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

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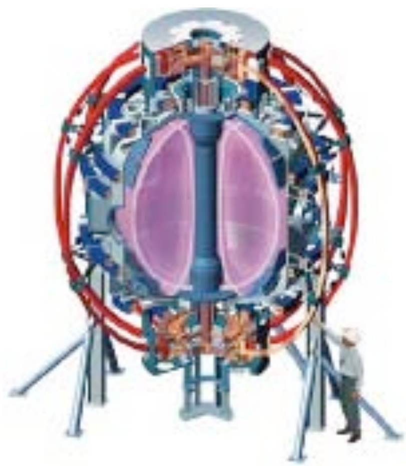

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Abstract (Revised)

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

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Neutral beam heated plasmas in NSTX exhibit a rich spectrum of fast-ion driven coherent modes that includes fishbones as well as toroidicity-induced and compressional Alfvén eigenmodes (TAE and CAE). These modes are of significant interest because they can induce fast-ion transport and channel fast-ion energy into the plasma. In recent experiments, the spatial structure of fishbone density perturbations has been investigated through the simultaneous application of a 288 GHz radial interferometer and three fixed-frequency microwave reflectometers operated by UCLA, three tangential far-infrared interferometers operated by UCD and an array of magnetic sensing coils external to the plasma. The coils and the UCLA diagnostics have also been utilized in a similar investigation of TAEs. The results may be compared with predictions from NOVA-K. Nonlinear three-wave interactions between fishbones, TAEs and CAEs are also studied. These interactions transfer energy in space and time and can significantly influence the effect of the modes on fast ions.

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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

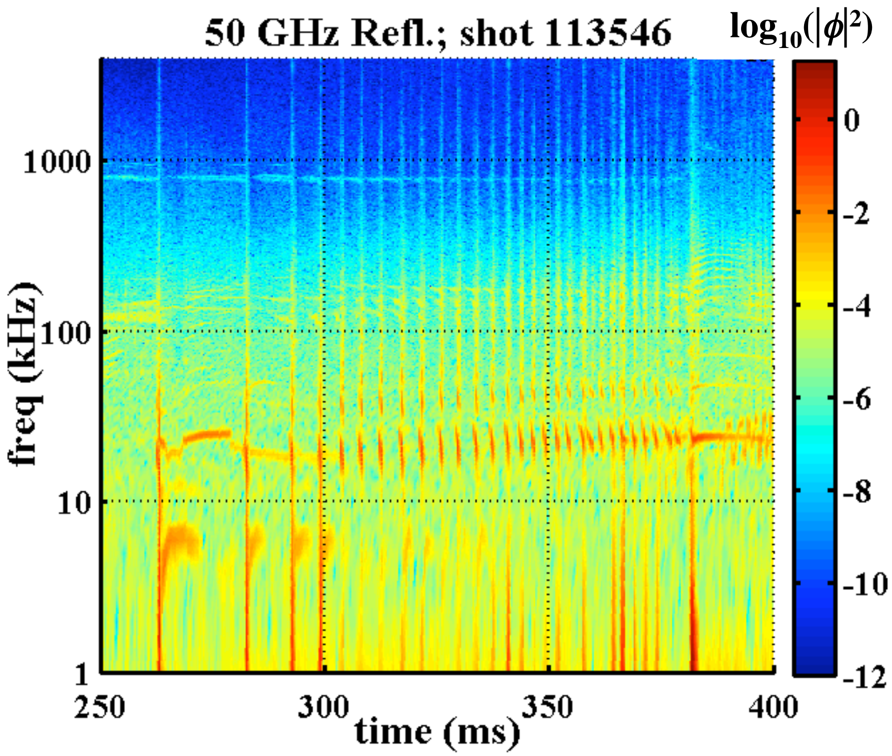
Summary of Results

- 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

- TAEs and EPMs structure measured - observed with array of diagnostics:
  - multiple reflectometers ⇒ radial structure
  - radial & tangential interferometers (EPMs only for tang. interf.) ⇒ constrain reconstruction
  - toroidal array of Mirnov coils outside plasma ⇒ determine toroidal mode number

- TAE mode structure calculated by NOVA-K (linear stability code)
  - calculation uses conditions similar to experiment - some refinement necessary
  - future work - compare calculated TAE structure to measurements

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)**
  - 40 – 200 kHz
  - natural plasma resonance
- **Energetic Particle Modes (EPM)**
  - ≲ 100 kHz
  - mode defined by fast-ion parameters
  - strong frequency chirping common

Fast-ion mode structure probed by internal density fluctuation diagnostics

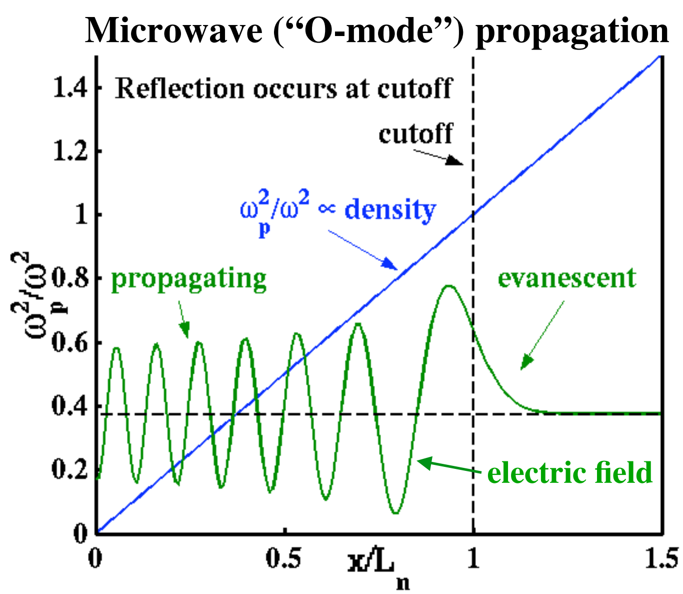
- Multiple reflectometers measure local density perturbation ⇒ radial structure of mode (low field side)
  - interpretation of reflectometer signal for coherent modes confirmed by comparison with BES data on DIII-D.

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

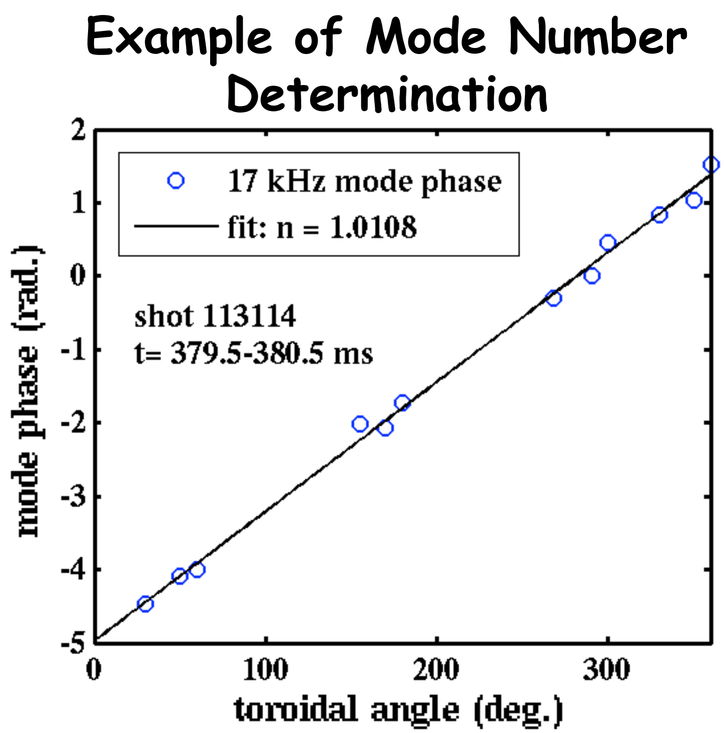
- Microwaves with low enough frequency ($\omega < \omega_p$) reflect from "cutoff" layer in plasma
  - ω_p^2 is proportional to density: $\omega_p^2 = e^2 n_0/\varepsilon_0 m_e$
  - Dispersion relation for "ordinary mode" ("O-mode") microwaves: $\omega^2 = \omega_p^2 + c^2k^2$
  - $k \rightarrow 0$ as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

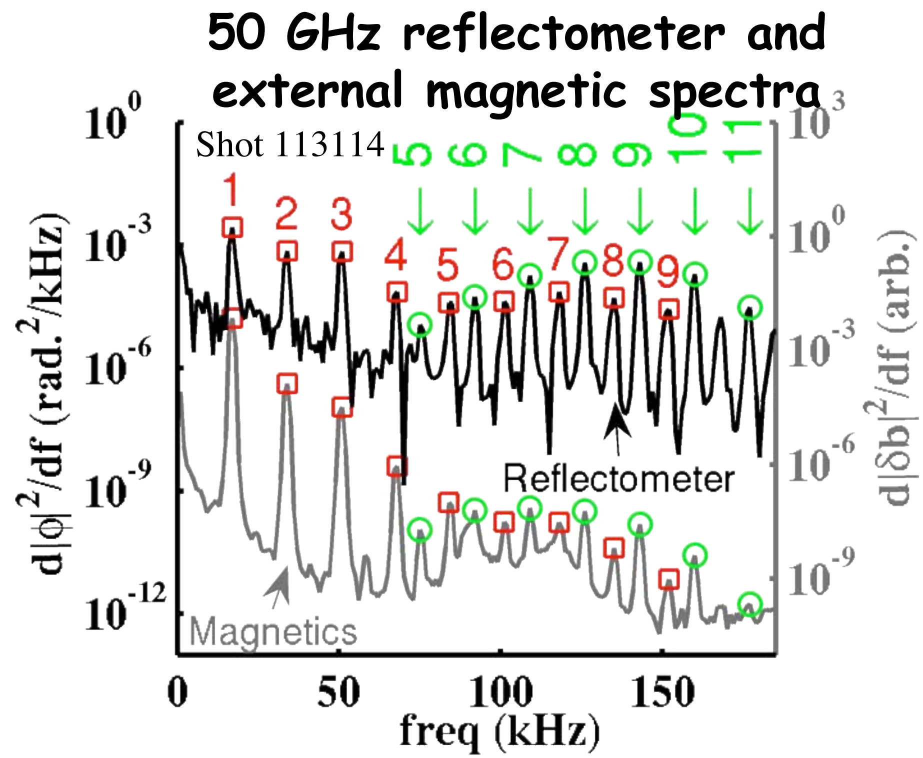


- Microwaves launched into plasma.
  Relative phase of reflected and launched waves determined

- 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

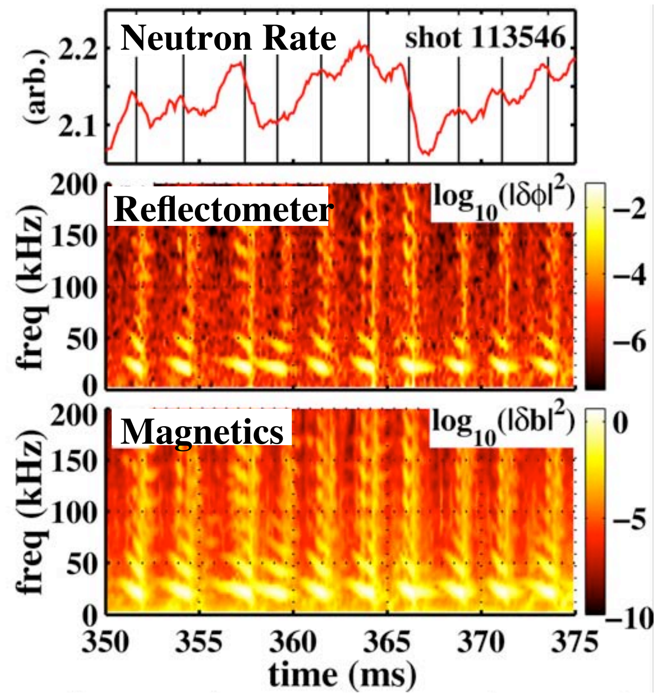


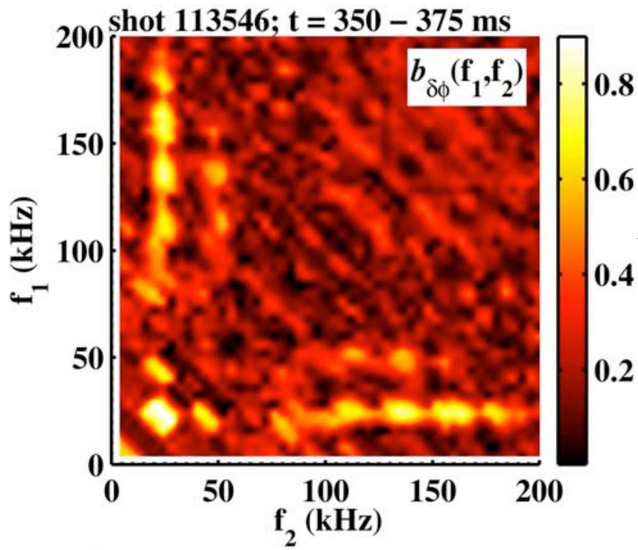


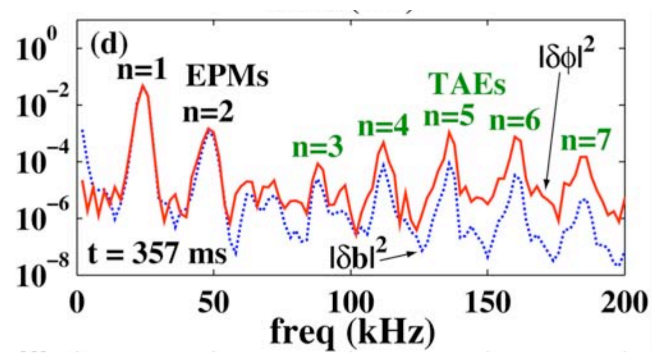
- **Toroidal array of Mirnov coils outside plasma**
  - modes visible in magnetic spectrum
  - mode phase varies with coil position ⇒ measure toroidal mode number
- **Many peaks in refl. spectrum also seen in magnetic spectrum**
  - if peaks in both spectra, mode number of refl. perturbation known

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)







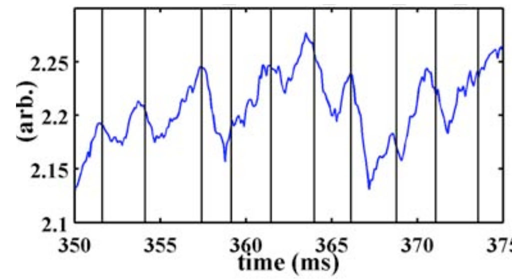
$$b_{\delta\phi}(f_1, f_2) = \frac{|\langle \delta\phi(f_1)\delta\phi(f_2)\delta\phi^*(f_1+f_2)\rangle|}{\left(\langle|\delta\phi(f_1)\delta\phi(f_2)|^2\rangle\langle|\delta\phi(f_1+f_2)|^2\rangle\right)^{1/2}}$$

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

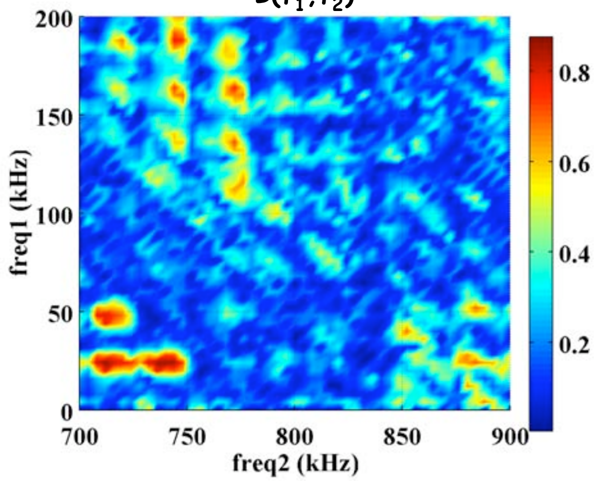
- CAE spectrum broadens during fast-ion loss events (drops in neutron rate) - sidebands appear

- bicoherence measurement indicates three-wave interactions cause broadening

Neutron Rate
(with fluctuation bursts marked)

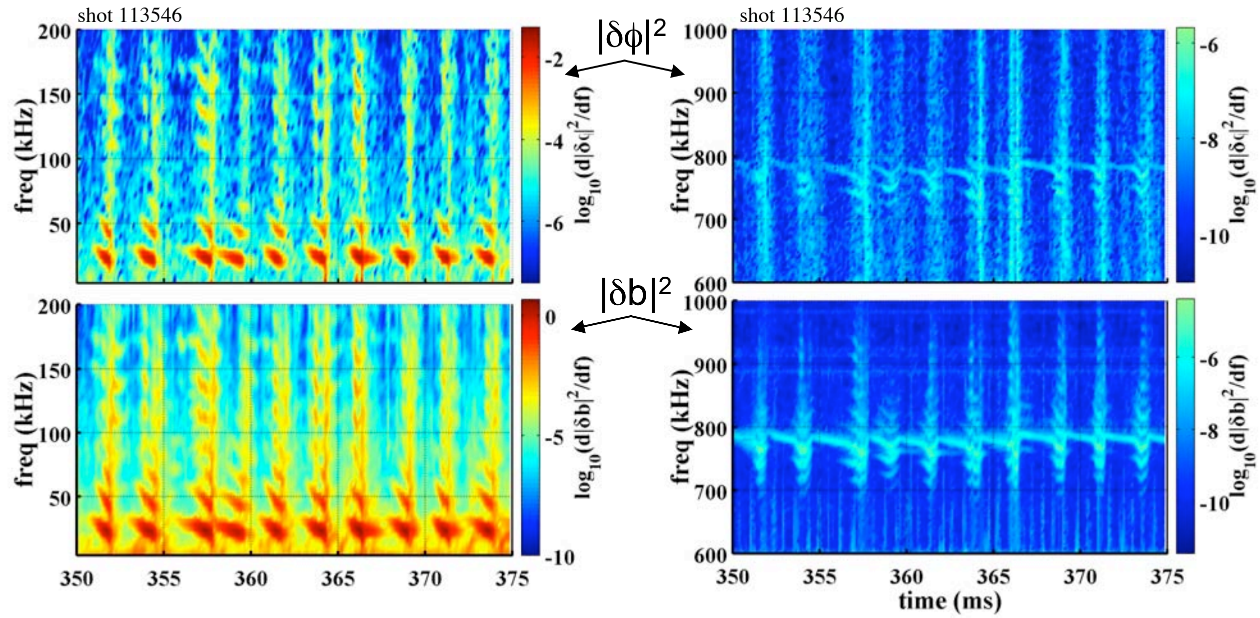


Bicoherence of δb
$B(f_1,f_2)$

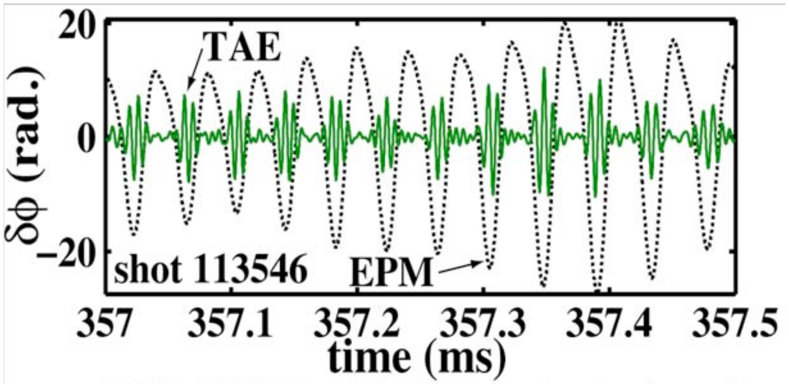


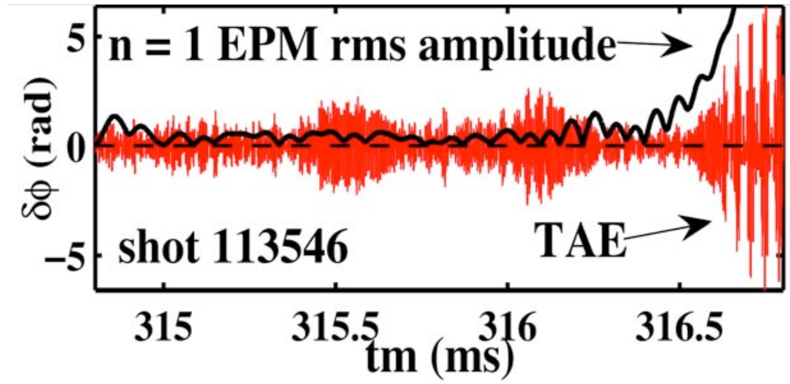
TAEs and EPMs
50 GHz reflectometer phase and edge magnetic spectra

CAEs
50 GHz reflectometer phase and edge magnetic spectra



Three-wave interactions with EPMs spatially concentrates TAE energy



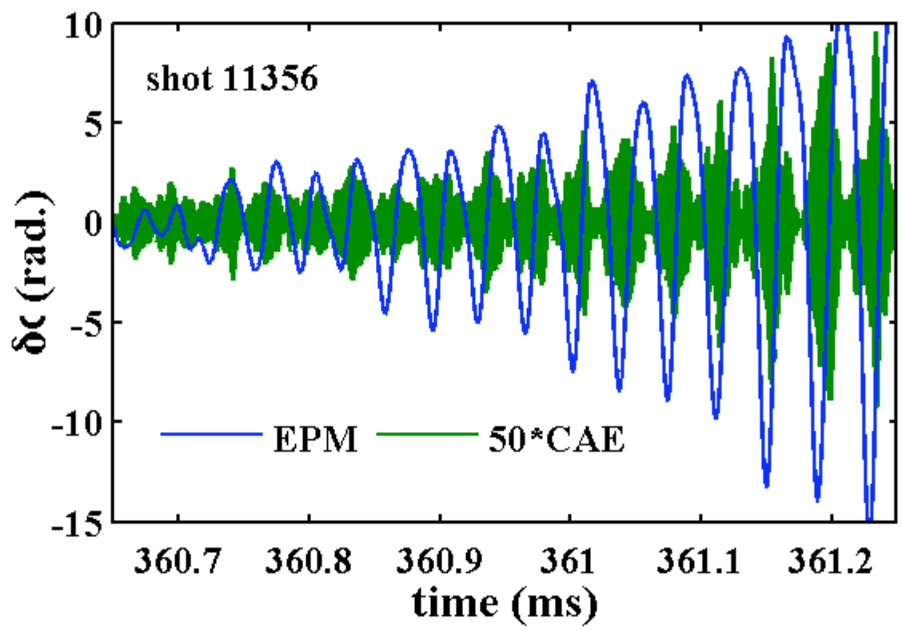


- **Interaction phase locks TAEs to form coherent structure:**
  - interaction with EPM TAEs imposes uniform frequency and wave number separation
  - uniform spacing ⇒ well defined group velocity = EPM phase velocity
  - TAEs form coherent (long-lived) structure that propagates in lock-step with EPM
- **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

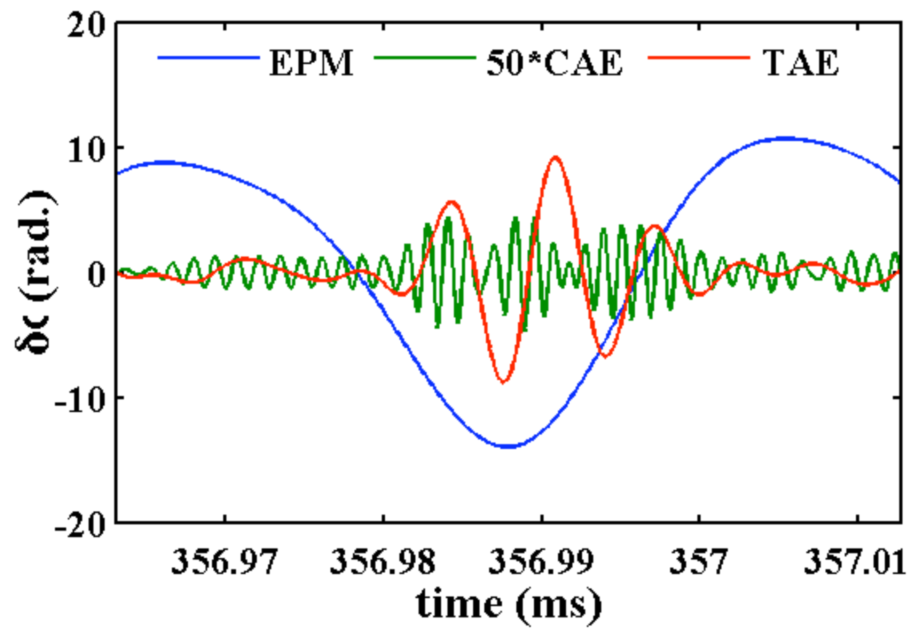
Three-wave interactions spatially concentrate CAE energy

- 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 form because fast-ion population (i.e. free energy source) localized toroidally by low-frequency mode.

CAE wave-packets formed by EPM interaction



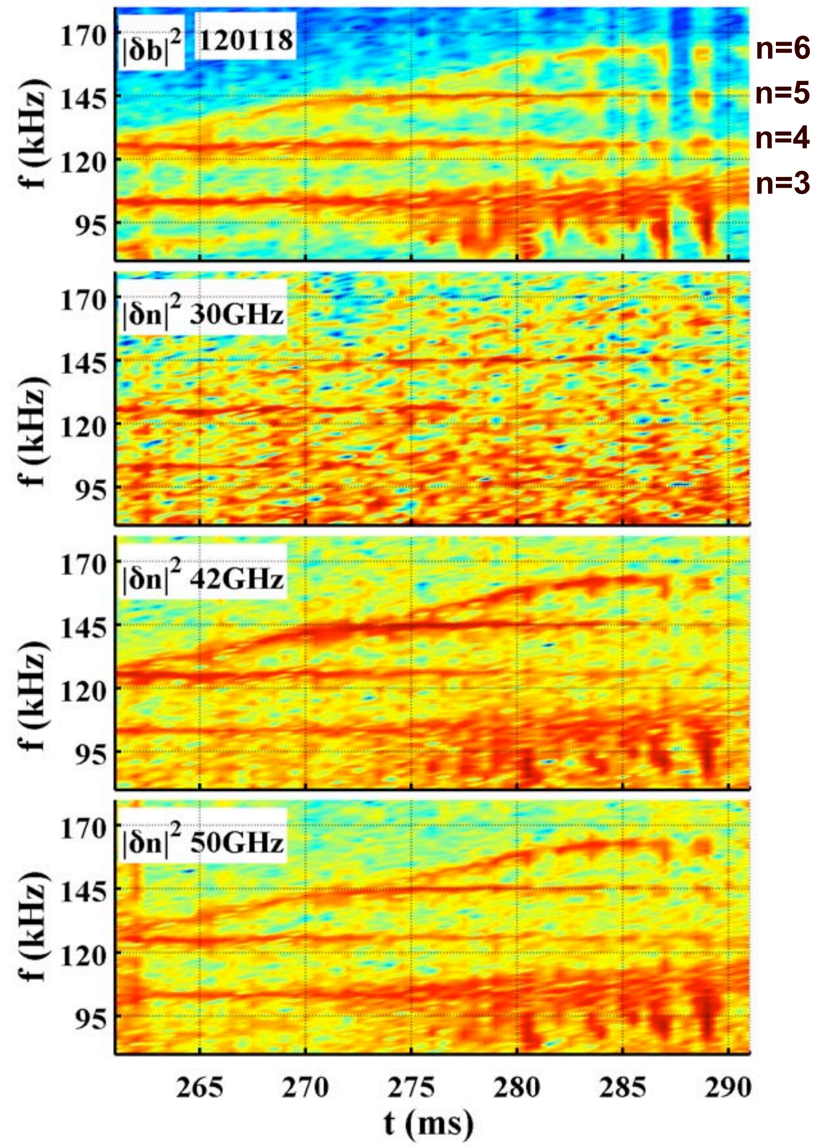
CAE wave-packets subdivided by TAE interaction



TAE spatial structure investigated

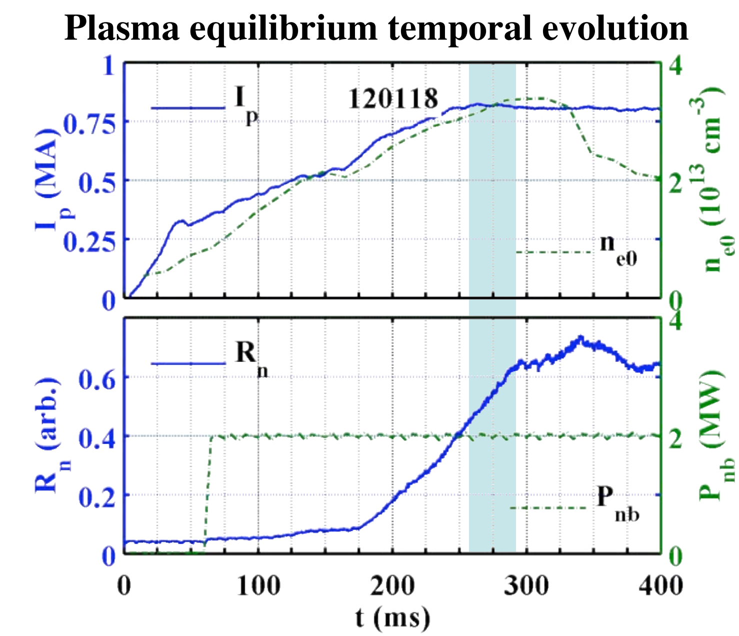
- **TAEs measurements available from:**
  - external toroidal Mirnov array (top right)
  - three fixed-frequency reflectometers (bottom right)
  - radial chord 1mm interferometer (not shown)

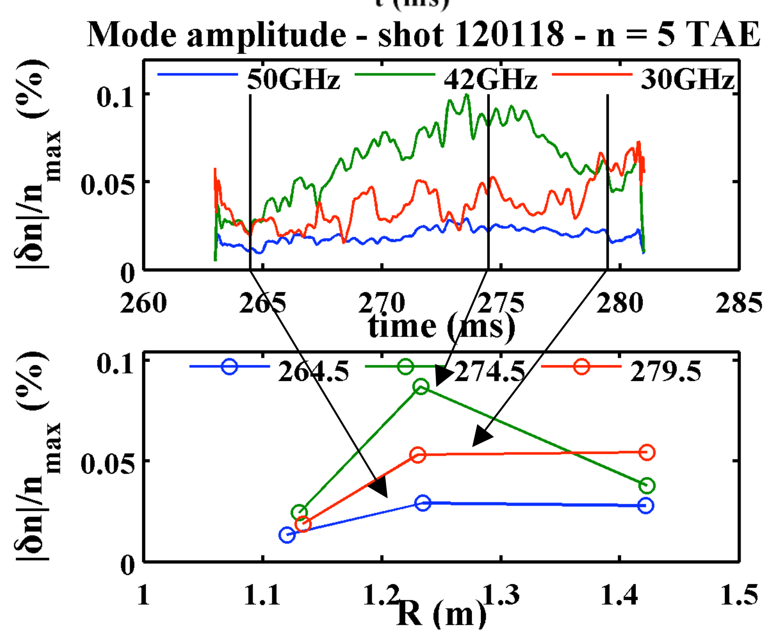
- **TAE measurements can be exploited in several ways:**
  - compare with NOVA-K — test usefulness to predict structure
  - understand effect on fast ions — compare with fast-ion measurements (NPA, SSNPA, sFLIP, neutrons, etc.)
  - learn to exploit diagnostic capabilities of TAEs — generally, AEs can burst or persist and chirp ⇒ behavior sensitive to fast-ion and plasma properties?



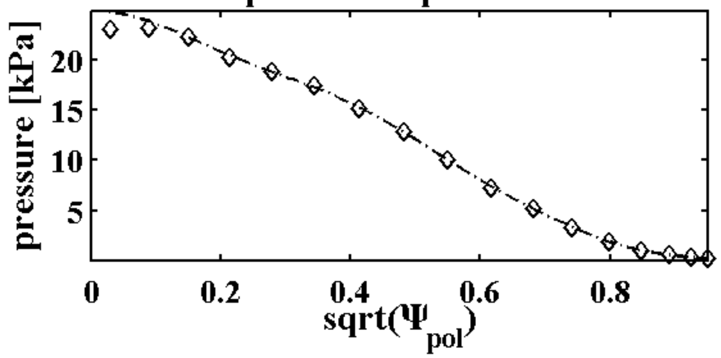
TAE structure evolves substantially over lifetime

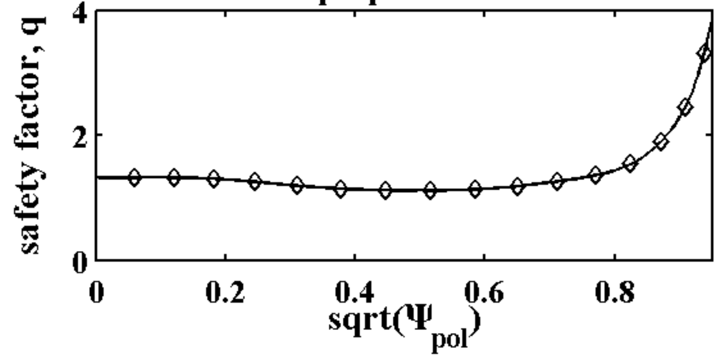
- **Typical TAE investigated**
  - frequency sweeps from *f* ~ 120 to 145 kHz during *t* ~ 263 — *t* ~ 271 ms
  - frequency stable after upsweep
  - *n* = 5 (from external Mirnov array)
- **$\Delta|\tilde{n}|/|\tilde{n}|$ ~ 300% in 20 ms at *R* ~ 122 cm**
  - possible causes of change:
    - radial mode structure evolves significantly (e.g. mode peak shifts radially)
    - mode amplitude evolves
  - Future work: use interferometer to distinguish between causes
- **Question: what causes rapid evolution?**
  - too rapid to be caused by equilibrium change?
  - controlled by changes in fast-ion population? must compare with fast-ion diagnostics
  - why is slope of *f* same for multiple modes? (see previous slide)



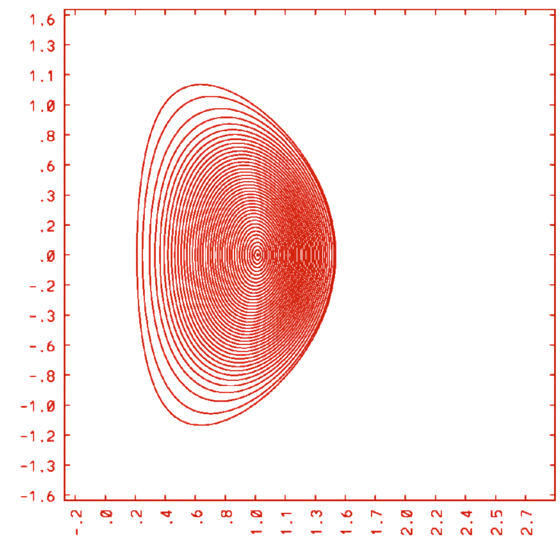


NOVA-K solves linear ideal MHD stability equation for eigenmodes





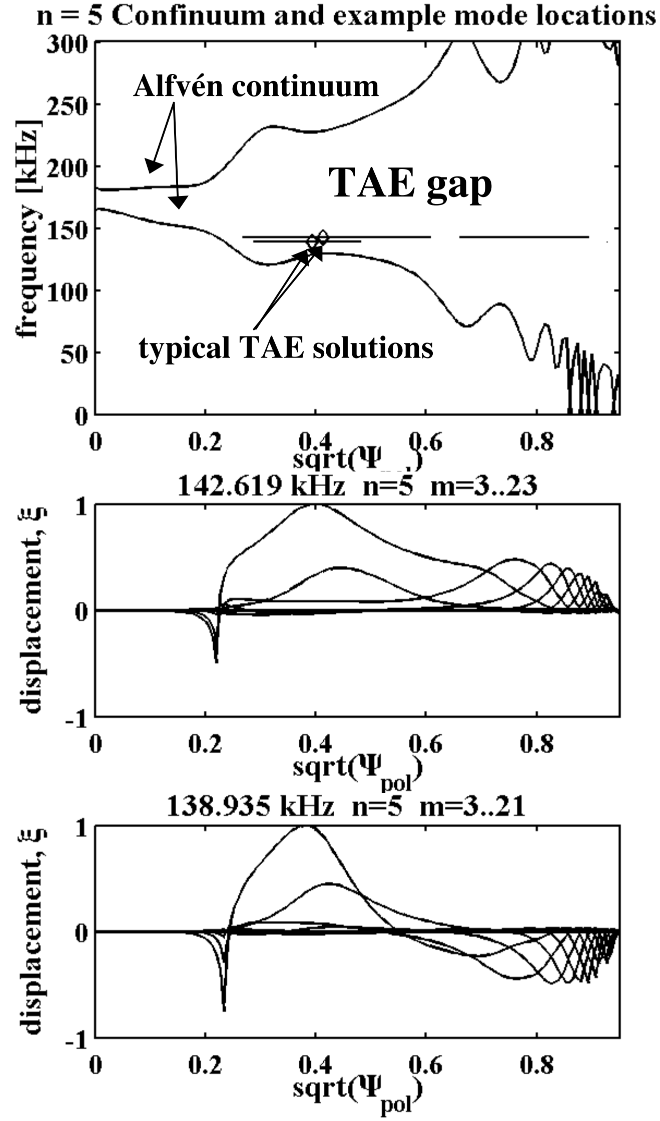
NOVAK input geometry - shot 120124



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

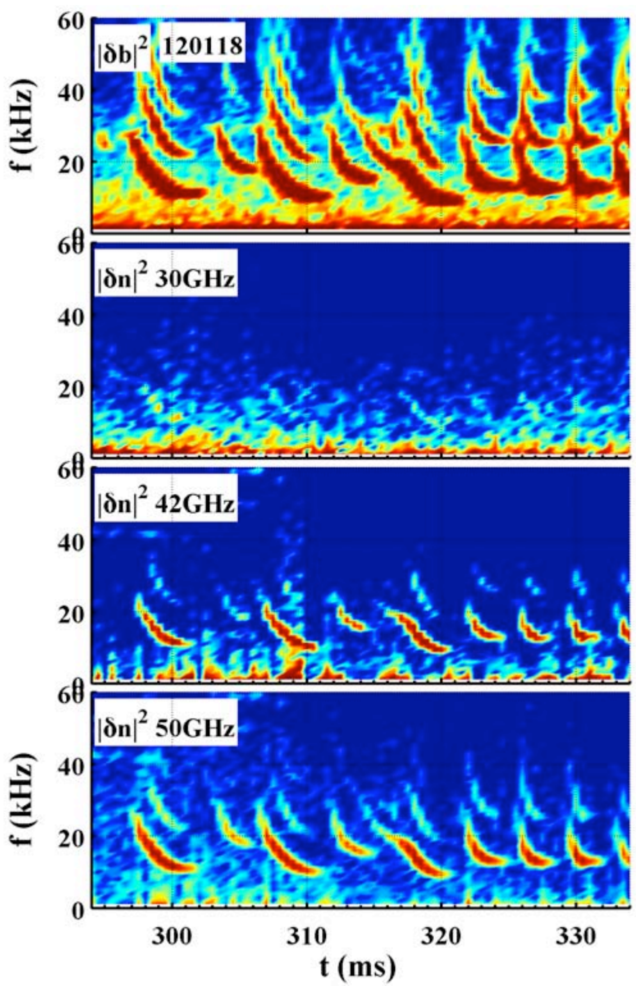
NOVA-K solutions include toroidicity-induced Alfvén eigenmodes (TAE)

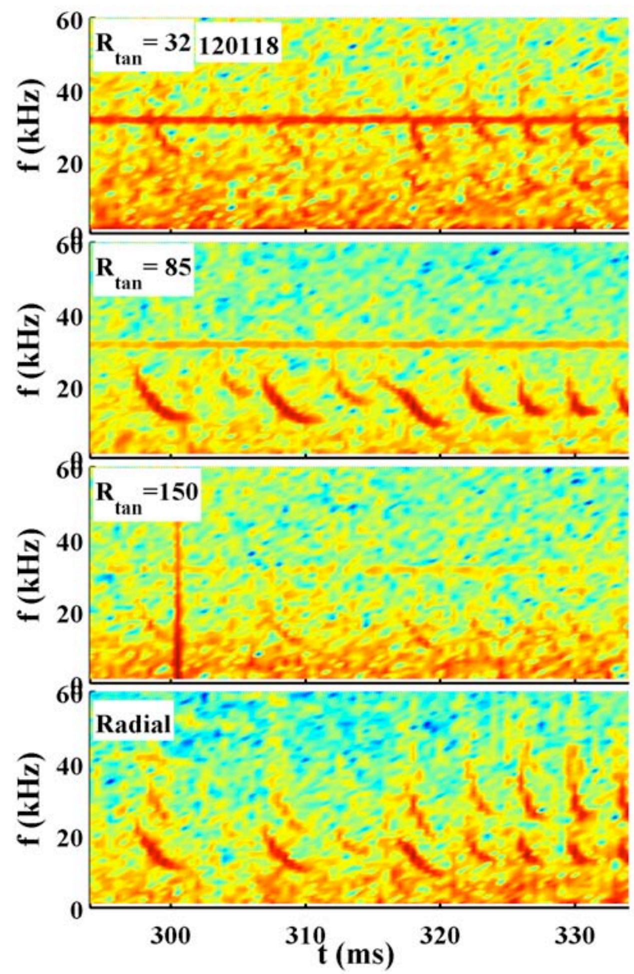
- TAEs are shear Alfvén waves
  - pure toroidal Fourier modes
  - multiple poloidal harmonics
- TAE frequencies lie in "TAE gap" in Alfvén continuum - heavily damped if intersect continuum
- Typical solutions shown on right
  - Calculated with "acoustic filtering" for speed. Must recalculate without. Structure may change substantially, but not frequency.
- Future work: Compare measurements to solutions with similar frequencies
  - frequency match may be inexact due to errors in plasmas equilibrium used by NOVAK



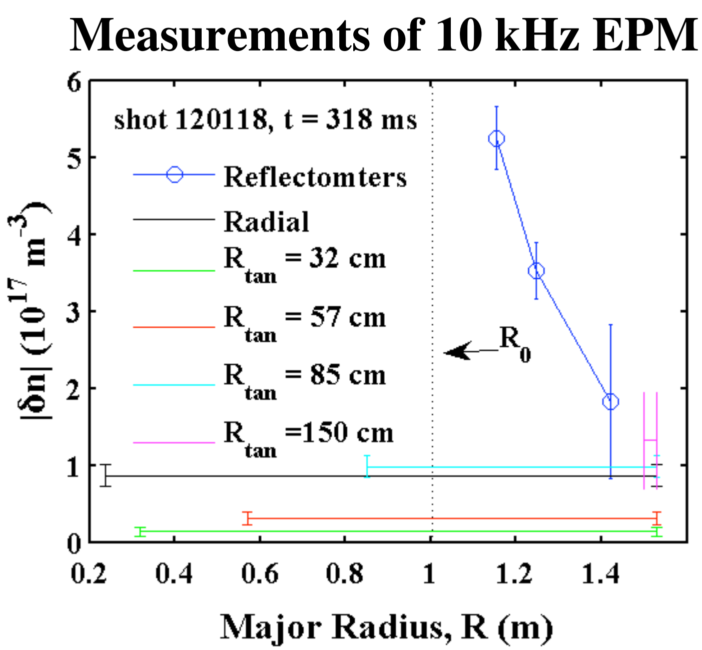
EPM spatial structure investigated

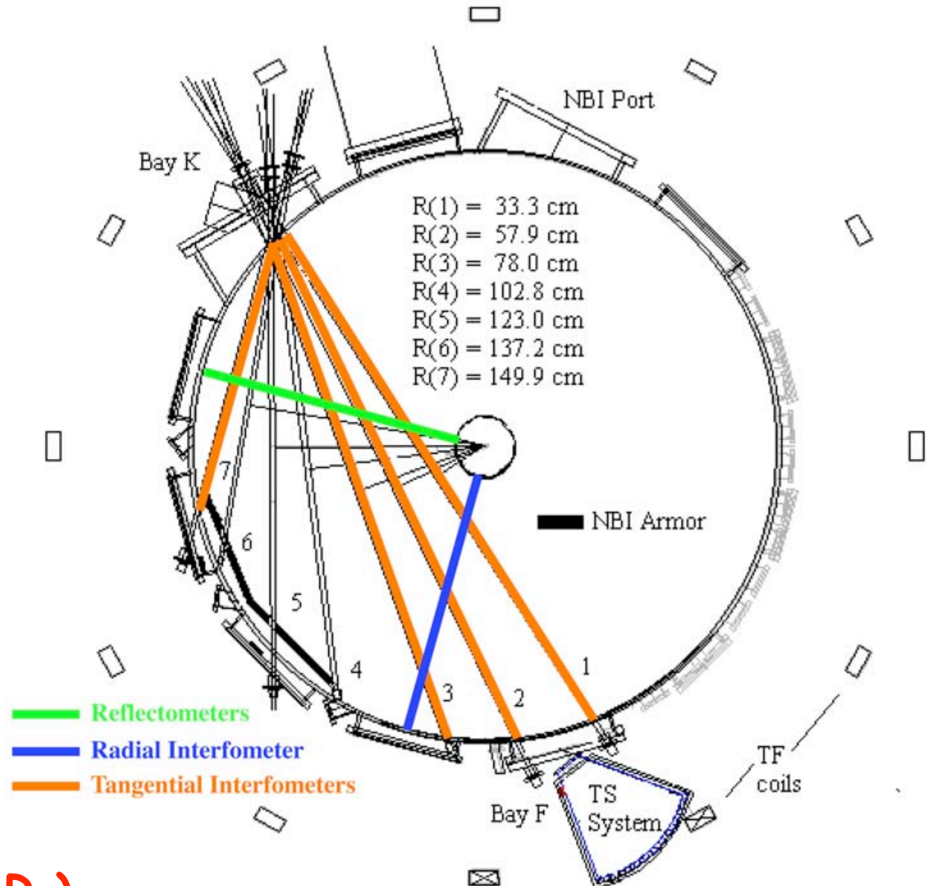
- **EPM measurements available from:**
  - external toroidal Mirnov array (top left)
  - three fixed-frequency reflectometers (bottom 3 left)
  - radial chord 1mm interferometer (bottom right) and tangential FIR interferometers (top 3 right)
  - complementary data available from USXR chord arrays (not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





EPM measurements indicate centrally peaked structure





- Reflectometer measurements of 10 kHz EPM indicate centrally peaked structure (i.e. peak near R_0)

- Future work: use interferometer measurements to constrain reconstruction of EPM
  - choose basis for reconstruction (e.g. splines)
  - consider relative phase of signals
  - consider simplifying assumptions (e.g. assume mode is antisymmetric flux function)

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

- **TAEs and EPMs structure measured - observed with array of diagnostics:**
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