NSTX-U

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

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X Science LLC

Neal A. Crocker

E. D. Fredrickson, N. N. Gorelenkov, W. A. Peebles, S. Kubota, R. E. Bell, B. P. LeBlanc, J. E. Menard, M. Podestà, K. Tritz and H. Yuh

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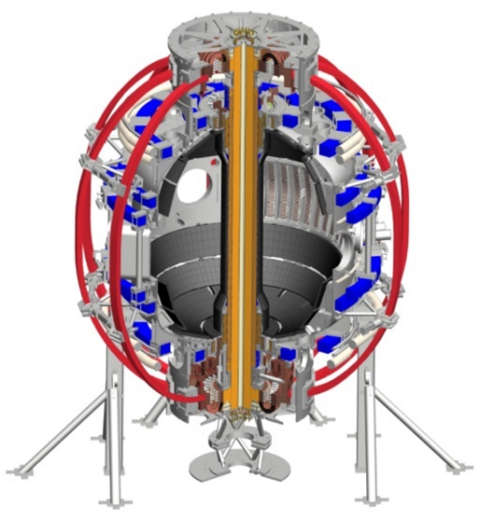

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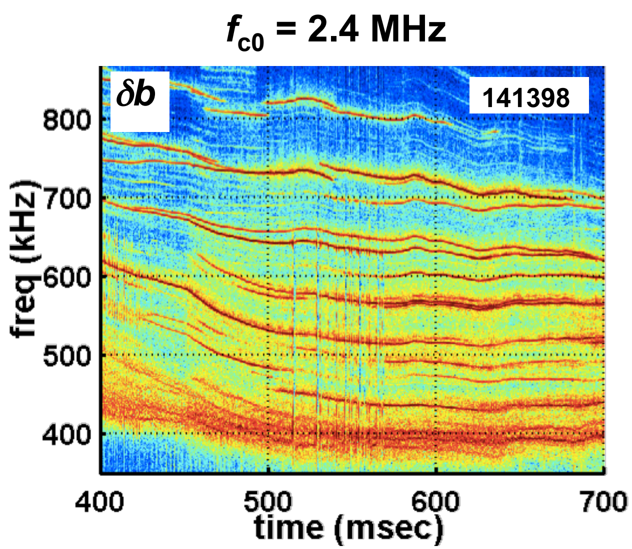
Summary

- 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 < ~ 600 kHz, n = -6 – -8, smaller core $|\xi|$ & larger edge δb
  - (2) strongly core localized with vanishing edge $|\xi|$: mostly f > ~ 600 kHz, n = -3 – -5, larger core $|\xi|$ & smaller edge δb
- 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} > ~ 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
- Can be excited by beam ions and α's in ITER & FNSF
  - investigation in NSTX furthers predictive capability for burning plasmas

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

- Enhanced χ_e observed in core of NSTX beam-heated H-mode plasmas
- High *f* AE activity 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

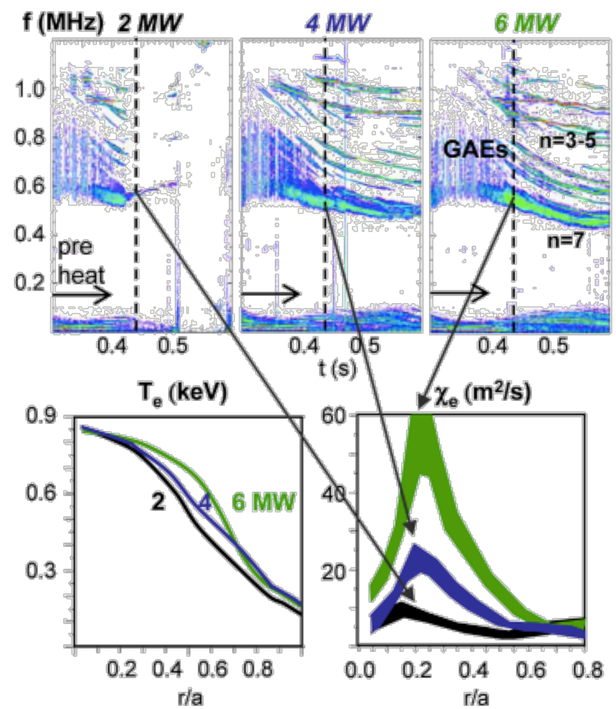
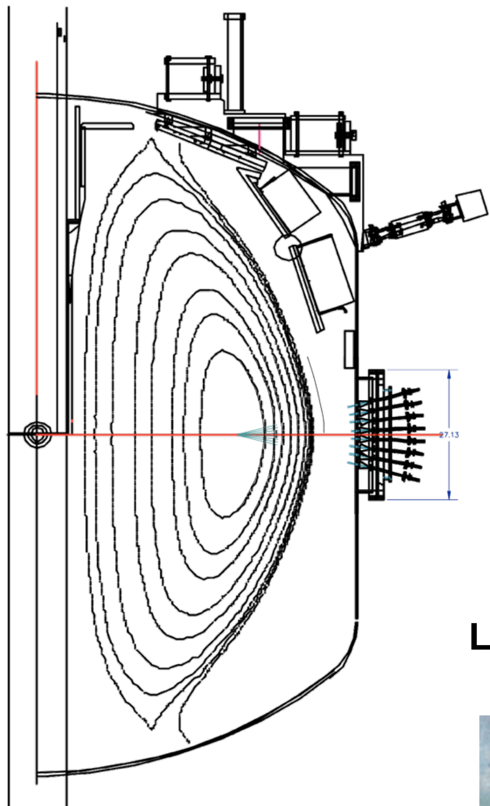


FIG. 3 (color online). Correlation between GAE activity, T_e flattening, and central χ_e increase in NSTX H modes heated by 2, 4, and 6 MW neutral beam, at $t \sim 0.44$ s. Within the uncertainties, the q, n_e, and $\omega_{E\times B}$ profiles are the same in all discharges at the time of the transport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

AE radial structure measured with array of reflectometers

NSTX cross-section



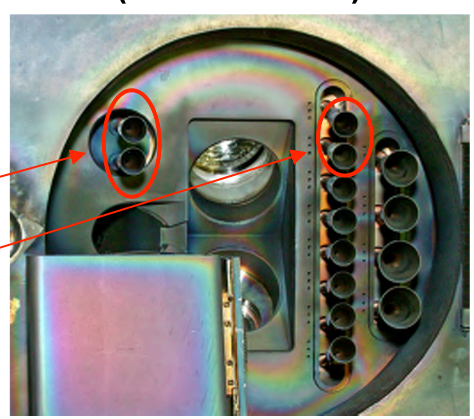
- Two arrays: “Q-band” & “V-band”
  - –Q-band: 30, 32.5, 35, 37.5, 42.5, 45, 47.5 & 50 GHz
  - –V-band: 55, 57.5, 60, 62.5, 67.5, 70, 72.5 & 75 GHz
- Arrays closely spaced (separated ~ 10° toroidal)
- Single launch and receive horn for each array
- Horns oriented perpendicular to flux surfaces ⇒ frequency array = radial array
- Cutoffs span large radial range in high density plasmas (n_0 ~ 1 – 7 x 10^{19} m^{-3})

30-50 GHz

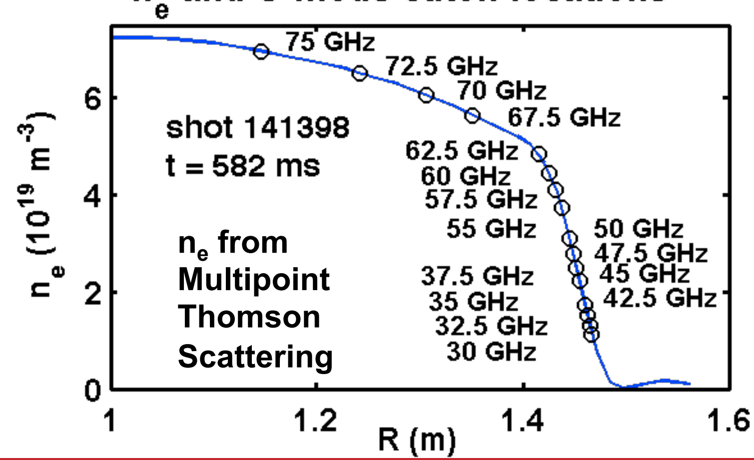
55-75 GHz

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

Launch and Receive Horns (Interior View)



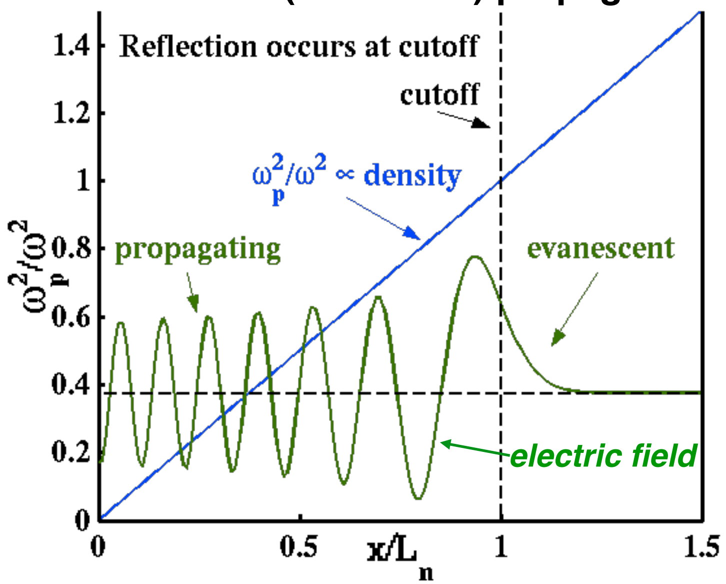
n_e and O-mode cutoff locations



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

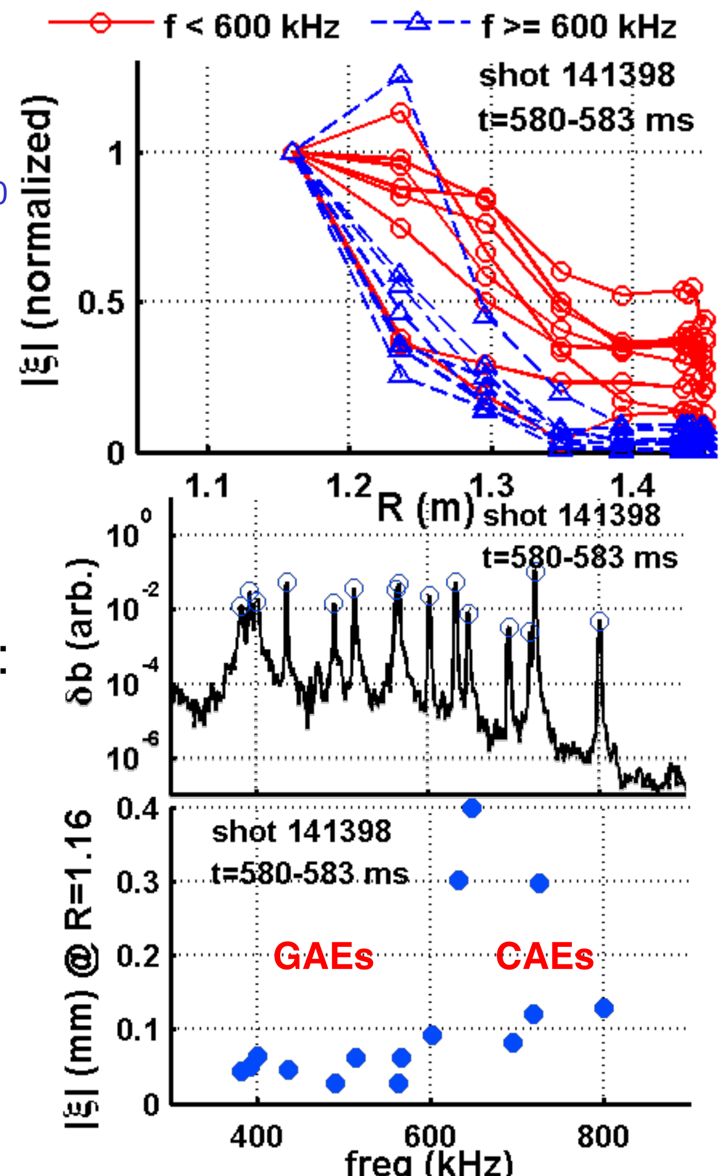
Microwave ("O-mode") propagation



- 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

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

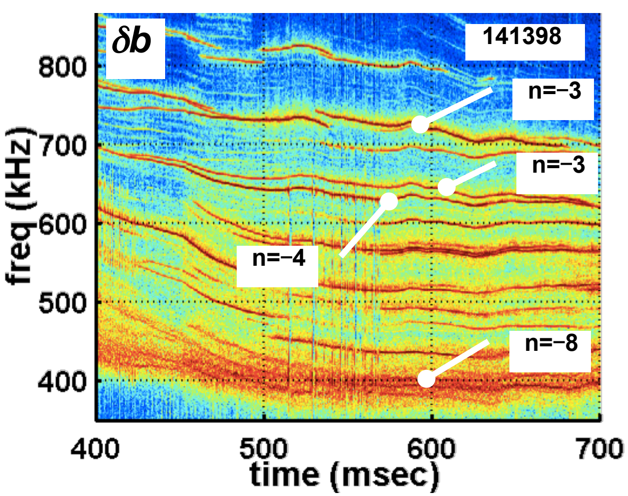
- Dispersion relation parameters measured:
  - q_0 and B_0 from equilibrium reconstruction using magnetic field pitch from Motional Start Effect
  - n_{e0} measured via Multipoint Thomson Scattering
  - Alfvén velocity, $v_{A0} = B_0/(\mu_0\rho_0)^{1/2}$
    - $\rho_0 = m_D n_{e0}$, m_D=Deuterium mass
  - 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

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

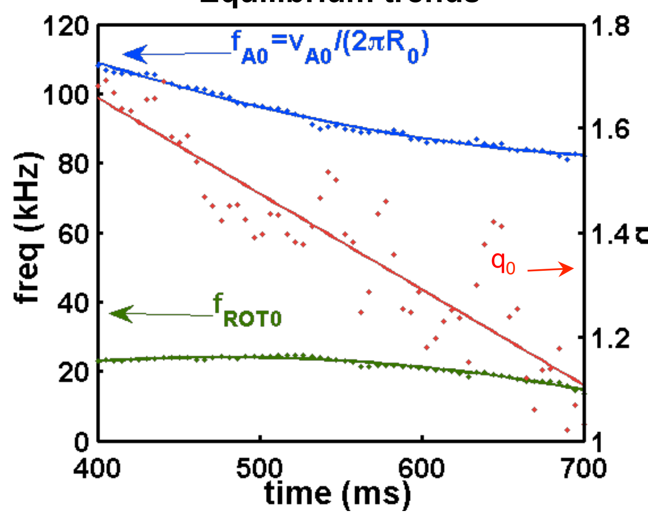
- Expect CAEs to fit in CAE "well", but not GAEs
  - compressional Alfvén waves propagate ONLY where: $\left(\frac{n}{R}\right)^2 v_A^2 - (\omega - n\omega_{ROT})^2 < 0$
  - "wavelength" in R-Z plane must fit inside "well"

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

AE frequency evolution



Equilibrium trends



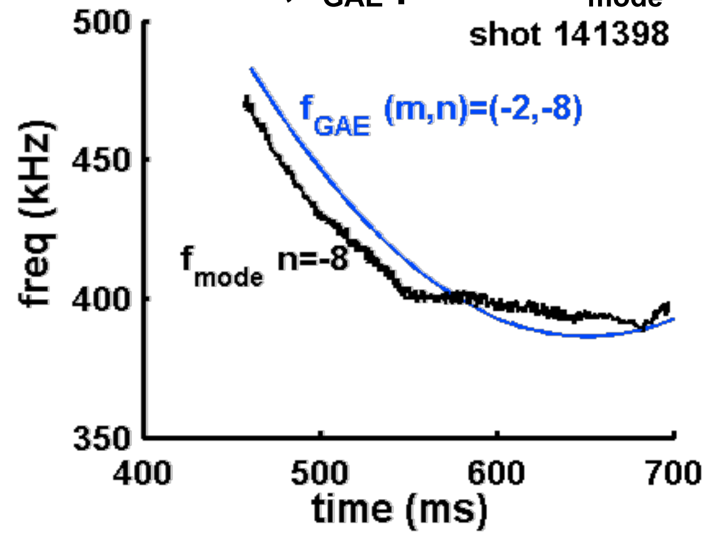
Sensitivity of f_{GAE} to q_0 helps distinguish CAEs & GAEs

- GAEs are shear Alfvén:

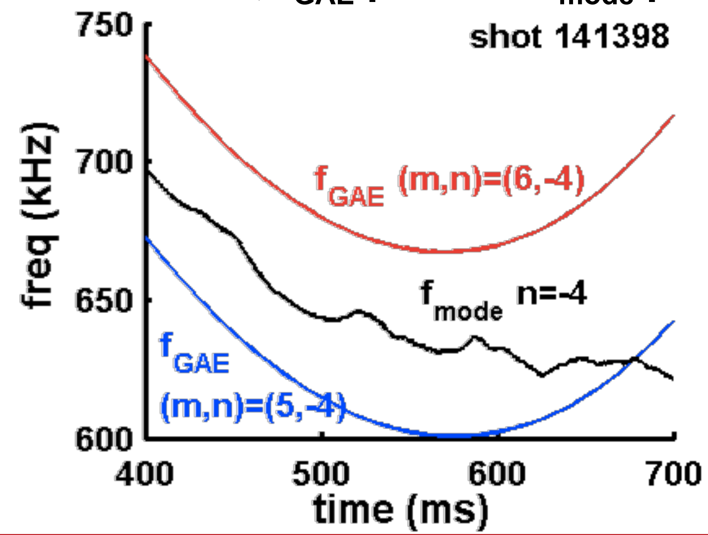
$$f_{GAE} = \frac{k_{\|} v_A}{2\pi} + n f_{ROT}, \; k_{\|} \approx \frac{1}{R}\left|\frac{m}{q} - n\right|$$

- $f_{GAE}(t)$ 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:

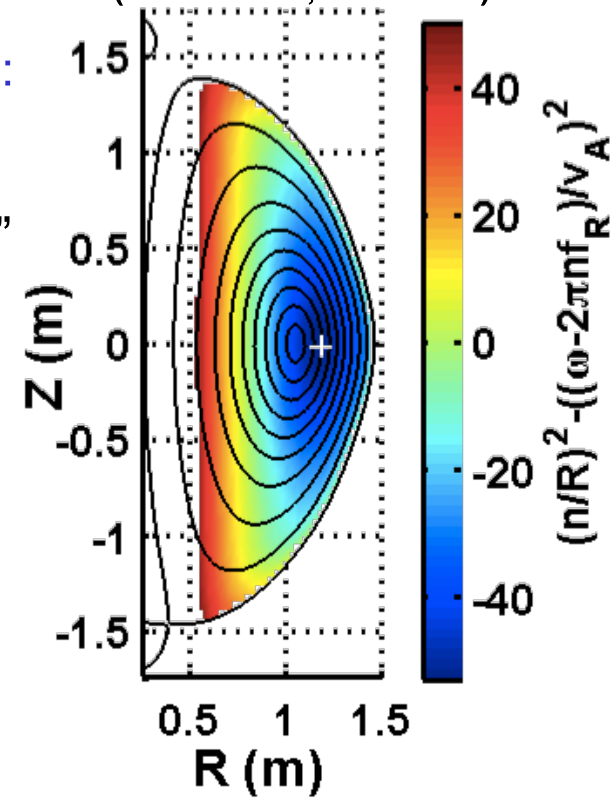
$$\left(\frac{n}{R}\right)^2 v_A^2 - (\omega - n\omega_{ROT})^2 < 0$$

- 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 flucttutation 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. α = 3.4 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
  - $k_{||}$ estimated from f using shear Alfvén dispersion relation
  - $k_\theta = m/r$, using m estimated from $k_{||} = |m/q - n|$, 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 χ_e

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

Conclusions

- High frequency Alfvén Eigenmodes (AE) excited by beam ions in NSTX $\Rightarrow$ can also be excited in ITER & FNSF by beam ions & α's
  - correlate with enhanced core electron thermal transport
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