Observable Properties of Compressional Alfven Eigenmode Instablility in NSTX.

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in collaboration with

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Outline

1. New strong toroidicity theory of CAEs for ST machines and numerical studies.

2. CAE properties:

   (a) dispersion

   (b) stability

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Summary of Experimental Observations

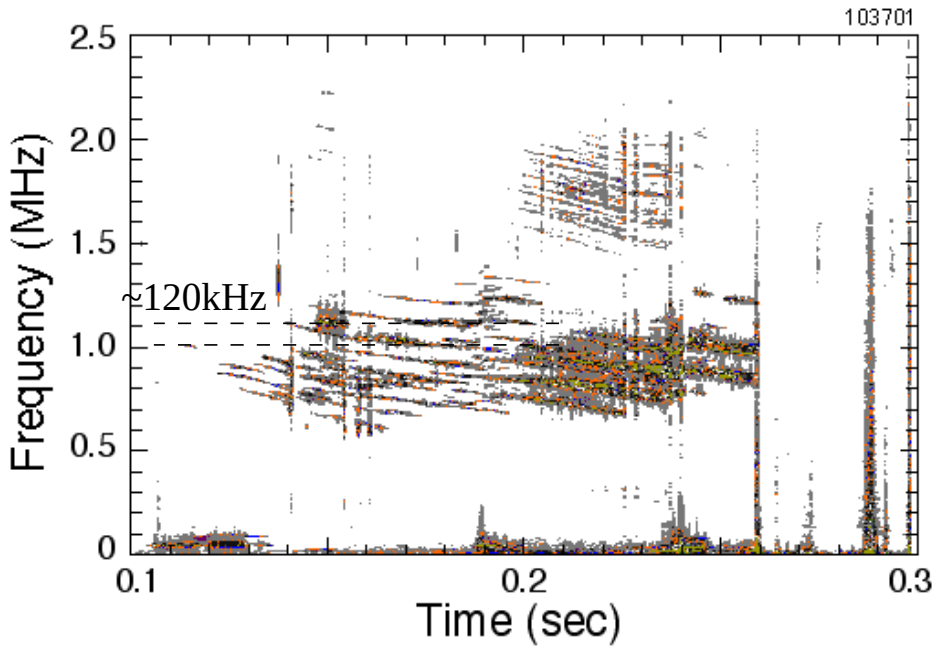
1. New sub-ion cyclotron frequency instabilities were observed in NSTX.
2. Frequency scales with Alfvén speed.
3. Instability is driven by fast super Alfvénic NBI particles.
4. The frequency spectrum has "bunches" of peaks almost evenly spaced in frequency. There are multiple peaks within each bunch.
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?

   ✓ CAEs are possible for energy channeling from fast ions to electrons and ions?

   ✓ Instability can be used to diagnose plasma edge: rotation, fast particles.

NSTX shot #103701 to be analyzed



✓ NBI source B ($R_{tang} = .592m$) starts at $t = 0.115sec$, ($\omega_{cDedge} \simeq 1.8MHz$).

✓ Add source C ($R_{tang} = .487m$) at $t = 0.135sec$, ($\omega_{cDedge} \simeq 2MHz$).

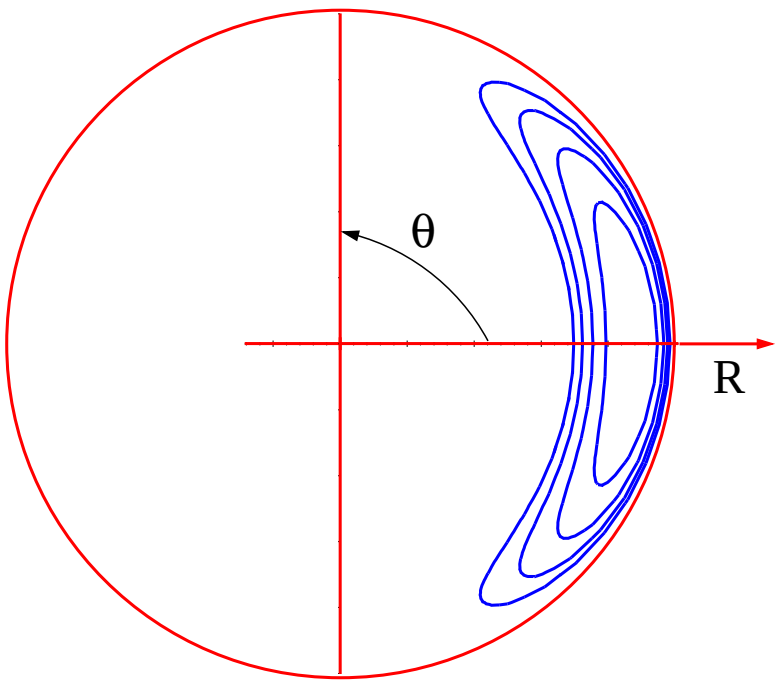
✓ C source induces higher frequency bunches ($f > 1MHz$).

✓ Modes with near edge deuterium cyclotron frequency $f \simeq \omega_{cDedge}$ occur at ($t > 0.2sec$) .

CAE Poloidal Structure in toroidal plasmas

✓ Magnetic field introduces poloidal localization through $v_A^{-2} \sim n_i/B^2$

✓ CAE is localized near the low field side of plasma cross section *Gorelenkov and Cheng, NF1995, Fulop et.al.Ph.Pl.2000.*



⇐ CAE localization

- Shown is case with $a/R = 0.3$
- NSTX has qualitatively similar structure , but more poloidally localized at $a/R = 0.8$.

CAE variational solution

Theory shows that modes are localized poloidally if

$$\frac{r}{R} > (\kappa^2 - 1)/\kappa^2.$$

With density given by

$$n = n_0(1 - r^2)^\sigma$$

L variation relative to r_0 gives $r_0/a = \sqrt{1/(1+\sigma)}$.
L variation relative to Θ and Δ gives for $m \gg s$

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

$\Theta^2 = 2/\left(\epsilon_0 - \alpha_0\right)(m + 1/2)$, $\Delta^2/r_0^2 = \kappa\sqrt{2\sigma/(1+\sigma)\left(\epsilon_0 - \alpha_0\right)}/(2m+1)$.
Magnetic well is reduced by $\alpha_0 = B_\theta^2/2B_\varphi^2$.
All quantities are estimated at $r = r_0$, $\theta = 0$.

New CAE theory agrees better with NSTX experiment

Ddifferent m's are separated in frequency by

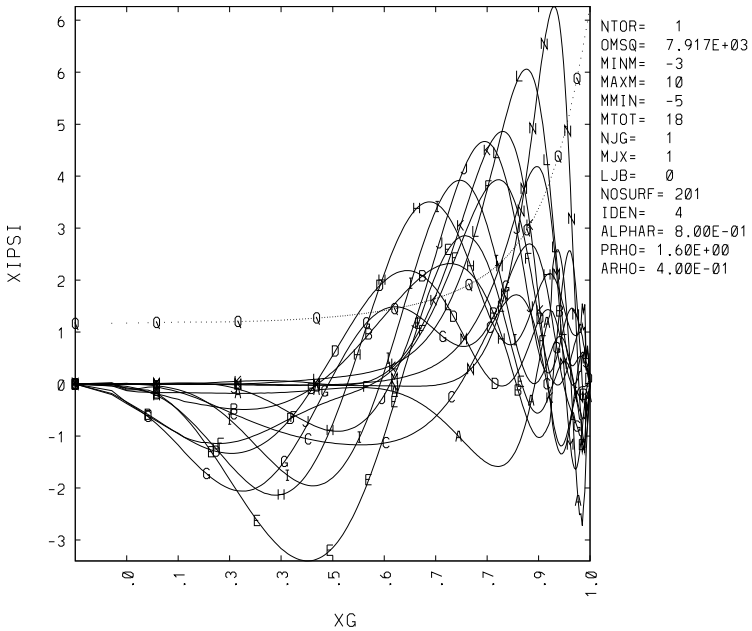
$$\Delta f_m \simeq \frac{2v_A}{2\pi\kappa r}\sqrt{\epsilon_0 - \alpha_0} < \Delta f_s \simeq \frac{v_A}{2\pi\kappa r}\sqrt{\frac{2\left(1+\sigma_i\right)}{\sigma_i}},$$

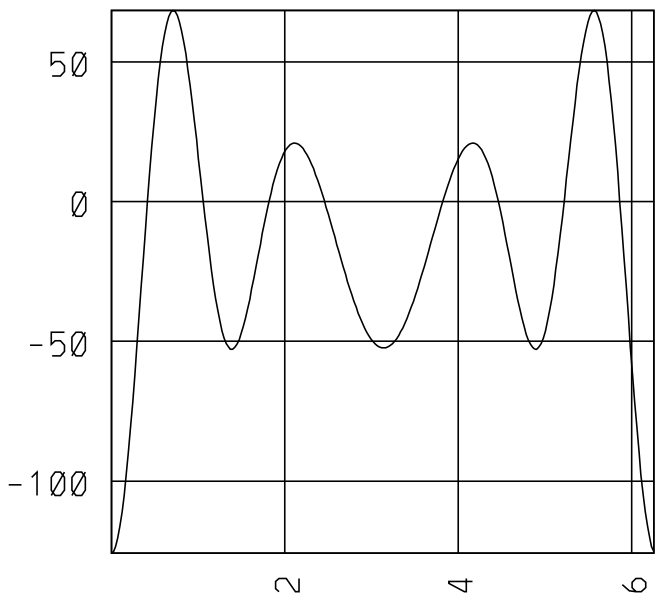
all variables are to be taken at the mode location, except the magnetic field B_{ax}.

- ✓ NSTX shot #103701 $B_{r=r_0} = 0.27T$, $r = 0.5m$, elongation $\kappa = 1.6$, $n_e = 2 \times 10^{13} cm^{-3}$ (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 $B = 0.32T$, $n_e = 4 \times 10^{13} cm^{-3}$, $\Delta f_m = 125kHz$, $\Delta f_s = 1MHz$.
- ✓ Observed $\Delta f_m \simeq 120kHz$ in #103701 and $\Delta f_m \simeq 110kHz$ in #103431 with the $\Delta f_s \simeq 1MHz$

Frequency is in reasonable agreement with NOVA ideal MHD code

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 Instability: Linear Drive

Drive comes from perpendicular energy of superalfvenic particles via particle - wave Doppler shifted cyclotron resonance.

N. N. Gorelenkov and C. Z. Cheng, PoP, 1995

$$\omega - k_{||} v_{||b} - k_\theta v_{dr} - l\omega_{cD} = 0, \; l = 1$$

✓ In STs Doppler shift $k_{||} v_{||b} \simeq \omega = k_\theta v_A \simeq \omega_{cD}/2$, can be larger than in tokamaks due to

$$k_{||}/k_\theta \simeq v_A/v_{||b} \ll 1,$$

✓ Velocity space anisotropy creates "bump on tail" - like distribution in $v_\perp$ direction. Its positive velocity gradient drives CAE instability:

$$\gamma_f \sim \frac{\partial f}{\partial v_\perp} > 0$$

✓ Fast particles can contribute to CAE damping too.

CAE instability is sensitive to beam pitch angle

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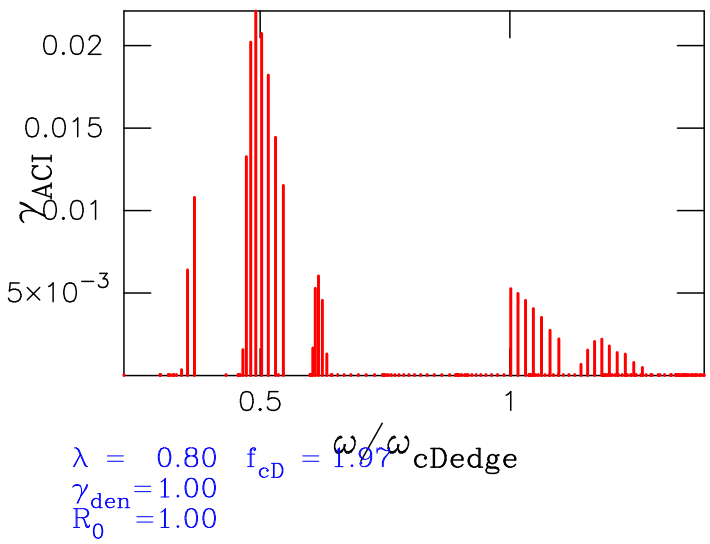
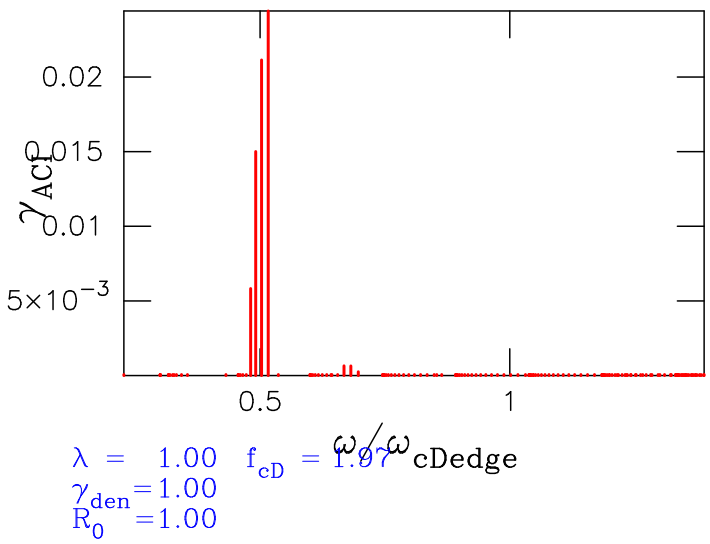
more pass., $R_{tan} = 0.592m$ $\lambda_B \simeq 0.9$ more trap., $R_{tan} = 0.487m$ $\lambda_C \simeq 1$





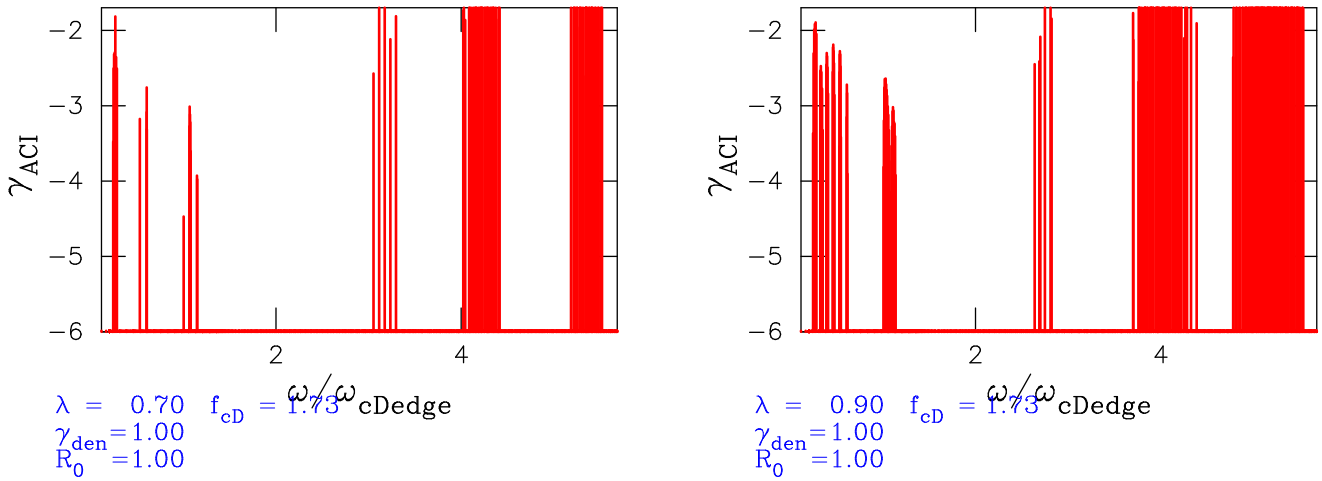
✓ Results qualitatively agrees with observations: Source C (more trapped) generally excites less modes at higher frequency than source B (more passing), since this is cyclotron resonance $\omega - k_{\|} v_{\|} - \omega_{cD} = 0$. We have $v_{\|C} < v_{\|B} \Rightarrow |\omega_C - \omega_{cD}| < |\omega_B - \omega_{cD}|$,

✓ Near Cyclotron Frequency Modes can be excited.

✓ Calculations with more accurate fast ion distributions are required.

CAE instability at higher frequency is expected

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



Modes are expected near the cyclotron harmonics of deuterium frequency.

CAE stability diagram is important to understand experiments

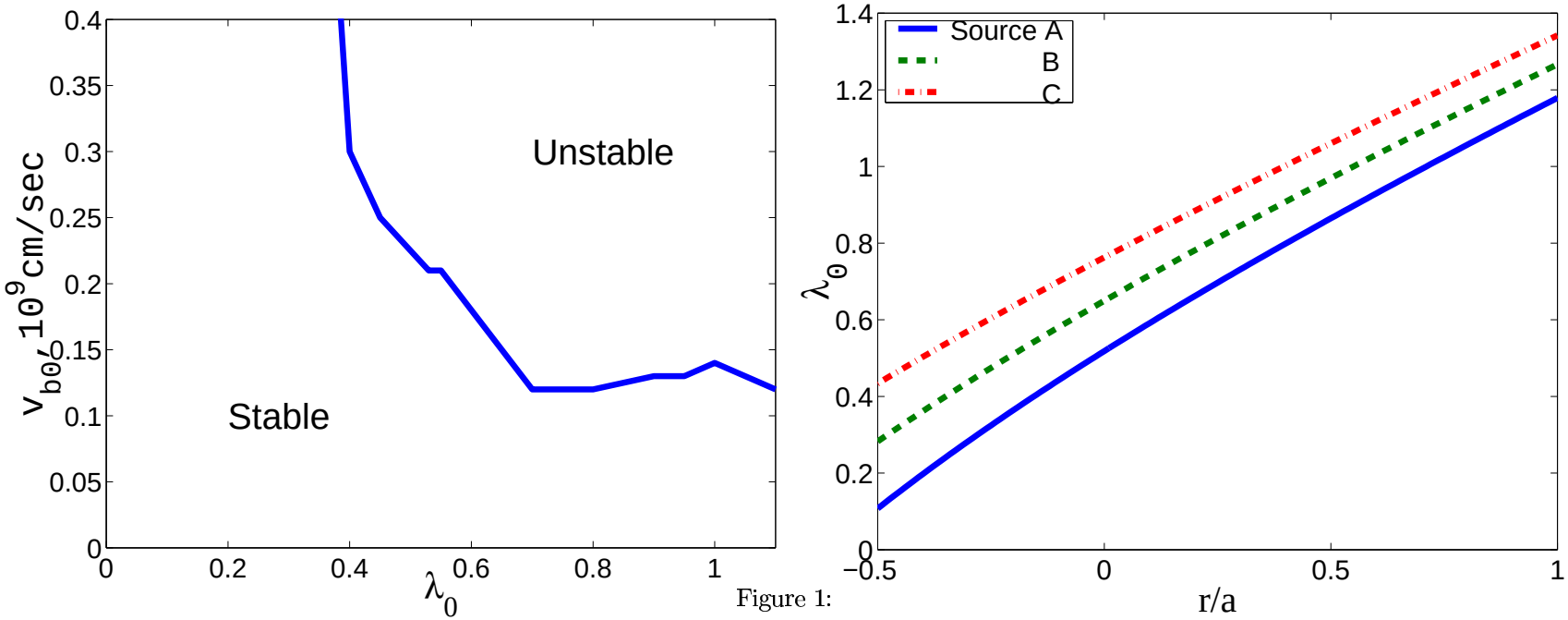


Figure 1:

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

Typical NSTX density profile evolution

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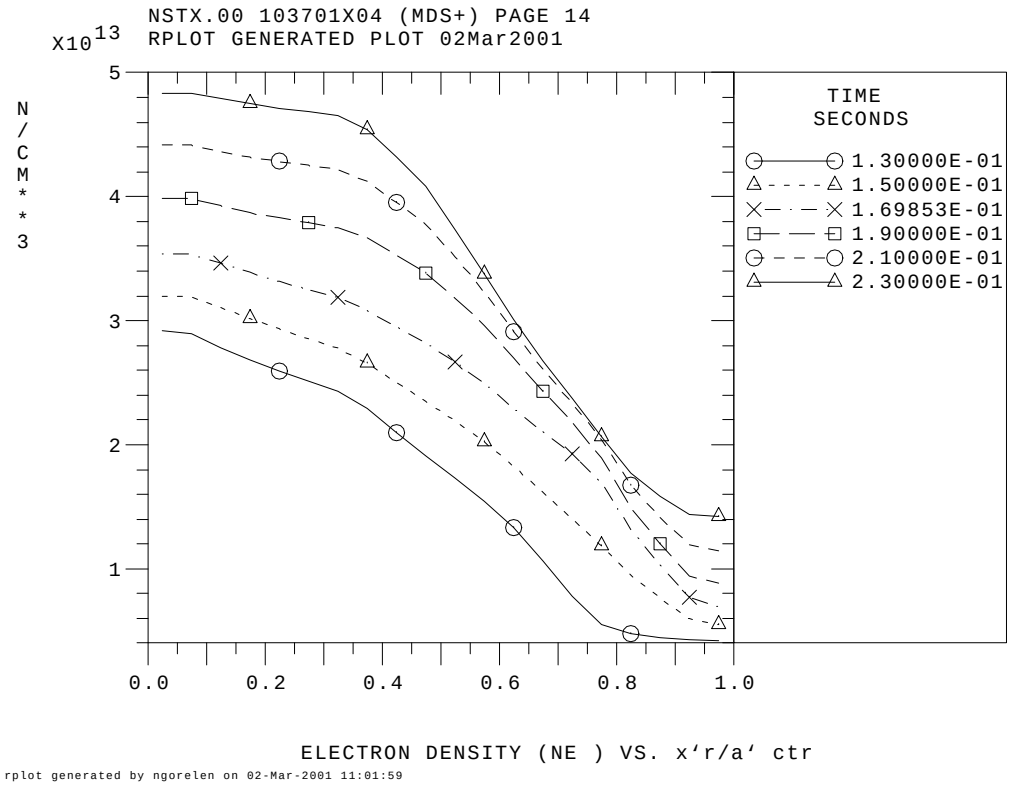

- ✓ Both density and local magnetic field at $r = r_0$ are increasing, which may cancel their effects on the frequency.
- ✓ Higher density increases number of trapped particles $\Rightarrow$ numerical distribution is urgent.

Conclusion

1. Observed sub-cyclotron oscillations in NSTX are likely to be Compressional Alfvén Instability driven by NBI ions.
2. Analysis of the spectra shows qualitative agreement with CAE theory.
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 needed.
5. Accurate mode characteristics study is needed to robustly identify high frequency modes with CAEs.
6. Would be interesting to compare results of MAST (Hydrogen NBI ions) with NSTX (Deuterium NBI ions). In both cases $v_b/v_A \simeq 4$.