Experimental Study of Parametric Dependence of Electron-gyro Scale Turbulence on NSTX

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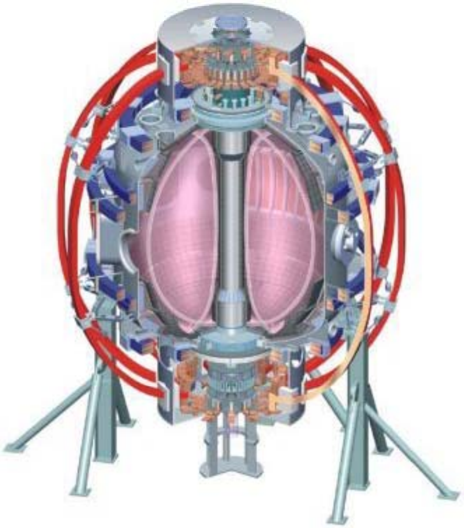
Y. Ren[1]

W. Guttenfelder[1], S.M. Kaye[1], E. Mazzucato[1], K.C. Lee[2], C.W. Domier[2] and the NSTX Team

1. PPPL 2. U.C. Davis

53rd Annual Meeting of the Division of Plasma Physics,
Salt Lake City, UT
November 17th, 2011



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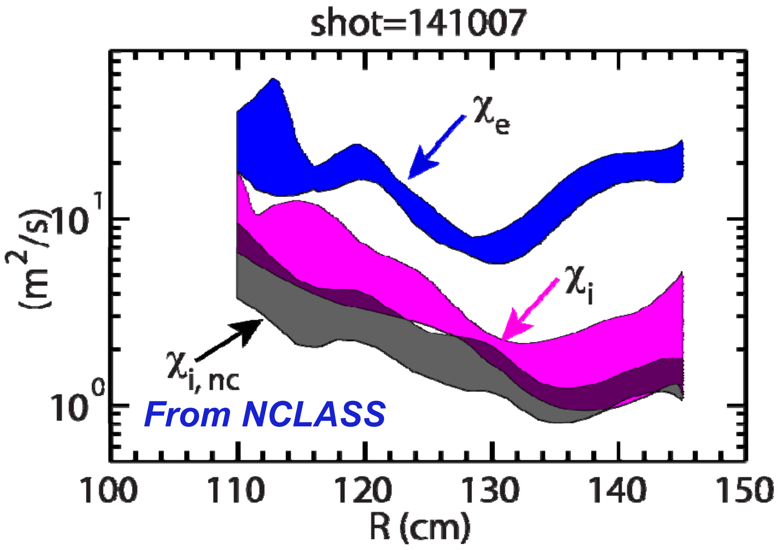
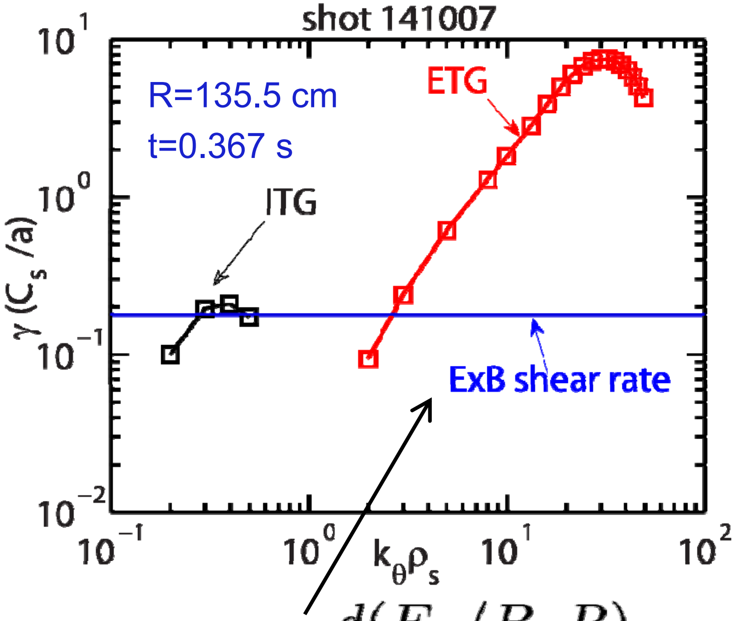
NSTX in a Unique Regime to Address Electron Scale Turbulence and Its Relation to Electron Thermal Transport

- Typical transport properties of NSTX NBI-heated H-mode plasmas
  - Neoclassical level of ion thermal transport due to large ExB shear and low aspect ratio
  - Dominant heat loss in the electron channel



- ETG potentially important for NSTX
  - Short wavelength on electron-gyro scale
  - Large growth rate, surviving large ExB shear



•Waltz and Miller, PoP, 1999

$$\gamma_E = \frac{r}{q}\frac{d(E_r/B_pR)}{dr}$$

NSTX in a Unique Regime to Address Electron Scale Turbulence and Its Relation to Electron Thermal Transport

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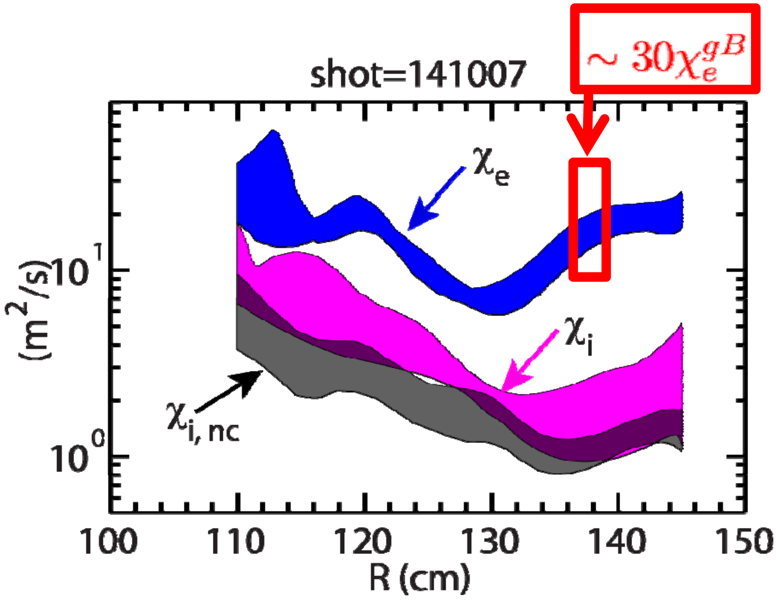


- ETG potentially important for NSTX
  - Short wavelength on electron-gyro scale
  - Large growth rate, surviving large ExB shear
  - Can generate larger normalized thermal transport than ITG due to weaker electron-scale zonal flow and secondary instability

$$\frac{\chi_i^{ITG}}{\chi_i^{gB}} \sim 1 \qquad \frac{\chi_e^{ETG}}{\chi_e^{gB}} \sim 10$$

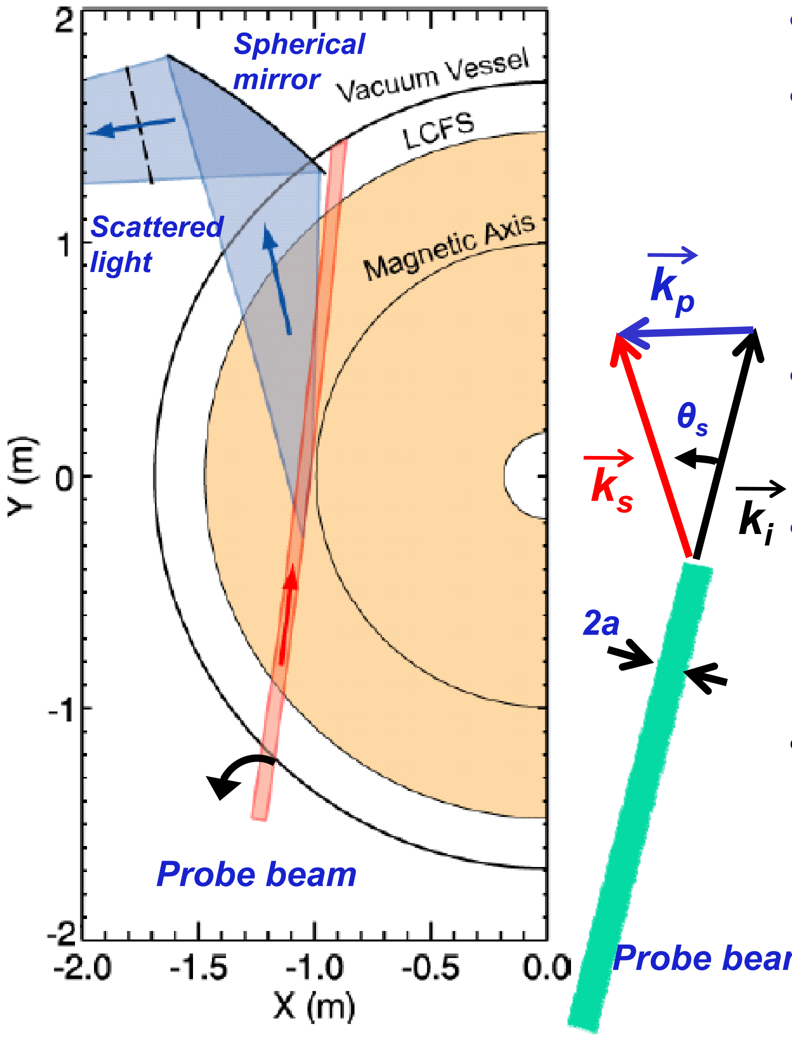
$$\chi_s^{gB} \equiv \frac{\rho_s^2 v_{Ts}}{L_{Ts}}$$

•Dorland et al., PRL 2000
•Jenko et al., PoP 2001
•Nevins et al., PoP, 2006

Outline

- Measurement method
- Study effects of density gradient on high-k turbulence
- Investigation of collisionality dependence of high-k turbulence
- Summary

High-k Microwave Scattering System Used to Measure 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:** $|\delta n_e(k)/n_e|^2 \approx 2\times10^{-11}$

Density Gradient Dependence

Density Gradient Stabilization of ETG Turbulence

- ETG turbulence can be stabilized by large density gradient, and the critical T_e gradient can be written as (Jenko et al., PoP 2001):

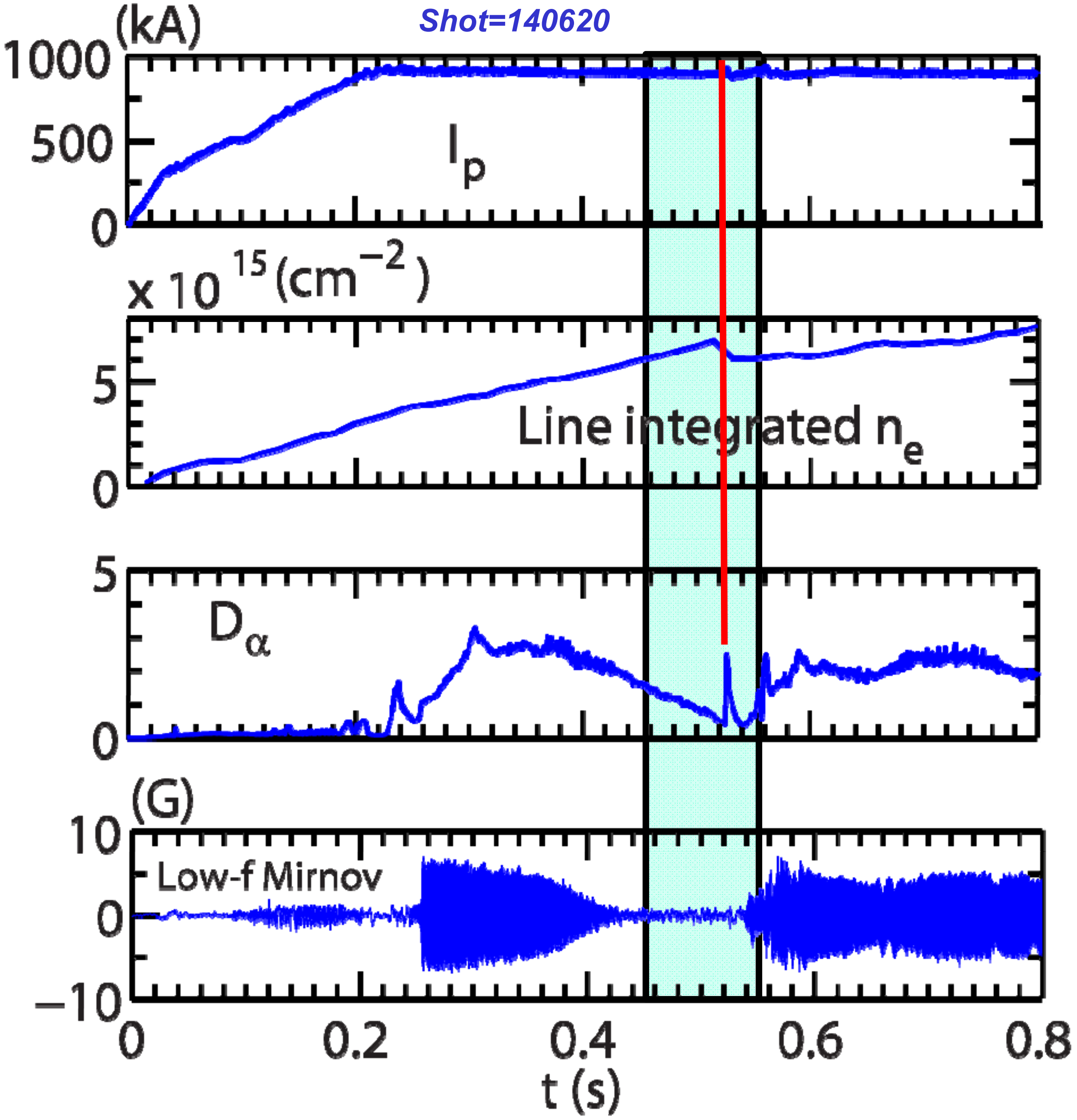
Geometric dependence no yet quantified for STs,

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

ϵ is aspect ratio; κ is elongation; δ is triangularity

  - The second term is solely determined by density gradient and can overcome the first term when density gradient is large enough
- TEM can be destabilized by density gradient (Romanelli and Briguglio, 1990)
  - Unless collisionality is large enough to detrap electrons which is not likely the case in NSTX

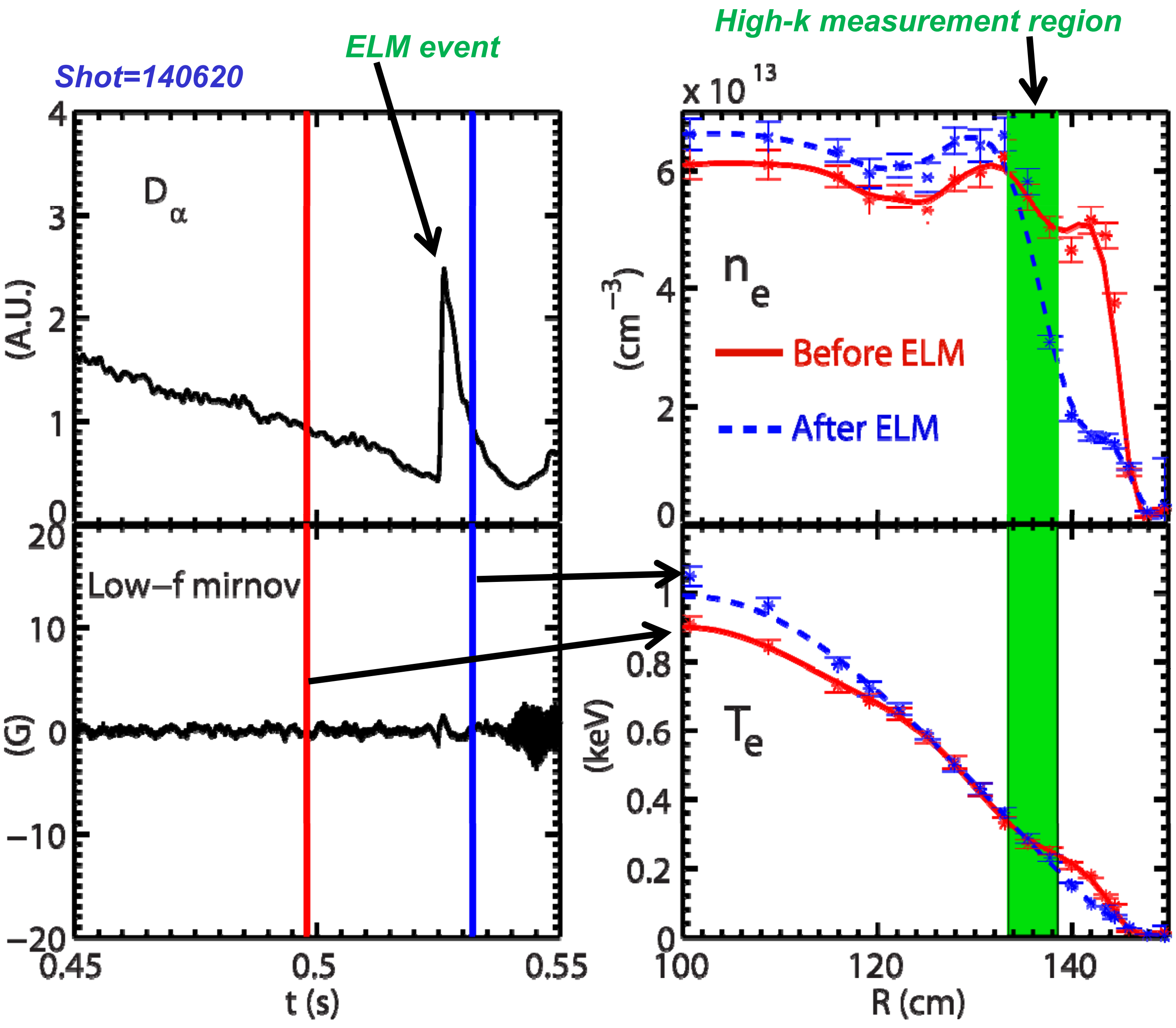
Large Density Decrease Observed after a Large ELM Event



B_T =4.5 kG

P_{NBI} =3 MW

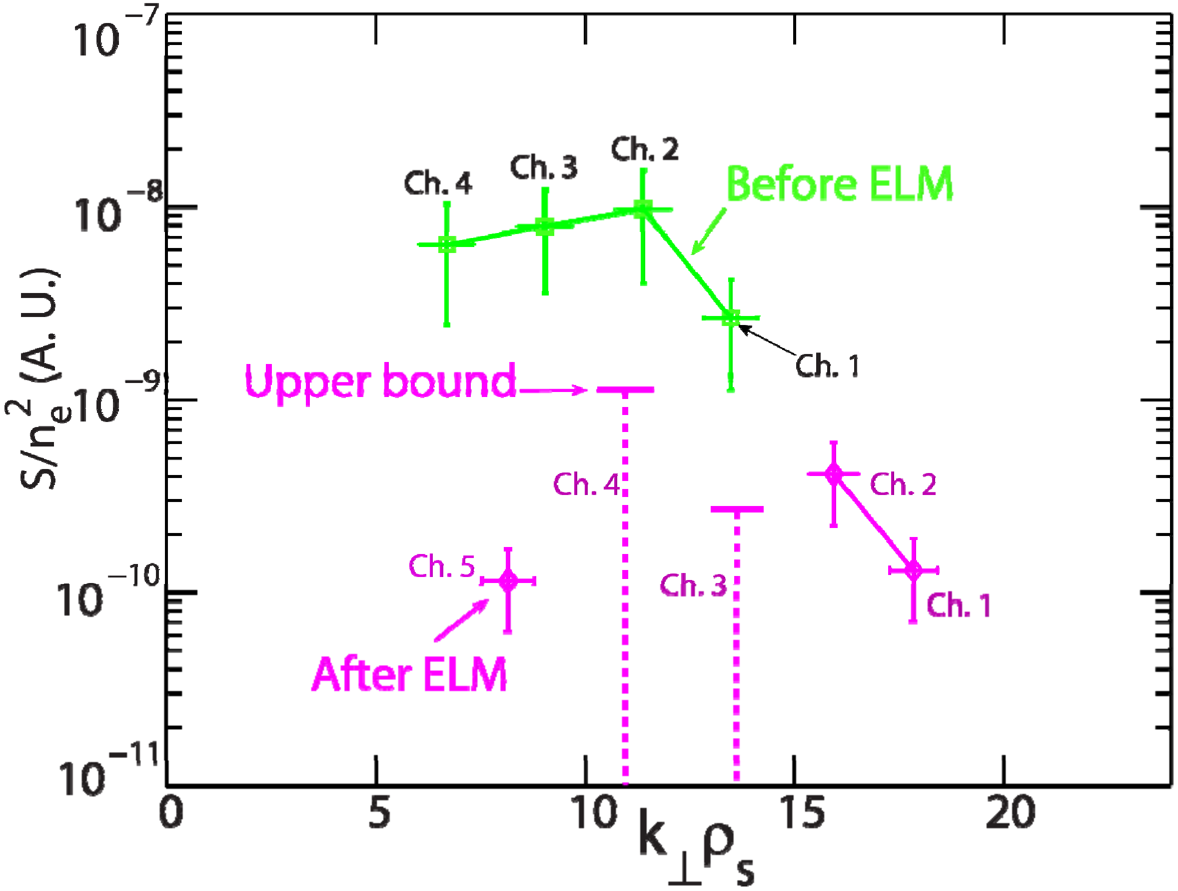
Large Density Gradient Induced by the ELM Event



- 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 rotating MHD mode before or right after ELM

Spectral Power of Modes at Smaller Wavenumber is Significantly Reduced After ELM

- Significant decrease in wavenumber spectral power is observed for modes with longer wavelength, $k_\perp \rho_s \lesssim 10$
- Before ELM, larger wavenumbers, $k_\perp \rho_s \gtrsim 15$, is beyond the maximum wavenumber range of the high-k system
  - Larger refraction after ELM leads to increase in $k_\perp \rho_s$ for each channel

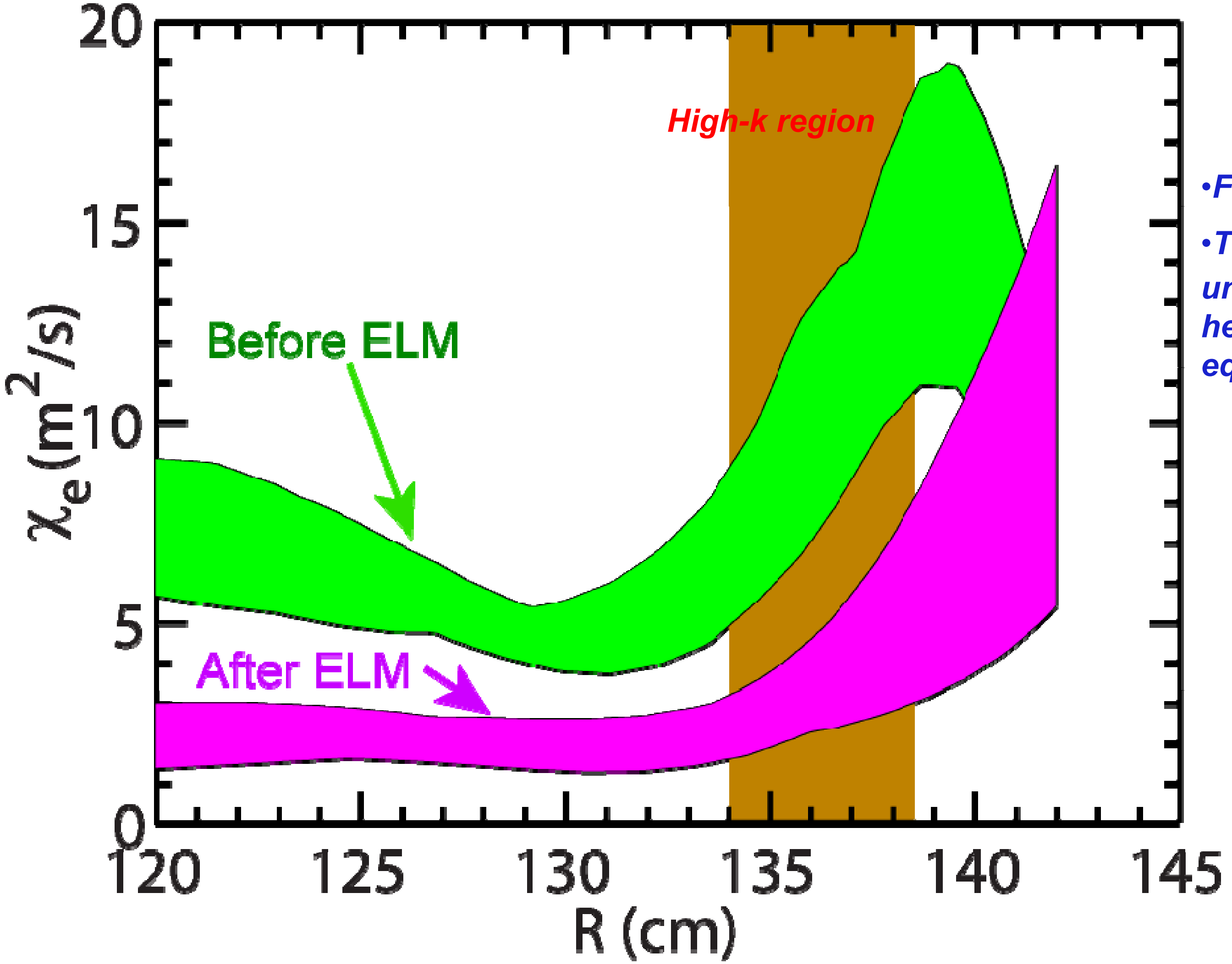


Ren et al., PRL 2011

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

Electron Thermal Diffusivity is Decreased by about a Factor of 2 after the ELM Event

- The decrease in electron thermal diffusivity correlates well with the decrease in measured turbulence spectral power

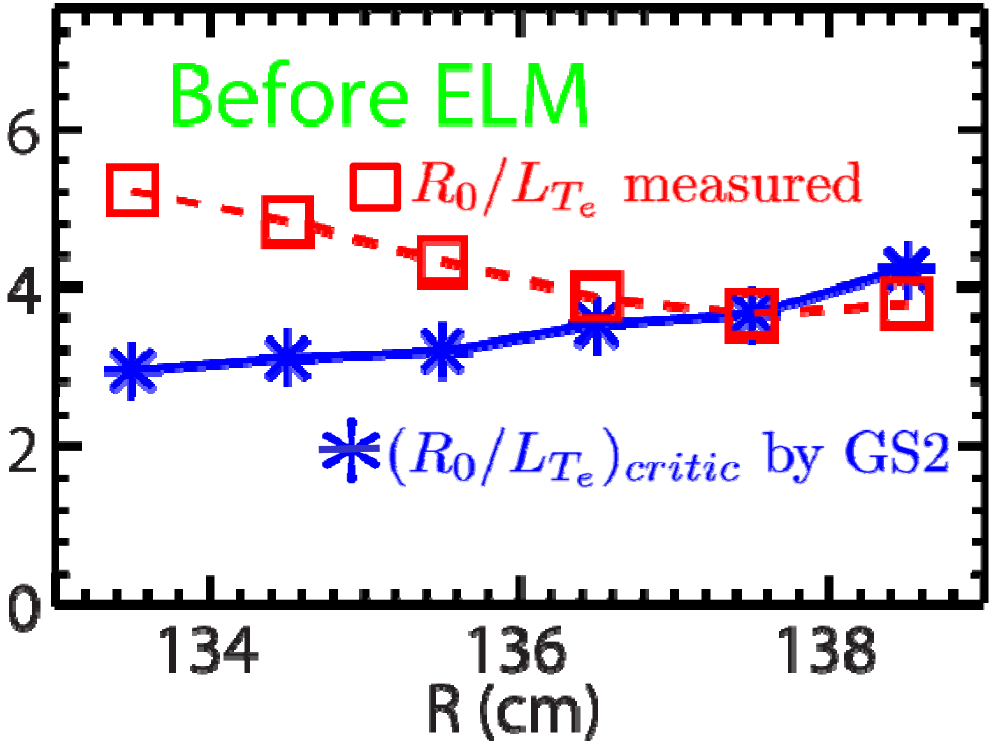


•From TRANSP analysis

•The range in χ_e due to uncertainties in ohmic heating and plasma equilibrium profiles

Linear Stability Analysis Showing Unstable ETG before the ELM Event

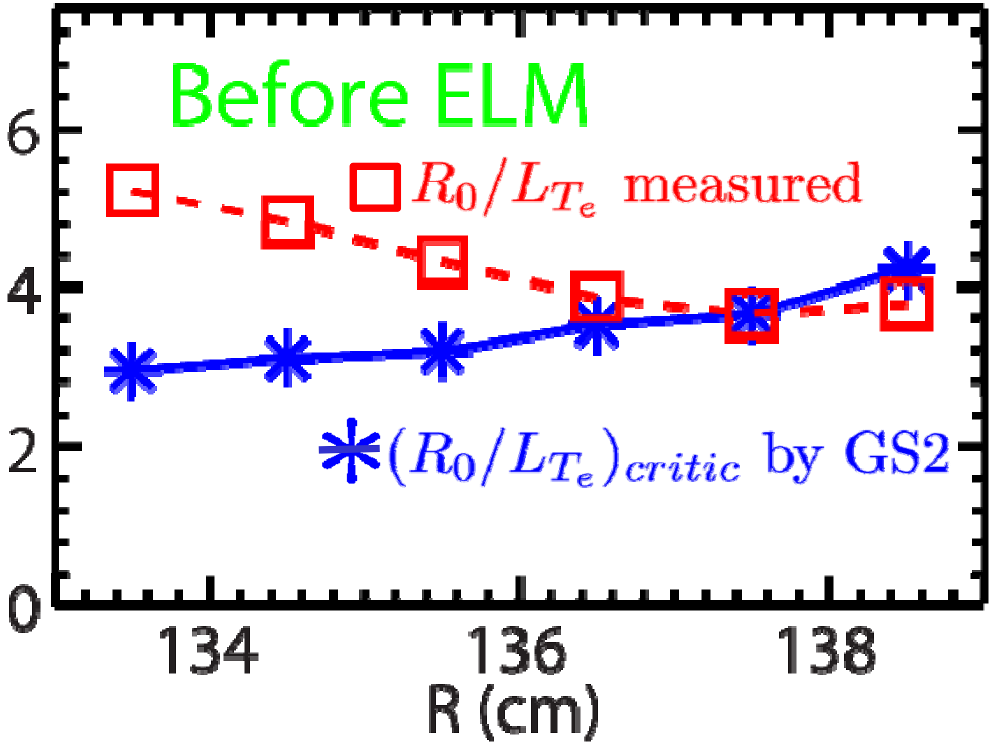
- Before ELM, ETG is largely unstable

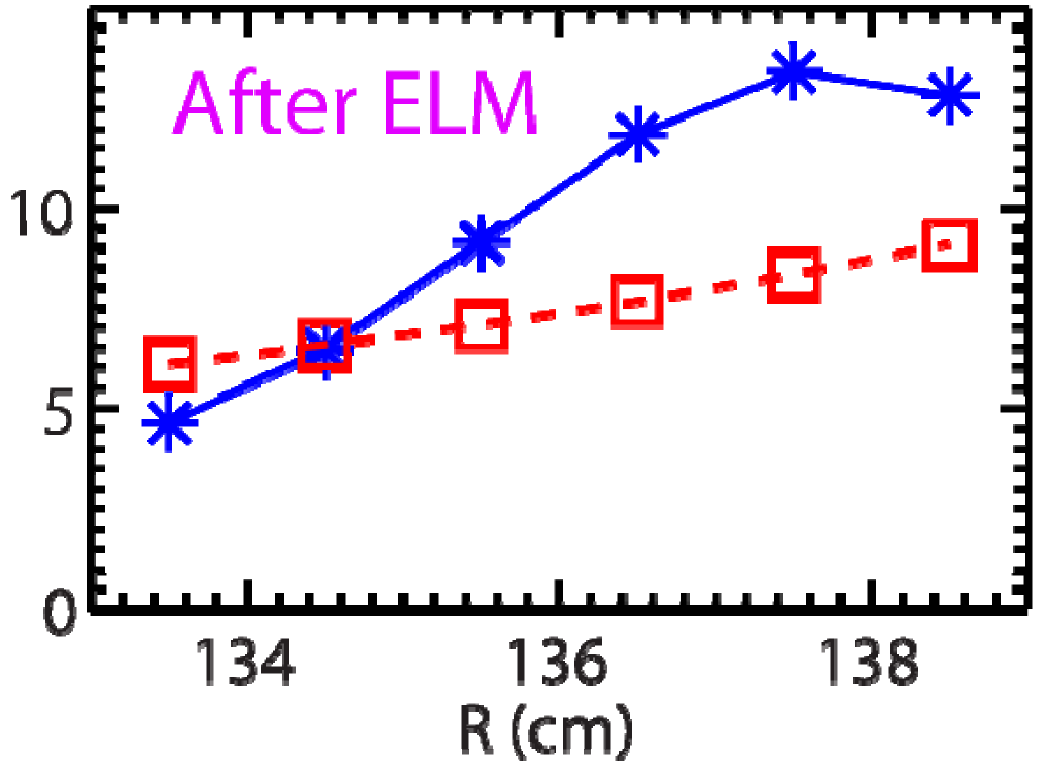


- Stability Analysis was performed with the GS2 code (Kotschenreuther et al., 1995)

Stabilization of ETG Modes Found after the ELM Event

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

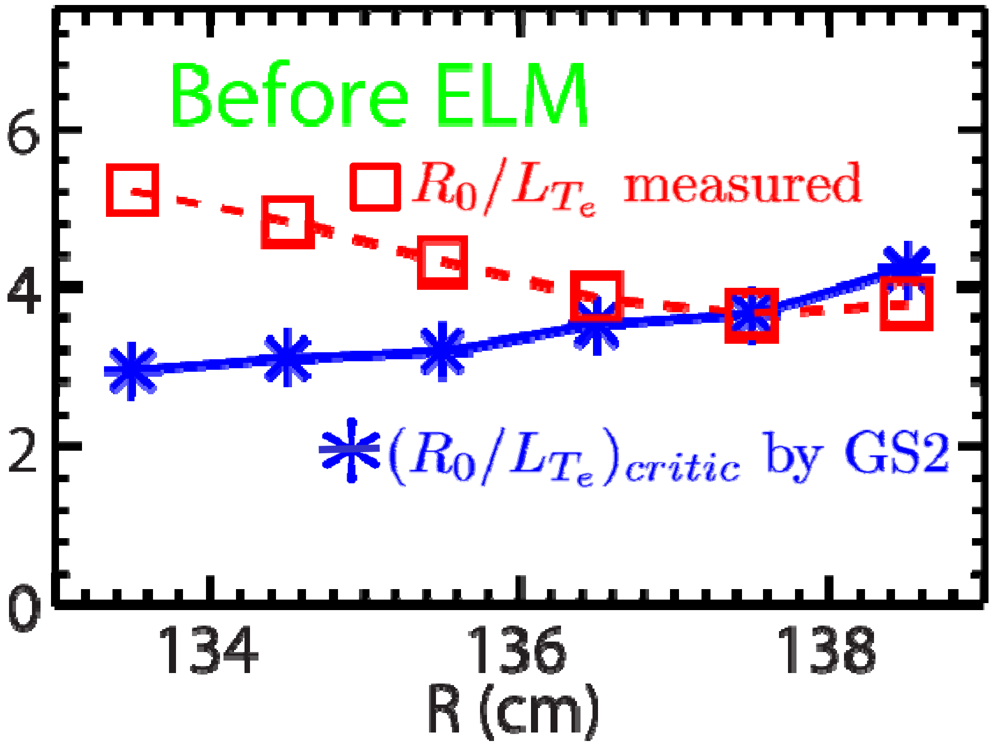




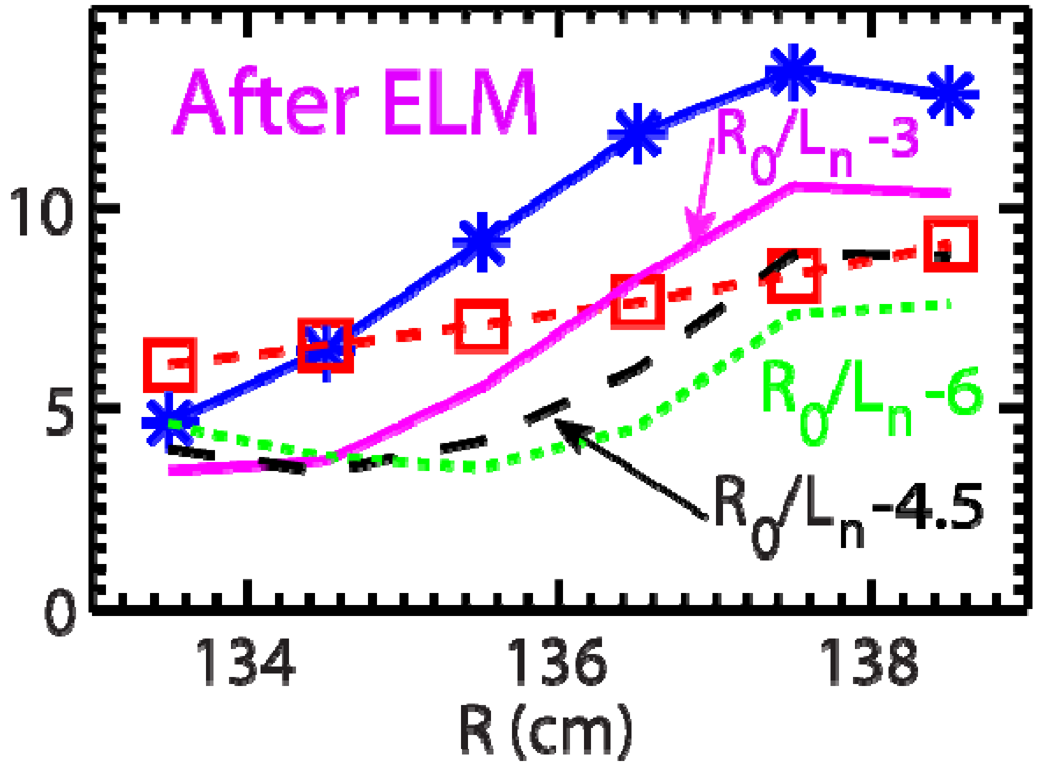
- Stability Analysis was performed with the GS2 code (Kotschenreuther et al., 1995)

Density Gradient Found to be Responsible for Increased Critical Temperature Gradient

- Before ELM, ETG is largely unstable

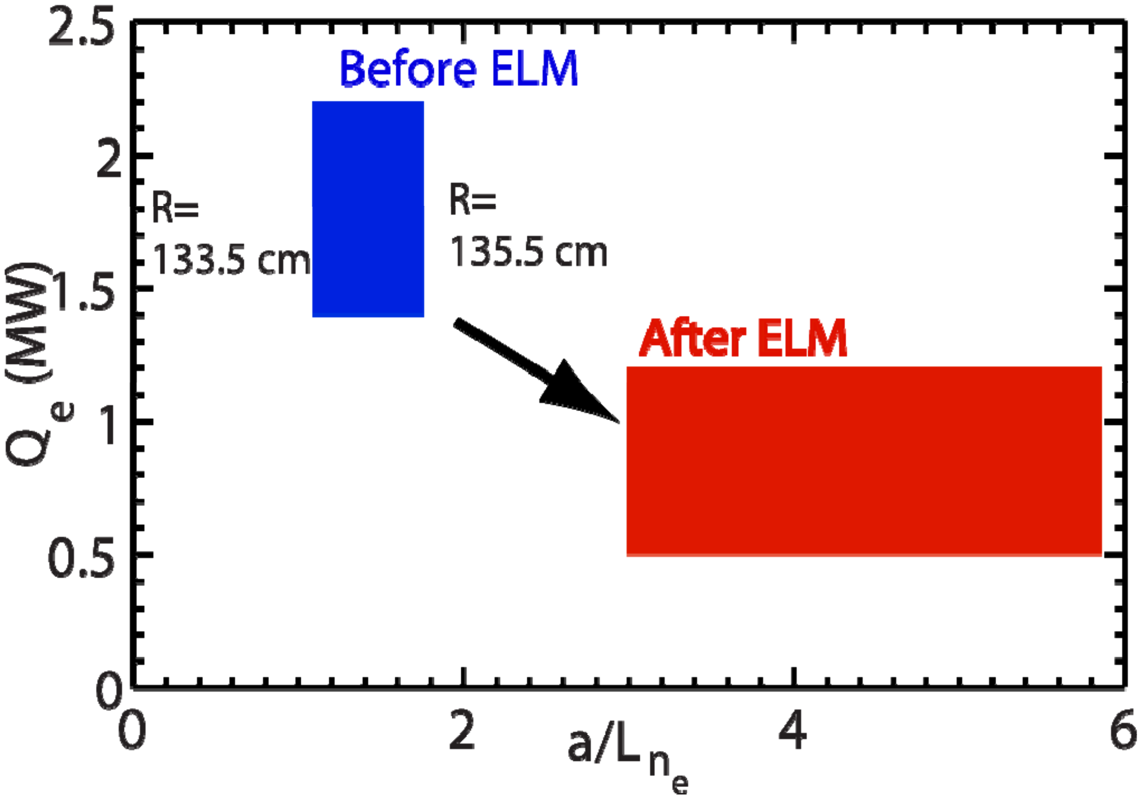


- Manually decreased R_0/L_{n_e} brings down critical gradient



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

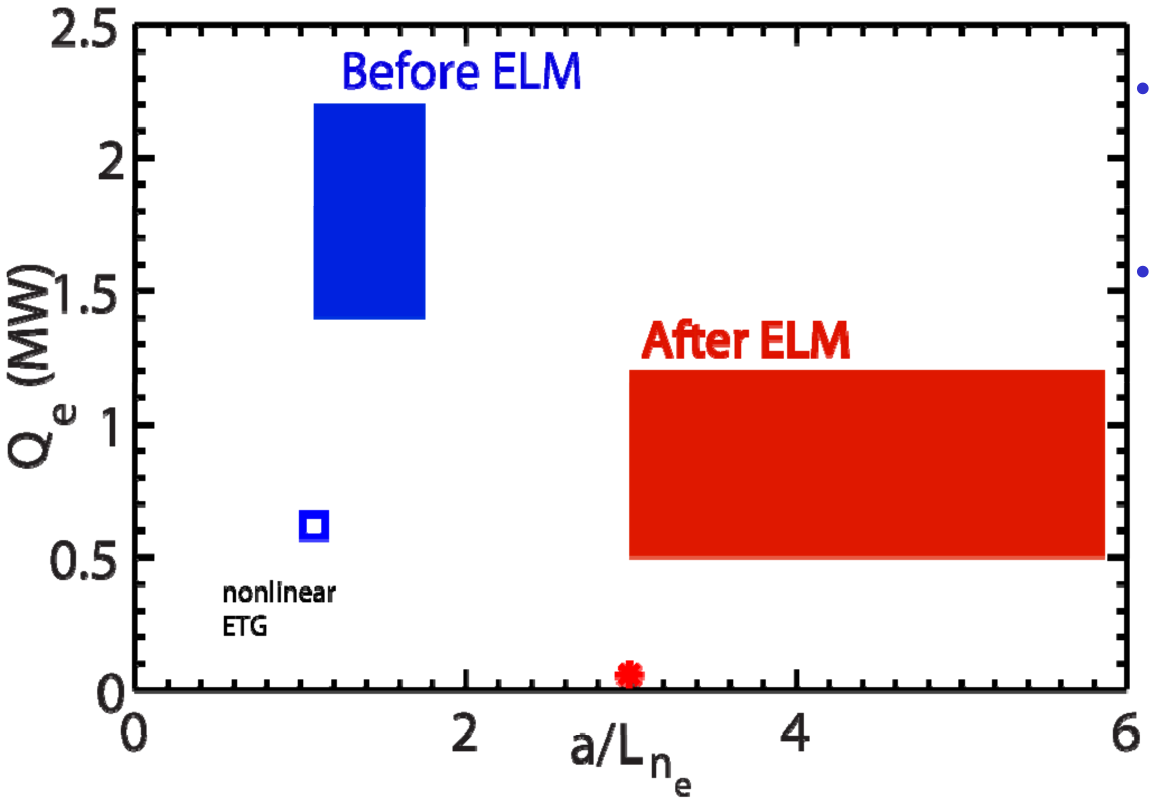
Electron Conduction Loss Found to Decrease after ELM with Large Density Gradient



- Experimental Q_e is from TRANSP analysis

Nonlinear ETG Simulation Reproducing 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

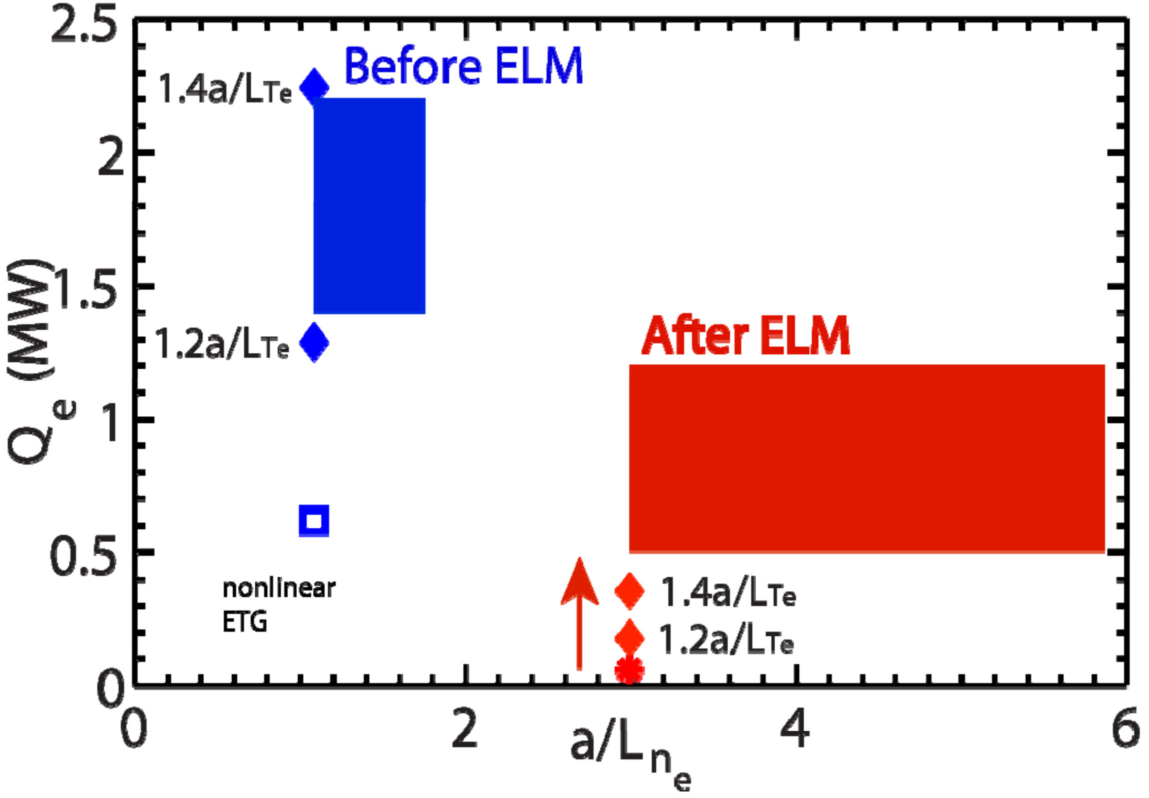


- All nonlinear ETG simulations were conducted with GYRO
- Full kinetic effects included : fully electromagnetic with local and general equilibrium, kinetic ion, ν_e , flow and flow shear

GYRO references: Candy and Waltz, PRL 2003; Belli and Candy, GYRO Technical Guide

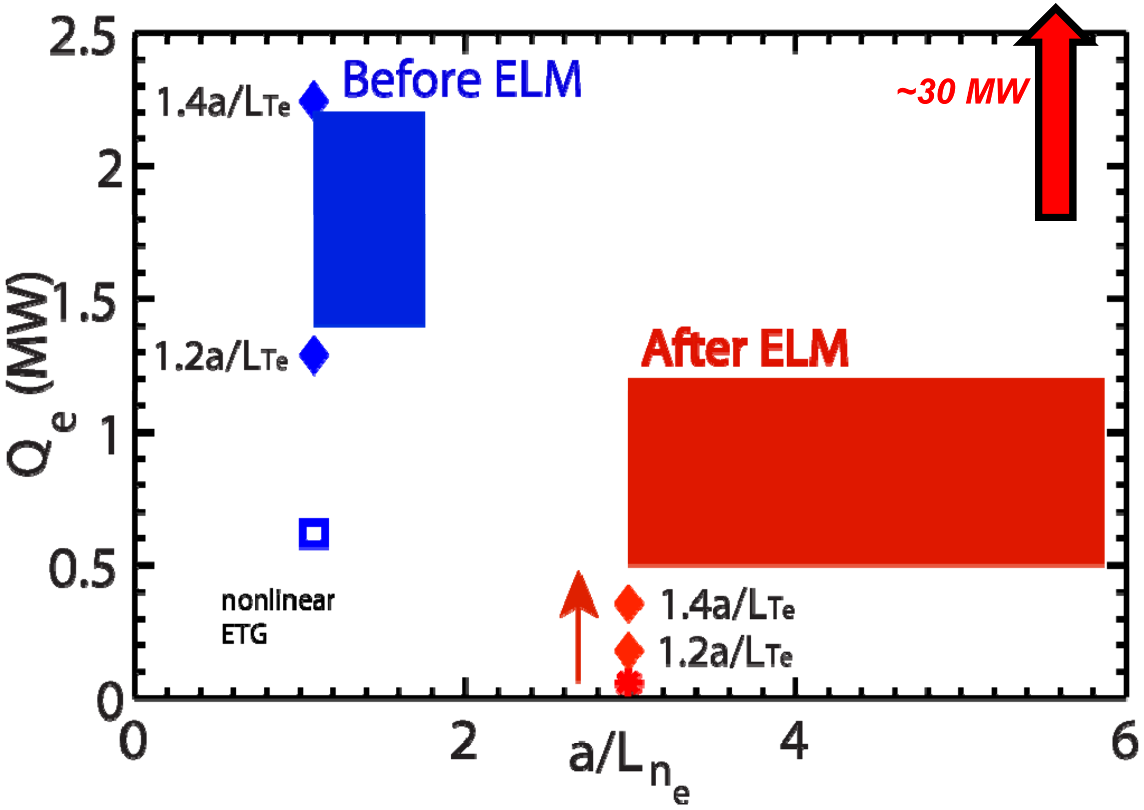
Nonlinear ETG Simulation Predicted Q_e Sensitive to Temperature Gradient

- Before ELM, a 40% 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



TEM Destabilized by Density Gradient Contributing to Transport

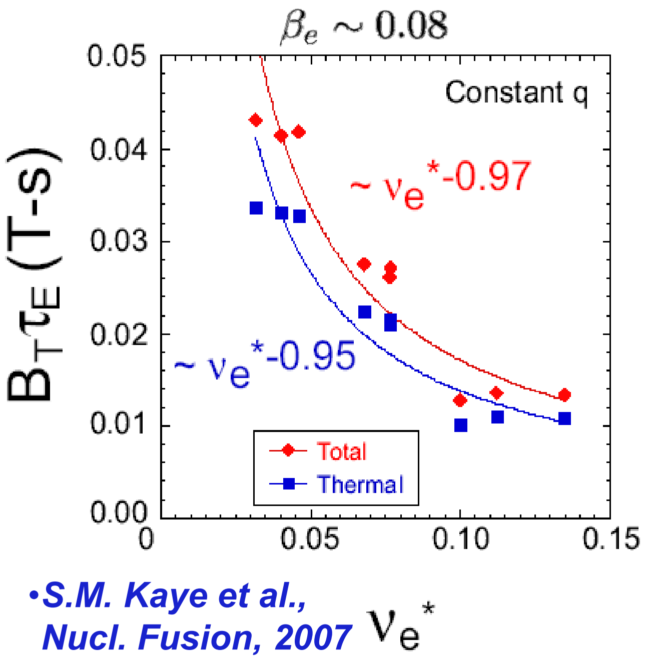
- Large TEM-induced transport (~30 MW) is found after ELM without ExB shear stabilization
  - Easily match experimental Q_e with experimental amount of ExB shear



Investigation of Collisionality Dependence

Strong Collisonality Dependence Observed in NSTX Confinement Scaling

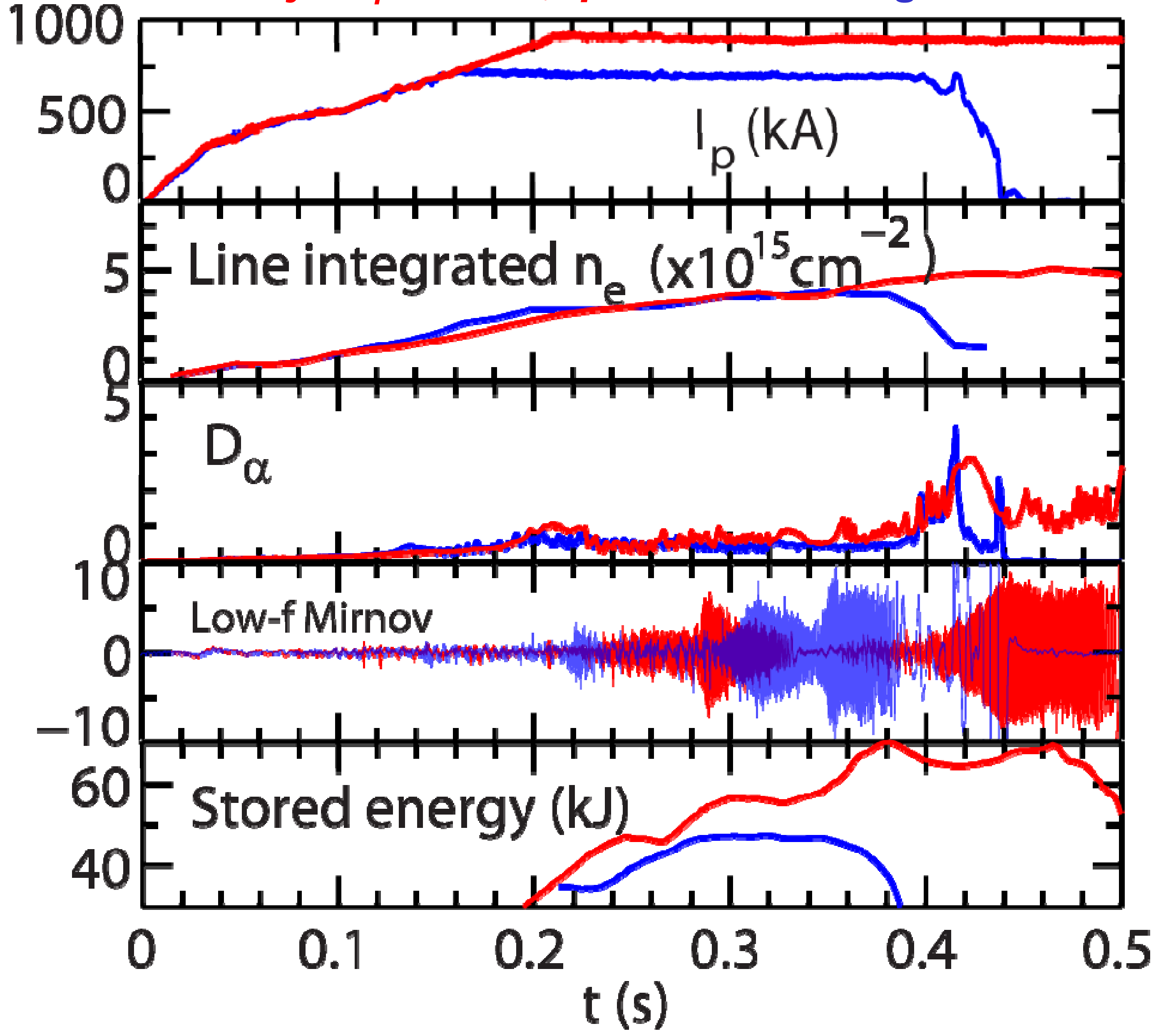
- NSTX confinement scales strongly with collisonality as $B_T \tau_E \propto \nu_e^{*-1}$
  - Mechanism behind the scaling is not understood
- Possible mechanisms:
  - Collisional damping of ETG zonal flow (Kim et al., PRL 2003)
  - Destabilizing of micro-tearing instability by collisionality in high beta plasmas (More in Guttenfelder's 12:00 talk)
- In this investigation, we concentrate on low beta plasmas, where micro-tearing instability is stable and ETG is unstable



- *S.M. Kaye et al., Nucl. Fusion, 2007*

Collisionality Scan Conducted with Constant B_T/I_p

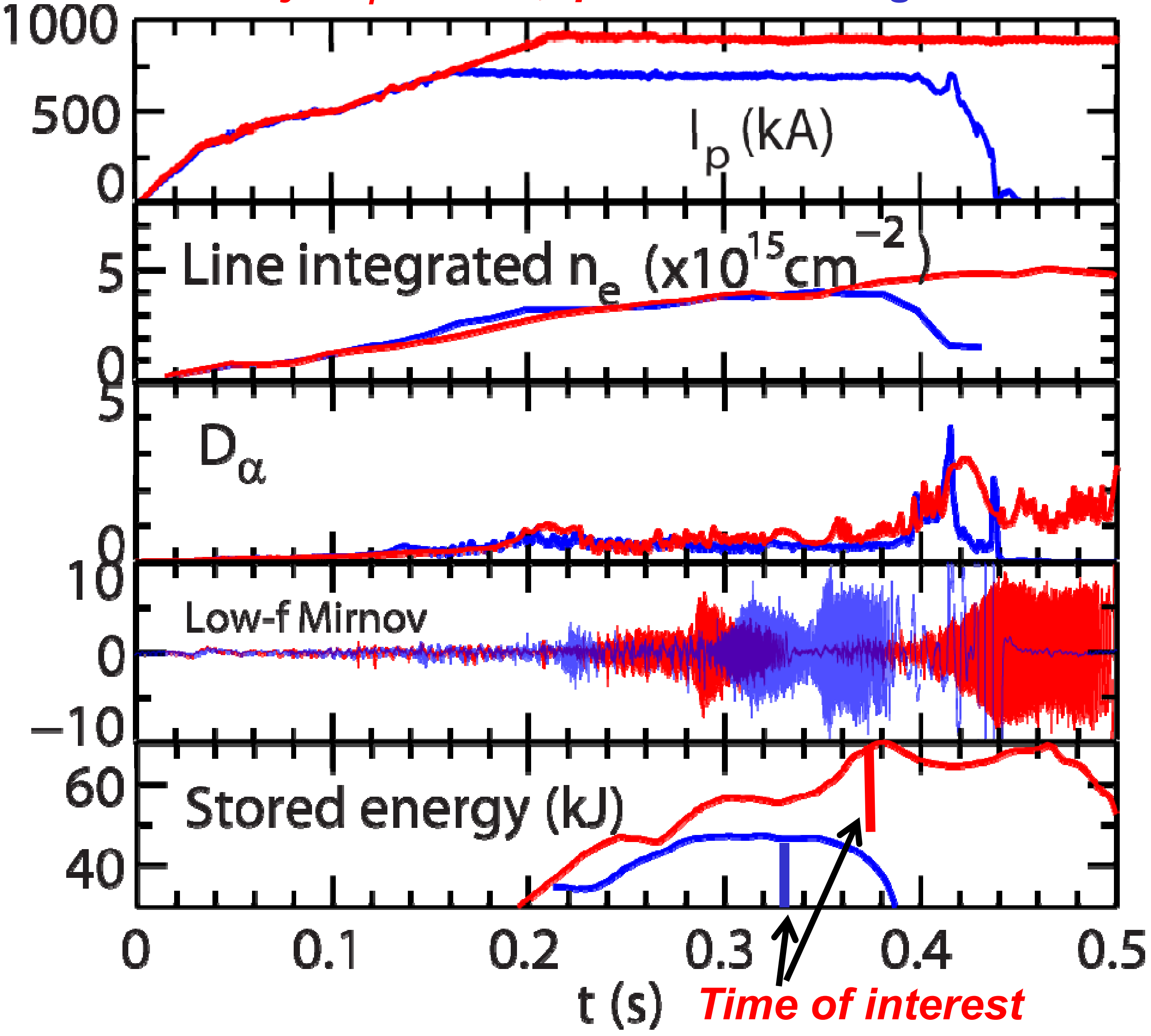
Low collisionality: B_T=4.5 kG, Ip=900 kA   *High collisionality: B_T=3.5 kG, Ip=700 kA*



P_{NBI} =3 MW

Collisionality Scan Conducted with Constant B_T/I_p

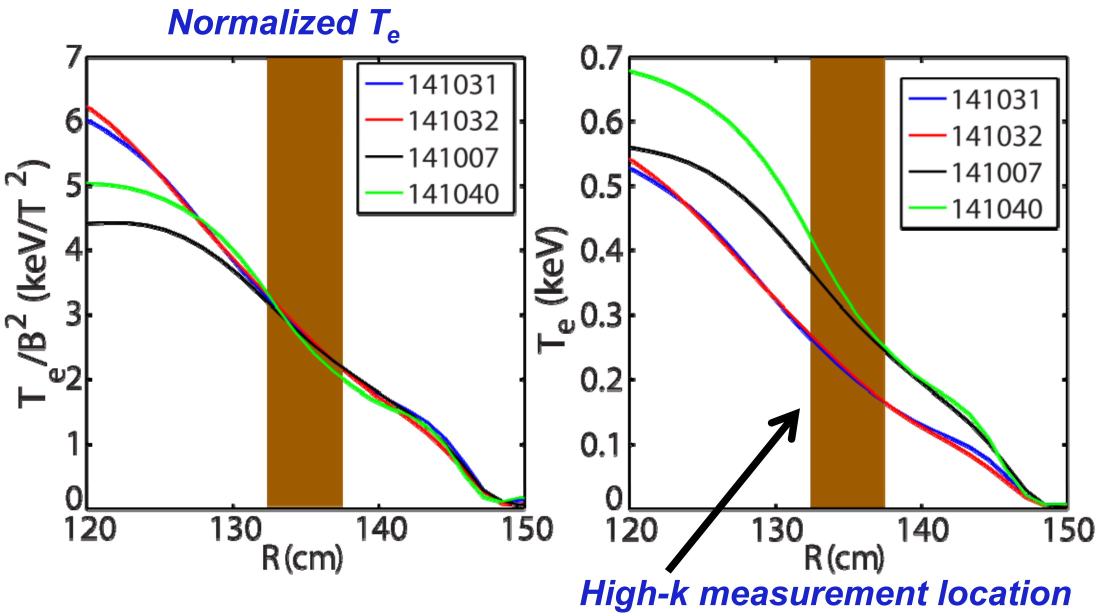
Low collisionality: B_T=4.5 kG, Ip=900 kA *High collisionality: B_T=3.5 kG, Ip=700 kA*



P_{NBI} =3 MW

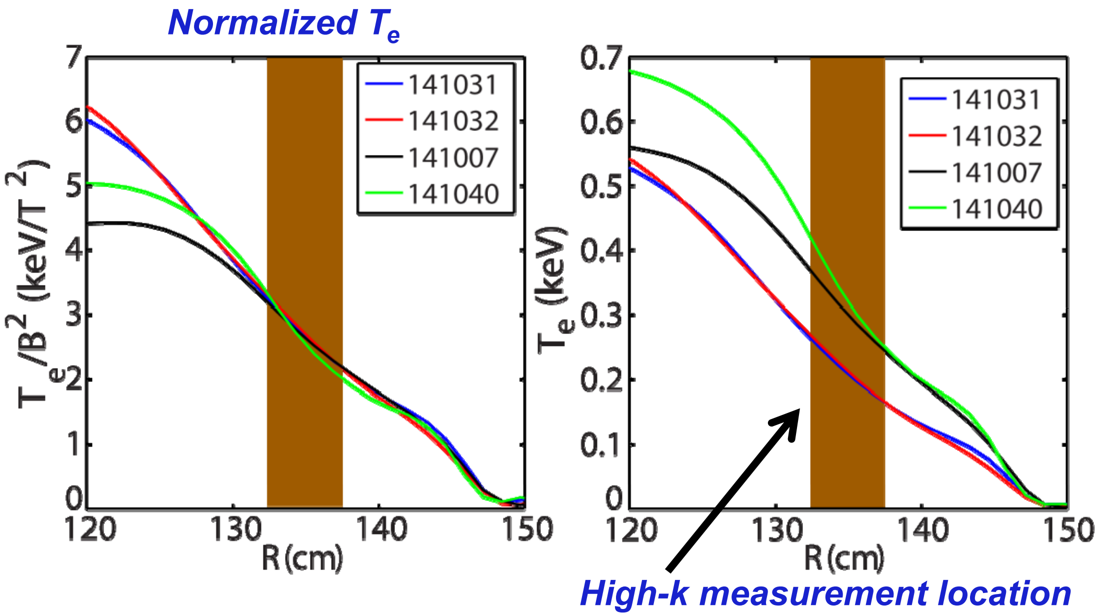
- The high collisionality shot has larger MHD activities due to an n=1 magnetic island which does not overlap with high-k measurement region
- Density perturbation due to the island in the high-k measurement region is found to be about 5% evaluated using a FIR interferometer

Local Collisionality Variation Achieved with Constant ρ_e, β_e and q_{95}

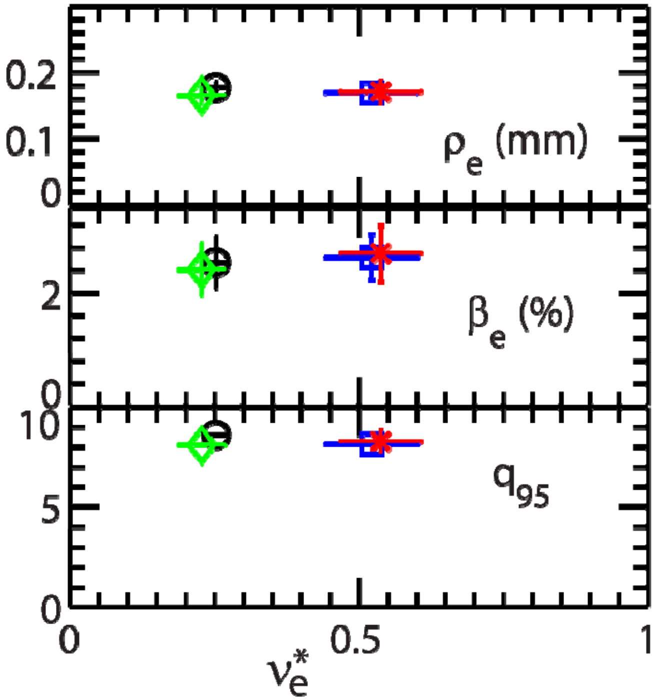


- Profiles chosen to have $T_e \propto B^2$ well maintained from R=130-145 cm: local ν_e^* was varied with constant ρ_e and β_e

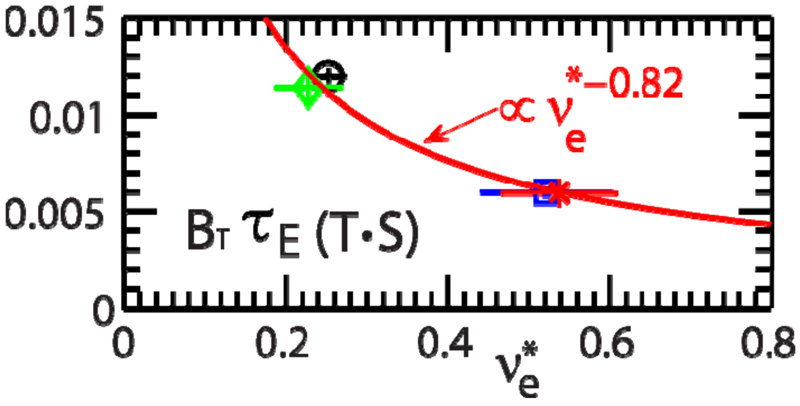
Local Collisionality Variation Achieved with Constant ρ_e, β_e and q_{95}



- Profiles chosen to have $T_e \propto B^2$ well maintained from R=130-145 cm: local ν_e^* was varied with constant ρ_e and β_e
- A factor of abut 2.5 change in ν_e^* is achieved
- q_{95} kept constant with fixed ratio of B_T/I_p
- ρ_e and β_e have only small variations against ν_e^*, ~10%
- Consistent with previous confinement scaling: $B_T \tau_E \propto \nu_e^{*-1}$

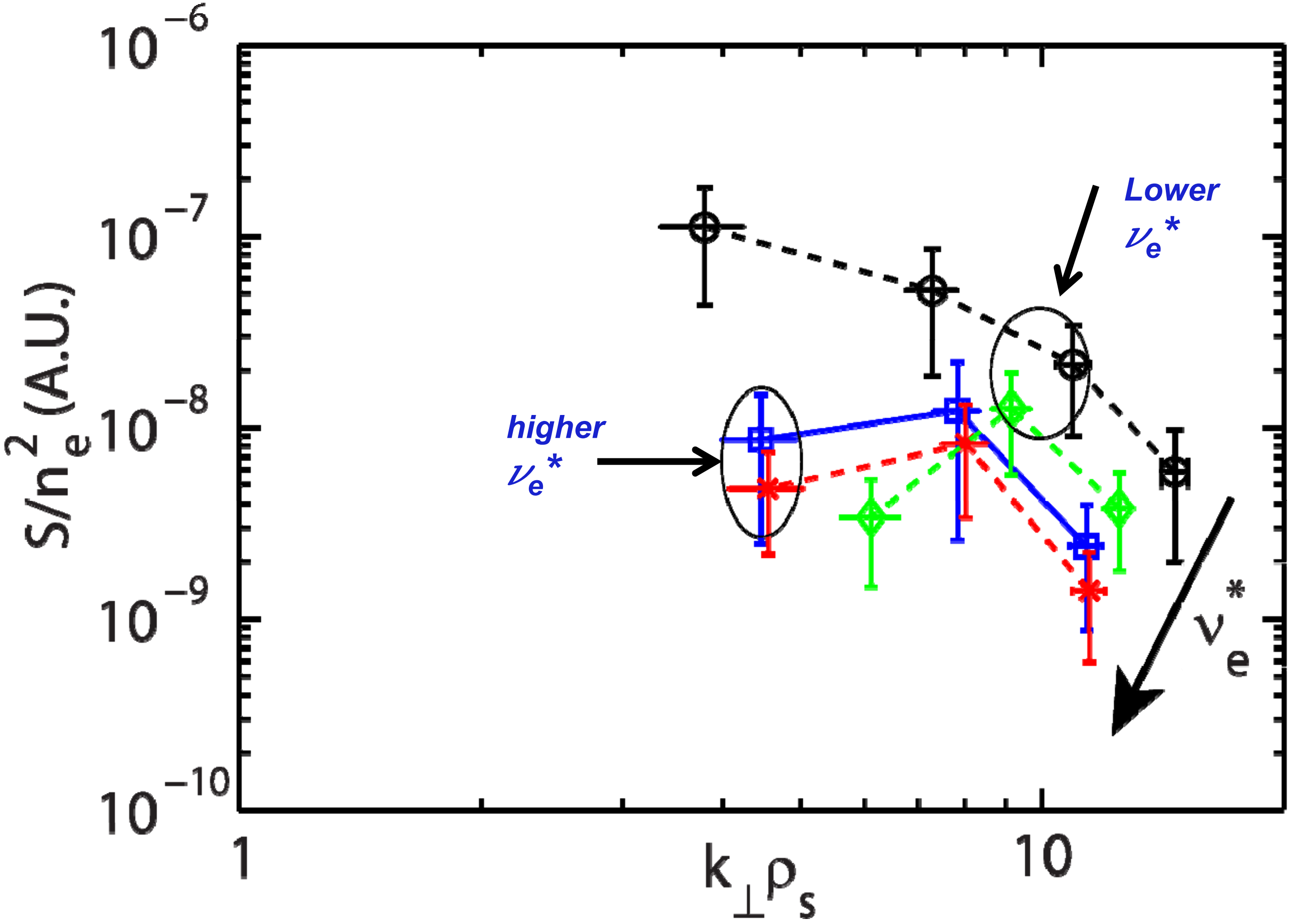


Consistent with Kaye et al., Nucl. Fusion, 2007



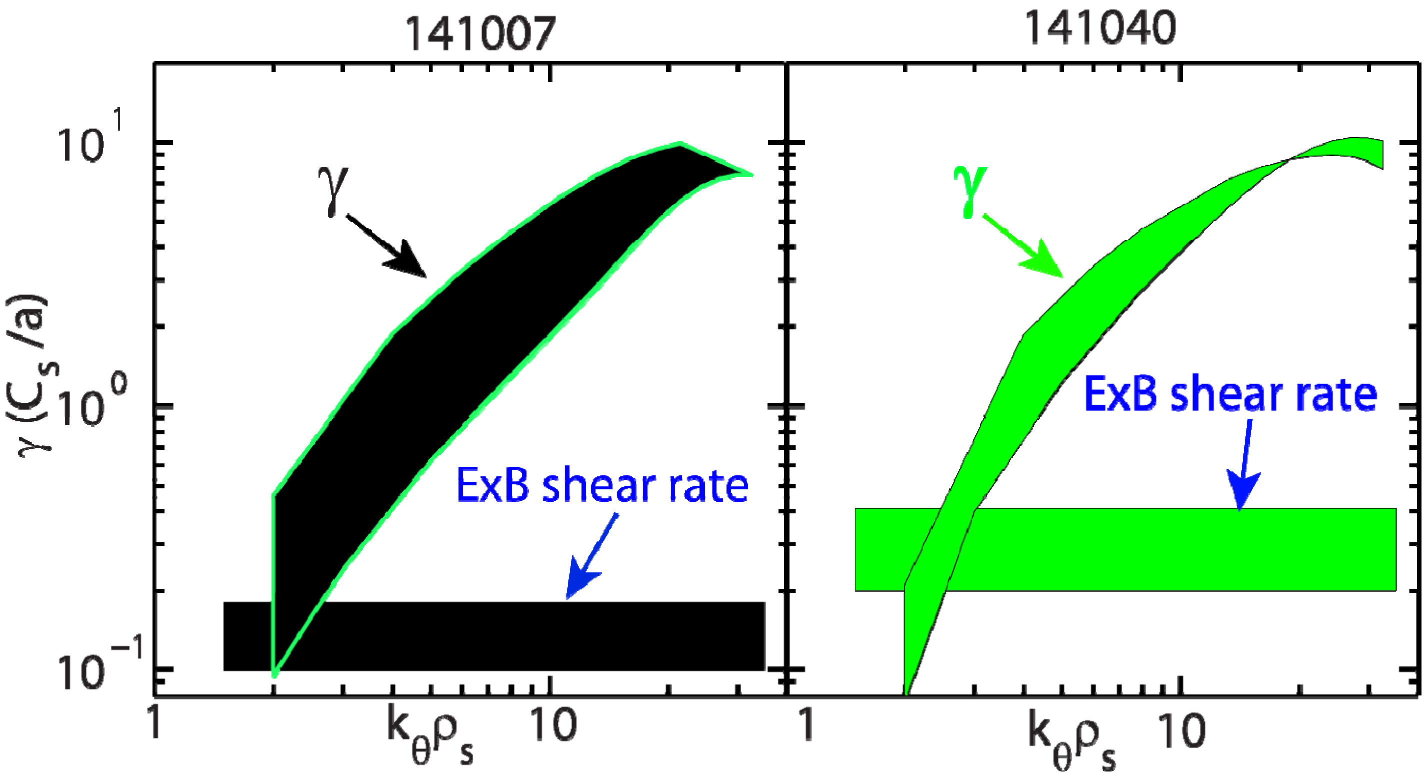
High-k Turbulence Power Appears to Increase as ν_e^* Decreases

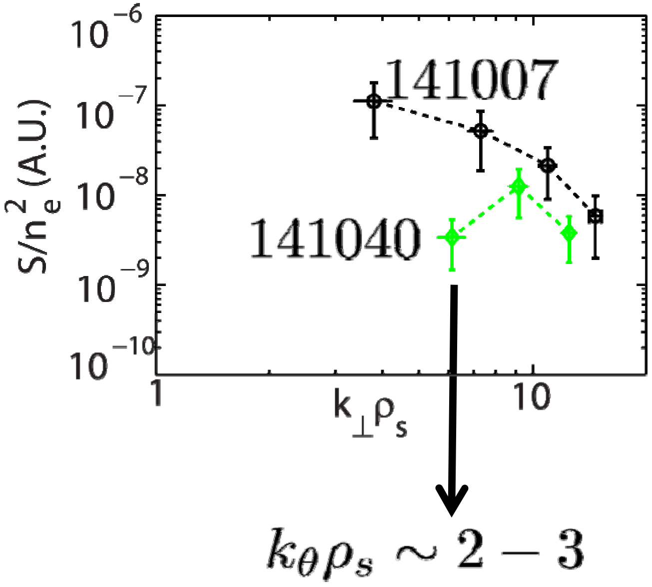
- High-k turbulence power at $k_\perp \rho_s$ >9 appears to decrease as ν_e^* increases



ExB Shear Maybe Responsible for the Spectral Difference in the Two Low ν_e^* Shots

- High-k turbulence power at $k_\perp\rho_s$ >9 appears to increase as ν_e^* decreases
- The same relationship may hold for $k_\perp\rho_s$ <9 if ExB shear stabilization is taken into account

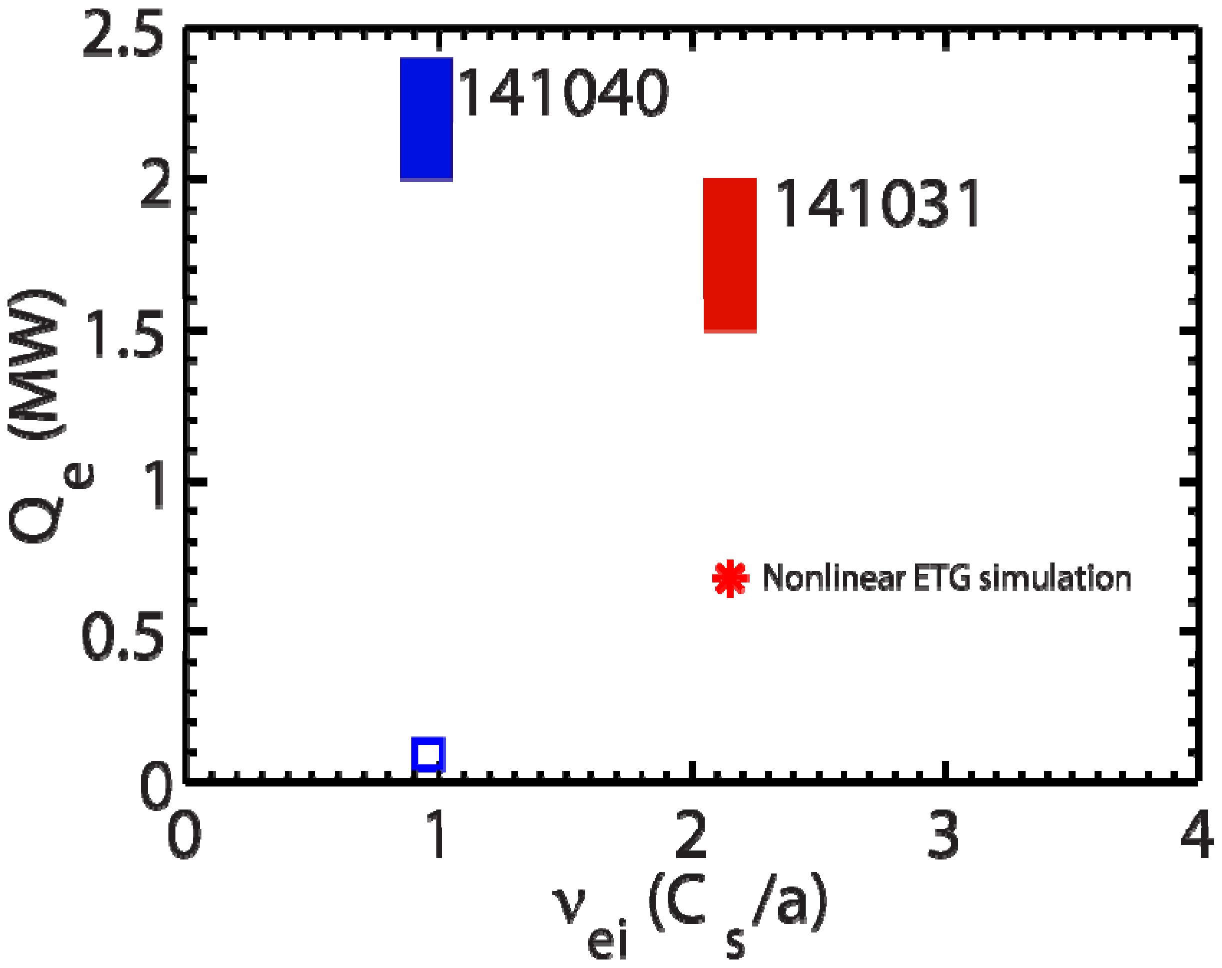




High-k measurements are spatially averaged over >~ 4 cm radial range

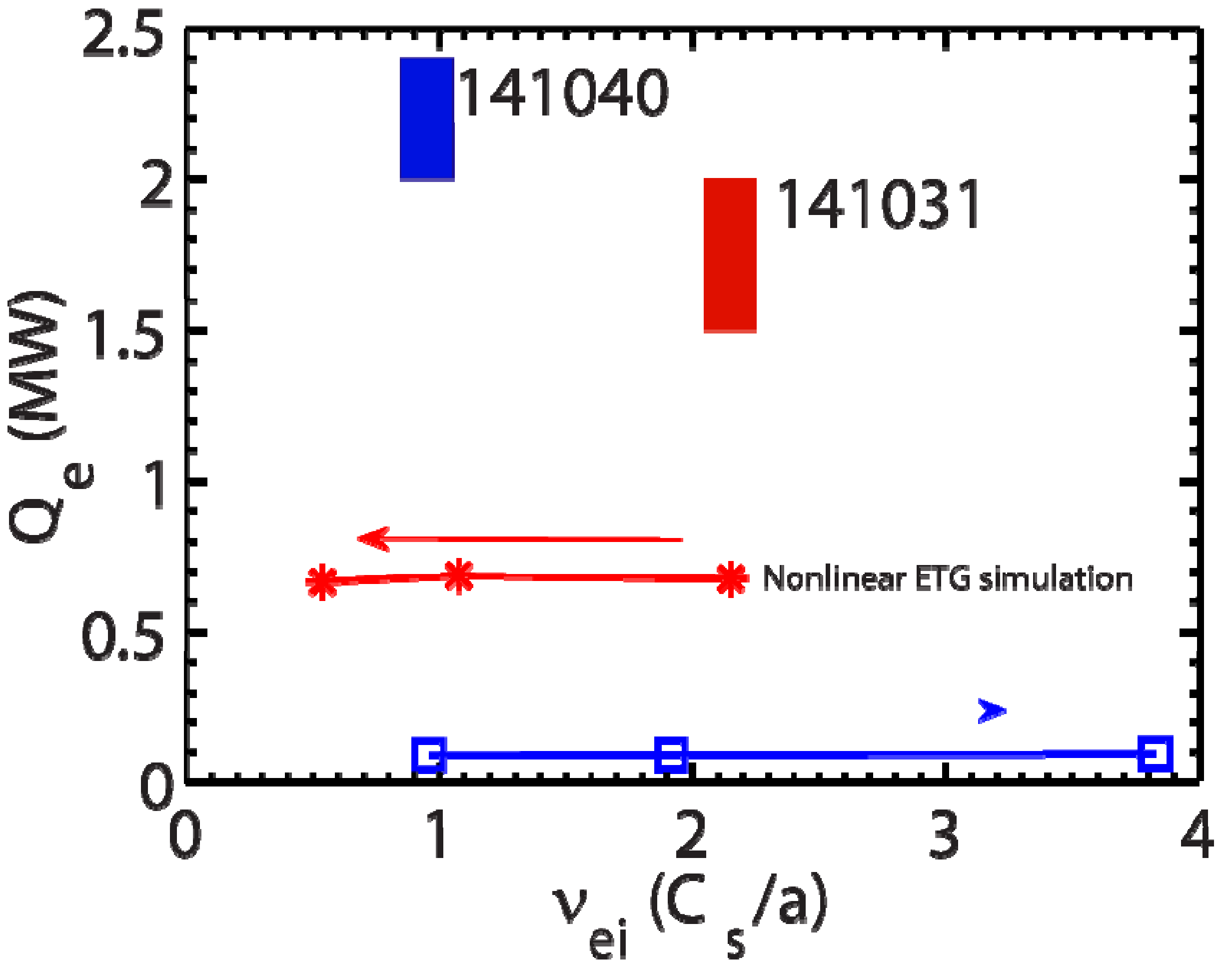
Local Nonlinear ETG Simulations Performed with Experimental Profiles

- Local nonlinear GYRO simulations show large deviation against experimental Q_e



Local Nonlinear ETG Simulations Showing Weak Collisionality Dependence

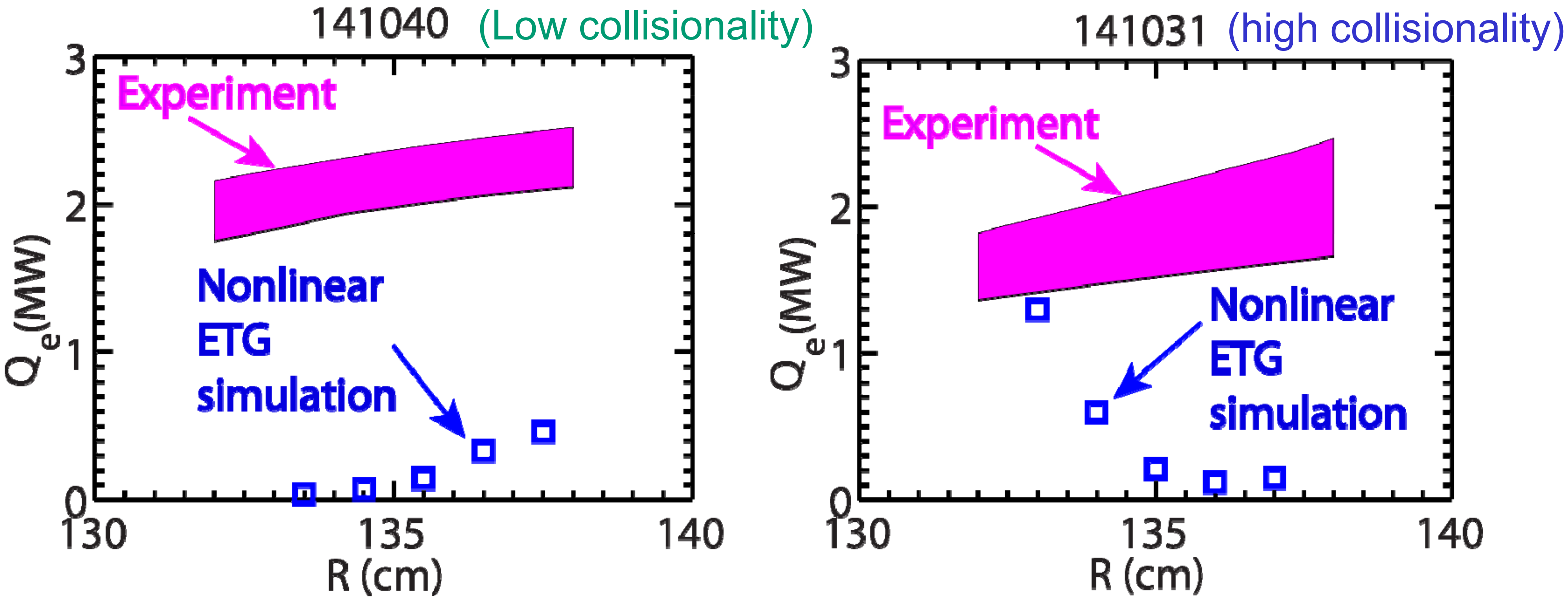
- Scans in ν_{ei} are based on both high and low collisionality shots
- Weak dependence on ν_{ei} is found



Large Profile Variations Requiring Nonlinear Simulation at Multiple Radial Locations

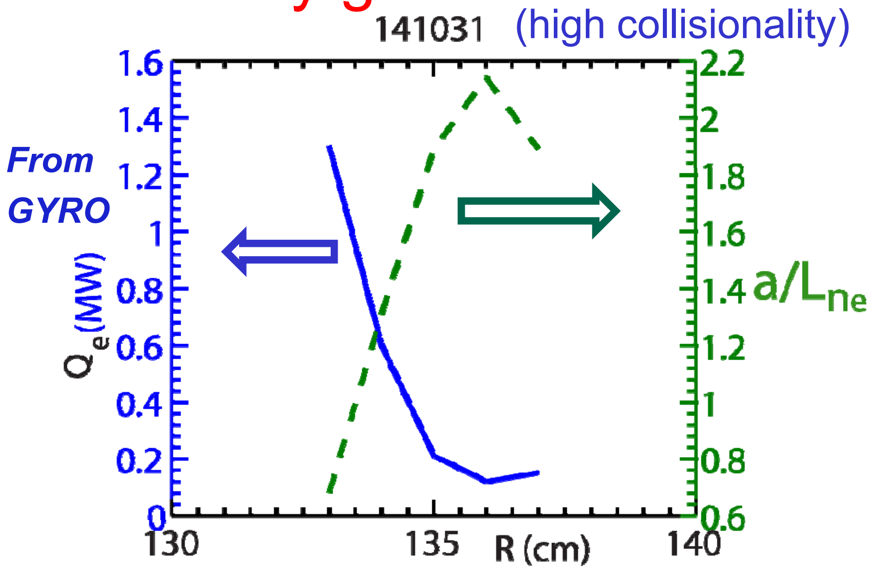
	r/a	q	s	a/L_{ne}	ν_{ei} (C_s/a)	γ_{ExB}
141040	.62-.71	1.8-2.1	0.8-1.9	0.7-2.7	0.7-1.3	0.2-0.5
141031	.57-.65	1.5-1.7	0.9-1.3	0.6-2.2	1.9-2.8	0.1-0.3

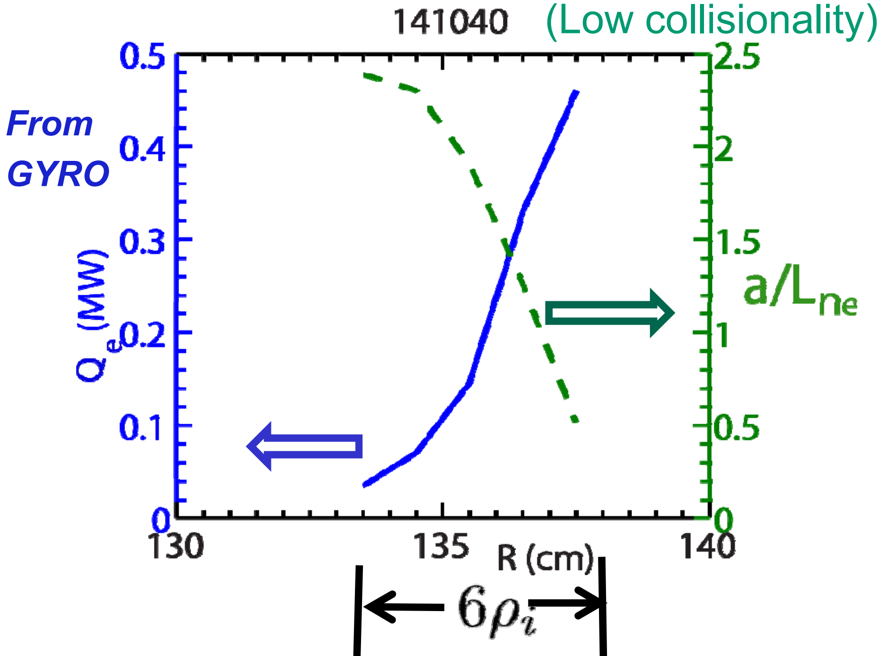
- Match with experimental Q_e found at one radii for the high collisionality shot
- Large discrepancy found for the low collisionality shot

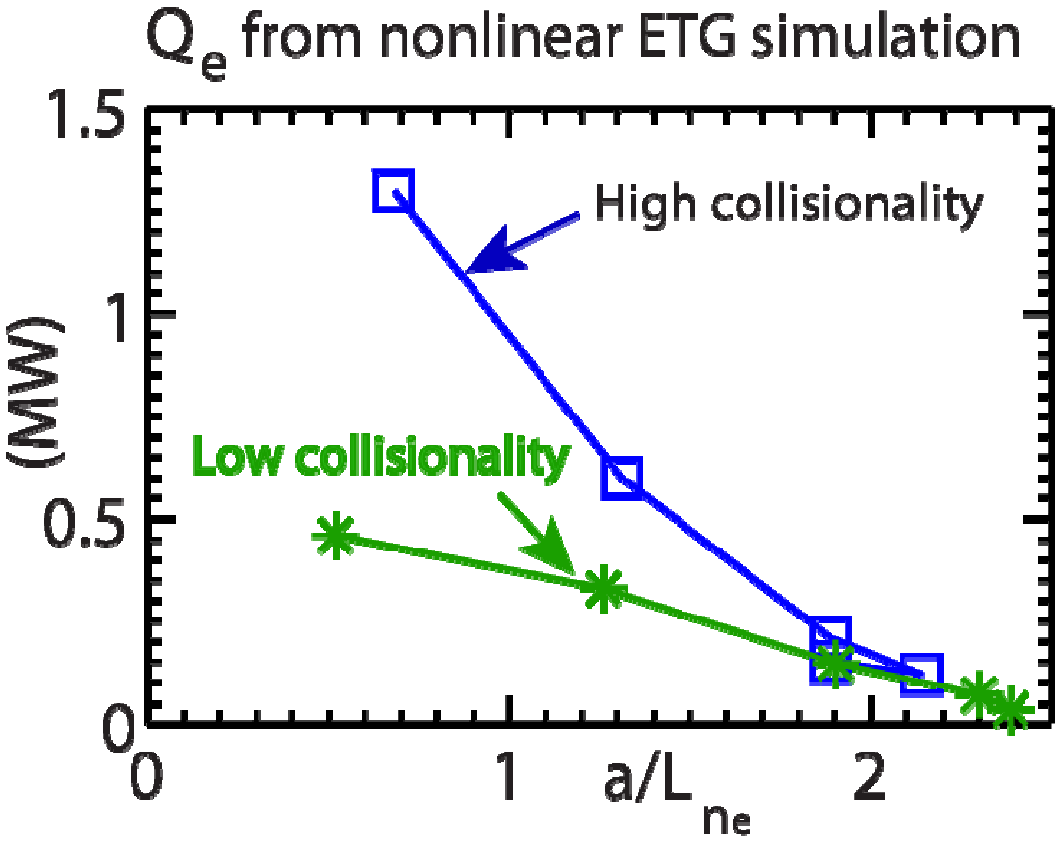


Density Gradient Important for Determining Predicted Electron Heat Flux in ETG Simulations

- Predicted electron heat flux is found to be anti-correlated with density gradient







Mechanisms in Addition to ETG Needed to Account for Observed Turbulence and Transport

- Previous confinement scaling observed: $B_T \tau_E \propto \nu_e^{*-1}$
- Here we found:
  - Observed change in high-k turbulence does not show a simple picture in the collisionality scan
  - Collisionality has no effects in the nonlinear ETG simulations
    - Predicted heat flux in agreement with experiment only at one position
    - Not able to reproduce observed change in the experimental Q_e or measured high-k turbulence in the scan
- Large profile variation, especially ExB shear and density gradient, may allow ion-scale turbulence to affect electron transport
  - ITG growth rate found to be 2 times larger than ExB shear rate at certain radial location
  - Spatial variation on several ion gyro-radius (~6ρ_i)
  - Large ITG eddies (~7ρ_i) expected to enhance transport
  - Global ion-scale simulations will be pursued

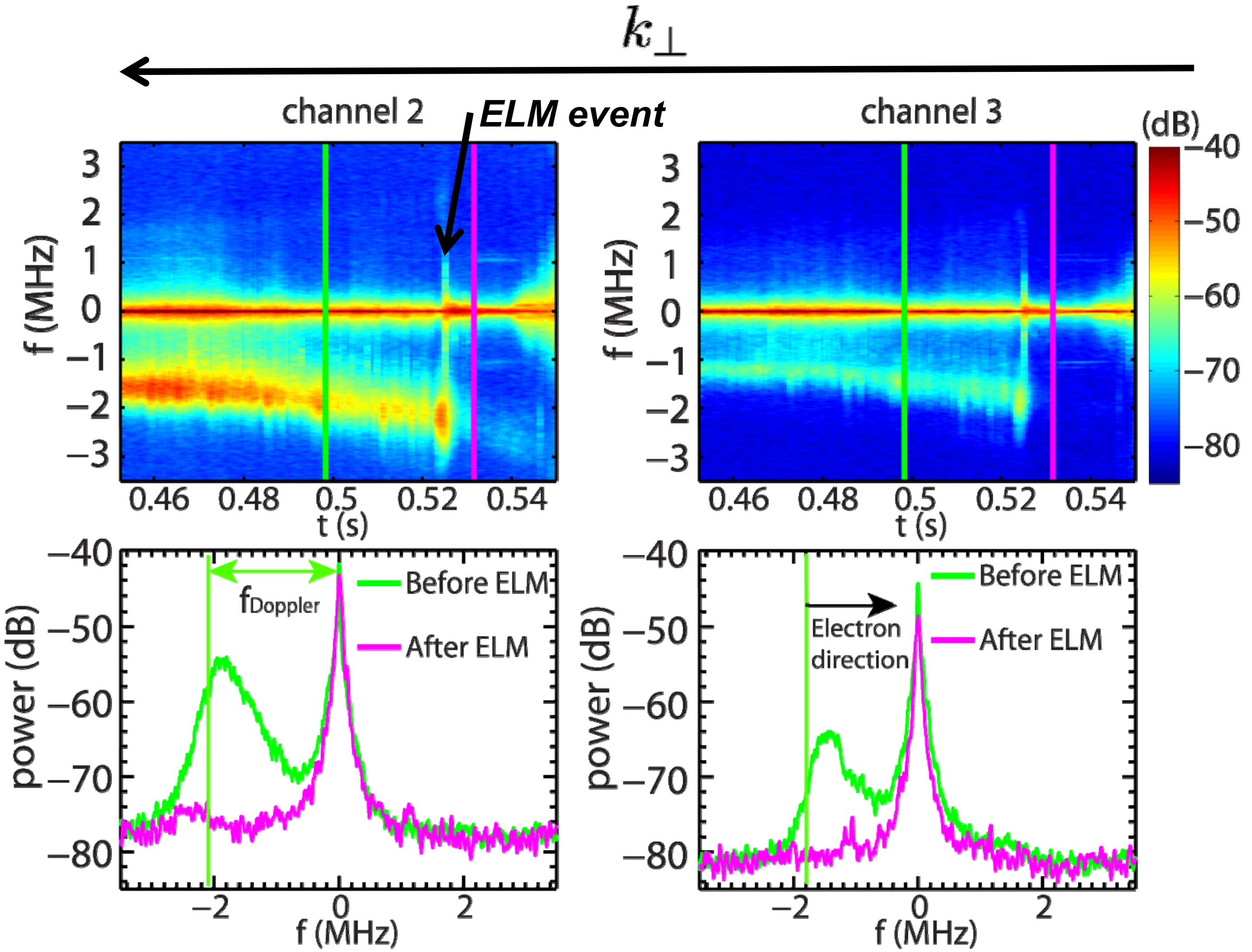
Summary

- Parametric dependence of high-k turbulence is investigated with a microwave scattering system on NSTX
- Density gradient stabilization of high-k turbulence and correlation with confinement improvement have been observed
  - Linear stability analysis supports the observed high-k turbulence is ETG
  - Nonlinear ETG simulation could predict experimental level of transport before ELM, but not after ELM
- Collisionality dependence of high-k turbulence is investigated
  - Measured high-k turbulence appears to decrease as collisionality increases
  - Nonlinear ETG simulations shows weak dependence on collisonality
  - Mechanisms in addition to ETG needed to account for observed turbulence and transport

Acknowledgement: Work supported by DoE and authors would like to thank NERSC for providing computation resources

Backup Slides

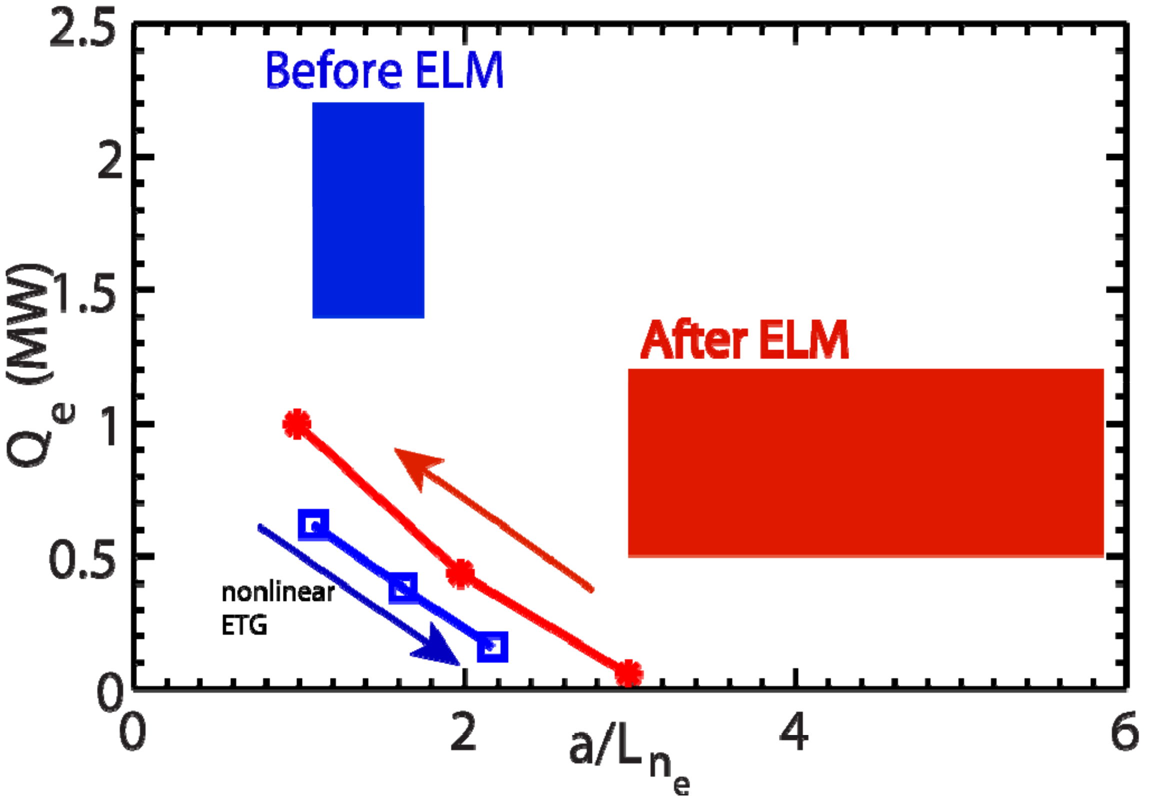
Significant Decrease in Scattering Signal Power Observed After the ELM Event



- Channels saw decreased scattering power after the ELM event
- Fluctuations propagate in the electron diamagnetic drift direction, consistent with ETG instability

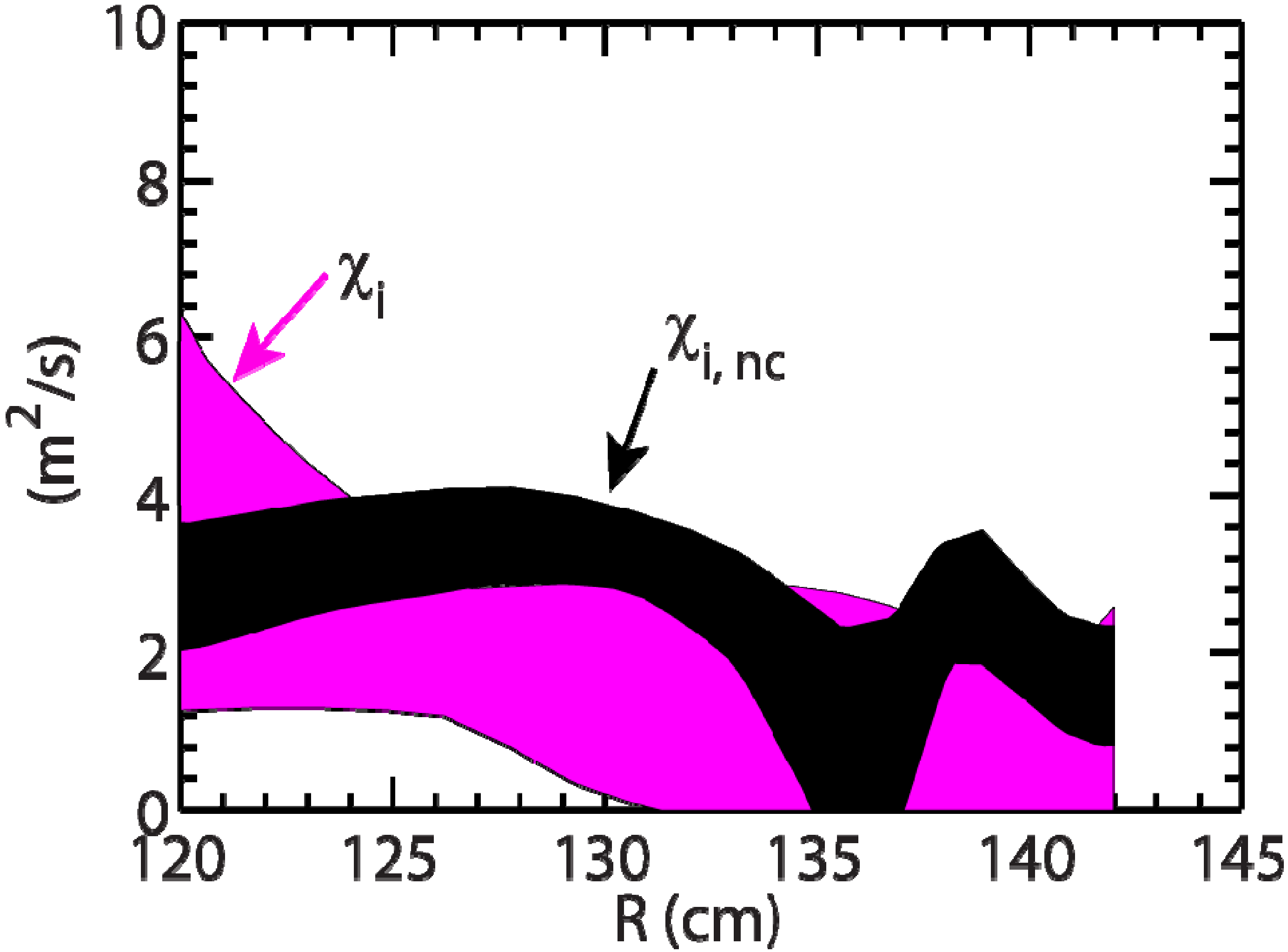
Nonlinear ETG Simulation Reproducing Observed Dependence of Electron Transport on Density Gradient

- Experimental Q_e is found to decrease after the ELM event with large density gradient
- The same trend is found from nonlinear ETG simulations
  - Trend confirmed by varying a/L_{ne} (increase and decrease)

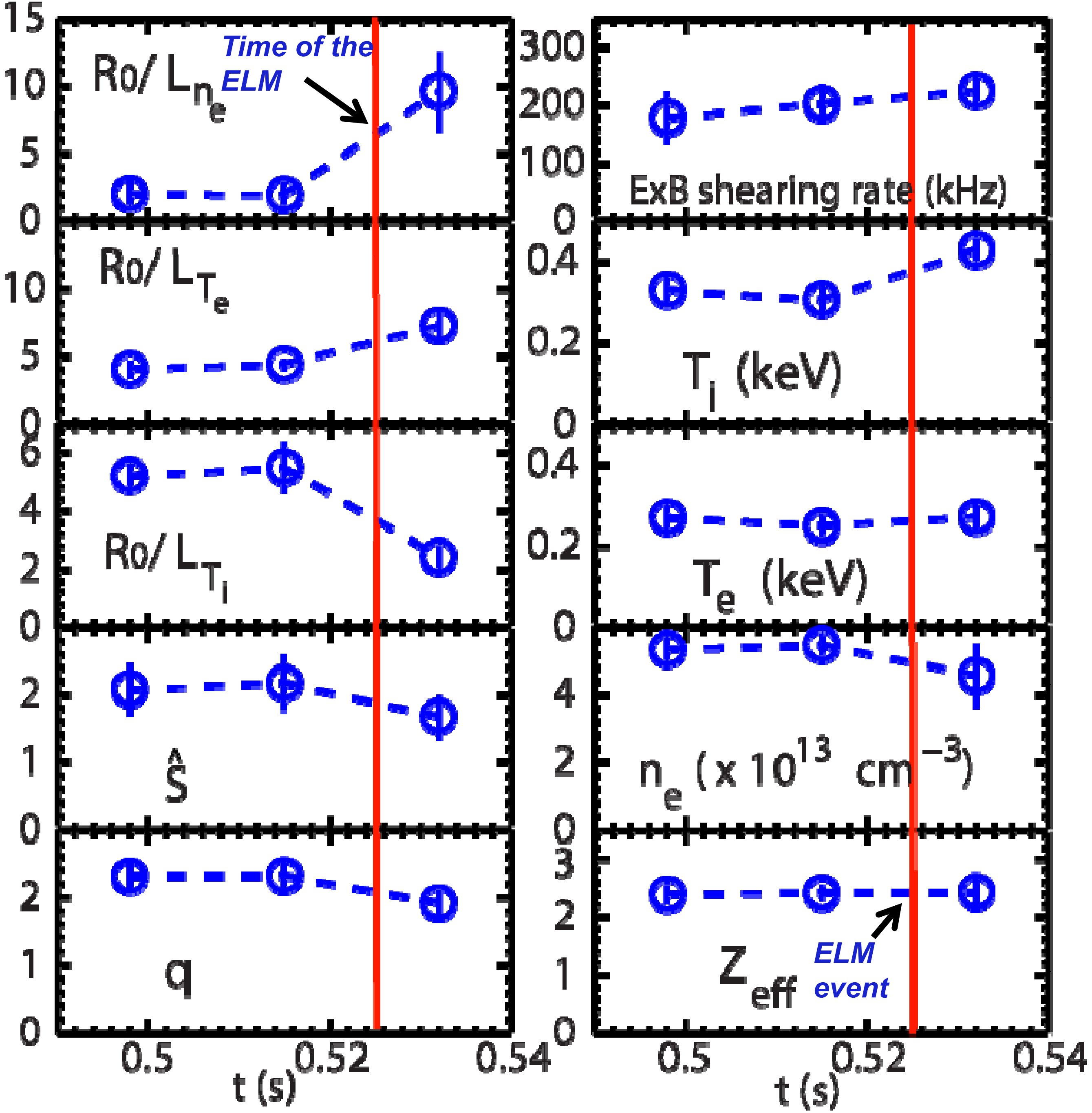


Ion Transport in Neoclassical Level

- Ion thermal transport is observed to be in neoclassical level
  - Neoclassical χ_i is calculated using NCLASS model implemented in TRANSP



Largest Change in Electron Density Gradient after the ELM Event

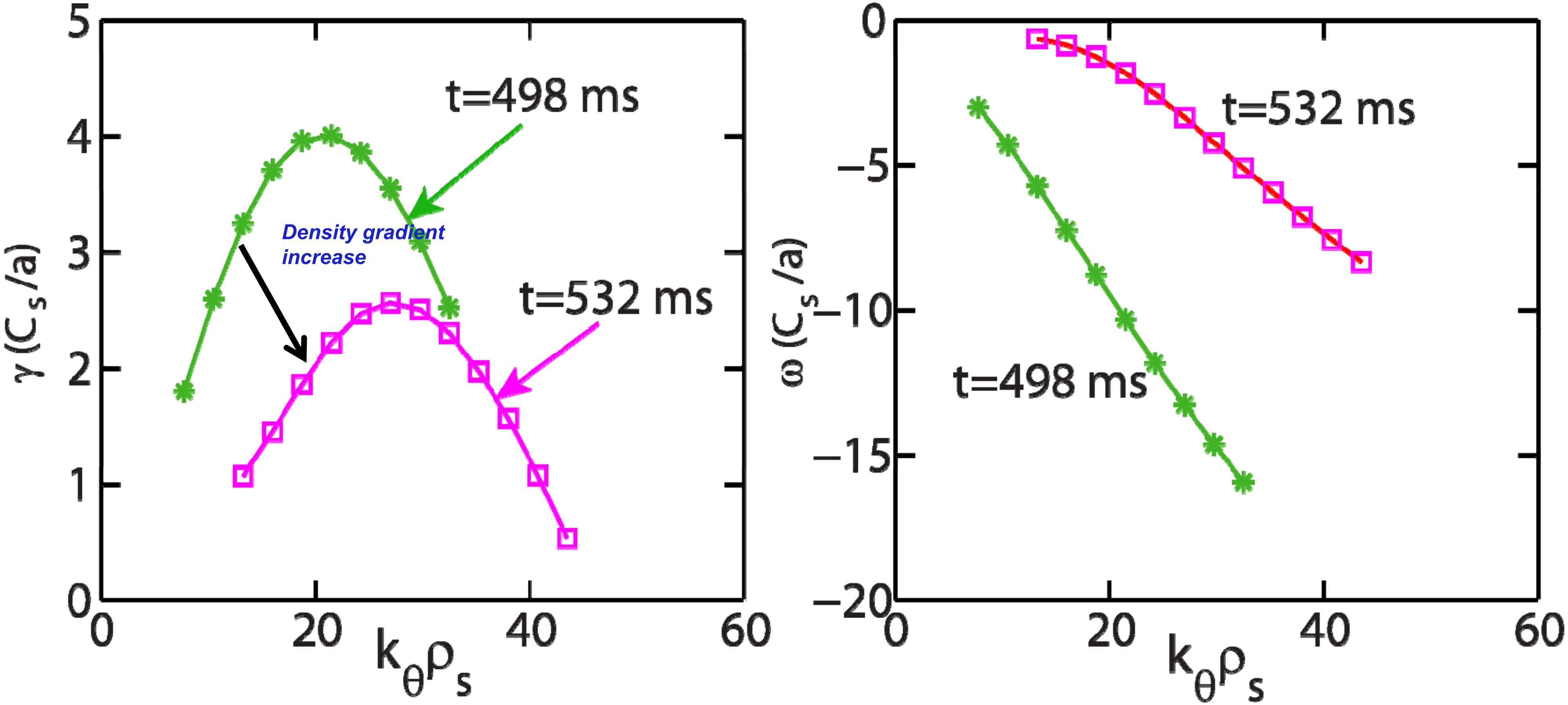


- A factor of five increase in the normalized density gradient after the ELM event
- 60% increase in the normalized T_e gradient and 60% decrease in T_i gradient
- The ion temperature has a 40% increase
- All other quantities have change no more than 25%

Density Gradient Increase Affects both the Linear Growth Rate and Mode Real Frequency

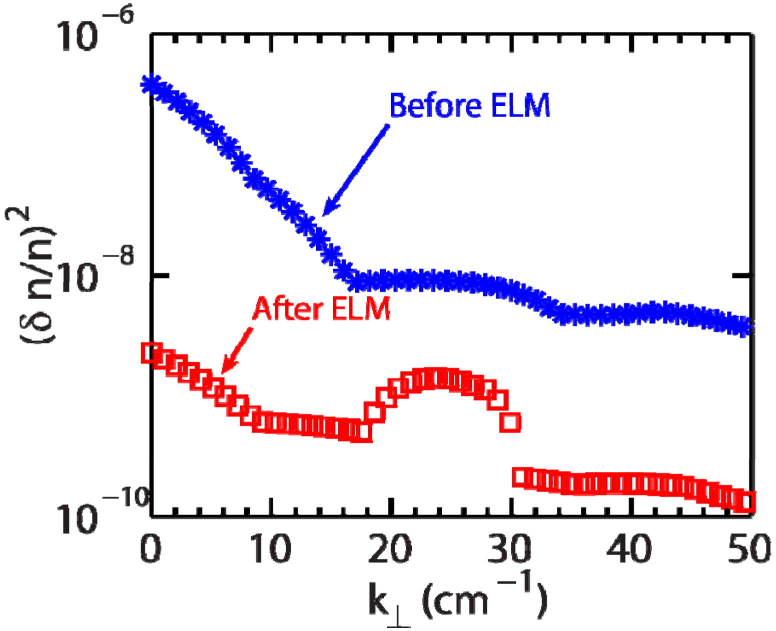
- Unstable mode propagates in the electron diamagnetic direction
- Density gradient increase no only reduces the peak linear growth, but also shift it to higher wavenumber
- Density gradient increase also reduces mode real frequency,

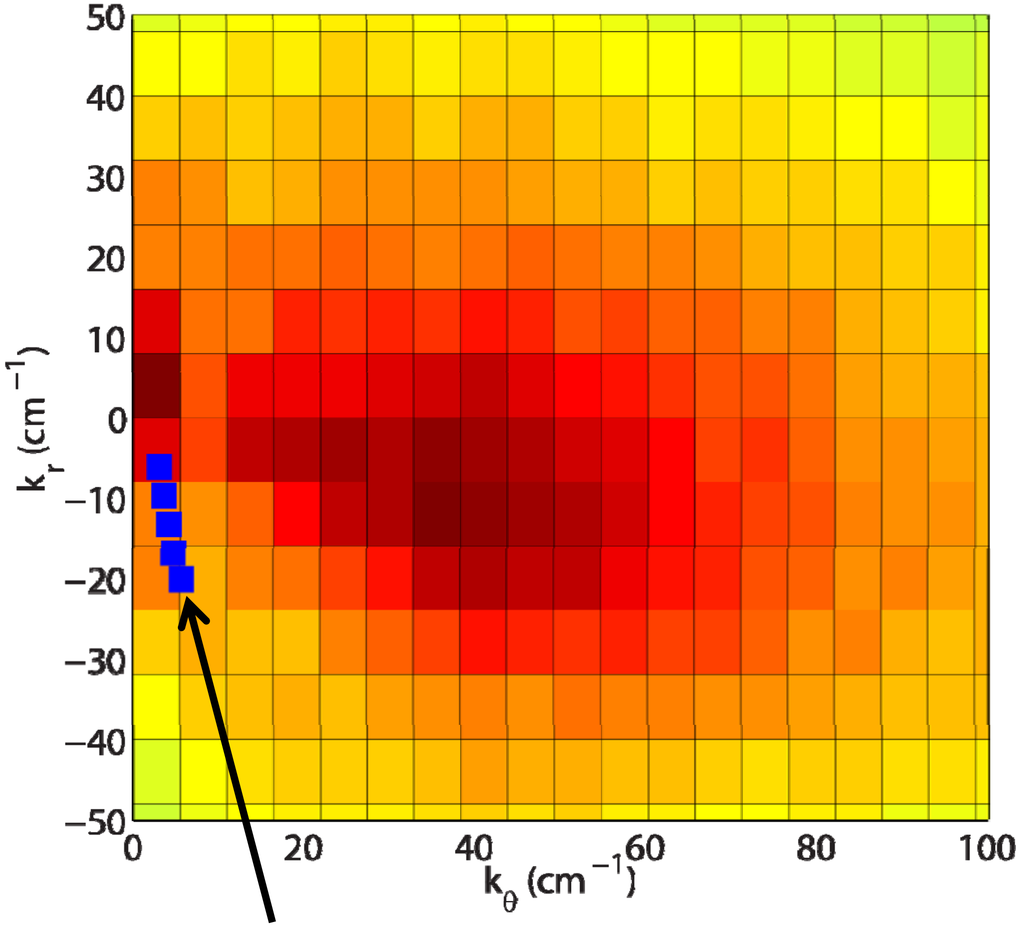
At R=133.5 cm



Comparison with High-k Measurements: A Challenging to Numerical Simulation

- High resolution in k space needed in simulations for comparison with measurements
  - High-k measured k_θ's fall between the zonal flow component ($k_\theta = 0$) and first finite k_θ mode
  - Need a better k_r resolution
- A high-k-like interpolation showing decrease of k spectral power after ELM



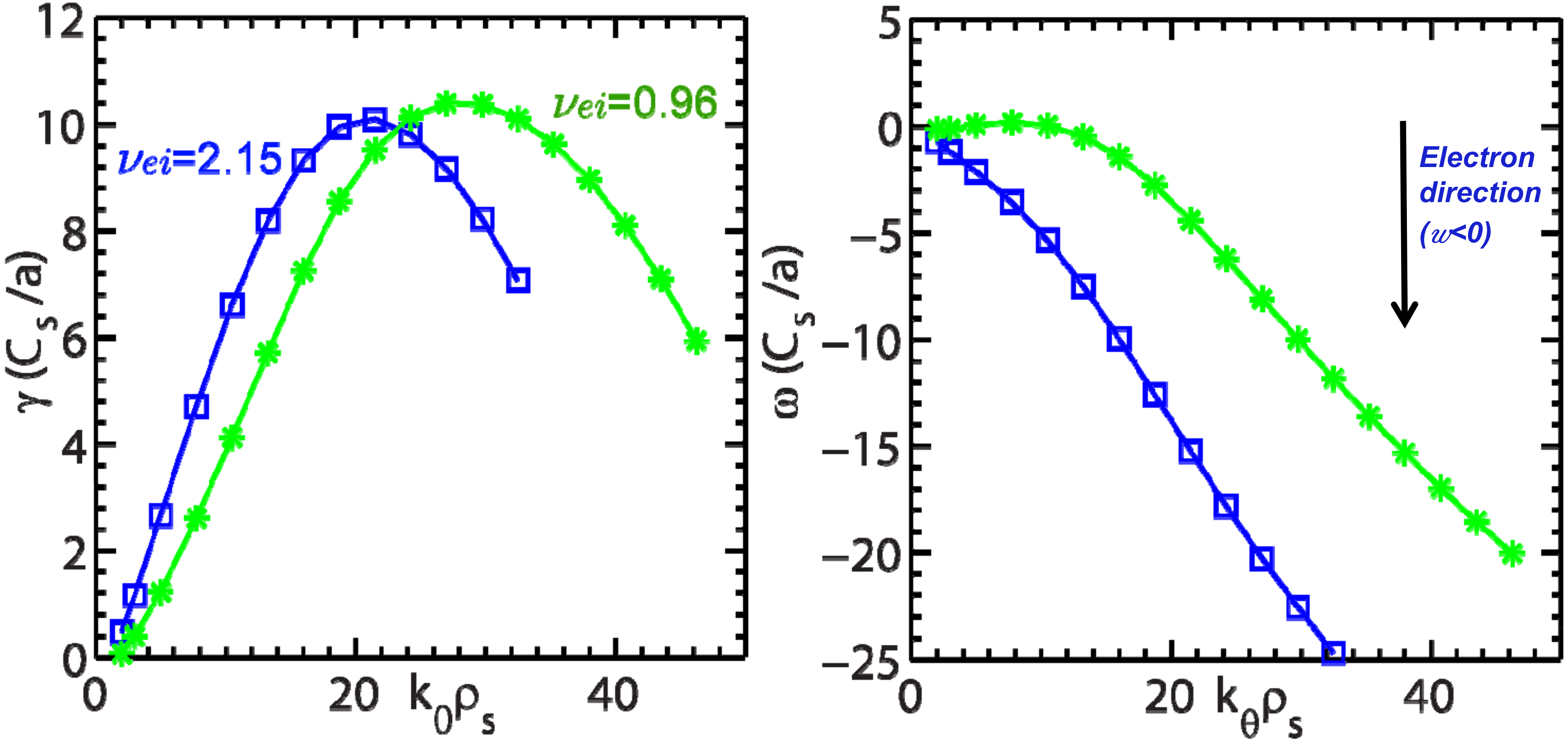


Five wavenumbers measured by the high-k scattering system

Linear Stability Analysis Showing ETG mode is Robustly Unstable

	r/a	T_i/T_e	q	s	s/q	a/L_{Te}	a/L_{ne}	Z_{eff}	ν_{ei}(C_s/a)	β_e	β'	γ_{ExB}
141040	0.66	1.12	**1.92**	**1.23**	0.64	4.64	**2.36**	1.19	0.96	0.012	-0.27	**0.45**
141031	0.6	1.18	**1.54**	**1.04**	0.672	4.56	**1.64**	1.22	2.15	0.014	-0.27	**0.21**

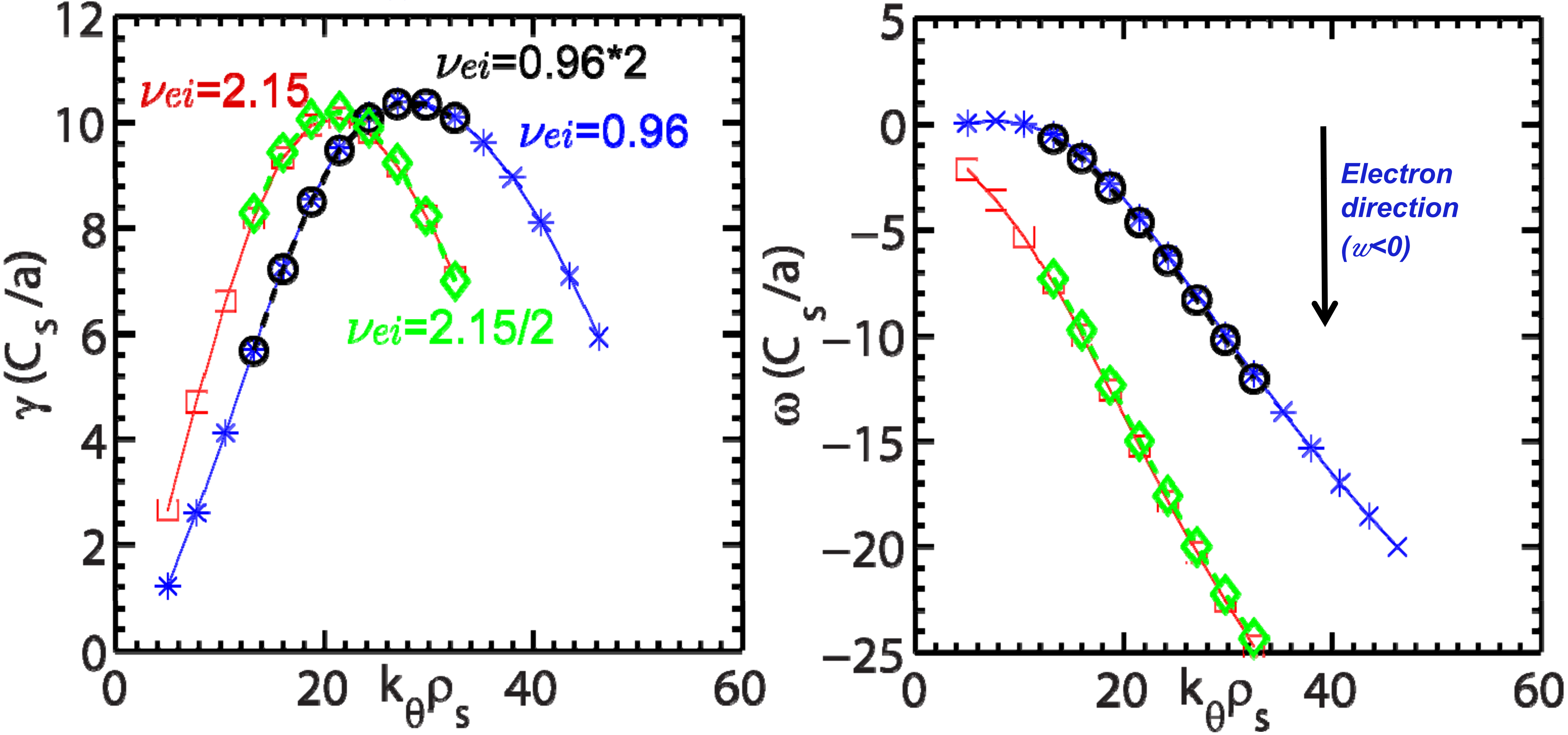
- q, s, $\gamma_{E\times B}$ and a/L_{ne} are not well matched
- ν_{ei} is varied by about factor of 2



ETG Modes Have Weak Collisionality Dependence

	r/a	T_i/T_e	q	s	s/q	a/L_{Te}	a/L_{ne}	Z_{eff}	$\nu_{ei}(C_s/a)$	β_e	β'	γ_{ExB}
141040	0.66	1.12	**1.92**	**1.23**	0.64	4.64	**2.36**	1.19	0.96	0.012	-0.27	**0.45**
141031	0.6	1.18	**1.54**	**1.04**	0.672	4.56	**1.64**	1.22	2.15	0.014	-0.27	**0.21**

- Growth rate calculated with doubled ν_{ei} for 141040 and with halved ν_{ei} for 141031



Electron direction (ω<0)

ETG Growth Rate Found More Sensitive to q and Density Gradient

	r/a	T_i/T_e	q	s	s/q	a/L_{Te}	a/L_{ne}	Z_{eff}	ν_{ei}	β_e	β'	γ_{ExB}
141040	0.66	1.12	1.92	1.23	0.64	4.64	2.36	1.19	0.96	0.012	-0.27	0.45
141031	0.6	1.18	1.54	1.03	0.67	4.56	1.64	1.22	2.15	0.014	-0.27	0.21

- q and a/L_{ne} contribute more to the change in γ than collisonality
- Change in s-hat has small effect on γ