Comparison of simulated heat transport in NSTX via high frequency Alfvén eigenmode-induced electron orbit modification with TRANSP power balance modeling*

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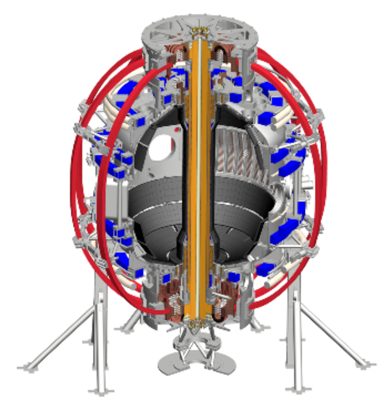
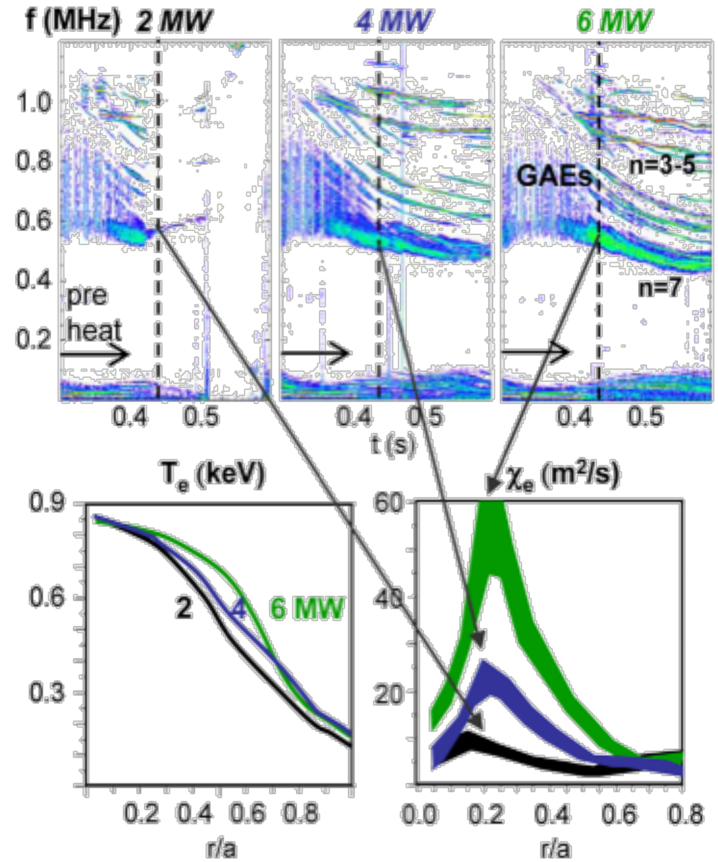


Overview

- CAEs & GAEs candidates for core electron thermal transport in NSTX
- Structure and amplitude of CAE & GAE δn measured in high performance NSTX-U plasma
  - frequency and toroidal mode number measured via edge b-dot array
  - internal amplitude (δn) measured with reflectometer array
  - CAEs and GAEs identified via local dispersion relations
- ORBIT simulates diffusivity (χ_e) from mode effects on e^- guiding center orbits in core ($\Psi_N{}^{1/2} = 0.15$) of high performance plasma
- Simulated χ_e from GAEs and CAEs (as shear modes) compared to TRANSP experimental transport analysis
- Simulated χ_e less than inferred from experiment (TRANSP)
- Future work includes more accurate treatment of modes

Motivation: CAEs & GAEs candidates for core electron thermal transport in NSTX

- Anomalous χ_e observed in core of NSTX beam heated plasmas
- Stochastization of e^- guiding center orbits proposed to enhance χ_e
  - compressional (CAE) & global (GAE) Alfvén eigenmodes excited by Doppler-shifted cyclotron resonance with beam ions [N. N. Gorelenkov, NF 2003]
  - 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; N. A. Crocker, PPCF 2011]



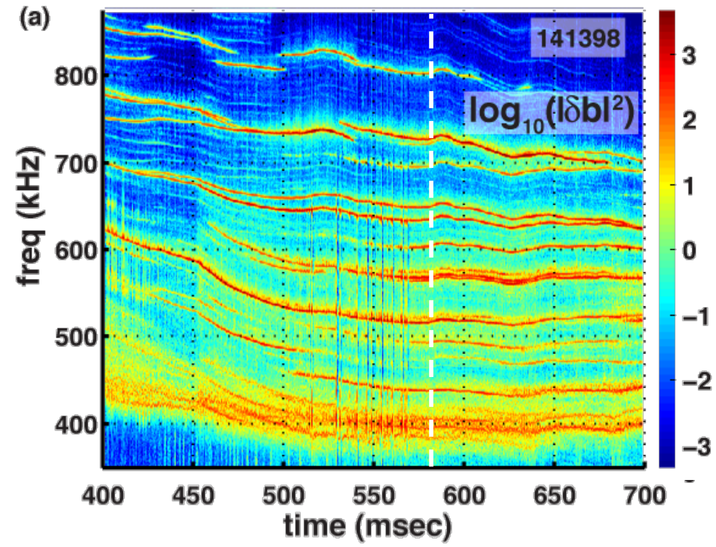
[D. Stutman et al., PRL 102 115002 (2009)]

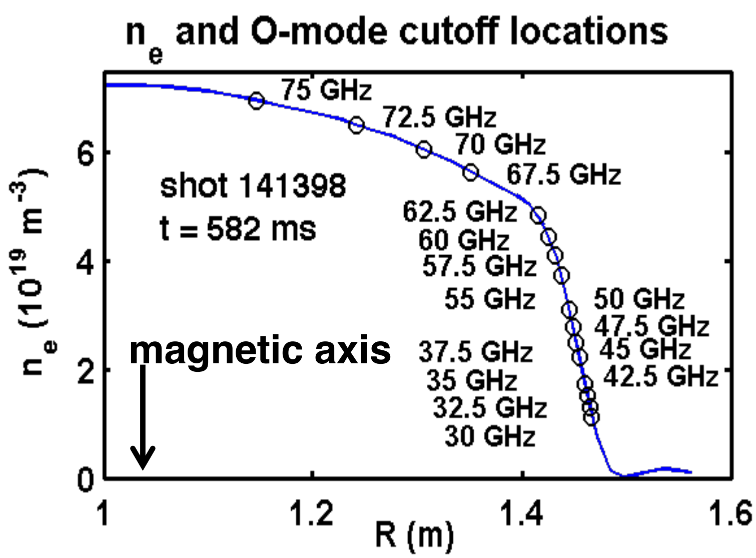
Structure and amplitude of CAE & GAE δn measured in high performance plasma

- High frequency AEs observed in 6 MW beam-heated H-mode plasma
- Structure measured with reflectometer array
- Toroidal mode numbers (n) and frequencies (f) determined with 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): $\omega^2 = k_{\parallel}^2 V_A^2$

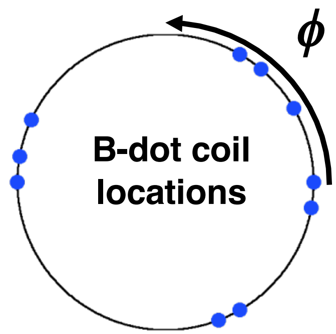




- ORBIT χ_e modeling with measured modes will be compared with experimental transport

Toroidal mode numbers and frequencies determined with edge B-dot array

- Modes appear as peaks in δb spectrum
- n determined from δb measured by edge toroidal array of B-dot coils

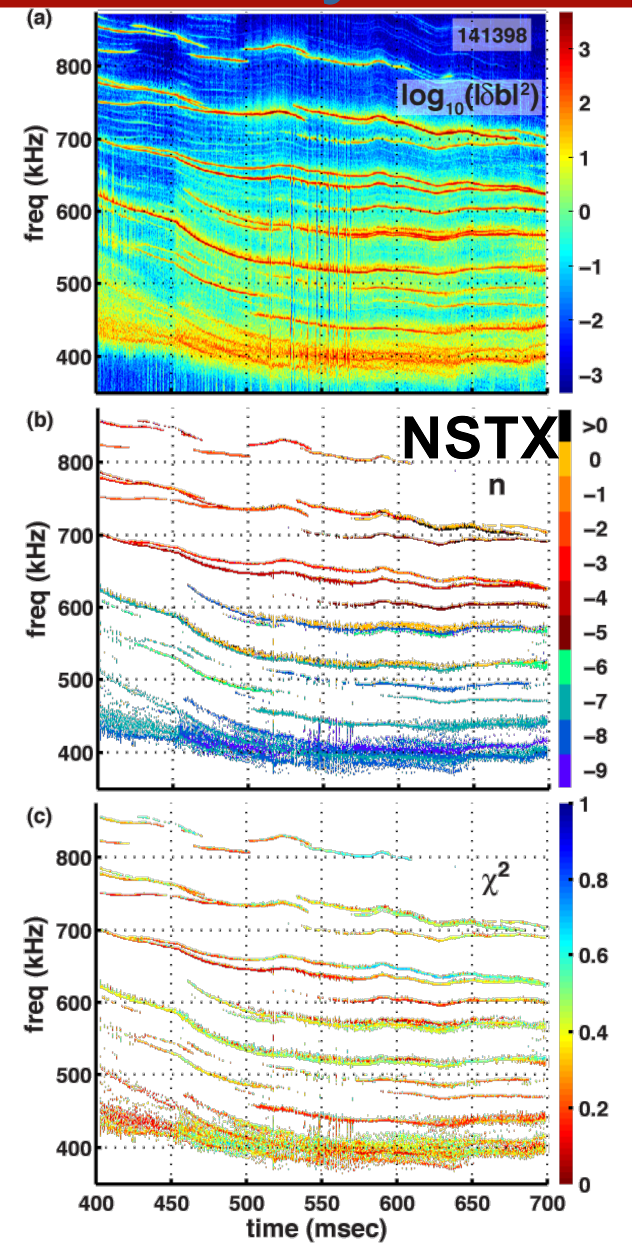


  – method: find n that minimizes χ^2:

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

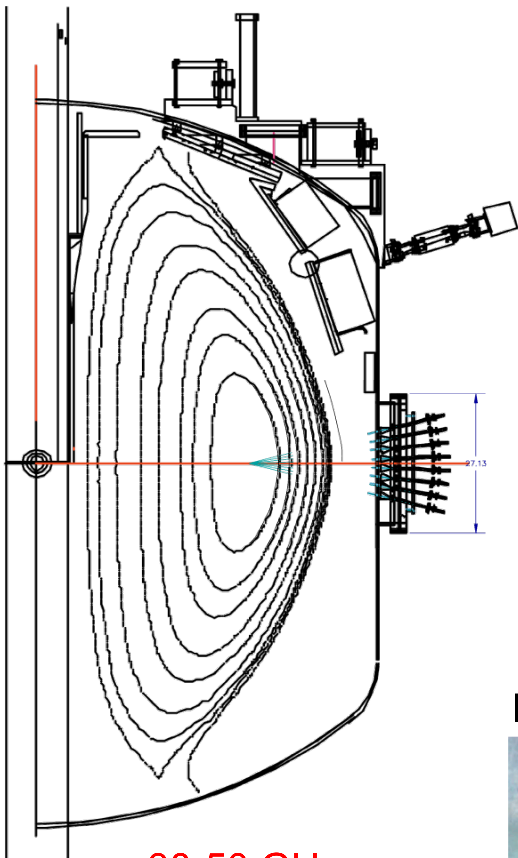
  N_ϕ=10 is number of coils.

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



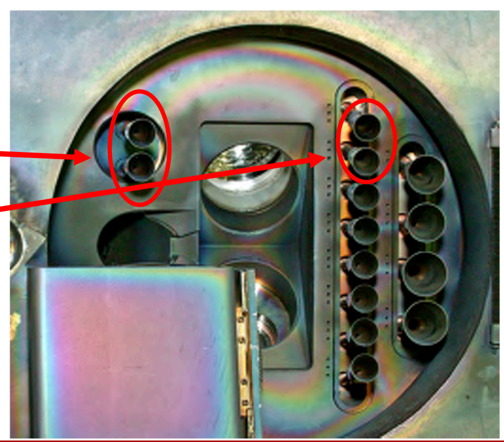
Reflectometers provide radial array of measurements

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})

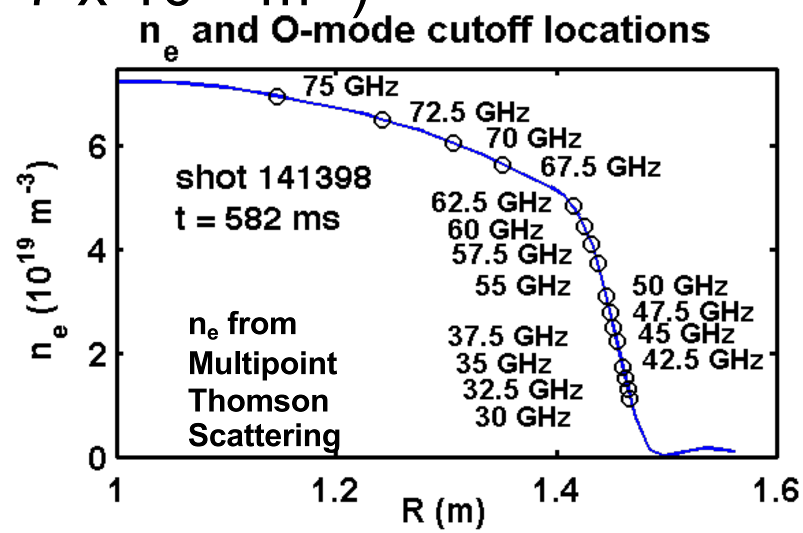
Launch and Receive Horns



30-50 GHz

55-75 GHz

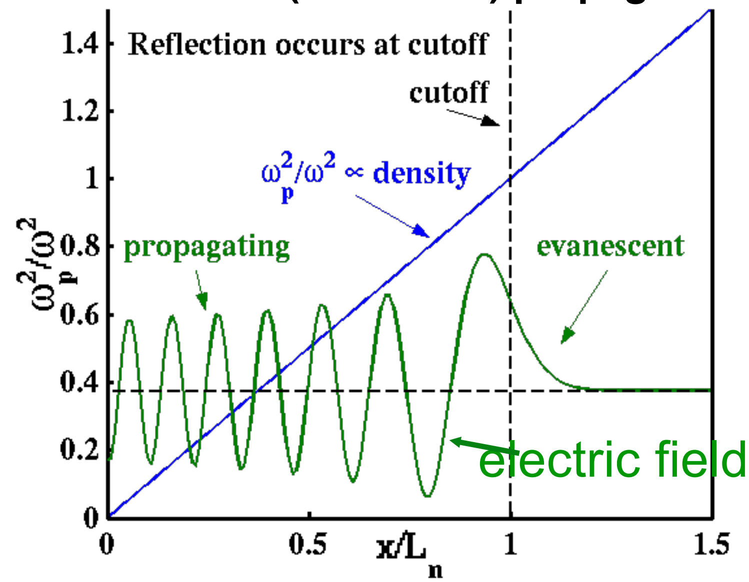
(not shown: horns modified to optimize for frequency range)



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: $\omega^2 = \omega_p^2 + c^2k^2$, ω_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 $k = 0$
- 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

Microwave ("O-mode") propagation



δn determined from reflectometer measurements using synthetic diagnostic

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

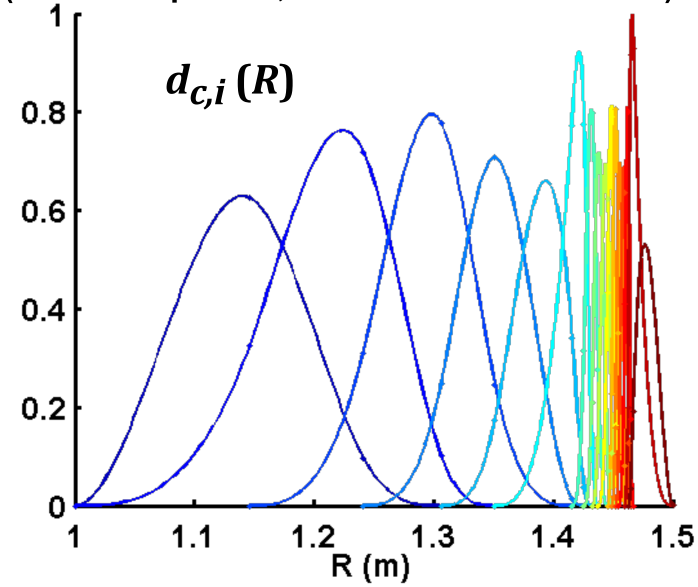
$$L = L_0 + \xi = \int_{edge}^{\omega_P^2(R)=\omega^2} \sqrt{1-\omega_P^2(R)/\omega^2}\, dR$$

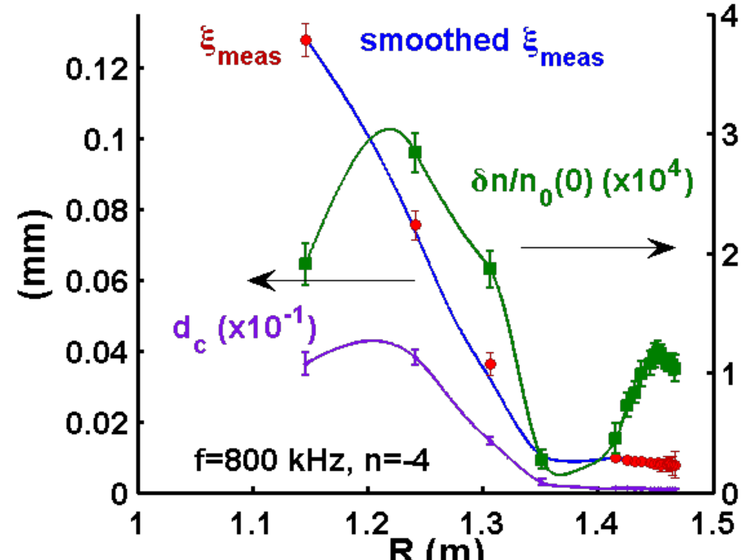
$$\omega_P^2 = \omega_{P0}^2 + \delta\omega_P^2 \propto n_0 + \delta n$$

- 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 $\chi^2=\Sigma_i(\xi_{i,meas}-\xi_{i,fit})/\sigma^2_{i,meas}$

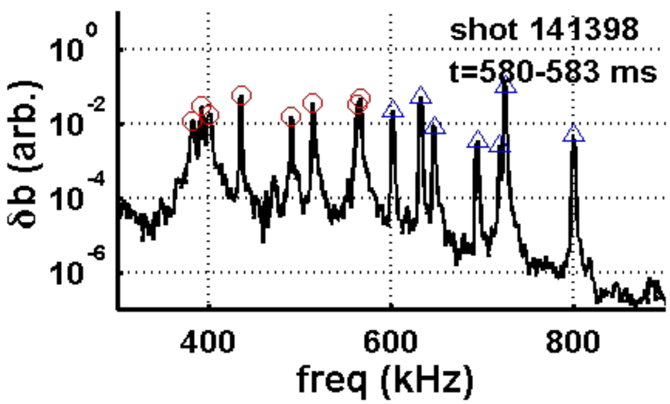
- Fit sensitive to noise in $\xi_{,meas}$ gradient
  $\Rightarrow$ *smoothed $\xi_{i,meas}$ used for inversion*

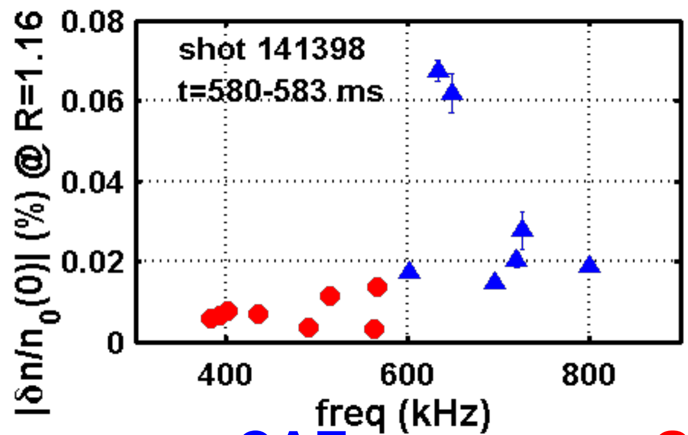
Cutoff displacement basis functions (cubic "B-splines"; cutoff locations as knots)



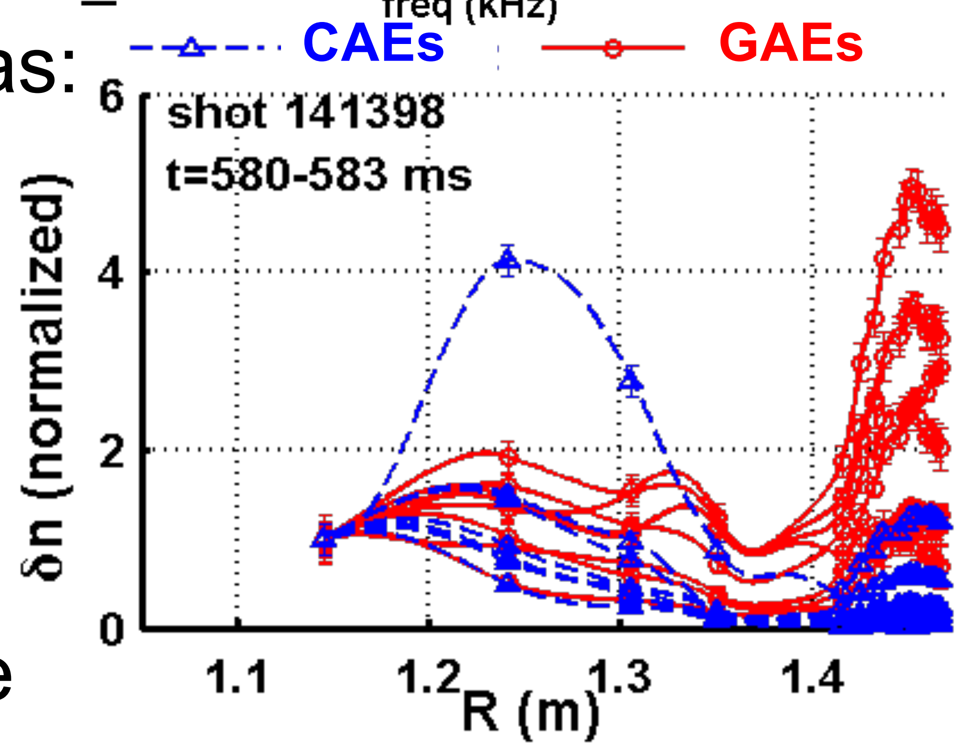


Structure and amplitude of CAE & GAE δn measured in high performance plasma





- Observed modes identified as:
  - GAEs: *f < ~ 600 kHz, n = -6 – -8*
  - CAEs: *f > ~ 600 kHz, n = -3 – -5*



- CAEs have larger δn in core
- GAEs have larger δn in edge

ORBIT used to simulate effects of modes on electron guiding center orbits

- Uses realistic equilibrium B-field:

  $B = \nabla\times(\psi\nabla\theta - \psi_p\nabla\zeta) = g\nabla\zeta + I\nabla\theta + \delta\nabla\psi_p$, and $\nabla\psi = q\nabla\psi_p$

- Includes time-dependent electromagnetic perturbations via perturbed vector and space potential:

  $\mathbf{E}=-(\partial_t\alpha\mathbf{B}+\nabla\phi)$, with ϕ chosen to ensure $E_\parallel\mathbf{=0}$

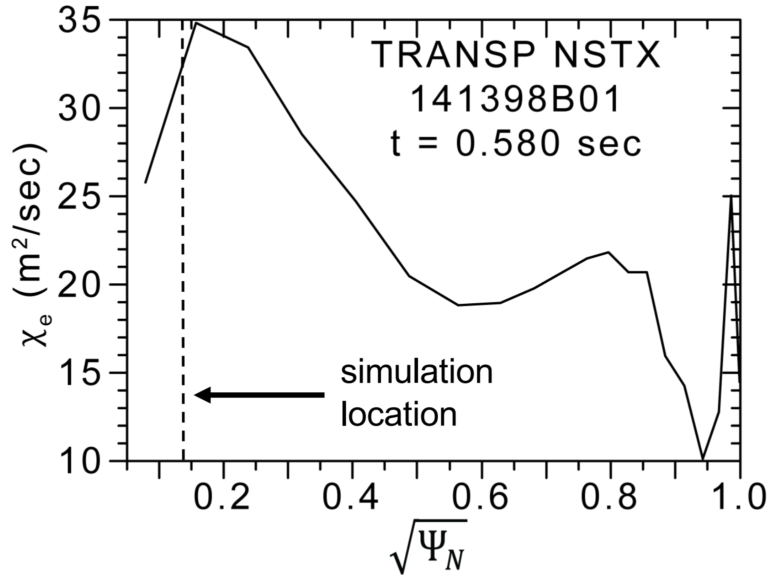
- Equations of motion from Lagrangian formalism:

  $L(\rho_\parallel, \psi_p, \theta, \zeta, \partial_t\rho_\parallel, \partial_t\psi_p, \partial_t\theta, \partial_t\zeta, t) =$
  $[\psi+(\rho_\parallel+\alpha)I]\partial_t\theta + [(\rho_\parallel + \alpha)g-\psi_p]\partial_t\zeta - H$
  where $H = \rho_{||}{}^2B^2/2 + \mu B + \phi$, and $\rho_{||}= v_{||}/B$

[R. B. White, PPCF 2010]

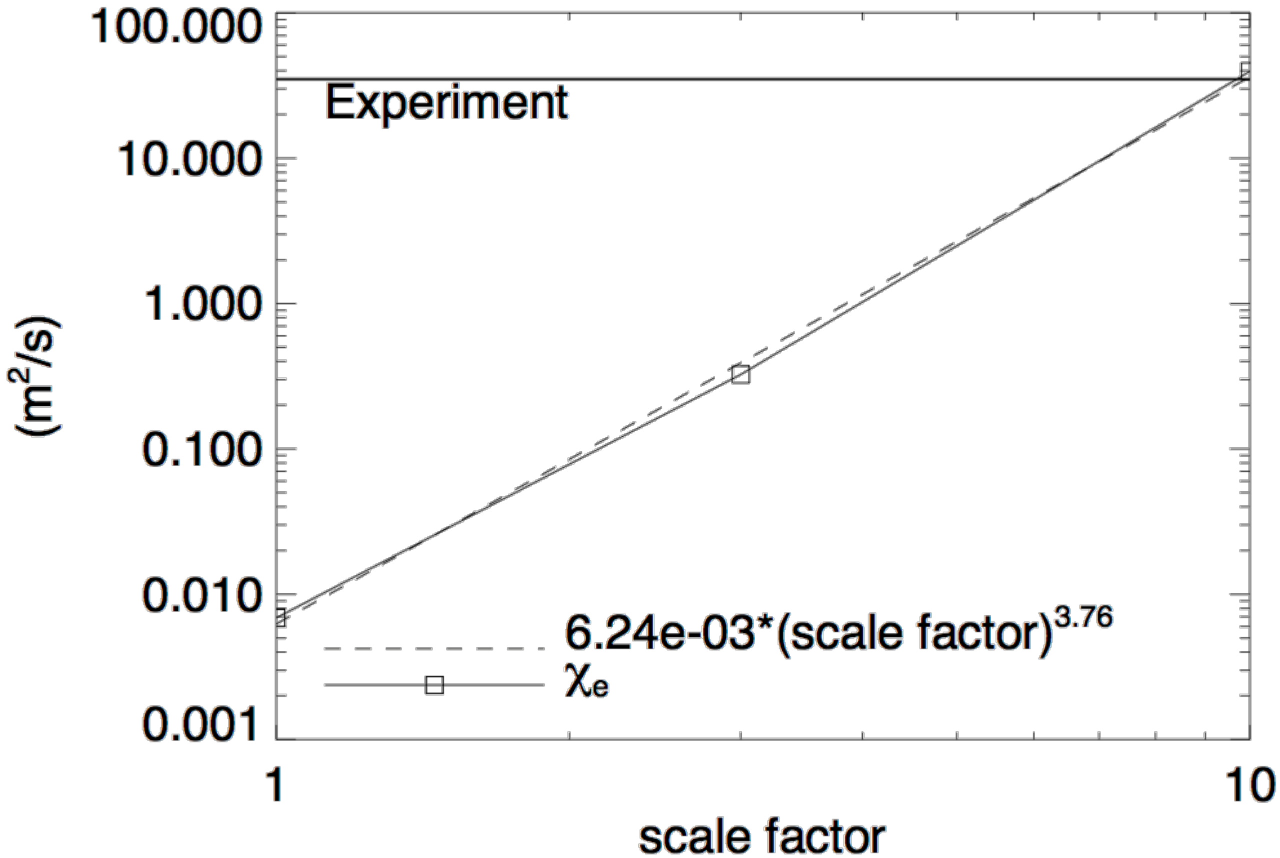
χ_e from GAEs simulated for 6 MW H-mode 141398, t = 0.58 sec

- Anomalous core χ_e (~ 35 m^2/s) in 6 MW H-mode (141398, t = 0.58 sec)
  - TRANSP experimental transport analysis
- e^- guiding center orbit spreading simulated by ORBIT => χ_e
  - initial isotropic thermal population (T_e = 1 keV) at $\Psi_N^{1/2}$ = 0.15
  - B-field from experiment (B_{T0}=0.45 T)
  - no collisions
  - spreading => D_e, $\chi_e = \frac{3}{2} D_e$
- 8 GAEs
  - $\xi_{rms} \sim 0.4$ mm
  - $\omega = k_{||} V_A$ => |m| = 0 – 2
  - poloidal+toroidal Fourier modes used



f (kHz)	n	m	ξ (mm)
383	-8	-2	0.1
393	-7	-1	0.11
401	-8	-2	0.13
436	-7	0	0.12
491	-8	0	0.06
515	-7	1	0.21
563	-6	2	0.05
567	-8	1	0.25

χ_e from GAEs in simulation much less than from experimental transport



- χ_e << 1 m^2/s at experimental amplitude, ξ_{expt}
- scaling study shows χ_e sensitive to amplitude: $\chi_e \propto \xi^{3.76}$
- need ξ = 10*(ξ_{expt}) for agreement with TRANSP

Inclusion of CAEs as shear modes increases simulated χ_e, but still not enough

f (kHz)	n	m	ξ (mm)
602	-5	4	0.31
633	-4	5	1.23
648	-1	8	1.05
695	-5	5	0.26
720	0	10	0.36
726	-3	7	0.57
800	-4	7	0.32

- 7 CAEs (15 CAEs+GAEs)
- δn typically much larger for CAEs => much larger ξ needed to explain δn
  - ξ_{rms} ~ 1.8 mm (CAEs+GAEs: 1.9 mm)
- much larger *m* needed
  - $\omega = k_{||} V_A$ => |m| = 4-10
- χ_e = 8 m^2/s at $\xi_{\text{expt,CAE+GAE}}$
  - expect 2 m^2/s from just GAEs at comparable ξ_{rms}
    - higher $k_{||}$ (or higher *m*) => more effective breaking of adiabatic constants of motion?
    - more modes = more stochastic?
- χ_e = 39 m^2/s ~ $\chi_{e,\text{expt}}$ at 3*($\xi_{\text{expt, CAE+GAE}}$)
- Treatment as CAEs would probably give smaller χ_e
  - $\xi \approx \delta n/\nabla n$ (GAE) vs. $\xi \lesssim \delta n/k_\theta$ (CAE)
  - shallow core ∇n: $n/\nabla n \ll k_\theta$

Conclusions

- CAEs & GAEs candidates for core electron thermal transport in NSTX
- Structure and amplitude of CAE & GAE δn measured in high performance NSTX-U plasma
- χ_e from GAEs simulated in core ($\Psi_N^{½}$ = 0.15) for high performance plasma
  - ORBIT used to simulate effects of modes on e^- guiding center orbits
- χ_e from GAEs in simulation much less than from TRANSP experimental transport analysis
- Inclusion of CAEs *as shear modes* increases simulated χ_e, but still not enough

Future Work

- Implement more physically realistic poloidal structure
  - currently, poloidal Fourier modes assumed
  - $k_{||} v_A$ and amplitude vary unphysically with poloidal position
- CAEs need to be included as compressional modes
  - compressional modes not fully implemented
  - ORBIT is currently being modified
- Simulation with eigenmodes from codes
  - HYM, CAE3B, CAE

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