Beam Ion Driven Instabilities in NSTX

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in collaboration with
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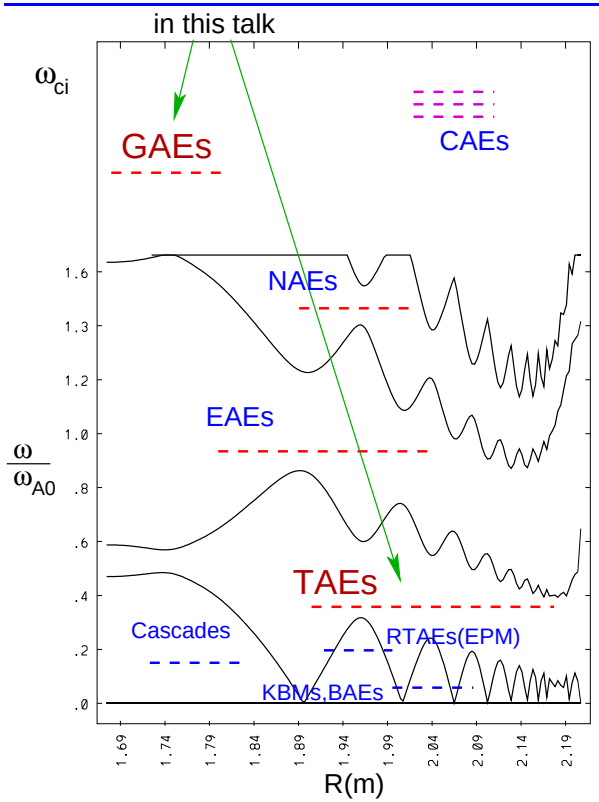
Supported by

Outline

1. Theoretical/computational basis for predicting Alfvén Eigenmode (AE) stability in burning plasmas
2. Observations of low-frequency AEs in NSTX, and Toroidicity induced AE (TAE) similarity experiments on NSTX and DIII-D - most unstable mode scaling is confirmed
3. NOVA-K numerical modeling of TAE stability:
   - thresholds and unstable mode numbers in NSTX/DIII-D
   - projection to ITER: TAEs are unstable in NBI heated plasma
4. Sub- ion cyclotron frequency modes: Compressional- and new Global shear- Alfvén Eigenmodes (CAE/GAE) in NSTX
   - observations of new shear Alfvén branch
   - developing stability theory and nonlinear modeling tools

Unstable high-n TAEs expected in large scale burning experiments



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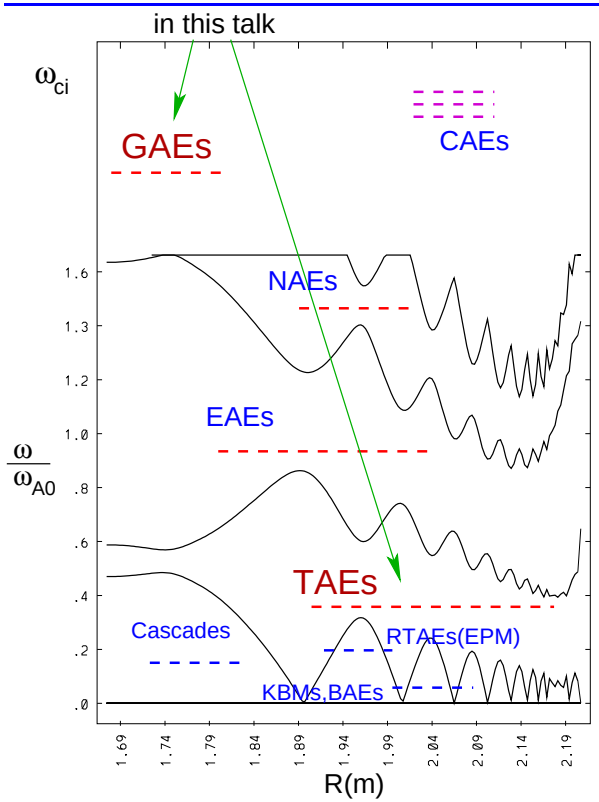

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$$k_\perp \Delta_b \simeq \frac{nq^2\rho_b}{r} \sim 1 \Rightarrow \frac{r}{R} n_{max} < n < n_{max} \simeq \frac{r\omega_{c\alpha}}{q^2 v_A}$$

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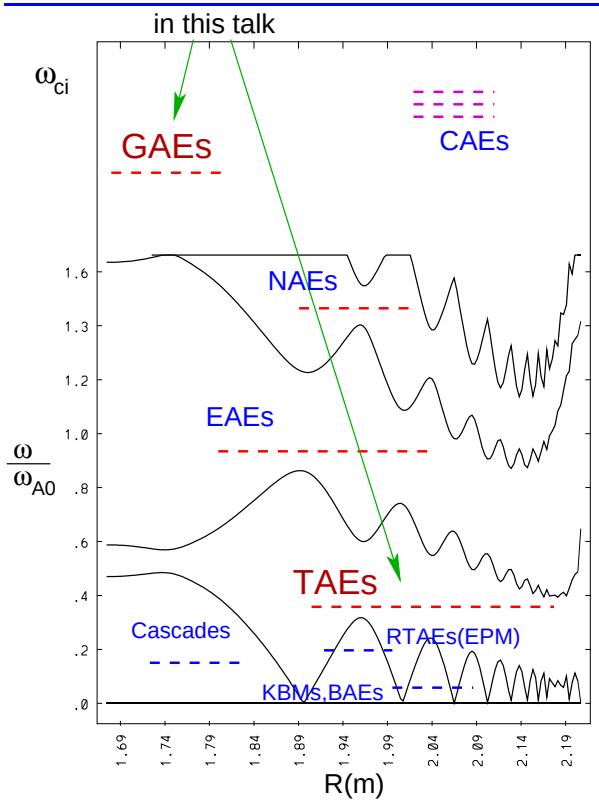

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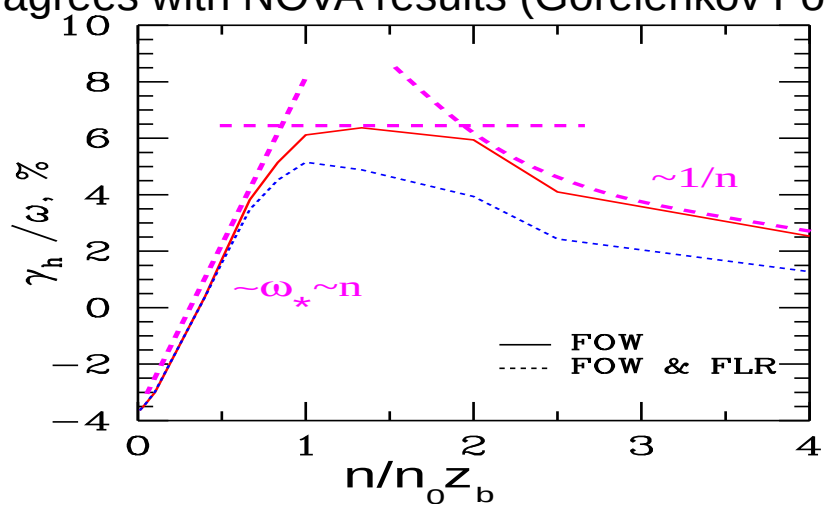

For fixed a/L_b, a/R, $n_0 = 2$
scale $n/n_0 z_b \sim k_\perp \Delta_b$

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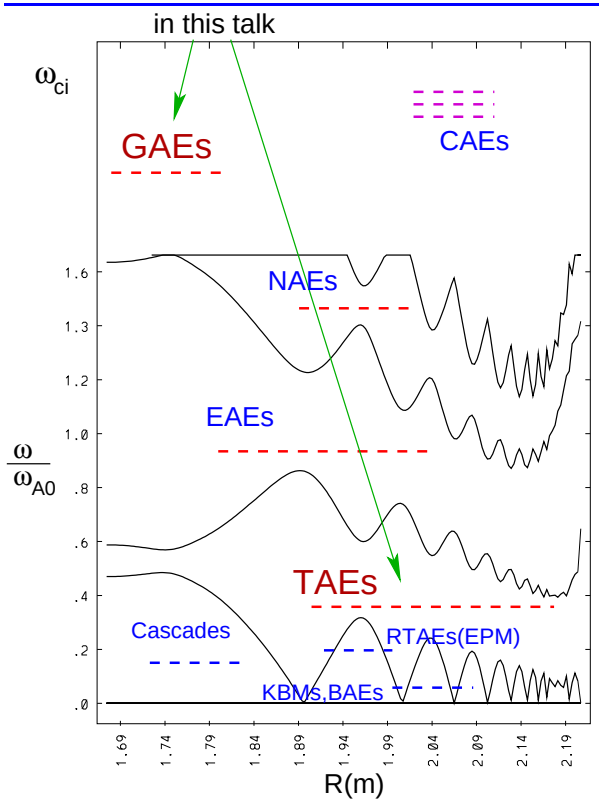

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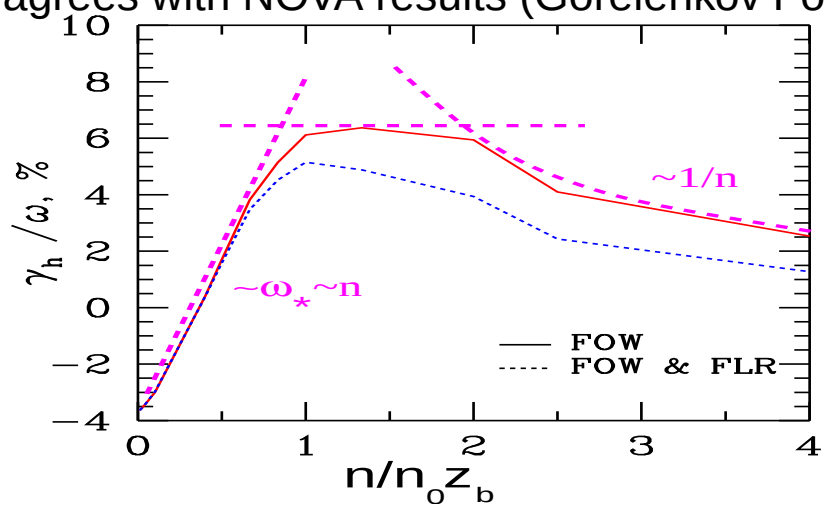
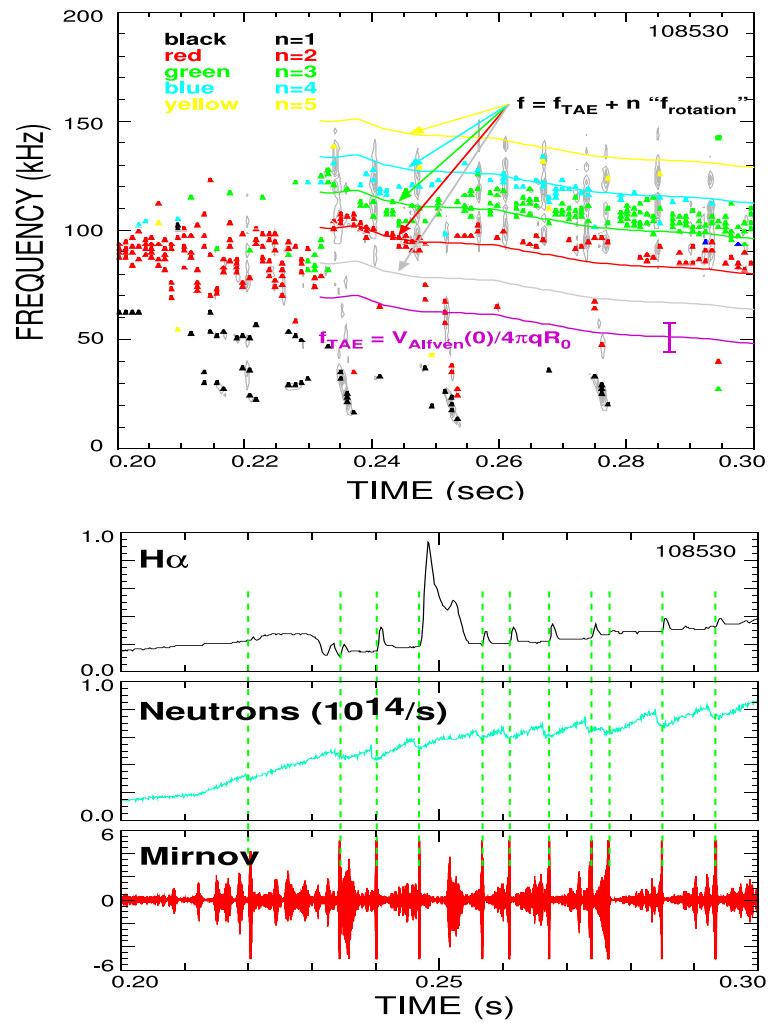


Need to validate theory by experiment!

For fixed a/L_b, a/R, $n_0 = 2$
scale $n/n_0 z_b \sim k_\perp \Delta_b$

Bursting TAEs often result in beam ions losses in NSTX

- Neutron flux drops by 10-15%
- Period of neutron drops is 10ms
- Bursting TAEs: fast amplitude change
- Edge amplitude: up to $\delta B/B = 3 \times 10^{-4}$
- Multiple modes are present



(Fredrickson PoP,'03)
also see NSTX session KO1 (wednesday)

NSTX and DIII-D similarity experiments are designed to validate theory

	R (m)	a (m)	B_0 (T)	β_{i0} $(\%)$	q_0	β_{b0} $(\%)$	$\frac{v_{b0}}{v_{A0}}$	$\frac{a}{\rho_{b,\alpha 0}}$	n_{max}
NSTX	0.77	0.6	0.5	1.1	1.6	4.2	1.85	6	1
DIIII-D*	1.63	0.6	0.63	2.6	0.9	4.4	1.5	6	4
ITER	6.2	2	5.3	2.2	1.2	1.2	1.4	50	15
$(r/a \sim 1/2)$						0.7(α's)	1.8	40	15

∗in NSTX/DIII-D similarity experiment

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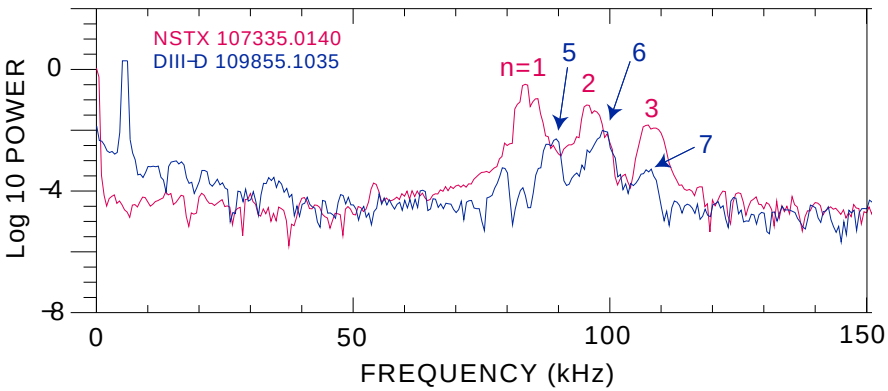
$*$in NSTX/DIII-D similarity experiment

DIII-D/NSTX similarity experiment (W. Heidbrink PPCF,'03) is designed to check theory

- Use (1) similar plasmas, (2) tangential NBI injection angle, (3) same NBI energy $E_{b0} = 80keV$, (4) similar trapped to passing particle ratio
- The major radii are different in NSTX and DIII-D
- Safety factor profiles are different

Observations confirm theory predictions



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- Modes have low edge amplitude $\delta B/B \sim 10^{-5}$.

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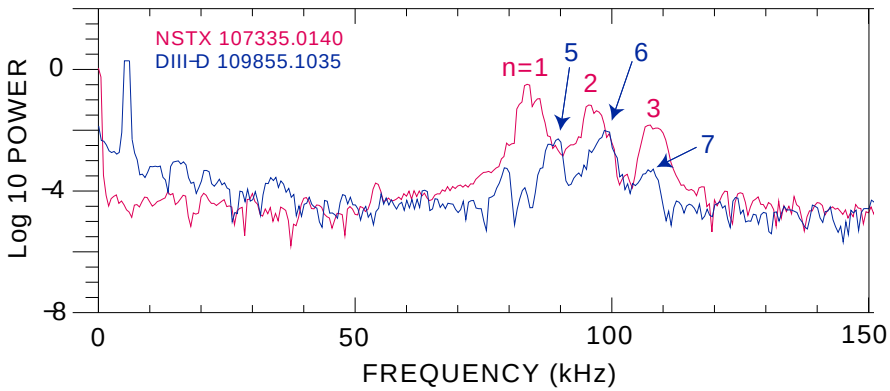

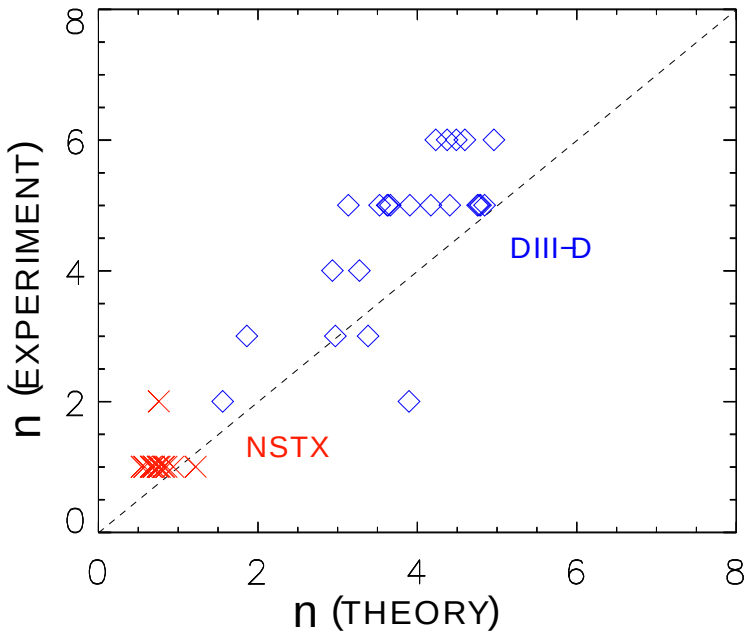

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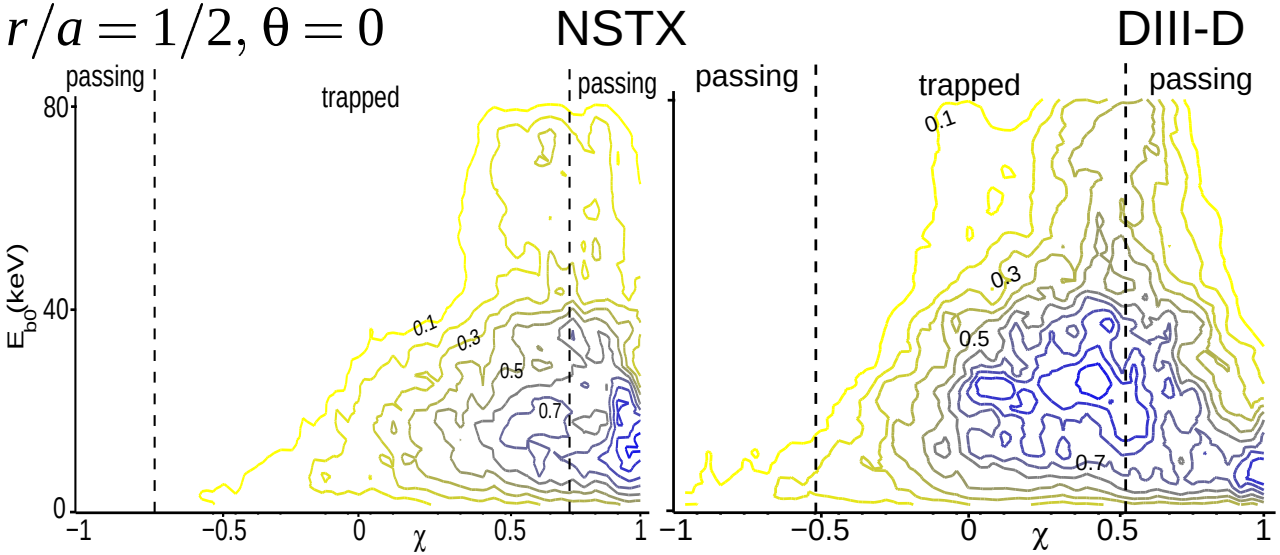
Simulate linear TAE stability with NOVA codes

NOVA (Cheng JCP,'87) and NOVA-K (Cheng PhR,'92) codes are used to compute TAE stability:

- NOVA uses TRANSP output for plasma parameters
- Mode structure is computed within ideal MHD (NOVA)
- Perturbative kinetic mode analysis is performed with NOVA-K code
- Fast ion drive includes: finite orbit width (FOW) and FLR effects (Gorelenkov PoP,'99)
- Damping mechanisms included are
  - ion/electron Landau
  - radiative
  - trapped electron collisional

Trapped/passing particle ratio is similar in both experiments

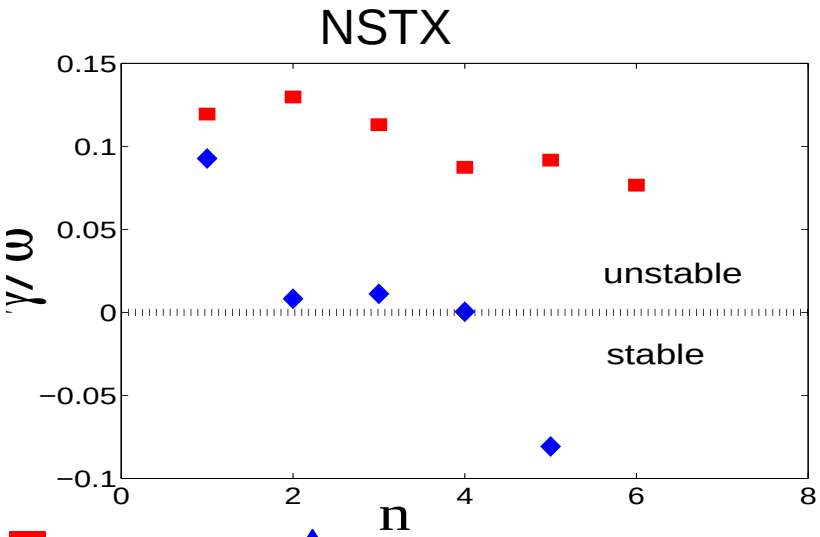


- Similar trapped/passing particle ratio achieved by adjusting the injection angle
- Distribution function is computed by TRANSP
- Pitch angle ($\chi \equiv v_{||}/v$) width is changing as particles are thermalized
- In NOVA beam distribution is approximated into a form

$$f_b(\psi, v, \chi) = n(\psi)\,\frac{e^{-(\chi-\chi_0)^2/\delta\chi^2(\psi,v)}}{v^3 + v_*^3(\psi)}$$

- Distribution function is critical for comparison with experiments

The trend of unstable TAE's n-dependence is recovered by NOVA-K



no damping, - with damping

- TAEs excitation thresholds are reproduced for medium-n numbers
- NOVA-K with isotropic distribution function does not predict observed unstable modes
- Main damping mechanisms are:
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- Stabilization of TAEs at higher end for n is due to FOW effects and higher damping

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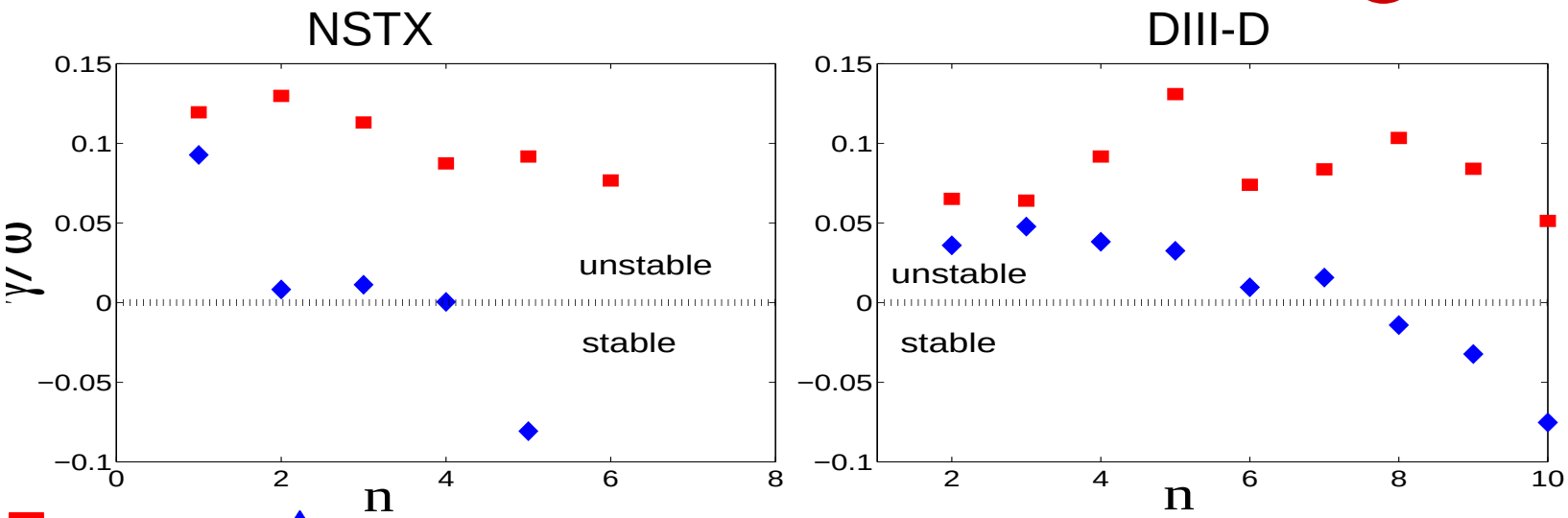

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Estimate of extra damping due to uncertainties in measurements/stability model

Experimental results:

- Near steady TAE amplitude evolution in NSTX and DIII-D
- Low amplitude $\delta B/B \sim 10^{-5}$at the plasma edge

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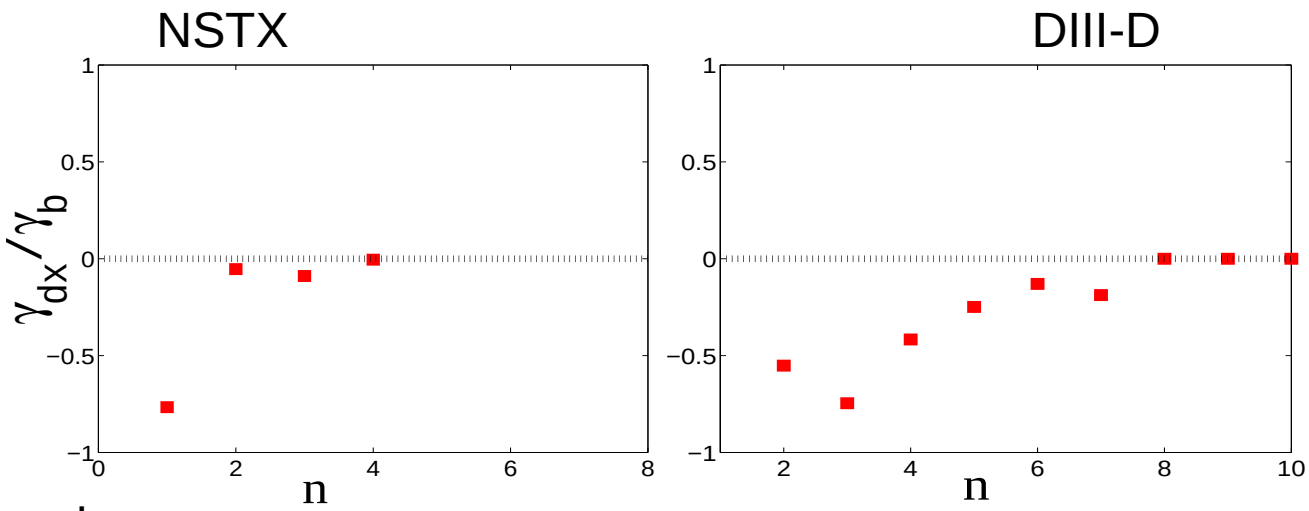
Theoretical results:

- TAE edge amplitude is close to the peak amplitude (global modes)
- NOVA-K applies nonlinear marginal stability theory (Berk PF,'90, PRL'96) $\Rightarrow$ If TAEs are near threshold, then $-\left(\gamma_d + \gamma_{dx}\right)/\gamma_b \simeq 1$
- Add new damping term (linear or nonlinear) $\Rightarrow \gamma_{dx} = -\gamma_b - \gamma_d$
- γ_{dx} is extra damping due to uncertainty in stability model/experimental measurements

Uncertainty in the damping rate is less than 20% of the drive for medium-/high-n modes



Low-n modes:

- Alfvén continuum gap is open $\Rightarrow$ no continuum damping is present
- very sensitive to details of $q-$profiles (global modes)
  - Small change in q or density profile may increase the damping of low-n modes

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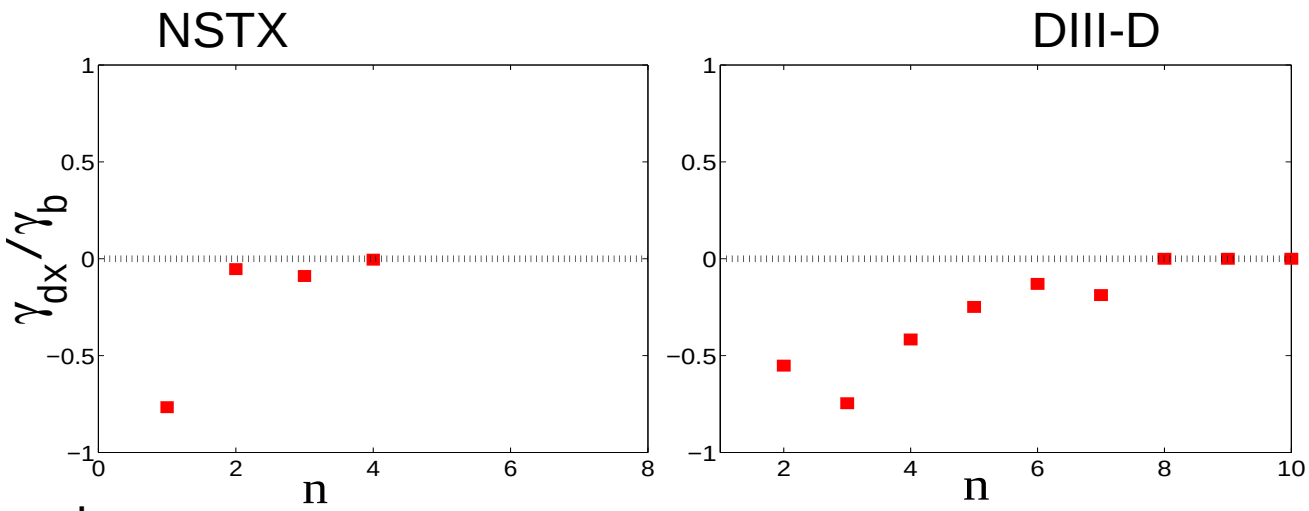

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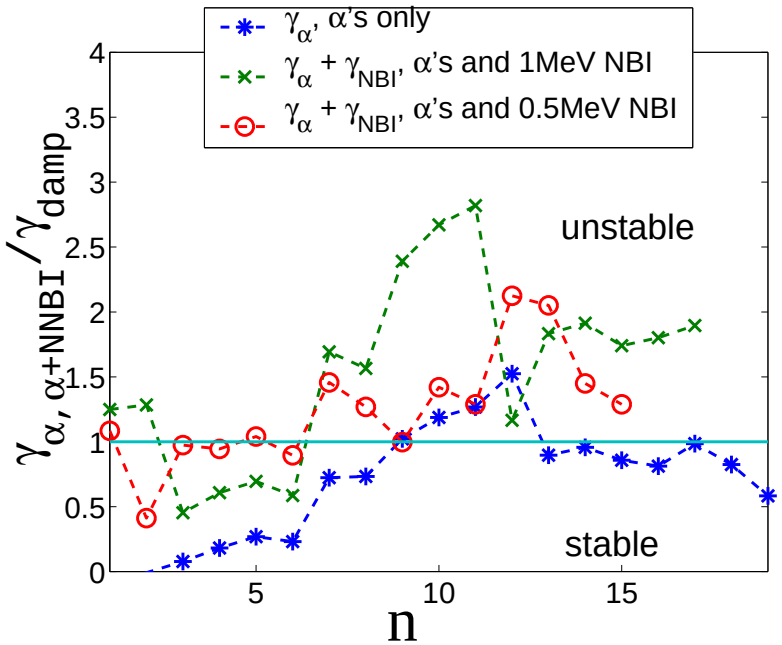
Medium-/high-n modes:

- more localized $\Rightarrow$ less sensitive to details of $q-$/density profiles
- gives small uncertainty in stability model/experimental measurements

Alphas and NBI ions both contribute to TAE instability in ITER

Gorelenkov NF,'03



- In ITER $1MeV$ tangentially injected beam ion TAE drive is comparable with the $\alpha-$drive.
  - Lowering NBI energy to $0.5MeV$ strongly reduces beam drive
  - $0.5MeV$ energy is enough for good beam penetration
- In ITER ion temperature $T_{i0} = 20keV$ seems to be marginal for TAE stability when both alphas and NBI ions are included. Plasmas with $T_{i0} > 20keV$ are TAE unstable.

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4. Sub- ion cyclotron frequency modes: Compressional- and new Global shear- Alfvén Eigenmodes (CAE/GAE) in NSTX
   - observations of new shear Alfvén branch - GAE
   - developing theory:
     – linear theory: analytical and numerical
     – nonlinear modeling tools: hybrid HYM code

New Features of Sub- Ion Cyclotron Instability Spectrum

Compressional AE (CAE) were observed in NSTX (Fredrickson PRL, '01, Gorelenkov NF,'02)

- Observations of new instabilities: frequencies of different (m,n) peaks intersect $\Rightarrow$ characteristic of shear Alfvén modes (vs. CAEs)

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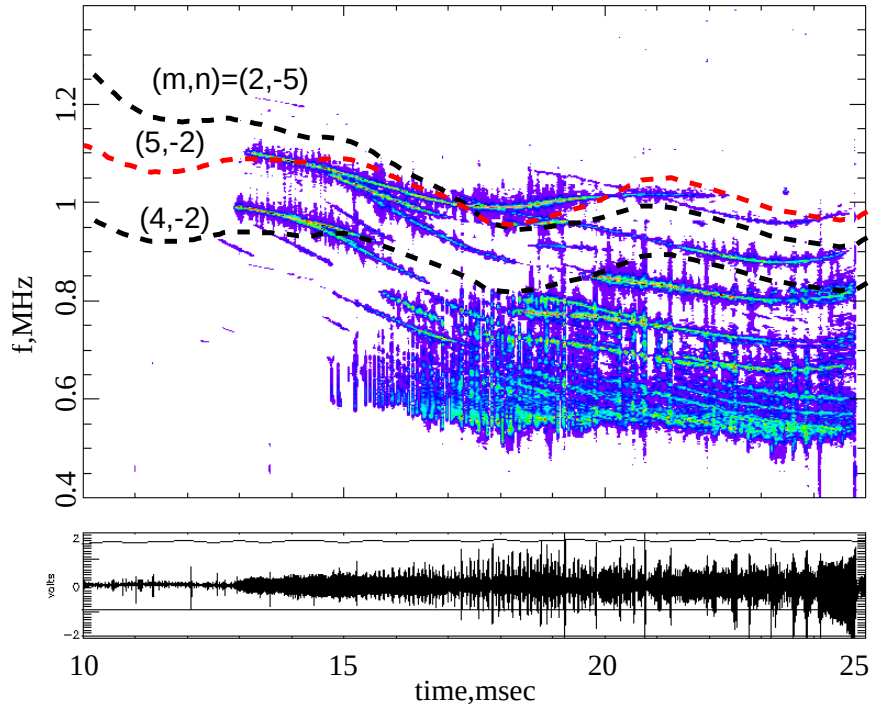
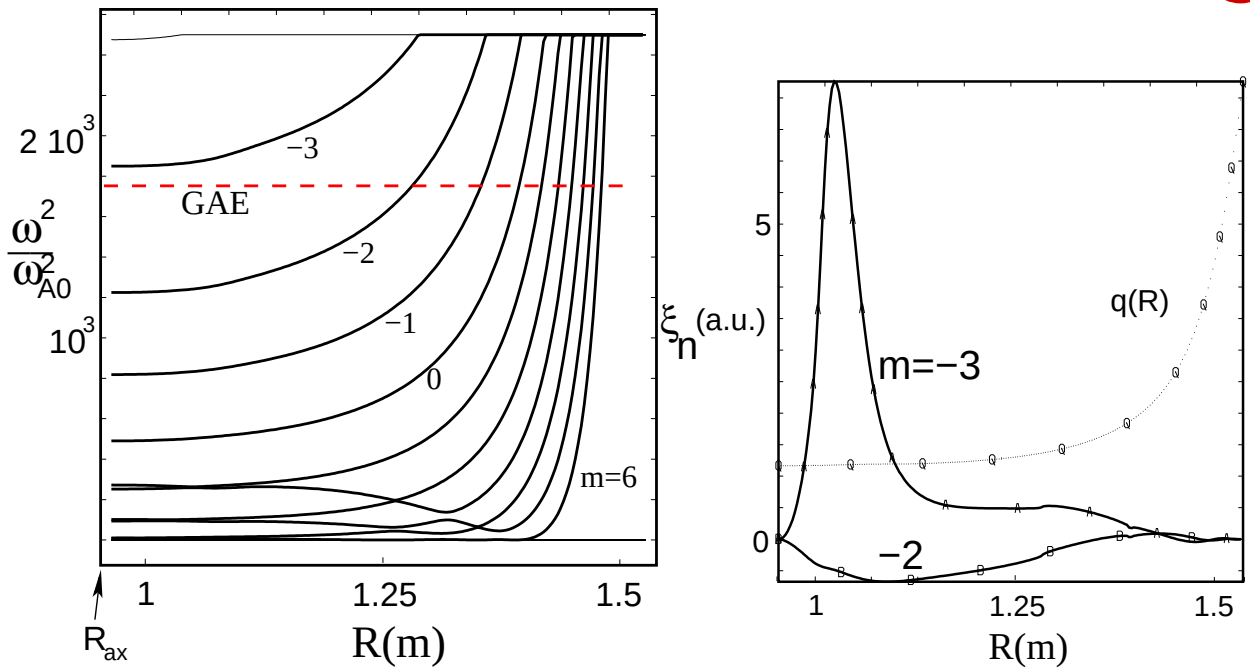
($f_{ci} \simeq 2.2$MHz)



- Observations of new instabilities: frequencies of different (m,n) peaks intersect $\Rightarrow$ characteristic of shear Alfvén modes (vs. CAEs)
- Dashed curves: GAEs with dispersion $\omega_{GAE} \simeq v_{A0}(m - nq_0)/q_0 R$
- Identify new modes as Global Alfvén Eigenmodes (GAE), (Appert PlP,'82)

Global Alfvén Eigenmode structure by NOVA code



$\omega_{GAE} \simeq v_{A0}(m - nq_0)/q_0 R$

- One poloidal mode number is dominant
- GAEs are radially localized
- Many radial GAEs may exist below the continuum
- m's GAEs can interact with the $m+1$ continuum $\Rightarrow$damping

GAE stability theory

GAE drive (Gorelenkov NF,'03):

- Velocity space gradient - bump on tail in $v_\perp$ direction due to tangential NBI injection in NSTX
- Doppler shifted particle - wave cyclotron resonance: $\omega - \omega_{cb} - k_{||} v_{||} - k_\perp v_{db} = 0$
- GAEs are unstable if $2 < (\omega/\omega_{cb})(v_{\perp b0}/v_A)(k_\perp/k_{||}) < 4$
  - and bump on tail width is less $\delta v_{\perp b} < 2 v_A \omega_{cb}/\omega$

Main GAE damping is continuum damping (VanDam FT,'90):

For high-m GAEs it is small (Gorelenkov NF,'03)

$$\frac{\gamma_d}{\omega} \sim \left(\frac{r_0}{r_s}\right)^{2m+\delta},$$

where r_0 is the mode location, r_s is the minor radius of $m+1$ resonance surface (continuum), $\delta = O(1)$

HYM hybrid code for nonlinear GAE/CAE study

Model (Linearized and nonlinear):

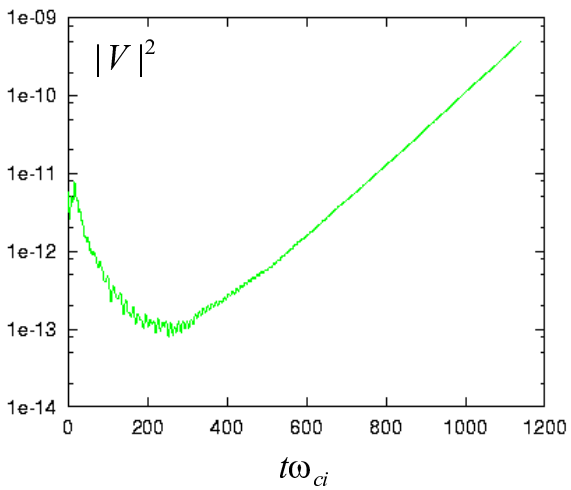
- Background MHD + kinetic fast ions
- Fluid electrons + particle background ions + fast ions

Method:

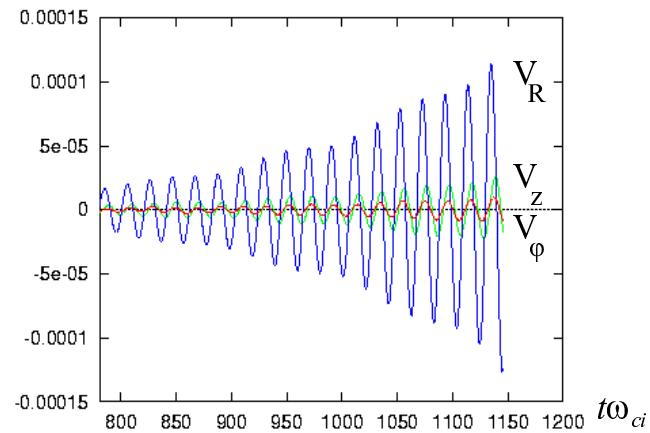
- explicit time scheme, 2nd order accuracy
- 4th order spatial derivatives
- particles are treated with the δf scheme
- anisotropic equilibrium (Belova PoP,'03)

HYM hybrid code finds unstable modes in linearized δf run

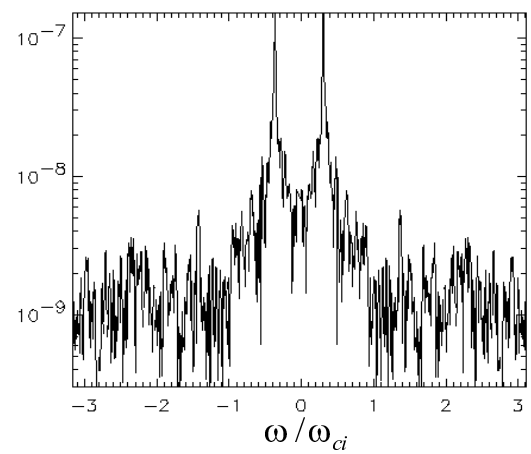
Simulations show instability for n=4
with $\gamma = 0.005\omega_{ci}$ and $\omega = 0.3\omega_{ci}$
for 3% beam ion density and E=80keV



Time evolution of bulk fluid kinetic energy for n=4.



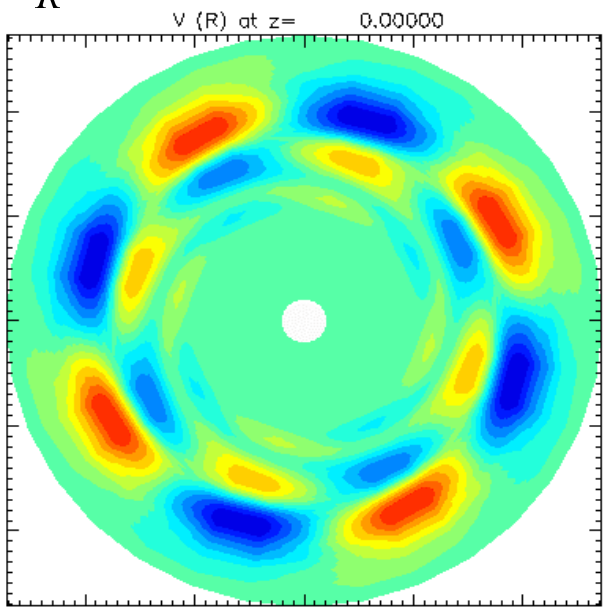
Fluid velocity at equatorial plane, $R=1.2R_0$



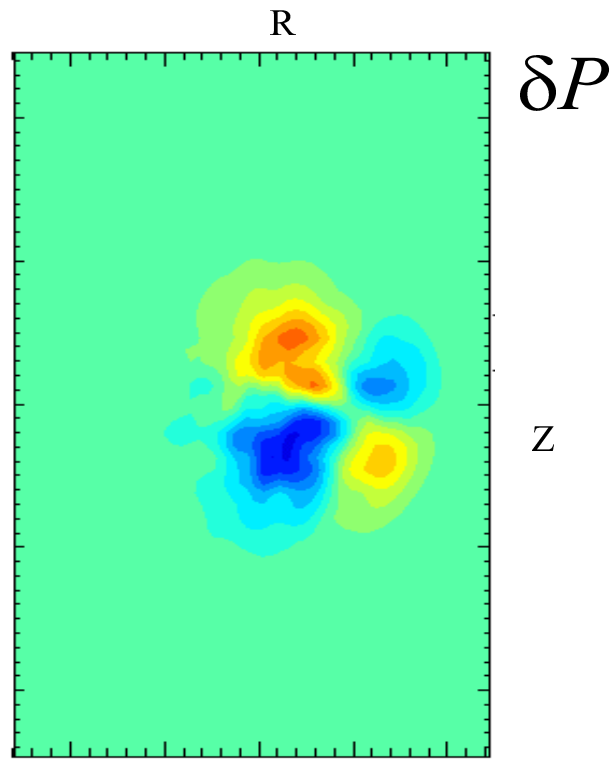
Frequency spectrum calculated from perturbed beam ion density.

HYM simulations show GAE mode structure

V_R



Contour plot of radial component of fluid velocity at equatorial plane.



δP

Contour plot of perturbed fluid pressure in poloidal plane.

Mode has characteristics of GAE with $n = 4$, $m = 2$

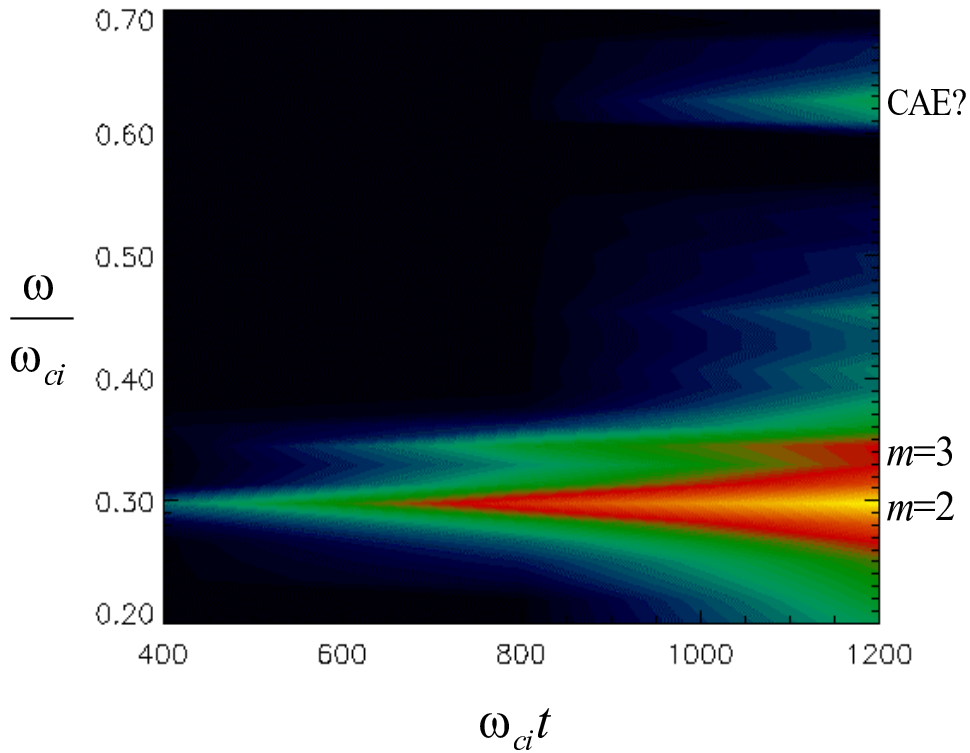
It has large $k_{||}$, and significant compressional component: $\delta B_{||} \simeq \delta B_{\perp}/3$

low-n GAEs are found in simulations for NSTX parameters

- Modes with $2<n<7$ are unstable.
- For each n, several m are unstable with large $k_{\parallel}$ and $n,m<0$.
- Localized near magnetic axis.
- Large $\delta B_{\perp}$ component.

- observed features agree with that of GAE mode, which exists just below the lower edge of the Alfven continuum [Appert et al.,1982].

Simulations with n=4

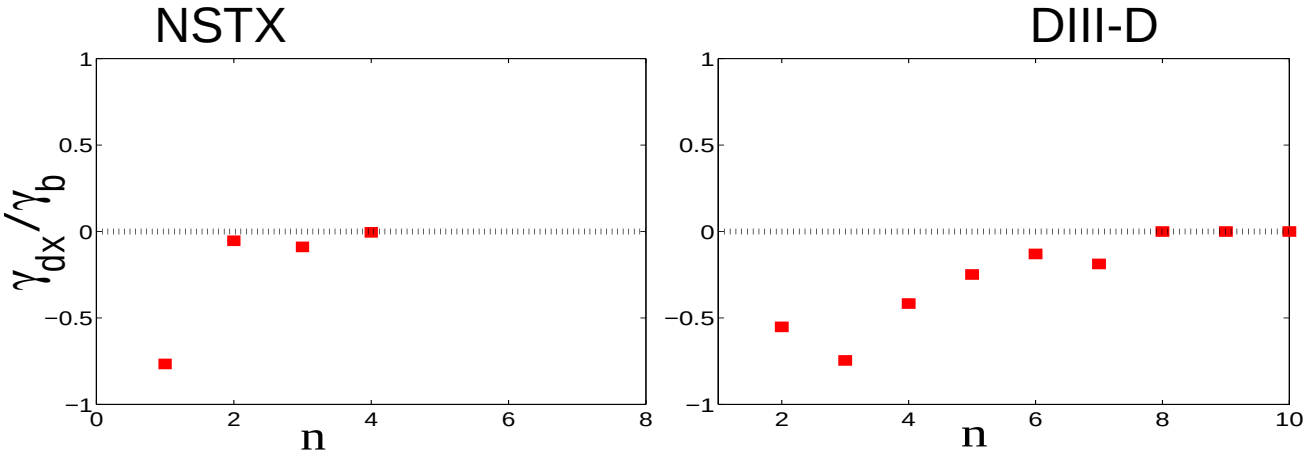
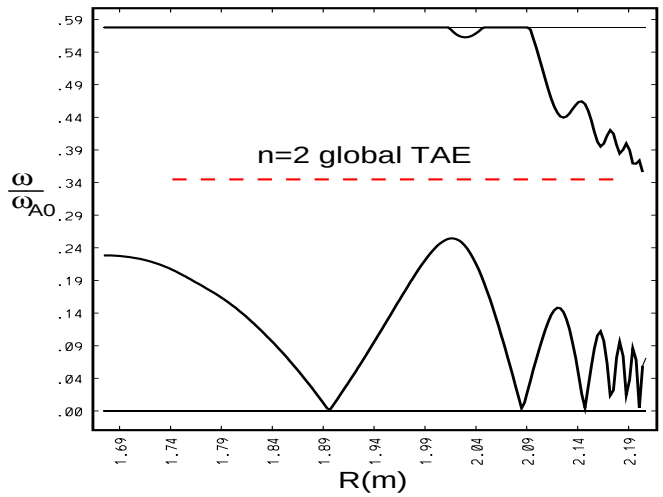


Preliminary nonlinear results show saturation of instability at amplitudes: $\delta B \approx 10^{-4} - 10^{-3} B_0$

SUMMARY

- Linear theory and numerical tools such as NOVA/NOVA-K predict TAE instability in burning plasmas, and have been validated by experiments in NSTX and DIII-D
  - Most unstable mode number scale with the minor radius of the plasma
  - NOVA predicts TAEs to be unstable in ITER with NBI
- Observed sub-cyclotron oscillations in NSTX are identified as Global shear Alfvén Eigenmode Instability driven by NBI ions
- GAEs are driven via the Doppler shifted cyclotron resonance with beam ions by the positive gradient in velocity space $v_\perp$ direction (“bump on tail” distribution).
- Both hybrid HYM code and NOVA code models agree with analytical theory on GAE mode structure and dispersion

Low- n modes are very sensitive to details of q- profiles



- Gap is open ⇒no continuum damping is present
- Small change in q or density profile may increase the damping of low-n modes