Structure, Amplitude and Identification of CAEs and GAEs in NSTX

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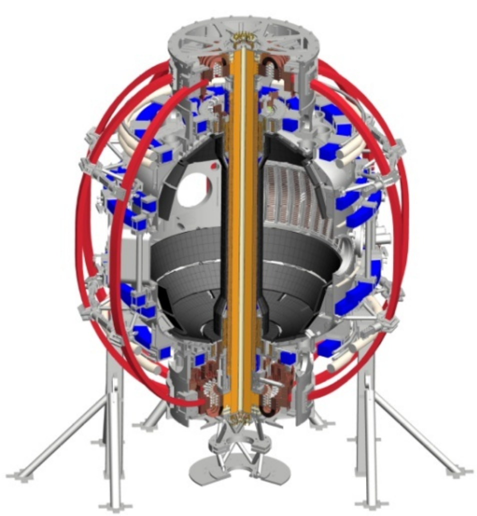
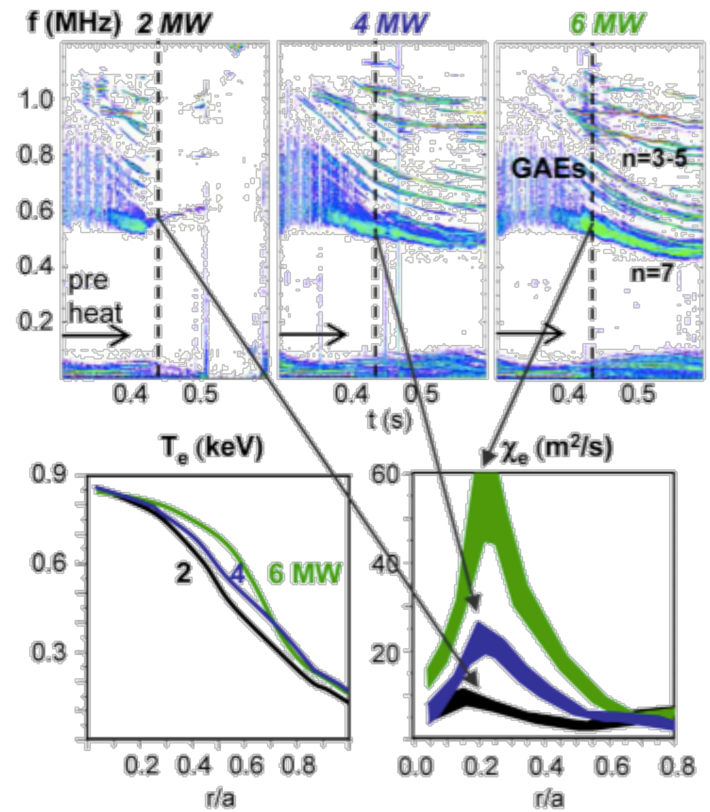


Observed χ_e enhancement motivates measurement and identification of high frequency AEs

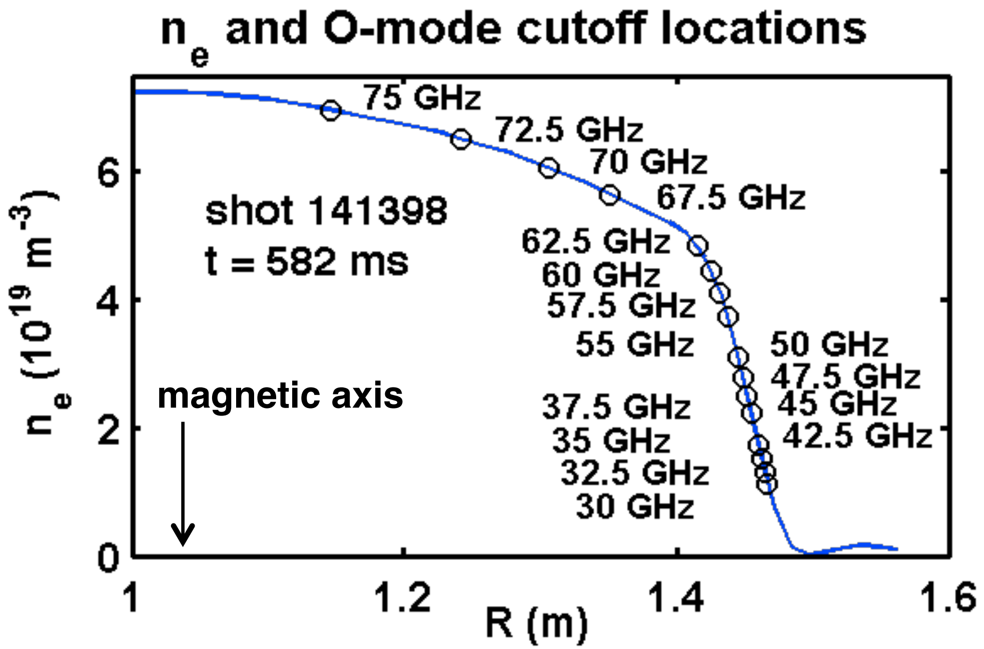
- Beam-ion-excited high frequency Alfvén Eigenmodes (AE) correlate with enhanced core χ_e
  - posited cause: resonant interaction of multiple modes with electron
- High frequency AE structure measured with reflectometer array
  - Measurements reveal two kinds of mode
- Local dispersion relations help identify modes
  - Two kinds of mode are CAEs and GAEs
- Measurements consistent with transport hypothesis

[N. N. Gorelenkov et al., Nucl. Fusion 50, 084012 (2010)]



[D. Stutman et al., PRL 102 115002 (2009)]

AE radial structure measured with array of reflectometers

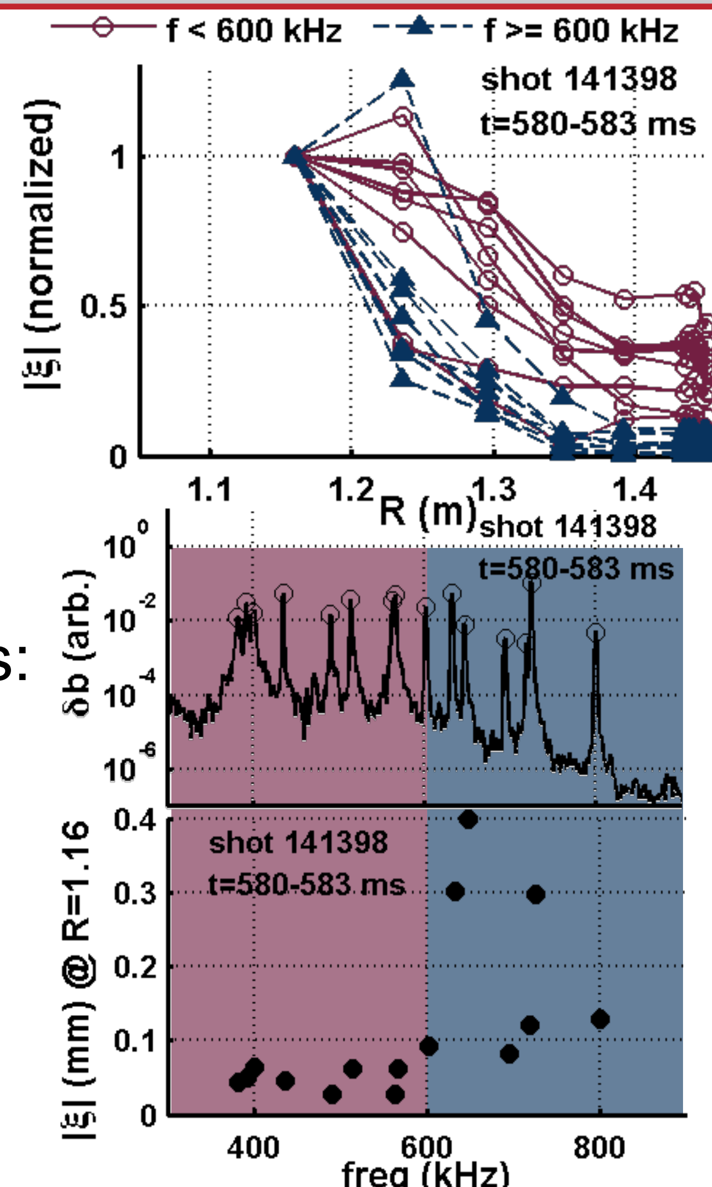


- Reflectometer measures path length change (δL) of microwaves reflected from plasma
  - Microwaves reach cutoff at $\omega^2 = \omega_p{}^2 = e^2 n_0/\varepsilon_0 m_e$
- For large scale modes, cutoff displaces due to δn at cutoff ⇒ "effective displacement" $\xi \equiv \delta L/2$ approximates cutoff displacement

Measurements reveal two kinds of high frequency AEs

- Structure measured with reflectometer array
- Toroidal mode number (*n*) measured with edge δb toroidal array
- Structures tend to fall in two categories:
  (1) broad structure, peaking toward core
  - mostly *f < ~ 600 kHz, n = -6 – -8*

  (2) strongly core localized
  - mostly *f > ~ 600 kHz, n = -3 – -5*

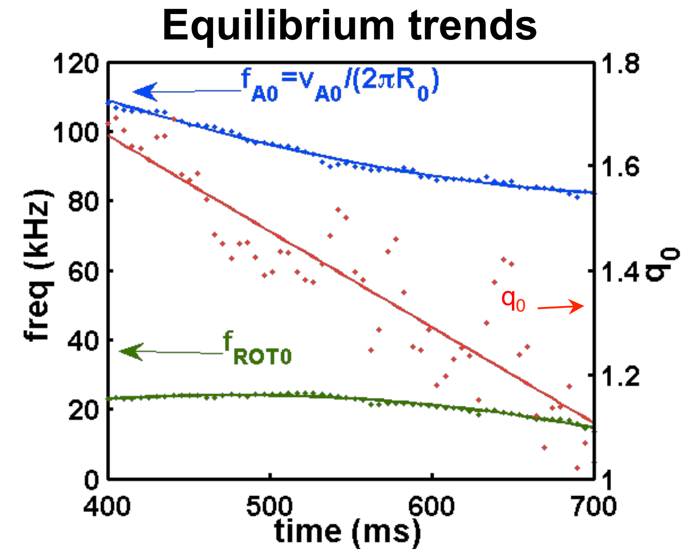


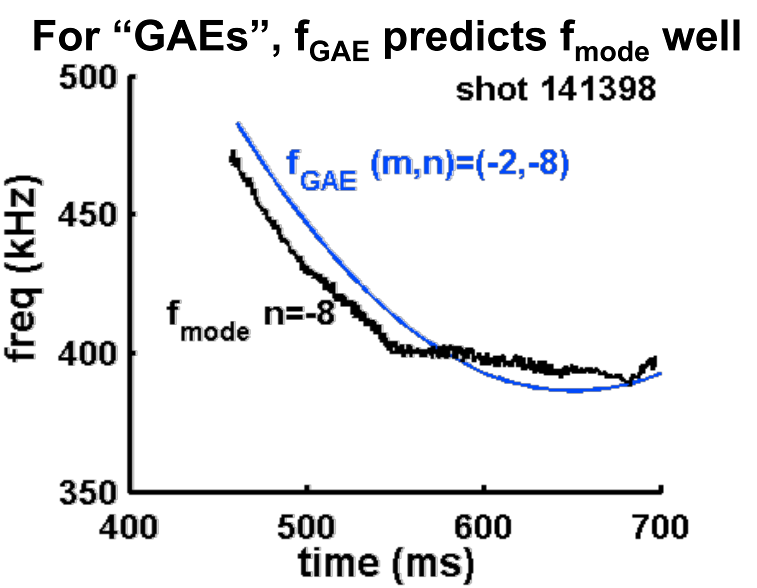
Broad structure (f < ~ 600 kHz) modes are GAEs

- GAEs are shear Alfvén:
  - peak at weak shear, e.g. at axis

$$f_{GAE} = \frac{k_{\|} v_A}{2\pi} + n f_{ROT}, \; k_{\|} \approx \frac{1}{R}\left|\frac{m}{q} - n\right|$$

- Strong q_0 variation ⇒ comparison with $f_{GAE}(t)$ stringent test of identity
  - Fit to $f_{GAE}(t) \Rightarrow m$
  - $f_{GAE}(t)$ sensitive to m/q if $|m| >> 1$
  - q_0 varies substantially (1.7 – 1.1) over t = 400 – 700 ms
- Modes with f < ~ 600 kHz: $f(t)$ ~ $f_{GAE}(t)$
  - Modes with f > ~ 600 kHz: $f(t)$ NOT consistent with $f_{GAE}(t)$





Strongly core localized modes are CAEs

- Compressional Alfvén waves propagate ONLY where:

$$\omega^2 > v_A^2 (n/R)^2$$

- "Well" formed in *R–Z* plane

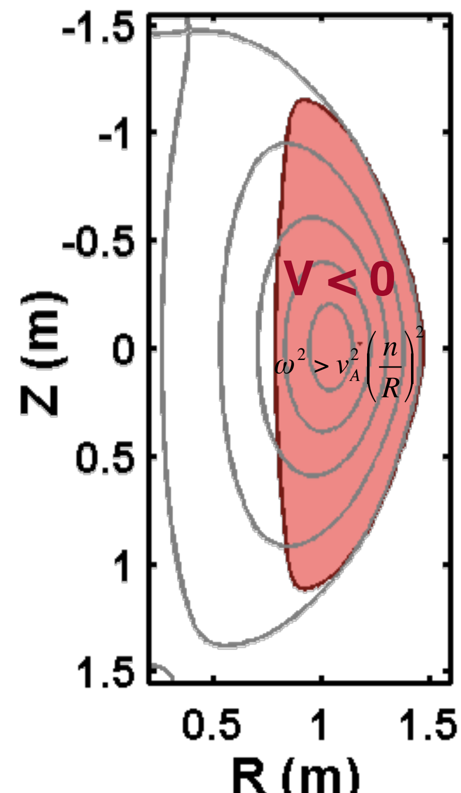
$$\omega^2 = v_A^2 k^2 \Leftrightarrow \nabla_{R-Z}^2 \zeta - V(R,Z)\zeta = 0$$

$$V(R,Z) = (n/R)^2 - (\omega/v_A)^2$$

- CAE must fit inside "well"
  - V ⇒ *R-Z* "wavelength": $\lambda_{R-Z} \propto \left(-V(R,Z)\right)^{-\frac{1}{2}}$
- Well width & λ_{R-Z} compared
  - λ_{R-Z} calculated at deepest point in well
  - Width (ΔR) determined in midplane
  - Toroidal Doppler shift taken into account

CAE "well"

f = 633 kHz, n = -4 (shot 141398, t = 582 ms)



- Modes with *f* > ~ 600 kHz: "well" is sufficiently deep
  - Modes with *f* < ~ 600 kHz: no "well", or "well" too shallow

Measurements consistent with ORBIT modeling prediction for enhanced χ_e

- ORBIT modeling ⇒ χ_e enhancement due to resonant electron interaction with multiple modes
  [N. N. Gorelenkov et al., Nucl. Fusion 50, 084012 (2010)]
  - total fluctuation level needed to explain χ_e ehancement: $\alpha = \delta A_{||}/B_0 R_0 = 4 \text{ x } 10^{-4}$
  - threshold at ~ 15 modes

- For GAEs, α = 3.4 x 10^{-4} in core, consistent with prediction
  - for shear Alvén modes: $\xi_r = \delta B_r / i k_{||} B_0 = \alpha R_0 k_\theta / k_{||}$
  - ξ_r estimated by reflectomter $|\xi|$ @ R = 1.16 m
  - $k_{||}$ & k_θ estimated using shear dispersion relation

- Number of modes (including CAEs) is 15, consistent with prediction

Summary

- Observed χ_e enhancement motivates measurement and identification of high frequency AEs
- Measurements reveal two kinds of mode
  (1) broad structure, mostly f < ~ 600 kHz, n = -6 – -8
  (2) strongly core localized, mostly f > ~ 600 kHz, n = -3 – -5
- Local dispersion relations help identify modes
  (1) broad structure modes are GAEs
  (2) strongly core localized modes are CAEs
- Amplitude and number of modes consistent with hypothesis for χ_e enhancement, resonant interaction with multiple modes.

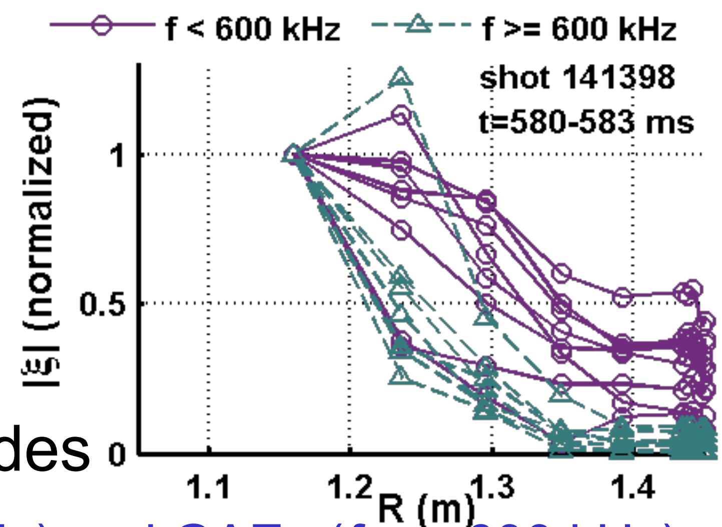
Future Work

- Use measurements to guide ORBIT modeling to predict χ_e (K. Tritz, GO6.00004)
- Validate simulations of HYM code (E. Belova, PP8.00022)

Backup Slides

Overview

- Motivation: beam-ion-excited high frequency Alfvén Eigenmodes (AE) correlate with enhanced core χ_e
  [D. Stutman et al., PRL 102 115002 (2009)]
  - posited cause: resonant interaction in presence of multiple modes
- Structure measurements: high frequency AE structure measured with reflectometer array
  - Measurements reveal two kinds of mode



- Identification analysis: local dispersion relations used with f & n to identify modes
  - Two kinds of mode are CAEs (f > ~ 600 kHz) and GAEs (f < ~ 600 kHz)
- Comparison with transport hypothesis:
  [N. N. Gorelenkov et al., Nucl. Fusion 50, 084012 (2010)]
  - Amplitude and number of modes consistent with posited cause of enhanced core electron thermal transport

High frequency AEs proposed as cause of observed χ_e enhancement [D. Stutman et al., PRL 102 115002 (2009)]

- high *f* AE activity in core of NSTX beam-heated plasmas – correlates with enhanced χ_e
- $f \sim f_{be} \sim 600$ kHz ⇒ resonant orbit modification
  - f_{be} ≡ trapped electron bounce frequency
- High *f* AEs identified as GAEs
- GAE core localization expected ⇒ active in region of enhanced χ_e
- Orbit modeling ⇒ significant χ_e enhancement from multiple modes [N. N. Gorelenkov et al., Nucl. Fusion 50, 084012 (2010)]
  - threshold at ~ 15 modes

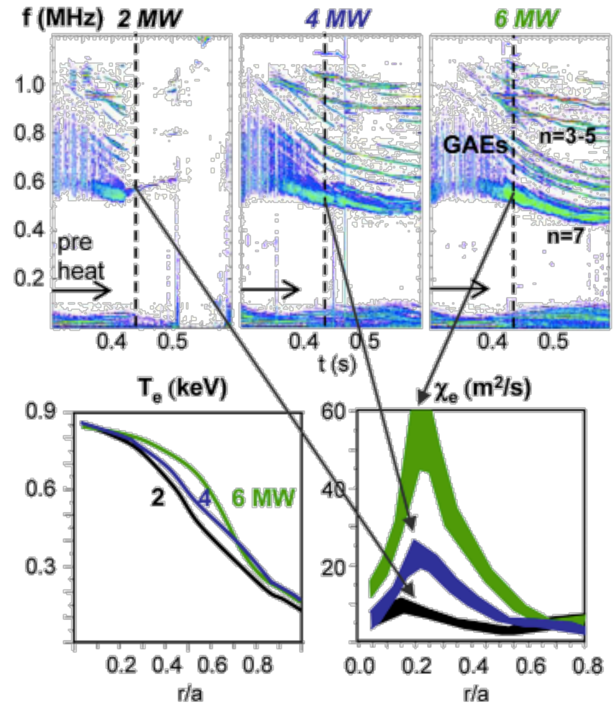
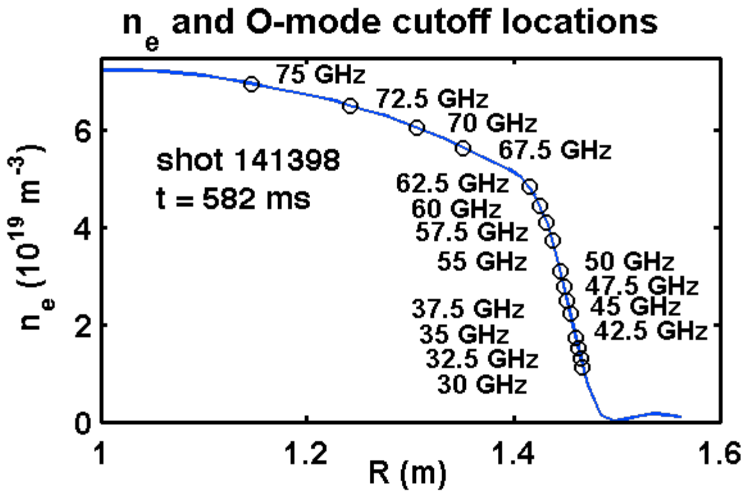


FIG. 3 (color online). Correlation between GAE activity, T_e flattening, and central χ_e increase in NSTX *H* modes heated by 2, 4, and 6 MW neutral beam, at $t \sim 0.44$ s. Within the uncertainties, the q, n_e, and $\omega_{E\times B}$ profiles are the same in all discharges at the time of the transport correlation [13].

AE radial structure measured with array of reflectometers

- Reflectometer measures path length change of microwaves reflected from plasma
  - Microwaves propagate to "cutoff" layer, where density high enough for reflection ($\omega^2 = \omega_p{}^2 = e^2 n_0/\varepsilon_0 m_e$)
- for large scale modes, cutoff displaces due to δn at cutoff ⇒ "effective displacement" $\xi \equiv \delta\phi/2k_{vac}$ approximates cutoff displacement
  - $\delta\phi$ = phase between reflected and launched waves changes
- Two arrays of reflectometers:
  - Q-band: 8 channels — 30–50 GHz
  - V-band: 8 channels — 55–75 GHz
- Cutoffs span large radial range in high density plasmas ($n_0 \sim 1 - 7 \times 10^{19}$ m^{-3})

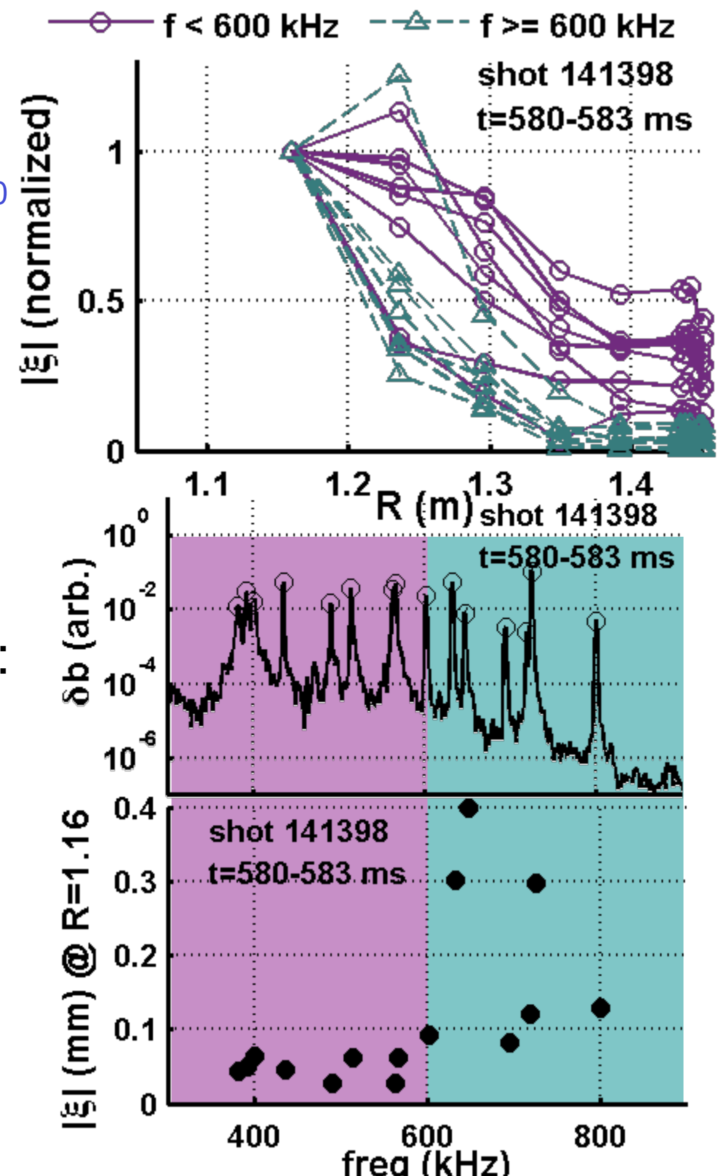


Measurements reveal two kinds of high frequency AEs in H-mode beam-heated plasmas

- *Effective displacement* (ξ) measured at 16 radii with reflectometer array
  - shear AEs: ξ dominated by displacement of ∇n_0
  - compressional AEs: compressional δn contributes to ξ
- Toroidal mode number (*n*) measured with δb_θ edge toroidal array
  - 12 locations, irregular spacing ($\Delta\phi$)
  - $10° \leq \Delta\phi \leq 180° \Rightarrow$ resolves $|n| \leq 18$
- Modes structures tend to fall in two categories:

  (1) broad structure, peaking toward core with significant edge |ξ|
  - mostly *f < ~ 600 kHz, n = -6 – -8*
  - typically larger core |ξ| & larger edge δb

  (2) **strongly core localized**, vanishing edge |ξ|
  - mostly *f > ~ 600 kHz, n = -3 – -5*
  - typically larger larger core |ξ| & smaller edge δb



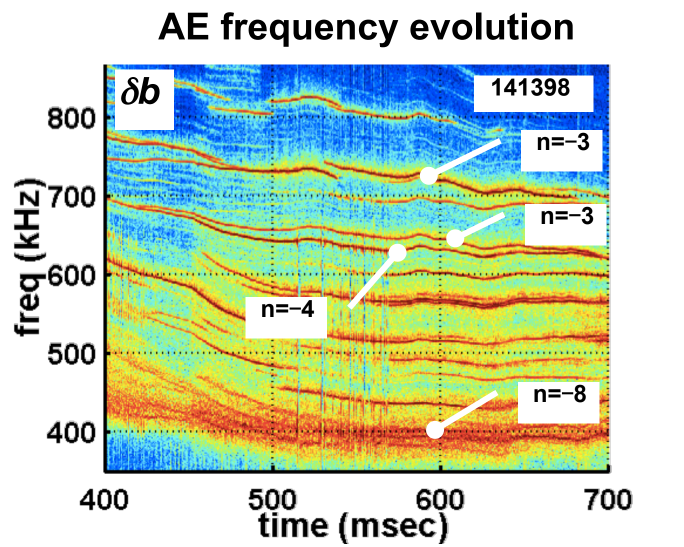
Modes can be identified as CAEs or GAEs via mode number and frequency evolution

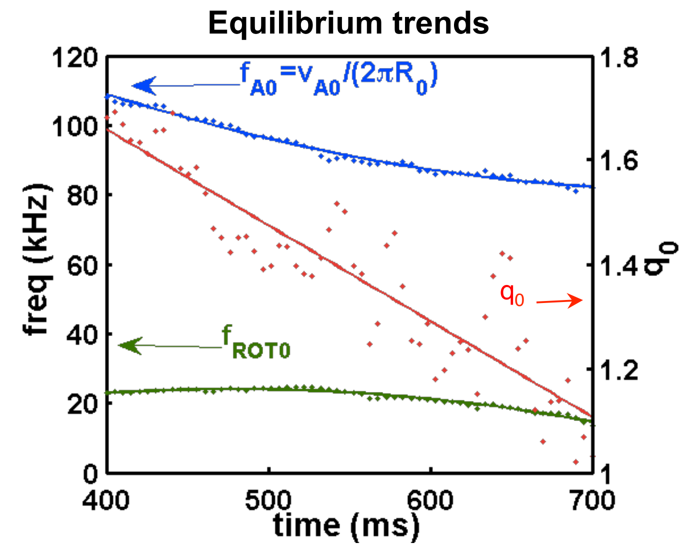
- Dispersion relation parameters measured:
  - q_0 and B_0 from equilibrium reconstruction using magnetic field pitch from Motional Start Effect
  - n_{e0} measured via Multipoint Thomson Scattering
  - Alfvén velocity, $v_{A0} = B_0/(\mu_0\rho_0)^{1/2}$
    - $\rho_0 = m_D n_{e0}$, m_D=Deuterium mass
  - Toroidal rotation frequency, f_{ROT0}, from Charge Exchange Recombination Spectroscopy
- For GAEs, expect $f(t)$ consistent with local shear Alfvén dispersion relation, but not CAEs

$$f_{GAE} = \frac{k_{\parallel} v_A}{2\pi} + n f_{ROT}, k_{\parallel} \approx \frac{1}{R}\left|\frac{m}{q} - n\right|$$

- Expect CAEs to fit in CAE "well", but not GAEs
  - compressional Alfvén waves propagate ONLY where: $\left(\frac{n}{R}\right)^2 v_A^2 - (\omega - n\omega_{ROT})^2 < 0$
  - "wavelength" in R-Z plane must fit inside "well"

$$\lambda_{R-Z} = \frac{2\pi}{k_{R-Z}} = 2\pi\left((\omega - n\omega_{ROT})^2 - \left(\frac{n}{R}\right)^2 v_A^2\right)^{-1/2}$$





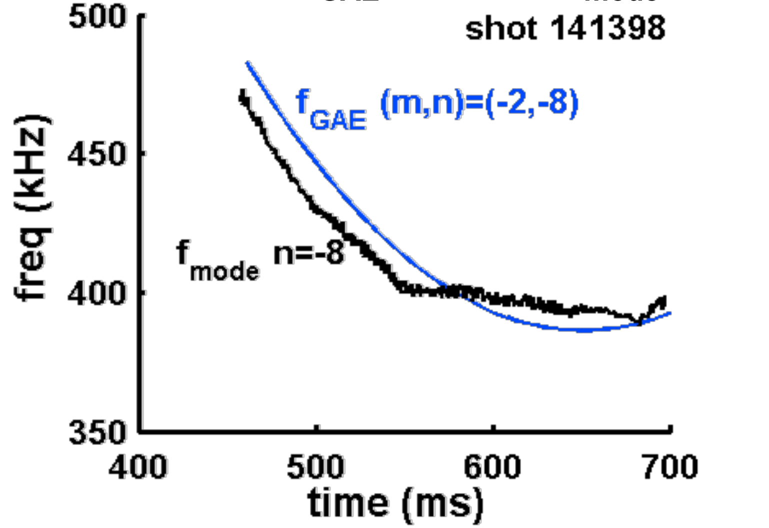
Sensitivity of f_{GAE} to q_0 helps distinguish CAEs & GAEs

- GAEs are shear Alfvén:

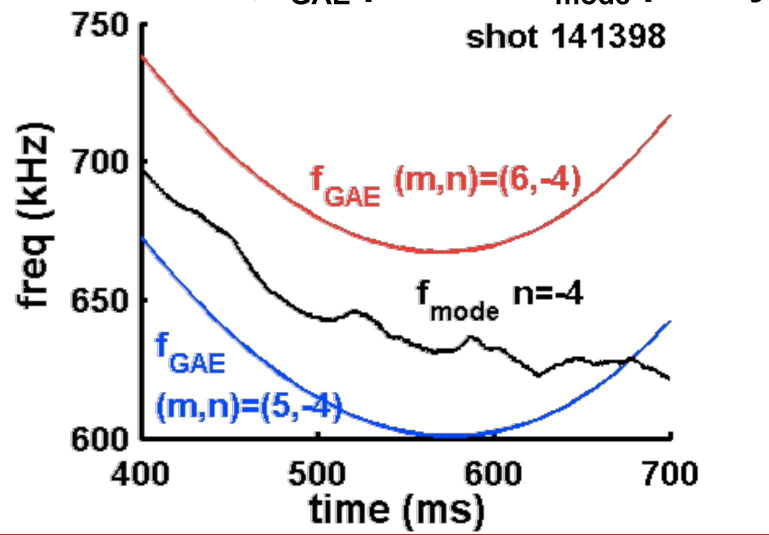
$$f_{GAE} = \frac{k_\parallel v_A}{2\pi} + n f_{ROT},\ k_\parallel \approx \frac{1}{R}\left|\frac{m}{q} - n\right|$$

- $f_{GAE}(t)$ sensitive to m/q_0 if $|m| >> 1$
- q_0 varies substantially (1.7 – 1.1) over t = 400 – 700 ms
- Modes with $f <\sim$ 600 kHz, n = -6 – -8: $f(t) \sim f_{GAE}(t)$
  - $|n| >> 1 \Rightarrow$ low $|m| \Rightarrow f_{GAE}$ insensitive to q_0
- Modes with $f >\sim$ 600 kHz, n = -3 – -5: $f(t)$ NOT consistent with $f_{GAE}(t)$
  - low $|n|$, high $f \Rightarrow$ high $|m| \Rightarrow$ strong q_0 sensitivity

For "GAEs", f_{GAE} predicts f_{mode} well



For "CAEs", f_{GAE} predicts f_{mode} poorly



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:

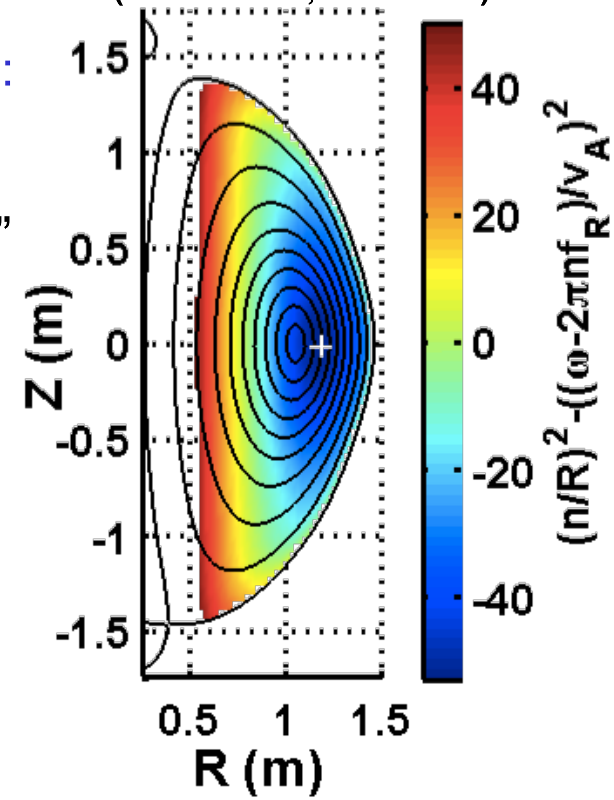
$$\left(\frac{n}{R}\right)^2 v_A^2 - (\omega - n\omega_{ROT})^2 < 0$$

- CAE "wavelength" in *R*-*Z* plane must fit inside "well"

$$\lambda_{R-Z} = \frac{2\pi}{k_{R-Z}} = 2\pi\left((\omega - n\omega_{ROT})^2 - \left(\frac{n}{R}\right)^2 v_A^2\right)^{-1/2}$$

- For observed modes, *f* & *n* used to determine well width and λ_{R-Z}
  - λ_{R-Z} calculated at deepest point in well
  - Width (ΔR) determined in midplane
- Modes with *f* > ~ 600 kHz, n = -3 – -5 sufficiently wide and deep
- Modes with *f* < ~ 600 kHz, *n* = -6 – -8 do not fit in "well"
  - For some *f* & *n*, $(n/R)^2 v_A^2 - (\omega - n\omega_{ROT})^2 > 0$ everywhere
  - For some *f* & *n*, $\lambda_{R-Z} >> \Delta R$

CAE "well" for *f* = 633 kHz, n = -4
(shot 141398, t = 582 ms)

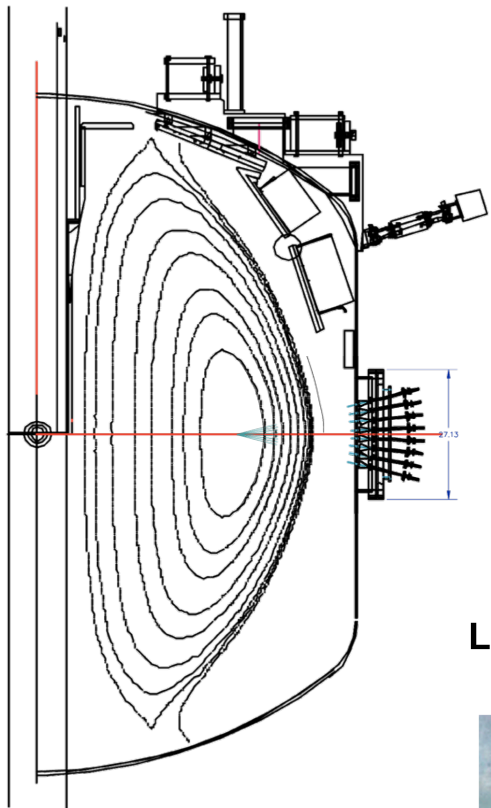


Amplitude and number of modes consistent with ORBIT modeling prediction for enhanced χ_e

- ORBIT modeling indicates significant χ_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 χ_e ehancement: $\alpha = \delta A_{\|}/B_0 R_0 = 4 \text{ x } 10^{-4}$
    - χ_e scales strongly with $\alpha \Rightarrow$ bursty fluctuations give more χ_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. $\alpha = 3.4 \text{ x } 10^{-4}$ in core, consistent with prediction for necessary fluctuation level
  - for shear Alvén modes: $\xi_r = \delta B_r / i k_{\|} B_0 = \alpha R_0 k_\theta / k_{\|}$
  - ξ_r estimated by reflectomter $|\xi|$ @ R = 1.16 m
  - $k_{\|}$ & k_θ estimated using $f \approx k_{\|} v_A / 2\pi + n f_{ROT}$, $k_\theta = m/r$, $k_{\|} = |m/q - n|/R$, taking $q = q_0$ and r = 1.16 m – R_0
- Number of modes (including CAEs) is 15, consistent with prediction for necessary fluctuation level
- Model needed for CAE effect on χ_e

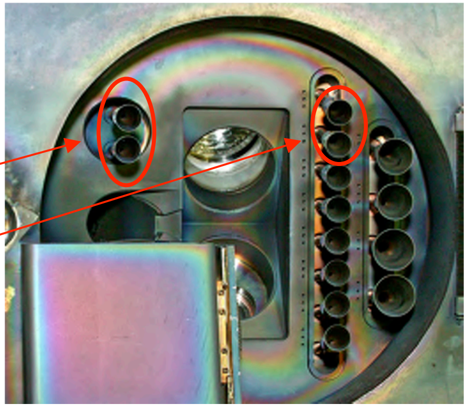
AE radial structure measured with array of reflectometers

NSTX cross-section



- 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 ~ 1 – 7 x 10^{19} m^{-3})

Launch and Receive Horns (Interior View)

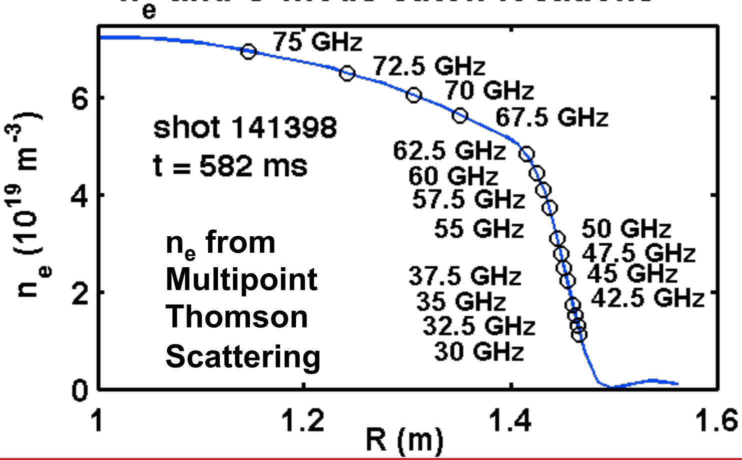


30-50 GHz

55-75 GHz

(not shown: horns modified to optimize for frequency range)

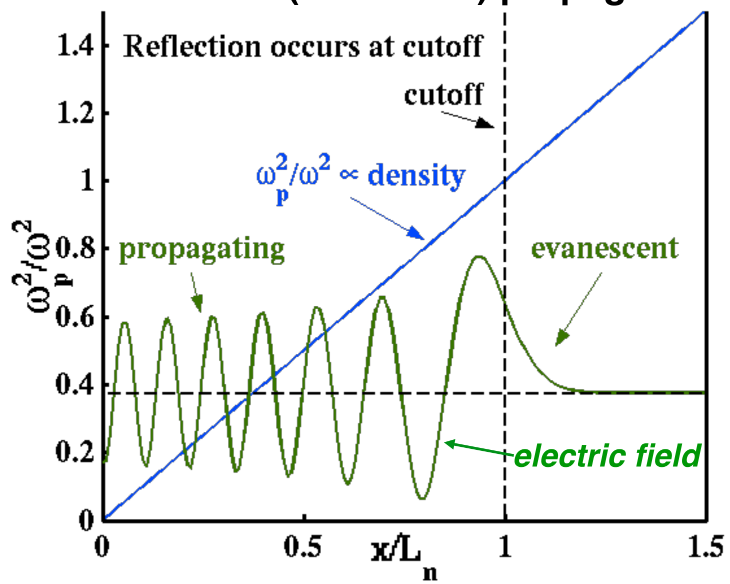
n_e and O-mode cutoff locations



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: $\omega^2 = \omega_p^2 + c^2k^2$, ω_p^2 proportional to density ($\omega_p^2 = e^2n_0/\varepsilon_0 m_e$)
  - $k \rightarrow 0$ as $\omega \rightarrow \omega_p$, microwaves reflect at $k = 0$

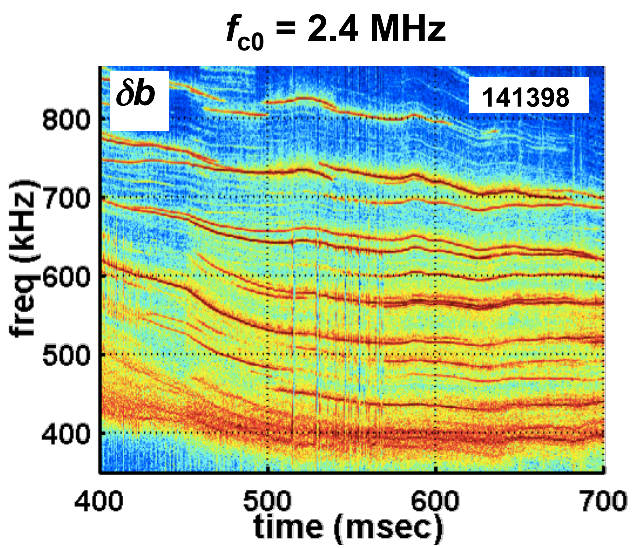
Microwave ("O-mode") propagation



- 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 δn at cutoff ⇒ "effective displacement" $\xi \equiv \delta\phi/2k_{vac}$ approximates cutoff displacement

High frequency AEs commonly excited by beam ions in NSTX

- High *f* AEs (f / f_{c0} > ~ 0.2) commonly observed in NSTX with reflectometers & edge δb
- Excited by Doppler-shifted resonance with beam ions
  - Edge δb_θ toroidal array typically shows |n| < ~ 15, propagation *counter* to beam ions ($n < 0$)
- High *f* AE activity correlated with enhanced χ_e
- Other significant effects on plasma
  - shown to cause fast-ion transport
  - postulated to cause ion heating



Future Work

- Extend ORBIT modeling to include CAEs in prediction of χ_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

Future Work

- Use mode structure measurements to guide inputs to ORBIT modeling
  - see GO6.00004: "Investigation of CAE/GAE-induced electron thermal transport for NSTX-U", K. Tritz
- Validate CAE/GAE simulations of HYM (HYbrid kinetic and MHD) code
  - see PP8.00022: "Numerical Simulations of NBI-driven CAE modes in H-mode Discharges in NSTX", E. Belova