NSTX-U

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Core electron thermal transport in NSTX due to orbit stochastization by high frequency Alfvén eigenmodes

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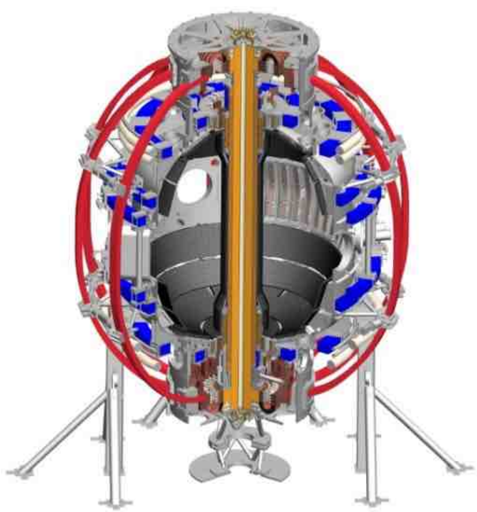

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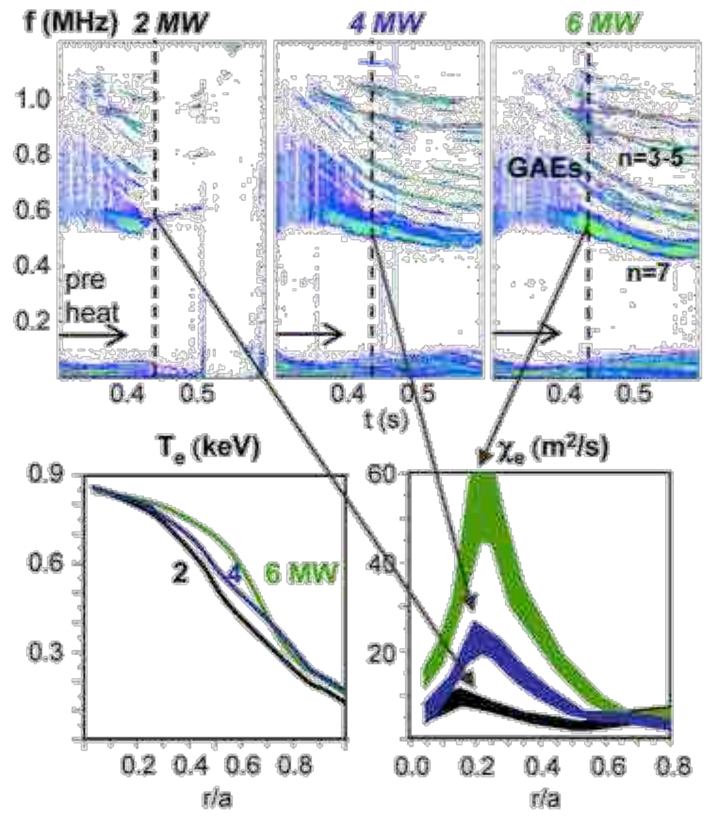
Overview

- Stochastization of e^- guiding center orbits by CAEs & GAEs posited to cause thermal transport in ST core
  - CAE/GAE activity correlates with enhanced χ_e in core of H-mode NSTX beam heated plasmas [D. Stutman, PRL 2009; K. Tritz, APS DPP 2010 Invited Talk]
- Early transport simulations with guiding-center code ORBIT promising – need more realistic experimental mode inputs
- Structure and amplitude of CAE & GAE δn measured in beam-heated NSTX H-mode ⇒ use for future ORBIT simulation
  - Radial structure & amplitude from inverted reflectometer array data
  - Toroidal mode numbers and frequencies from edge B-dot array
  - Modes identified local dispersion relations
- Simulation of CAEs & GAEs by HYM code compared with experiment ⇒ promise for transport prediction capability
  - substantial validation efforts needed!

CAEs and GAEs potentially cause significant core electron thermal transport in STs

- Beam-heated spherical torus plasmas feature high frequency Alfvén eigenmodes (AE) (f > ~ 400 kHz): Compressional (CAE) & Global (GAE)
- CAEs & GAEs correlate with enhanced core χ_e in NSTX
- Resonant interaction of multiple modes with e^- guiding center orbits proposed to stochastize orbits, enhancing thermal transport



[D. Stutman et al., PRL 102 115002 (2009)]

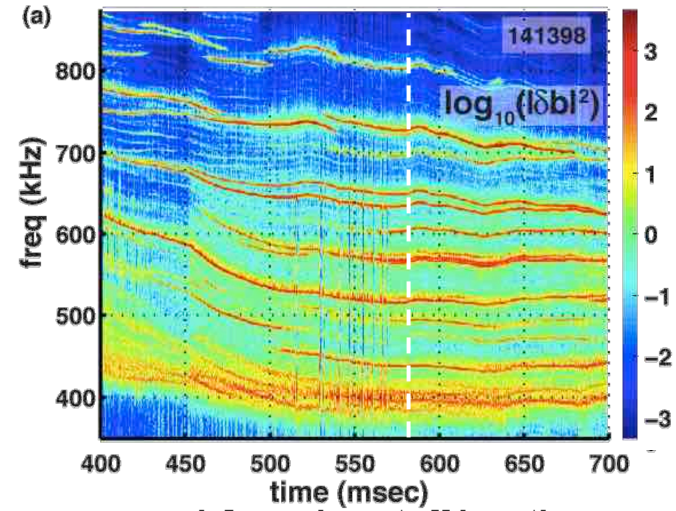
Testing hypothesis requires comparison of experimental transport with realistic orbit simulation

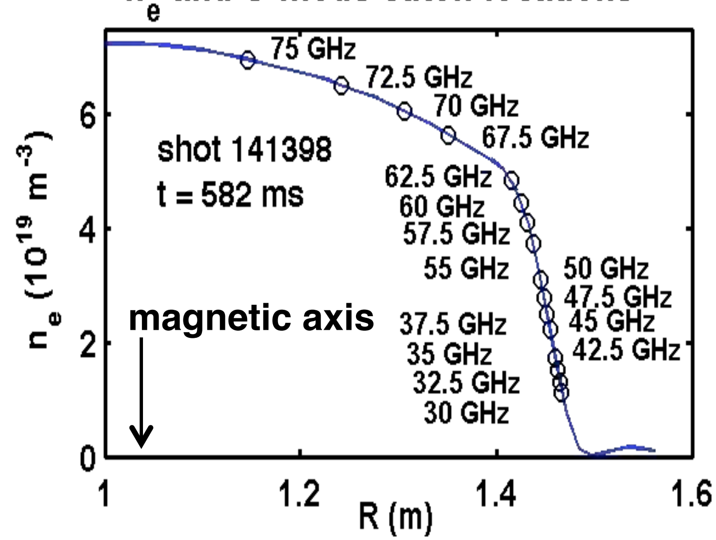
- Early transport simulations with guiding-center code ORBIT consistent with hypothesis
  [N. N. Gorelenkov et al., NF 2010; K. Tritz, APS DPP meeting 2012; N. A. Crocker et al., NF 2013]
  - assumed mode structures (e.g. Gaussian radial structure)
  - amplitudes from interferometer & simplified analysis of reflectometer measurements

- More realistic representation of modes needed for more stringent test
  - Toroidally distributed Mirnov array: experimental spectrum with measured frequencies & mode numbers
  - δn mode structure & amplitude from inversion of reflectometer array measurements
  - Mode polarization (shear/GAE or compressional/CAE) from Mirnov & reflectometer measurements + local dispersion relations

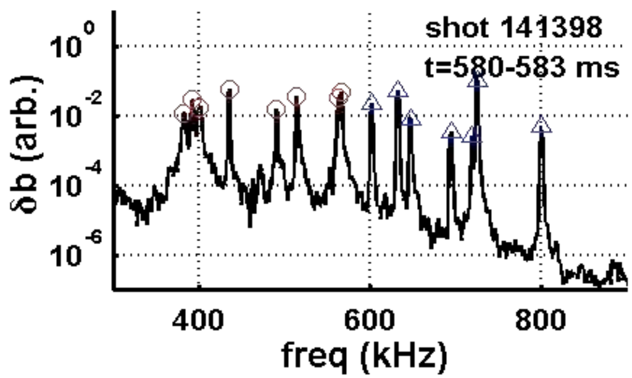
Structure and amplitude of CAE & GAE δn measured in high performance plasma

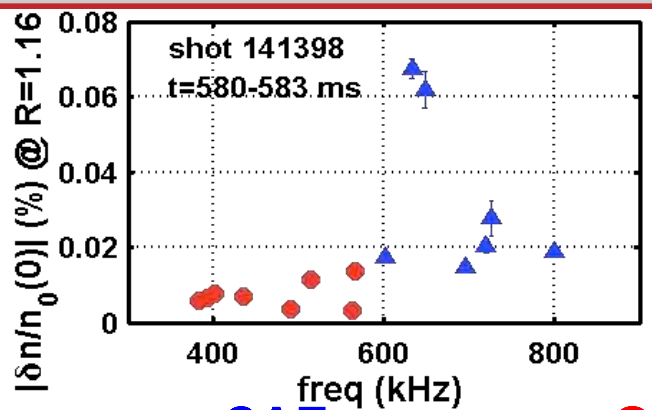
- High frequency AEs observed in 6 MW beam-heated H-mode plasma
- High frequency AE structure measured with reflectometer array
- Toroidal mode numbers (n) and frequencies (f) determined using edge B-dot array
- Modes identified using:
  - measured mode structures, f & n
  - local dispersion relations:
    - CAE (compressional Alfvén): $\omega^2 = k^2 V_A^2$
    - GAE (shear Alfvén): $\omega^2 = k_{||}^2 V_A^2$
- ORBIT transport modeling with measured modes will be compared with experimental transport

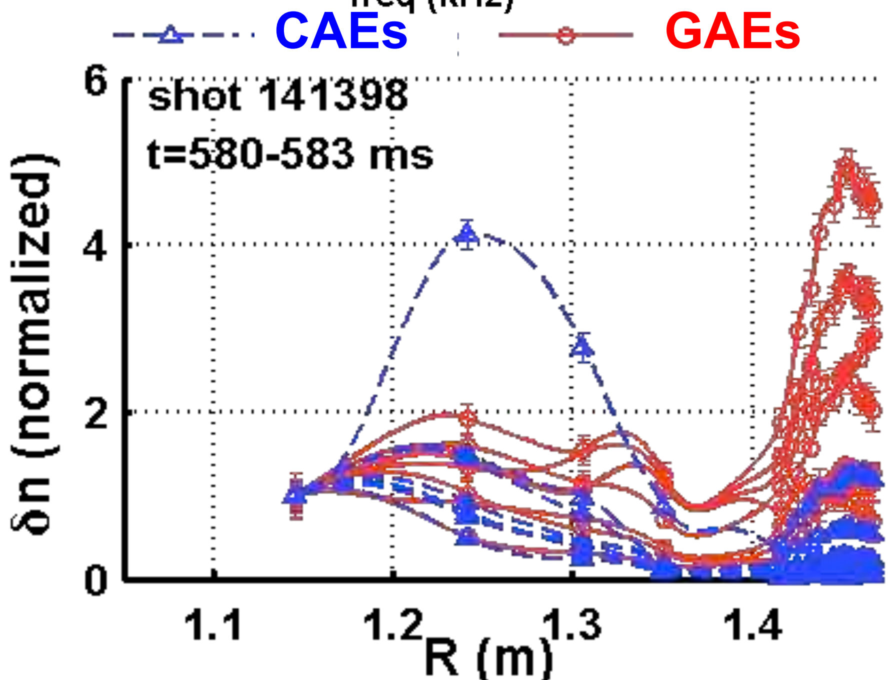




Structure and amplitude of CAE & GAE δn measured in high performance plasma

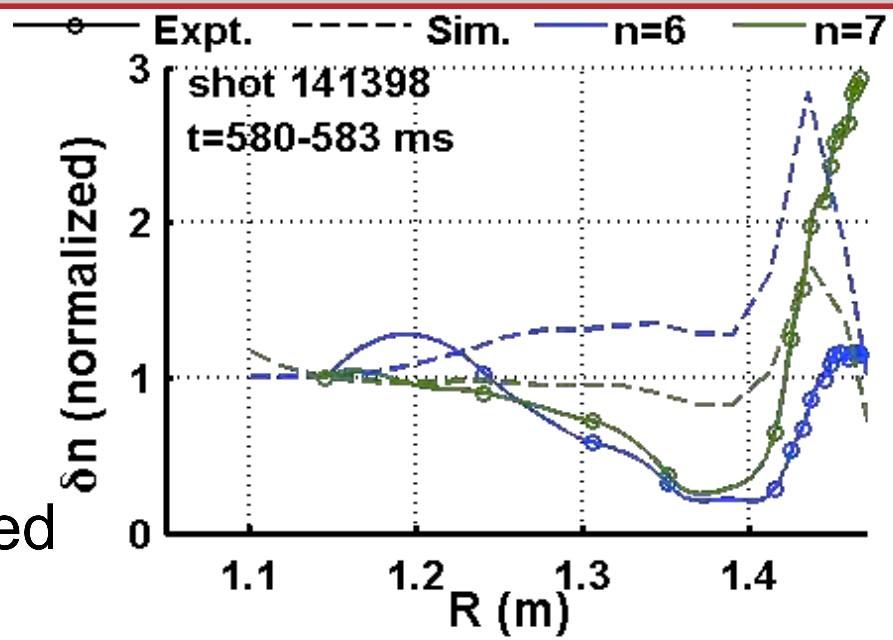






- Observed modes identified as:
  - GAEs: *f* < ~ *600 kHz, n = -6 – -8*
  - CAEs: *f* > ~ *600 kHz, n = -3 – -5*
- GAEs and CAEs have distinct δn structural differences
  - Edge: GAE δn > CAE δn
  - Core: CAE δn > GAE δn
  - CAES: strongly peak toward core
  - GAES: broad structure, peaking toward core; large edge peaks ⇒ edge displacement + large $|\nabla n_0|$

CAE+GAE simulation shows promise for first principles transport prediction

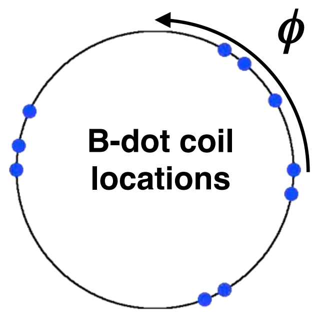


- Hybrid MHD (HYM) code simulates CAE structure and stability
  - 3D, coupled MHD fluid & fully kinetic fast-ions
  - realistic equilibrium
- Simulation & experiment compared for beam heated H-mode plasma
  - most unstable CAEs and GAEs have similar frequencies and mode numbers to observed experimental spectrum [see E. Belova YI1.6]
  - GAEs structures compared: similar broad structures & strong edge peaking
- predictive capability for CAEs & GAEs + transport simulation ⇒ predictive capability for core electron thermal transport
  - substantial model validation efforts required!

Measurement Technique

Toroidal mode numbers and frequencies determined 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

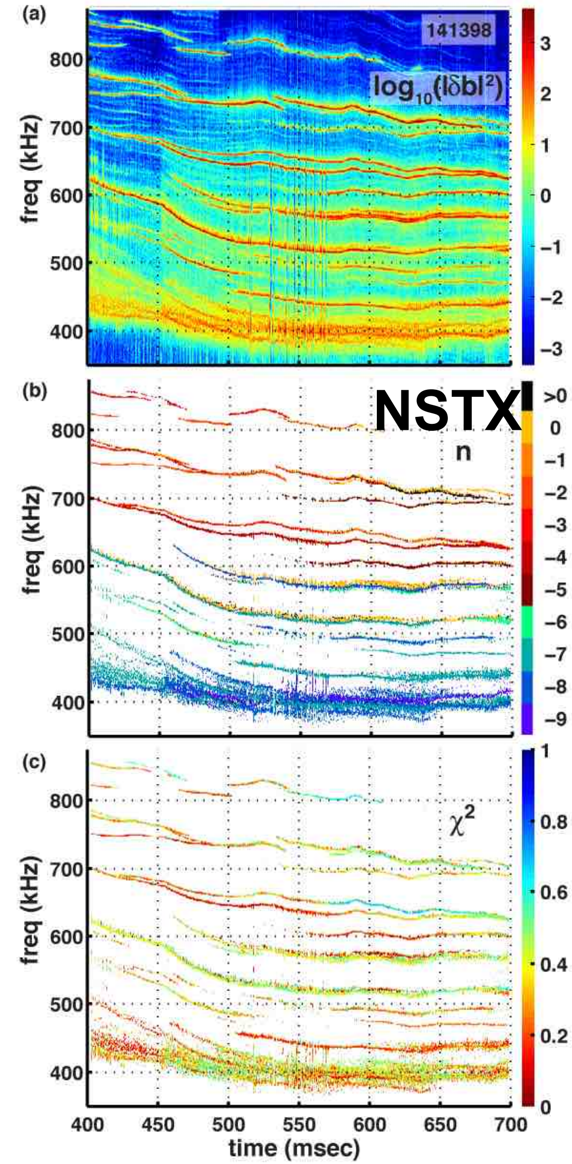


  – method: find n that minimizes χ^2:

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

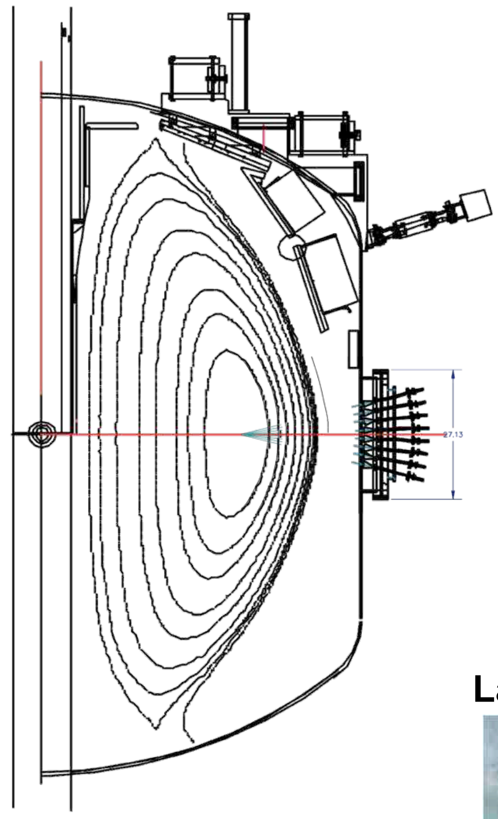
  N_ϕ=10 is number of coils.

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



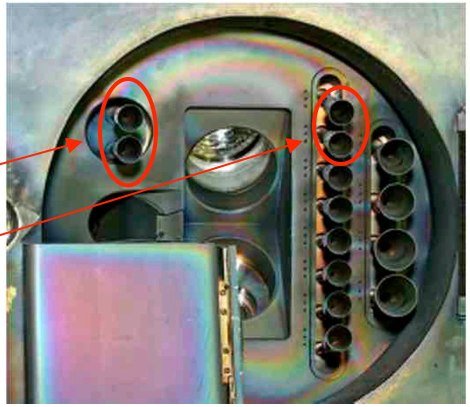
Reflectometers provide radial array of measurements

NSTX cross-section



- Two arrays: “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
- Arrays closely spaced (separated ~ 10° toroidal)
- Single launch and receive horn for each array
- Horns oriented perpendicular to flux surfaces ⇒ frequency array = radial array
- Cutoffs span large radial range in high density plasmas (n_0 ~ 1 – 7 x 10^{19} m^{-3})

Launch and Receive Horns

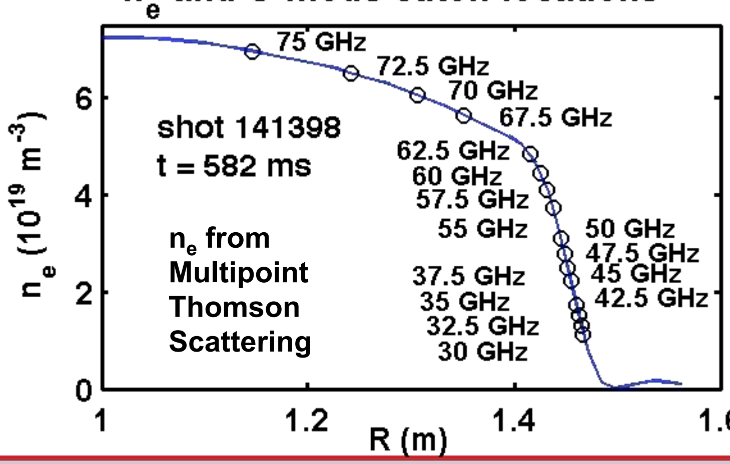


30-50 GHz

55-75 GHz

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

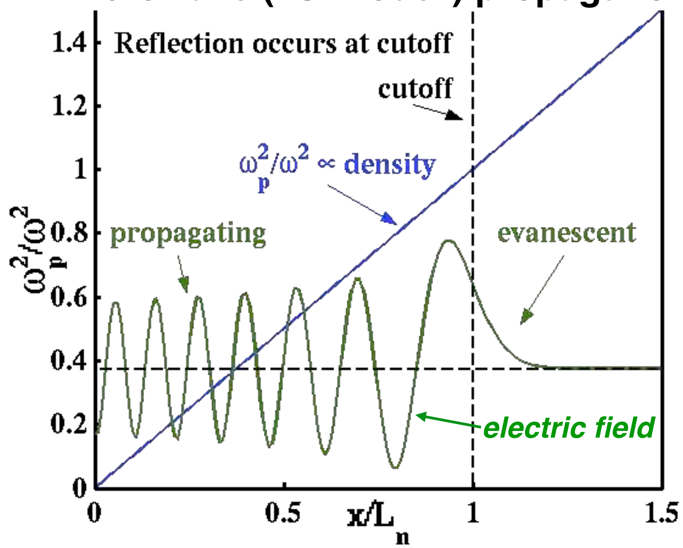
n_e and O-mode cutoff locations



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 ($\omega_p{}^2 = e^2n/\varepsilon_0 m_e$)
  - $k \rightarrow 0$ as $\omega \rightarrow \omega_p$, microwaves reflect at $k = 0$

Microwave ("O-mode") propagation



- Reflectometer measures path length changes of microwaves reflected from plasma
  - phase between reflected and launched waves changes ($\delta\phi$)
- Wave propagation controlled by density – $\delta\phi$ depends on δn

δn determined from reflectometer measurements using synthetic diagnostic

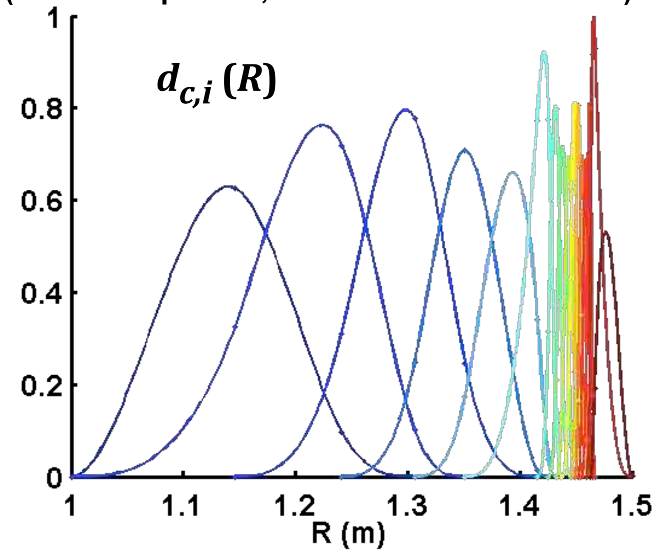
- Synthetic diagnostic used to model reflectometer response (ξ) to δn
  - WKB path length (L) approximation:

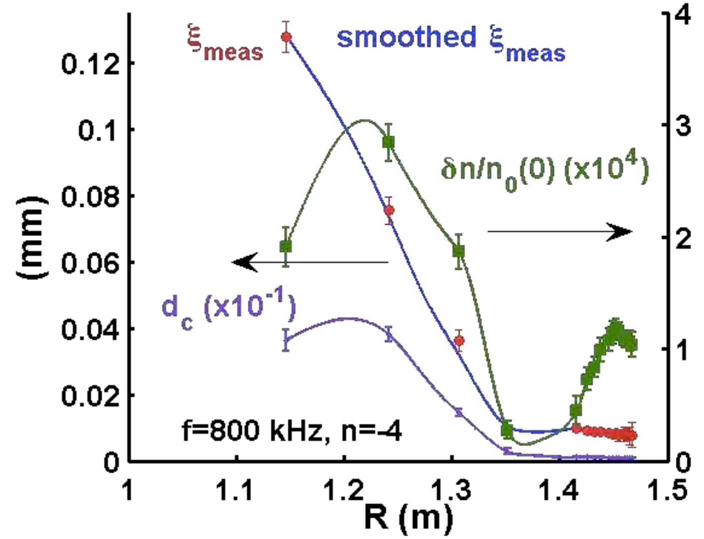
$$L = L_0 + \xi = \int_{edge}^{\omega_P^2(R)=\omega^2} \sqrt{1-\omega_P^2(R)/\omega^2}\, dR$$

$$\omega_P^2 = \omega_{P0}^2 + \delta\omega_P^2 \propto n_0 + \delta n$$

- Perturbation modeled with *cutoff displacement* (d_c):
  - $\delta\omega_P^2 \propto \delta n(R) = \Sigma_i a_i d_{c,i}(R) \nabla n_0(R)$
  - Find a_i to minimize $\chi^2 = \Sigma_i(\xi_{i,meas} - \xi_{i,fit})/\sigma^2_{i,meas}$
- Fit sensitive to noise in $\xi_{,meas}$ gradient $\Rightarrow$ *smoothed $\xi_{i,meas}$ used for inversion*

Cutoff displacement basis functions (cubic "B-splines"; cutoff locations as knots)





Summary

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  - Early transport simulations with guiding-center code ORBIT promising — need more realistic experimental mode inputs
- CAE & GAE δn have distinct structural differences in beam-heated NSTX H-mode
  - Radial structure & amplitude from inverted reflectometer array data
  - Toroidal mode numbers and frequencies from edge B-dot array
  - Modes identified local dispersion relations
- Future work: measurements will be used in ORBIT simulation for comparison with experimental transport
- HYM simulation of CAEs and GAEs compared
  - Unstable mode numbers and frequencies similar to experiment
  - GAEs have similar structures

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