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High resolution global mode structure measurements via multichannel reflectometry in NSTX*

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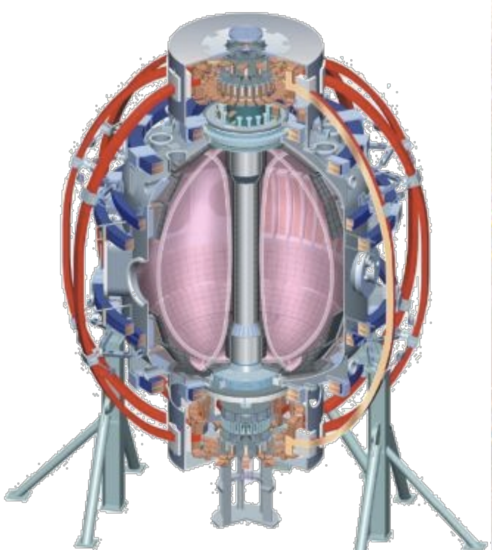

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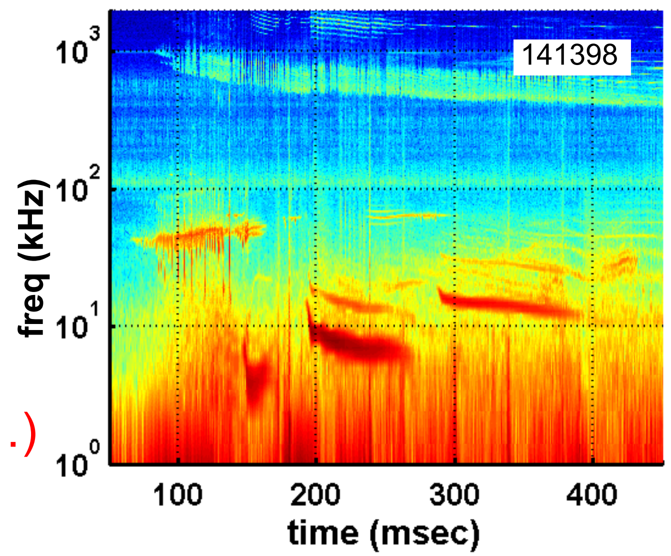
Summary

- Global modes—kinks, tearing modes, Alfvén eigenmodes (AE)—play critical role in many aspects of plasma performance
- Global mode structure routinely measured in NSTX via array of fixed frequency reflectometer to facilitate comparison with theory
- *Reflectometer array upgraded* to increase spatial resolution and range of accessible plasma densities
  - 16 channels ⇒ significantly improved spatial sampling
  - cutoff $n_0 \sim 1 - 7 \times 10^{19}$ m^{-3} (30 – 75 GHz) ⇒ improved access to H-mode plasmas
- Initial results from new array include structure measurements of global & toroidicity-induced AEs (GAE & TAE), as well as coupled kink-tearing modes (NTM)
- GAEs highly core localized, consistent with expectation
  - structure measured in *previously inaccessible* high density H-mode plasmas
  - advances study of GAE-induced electron thermal transport (K. Tritz, P-2)
- TAEs exhibit strong phase variation with radius in midplane
  - suggests non-ideal MHD effects
  - roughly consistent with M3D-K prediction (G. Fu, EP-I)
- Tearing mode structure shows coupling to external kink
  - Measurement illustrates potential for investigation of tearing modes

Motivation: measurement of global mode structure promotes better understanding of plasma performance

- Global modes—kinks, tearing modes, Alfvén eigenmodes (AE)—play critical role in many aspects of plasma performance
  - kinks & tearing modes: change profiles and cause bulk transport
  - AEs cause fast-ion transport and loss:
    - change equilibrium sources (momentum, energy …)
    - damage plasma facing components

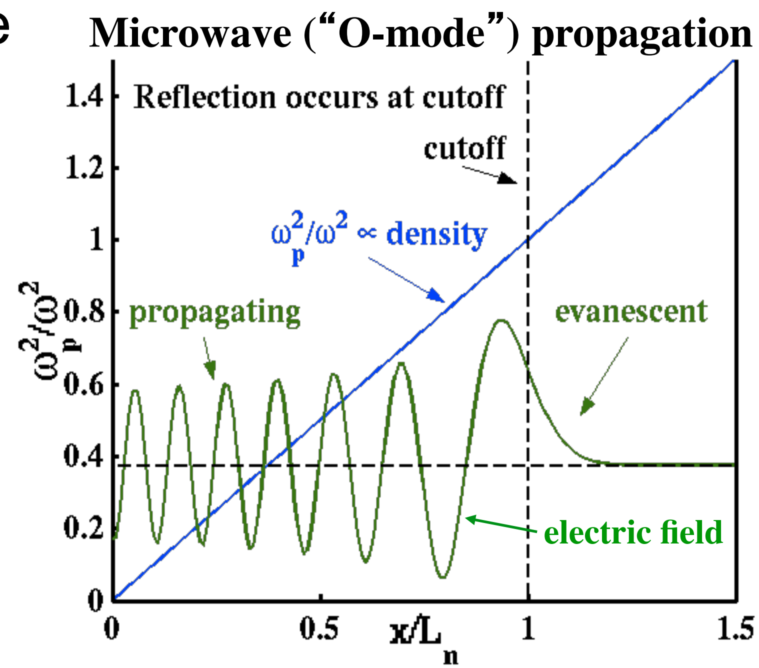
δb spectrum of
beam-heated NSTX plasmas



- NSTX plasmas feature rich spectrum of global modes
- Mode δn structure routinely measured in NSTX via fixed-frequency reflectometer radial array— upgrade improves spatial resolution & range of accessible plasma conditions
  - 16 channels, $n_0 \sim 1 – 7 \times 10^{19}$ m^{-3} (30 – 75 GHz)

Reflectometers measure local density fluctuation in plasma

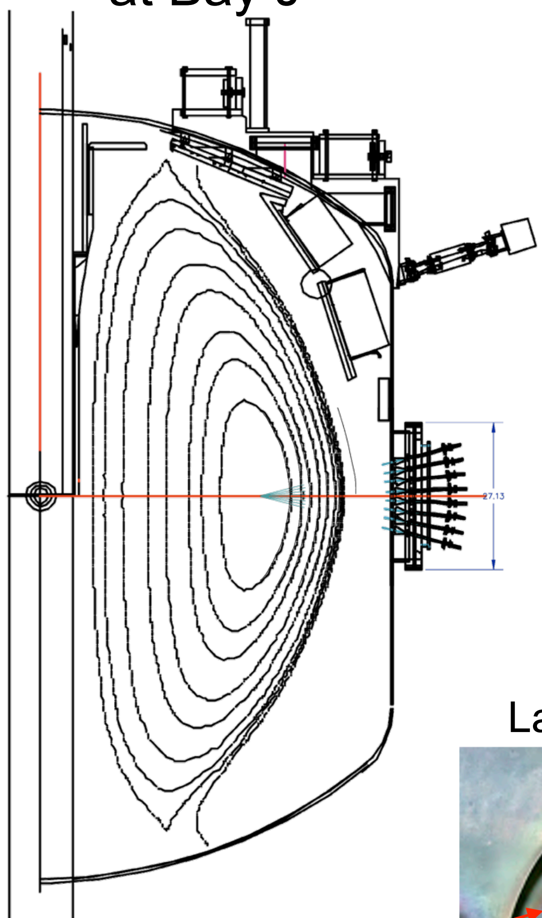
- Microwaves propagate to "cutoff" layer, where density high enough for reflection ($\omega_p = \omega$)
  - Dispersion relation of "ordinary mode" microwaves: $\omega^2 = \omega_p{}^2 + c^2k^2$, $\omega_p{}^2$ proportional to density ($\omega_p{}^2 = e^2n_0/\varepsilon_0 m_e$)
  - $k \rightarrow 0$ as $\omega \rightarrow \omega_p$, microwaves reflect at $k = 0$



- Reflectometer measures path length changes of microwaves reflected from plasma
  - phase between reflected and launched waves changes ($\delta\phi$)
- Wave propagation controlled by density
  - for large scale modes $\delta n/n_0 \sim \delta\phi/(2k_{vac}L_n)$, $L_n = n_0/|\nabla n_0|$

Reflectometers provide radial array of measurements

NSTX cross-section at Bay J



- Two arrays of reflectometers: “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
- Single launch and receive horn for each array.
  - –Arrays separated ~ 10° toroidally
- Horns oriented perpendicular to flux surfaces ⇒ frequency array = radial array
- Reflectometer cutoffs span large radial range in high density plasmas (n_0 ~ 7 x 10^{19} m^{-3})

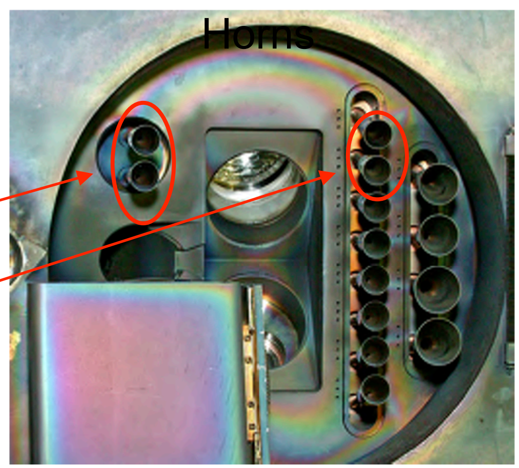
Bay J Flange

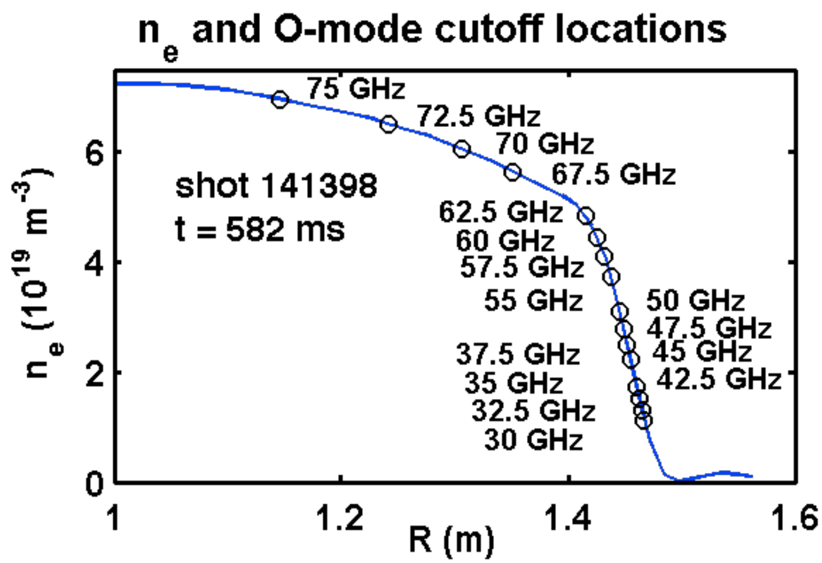
Launch and Receive Horns

30-50 GHz

55-75 GHz

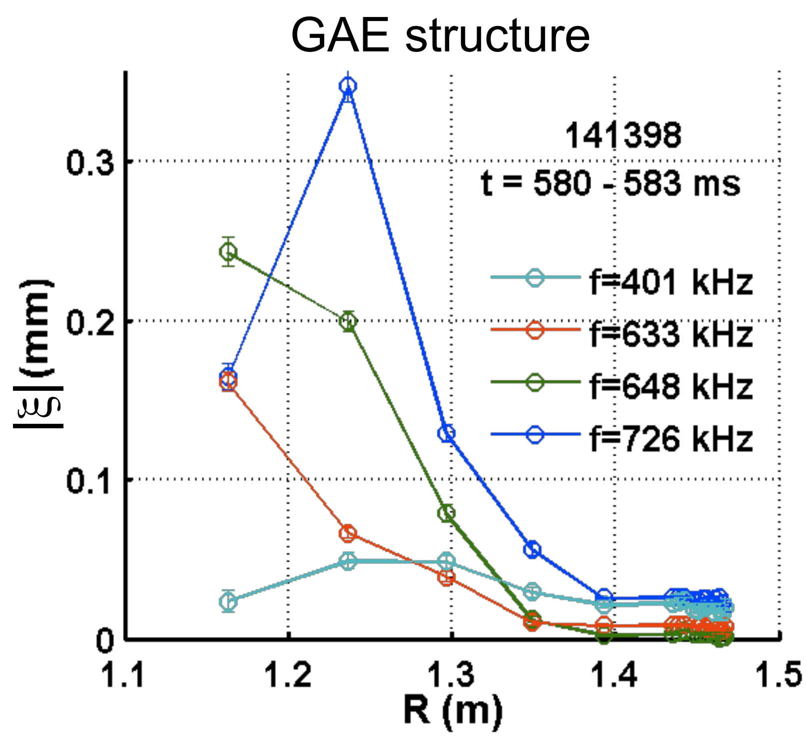
(not shown: horns modified to optimize for frequency range)

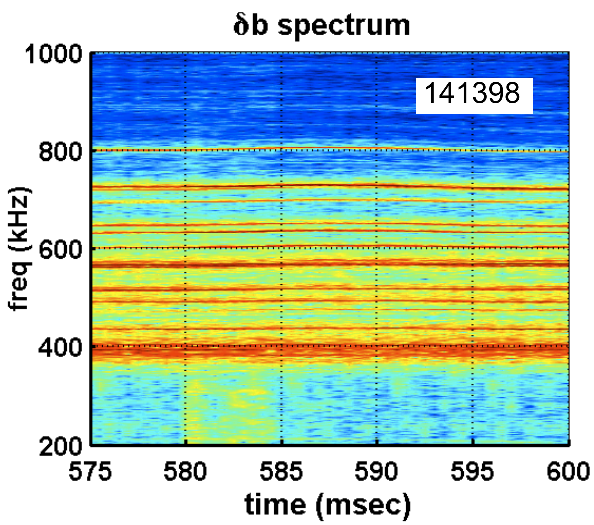


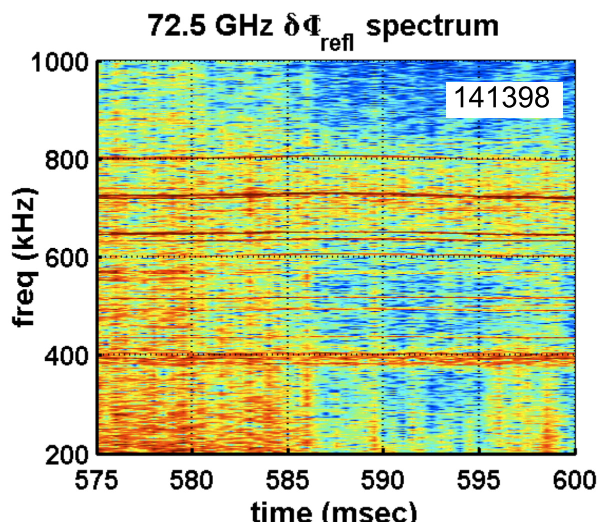


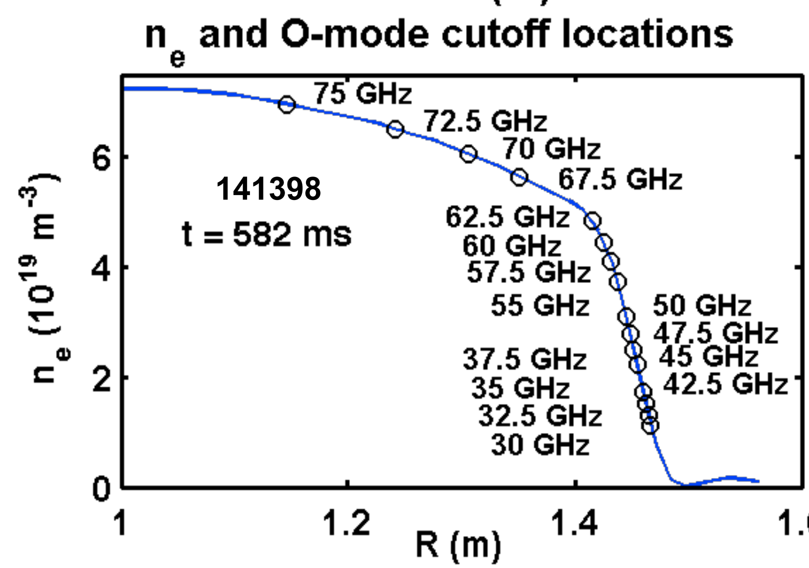
GAEs localized to plasma core

- GAE structure measured in H-mode plasma – GAEs core localized
- Activity correlates with enhanced electron thermal transport in plasma core (K. Tritz, P-2)
- Measurements aid investigation
  - will be compared with theory (HYM, NOVA-K)
  - will be used in predicting thermal transport via perturbed electron orbit calculation (ORBIT, SPIRAL)



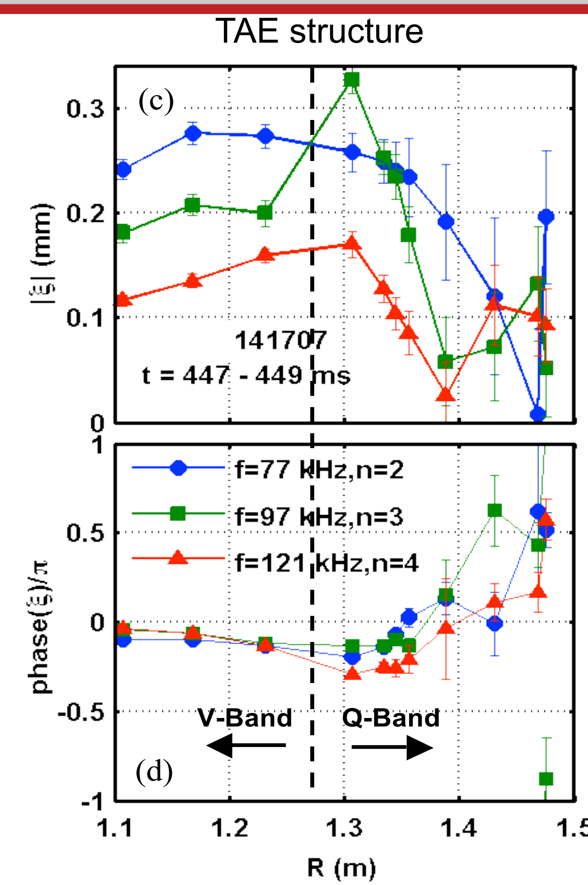


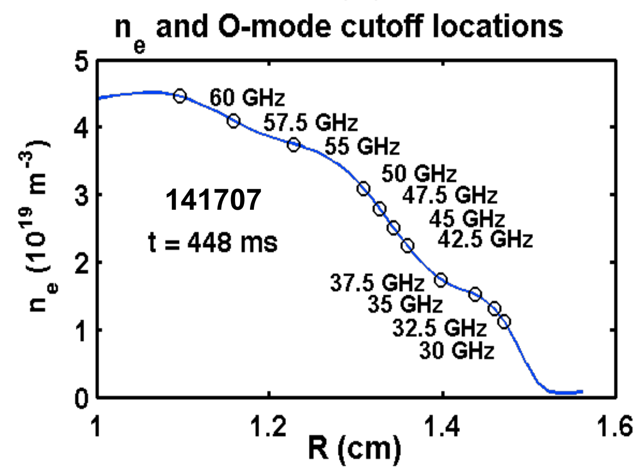


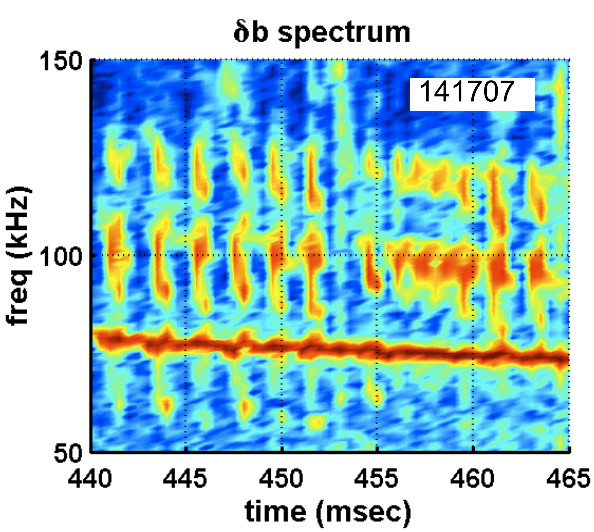


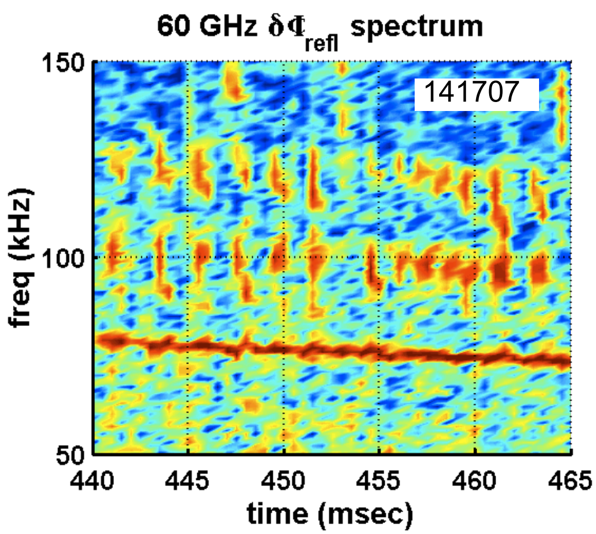
TAEs show strong radial phase variation

- Reflectometers measure strong radial TAE phase variation ($\Delta\Phi \sim \pi/2$) near midplane
  - XP 1015 – M3D-K validation
- Ideal MHD predicts no phase variation in up-down symmetry plane
  - only sign changes allowed (Φ = 0 or 180°)
- Phase variation caused by coupling to fast-ions (and other non-ideal effects)?
  - suggested by recent DIII-D simulation + experiment & NSTX simulation







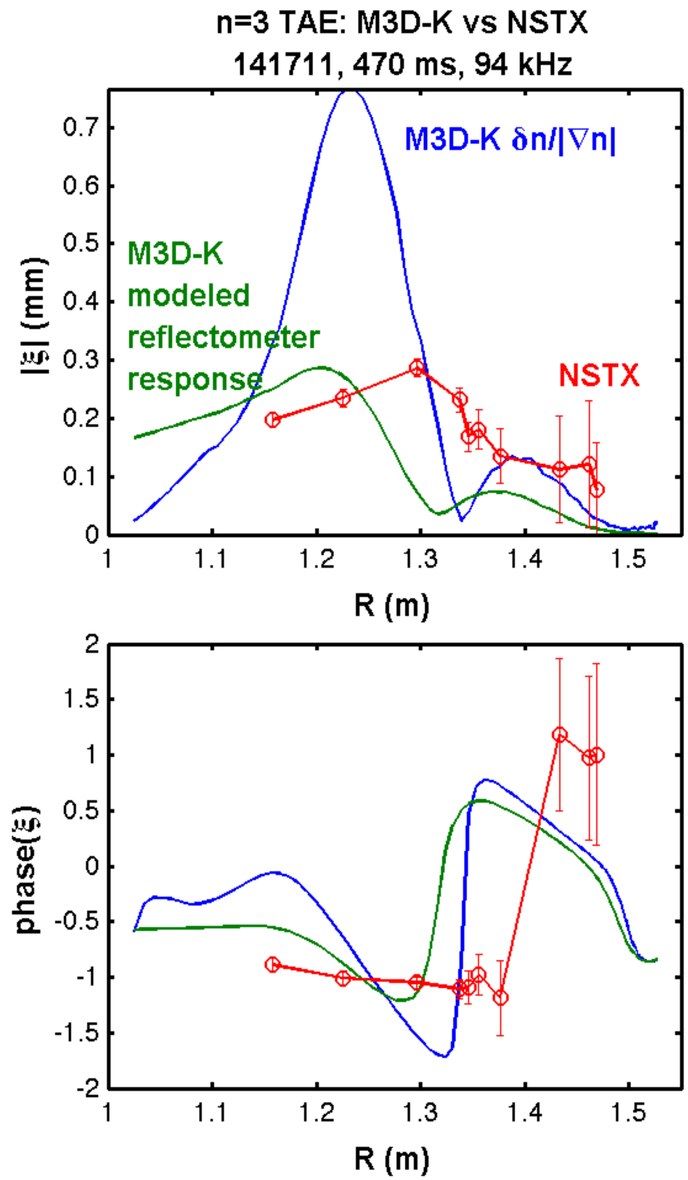


TAE phase variation similar to M3D-K prediction
(see also G. Fu, EP-II)

- M3D-K solves for TAE eigenmode in NSTX plasma
  - initial value code
  - MHD plasma coupled to kinetically treated energetic ions
- Reflectometer response (ξ) modeled for M3D-K δn (i.e. “synthetic diagnostic”)
  - WKB approximation for path length (L) used:
    - L = integral of sqrt(1-ω_p^2/ω^2) from edge to Rc,

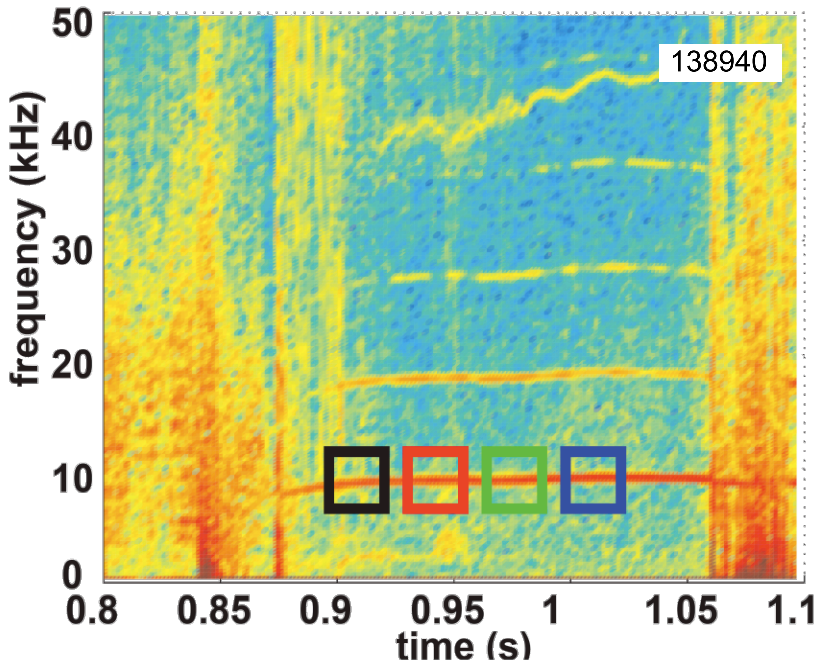
$$L = L_0 + \xi = \int_{edge}^{\omega_P^2(R)=\omega^2} \sqrt{1-\omega_P^2(R)/\omega^2}\, dR$$

- M3D-K structure [$|\xi|$ & phase(ξ)] similar to NSTX, but shifted radially inward ~ 7 cm
  - further work needed to understand shift

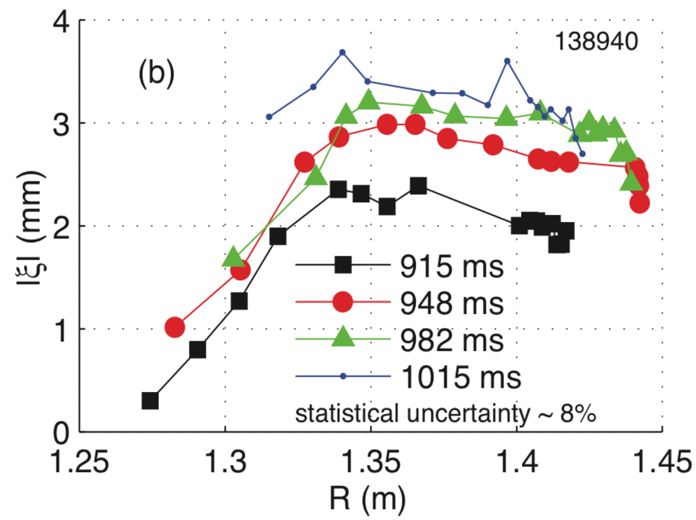


Measurement of tearing mode structure shows evidence of coupling to external kink

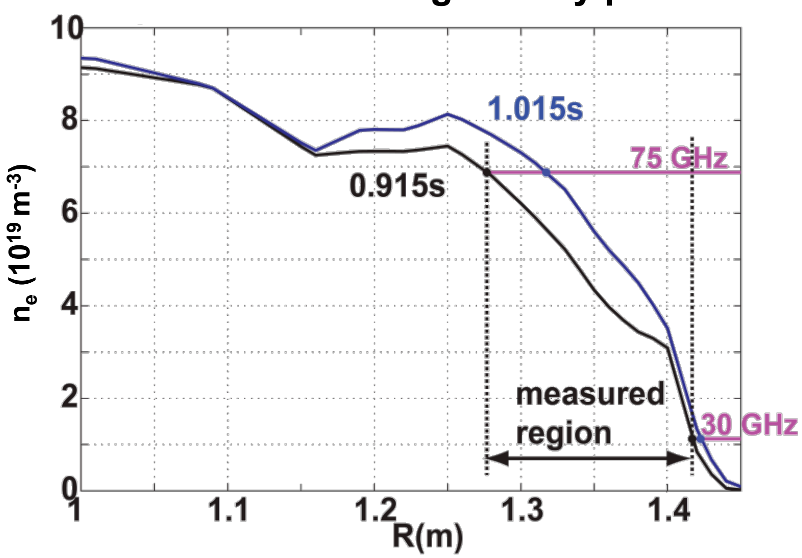
Phase spectrum of 30 GHz reflectometer



Temporal evolution of displacement



Thomson Scattering density profiles



- Reflectometers show 9 kHz, n=1 tearing mode emerge at t ~ 0.865 sec
  - MPTS shows flattening of n_e & T_e at R ~ 1.21 m develop between t ~ 0.865 – 0.9 sec
- Structure measured for R > ~ 1.27 m: resembles external kink
  - ξ growing R ~ 1.27 – 1.34 m
  - ξ constant R ~ 1.34 m to edge
- Measurement illustrates potential for investigation of kink-tearing mode coupling

Conclusions

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- Global mode structure routinely measured in NSTX via array of fixed frequency reflectometer to facilitate comparison with theory
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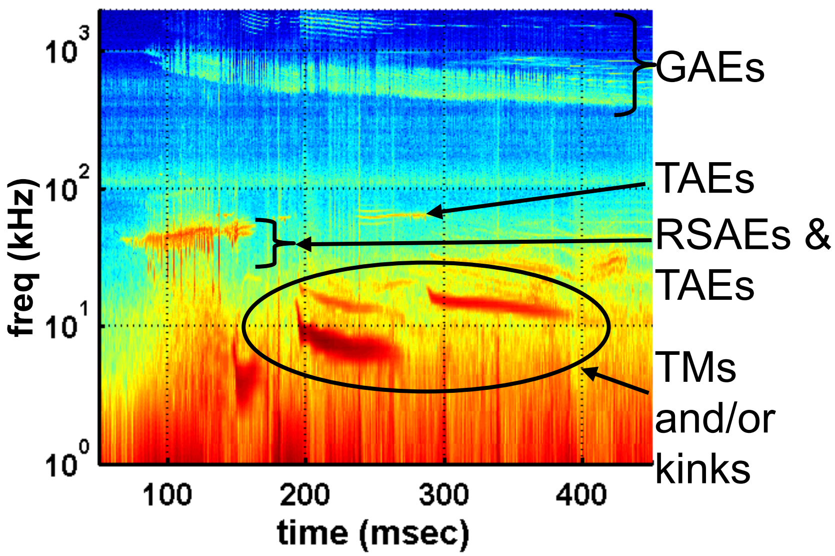
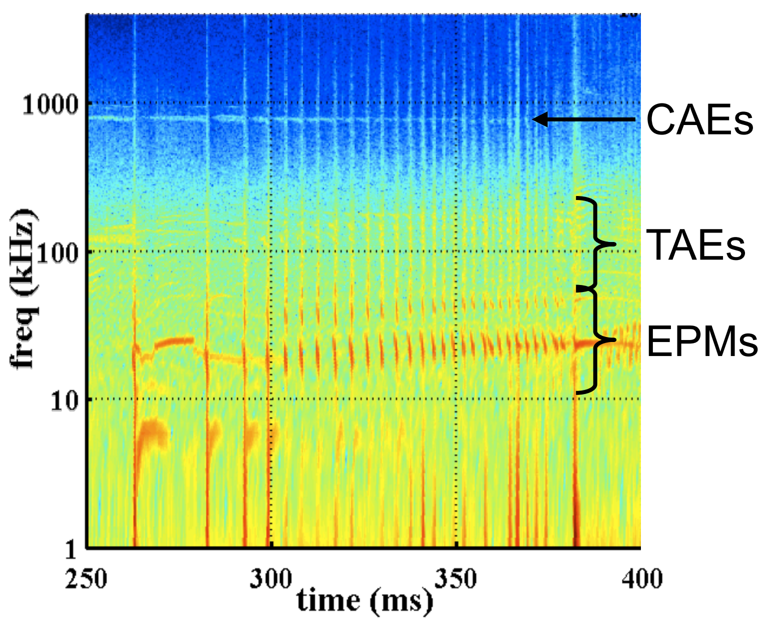
Backup Slides

NSTX plasmas feature rich spectrum of global modes

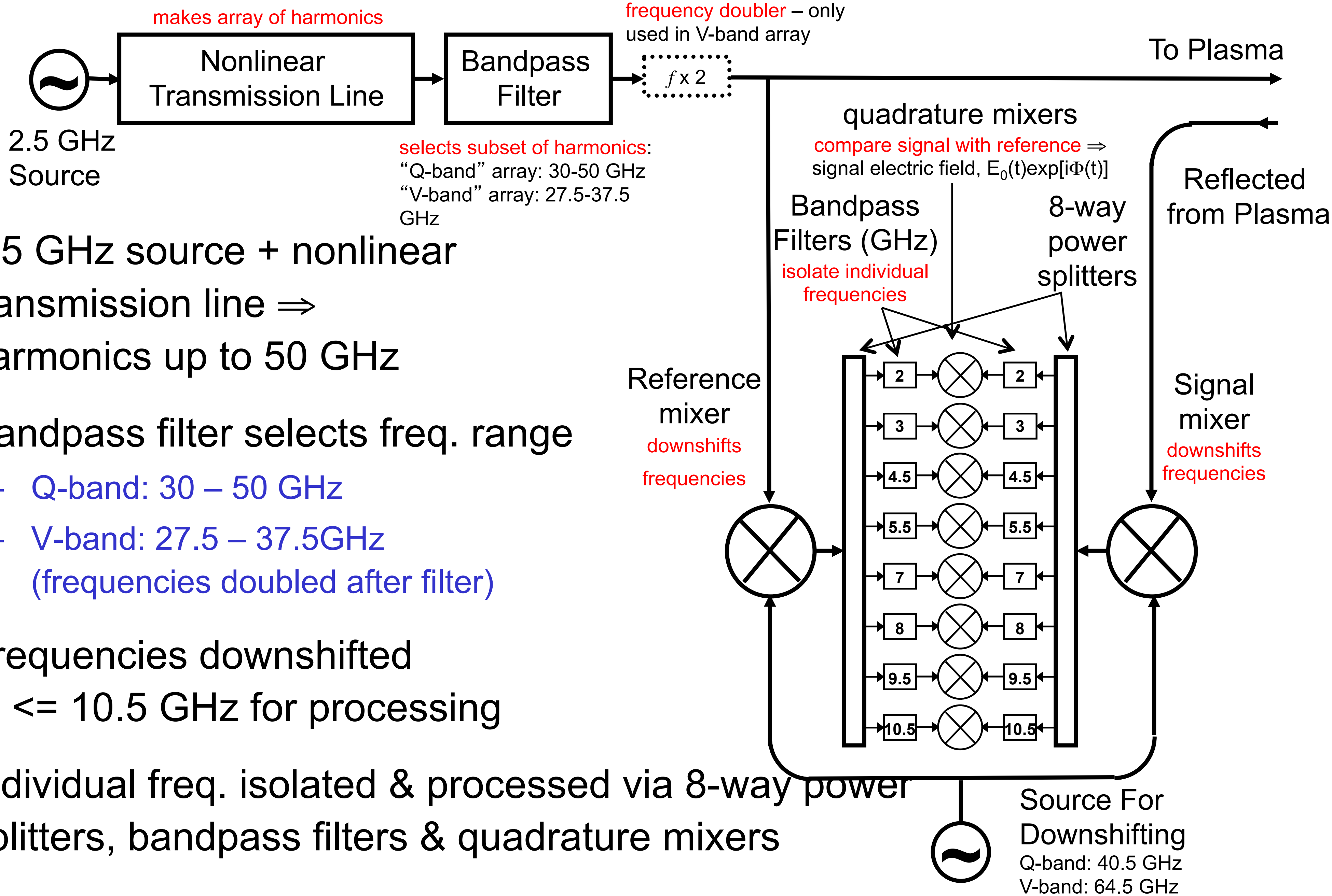
Fluctuation spectra of
beam-heated NSTX plasmas





- Tearing modes (TM) and internal kinks – $f \lesssim$ 25 kHz
- Energetic particle modes (EPM) – $f \lesssim$ 75 kHz
- Reversed shear and toroidicity-induced Alfvén eigenmodes (RSAE & TAE) – 50 kHz $\lesssim f \lesssim$ 250 kHz
- Global and compressional Alfvén eigenmodes (GAE & CAE) – 400 kHz $\lesssim f \lesssim$ 3 MHz

Reflectometer array design exploits nonlinear transmission line



- 2.5 GHz source + nonlinear transmission line ⇒ harmonics up to 50 GHz
- Bandpass filter selects freq. range
  - Q-band: 30 – 50 GHz
  - V-band: 27.5 – 37.5GHz (frequencies doubled after filter)
- Frequencies downshifted to <= 10.5 GHz for processing
- Individual freq. isolated & processed via 8-way power splitters, bandpass filters & quadrature mixers