# Recent Progress in Understanding Electron Thermal Transport in NSTX and NSTX-U

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**5. NFRI 6. UC-Davis**

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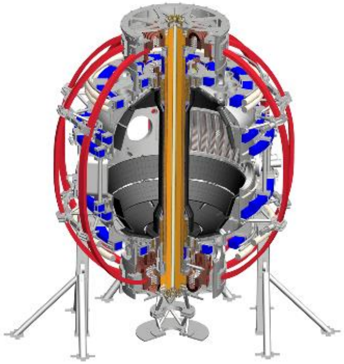
PPPL

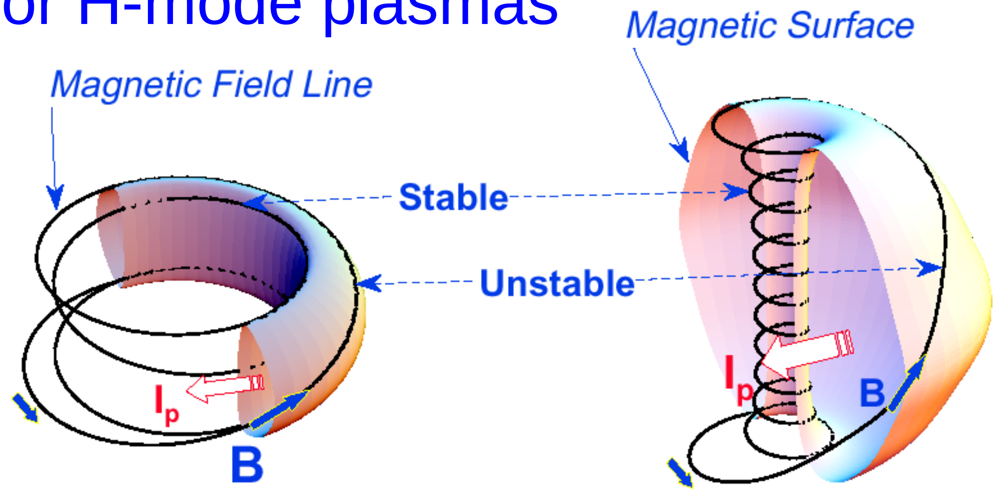


# Outline

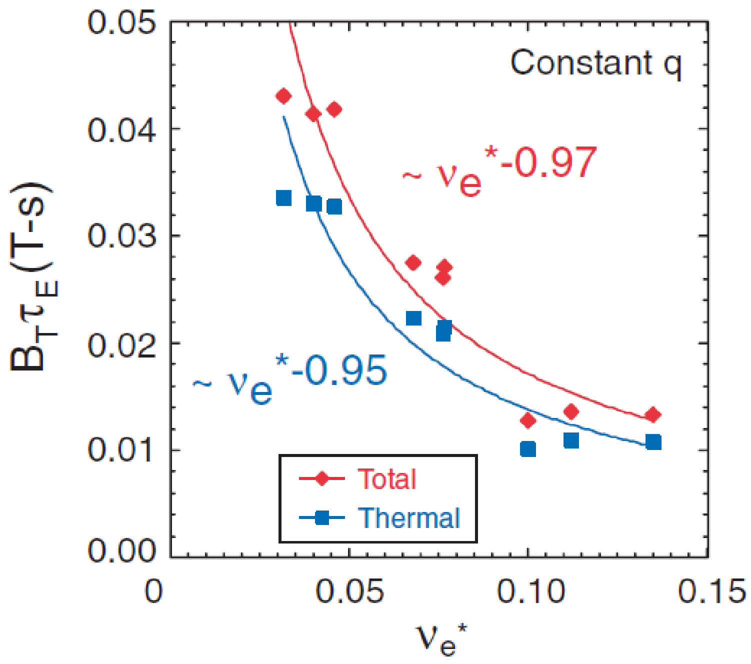
- Introduction
- Recent results on electron thermal transport in NSTX
  - Micro-tearing turbulence in NSTX high-beta and high-collisionality H-mode plasmas
  - ETG turbulence in NSTX L and H-mode plasmas
  - Fast-ion-driven Alfven eigenmodes in the core region of NSTX high-power H-mode plasmas
- NSTX-U Plans for electron thermal transport
- Summary

# Spherical Tokamaks Have Some Significant Advantages over Conventional Tokamak

- The low aspect ratio of spherical tokamaks leads to improved $\beta$ limit than conventional tokamaks
  - More compact and lower-cost future devices, e.g. Fusion Nuclear Science Facility (FNSF) and power plant
- The effective shaping and/or strong ExB shear from low aspect ratio lead to reduced ion-scale turbulence
  - Neoclassical ion thermal transport and different confinement scaling for H-mode plasmas

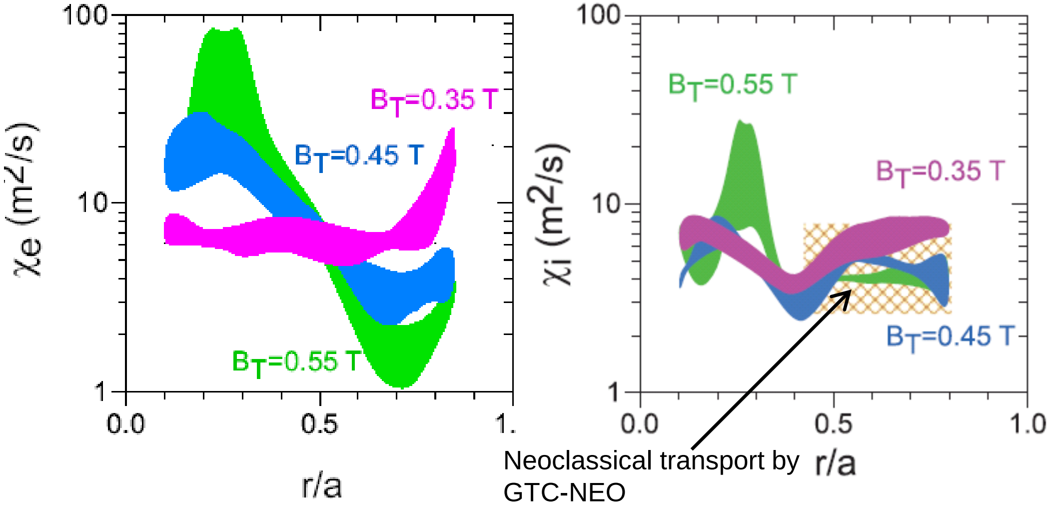


# NSTX Thermal Confinement Has Strong Collisionality Scaling in H-mode Plasmas



| | |
|---|---|
| NSTX | $\Omega\tau_E^{th} \sim \nu_{*e}^{-0.95}$ |
| MAST | $\Omega\tau_E^{th} \sim \nu_{*e}^{-0.82}$ |
| ITER | $\Omega\tau_E^{th,04(2)} \sim \nu_{*e}^{-0.2}$ |

Kaye et al., Nucl. Fusion, 2007
Valovič et al.,Nucl. Fusion, 2013
Doyle et al., Nucl.Fusion 2007

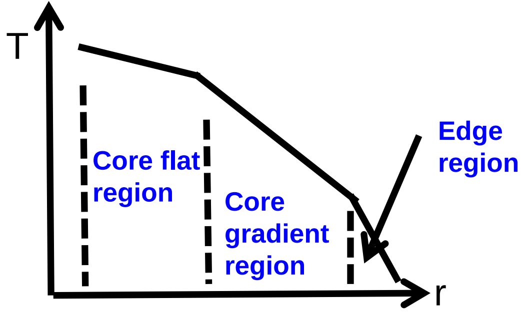


Neoclassical transport by GTC-NEO

- Ion transport is neoclassical, consistent with strong flow shear and strong shaping
- The confinement scaling is determined by electron thermal transport

# Multiple Mechanisms should be Responsible for Anomalous Electron Thermal Transport

- Different mechanisms needed to account for the always anomalous electron thermal transport
  - Different radial regions
    - Core flat region (small gradient drive)
    - Core gradient region (large gradient drive)
    - Edge region (steepest gradient, connection to SOL, e.g. H-mode pedestal)
  - Different parametric regimes
    - Large/small plasma beta/collisionality, magnetic shear, ExB shear, etc.



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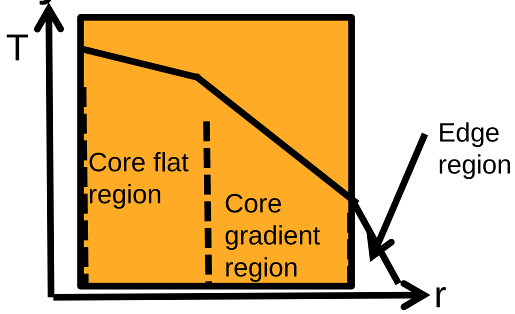
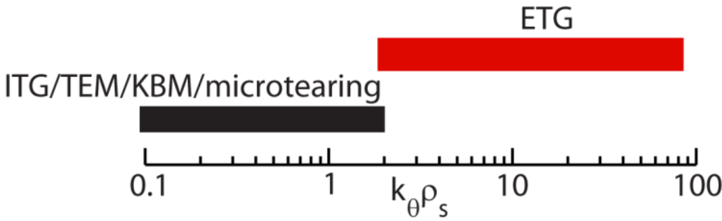
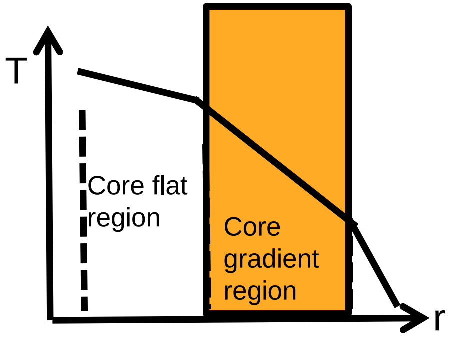


- Evidence exists for gradient driven electrostatic and electromagnetic ballooning drift instabilities:
  - Low-k (ion-scale): ITG/TEM/KBM/microtearing modes
  - High-k (electron-scale): ETG modes
  - Turbulent ExB drift and magnetic flutter effects

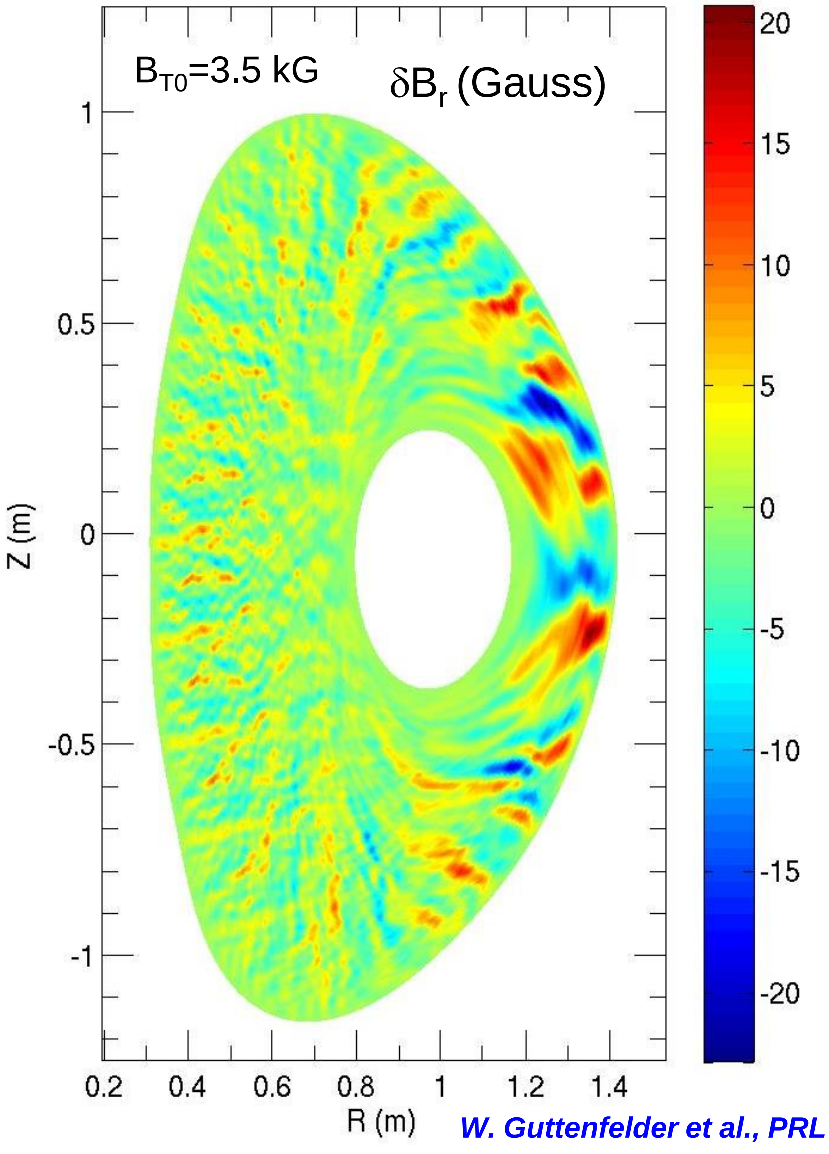


- Fast ion driven Alfvenic eigenmodes found relevant
  - GAE and/or CAE modes
  - Alfvenic eigenmode induced electron drift orbit stochasticity

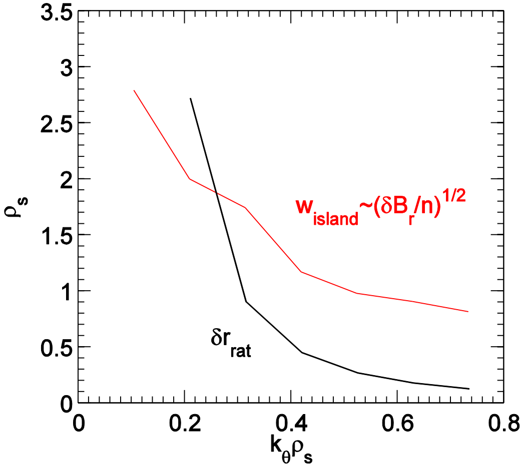
# Micro-tearing turbulence in high-collisionality and high-beta H-mode plasmas

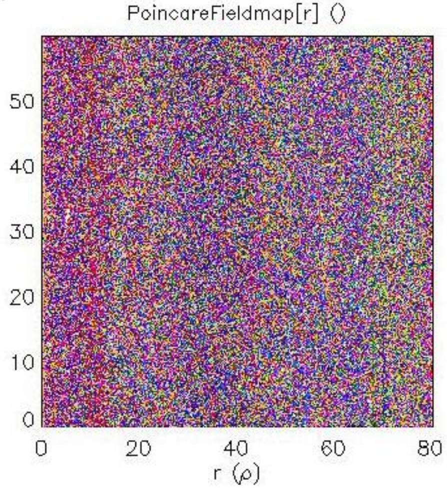


# First Successful Nonlinear Microtearing Simulations for NSTX



- ~98% of transport due to magnetic “flutter” contribution
- $w_{island}(n) > \delta r_{rat}(n)$, island overlap → perturbed field line trajectories are stochastic*
- $\chi_{e,EM} = 1.25\ \rho_s c_s^2/a$ close to *collisionless* Rechester-Rosenbluth** ($\lambda_{mfp}$=12 m, $L_c \approx 2.5$ m)





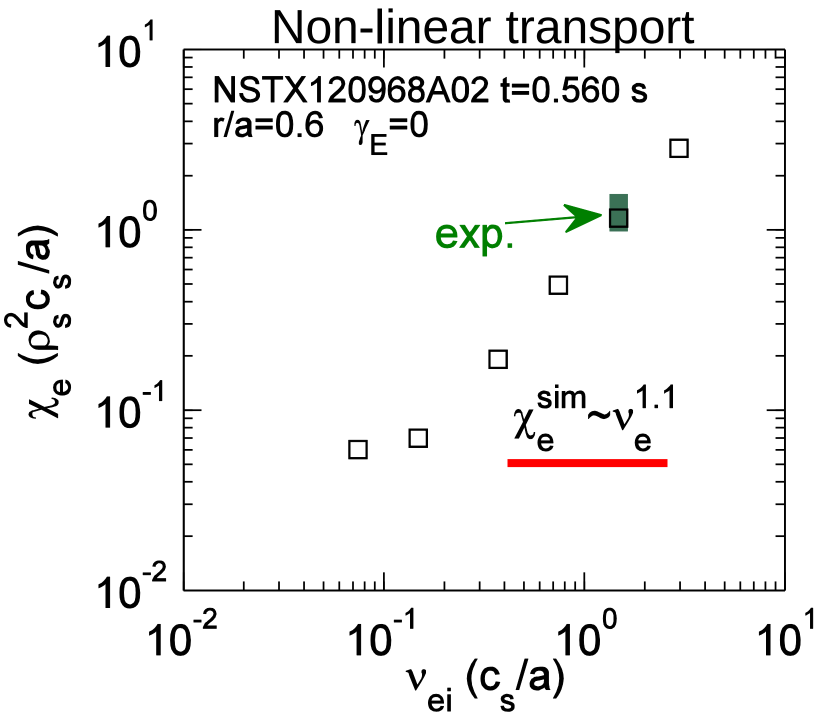
*E. Wang et al., PoP (2011).

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

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

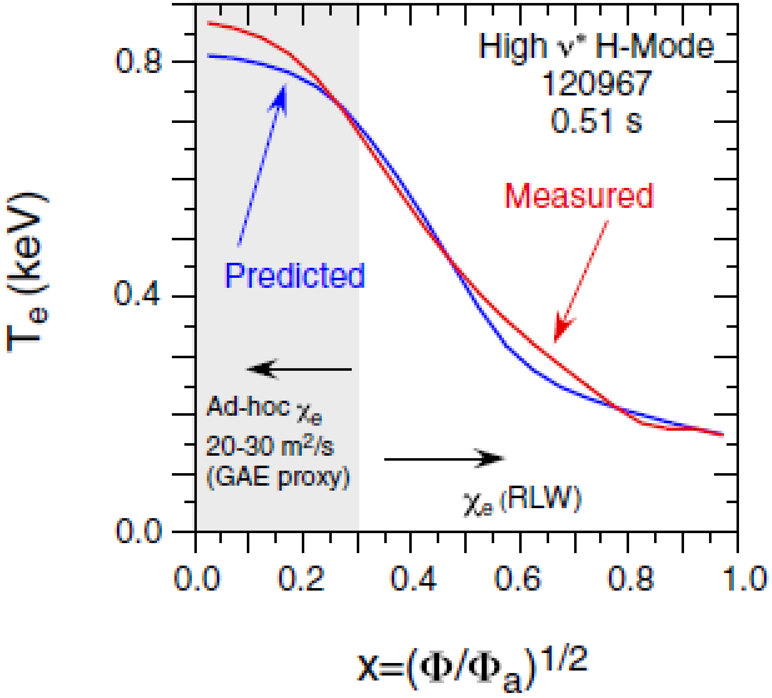
***W. Guttenfelder et al., PRL (2011)***

# Micro-tearing Mode Predictions are Consistent with NSTX H-mode Plasmas



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

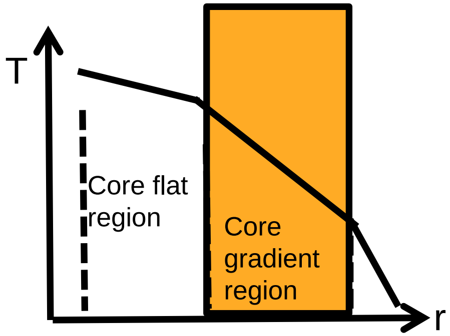
*W. Guttenfelder et al., PRL (2011)*



- A representative NSTX H-mode
- Using micro-tearing-based RLW electron thermal diffusivity model
- Good agreement seen when micro-tearing linearly important

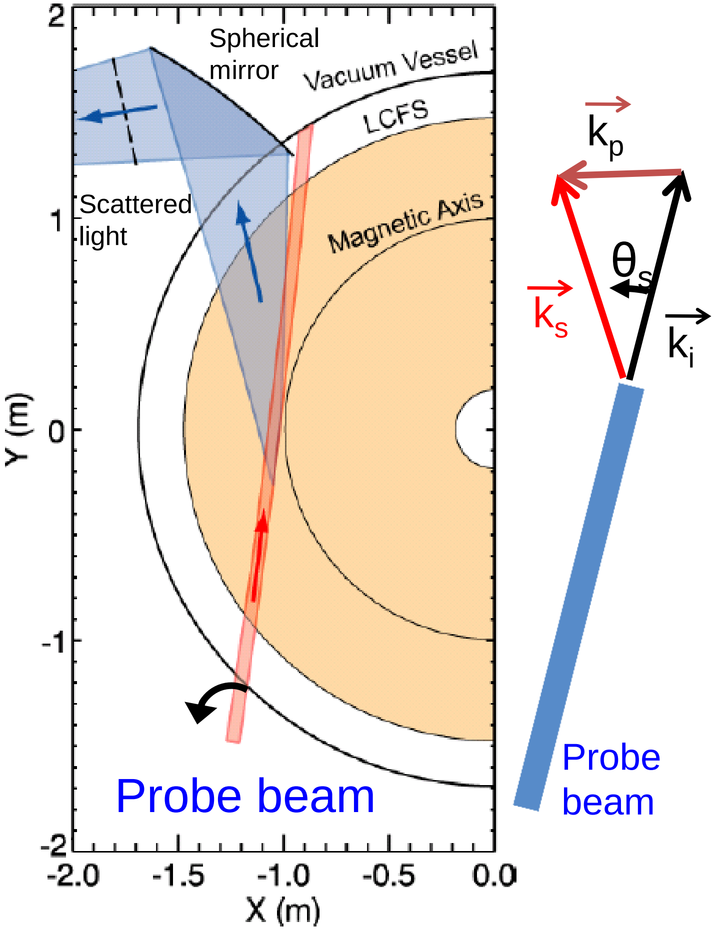
*Kaye et al., NF (2015)*

# ETG turbulence in NSTX L and H-mode plasmas



# A High-k Microwave Scattering System was Used to Measure Electron-scale Turbulence in NSTX

| **High-k turbulence measurement** | | | |
|---|---|---|---|
| | r/a | Measured quantity | Spatial & temporal resolution |
| 280 GHz microwave scattering system | ~0.2-1 from core to edge | Density fluctuation | $3 \leq k_\perp \rho_s \leq 12$<br>$\Delta R \sim \pm 2$ cm<br>f~ 5 MHz |

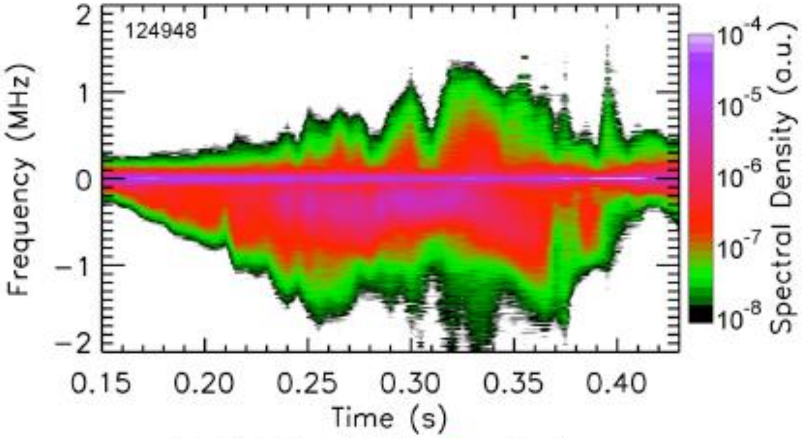


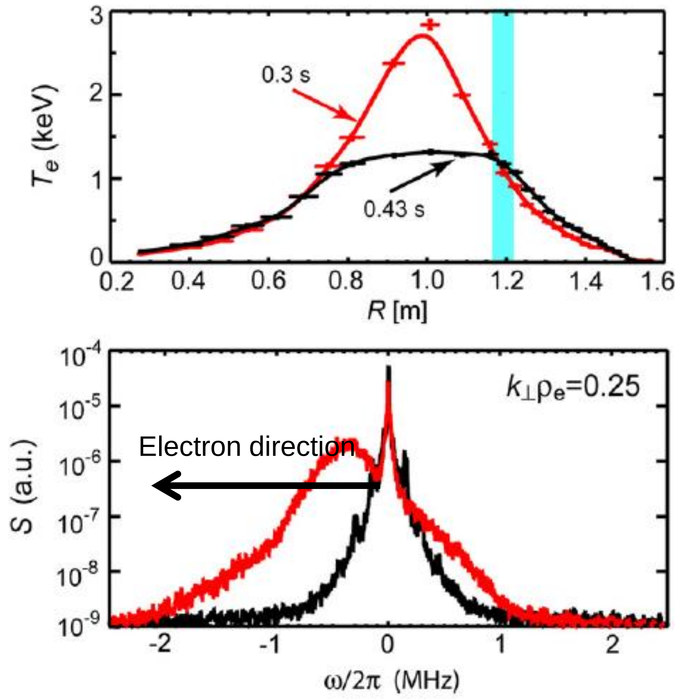
*D.R. Smith, PhD thesis, 2009*

# First Identification of ETG Turbulence in NSTX RF-heated L-mode Plasmas

- The measured high-k turbulence is shown to be driven by electron temperature
  - In RF-heated helium L-mode plasma (1.2 MW, 5.5 kG, 700 kA)
  - Fluctuation propagates in the electron diamagnetic direction
  - Clear reduction in turbulence spectral power at lower electron temperature gradient

$$k_{\perp} = 14\ cm^{-1}, k_{\perp}\rho_s = 8 - 10$$

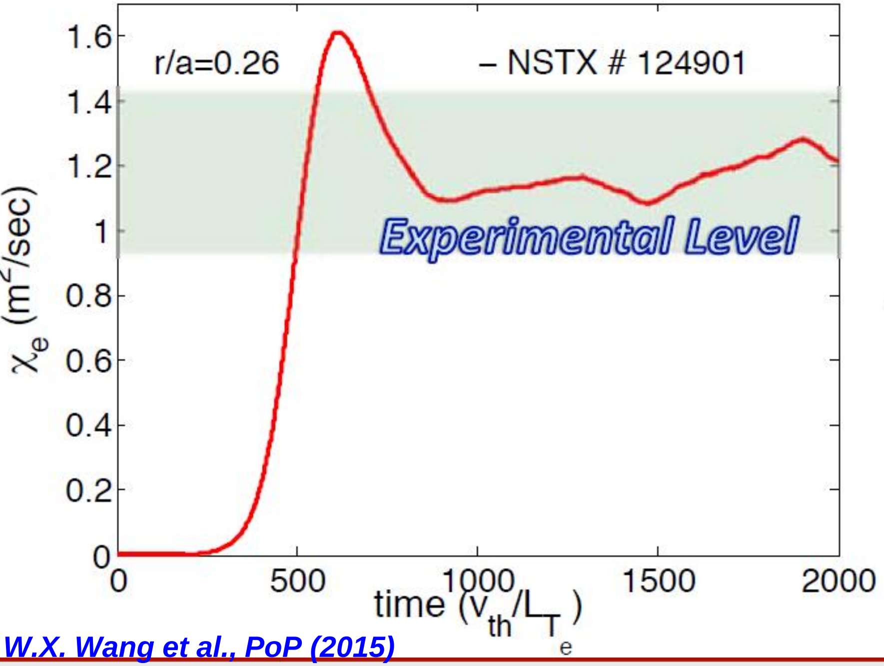


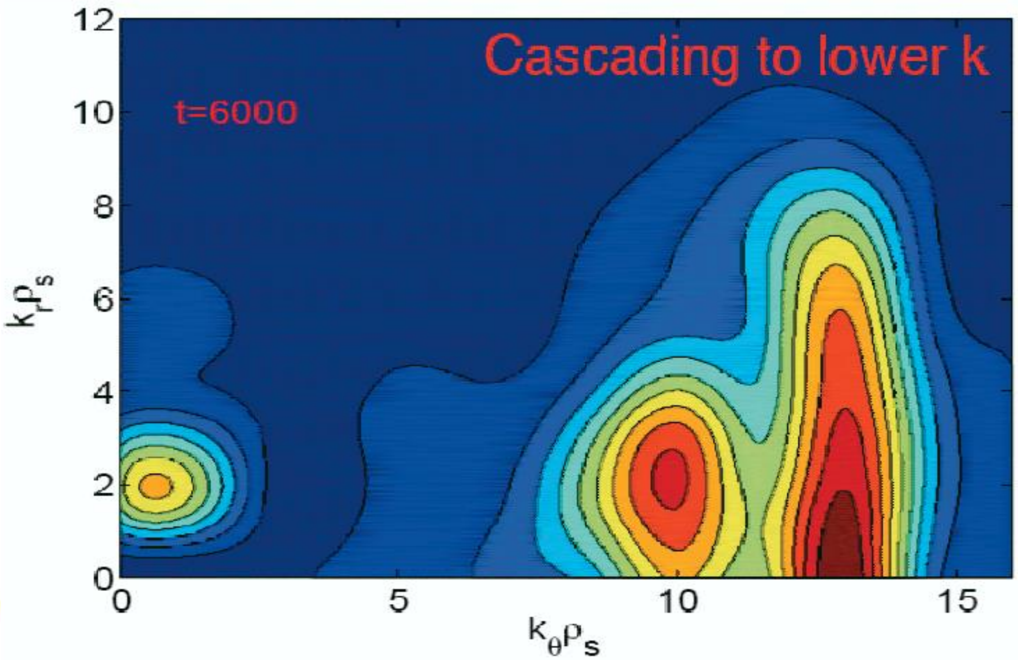


*Mazzucato et al., PRL 2008, NF 2009*

# ETG Turbulence can Produce Experimentally Relevant Electron thermal Transport

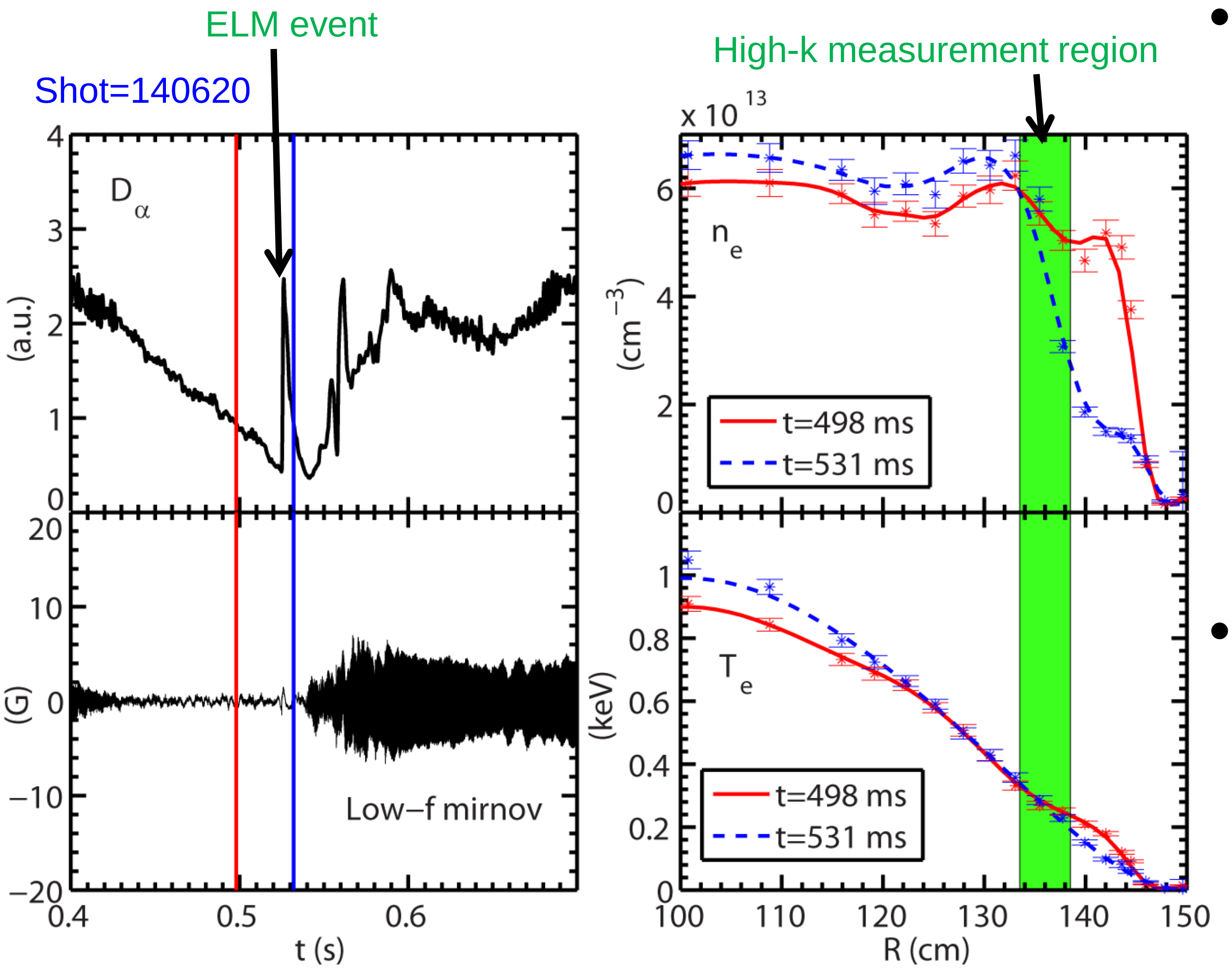
- Significant ETG-induced contributions to anomalous $\chi_e$ confirmed with global gyrokinetic code GTS
- Strong energy coupling to electron version of GAM (very high-ω ZF)





*W.X. Wang et al., PoP (2015)*

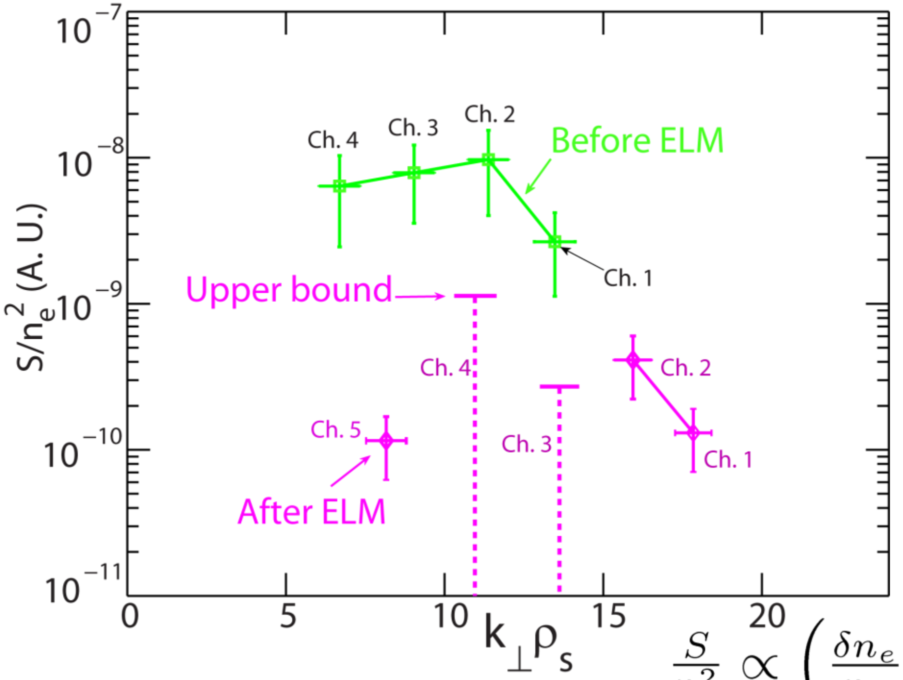
# Large ELM Event induces Density Profile Steepening in the Core Region



- 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

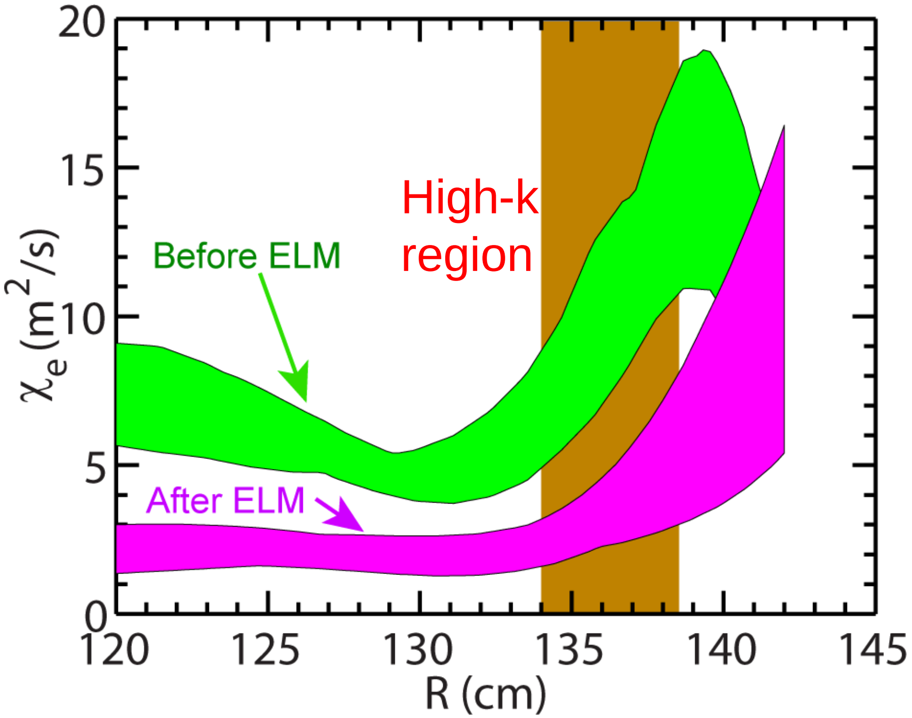
# Reduced ETG Turbulence Intensity and Electron Thermal Transport is Observed with Density Profile Steepening

- Significant decrease in spectral power in electron-scale observed for $k_\perp \rho_s \lesssim 10$



$$\frac{S}{n_e^2} \propto \left(\frac{\delta n_e}{n_e}\right)^2$$

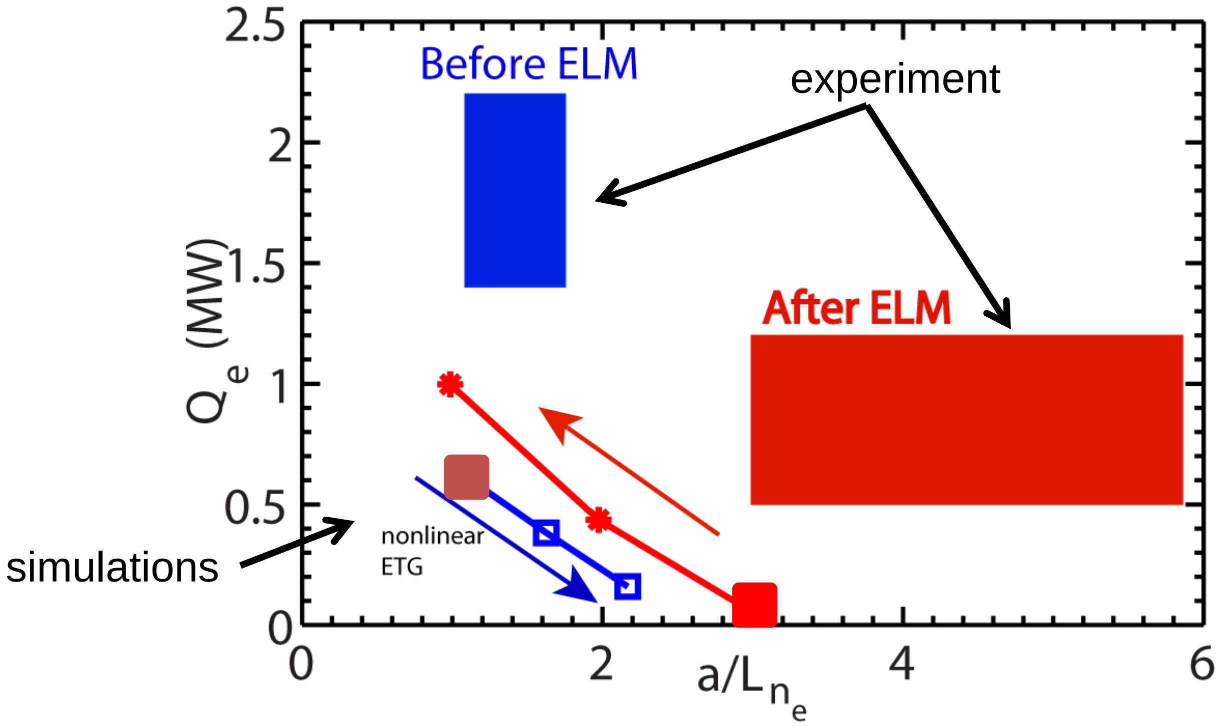
- Electron thermal diffusivity is decreased by a factor of ~2 after the ELM event



- **See Y. Ren et al., PRL 2011, PoP 2012**
- **Density gradient stabilization of high-k turbulence further confirmed in J. Ruiz-Ruiz et al., PoP 2015**

# Nonlinear ETG Simulations Reproduce Observed Dependence of Electron Transport on Density Gradient

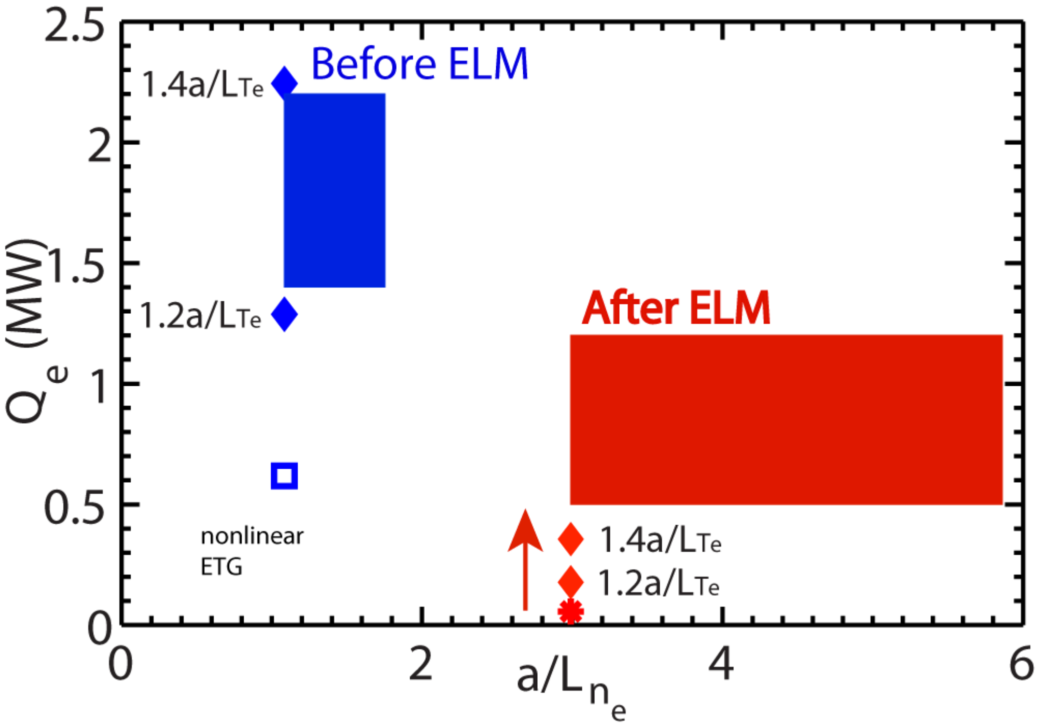
- Experimental $Q_e$ is found to decrease after the ELM event with large density gradient
- The same trend is found from nonlinear ETG simulations, but does not agree quantitatively



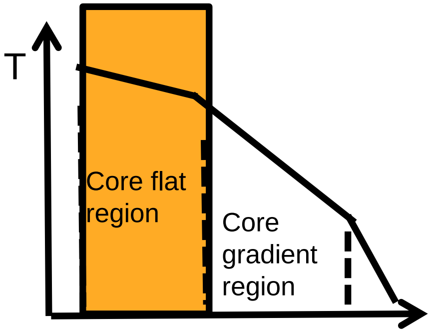
Nonlinear GYRO ETG simulations with: local general equilibrium, kinetic ions and electrons, collisions, electromagnetic, flow and flow shear

# Predicted $Q_e$ is Sensitive to Electron 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 $Q_e$

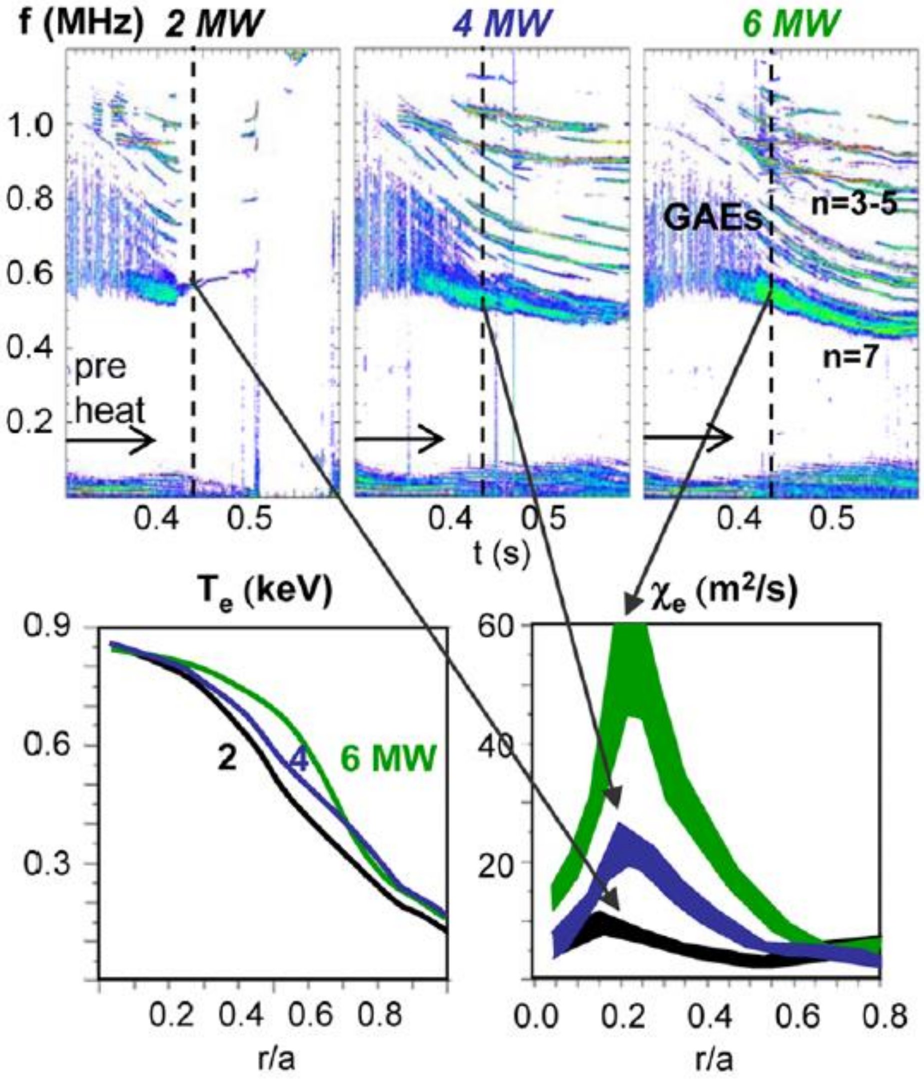


# Fast-ion-driven Alfven eigenmodes in the core region of NSTX high-power H-mode plasmas



# Core $T_e$ Flattening in High-power NBI H-mode plasmas is Observed to be Correlated with *AE Activities

- Core $T_e$ flattening correlated with NBI power
  - No simultaneous increase in central $T_e$
- Almost a factor of 10 increase in core $\chi_e$ (r/a~0.2)
  - $\chi_e$ calculated with TRANSP power balance analysis
  - Calculated neutron rate with classical fast particle slowing-down in good agreement with measured neutron rate
- Increased *AE (GAE/CAE) activity observed from edge Mirnov measurement

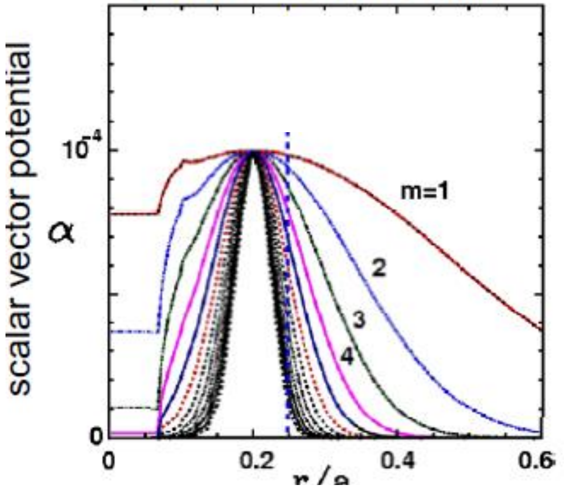


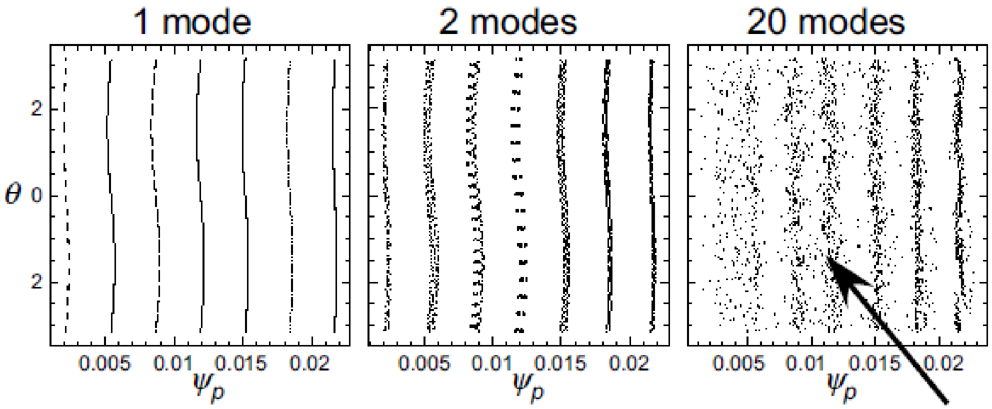
*D. Stutman et al., PRL (2009)*

# ORBIT Guiding Center Code is Used to Simulate GAE Effects on Electron Thermal Transport

*N. Gorelenkov Nucl. Fus. 2010*

GAE Model used in ORBIT calculations

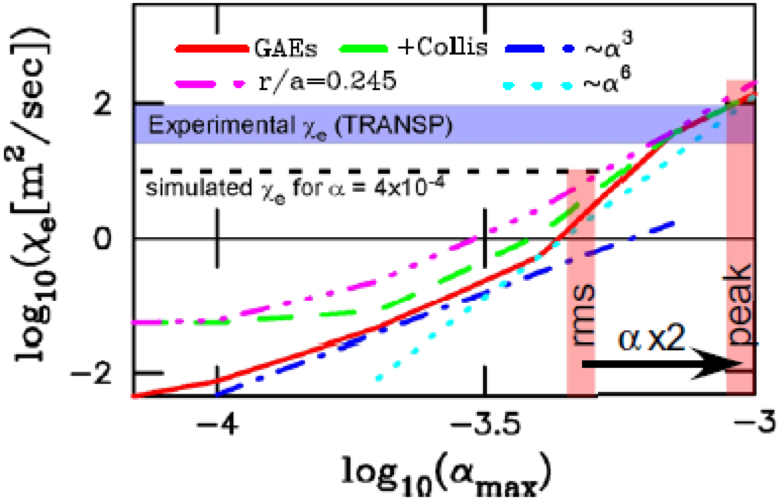




Poincaré plot of electron trajectory

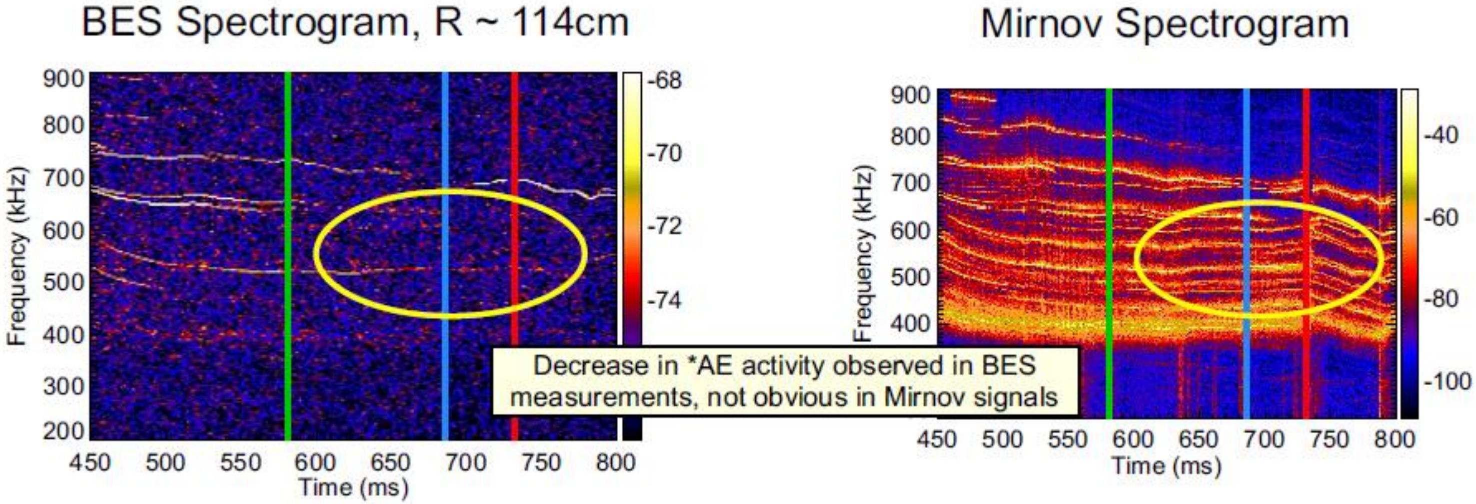
stochastic particle trajectories

Simulated electron thermal transport

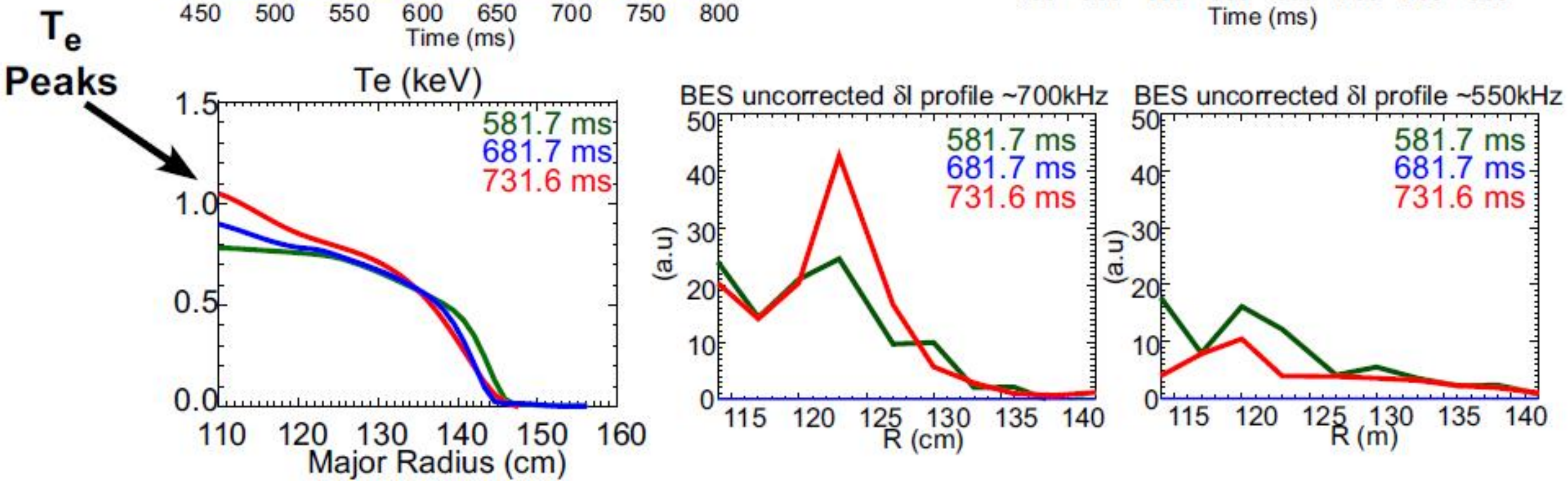


- Ad-hoc model used to study transport vs. mode amplitude and number
- $\chi_e > 10m^2/s$ for GAE mode amplitude: $\alpha > 4x10^{-4}$, number: N > 16
- 'stochastic' transport sensitive to mode structure and amplitude $(\sim\alpha^3\text{-}\alpha^6)$

# Decrease in *AE Activity Measured by BES Corresponds with Peaking of Central Electron Temperature



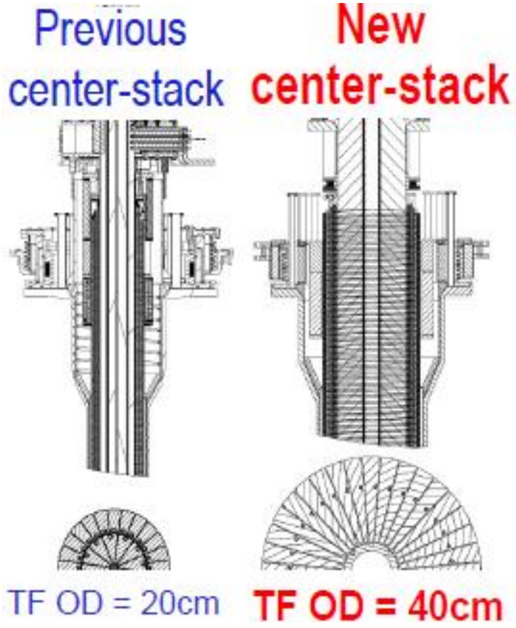
Decrease in *AE activity observed in BES measurements, not obvious in Mirnov signals

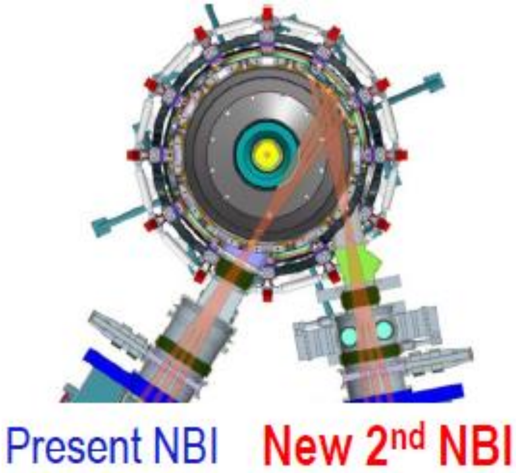


- $T_e$ remains peaked even with large single mode (bulk *AE still largely suppressed)
  - Consistent with that large number of modes needed to induce stochastic thermal transport

# Improved Capabilities of NSTX-U will Strongly Support the Study of Electron Thermal Transport

- Doubled $B_T$, $I_P$ and NBI-heating power
  - 3-6 times lower in $\nu_e^*$; flow/q profile control





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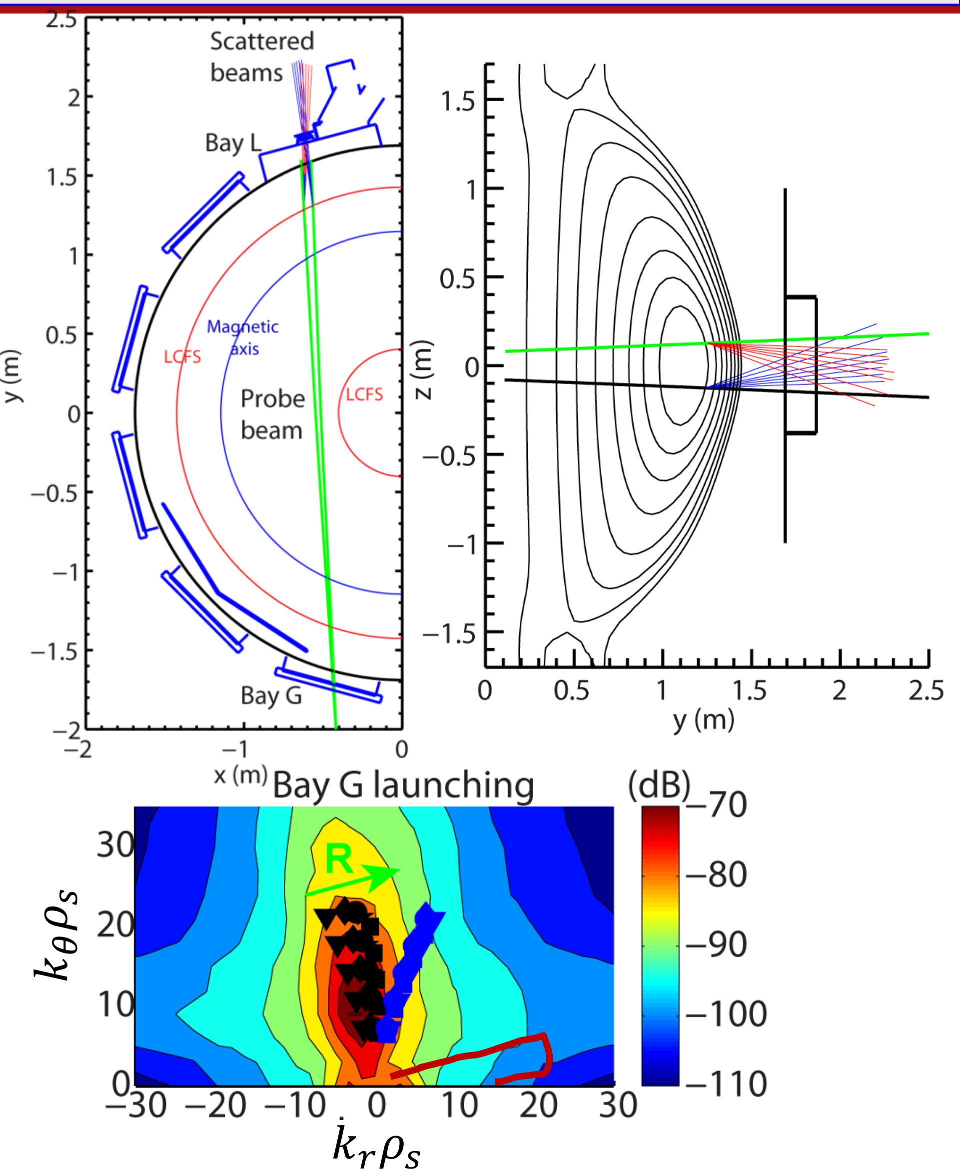
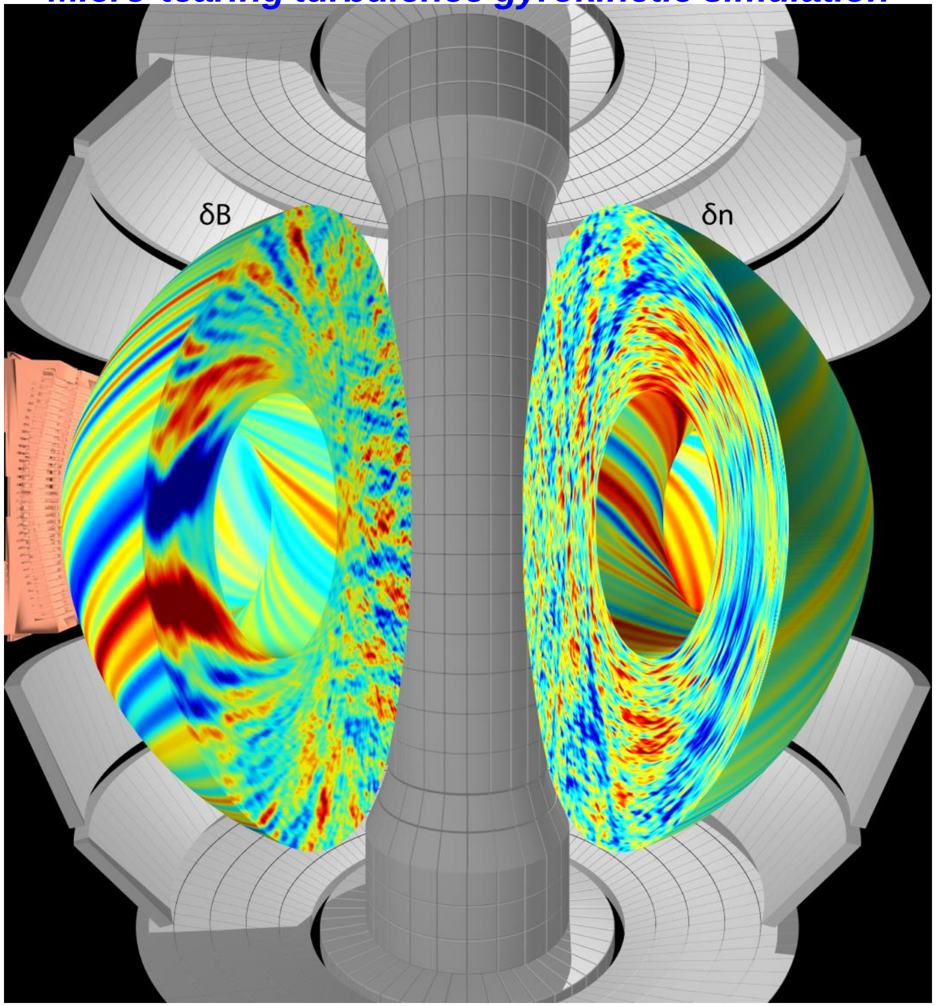
- A new FIR high-$k_\theta$ scattering system being designed at UC-Davis
  - To be installed for FY17 run campaign



# Improved Diagnostics on NSTX-U will Strongly Support the Study of Electron Thermal Transport

- Doubled $B_T$, $I_P$ and NBI-heating power
  - 3-6 times lower in $\nu_e^*$; flow/q profile control
- A new FIR high-$k_\theta$ scattering system being designed at UC-Davis
  - To be installed for FY17 run campaign
- A DBS/CPS system will be installed for FY17 run campaign
  - Measure ion-scale turbulence
  - Able to measure magnetic fluctuations (CPS)
- 48 BES channels are now available on NSTX-U
  - 16 more than NSTX

***Micro-tearing turbulence gyrokinetic simulation***



# NSTX-U T&T Research Plan Aims to Identify Operational Regimes of Instabilities Responsible for Electron Thermal Transport

- Near-term plan
  - Identify dominant modes in lower $\nu_e$* H-mode plasmas of NSTX-U
  - Characterize low/high-k turbulence and electron thermal transport in isolated regimes of micro-instabilities guided by GK simulations
  - BES/reflectometry for CAE/GAE measurements with a range of $B_T$, $I_p$, $\nu_e$* and $P_{NBI}$, coupled with ORBIT code
  - Cold pulse propagation (Laser Blow-off and ME-SXR) for profile stiffness
  - Couple with turbulence diagnostics, GK simulations and experimental tools
- Long term plan
  - Identify operational regimes of ETG, microtearing, AE (CAE/GAE) and ITG/TEM/KBM using the full set of turbulence diagnostics
  - Expand turbulence and electron thermal transport parametric dependence, e.g. on $\beta$, $\rho^*$, $T_i/T_e$ and $Z_{eff}$
  - Study electron thermal transport and turbulence in long pulse and fully non-inductive scenario
  - Develop physics-based reduced models for electron thermal transport

# Summary

- NSTX has made significant progress towards understanding anomalous electron thermal transport
  - First nonlinear gyrokinetic simulation of microtearing turbulence to produce experimental confinement scaling and transport in NSTX H-mode plasmas
  - ETG turbulence driving electron thermal transport in L and H-mode plasmas, supported by linear and nonlinear gyrokinetic simulations
  - *AE-induced core Te flattening, consistent with electron stochastic transport from ORBIT simulations
- Electron thermal transport will be the key part of the transport and turbulence research plan for NSTX-U
  - Ip ~2 MA, BT ~1 T, 2nd NBI (~12 MW), a suite of turbulence diagnostics, e.g. new high-k scattering system and DBS/CPS

# Backup slides

# Beam Emission Spectroscopy (BES) Diagnostic Provides the Capability of Measuring Internal *AE Mode Structure

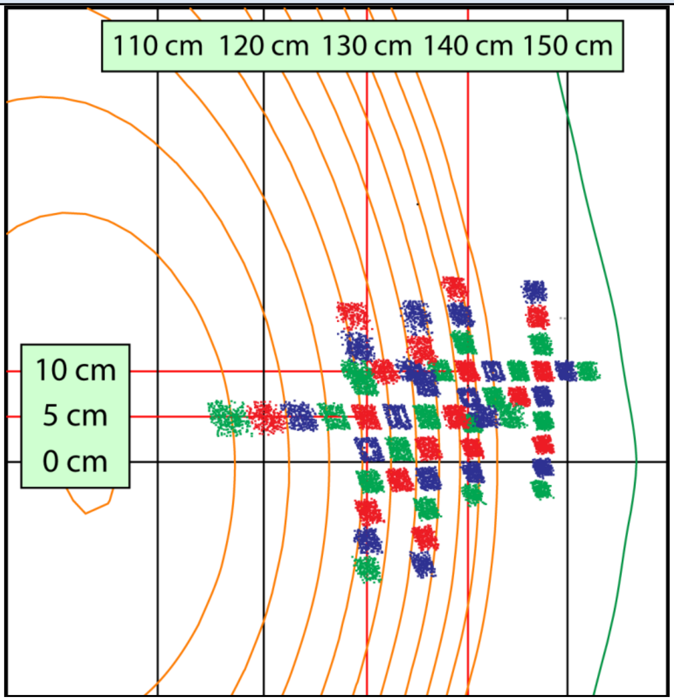
- 32 detection channels for NSTX and to be upgraded to 48 channels for NSTX-U
- 56 sightlines in radial and poloidal arrays spanning core to SOL
- 2 MHz sampling
- $k_\perp \rho_i \leq 1.5$ & 2-3 cm spot size
- Field-aligned optics with high throughput (etendue = 2.3 mm$^2$-ster)

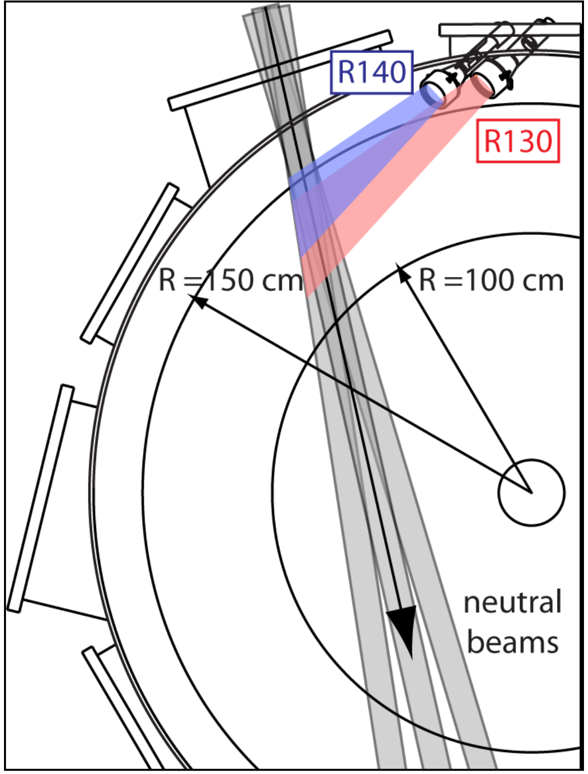
$$\frac{\delta I_{D\alpha}}{I_{D\alpha}} = \frac{\delta n}{n} \times C\left(E_{NB}, n, T_e, Z_{eff}\right)$$

neutral beam $D_\alpha$ emission

density fluctuation

C ≈ 1/2

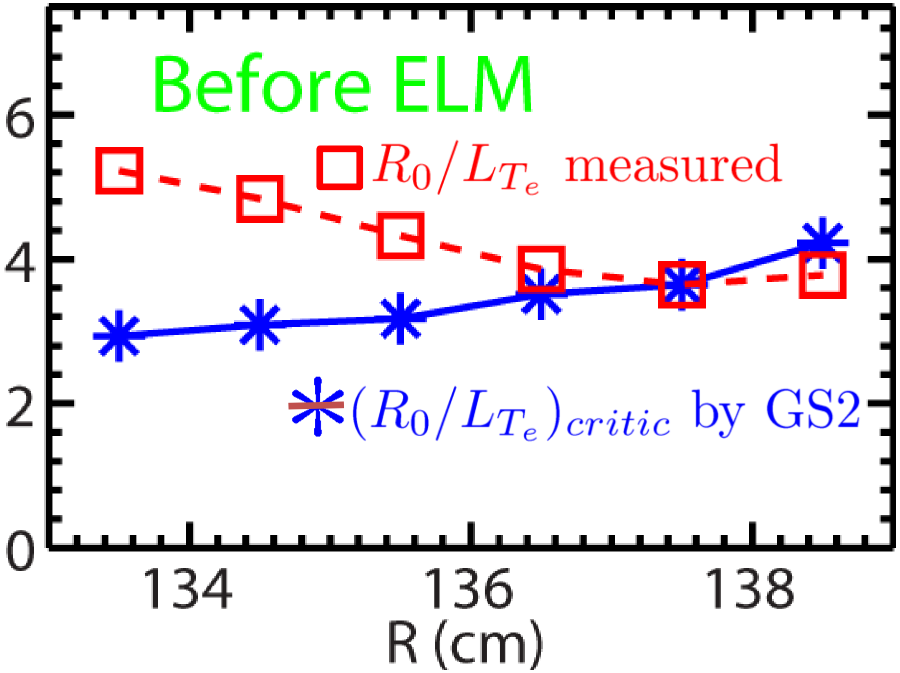




*D.R. Smith et al., Rev. Sci. Instrum (2010)*

# Threshold Gradients for ETG modes are much Higher after the ELM

- Before ELM, ETG is largely unstable



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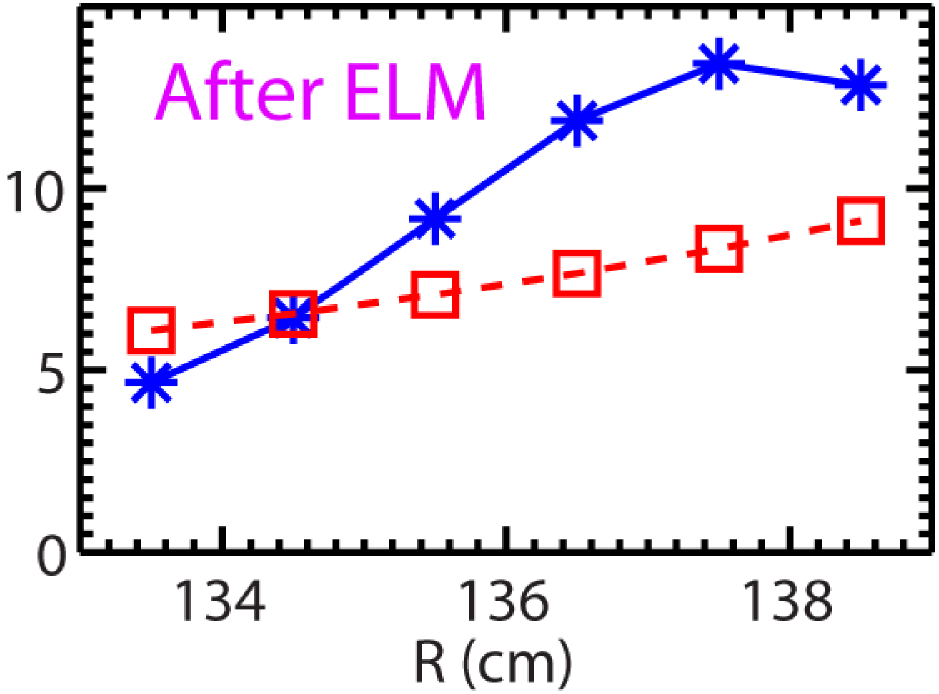
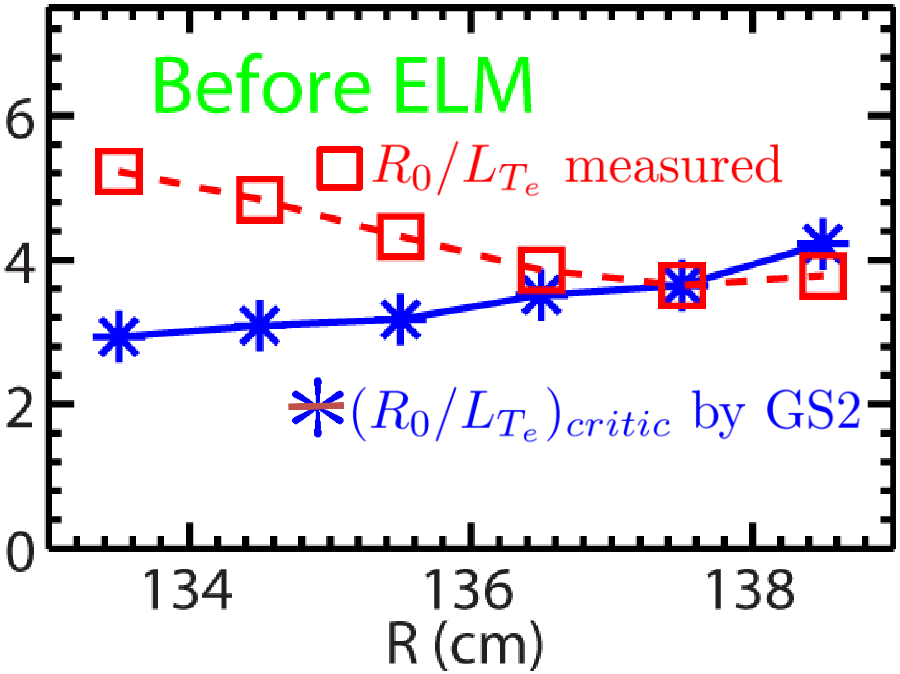


Stability analysis performed with GS2 code (Kotschenreuther et al., 1995)

# Increase in ETG Threshold Gradient is due to Large Density Gradient

- Before ELM, ETG is largely unstable



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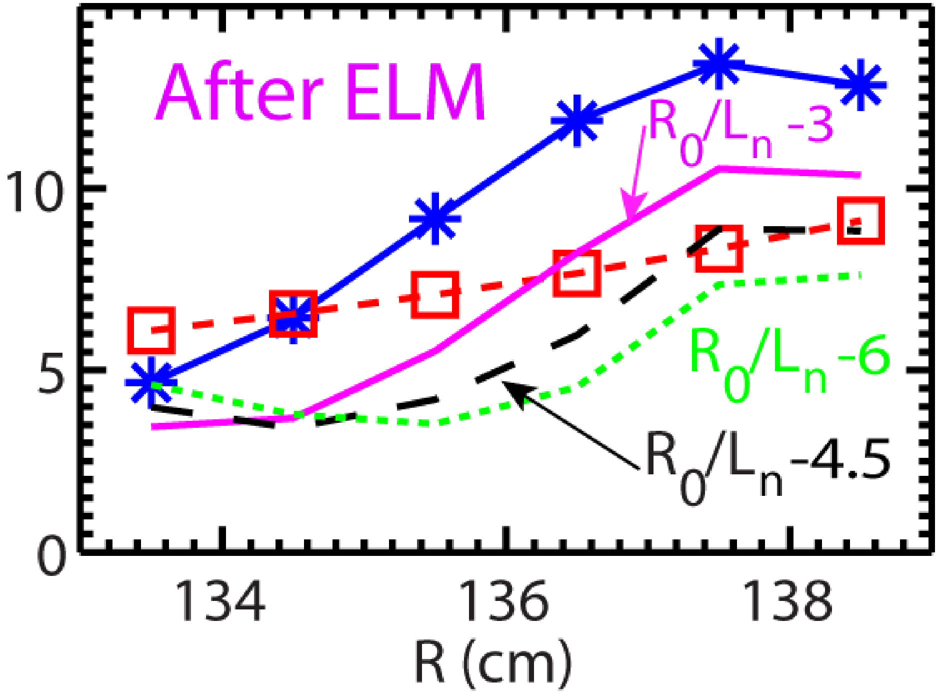
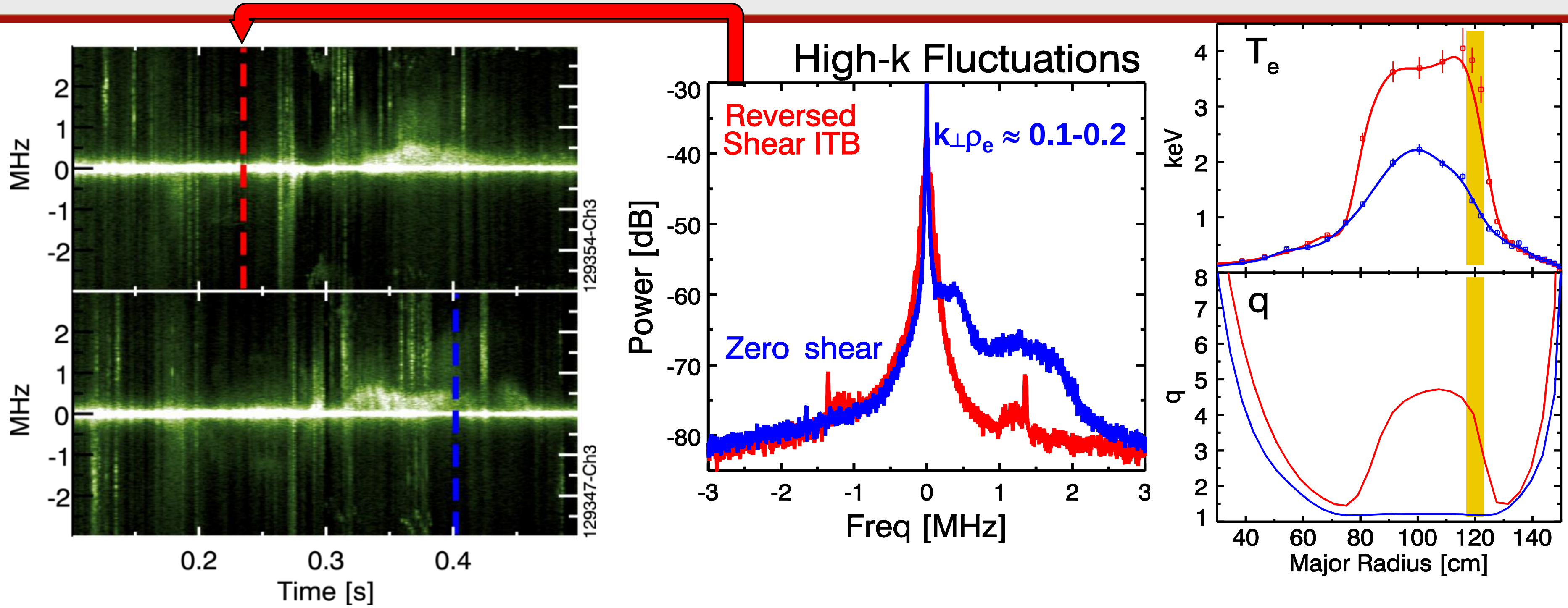


- Manually decreasing R/$L_{ne}$ brings down critical gradient as expected from linear theory (e.g. Jenko et al, 2001)

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

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

# ETG Turbulence Stabilization by Reversed Magnetic Shear is Responsible for ITB Formation



- HHFW only with beam blips

*Yuh et al., NF 2009 and PRL 2011*

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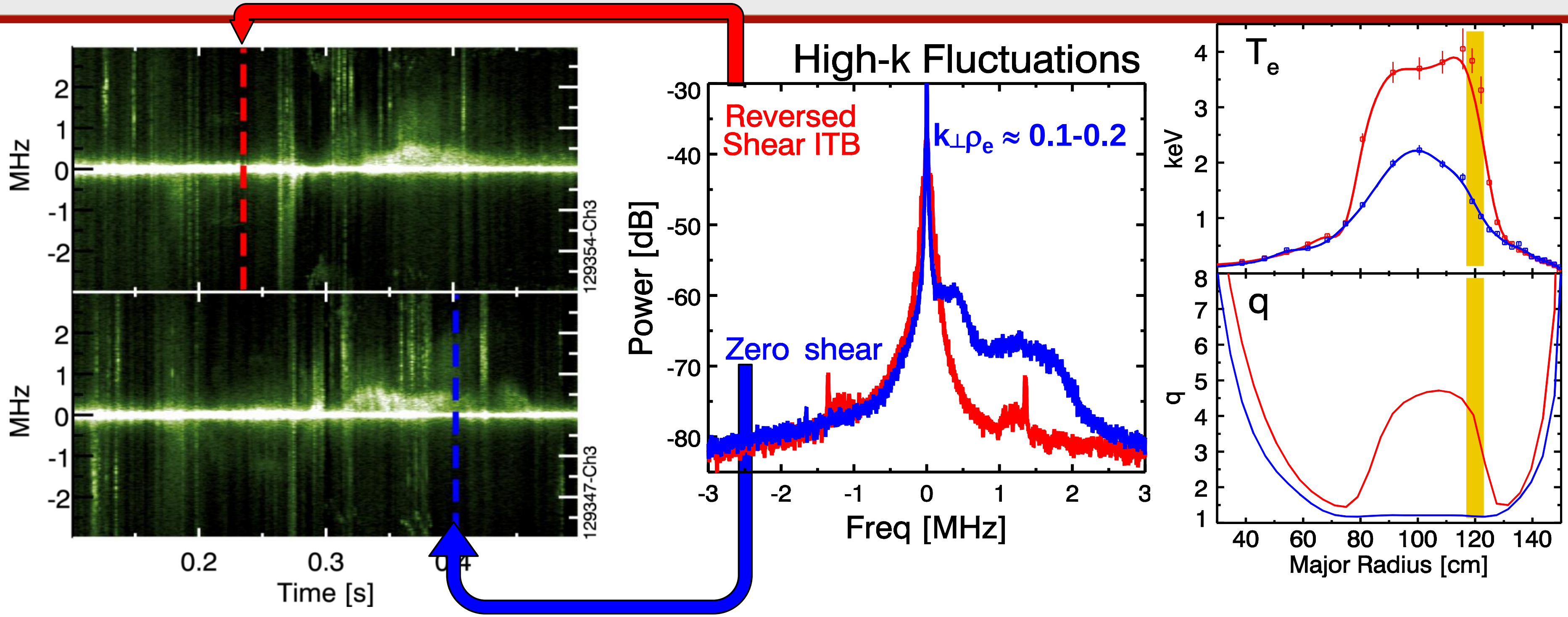

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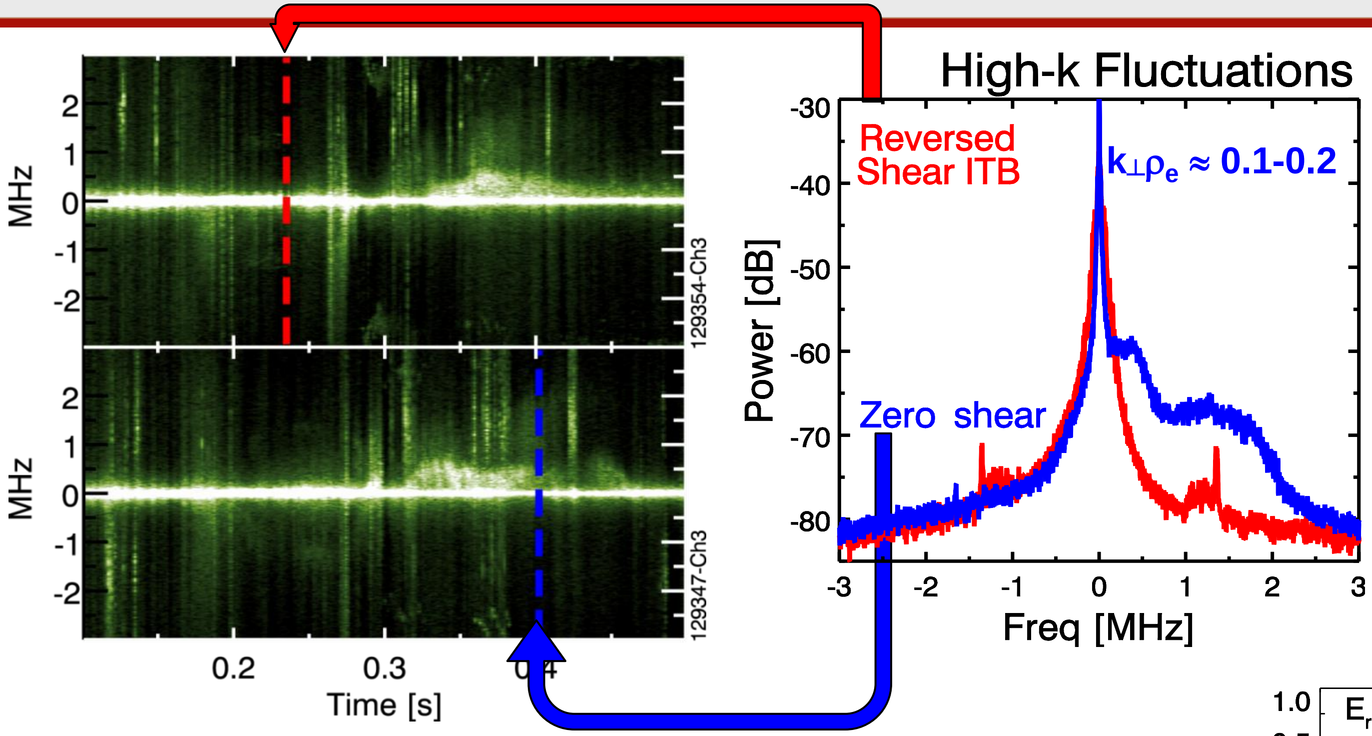
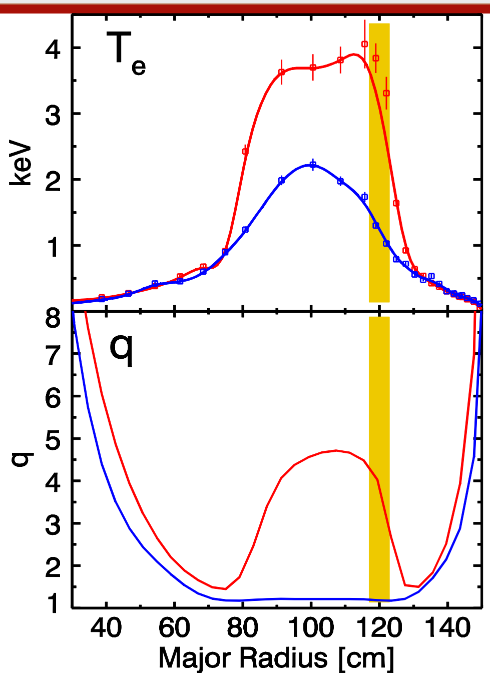
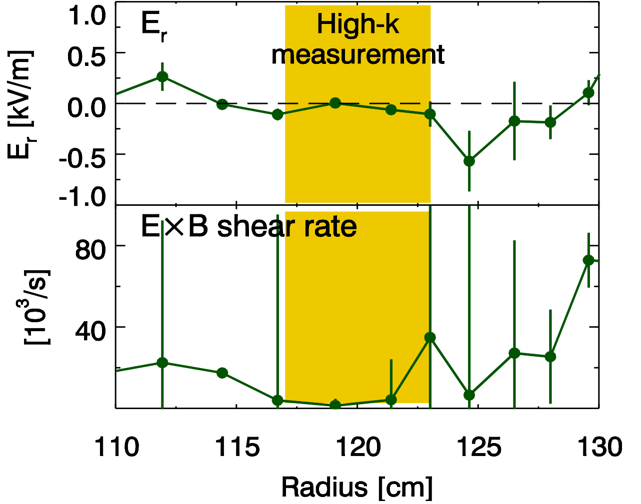




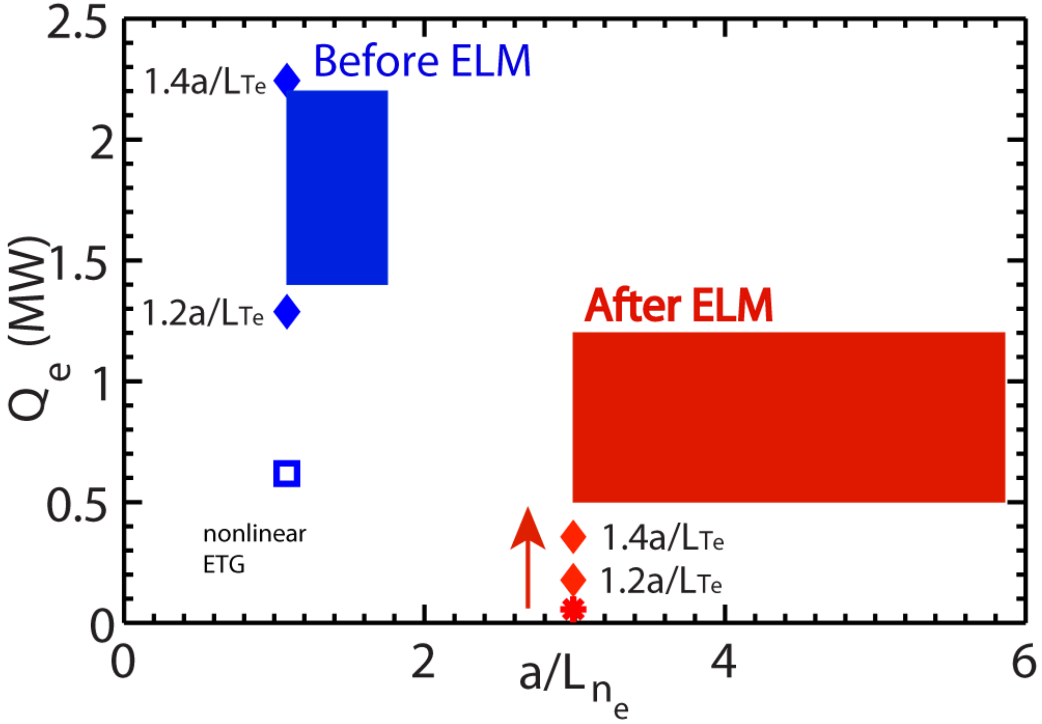
- HHFW only with beam blips
- Minimal ExB shearing rate due to cold ions with low toroidal rotation
- **Magnetic shear alone suppresses electron turbulence**



*Yuh et al., NF 2009 and PRL 2011*

# Predicted $Q_e$ is Sensitive to Electron 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 $Q_e$