NSTX-U

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Recent Progress in Understanding Anomalous Electron Thermal Transport in NSTX

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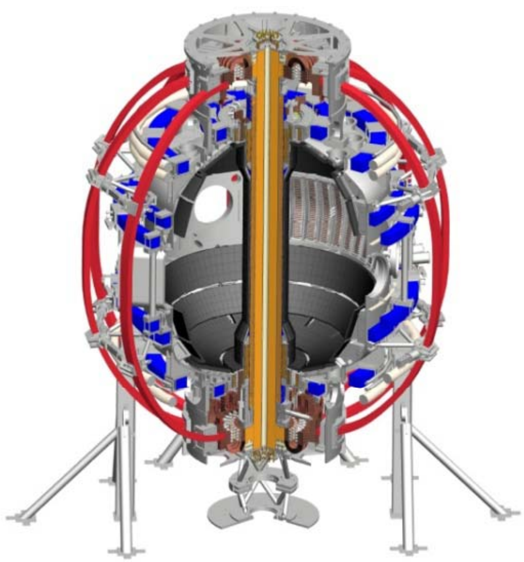

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ASCR, Czech Rep

Outline

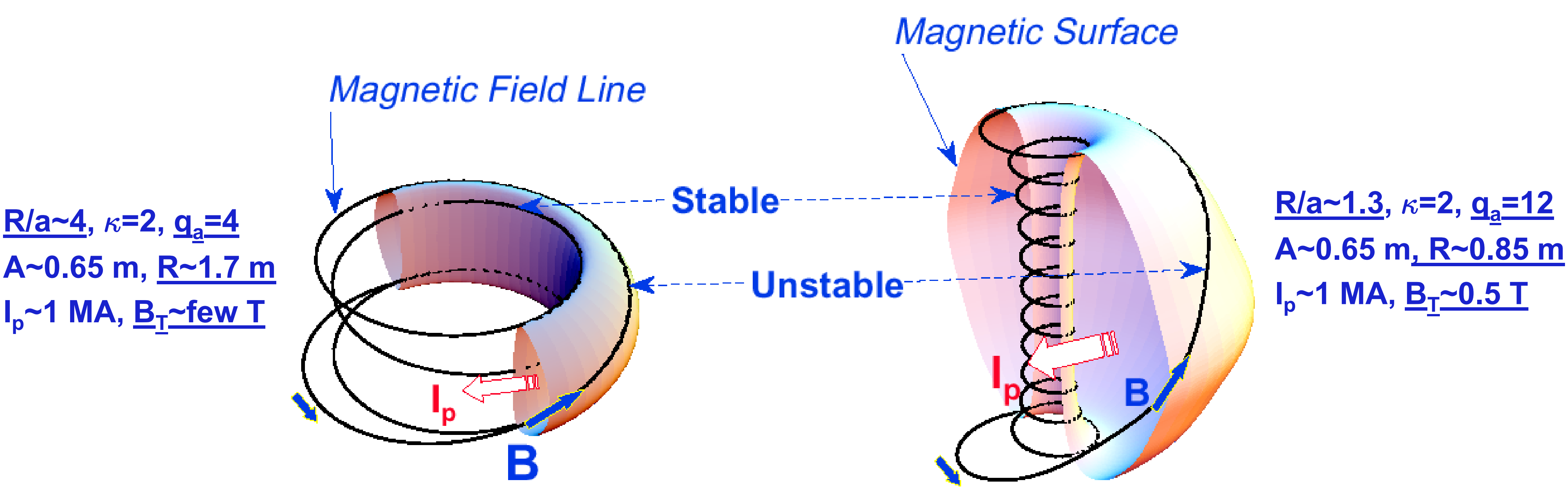
- Motivations
- First nonlinear gyrokinetic simulation of micro-tearing turbulence in a NSTX high collisionality H-mode plasma
  - Predicting experimentally relevant level of electron thermal transport
- Studies of parametric dependence of high-k turbulence using a microwave scattering diagnostic in NSTX H-mode plasmas
  - Density gradient stabilization of ETG turbulence
  - Suppression of ETG turbulence in reversed shear L-mode plasmas
  - ExB shear induced reduction of electron thermal transport and electron-scale turbulence
- Mechanisms underlying the flattening of central T_e profile in NSTX high-power NBI-heated H-mode plasmas
- Summary

NSTX is in an Unique Regime for Studying Electron Thermal Transport

- Understanding and controlling electron thermal transport important for future devices, e.g. ST-FNSF and ITER
  - Dominant electron heating from NBI and/or α particle heating

NSTX is in an Unique Regime for Studying Electron Thermal Transport

- Understanding and controlling electron thermal transport important for future devices, e.g. ST-FNSF and ITER
- Strong ExB flow shear and low aspect ratio stabilizing low-k turbulence: <u>ions close to neoclassical in H-mode</u>



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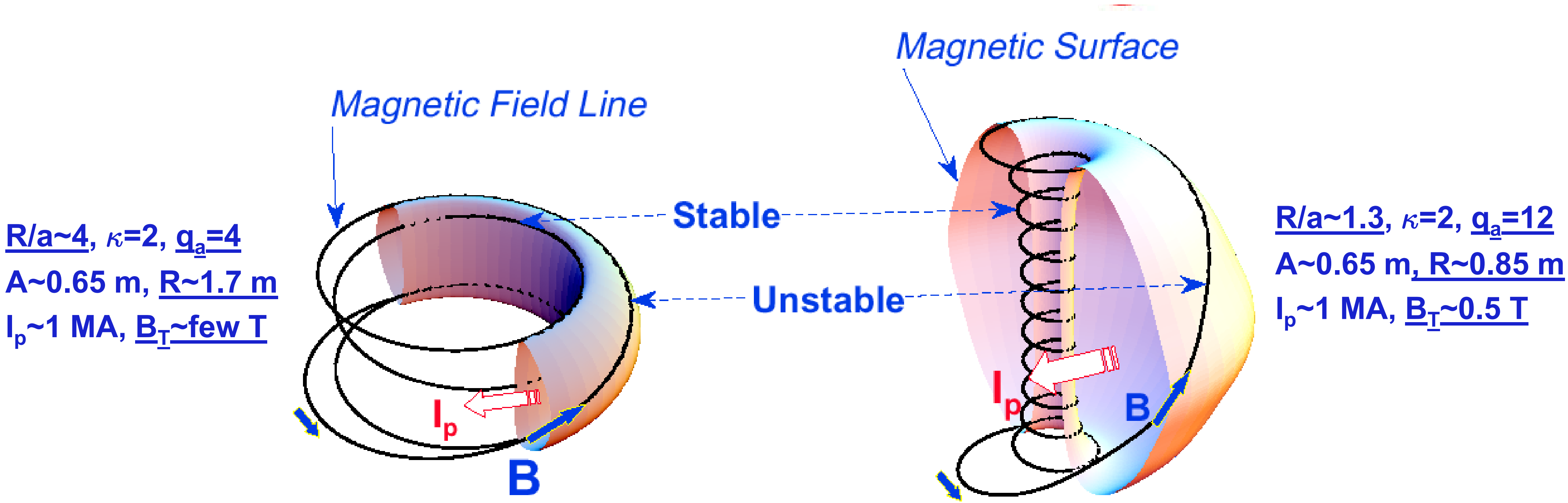
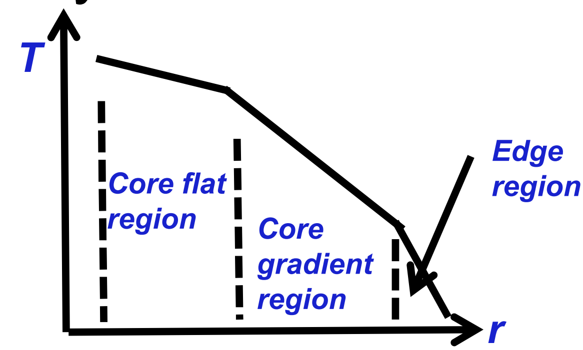
- Understanding and controlling electron thermal transport important for future devices, e.g. ST-FNSF and ITER
- Strong ExB flow shear and low aspect ratio stabilizing low-k turbulence: ions close to neoclassical in H-mode
- Achievable range of β_T can lead to significant EM contribution: assessing magnetic flutter effect, e.g. micro-tearing turbulence
- Large ρ_e makes localized electron-scale measurement possible



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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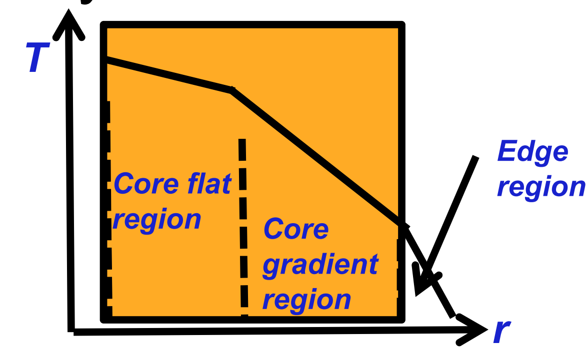
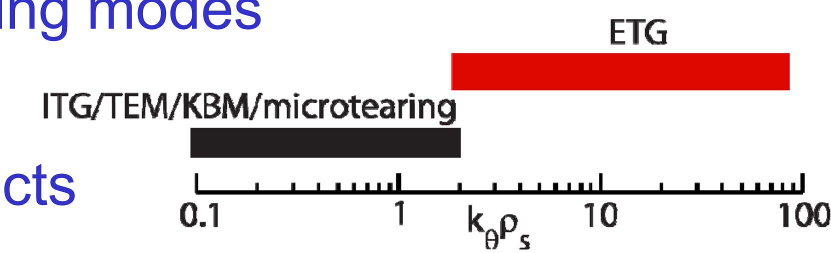
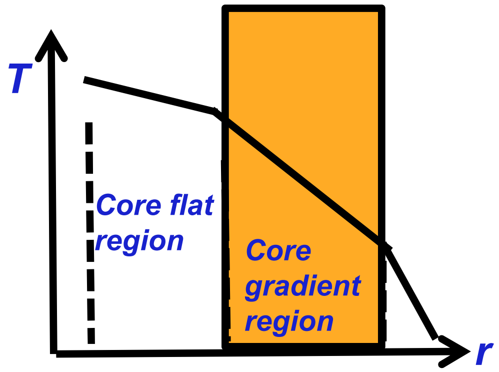


- Gradient driven electrostatic and electromagnetic ballooning drift instabilities:
  - Low-k (ion-scale): ITG/TEM/KBM/microtearing modes
  - High-k (electron-scale): ETG modes
  - Turbulent ExB drift and magnetic flutter effects

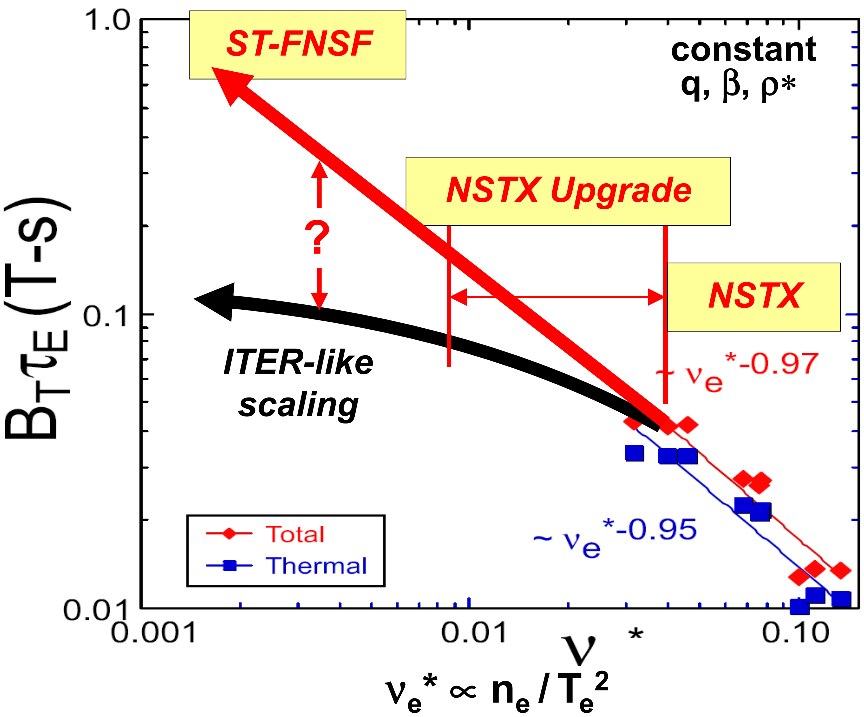


- Fast ion driven Alfvenic eigenmodes
  - GAE and/or CAE modes
  - Alfvenic eigenmode induced electron phase space stochasticity

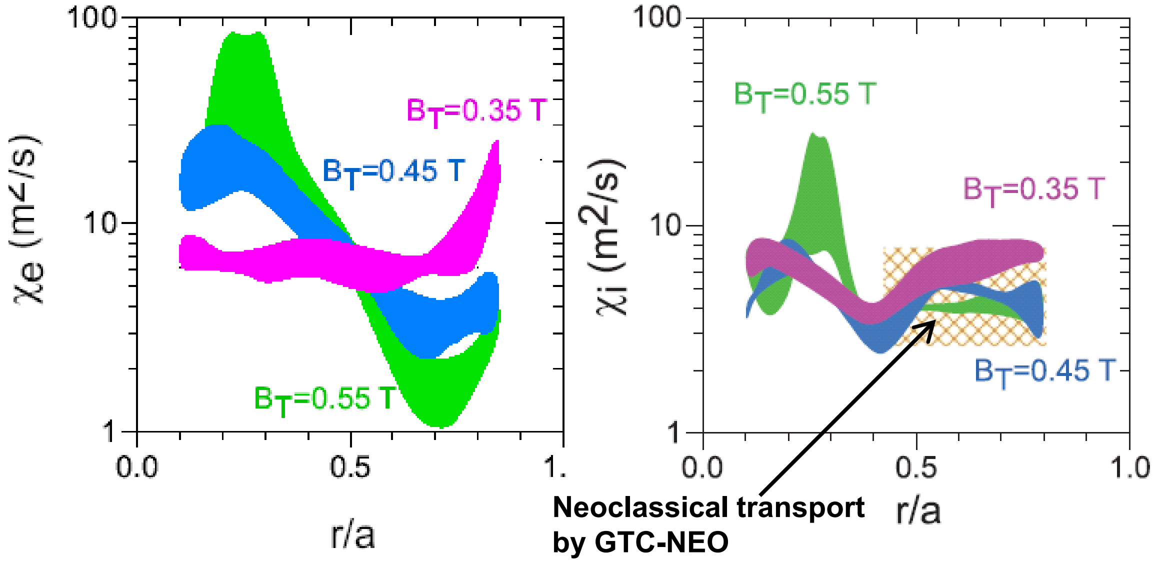
First nonlinear gyrokinetic simulation of micro-tearing turbulence in a H-mode plasma



NSTX Thermal Confinement has Strong Collisionality Scaling in H-mode Plasmas



- •NSTX $\Omega\tau_E^{th} \sim \nu_{*e}^{-0.95}$ Kaye et al. (Nucl. Fusion, 2007)
- •MAST $\Omega\tau_E^{th} \sim \nu_{*e}^{-0.82}$ (Valovič et al.,Nucl. Fusion, in press)
- •ITER $\Omega\tau_E^{th,04(2)} \sim \nu_{*e}^{-0.2}$ (Doyle et al., Nucl.Fusion 2007)



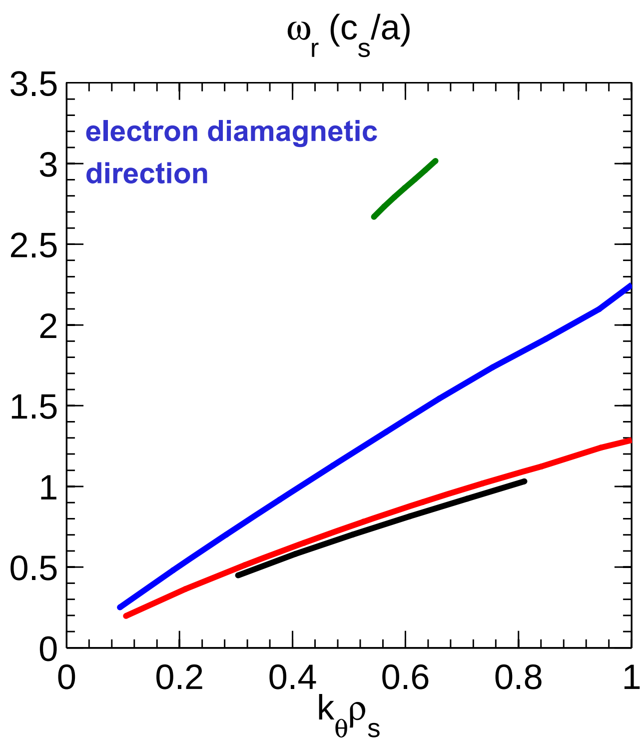
- Ion transport is neoclassical, consistent with strong toroidal flow and flow shear
- What is the cause of anomalous electron thermal transport?
- Will favorable τ_E scaling hold at lower ν_* envisioned for ST-FNSF?

Microtearing Modes are Found to be Unstable in Many High ν_* H-mode Discharges

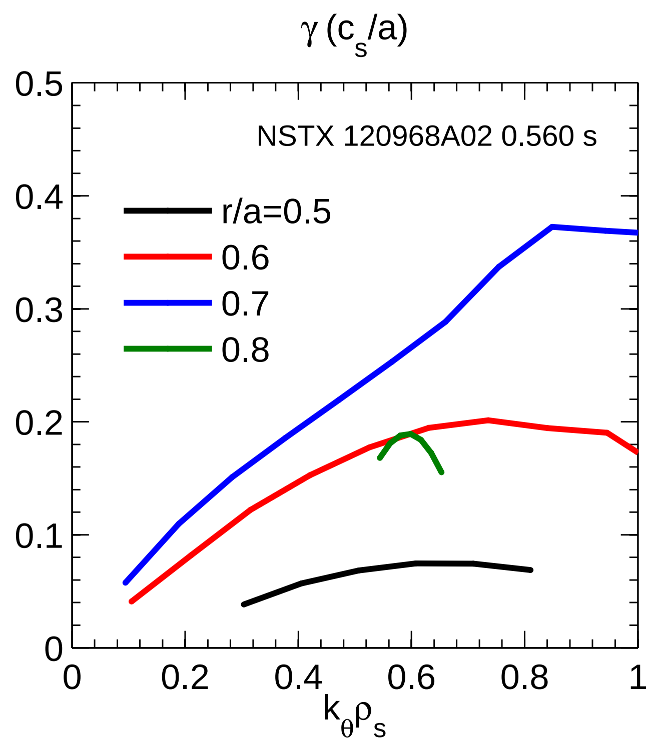
- Microtearing dominates over r/a=0.5-0.8, $k_\theta\rho_s$<1 (n≈5-70)
- Real frequencies in electron diamagnetic direction, $\omega \approx \omega_{*e} = (k_\theta\rho_s)\cdot(a/L_n + a/L_{Te})\cdot(c_s/a)$
- ETG mostly stable due to larger Z_{eff}≈3, $(R/L_{Te})_{crit,ETG} \sim (1+Z_{eff}T_e/T_i)$

B_T=0.35 T, I_p=700 kA, P_{NBI}=4 MW

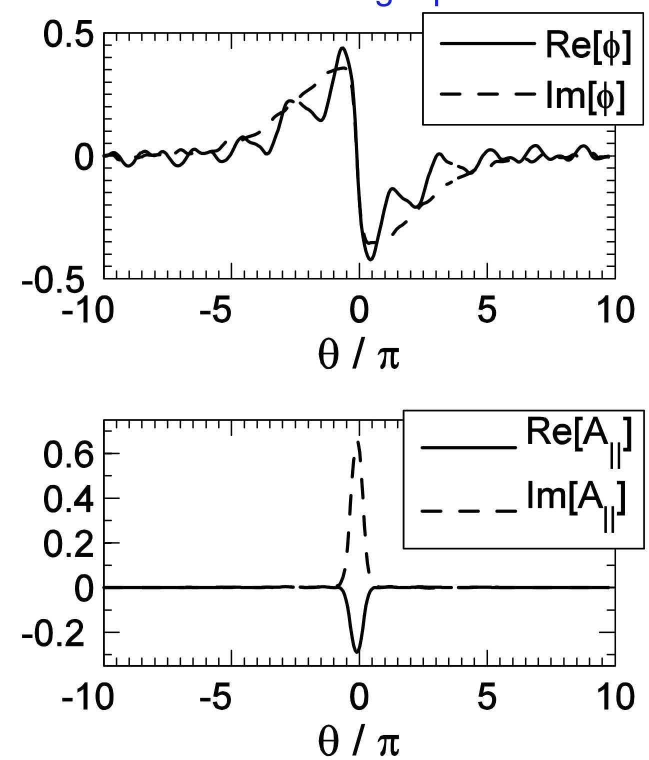
real frequencies



growth rates

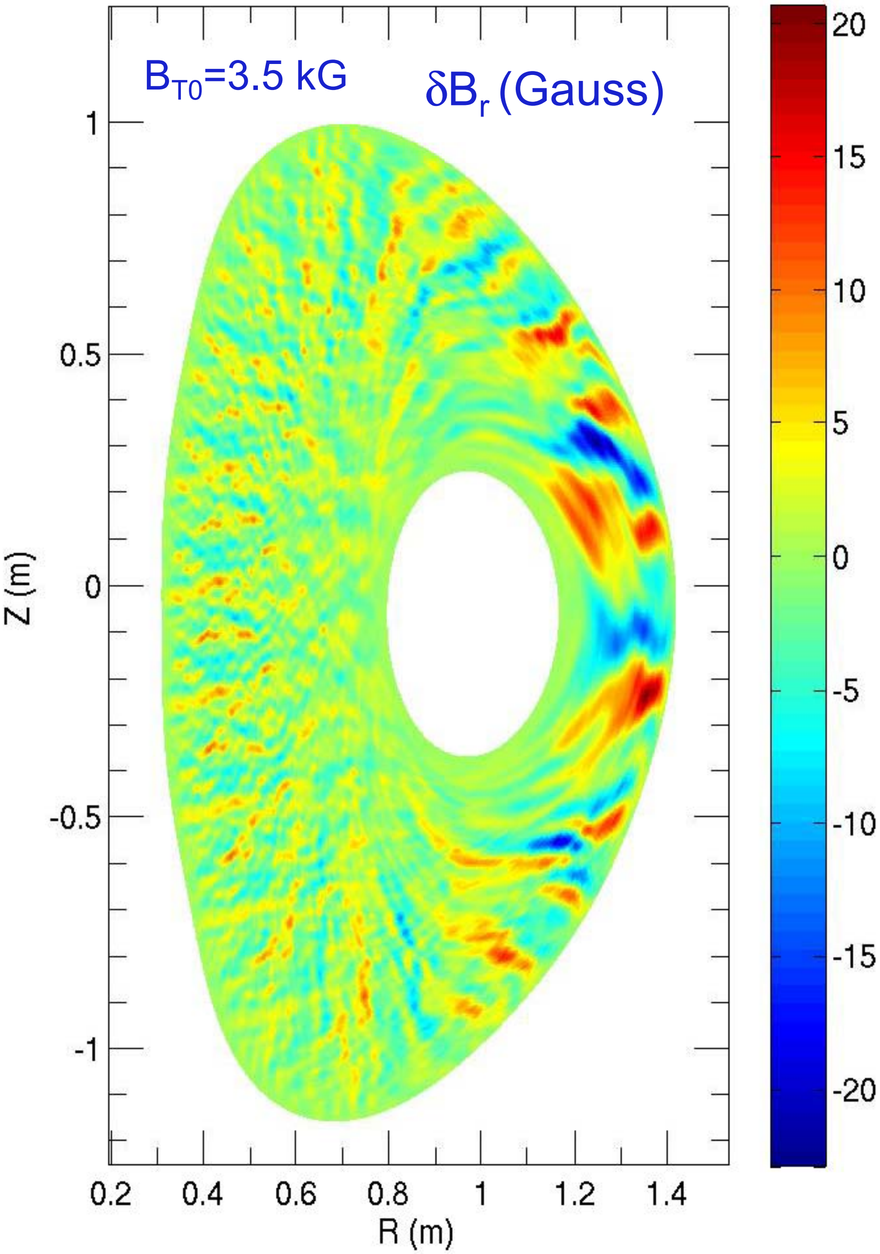


eigenfunctions in "ballooning" space

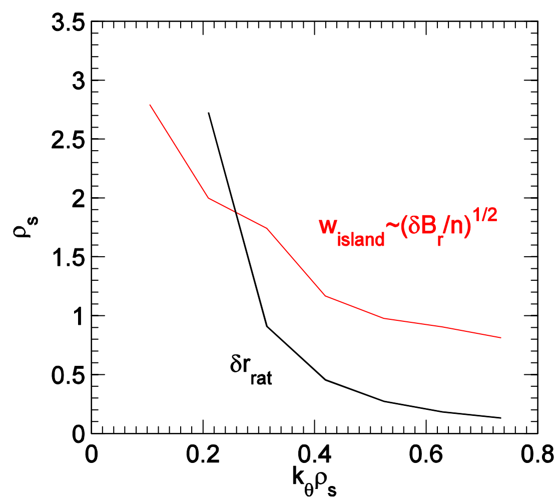


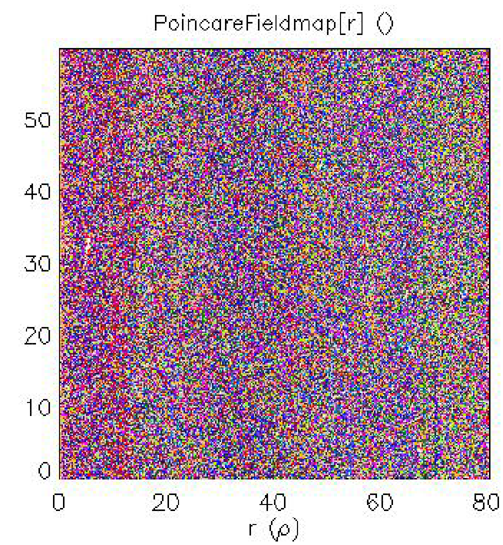
- Linear GYRO simulations [Candy & Waltz, Phys. Rev. Lett. (2003); https://fusion.gat.com/theory/Gyro] using local general equilibrium, kinetic ions (D+C) and electrons, collisions, fully electromagnetic

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** (λ_{mfp}=12 m, $L_c \approx$2.5 m)





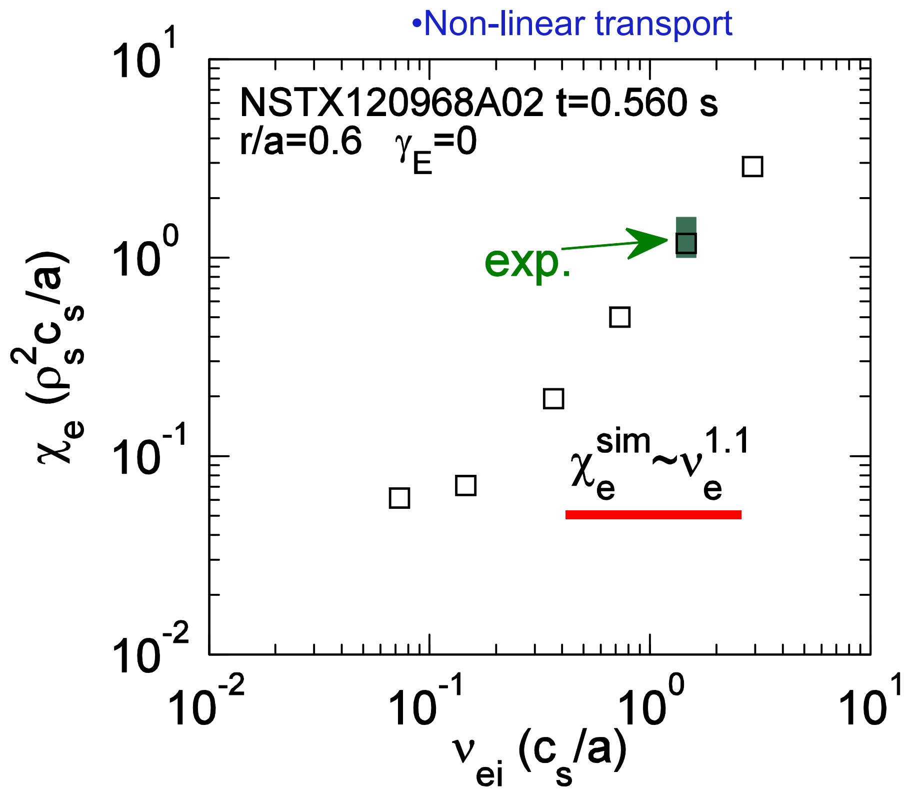
*E. Wang et al., PoP (2011).

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

•W. Guttenfelder et al., PRL (2011)

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

Near Linear Scaling of Transport with ν_e Consistent with Experimental Scaling



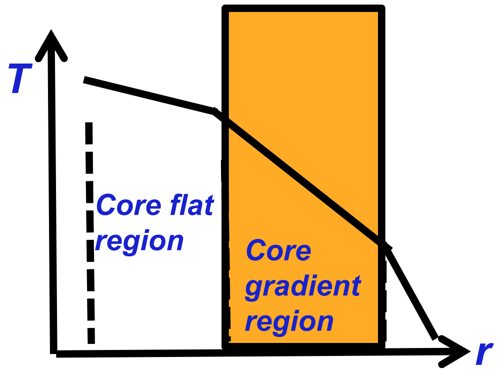
•NSTX experimental scaling

•(Kaye et al., 2007)

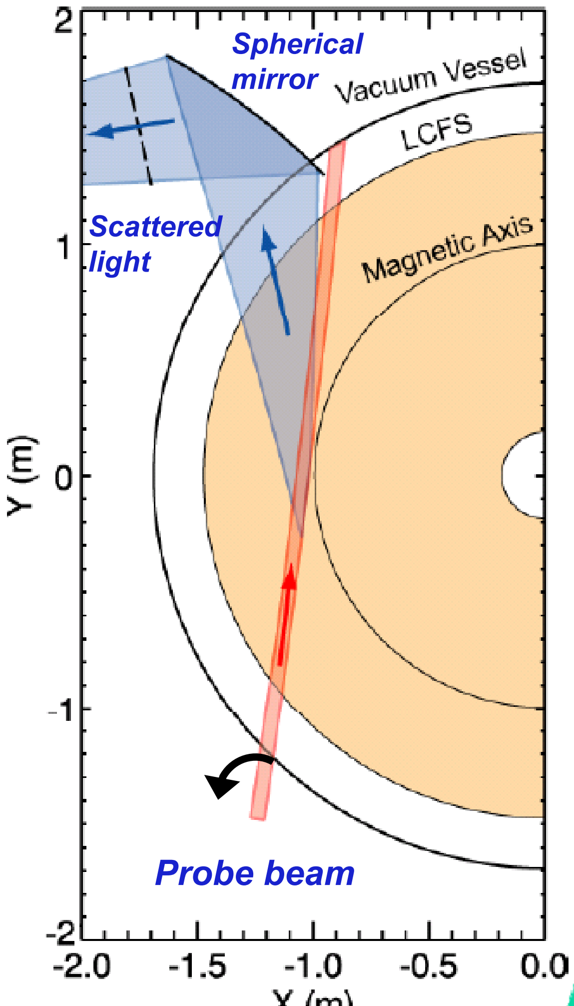
$\Omega_i \tau_E \sim \nu_*^{-0.95}$

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

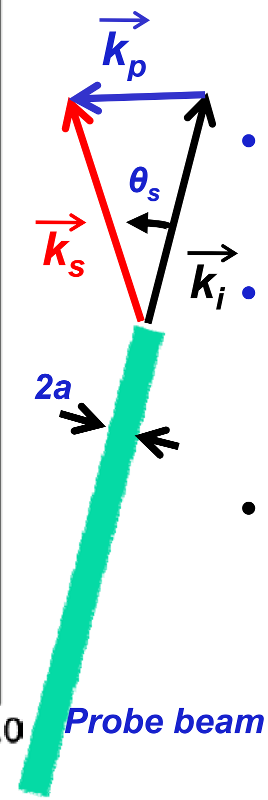
Density gradient stabilization of ETG turbulence



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:

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

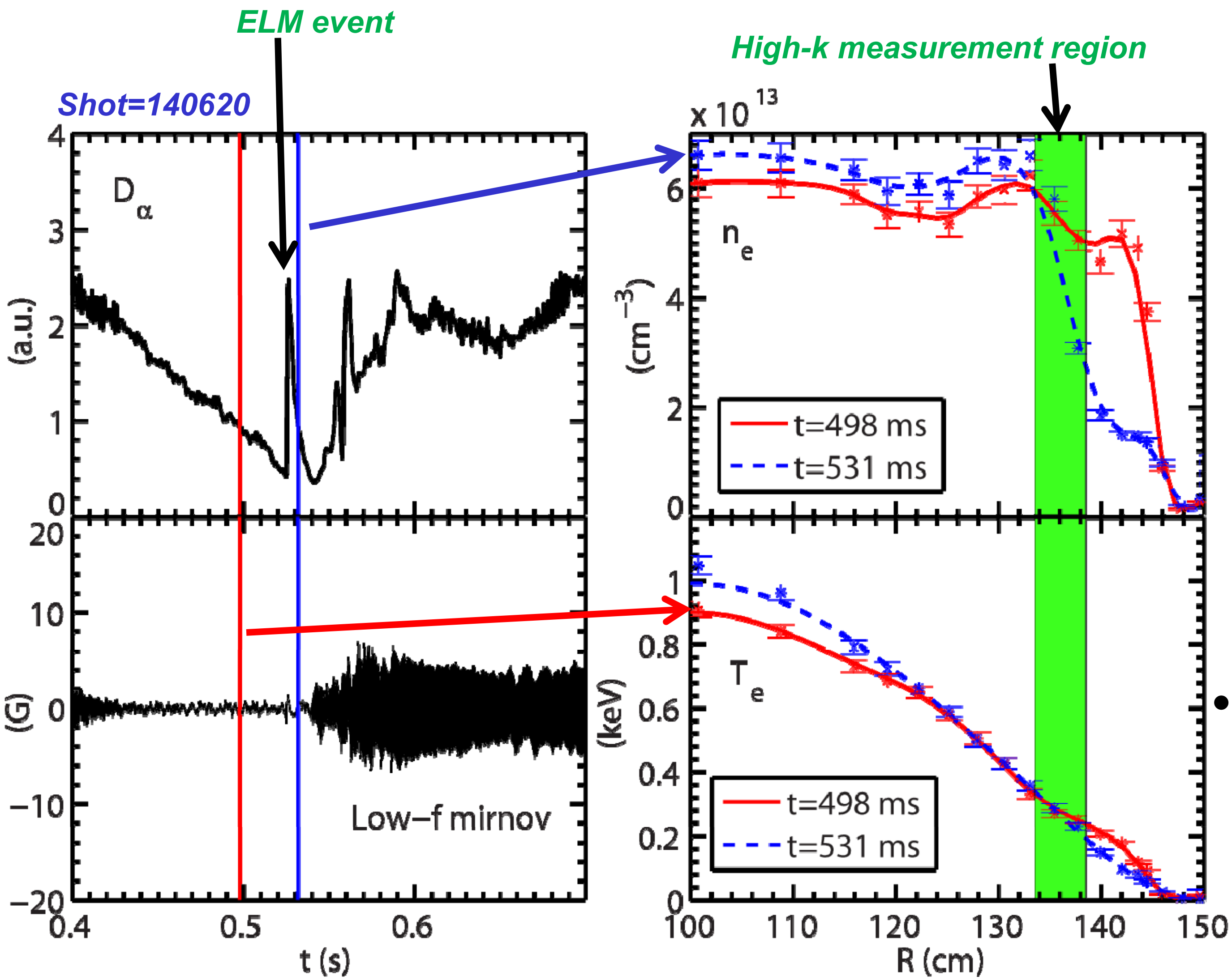
- The scattered light has a frequency of:

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

with ω_s and $\omega_i >> \omega_p$

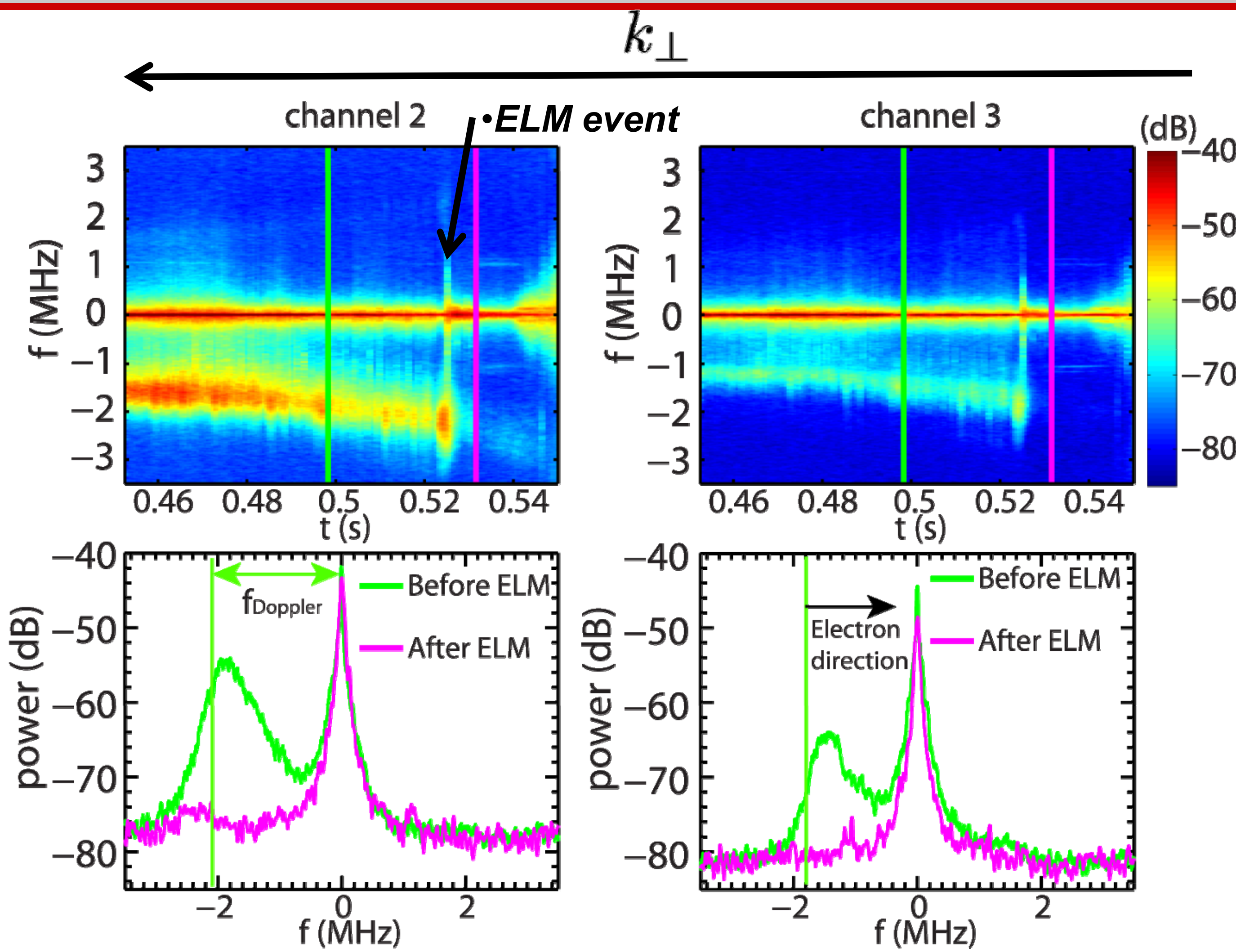
- The scattering system characteristics are:
  - **Frequency bandwidth: 5 MHz**
  - **Heterodyne receiver: Wave propagation direction resolved**
  - **Measurement: k_r spectrum**
  - **Wavenumber resolution: 0.7 cm^{-1} (2/a with a ≈ 3 cm)**
  - **Wavenumber *range* (k_r): 5-30 cm^{-1} (~5-30 ρ_s^{-1})**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

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

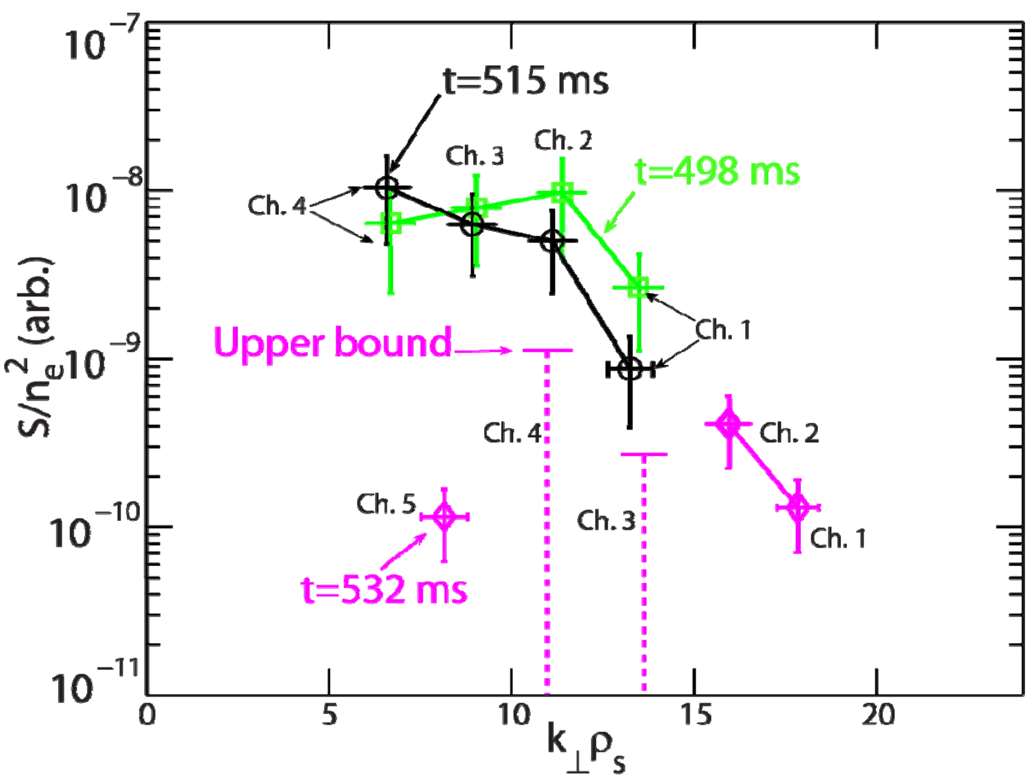
Significant decrease in scattering signal power observed after the ELM

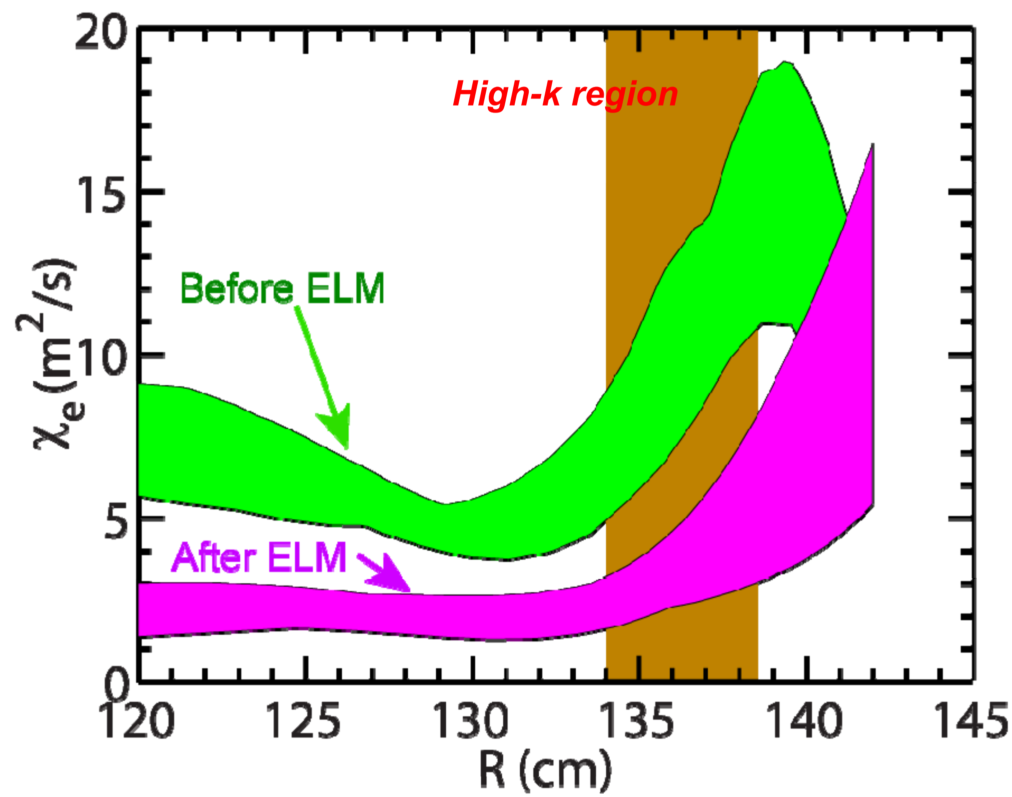


- Significant fluctuations before ELM, in electron diamagnetic direction
- Interpretation has to take into account the change of wavenumber measured by each channel due to the increase density gradient & refraction after the ELM event

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

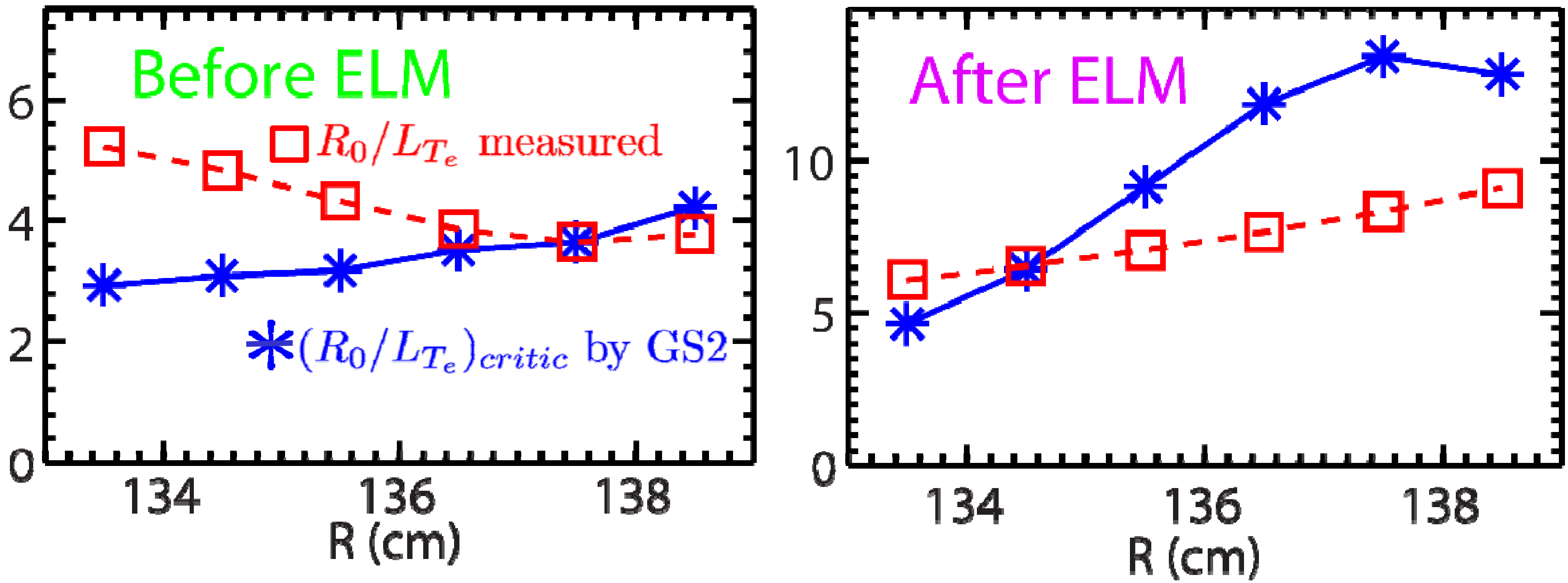




*Y. Ren et al., PRL 106, 165005 (2011)

Threshold Gradients for ETG modes are much Higher after the ELM

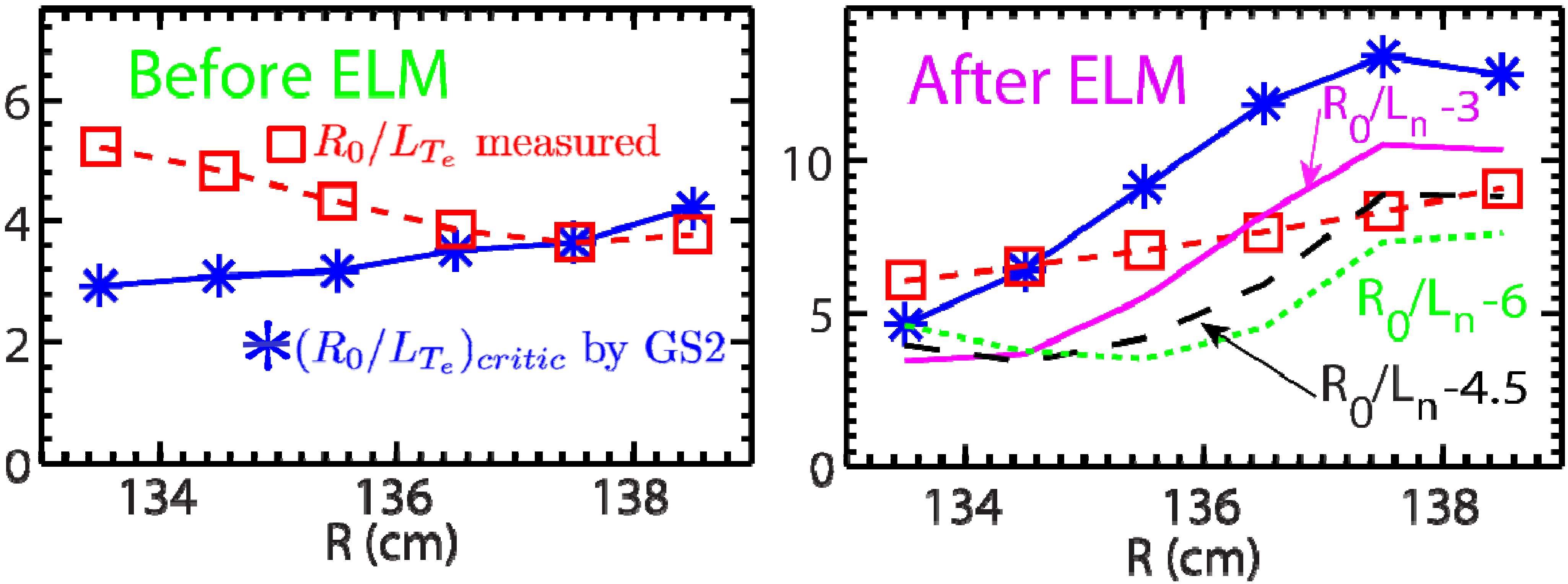
- Before ELM, ETG is largely unstable
- After ELM, ETG is largely stable



- 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



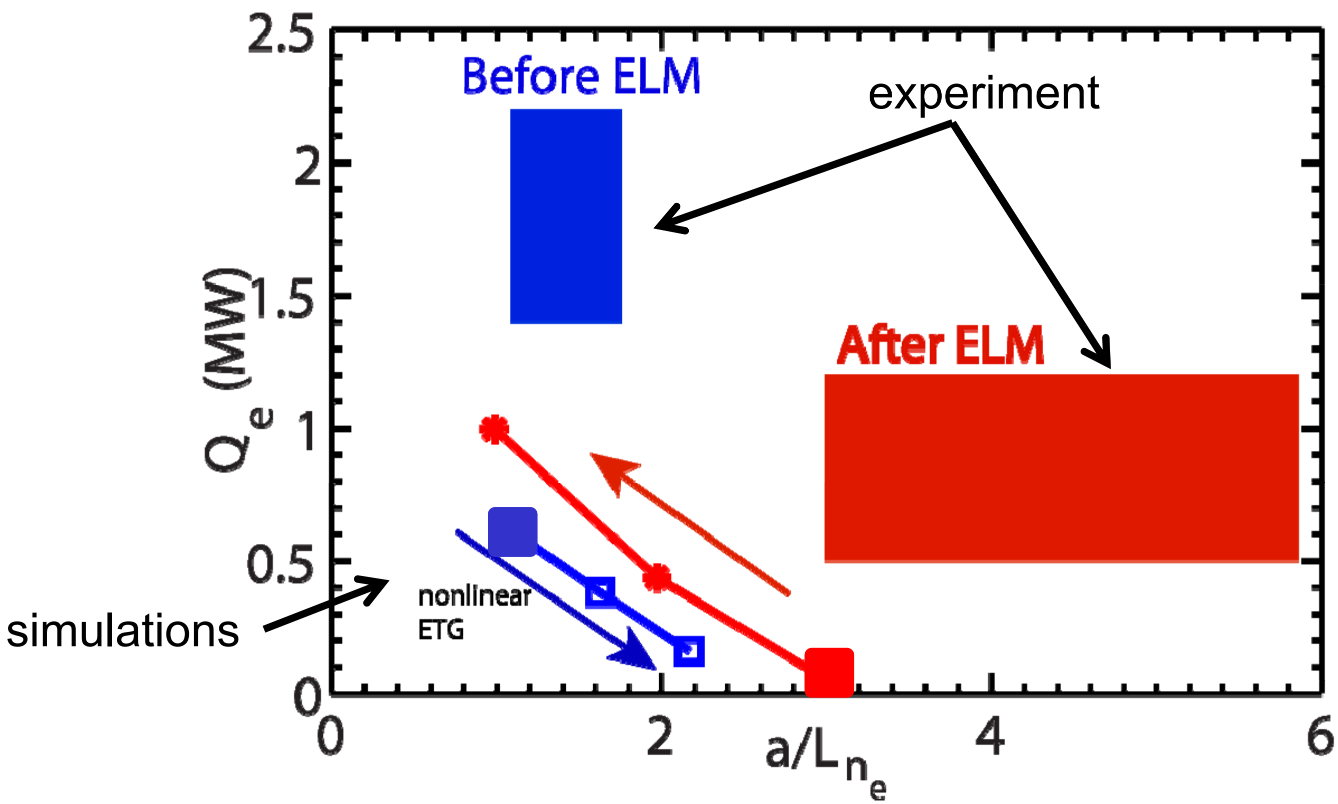
- Manually decreasing R/L_{ne} brings down critical gradient as expected from linear theory (e.g. Jenko et al, 2001)

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

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

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

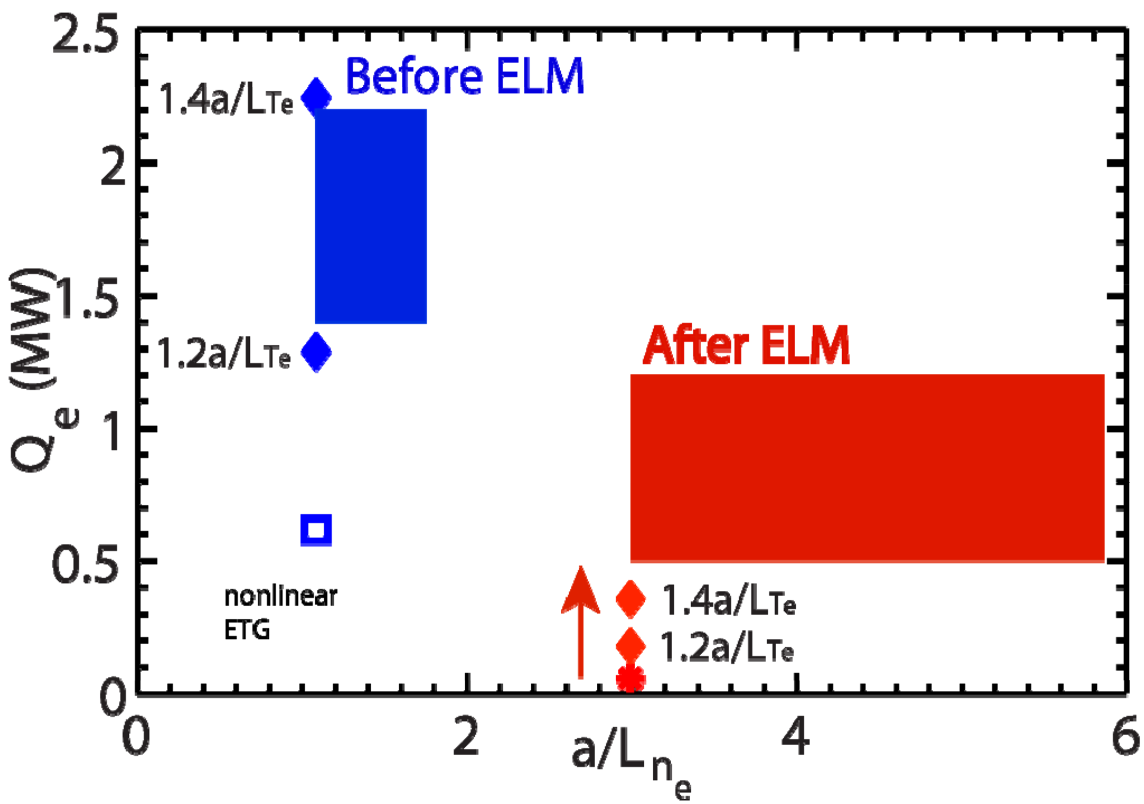
- Experimental Q_e is found to decrease after the ELM event with large density gradient
- The same trend is found from nonlinear ETG simulations, but does not agree quantitatively



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

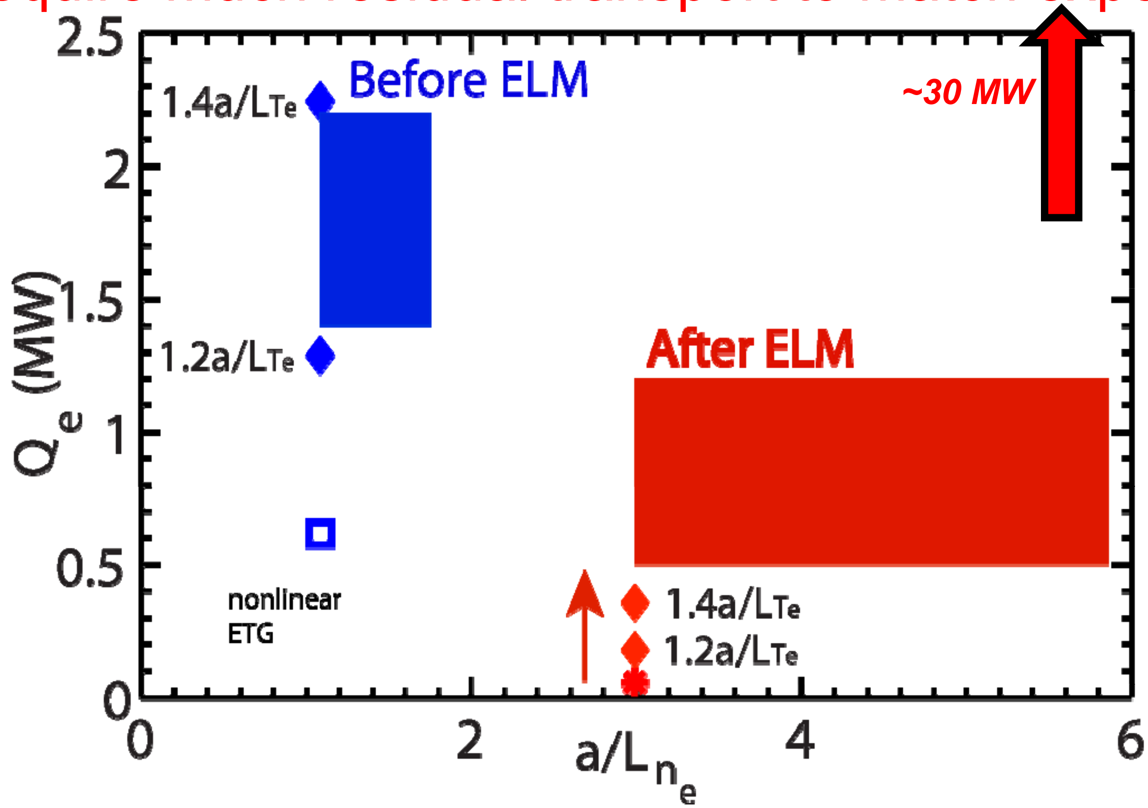
- Before ELM, a 20-30% increase in a/L_{Te} is able to match the experimental Q_e
- After ELM, increasing a/L_{Te} by 40% after still cannot match experimental Q_e



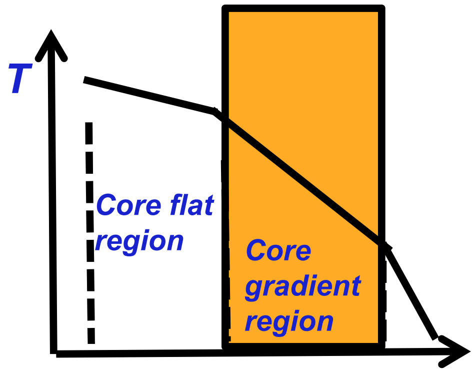
Trapped Electron Mode (TEM) Destabilized by Large Density Gradient may Contribute to Transport

- 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

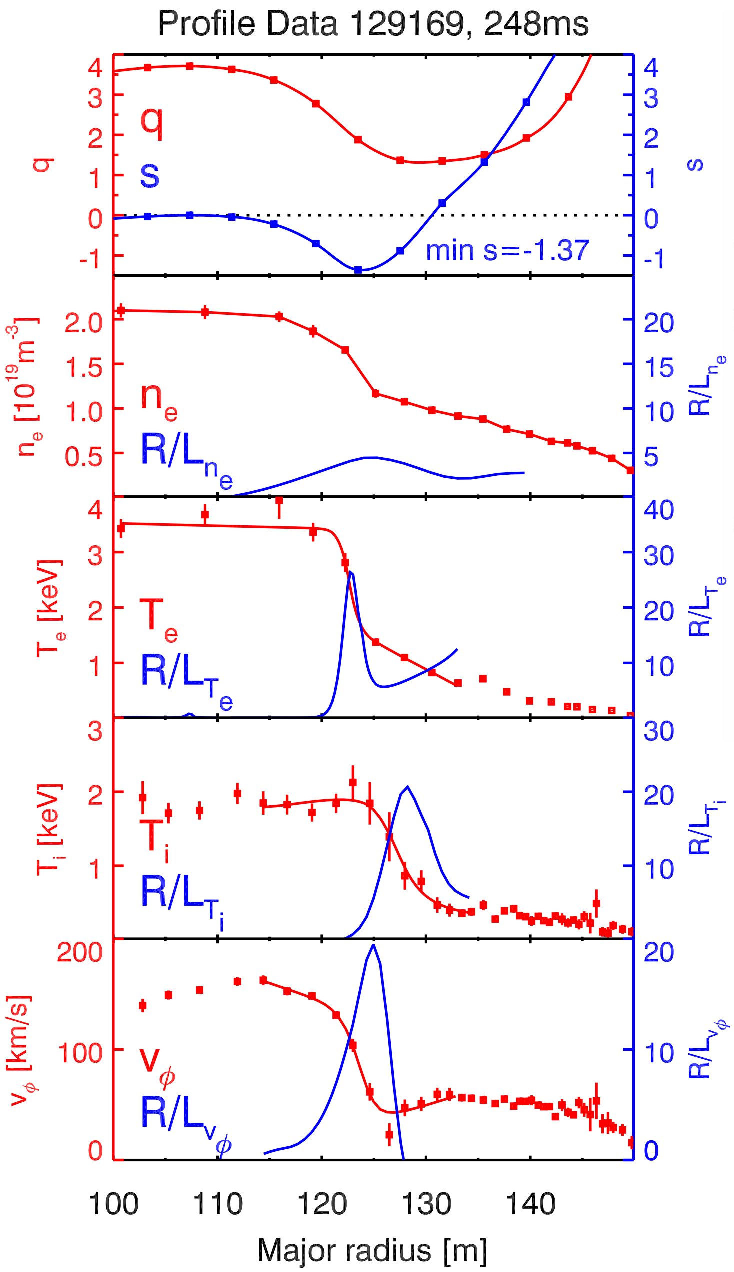
  → does not require much residual transport to match experimental Q_e

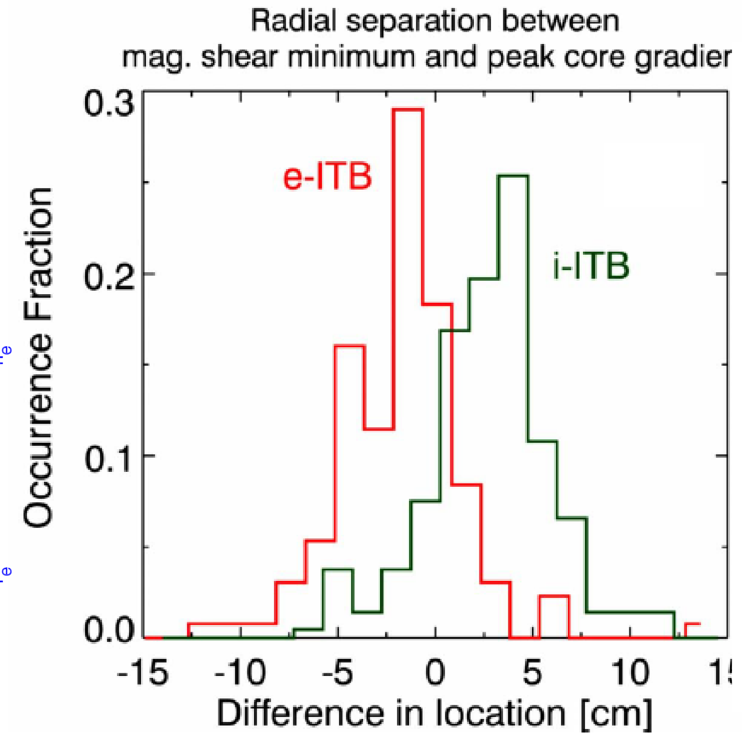


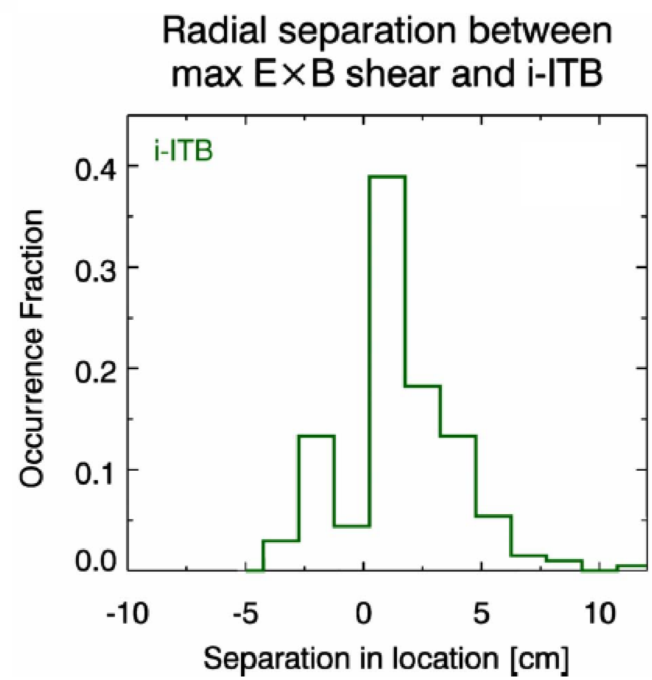
Suppression of ETG turbulence in reversed shear L-mode plasmas



Electron Internal Transport Barrier Location is better Correlated with S_{min} Location

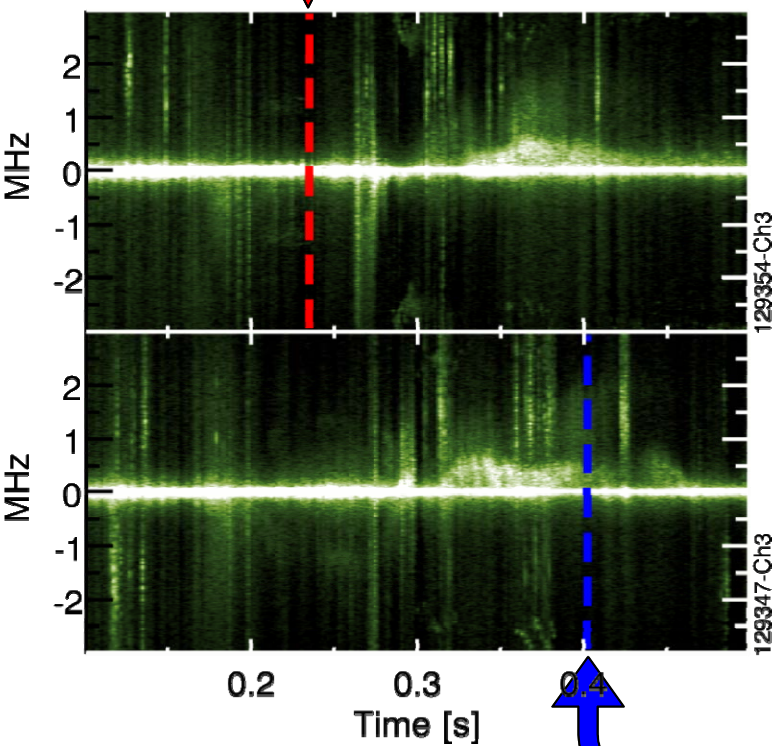


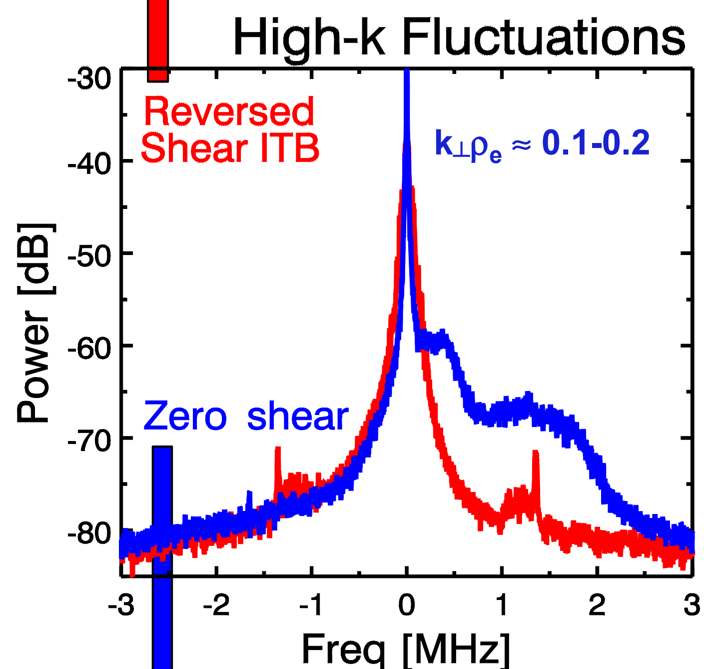


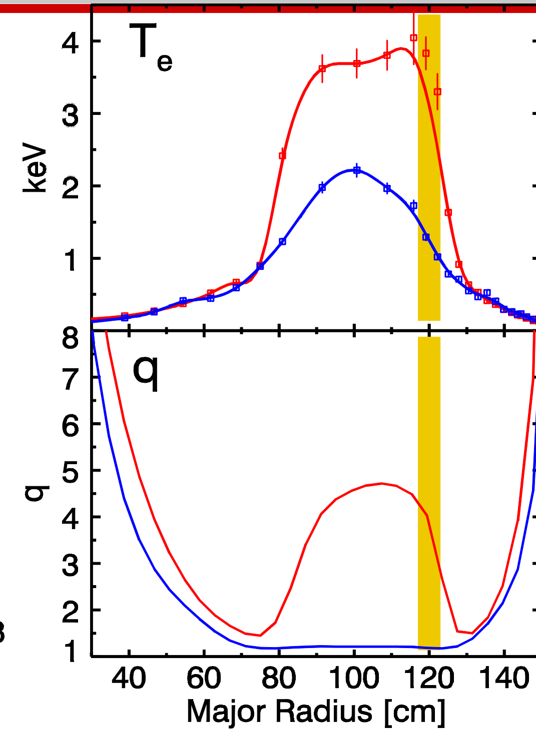


- In e-ITBs, local χ_e can improve by nearly two orders of magnitude (>~0.1 m^2/s and >~10 m^2/s)
- For these lower β, L-mode discharges, Electron Temperature Gradient (ETG) mode suppression may be responsible for improvement

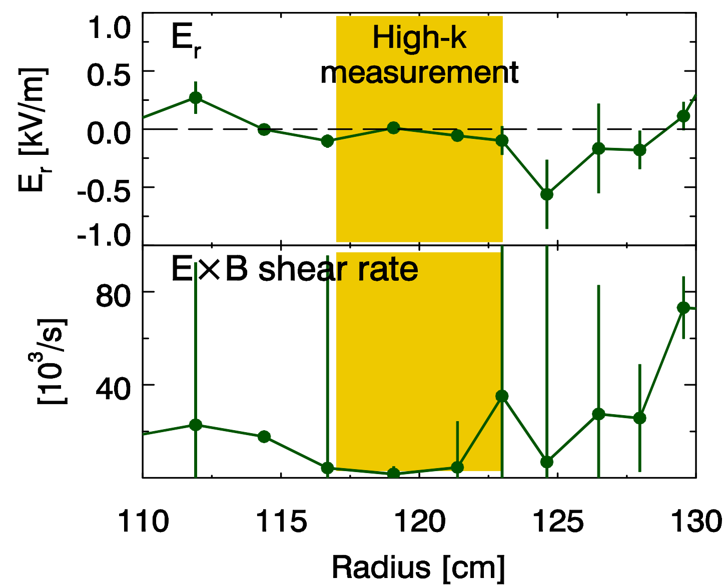
Negative Magnetic Shear can Suppress Electron Thermal Turbulence without Flow Shear





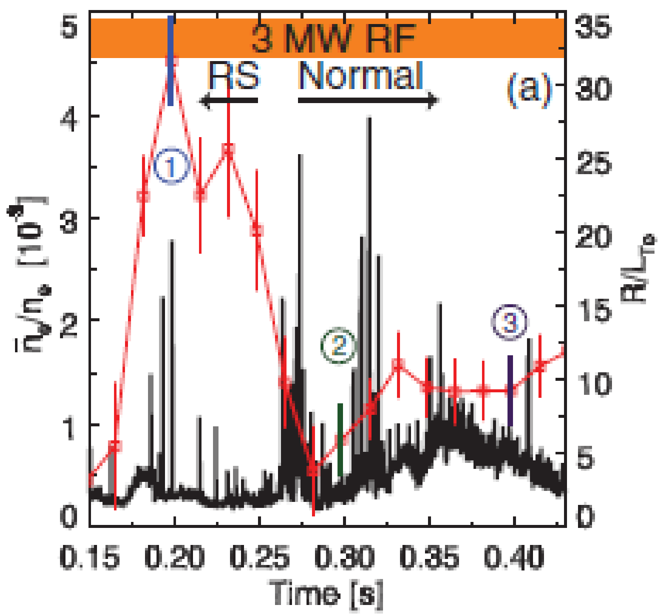


- HHFW only with beam blips
- Minimal ExB shearing rate due to cold ions with low toroidal rotation
- **Magnetic shear alone suppresses electron turbulence**

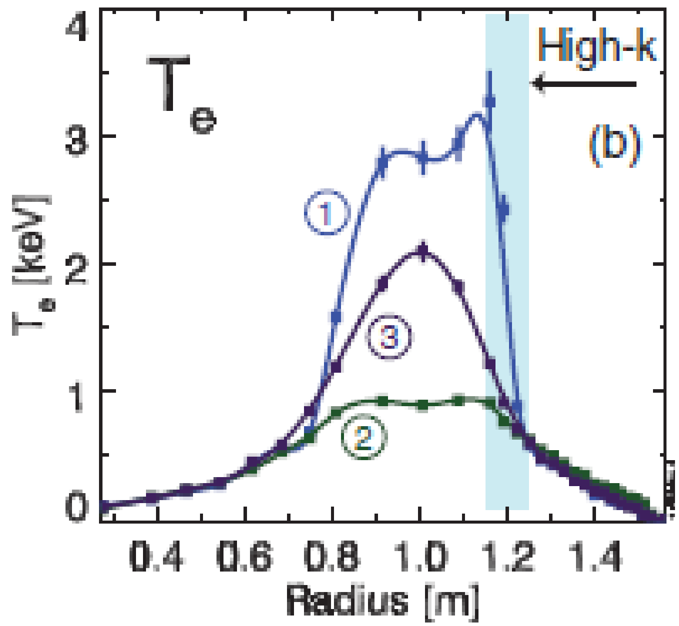


eITB occurs in L-mode with large reverse magnetic shear, s<<0, and Low/ bursty High-k Fluctuations

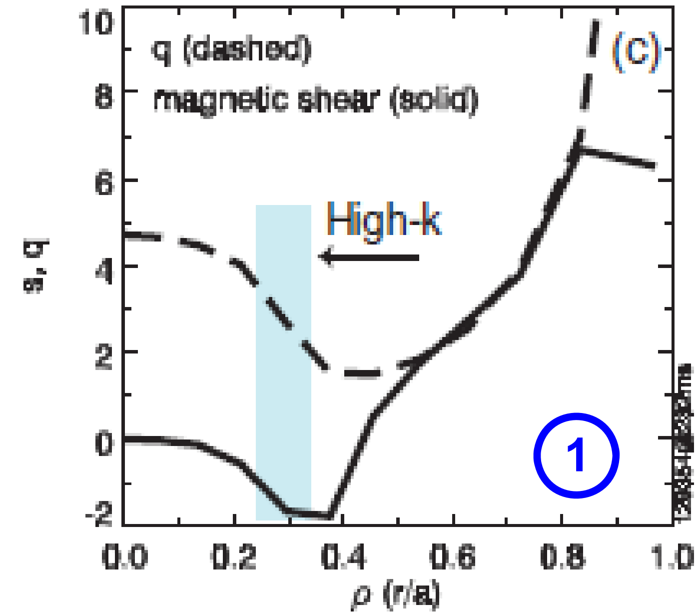
δn/n and R/L_{Te} vs. time



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

Supercritical T_e Gradients are Correlated Weak High-k Turbulence with Largest Negative Shear

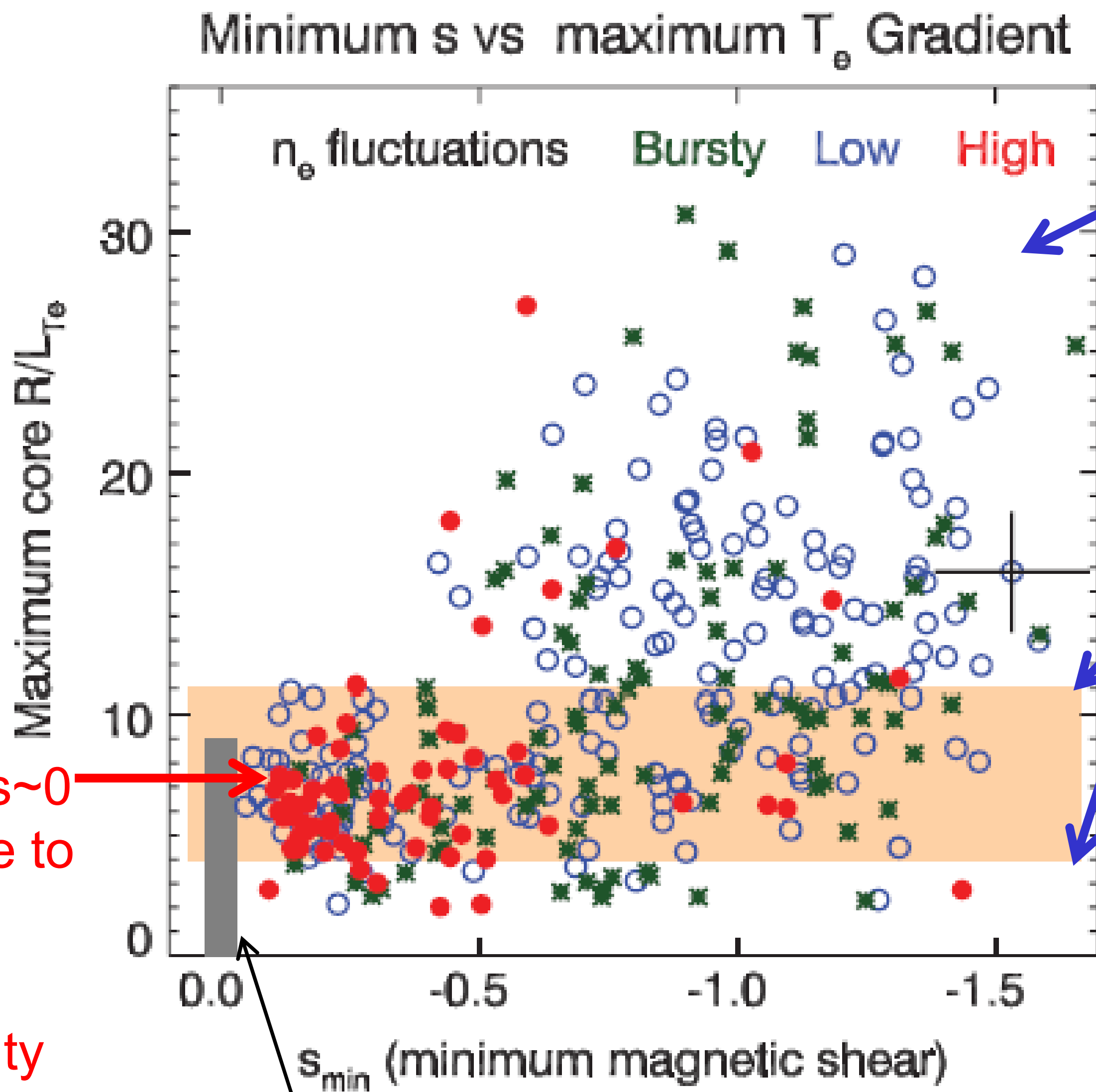
Many discharges

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)

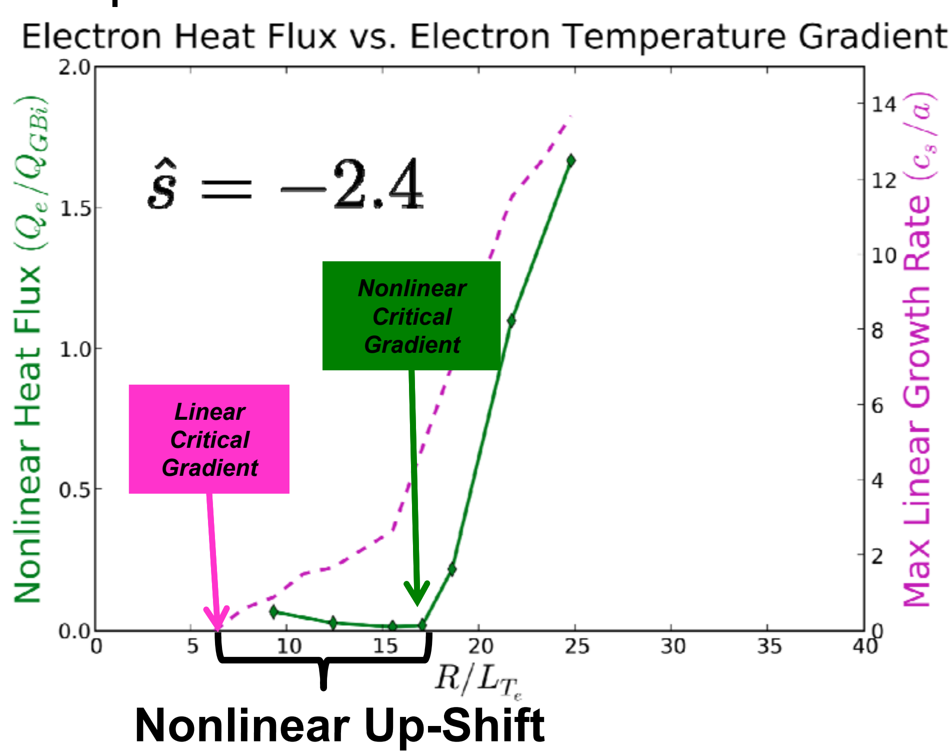
- For weak shear, s~0 R/L_{Te} limited close to linear threshold
- Large high-k fluctuation intensity

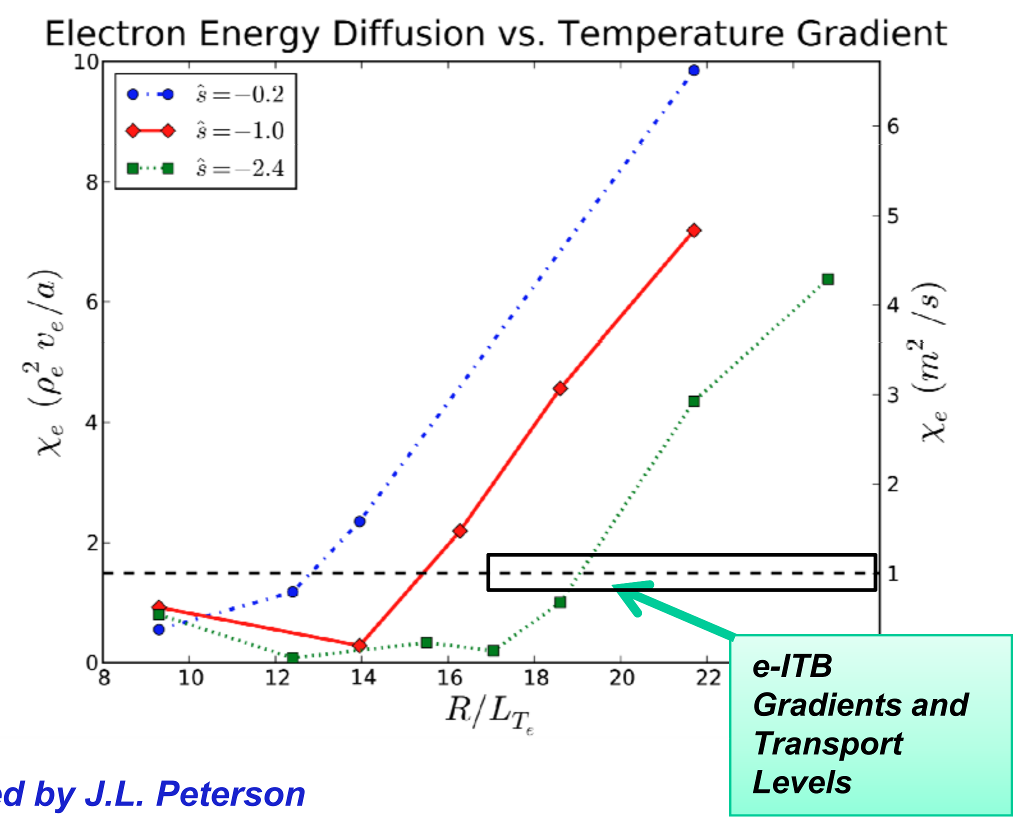
Characteristic H-mode values

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

Nonlinear ETG GYRO Simulations Demonstrate the Role of ETG in e-ITB Formation

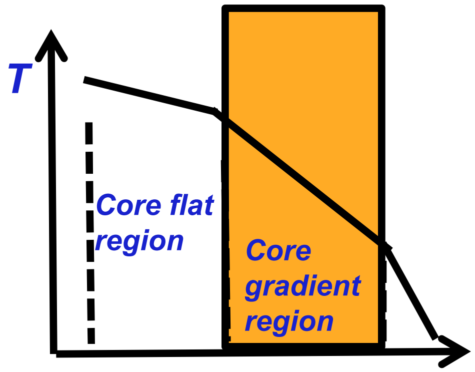
- Large nonlinear up shift in critical gradient with negative magnetic shear
- In agreement with supercritical ETG gradients observed in experiments
- Transport threshold is shown to increase with reversed shear
- The predicted transport trends in agreement with experiments





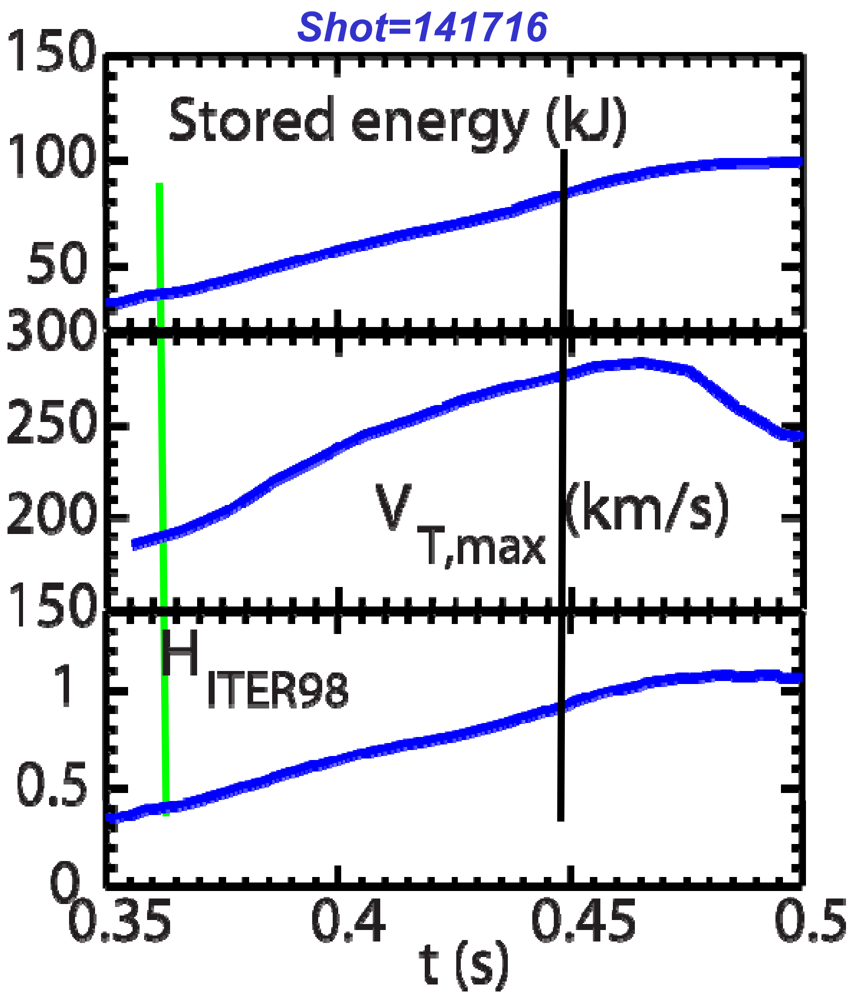
•Simulation performed by J.L. Peterson

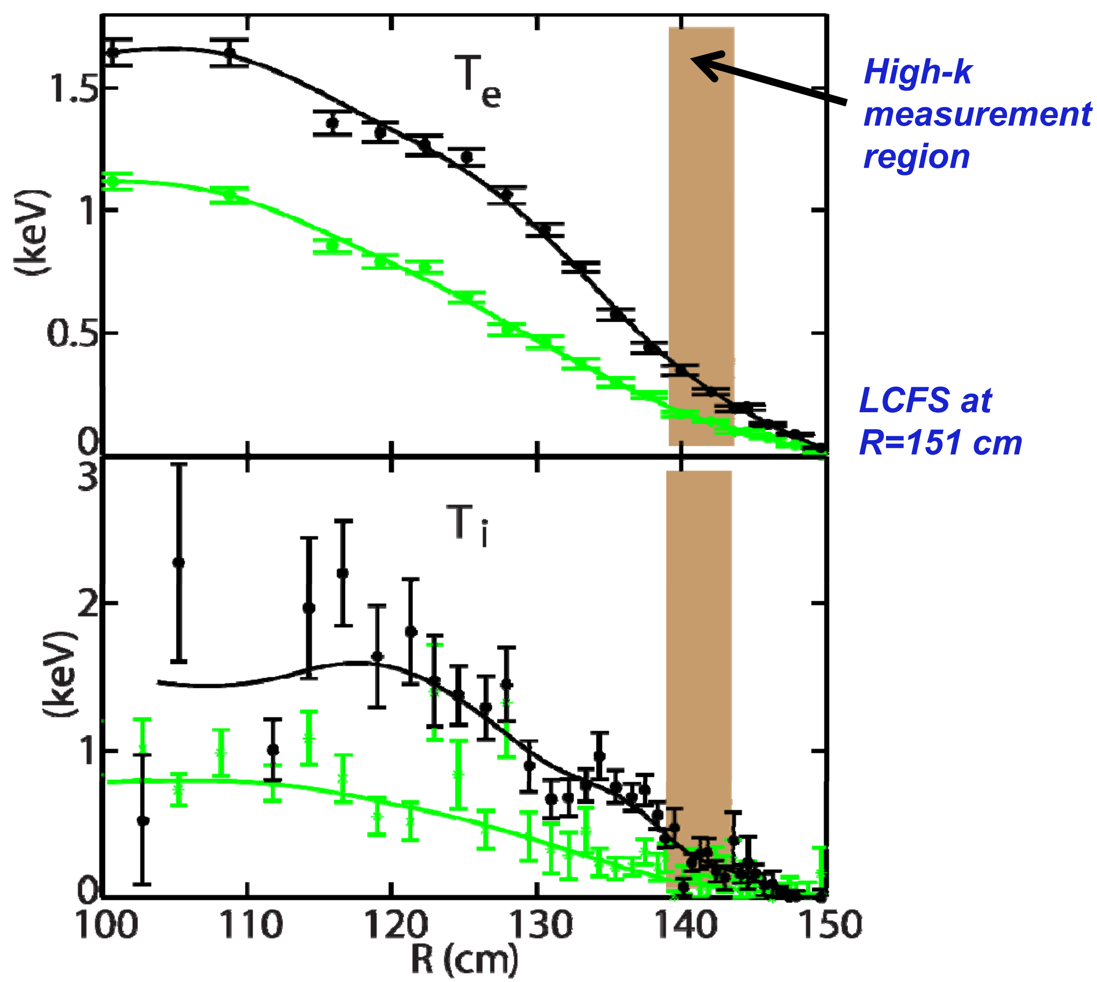
ExB shear induced reduction of electron thermal transport and electron-scale turbulence



L-mode Plasma Confinement Reaches that of the H-mode of Conventional Tokamaks

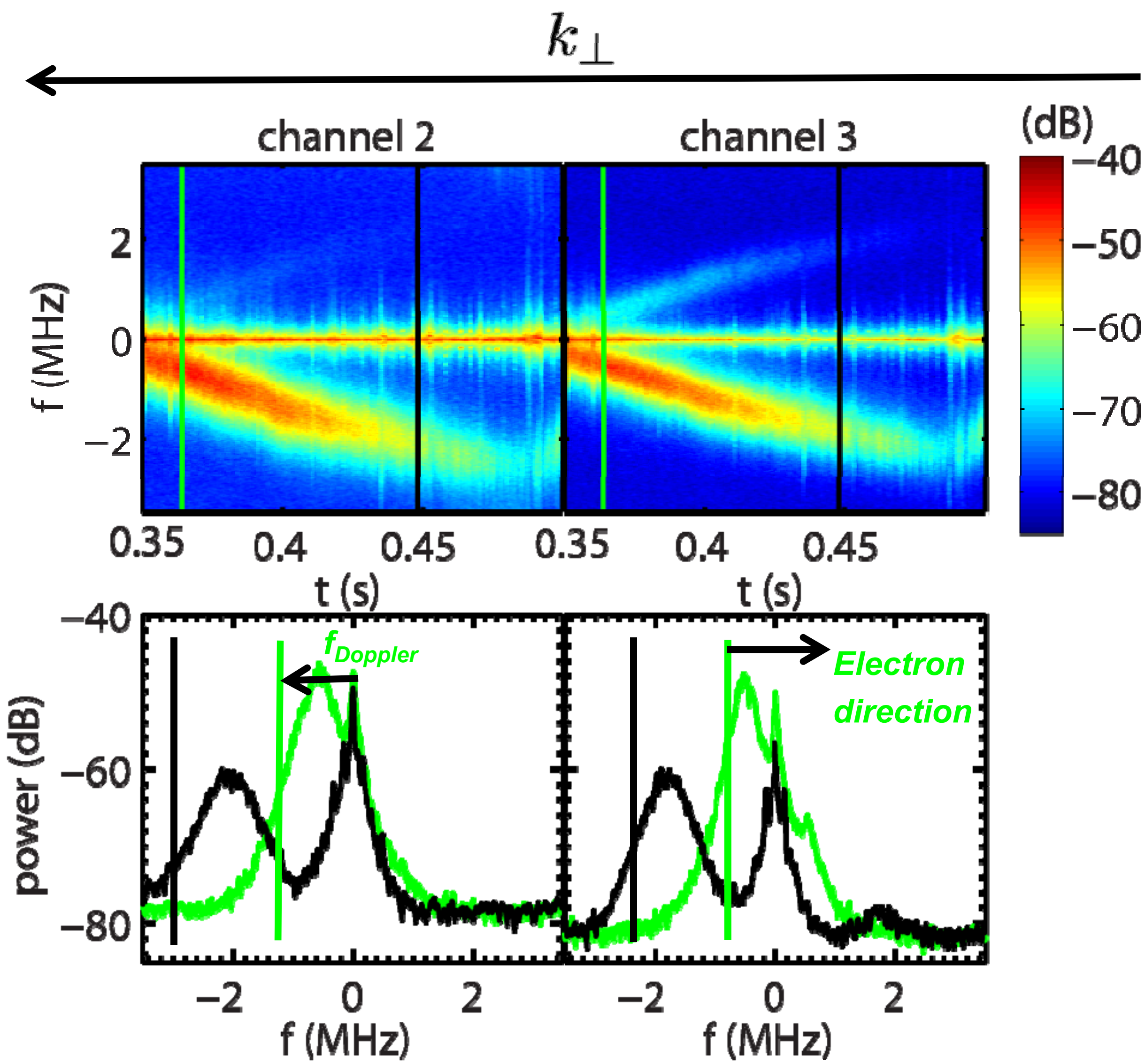
- Center-stack limited and NBI-heated L-mode plasmas with B_T =5.5 kG, I_p=900 kA, P_{NBI}=2 MW
- Both T_i and T_e increases as plasma poroidal velocity Increases
- No formation of a transport barrier observed





Decrease in Scattering Power has been Observed as Plasma Spins up

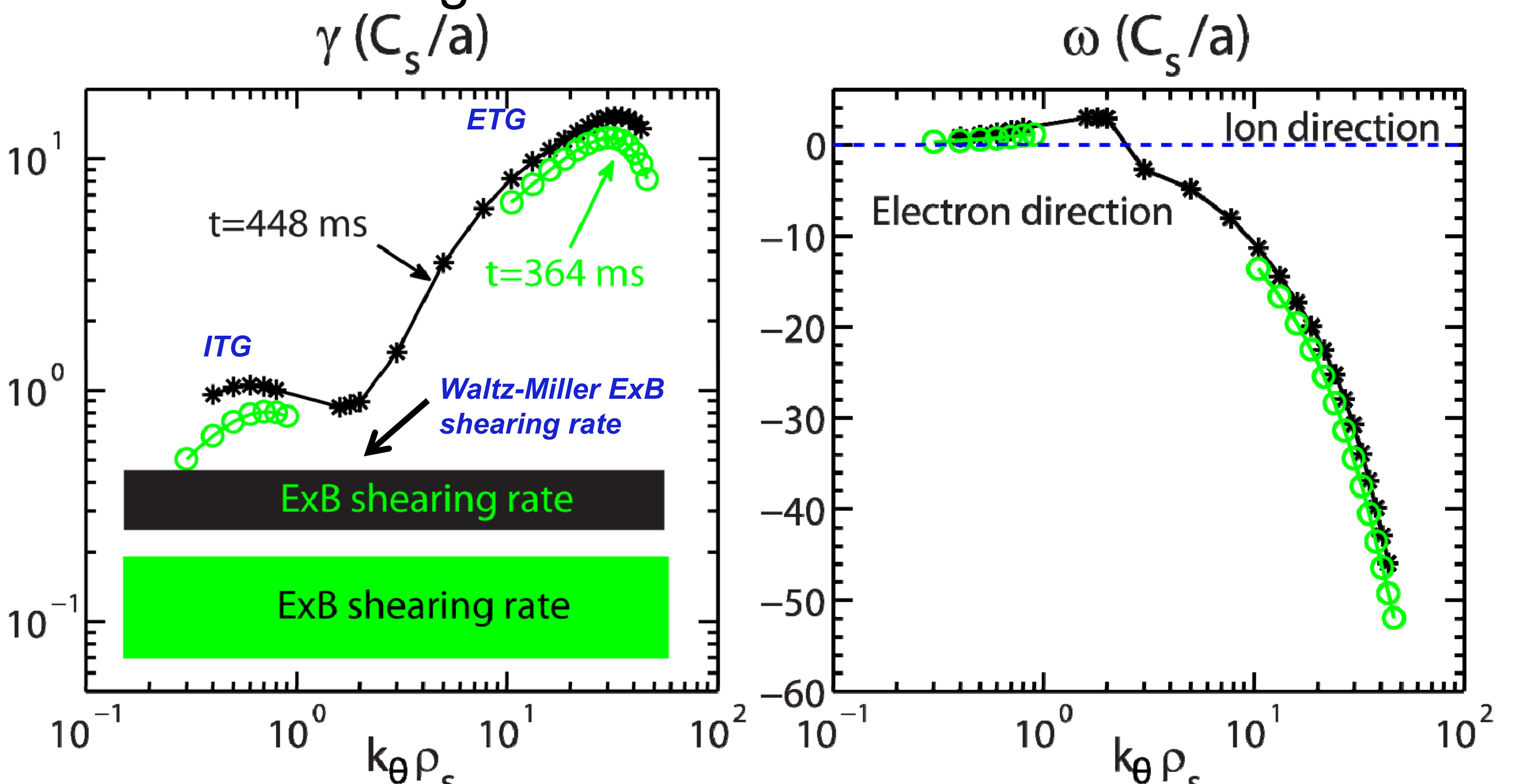
- Plasma rotation leads to large Doppler shift frequency



- *Off-center peak denotes the scattered signal*
- *f=0 peak is from stray radiation*

Linear Stability Analysis Shows that ITG and ETG are both Unstable

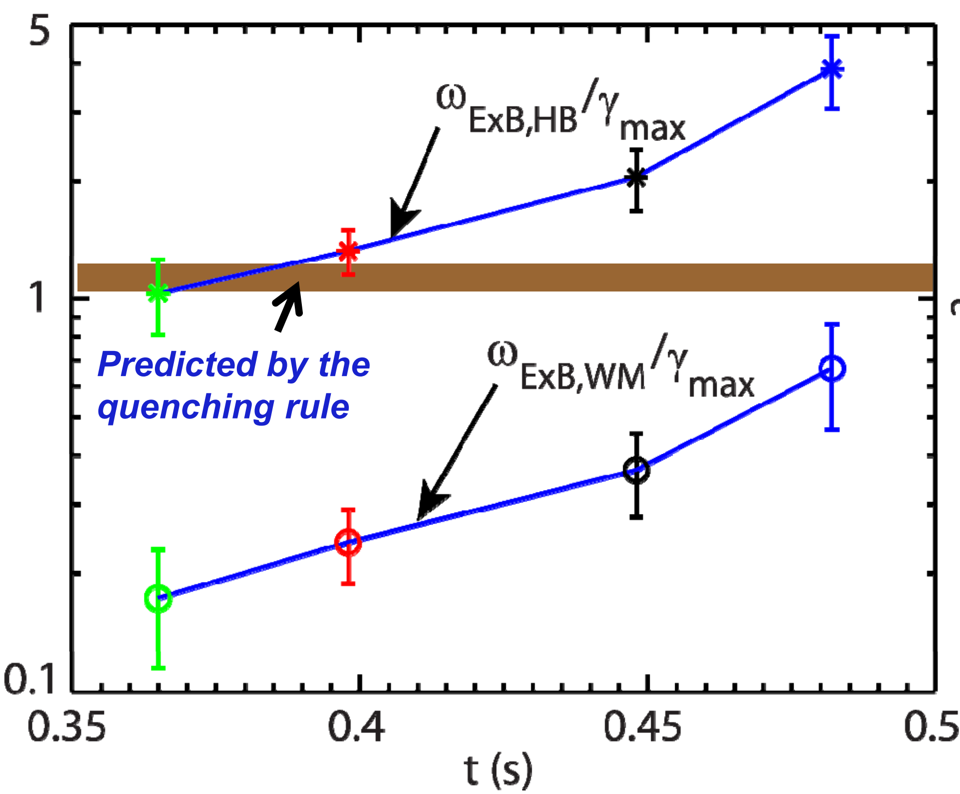
- The maximum ITG growth rate is comparable to the ExB shearing rate
- The maximum ETG growth rate is more than 10 times larger the ExB shearing rate

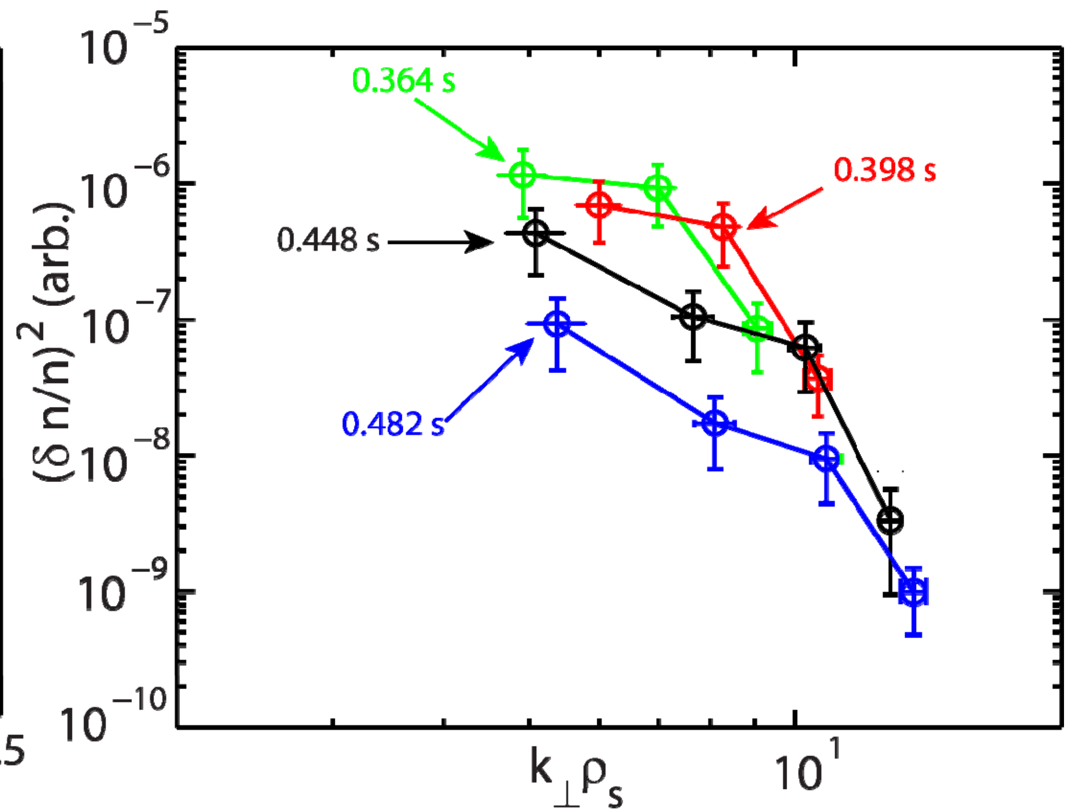


Stability Analysis was performed with the GS2 code (Kotschenreuther et al., 1995) with Miller local equilibrium

Reduction in Peak Spectral Power in the High-k Measurement Region is Correlated with Increase in $\omega_{E\times B}/\gamma_{max}$

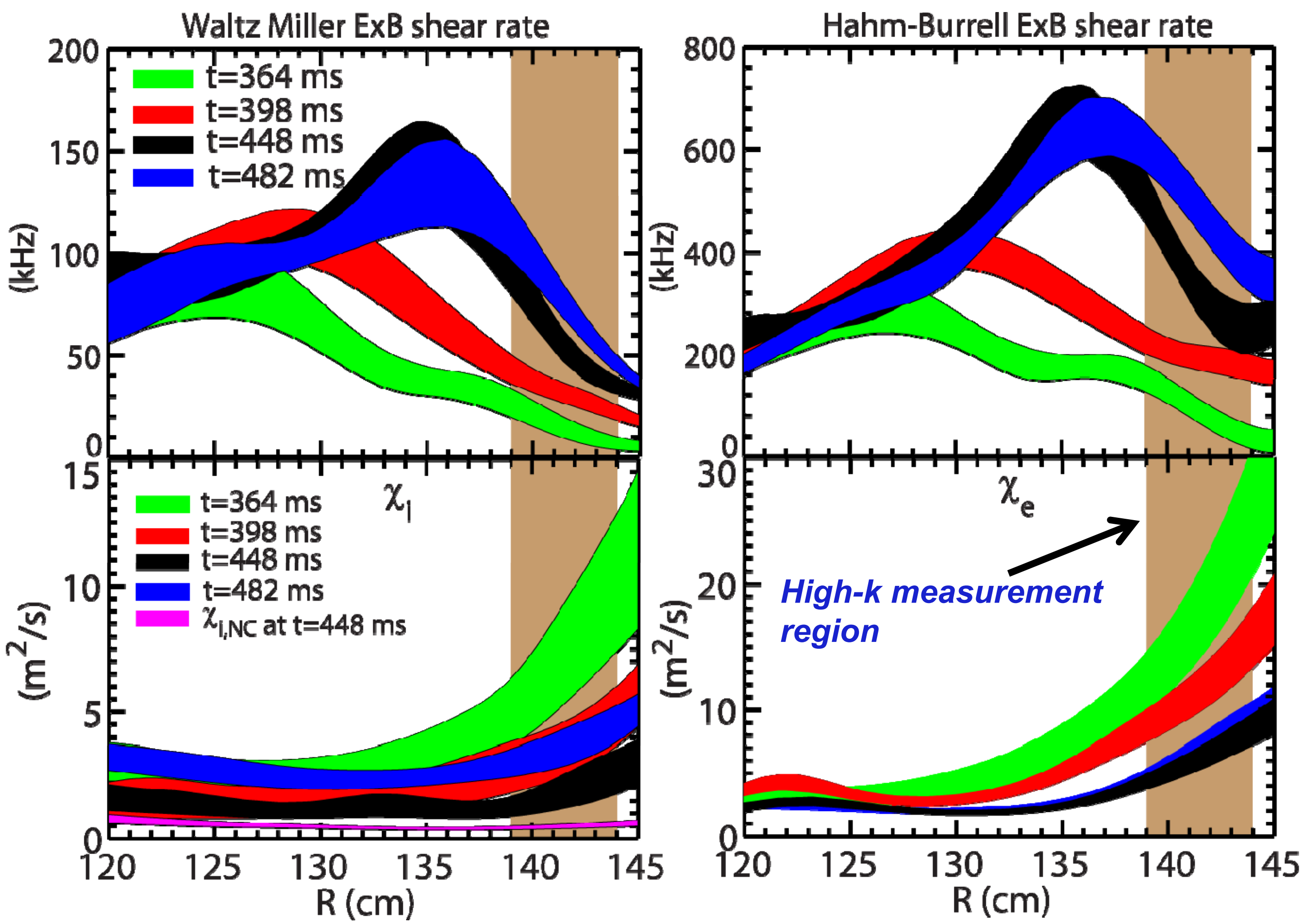
- Quenching rule for ion-scale turbulence for shaped plasma is shown as $\omega_{E\times B,WM}/\gamma_{max} \approx 1.41(A/3)^{0.6}/(\kappa/1.5)$ *Kinsey et al., PoP 2007*
- $\omega_{E\times B,WM}/\gamma_{max}$ continuously increases to approach 1.1-1.2 predicted by the quenching rule with $A_{local} \approx$ 1.9-2.1 and $\kappa_{local} \approx$ 1.5
- Observed reduction in the high-k turbulence indicates a coupling between low-k and high-k





Decrease in Thermal Diffusivities is Correlated with Increase in the ExB Shearing Rate ($r/a \gtrsim 0.5$)

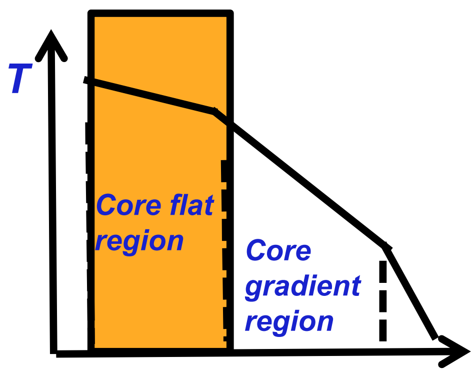
- Large decrease in electron and ion thermal diffusivity in the outer half of the plasma, $R \gtrsim 130$ cm ($r/a \gtrsim 0.5$)
- Decrease in χ_i and χ_e correlates with the decrease in peak spectral power in the high-k measurement region



- Increase in χ_i at t=482 ms may be due to MHD activities

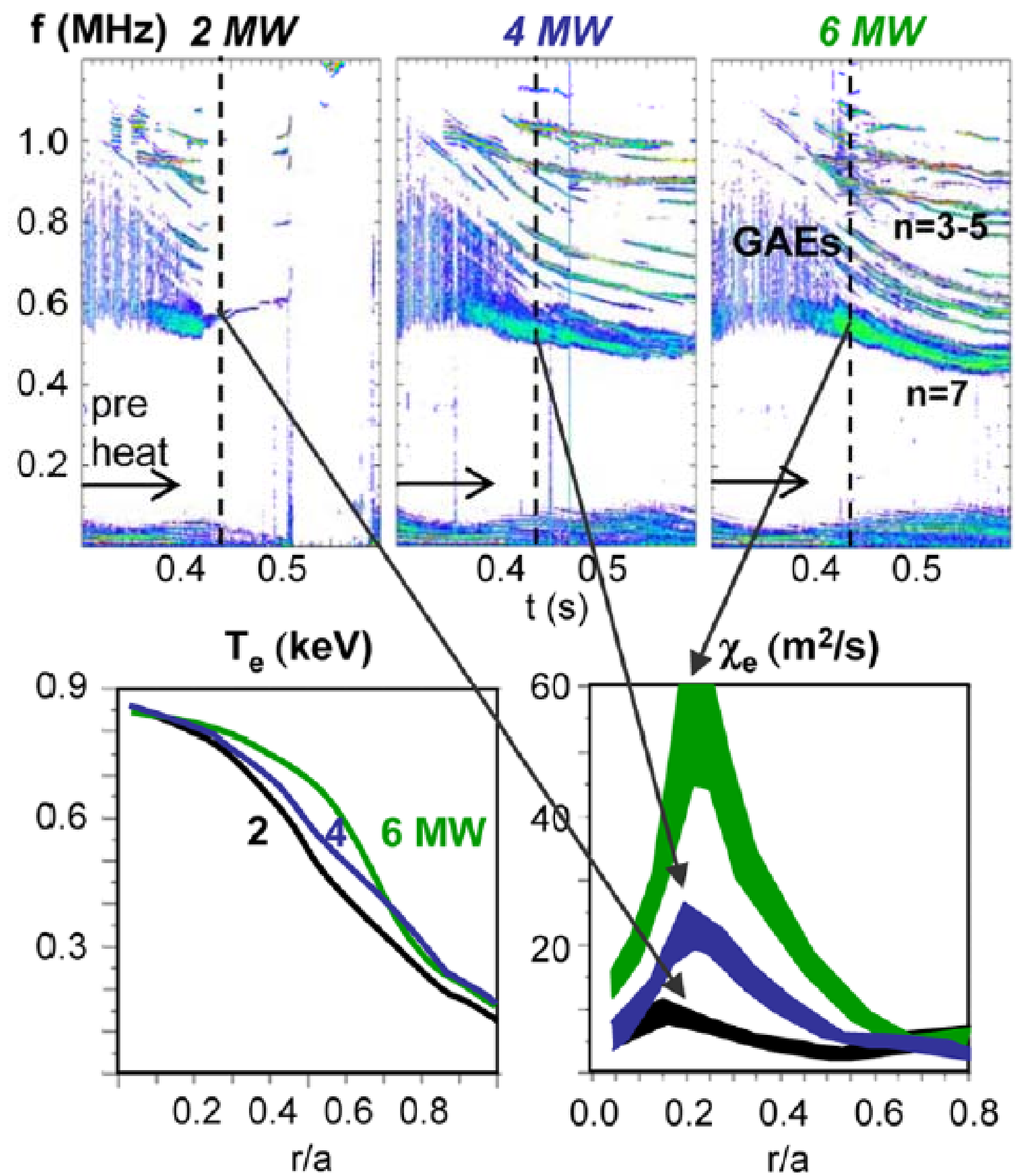
- *From TRANSP analysis*
- *The range in χ_i and χ_e due to uncertainties in ohmic heating and plasma equilibrium profiles*

Mechanisms underlying central electron thermal transport in NSTX high-power NBI-heated 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 χ_e (r/a~0.2)
  - χ_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

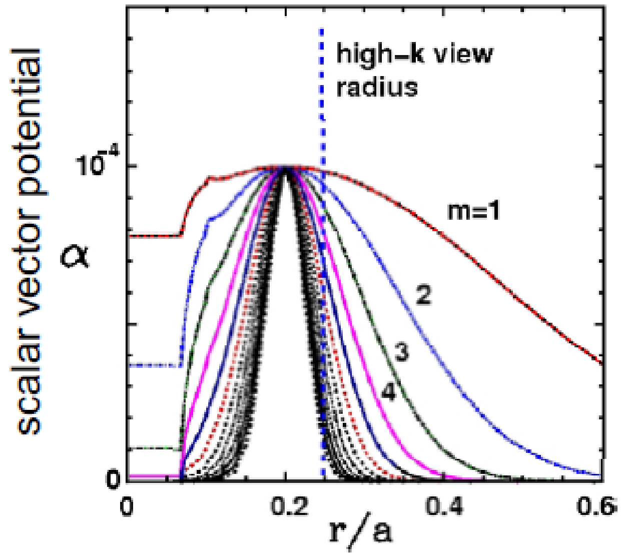


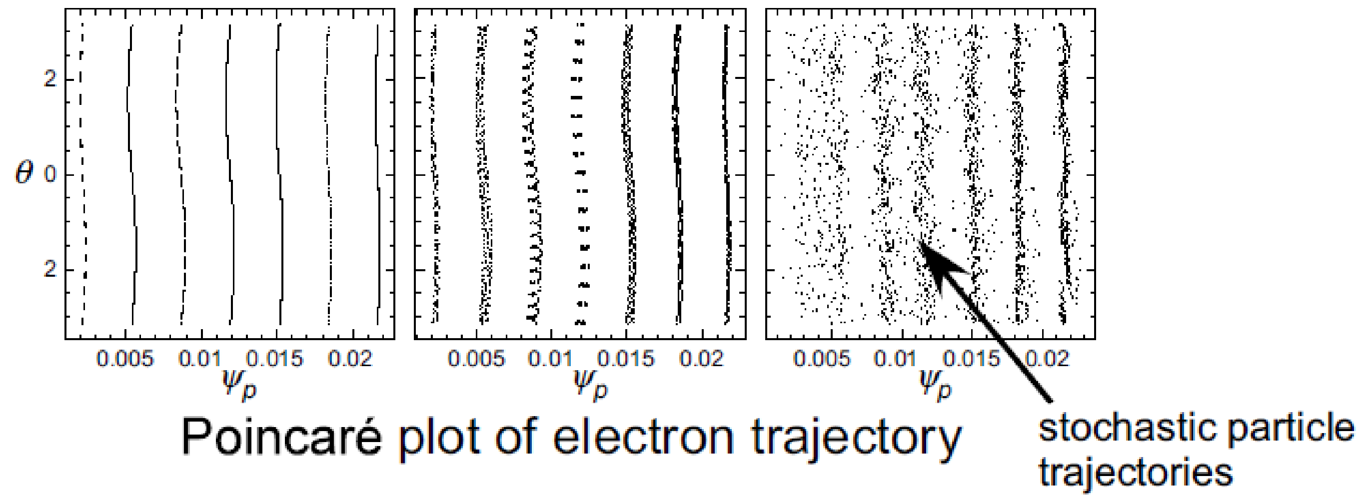
D. Stutman et al., PRL (2009)

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

N. Gorelenkov Nucl. Fus. 2010

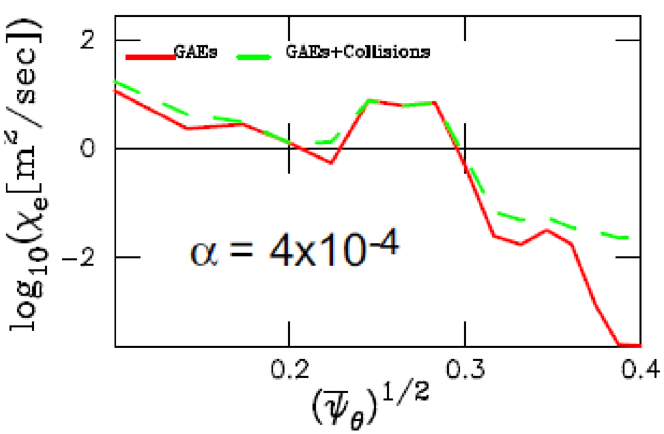
GAE Model used in ORBIT calculations





Poincaré plot of electron trajectory

Simulated electron transport



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

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

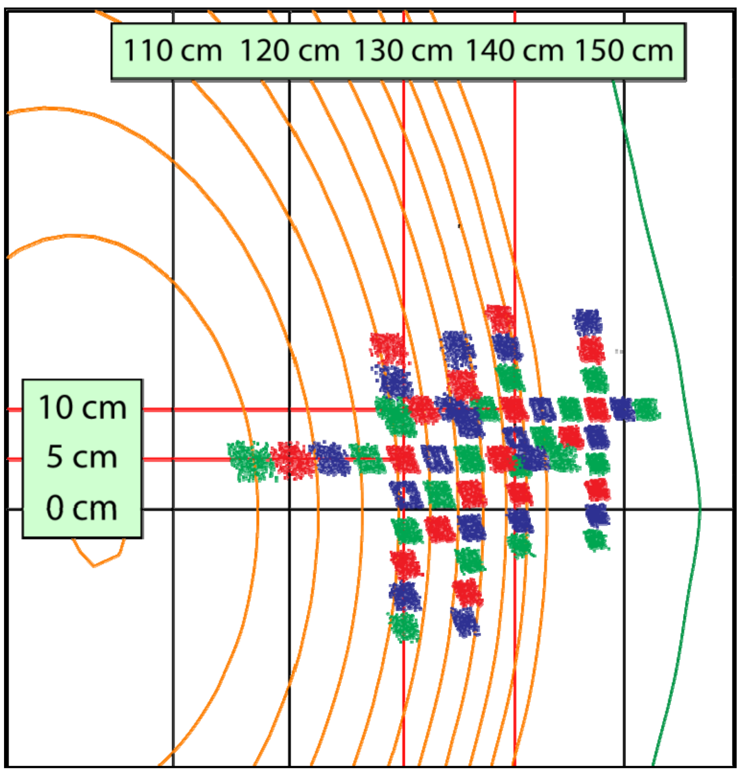
- Presently 32 detection channels
- 56 sightlines in radial and poloidal arrays spanning core to SOL
- 2 MHz sampling
- $k_{\perp}\rho_i \leq 1.5$ & 2-3 cm spot size
- Field-aligned optics with high throughput (etendue = 2.3 mm^2-ster)

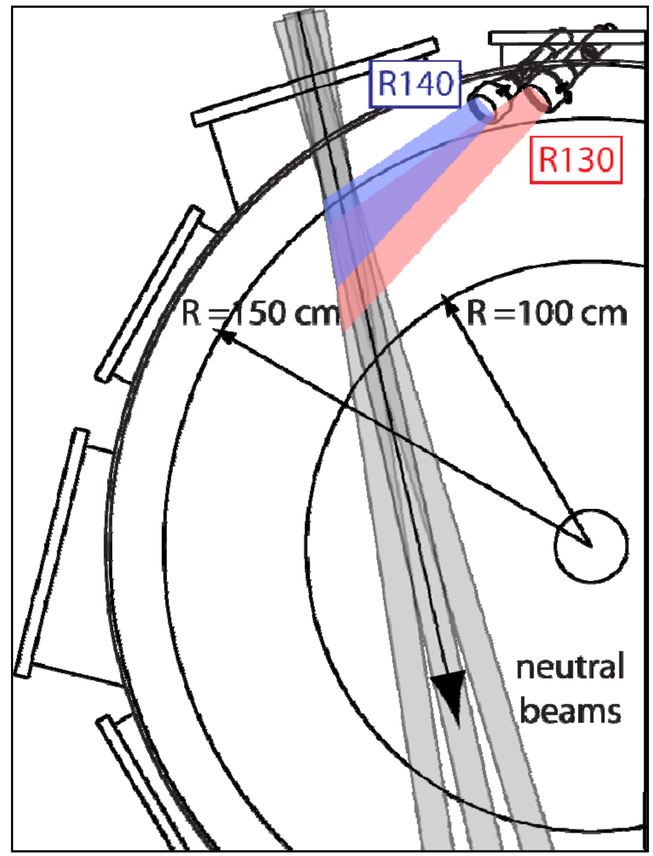
$$\frac{\delta I_{D\alpha}}{I_{D\alpha}} = \frac{\delta n}{n} \times C\left(E_{NB}, n, T_e, Z_{eff}\right)$$

neutral beam D_α emission

density fluctuation

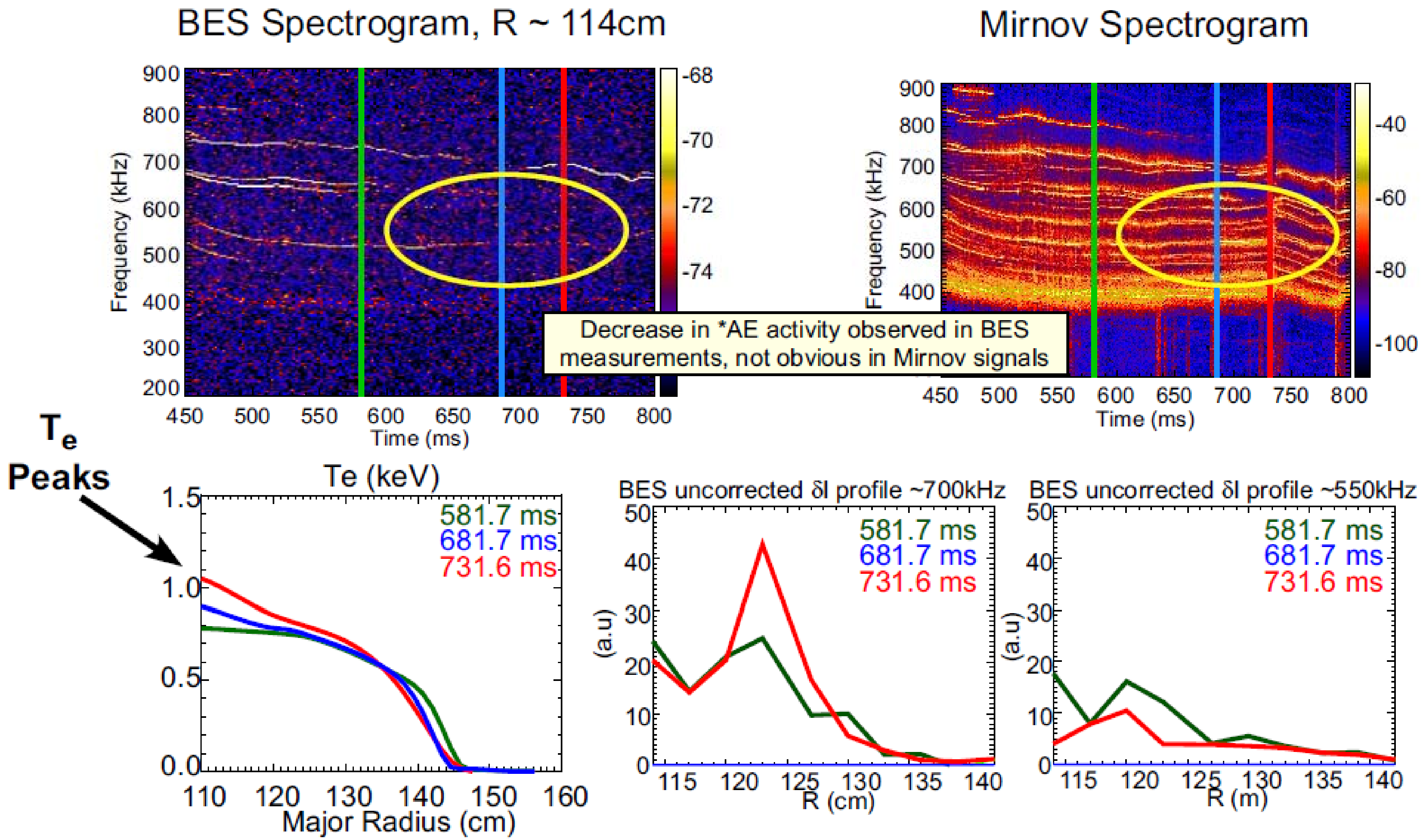
C ≈ 1/2





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

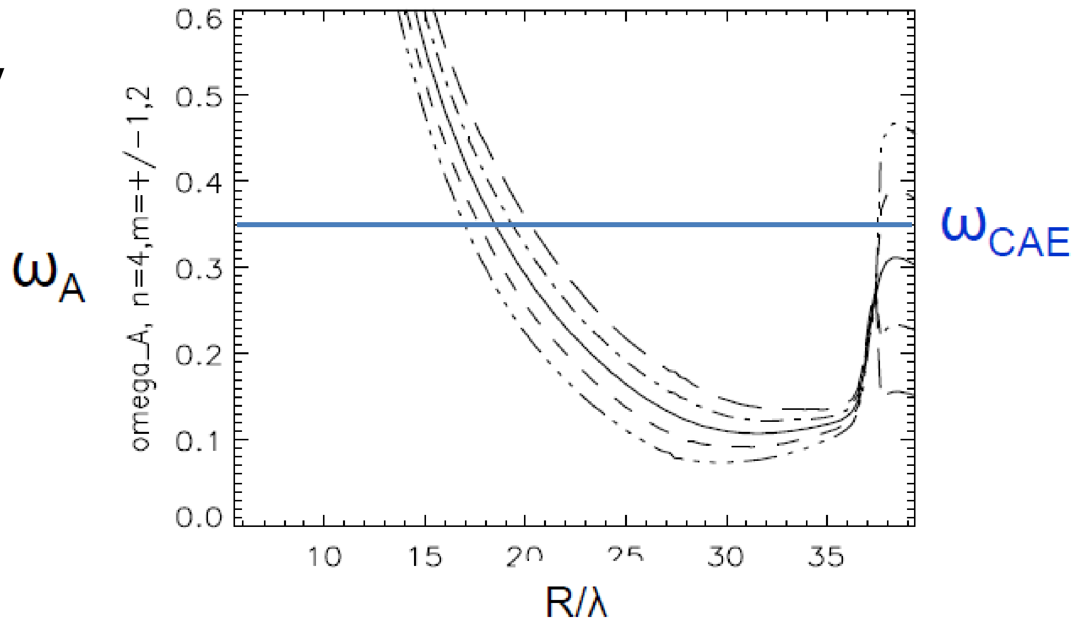
Decrease in *AE Activity Measured by BES Corresponds with Peaking of Central Electron Temperature

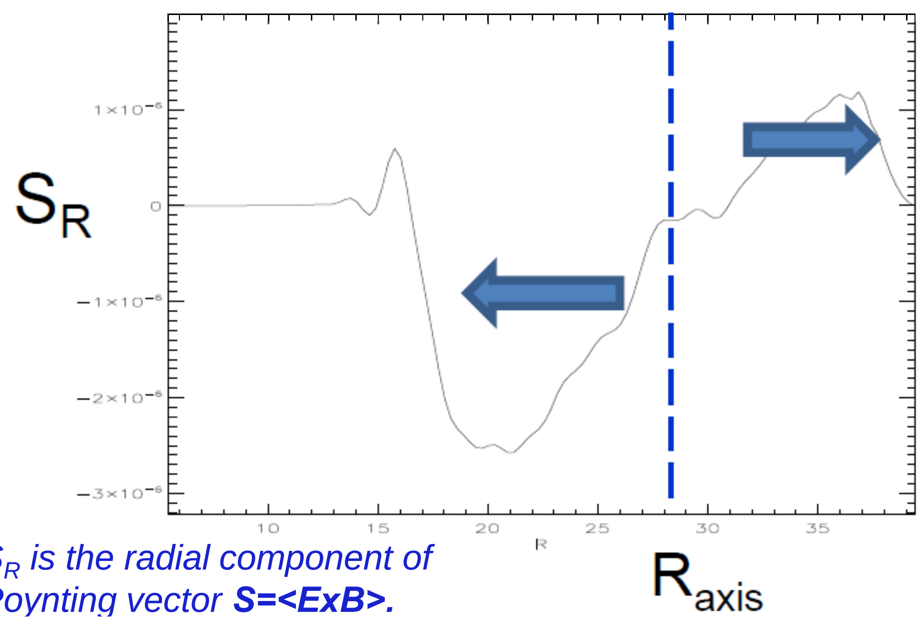


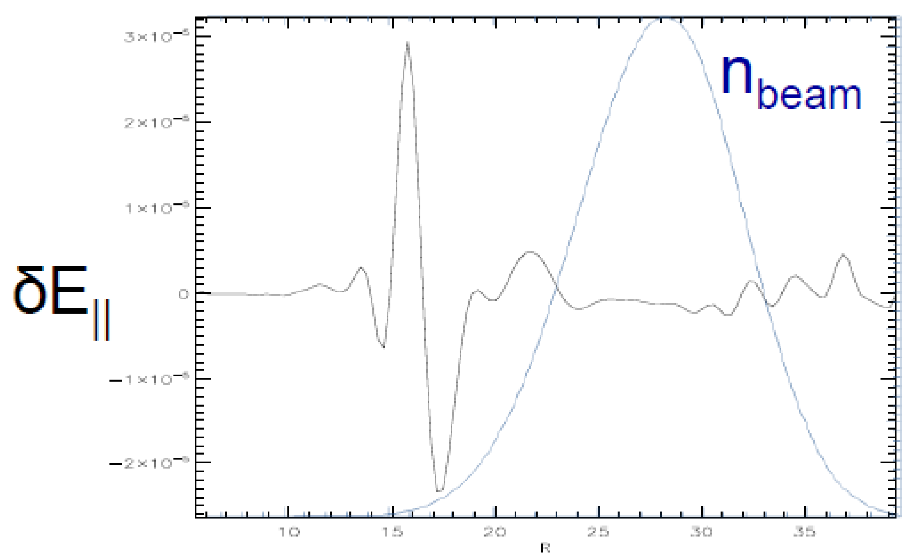
- T_e remains peaked even with large single mode (bulk *AEs still largely supressed)
- BES sensitivity to *AEs marginal at later times, density rise limits reflectometer data
- Need high-k core data to determine if high-k turbulence limits central T_e gradient

Coupling of CAE Modes to KAW may Lead to a Redistribution of Electron Heating Profile

- CAE frequency and Alfven continuum overlapping resonantly excites kinetic Alfven wave (KAW)
- KAW can have strong effect on electron due to finite $\delta E_{||}$
- Energy flux is directed away from magnetic axis and dissipated at the resonant location (work ongoing)







*S_R is the radial component of Poynting vector **S=<ExB>.***

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
  - Density gradient stabilization of ETG turbulence and the correlation with electron thermal transport reduction, supported by linear and nonlinear gyrokinetic simulations
  - Suppression of ETG turbulence leading to the formation of eITB in reversed shear L-mode plasmas, reproduced by nonlinear GYRO simulations
  - ExB shear stabilization of electron-scale turbulence and thermal transport observed in L-mode plasmas, indicating a low-k and high-k coupling
  - *AE-induced core Te flattening, consistent with electron stochastic transport from ORBIT simulations; Alternative mechanism of coupling CAE to KAW also presented
- Electron thermal transport will be signified in the transport and turbulence research plan for NSTX-U
  - Ip ~2 MA, BT ~1 T, 2nd NBI (~12 MW), new high-k scattering system etc.