NSTX

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Recent progress in transport and turbulence research at NSTX

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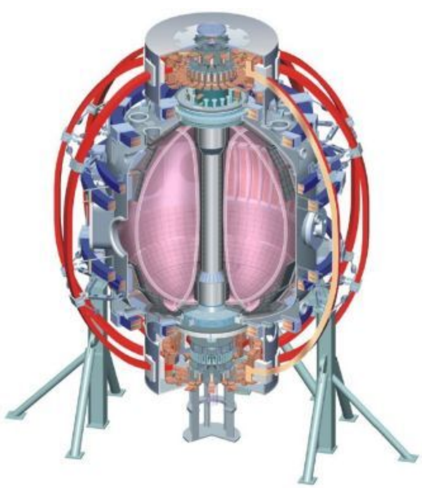

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NSTX accesses a broad range of parameter space to address many turbulence and transport issues

- Low aspect ratio, high β (high ∇P), and strong $E \times B$ flow shear in NSTX stabilize "traditional" electrostatic low-k turbulence, such as Ion Temperature Gradient (ITG) and Trapped Electron Mode (TEM)

- Ion thermal transport is close to neoclassical (collisional) in NSTX H-modes

  → electron and ion thermal transport is largely decoupled

- With relatively small magnetic field Electron Temperature Gradient (ETG) turbulence can cause significant transport at ρ_e-scales (high-k)

  → desire for high-k turbulence measurements to correlate with electron transport and validate with nonlinear ETG simulations

- Achievable range of $\beta_T \leq 40\%$ can also lead to significant EM contribution

  → micro-tearing turbulence can cause electron transport through magnetic flutter

- Must still consider low-k turbulence, for example in L-mode (ITG/TEM) and in H-mode pedestal region (ITG/TEM/KBM)

  → desire for large scale (low-k) turbulence measurements such as BES

Overview

- First nonlinear gyrokinetic simulations of micro-tearing turbulence for "high beta" NSTX H-mode plasmas
- Parametric dependence of high-k turbulence measured by a microwave scattering diagnostic in "low beta" plasmas
- First low-k turbulence measurements from a newly implemented BES diagnostic
- Summary

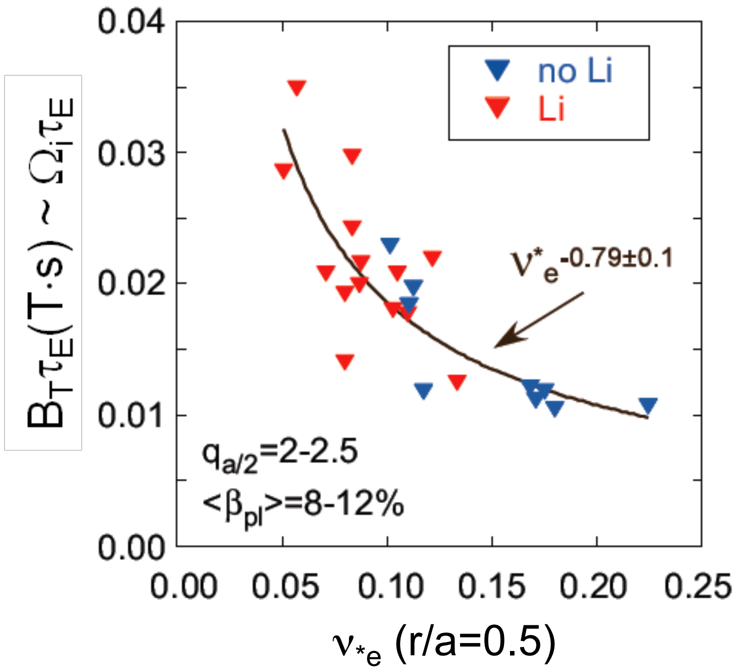
See website for recent APS presentations:

http://nstx.pppl.gov/DragNDrop/Scientific_Conferences/APS/APS-DPP_11/

NSTX H-mode thermal confinement scaling shows strong dependence on collisionality

- Dimensionless collisionality (ν_*) scan holding q, β, $\rho_*=\rho_i/a$ constant without or with Lithium wall conditioning

$$\nu_{*e} = \frac{\nu_{ei}/\varepsilon}{\varepsilon^{1/2} v_{Te}/qR}$$



NSTX (Kaye et al., Nucl. Fusion 2007; APS 2011)

$$\Omega\tau_E^{th} \sim \nu_{*e}^{-0.8}$$

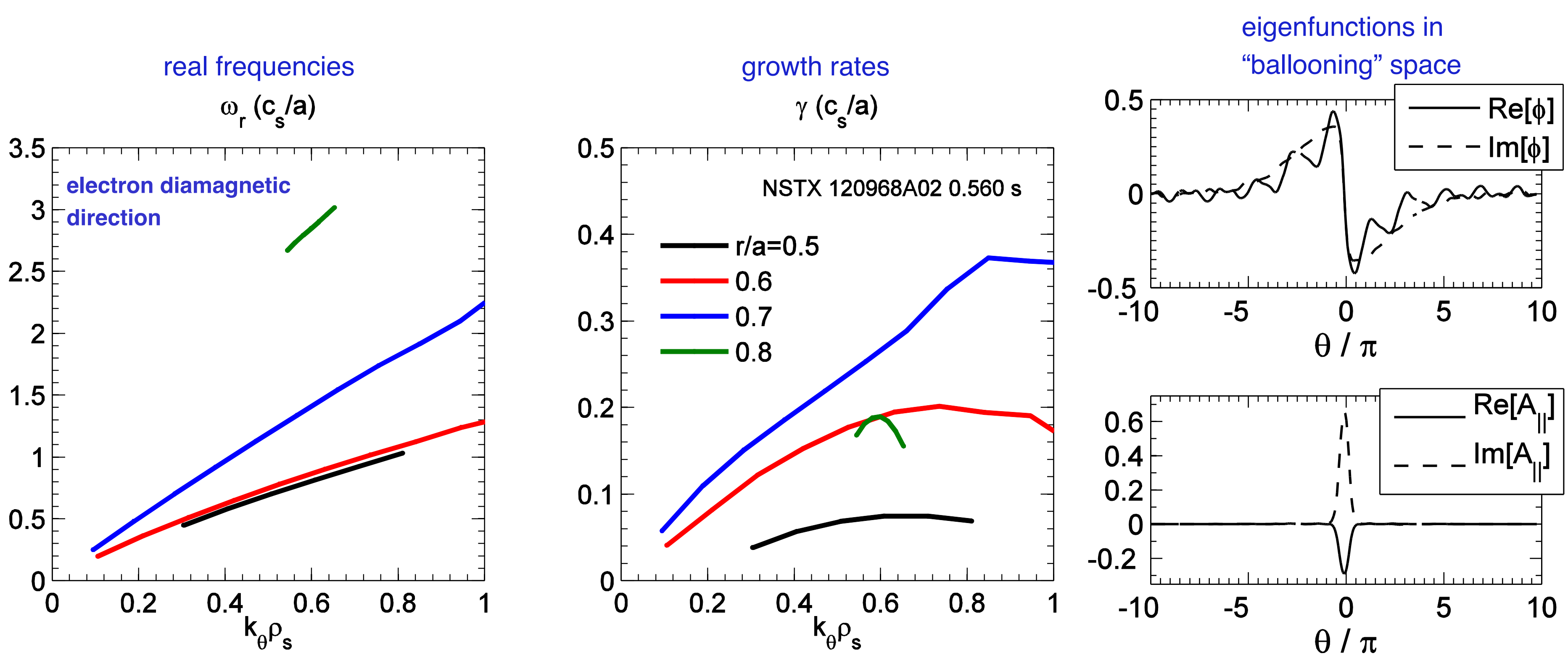
ITER (PIPB, Doyle et al., Nucl.Fusion 2007)

$$\Omega\tau_E^{th,04(2)} \sim \nu_{*e}^{-0.2}$$

- Ion transport is neoclassical, consistent with strong toroidal flow and flow shear
- What is the cause of anomalous electron thermal transport?
- Will favorable τ_E scaling hold at lower ν_* envisioned for next generation ST (high heat flux, CTF, …)?

Microtearing modes found to be unstable in many high ν_* discharges

- Microtearing dominates over r/a=0.5-0.8, $k_\theta\rho_s$<1 (n≈5-70)
- Real frequencies in electron diamagnetic direction, $\omega \approx \omega_{*e} = (k_\theta\rho_s)\cdot(a/L_n+a/L_{Te})\cdot(c_s/a)$
- ETG mostly stable due to larger Z_{eff}≈3, $(R/L_{Te})_{crit,ETG}$~$(1+Z_{eff}T_e/T_i)$



Linear GYRO simulations [Candy & Waltz, Phys. Rev. Lett. (2003); https://fusion.gat.com/theory/Gyro] with kinetic ions and electrons, fully electromagnetic, collisions, local general equilibrium

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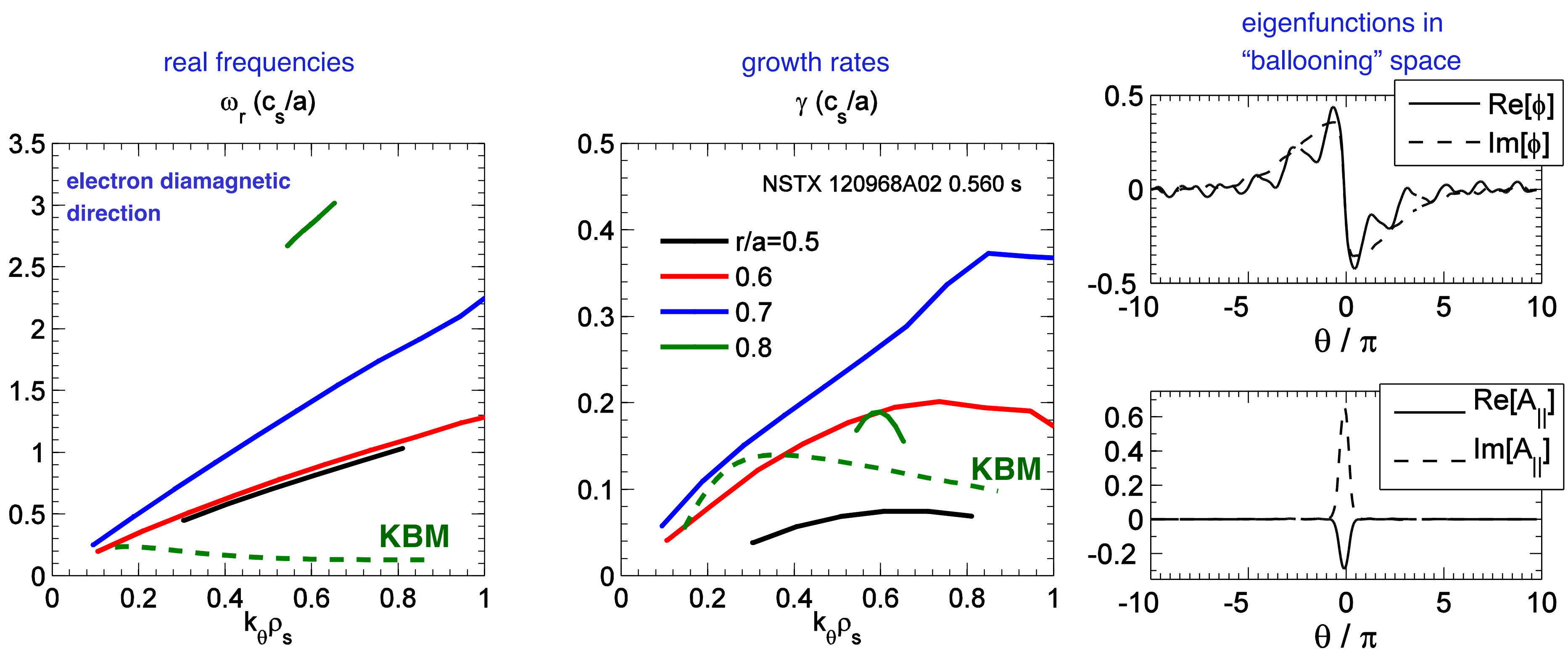
- Real frequencies in electron diamagnetic direction, $\omega \approx \omega_{*e} = (k_\theta\rho_s)\cdot(a/L_n + a/L_{Te})\cdot(c_s/a)$
- ETG mostly stable due to larger $Z_{eff}\approx3$, $(R/L_{Te})_{crit,ETG} \sim (1+Z_{eff}T_e/T_i)$
- KBM competes farther out (r/a≥0.8) where $\alpha_{MHD}=-q^2R\beta'$ much larger (larger q, a/L_n)



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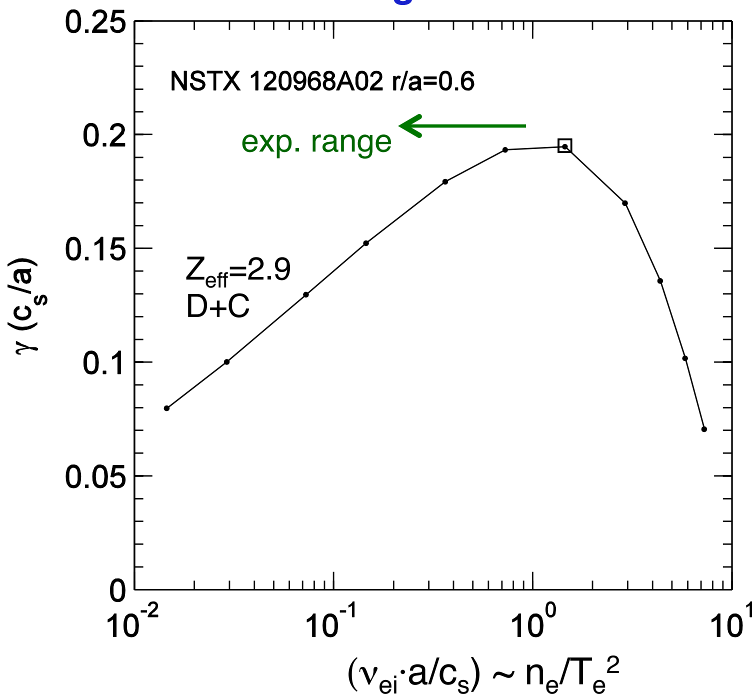
A distinguishing feature of the microtearing mode is the non-monotonic dependence on $\nu^{e/i}/\omega$

- Peak γ occurs for $\nu^{e/i}/\omega = Z_{eff} \cdot \nu_{ei}/\omega \sim$ 1-6, similar to slab calculations (Gladd et al., 1980)
- γ decreases with ν_e in experimental range → qualitatively consistent with observed confinement scaling

Linear growth rates



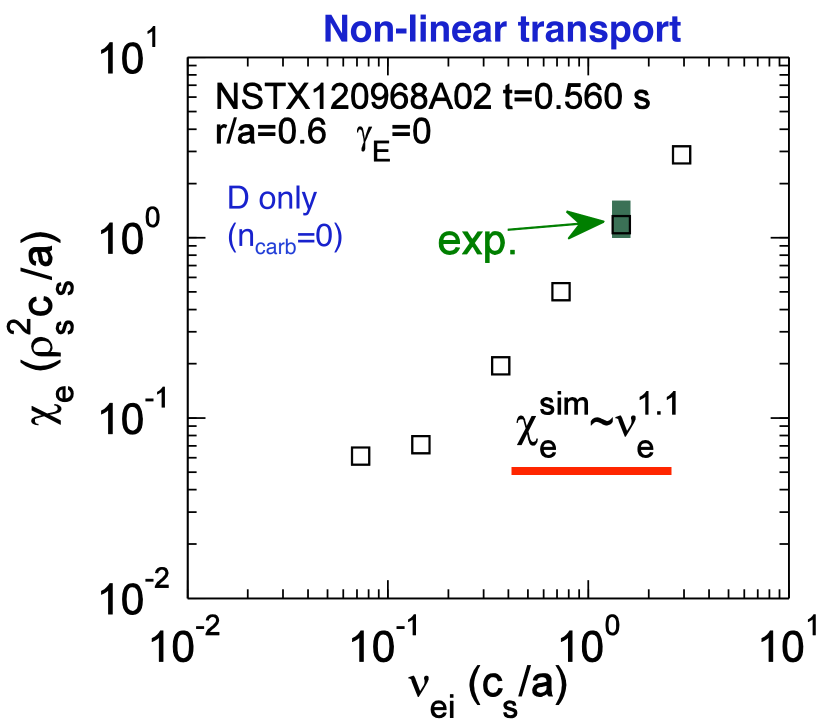
$$\nu^{e/i} = Z_{eff}\nu_{ei} \propto Z_{eff}\frac{n_e}{T_e^{3/2}}$$

* Guttenfelder et al., *Scaling of linear microtearing stability for a high collisionality NSTX discharge*, submitted to Phys. Plasmas (Oct, 2011)

Predicted nonlinear transport comparable to experiment, scales with ν_e similar to experimental confinement scaling*

Nonlinear GYRO simulations with: local general equilibrium, kinetic ions and electrons, collisions, electromagnetic

Very fine radial resolution, $\Delta x=0.2\rho_s$ required to resolve rational surfaces



NSTX experimental scaling

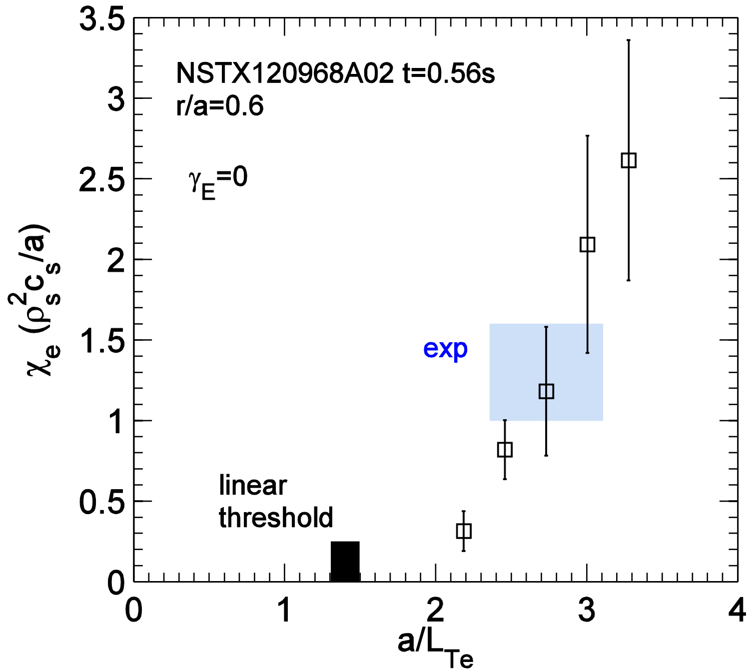
$\Omega_i\tau_E \sim \nu_*^{-0.95}$

- As transport drops, a/L_{Te} will increase (for fixed heat flux), at some point ETG (TEM?) should become important
- This transition likely to determine limit of “favorable” ν_* scaling

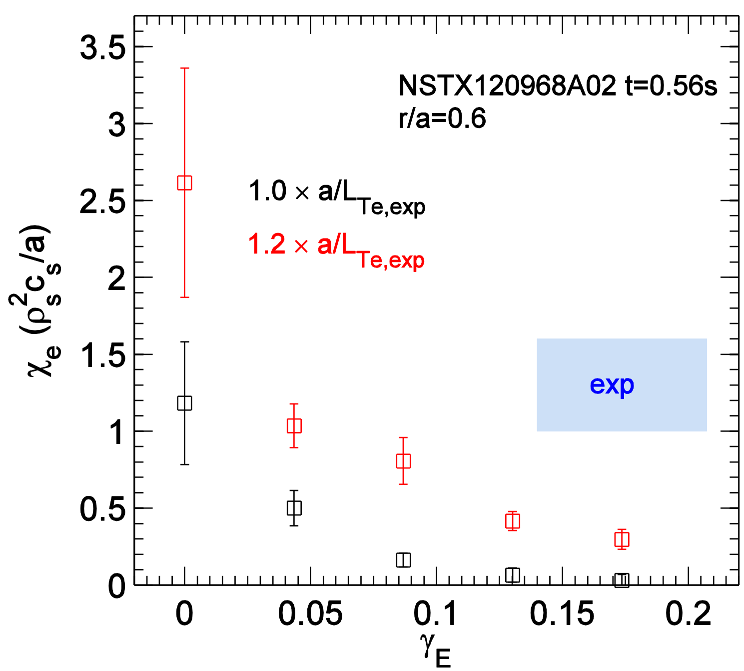
* Guttenfelder et al., *APS-DPP invited talk TI2.06, Salt Lake City* (2011)

Predicted transport "stiff" with ∇T_e, susceptible to suppression via E×B shear

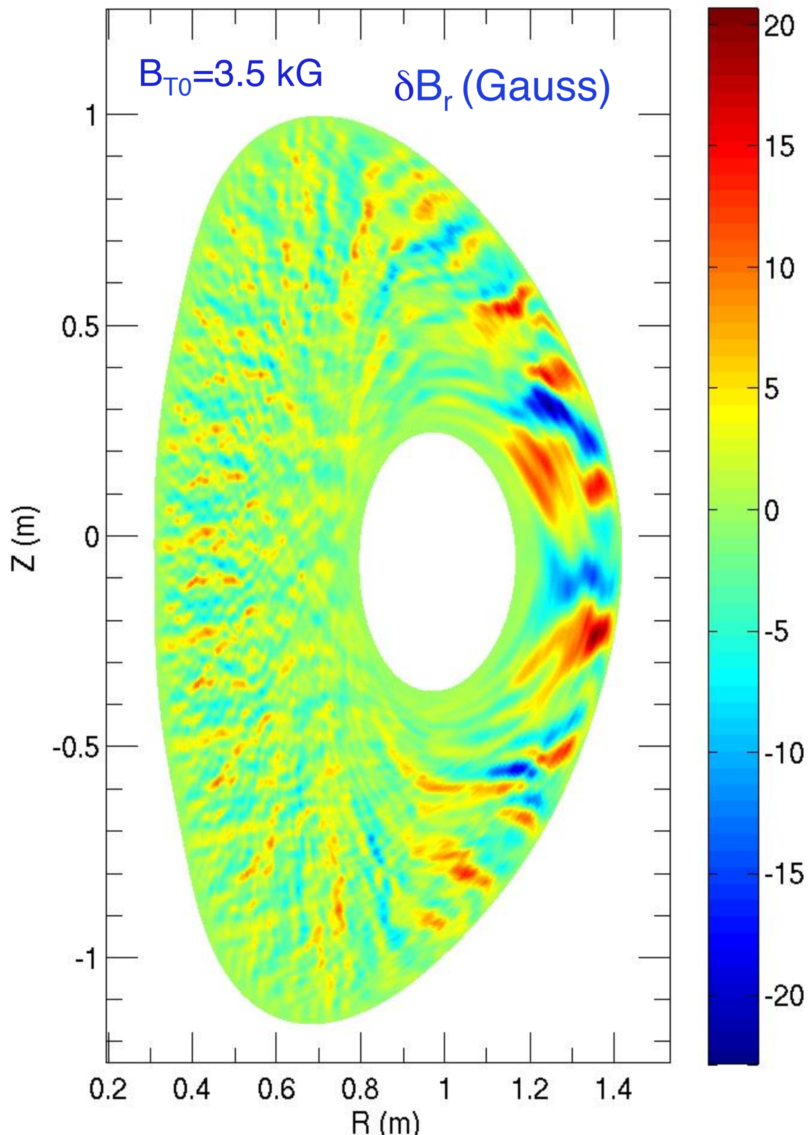
- Complicates simple interpretation from $\chi_{e,sim} \sim \nu_e^{1.1}$ scaling
- Useful to characterize scaling of threshold gradient
- Transport reduced when increasing γ_E to local experimental value, partially recovered with increase in ∇T_e



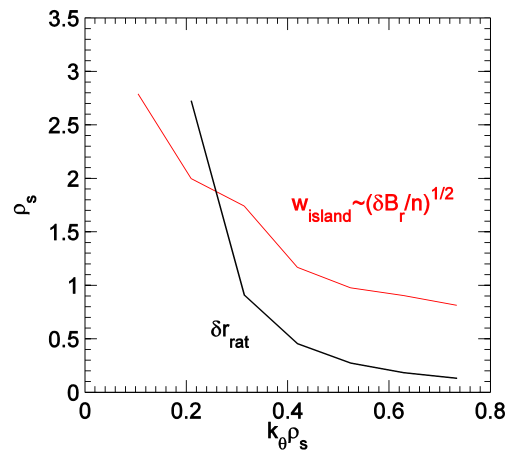
Error bars represent rms variation in transport, not standard error

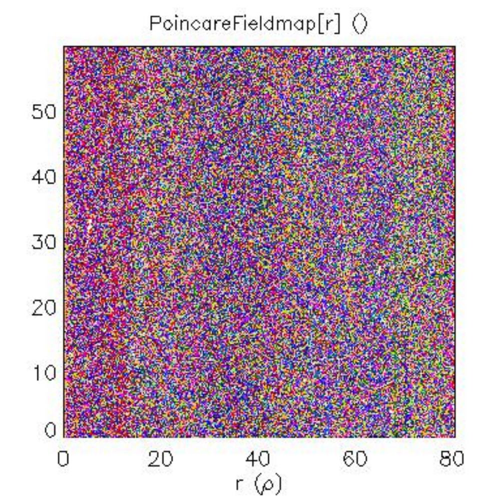


~98% of transport due to magnetic "flutter" contribution



- Large magnetic perturbations, $\delta B_r/B \approx 0.15\%$
- $w_{island}(n) > \delta r_{rat}(n)$, island overlap → field line trajectories are stochastic*
- $\chi_{e,EM} = 1.25\, \rho_s c_s^2/a$ close to *collisionless* Rechester-Rosenbluth* (λ_{mfp}=12 m, $L_c \approx 2.5$ m)





- New polarimetry system proposed for NSTX-Upgrade (UCLA, Jie Zhang et al. RSI, 2010) may be able to detect $(\delta B/B)_{internal} \leq 0.1\%$ (1-2^0 or ~0.3^0 rms

W. Guttenfelder et al., PRL 106, 155004 (2011)

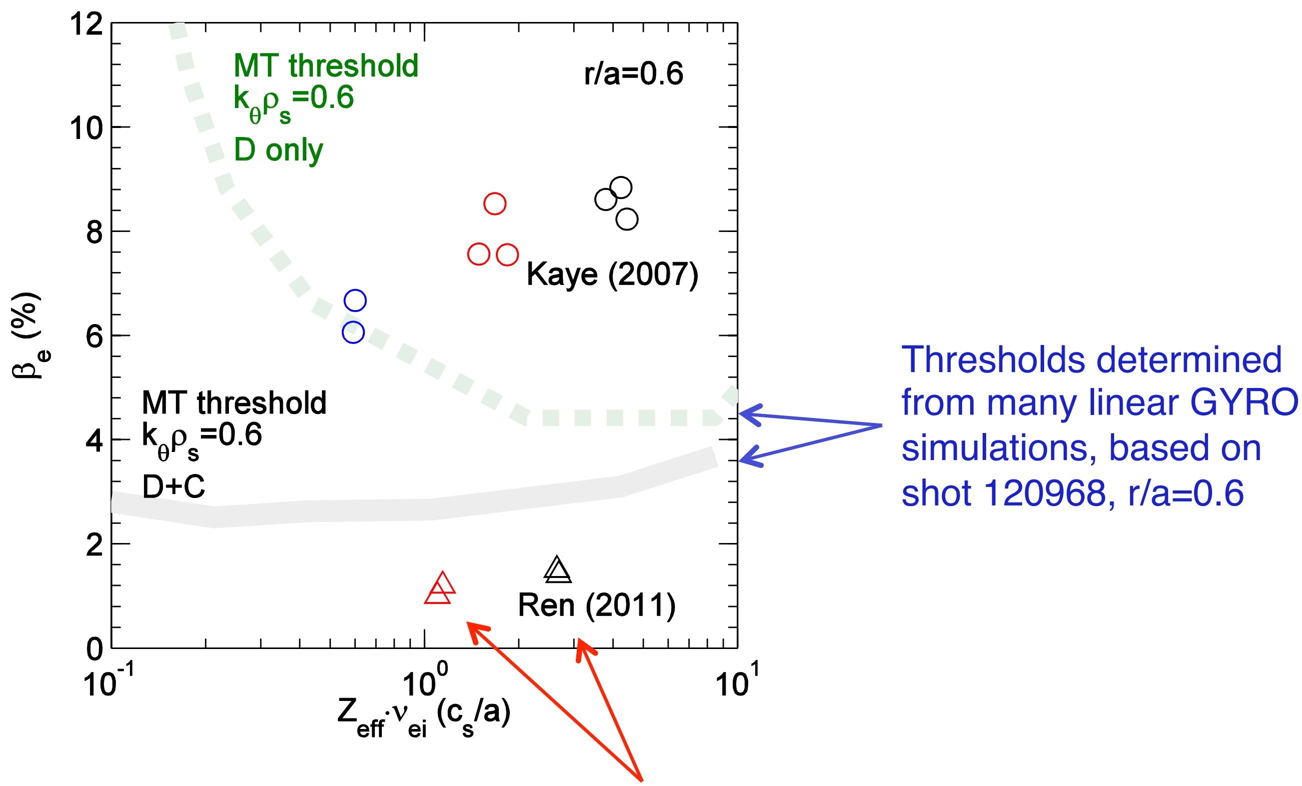
Movies at http://www.pppl.gov/~wgutten/

E. Wang et al., PoP (2011).

A.B. Rechester & M.N. Rosenbluth, PRL (1978)

NSTX has studied electron transport for a range of beta and collisionality

- Microtearing exhibits a threshold in β_e (or a/L_{Te}) that depends on ν_{ei}, Z_{eff}, etc…
- Distinguishes earlier scaling studies (Kaye, 2007) at higher beta compared to more recent studies (Ren, 2011)



- Following studies investigate ETG turbulence at "low β_e" where microtearing is predicted to be stable

Overview

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  - Improve understanding of core anomalous electron thermal transport in NSTX
  - Attempt to validate with turbulence simulations
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  - Predicts experimental level of electron thermal transport
  - Scaling of transport with collisionality ($\chi_{e,sim} \sim \nu_e$) consistent with confinement ($\Omega_i \tau_E \sim \nu_*^{-0.8}$)
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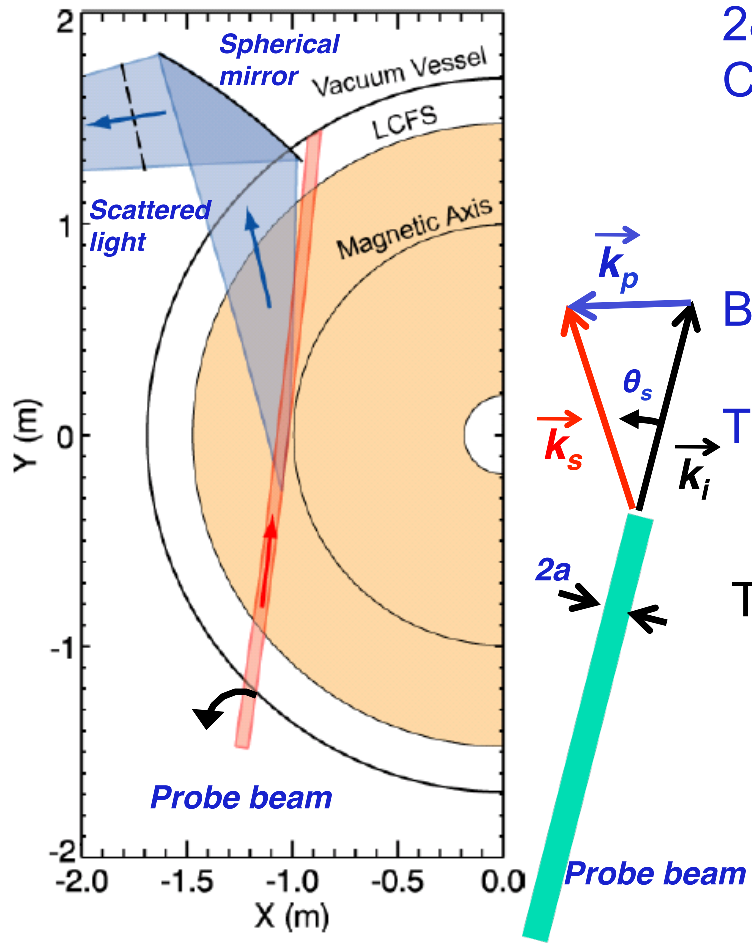
High-k microwave scattering system capable of measuring electron-scale turbulence



D.R. Smith, PhD thesis, 2009

280 GHz microwave is launched as the probe beam.

Coherent scattering by plasma density fluctuations occurs when the three-wave coupling condition is satisfied:

$$\vec{k}_s = \vec{k}_p + \vec{k}_i$$

Bragg condition determines k_p:

$$k_p = 2k_i \sin(\theta_s/2)$$

The scattered light has a frequency of:

$$\omega_s = \omega_p + \omega_i$$

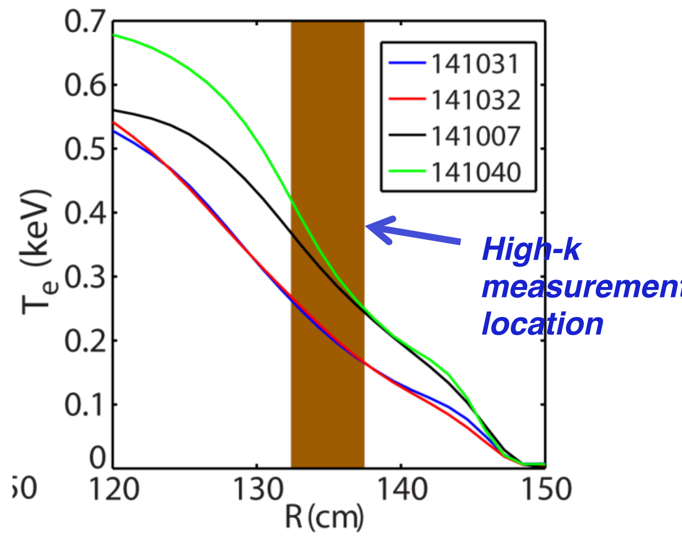
with ω_s and $\omega_i >> \omega_p$

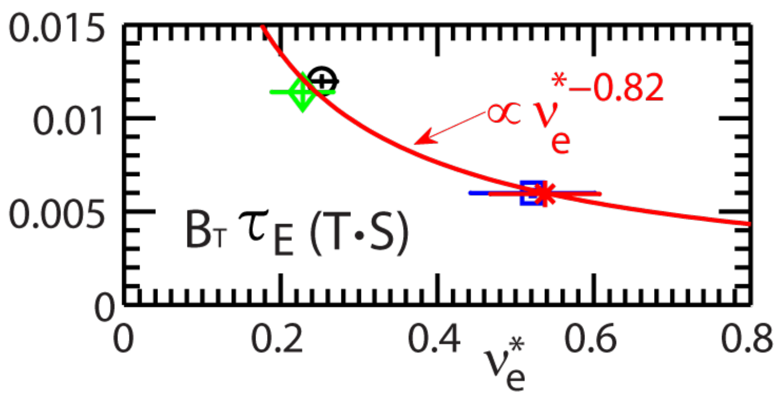
The scattering system characteristics are:

- **Frequency bandwidth: 5 MHz**
- **Heterodyne receiver: Wave propagation direction resolved**
- **Measurement: k_r spectrum**
- **Wavenumber resolution: 0.7 cm^{-1} (2/a with a ≈ 3 cm)**
- **Wavenumber *range (k_r): 5-30 cm^{-1} (~5-30 ρ_s^{-1})***
- **Radial resolution: ±2 cm**
- **Tangential resolution: 5-15 cm**
- **Radial range: R=106 – 144 cm**
- **Minimal detectable density fluctuation:** $|\delta n_e(k)/n_e|^2 \approx 2\times10^{-11}$

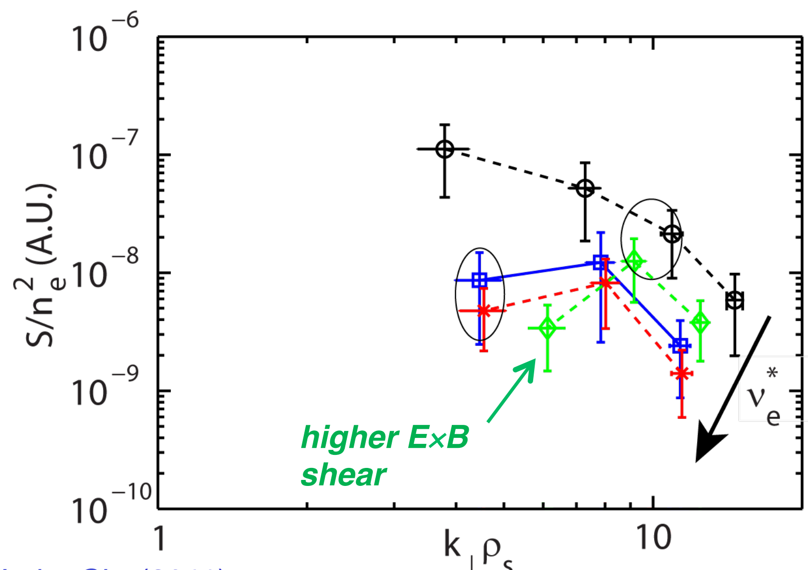
More recent experiment to study ν_{*e} scaling of electron scale turbulence using high-k scattering

- Factor ~2.5 change in ν_{*e}; local ρ_e, β_e, q_{95} are well matched around high-k measurement region (R=130-140 cm)
- Confinement scaling $\Omega_i\tau_E \sim \nu_*^{-0.82}$, similar to previous scaling $\Omega_i\tau_E \sim \nu_*^{-0.95}$





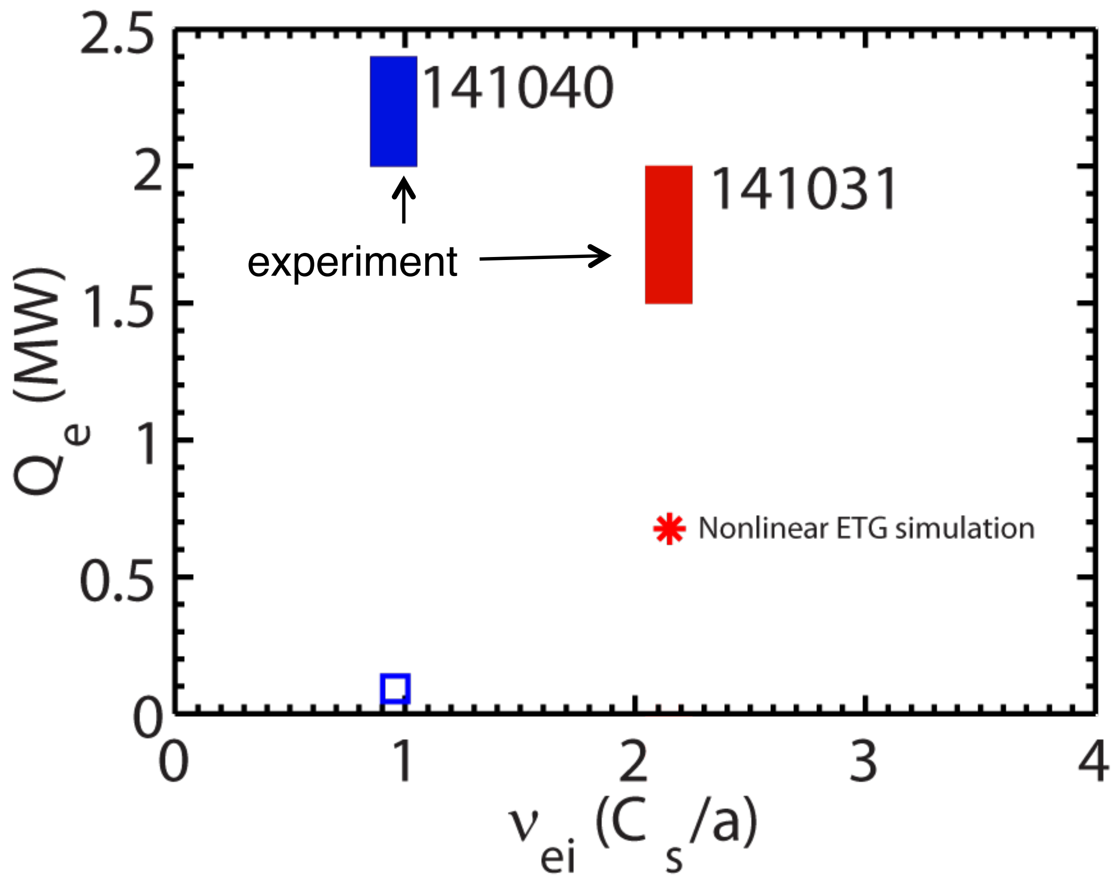
- High-k turbulence intensity decreases with increasing ν_{*e}
- Trend holds at all $k_\perp\rho_s$ except for one case where local E×B shear is ~2× larger



* Ren et al., *APS-DPP invited talk TI2.02, Salt Lake City* (2011)

Local nonlinear ETG simulations show large deviation from experimental transport

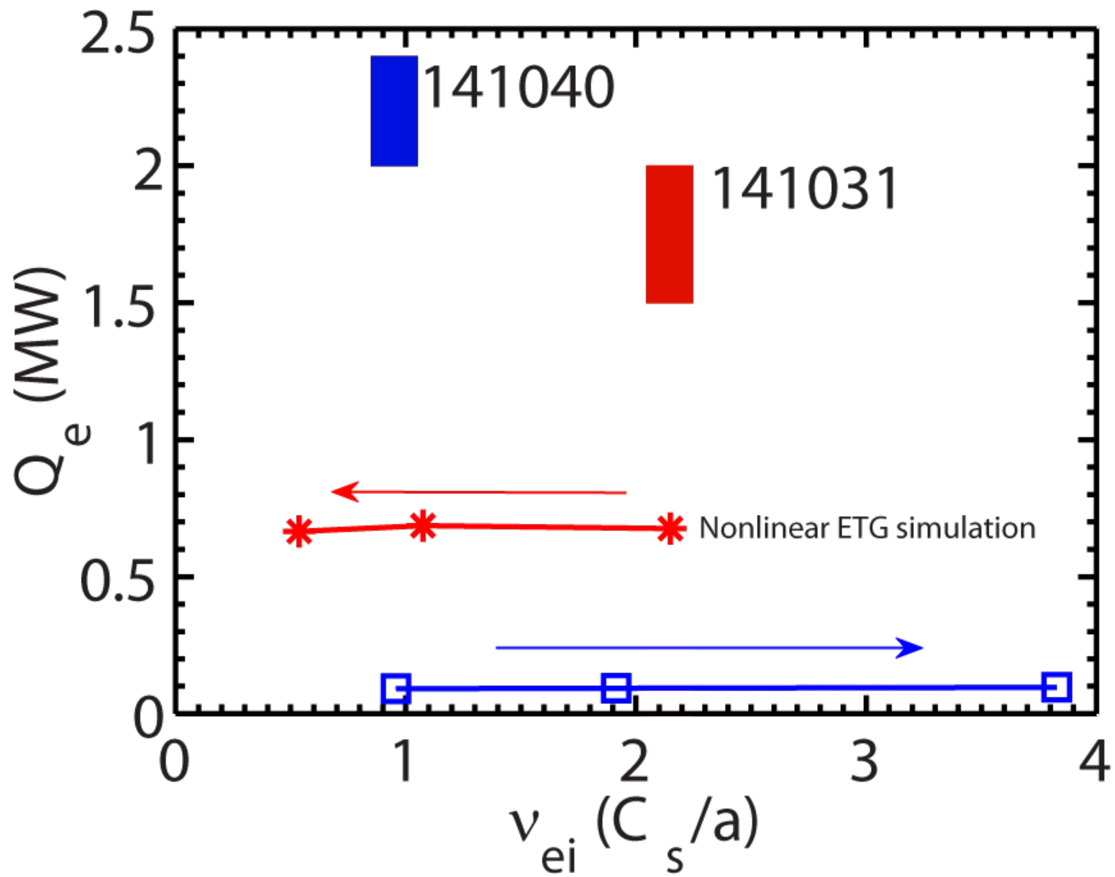
- In these lower beta discharges ETG is locally unstable (no microtearing)
- Predicted heat flux much smaller than experiment
- Can not be accounted for by sensitivity in a/L_{Te}



Nonlinear GYRO ETG simulations with: local general equilibrium, kinetic ions and electrons, collisions, electromagnetic, flow and flow shear

Local nonlinear ETG simulations show weak collisionality dependence

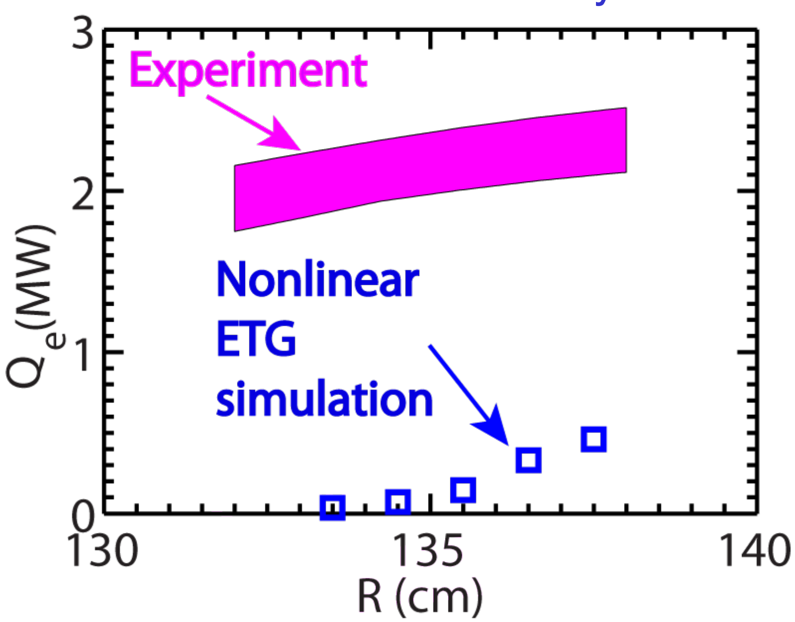
- No dependence of predicted ETG transport on ν_e
- Can not explain confinement scaling through ETG dependence on ν_e alone



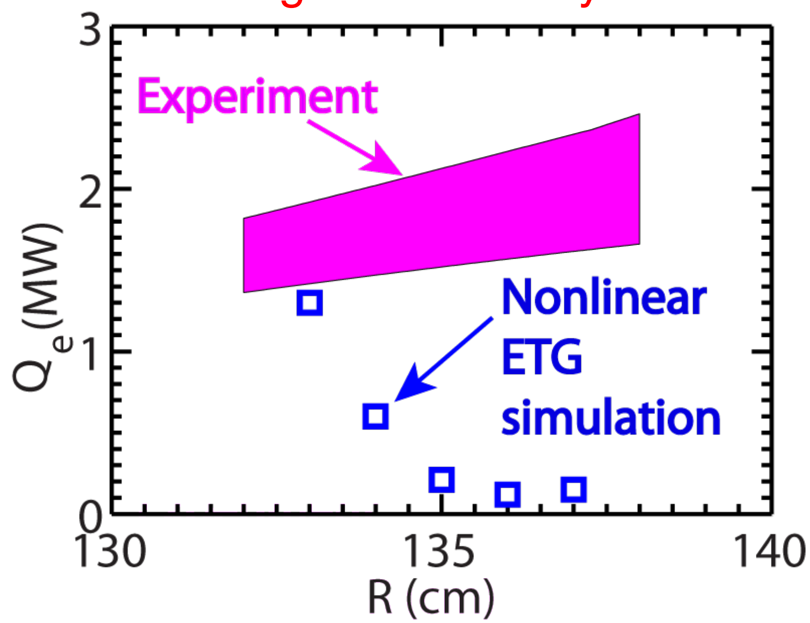
Profile variations lead to significant variation in local transport predictions

- Radial variation in other parameters (notably a/L_n, q & s) cause dramatic change in predicted transport over high-k measurement region (ΔR~4 cm)
- Large discrepancy remains for the low collisionality shot
- Match with experimental Q_e found at inner radii for the high collisionality shot

Low collisionality



high collisionality



- Pursuing "global" ETG simulations with profile variations
- ITG also found to be unstable at different radii with $\gamma_{lin} > \gamma_E \rightarrow$ ion scale (~7 ρ_i) turbulence spreading may also be important

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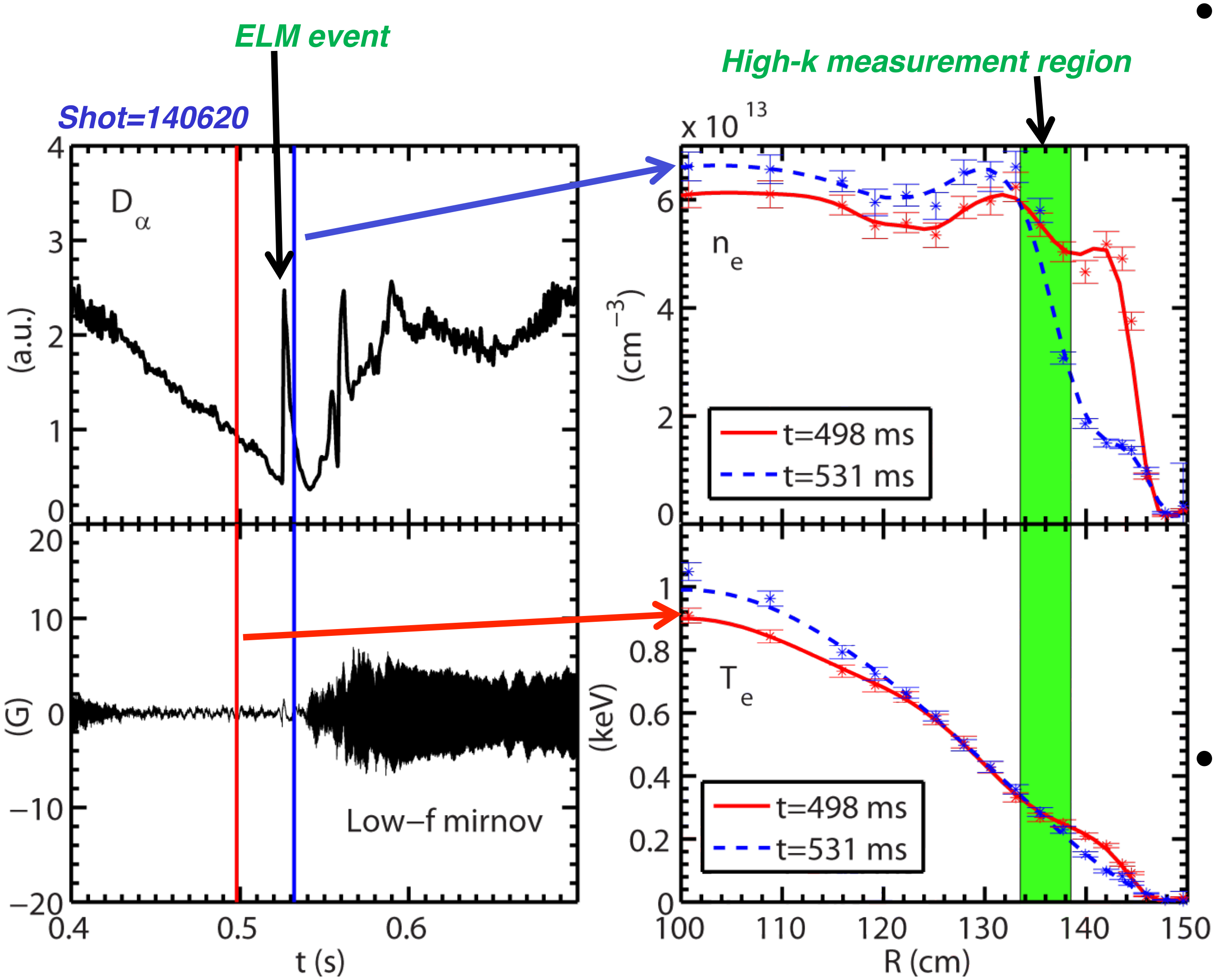
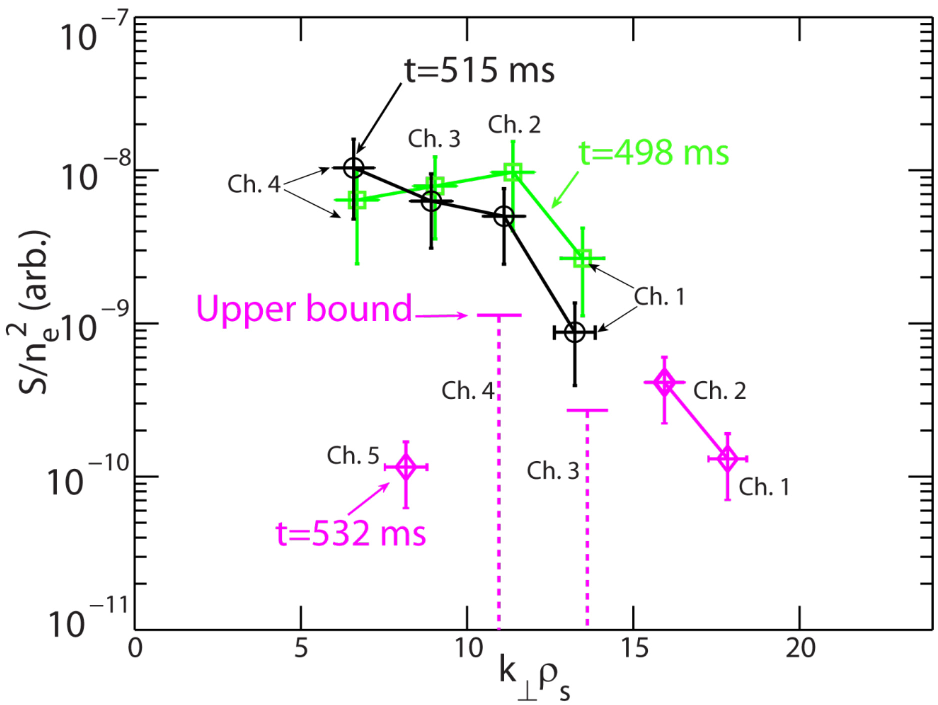
Using increased density gradient induced by a large ELM as a tool for local turbulence studies

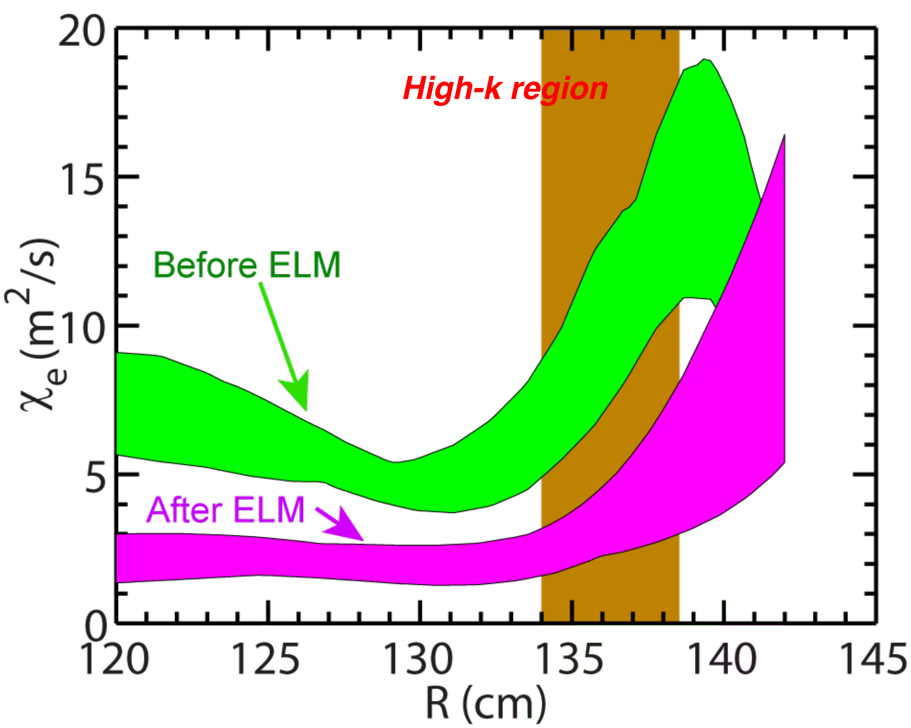


- After the ELM event:
  - Large density gradient developed in the high-k measurement region.
  - Electron temperature gradient also increases
  - Electron density has only a moderate decrease
  - Electron temperature remains essentially constant
- No large MHD mode appears before and right after the ELM event

Correlation between reduced measured turbulence intensity and improved plasma thermal confinement*

- Significant decrease in spectral power observed for $k_\perp \rho_s \lesssim 10$
- Electron thermal diffusivity is decreased by a factor of ~2 after the ELM event

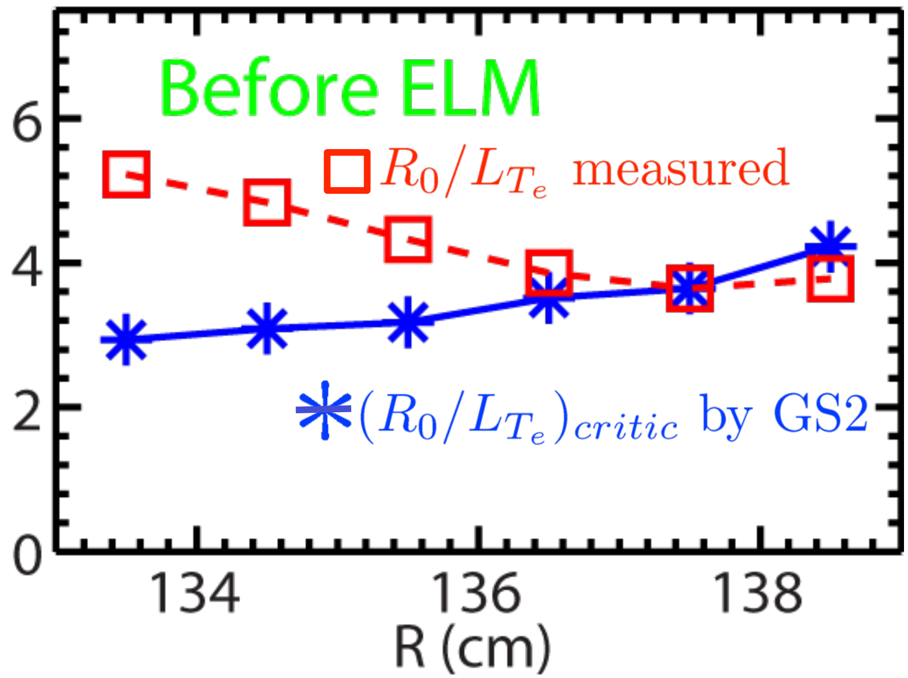


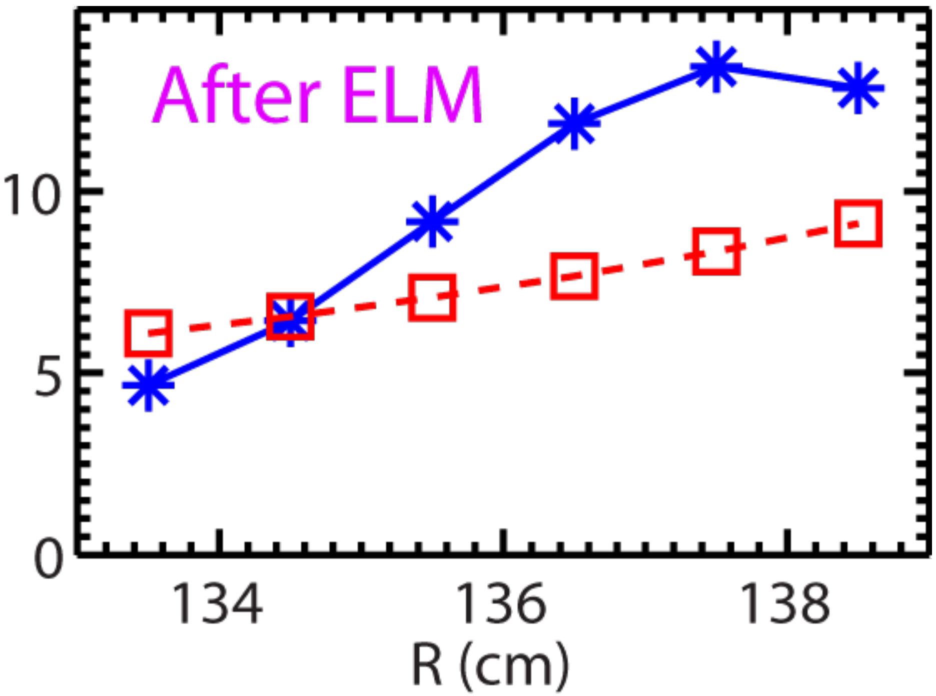


*Y. Ren et al., PRL 106, 165005 (2011)

Threshold gradients for ETG modes are much higher after the ELM

- Before ELM, ETG is largely unstable
- After ELM, ETG is largely stable

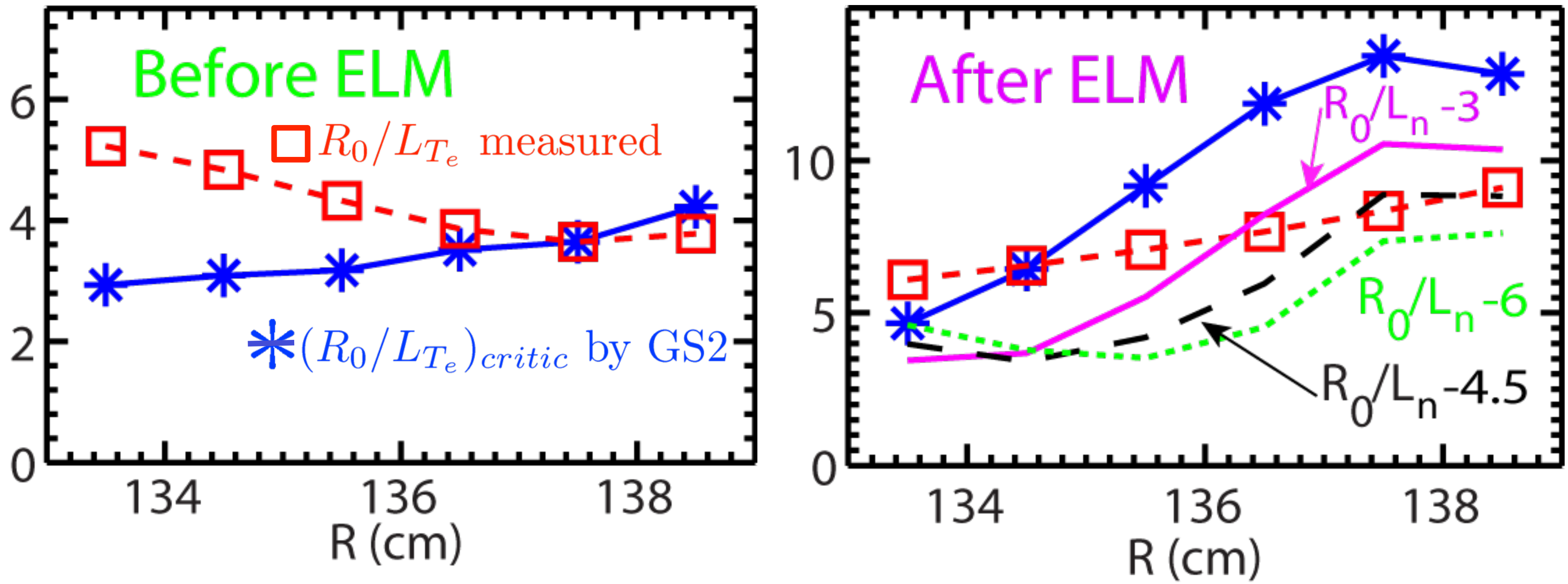




- Stability analysis performed with GS2 code (Kotschenreuther et al., 1995)

Increase in ETG threshold gradient is due to large density gradient

- Before ELM, ETG is largely unstable
- After ELM, ETG is largely stable



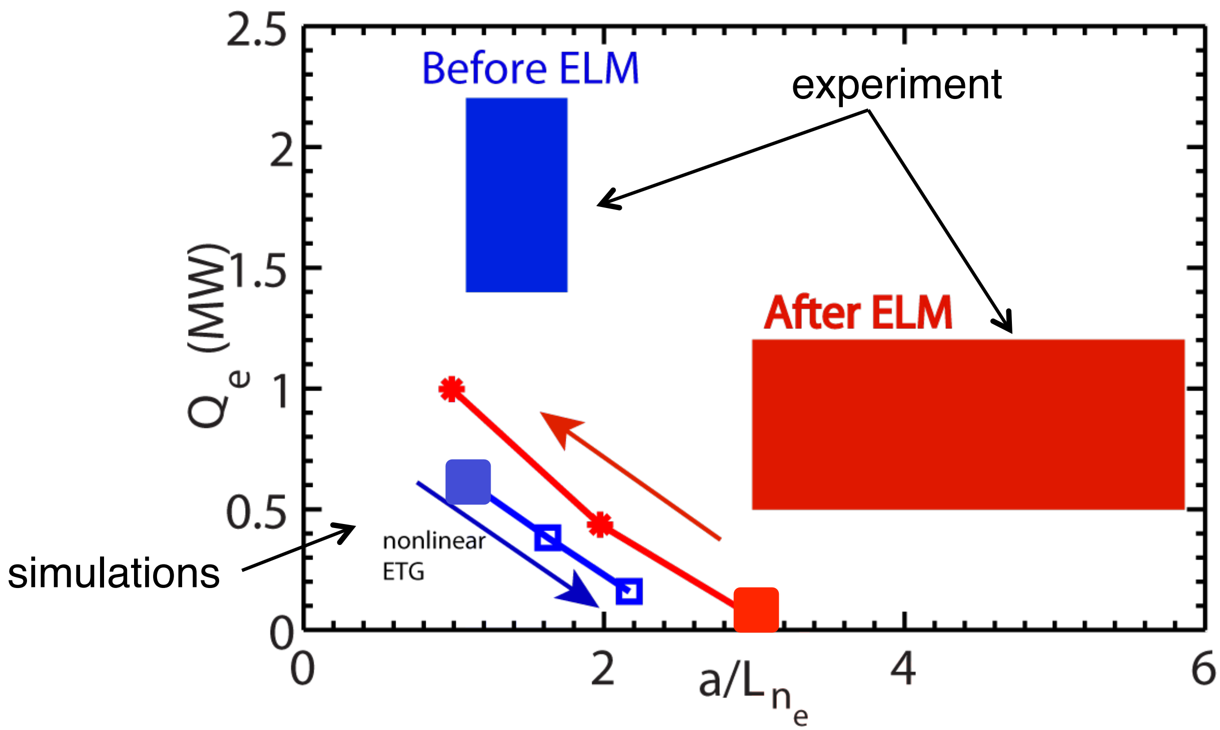
- Manually decreasing R/L_{ne} brings down critical gradient as expected from linear theory (e.g. Jenko et al, 2001)

$$(R_0/L_{T_e})_{crit} = \underline{max}\{(1+Z_{eff}\frac{T_e}{T_i})(1.33+1.99\hat{s}/q)f(\epsilon,\kappa,\delta,\cdots),\ \underline{0.8R_0/L_{n_e}}\}$$

  - Stability analysis performed with GS2 code (Kotschenreuther et al., 1995)

Nonlinear ETG simulations reproduce observed dependence of electron transport on density gradient

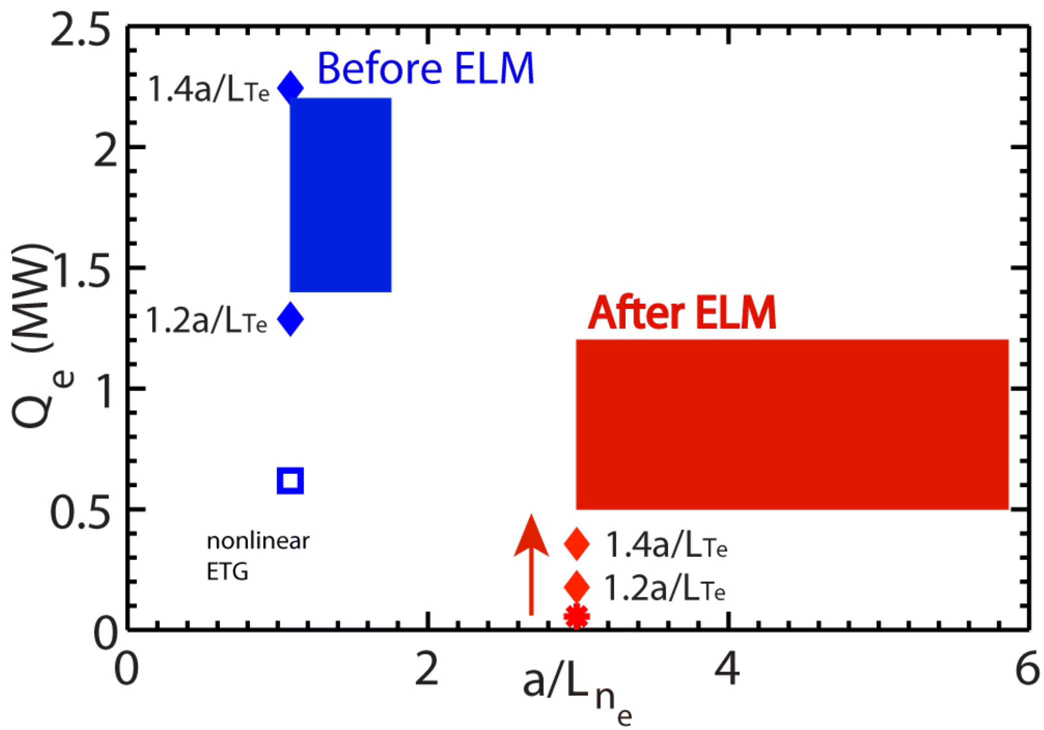
- Experimental Q_e is found to decrease after the ELM event with large density gradient
- The same trend is found from nonlinear ETG simulations, but does not agree quantitatively



Nonlinear GYRO ETG simulations with: local general equilibrium, kinetic ions and electrons, collisions, electromagnetic, flow and flow shear

Predicted Q_e sensitive to temperature gradient

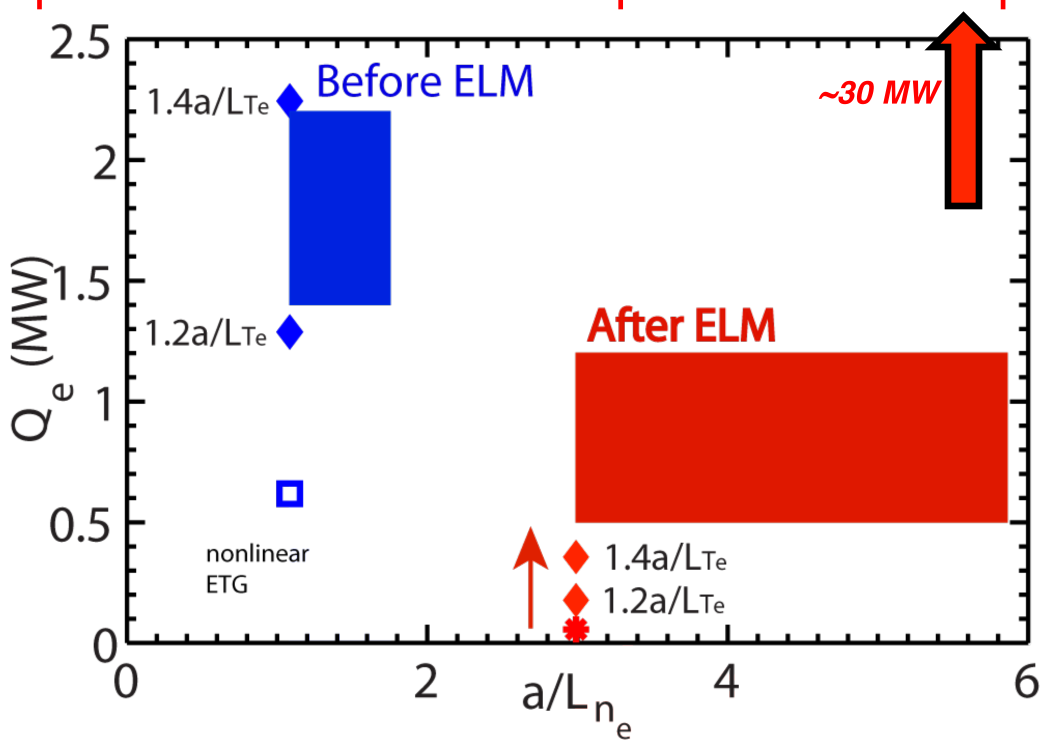
- Before ELM, a 20-30% increase in a/L_{Te} is able to match the experimental Q_e
- After ELM, increasing a/L_{Te} by 40% after still cannot match experimental Q_e



Trapped Electron Mode (TEM) destabilized by large density gradient may contribute to transport

- Before ELM, a 20-30% increase in a/L_{Te} is able to match the experimental Q_e
- After ELM, increasing a/L_{Te} by 40% after still cannot match experimental Q_e
- Large TEM-induced transport (~30 MW) is predicted after ELM without E×B shear stabilization
- Using experimental E×B shear almost completely suppresses transport

→ does not require much residual transport to match experimental Q_e



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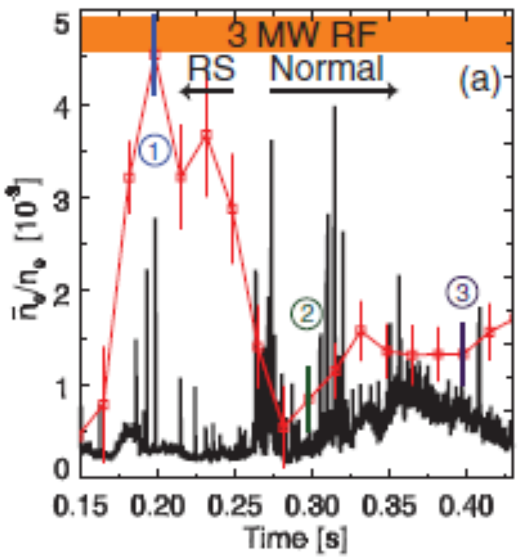
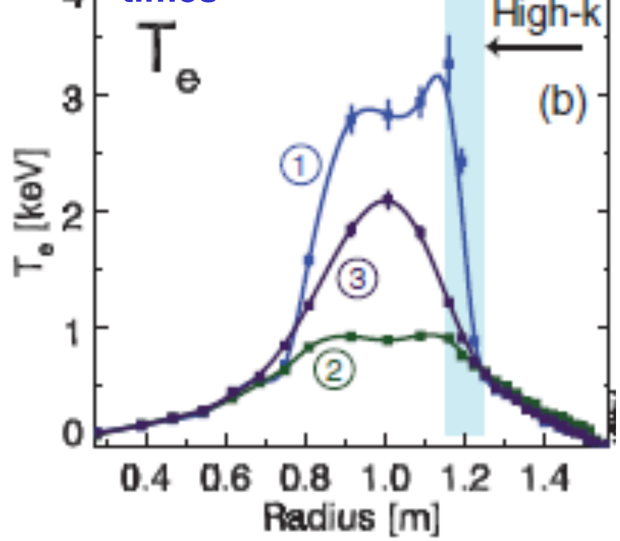
Electron internal transport barrier (e-ITB) occurs in L-mode with large reverse magnetic shear, s<<0

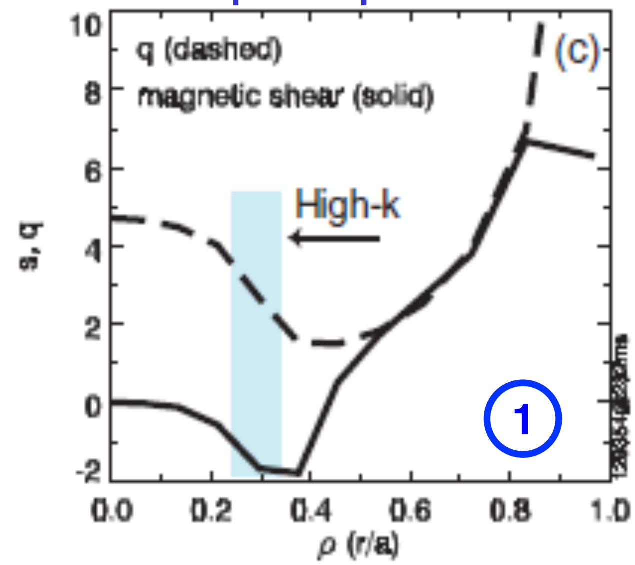
δn/n and R/L_{Te} vs. time



T_e profiles at three times



q and s profiles



① e-ITB occurs only during reversed shear portion of discharge, even in the absence of E×B shear

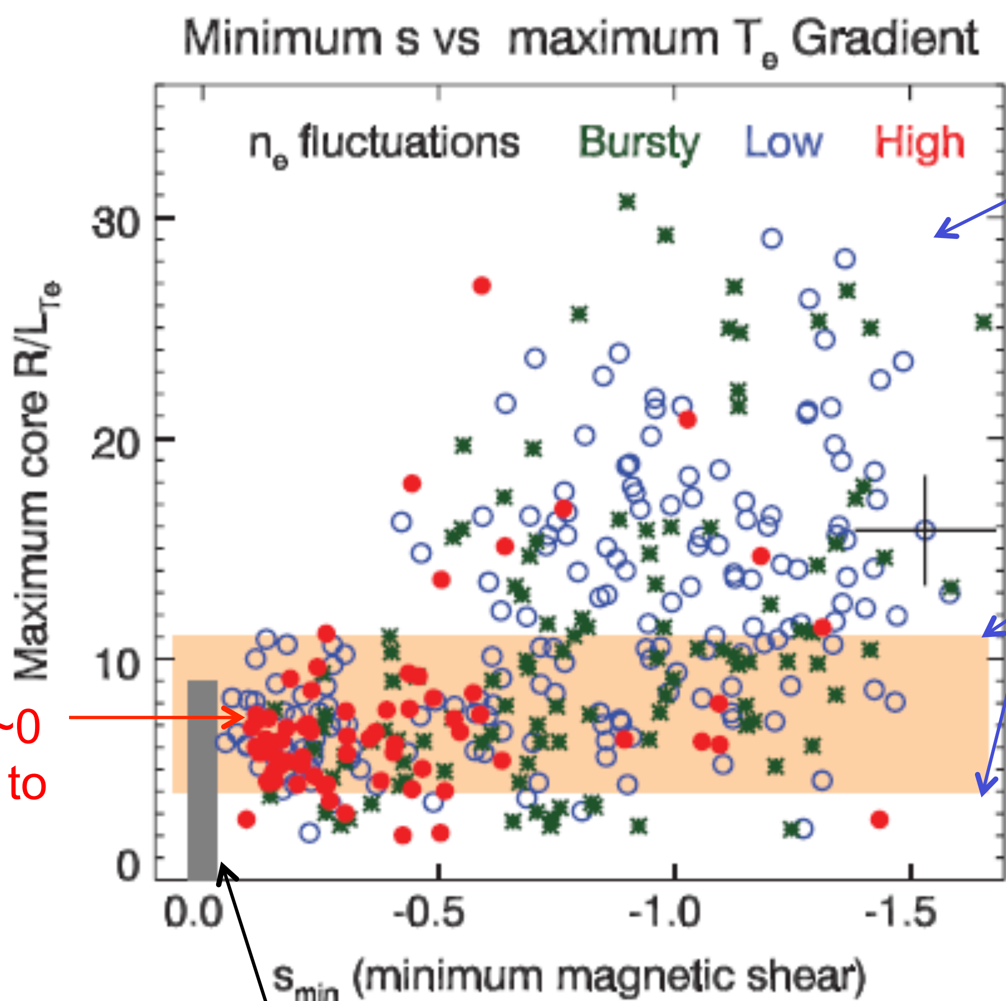
Very low, or bursty, high-k fluctuations in e-ITB

② Current is suddenly redistributed by MHD leading to monotonic q profile

③ → near zero or positive s, larger high-k fluctuations, smaller maximum gradient

Largest gradients and weak high-k turbulence correlated with largest negative shear

Many discharges
2 MW NBI
0-3 MW RF
$1\text{-}4\times10^{19}$ m^{-3}
Z_{eff}=1.1-4 (D, He)



Highest R/L_{Te} occur for s<<0

Low or bursty high-k fluctuation intensity

Well above linear thresholds (supercritical)

For weak shear, s~0 R/L_{Te} limited close to linear threshold

Large high-k fluctuation intensity

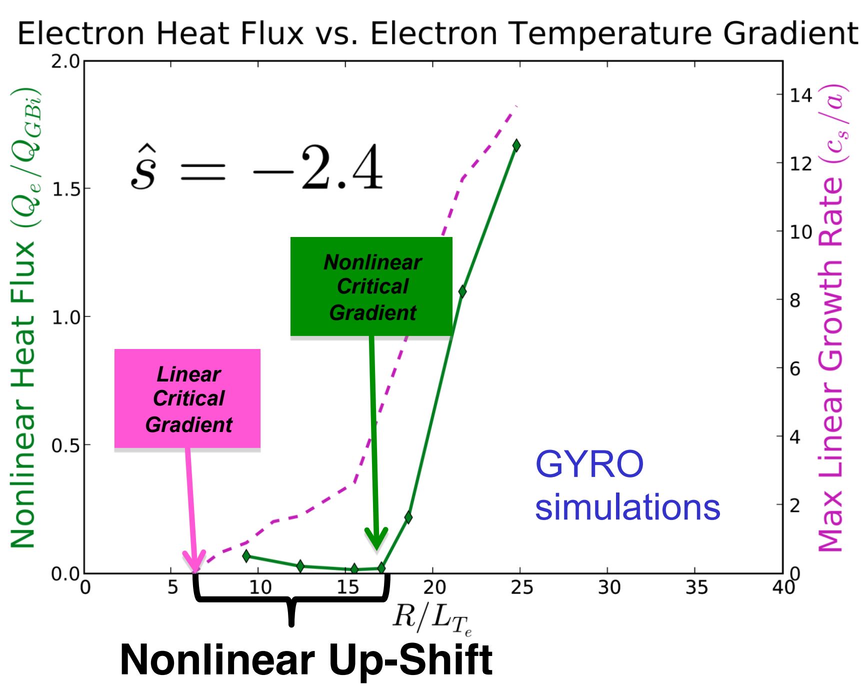
Characteristic H-mode values

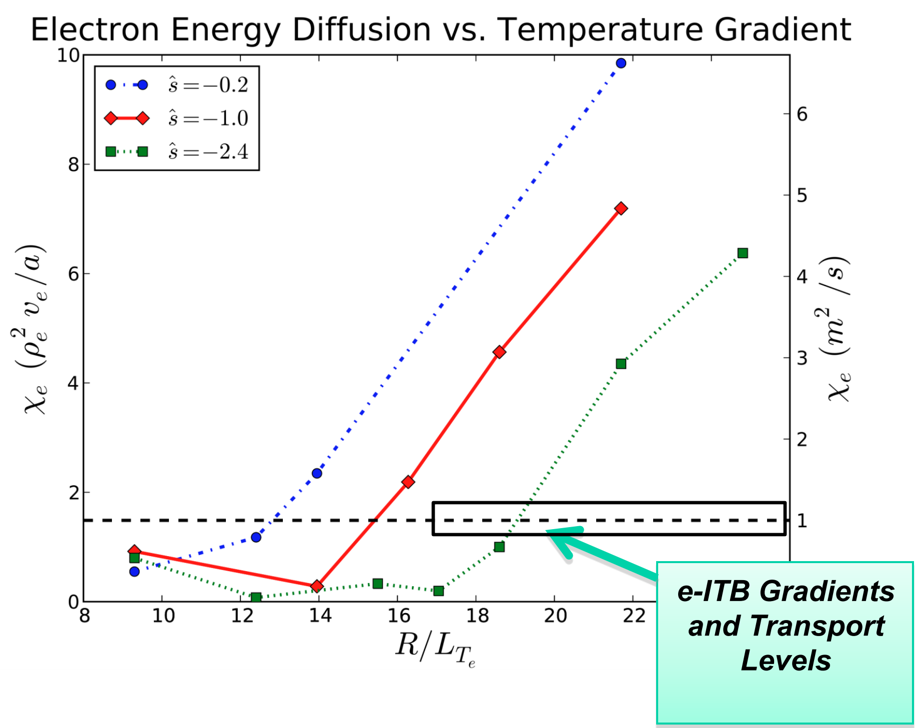
H. Yuh, Phys. Rev. Lett. 106, 055003 (2011)

Large negative magnetic shear causes strong upshift in effective non-linear ETG threshold

- Nonlinear threshold much larger than linear threshold for large negative shear in agreement with supercritical ETG gradients observed in experiments

- Nonlinear threshold increases with reverse shear magnitude, s<0
- Magnitude and scaling of predicted transport consistent with experiment





J.L. Peterson, Ph.D. Thesis, PPPL (2011); APS invited talk TI2.03, Salt Lake City (2011)

Overview

- Motivation
  - Improve understanding of core anomalous electron thermal transport in NSTX
  - Attempt to validate with turbulence simulations
- First nonlinear gyrokinetic simulations of micro-tearing turbulence for "high beta" H-mode plasmas
  - Predicts experimental level of electron thermal transport
  - Scaling of transport with collisionality ($\chi_{e,sim} \sim \nu_e$) consistent with confinement ($\Omega_i \tau_E \sim \nu_*^{-0.8}$)
- Parametric dependence of high-k turbulence measured by a microwave scattering diagnostic in "low beta" plasmas
  - Collisionality dependence of high-k turbulence in H-mode
  - Density gradient stabilization of ETG turbulence in H-mode, partially validated with non-linear simulations
  - Suppression of ETG turbulence in reverse shear L-mode plasmas with e-ITB, partially validated with non-linear simulations
- First low-k turbulence measurements from a newly implemented BES diagnostic
  - Decrease in low-k turbulence from L-H mode transition, from edge to core
  - Poloidal correlation lengths in the edge pedestal region correlated with q, s^{-1}, ∇n
- Summary

Beam Emission Spectroscopy (BES) diagnostic recently commissioned, obtained data routinely during FY10-11

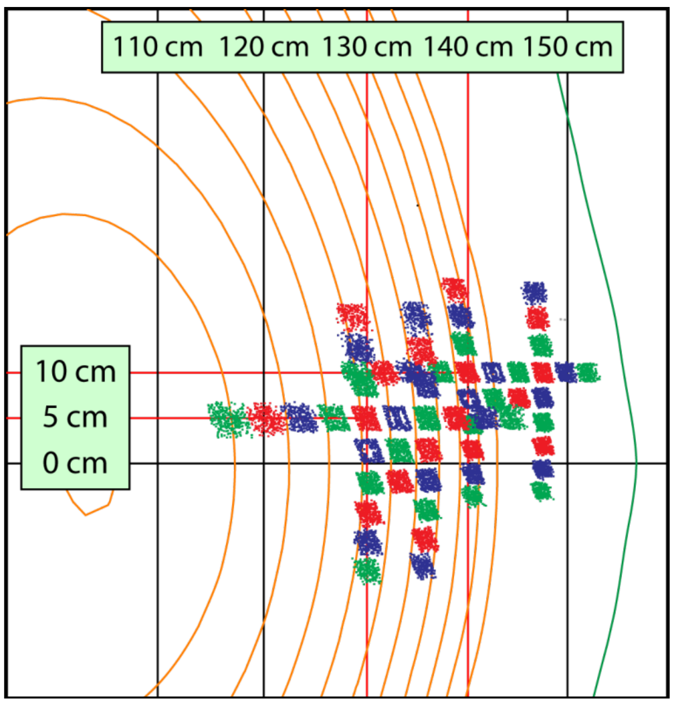
- Presently 32 detection channels
- 56 sightlines in radial and poloidal arrays spanning core to SOL
- 2 MHz sampling
- $k_\perp \rho_i \leq 1.5$ & 2-3 cm spot size
- Field-aligned optics with high throughput (etendue = 2.3 mm^2-ster)

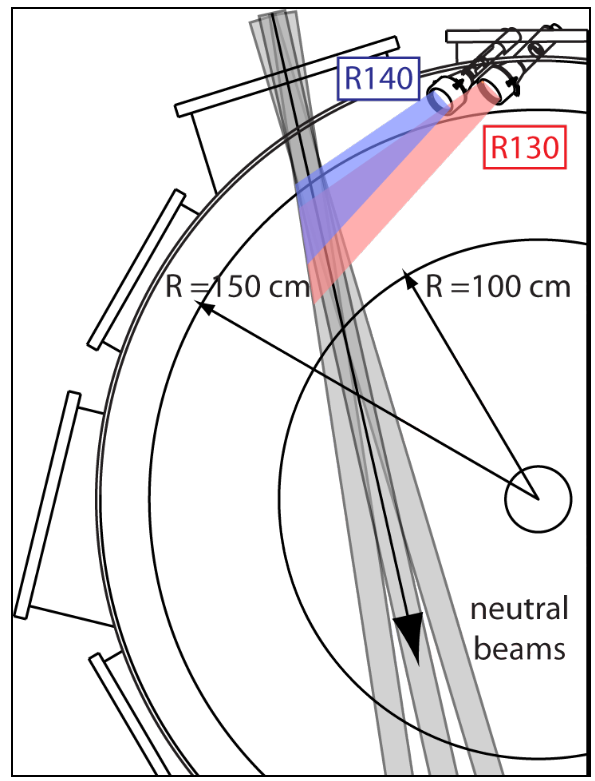
$$\frac{\delta I_{D\alpha}}{I_{D\alpha}} = \frac{\delta n}{n} \times C\left(E_{NB}, n, T_e, Z_{eff}\right)$$

neutral beam D_α emission

density fluctuation

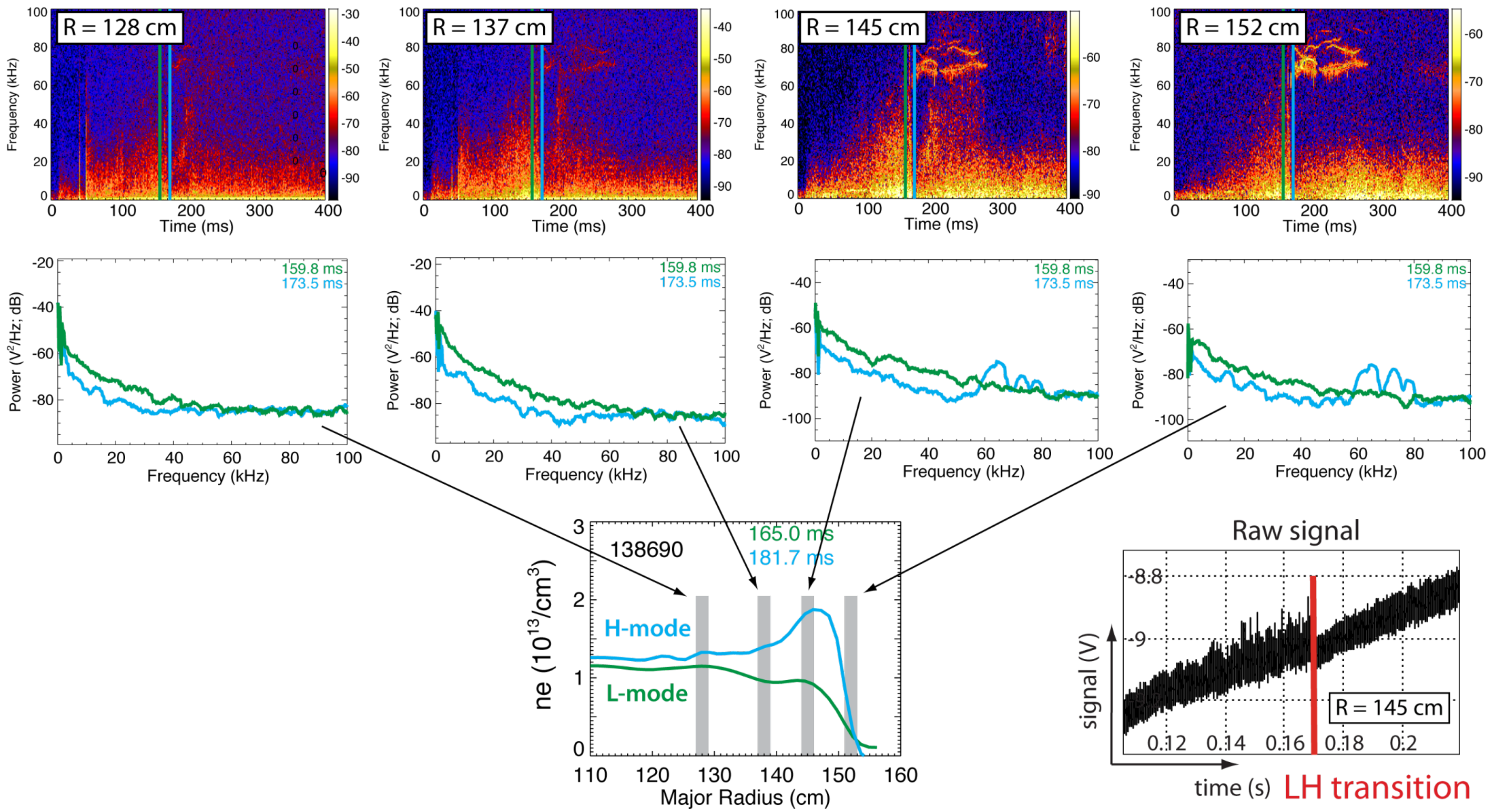
C ≈ 1/2





*D.R. Smith et al., Rev. Sci. Instrum (2010)

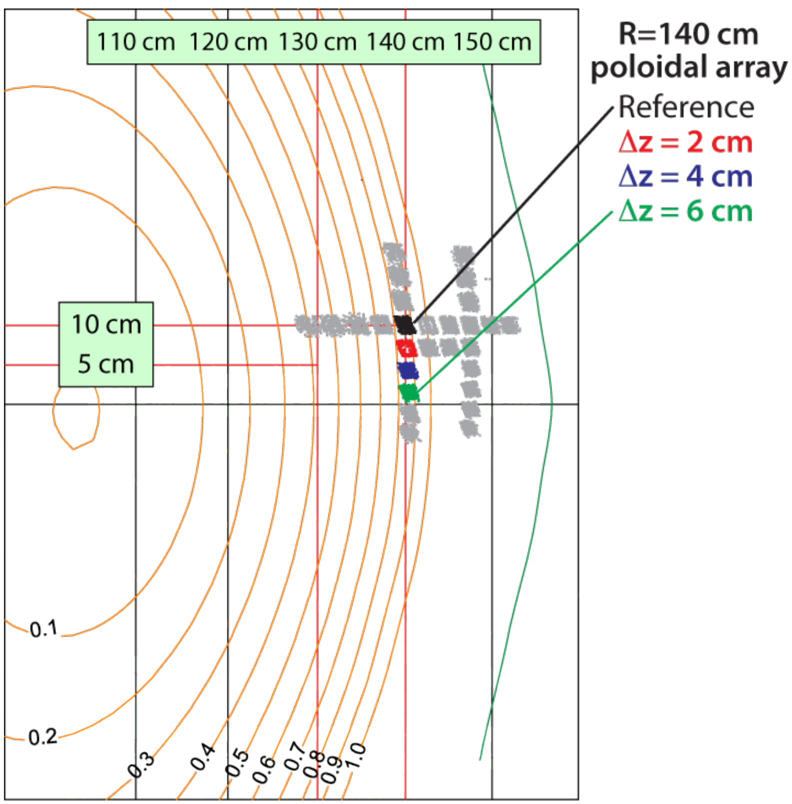
Decrease in low-k turbulence observed at L-H transition from edge to core

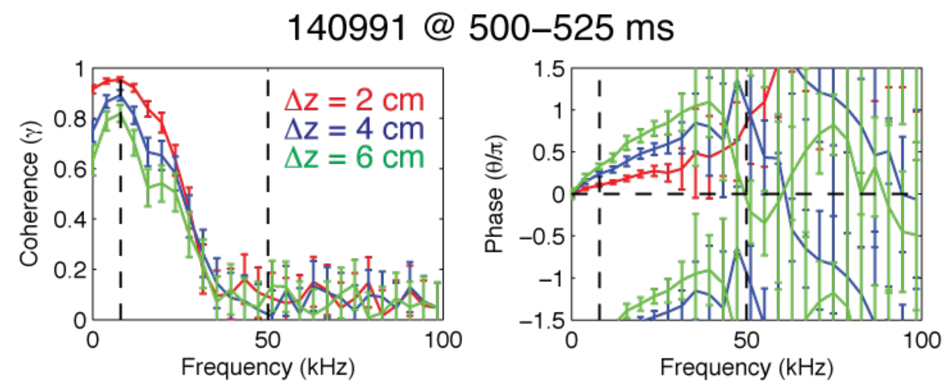


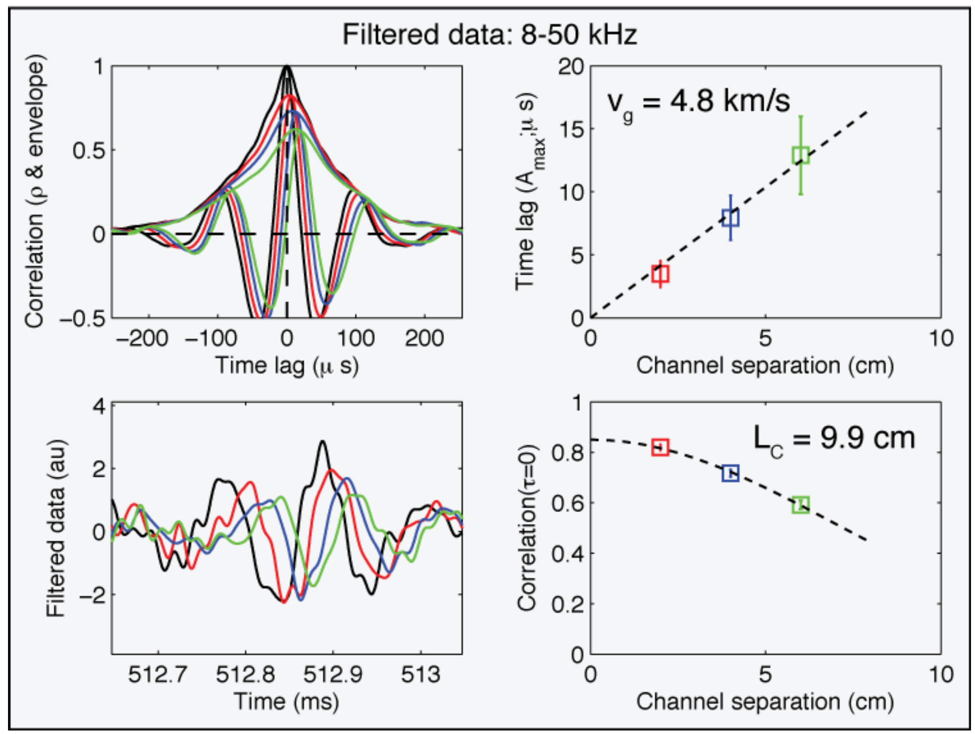
R. Fonck, G. McKee, D. Smith, and I. Uzun-Kaymak (UW-Madison) and B. Stratton (PPPL)

Poloidal correlation length (L_C) obtained from BES poloidal array at R=140 cm (r/a ≈ 0.8-0.95)

- Correlation functions and coherence spectra indicate:
  k_θ ≈ 0.2-0.4 cm^{-1} and **$k_\theta\rho_i$ ≈ 0.1-0.25**
- Cross-phase and time-lags show eddy advection in **ion diamagnetic direction**







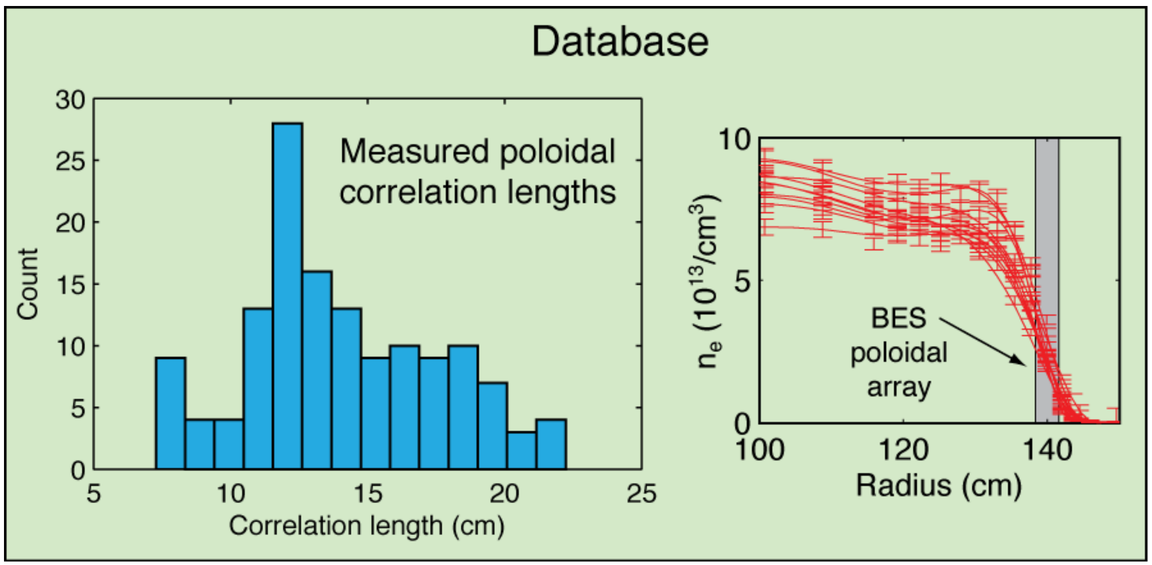
Poloidal L_c in pedestal region are 7-22 cm, appear to be correlated with q, 1/s, ∇n_e

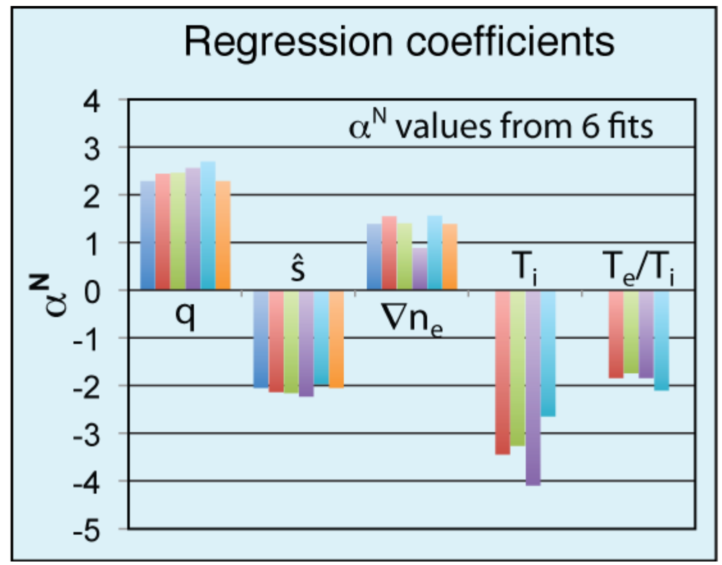
- Poloidal L_c database for ELM-free, MHD-quiescent H-mode contains 130 entries from 29 shots (fixed B_{T0} = 4.4 kG), in the pedestal region
- Regression analysis attempts to fit scaling of L_c to different parameters, e.g. n_e, T_e, T_i, $\nabla(n_e,T_e,T_i)$, $a/L_{(ne,Te,Ti)}$, q, ŝ, ν, β, etc…

$$L_C = \bar{L}_C + \sum \alpha_i^N \frac{x_i - \bar{x}_i}{\sigma_{xi}}$$

scaling coefficient (α_i^N); plasma parameters (x_i)

- Best fits find poloidal L_c increases with q, ∇n_e, decreases with s, T_i, T_e/T_i



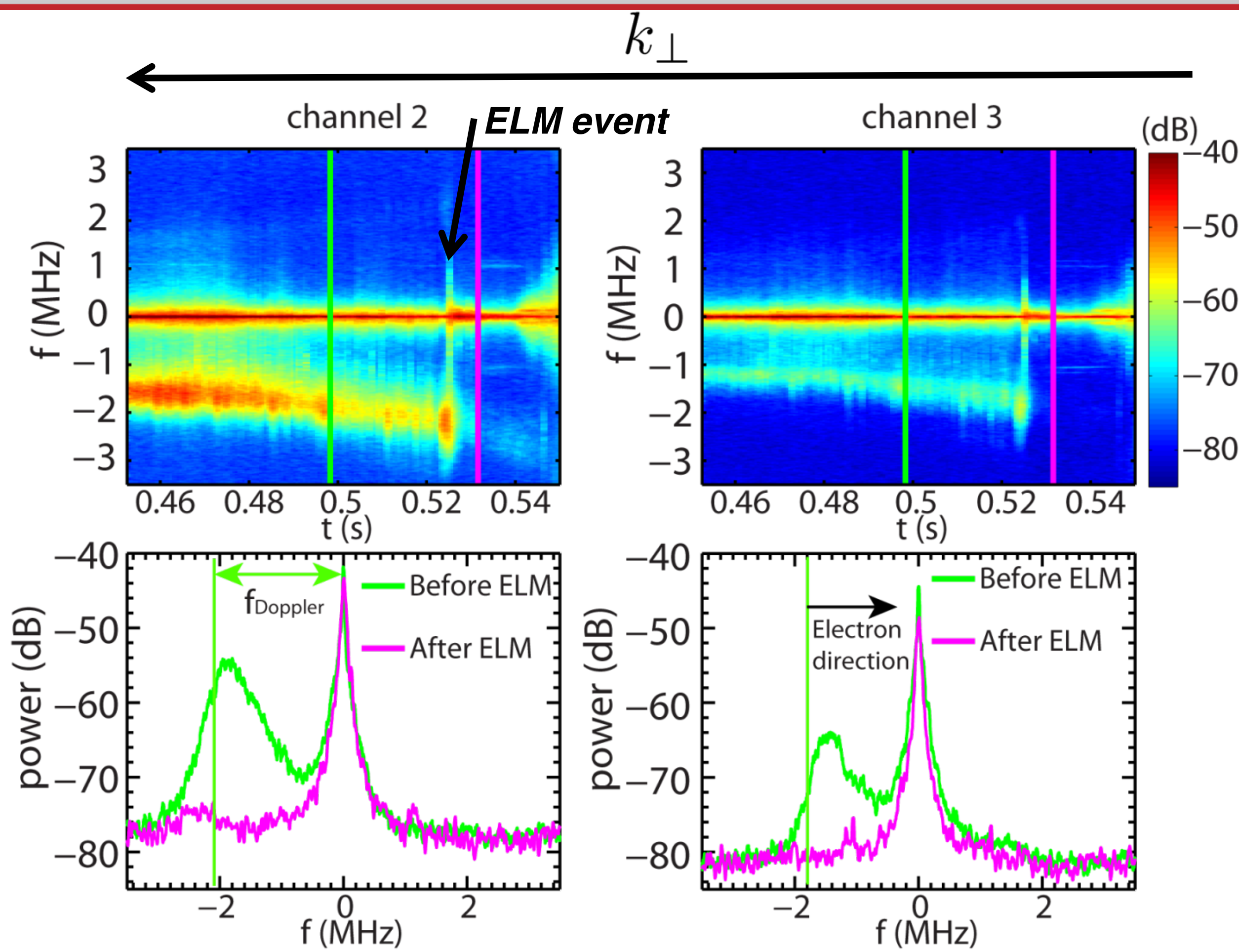


D.R. Smith et al., APS-DPP, Salt Lake City (2011)

Summary: NSTX is making progress towards understanding anomalous electron thermal transport

- First nonlinear gyrokinetic simulation of micro-tearing turbulence in NSTX H-mode "high beta" plasmas reproduce magnitude and ν_* scaling of electron transport
- In "lower beta" plasmas, where microtearing is stable:
  - High-k scattering intensity increases with decreasing ν_* → ETG appears to be relevant at limited radial locations, doesn't directly account for ν_* scaling, requires more work to include profile effects, ITG may also be important
  - High-k turbulence stabilized by large density gradient → scaling reproduced by non-linear ETG simulations, TEM may become important at large a/L_{ne}
  - e-ITB occurs at large negative magnetic shear in L-mode plasmas → large non-linear threshold reproduced by ETG simulations
- The newly implemented BES diagnostic provides first low-k turbulence measurements in NSTX
  - Decrease in low-k turbulence during L-H transition, from core to edge
  - Poloidal correlation lengths increase with q, a/L_n, decrease with s, T_i, T_e/T_i
- Please note, I have not covered many transport and turbulence topics: (1) core impurity and momentum transport, (2) transport driven by energetic particle modes, GAEs, CAEs, (3) many other edge/pedestal/SOL measurements→see NSTX website!

Significant decrease in scattering signal power observed after the ELM



- All five channels saw decreased scattering power after the ELM event
- Interpretation has to take into account the change of wavenumber measured by each channel due to the increase density gradient & refraction after the ELM event

Linear microtearing instability

- High-m tearing mode around a rational $q(r_0)=m/n$ surface ($k_{||}(r_0)=0$)
  (Classical tearing mode stable for large m, $\Delta' \approx -2m/r<0$)
- Driven by ∇T_e with time-dependent parallel thermal force* $\Rightarrow$ *requires e-i collisions*

<u>Conceptual linear picture</u>

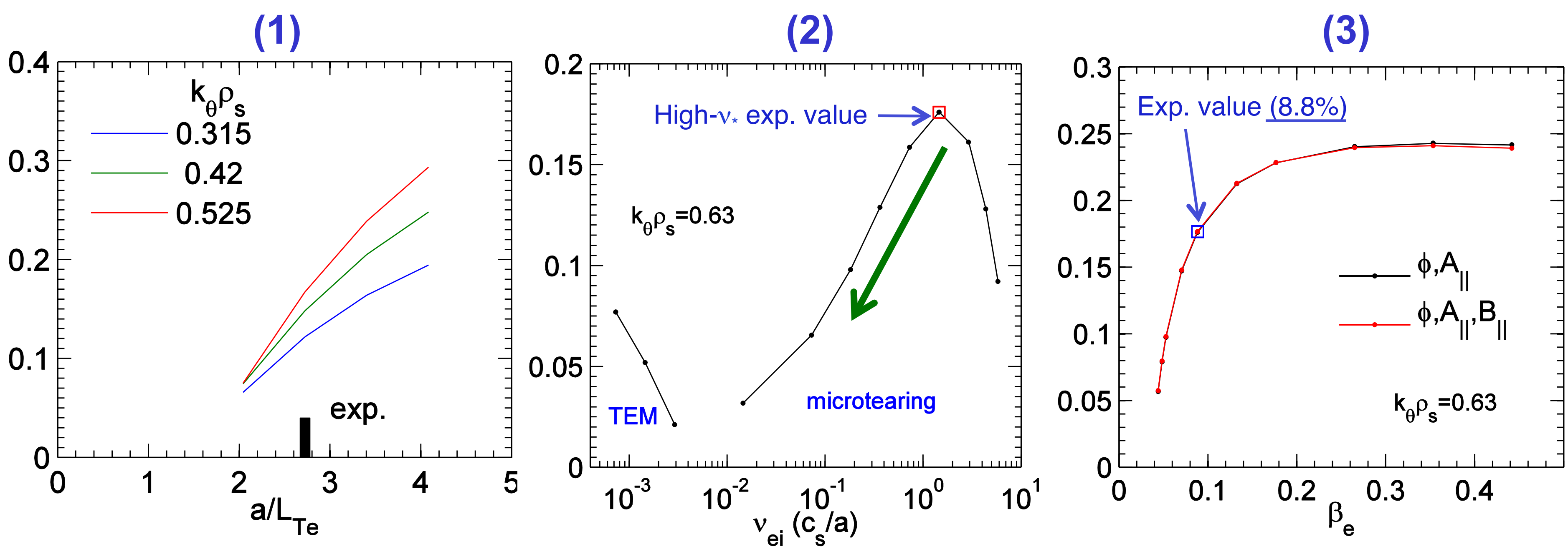
- Imagine helically resonant (q=m/n) δB_r perturbation $\quad \delta B_r \sim \cos(m\theta - n\varphi)$
- δB_r leads to radially perturbed field line, finite island width $\quad w = 4\left(\frac{\delta B_r}{B}\frac{rR}{n\hat{s}}\right)^{1/2}$
- ∇T_e projected onto field line gives parallel gradient $\quad \nabla_{||} T_{e0} = \frac{\vec{B}\cdot\nabla T_{e0}}{B} = \frac{\delta B_r}{B}\nabla T_{e0}$
- Parallel thermal force ($R_{T||} \sim -\alpha(\omega) n_e \nabla_{||} T_e$) drives parallel electron current that reinforces δB_r via Amperes's law $\quad k_\perp^2 \rho_s^2 \hat{A}_{||} = \frac{\beta_e}{2}\hat{j}_{||} \quad , \quad B_r = ik_\theta A_{||}$
- Instability requires sufficient ∇T_e, β_e, ν_e, and time dependence (ω) important

*e.g. Hazeltine et al., Phys. Fluids 18, 1778 (1975); Gladd et al., Phys. Fluids 23, 1182 (1980); D'Ippolito et al., Phys. Fluids 23, 771 (1980); M. Rosenberg et al., Phys. Fluids 23, 2022 (1980).

Microtearing Modes Found to be Unstable in High ν_* Discharge

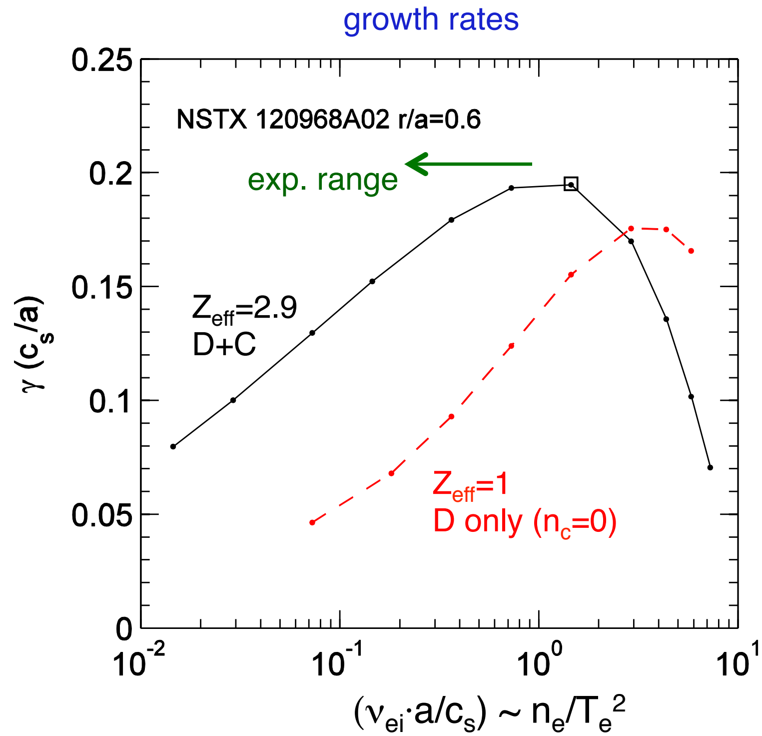
- Focusing on high-ν_* NSTX discharge, part of dimensionless scaling experiments where favorable scaling found $\Omega\tau_E \sim \nu_*^{-0.95}$ [S.M. Kaye et al., Nucl. Fusion 47, 499 (2007)]
- Microtearing dominates $k_\theta\rho_s<1$ ($n\approx5$-70) in outer half-radius ($r/a=0.5$-0.8)
- ETG stable due to higher $Z_{eff}=2.5$-3.0 $(R/L_{Te})_{crit,ETG} \sim (1+Z_{eff}T_e/T_i)$
- Microtearing exhibits threshold in ∇T_e, ν_e, β_e
- Growth rates decrease with $\nu_e < \nu_{e,exp}$ (consistent with experimental ν_* scan)

Linear growth rates ($\gamma\cdot a/c_s$) for NSTX 120968 t=0.56 s r/a=0.6 with B_T=0.35T, I_p=0.7 MA, P_{NBI}=4 MW, $n_e\approx6\times10^{19}$ m^{-3}, $T_e(0)$~1 keV



A distinguishing feature of the microtearing mode is the non-monotonic dependence on $\nu^{e/i}/\omega$

- Peak γ occurs for $\nu^{e/i}/\omega = Z_{eff} \cdot \nu_{ei}/\omega \sim$ 1-6, similar to slab calculations (Gladd et al., 1980)
- γ decreases with ν_e in experimental range, qualitatively consistent with confinement scaling
- In addition to shifting peak in $\nu^{e/i}/\omega$, Z_{eff} can enhance instability through shielding potential (from adiabatic ion response, $\delta n_i \sim -Z_{eff}\delta\varphi/T_i$)



$$\nu^{e/i} = Z_{eff}\nu_{ei} \propto Z_{eff}\frac{n_e}{T_e^{3/2}}$$

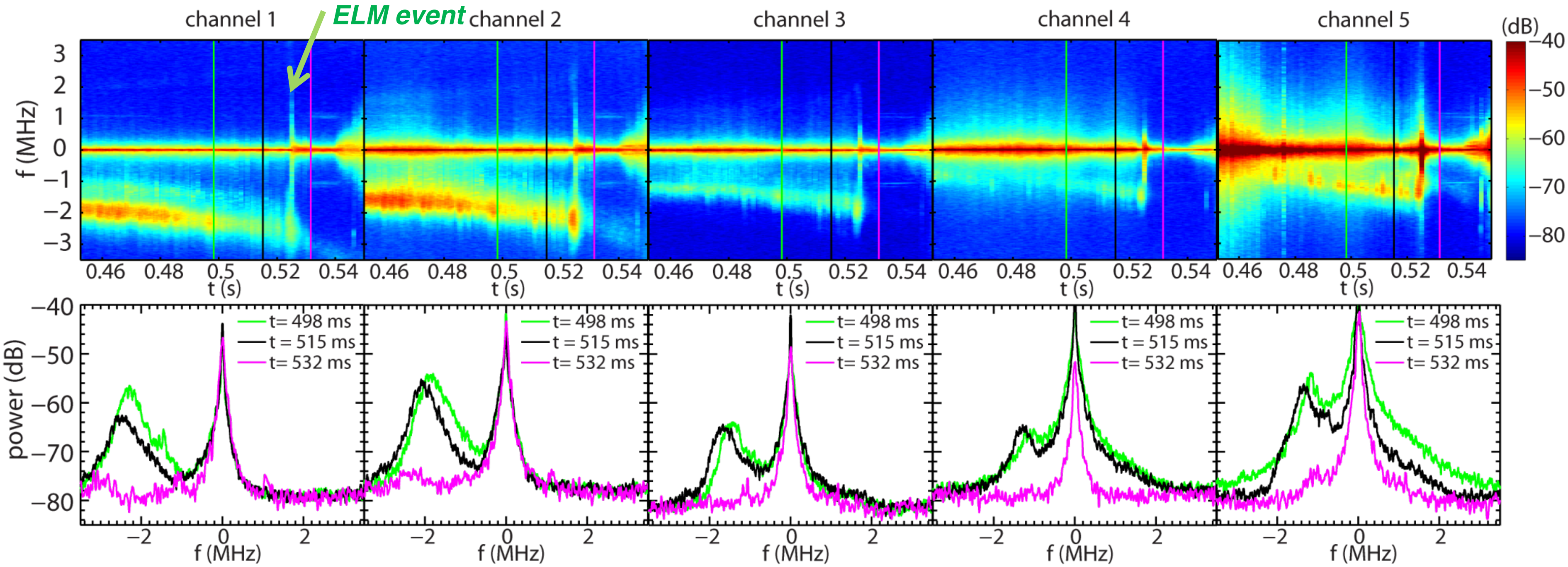
Jenko et al. (2001)

- Z_{eff} (and s/q)* dependence opposite to ETG expectations

$$\left(\frac{R}{L_{Te}}\right)_{crit}^{ETG} \sim \left(1+Z_{eff}\frac{T_e}{T_i}\right)\left(1.3+1.9\frac{s}{q}\right)(\cdots)$$

* Guttenfelder et al., *Scaling of linear microtearing stability for a high collisionality NSTX discharge*, submitted to Phys. Plasmas (Oct, 2011)

Significant Decrease in Scattering Signal Power Observed After the ELM Event



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- However, interpretation has to take into account the change of wavenumber measured by each channel due to the increase density gradient after the ELM event