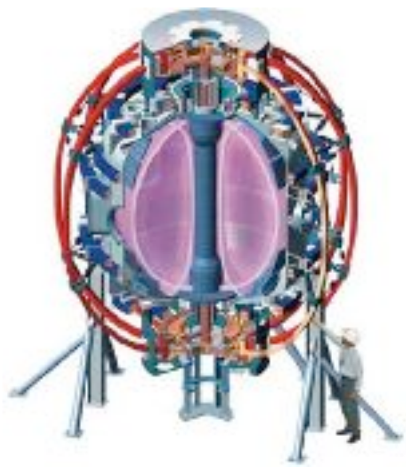
Investigation of fast-ion mode nonlinear dynamics and spatial structure in NSTX*



by NA Crocker[1], WA Peebles[1], S. Kubota[1], ED Fredrickson[2], NN Gorelenkov[2], GJ Kramer[2], H Park[2], WW Heidbrink[3], KC Lee[4], CW Domier[4] and NC Luhmann Jr[4]

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Abstract (Revised)

Investigation of fast-ion mode nonlinear dynamics and spatial structure in NSTX*

NA Crocker, WA Peebles, SK Kubota (UCLA); ED Fredrickson, NN Gorelenkov, GJ Kramer, H Park (PPPL); WW Heidbrink (UCI); KC Lee, CW Domier, NC Luhmann Jr (UCD)

Neutral beam heated plasmas in NSTX exhibit a rich spectrum of fast-ion driven coherent modes that include energetic particle modes (EPM), toroidicity-induced and compressional Alfvén eigenmodes (TAE and CAE) and Alfvén Cascade modes (AC). These modes are of significant interest because they can induce fast-ion transport and channel fast-ion energy into the plasma. In recent experiments, nonlinear three-wave interactions between low frequency chirping modes (EPMs), TAEs and CAEs are studied. These interactions potentially transfer energy in space and time and significantly influence the effect of the modes on fast ions. One observed effect is to organize multiple AEs (CAE and TAE), spatially concentrating their energy to form a toroidally localized wave-packet. Additionally, in recent experiments, the spatial structures of EPMs, TAEs and ACs have been investigated through the simultaneous application of a millimeter-wave radial interferometer and three fixed-frequency millimeter-wave reflectometers operated by UCLA and an array of magnetic sensing coils external to the plasma. Four tangential far-infrared interferometers operated by UCD were also used to study EPMs. Preliminary calculations of TAE structure have been made with NOVA-K.

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Why study global modes excited by fast ions?

- **Fast ions important in fusion plasmas**
  - produced by
    - heating techniques: neutral beams, radio frequency power
    - fusion products: alpha particles
  - must be confined to heat plasma

- **Fast-ion modes affect fast-ion transport**
  - modes may modify orbits
    - redistribute fast ions ⇒ change heat deposition, force balance, etc.
    - degrade fast-ion confinement

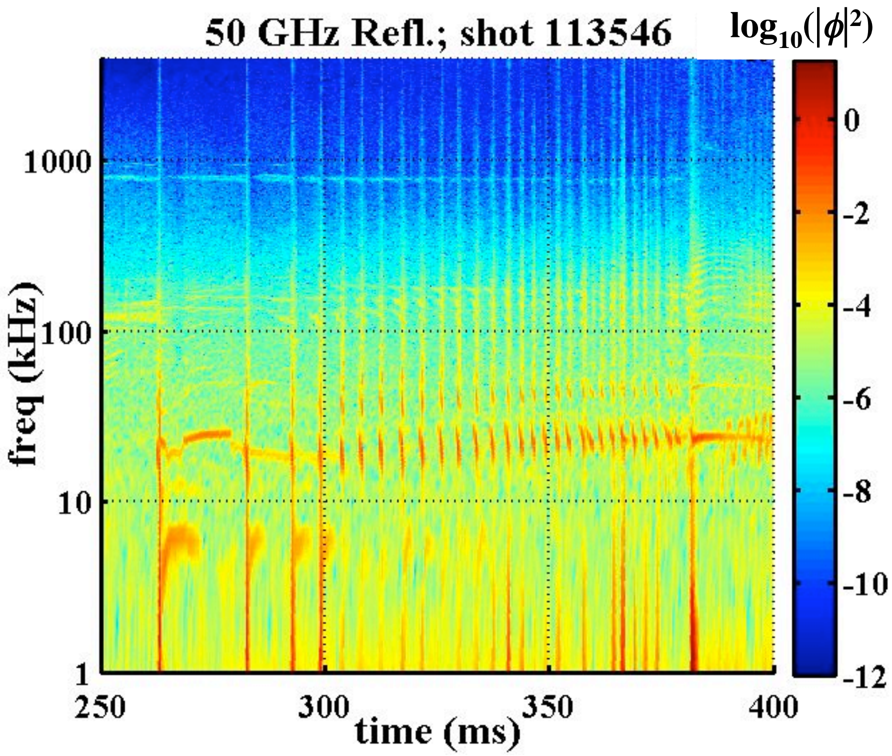
Summary of Results

- **Three wave interactions between fast-ion modes observed for first time**
  - interaction across multiple scales: EPM—TAE, EPM—CAE, TAE—CAE
  - fast-ion loss events influenced
  - universal effect: wave-packet formation - lower frequency mode spatially concentrates energy of higher frequency mode

- **Structure of Alfvén Cascade Modes and TAEs measured**
  - structure measurements: multiple reflectometers ⇒ radial structure; radial interferometer ⇒ constrain reconstruction; toroidal mode number from array of Mirnov coils outside plasma
  - Alfvén Cascade Modes and evolution to TAEs observed
  - preliminary mode structure calculated by NOVA-K (linear stability code): calculated modes peak near minimum q - significant further work necessary

- **EPM structure measured**
  - structure measurements: multiple reflectometers; tangential and radial interferometers; array of Mirnov coils
  - mode structure may be calculated by NOVA-K (linear stability code) - significant further work necessary

Neutral beam heated plasmas in NSTX exhibit rich spectrum of fast-ion modes



- Compressional Alfvén Eigenmodes (CAE)
  - 0.4 to > 2 MHz
  - natural plasma resonance
- Toroidal Alfvén Eigenmodes (TAE) Alfvén Cascade Modes (AC)
  - $\lesssim$ 200 kHz
  - natural plasma resonance
- Energetic Particle Modes (EPM)
  - $\lesssim$ 100 kHz
  - mode defined by fast-ion parameters
  - strong frequency chirping common

Fast-ion mode structure probed by internal density fluctuation diagnostics

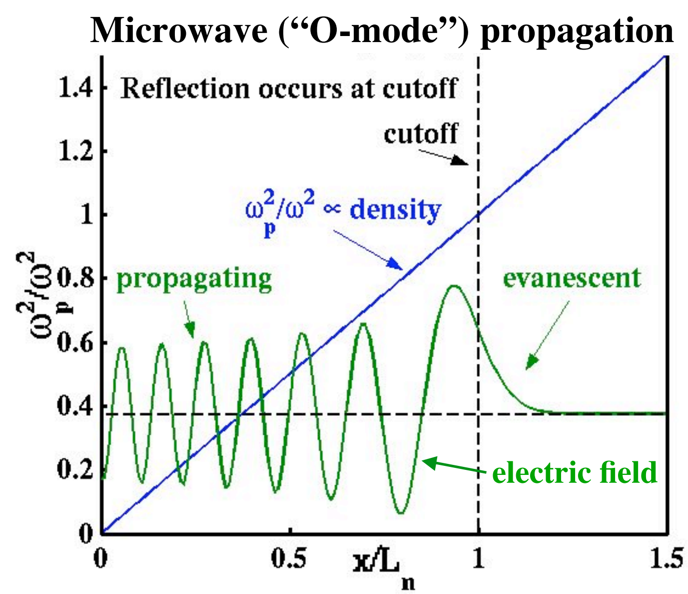
- Multiple reflectometers measure local density perturbation ⇒ radial structure of mode (low field side)
  - interpretation of reflectometer signal for coherent modes confirmed by comparison with BES data on DIII-D.

- Radial 1mm & tangential FIR interferometers
  - survey of mode activity across entire plasma diameter
  - detection of modes localized on high field side
  - constraint on reconstruction of spatial structure

- Plans to upgrade 1mm interferometer to multi-channel radially viewing polarimeter
  - allows measure of magnetic fluctuations

Reflectometers measure local density fluctuation in plasma

- Microwaves with low enough frequency ($\omega < \omega_p$) reflect from "cutoff" layer in plasma
  - ω_p^2 is proportional to density: $\omega_p^2 = e^2 n_0/\varepsilon_0 m_e$
  - Dispersion relation for "ordinary mode" ("O-mode") microwaves: $\omega^2 = \omega_p^2 + c^2k^2$
  - $k \rightarrow 0$ as $\omega \rightarrow \omega_p$
  - Microwaves reflect at "cutoff" surface, where $\omega = \omega_p$, $k = 0$

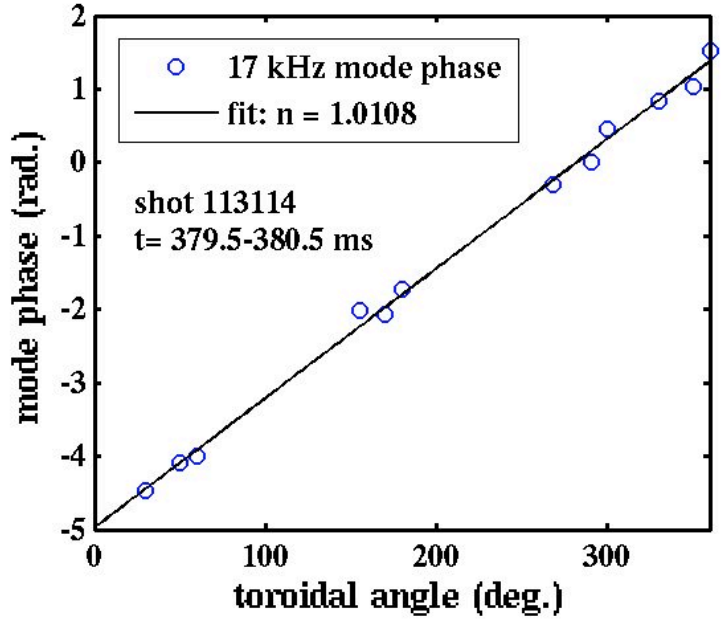


- Microwaves launched into plasma. Relative phase of reflected and launched waves determined

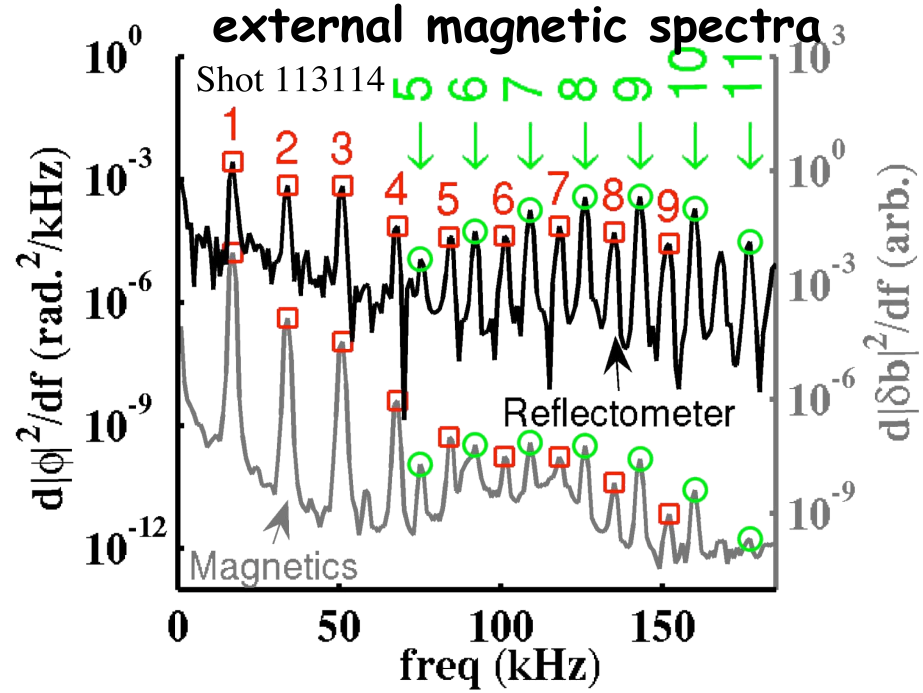
- Wave propagation controlled by density ⇒ phase fluctuations proportional to density fluctuations (for large scale modes): $\delta n/n_0 \sim \delta\phi/(2k_{vac}L_n)$

Toroidal mode numbers of coherent modes may be determined from Mirnov array

Example of Mode Number Determination



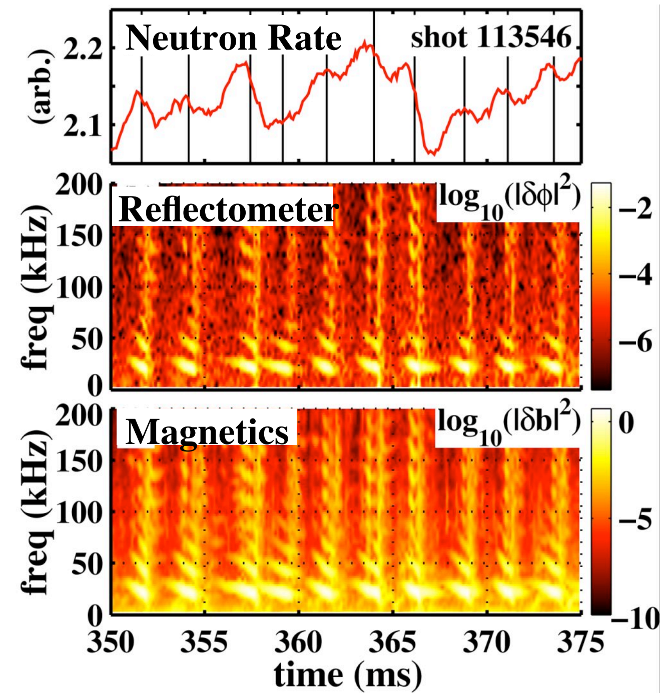
50 GHz reflectometer and external magnetic spectra

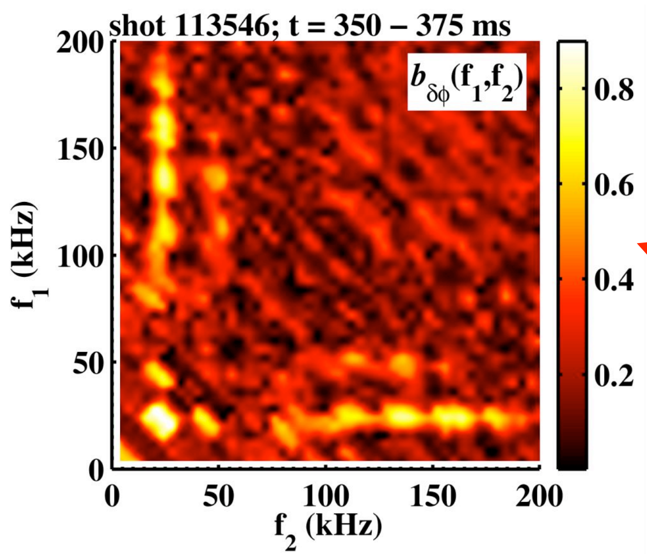


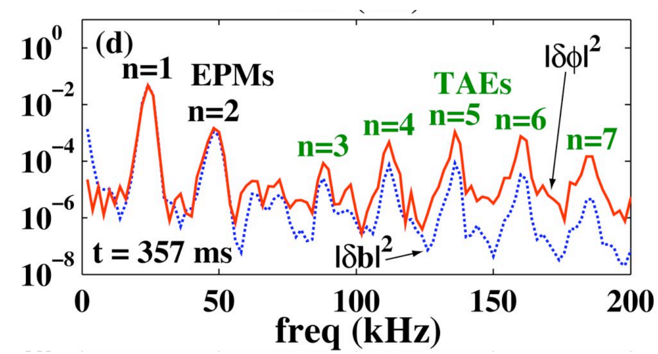
- Toroidal array of Mirnov coils outside plasma
  - modes visible in magnetic spectrum
  - mode phase varies with coil position ⇒ measure toroidal mode number
- Many peaks in refl. spectrum also seen in magnetic spectrum
  - if peaks in both spectra, mode number of refl. perturbation known

Three-wave interactions influence fast-ion loss

- **EPMs, TAEs active during fast-ion loss events:**
  - EPM: Harmonic, $f \sim 24$ kHz, 48 kHz, $n = 1,2$
  - TAEs: $f \sim 80$ - 200 kHz, n = 3 - 7
    - uniformly spaced in f and n: $\Delta f \sim 24$ kHz, $\Delta n = 1$
- **EPMs interact with pairs of TAEs:**
  - neighboring TAEs satisfy matching requirements:
    $\Delta f_{TAE} = f_{EPM}$ and $\Delta n_{TAE} = n_{EPM}$,
    so for TAE pair (f,n) and (f',n'):
    $f' = f + \Delta f_{TAE} = f + f_{EPM}$ and $n' = n + \Delta n_{TAE} = n + n_{EPM}$
  - interacting modes show high bicoherence (bottom left)





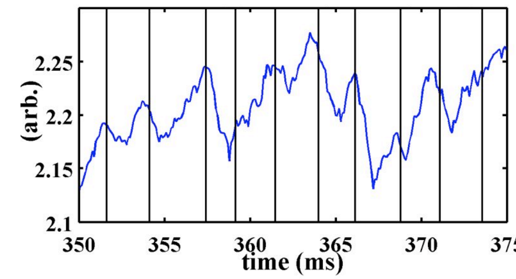


$$b_{\delta\phi}(f_1,f_2) = \frac{|\langle \delta\phi(f_1)\delta\phi(f_2)\delta\phi^*(f_1+f_2)\rangle|}{\left(\langle|\delta\phi(f_1)\delta\phi(f_2)|^2\rangle\langle|\delta\phi(f_1+f_2)|^2\rangle\right)^{1/2}}$$

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

- CAE spectrum broadens during fast-ion loss events (drops in neutron rate) - sidebands appear
- bicoherence measurement indicates three-wave interactions cause broadening

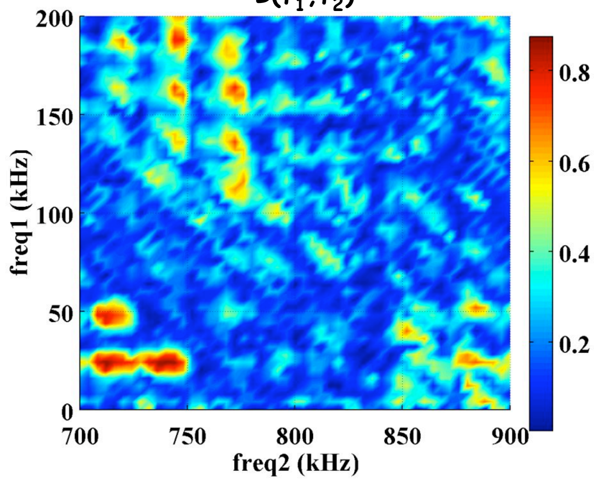
Neutron Rate
(with fluctuation bursts marked)

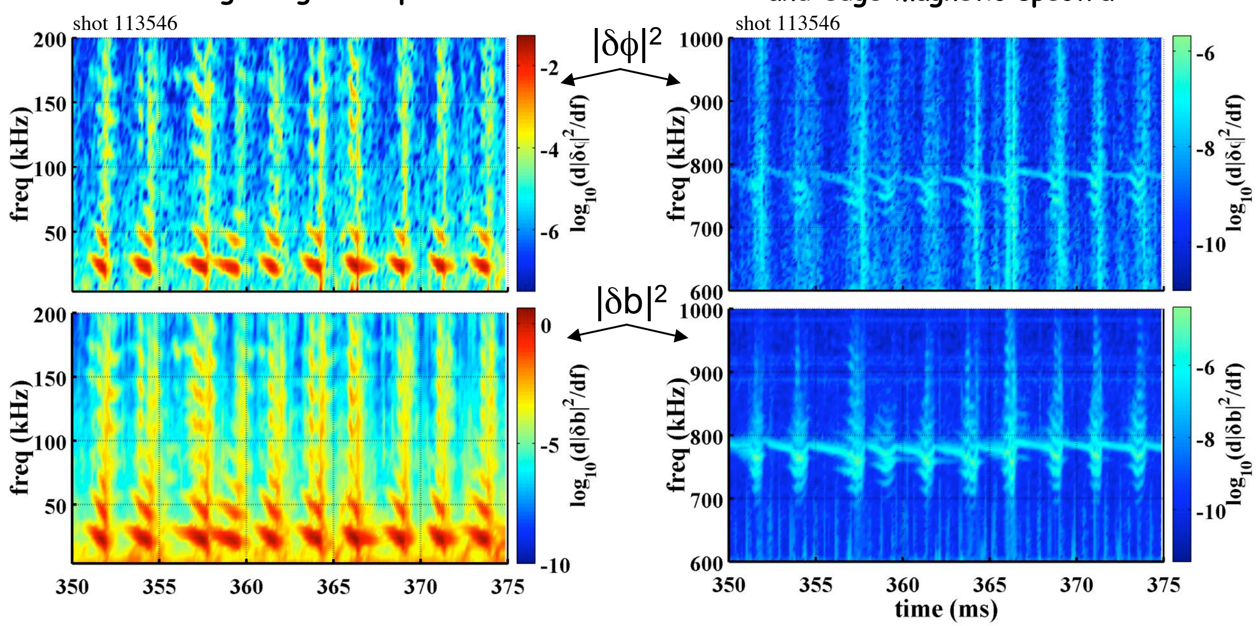


TAEs and EPMs
50 GHz reflectometer phase and edge magnetic spectra

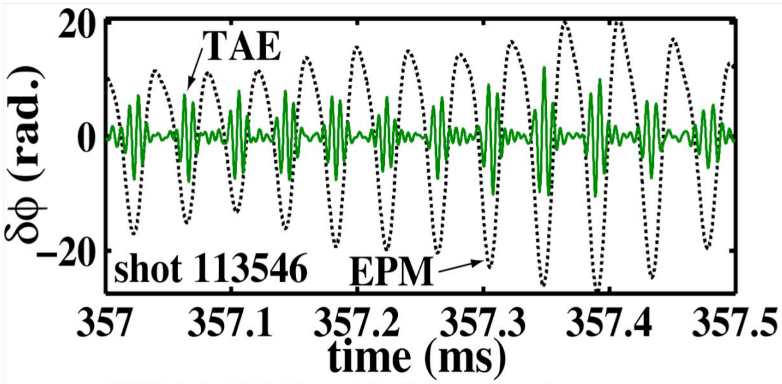
CAEs
50 GHz reflectometer phase and edge magnetic spectra

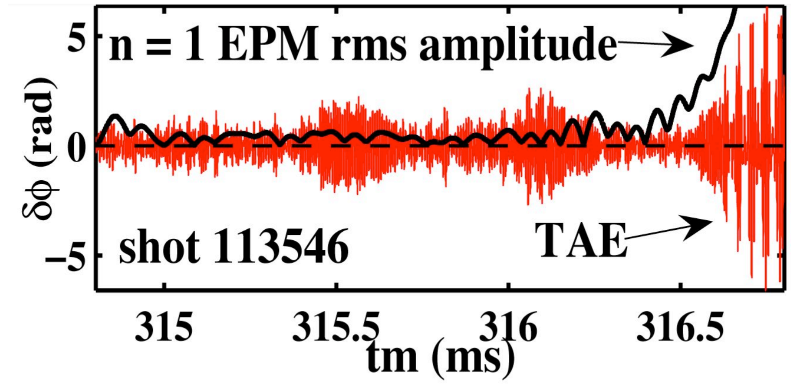
Bicoherence of δb
$B(f_1,f_2)$





Three-wave interactions with EPM spatially concentrates TAE energy



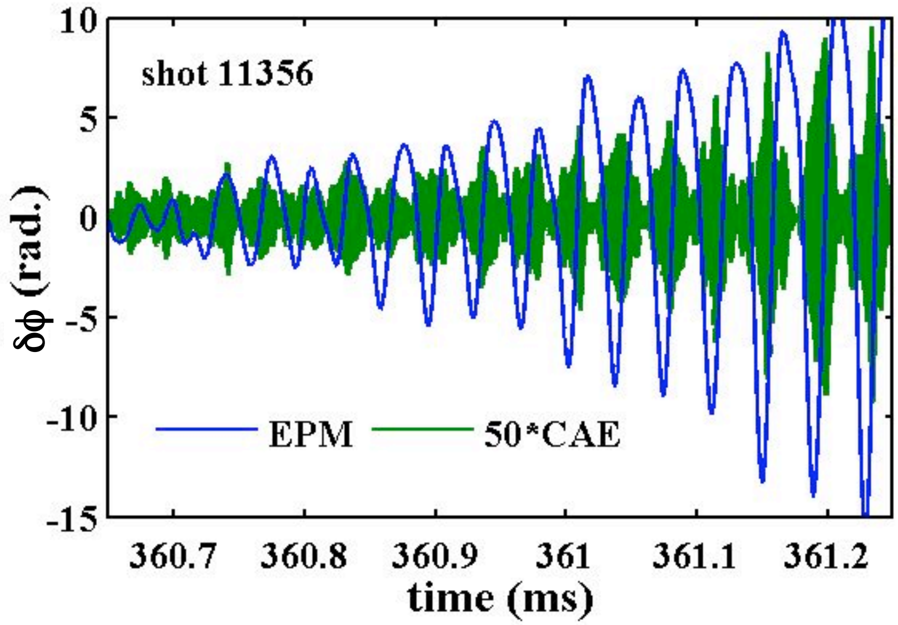


- **Interaction phase locks TAEs to form coherent structure:**
  - uniform frequency and wave number separation imposed ⇒ TAE superposition has well defined group velocity which equals EPM phase velocity
  - TAEs form coherent (long-lived) structure that propagates in lock-step with EPM
- **Coherent TAE structure is toroidally localized "wave-packet" (top left)**
  - reflectometer phase band-pass filtered to extract TAE and EPM components
  - TAE component shows wave-packet: seen as pulse every time it passes reflectometer
  - pulse always occurs in same phase of EPM
- **TAE energy "spatially concentrated" ONLY when EPM active (top right)**
  - TAEs frequently active without EPMs
  - Wave-packet forms only when EPM strong

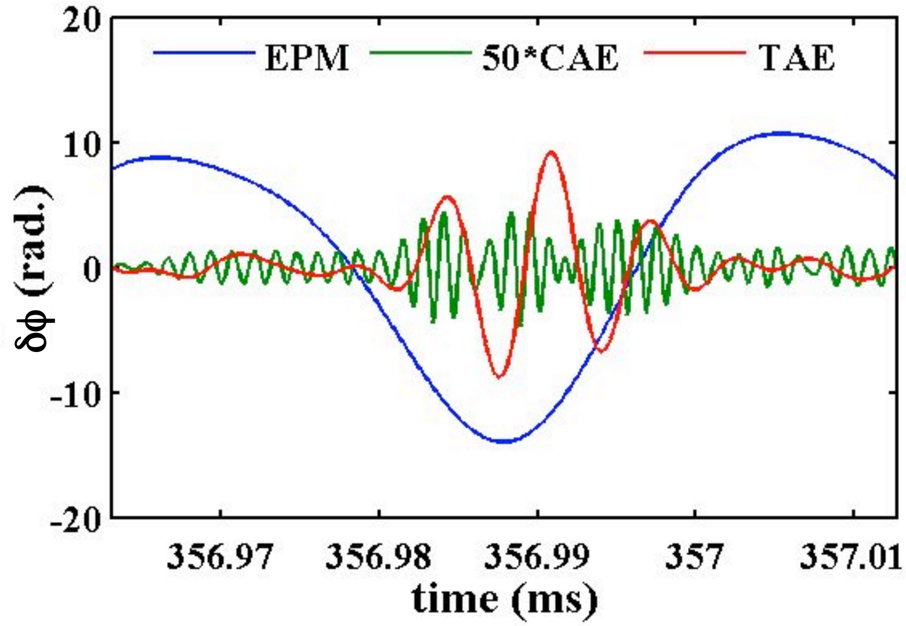
Three-wave interactions spatially concentrate CAE energy

- Interaction with EPMs forms CAEs into wave-packet (bottom left) - analogous to EPM—TAE interaction
- Interaction with TAEs subdivides CAE wave-packets into smaller packets (bottom right)
- Conjecture: high frequency wave-packets forms because low-frequency modes toroidally perturb fast-ion population (i.e. free energy source).

CAE wave-packets formed by EPM interaction



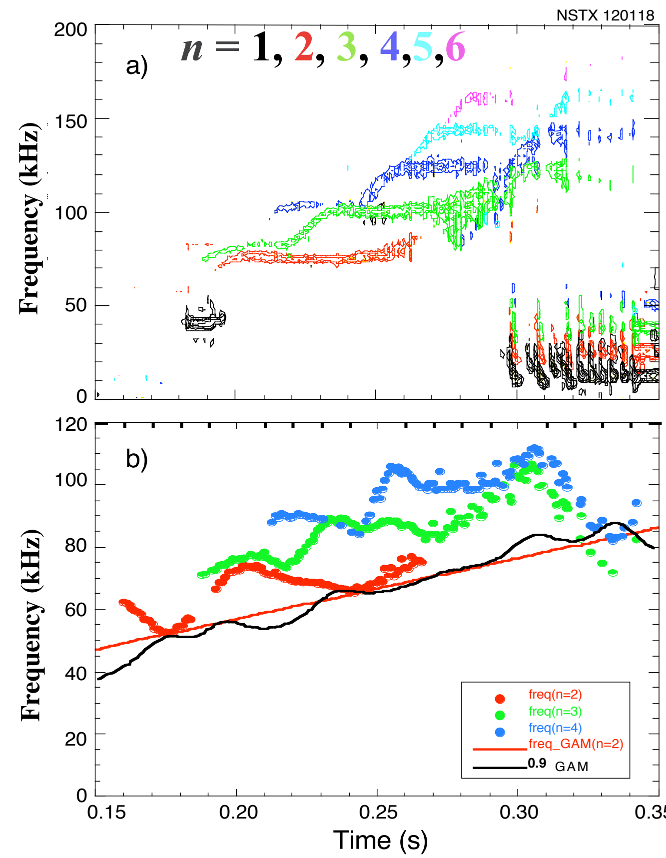
CAE wave-packets subdivided by TAE interaction



Alfvén Cascade Modes observed in NSTX

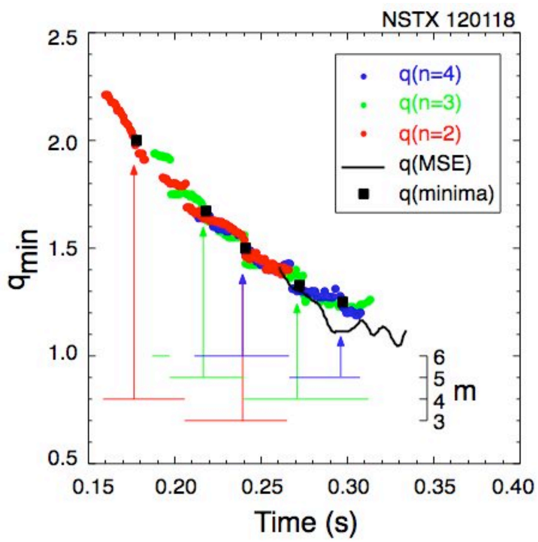
- Series of upward chirps observed (top right)
  - increasing toroidal mode numbers
- Doppler corrected f (bottom right) shows up-chirp followed by down-chirp
  - Doppler shift resulting from plasma rotation measured at the assumed mode location near q_{min}, R = 1.25 m
- Up-chirp consistent with Alfvén Cascade (AC) mode: ACs chirp up from f_{GAM} as q_{min} falls (bottom right).
  - AC chirp start frequency due to coupling with GAMs or BAEs
  - The red curve is the interpolated n = 2 GAM frequency evolution
  - the black is the local f_{GAM} scaled by 0.9 to match the data

$$f_{GAM}^2 = \frac{1}{(2\pi)^2}\frac{2C_S^2}{R^2}\left(1+\frac{7}{4}\frac{T_i}{T_e}\right)$$



Alfvén Cascade Modes observed in NSTX (cont.)

- Using measured *n* and reasonable *m*, can infer $q_{min}(t)$ from AC frequency (below)
  - choice of m must yield consistent $q_{min}(t)$ when multiple modes coexist
  - consistent $q_{min}(t)$ given by (m,n) = (5,2), (4,2)+(2,1), (5,3), (3,2), (4,3), (5,4)
  - times of mode frequency minima (chirp start) marked with black squares

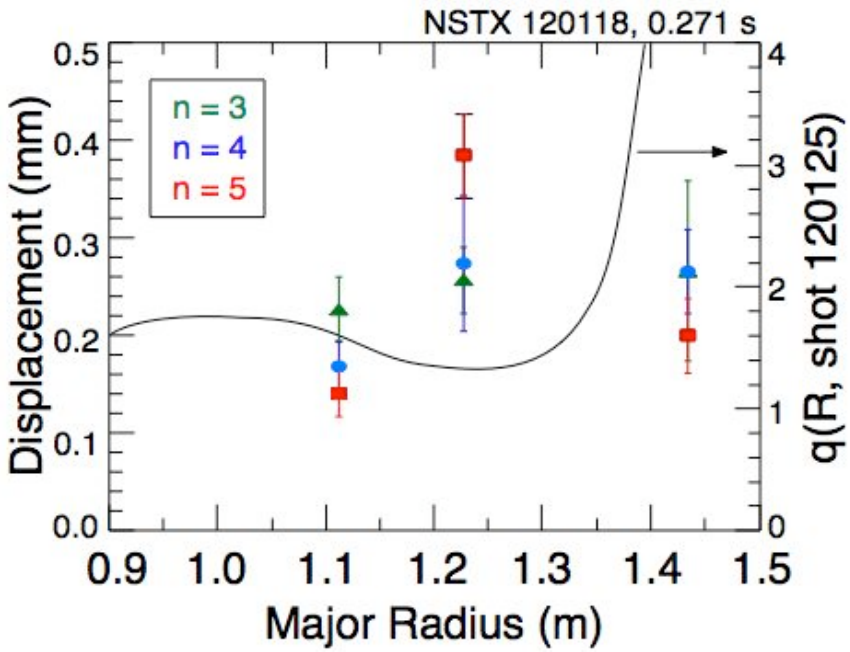


$$q_{min} = \frac{mV_{Alfvén}}{nV_{Alfvén} + R(\omega^2_{mode} - \omega^2_{min})^{1/2}}$$

$$\omega_{min} = 2\pi f_{GAM}$$

- Reconstructed $q_{min}(t)$ compares well with $q_{min}(t)$ (black line) from MSE in similar shot (with ~ 10% higher peak density)

Alfvén Cascade Modes observed in NSTX (cont.)

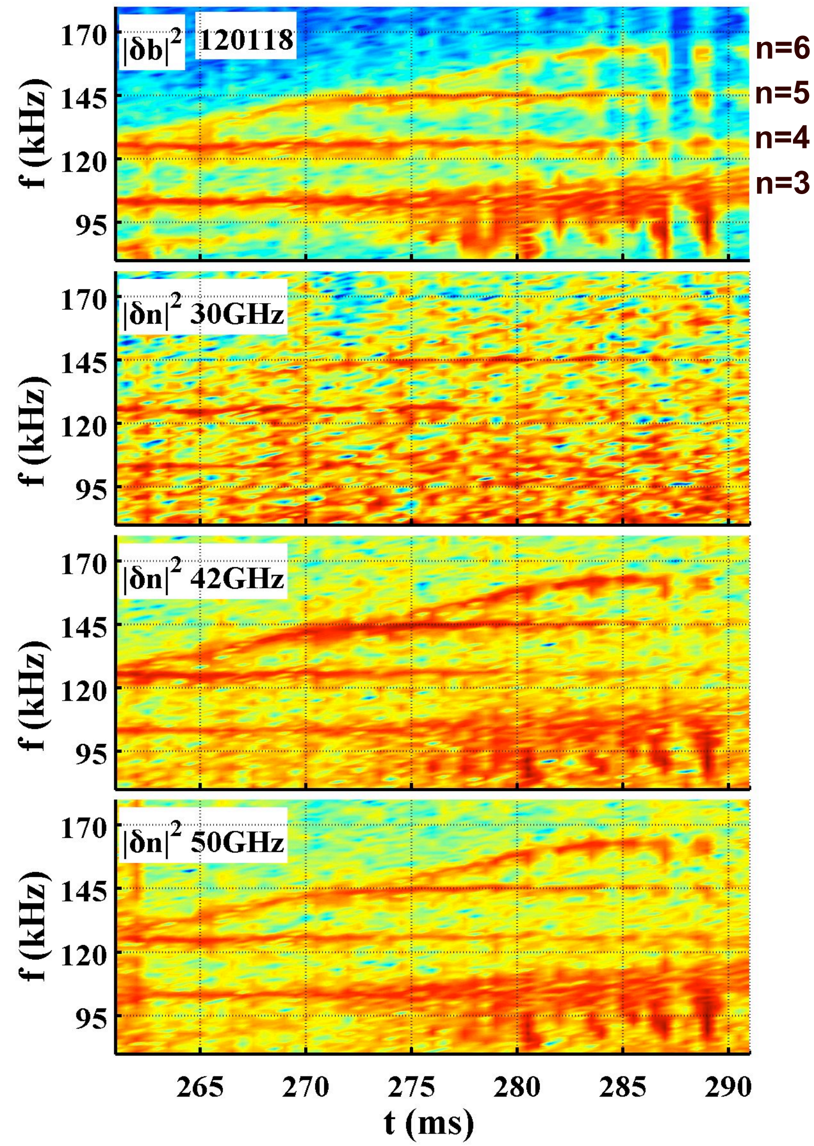


- Internal structure of modes measured with reflectometers
- q profile from similar (but ~ 10% higher peak density) shows minimum at R ~ 1.25 m.
- Structure consistent with localization at q_{min}
  - Strong localization for highest *n* mode, as expected from theory

TAE spatial structure investigated

- **TAEs measurements available from:**
  - external toroidal Mirnov array (top right)
  - three fixed-frequency reflectometers (bottom right)
  - radial chord 1mm interferometer (not shown)

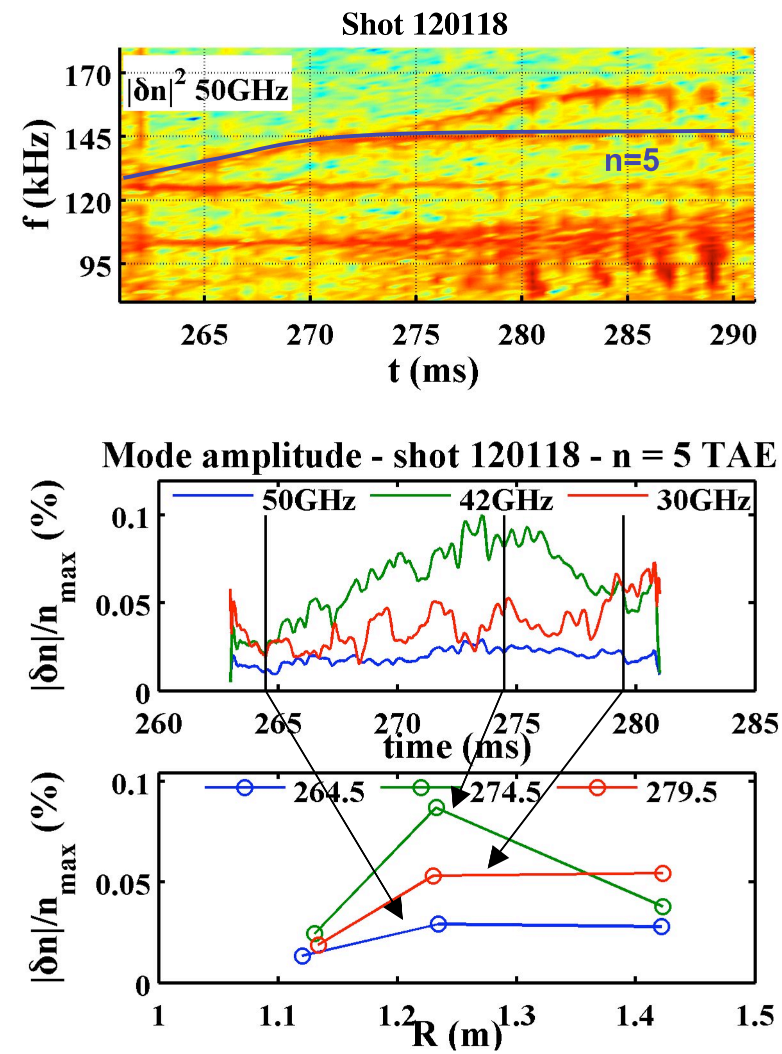
- **TAE measurements can be exploited in several ways:**
  - compare with NOVA-K — test usefulness to predict structure
  - understand effect on fast ions — compare with fast-ion measurements (NPA, SSNPA, sFLIP, neutrons, etc.)
  - variable behavior — bursting vs. persistent and fast chirp vs. slow frequency sweep — may be sensitive diagnostic of plasma and fast ion properties



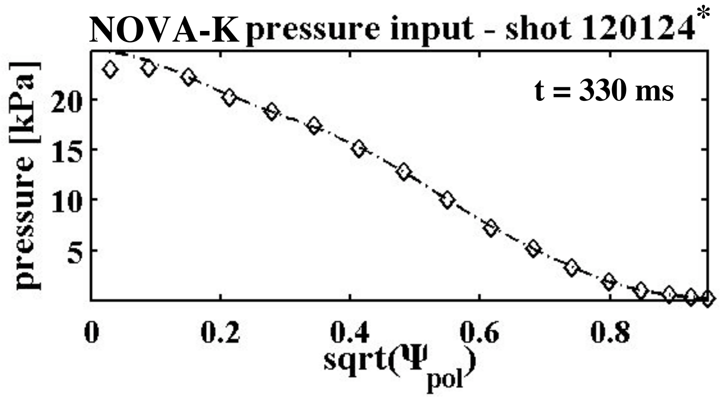
Mode structure investigated during typical evolution from Alfvén Cascade to TAE

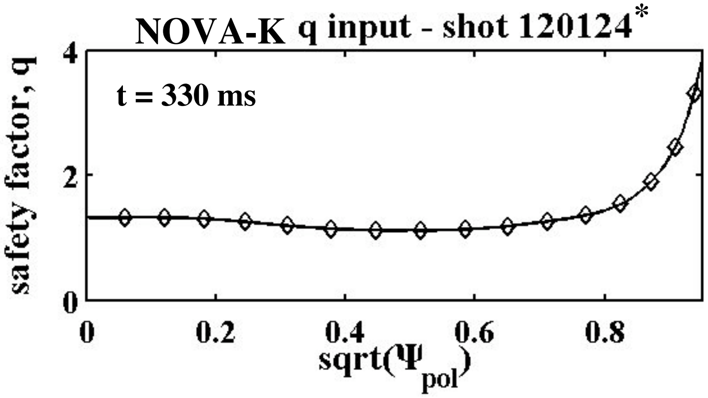
- *n* = 5 mode evolves substantially over lifetime
  - mode is AC from *t* ~ 263 — 271 ms — frequency sweeps up from *f* ~ 120 to 145 kHz
  - mode is TAE around *t* ~ 271 ms — *f* peaks
  - is mode AC after *t* ~ 271 ms — *f* constant (actually sweeps *down* in plasma frame)?

- $\delta n/n_0$ varies 300% at *R* ~ 122 cm
  - variation may be due to changing radial mode structure - ACs more localized than TAEs
  - amplitude change due to stability may also be a factor

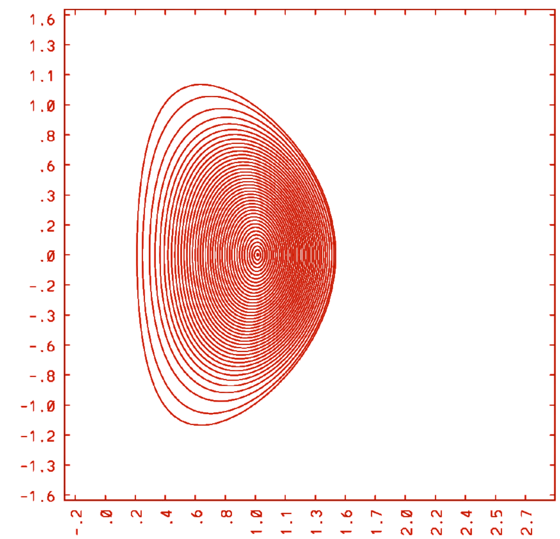


NOVA-K solves linear ideal MHD stability equation for eigenmodes





NOVA-K input geometry - shot 120124



- **Solves in "perturbative" limit**
  - fast ions affect growth rate, not mode structure and frequency
- **Input from experiment:**
  - equilibrium geometry
  - pressure profile
  - q profile
- **Solution assumes no rotation**
  - must account for rotation in experiment – typically, mode considered Doppler-shifted by rotation at mode peak

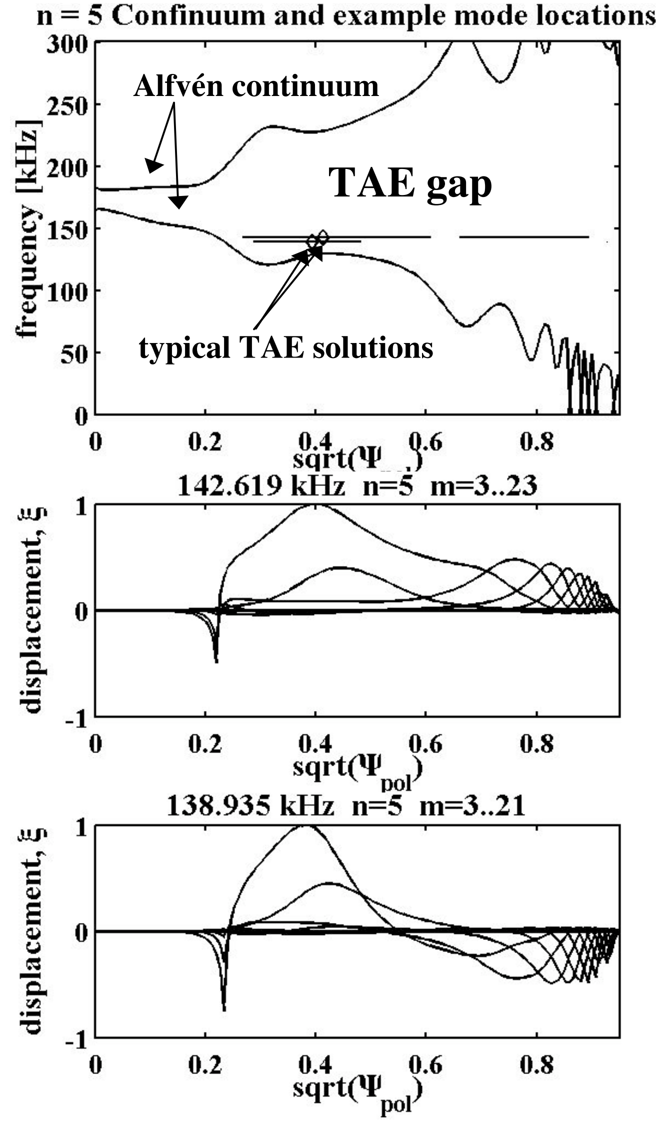
*Shot 120124 analyzed since it has MSE data and is very similar (except ~ 10% higher peak density) to 120118 shown in previous slides.

NOVA-K solutions include toroidicity-induced Alfvén eigenmodes (TAE)

- TAEs are shear Alfvén waves
  - pure toroidal Fourier modes
  - multiple poloidal harmonics
  - TAE frequencies lie in "TAE gap" in Alfvén frequency continuum (top right) - heavily damped if intersect continuum

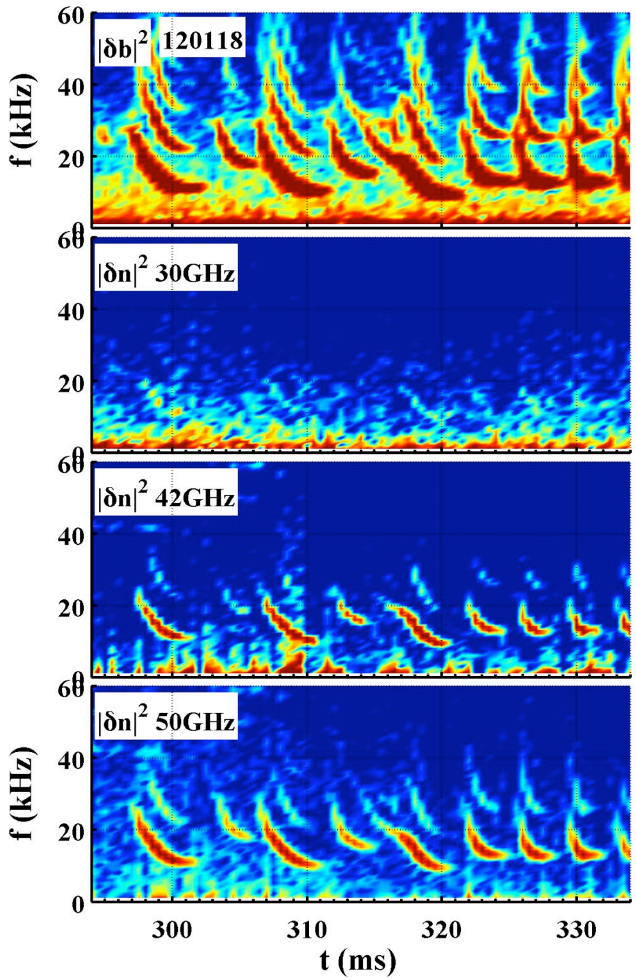
- Typical solutions (middle right) peak near region of q_{min}, in agreement with reflectometer measurements

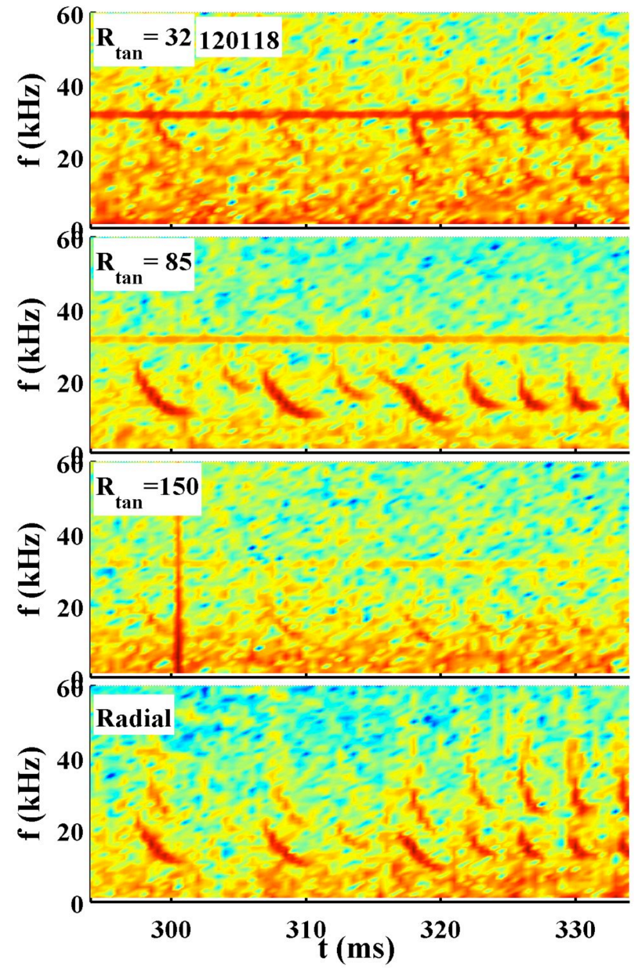
- Future work: Identify (if possible) eigenmodes that best fit measurements
  - frequency match may be inexact due to errors in plasmas equilibrium used by NOVA-K
  - calculate without "acoustic filtering". Slower, but calculated structure may change substantially.



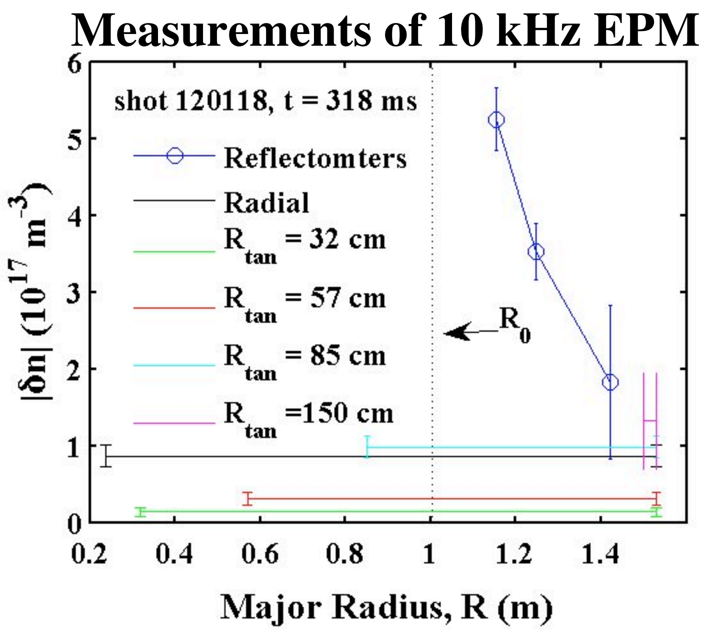
EPM spatial structure investigated

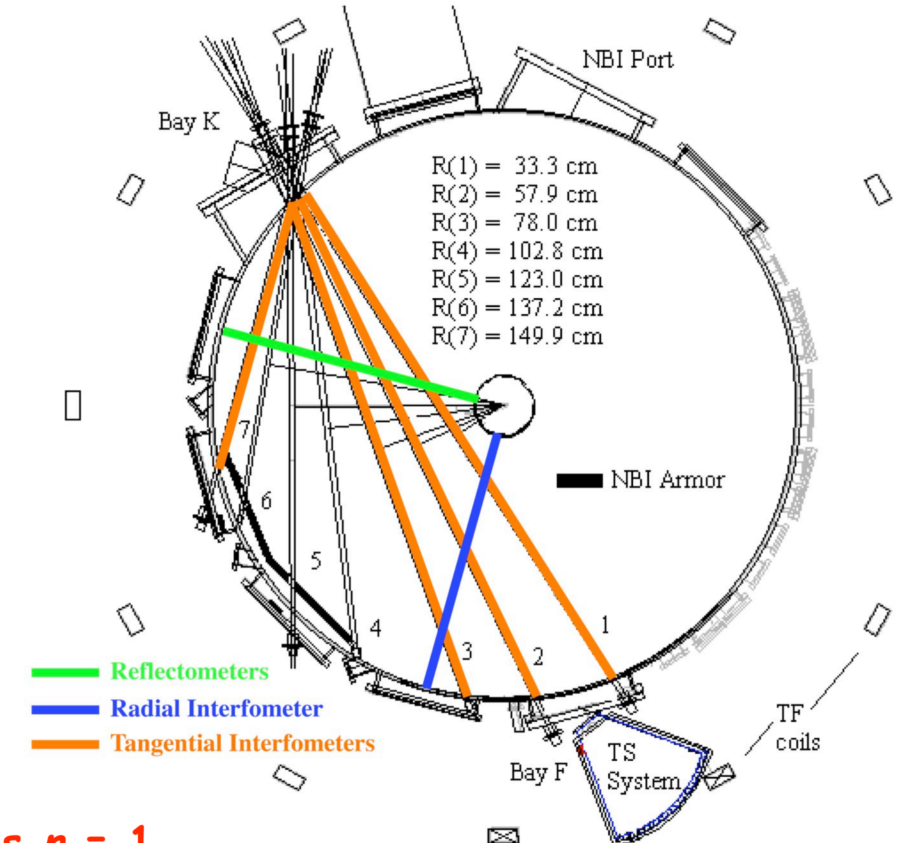
- **EPM measurements available from:**
  - external toroidal Mirnov array (top left)
  - three fixed-frequency reflectometers (bottom 3 left)
  - radial chord 1mm interferometer (bottom right) and tangential FIR interferometers (top 3 right)
  - complementary data available from USXR chord arrays (not shown)





EPM measurements indicate structure peaked near center





- Mirnov array indicates 10 kHz EPM is n = 1
- δn from reflectometer (above) shows structure peaked near center — radial displacement (not shown) similar ⇒ not consistent with (n,m) = (1,1) fishbone
  - low frequency, chirping n = 1 typically assumed to be (n,m) = (1,1) fishbone (fast-ion internal kink)
  - minimum q > 1 in similar shot (120124) (shown in previous slide) ⇒ no q = 1 surface
- Future work: use interferometers to constrain more detailed reconstruction

Conclusions

- **Three wave interactions between fast-ion modes observed for first time**
  - interaction across multiple scales: EPM—TAE, EPM—CAE, TAE—CAE
  - fast-ion loss events influenced
  - universal effect: wave-packet formation - lower frequency mode spatially concentrates energy of higher frequency mode

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