Study of High-k Turbulence with Microwave Scattering on NSTX

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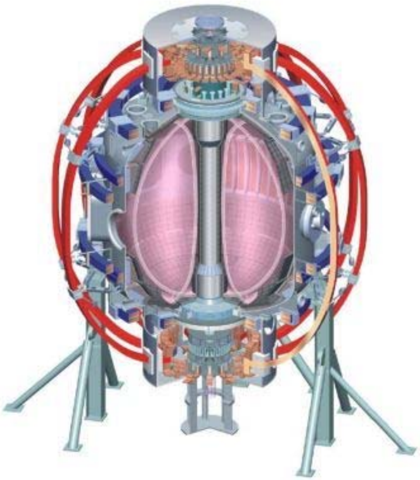

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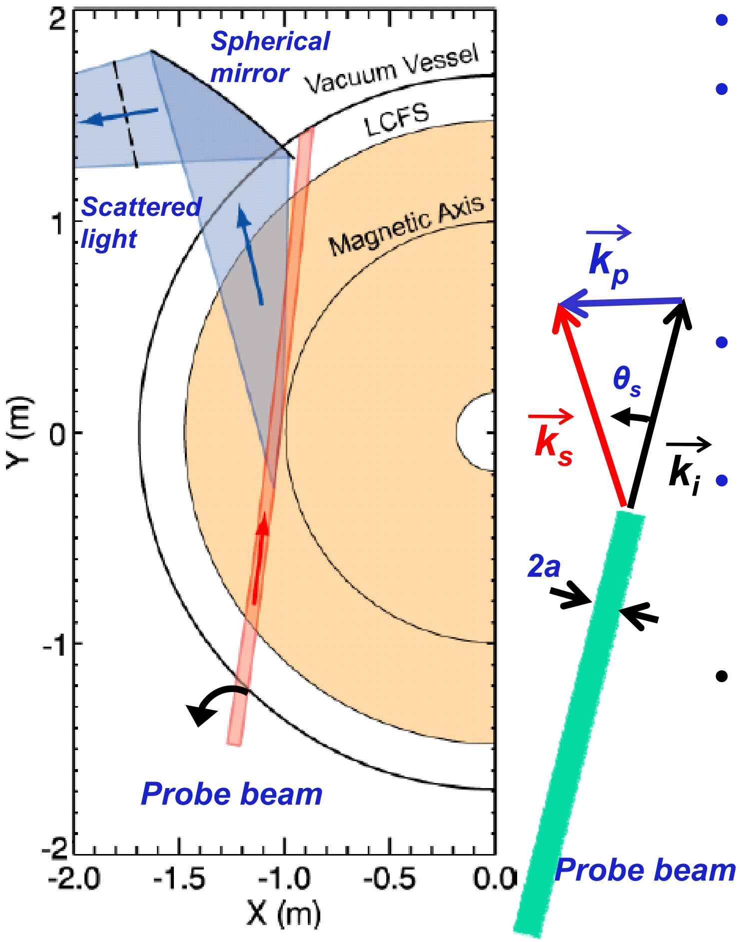
Highlights

- The high-k scattering system capability has been enhanced.
  - Full and partial remote control of launching and receiving optics
  - Simultaneous operation of all five channels *vs.* at most three previously
  - Solid-state source upgrade for stability and reliability
- Steep density gradient has been observed to stabilize electron-scale (high-k) turbulence.
  - Large density increase induced by an ELM event
  - All other equilibrium quantities experiencing much smaller variation.
  - Density gradient stabilization most effective on longer wavelength modes ($k_\perp \rho_s \lesssim 10$)
- High-k turbulence has collisionality dependence.
  - Factor of three change in collisionality achieved
  - Local ρ_e, β_e , ne and q kept approximately constant
  - Turbulence spectral power decreased as collisionality increases.
- Similar neutral beam-heated L and H-mode plasmas show decreased high-k power at longer wavelength ($k_\perp \rho_s \lesssim 10$).

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:

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

- Since k_i , $k_s >> k_p$, 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 bandwith: 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): 5-20 cm^{-1} (~5-20 ρ_s^{-1})***
    - **Radial resolution: ±2 cm**
    - **Tangential resolution: 5-15 cm**
    - **Radial range: R=106 – 144 cm**
    - **Minimal detectable density fluctuation: $|\delta n_e(k)/n_e|^2 \approx 2\times10^{-11}$**

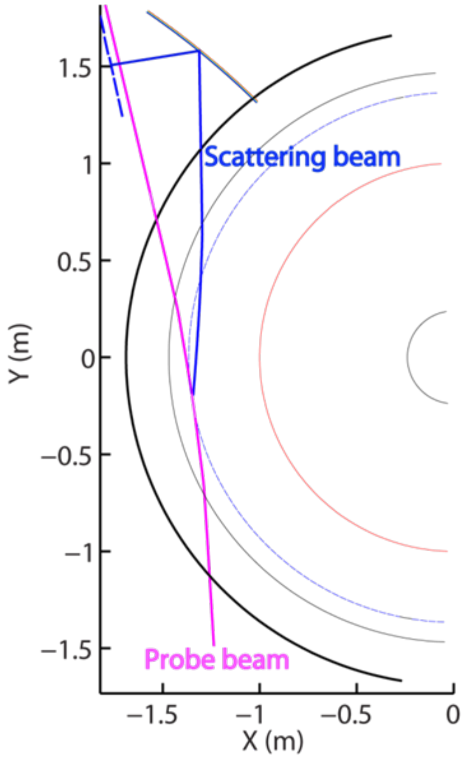
Improved Radial Localization due to Toroidal Magnetic Field Curvature

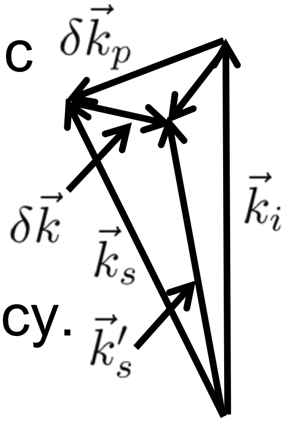
- The tangential scattering volume is reduced by the toroidal magnetic field curvature which is particularly large in NSTX due to its low aspect ratio.
- The scattering volume for a Gaussian probe beam is determined by an instrument selection function:

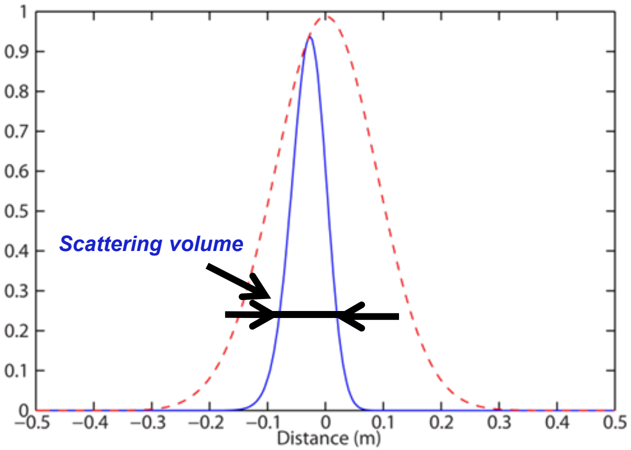
$$f(l) = e^{-\left(\frac{\delta k(l)}{2/a}\right)^2}$$

  where l is length along the probe beam and a is the radius of the probe beam.

- δk is determined by magnetic field directional change relative to the position of maximum collection efficiency.

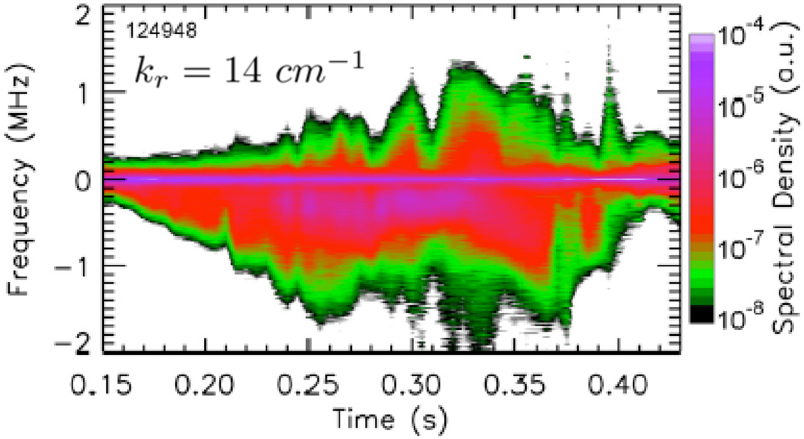


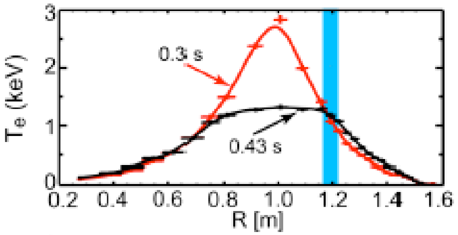


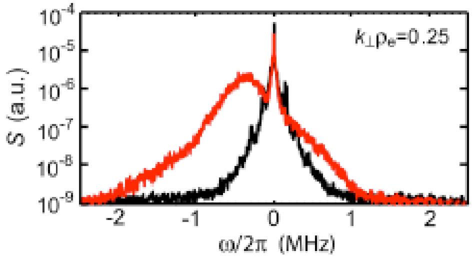


Previously Measured High-k Turbulence Consistent with ETG

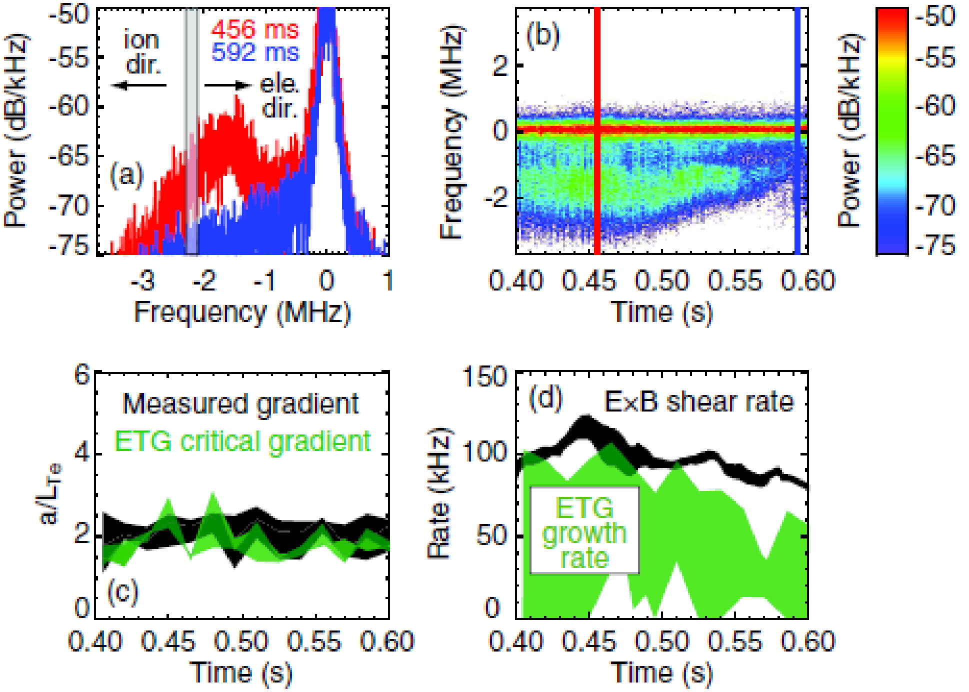
- The measured high-k turbulence is shown to be driven by electron temperature gradient (Mazzucato et al., PRL, 2008).







- The measured high-k turbulence power is shown to be reduced by ExB flow shear (D.R. Smith et al., PRL, 2009).



Recent Enhancement of the High-k Scattering System

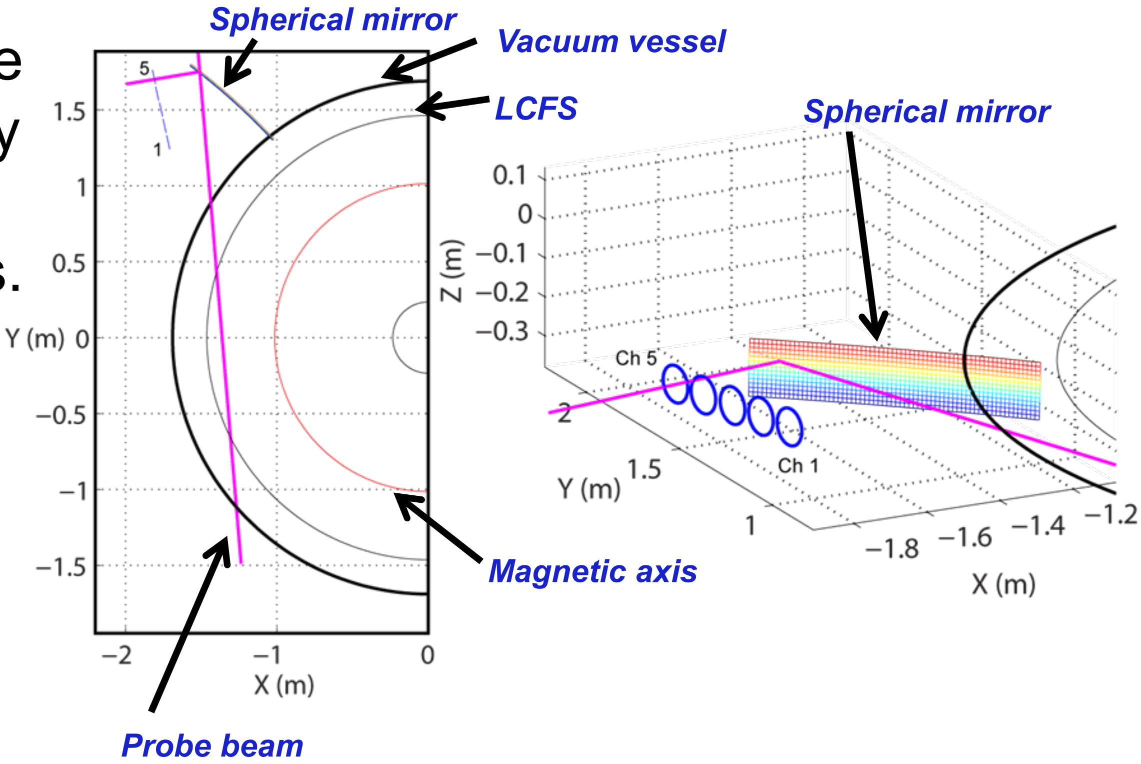
- A solid-state microwave source was successfully tested and has replaced the carcinotron as the probe beam source.
  - Reliable and adjustment-free operation.

- Several upgrades have been implemented to enhance the control capability of high-k system:
  - Full remote control capability of high-k system mirrors: between-shot adjustments according to realized plasma equilibrium without controlled access.
  - Integrated user interface implemented for efficiently setting mirrors angles.
  - Remote control of electrical attenuations installed and working well.

- All five channels can operate simultaneously resulting from improvements in scattering configuration.

Improved Scattering Configuration

- Previous experiments were only able to simultaneously utilize at most three out of the five receiving channels.
  - The probe beam hits the spherical mirror and some of the channels have to be fully attenuated to protect detectors.
  - Adjacent channels can be overwhelmed by the stray radiation.



Spherical mirror

Vacuum vessel

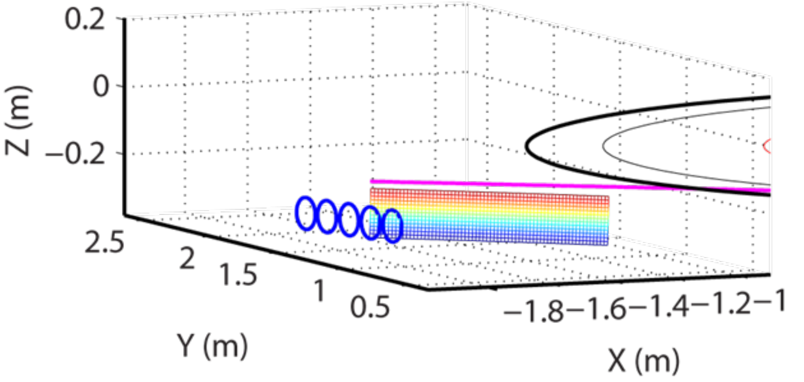
LCFS

Spherical mirror

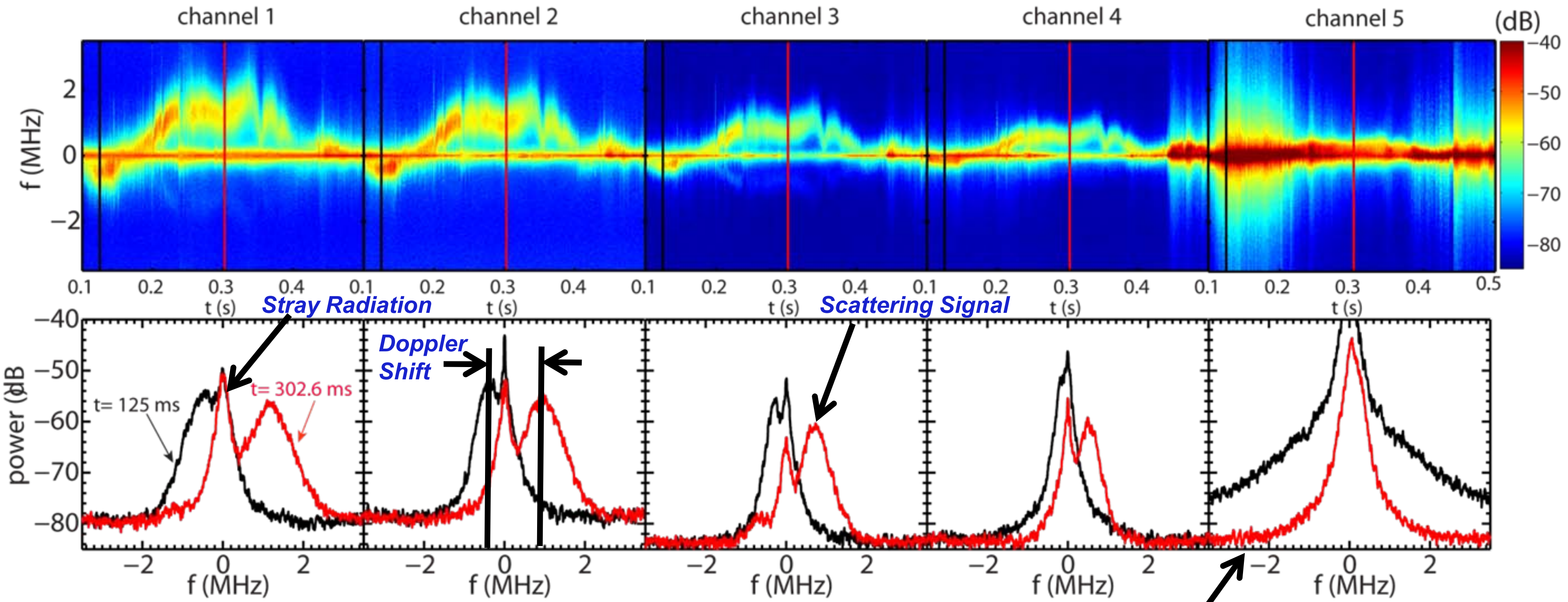
Magnetic axis

Probe beam

- To Launch the probe beam upward to prevent it from directly hitting the mirror.
  - No channel has to be fully attenuated.
  - Stray radiation on all channels is reduced.



Simultaneous Operation of All Five Channels



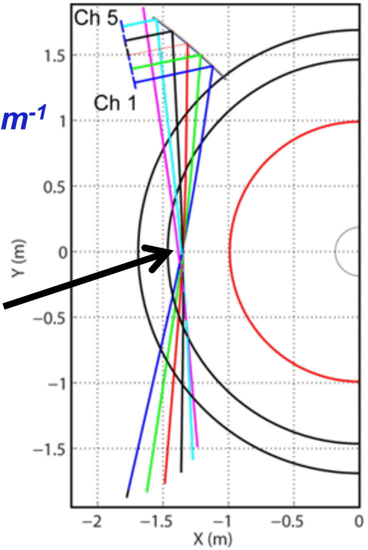
Stray Radiation

Doppler Shift

Scattering Signal

$k_r \rho_s \approx -10.8$	$k_r \rho_s \approx -8.4$	$k_r \rho_s \approx -6.1$	$k_r \rho_s \approx -3.4$	$k_r \rho_s \approx -1.1$
$k_\theta \rho_s \approx 2.9$	$k_\theta \rho_s \approx 2.3$	$k_\theta \rho_s \approx 1.94$	$k_\theta \rho_s \approx 1.49$	$k_\theta \rho_s \approx 0.9$
$k_\varphi \approx 2.3\ \mathrm{cm}^{-1}$	$k_\varphi \approx 1.8\ \mathrm{cm}^{-1}$	$k_\varphi \approx 1.4\ \mathrm{cm}^{-1}$	$k_\varphi \approx 1.1\ \mathrm{cm}^{-1}$	$k_\varphi \approx 0.8\ \mathrm{cm}^{-1}$

- **An example of all five-channel scattering signals obtained from a beam heated L-mode plasma.**



r/a ≈ 0.73 , R ≈ 137 cm

Density Gradient Stabilization of ETG Turbulence

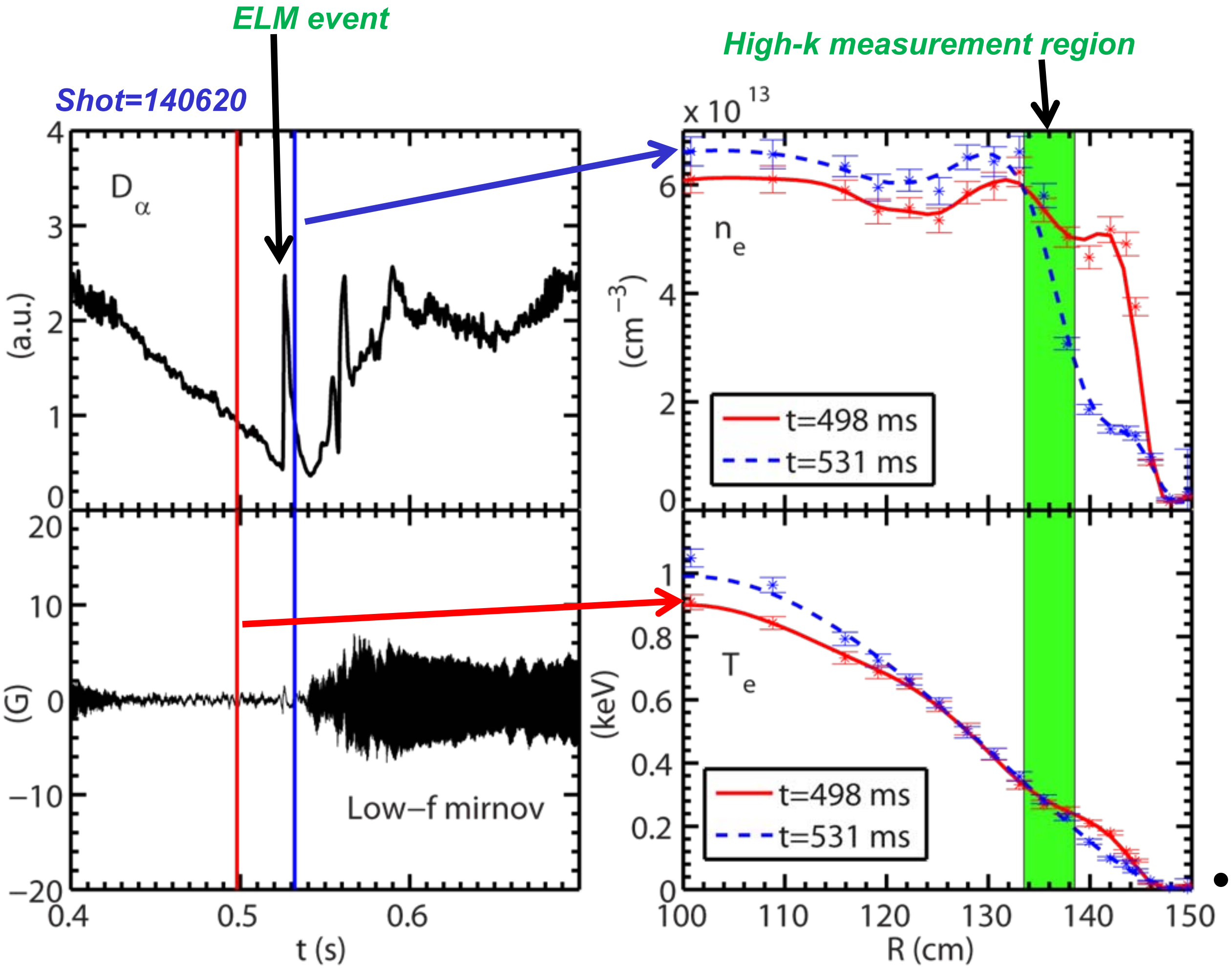
- ETG turbulence can be stabilized by large density gradient, for example, the critical T_e gradient can be written as (Jenko et al., 2001):

$$(R_0/L_{T_e})_{crit} = max\{(1+Z_{eff}\frac{T_e}{T_i})(1.33+1.99\hat{s}/q)(1-1.5\epsilon)(1+0.3\epsilon\frac{d\kappa}{d\epsilon}), 0.8R_0/L_{n_e}\}$$

  - The second term is solely determined by density gradient and can overturn the first term when density gradient is large enough.

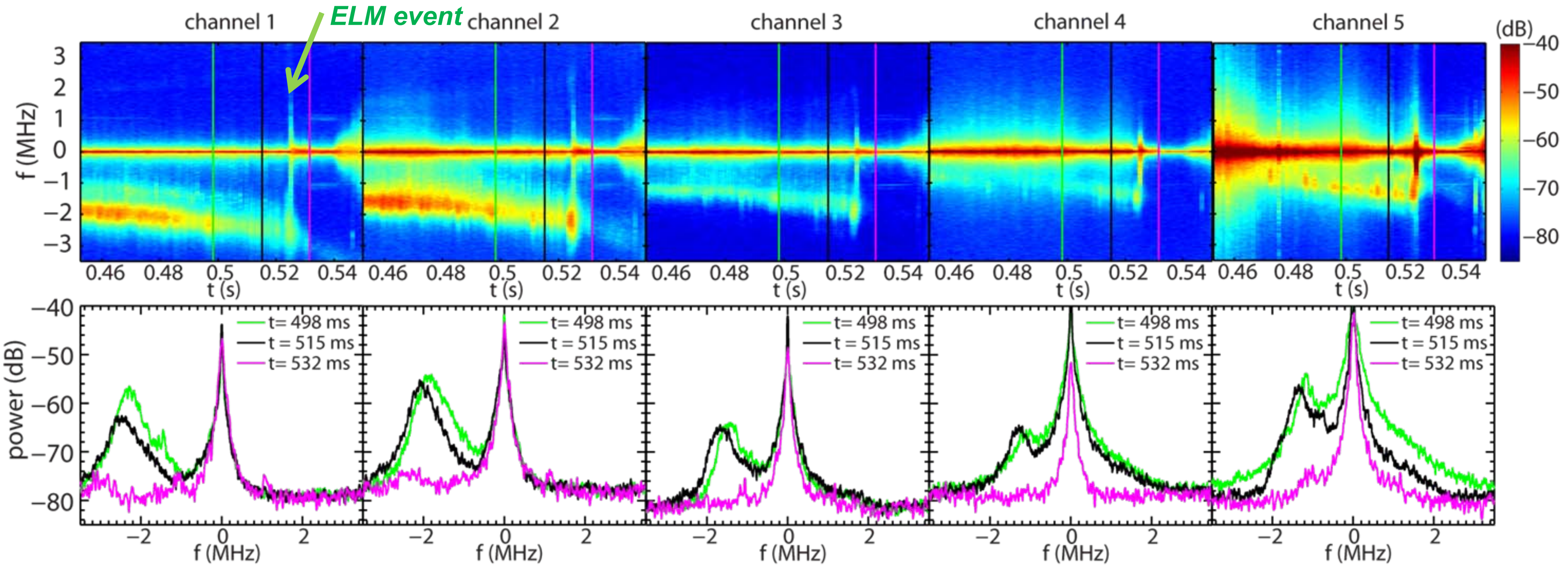
- On the other hand, TEM can be destabilized by density gradient.
  - Unless collisionality is large enough to detrap electrons which is not likely the case in NSTX.

Large Density Gradient Induced by An 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 MHD mode appears before and right after the ELM event.

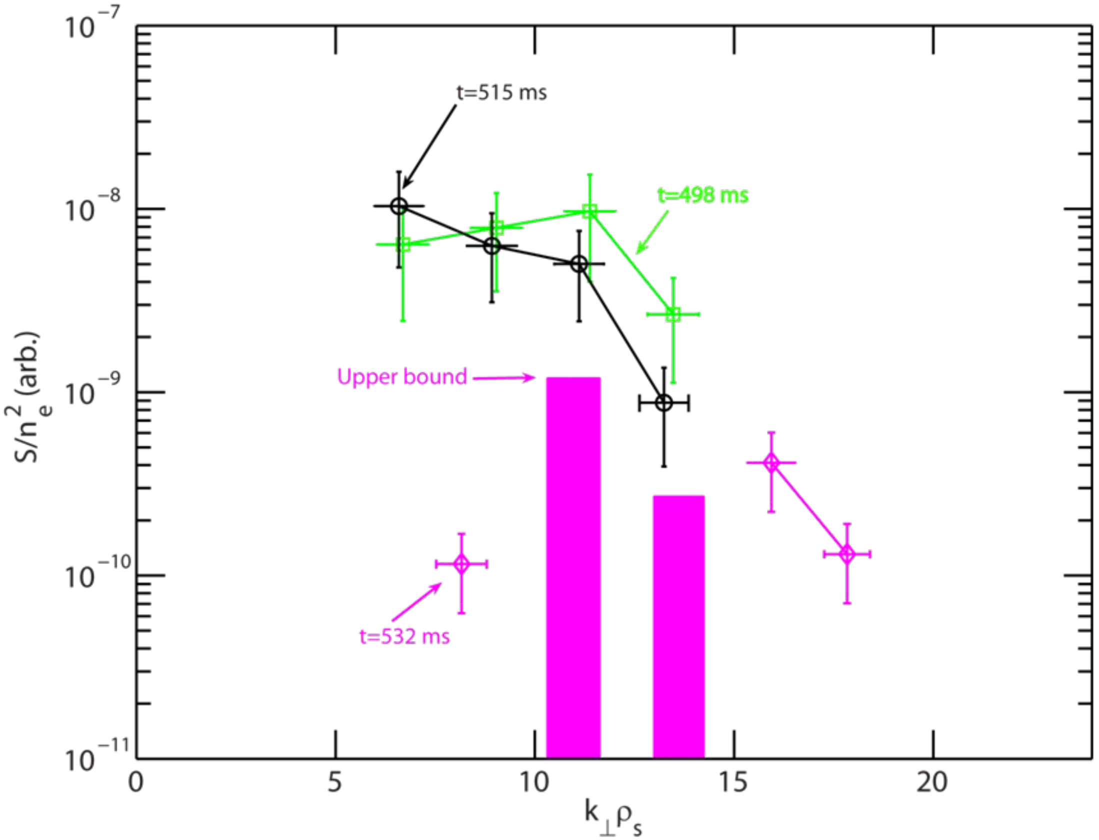
Significant Decrease in Scattering Signal Power Observed After the ELM Event



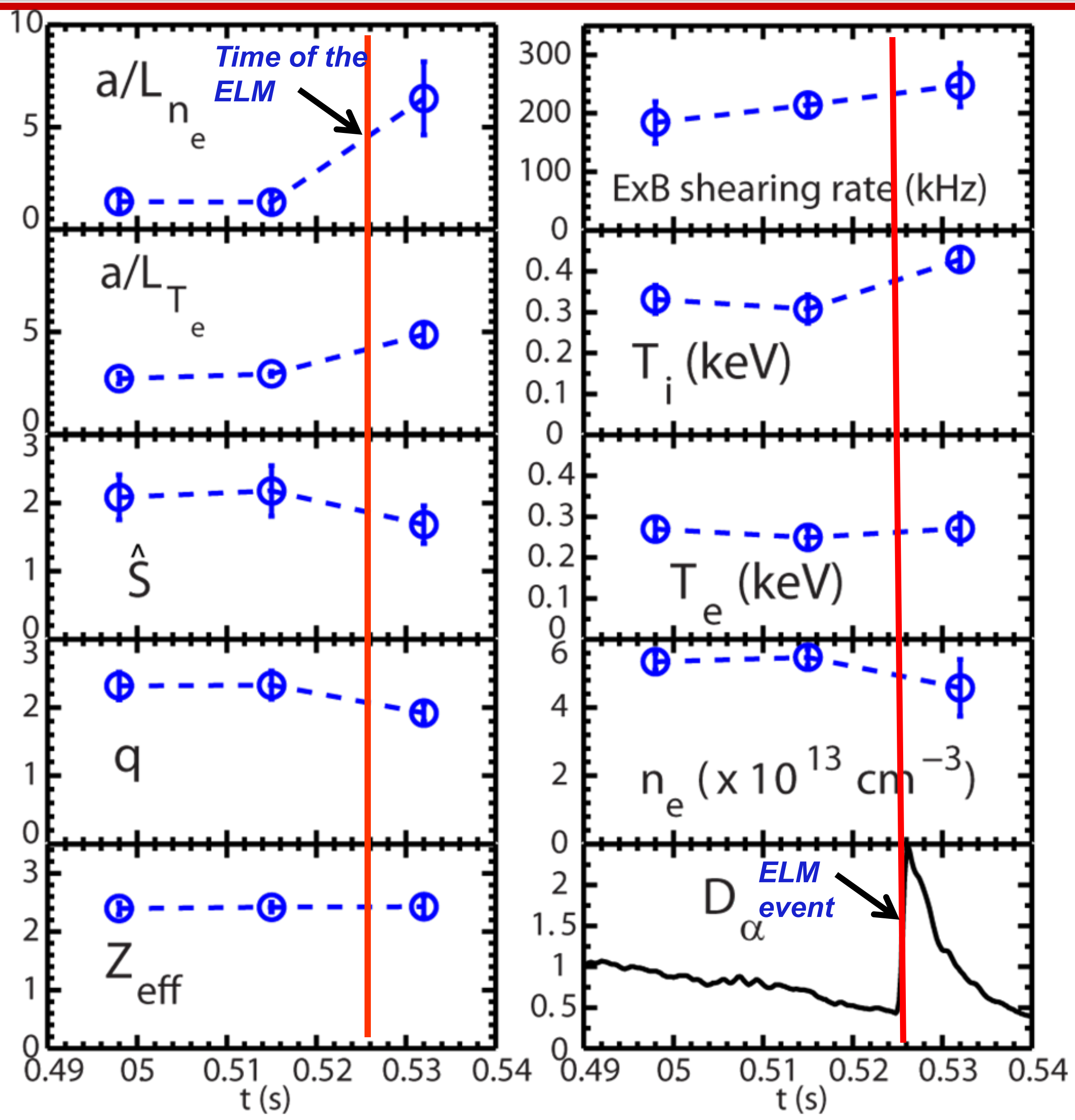
- All five channels saw decreased scattering power after the ELM event.
- However, interpretation has to take into account the change of wavenumber measured by each channel due to the increase density gradient after the ELM event.

The Spectral Power of Modes at Smaller Wavenumber is Significantly Reduced

- Significant decrease in wavenumber spectral power is observed for modes with longer wavelength, $k_\perp \rho_s \lesssim 10$.
- The spectral power of the large wavenumbers, $k_\perp \rho_s \gtrsim 15$, is unaffected.
  - The decrease in scattered signals after the ELM event in those channels mainly come from the fact that they measure larger wavenumbers.
- Simultaneous operation of all five channels is essential to this observation.

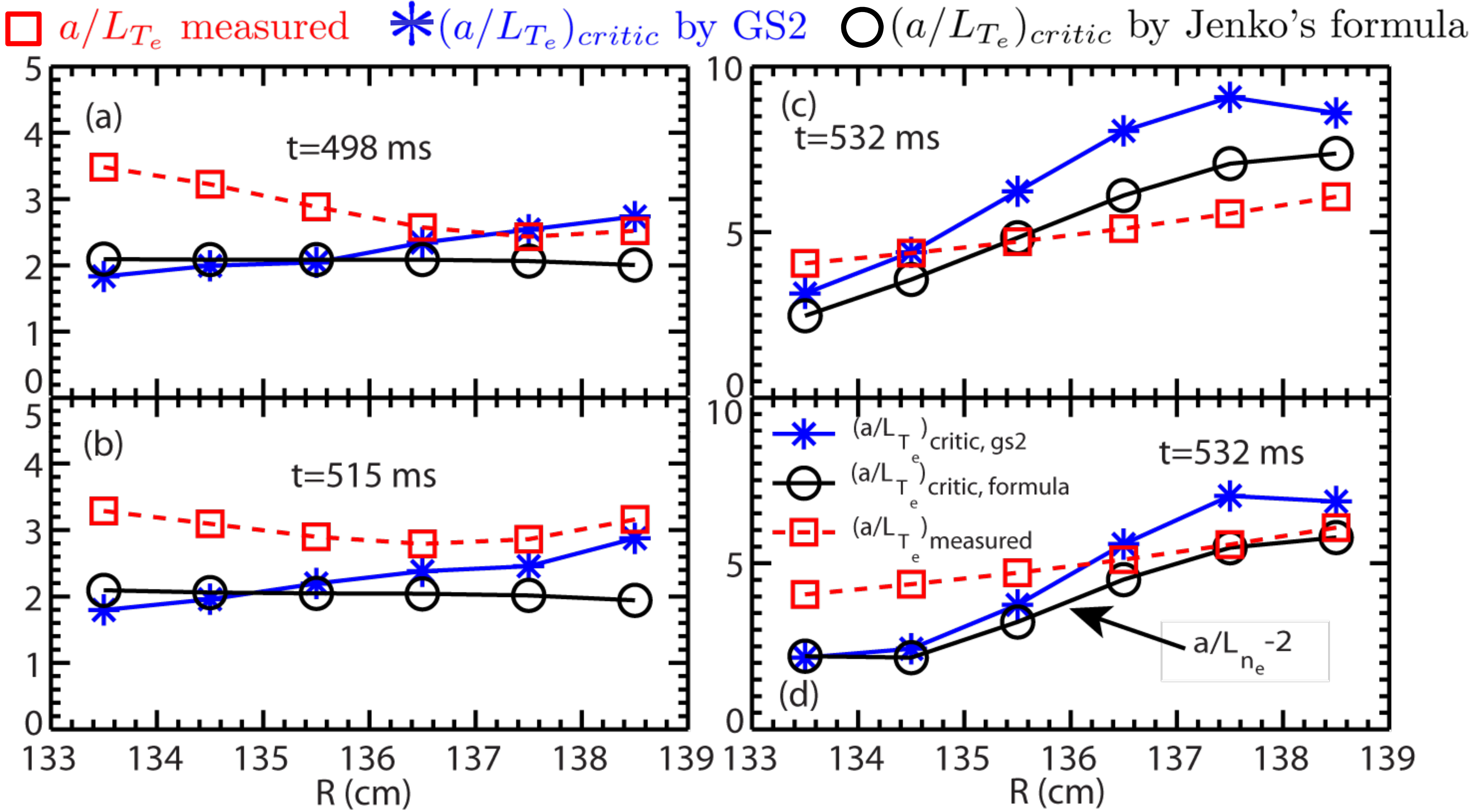


Other Important Equilibrium Quantities Have Small Changes After the ELM Event



- The normalized density gradient (by last closed flux surface minor radius) has a factor of four increase after the ELM event.
- The normalized T_e gradient increases by about 60%.
- The ion temperature has a 40% increase.
- All other quantities have change no more than 25%.

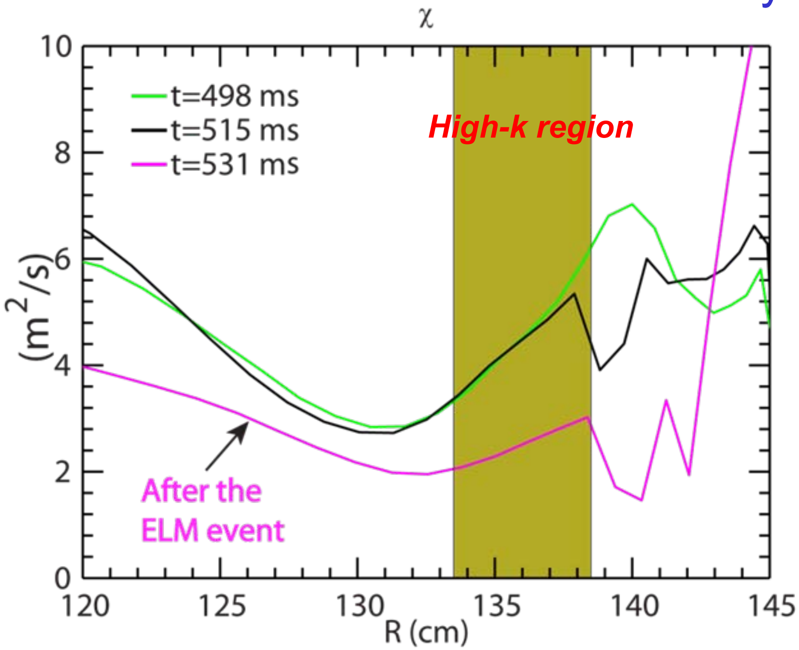
Linear Stability Analysis Showing the Stabilization of ETG Modes After the ELM Event

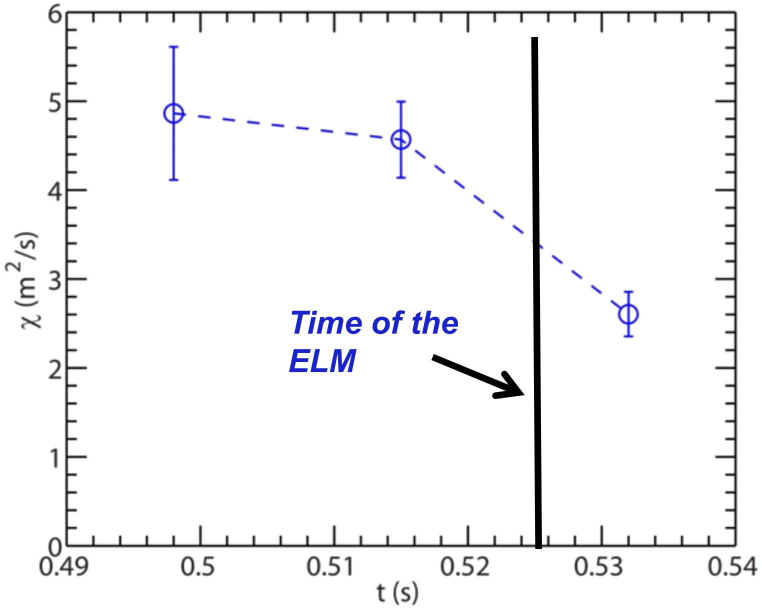


- Before the ELM, ETG is largely unstable.
- Stability Analysis was performed with the GS2 code (Kotschenreuther et al., 1995)
- After the ELM, ETG is largely stable.
- With manually decreased a/L_{n_e}, ETG is largely unstable again.

Plasma Confinement Improved after the ELM Event

- Plasma thermal diffusivity is decreased by about a factor of 2 after the ELM event.
  - Large density and higher ion temperature leads to strong coupling between electron and ions.
  - One-fluid effective thermal diffusivity is ued to show the confinement improvement.

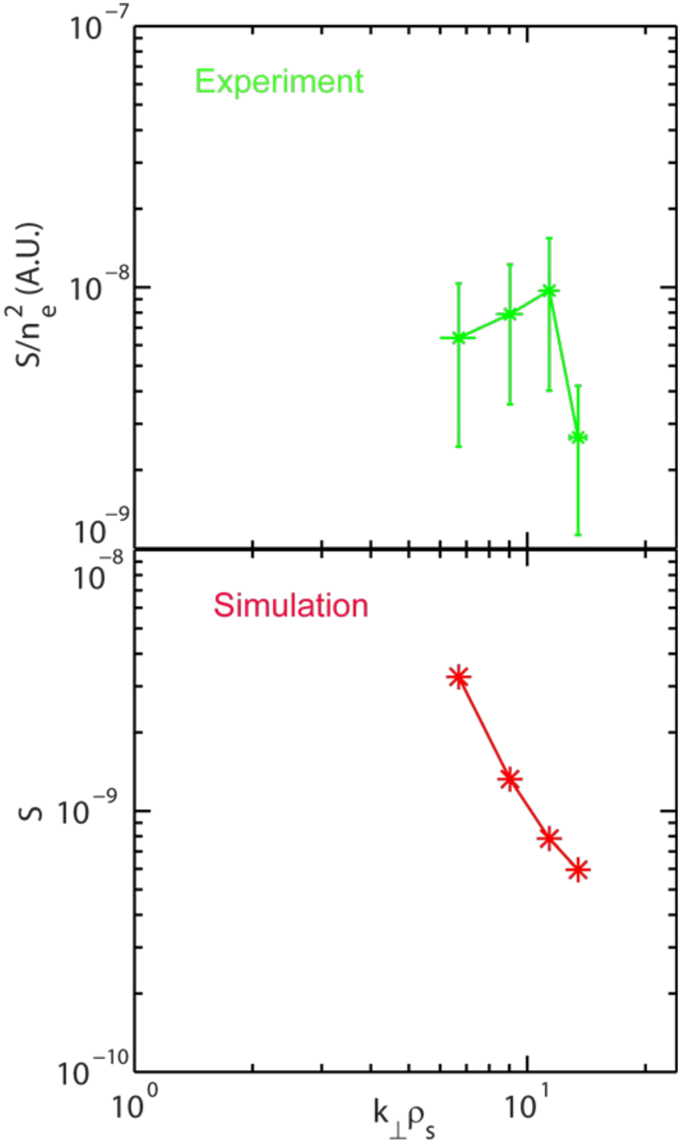




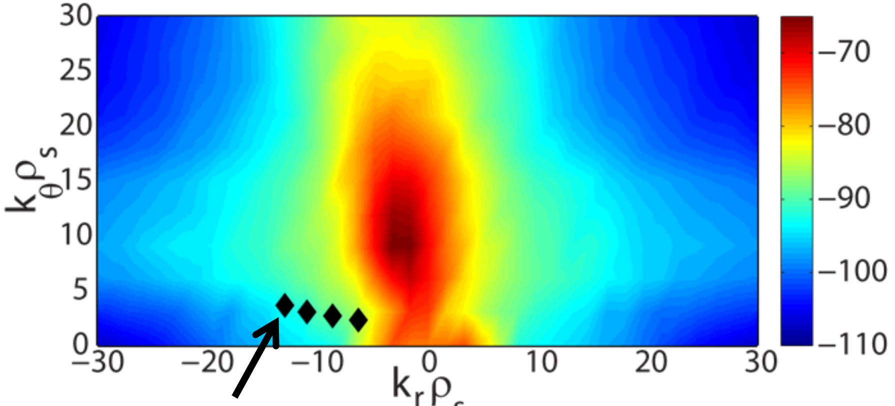
- This increase correlates well with the decrease of the spectral power of the longer wavelength modes.

Comparison with the Non-linear GYRO Simulation of Shot 140620 before the ELM Event

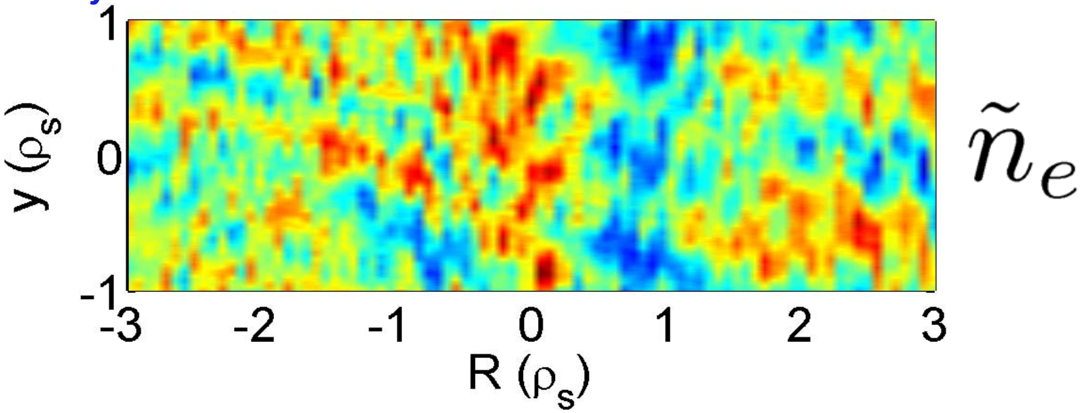
Non-linear GYRO Simulation by W. Guttenfelder



- Direct comparison between the measured spectrum and simulated spectrum shows large difference in spectral shape.
- Synthetic diagnostics is in development to resolve this difference (See F. Poli’s poster).



Four wavenumbers measured by the high-k scattering system



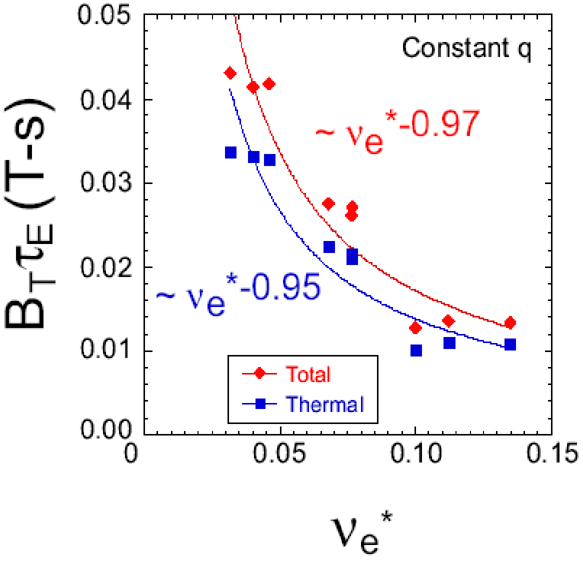
Strong Collisonality Dependence Observed in NSTX Confinement Scaling

- NSTX confinement time scales strongly with collisonality as

$$B_T \tau_E \propto \nu_e^{*-1}$$

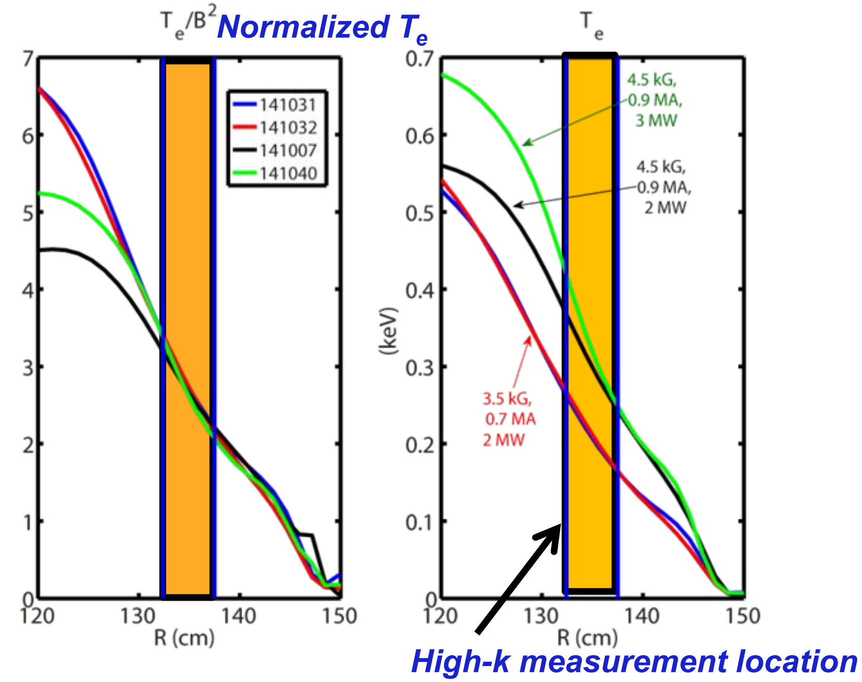
and the mechanism behind this scaling is not understood.

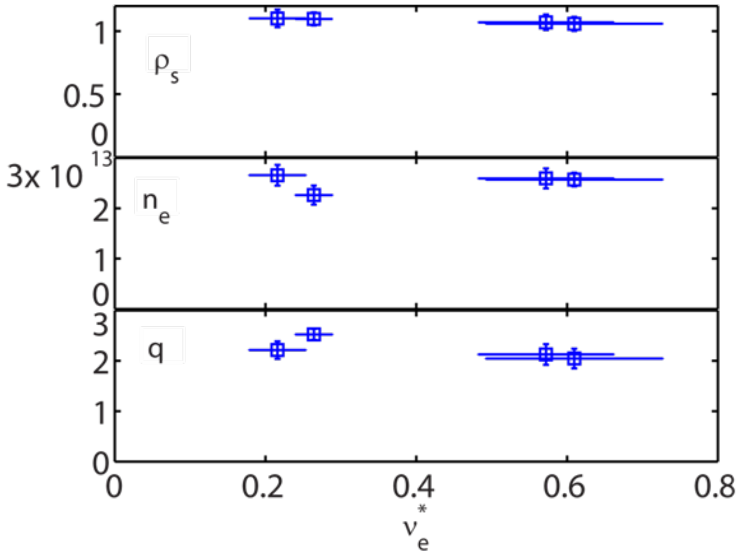
- A study of the high-k turbulence dependence on collisionality is important for understanding this scaling.
- Analytical theory has predicted that collisonal damping of ETG zonal flow can lead to stronger ETG turbulence (streamers) and thus lead to larger electron thermal transport (Kim et al., 2003).



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

A Factor-of-Three Local Collisionality Scan Achieved



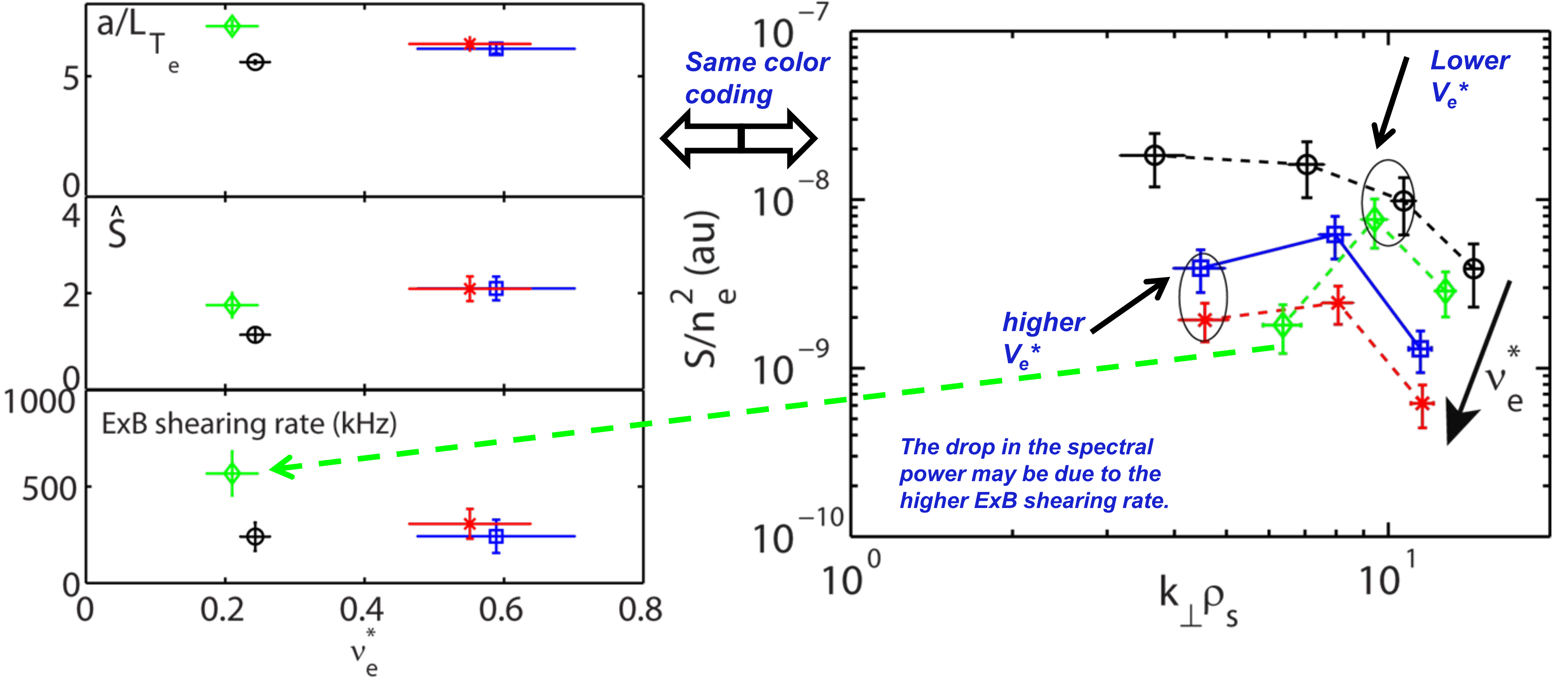


- Time points chosen so that $T_e \propto B^2$ was well maintained from R=130-145 cm: local ν_{e*} was varied with constant ρ_e and β_e .
- I_p and B_T were varied with a constant ratio to keep constant q.
- Neutral beam power was adjusted to have a better match in T_e profile.
- The scan was carried out with (I_p(MA), B_T (kG))=(0.7,3.5), (0.9, 4.5) and (1.1, 5.5).
- (1.1 MA, 5.5 kG) shots have much high density and Z_{eff} and are not used.
- Factor of three change in ν_{e*} is achieved.
- ρ_s , n_e and q have only small variations against ν_{e*}.

High-k Turbulence Power Seems to Increase as v_{e*} Decreases

- T_e gradient variations are up to 30%.
- Variation in magnetic shear is larger, up to 90%.
- Variation in ExB shearing rate can be up to factor of two.

- High-k turbulence power appears to increase as v_{e*} decreases at $k_\perp\rho_s > 9$.
- The same relationship may hold for $k_\perp\rho_s < 9$ if ExB shearing stabilization is taken into account.
- Larger variation in v_{e*} and 2D k spectrum will be important to pin down the relationship



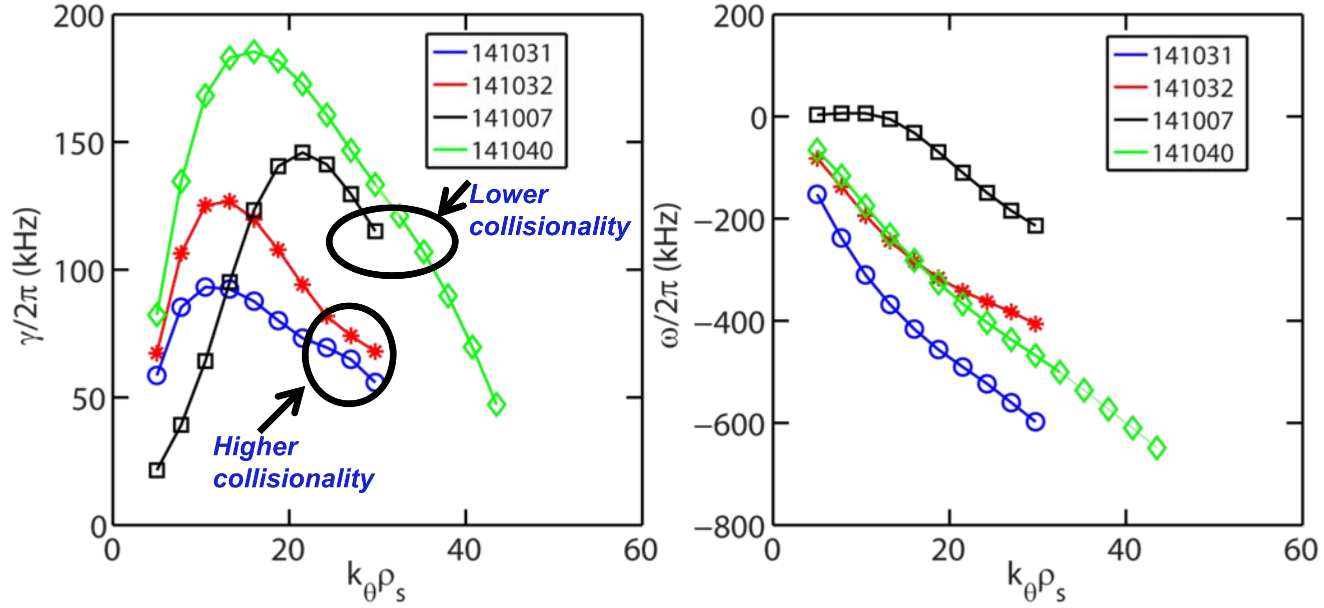
Same color coding

*Lower V_e**

*higher V_e**

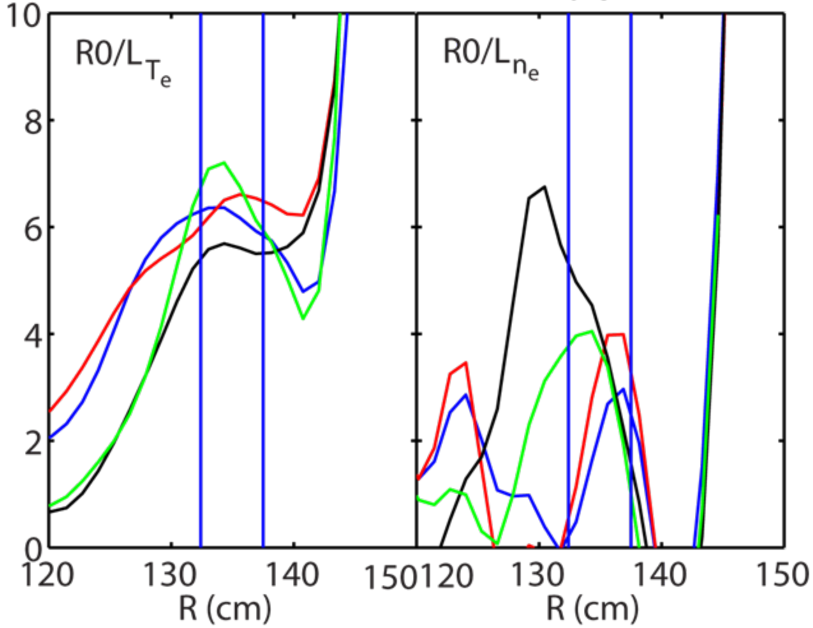
The drop in the spectral power may be due to the higher ExB shearing rate.

ETG Turbulence Linearly Unstable in All These Discharges



Lower collisionality

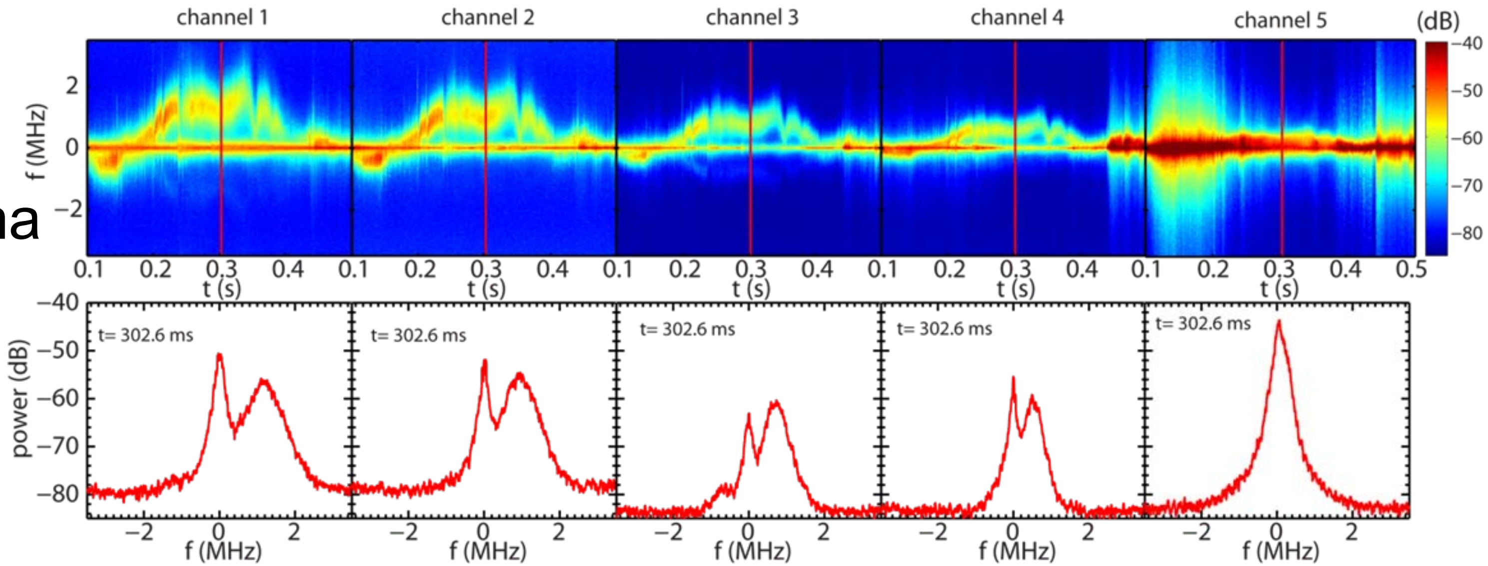
Higher collisionality



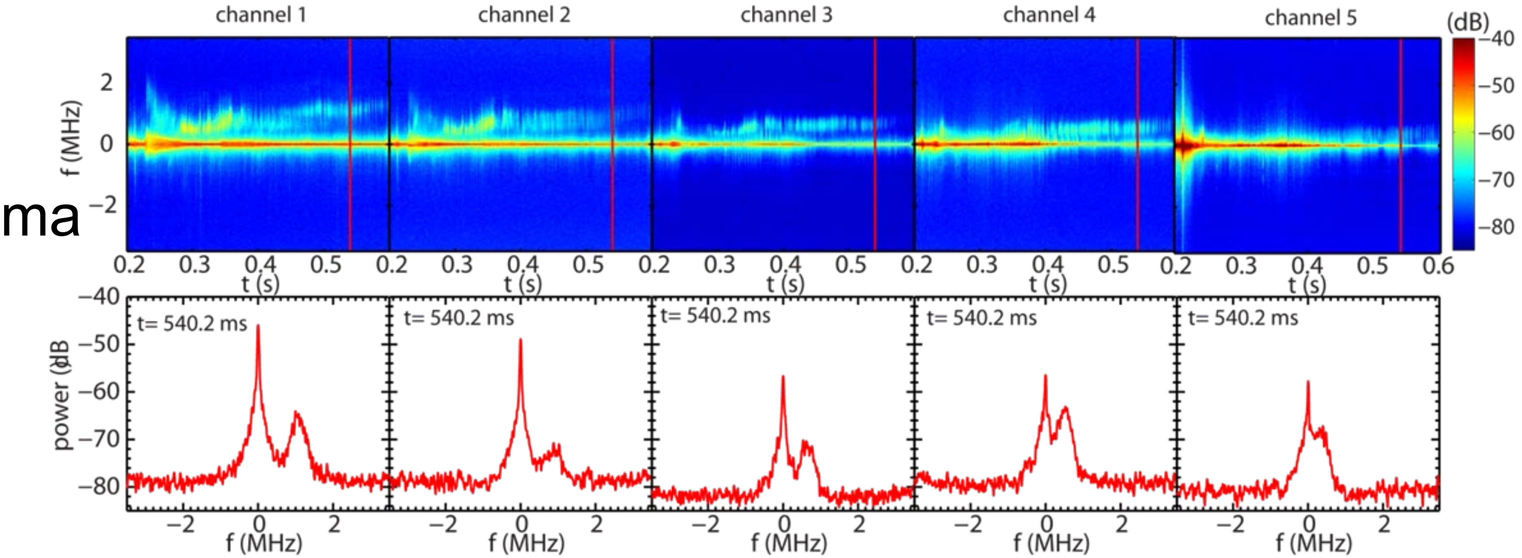
- Comparable R_0/L_{n_e} between these shots.
- Maximum ETG growth rates are higher for the lower collisionality cases, the same trend as wavenumber spectral power.
- Nonlinear simulations will be conducted.

L and H-mode Comparison Showing Difference in Turbulence Evolution

- L-mode plasma

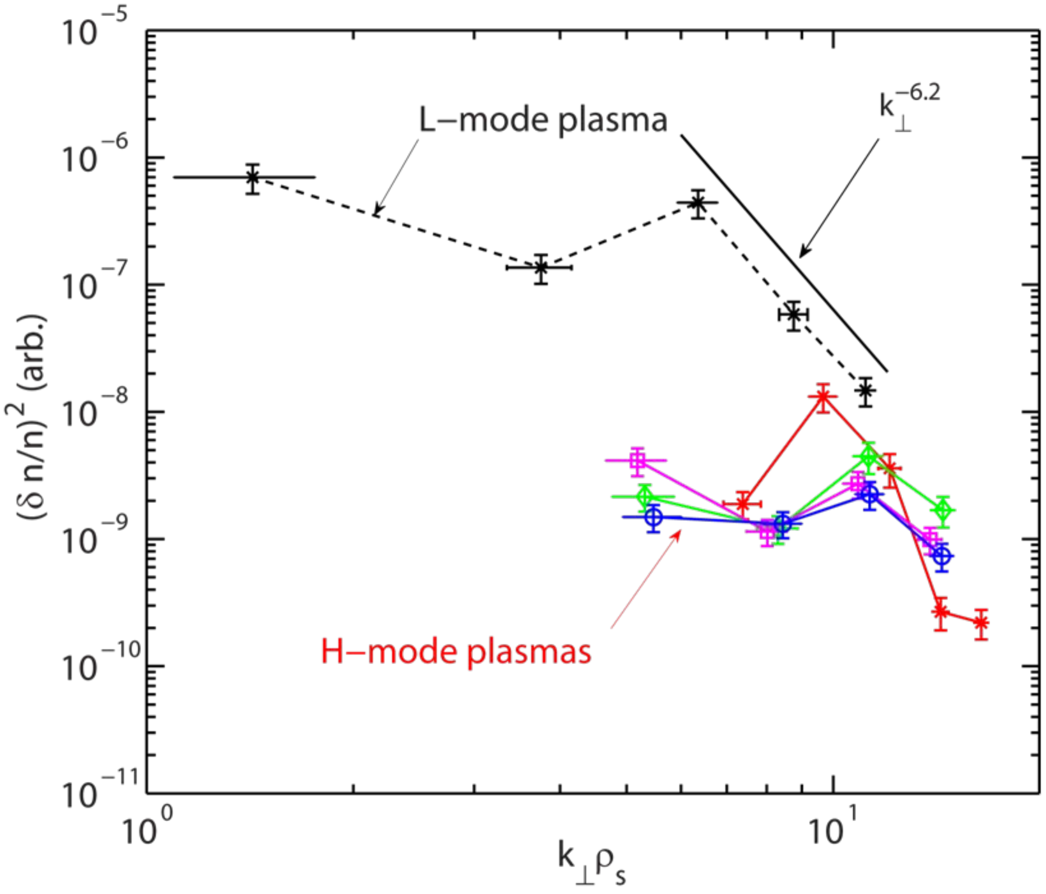


- H-mode plasma



Spectral Power Differences in L and H-Mode Plasmas Implying Lower-k ($k_\perp \rho_s$ <10) Turbulence Is Important in Driving Anomalous Transport

k spectra of normalized density fluctuations in beam-heated L and H-mode plasmas



- Spectral power close to each other at $k_\perp \rho_s$ >10 for L and H-mode plasmas.
- Large differences, more than 2 orders of magnitude, in spectral power found at $k_\perp \rho_s$ <10 between L and H-mode plasmas.
- Consistent with long wavelength turbulence being more important for driving anomalous transport.
- Beam Emission Spectroscopy will give information for $k_\perp \rho_s$ <1.

Summary

- High-k scattering system is now able to operate with all five channels simultaneously.
  - Crucial for examining spectral changes when large change in the wavenumbers measured is expected: density gradient change, long time density built-up.
- Stabilization effect of large density gradient induced by an ELM event and simultaneous confinement improvement have been observed
  - Significantly reduction of high-k fluctuations at smaller $k_\perp$, $k_\perp \rho_s \lesssim 10$, and spectral power at large $k_\perp$, $k_\perp \rho_s \gtrsim 15$, is not affected.
  - Linear stability analysis demonstration of the stabilization effect of large density gradient
- High-k turbulence has collisionality dependence and the measured spectral power decreases as collisonality increases with the same trend as in linear growth rate.
- Comparison of L and H-mode plasmas show significant reduction of fluctuation power at $k_\perp \rho_s < 10$, consistent with the importance of long wavelength fluctuations in driving transport.