Gyrokinetic Simulation of Energetic Particle Turbulence and Transport

Z. Lin

for SciDAC GSEP Team

PSACI Meeting, 2008

I. Motivation

Kinetic Effects of Thermal Particle on EP Physics

- In a burning plasma, e.g., ITER, shear Alfven wave (SAW) instability excited by fusion products (energetic α-particle) can be dangerous to energetic particle (EP) confinement

- SAW instability, e.g., toroidal Alfven eigenmode (TAE) and energetic particle mode (EPM), has thresholds that are imposed by damping from both thermal ions and trapped electrons

- Significant damping of *meso*-scale SAW (EP gyroradius ρ_{EP}) via resonant mode conversion to kinetic Alfven waves (KAW)
  - Finite parallel electric field
  - Radial wavelengths comparable to thermal ion gyroradius ρ_i (*micro*-scale)

- Wave-particle resonances of thermal particles are important in compressible Alfven-acoustic eigenmodes, e.g., BAE, BAAE, AITG

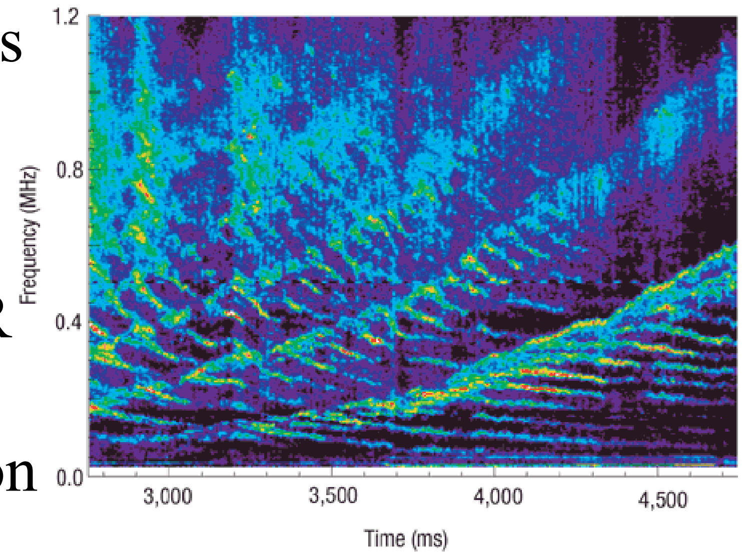
Nonlinear Mode Coupling, Turbulence & Transport

- Effects of collective SAW instabilities on EP confinement depend on self-consistent nonlinear evolution of SAW turbulence
  - Complex nonlinear phase space dynamics of EP
  - Complex nonlinear mode-mode couplings among multiple SAW modes
- Both nonlinear effects, in turn, depend on global mode structures and wave-particle resonances
  - Nonlinear mode coupling induced by *micro*-scale kinetic physics
- Physics of couplings between *meso*-scale SAW and *micro*-scale drift-Alfven wave (DAW) turbulence is even more challenging
- Current nonlinear paradigm of coherent SAW cannot fully explain EP transport level observed in experiments. Possible new physics:
  - Parallel electric field can break EP constant of motion, thus leads to enhanced EP transport
  - KAW can propagate/spread radially
  - Nonlinear mode coupling

Gyrokinetic Turbulence Approach

- Fully self-consistent simulation of EP turbulence and transport must incorporate three new physics elements
  - Kinetic effects of thermal particles
  - Nonlinear interactions of *meso*-scale SAW modes with *micro*-scale kinetic effects and wave-particle resonances
  - 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 EP physics in ITER burning plasmas call for a new approach of global nonlinear gyrokinetic simulation

Spectrum of Alfvén eigenmodes in DIII-D [Nazikian et al, PRL06]



SciDAC GSEP Center: Gyrokinetic Simulation of Energetic Particle Turbulence and Transport

- Develop gyrokinetic EP simulation codes based on complementary PIC GTC & continuum GYRO
- Participants:
  - *UCI*: Z. Lin (PI), L. Chen (Co-PI), W. Heidbrink, A. Bierwage, I. Holod, Y. Xiao, W. Zhang
  - *GA*: M. Chu (Co-PI), R. Waltz, E. Bass, M. Choi, L. Lao, A. Turnbull, M. Van Zeeland
  - *ORNL*: D. Spong (Co-PI), E. D'Azevedo, S. Klasky, R. Mills
  - *UCSD*: P. H. Diamond (Co-PI)
  - *LLNL*: C. Kamath (Co-PI)
  - *International collaborators*: F. Zonca, S. Briguglio, G. Vlad
- Advisory Committee: R. Nazikian, S. Pinches, M. Porkolab, Y. Todo, R. White
- Leverage fusion theory/experiment base programs, and other fusion SciDAC projects (GPS-TTBP, CSPM, CPES, SWIM, FACETS)

II. Gyrokinetic Simulation Using GTC & GYRO

GTC Physics Module Developed for Specific Application

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

[Lin et al, Science98]

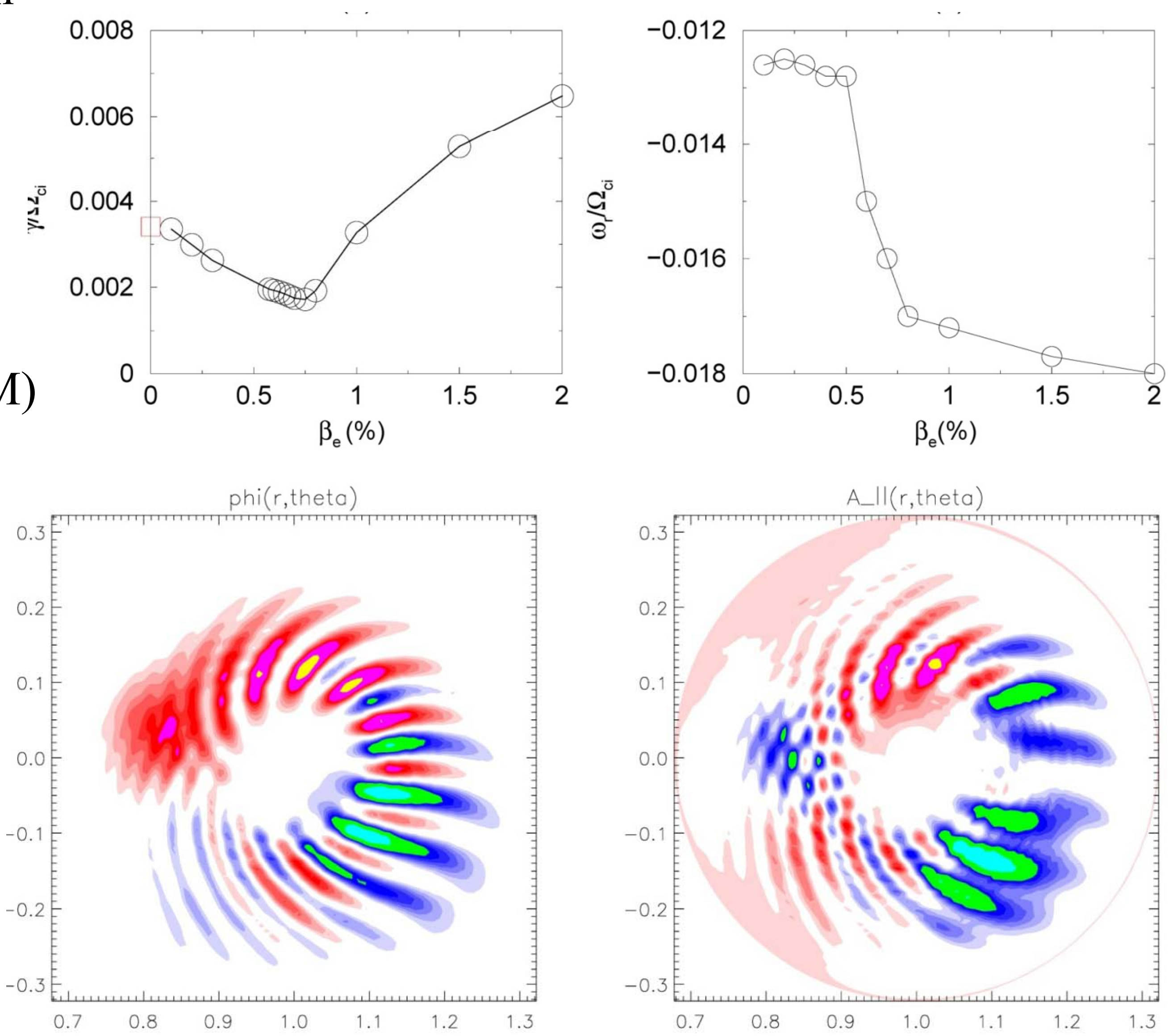
- Perturbative (δf) method for ions
  - Momentum transport by ITG turbulence
- Fluid-kinetic hybrid electron model for electrons
  - Electromagnetic turbulence with kinetic electrons
  - Shear Alfven wave (SAW) excited by energetic particles
- Multi-species via OO Fortran
  - Energetic particle diffusion by microturbulence
- Guiding center Hamiltonian in magnetic coordinates
- Global field-aligned mesh for truly global geometry
- General geometry MHD equilibrium using spline fit
- Fokker-Planck collision operators via Monte-Carlo method

GTC Simulation of Electromagnetic Turbulence with Kinetic Electrons

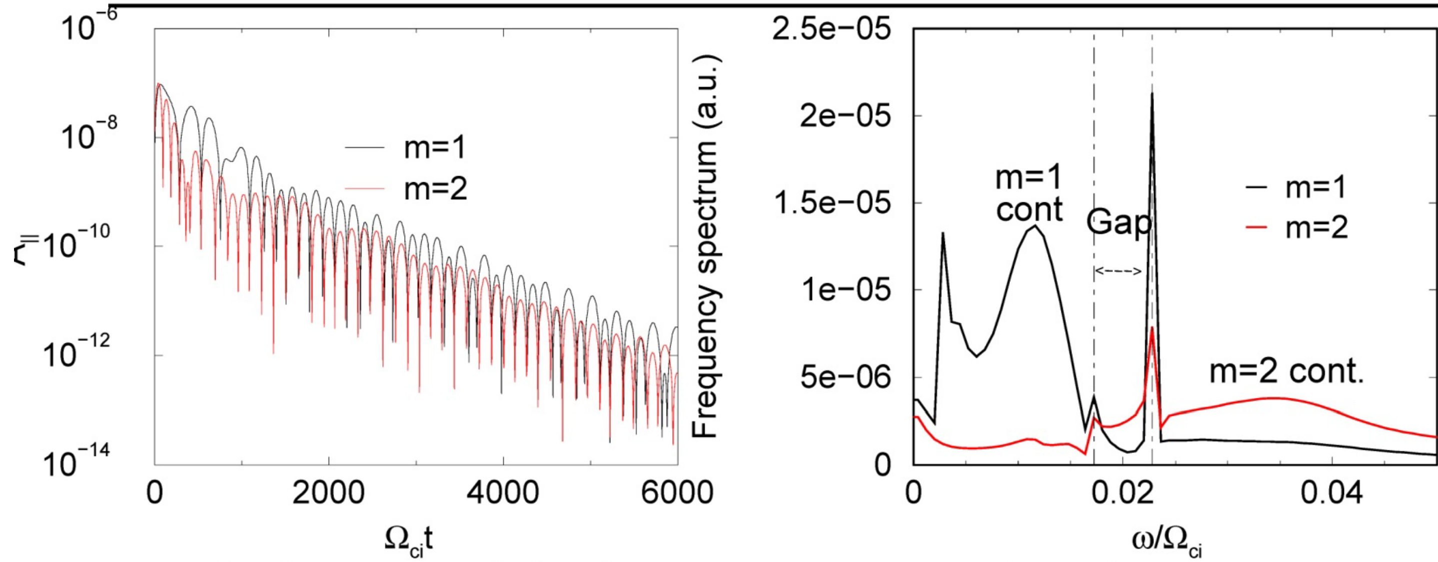
- Global GTC simulation using fluid-kinetic hybrid electron model
- Stabilization of ITG mode by finite beta
- Excitation of kinetic ballooning mode (KBM)
- Enhancement of ITG & KBM growth rate by kinetic electrons

Lin et al, PPCF07

Nishimura, Lin & Chen, CiCP08]



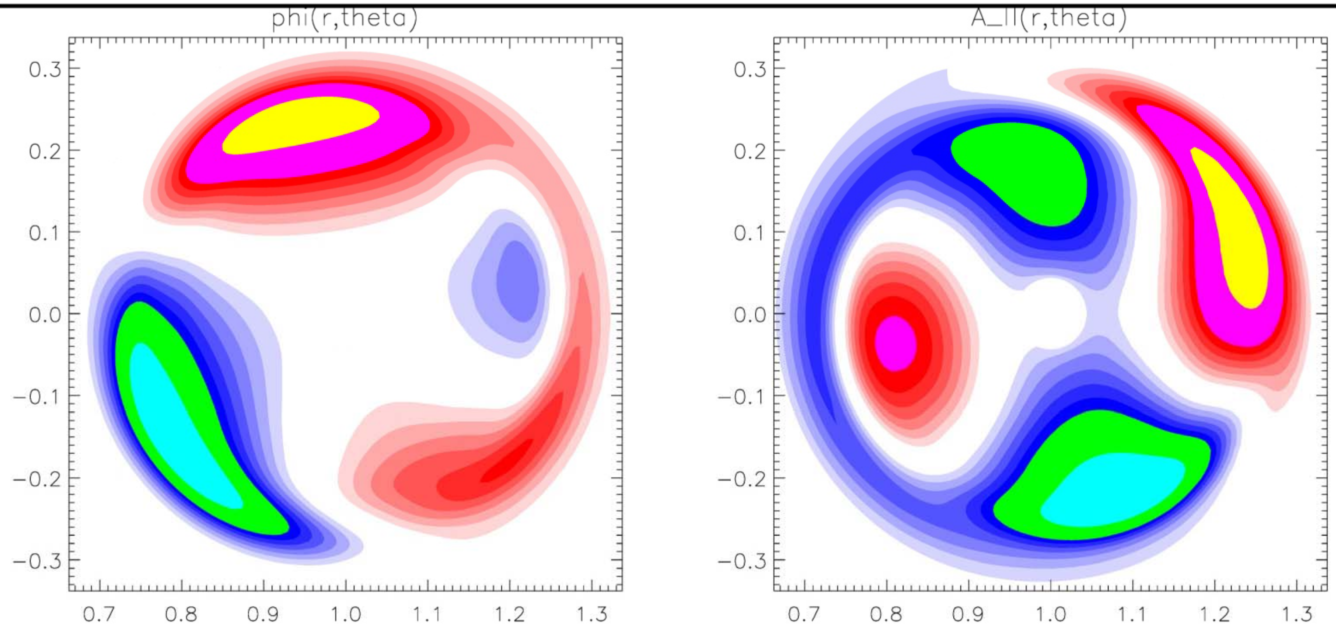
Generation of the frequency gap in the toroidal geometry is observed



- The location of the frequency gap matches the theory.
- Dominant $B \sim 1/R$ in GKP: "$\Phi - \tilde{\Phi}$" $\sim (\rho_s/\lambda_d)^2 \nabla_\perp^2 \Phi$.

Nishimura, Lin, & Wang, PoP07

With additional energetic particle drive, TAE can be excited within the gap



- Energetic particles of $\sim 10v_{thi}$ are incorporated.
- The TAE frequency ($\omega/\Omega_c \sim -0.02$) found within the gap. Linear growth rate $\gamma/\Omega_c \sim 0.0012$.

Nishimura
TTF08

GYRO Summary

- GYRO is a flexible and physically comprehensive δf gyrokinetic code
  - *nonlocal global (full or partial torus) or local flux-tube (cyclic or 0 BC)*
  - *equilibrium ExB and profile stabilization*
  - *transport at fixed profile gradients or fixed flow*
  - *electrostatic or electromagnetic*
  - *multi-species ion (impurities or fast particles) and electrons*
  - *covers all turbulent transport channels: energy(plus e-i exchange), plasma & impurity, momentum, pol. rotation shift, current-voltage (small dynamos), ExB & magnetic flutter, ITG/TEM/ETG; also has neoclassical driver*
  - *electron pitch angle collisions and ion-ion (all conserving) collisions*
  - *"s-alpha" circular or Miller shaped (real) geometry*
  - *reads experimental data (or selected) input profiles and transport flows*
- Pre-run data tools & post-run analysis graphics code VuGYRO
- New TGYRO driver code is a steady state gyrokinetic transport code for analyzing experiments or predicting ITER performance
- More than >10 regular users at >7 institutions and >30 publications (with >7 first authors); parameter scan transports database +400 runs.
- Documented (publications & manuals): http://fusion.gat.com/theory/Gyro

GYRO five year synopsis of physics results

GYRO [Candy 2003a] publications demonstrating:

[2002] * Bohm to gyroBohm transition at decreasing rho-star in global gyrokinetic ITG- adiabatic electron simulations [Waltz 2002].

[2003] * Bohm scaling in physically realistic+ gyrokinetic simulations of DIII-D L-mode rho-star pair matching transport within error bars on ion temperature gradients [Candy 2003b]

[2004] * small turbulent dynamo in tokamak current-voltage relation [Hinton 2004]

* local gyrobohm flux simulations to be vanishing rho-star limit of global simulations [Candy 2004].

* transport is smooth across minimum-q surface [Candy 2004b]

[2005] * global gyrokinetic transport solutions, i.e. predicted temperature and density profiles from balance of transport and source flows [Waltz 2005a].

I * electron temperature gradient drives plasma flow pinches and recovered the D-V description of experimental Helium transport studies [Estrada-Mila 2005].

* weak beta scaling of transport up to about half the MHD beta limit [Candy 2005]

* turbulence draining from unstable radii and spreading to stable radii providing a heuristic model of non-local transport [Waltz 2005b, Waltz 2005c].

[2006] * connection between velocity space resolution, entropy saturation and conservation, and numerical dissipation [Candy 2006a].

***** perfectly projected experimental profiles in rho-star gyroBohm-like DIII-D H-modes to Bohm-scaled local diffusivity while simulation of actual profiles showed gyroBohm scaling and match transport within error bars. Perfectly project Bohm-like DIII-D L-mode simulations remained Bohm [Waltz 2006a]

GYRO five year synopsis of physics results (cont'd)

* profile corrugations at low-order rational surfaces observed in DIII-D minimum q=2 discharges providing an ExB shear layer to initiate a transport barrier [Waltz 2006b].

* that including so-called parallel nonlinearity has no effect on simulated energy transport at rho_stars less than one percent [Candy 200b]

* density peaking from plasma pinch in DIII-D L-mode simulations with actual collisionality [Estada-Mila 2006b].

* first simulation of fusion hot alpha transport from ITG/TEM micro-turbulence found to be small with ITER parameters [Estada-Mila 2006b].

[2007] * ETG simulations with kinetic ion cures unphysically large saturation levels in controversial and conventional ETG simulations with adiabatic ions [Candy 2006c, Candy 2007]

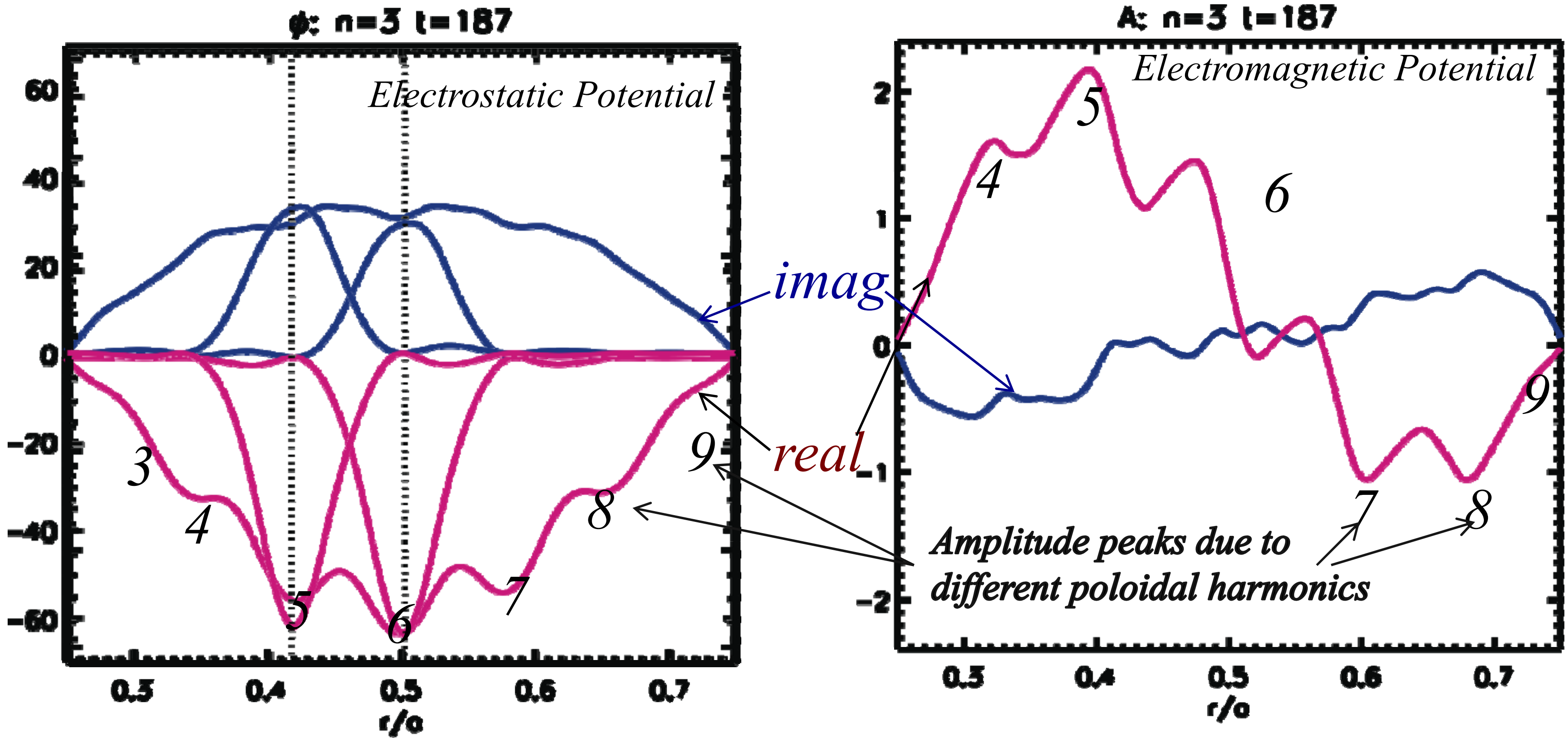
* high-Rynolds number coupled ITG/TEM-ETG simulations (at close to physical ion to electron mass ratio) show low-k ITG/TEM and high-k ETG transport decoupled when both strongly driven but ITG/TEM can drive ETG transport in ETG stable plasmas; high-k spectrum tends to be isotropic [Waltz 2007a]

* 400+ web parameter scan database of flux tube simulations used to fit nonlinear saturation rule with ExB shear stabilization in TGLF [Staebler 2005, Staebler 2007] theory based transport code model [Kinsey 2005, Kinsey 2006, Kinsey 2007]

* angular momentum pinch from ExB shear and pinch from "coriolis" force important for understanding experiments with intrinsic toroidal rotation; turbulent shift from neoclassical poloidal rotation is small [Waltz 2007b]

[2008] * radially integrated turbulent ohmic heating from parallel and drift currents is actually close to an electron-ion energy exchange and small compared to energy transport flow [Waltz 2008]

TAE Modes Driven by α's in Plasmas with Full Gyro-Kinetic Plasma Dynamics Identified by GYRO

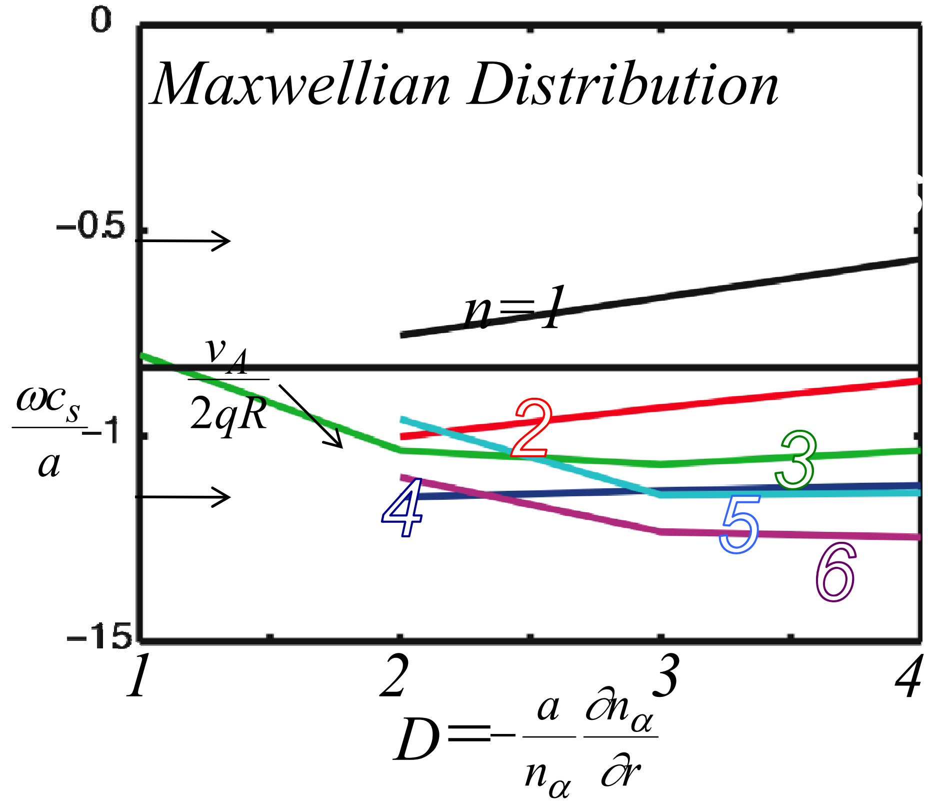


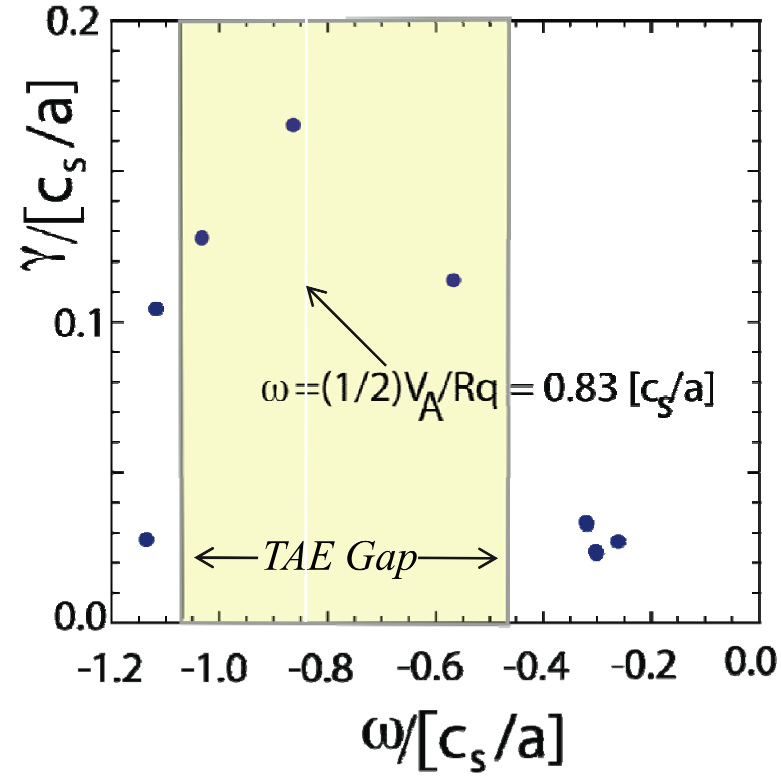
Chu & Waltz,
TTF08

Maxwellian distribution for α particles

No background plasma density or temperature gradients

Simulations Using GYRO in Flux Tube Geometry Verifies Predictions from MHD Theories





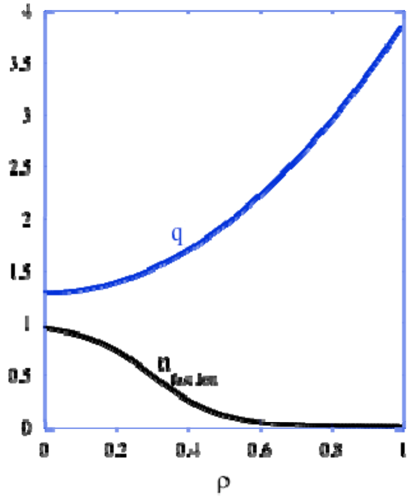
- *Dependence of ω and γ on equilibrium q and β values verified*
- *Dependence of ω and γ on temperature and density gradient of α's observed*
- *Growth rate γ reduced when ω falls outside of gap indicating continuum damping*
- *Modes other than TAE's found, could be due to inclusion of parallel electric fields*

III. GSEP Verification Plan

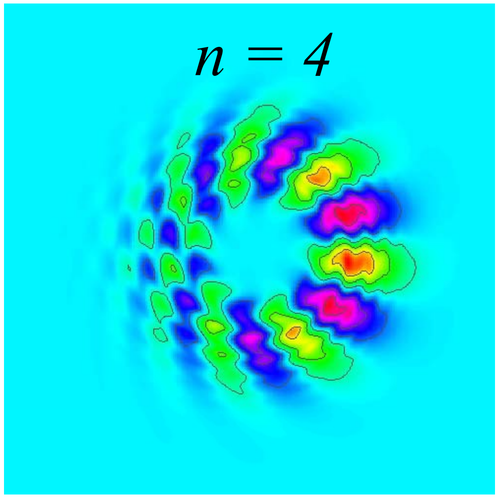
- First benchmark case using GTC, GYRO, HMGC, & TAEFL
- In initial simulations, all find gap modes; agree within 20%

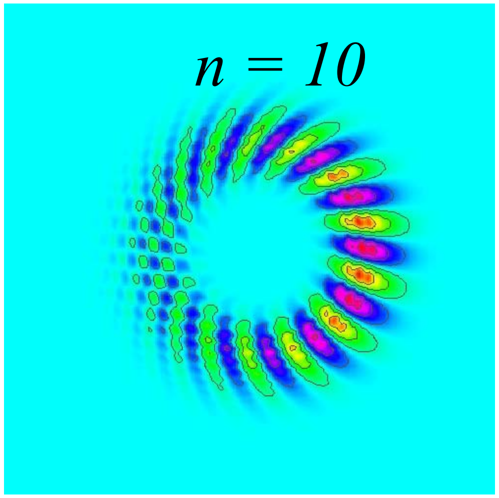
Code	Reference	Capability	Role in verification
GTC	Lin et al, *Science* **281**, 1835 (1998)	Global, gyrokinetic, turbulence	Production codes for EP simulations; Benchmark between GTC and GYRO
GYRO	Candy and Waltz, *J. Comput. Phys*. **186**, 545 (2003)		
HMGC	Briguglio et al, *Phys. Plasmas* **5**, 301 (1998)	Global, hybrid MHD-guiding center turbulence	Nonlinear benchmark with GTC & GYRO
NOVA-K	Cheng, *Phys. Report* **211,** 1 (1992)	Global, linear eigenmode	Linear benchmark with GTC & GYRO
TAEFL/ AE3D	Spong et al, *Phys. Plasmas* **10**, 3217 (2003)		
AWECS	Bierwage and Chen, *Comm. Comput. Phys.*,2008	Local, linear gyrokinetic PIC	

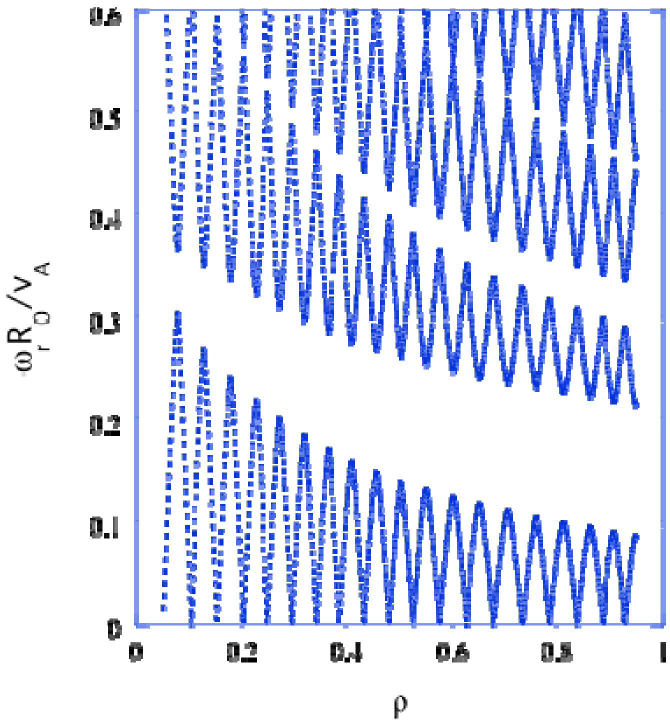
Benchmarking is in progress – initial comparisons show reasonable agreement



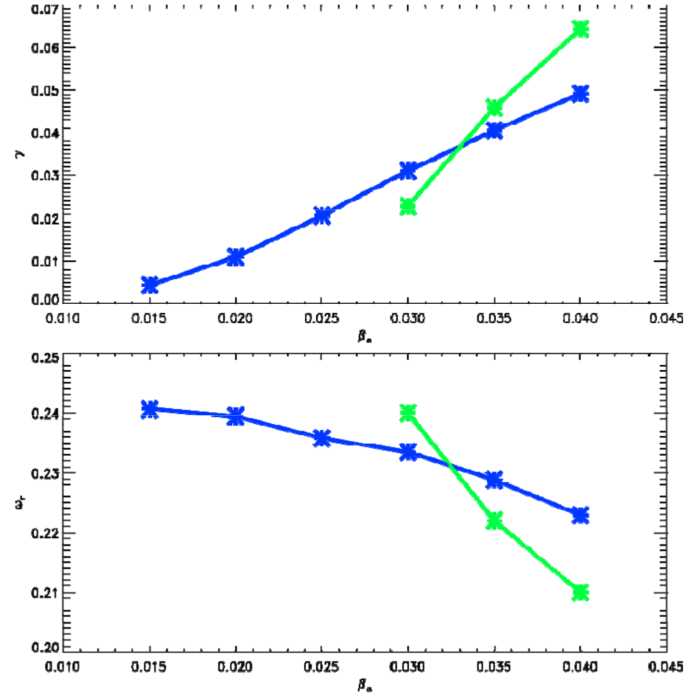
Typical range of TAE mode structures for benchmark case







Spong & Zhang verification



Example of n = 3 comparison between GTC (green) and TAEFL (blue) codes

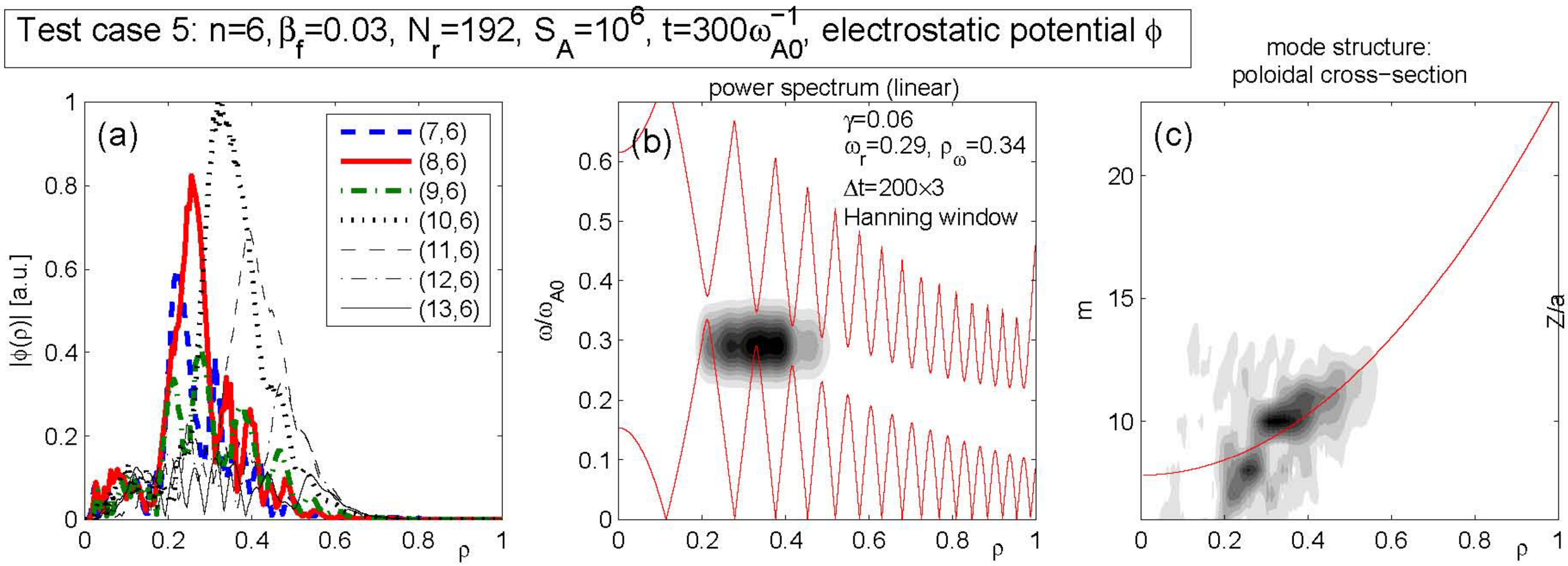
Nonlinear Global Gyrokinetic/MHD Hybrid Code HMGC

- Established EP code HMGC deployed for linear/nonlinear benchmark and for initial physics studies
- HMGC will be used for simulation of DIII-D dedicated experiment

Briguglio et al, PoP98

Vlad et al, IAEA08, oral

Bierwage, verification



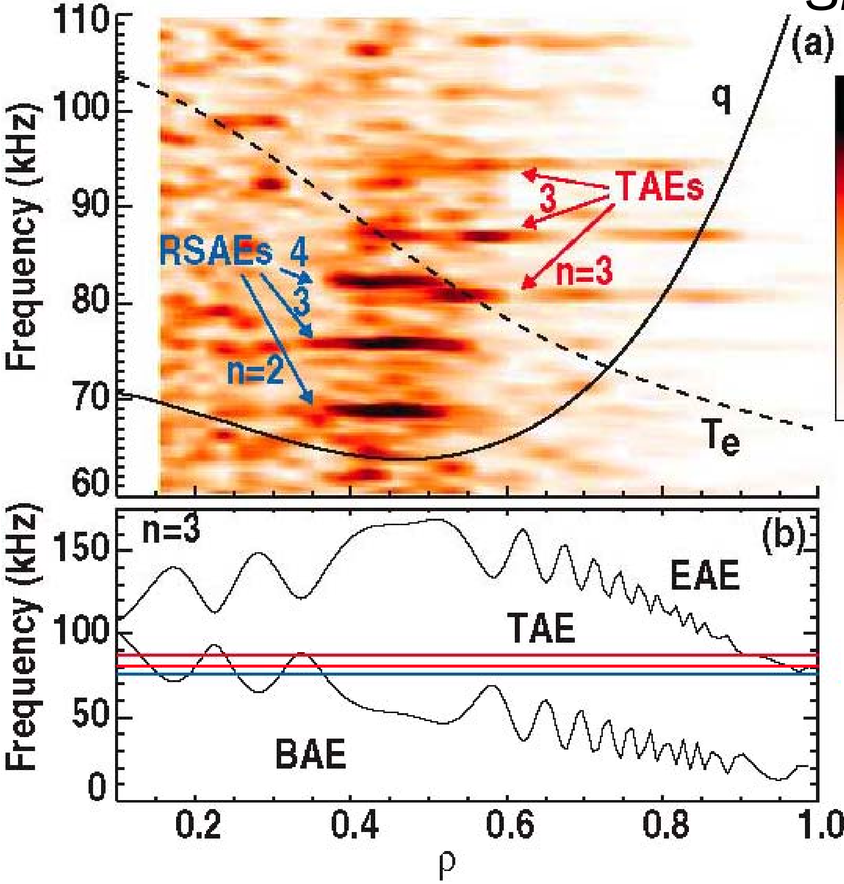
IV. GSEP Validation Plan

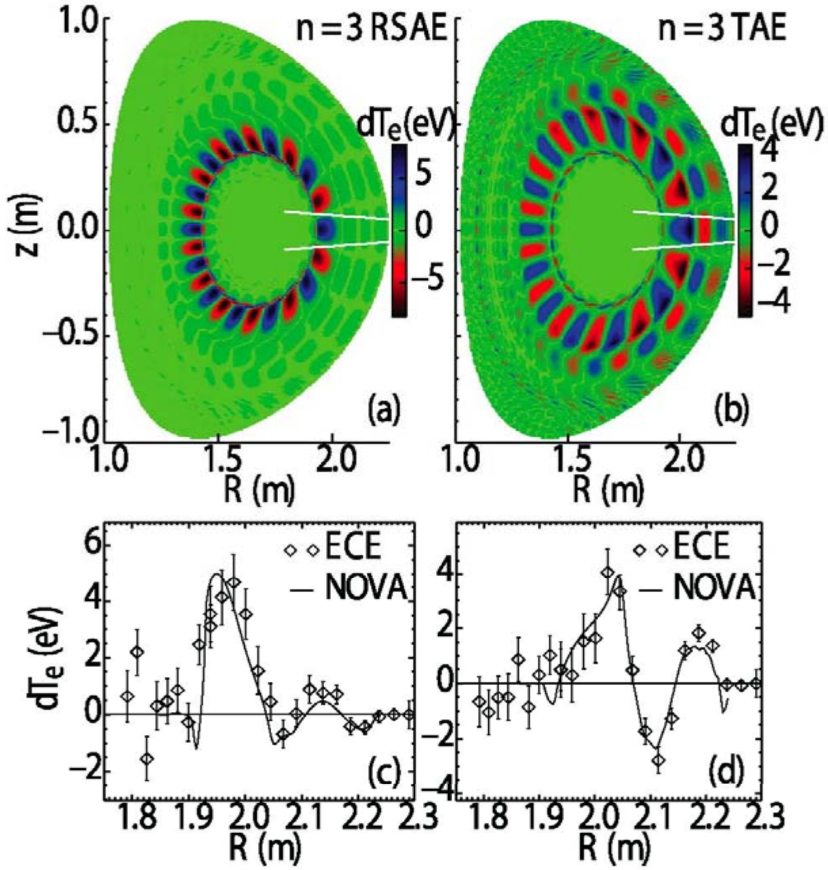
- Initial validation targets DIII-D dedicated experiment #132707
- Subsequent studies focus on related DIII-D experiment #*122117* (identified for ITPA database)

	Fundamental constituents		⇒		Derived Observables
Primacy hierarchy	Linear SAW wave	Nonlinear saturation	Transport	Scaling Trend	Statistics
Observable	Polarization, structure, frequency, threshold	Spectral intensity, bispectra, zonal flows/fields	EP PDF, transport	Similarity experiment	ITPA database
Agent/ mechanism	EP spatial gradient, velocity anisotropy	Wave-wave, wave-particle interaction	Cross-phase, relaxation	Dimensionless scaling	Inter-machine

A Well Diagnosed DIII-D Shot with Observed TAE and RSAE Activity Chosen as Target of Validation Plan

Shot #122117





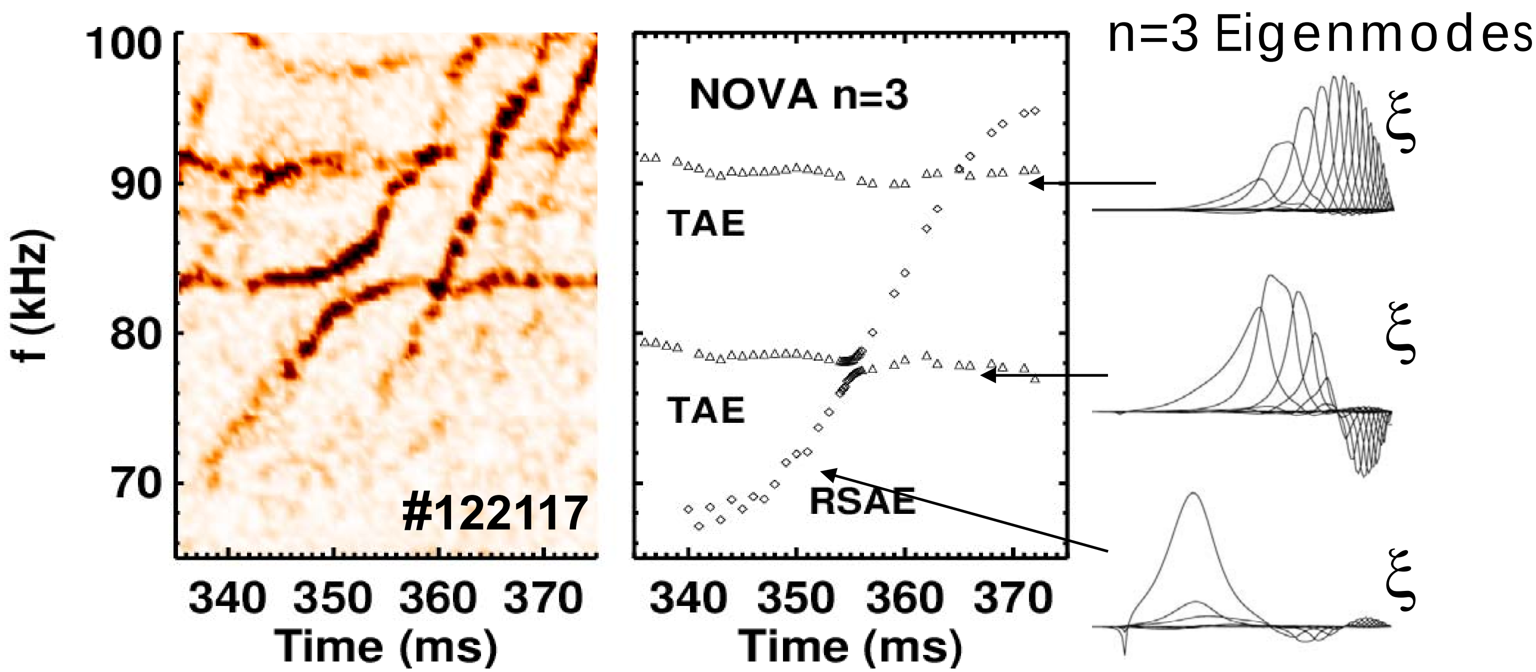
*VanZeeland et al, PRL **97**,135001 (2006)*

Heidbrink et al, NF08, in press

Anomalous Loss of Energetic Particles Observed

DIII-D
NATIONAL FUSION FACILITY

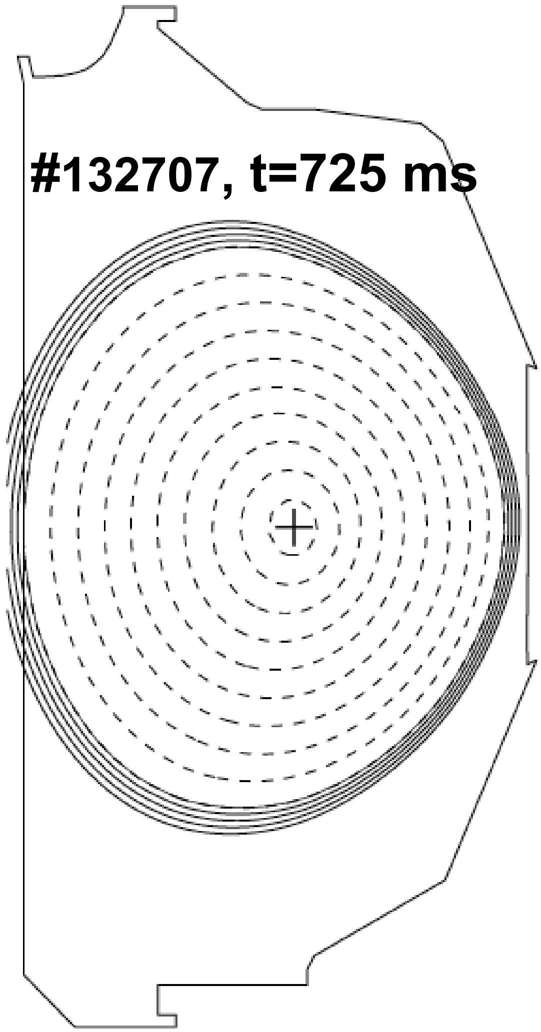
Validation Will Focus on Time Window Around RSAE / TAE Linear Mode Coupling Event

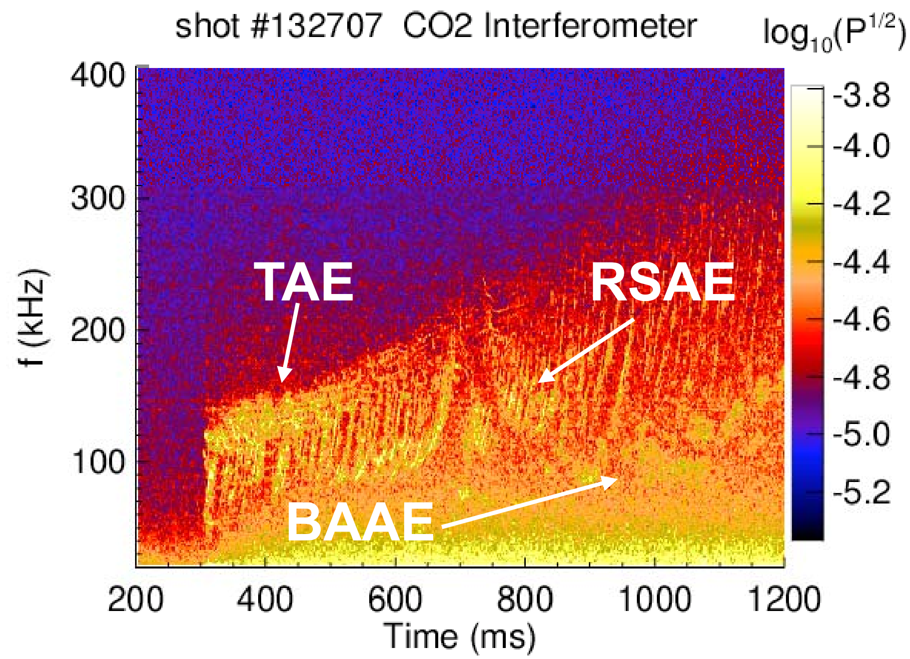


MA Van Zeeland *et.al.*, *PoP*, **14** (2007); IAEA08, oral

- Coupling event provides well defined phenomena with multiple unstable modes of different type rather than just one timestep
- Mode structure measurements are available throughout coupling process as well as fast ion profile data
- This time window is currently the focus of a similar study using ORBIT in combination with NOVA calculated eigenmodes

Recent DIII-D Discharge Dedicated to GSEP

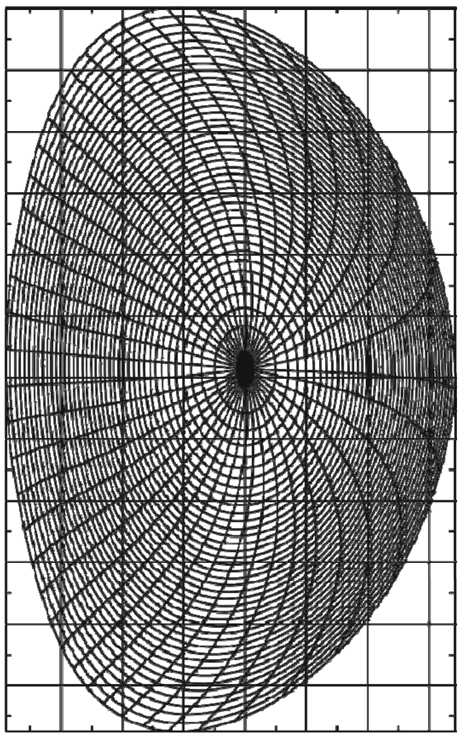




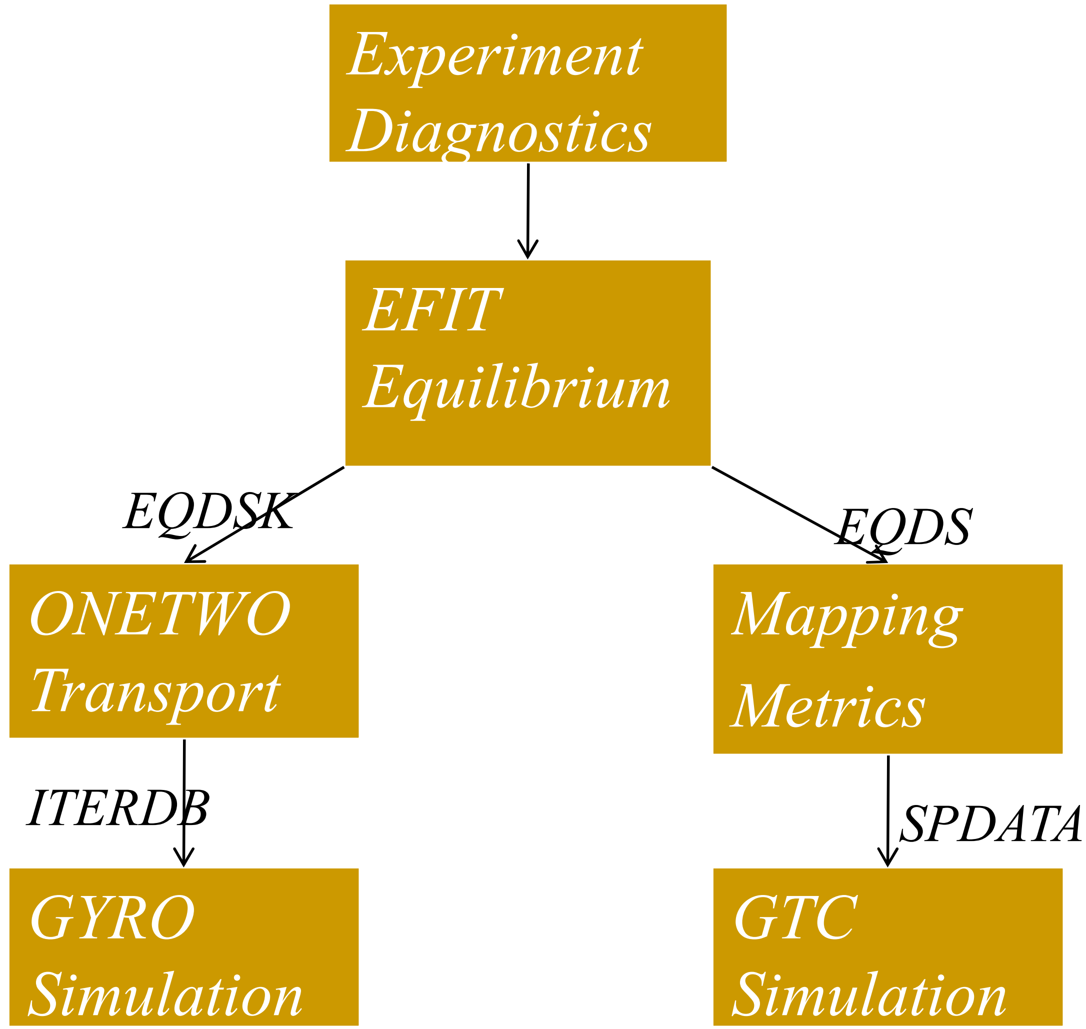
- Circular (κ~1.15) version of 122117 created for ease of comparison to codes and theory
- Discharge has very similar AE activity to 122117
- Many diagnostic improvements have been made since 122117 (2005) including more Fast Ion D-alpha channels and a linear BES array

DIII-D NATIONAL FUSION FACILITY

Electronic Data of Target Plasma and Linkage with Codes initiated; Validation Studies Started



Mapped Geometry of Shot #122117

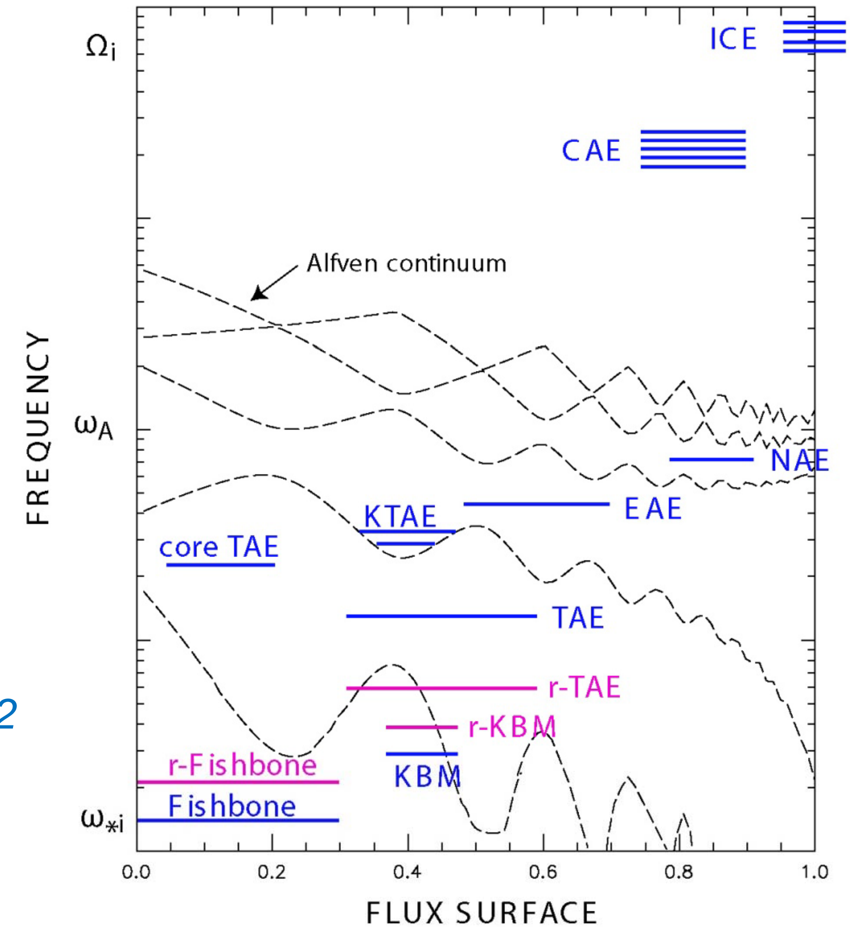


DIII-D NATIONAL FUSION FACILITY

Chu, Waltz, & Lin, validation

V. GSEP Physics Studies

- Linear and nonlinear single-n EP mode (AEs and EPMs) in both toroidal Alfven gap and lower-frequency kinetic thermal ion gap
- *Meso*-scale EP turbulence of interacting multi-n modes within and across spectral gaps
- *Meso-micro* cross-scale couplings between EP turbulence and microturbulence driven by thermal particles



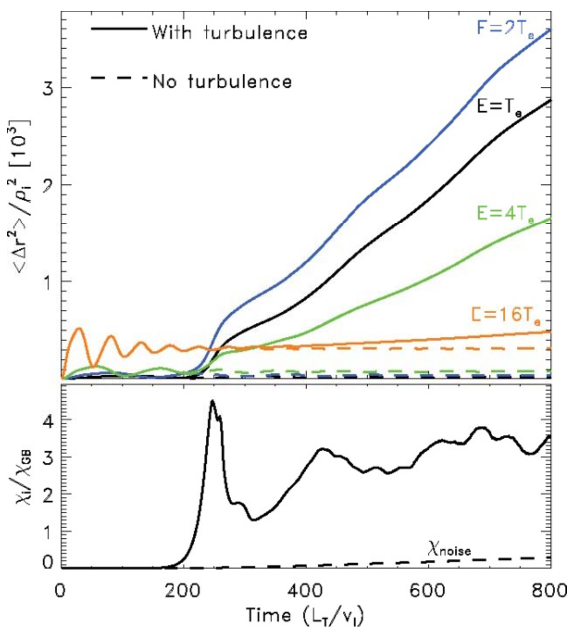
Heidbrink, PoP02

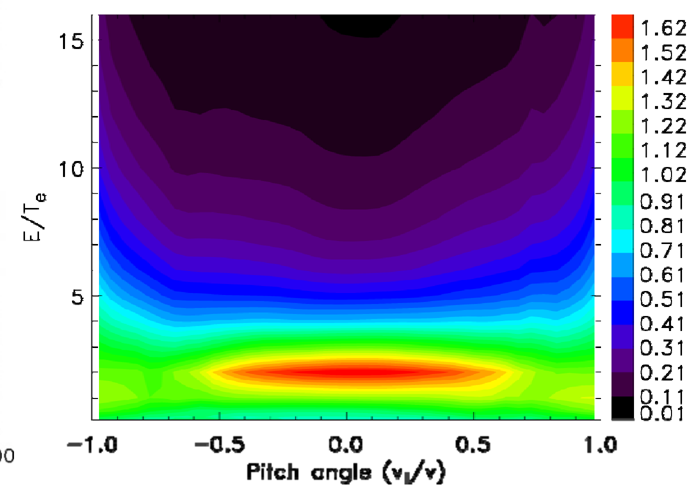
GTC Simulation of Energetic Particle Transport

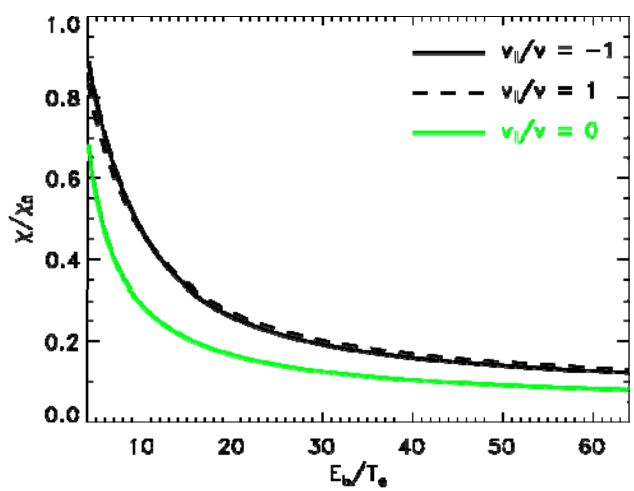
- Recent tokamak experiments revive interest of fast ions transport induced by microturbulence *[Heidbrink & Sadler, NF94; Estrada-Mila et al, PoP06; Gunter et al, NF07]*
- Radial excursion of test particles found to be diffusive in GTC global simulation of ion temperature gradient (ITG) turbulence
- Detailed studies of diffusivity in energy-pitch angle phase space
  - ▸ Diffusivity drops quickly at higher particle energy due to averaging effects of larger Larmor radius/orbit width, and faster wave-particle decorrelation
- NBI ions: lower diffusivity for higher born energy

Zhang, Lin, & Chen, TTF08

In collaboration with GPS-TTBP







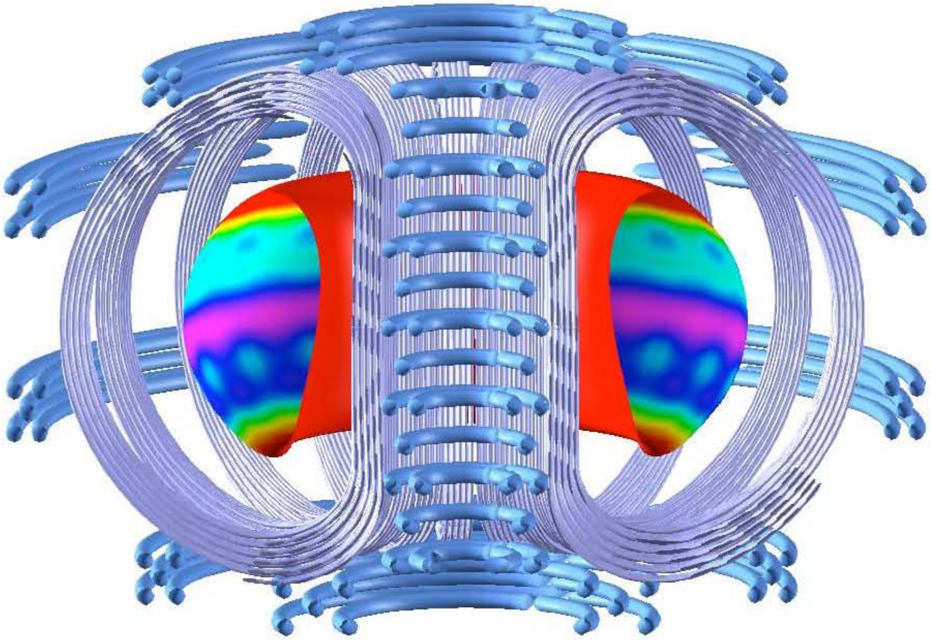
3D Magnetic Field Effects on EP Physics

- Alfven spectra analysis for 3D configuration carried out by AE3D
- Alpha ripple loss in ITER calculated by Monte-Carlo DELTA5D

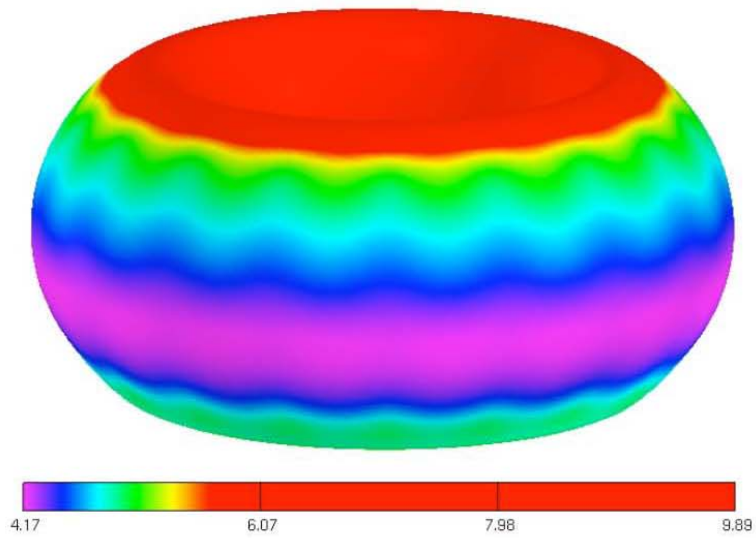
Spong et al, IAEA08, oral

ITER free boundary VMEC equilibria have been calculated using a filamentary coil model:

Coil model: 18 TF's with 25 filaments each 5 filaments per PF



|B| contours on outer flux surface (compressed color map)



GAM Radial structures and nonlinear excitations

- Both SAW and DAW nonlinearly generate zonal flow (ZF)/GAM
- ZF/GAM in turn regulate thermal particle turbulence & transport
- Analytical studies find GAM linear mode conversion to kinetic GAM, which propagates radially
- Possible nonlocal effect such as turbulence spreading

Zonca and Chen, Euro. Phys. Lett,, submitted (2008)

Discrete SAW Mode in High-β Plasmas

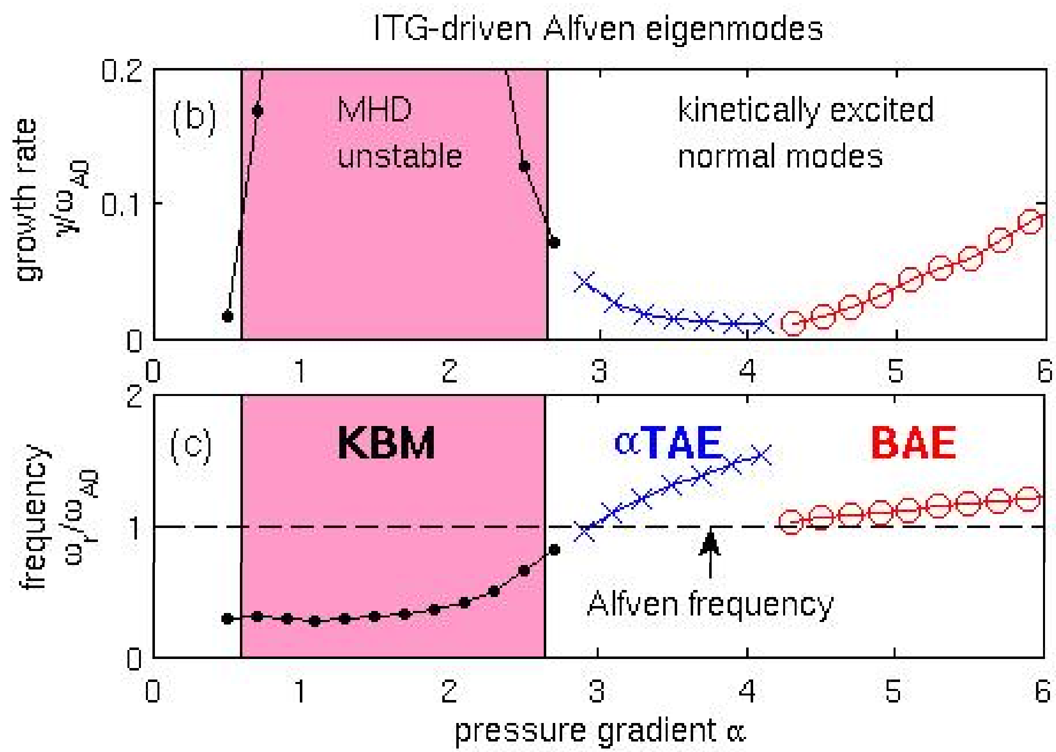
- AWECS: linear high-β GK PIC code, flux tube, simple model equilibrium, kinetic thermal ion and energetic ions

- Find discrete modes in 2nd MHD stable domain
  - Destabilized by thermal ions

- Identified nature of modes:
  - alphaTAEs
  - BAEs

- Interaction with energetic ions expected since $\omega \sim \omega_A$

Bierwage & Chen, CiCP08



VI. High-performance Computing

- Deployment of advanced computational tools for GSEP project via collaboration with SciDAC IUSV, PERI, & SDM
- INCITE with 8M hours of ORNL jaguar computer awarded to a joint proposal of GPS-TTBP, GSEP & CPES; Two INCITE awards made to GYRO
- GTC key code for SciDAC GPS-TTBB & GSEP; GYRO for CSPM, GSEP, & FACETS SAP
- GTC part of pioneering application on 250TF jaguar computer at ORNL & part of NERSC benchmark suite.

VII. GSEP Activities

- GSEP project webpage: http://gk.ps.uci.edu/gsep
- *GSEP* kickoff meeting: 1/25/2008 at UC Irvine
- annual GSEP project workshop: 8/11-8/12 at GA
- Annual winter school on EP and turbulence
- GSEP partially support four postdocs and 2 students
- Monthly teleconference of Executive Committee
- Quarterly progress report to PAC & OFES
- **2008 Hannes Alfvén Prize by EPS to Liu Chen**

"for his many seminal works on Alfvén wave physics in laboratory and space plasmas and his continuing contribution of new ideas, including: the theories of geomagnetic pulsations, Alfvén wave heating, fishbone oscillations, the formulation of the nonlinear gyrokinetic equations and fundamental contributions to drift wave instabilities and turbulence"

VIII. GSEP Publications and presentations in 2008

- ***GSEP related Publications in 2008***
- M.A. Van Zeeland et al, Reversed Shear Alfvén Eigenmode Stabilization by Localized Electron Cyclotron Heating, Plasma Phys. Control. Fusion 50, 035009 (2008).
- F. Zonca, The physics of burning plasmas in toroidal magnetic field devices, Intern. J. Modern Phys. A 23, 1165 (2008).
- W.W. Heidbrink, Basic physics of Alfvén instabilities driven by energetic particles in toroidally confined plasmas, Phys. Plasmas 15, 055501 (2008).
- A. Bierwage and L. Chen, AWECS: A linear gyrokinetic delta-f particle-in-cell simulation code for the study of Alfvénic instabilities in high-beta tokamak plasmas, Commun. Comput. Phys., 4, 457 (2008).
- W.W. Heidbrink et al, Central Flattening of the Fast-ion Profile in Reversed-Shear DIII-D Discharges, Nuclear Fusion 48, 2008, in press.
- Y. Nishimura, Z. Lin, and L. Chen, Full torus electromagnetic gyrokinetic particle simulations with kinetic electrons, Commun. Comput. Phys. 4, 2008, in press.

- ***GSEP related oral presentations at TTF2008***
- *M. Chu, Gyrokinetic Simulation of Energetic Particle Driven TAE Modes*
- *Z. Lin, Gyrokinetic simulation of energetic particle turbulence and transport*
- *Y. Nishimura, Gyrokinetic particle simulation of toroidicity induced Alfven eigenmode*
- *D. A. Spong, Energetic Particle Stability and Confinement Issues in 3D Configurations*
- *W. L. Zhang, Turbulent Transport of Energetic Particles by Microturbulence*

- ***GSEP related presentations at EPS2008***
- *L. Chen, Alfvén Waves: A Journey between Space and Fusion Plasmas (Alfven Prize address)*
- *Z. Lin, Gyrokinetic simulation of energetic particle turbulence and transport (poster)*

- ***GSEP related papers at IAEA2008***
- *L. Chen et al, Gyrokinetic simulation of energetic particle turbulence and transport (poster)*
- *D. Spong et al, energetic particle physics issues for three-dimensional toroidal configuration (oral)*
- *M. Van Zeeland et al, Alfvenic instabilities and fast ion transport in the DIII-D tokamak (oral)*