Sub-cyclotron Alfven Instablilities in Spherical Tokamaks

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Outline

1. Shear (GAE) versus Compressional (CAE) Alfvén Eigenmodes.

2. AEs properties:

   (a) dispersion

   (b) stability domains

NSTX Research Forum, PPPL, September 9-11, 2002.

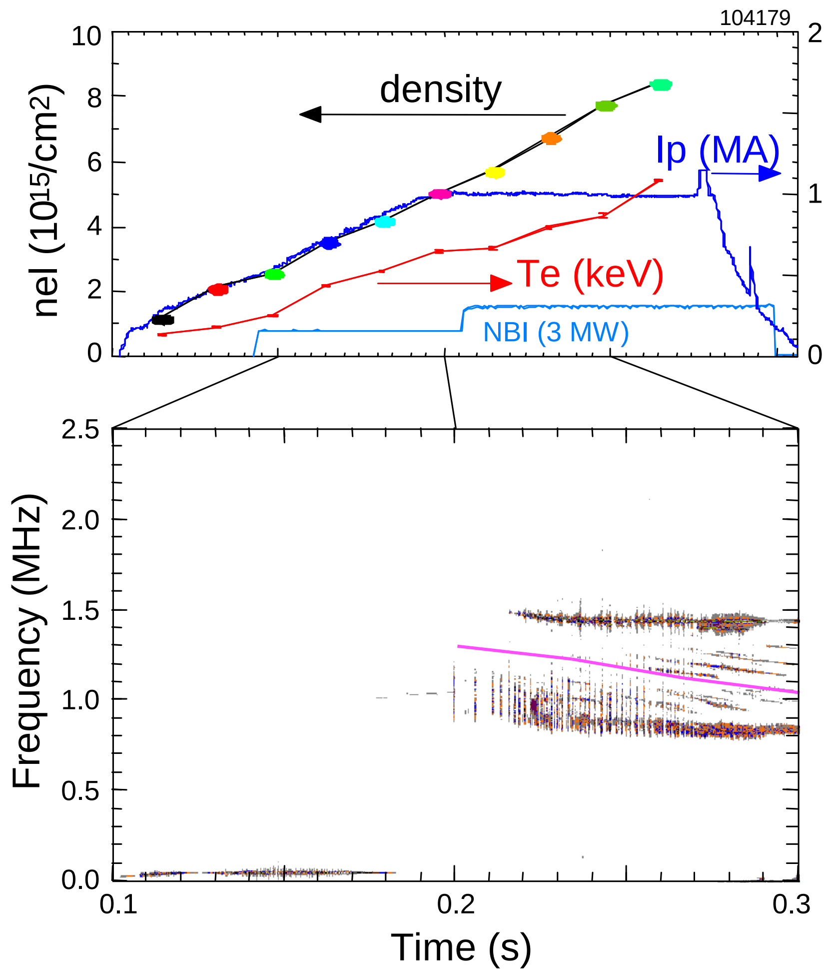
PRINCETON PLASMA PHYSICS LABORATORY

Summary of Experimental Observations

1. Multiple sub-ion cyclotron frequency instabilities were observed in NSTX.
2. Frequency $typically$ scales with Alfvén speed, but not always.
3. Instability is driven by fast super Alfvénic ions, $v_{b0} \simeq 3v_A$ due to $80keV$ NBI.
4. $Typically$ the frequency spectrum has "bunches" of peaks almost evenly spaced in frequency. There are multiple peaks within each bunch.
5. Instability is sensitive to the injection angle of different tangential NBI sources having tangential radius $R_{tan} = 69.4,\ 59.2,\ and\, 48.7\, cm$ (from more passing to more trapped).
6. Instability has dependence on energy distribution.
7. Theory motivation
   - ✓ Are they CAEs? HYM shows shear Alfvén polarization (see next, Elena's talk), GAEs?
   - ✓ AEs can be used for energy channeling from fast ions to electrons and ions?
   - ✓ Instability can be used to diagnose plasma edge: rotation, fast particles.

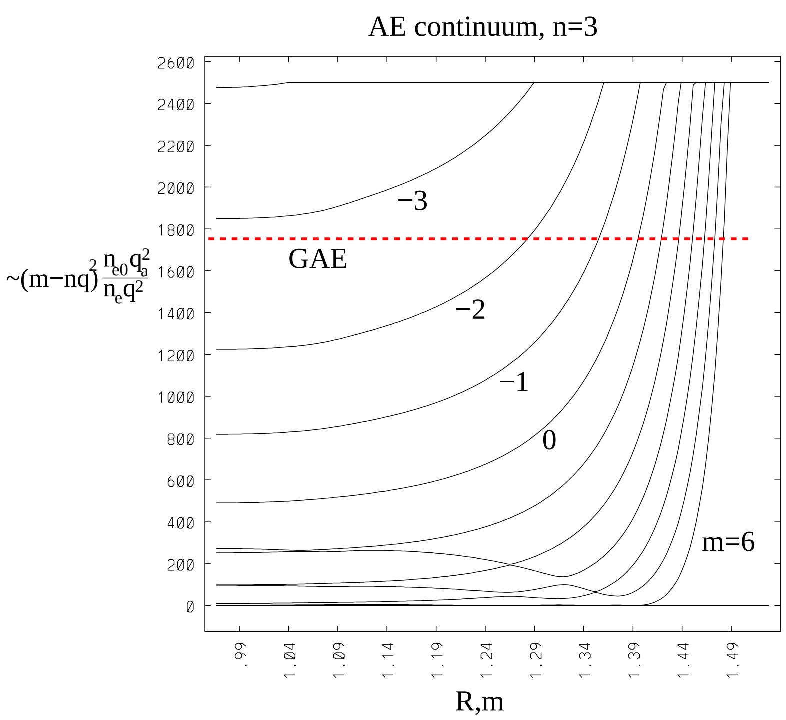
NSTX shot #104179, Mirnov signal

1) Modes with sub- edge deuterium cyclotron frequency $f \leq \omega_{cDedge}$ occur during NBI.
2) Time evolution of two Mirnov signal peaks seems to deviate from Alfven frequency evolution.
3) Is it nonlinear saturation effect or linear system response?



Instabilities seen in HYM with shear Alfven polarization

Use NOVA to identify such modes as Global Alfven Eigenmodes (GAE).



1) AE continuum shows possibility for GAE in the center to exist.
2) For each (n,m) there may be a mode.
3) The mode is primarily cylindrical.
4) Damping on the continuum is dominant damping mechanism HYM may not have good model for continuum damping.

GAE Radial Structure is close to cylindrical, single m

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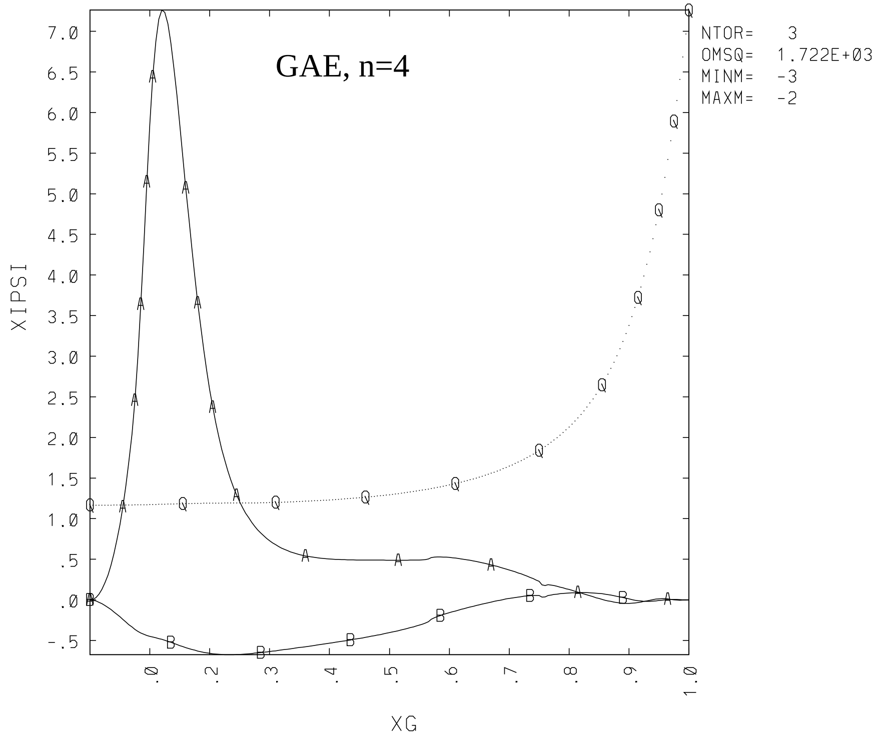


damping on the continuum is dominant

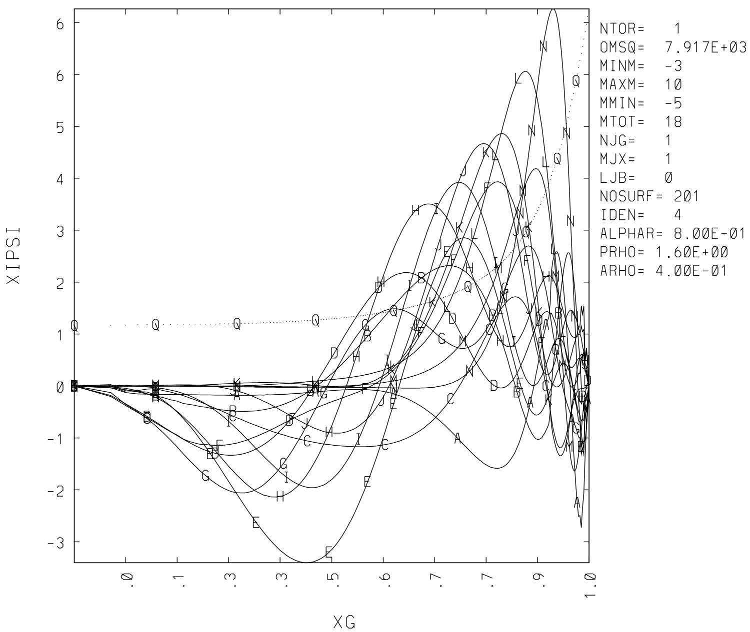
$\sim e^{-m}$, higher m's are less stable.

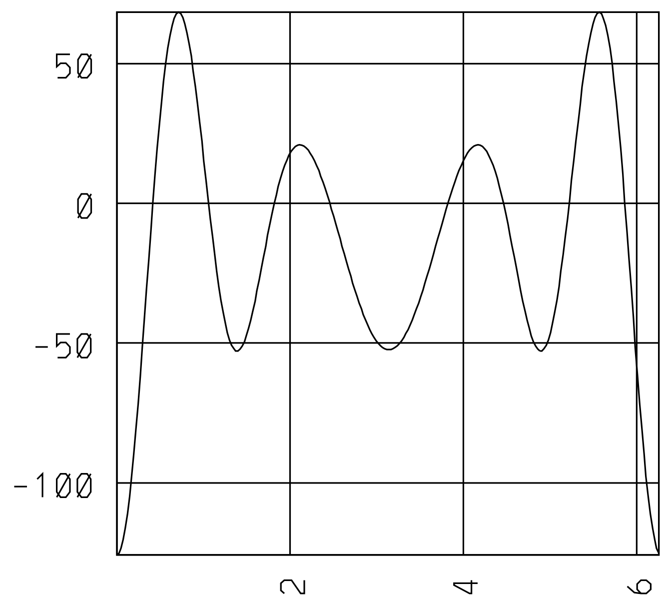
Such GAEs were studied by Appert, '82:

$$\omega = k_{\|} v_{A0} \simeq \left(\frac{m}{q_0} - n \right) \frac{v_{A0}}{R_0}.$$

CAE Radial Structure is Localized at LFS

Plasma radial displacement ($\sim E_\theta \sim \partial E_r/\partial r$ for ideal MHD part) and parallel poloidal variation of perturbed magnetic field at half of minor radius





Use this $m = 4$, $s = 0$, we have $f = 1.45MHz$ and $\omega a/v_{A0} = 9.4$ in low beta NSTX equilibrium vs. our theoretical prediction of $\omega a/v_A \simeq 8$.

CAE variational solution and dispersion

With density given by $n = n_0(1-r^2)^\sigma$, at $r_0/a = \sqrt{1/(1+\sigma)}$:

$$\omega_0 = \frac{v_{A0}}{r_0\kappa}\left[(2m+1)\sqrt{\epsilon_0-\alpha_0} + 2(2s+1)\kappa\sqrt{\frac{1+\sigma}{2\sigma} + \frac{n^2 r_0^2\kappa^2}{R^2(2m+1)\sqrt{\epsilon_0-\alpha_0}}}\right],$$

where $\alpha_0 = B_\theta^2/2B_\varphi^2$ and all quantities are estimated at $r = r_0$, $\theta = 0$.

Instabilities with different m's are separated in frequency by

$$\Delta f_m \simeq \frac{2v_A}{2\pi\kappa r}\sqrt{\epsilon_0-\alpha_0} < \Delta f_s \simeq \frac{v_A}{2\pi\kappa r}\sqrt{\frac{2(1+\sigma_i)}{\sigma_i}}.$$

- ✓ NSTX shot #103701 $B_{r=r_0} = 0.27T$, $r = 0.5m$, elongation $\kappa = 1.6$, $n_e = 2\times10^{13}cm^{-3}$ (TRANSP).
  Use also parameter: $\epsilon_0 = r/(R_0+r) = 0.3$, $\alpha_0 = 1/8$: $\Delta f_m = 150kHz$, $\Delta f_s = 1.1MHz$.
  For #103431 $B = 0.32T$, $n_e = 4\times10^{13}cm^{-3}$, $\Delta f_m = 125kHz$, $\Delta f_s = 1MHz$.
- ✓ Observed $\Delta f_m \simeq 120kHz$ in #103701 and $\Delta f_m \simeq 110kHz$ in #103431 with the $\Delta f_s \simeq 1MHz$

CAE versus GAE: drive source

Driving terms are (f_b is beam distribution function):

$$\left(\omega\frac{\partial}{\partial\mathcal{E}} + l\omega_c\frac{\partial}{\partial\mathcal{E}_\perp} + \omega_*\frac{\partial}{\partial\mathcal{E}}\right) f_b$$

1. $\Rightarrow$ For slowing down f and trapped ions only $l = \pm 1$ are possible. For tangential injection $l = 0$, Cherenkov resonance, is possible
   (a) $l = 0$ GAEs can not be excited since $v_A = v_{||} \ll v_{b0}$, where there is no $\frac{\partial}{\partial\mathcal{E}}$ drive,
   (b) $l = 0$ CAEs may have a weakly unstable modes due to passing ions.
2. In NSTX these terms are related to each other as

$$1 \,:\, \frac{\omega_c}{\omega} \,:\, \frac{1}{2\epsilon}\frac{\rho_b}{R}\frac{v_b}{v_A}$$

3. Realistically only second term is important for drive.

CAE versus GAE: growth rates

$$\frac{\gamma}{\omega} = \frac{1}{4}\frac{\omega_c^2}{\omega^2}\frac{\omega_{pb}^2}{\omega_{pi}^2}\int dv dv_\perp v_\perp^2 \frac{\partial f}{\partial v_\perp} G,$$

where $G = \frac{\omega}{\omega_c}(J_0 + J_2)^2$ for CAEs, and $G = (J_0 - J_2)^2$ for GAEs. $\Rightarrow$

1. Instability favors lower frequency and more stronger for GAEs.
2. Typical increments are of order $\gamma/\omega \sim n_b/n_i \simeq 1\%$.
3. For the instability to exist: $k_\perp \rho_{\perp b} > 1$.
4. Possible resonance velocities are within the range $\mathcal{E}_* < \mathcal{E} < \mathcal{E}_{b0} \Rightarrow$ $20keV < \mathcal{E} < 80keV \Rightarrow v_{b0}/2 < v < v_{b0}$.

CAE versus GAEs: resonance condition

$$\omega \pm \omega_{cD} - k_{\|} v_{\| b} \simeq 0$$

mode →	CAE	GAE
dispersion	$\omega = k v_A$	$\omega = k_{\|} v_A$
resonance $v_{\|}$	$\frac{v_{\|}}{v_A} > \frac{k_{\perp}}{k_{\|}} \left(\frac{\omega_c}{\omega} - 1\right)$	$\frac{v_{\|}}{v_A} > \frac{\omega_c}{\omega} - 1$
$k_{\|}$	$k_{\|} \simeq \left(\omega - \omega_c\right)/v_{\| b}$, $k_{\|} < 0$	$k_{\|} \simeq \omega_c / v_{b0}$, $k_{\|} < 0$
$v_{\perp}$	$\frac{v_{\perp}}{v_A} \frac{\omega}{\omega_c} > 1$	$\frac{k_{\perp}}{k_{\|}} \frac{v_{\perp}}{v_A} \frac{\omega}{\omega_c} > 1$

CAE stability diagram is important to understand experiments

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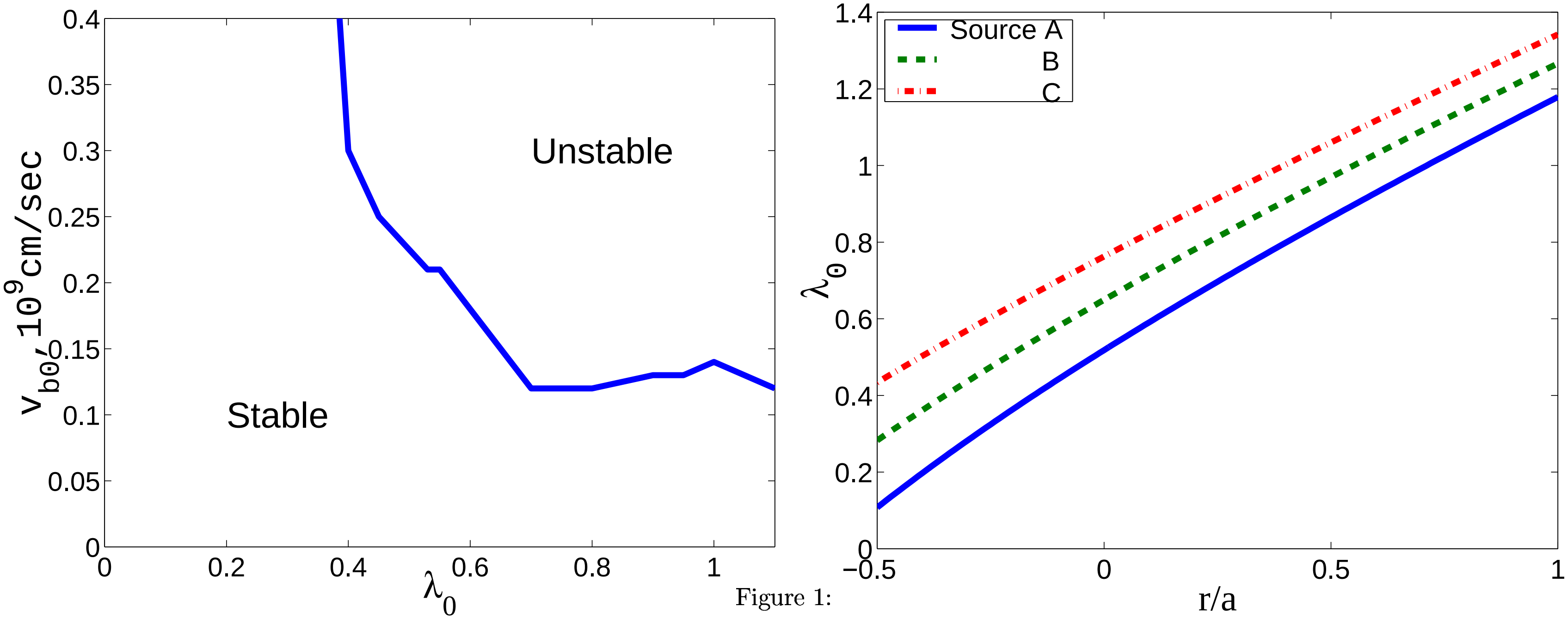

Figure 1:

Stability diagram with $\omega < \omega_{cD}$ can be measured by changing density of the plasma.

CAE instability at higher frequency is expected

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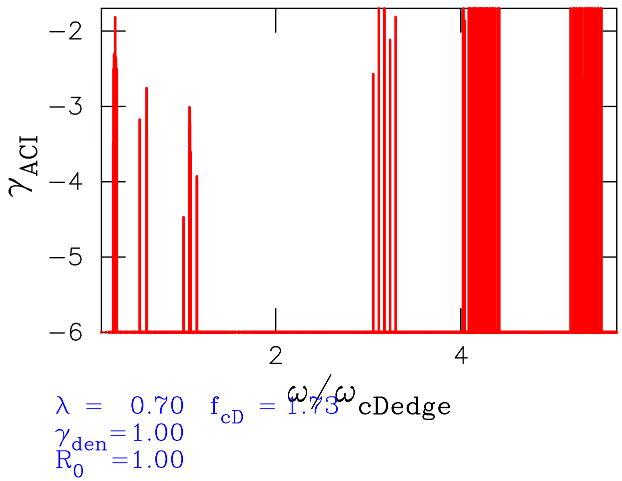
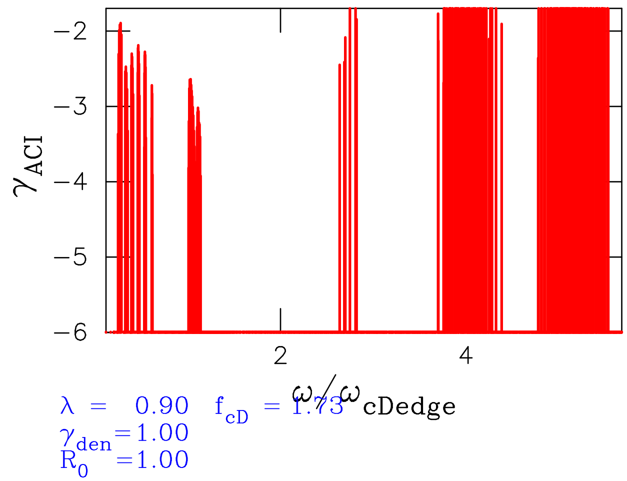
More unstable modes is exprected at $\omega > \omega_{cD}$ similar to ICE in tokamaks.





Modes are expected near the cyclotron harmonics of deuterium frequency. GAE may be stable due to cyclotron damping on background ions.

Conclusion

1. Observed sub-cyclotron oscillations in NSTX are likely to be Compressional and/or Global Alfvén Eigenmode Instability driven by NBI ions.
2. Analysis of the spectra shows qualitative agreement with theory, but more work is needed.
3. New finite aspect ratio analysis of CAE instability gives correct frequency spacing between the m and $m+1$, s and $s+1$ bunches of instable CAEs.
4. More accurate analysis including realistic distribution function for growth rate calculations is in progress using HYM code. Saturation is to be understood theoretically.
5. Accurate mode characteristics study is needed to robustly identify high frequency modes with CAEs. The measurements of the polarization is required.
6. Damping mechanisms are to be studied and modeled, such as continuum damping and stochastic dampings.