

Electron gyro-scale fluctuations in NSTX plasmas

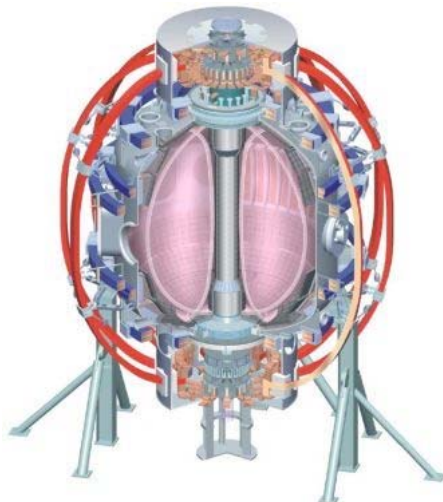
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C. W. Domier³, N. C. Luhmann, Jr.³,
and the NSTX Research Team*

¹PPPL, ²POSTECH, ³UC-Davis

**Plasma Physics Seminar
UW-Madison
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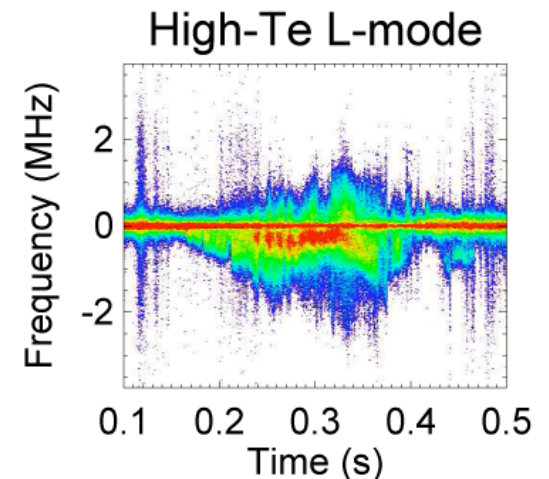
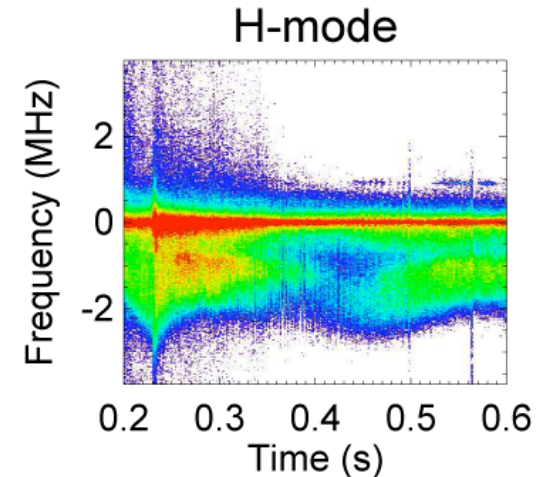


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Outline

- Turbulence and transport in NSTX
- The NSTX collective scattering system
- Analysis tools
 - Ray tracing calculations
 - Linear gyrokinetic calculations
- Fluctuation measurements and analysis
 - Enhanced fluctuations and the ETG critical gradient
 - Reduced fluctuations, ETG growth rates, and $E \times B$ flow shear
 - Fluctuations and transport
 - Fluctuation magnitudes and k-spectra
- Summary

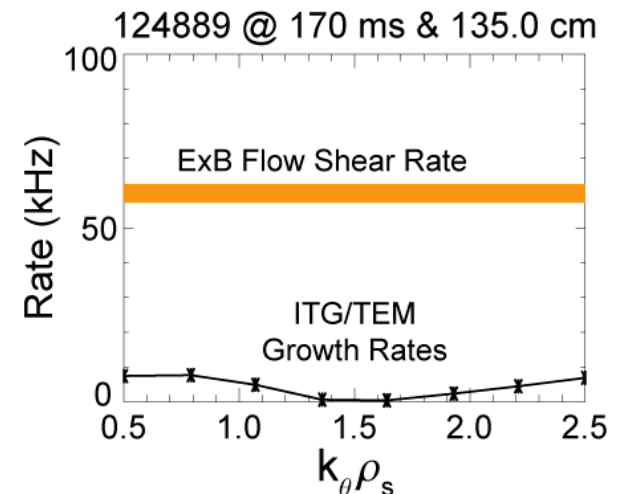
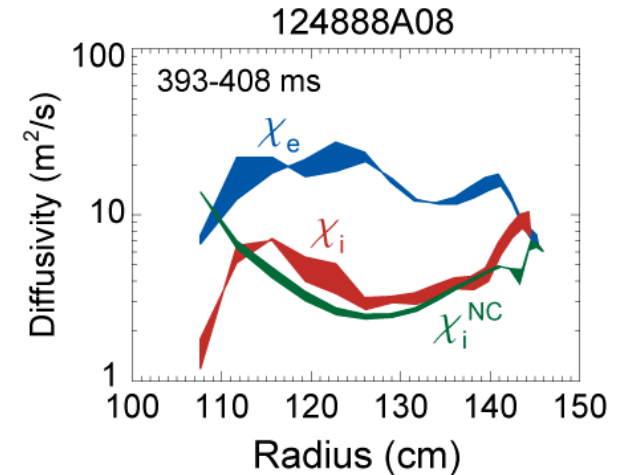


Outline

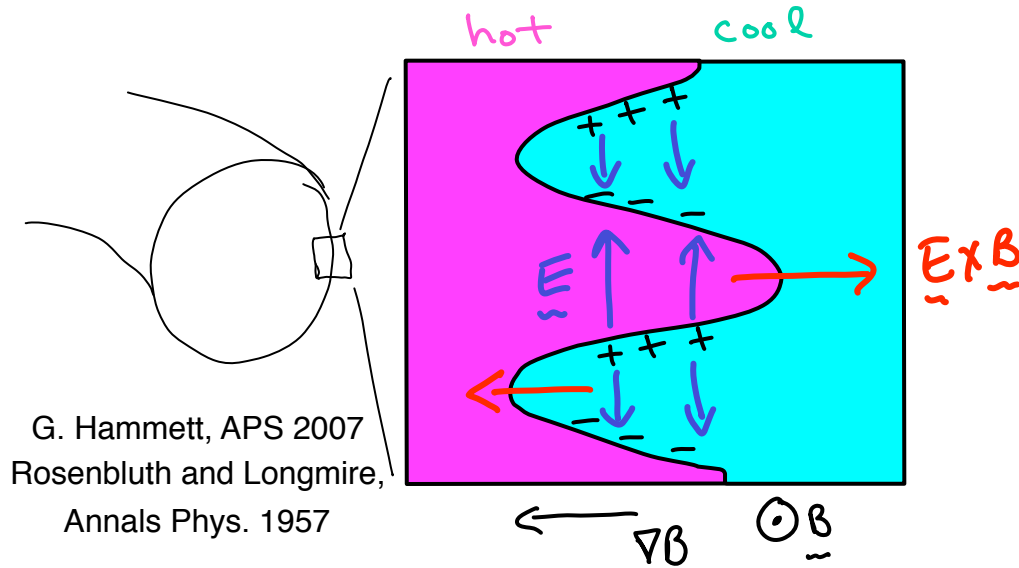
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NSTX is well-suited to investigate the connection between ETG turbulence and electron thermal transport

- Turbulence & transport in NSTX
 - Large $E \times B$ flow shear with NBI \rightarrow inferred ITG/TEM suppression (no direct evidence) \rightarrow ion thermal transport is near neoclassical in H-mode (Kaye et al, NF, 2007 & PRL, 2007)
 - Electron thermal transport remains anomalous \rightarrow what is the mechanism?
- Electron temperature gradient (ETG) turbulence
 - ETG modes can be linearly unstable with growth rates exceeding $E \times B$ flow shear rates
 - NL GK simulations predict experimentally-relevant electron thermal transport for $\hat{s} > 0.4$ for typical tokamak parameters (Nevins et al, PoP 2006)
 - Electron gyro-scale fluctuations $\rightarrow k_{\perp} \rho_e \leq 1$
 - Propagate in electron diamagnetic direction



ETG turbulence can generate greater normalized transport than ITG turbulence due to a weak secondary instability



ETG and ITG modes are **isomorphic** for linear, electrostatic dynamics with adiabatic background species

$$\gamma_{etg} \sim \frac{V_{te}}{\sqrt{RL_{Te}}} \quad \chi_e^{gB} \equiv \frac{\rho_e^2 V_{te}}{L_{Te}}$$

For nonlinear ETG dynamics, the **ion response weakens the secondary Kelvin-Helmholtz instability** and ρ_e -scale zonal flows

Consequently, ETG turbulence can saturate at higher normalized amplitudes and generate greater normalized transport than ITG turbulence for typical tokamak parameters

$$\frac{\chi_i^{itg}}{\chi_i^{gB}} \leq 2 \quad \frac{\chi_e^{etg}}{\chi_e^{gB}} \leq 15$$

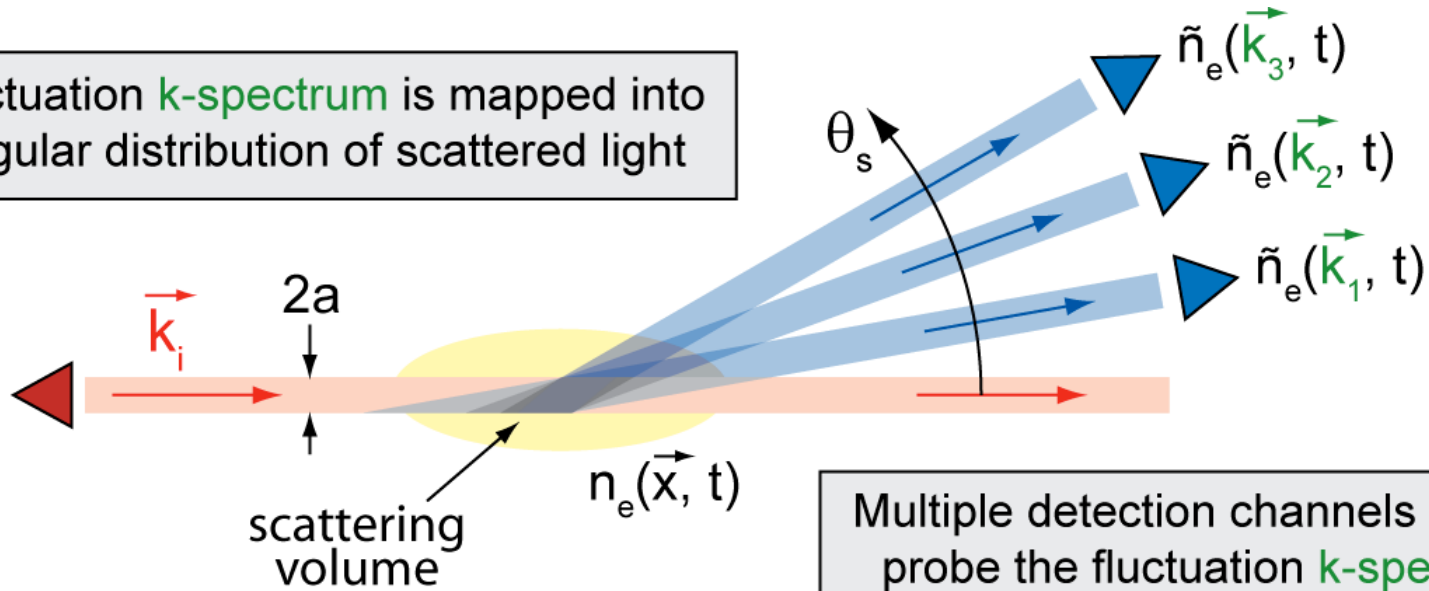
F. Jenko et al, PoP 2001
W. Nevins et al, PoP, 2006

Outline

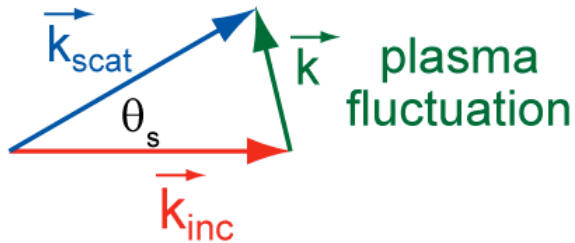
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- **The NSTX collective scattering system**
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Collective scattering measures density fluctuations with spatial and k-space localization

The fluctuation **k-spectrum** is mapped into the angular distribution of scattered light



3-wave coupling among 2 high-frequency EM waves and 1 low-frequency plasma fluctuation



k-matching: $\vec{k}_s = \vec{k}_i + \vec{k}$

Bragg condition: $k = 2k_i \sin(\theta_s/2)$

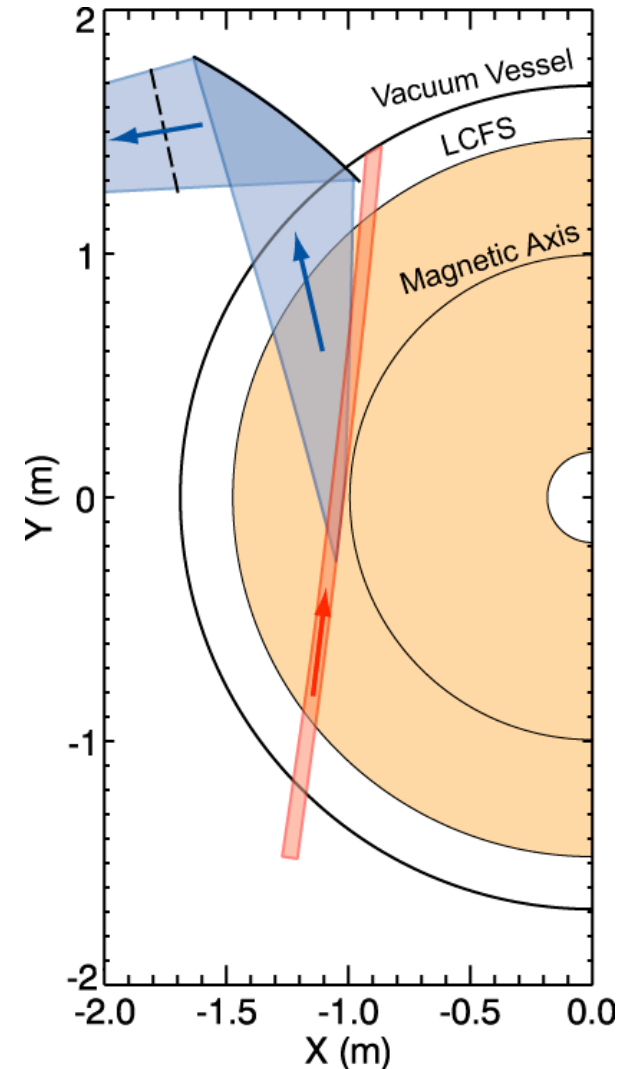
k-space resolution: $\Delta k = 2/a$

frequency matching: $\omega_s = \omega_i + \omega$

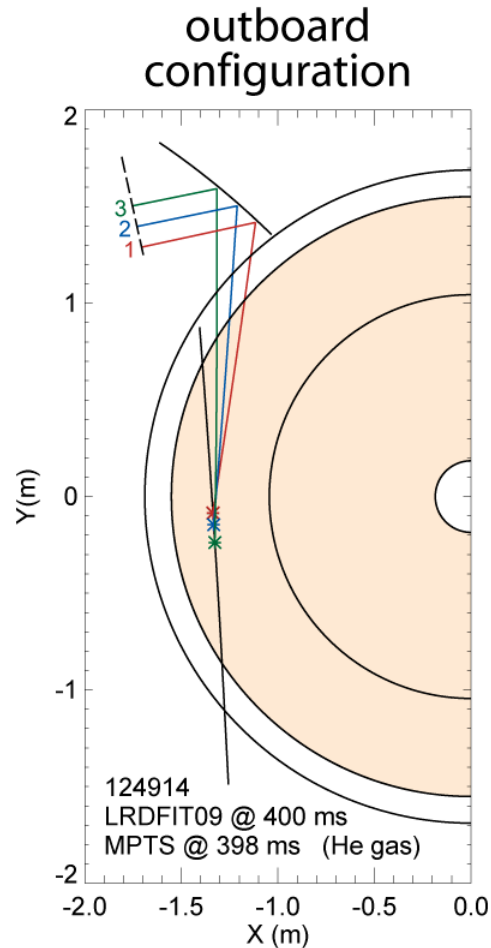
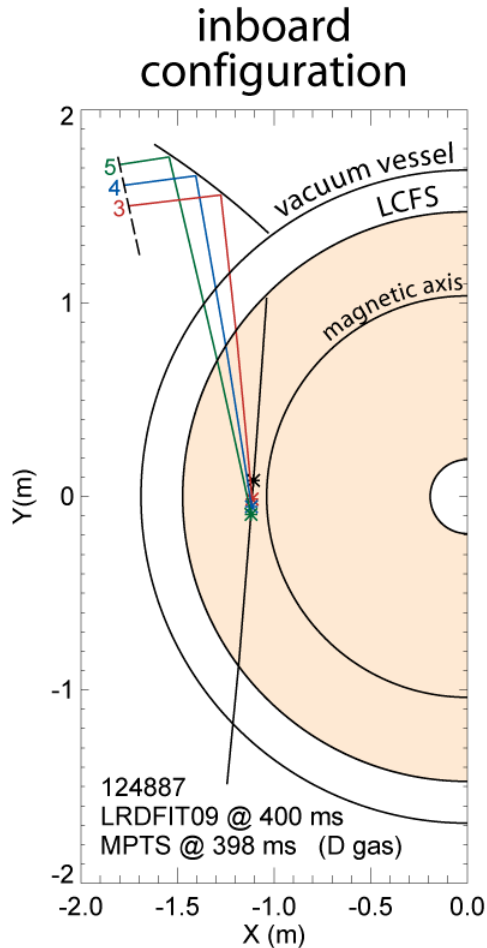
high-freq EM waves: $\omega_i, \omega_s \gg \omega$

The NSTX collective scattering system measures fluctuations up to $k_{\perp}\rho_e < 0.6$

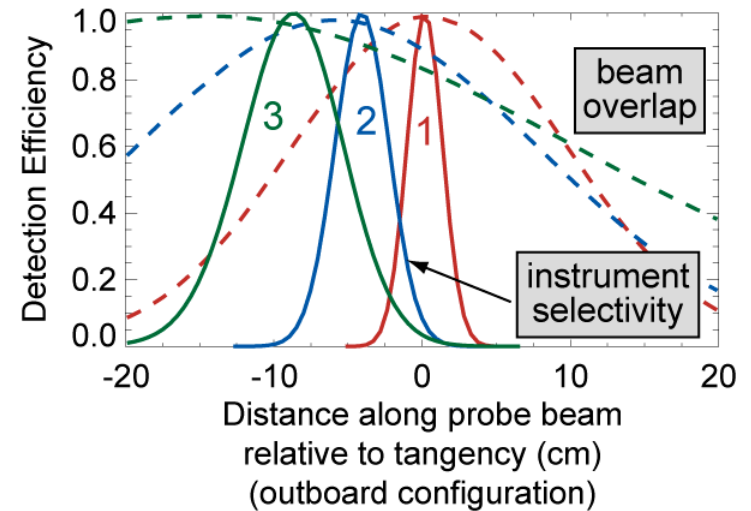
- 280 GHz collective scattering system
- Five detection channels
 - k_{\perp} spectrum for up to **five** discrete k_{\perp}
 - $k_{\perp}\rho_e < 0.6$ and $k_{\perp} < 20 \text{ cm}^{-1}$
 - ω spectrum from time-domain sampling
 - $7.5 \text{ MS/s} \rightarrow f \leq 3.25 \text{ MHz}$
 - Heterodyne detection
- Tangential scattering
 - Beams nearly on equatorial midplane
 - **Sensitive to radial fluctuations**
 - Toroidal curvature **enhances spatial localization** along probe beam, $\Delta L \approx 10 \text{ cm}$
 - Radial localization, $\Delta R \approx \pm 2.5 \text{ cm}$
- Steerable optics
 - Scattering volume can be positioned throughout the **outer half-plasma**



Steerable optics enable good radial coverage; toroidal curvature enhances spatial localization



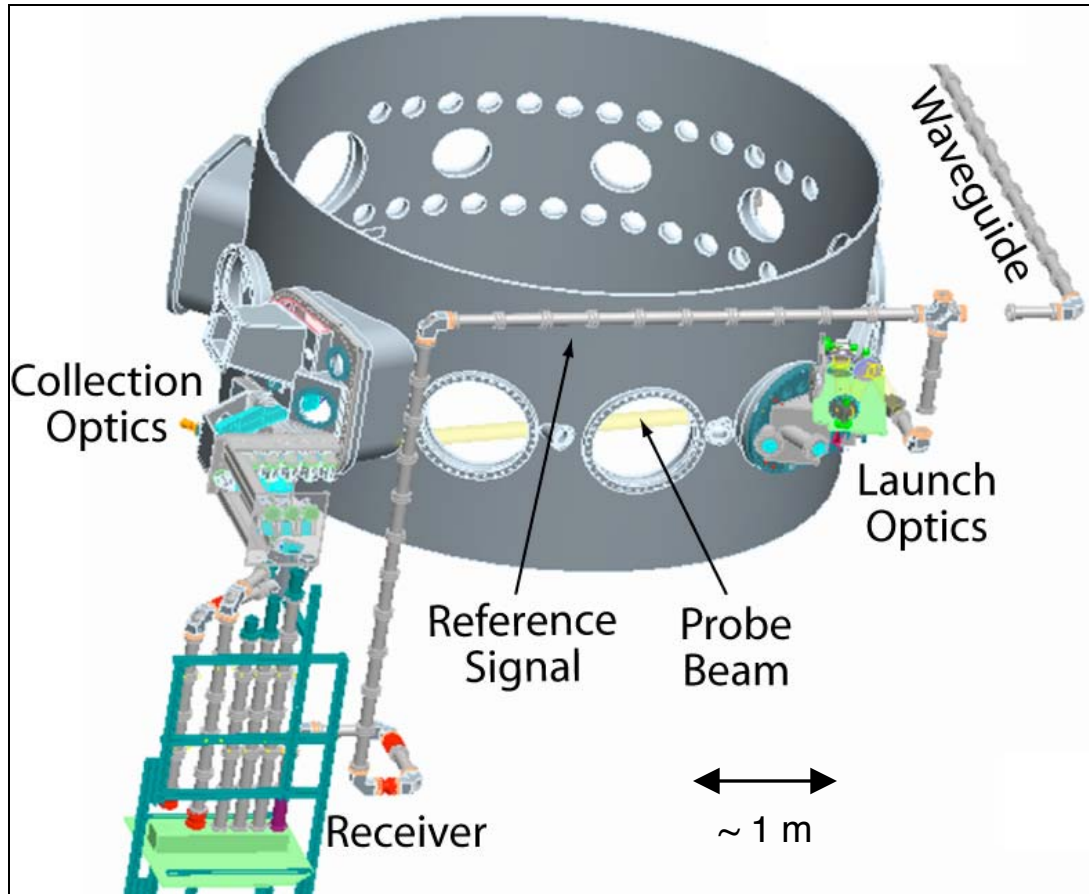
Large toroidal curvature imposes an **instrument selectivity function** that **constricts** the scattering volume within the overlap volume along the probe beam.



E. Mazzucato, PoP, 2003

E. Mazzucato, PPCF, 2006

Scattering system hardware



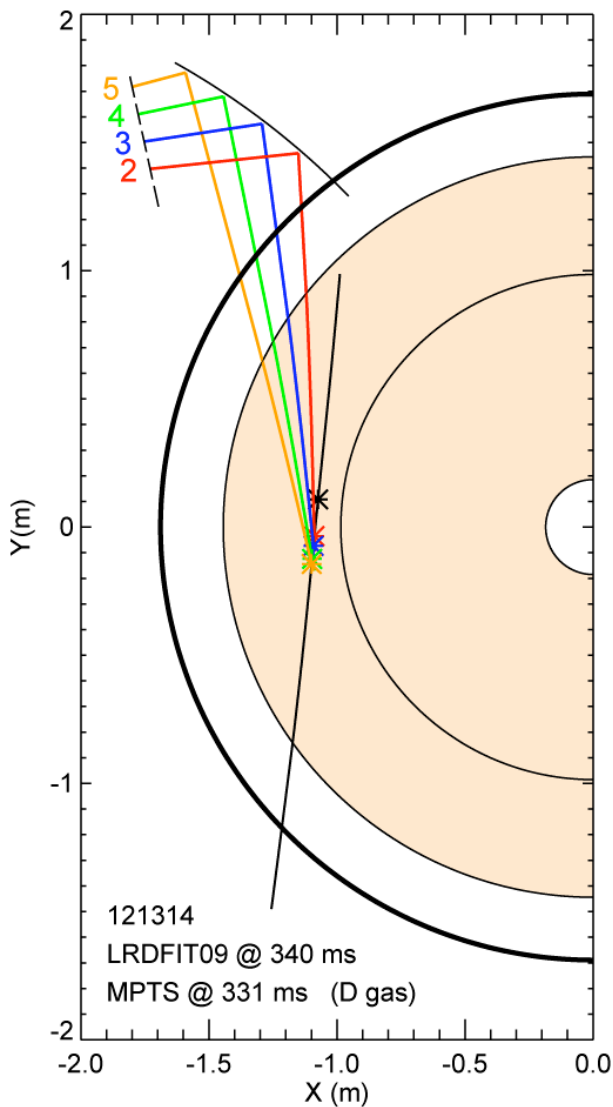
- BWO source
 - ~200 mW at 280 GHz
- Overmoded, corrugated waveguide
 - low-loss transmission
 - delivers ~100 mW for PB
- Probe & receiving beams
 - quasi-optically coupled with 5 cm dia. waist
- Heterodyne receiver
 - five channels
 - two mixing stages
 - quadrature detection with 7.5 MHz bandwidth
 - reference signal from BWO

D. R. Smith et al, RSI, 2008

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Ray tracing calculations optimize configurations and provide measurement parameters



Measurement parameters

	Ch. 2	Ch. 3	Ch. 4	Ch. 5
r/a	0.27	0.28	0.29	0.30
d_{\min} (cm)	0.1	0.1	0.1	0.1
k_{\parallel} (cm^{-1})	0.1	0.0	0.2	0.0
k_r (cm^{-1})	6.9	11.0	14.6	17.8
k_{θ} (cm^{-1})	-1.6	-3.4	-4.4	-5.5
k_{\perp} (cm^{-1})	7.1	11.5	15.2	18.6
$ k_{\theta}/k_r $	0.23	0.30	0.30	0.31
$k_{\perp}\rho_e$	0.23	0.38	0.51	0.62
$k_{\perp}\rho_s$	14	22	30	37
k_T (cm^{-1})	-0.4	-0.7	-1.2	-1.3
f_D (MHz)	-1.0	-1.8	-3.0	-3.3

Alignment

Ion/electron drift direction

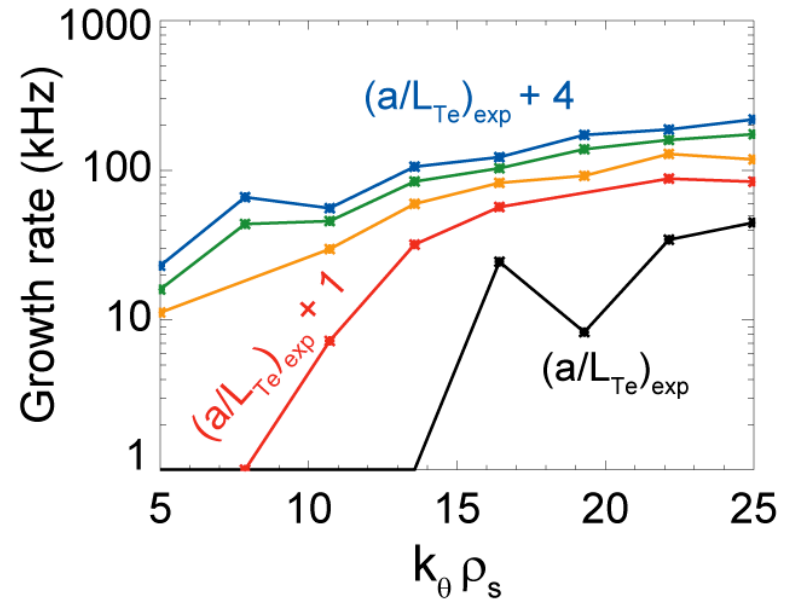
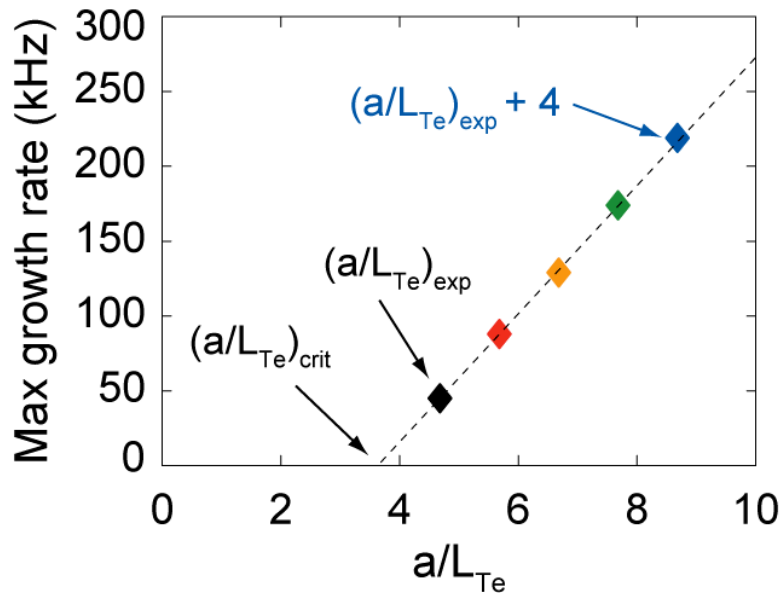
ETG scale

Doppler shift

Linear GS2 calculations provide ETG growth rates and critical gradients

GS2 is an initial value, flux tube code that evolves the gyrokinetic Vlasov-Maxwell equations

124948 @ 250 ms & 121 cm



$$\left(\frac{R}{L_{Te}}\right)_{crit} \propto \left(1 + \frac{Z_{eff} T_e}{T_i}\right) \left(1.33 + 1.91 \frac{\hat{s}}{q}\right)$$

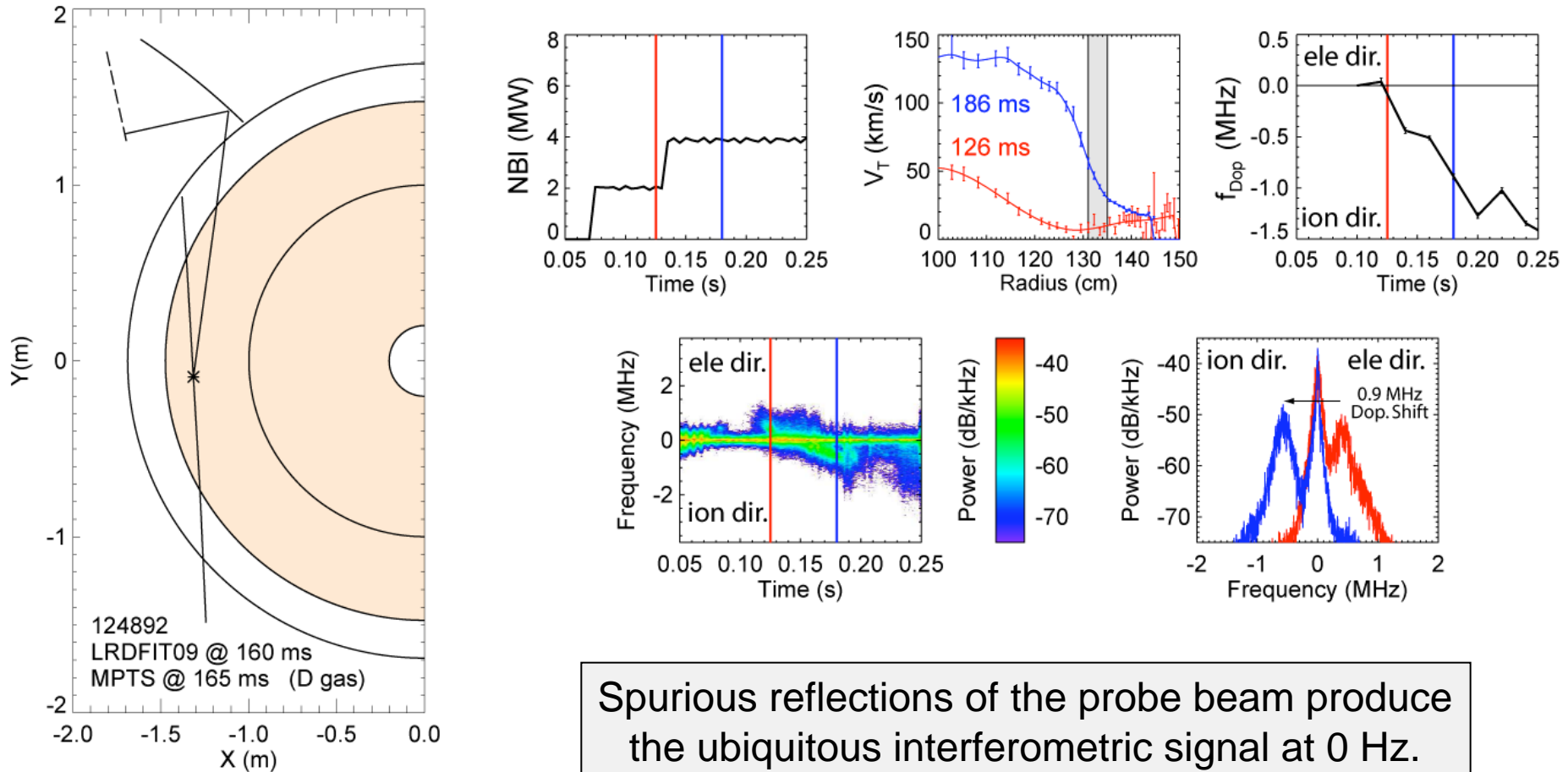
F. Jenko, Comp Phys Comm 2000
F. Jenko et al, PoP 2001

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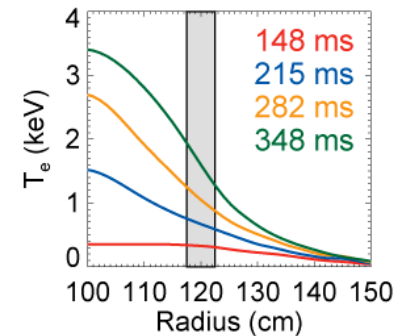
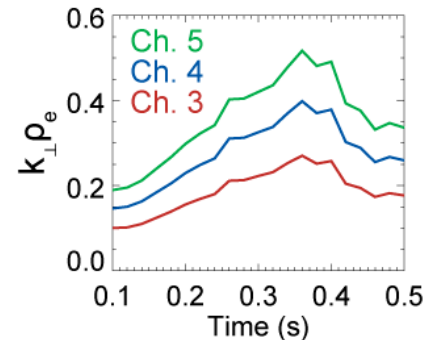
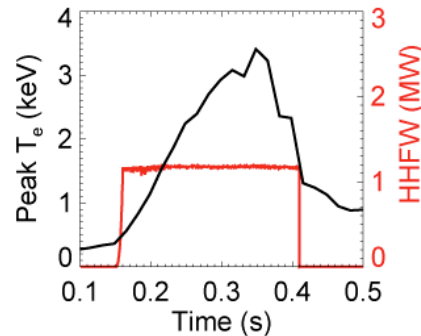
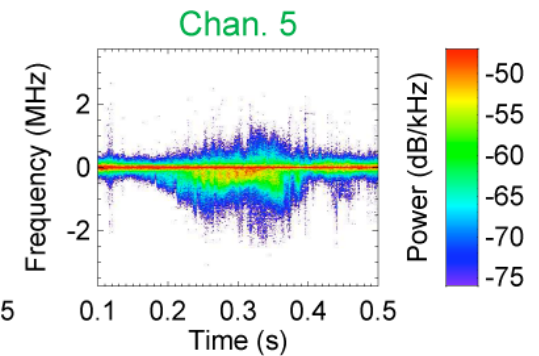
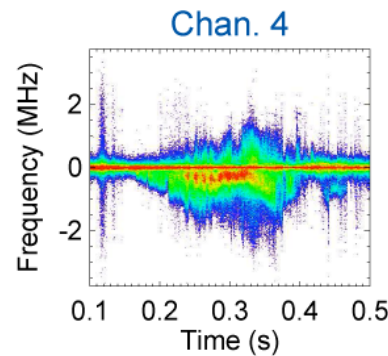
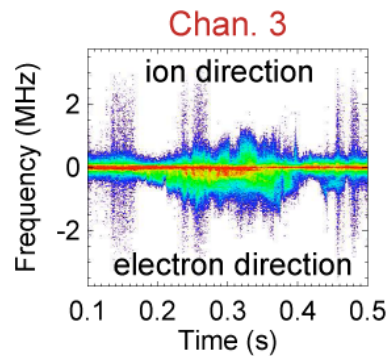
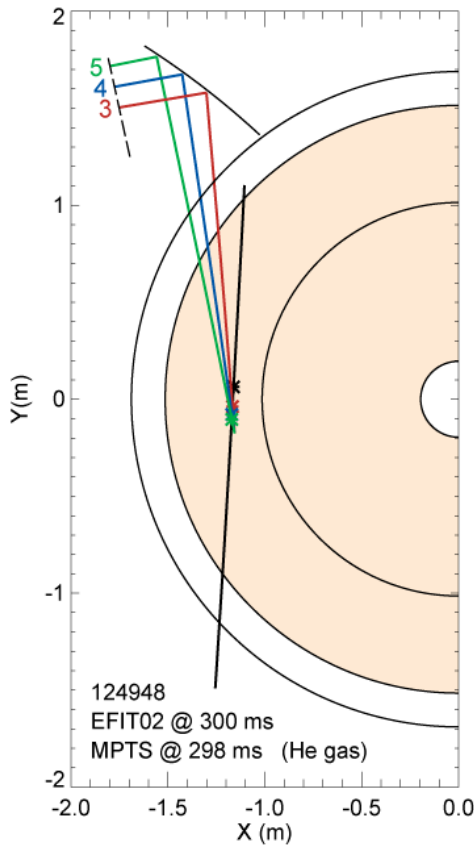
Toroidal rotation from NBI (co- I_p) produces a Doppler shift in fluctuation spectra toward the ion diamagnetic direction

3.5 kG, 700 kA, 4 MW NBI, $R=133\pm 2$ cm, $r/a\approx 0.55$

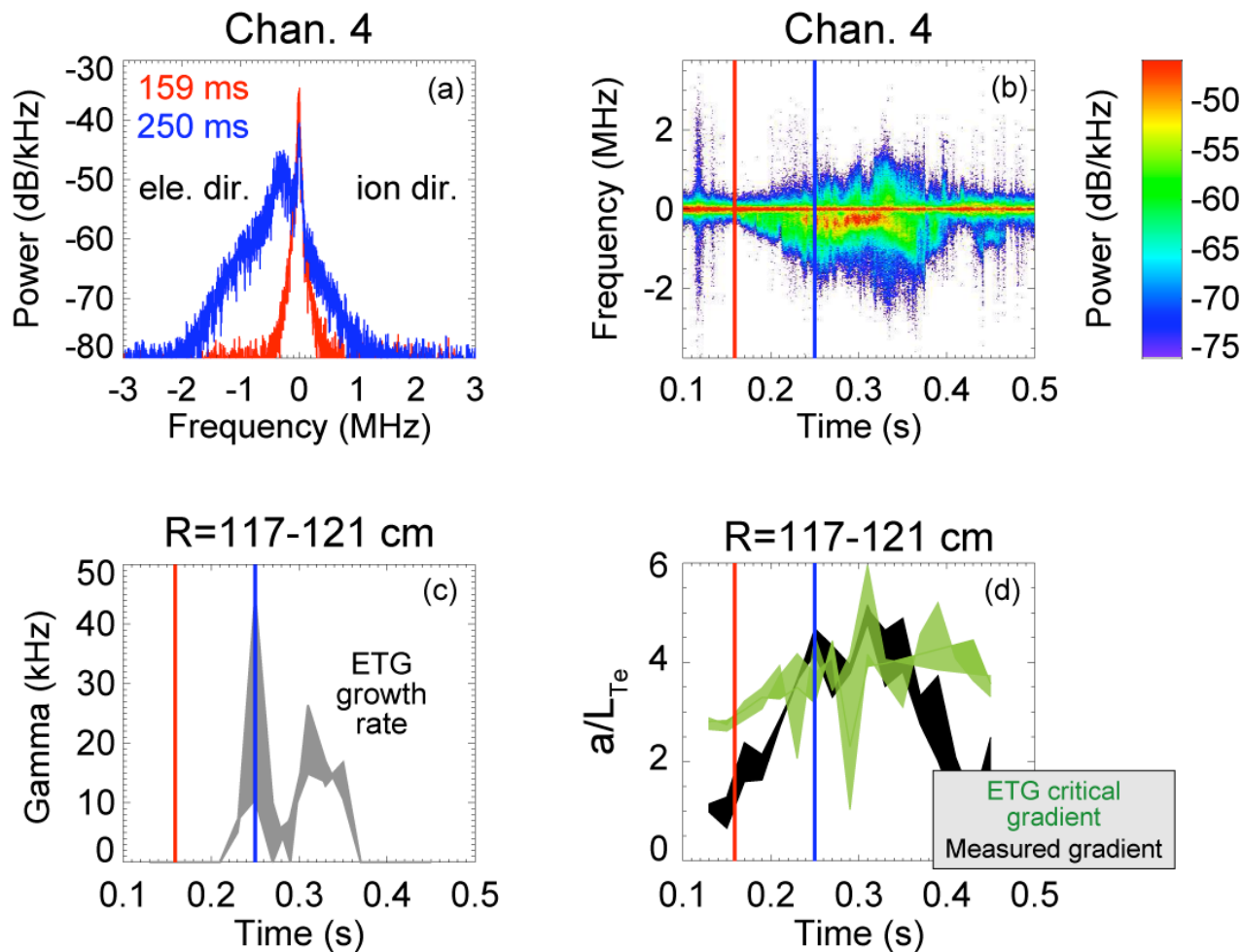


Enhanced fluctuations observed in core region of high-Te L-mode plasma

5.5 kG, 600 kA, 1.2 MW HHFW, $R=119\pm 2$ cm, $r/a\approx 0.28$



Enhanced fluctuations occur when Te gradient is comparable to the ETG critical gradient

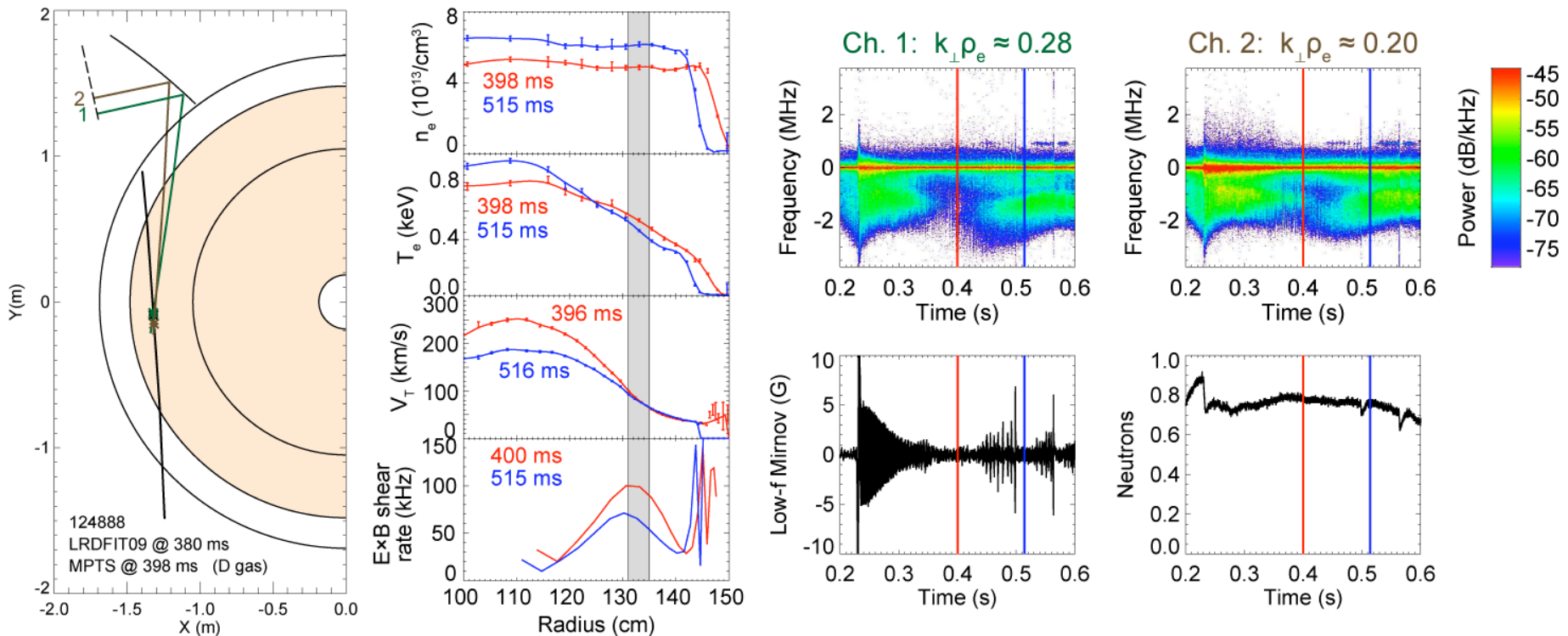


Similar observation at $R=134\pm 2$ cm

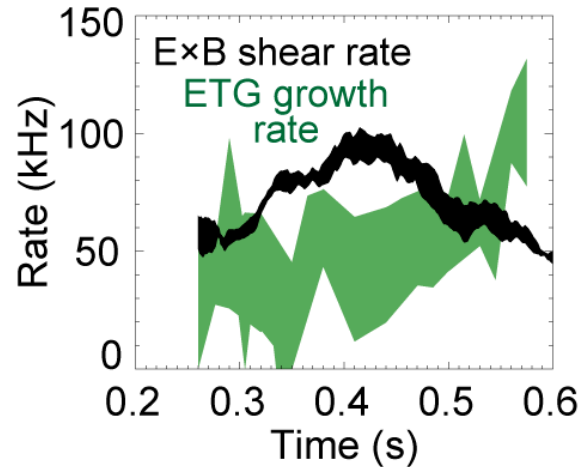
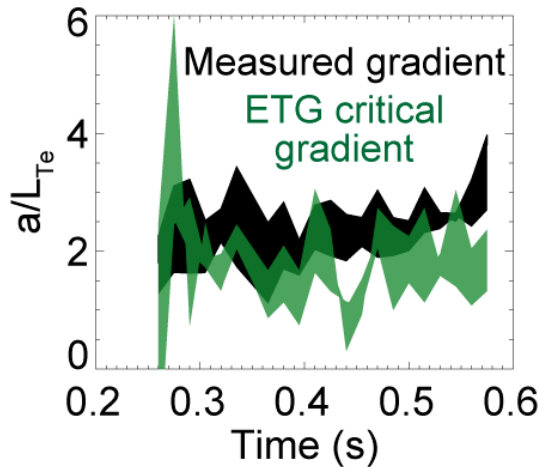
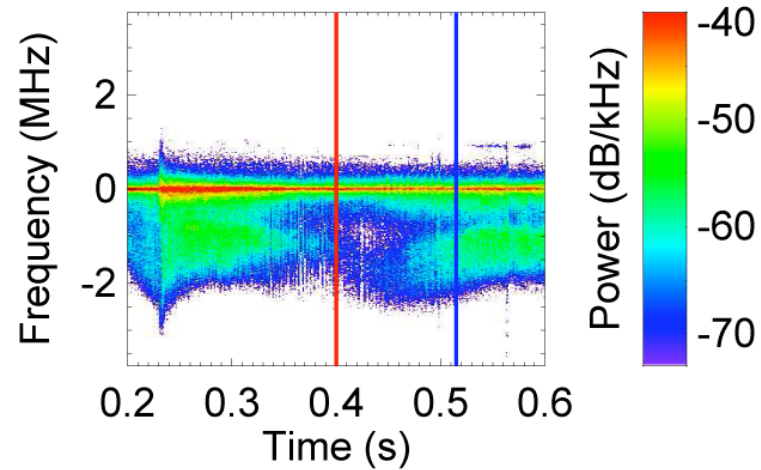
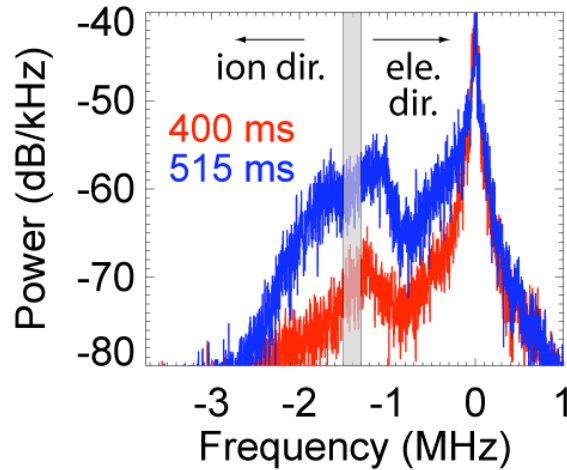
Mazzucato, Smith, et al, PRL, 2008

Enhanced fluctuations observed at mid-radii in NBI-heated H-mode plasma

4.5 kG, 700 kA, 4 MW NBI, $R=133\pm 2$ cm, $r/a\approx 0.55$



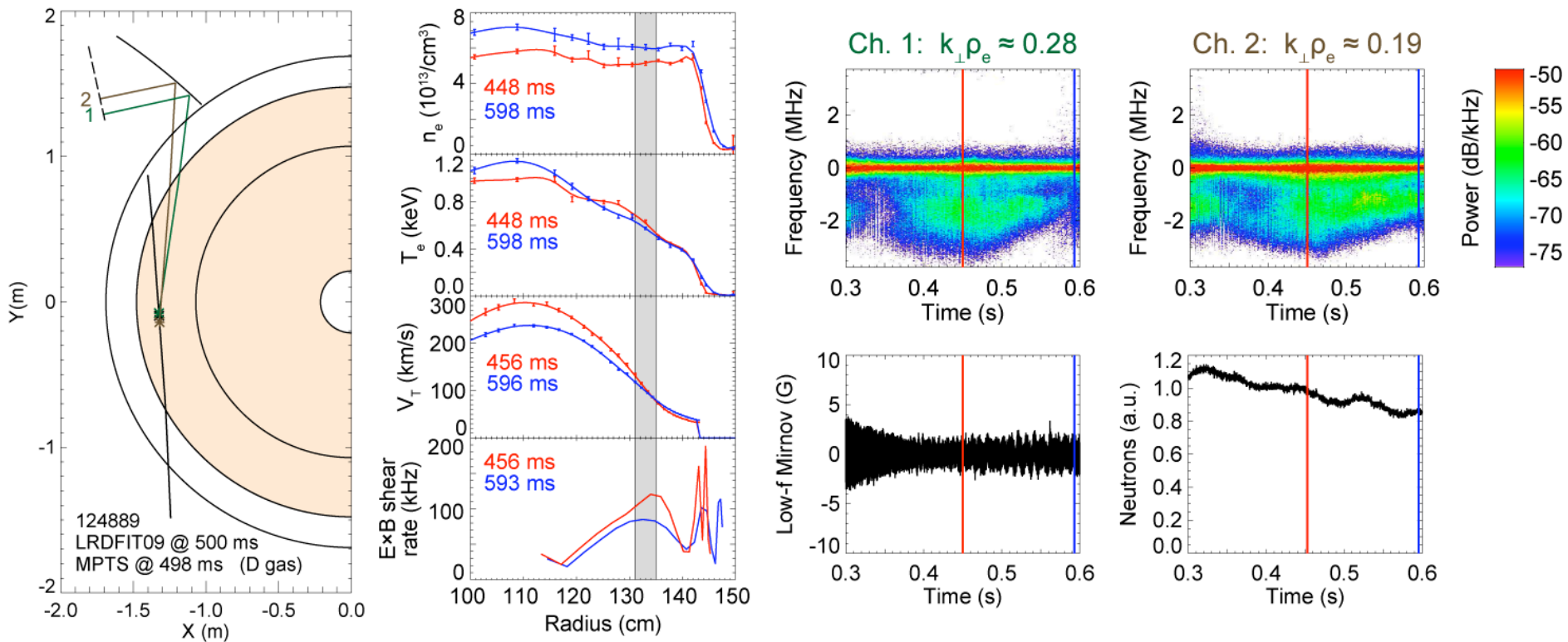
Near ETG marginal stability, fluctuation amplitudes decrease when the $E \times B$ shear rate exceeds the ETG growth rate



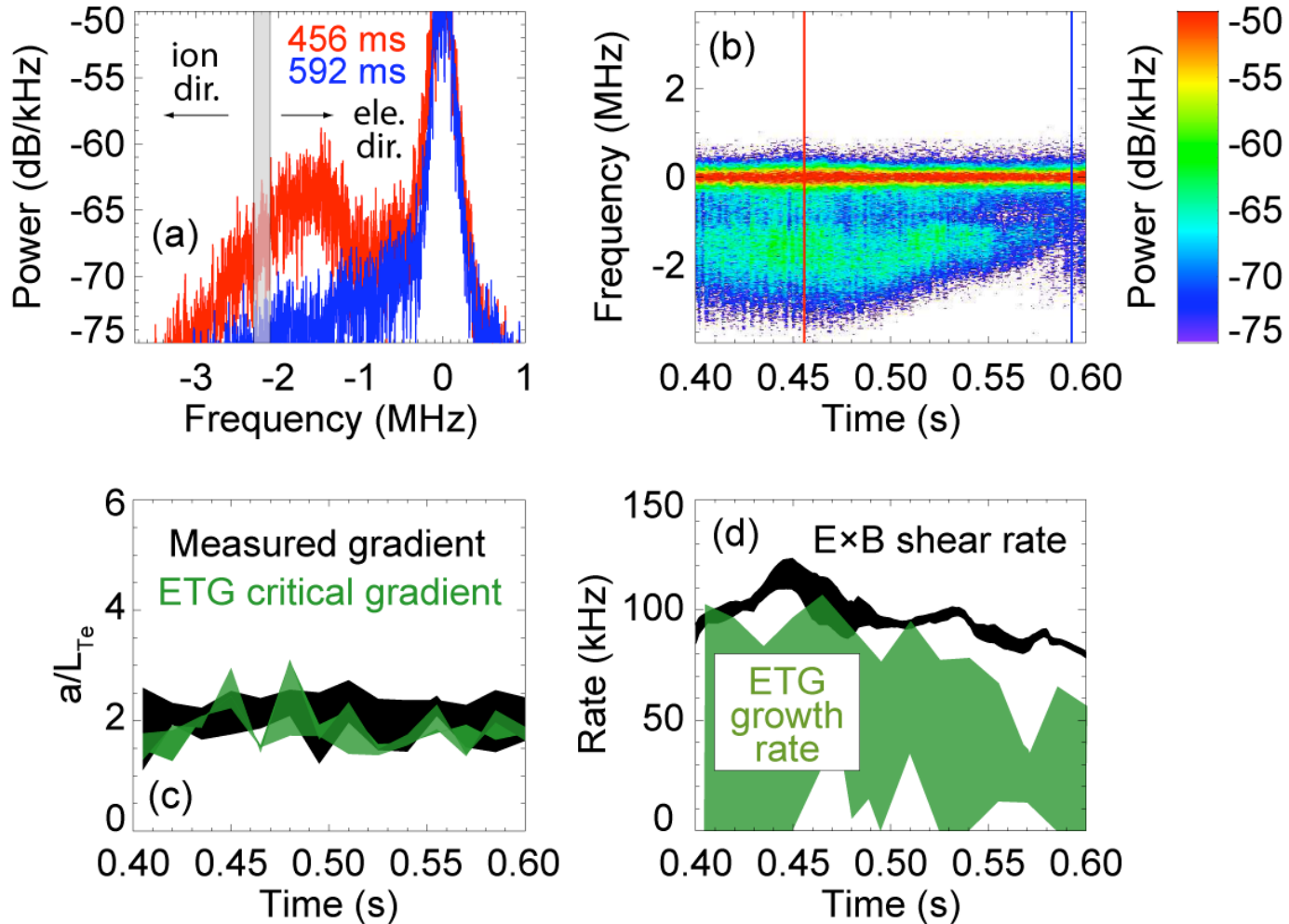
D. R. Smith et al, PRL, 2009

$E \times B$ shear rate is larger at higher B_T , yet enhanced fluctuations are still observed

5.5 kG, 700 kA, 4 MW NBI, $R=133 \pm 2$ cm, $r/a \approx 0.55$

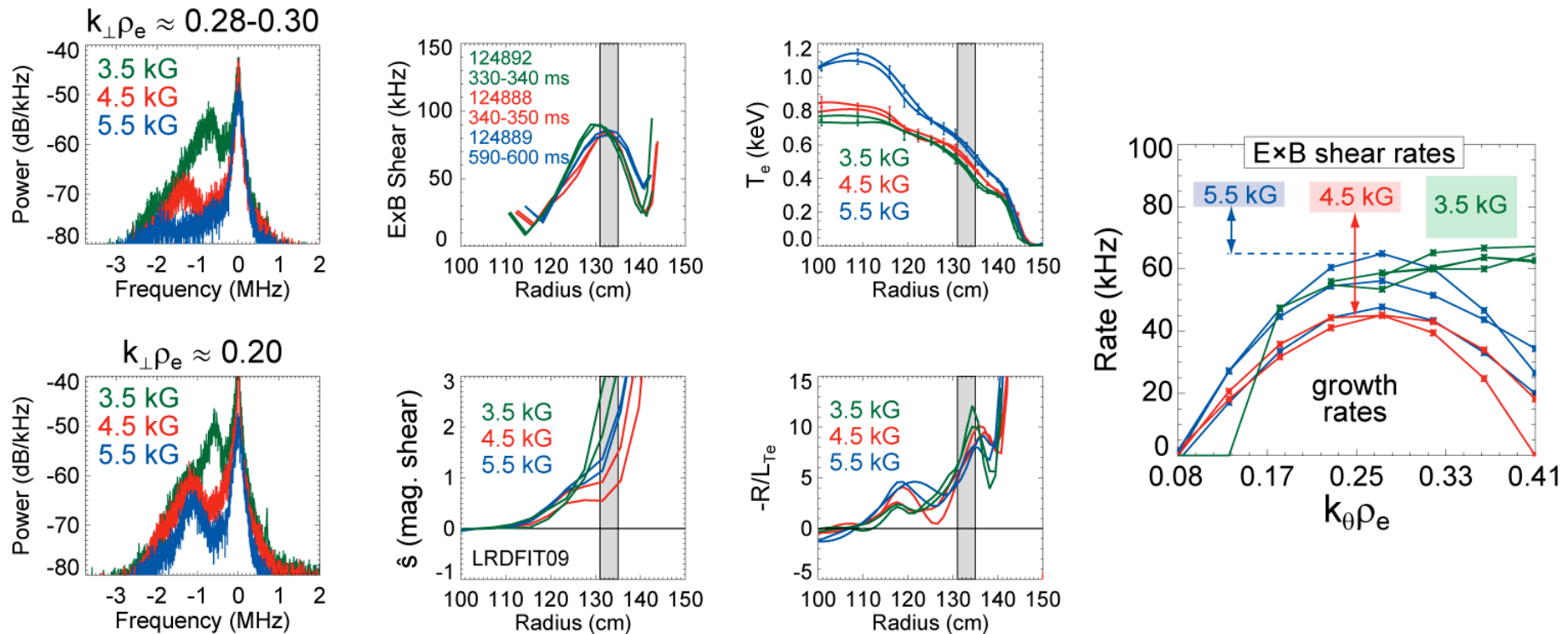


Near ETG marginal stability, fluctuation amplitudes decrease when the ETG growth rate drops below the E×B shear rate



D. R. Smith et al, PRL, 2009

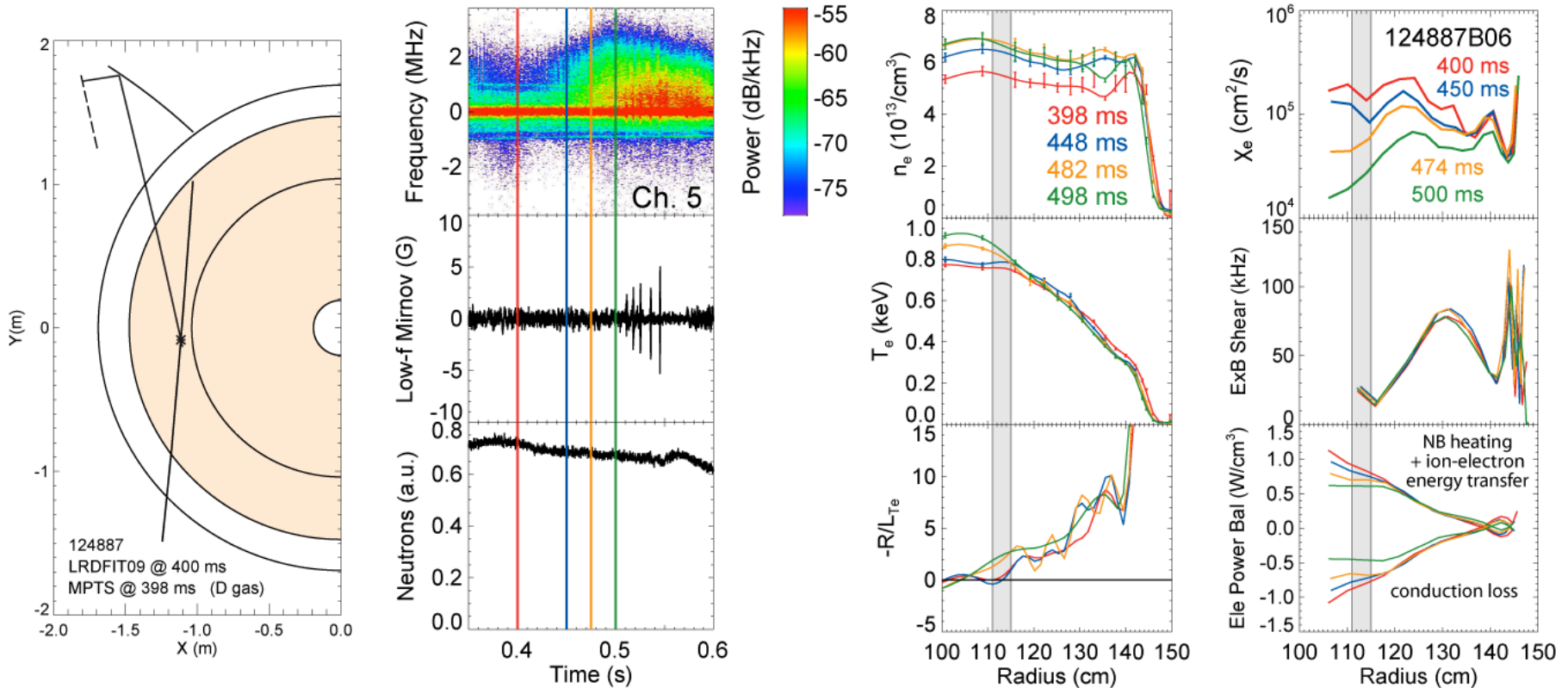
Fluctuation amplitudes decrease at higher B_T with similar $E \times B$ shear rates, ETG growth rates, and ∇T_e



Note that the 4.5 kG case exhibits the largest difference between $E \times B$ shear rates and ETG growth rates.

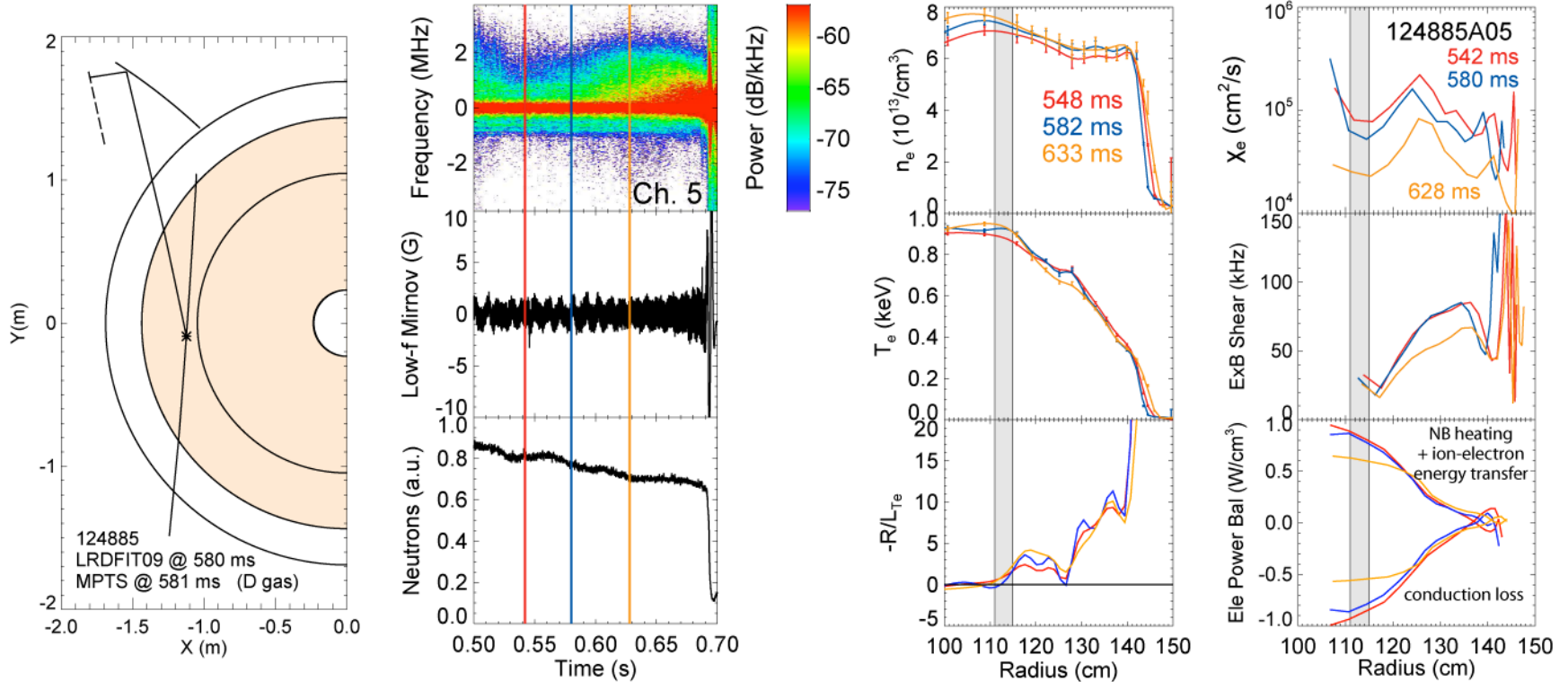
D. R. Smith et al, PoP, 2009

Observation suggests no simple relation between measured fluctuation amplitude and transport



D. R. Smith et al, PoP, 2009

Again, electron thermal diffusivity decreases when fluctuation amplitudes increase



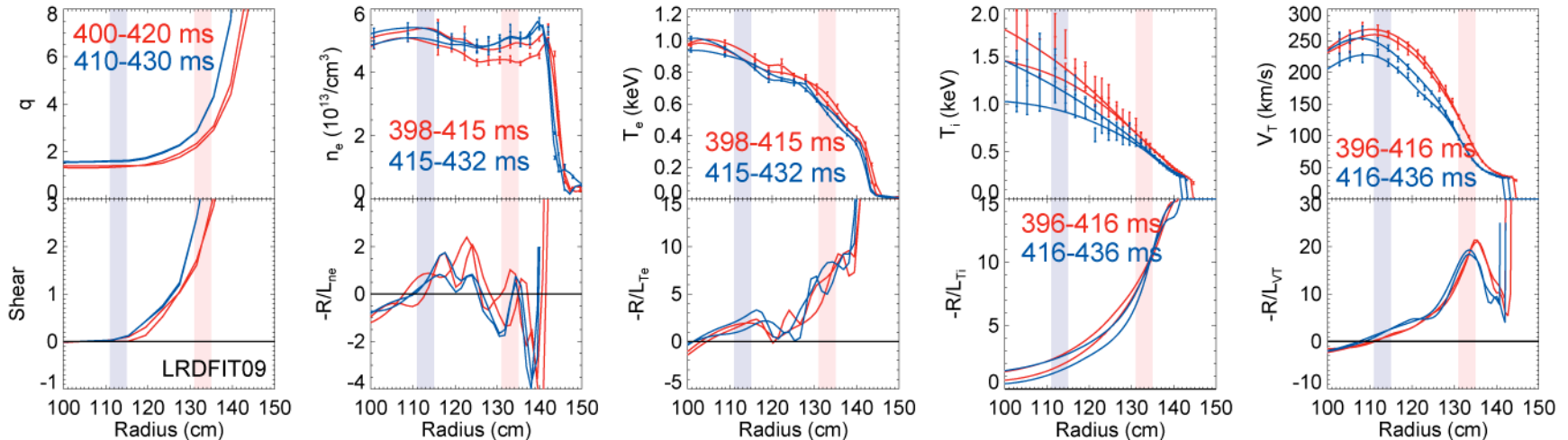
D. R. Smith et al, PoP, 2009

Fluctuation magnitudes and wavenumber spectral exponents

5.5 kG discharges

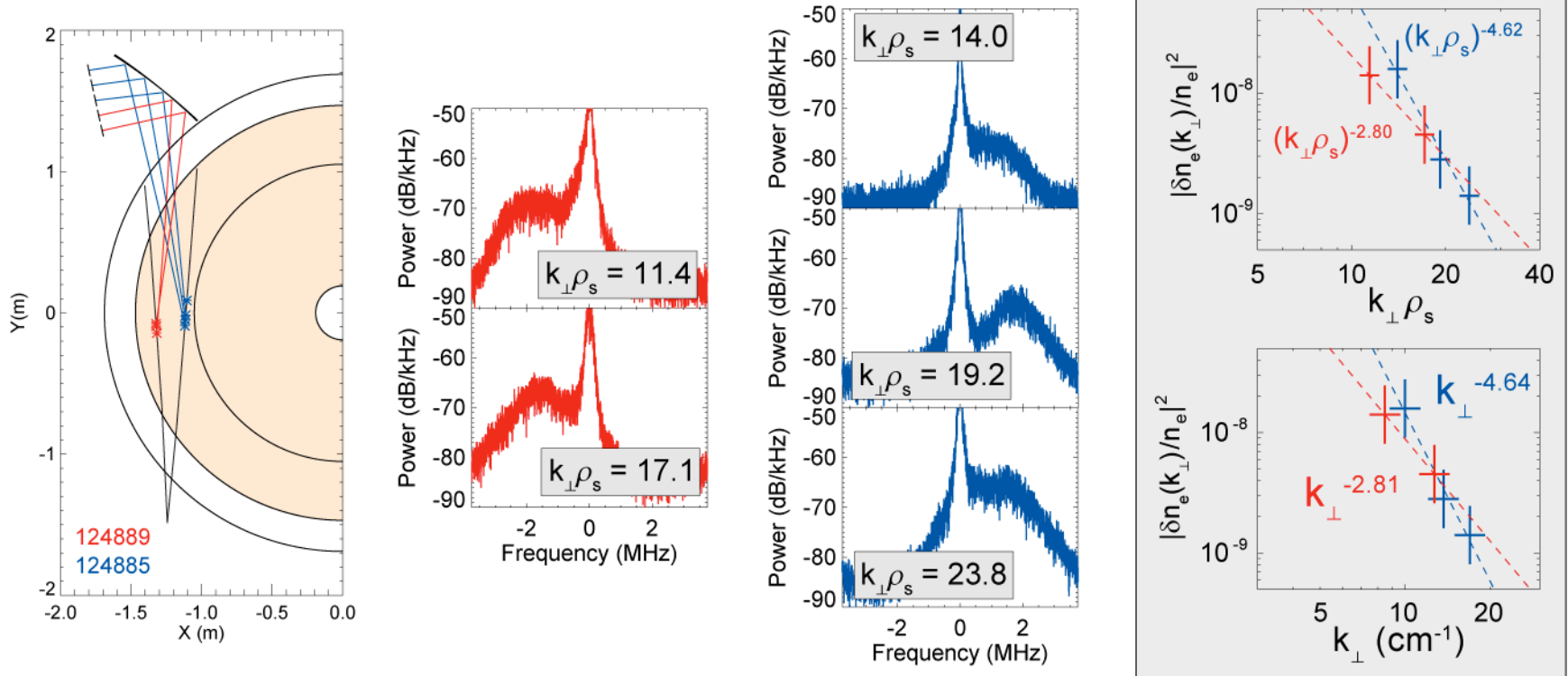
124885 @ R=111-115 cm

124889 @ R=131-135 cm



$$k \text{ - spectrum : } \left| \frac{\delta n_e(k_r)}{n_e} \right|^2 \propto k_r^{-\alpha}$$

Fluctuation magnitudes are in order-of-magnitude agreement with NL GK simulations for typical tokamak parameters



- **Spectral exponent** is $\alpha = 4.6$ near magnetic axis and $\alpha = 2.8$ at mid-radius ($\Delta\alpha \approx 0.5-0.6$)
- ETG simulations with GYRO predict $|\delta n_e(k_r)/n_e|^2 \sim 10^{-10} - 10^{-11}$ for $k_r \rho_s \sim 10 - 20$, but **spectral resolution** is about $10\times$ greater; synthetic diagnostics needed (R. Waltz et al, PoP 2007)

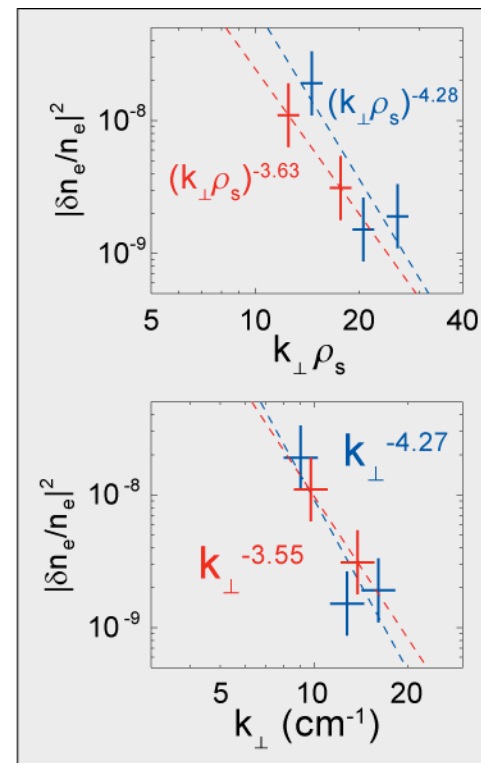
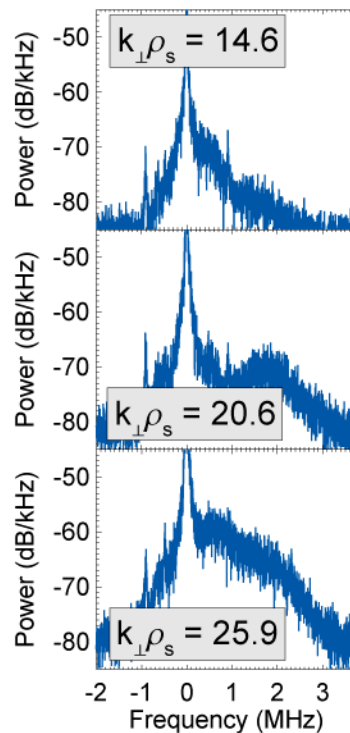
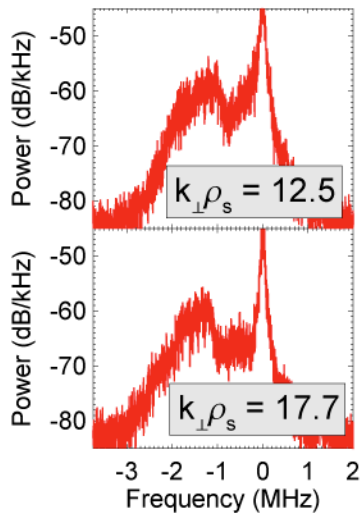
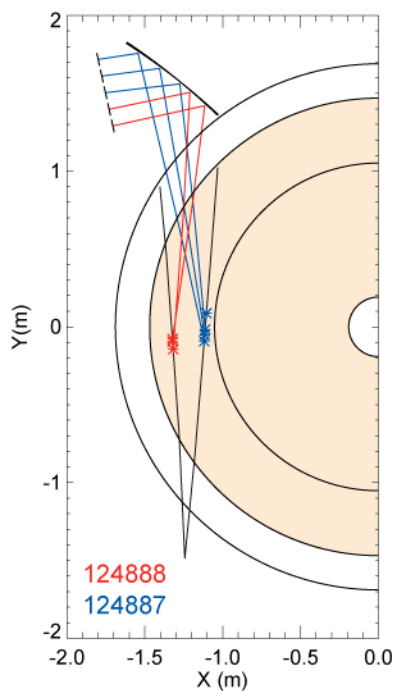
D. R. Smith et al, PoP, 2009

Similar magnitudes and exponents at lower TF

4.5 kG discharges

124887 @ R=111-115 cm

124888 @ R=131-135 cm



Ideas to extend high-k measurements and analysis

- Nonlinear gyrokinetic simulations
 - Saturation amplitudes
 - Turbulence spreading into core
 - Synthetic diagnostics
- ETG isotropy in k_r - k_θ plane
 - Adjust vertical position of scattering volume to vary k_r/k_θ
 - Radial streamers
 - Unique capability for NSTX
- Mode coupling coefficients
 - Mode coupling is necessary for turbulence
 - Calculate mode coupling coefficients with bicoherence analysis (see Itoh et al, PoP, 2005)
 - Unique capability for NSTX
- Low-k fluctuation measurements with BES
 - Coupling between low-k ITG and high-k ETG
 - ETG saturation via ion-scale zonal flows

Summary

- In L-mode plasmas, enhanced fluctuation amplitudes occur when ∇T_e is comparable to or exceeds the **ETG critical gradient**
- At mid-radii in H-mode plasmas with large toroidal rotation, fluctuation amplitudes decrease when the **E×B shear rate** exceeds the **ETG growth rate**
- For similar ∇T_e , ETG growth rates, and E×B shear rates, **fluctuation amplitudes decrease at higher B_T** at mid-radii in H-mode plasmas
- No simple relation between transport and measured fluctuation amplitudes
- Fluctuation magnitudes, $|\delta n_e(k_r)/n_e|^2 \sim 10^{-9} - 10^{-8}$, are within order-of-magnitude agreement with NL GK simulations for typical tokamak parameters
- Wavenumber spectral exponents are in the range $\alpha = 2.8 - 4.6$ in H-mode plasmas

For more information...

- Instrument papers:
 - D. R. Smith et al, RSI 79, 123501 (2008)
 - D. R. Smith et al, RSI 75, 3840 (2004)
- Physics results:
 - D. R. Smith et al, PoP 16, 112507 (2009)
 - E. Mazzucato et al, NF 49, 055001 (2009)
 - D. R. Smith et al, PRL 102, 225005 (2009)
 - E. Mazzucato et al, PRL 101, 075001 (2008)
- Dissertation and additional information at website:
 - <http://homepages.cae.wisc.edu/~drsmith>