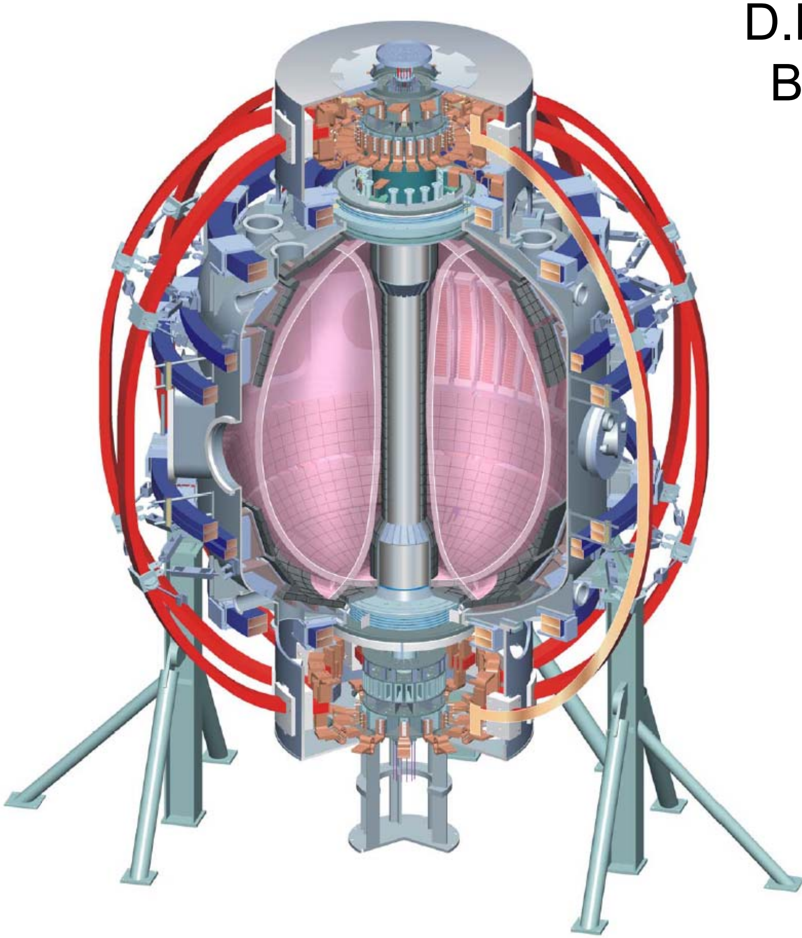
Investigation of electron gyro-scale fluctuations in NSTX plasmas



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Abstract

Electron gyro-scale fluctuations are studied to reveal the existence and nature of **electron temperature gradient (ETG) turbulence** in NSTX plasmas. The role of parameters relevant to ETG turbulence, such as ∇T_e, $\hat{s}$, and T_e/T_i, are highlighted. Fluctuation spectra are obtained using a **multi-channel, collective scattering system** that measures fluctuations with $k_\perp \leq 20\ \mathrm{cm}^{-1}$ and $\mathbf{k_\perp \rho_e \leq 0.6}$. The system measures up to **five distinct wavenumbers** simultaneously, and the k-space resolution is $\delta k_\perp \cong 0.7\ \mathrm{cm}^{-1}$. The probe and receiving beams are positioned nearly on the equatorial midplane and configured for tangential scattering, so measured fluctuations are primarily radial. Steerable optics can position the scattering volume throughout the outer half-plasma from the magnetic axis to the edge. In addition to fluctuation spectra, transport calculations using TRANSP and linear gyrokinetic calculations using GS2 are also presented.

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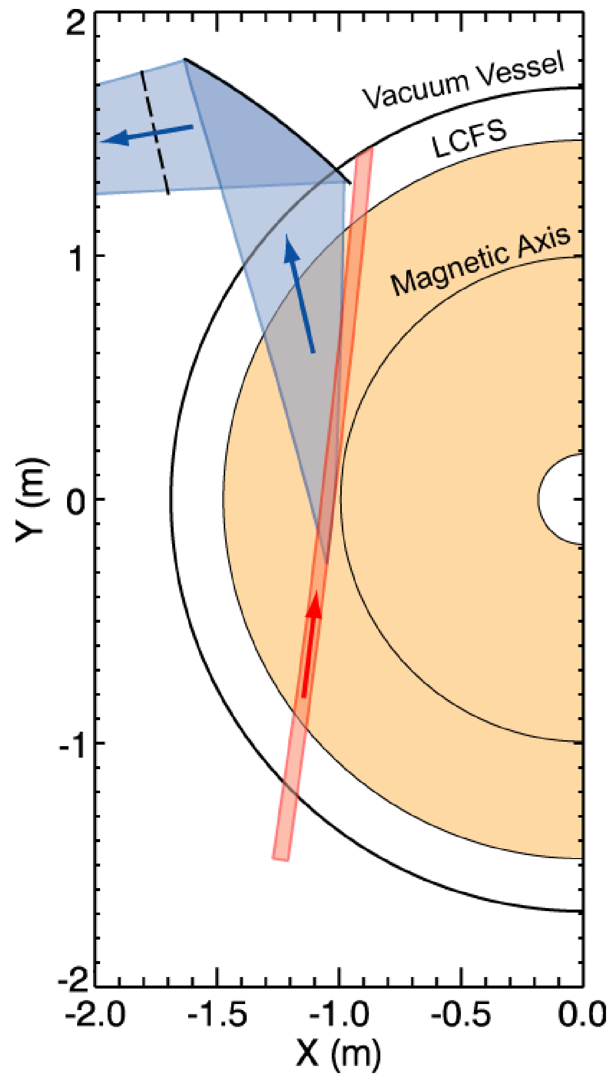
NSTX "high-k" scattering system measures fluctuations up to $k_\perp \rho_e \cong 0.6$

- 280 GHz (λ=1 mm) scattering system
- Instrumental minimum detectable fluctuation is $\tilde{n}_e/n_e \sim 10^{-5}$
- 5 detection channels
  - $k_\perp$ spectrum with up to 5 discrete $k_\perp$
  - ω spectrum from time domain sampling
- Probe and receiving beams positioned nearly on equatorial midplane
  - System sensitive to radial fluctuations
- Steerable optics
  - Scattering volume can be positioned throughout the outboard minor radius
- First data during FY06 run campaign



Electromagnetic waves scatter off density fluctuations

- Wavenumber and frequency matching conditions

$$\vec{k}_s = \vec{k}_i + \vec{k} \quad \text{and} \quad \omega_s = \omega_i + \omega$$

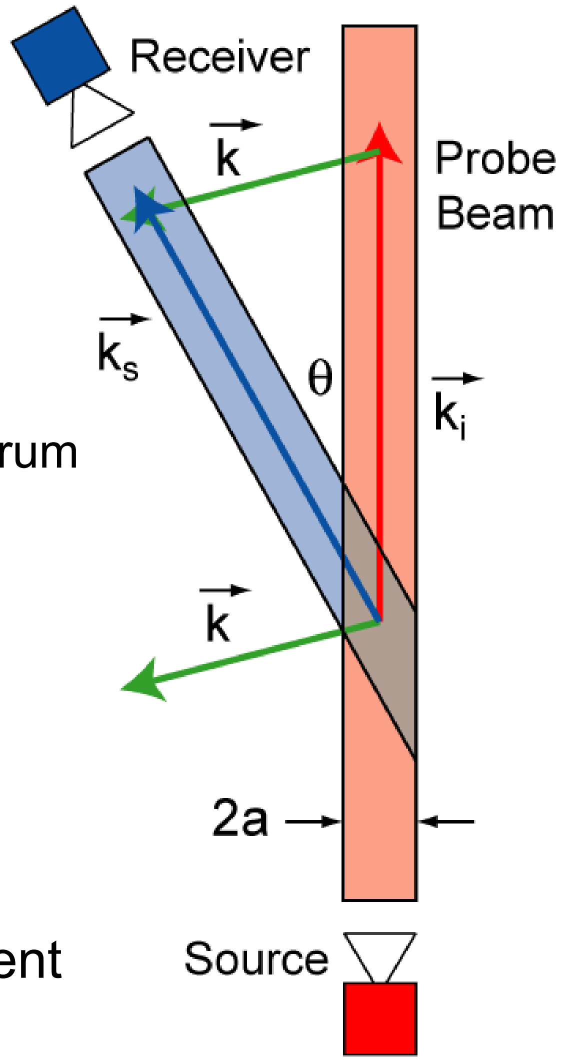
- Bragg condition
  - high frequency probe beam: $\omega_i >> \omega \rightarrow k_i = k_s$
  - need multiple detection channels to construct k-spectrum

$$k = 2k_i \sin(\theta / 2)$$

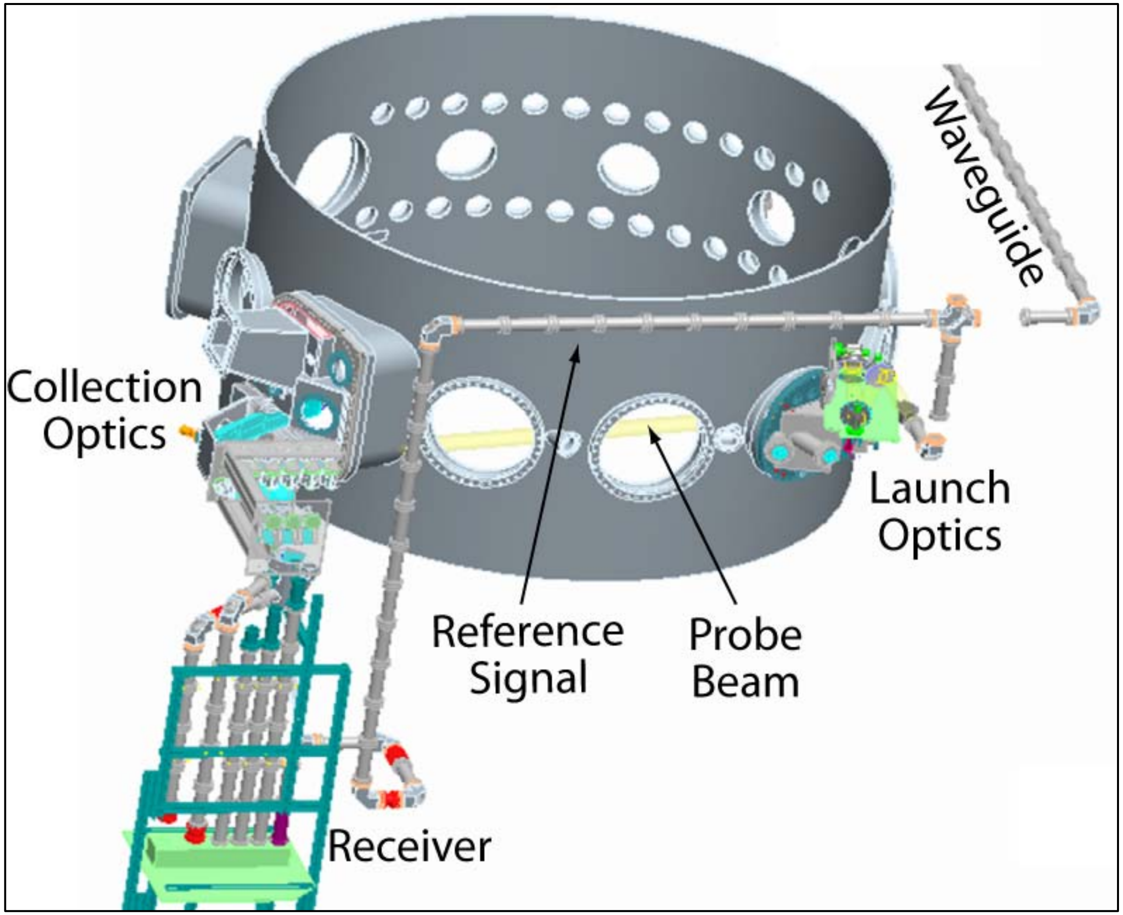
- k-space resolution is set by the beam size
  - trade-off between spatial and k-space resolution

$$\Delta k_\perp = 2 / a$$

- Scattering volume → spatially localized measurement



Scattering system layout

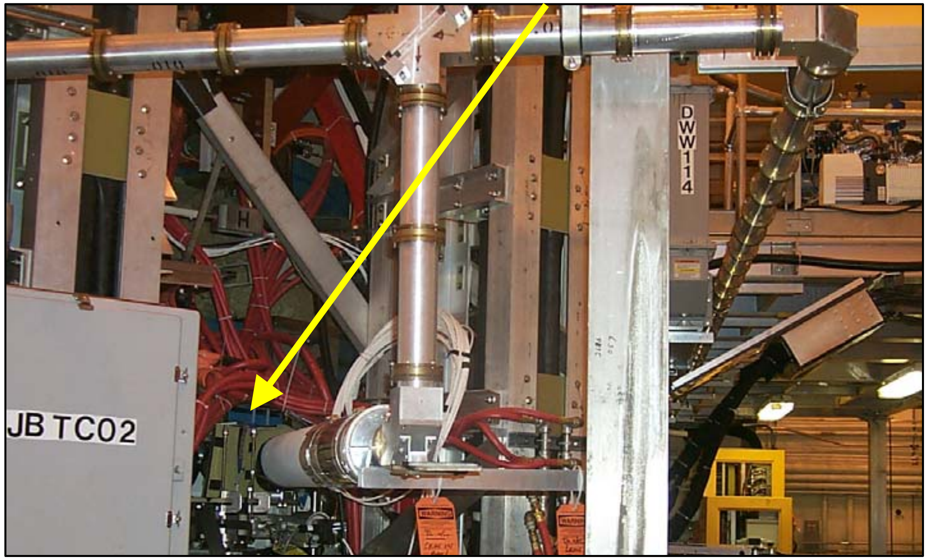


- BWO source
  - outside test cell
  - ~100 mW at 280 GHz
- Overmoded, corrugated waveguide
  - low-loss transmission
- Steerable optics
  - quasi-optical design
- Heterodyne receiver
  - 5 channels
  - reference signal extracted from main beam

Scattering system pictures

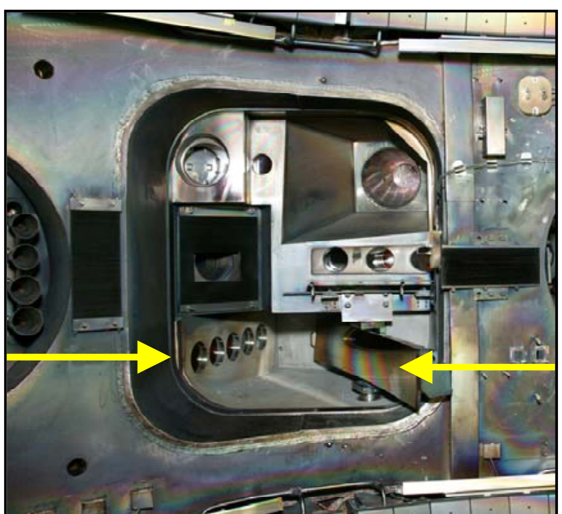
NSTX

waveguide and launch optics



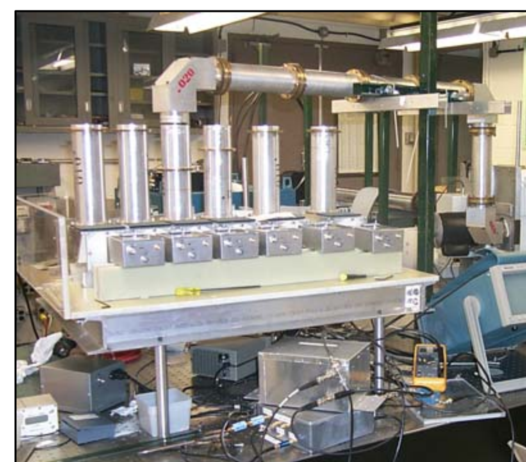
collection
optics

exit
windows

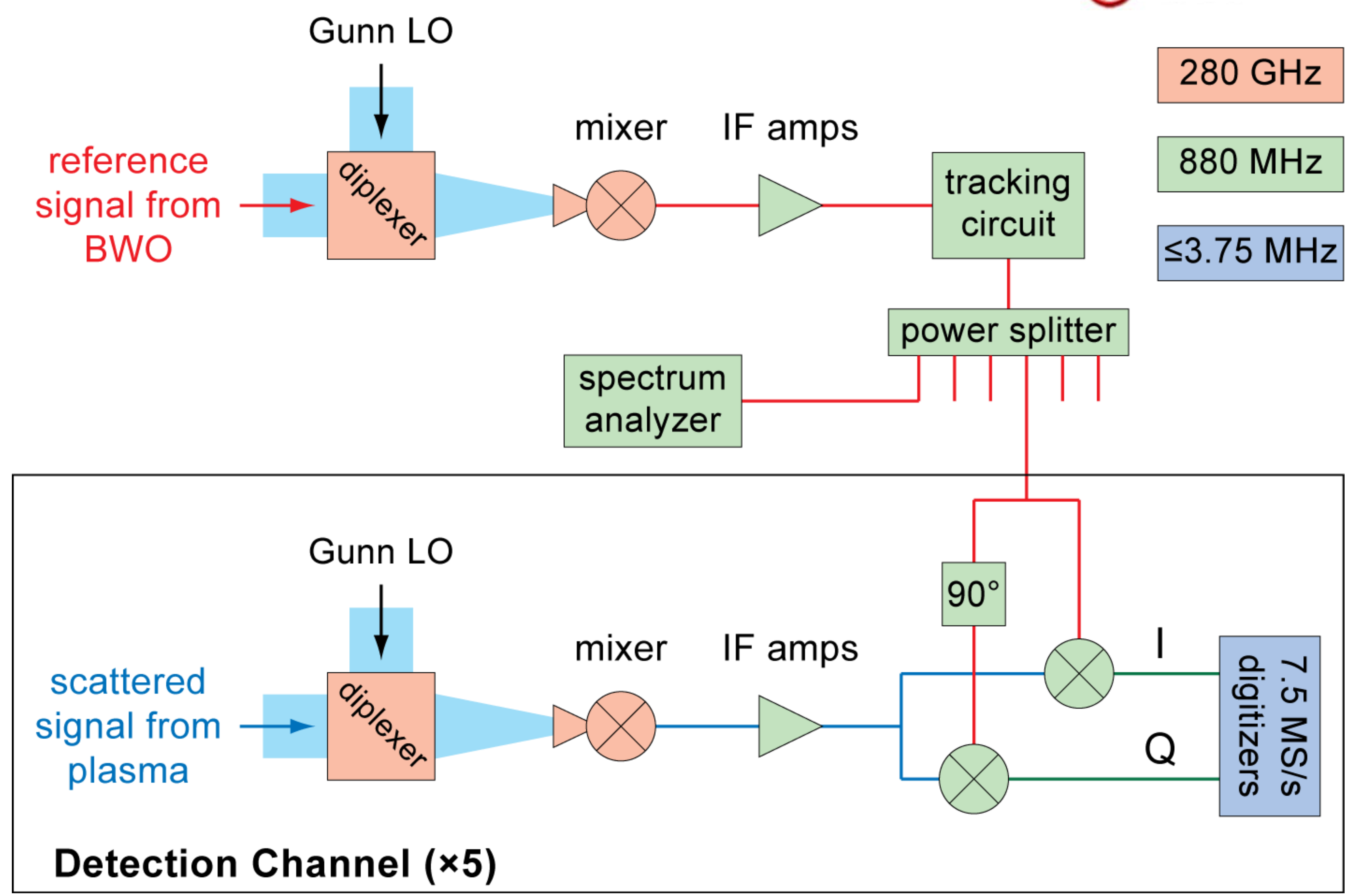


collection
mirror

heterodyne
receiver



Heterodyne receiver



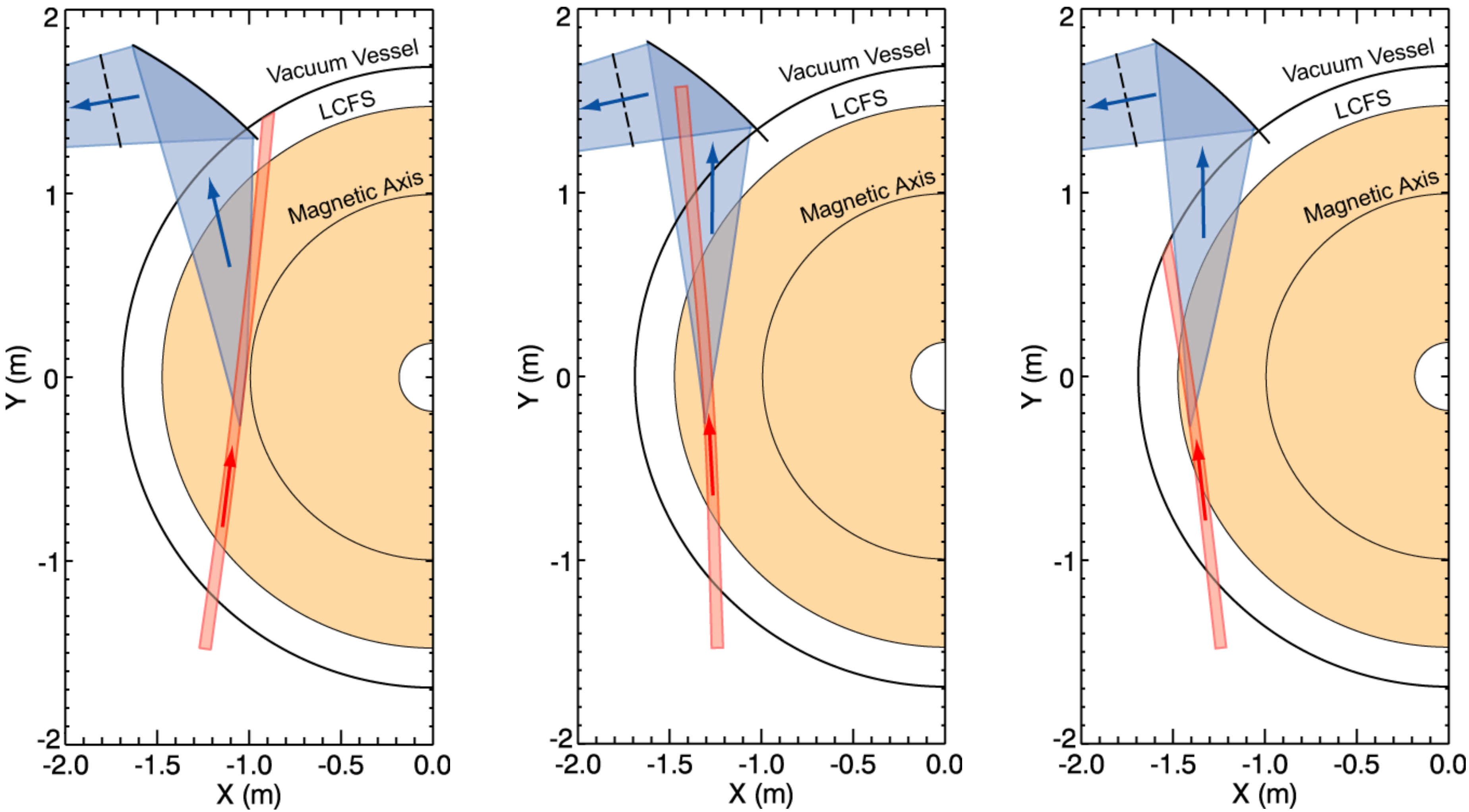
Steerable optics enable good radial coverage

NSTX

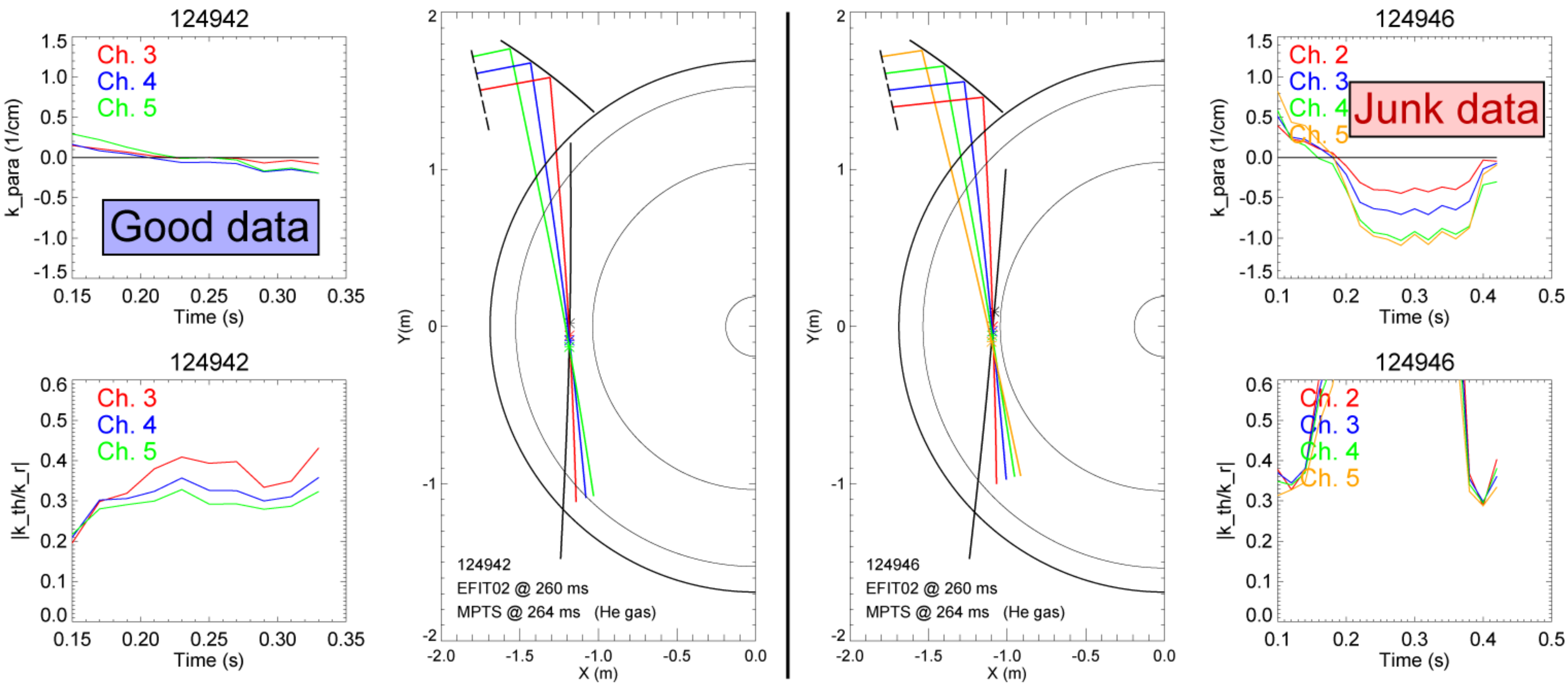
Inboard r/a = 0.05
$k_\perp \rho_e$ up to 0.7

Intermediate r/a = 0.4
$k_\perp \rho_e$ up to 0.3

Outboard r/a = 0.75
$k_\perp \rho_e$ up to 0.2



Ray tracing calculations needed to ensure k-space alignment & to interpret measurements



$k_{||}$ distinguishes good data from junk data because plasma turbulence satisfies **k•B**=0. k_θ/k_r is needed when comparing to nonlinear GK simulations.

ETG critical gradient, based upon linear GS2 simulations, predicts onset of fluctuations

From Jenko et al., PoP 8, 4096 (2001):

$$\left(\frac{R}{L_{Te}}\right)_{crit} = \mathrm{Max}\left\{\left(1+\frac{Z_{eff}T_e}{T_i}\right)\left(1.33+1.91\frac{\hat{s}}{q}\right)(1-1.5\varepsilon)\left(1+0.3\varepsilon\frac{d\kappa}{d\varepsilon}\right),\ 0.8\frac{R}{L_{ne}}\right\}$$

Range of validity: q=0.5-4.0, ŝ=0.2-3.0, R/L_{ne}=0-10, ε=0.1-0.3, κ=1.0-2.0

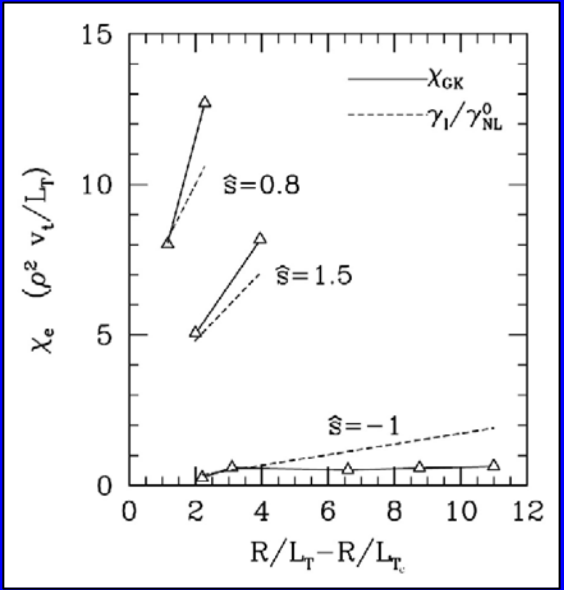
Linear GK simulations

Nonlinear GK simulations

From Jenko et al., PRL 89, 225001 (2002):

"However, for negative shear, ŝ=-1, the transport level drops down to the mixing length level and streamers are not observed."

Jenko's Figure 2 at right.



Key questions and answers

Question: Do turbulence-like **electron gyro-scale fluctuations** exist in NSTX plasmas?

Answer: **Yes.**

Question: Do electron gyro-scale fluctuations in NSTX plasmas exhibit **ETG turbulence** characteristics?

Answer: **Yes.**

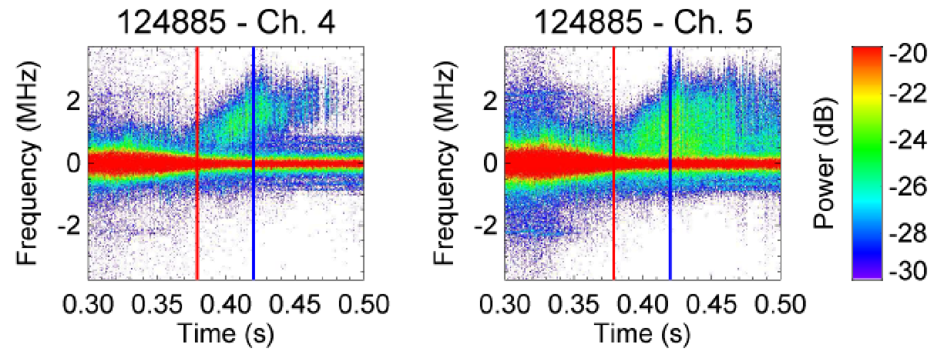
Question: Can high-k turbulence impact **electron thermal transport** in NSTX plasmas?

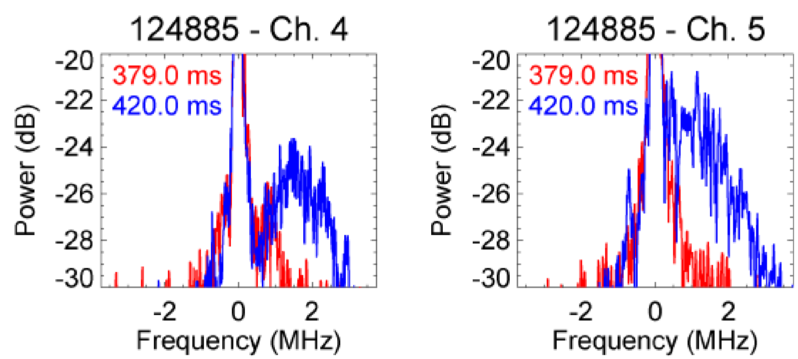
Answer: **Yes.**

Case 1: R/L_{Te} and neutron emission fall when core fluctuations saturate

- 124885: 4 MW NBI, 0.7 MA, 5.5 kG, D fuel
- High-k measurements at R ≅ 113 cm, r/a ≅ 0.25

@ 400 ms	$k_\perp \rho_e$	$k_\perp \rho_s$	k_θ / k_r
Ch. 4	0.28	17.1	0.37
Ch. 5	0.36	21.8	0.34

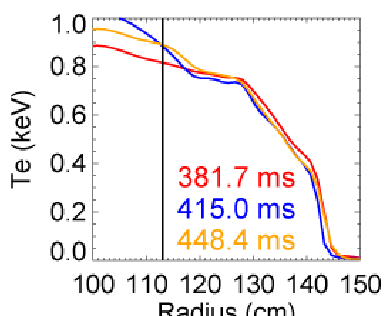


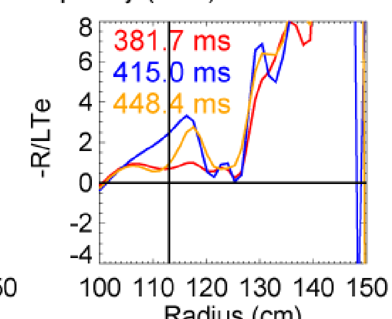


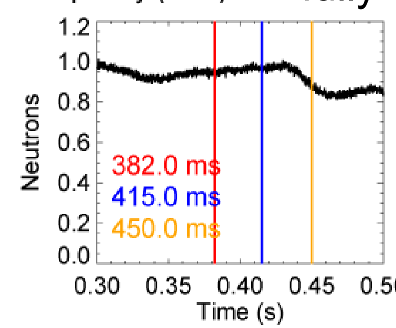
neutrons fall when turb. is fully developed

only core Te and R/L_{Te} change

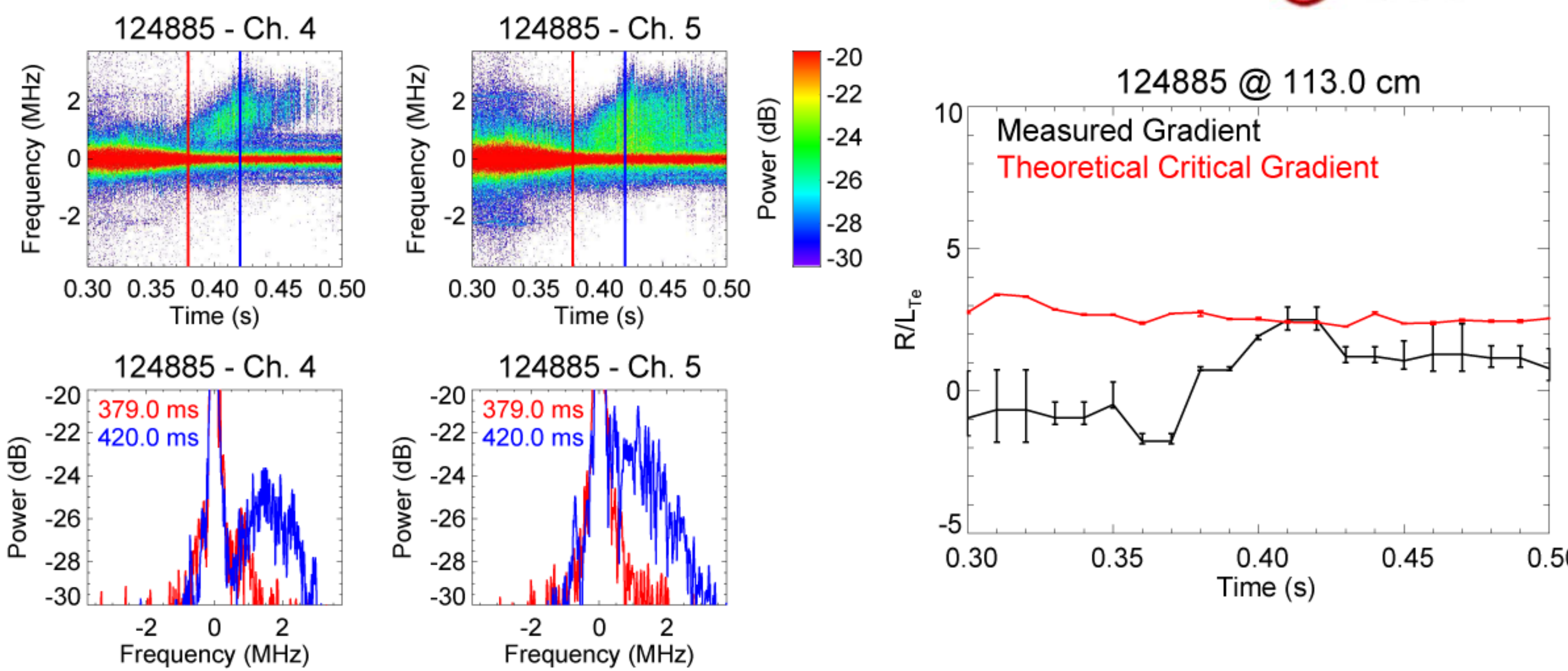
R/L_{Te} rises with fluctuations and falls with neutrons







Case 1: Core fluctuations appear as R/L_{Te} approaches critical value



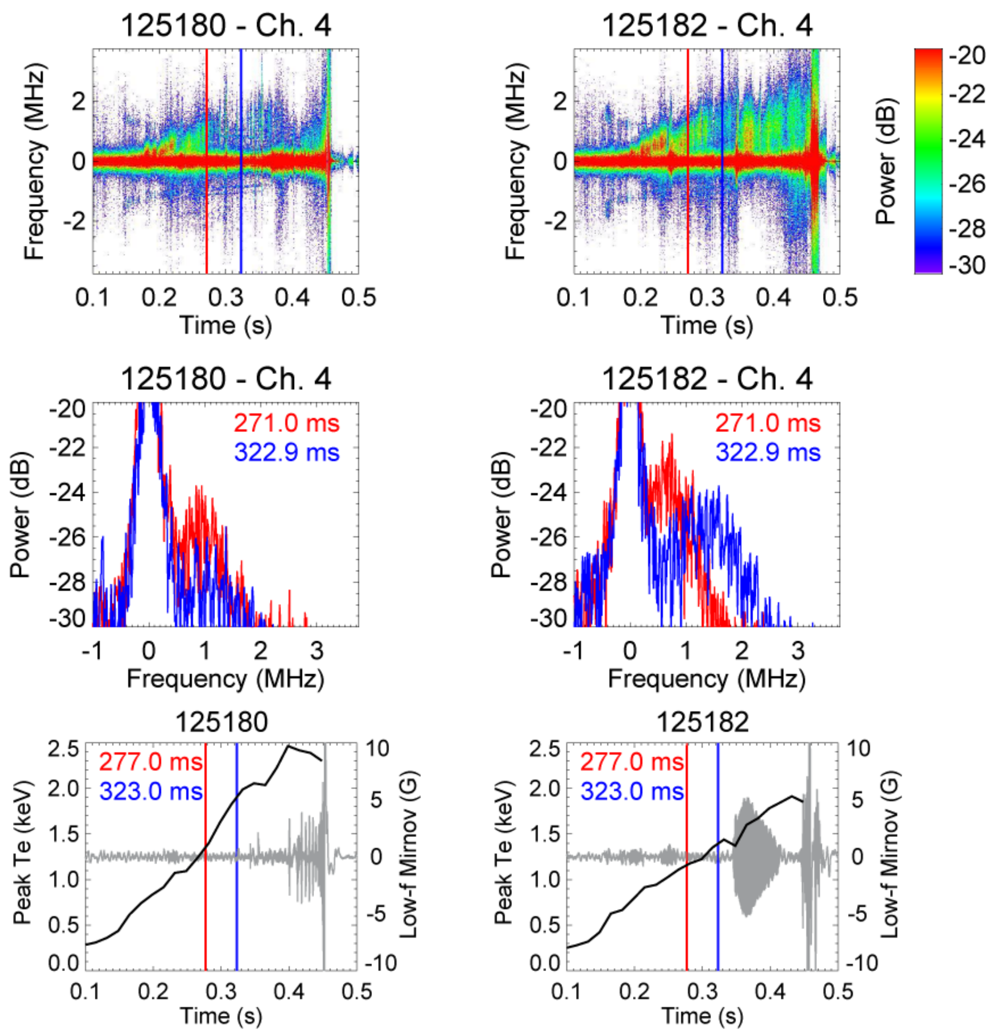
Fluctuations grow before R/L_{Te} reaches the critical value.

Note: The magnetic shear at the measurement location, $\hat{s}$ = 0.05, is not within the validity range for the critical gradient formula.

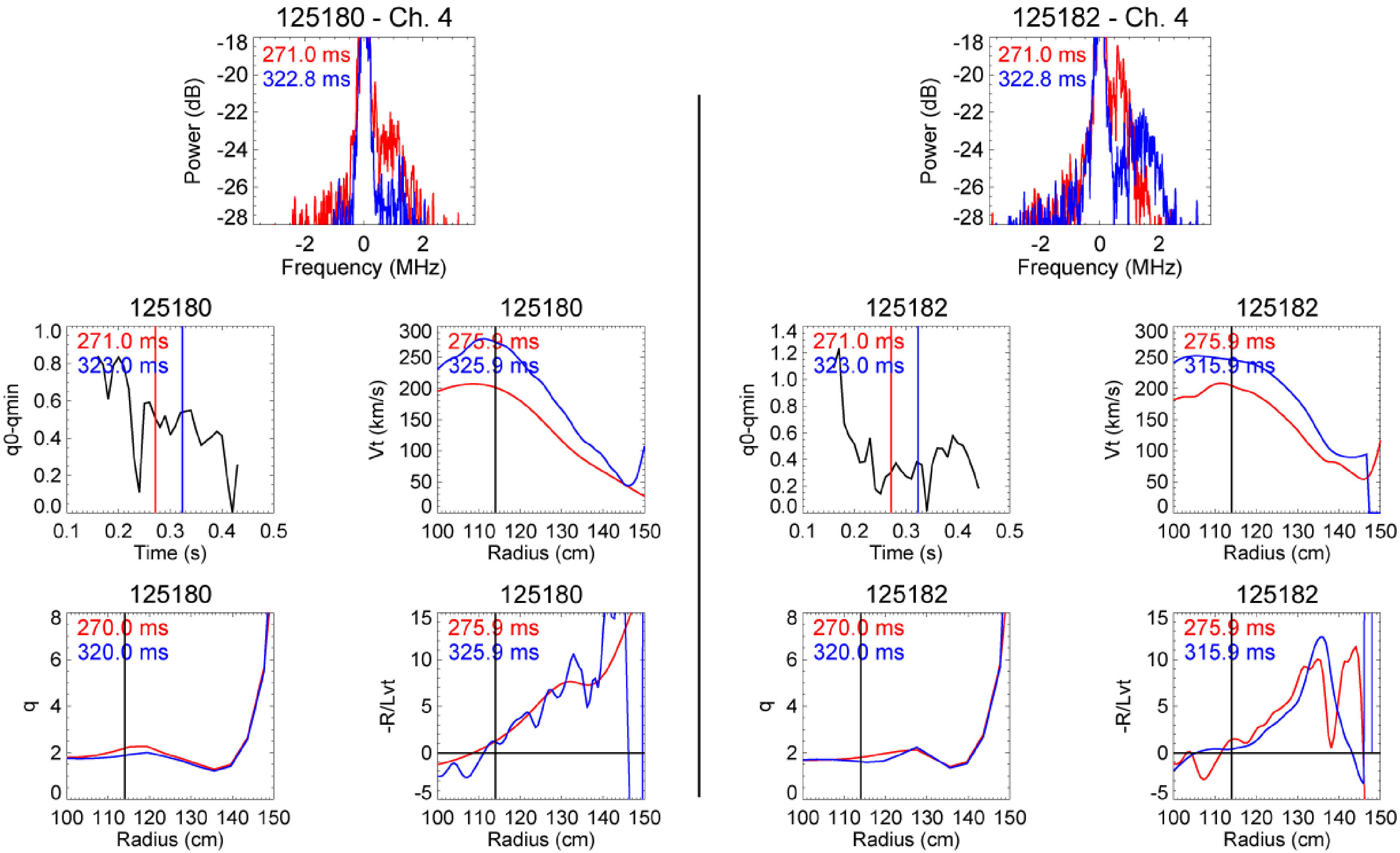
Case 2: Higher Te achieved when core fluctuations are reduced in similar discharges

- 125180 & 125182:
  2 MW NBI, 1 MA,
  5.5 kG, He fuel
- High-k measurements at R ≅ 115 cm, r/a ≅ 0.25
- At 300 ms, $k_\perp \rho_e \cong 0.33$, $k_\perp \rho_s \cong 14.2$, $k_\theta/k_r \cong 0.5$

- 125180 exhibits lower core fluctuations and more aggressive Te rise than 125182.



Case 2: Only slight difference in magnetic and rotational shear observed

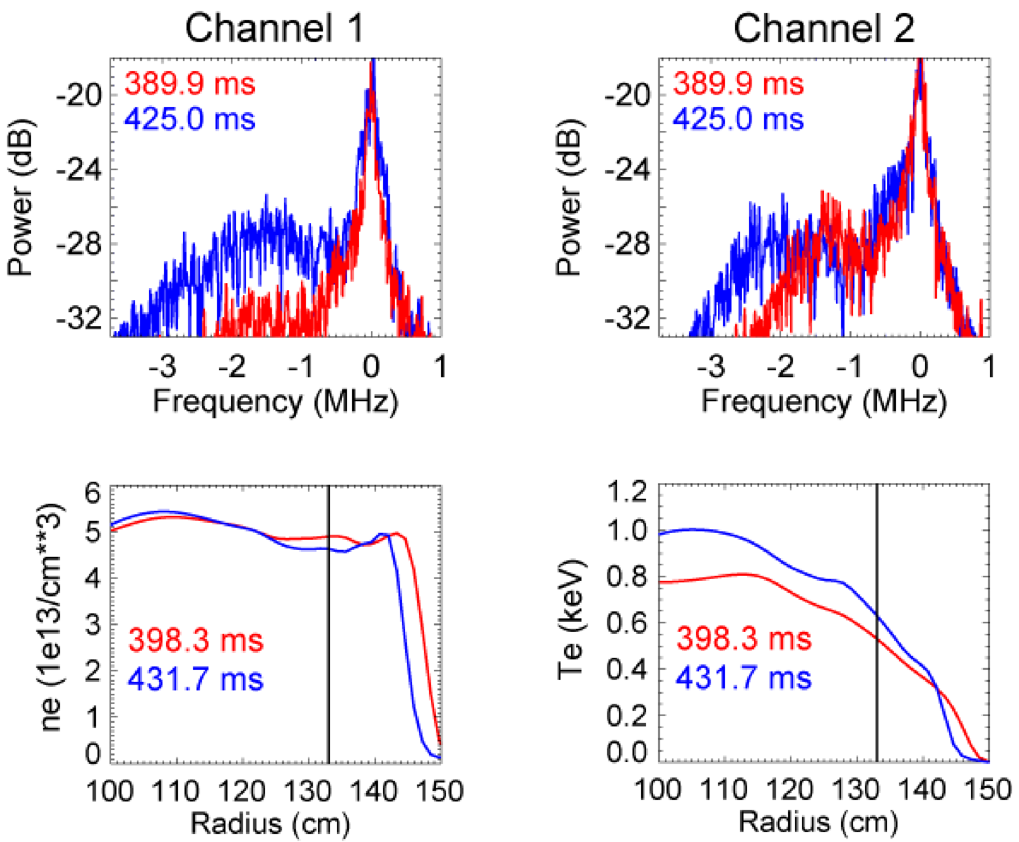


Case 3: Fluctuations increase in confinement region at higher B_T

- 124888 & 124889:
  4 MW NBI, 0.7 MA, D fuel
- High-k measurements at
  R ≅ 133 cm, r/a ≅ 0.68

400/420 ms	$k_\perp \rho_e$	$k_\perp \rho_s$	k_θ / k_r
Ch. 1	0.34	20.7	0.21
Ch. 2	0.25	15.3	0.21
Ch. 1	0.30	18.3	0.23
Ch. 2	0.22	13.5	0.22

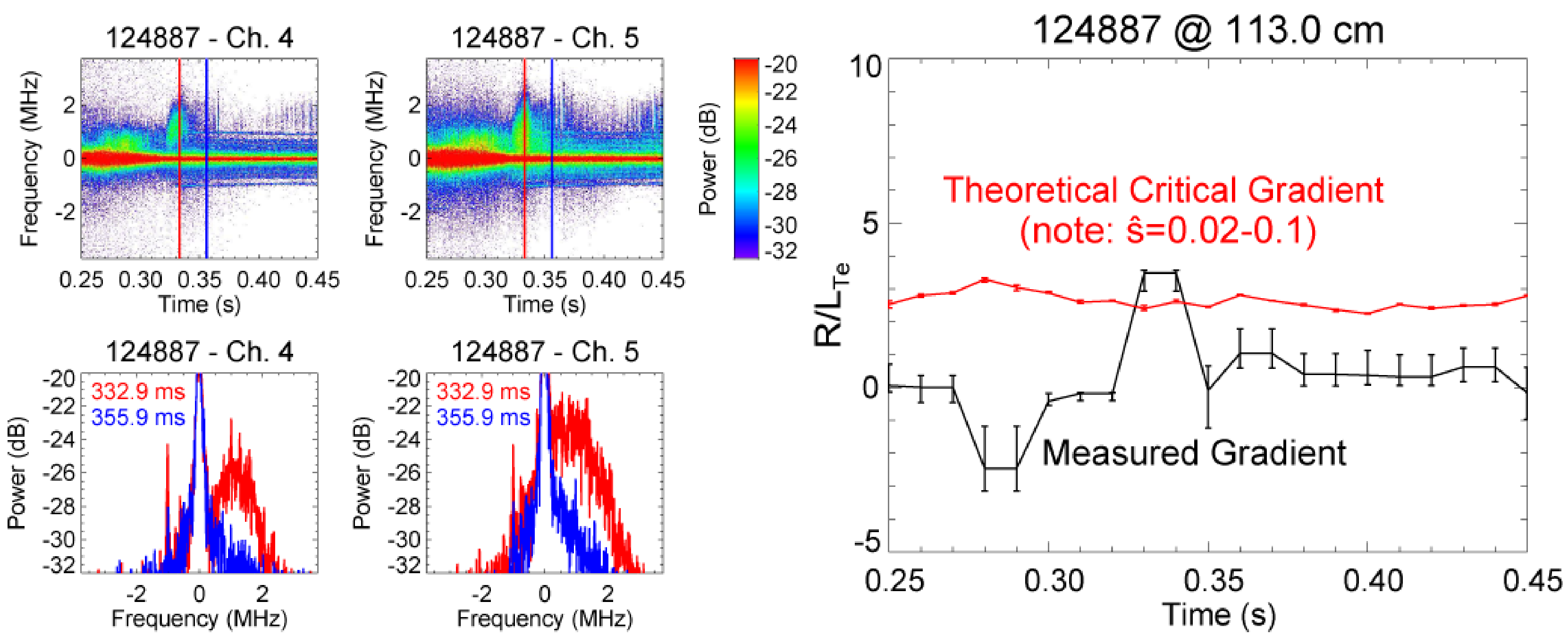
124888 - 4.5 kG
124889 - 5.5 kG



Case 4: Appearance of core fluctuations coincides with R/L_{Te} exceeding critical value

- 124887: 4 MW NBI, 0.7 MA, 4.5 kG, D fuel
- High-k measurements at $R \cong 113$ cm, $r/a \cong 0.25$

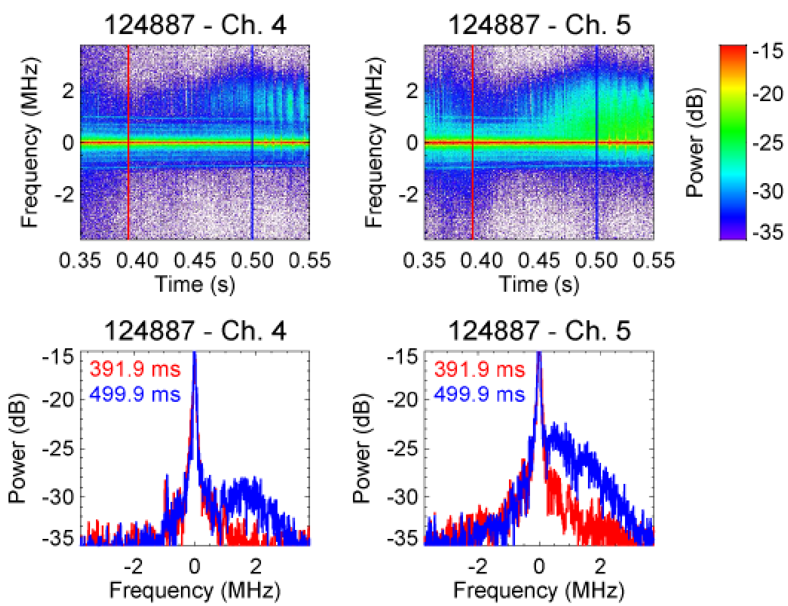
@ 300 ms	$k_\perp \rho_e$	$k_\perp \rho_s$	k_θ / k_r
Ch. 4	0.30	18.3	0.37
Ch. 5	0.39	23.4	0.34

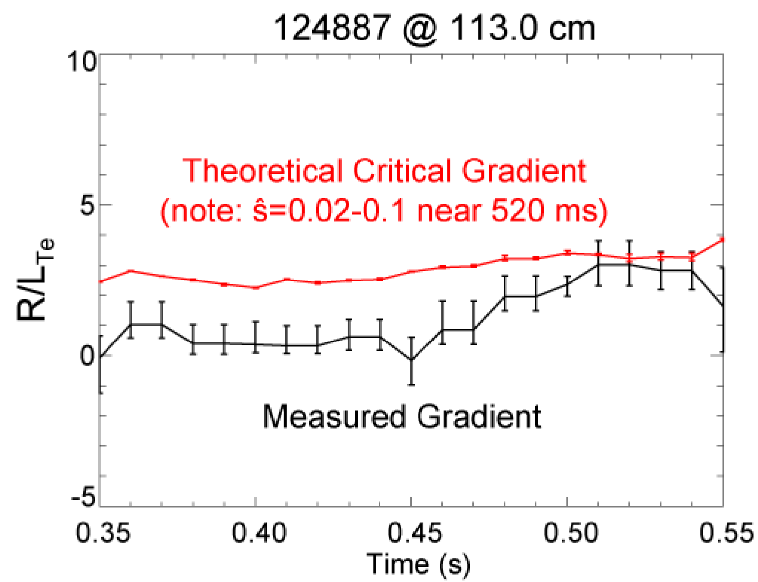


Case 5: Core fluctuations grow as R/L_{Te} approaches critical value

- 124887: 4 MW NBI, 0.7 MA, 4.5 kG, D fuel
- High-k measurements at $R \cong 113$ cm, $r/a \cong 0.25$

@ 420 ms	$k_\perp \rho_e$	$k_\perp \rho_s$	k_θ / k_r
Ch. 4	0.28	16.7	0.55
Ch. 5	0.37	22.2	0.49



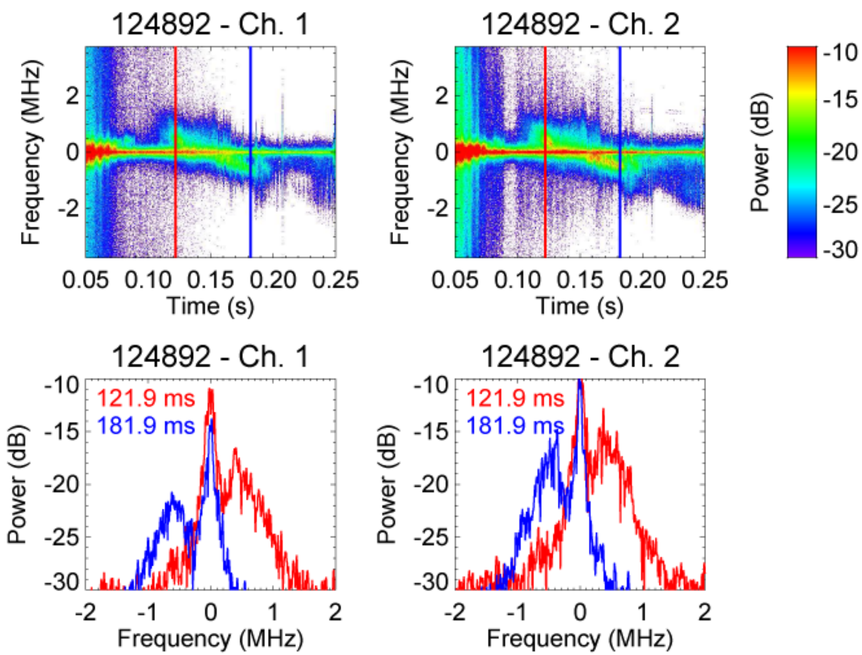


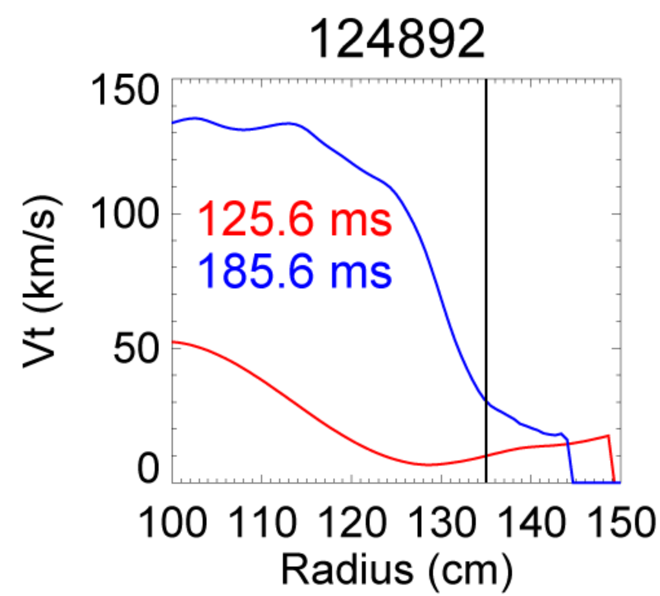
Fluctuations grow before reaching critical gradient.

Case 6: Turbulence exhibits Doppler shift as plasma spins up due to NBI

- 124892: 4 MW NBI, 0.7 MA, 3.5 kG, D fuel
- High-k measurements at R ≅ 135 cm, r/a ≅ 0.68

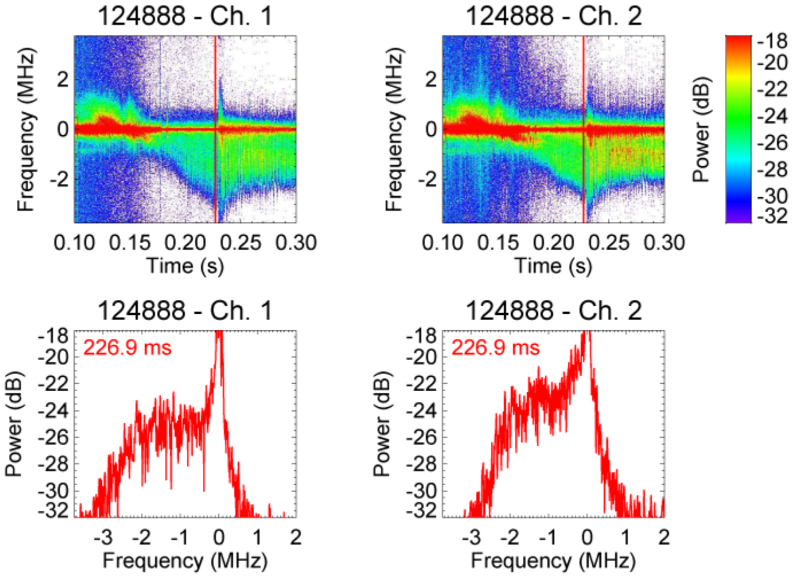
@ 160 ms	$k_\perp\rho_e$	$k_\perp\rho_s$	k_θ/k_r	$k_T(cm^{-1})$
Ch. 1	0.32	19.4	0.26	1.24
Ch. 2	0.21	12.9	0.29	0.96



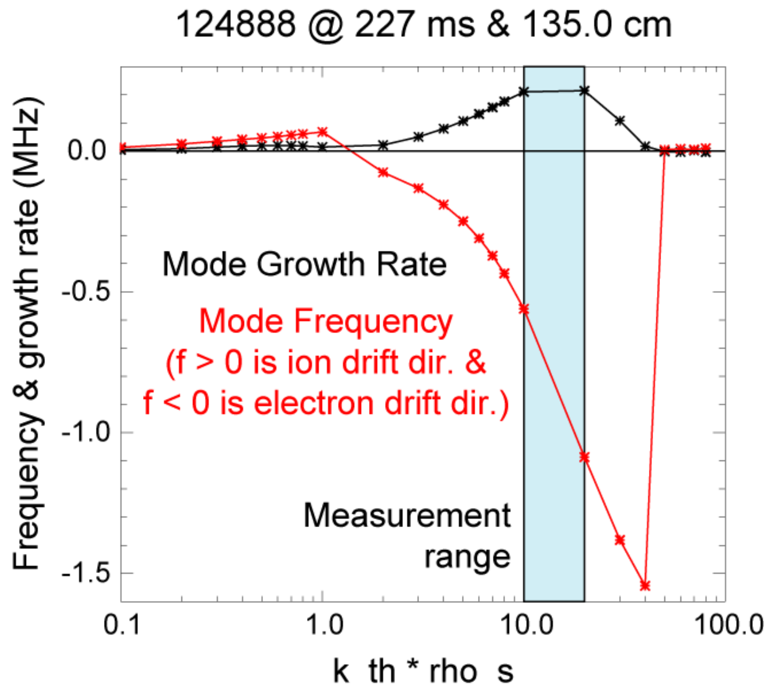


Fluctuations propagating in the electron drift direction (f>0)
Doppler shift to the ion drift direction (f<0).

Case 6: Mode frequency, Doppler shift, & observed frequency are qualitatively consistent



f > 0 is electron drift direction and
f < 0 is ion drift direction



@220 ms	$k_\perp\rho_e$	$k_\perp\rho_s$	k_T (cm^{-1})	v_T (km/s)	$f_{dop}=k_T v_T/2\pi$ (MHz)	f_{ETG} (MHz)	$f=f_{dop}+f_{ETG}$ (MHz)
Ch. 1	0.29	17.7	1.25	77.4	1.54	-1.1	0.44
Ch. 2	0.19	11.7	0.96	76.6	1.17	-0.6	0.57

ETG fluct. shift to ion drift direction

Summary

- The NSTX "high-k" scattering system measures electron gyro-scale fluctuations at multiple wavenumbers; scattering volume can be positioned throughout r/a ~ 0.1– 0.9
- Electron gyro-scale fluctuations in NSTX plasmas exhibit ETG turbulence characteristics and appear to impact electron thermal transport
- ETG-like fluctuations observed in both core region (r/a~0.25) and confinement region (r/a~0.7)
- Fluctuations can appear when the measured gradient is below the critical gradient
- Fluctuations in the confinement region increase with higher B_T (preliminary)