21st US Transport Task Force Workshop
Boulder, Colorado
March 25 - 28, 2008

SUMMARY of ENERGETIC PARTICLE SESSIONS

Boris Breizman, Nikolai Gorelenkov
and Energetic Particle Group

Statistics:

22 talks = 10(experiment)+12(theory/modeling)
7 talks by students

Trends and Developments in Energetic Particle Area

- Continuing interest to low-frequency perturbations (GAM & acoustic modes) (Edlund, Gorelenkov, Fu, Nazikian, Nguyen)
- Experimental evidence for avalanche particle losses in NSTX (Fredrickson, Darrow, Liu)
- Fundamental examination of wave-particle physics in LAPD (Y.Zang, Carter, Pratt)
- Fast electron driven modes (Brower, Macor, Snipes)
- Progress in modeling 3-D configurations (Spong)
- Integrated ITER-oriented modeling (Budny)
- Gyrokinetic simulations take-off (Chu, Lin, Nishimura, Lang, W.Zhang, Dannert)

Highlights
of Presentations

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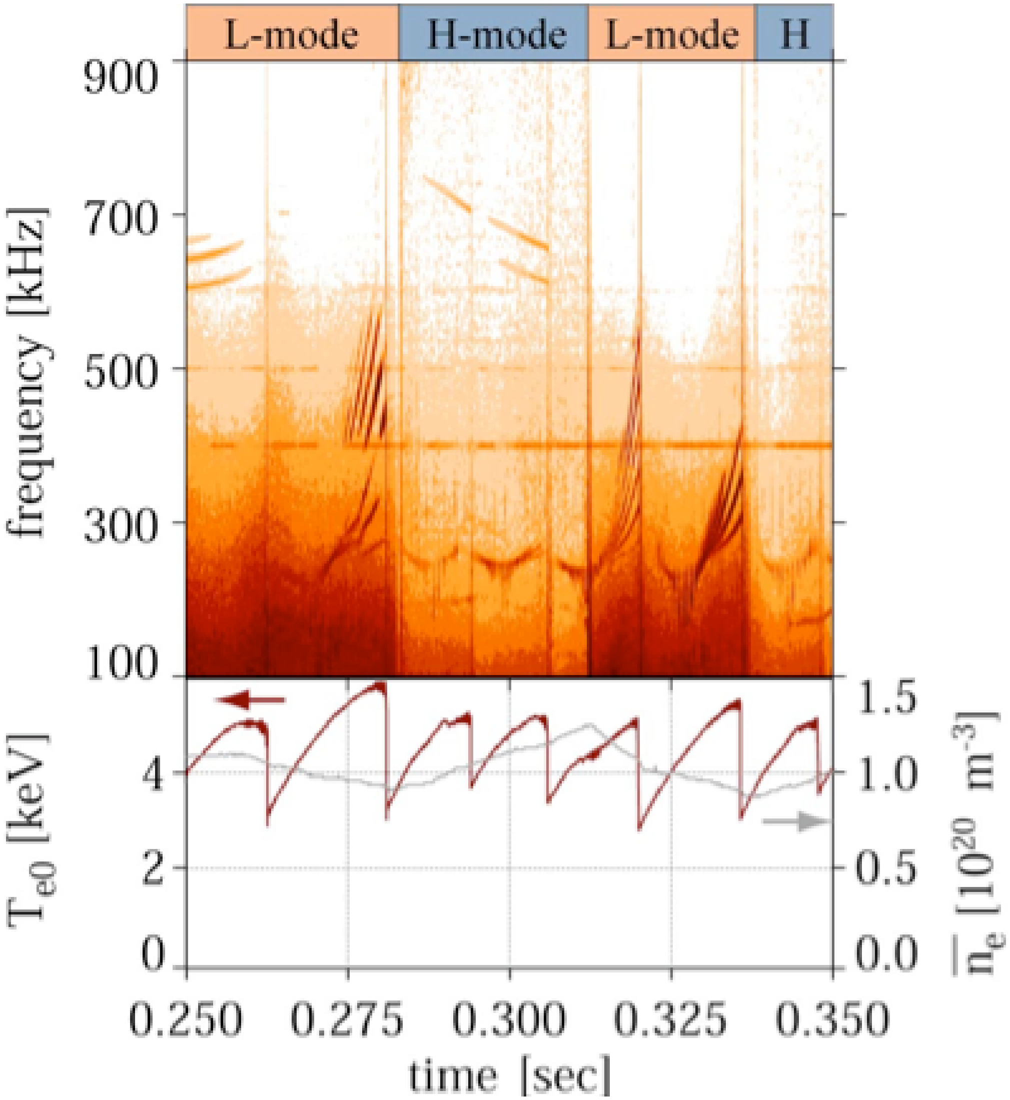
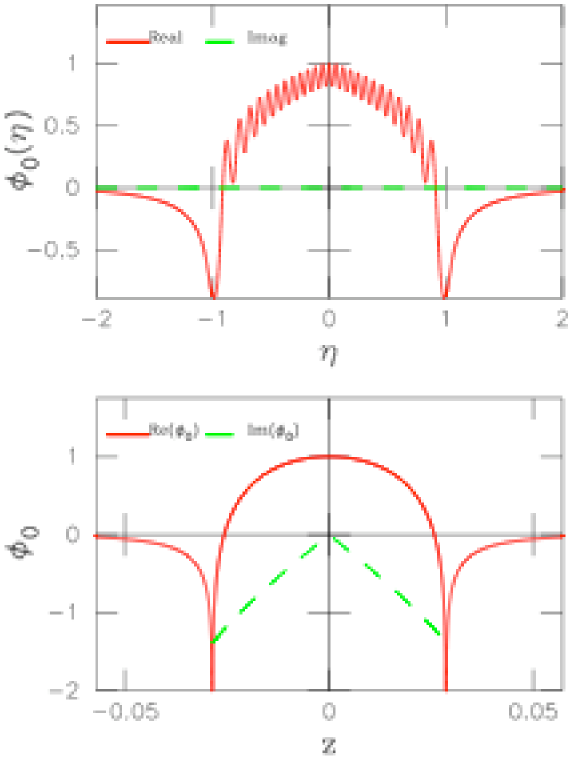
E. E. Edlund (presented by M. Porkolab) *"Experimental study of reversed shear Alfvén eigenmodes during ICRF minority heating and relationship to sawtooth crash phenomena in Alcator C-Mod"*



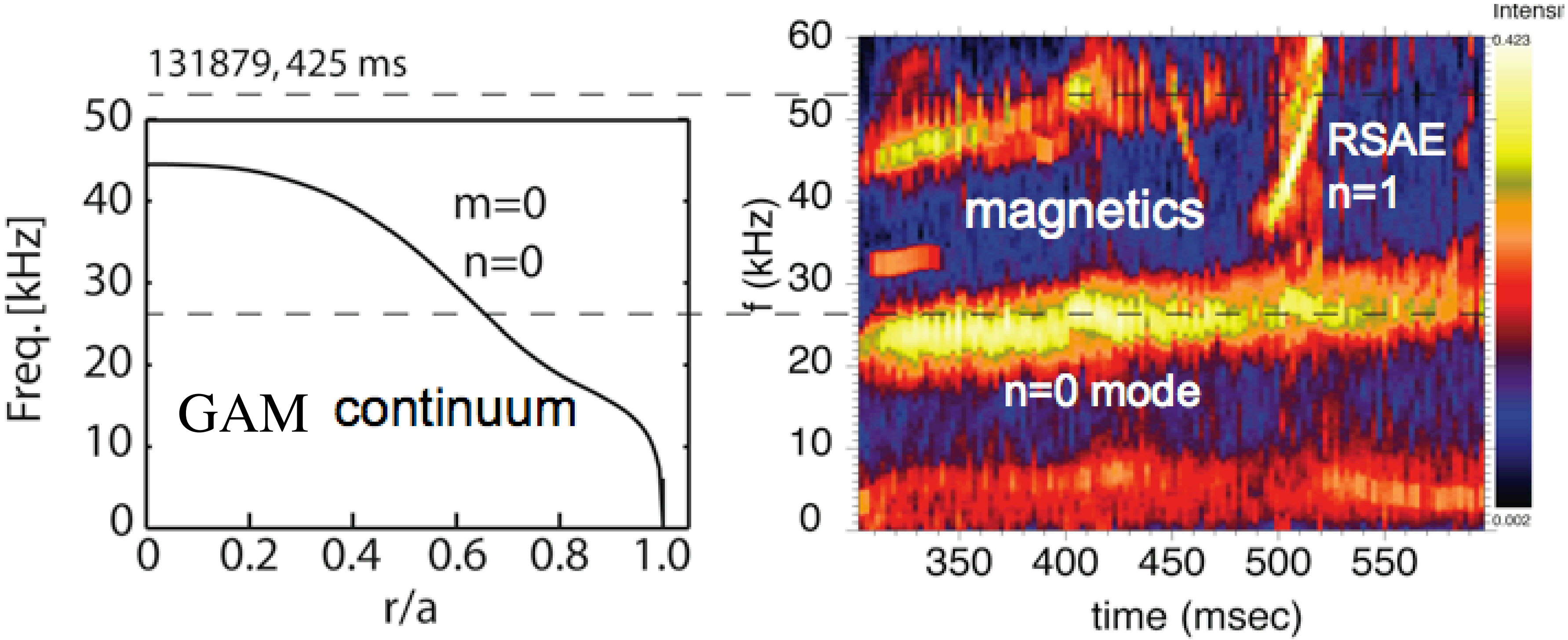
- From the frequency spectra of these modes q_{min} prior to the sawtooth crash has been determined to be about 0.92

N.N. Gorelenkov *“Properties of reversed shear Alfvén eigenmodes in ideal MHD”*

- Kinetic treatment developed for reversed shear Alfvén eigenmodes (Alfvén cascades with downward frequency sweeping)
- Slowly varying part of the mode agrees with MHD theory



R. Nazikian *“N=0 axisymmetric mode in DIII-D”*

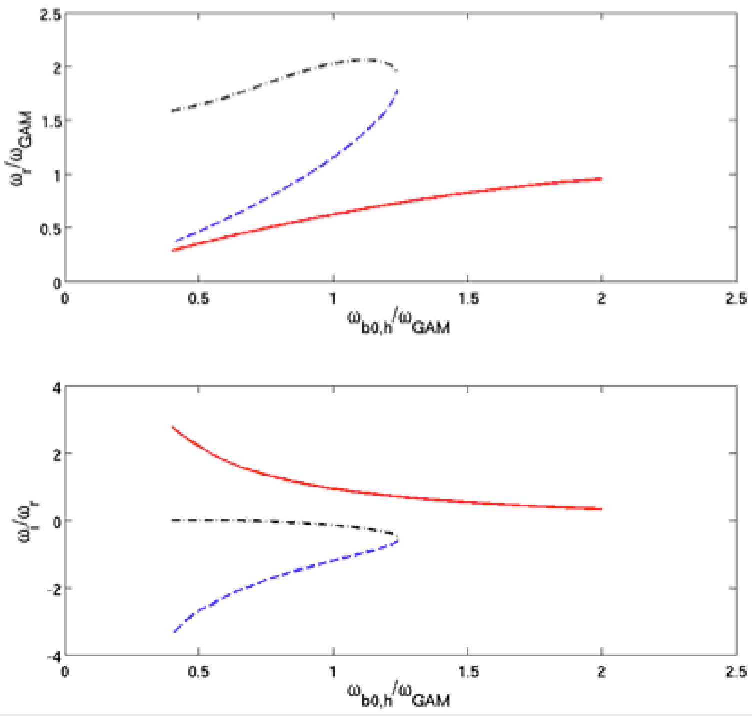


G.Y. Fu *"Energetic particle-induced geodesic acoustic mode "*

$$\frac{d}{dr}\left[\frac{<\delta P_{\|}+\delta P_{\perp}>}{\rho R^2}(q\rho_h)^2 W\left(\frac{\omega}{\omega_{b0}}\right)\right]\frac{d}{dr}E_r+(\omega^2-\omega_{EGAM}^2)E_r=0$$

$$\omega_{EGAM}^2=\frac{2(P_e+(7/4)P_i)}{\rho R^2}+\frac{<\delta P_{\|}+\delta P_{\perp}>}{\rho R^2}Q_h\left(\frac{\omega}{\omega_{b0,h}}\right)$$

There are up to three modes



GAM (black);

EGAM (blue and red)

C. Nguyen *"Theoretical and experimental study of the threshold for kinetic-MHD beta Alfvén eigenmode destabilization in Tore-Supra"*

$$\delta W_{tot} = \int d^3\mathbf{x}\frac{1}{2\mu_0}\left|\frac{\nabla_\perp\nabla_\parallel\psi_\omega^m}{-i\omega}\right|^2 - \frac{1}{2}\int d^3\mathbf{x}\frac{ne^2}{T_{i,eq}}\left[\frac{\omega_A^2}{\omega^2}\Lambda^2(\omega)\,\rho_i^2\left|\nabla_\perp\phi_\omega\right|^2 - k_\theta^2\rho_i^4 s^2 Q^2\left|\nabla_\perp^2\phi_\omega\right|^2\right]$$

Mode structure

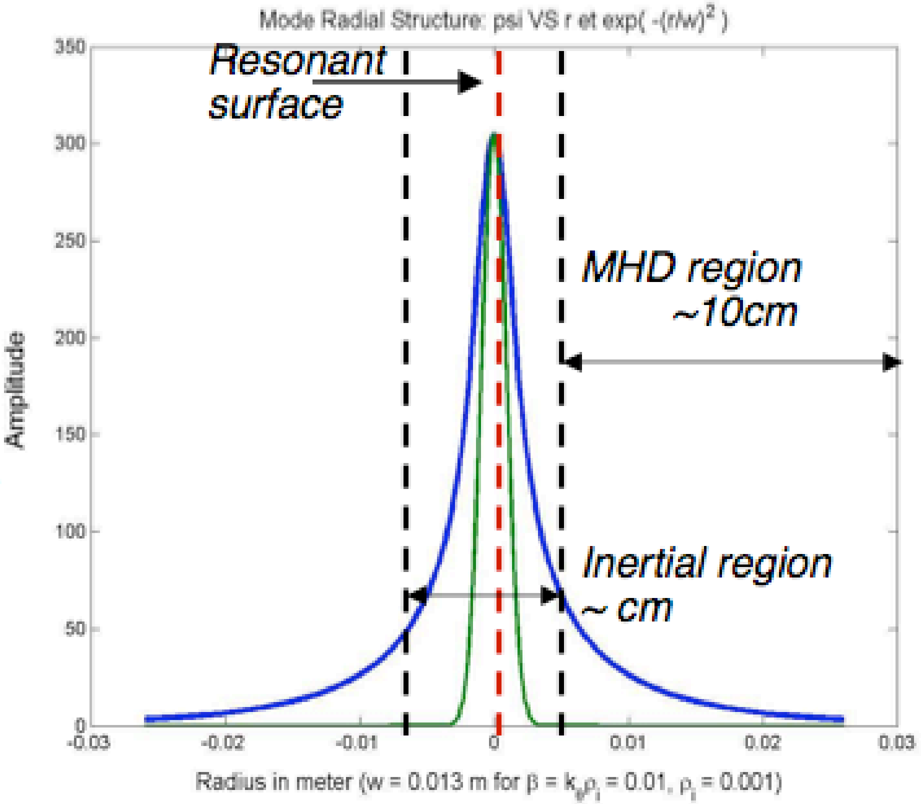
MHD + Inertial part

Asymptotic matching in real space:

$$-2Q^{1/2}\frac{\Gamma(\frac{3}{4}-\frac{\Lambda^2}{4Q})}{\Gamma(\frac{1}{4}-\frac{\Lambda^2}{4Q})} = \delta\hat{W}_{MHD}$$

$\Lambda^2(\frac{\omega}{\omega_A},\frac{Te}{Ti})$ Lower order inertia

$Q(\frac{\omega}{\omega_A},\frac{Te}{Ti})$ FOW



Mode real frequency

$\Lambda^2 = 0$ BAE usual formula: $\omega = \frac{v_{Ti}}{R}\sqrt{\frac{7}{2}+\frac{T_e}{T_i}}$

FOW correction: $\frac{\Lambda^2}{Q} = 1 + 4l,\ l = 0, 1, 2\ldots$

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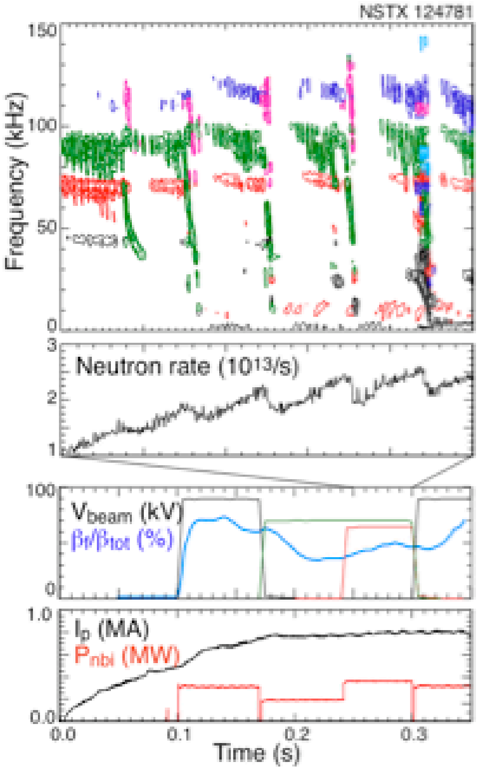
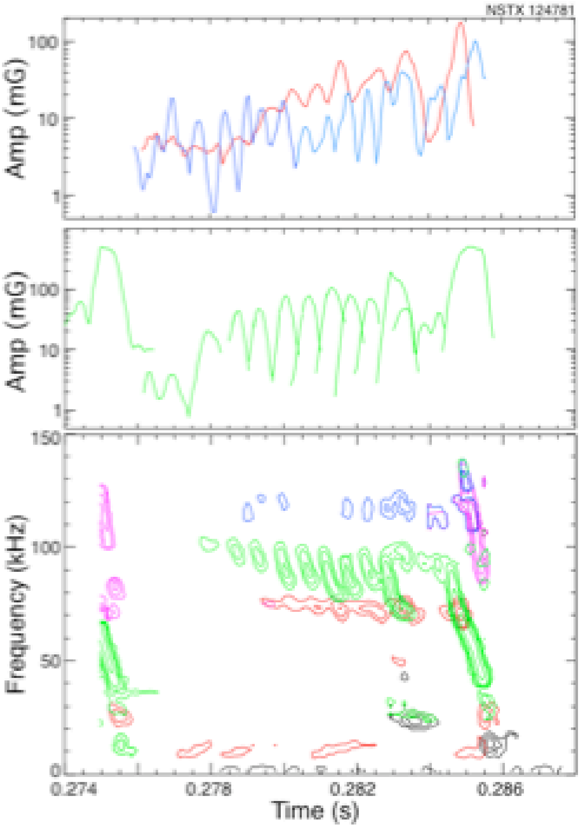
Mode amplitude increases x10 during avalanche sequence

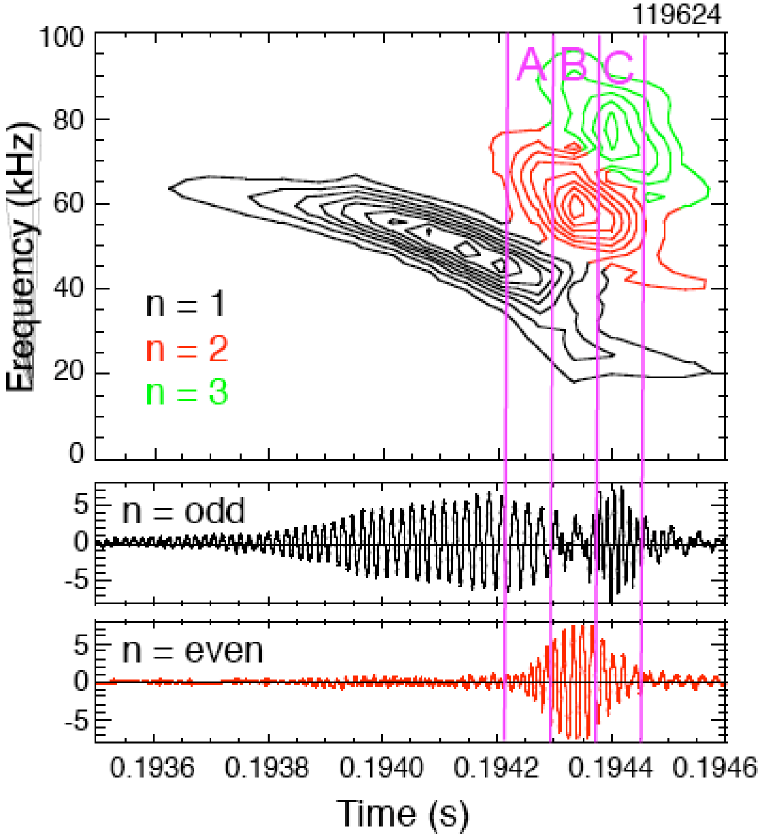


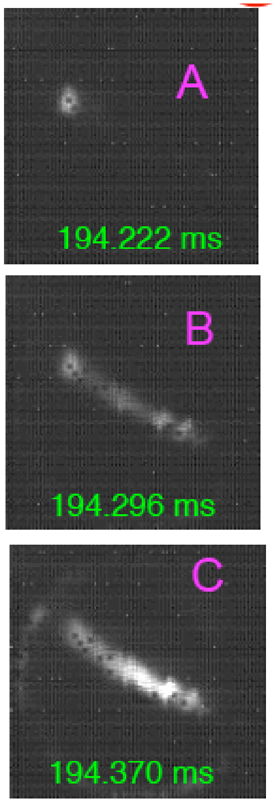
- Three independent TAE modes all show similar evolution of burst amplitude.



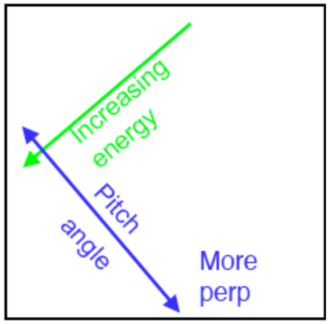
- Bursts here are weakly correlated.
- In final large bursts, TAE bursts are accompanied by EPMs, additional modes.
- TAE also show large downward frequency chirps.

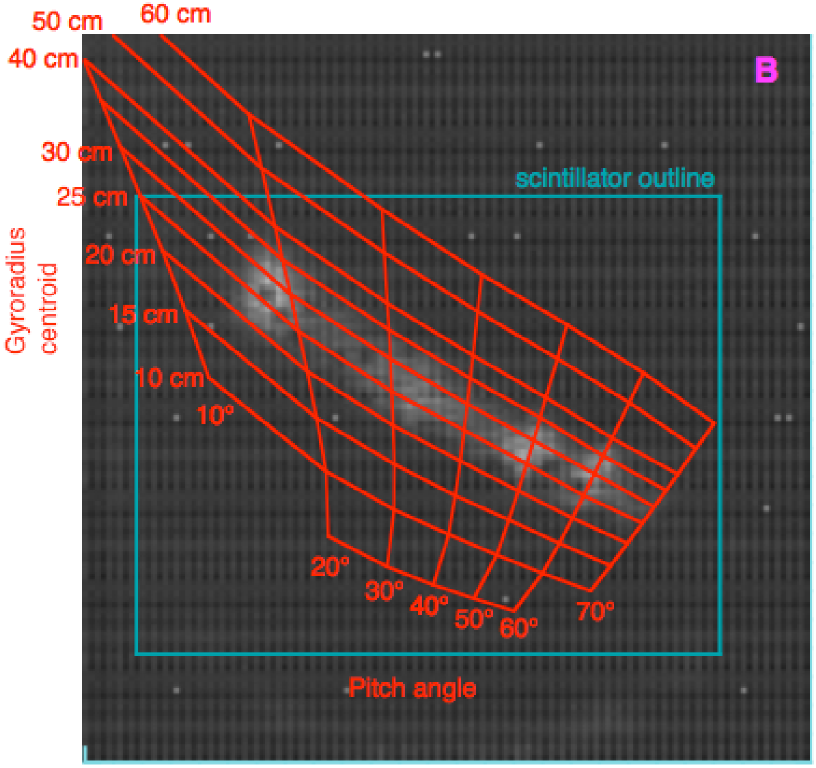
D. S. Darrow *“Neutral beam ion loss during EPMs and RSAEs in NSTX plasmas”*





- ☐ Scintillator images recorded by fast videocamera
- ☐ Particles with a broad range of pitch-angles are lost when multiple modes are present



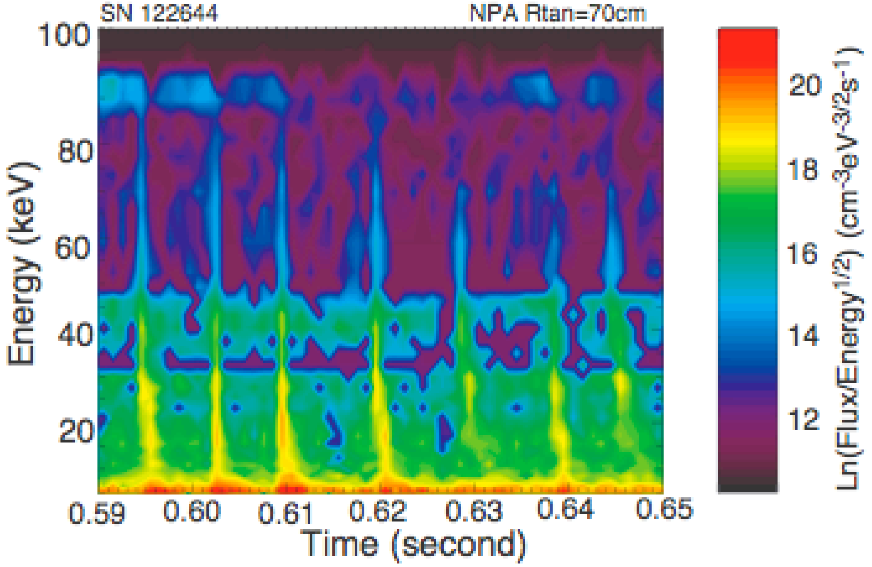


D. Liu *“Correlations of signals of neutral particle analyzer diagnostics with instability bursts”*

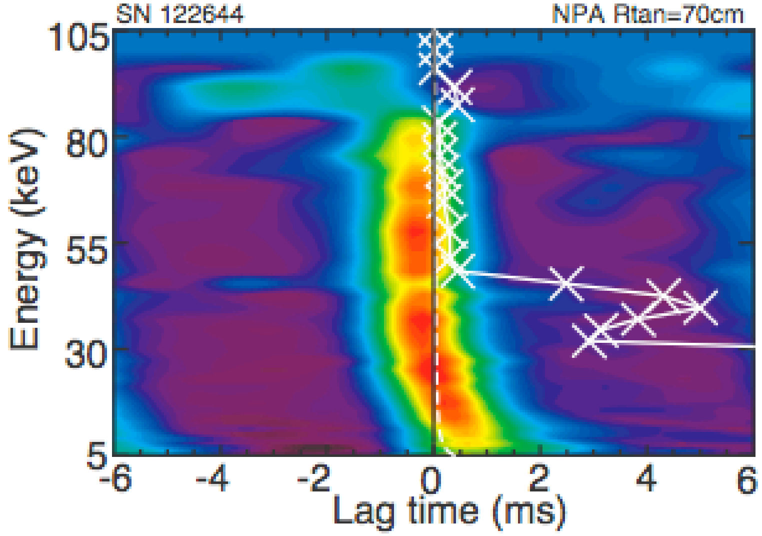
The Correlation of NPA/SSNPA Signals with Instability Bursts is Checked via Cross-correlation Function.

NSTX

Raw Data



Cross-correlation analysis



- **The normalized cross-correlations of neutron derivative and NPA/SSNPA P_{xy}:**

$$P_{xy}(l)\frac{\sum_i (x_i-\bar{x})(y_{i+l}-\bar{y})}{\sqrt{\sum(x-\bar{x})^2\sum(y-\bar{y})^2}}$$

- **Coherence technique is useful for detecting temporal correlation of NPA/SSNPA with instability bursts and makes energy dependence more obvious, but amplitude information is obscured.**

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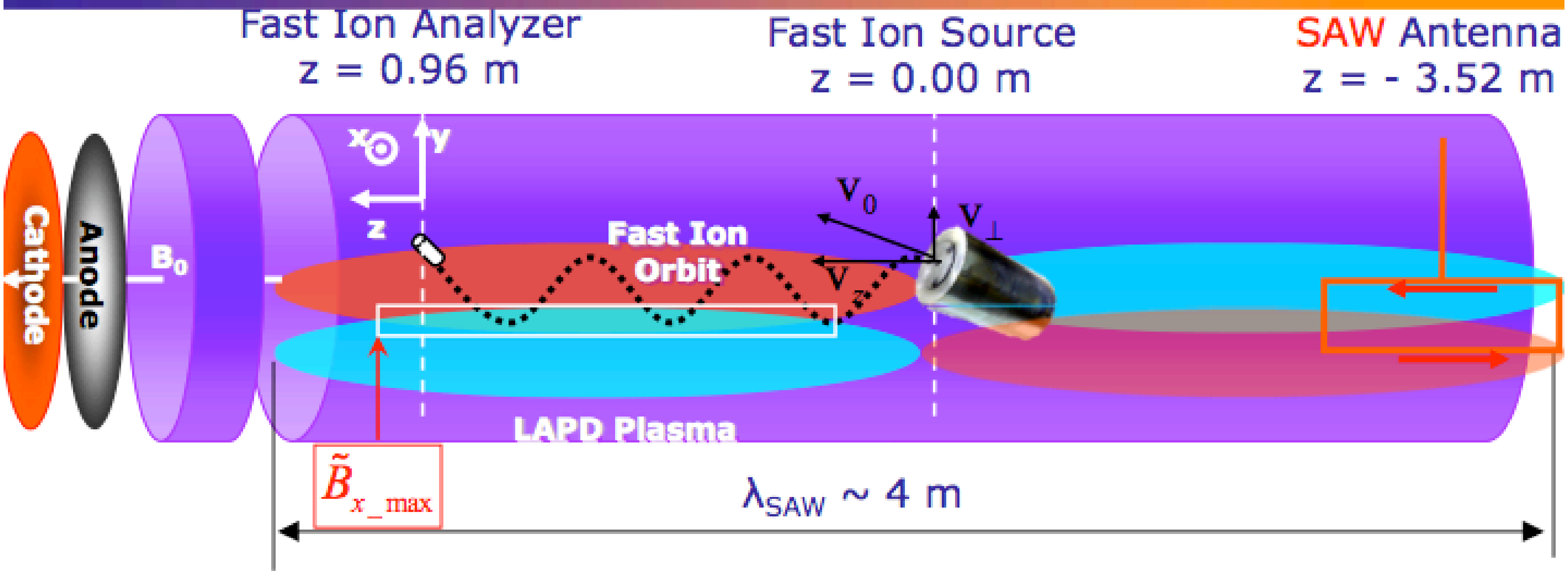
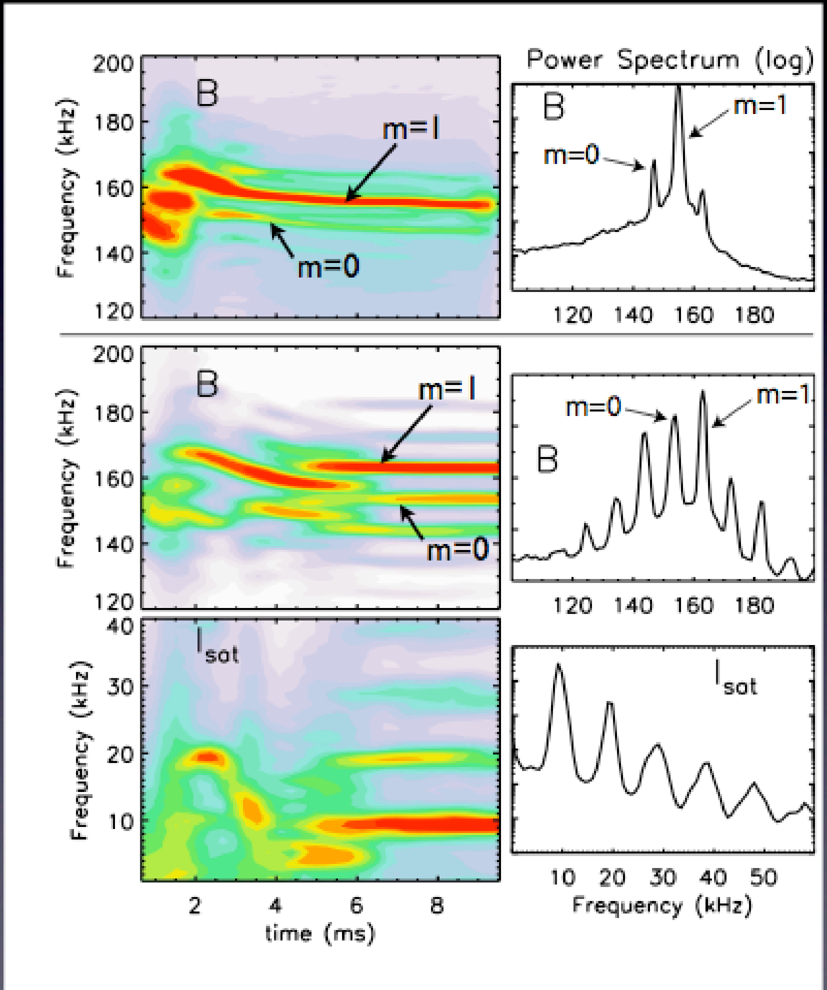
Fast Ion Alfvén Resonance Setup



- **Lithium fast-ion source** launches ~600 eV Li$^+$ beam with initial pitch angle at > 28^o relative to B$_0$
- Fast ions complete 3 - 4 gyro-periods before collected by **Collimated/Gridded fast-ion Analyzer,** with incident angle matching the initial pitch angle
- **Shear Alfvén waves (SAW) antenna** (15x30 cm) generates two interacting SAW channels // B$_0$
- Li$^+$ beam orbit overlaps partially with SAW for **wave-particle interaction**

Nonlinear interaction observed during simultaneous emission of two waves



- Simultaneous emission of large amplitude m=0 and m=1 cavity modes
- Copropagating waves beat together, generate strong nonlinear quasimode at beat frequency ($\delta n/n \sim 10\%$)
- Pump Alfvén waves scatter off of low-frequency quasimode, generating a series of sidebands
- Consistent with nonlinear Braginskii two-fluid theory (drive is nonlinear ion polarization drift)

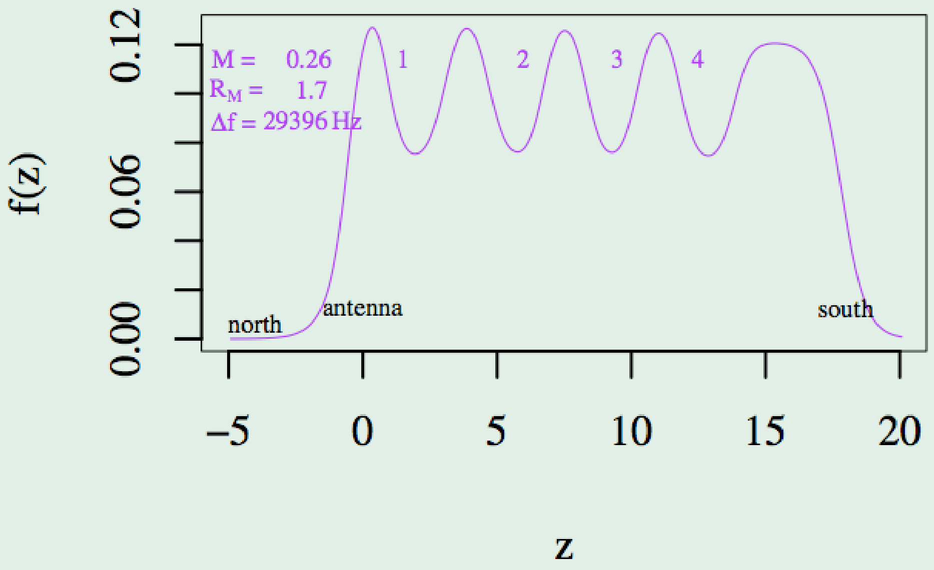
[T.A. Carter, B. Brugman, et al., PRL 96, 155001 (2006)]

J. Pratt *“Drft-wave eigenmopdes and spectral gaps in tandem mirrors”*

Eigenmode Equation

$$\frac{f^3}{|\nabla S|^2}\frac{\partial}{\partial z}\left[\frac{1+k_\perp^2\rho_s^2}{1+k_\perp^2\delta^2}\,\frac{|\nabla S|^2}{f}\,\frac{\partial}{\partial z}\right]\phi + \left[\omega^2\mu_0\rho - \frac{4\mu_0\beta}{L_p r}\,\frac{S_\theta\left(\boldsymbol{\kappa}_\psi S_\theta - \boldsymbol{\kappa}_\theta S_r/rf\right)}{|\nabla S|^2}\right]\phi = 0$$

Model of the modulated LAPD field



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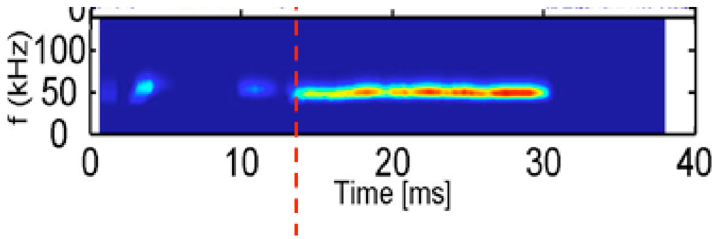
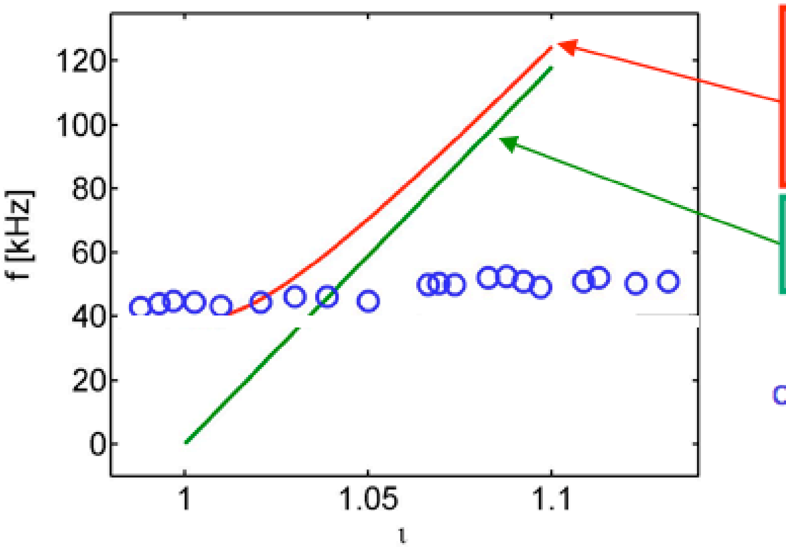
C. Deng (presented by D. Brower) *“Fast-electron-driven instabilities in the HSX stellarator ”*



For P_{ECRH} > 100 kW, mode degrades confinement,
- perturbs particle orbits leading to enhanced loss

Mode Frequency Scaling with iota (ι=1/q)



$$\omega = \left(\omega_A^2 + \omega_{GAM}^2\right)^{1/2} = \left[(m\iota - n)^2 \frac{V_A^2}{R^2} + \frac{2T_e}{m_i R^2}\left(1+\frac{7}{4}\frac{T_i}{T_e}\right)\left(1+\frac{\iota^2}{2}\right)\right]^{1/2}$$

$$\omega = \omega_{Alfven} = (m\iota - n)\frac{V_A}{R}$$

(1,1)

o: f_{mode} measured

for fixed density and temperature….

1. *no frequency scaling for (ι< 1.04) is consistent with finite pressure effects*
2. *no frequency scaling for (1.04 < ι<1.10) suggests mode is not Alfvenic…*

……..acoustic mode insensitive to iota

A. Macor *"Fast particle triggered modes: experimental investigation of electron fishbones"*

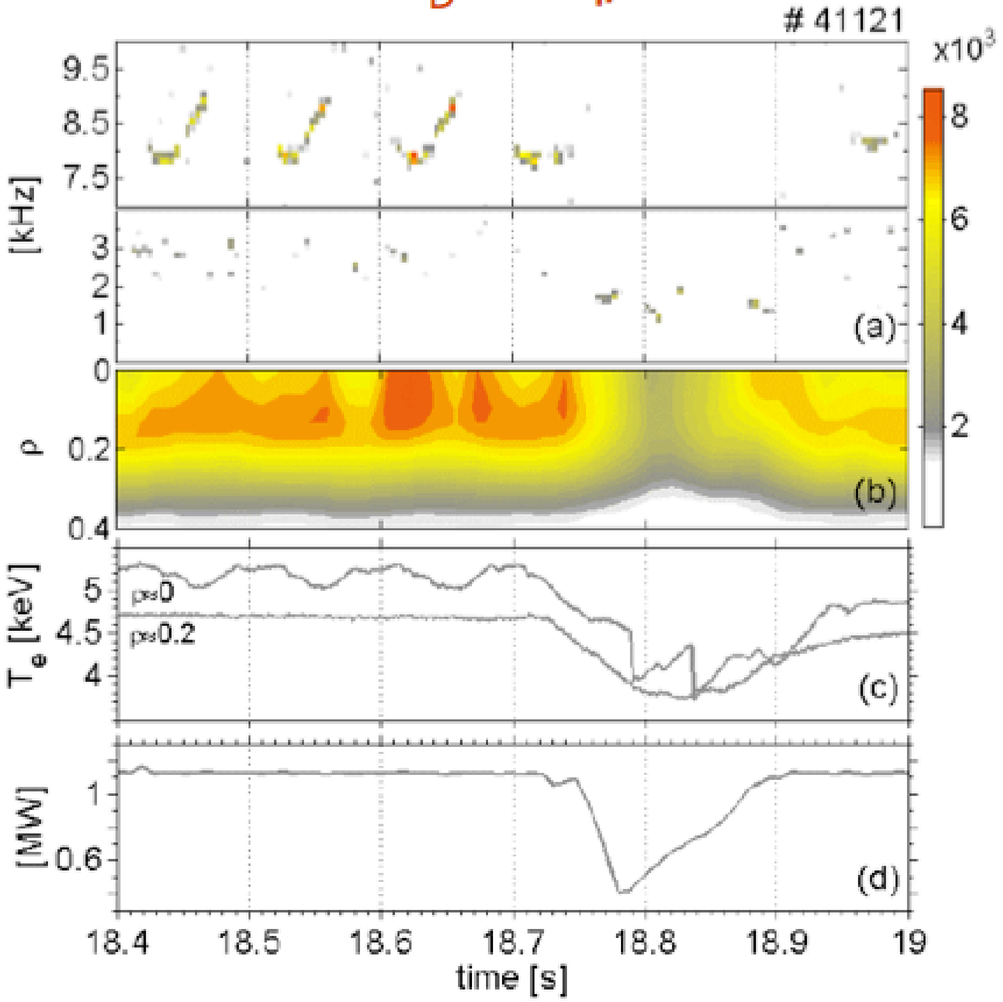
EURATOM

Evidence of precessional fishbone on TORE SUPRA

$$\omega \approx n\omega_D = nEq/rRB$$

[McGuirePRL1983]

[WongPRL2000]



Cross-ECE diagnostic
0-200 kHz range
up to 1s acquisition
$\rho = r/a = 0.2$
$R = 2.34 \pm 0.02$ m

Hard-X ray diagnostic
60-80 keV range
16ms time resolution

Standard ECE
32 channels
2cm space resolution

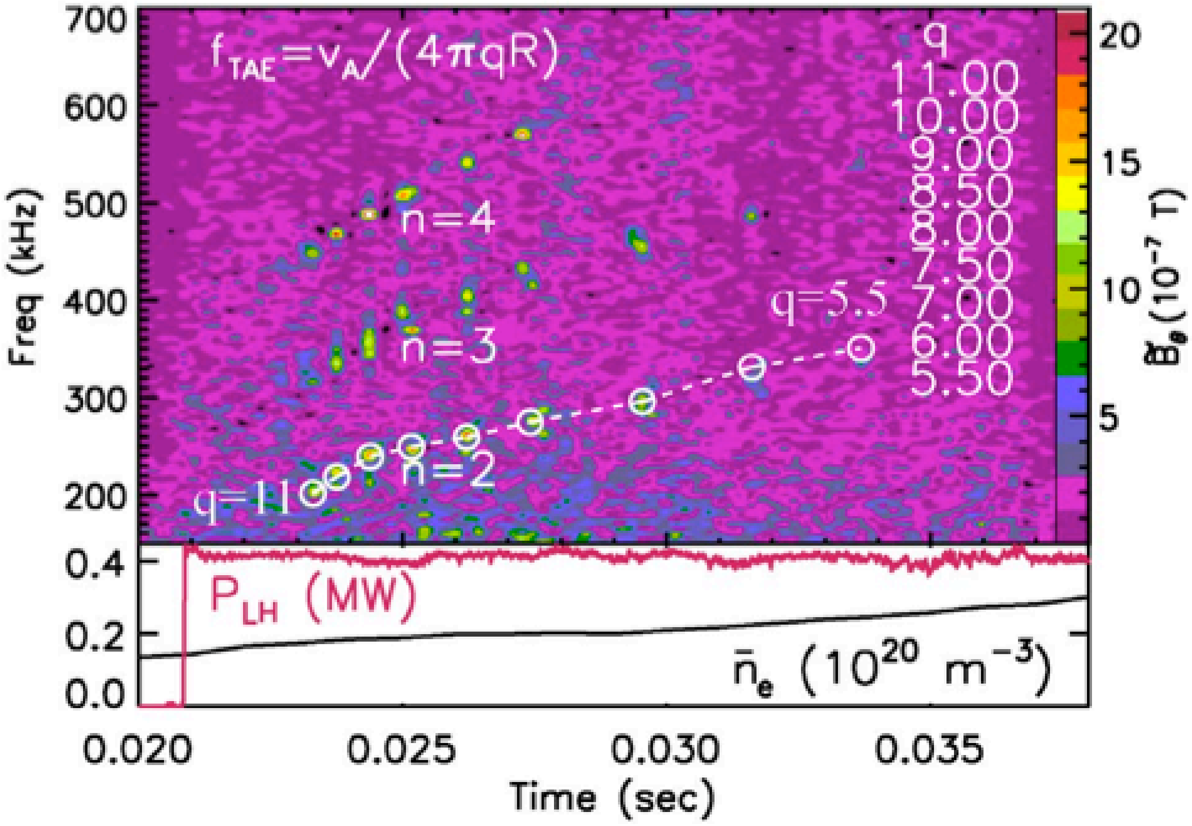
1.1 MW total LH
absorbed power

$nl = 2.3 \cdot 10^{19}$ m^{-3}
$I_p = 0.6$ MA
$B = 3.8$ T
$V_{loop} = 0.18$ V

A.Macor et al., submitted

Mode Frequencies Scale as TAEs for Intermediate q Values

Alcator C-Mod



- Mode frequencies fit well $f_{TAE} = v_A/(4\pi qR)$ for intermediate q values and bursts occur at ~ integer and half-integer q values from 11 down to 5.5
- Three frequency bands scale as n=2, 3, 4 but cannot have f_ϕ = 100 kHz!

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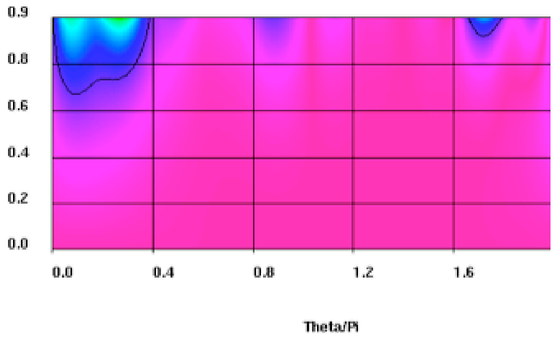
- **ITER rippled equilbria calculated with VMEC and used for alpha loss calculations**
  - Self-consistent finite β 3D model including ripple
    - future upgrades to include effects of ferritic steel inserts, RWM coils, etc.
  - Coupled to Monte Carlo alpha loss code (DELTA5D)
  - Can be extended to include turbulence/follow alphas to the 1st wall

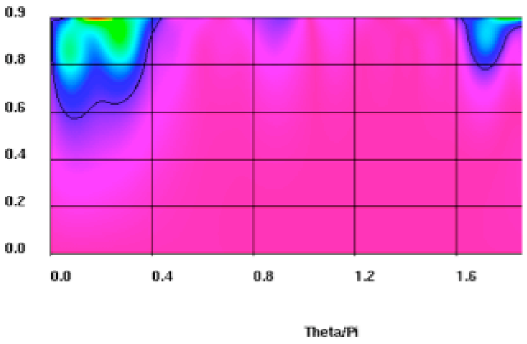
At finite β's ripple contours permeate somewhat further into core
(i.e., ripple amplification by diamagnetic currents)

note: edge ripple(δ) ~ $B_{n=18}/5$ ~ 0.2 - 1%

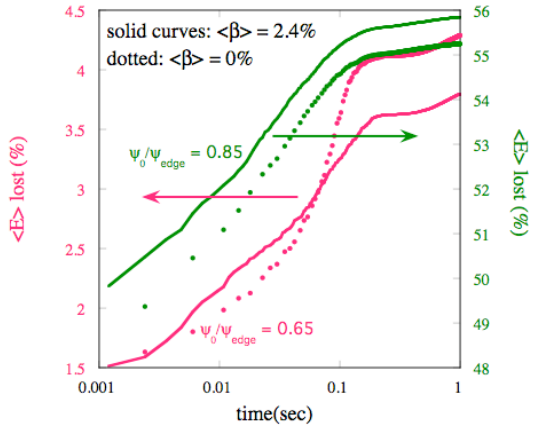
Contours of $|B_{n=18}(\theta,s)|$ for $\langle\beta\rangle$ = 0%



Contours of $|B_{n=18}(\theta,s)|$ for $\langle\beta\rangle$ = 2.4%



Variation of losses with equilibrium <β>



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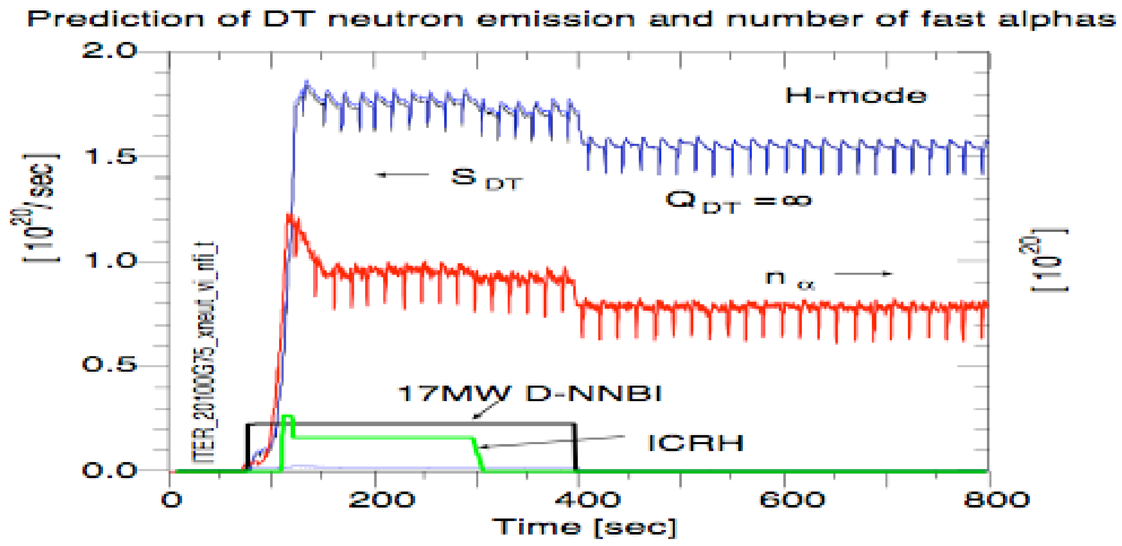
S_{DT}, n_α in a standard ITER H-mode



- Alpha heating balances losses (convection, condustion, radiation, net charge exchange)

Minor uncertainties for predicting ITER performance

- Power threshold for L⟶H (e.g., density, isotopic mass, heat source)
- pedestal T_i, T_e, density
- validity of GLF23 for T_i, T_e, and v_ϕ
- density prediction
- ash and impurity transport and recycling
- Radiation predictions
- MHD (e.g., sawteeth, ELMs, NTMs)
- atomic cross sections (e.g., 1 MeV D^0)
- anomalous fast ion transport

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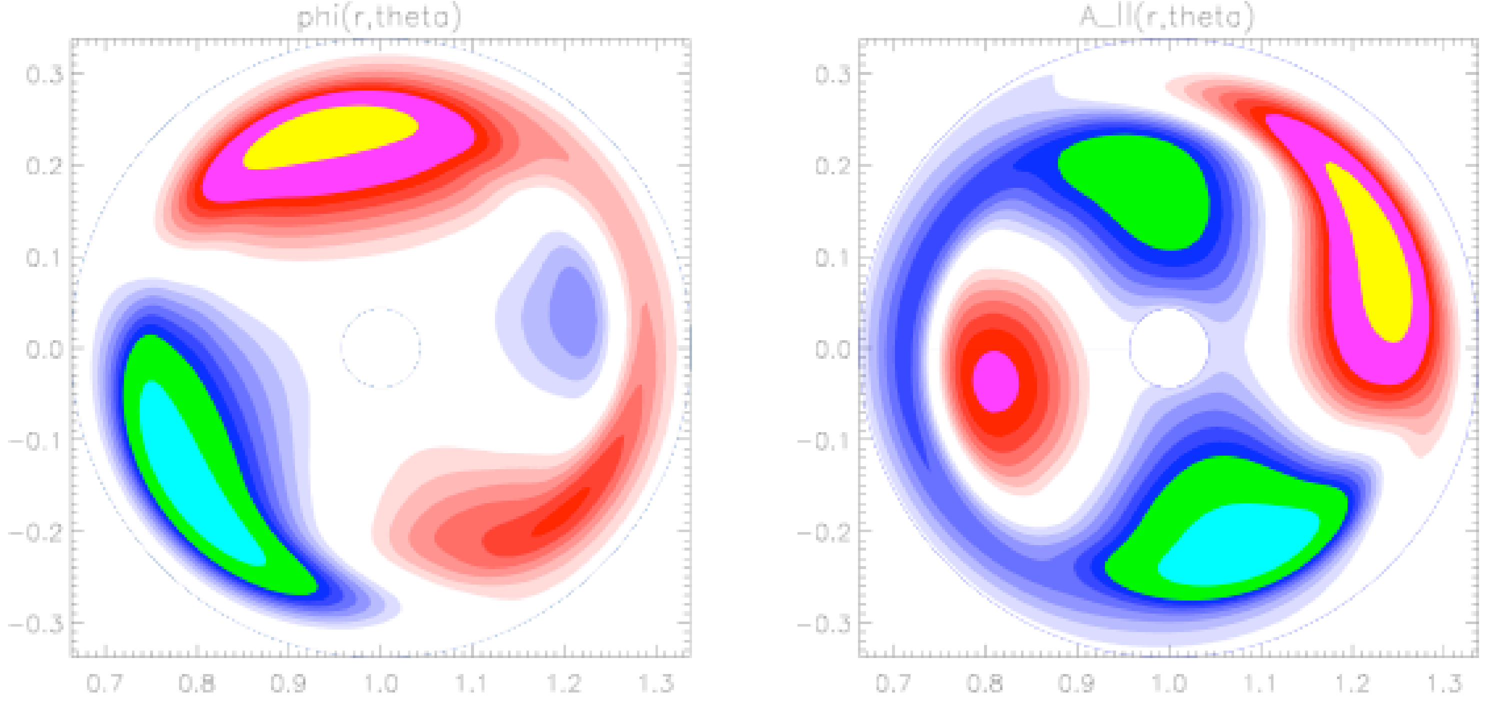
SciDAC GSEP Project

- Gyrokinetic Simulation of Energetic Particle Turbulence and Transport
- Develop gyrokinetic simulation codes for EP turbulence based on PIC GTC & continuum GYRO
- Predictive EP capability via physics simulation, verification & validation
- Participants: UCI, GA, ORNL, UCSD, LLNL
- Leverage fusion theory/experiment base programs, and other fusion SciDAC projects (e.g., GPS-TTBP, GSPM)
  - INCITE (GPS-TTBP, GSEP, CPES) computing allocation awarded
  - GSEP 2008 computer time: 2.7M hours @ORNL; 5M hours @ NERSC

With additional energetic particle drive, TAE can be excited (GTC)



- Energetic particles of $\sim 10 v_{thi}$ are incorporated. The energetic particles at the Alfven velocity resonate with the wave and excite the instability.[a]

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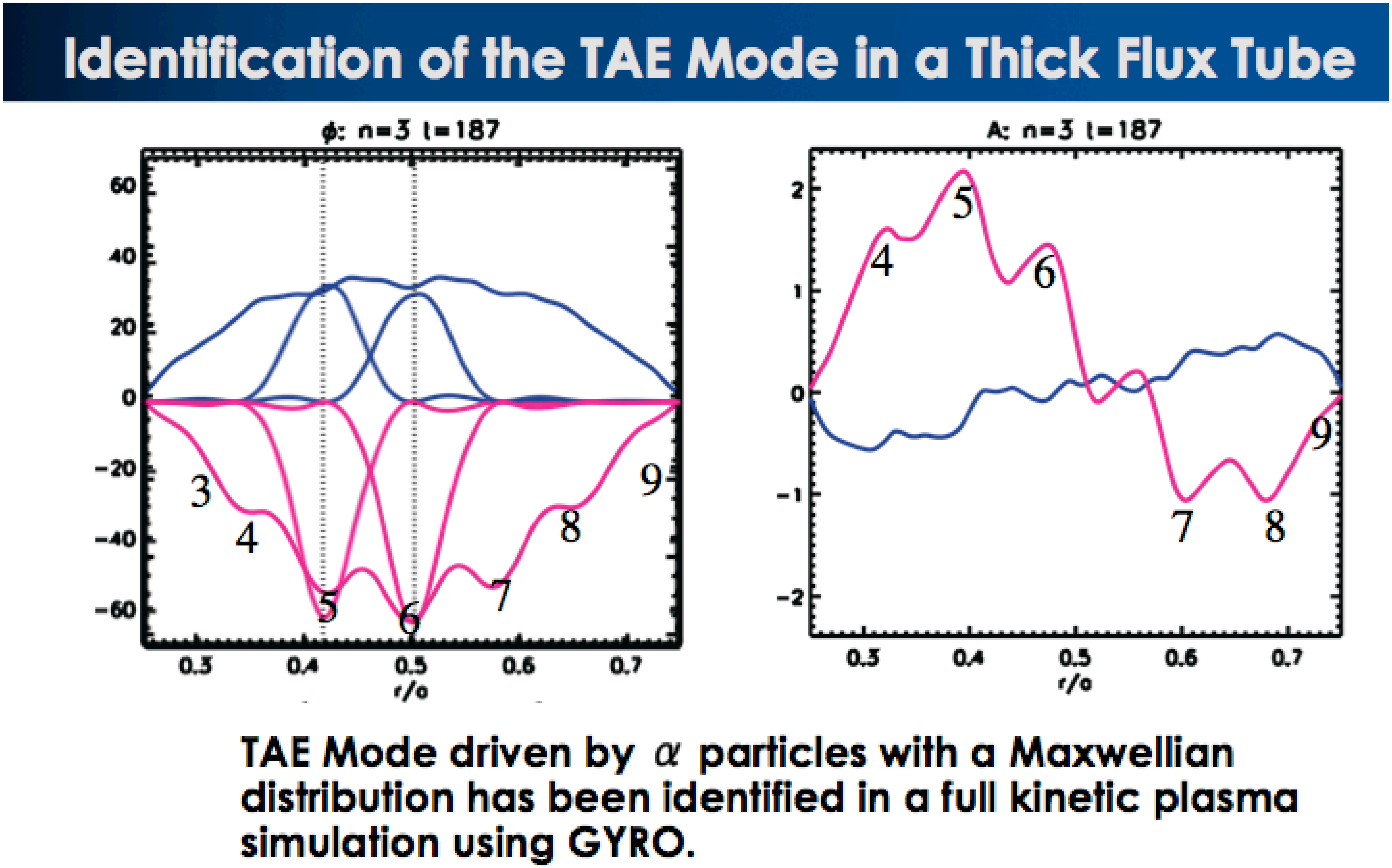
[a] *Inverse* Landau damping in this case.

M. Chu *"Gyrokinetic simulation of energetic particle driven TAE modes"*

GYRO



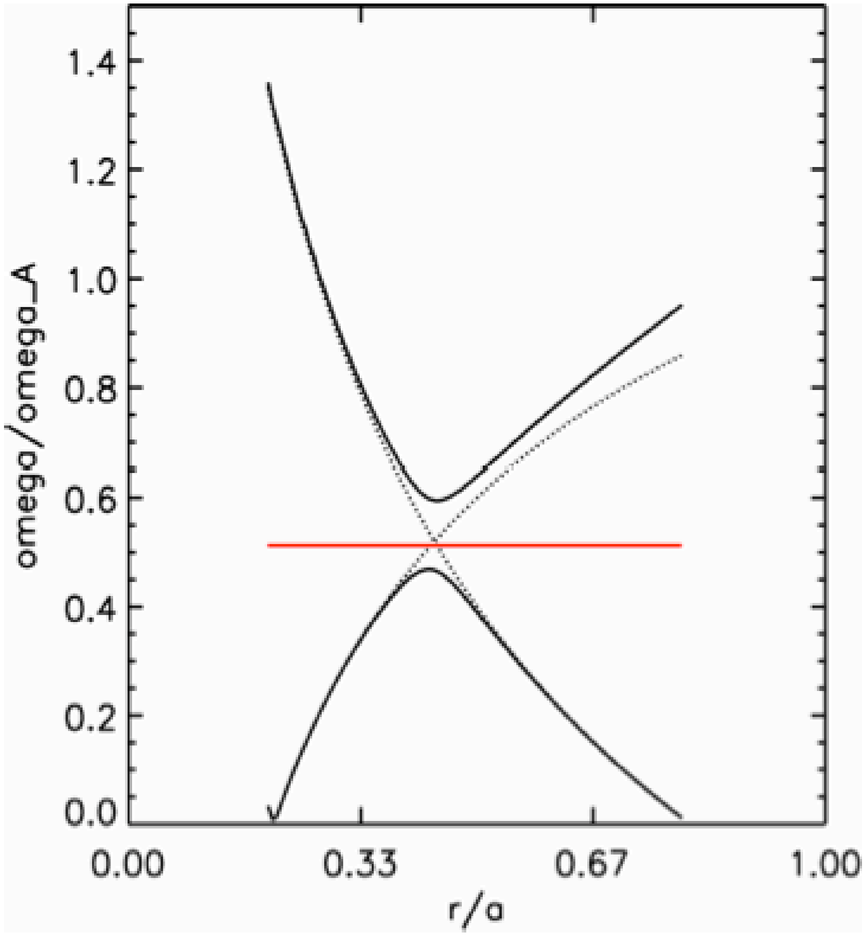
Identification of the TAE Mode in a Thick Flux Tube

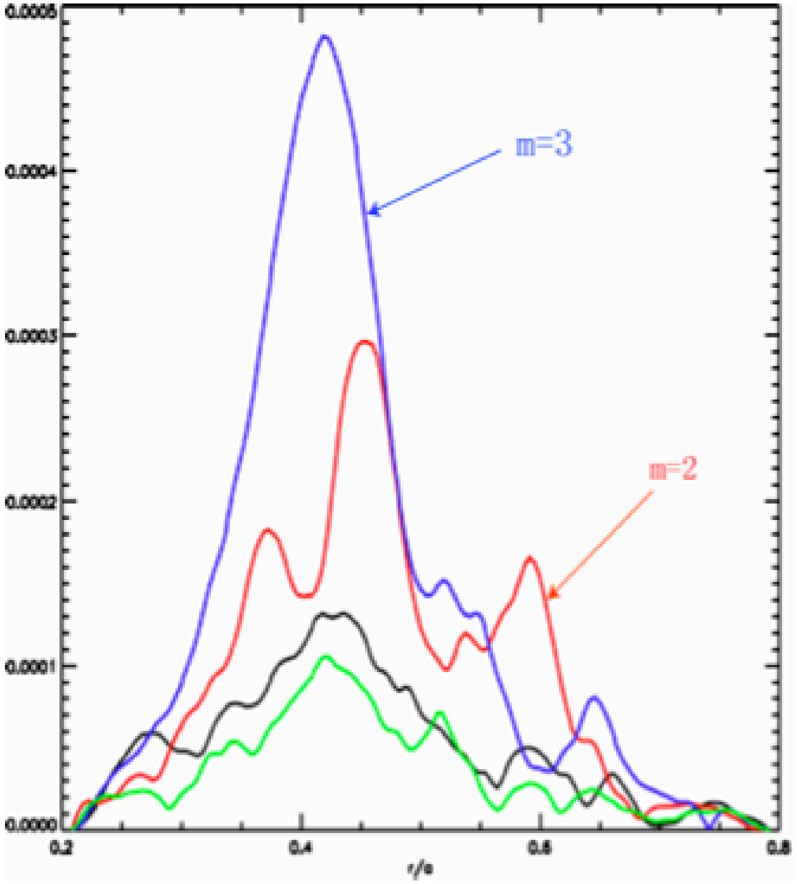
TAE Mode driven by α particles with a Maxwellian distribution has been identified in a full kinetic plasma simulation using GYRO.

J. Lang *"Gyrokinetic delta-f simulation of energetic particle driven modes"*

GEM

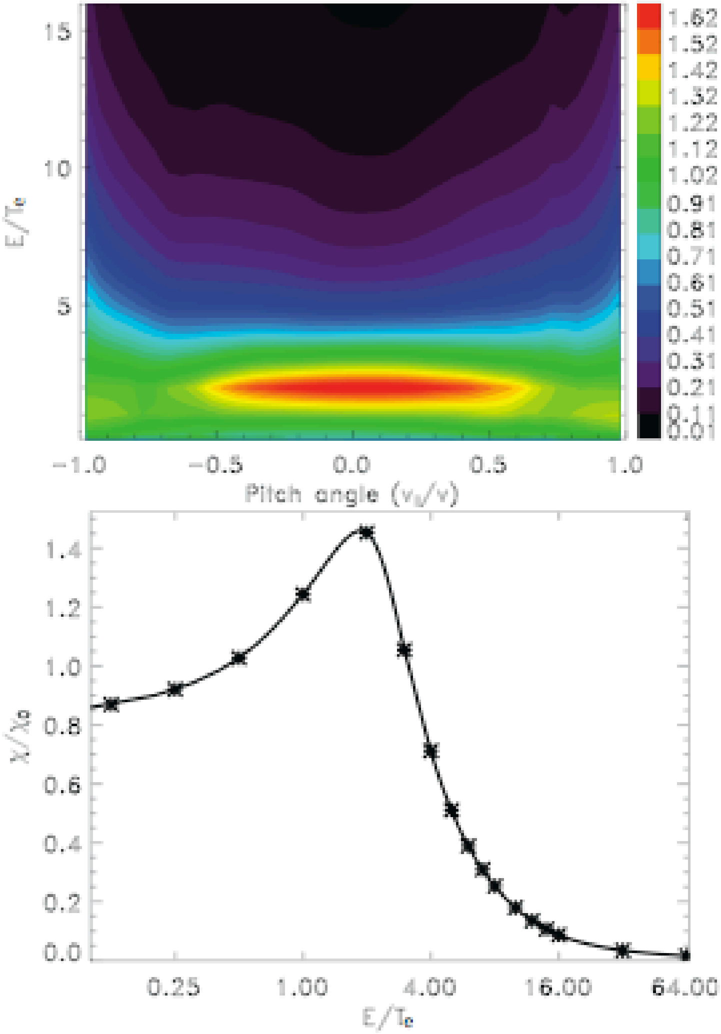
TAE frequency eigenmode observed at low β with kinetic electrons





W. Zhang *“Turbulent transport of energetic particles by microturbulence”*

Phase-space Structure of Radial Diffusivity (GTC)



Diffusivity is calculated based on random walk model

$$\chi = \frac{3D}{2}, \qquad D = \frac{<\Delta x^2>}{2\tau}$$

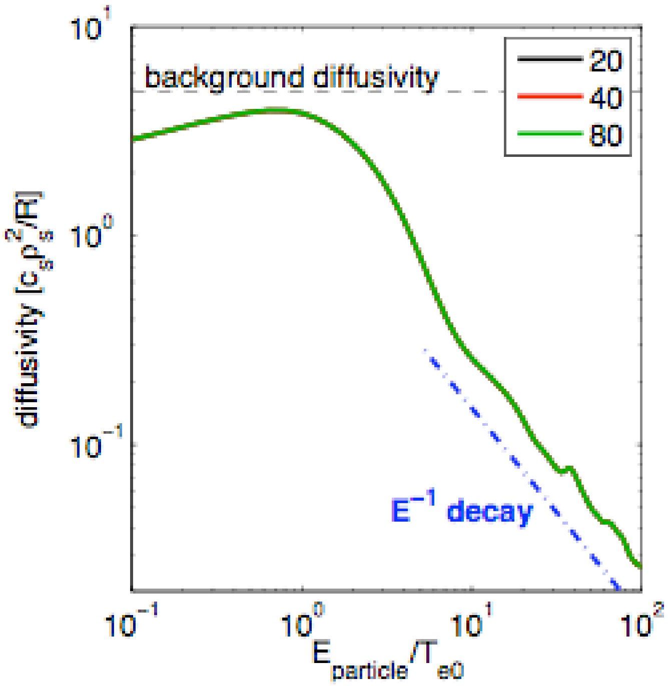
High energy transport is ignorable:

- Diffusivity decays drastically for high energy particles
- Diffusivity of $E/T_e = 16$ only $1/10$ of maximum value
- Maximum diffusivity is contributed by deeply trapped low energy resonance particles, $E/T_e \sim 2$

$$\mathcal{R} \equiv \omega - \bar{\omega}_d \propto 1 - (L_n/R)E/T_e$$

- For nonresonance particles, diffusivity of the passing particles usually larger than that of trapped particles

Beam ion diffusivity (GENE)



- shape is similar to the linearly calculated curves
- difference for higher particle energies: nonlinearly we get a $(E_{\mathrm{particle}}/T_{\mathrm{e0}})^{-1}$ decrease for $E_{\mathrm{particle}} \gtrsim 10T_{\mathrm{e0}}$