Fast ion effects on fishbones and n=1 kinks in JET simulated by a non-perturbative NOVA-KN code

TH/5-2Rb

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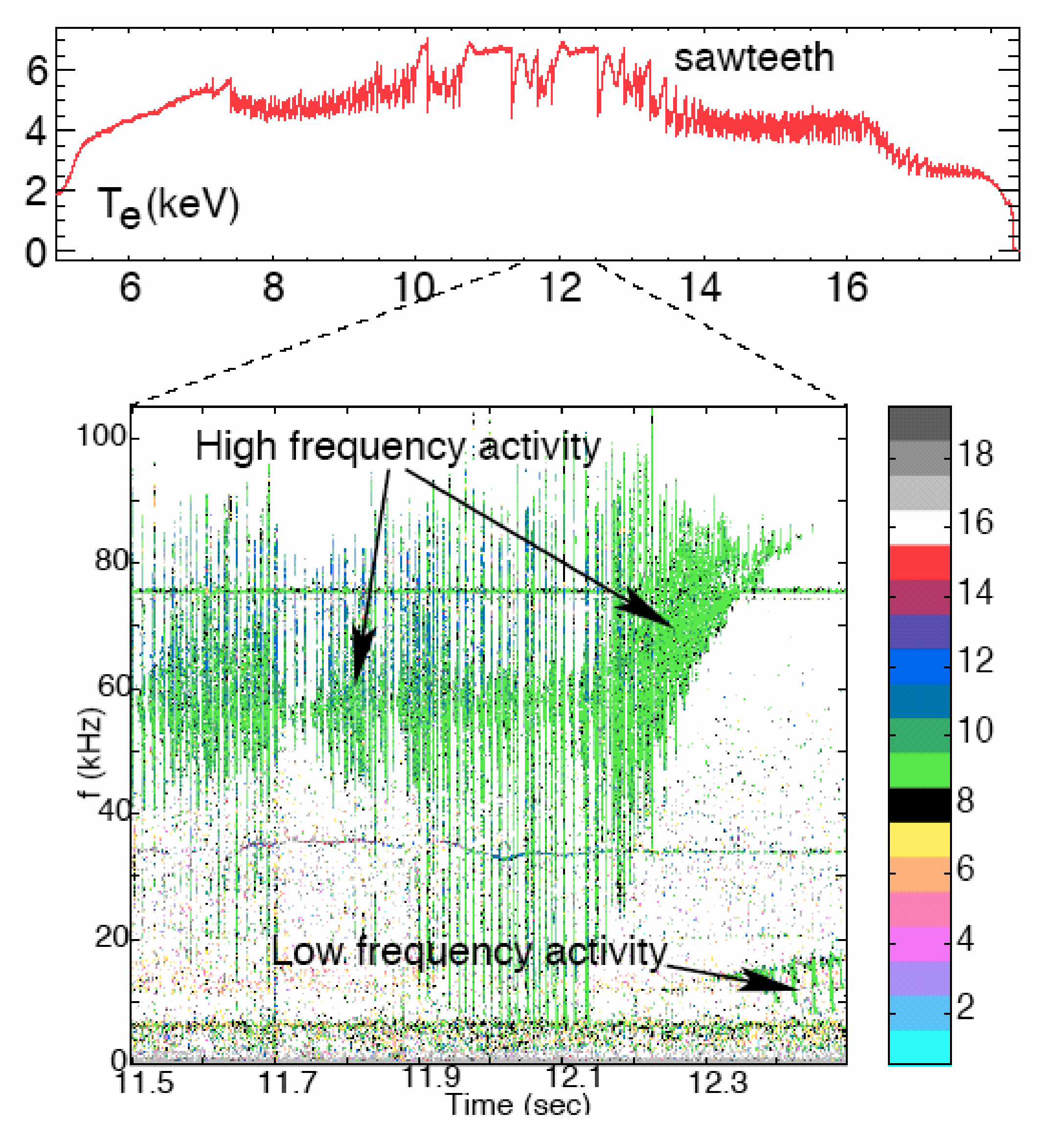
Non-perturbative kinetic-MHD code

1. Energetic Particles cause instability at frequencies not found in MHD and non-perturbative theory required.
2. Reliable kinetic-MHD hybrid code is needed.
3. NOVA-KN has been developed to include fast ion finite orbit width effect in realistic tokamak geometries.
4. n=1 modes in JET ICRH discharge (# 54285) are studied.
5. Two modes are excited by fast H-minority ions:
   I-mode: low frequency internal kink
   R-mode: higher frequency fishbone destabilized via wave- particle precessional drift resonance

JET ICRH shot # 54285

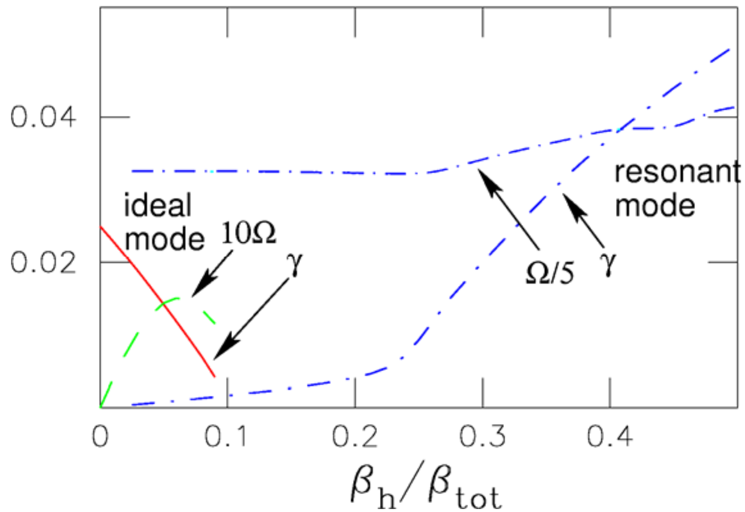


- Fast H-minority ion ($T_H \sim 1$ MeV) excites two n =1 modes in two frequency bands:
50 - 80 khz
10 - 20 khz

- What is the nature of these modes?

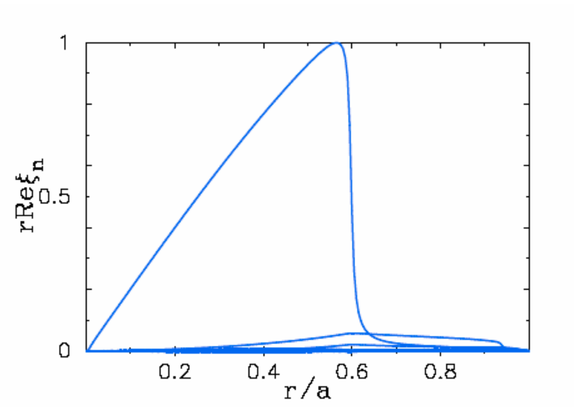
- Employ NOVA-KN to study these modes.

Eigenvalues and Eigenmodes

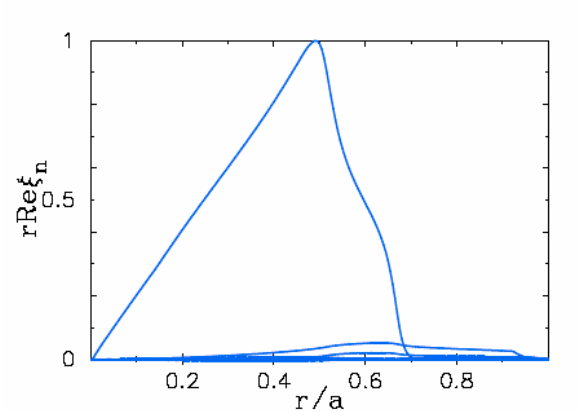


1. Low frequency I-mode stabilizes at $\beta_h/\beta_{tot} > 0.1$
2. High frequency mode excited at higher $\beta_h/\beta_{tot} > 0.2$; Observed frequency matches experiment with a doppler shift

Eigenmodes



Low frequency response ~ 2 kHz



Higher frequency response ~ 40 kHz
Structure due to separate Alfven continuum resonances

Theoretical Studies of Alfvén Wave–Energetic Particle Interactions, Th/5-2Ra

Presented by H. L. Berk 1)

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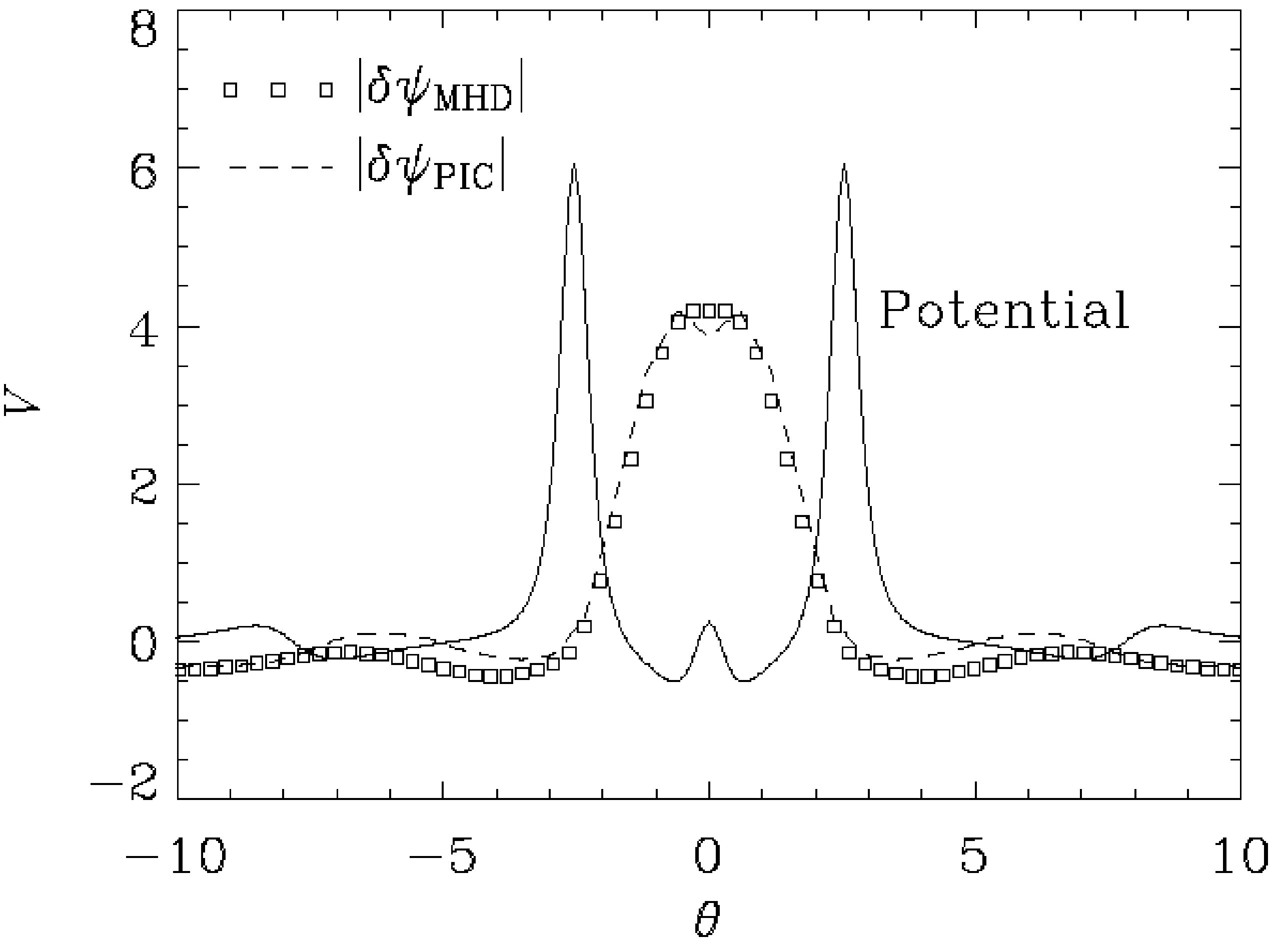
Topics Covered

- Toroidal Alfvèn Mode in Second Stability
  (Hu and Chen)
- Low Frequency Response of Cascade Mode
  (Breizman and Pekker)
- Effect of Neutral Beam on TAE’s in ITER
  (Gorelenkov and Berk)
- Spectral Determination of Internal Fields due to Frequency Sweeping
  (Berk, Gryaznevich, Pinches, and Sharapov)
- Damping Due to Kinetic Alfvén Wave
  (Fu and Berk)

α–TAE in Second Stability Regime

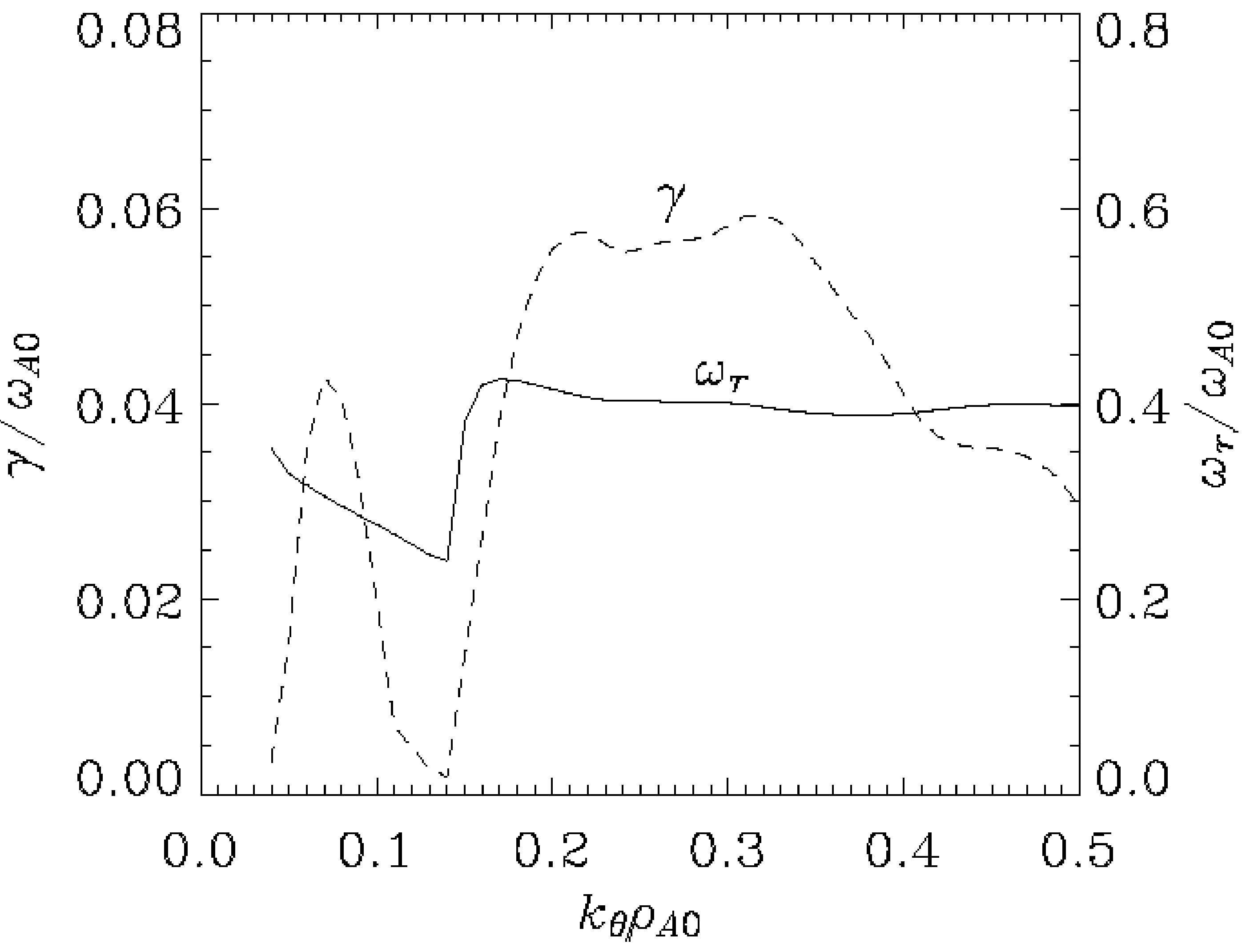
$$\frac{\left(1+2\varepsilon_0\cos\theta\right)}{\omega_{A0}^2}\frac{\partial^2\delta\psi}{\partial t^2}=\frac{\partial^2\delta\psi}{\partial\theta^2}-\left[(s-\alpha\cos\theta)^2/f^2\ \text{Š}\ \alpha\cos\theta/f\right]\delta\psi$$

$$f=1+\left[s(\theta-\theta_k)-\alpha\sin\theta\right]^2$$



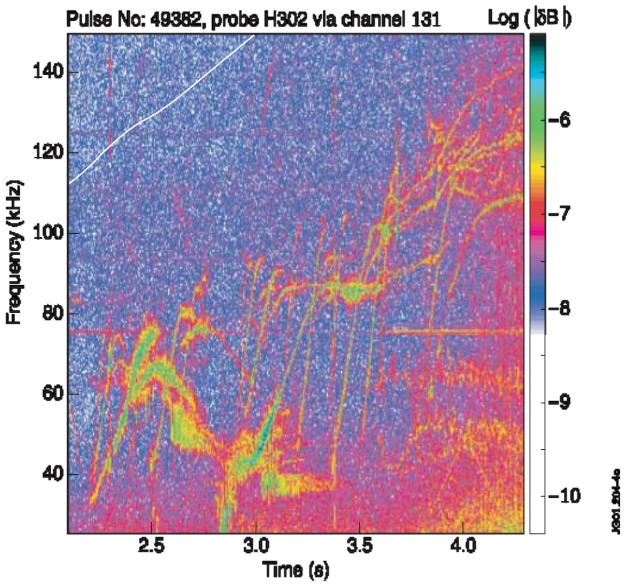
The modulation of shear along field line in second stability regime establishes a wave potential well

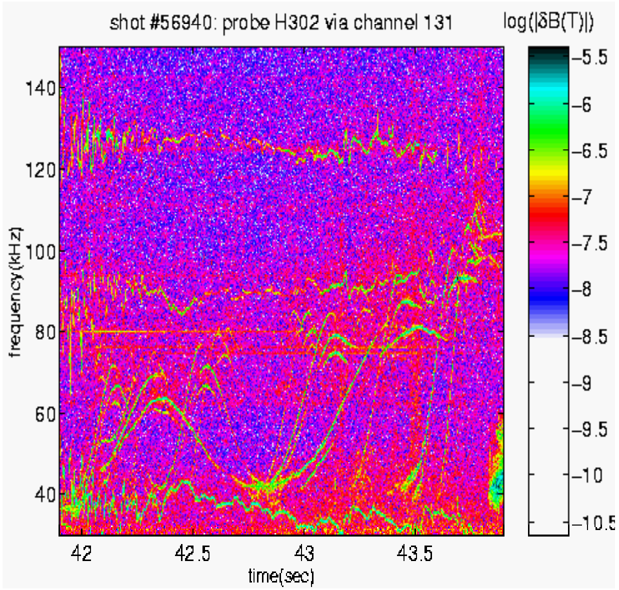
Energetic Particle Driven Instability



- Exponentially small tunneling leads to negligible continuum damping
- Energetic particles readily destabilizes mode

Why do Cascades Begin at Finite Frequency?





- Normally Cascades upshift in frequency as q_{min} decreases
- In rare events it downshifts in frequency as q_{min} decreases
- "Bowl" shape of shape of spectra suggests presence of continuum boundary

Relevant Issues

• Chu et. al. showed finite beta prevents continuum from reaching zero frequency

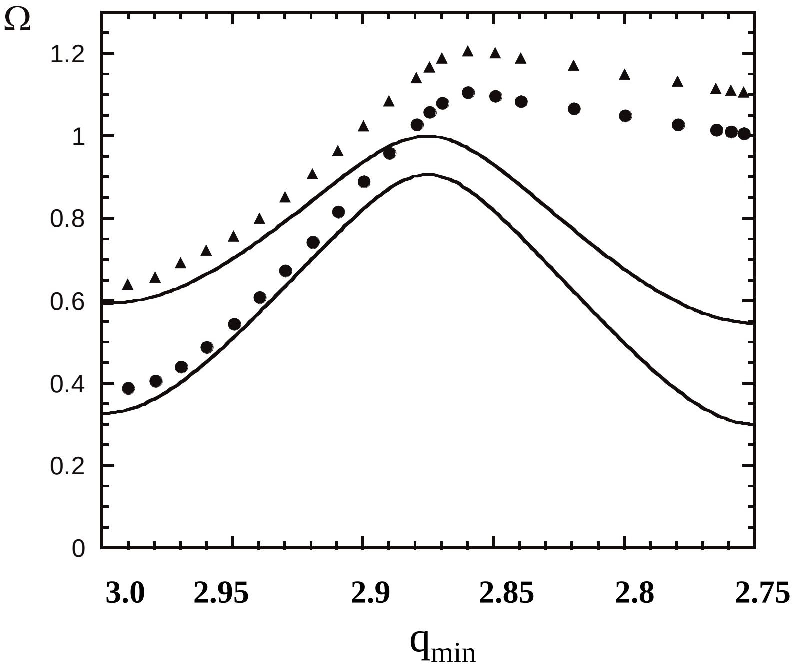
• Breizman finds most important effect at high q_{min} is plasma compressibility induced by induced by geodesic curvature which even occurs in uniform pressure plasma

•Numerical codes need to filter acoustic resonances to treat compression

•**Minimum frequency found at $\omega_{min} = \sqrt{2} C_s / R$**

•Acoustic resonance at lower frequency $\omega_{acous} = C_s / q_{min} R$ and thus induced continuum damping, as well as ion Landau damping, are important which leads to justification of the fluid treatment.

Numerical Results



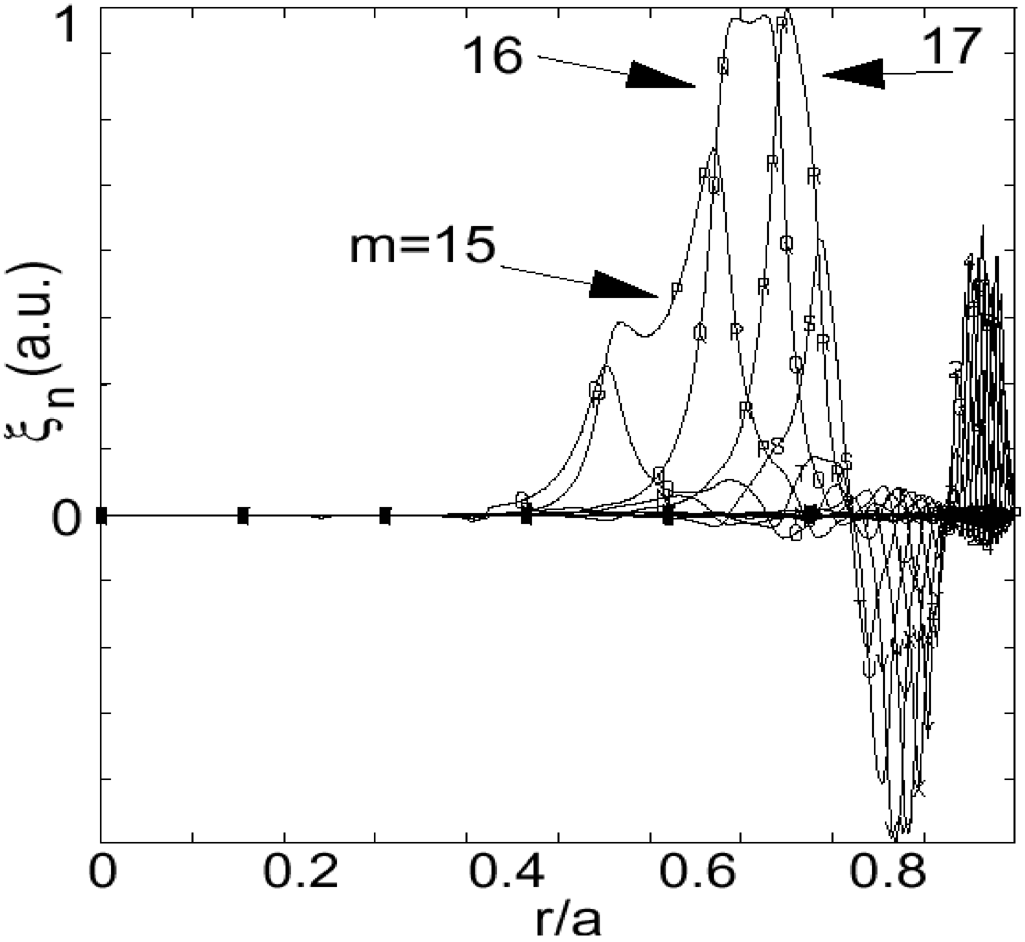
$\Omega = \omega/\omega_{TAE}$ ——— continuum curves

• $\beta = .0015$, ▴ $\beta = .005$

Effect of Neutral Beam on TAE's in ITER

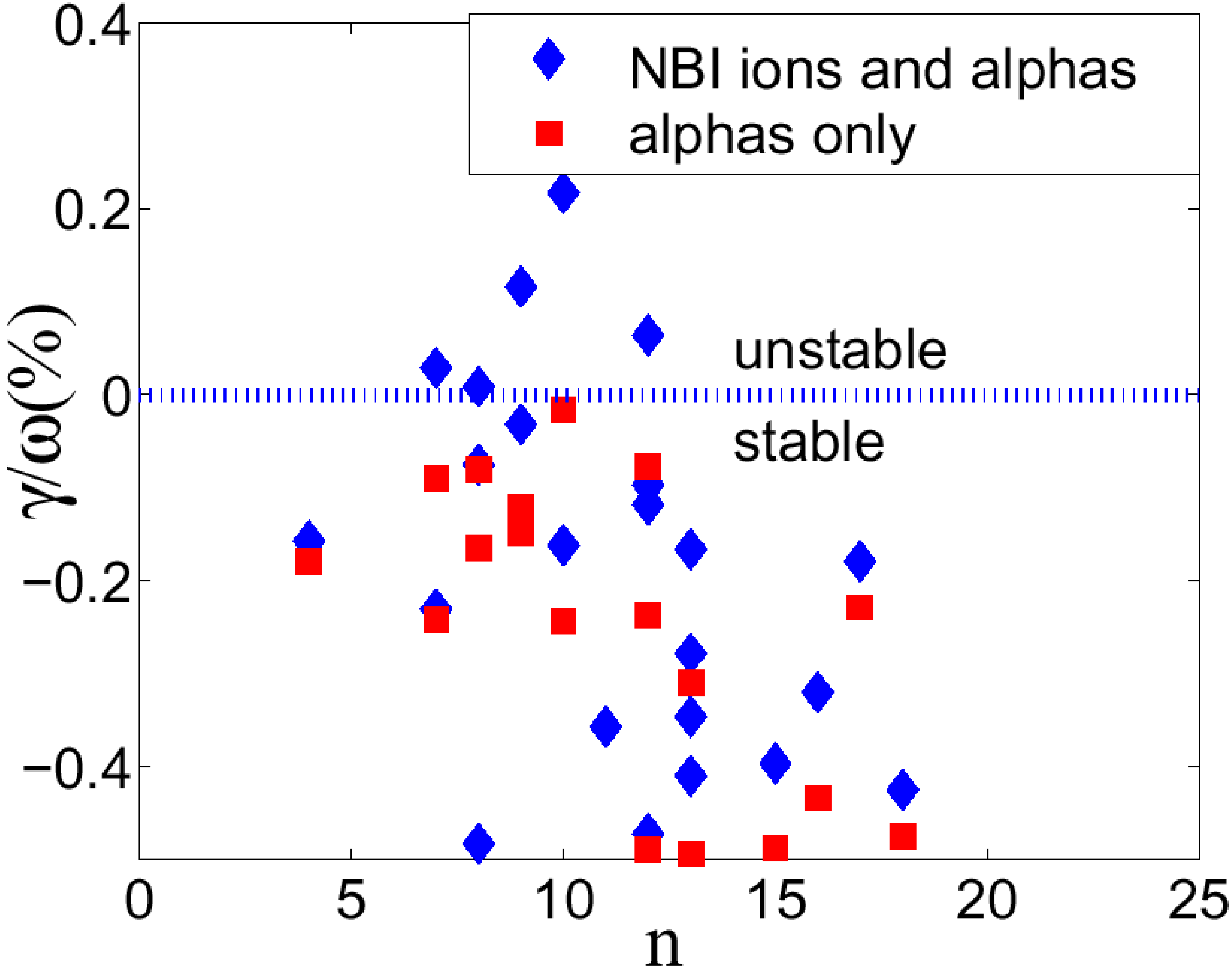
1. 1 MeV (super-Alfvenic) NBI are planned, for current drive, etc.
2. Neutral beams will have comparable instability drive as alphas
3. Current drive can cause low shear in central region
4. q-profile shape can induce global modes
5. Analytic forms for new beam distribution with pitch scattering and particle trapping calculated
6. Including neutral beam drive changes TAE stability prediction for 20kev temperature from near marginality to definitive instability prediction
7. Model quasi-linear calculation performed, predicts negligible to modest losses up to 23 kev temperature

Global Eigenmodes



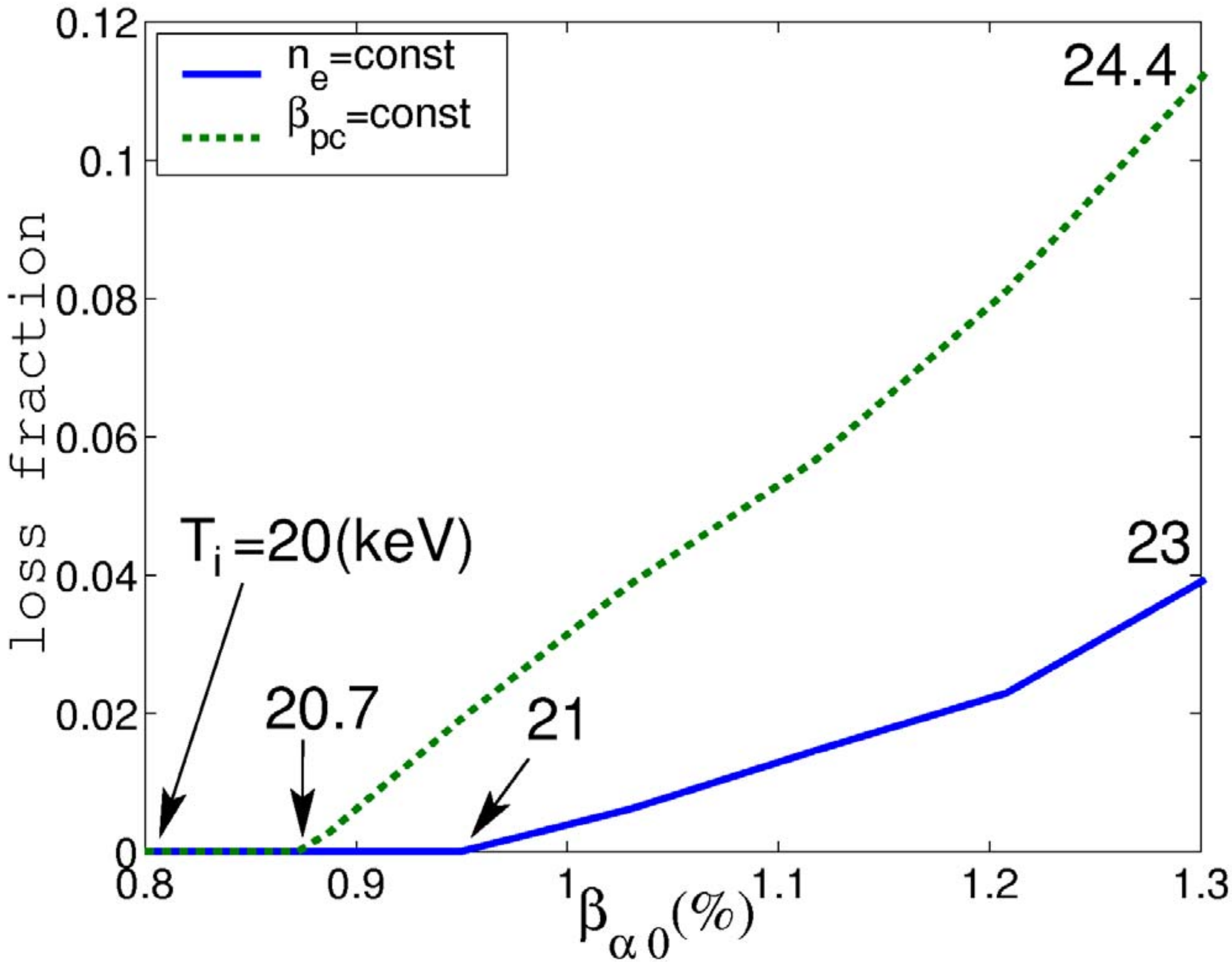
Low shear in central region prevents “propagation” of TAE “couplet” to central region where continuum damping lies

Beam Effect on Instability

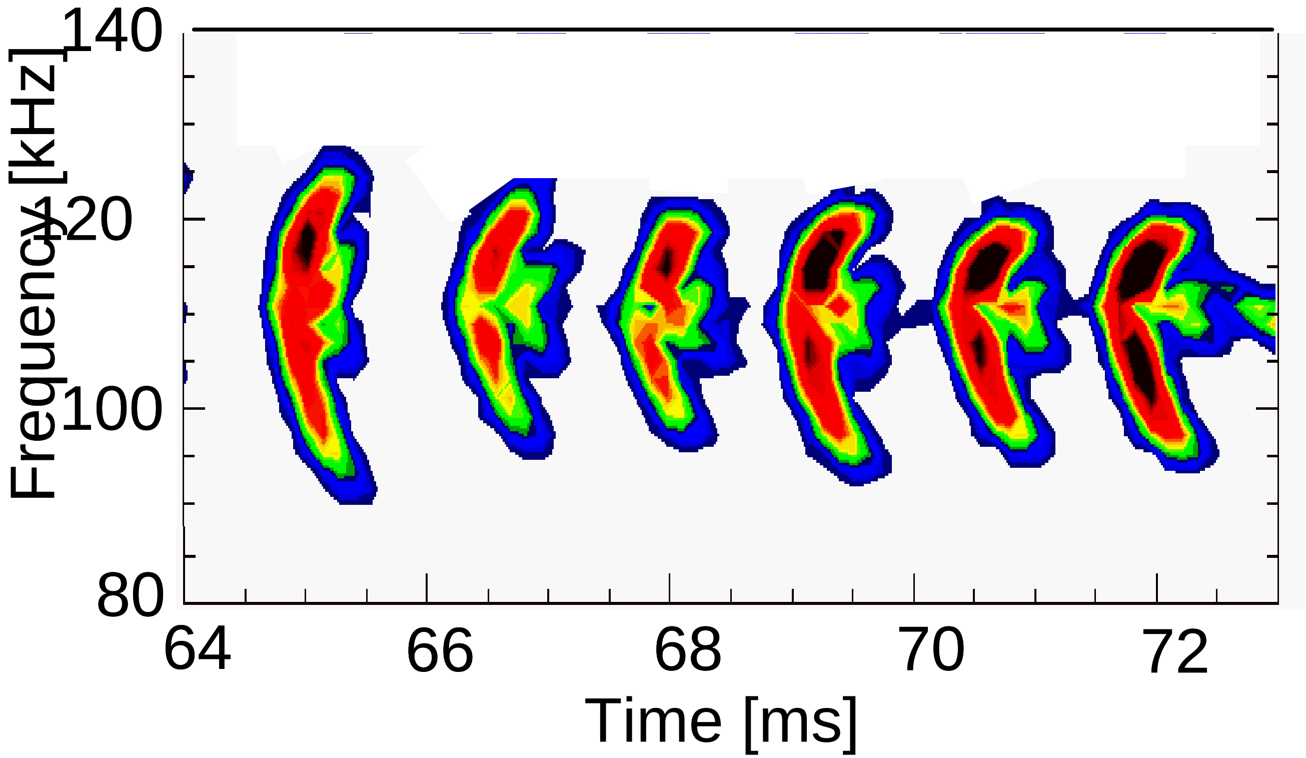


α –particle quasi-linear confinement

Result of quasi-linear model, no beams



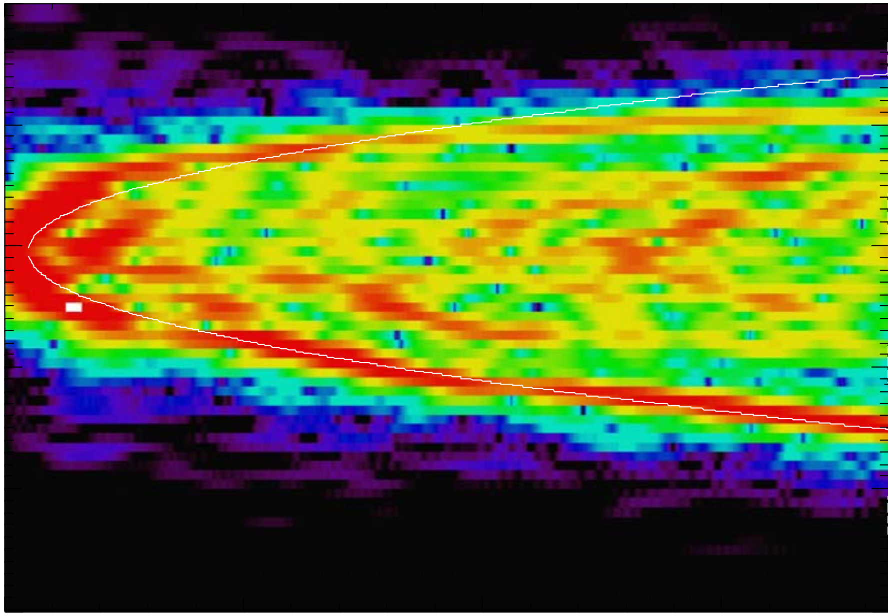
Spectral Determination of Internal Fields due to Frequency Sweeping in MAST



$$\omega_b \propto \delta B_r^{1/2}, \quad \delta\omega = C_1 \omega_b^{3/2} \delta t^{1/2}$$

Chirp rate depends on internal field; $\delta\omega \propto \delta B^{3/4} \delta t^{1/2}$

Simulation from Hagis Code



Interpretation of Sweep Signal

Mishka (eigenfunction) and Hagis (simulation) codes
Relate trapping frequency ω_b and external Mirnov coil signal to perturbed field, δB_r

Inferred maximum fields

From processing of observed frequency sweep:

$$\delta B_{max} = 2 \times 10^{-4}\ \mathrm{T}$$

From Mirnov Coil Measurement:

$$\delta B_{max} = 5 \times 10^{-4}\ \mathrm{T}$$

Damping Due to Kinetic Alfvén Wave

Model 4 th Order Equations:

$$\nabla_\perp^2 g_{Km} \nabla_\perp^2 \Phi_m + L_m \Phi_m = L_{m-1}\Phi_{m-1} + L_{m+1}\Phi_{m+1}$$

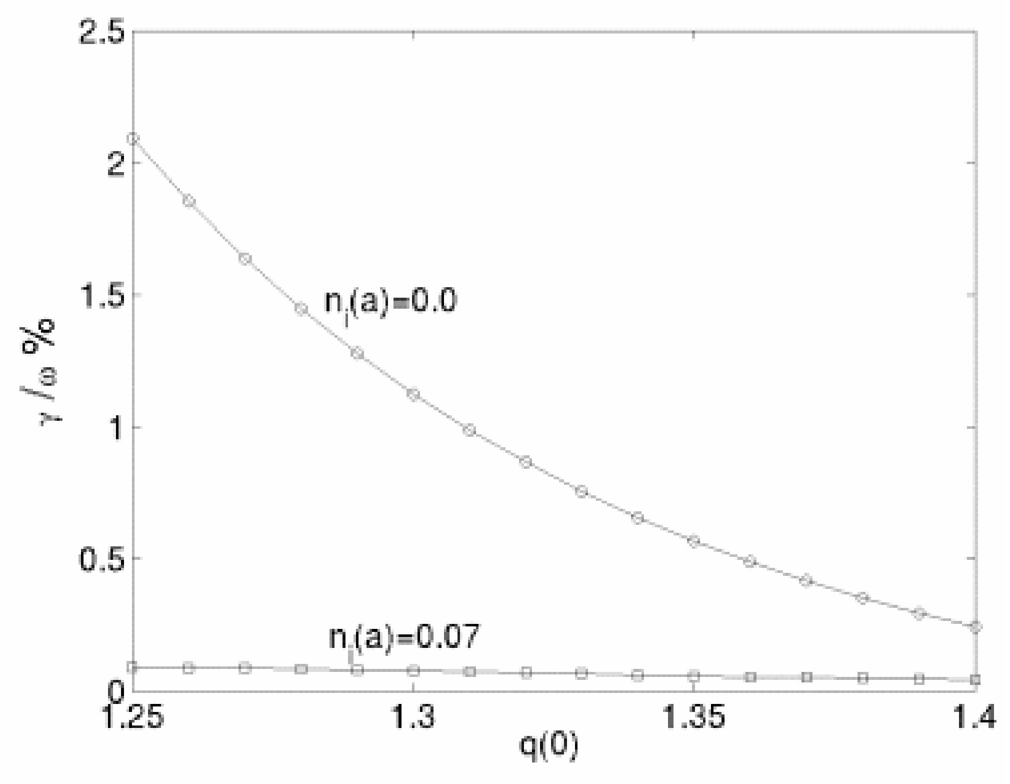
$$L_m = \frac{1}{r}\frac{d}{dr} r\left(\rho\omega^2 - k_{\perp m}^2\right)\frac{d}{dr} - \left(\rho\omega^2 - k_{\perp m}^2\right)\frac{m^2}{r^2} + \left(k_{\perp m}^2\right)'\frac{1}{r}, \quad L_{m-1} = \frac{1}{r}\frac{d}{dr} r\,\epsilon\,\rho\omega^2\frac{d}{dr} + 2\rho\omega^2\Delta'\frac{m(m-1)}{r^2}$$

$$L_{m+1} = \frac{1}{r}\frac{d}{dr} r\,\epsilon\,\rho\omega^2\frac{d}{dr} + 2\rho\omega^2\Delta'\frac{m(m+1)}{r^2}, \quad g_{Km} = k_{\perp m}^2\left[\frac{3}{8}\rho_i^2 + \frac{1}{2}\rho_s^2\left(1 - 2x_e^2 - ix_e \exp\left(-x_e^2\right)\right) - i\eta\omega\right]$$

Equations include following effects

- continuum damping made regular through resistivity,
- electron Landau damping
- mode conversion to kinetic Alfvén waves
- arbitrary ratio of Alfvén velocity to electron thermal velocity

Damping Sensitive to Edge



Density vanishing at plasma edge generally induces an edge resonance providing significant damping

No indication of conversion to KAW

Summary

- Development of Realistic MHD-Kinetic Hybrid Eigenvalue code

NOVA-KN developed, giving plausible results, applied to JET fishbones

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- Toroidal Alfvèn Mode in Second Stability

In second stability region α–TAE can be driven unstable by energtic particles

- Low Frequency Response of Cascade Mode

Finite β continuum set minimum frequency for Cascade mode ($\omega=\sqrt{2}C_s/R$)

Effect of Neutral Beam on TAE's in ITER

Neutral beams enhance energetic particle drive and may enhance global TAE

Quasi-linear model predicts a band of acceptable TAE'sin ITER (20--23kev)

- Spectral Determination of Internal Fields due to Frequency Sweeping

Frequency sweeping theory, coupled simulation used to estimate internal fields

- Damping Due to Kinetic Alfvén Wave

Damping primarily due to edge resonance interaction at edge,

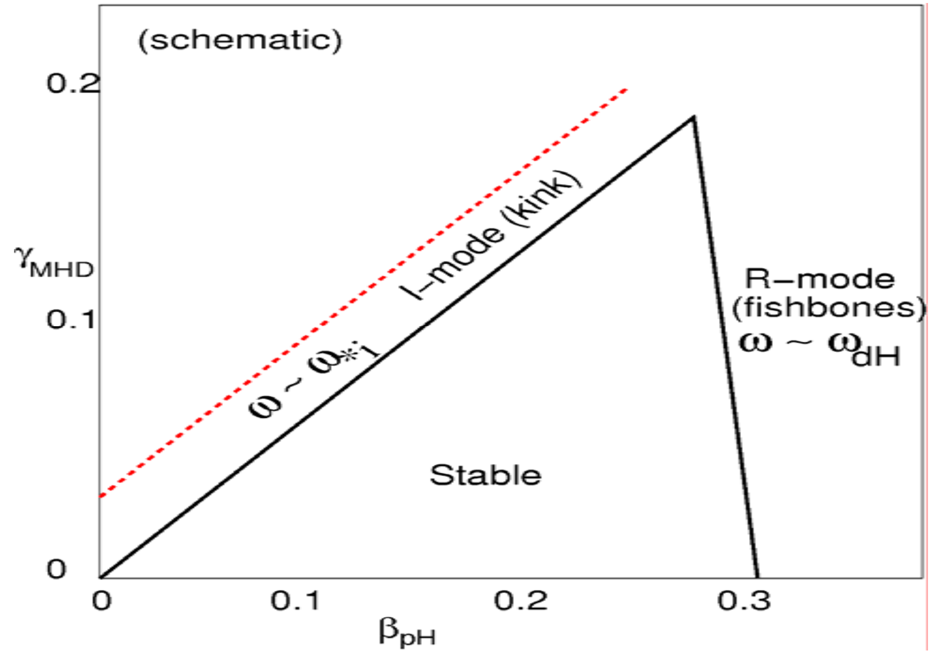
No mode conversion observed in the center

Summary

1. A non-perturbative kinetic-MHD stability code, NOVA-KN, has been developed to include fast ion finite orbit width effect.
2. NOVA-KN code has been successfully applied to study two n=1 modes (in 10-70 kHz range) in JET ICRH discharge (# 54285).
3. Two modes excited by fast H-ions (T_H = 1 MeV) are identified:
   - Low frequency (f = 10 -20 kHz) mode is identified as I-mode (internal kink modes modified by fast ions)
   - High frequency (f = 50-80 kHz) mode is identified as R-mode (fishbones destabilized by fast ion pressure gradient via wave- particle precessional drift resonance)
4. Doppler frequency shift due to plasma rotation and thermal ion diamagnetic drift must be considered to explain observed frequency.

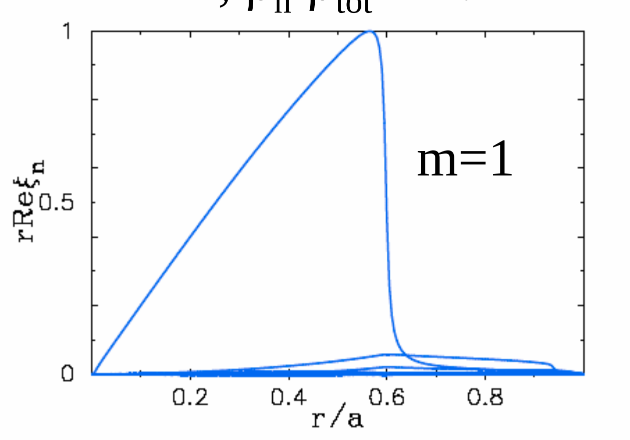
NOVA-KN Results Consistent with Theory

Theory (Chen et al., 84;
Coppi et al., ’86; Cheng, ’90;
Wu et al., ’94; Porcelli, ’01)
predicts two branches:
- I-mode, low frequency $\omega \sim \omega_{*i}$
- R-mode, high frequency $\omega \sim \omega_{dH}$



Eigenmode Structure

I-mode, β_h/β_{tot} = 0.02



R-mode, β_h/β_{tot} = 0.5