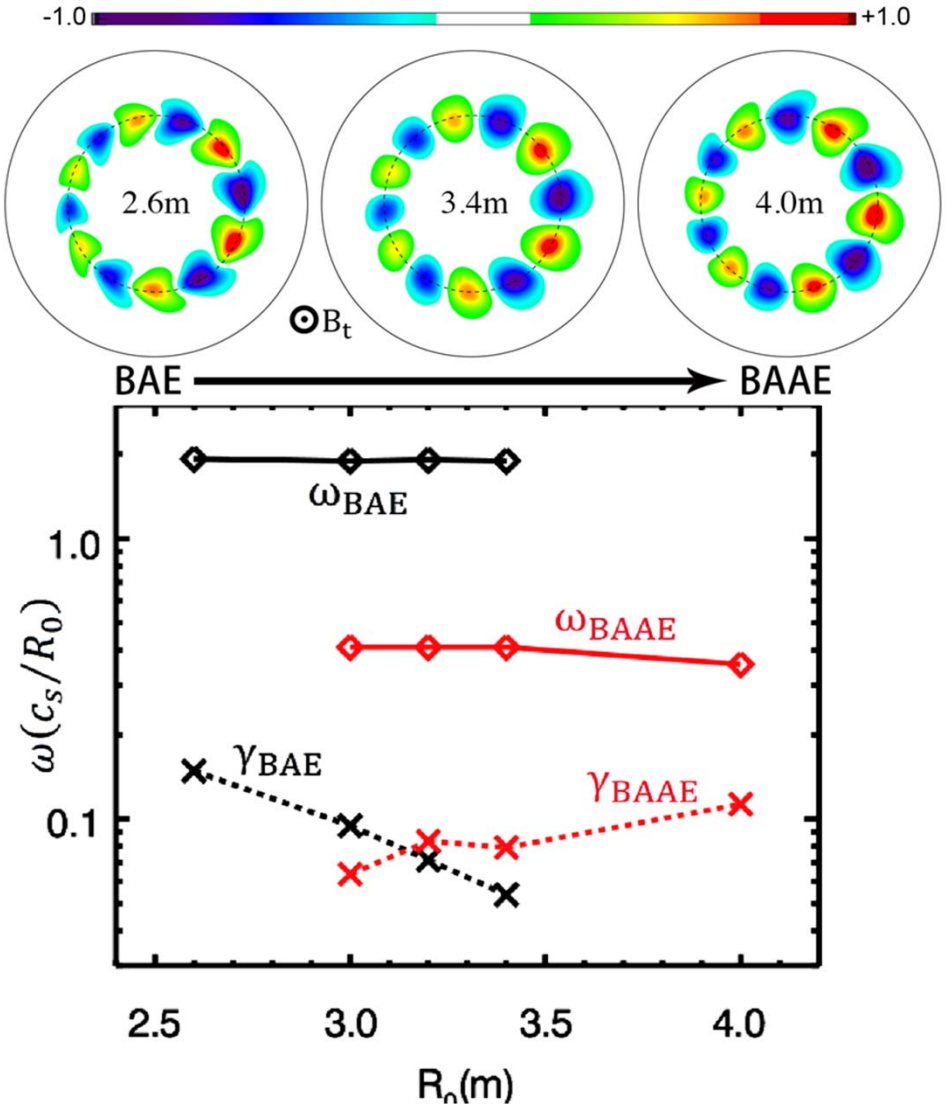


Low Frequency Alfven Eigenmodes

- Motivation
  - Loss of energetic particles due to low frequency BAAE & BAE
  - Strong coupling of BAAE & BAE with thermal plasmas: impact on confinement of thermal plasmas, transfer of energy from energetic to thermal ions?
- Existence & excitation of BAAE
  - Discrete BAAE has not been predicted by MHD or kinetic analytic theory
  - Does BAAE exist despite heavy damping by thermal ions?
  - Can BAAE be excited by realistic fast ion density gradient?
- Nonlinear interaction between BAAE & BAE
  - Can BAAE be nonlinearly generated?
  - What is nonlinear dynamics of BAAE?

Transition from BAE to BAAE for Larger Device $T_i=0.5T_e$

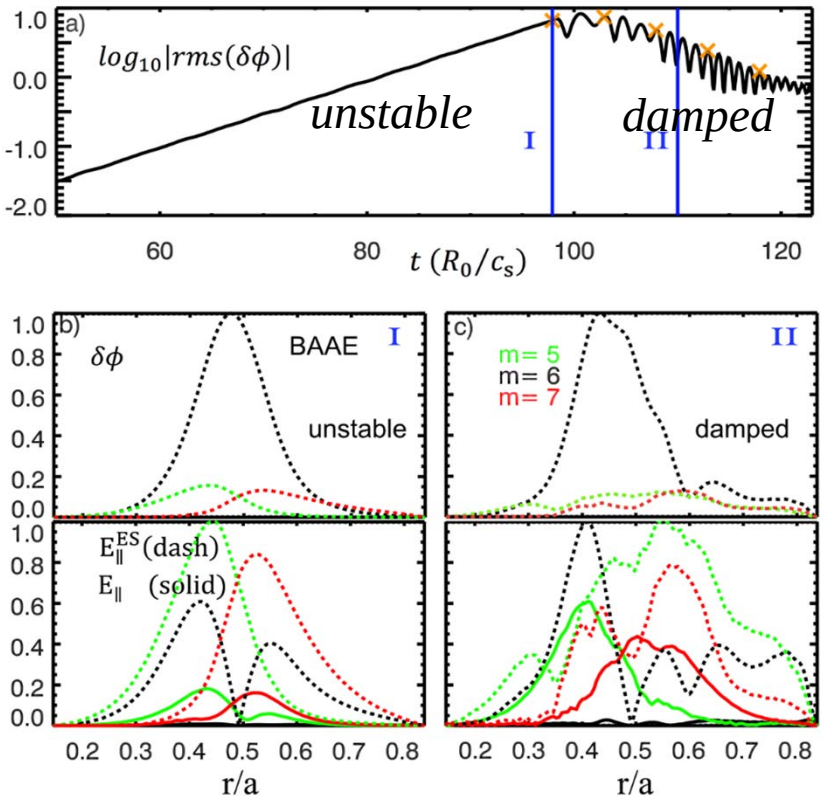




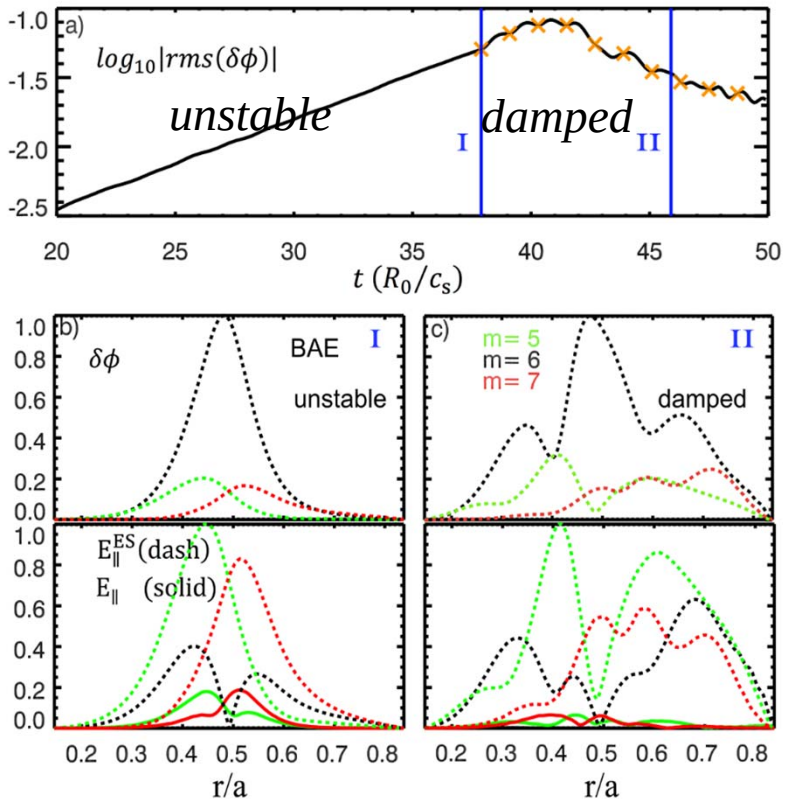
Excitation of Low Frequency Alfven Eigenmodes in Toroidal Plasmas, Yaqi Liu, Zhihong Lin, Huasen Zhang, Wenlu Zhang, *Nuclear Fusion* **57**, 114001 (2017)

Polarization of Unstable BAAE and BAE Alfvenic

BAAE(R=400cm)



BAE(R=260cm)



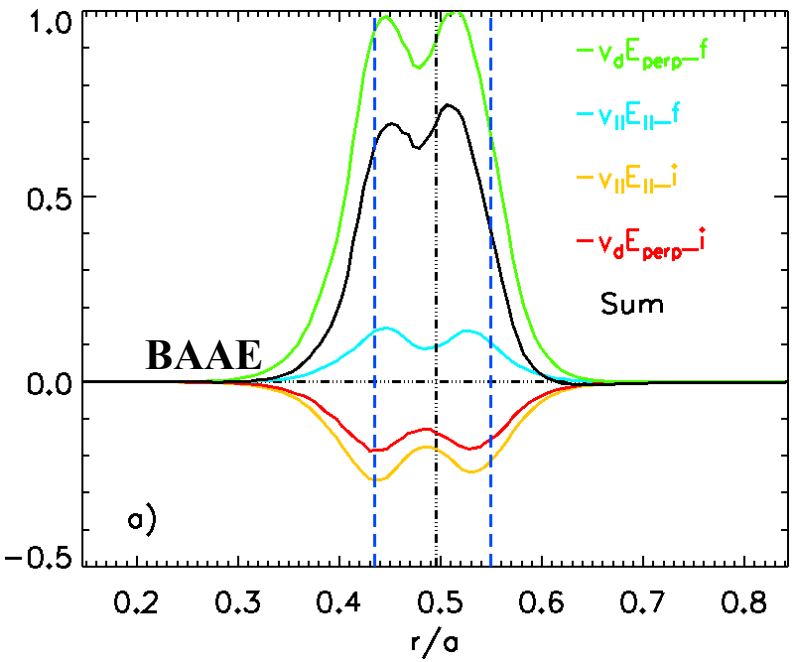
- All poloidal harmonics of unstable BAAE and BAE are Alfvenic
- Gradually decrease the drive → damped modes.

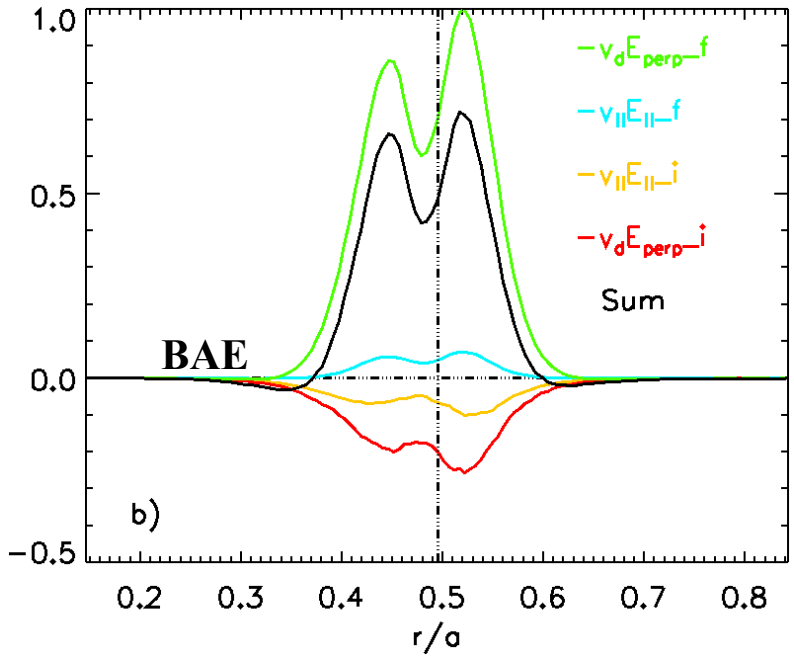
$E_\parallel/E_{\parallel ES}$ (**BAAE**) $\begin{cases} \ll 1, \text{m=6 Alfvénic} \\ \sim 1, \text{m} = 5,7 \text{Acoustic} \end{cases}$ $E_\parallel/E_{\parallel ES}$ (**BAE**) $\ll 1$, m=5,6,7 Alfvénic

- Perturbative, radially local theory not valid for BAAE

Linear Wave-Particle Energy Exchanges

- BAAE & BAE excited by transferring from fast ion perpendicular energy
- BAAE damped by transferring to thermal ion parallel & perpendicular energy
- BAE damped by transferring to thermal ion perpendicular energy
- BAAE: $\omega_r=0.50v_i/R_0$, $\gamma=0.04$, $\gamma_{EP}=0.08$, $\gamma_{D_unstable}=-0.04$, $\gamma_{D_stable}=-0.22$
- BAE: $\omega_r=2.5v_i/R_0$, $\gamma=0.28$, $\gamma_{EP}=0.44$, $\gamma_{D_unstable}=-0.16$, $\gamma_{D_stable}=-0.05$
- BAAE excited even $\gamma_{EP} \ll \gamma_{D_stable}$: perturbative theory not valid for BAAE

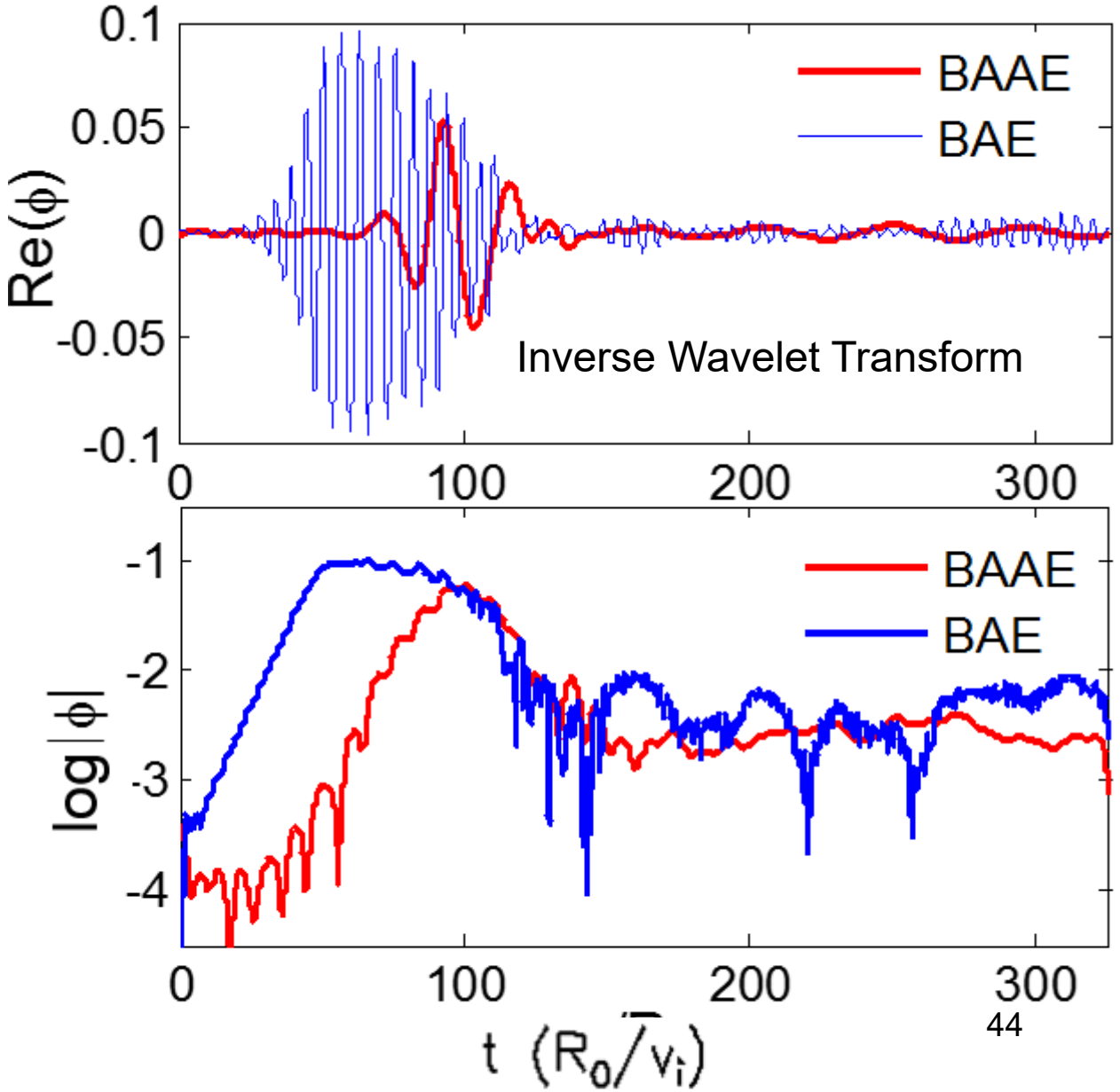




Excitation of Low Frequency Alfven Eigenmodes in Toroidal Plasmas, Yaqi Liu, Zhihong Lin, Huasen Zhang, Wenlu Zhang, *Nuclear Fusion* **57**, 114001 (2017)

Nonlinear Generation of BAAE by BAE

- **Linearly stable** BAAE **NL driven** by BAE with $n_\mathrm{f} = 9.5\% n_e$
- $\gamma_{BAAE} \sim const$ when BAE saturates
- NL generation of BAAE by BAE in DIII-D?
- Threshold $n_\mathrm{f} = 9\% n_e$



POSTDOCTORAL SCHOLAR POSITION
FUSION SIMULATION
UNIVERSITY OF CALIFORNIA, IRVINE

The University of California, Irvine (UCI) invites applications for two Postdoctoral Researcher positions in integrated fusion simulation beginning in September 2018. The fusion simulation group at UCI is led by Professor Zhihong Lin, who directs the Center for Integrated Simulation of Energetic Particles (ISEP), part of US Department of Energy (DOE) Scientific Discovery through Advanced Computing (SciDAC) initiative. The successful candidates will develop advanced simulations on the world's fastest supercomputers to study energetic particle confinement and turbulent transport in fusion experiments including tokamak, stellarator, and field reversed configuration. See http://phoenix.ps.uci.edu/zlin/ for additional information.

The successful applicants will have a Ph.D. degree in plasma physics or fusion energy science; salary will be commensurate with experience and qualifications. Applicants should submit a curriculum vitae, statement of research interests, a list of publications, and three names for letters of recommendation to Professor Zhihong Lin by email zhihongl@uci.edu.