

Effects of Global Alfvén Eigenmodes on Electron Thermal Transport in NSTX

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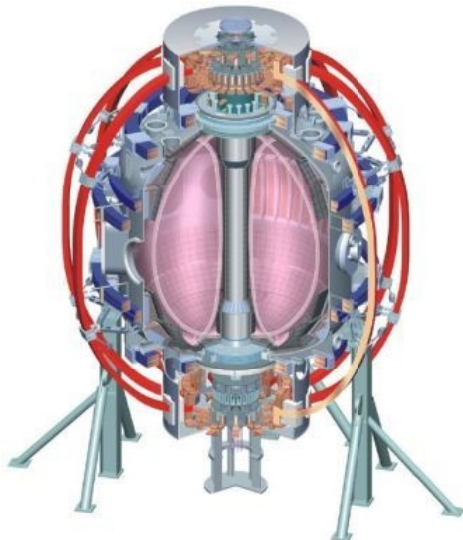
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and the NSTX Team

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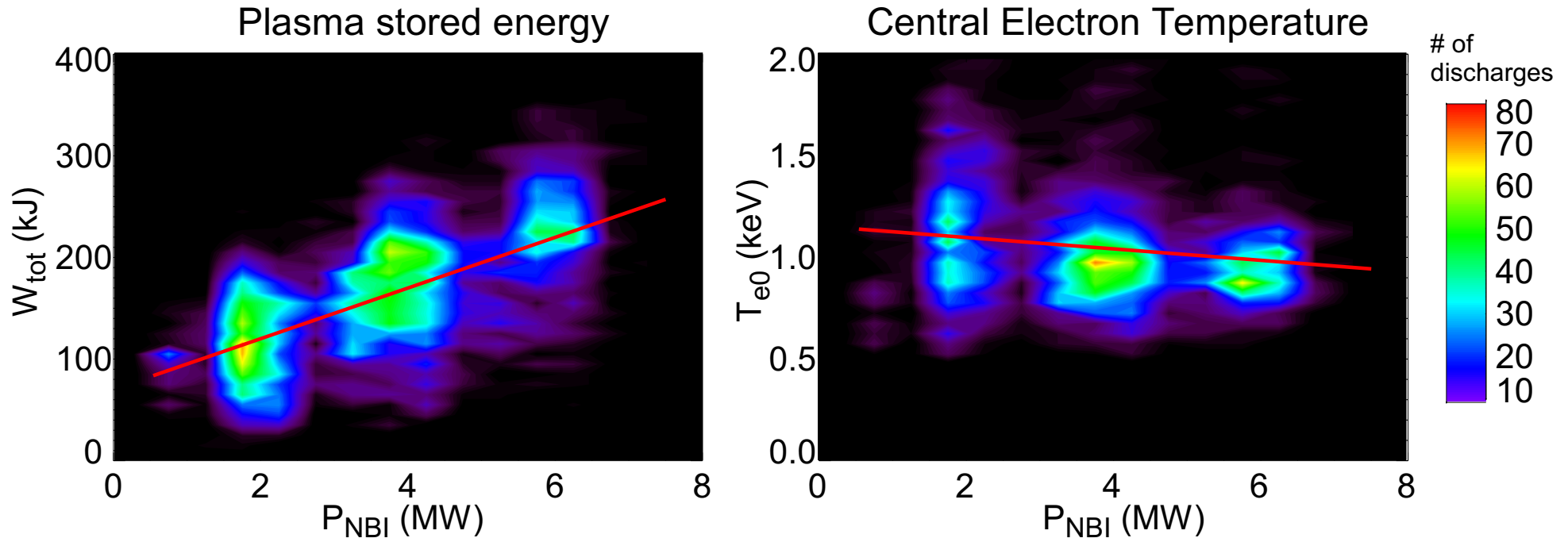
Fast ion-induced GAEs are a good candidate to explain the unusually high levels of electron thermal transport in the core of high power H-mode NSTX plasmas.

Outline

- Background and Motivation
- Observations of GAEs and correlation to transport
- Numerical predictions of GAE-induced transport
- Experimental measurements of GAE mode structure
- Comparison to numerical predictions and theories

NB power has little effect on T_{e0}

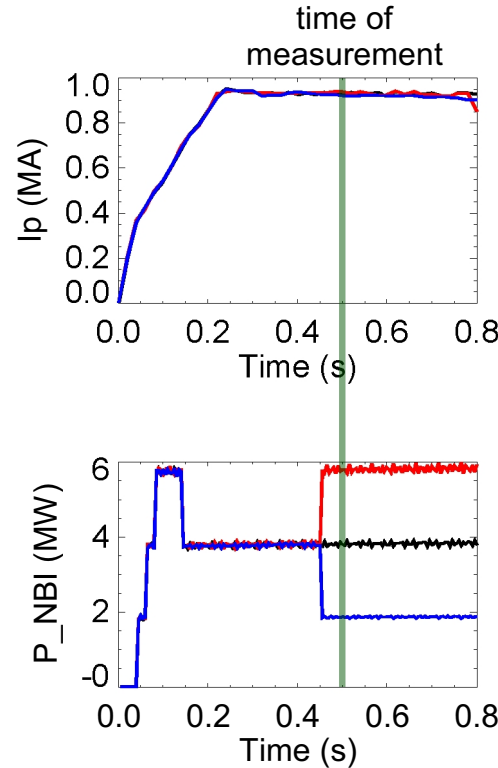
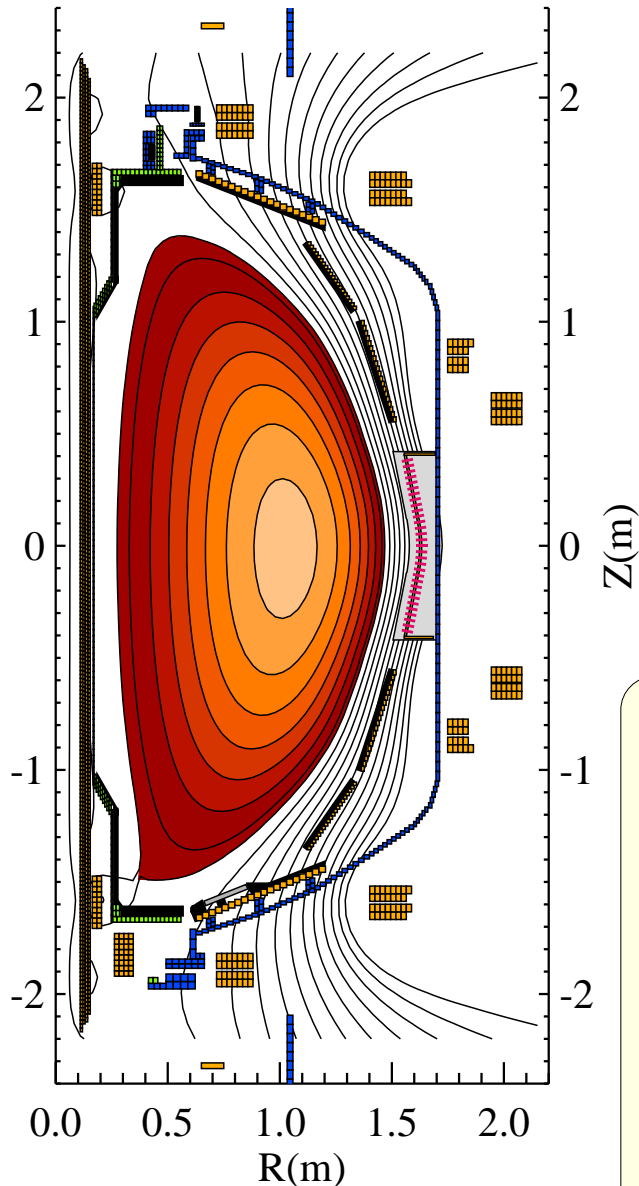
Plasma Discharge Histograms



- Database scan of >4000 NBI plasma discharges on NSTX
 - Identify central electron temperature at maximum stored energy
- Large scatter observed, wide range of plasma discharges
- Small but noticeable decrease in T_{e0} vs. P_{NBI}
 - Overall plasma stored energy increases with P_{NBI}

Experimental reference discharges use LSN H-mode with NBI preheat and beam steps for repeatable plasma conditions

\EFIT02, Shot 141387, time=487ms

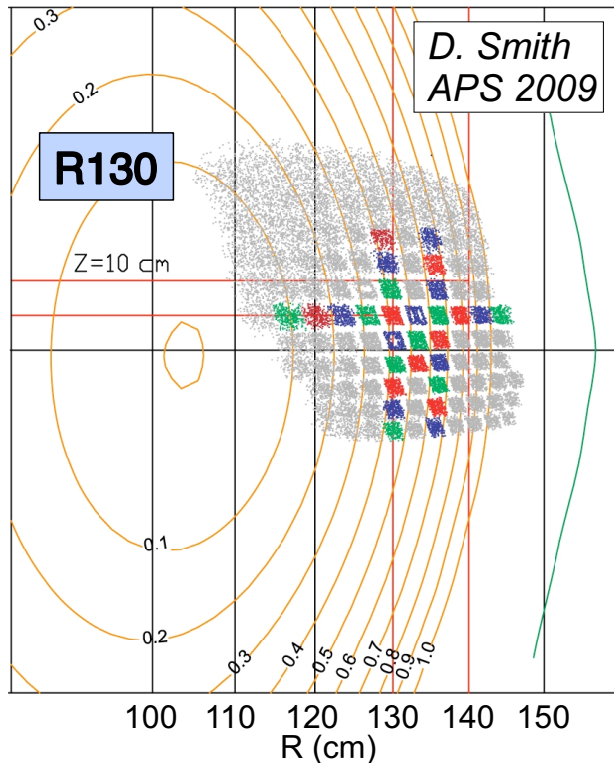


Mag. axis R_{mag}	1.03m
Aspect Ratio A	1.4
Elongation κ	2.4
Triangularity δ	~ 0.6
Plasma Current I_p	0.9MA
Toroidal Field B_T	0.45T
Pulse Length	~ 1 s
P_{NB} (100keV)	2-6MW
$\beta_{T,\text{tot}}$	$\sim 15\%$

- NBI pre-heat used to ‘freeze’ in current profiles with $q_0 > 1$
- Beam steps at 0.45s used to change input power
- Measurements 50ms later, before relaxation of current profile

Low and high- k diagnostic systems available to measure high- f modes and turbulent fluctuations in plasma core

Beam Emission Spectroscopy



BES parameters

16 channels

~3cm resolution

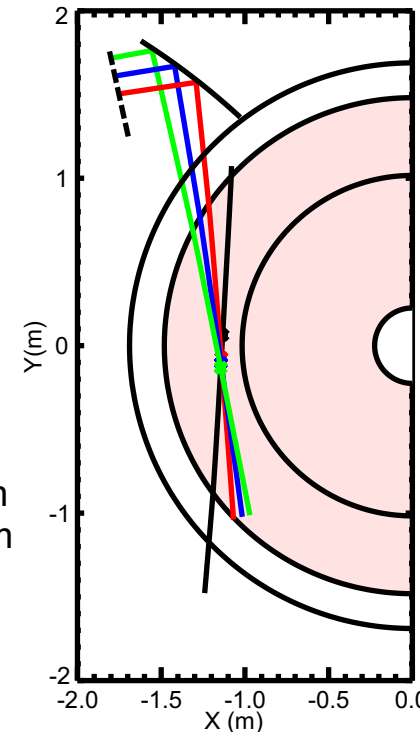
1MHz bandwidth

2MHz sampling
w/ x16 oversampling

'inner' view ~114-142cm
'outer' view ~131-155cm

$k_r \rho_i < 1 \text{cm}^{-1}$

Microwave Scattering Diagnostic



μ -wave scattering parameters

5 channels

+/- 3cm resolution

2MHz bandwidth

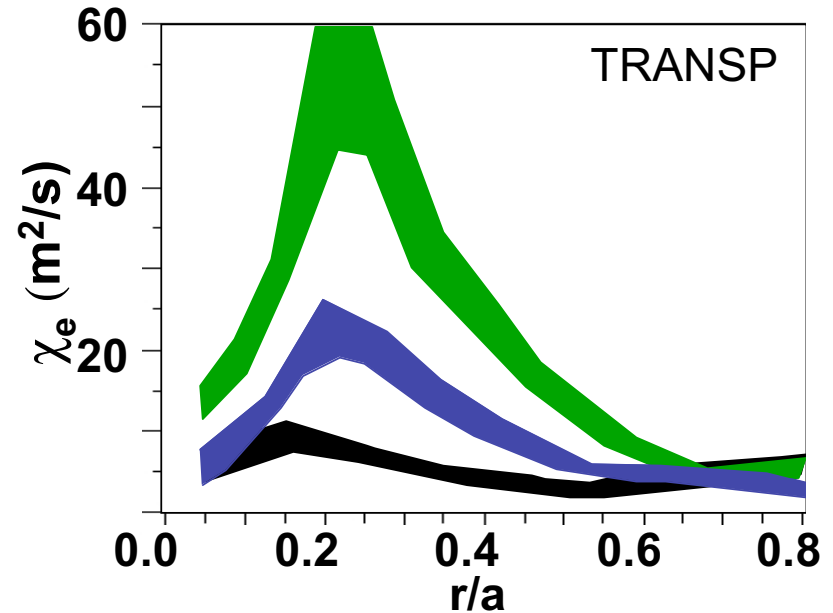
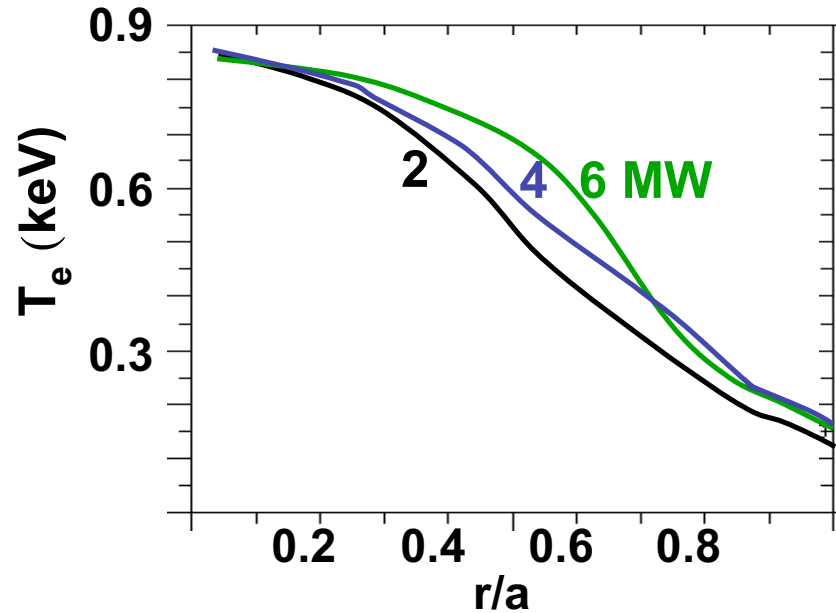
4MHz sampling

remote control over
radial position

$k_r \sim 4 - 24 \text{cm}^{-1}$

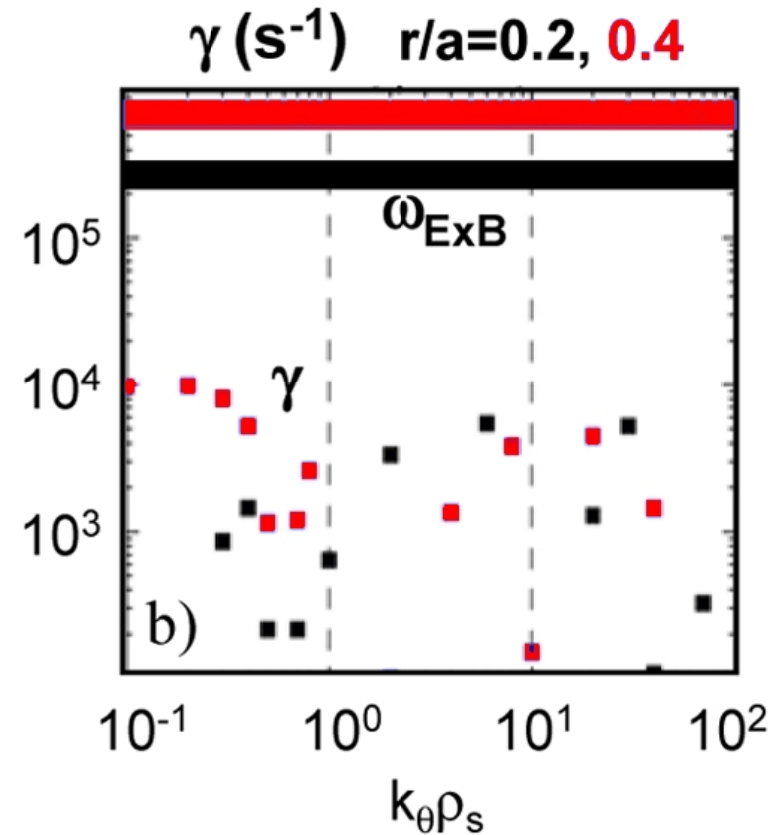
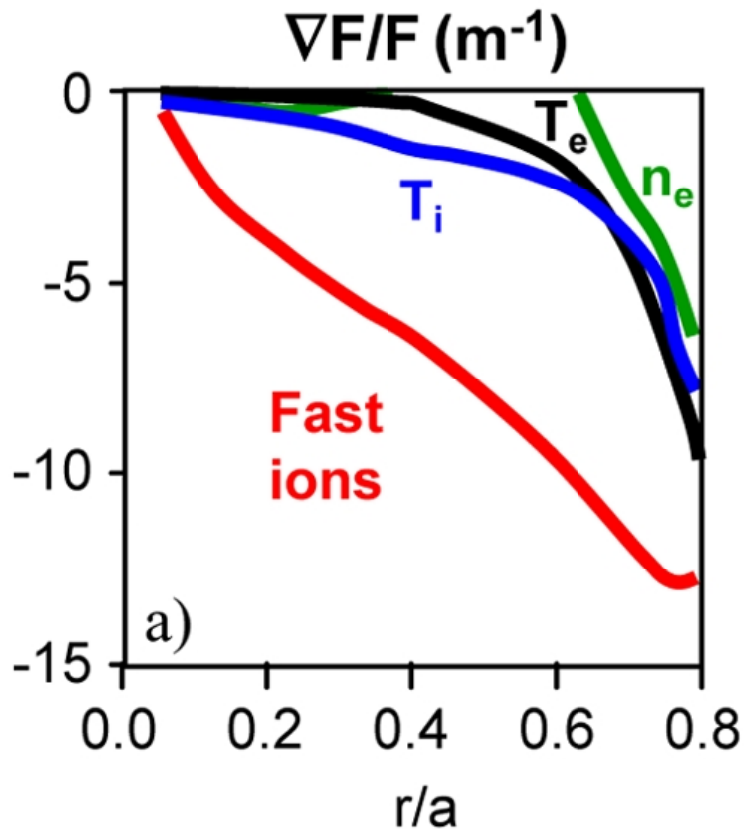
- BES provides low- k $\delta n/n$ fluctuations in plasma
- μ -wave system measures line-integrated density in 'interferometric' mode and scattered high- k $\delta n/n$ turbulence
- Combination of systems provides coverage of low/high k_r

Strong enhancement of core transport is observed with increasing power in NBI discharges



- 3x increase in P_{NBI} with no increase in T_{e0}
- Broader electron temperature profile consistent with database showing increase in W_{tot}
- TRANSP calculates high χ_e in region of flattened T_e
- Perturbative transport measurements consistent with core $\chi_e \sim 100 \text{m}^2/\text{s}$ (Tritz PoP 2008)

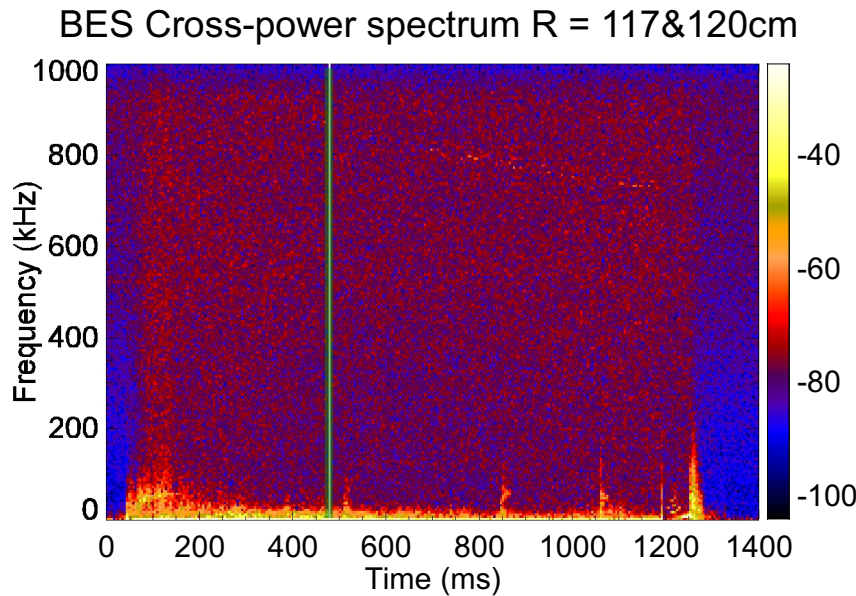
Flat plasma profiles and high rotation shear suggest suppression of electrostatic turbulence



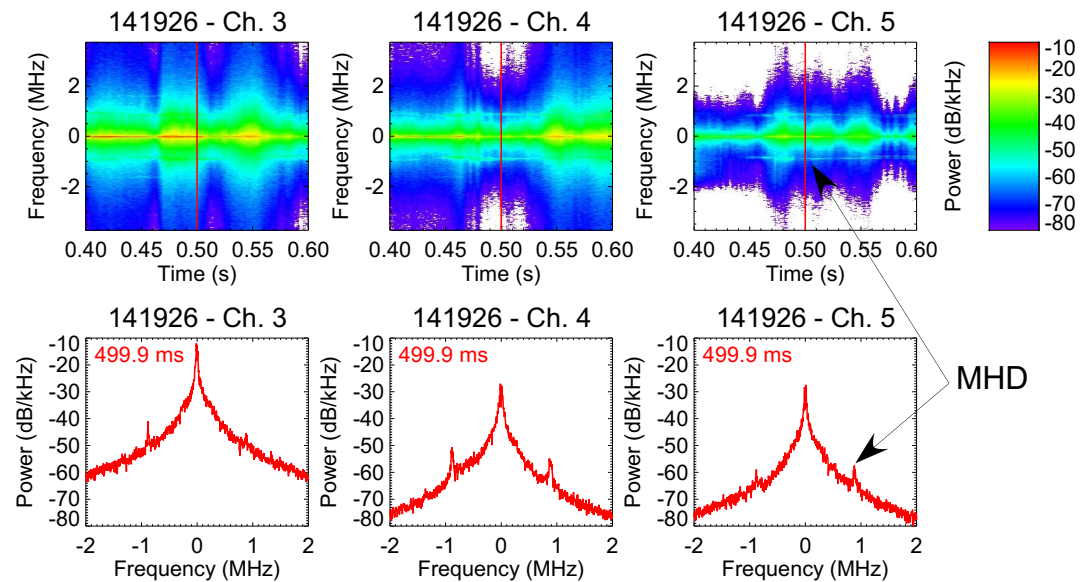
- Linear GS2 calculations show growth rates 20-100x lower than shearing rate in plasma core over high and low- k range
- TRANSP calculated fast ion profile shows gradient which can drive fast ion modes in plasma

No evidence of short or long wavelength turbulence in core of many NBI-heated discharges in NSTX

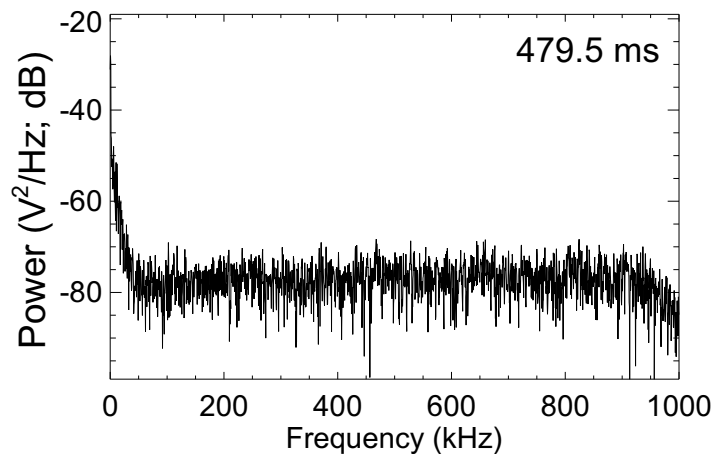
Preliminary BES data



High-k fluctuation spectrum R=123cm $k_r = 9-16 \text{ cm}^{-1}$

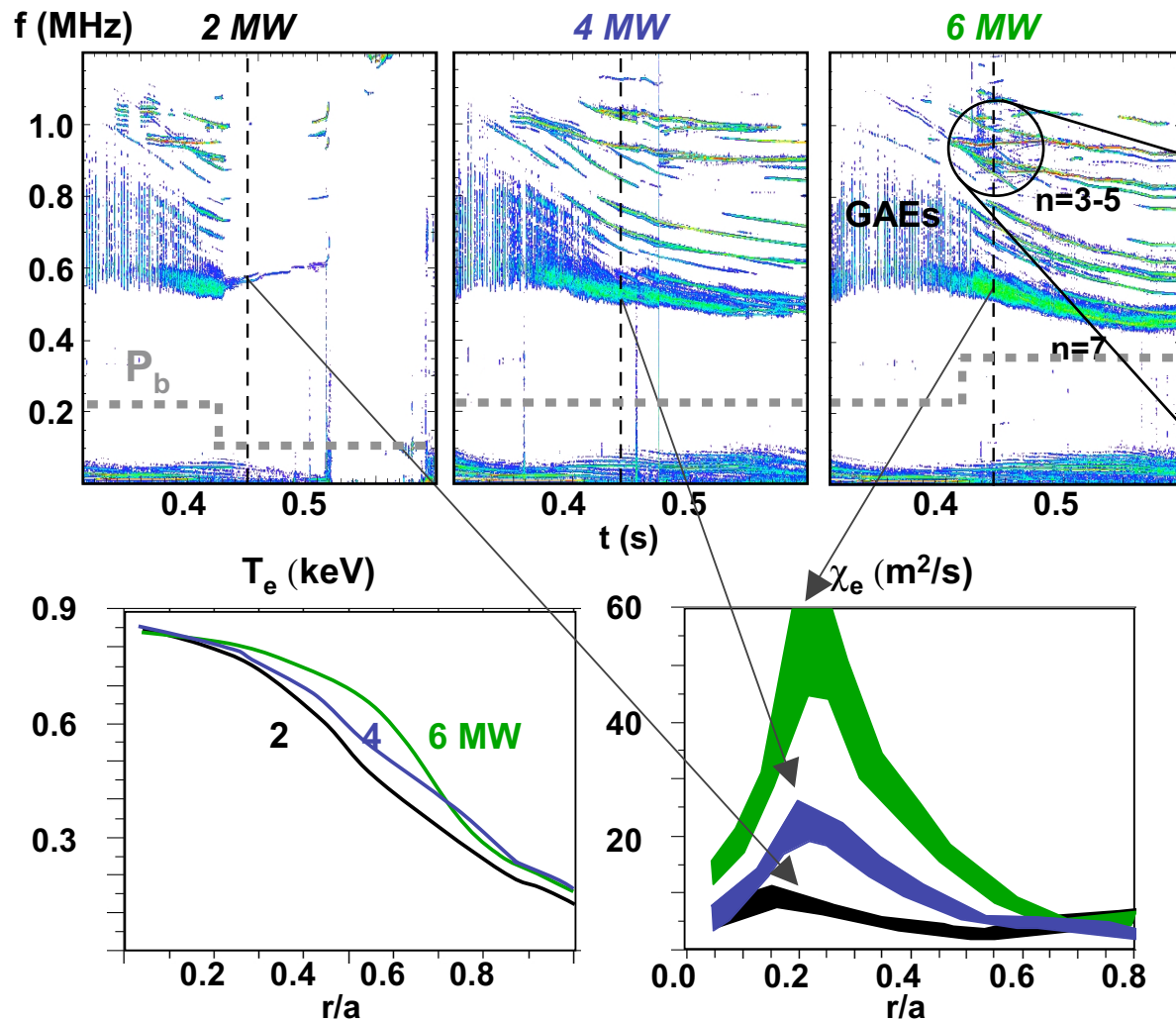


BES Cross-power spectrum R = 117&120cm



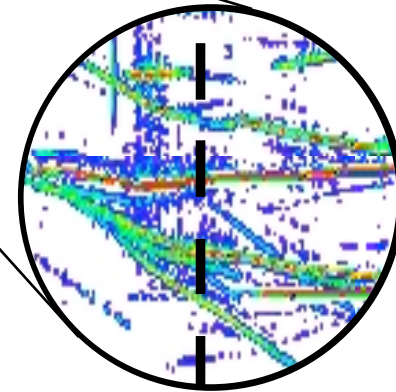
- No evidence of broadband low-k turbulent fluctuations on BES
- High-k system also shows little to no broadband high-k activity in plasma (R=123cm)

GAE modes proposed as possible mechanism for rapid electron thermal transport in plasma core



D. Stutman, PRL 2009

Power spectra from magnetic pickup coils



Convergence/divergence of mode frequencies evidence of GAEs

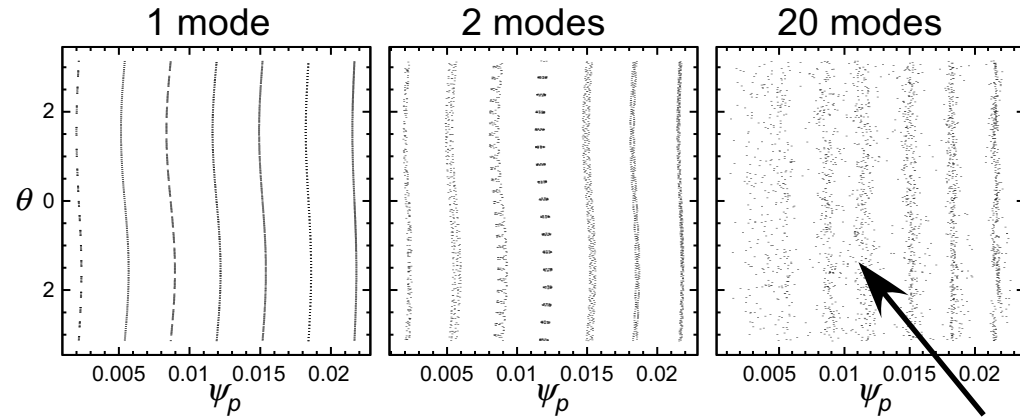
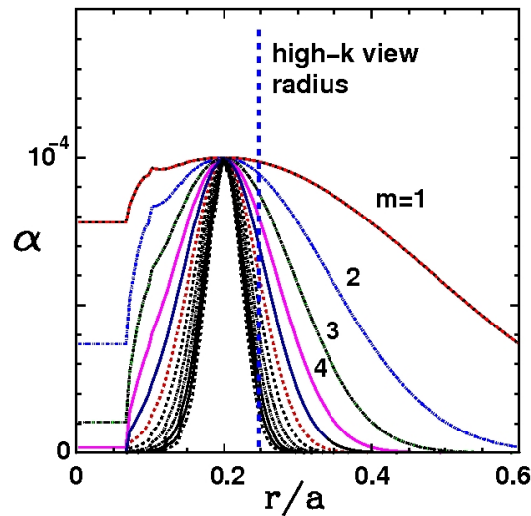
$$\omega_j = v_A k_{||j} \approx v_A \frac{m_j - n_j q}{q R_0}$$

- GAE activity correlates strongly with P_{NBI} steps and enhanced core electron thermal transport

ORBIT guiding center code used to simulate GAE effects on electron thermal transport

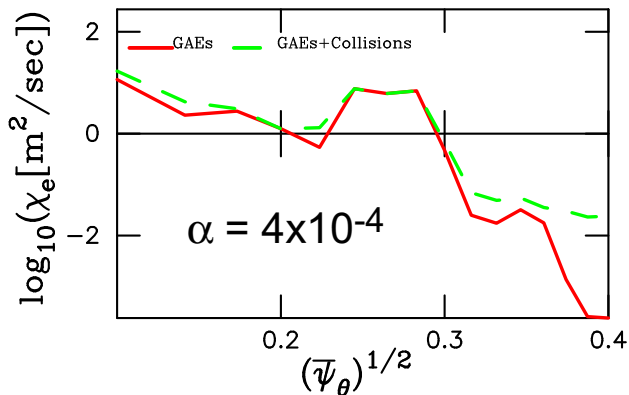
N. Gorelenkov Nucl. Fus. 2010

GAE Model used in ORBIT calculations



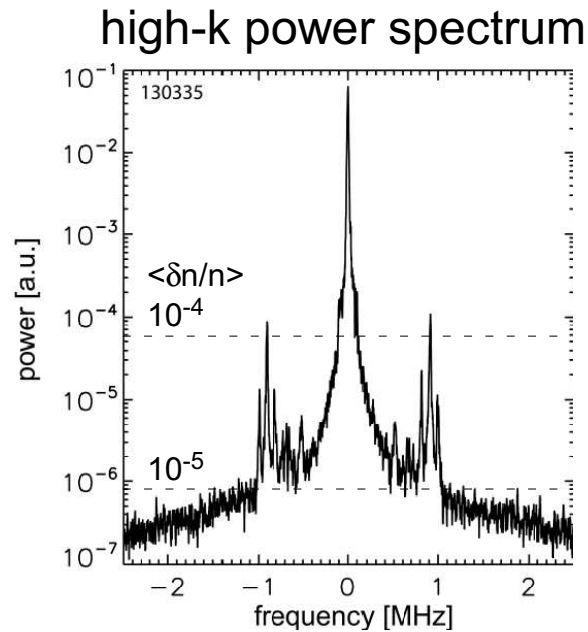
Poincaré plot of electron trajectory stochastic particle trajectories

Simulated electron transport

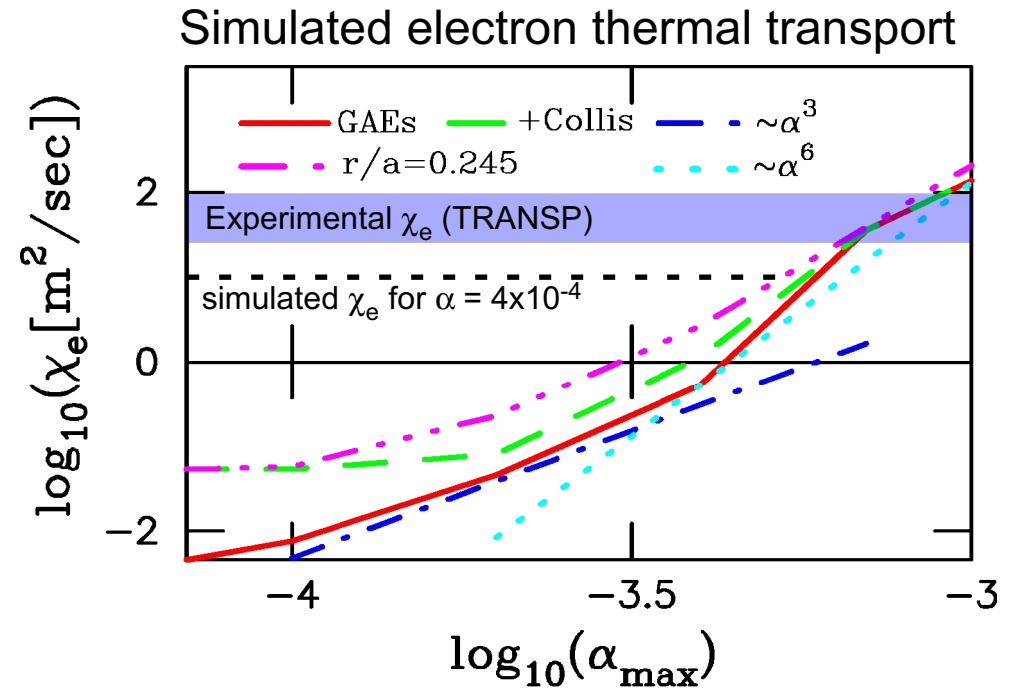


- Ad-hoc model used to study transport vs. mode amplitude and number
- $\chi_e > 10 \text{m}^2/\text{s}$ for GAE mode amplitude: $\alpha > 4 \times 10^{-4}$, number: $N > 16$
- 'stochastic' transport sensitive to mode structure and amplitude ($\sim \alpha^6$)

GAE ORBIT model using measured amplitudes under-predicts TRANSP χ_e by x4-10

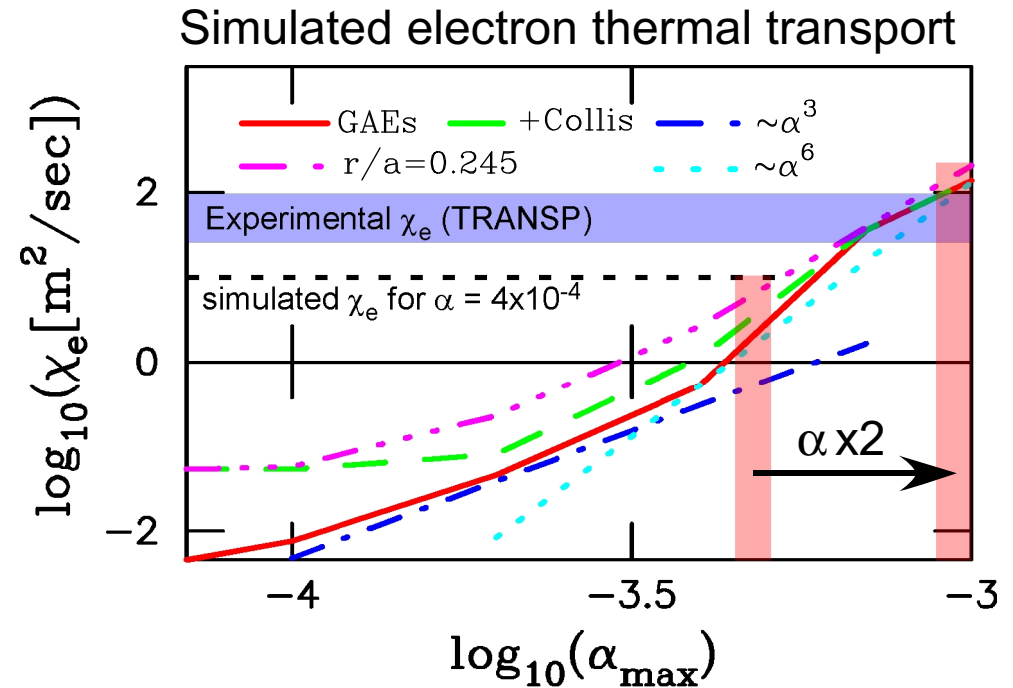
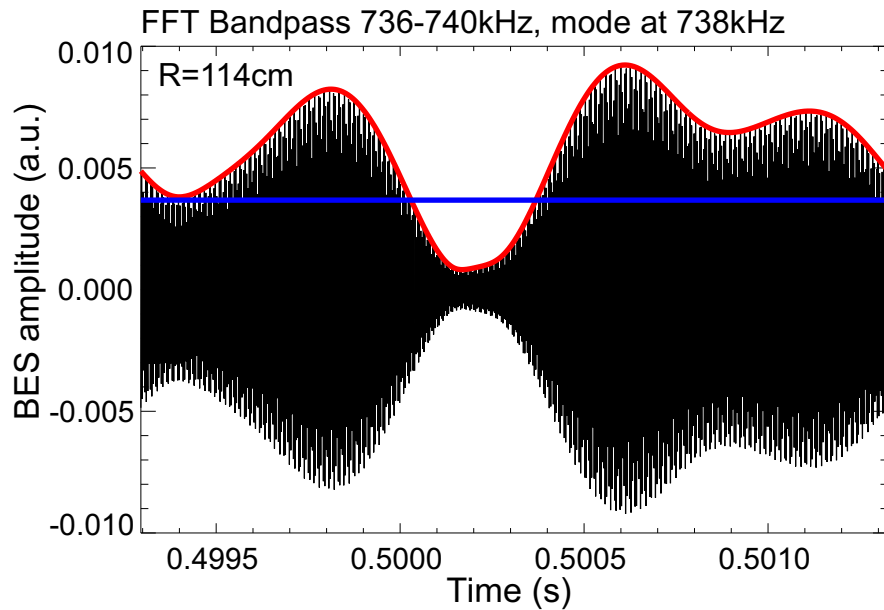


$\langle \delta n_{\text{rms}}/n \rangle \sim 1.5 \times 10^{-4} \rightarrow \text{local } \delta n/n \sim 9 \times 10^{-4}$



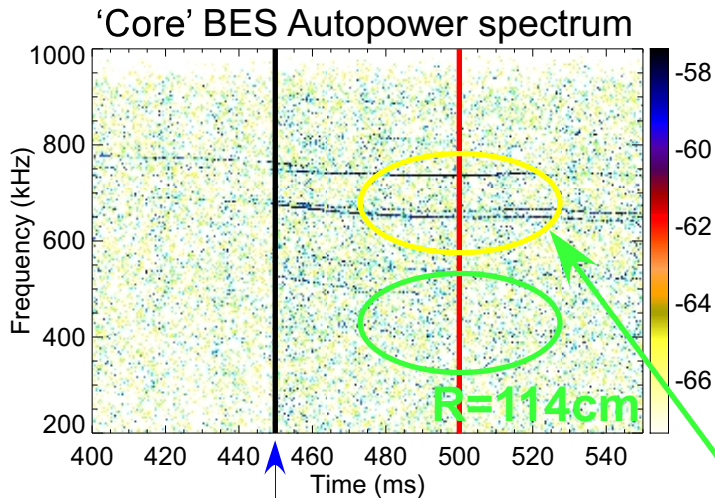
- $\alpha=4 \times 10^{-4}$ used in simulation corresponds to $\zeta/R \sim \delta n/n \sim 10^{-3}$
- TRANSP experimental $\chi_e \sim 40\text{-}100 \text{ m}^2/\text{s}$
- Peak amplitudes and bursting of modes can be x2-3 higher than measured rms, time-averaged values
- Sensitivity to r/a indicates importance of mode structure

'Bursting' GAE mode activity may strongly affect predicted electron thermal transport

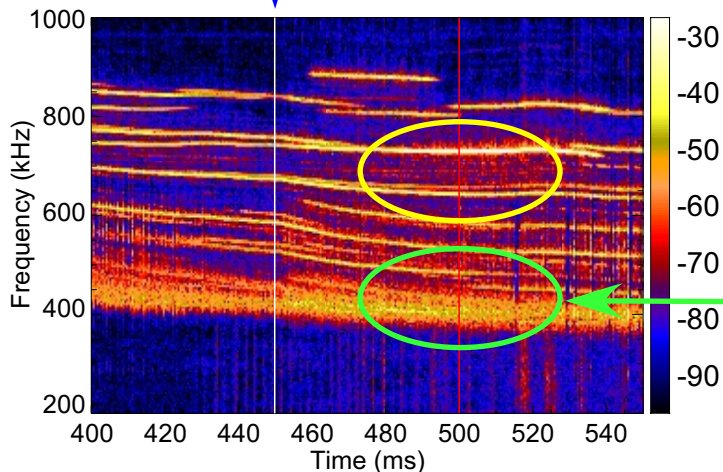


- Strong scaling of transport with α indicates mode amplitude peak values dominate χ_e
- Peak amplitudes $\sim x2$ to $x3$ higher than time-averaged, rms values from BES and magnetics
- Calculated electron thermal transport from peak GAE mode amplitudes roughly agrees with experimental TRANSP values

Initial BES measurements show GAE peaking at $R \sim 120\text{cm}$ ($r/a \sim 0.36$) in region of enhanced transport

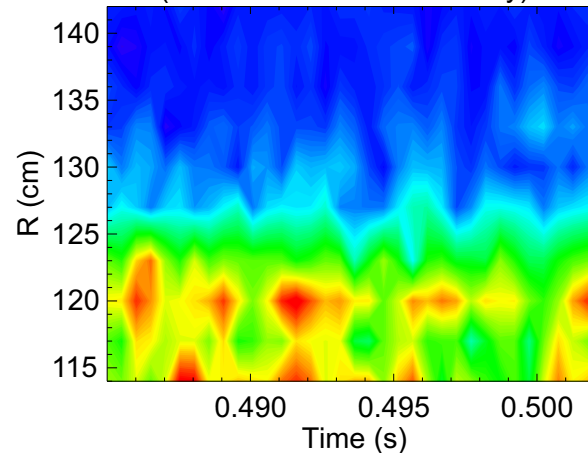


PNBI 4- \rightarrow 6MW

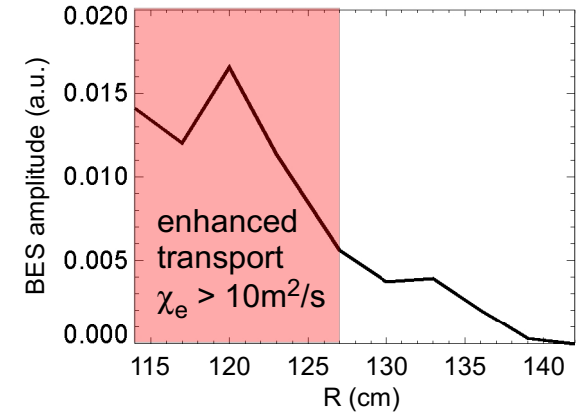


Mirnov magnetic pickup coil

$\sim \delta n$ amplitude of 738kHz GAE (δI normalized to NB density)



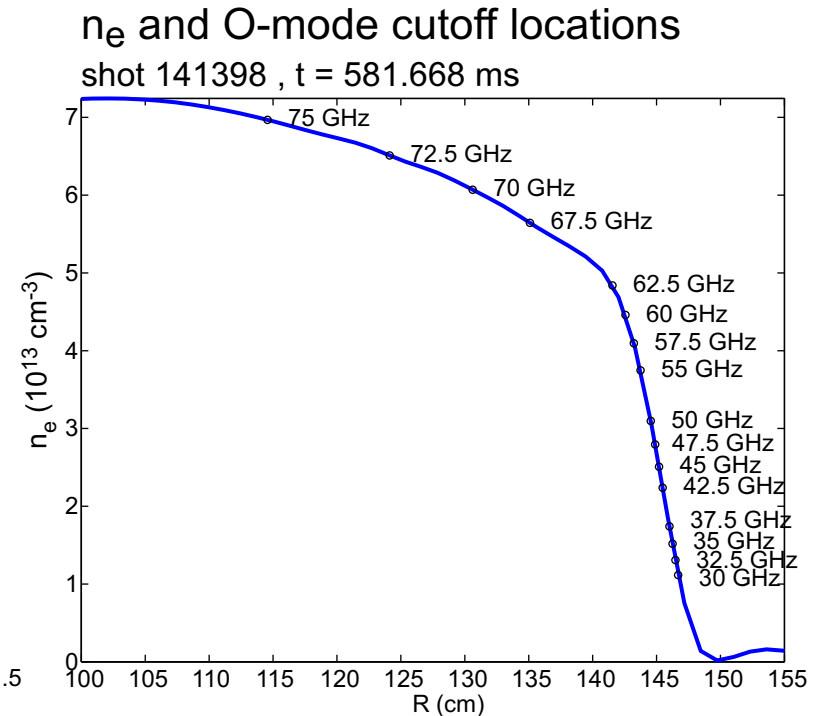
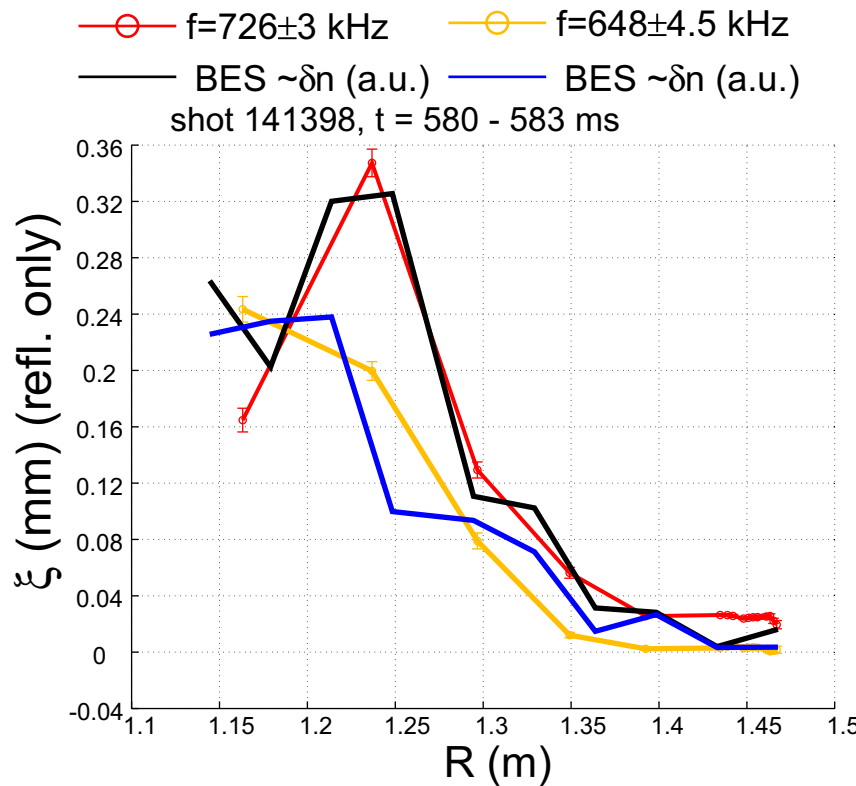
$\delta I/I$ amplitude of 738kHz GAE (17ms average)



- BES spectrogram shows high-intensity GAE modes $R < \sim 135\text{cm}$ $\sim 5\text{-}10\text{dB}$ above background
- Mirnov pickup coils reveal additional, lower amplitude modes below BES detector limit

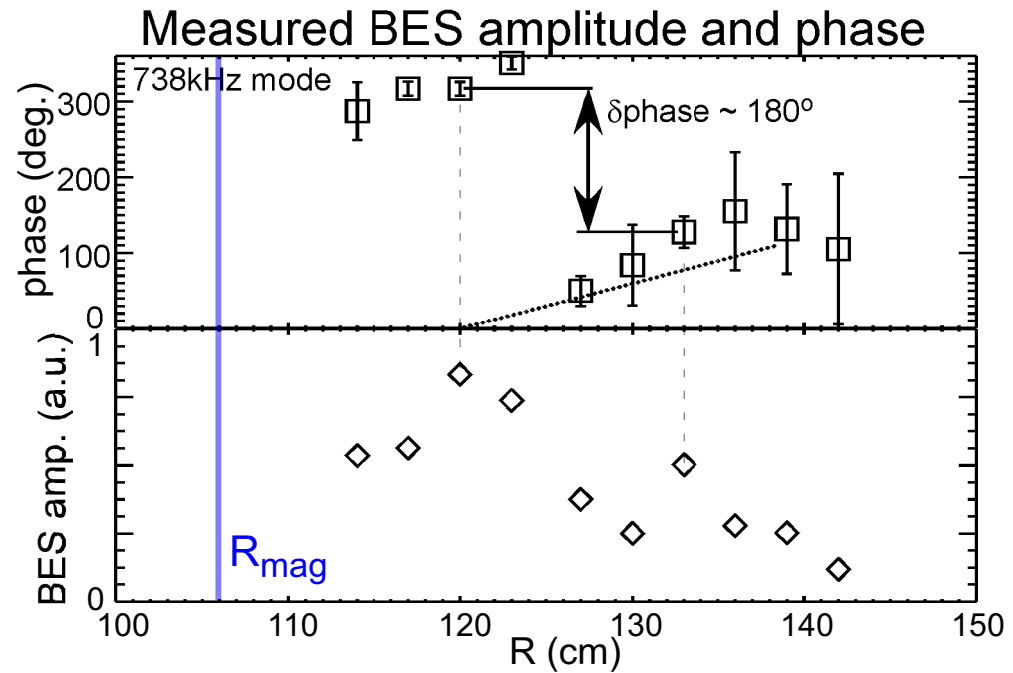
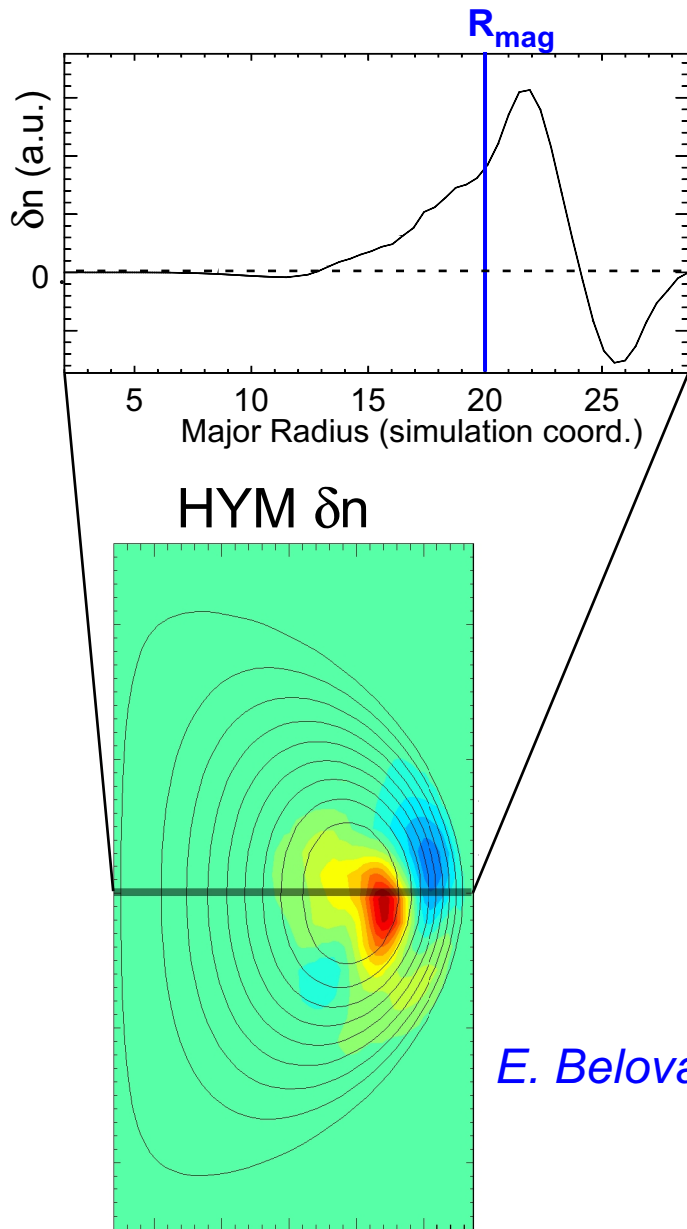
Measured mode displacement profiles from high-frequency reflectometry matches BES profile data

N. Crocker (UCLA) BP9.58



- Displacement of 0.35mm rms ($\zeta/R \sim 4 \times 10^{-4}$) indicates $\delta n/n \sim 4.5 \times 10^{-4}$ roughly consistent with high- k in similar discharge
- Raw phase reflectometer signal shows strong 50kHz beating of 700kHz oscillation with maximum amplitude ~ 0.9 mm

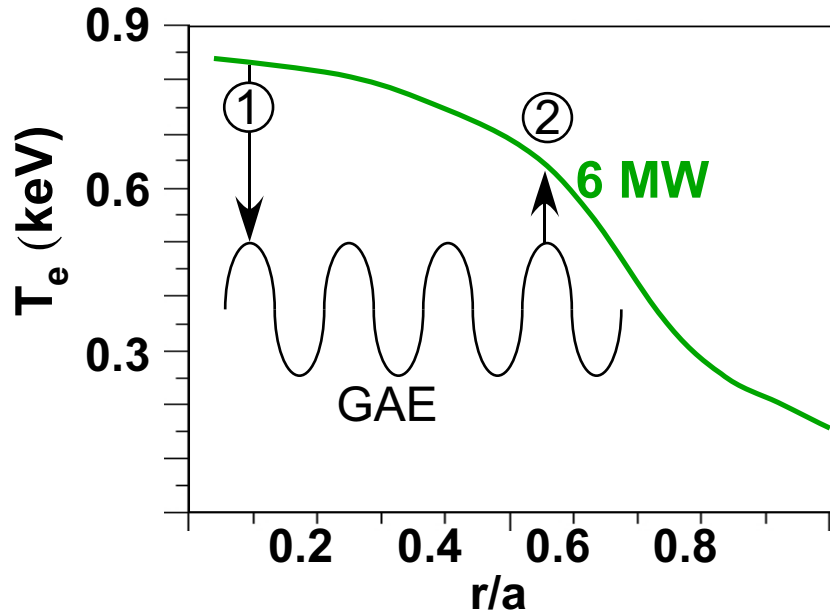
Measured phase of GAE mode structure consistent with predictions from HYbrid MHD (HYM) code



- HYM code predicts δn inversion across plasma radius
- BES measures smooth radial phase variation with 180 degree inversion roughly matching HYM predictions

Alternative explanation invokes wave ‘channeling’ of thermal energy via GAE mode coupling

Kolesnichenko PRL 2010



1) GAE mode absorbs power from NBI

$$P_{\text{GAE}} \sim P_{\text{NBI}}$$

core T_e is lowered due to diverted power

2) GAE mode damps on electrons

transfers energy to electrons at larger radius
mid-radius T_e is raised

given above mechanism: TRANSP estimates high χ_e from incorrect power balance

Complications

- High χ_e from GAE induced stochastic transport also supported with perturbative expts.
- Initial measurements of mode structure show small amplitude for $r/a > 0.5$, inconsistent with transfer of large P_{NBI} ?
- **Calibrated mode amplitudes may help distinguish mechanisms**

Summary

- Flat core profiles and high χ_e not explained with electrostatic turbulence in high power NSTX H-modes
- Strong correlation of GAE activity with NBI power and high electron thermal transport
- Measured GAE mode structure and amplitude roughly consistent with predicted values of transport using ORBIT code

Future Work

- Calibrated amplitude and time history data will be used with ORBIT to further validate predictions of χ_e
- Validation of the HYM code using GAE mode structure and phase measurements
- JHU proposed Ultra-Fast Dual-Energy SXR system will measure poloidal structure of GAE mode, δn_e and δT_e in NSTX-U plasmas