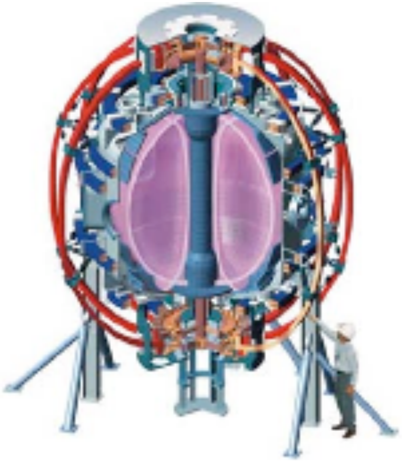
Using microwaves to study fast ion driven modes in NSTX



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NSTX Results Forum, Dec. 2005

Microwaves allow coherent modes to be probed in NSTX

- Reflectometry measures local density perturbation and “plasma displacement” (if motion incompressible)
  - Interpretation of reflectometry signal for coherent modes confirmed by comparison with BES data on DIII-D.
- Multiple reflectometers ⇒ radial structure of mode
  - test theory predictions
  - infer magnetic fluctuation amplitude (affects fast ion transport)
- Sensitive 1mm interferometer data also available
  - provides a survey of mode activity across entire plasma diameter
  - allows detection of modes localized on high field side
  - Provides additional constraint on spatial structure
- Plans to upgrade interferometer to multichannel radially viewing polarimeter
  - Allows measure of magnetic fluctuations

Fast Ion Modes dominate spectrum in NSTX

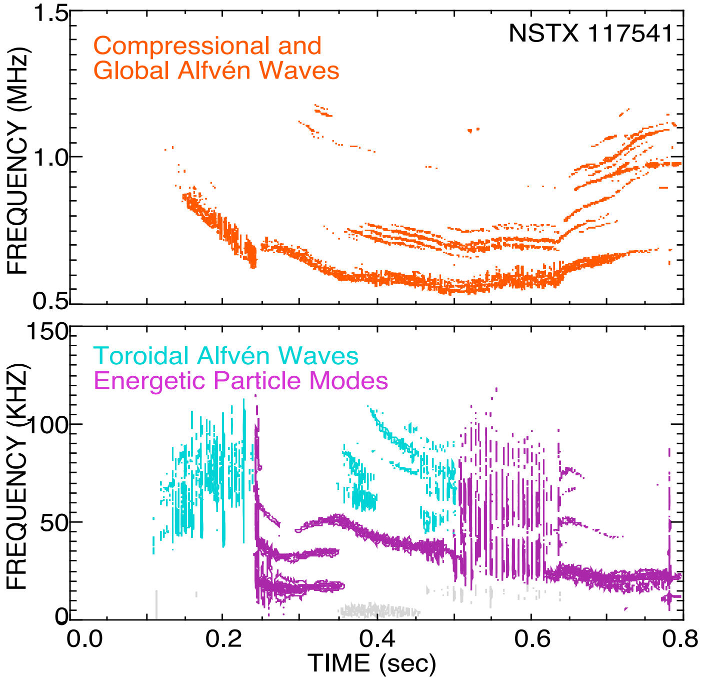


Figure from APS DPP 2005 invited talk by E.D. Fredrickson

- **Compressional and Global Alfvén Eigenmodes (CAE and GAE)**
  - 0.4 to > 2 MHz
  - Natural plasma resonance
  - CAE parallel δB, δE is transverse
  - GAE mixed transverse/parallel δB
- **Toroidal Alfvén Eigenmodes (TAE)**
  - ~ 40 - 150 kHz
  - Natural plasma resonance
- **Energetic Particle Modes (EPM)**
  - $\lesssim$ 100 kHz
  - Mode defined by fast ion parameters
  - Frequency chirping common
  - Includes non-fishbones, n > 1
- **Other types observable?**

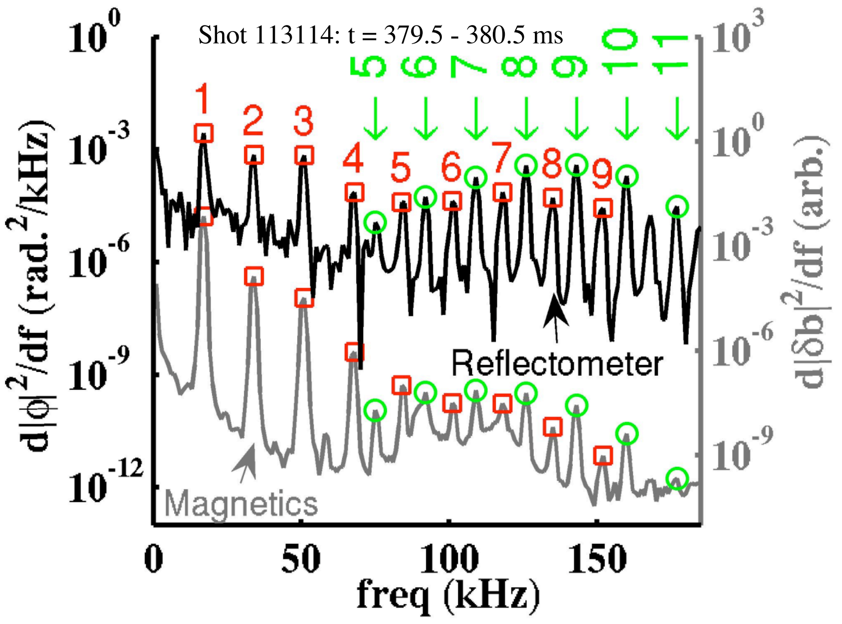
Microwaves used to probe mode activity:

- Reflectometry provides a *local* measure of mode density perturbation
- Interferometry provides a *sensitive internal monitor* of mode activity across the entire plasma diameter

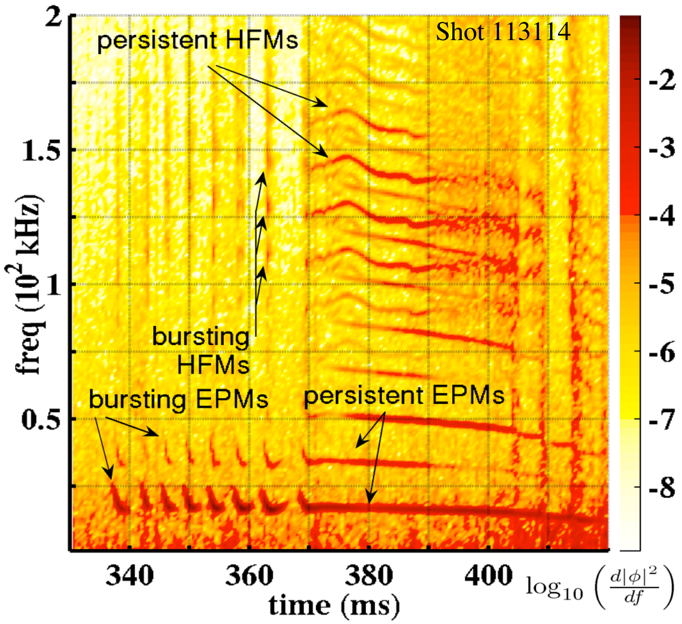
Three-wave interactions sometimes observed to couple different types of modes

- For example, shot 113114: two types of modes interact, EPMs and higher frequency modes (HFMs - of unknown mode type).
  - neighboring HFMs, (f,n) and (f',n'), satisfy $(f',n') \equiv (f+\Delta f_{HFM}, n+\Delta n_{HFM})$.
  - $\Delta f_{HFM} = f_{EPM} \sim 17$ kHz and $\Delta n_{HFM} = n_{EPM} = 1$, so $f' = f + f_{EPM}$ and $n' = n + n_{EPM}$
- Three-wave interactions can transfer energy between modes and broaden mode spectrum, affecting fast ion transport

50 GHz reflectometer and edge magnetic spectra



50 GHz reflectometer phase spectrum



High bicoherence *confirms* three-wave interaction

- Mode triplets that satisfy matching conditions show high bicoherence $\Rightarrow$ confirms three-wave interaction
  - Mode amplitudes and phases ($A(t)$ and $\phi(t)$) extracted during t = 369.5 to 394 ms by filtering (complex demodulation)
    - Mode frequencies determined with 1 ms resolution
    - Signal filtered with 5 kHz bandwidth around mode frequency
  - Bicoherence given by $B[\psi, \psi', \psi''] = |\langle \psi' \psi'' \psi^* \rangle| / (\langle |\psi' \psi''|^2 \rangle \langle |\psi|^2 \rangle)^{1/2}$, where $\psi(t) = A(t)\exp(i\phi(t))$ and $\langle\,\rangle$ is average over time
    - Bicoherence tests coherence of $\psi' \psi''$ with ψ
    - Bicoherence ranges from 0 to 1. High bicoherence needed for interaction

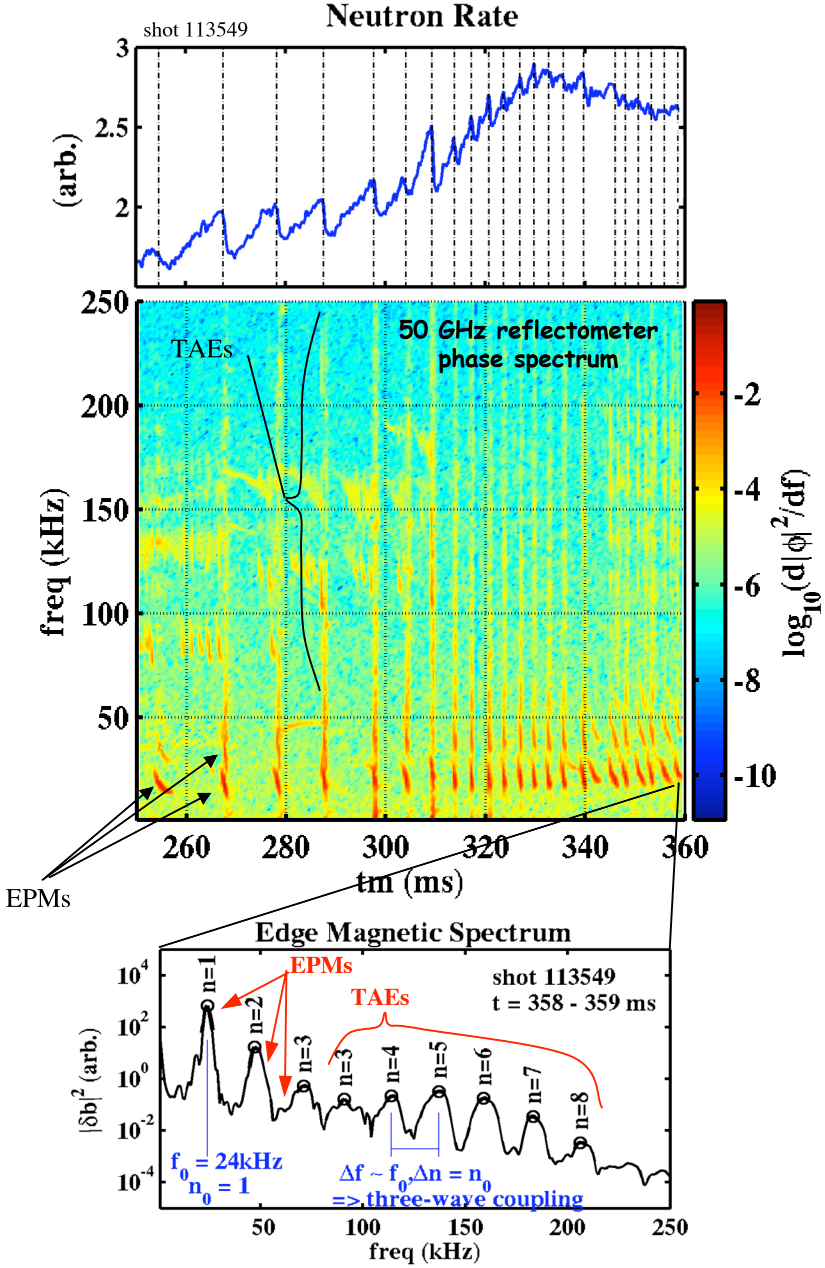
Bicoherence of mode triplets (noise level ~ .09)

($B[HFM_1, EPM_{n=1}, HFM_2]$)

n of HFM_1	n of HFM_2	Bicoherence (50 GHz)	Bicoherence (42 GHz)
5	6	0.3117	0.4333
6	7	0.561	0.7691
7	8	0.6497	0.8816
8	9	0.6451	0.8841
9	10	0.6257	0.8458
10	11	0.6389	0.7182
11	12	0.4055	0.5985

Three-wave interactions influence mode energies and thereby fast ion loss

- EPMs, TAEs active during fast ion loss events:
  - EPM: Harmonics, low frequency and toroidal mode number; *f* ~ 24 kHz, 48 kHz, *n* = 1,2
  - TAEs: higher frequencies and mode numbers; f ~ 80 - 200 kHz, n = 3 - 8
    - uniformly spaced in *f* and n: Δf ~ 25 kHz, Δn = 1
- Three-wave interactions couple n = 1 EPM to pairs of TAEs:
  - neighboring TAEs satisfy f and n matching requirements to couple with n = 1 EPM
  - matching mode triplets show high bicoherence



Bicoherence of mode triplets (noise level ~ .06)
(i.e. B[TAE_1,$EPM_{n=1}$, TAE_2])
(t = 345 - 360 ms; ~ 20 kHz bandwidth)

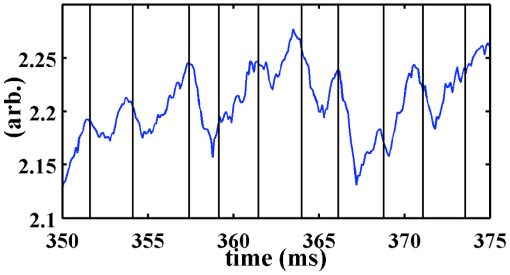
n of TAE_1	n of TAE_2	Bicoherence (50 GHz)	Bicoherence (42 GHz)
4	5	0.5587	0.3865
5	6	0.603	0.4423
6	7	0.5745	0.4341

Three-wave interactions can couple disparate scales (TAEs or EPMs to CAEs)

- CAE spectrum broadens thru sideband generation during fast ion loss events (drops in neutron rate)
- broadening appears to result from three-wave coupling
- bicoherence measurements indicate three-wave coupling occurs
  - Bicoherence of “x” defined here as $B(f1,f2) = |\langle x(f_1)x(f_2)x^*(f_1+f_2)\rangle| / (\langle|x(f_1)x(f_2)|^2\rangle\langle|x(f_1+f_2)|^2\rangle)^{1/2}$

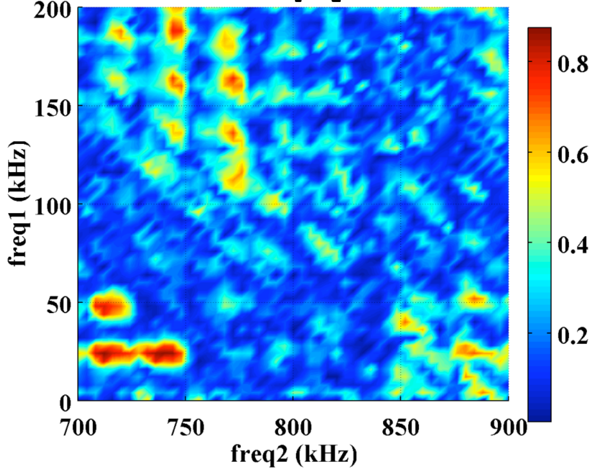
Neutron Rate

(with fluctuation bursts marked)



Bicoherence of δb

$B(f_1,f_2)$

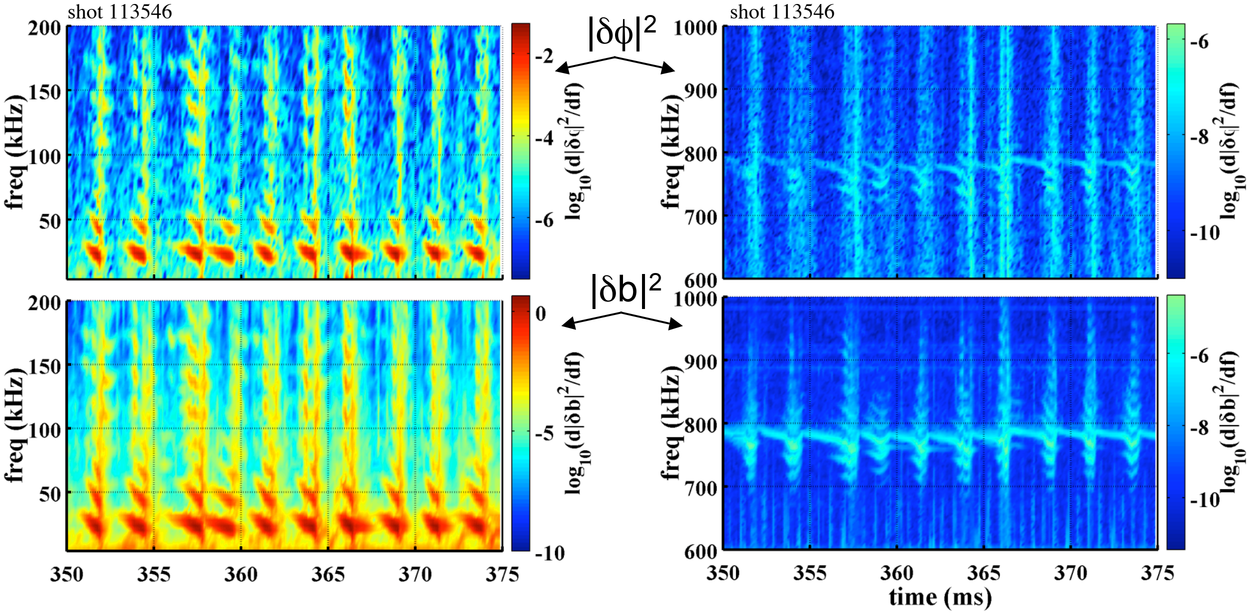


TAEs and EPMs

50 GHz reflectometer phase and edge magnetic spectra

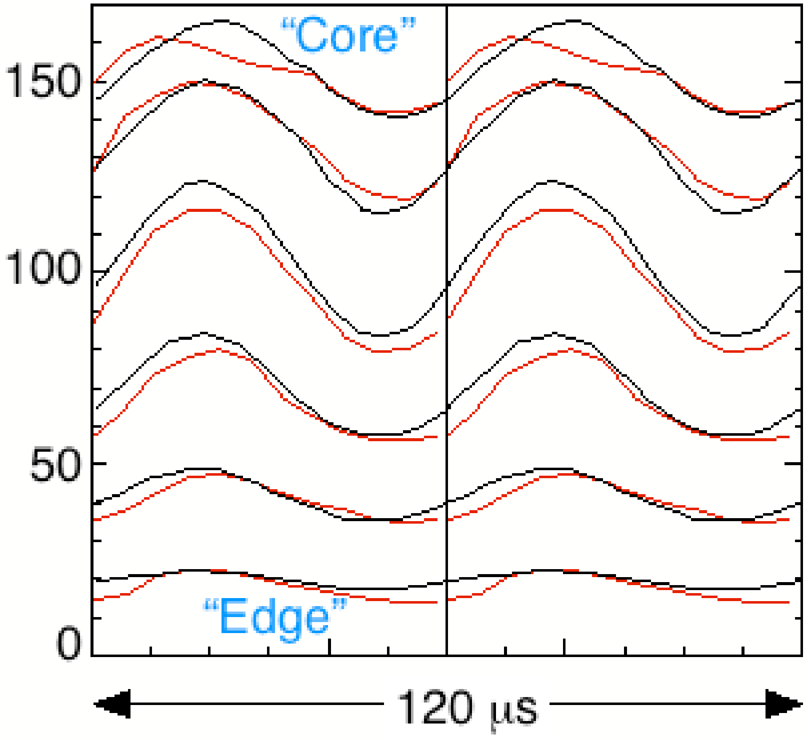
CAEs

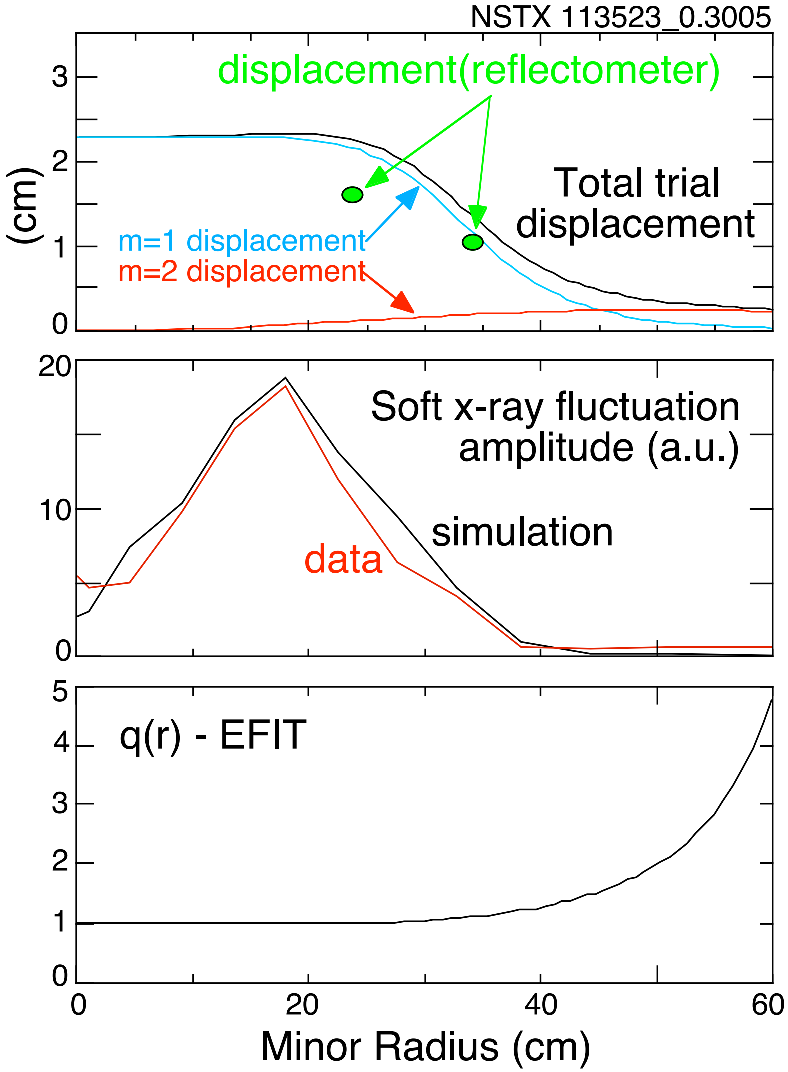
50 GHz reflectometer phase and edge magnetic spectra



Reflectometry measurements utilized together with soft x-ray to reconstruct structure of EPM (n = 1 kink)

- Inverted SX emission profile and EFIT equilibrium, used to "invert" soft x-ray data.





SXR data: Johns Hopkins Univ. group

Figures from APS DPP 2005 invited talk by E.D. Fredrickson

Preliminary measurement of TAE structure and comparison with theory

- single TAE amplitude is of the order $\delta n/n \approx 1\%$.
- node in radial structure (180° phase change) consistent with NOVA modeling of the higher n TAE

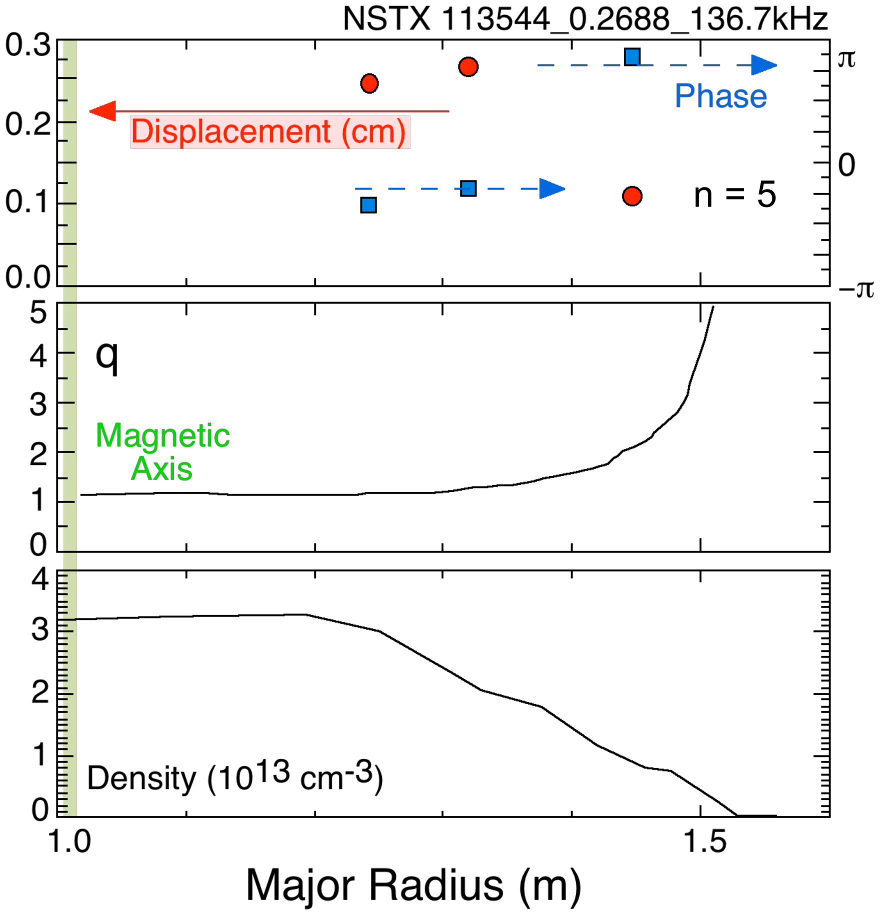
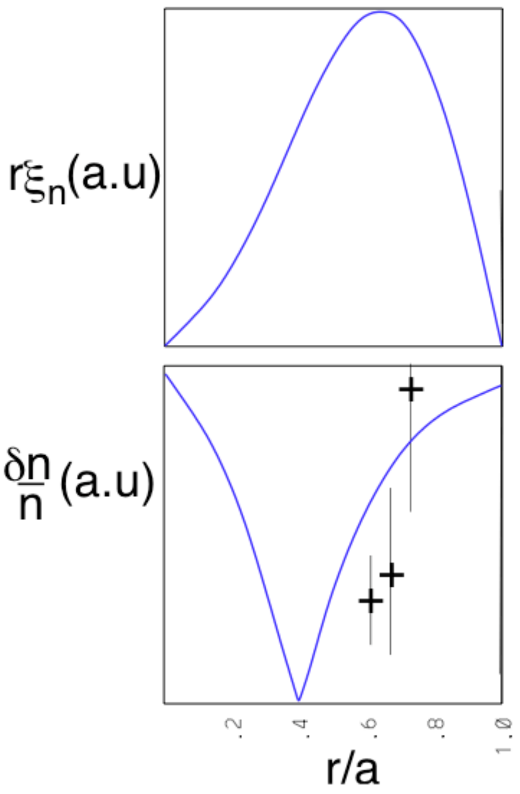


Figure from APS DPP 2005 invited talk by E.D. Fredrickson

Preliminary comparison of measured CAE structure with theory (NOVA-K code)



- Reflectometer measurements of CAEs can validate simulations and theory (NSTX)*
  - Figure shows reflectometer measurements (+ marks) of f = 0.81 MHz CAE vs simulated CAE f = 0.93 MHz CAE (f = 0.81 MHz CAE does not agree in structure)
  - Hall effect may be needed for better agreement: frequency shift and radial structure change
  - Compressional effects are critical: $\delta n/n \not\propto \xi_n$
  - Error bars are large 20 - 60%

*N.N. Gorelenkov, et al., 9th IAEA TCM on Energetic Particles in Magnetic Confinement Systems, November 9 - 11, 2005, Takayama, Japan

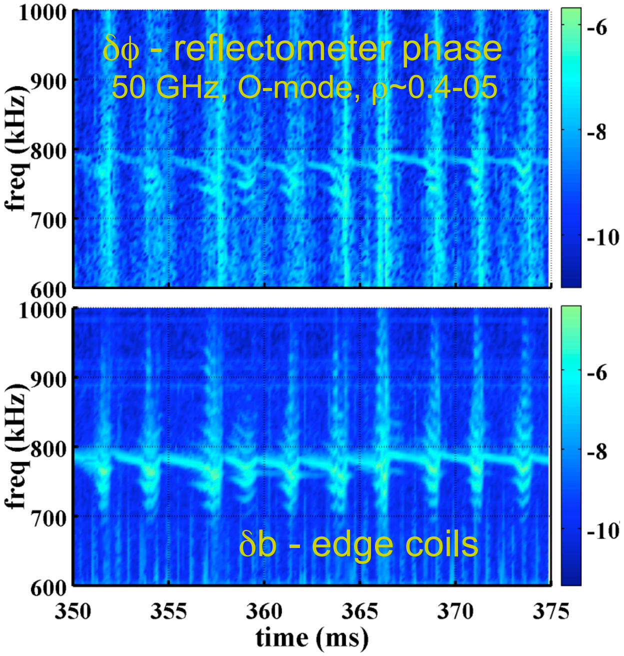
Cross-Machine Studies of Fast Ion Driven Modes

- Cross-machine studies of fast ion driven modes is an on-going effort

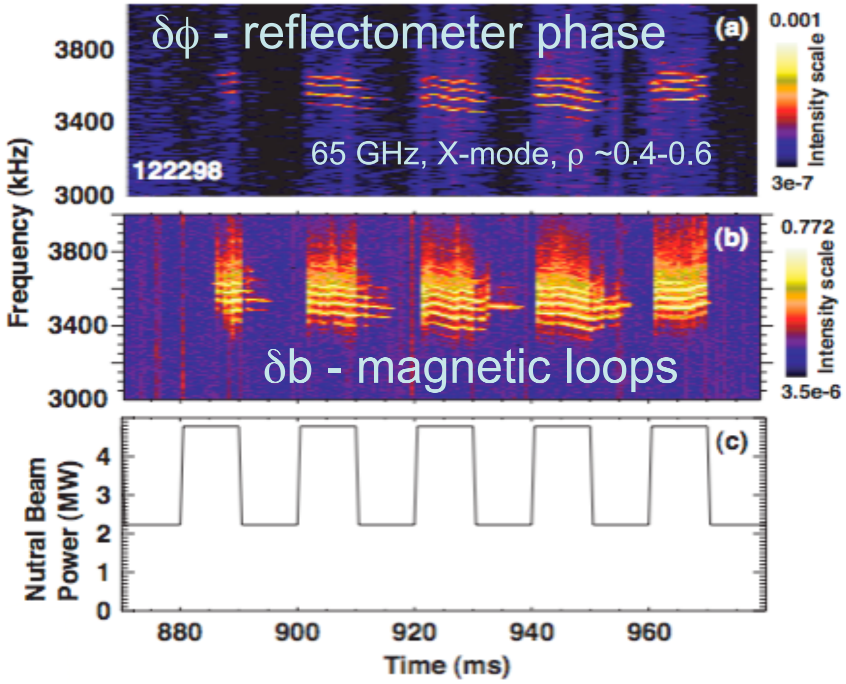
  For example:

  - TAEs: W.W. Heidbrink, et al., Plasma Phys. Control. Fusion vol. 45 (2003) pg. 983
  - CAEs: N.N. Gorelenkov, et al., 9th IAEA TCM on Energetic Particles in Magnetic Confinement Systems, November 9 - 11, 2005, Takayama, Japan

CAE measurements on NSTX



CAE measurements on DIII-D



- UCLA Team uses microwaves to study fast ion driven modes in DIII-D and NSTX ⇒ contributing to cross-machine studies

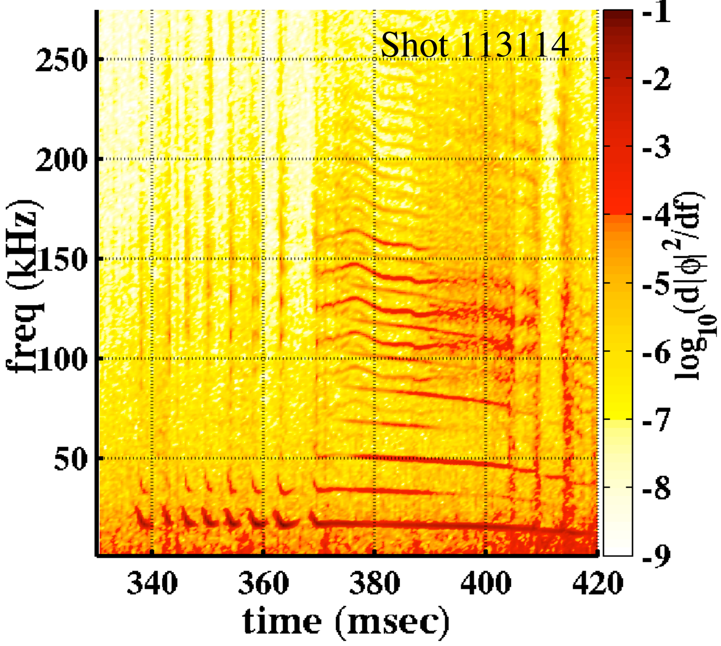
Summary

- Three-wave interactions observed
  - Interactions couple various sets of modes: TAEs to EPMs, TAEs to CAEs and CAEs to EPMs. Also couple EPMs to an unknown type of mode, "HFM".
  - Interaction occurs during fast ion loss events ⇒ can influence fast ion confinement
- Preliminary measurements of mode structure
  - EPM (n=1 kink): consistent with soft x-ray measurement of structure
  - TAE: radial node observed consistent with NOVA predictions for high-n TAEs
  - CAE: preliminary comparison with NOVA-K suggests code modification need for better agreement
- Contributing to cross-machine studies of modes: multiple microwave diagnostics
- Future plans
  - Polarimetry - magnetic fluctuations
  - More reflectometry channels - improved spatial coverage

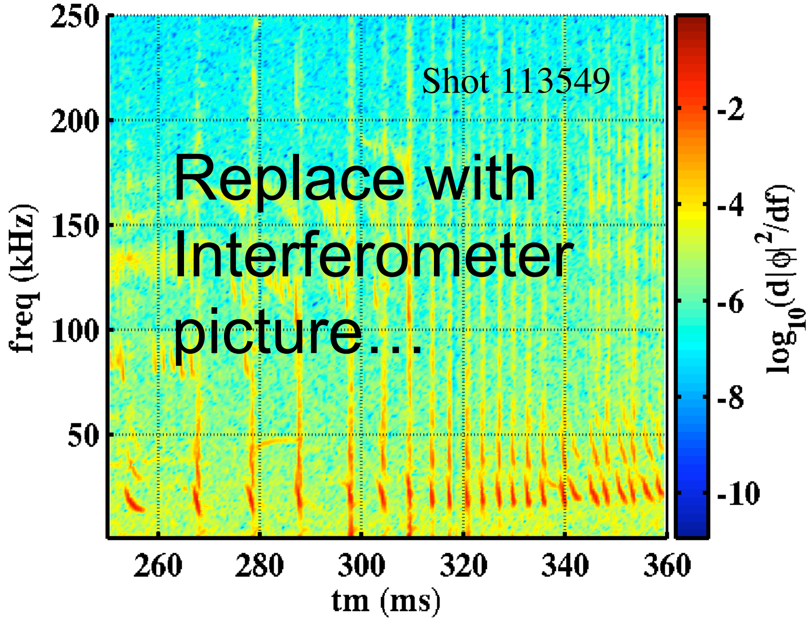
Microwaves used to probe coherent modes in plasma

- **reflectometer makes localized measurements:**
  - measures density perturbation and “plasma displacement” (if motion incompressible); tested against BES in DIII-D
  - core localized - difficult for other diagnostic
  - can only reach low-field side
  - multiple reflectometers ⇒ radial mode structure
  - infer magnetic fluctuation amplitude (affects fast ion transport)

50 GHz reflectometer phase spectrum



50 GHz reflectometer phase spectrum



Replace with Interferometer picture…

- **interferometer probes whole plasma**
  - detect localized modes on high field side
  - in conjunction with reflectometer, test theory
  - look for reverse shear Alfvén eigenmodes, which are localized
- **evidence of three-wave coupling**
  - not considered in fast ion mode theory