NSTX-U

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Investigation of Alfvén eigenmode structure in NSTX and MAST

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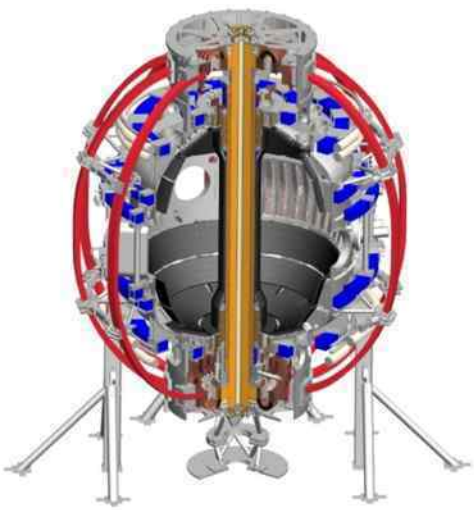

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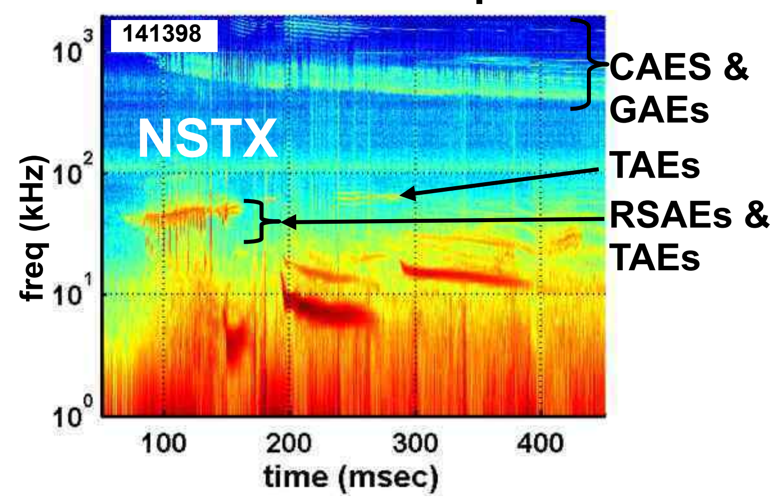
Overview

- Motivation: Alfvén eigenmodes play significant role in performance of spherical torus beam-heated plasmas
- Significant advances in high frequency AE identification facilitate investigation of enhanced core χ_e in NSTX beam-heat plasmas
  - identification via *measured mode structure & local dispersion relations*
    - AE radial structure measured in NSTX with array of reflectometers
    - Toroidal mode numbers and frequencies determined in NSTX using edge B-dot array
  - analysis shows combination of CAEs and GAEs
- UCLA & CCFE collaborated to implement Doppler Backscattering on MAST (see also NP8.00022)
- DBS sensitive to broad spectrum of AEs in MAST
- UCLA DBS at MAST facilitates investigation of many other physics topics in STs
  - Transport & Turbulence: Intrinsic Rotation (see also NP8.00022)
  - Transport & Turbulence: Geodesic Acoustic Modes
  - Boundary Physics: Edge Localized Modes

Motivation: Alfvén eigenmodes play significant role in performance of spherical torus beam-heated plasmas

- Beam-heated spherical torus plasmas feature rich spectrum of Alfvén eigenmodes
  - low frequency AEs (f < ~ 200 kHz): Toroidicity-induced (TAE) & Reversed shear (RSAE)
  - high frequency AEs (f > ~ 400 kHz): Compressional (CAE) & Global (GAE)

δb spectrum of typical beam-heated NSTX plasma



- Alfvén eigenmodes (AE) play critical role in many aspects of plasma performance
  - **Low frequency AEs cause fast-ion transport and loss:**
    - change equilibrium sources (momentum, energy …)
    - damage plasma facing components
  - **High frequency AE activity correlates with enhanced χ_e in core of H-mode beam heated plasmas (in NSTX)**

  D. Stutman *et al.,* PRL 102 115002 (2009); K. Tritz, APS DPP 2010 Invited PI2.2

Significant advances in high frequency AE identification facilitate investigation of enhanced core χ_e in NSTX

- Identification of high frequency AEs (as CAE or GAE) necessary to understand role in enhanced core χ_e but, traditionally difficulty

- New analysis techniques facilitate identification using:
  - measured mode structures (via e.g. reflectometry),
  - measured *f* (frequency) and *n* (toroidal mode number) &
  - local dispersion relations:

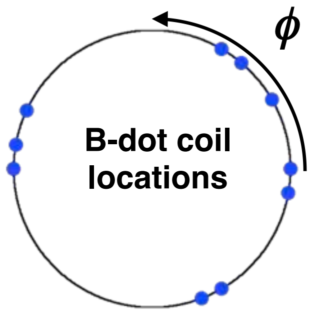
    CAE (compressional Alfvén): $\omega^2 = k^2 V_A^2$

    GAE (shear Alfvén): $\omega^2 = k_{||}^2 V_A^2$

- Analysis shows high frequency AE spectrum in H-mode beam heated NSTX plasmas include CAEs and GAEs

Toroidal mode numbers and frequencies determined in NSTX using edge B-dot array

- Modes appear as peaks in δb spectrum
- n determined from δb measured by edge toroidal array of B-dot coils

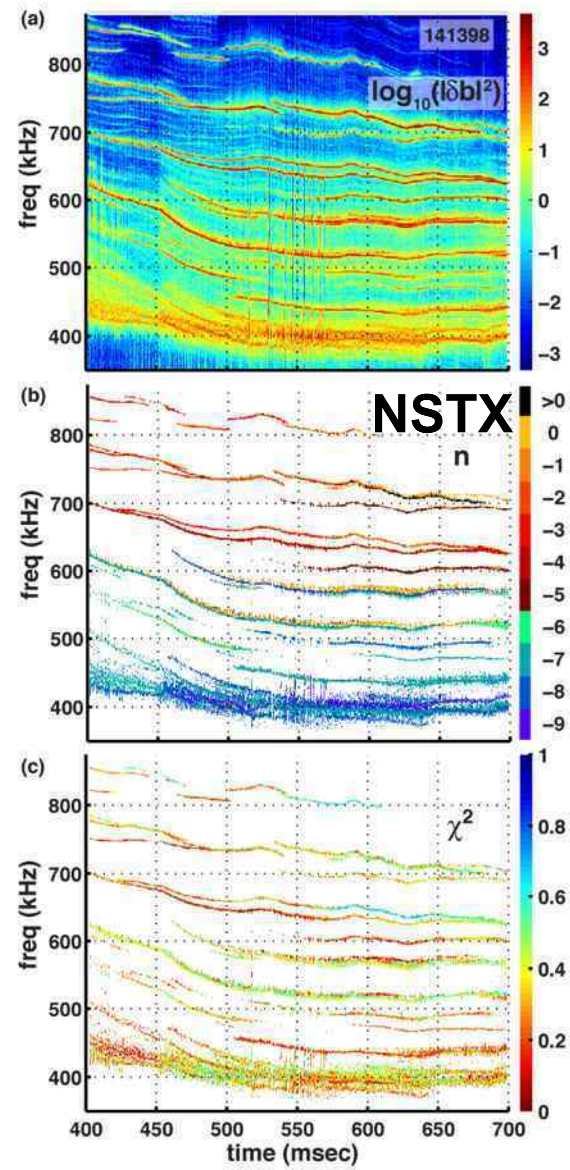


  – method: find n that minimizes χ^2:

$$\chi^2 \equiv 1 - \left|\sum_{\forall\phi} \delta b e^{-in\phi}\right|^2 \Big/ \left(N_\phi \sum_{\forall\phi} |\delta b|^2\right)$$

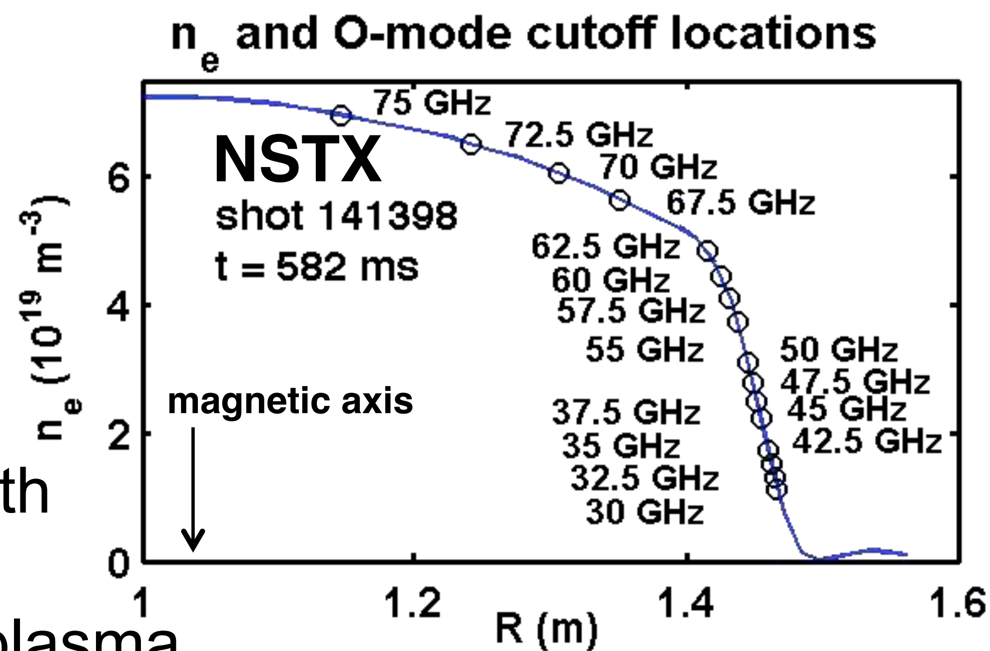
  where N_ϕ=10 is the number of coils.

- Smallest coil spacing is 10° ⇒ can distinguish $|n| \leq 18$



AE radial structure measured in NSTX with array of reflectometers

- AE structure measured via 16-channel reflectometer array, $n_0 \sim 1 - 7 \times 10^{19}$ m^{-3} (30 – 75 GHz) in O-mode



- Reflectometer measures path length change (δL) of microwaves reflected from plasma
  - Microwaves reach cutoff at $\omega^2 = \omega_p^2 = e^2 n_0/\varepsilon_0 m_e$

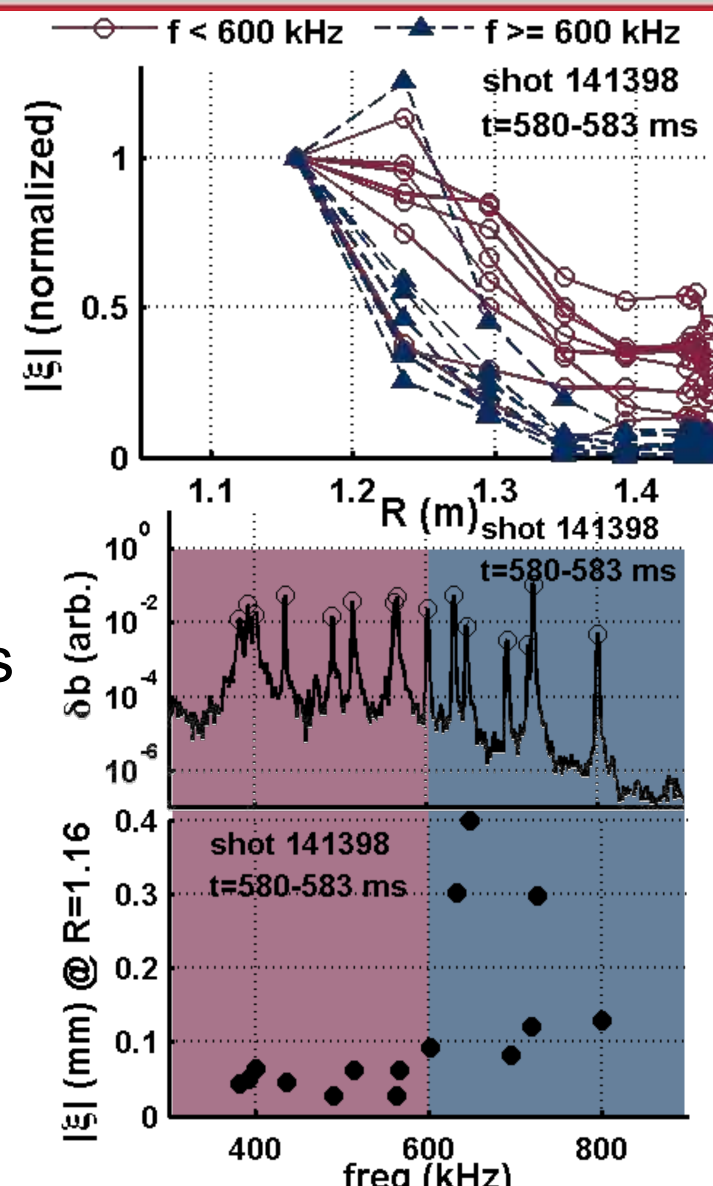
- For large scale modes, cutoff displaces due to δn at cutoff ⇒ "effective displacement" $\xi \equiv \delta L/2$ approximates cutoff displacement

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 suggesting two types of modes:

  (1) broad structure, peaking toward core
  - mostly *f < ~ 600 kHz, n = -6 – -8*

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

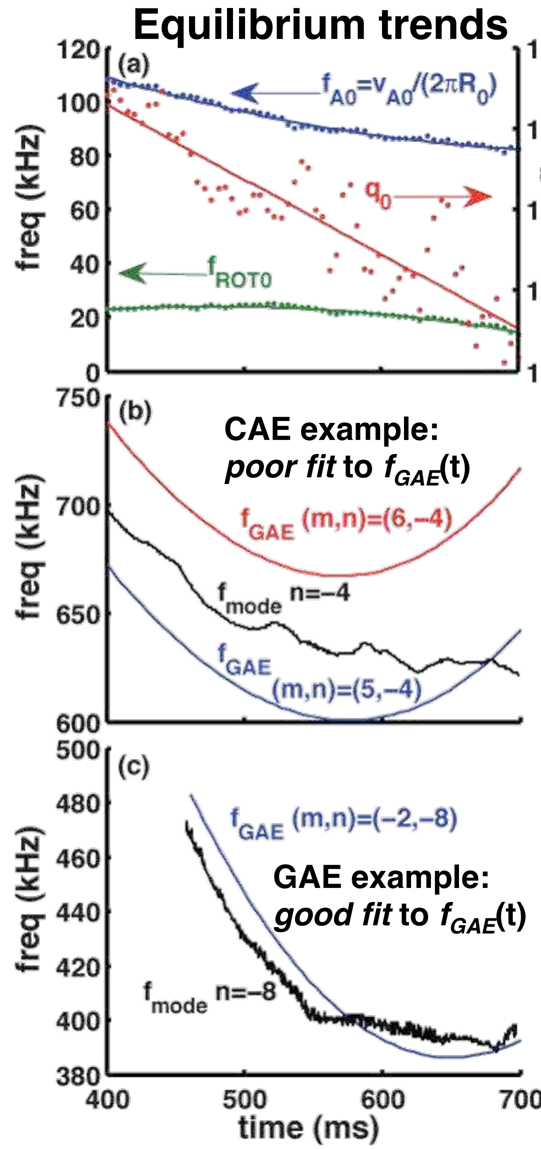


Broad structure (f < ~ 600 kHz) modes consistent with GAE dispersion relation

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

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

- Strong q_0 variation ⇒ comparison with $f_{GAE}(t)$ stringent test of identity
  - Fit to $f_{GAE}(t)$ ⇒ 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: $f(t) \sim f_{GAE}(t)$ (bottom)
  - Modes with f > ~ 600 kHz: $f(t)$ NOT consistent with $f_{GAE}(t)$ (middle)



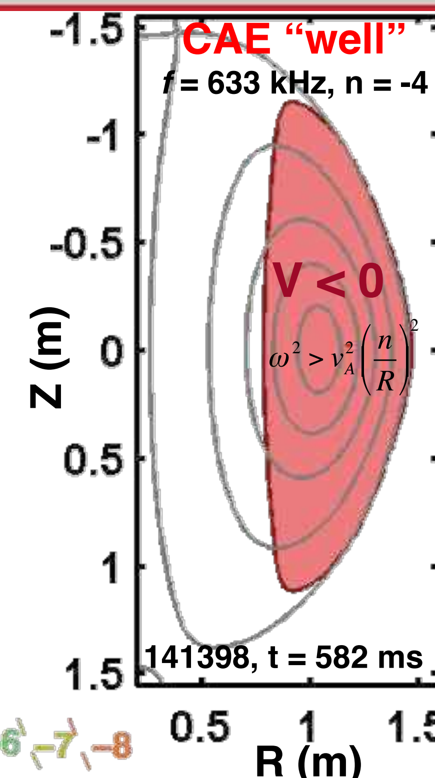
Strongly core localized (f > ~ 600 kHz) modes consistent with CAE dispersion relation

- Compressional Alfvén waves propagate ONLY where: $\omega^2 > v_A^2 (n/R)^2$
- "Well" formed in *R*–*Z* plane

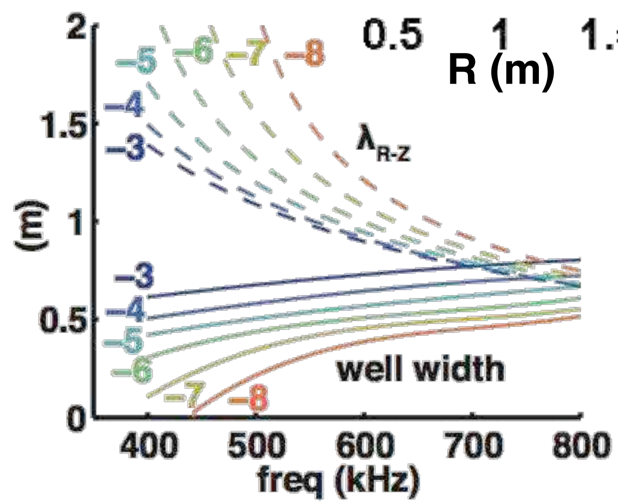
$$\omega^2 = v_A^2 k^2 \Leftrightarrow \nabla_{R-Z}^2 \zeta - V(R,Z)\zeta = 0$$

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

  - toroidal Doppler shift must be taken into account

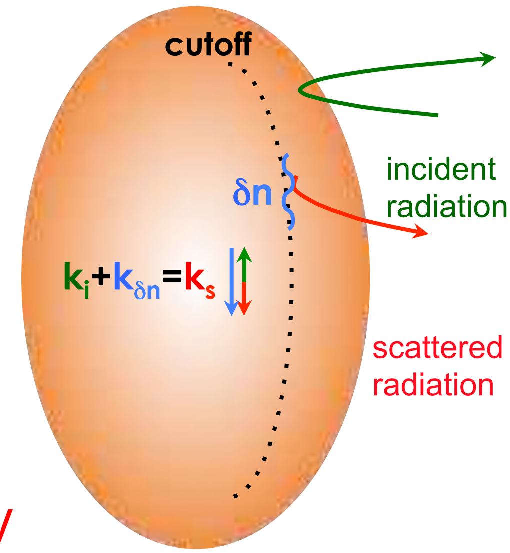


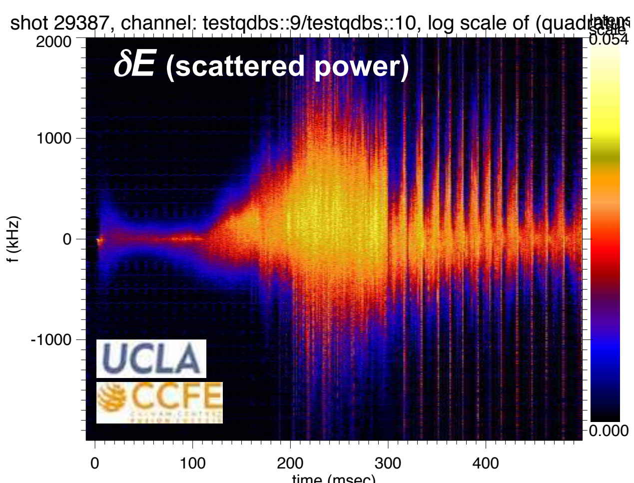
- CAE must fit inside "well"
  - $V \Rightarrow R$-Z "wavelength": $\lambda_{R-Z} \propto (-V(R,Z))^{-\frac{1}{2}}$
- Well width ~ $\lambda_{R\text{-}Z}$ for modes with f > ~ 600 kHz, n = -3 – -5
  - Well width >> $\lambda_{R\text{-}Z}$ for modes with f < ~ 600 kHz, n = -6 – -8



UCLA & CCFE collaborated to implement Doppler Backscattering on MAST for 2013 campaign

- DBS measures poloidal flow (i.e. $\delta \boldsymbol{v} \cdot \nabla \psi x \boldsymbol{B}$) – yielding E_r– and intermediate-k turbulence near cutoff
- UCLA worked with Dr. Jon Hillesheim of Culham Centre for Fusion Energy (see also NP8.00022)
- Q-band and V-band systems installed on MAST
  - 16 channels, 30 – 75 GHz; cutoffs @1 – 7 x 10^{13} cm^{-3} in O-mode
  - steerable for DBS or reflectometry
- Successful operation yielded promising results in many areas of physics

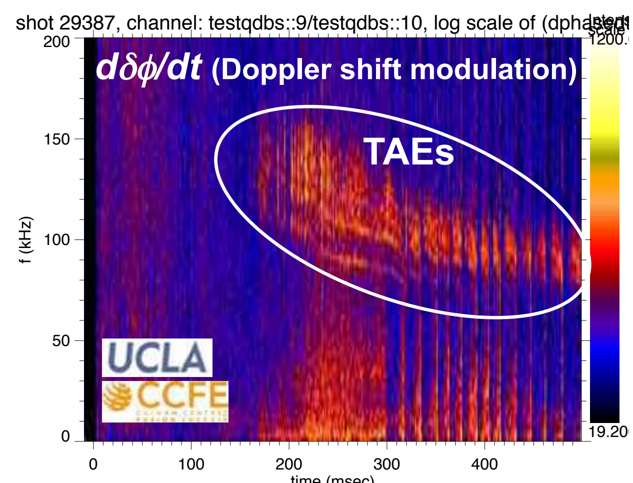




DBS DATA from MAST

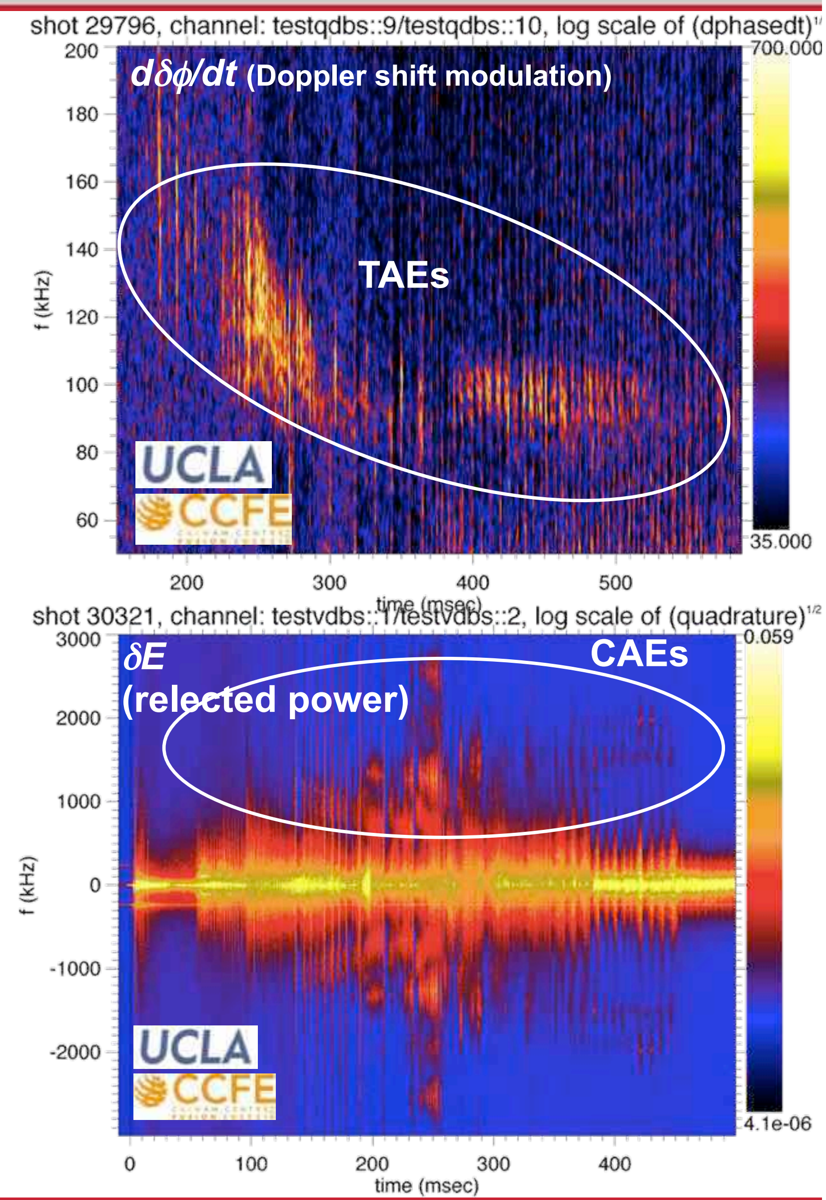
42.5 GHz backscattered microwave spectra:

$$E = A\exp(i\phi)$$



UCLA DBS Sensitive to Broad Spectrum of AEs in MAST

- DBS systems steerable for back-scattering or reflectometry
  - Reflectometry: sensitive to AE δn (cutoff displacement)
  - Back-scattering: sensitive to AE modulation of Doppler shift:
    - $\delta v = \delta E \times B_0 / B_0^2$
    - δn via "interferometer" effect
- DBS detects low (TAE) and high (CAE) frequency AEs in both modes
- Analysis of measurements will give mode structure
  - will compare with theory code simulation via "synthetic diagnostic"

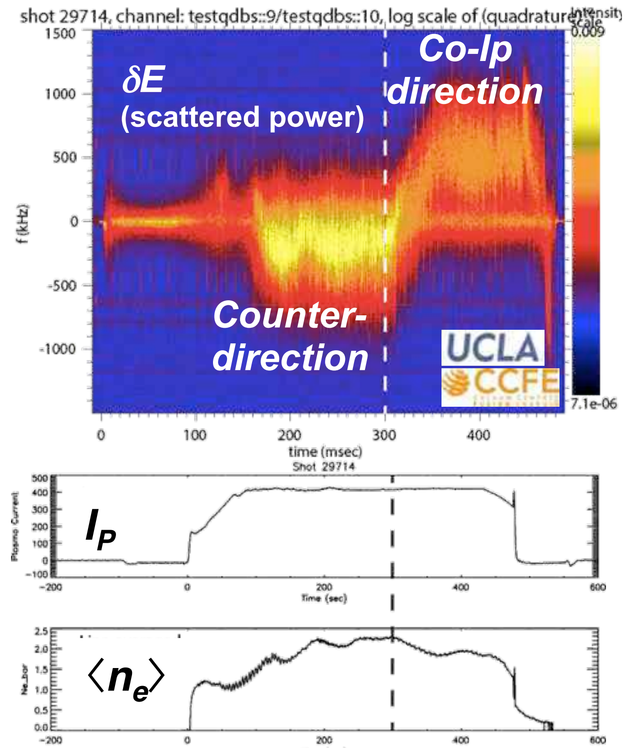


UCLA DBS at MAST facilitates investigation of many physics topics in STs

Transport & Turbulence: Intrinsic Rotation

see also NP8.00022

- Intrinsic rotation potentially useful, but not fully understood
  - Rotation can aid stability and confinement but can be difficult to drive (*e.g.* in ITER)
- DBS reveals intrinsic rotation reversals:
  - Core poloidal flow in Ohmic plasmas observed to reverse (see e.g. right – ΔV ~ 10 km/s with ~ 20 % change of $\langle n_e \rangle$)
  - *first observation* in low aspect ratio tokamaks
  - previously been observed in TCV [Bortolon, PRL 2006] and Alcator C-mod [Rice, PRL 2011].
  - thought to be related to collisionality dependence of turbulent momentum transport [e.g. Barnes, PRL 2013]



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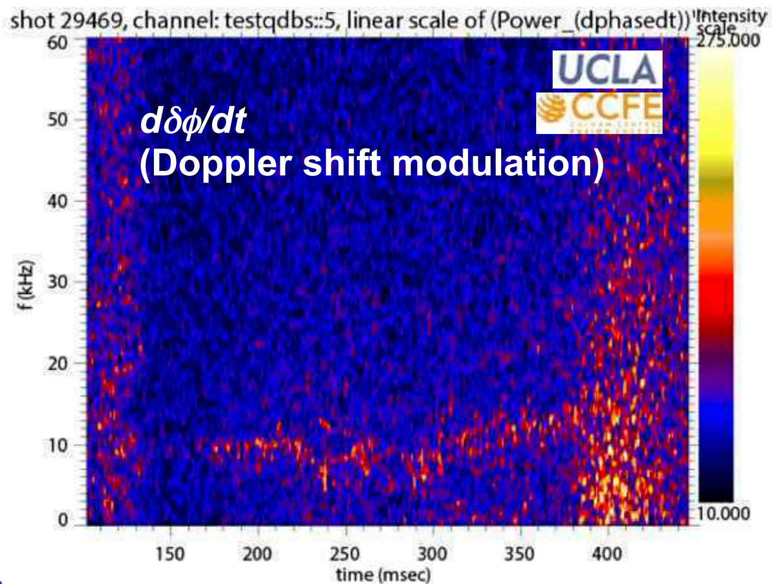
Transport & Turbulence: Geodesic Acoustic Modes

- GAMs play role in transition from L- to H-mode confinement



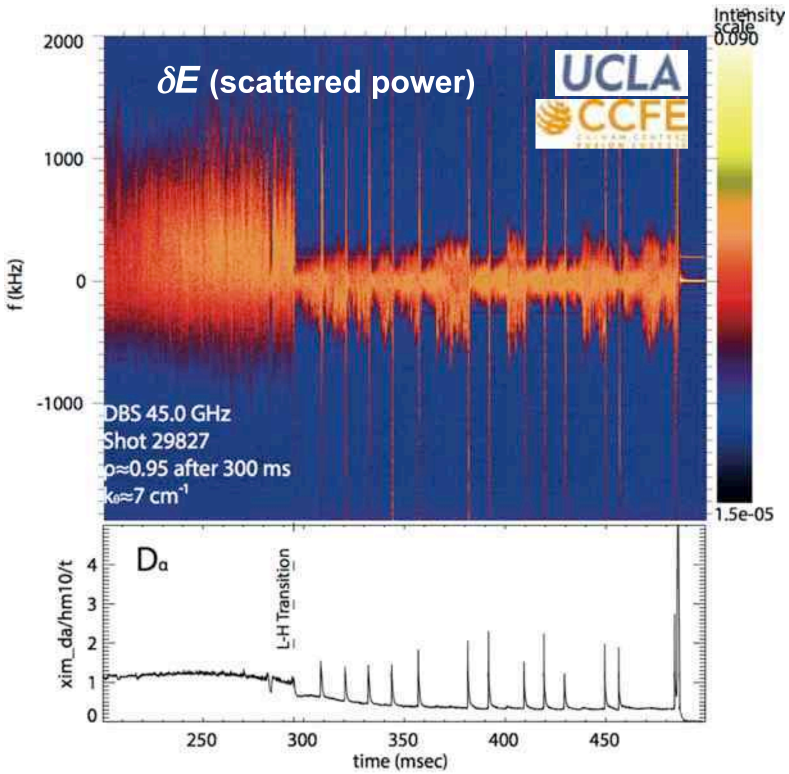
- f ~ 10 kHz poloidal flow modulation observed near last closed flux surface (LCFS) in Ohmic discharge.
  - Similar oscillations — observed by Langmuir probe near LCFS — previously identified as GAMs [Robinson PPCF 2012; Robinson Phys. Plasma 2013].

- Possible GAM flow modulation also observed in beam-heated discharges (not shown)

UCLA DBS at MAST facilitates investigation of many physics topics in STs

Boundary Physics: Edge Localized Modes

- ELMs significantly impact global particle confinement
- intermediate-k ($k_\theta \approx 7$ cm^{-1}) δn probed during pedestal scaling experiment
  - Experiment was CCFE/NSTX-U collaboration
- Variation of turbulent spectrum in pedestal observed during ELM cycle



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