Internal Amplitude, Structure and Identification of CAEs and GAEs in NSTX

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Summary

- High frequency Alfvén Eigenmodes (AE) excited by beam ions in NSTX ⇒ can also be excited in ITER & FNSF by beam ions & α’s
  - correlate with enhanced core electron thermal transport
  - posited cause: resonant interaction in presence of multiple modes

- Measurements reveal two kinds of mode
  1. broad structure, peaking toward core with significant edge $|\xi|$: mostly $f < \sim 600$ kHz, $n = -6 \sim -8$, smaller core $|\xi|$ & larger edge $\delta b$
  2. strongly core localized with vanishing edge $|\xi|$: mostly $f > \sim 600$ kHz, $n = -3 \sim -5$, larger core $|\xi|$ & smaller edge $\delta b$

- Local dispersion relations used with $f$ & $n$ to identify modes
  1. broad structure modes are global AEs (GAE): $f$ evolves consistently with shear dispersion relation & cannot fit in CAE “well”
  2. strongly core localized modes are compressional AEs (CAE): $f$ evolves inconsistently with shear dispersion relation & can fit in CAE “well”

- Amplitude and number of modes consistent with posited cause of enhanced core electron thermal transport
High frequency AEs commonly excited by beam ions in NSTX: Possible implications for burning plasmas

- High $f$ AEs ($f/f_{c0} > \sim 0.2$) commonly observed in NSTX with reflectometers & edge $\delta b$
- Excited by Doppler-shifted resonance with beam ions
  - Edge $\delta b_\theta$ toroidal array typically shows $|n| < \sim 15$, propagation counter to beam ions ($n < 0$)
- High $f$ AE activity correlated with enhanced $\chi_e$
- Other significant effects on plasma
  - shown to cause fast-ion transport
  - postulated to cause ion heating
- Can be excited by beam ions and $\alpha$'s in ITER & FNSF
  - investigation in NSTX furthers predictive capability for burning plasmas

\[ f_{c0} = 2.4 \text{ MHz} \]
High frequency AEs proposed as cause of observed $\chi_e$ enhancement [D. Stutman et al., PRL 102 115002 (2009)]

- Enhanced $\chi_e$ observed in core of NSTX beam-heated H-mode plasmas
- High $f$ AE activity correlates with enhanced $\chi_e$
  - $f \sim f_{be} \sim 600$ kHz $\Rightarrow$ resonant orbit modification
    - $f_{be} \equiv$ trapped electron bounce frequency
- High $f$ AEs identified as GAEs
- GAE core localization expected $\Rightarrow$ active in region of enhanced $\chi_e$
- Orbit modeling $\Rightarrow$ significant $\chi_e$ enhancement from multiple modes
  - threshold at $\sim 15$ modes

FIG. 3 (color online). Correlation between GAE activity, $T_e$ flattening, and central $\chi_e$ increase in NSTX H modes heated by 2, 4, and 6 MW neutral beam, at $t \sim 0.44$ s. Within the uncertainties, the $q$, $n_e$, and $\omega_{E\times B}$ profiles are the same in all discharges at the time of the transport correlation [13].
Two arrays: “Q-band” & “V-band”
- Q-band: 30, 32.5, 35, 37.5, 42.5, 45, 47.5 & 50 GHz
- V-band: 55, 57.5, 60, 62.5, 67.5, 70, 72.5 & 75 GHz

Arrays closely spaced (separated ~ 10° toroidal)
Single launch and receive horn for each array
Horns oriented perpendicular to flux surfaces ⇒ frequency array = radial array
Cutoffs span large radial range in high density plasmas ($n_0 \sim 1 – 7 \times 10^{19} \text{ m}^{-3}$)

Launch and Receive Horns (Interior View)

30-50 GHz
55-75 GHz
(not shown: horns modified to optimize for frequency range)
Reflectometers used to measure local AE density fluctuation

- Microwaves propagate to “cutoff” layer, where density high enough for reflection \((\omega_p = \omega)\)
  - Dispersion relation of “ordinary mode” microwaves: \(\omega^2 = \omega_p^2 + c^2k^2\), \(\omega_p^2\) proportional to density \((\omega_p^2 = e^2n_0/\varepsilon_0m_e)\)
  - \(k \to 0\) as \(\omega \to \omega_p\), microwaves reflect at \(k = 0\)
- Reflectometer measures path length change of microwaves reflected from plasma
  - phase between reflected and launched waves changes \((\delta \phi)\)
- for large scale modes, cutoff displaces due to \(\delta n\) at cutoff \(\Rightarrow\)
  “effective displacement” \(\xi \equiv \delta \phi/2k_{\text{vac}}\) approximates cutoff displacement
Measurements reveal two kinds of high frequency AEs in H-mode beam-heated plasmas

- **Effective displacement** ($\xi$) measured at 16 radii with reflectometer array
  - shear AEs: $\xi$ dominated by displacement of $\nabla n_0$
  - compressional AEs: compressional $\delta n$ contributes to $\xi$

- Toroidal mode number ($n$) measured with $\delta b_\theta$ edge toroidal array
  - 12 locations, irregular spacing ($\Delta \phi$)
  - $10^\circ \leq \Delta \phi \leq 180^\circ \Rightarrow$ resolves $|n| \leq 18$

- Modes structures tend to fall in two categories:
  1. **broad structure**, peaking toward core with significant edge $|\xi|$  
     - mostly $f < \sim 600 \text{ kHz}$, $n = -6 \text{ to } -8$
     - typically larger core $|\xi|$ & larger edge $\delta b$
  2. **strongly core localized**, vanishing edge $|\xi|$  
     - mostly $f > \sim 600 \text{ kHz}$, $n = -3 \text{ to } -5$
     - typically larger core $|\xi|$ & smaller edge $\delta b$
Modes can be identified as CAEs or GAEs via mode number and frequency evolution

- Dispersion relation parameters measured:
  - \( q_0 \) and \( B_0 \) from equilibrium reconstruction using magnetic field pitch from Motional Start Effect
  - \( n_{e0} \) measured via Multipoint Thomson Scattering
  - Alfvén velocity, \( \nu_{A0} = B_0/(\mu_0 \rho_0)^{1/2} \)
    - \( \rho_0 = m_D n_{e0}, m_D \) = Deuterium mass
  - Toroidal rotation frequency, \( f_{\text{ROT0}} \), from Charge Exchange Recombination Spectroscopy

- For GAEs, expect \( f(t) \) consistent with local shear Alfvén dispersion relation, but not CAEs
  \[
  f_{\text{GAE}} = \frac{k_{||} \nu_A}{2\pi} + n f_{\text{ROT}}, \quad k_{||} \approx \frac{m}{R} \left| \frac{q}{\nu} - n \right|
  \]

- Expect CAEs to fit in CAE “well”, but not GAEs
  - Compressional Alfvén waves propagate ONLY where:
    \[
    \left( \frac{n}{R} \right)^2 \nu_A^2 - \left( \omega - n \omega_{\text{ROT}} \right)^2 < 0
    \]
  - “wavelength” in \( R-Z \) plane must fit inside “well”
    \[
    \lambda_{R-Z} = \frac{2\pi}{k_{R-Z}} = 2\pi \left( \frac{\nu_A^2}{\omega - n \omega_{\text{ROT}}} \right)^{1/2}
    \]
Sensitivity of $f_{\text{GAE}}$ to $q_0$ helps distinguish CAEs & GAEs

- GAEs are shear Alfvén:
  $$f_{\text{GAE}} = \frac{k_{||} v_A}{2\pi} + n f_{\text{ROT}}, \ k_{||} \approx \frac{1}{R} \left| \frac{m}{q} - n \right|$$
  - $f_{\text{GAE}}(t)$ sensitive to $m/q_0$ if $|m| >> 1$
  - $q_0$ varies substantially $(1.7 - 1.1)$ over $t = 400 - 700 \text{ ms}$
  - Modes with $f < \sim 600 \text{ kHz}$, $n = -6 - -8$:
    - $f(t) \sim f_{\text{GAE}}(t)$
    - $|n| >> 1 \Rightarrow$ low $|m| \Rightarrow f_{\text{GAE}}$ insensitive to $q_0$
  - Modes with $f > \sim 600 \text{ kHz}$, $n = -3 - -5$:
    - $f(t)$ NOT consistent with $f_{\text{GAE}}(t)$
    - low $|n|$, high $f \Rightarrow$ high $|m| \Rightarrow$ strong $q_0$ sensitivity
For identification as CAE, sufficiently wide & deep “well” must exist for mode with measured $f$ and $n$

- For $n \neq 0$, compressional Alfvén “well” formed:
  - compressional Alfvén waves propagate ONLY where:
    \[
    \left( \frac{n}{R} \right)^2 v_A^2 - \left( \omega - n\omega_{\text{ROT}} \right)^2 < 0
    \]
- CAE “wavelength” in $R-Z$ plane must fit inside “well”
  \[
  \lambda_{R-Z} = \frac{2\pi}{k_{R-Z}} = 2\pi \left( \frac{\omega - n\omega_{\text{ROT}}}{\left( \frac{n}{R} \right)^2 v_A^2} \right)^{1/2}
  \]
- For observed modes, $f$ & $n$ used to determine well width and $\lambda_{R-Z}$
  - $\lambda_{R-Z}$ calculated at deepest point in well
  - Width ($\Delta R$) determined in midplane
- Modes with $f > \sim 600$ kHz, $n = -3 - -5$ sufficiently wide and deep
- Modes with $f < \sim 600$ kHz, $n = -6 - -8$ do not fit in “well”
  - For some $f$ & $n$, $\left( \frac{n}{R} \right)^2 v_A^2 - \left( \omega - n\omega_{\text{ROT}} \right)^2 > 0$ everywhere
  - For some $f$ & $n$, $\lambda_{R-Z} >> \Delta R$
Amplitude and number of modes consistent orbit modeling prediction for enhanced $\chi_e$ 

- ORBIT modeling indicates significant $\chi_e$ enhancement due to resonant electron interaction of multiple modes  
  [N. N. Gorelenkov et al., Nucl. Fusion 50, 084012 (2010)]
  - total fluctuation level needed to explain $\chi_e$ enhancement: $\alpha = \delta A_\parallel/B_0 R_0 = 4 \times 10^{-4}$
    • $\chi_e$ scales strongly with $\alpha \Rightarrow$ bursty fluctuations give more $\chi_e$ than would expect from r.m.s $\alpha \Rightarrow$ should evaluate time dependence carefully
  - threshold at ~ 15 modes
- For modes with $f < 600$ kHz, calculated r.m.s. $\alpha = 3.4 \times 10^{-4}$ in core, consistent with prediction for necessary fluctuation level
  - for shear Alvén modes: $\xi_r = \delta B_r/ik_\parallel B_0 = \alpha R_0 k_\theta/|k_\parallel|
    - $\xi_R$ estimated by reflectomter $|\xi| @ R = 1.16$ m
    - $k_\parallel$ estimated from $f$ using shear Alvén dispersion relation
      - $k_\theta = m/r$, using $m$ estimated from $k_\parallel = |m/q - n|$, taking $q = q_0$ and $r = 1.16$ m $- R_0$
      - Future comparison must account for bursty fluctuation level
- Number of modes (including CAEs) is 15, consistent with prediction for necessary fluctuation level
- Model needed for CAE effect on $\chi_e$
Future Work

- Extend ORBIT modeling to include CAEs in prediction of $\chi_e$ enhancement
- Use mode structure measurements to guide inputs to ORBIT modeling
- Investigate effects of CAEs and GAEs on fast-ion transport using ORBIT modeling with measured mode structures
- Compare CAE/GAE amplitude and structure measurements with theory predicting ion heating
Conclusions

• High frequency Alfvén Eigenmodes (AE) excited by beam ions in NSTX \( \Rightarrow \) can also be excited in ITER & FNSF by beam ions & \( \alpha \)'s
  – correlate with enhanced core electron thermal transport
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  (2) strongly core localized with vanishing edge \(|\xi|\):
    mostly \( f > \sim 600 \text{ kHz}, \ n = -3 \ - -5 \), larger core \(|\xi|\) & smaller edge \( \delta b \)

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  (1) broad structure modes are *global AEs (GAE)*: \( f \) evolves *consistently* with shear dispersion relation & *cannot fit* in CAE “well”
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