NSTX

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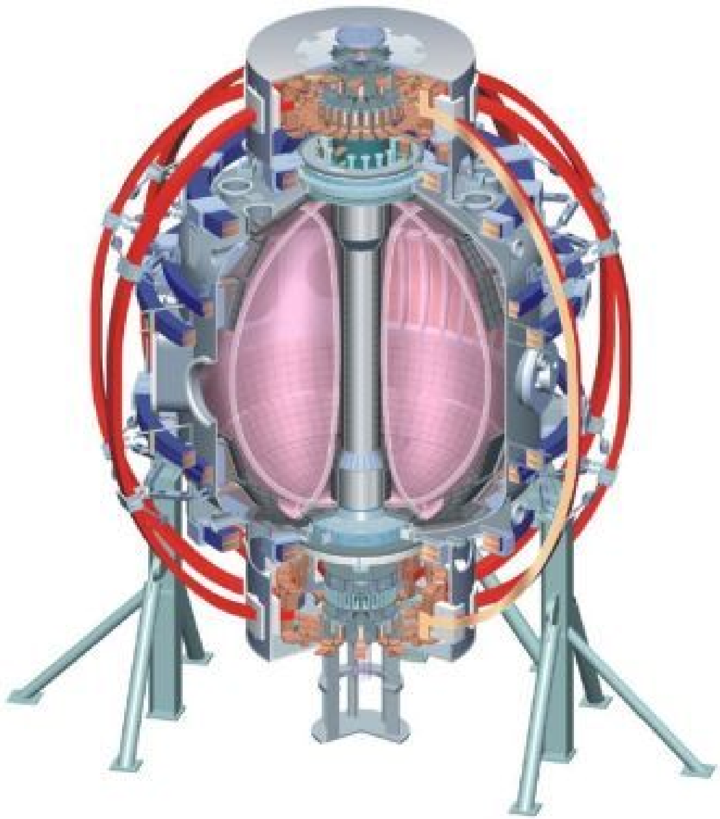
Investigation of electron gyro-scale fluctuations in the National Spherical Torus Experiment



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Advisor:
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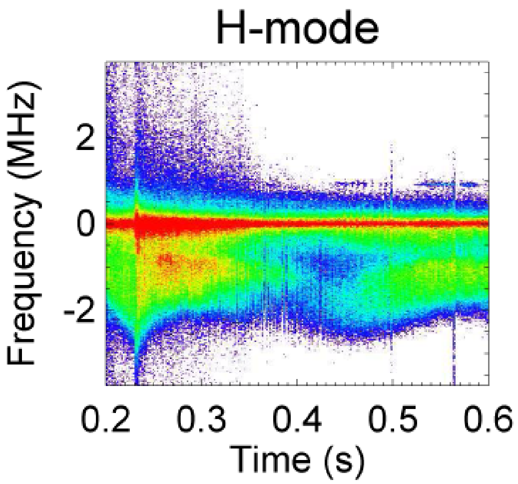
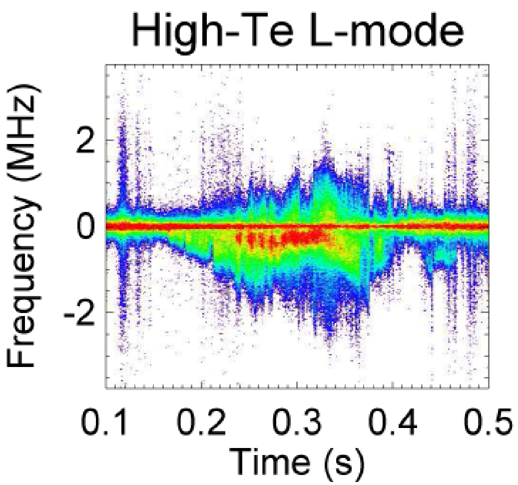
Final public oral exam
February 26, 2009

Investigation of electron gyro-scale fluctuations in the National Spherical Torus Experiment

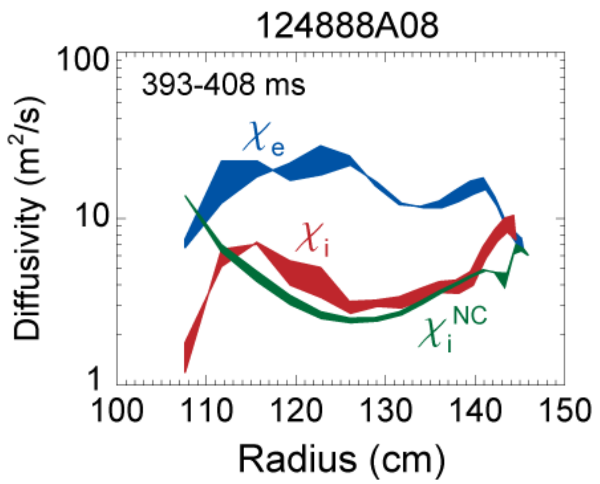
- Transport in NSTX and ETG turbulence
- The NSTX collective scattering system
- Analysis tools
  - Ray tracing calculations
  - Linear gyrokinetic calculations
- Fluctuation measurements and analysis
  - Enhanced fluctuations and the ETG critical gradient
  - Reduced fluctuations, ETG growth rates, and E×B flow shear
  - Fluctuations and transport
  - Fluctuation magnitudes and k-spectra
- Future work and summary



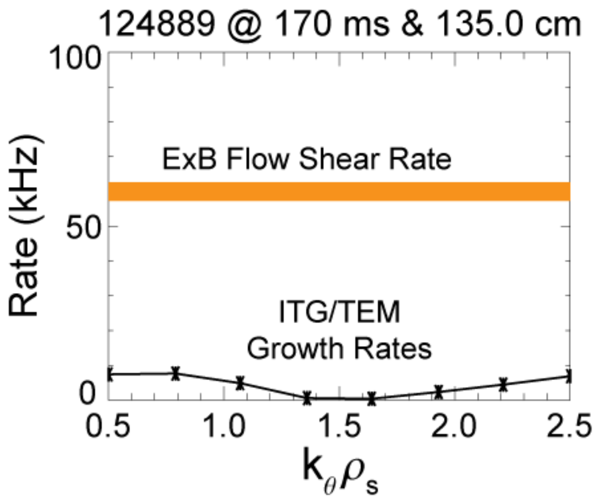


NSTX is well-suited to investigate the connection between ETG turbulence and electron thermal transport

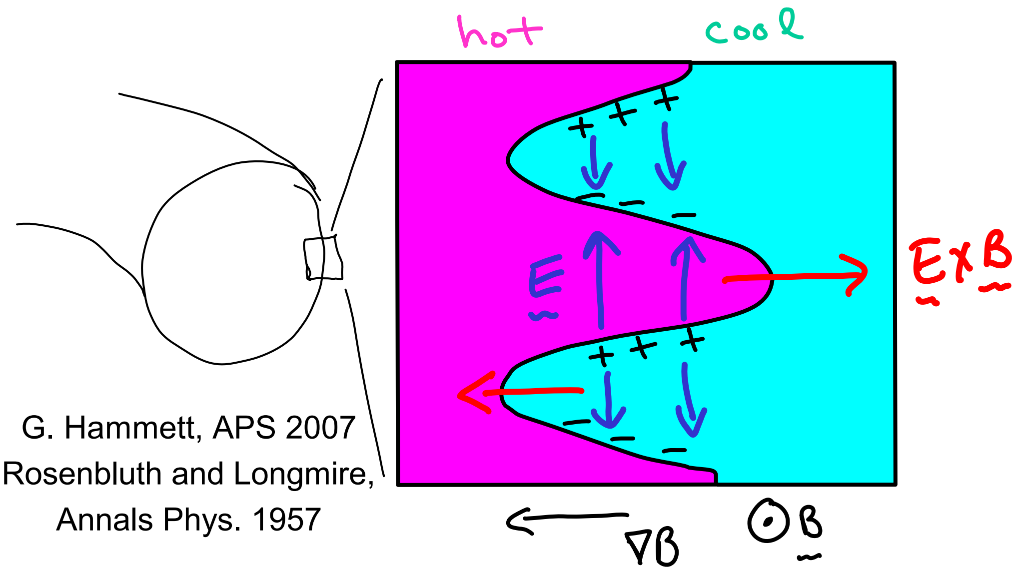
- Turbulence & transport in NSTX
  - Large E×B flow shear with NBI → inferred ITG/TEM suppression (no direct evidence) → ion thermal transport is near neoclassical in H-mode (Kaye et al, NF, 2007 & PRL, 2007)
  - Electron thermal transport remains anomalous → what is the mechanism?



- Electron temperature gradient (ETG) turbulence
  - ETG modes can be linearly unstable with growth rates exceeding E×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 → $k_\perp \rho_e \lesssim 1$
  - Propagate in electron diamagnetic direction



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



G. Hammett, APS 2007
Rosenbluth and Longmire, Annals Phys. 1957

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

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

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

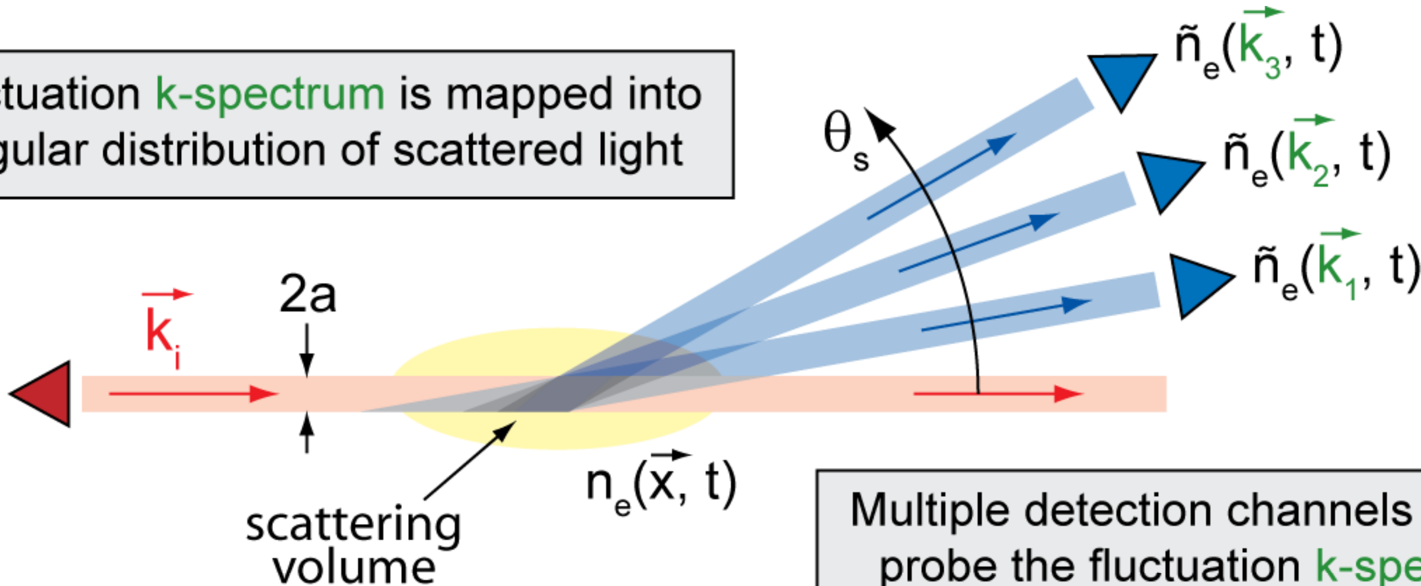
Consequently, ETG turbulence can saturate at higher normalized amplitudes and generate greater normalized transport than ITG turbulence for typical tokamak parameters

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

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

Collective scattering measures density fluctuations with spatial and k-space localization

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



Multiple detection channels directly probe the fluctuation k-spectrum

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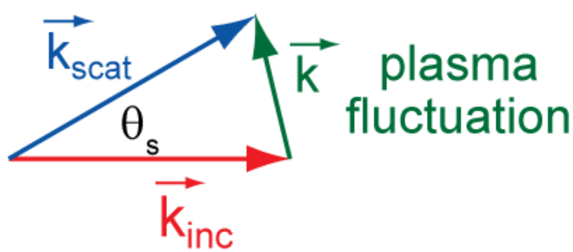
3-wave coupling among 2 high-frequency EM waves and 1 low-frequency plasma fluctuation



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

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

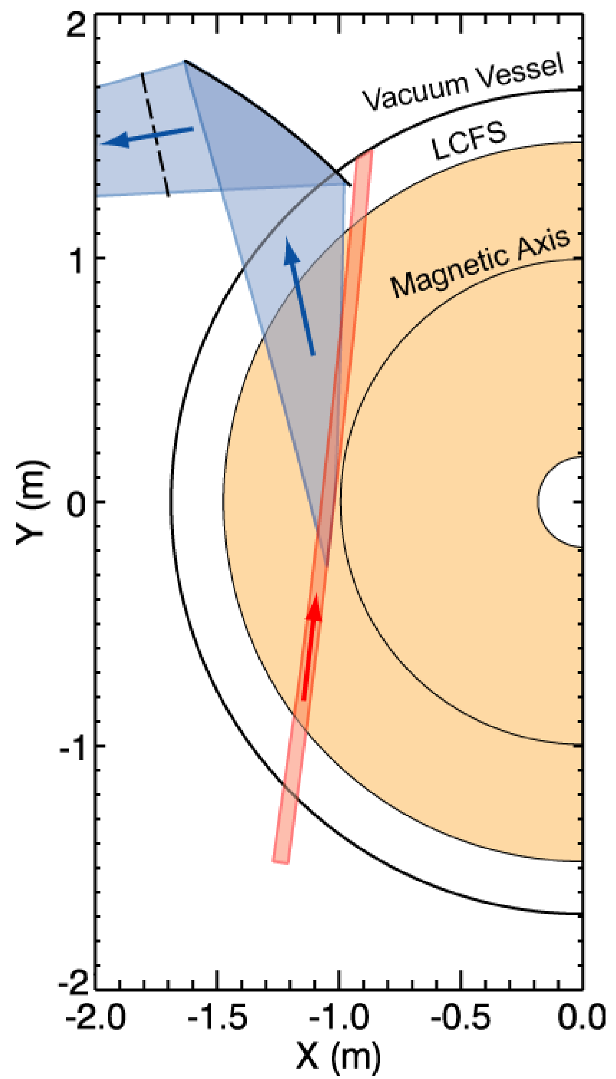
k-space resolution: $\Delta k = 2/a$

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

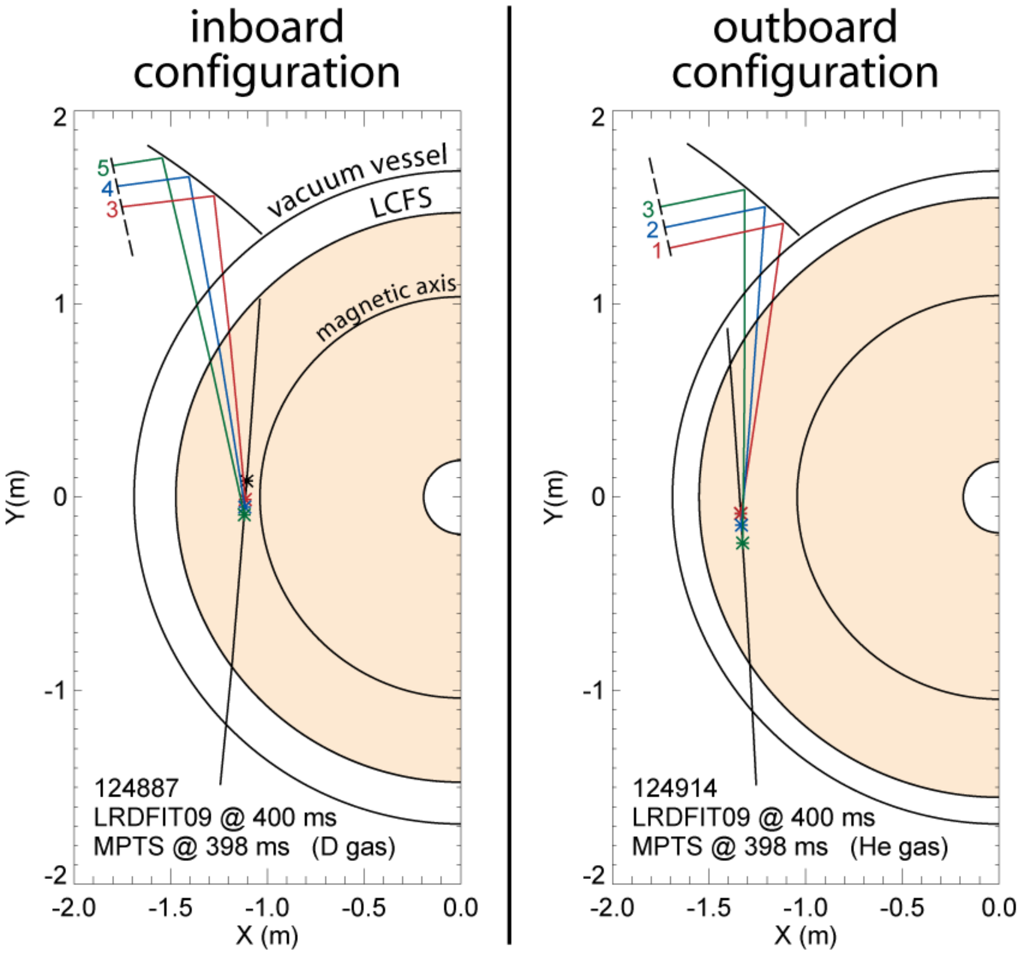
high-freq EM waves: $\omega_i, \omega_s >> \omega$

The NSTX collective scattering system measures fluctuations up to $k_\perp \rho_e \approx 0.6$

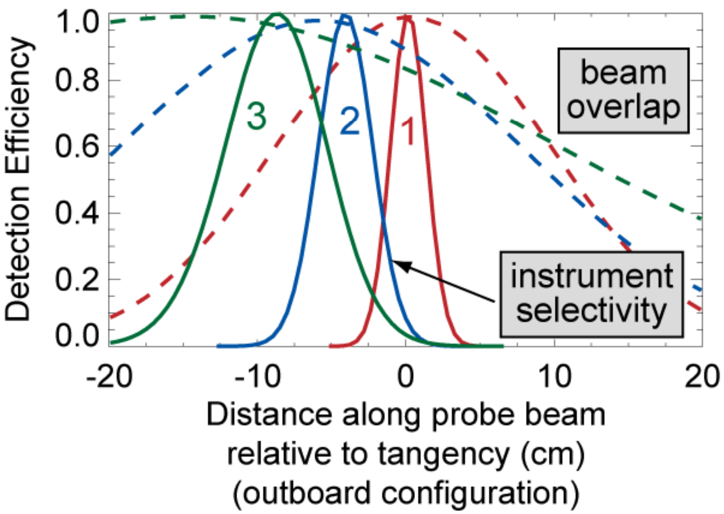
- 280 GHz collective scattering system
- Five detection channels
  - $k_\perp$ spectrum for up to five discrete $k_\perp$
    - $k_\perp \rho_e \lesssim 0.6$ and $k_\perp \lesssim 20\ \mathrm{cm}^{-1}$
  - ω spectrum from time-domain sampling
    - 7.5 MS/s $\rightarrow$ f $\leq$ 3.25 MHz
  - Heterodyne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



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

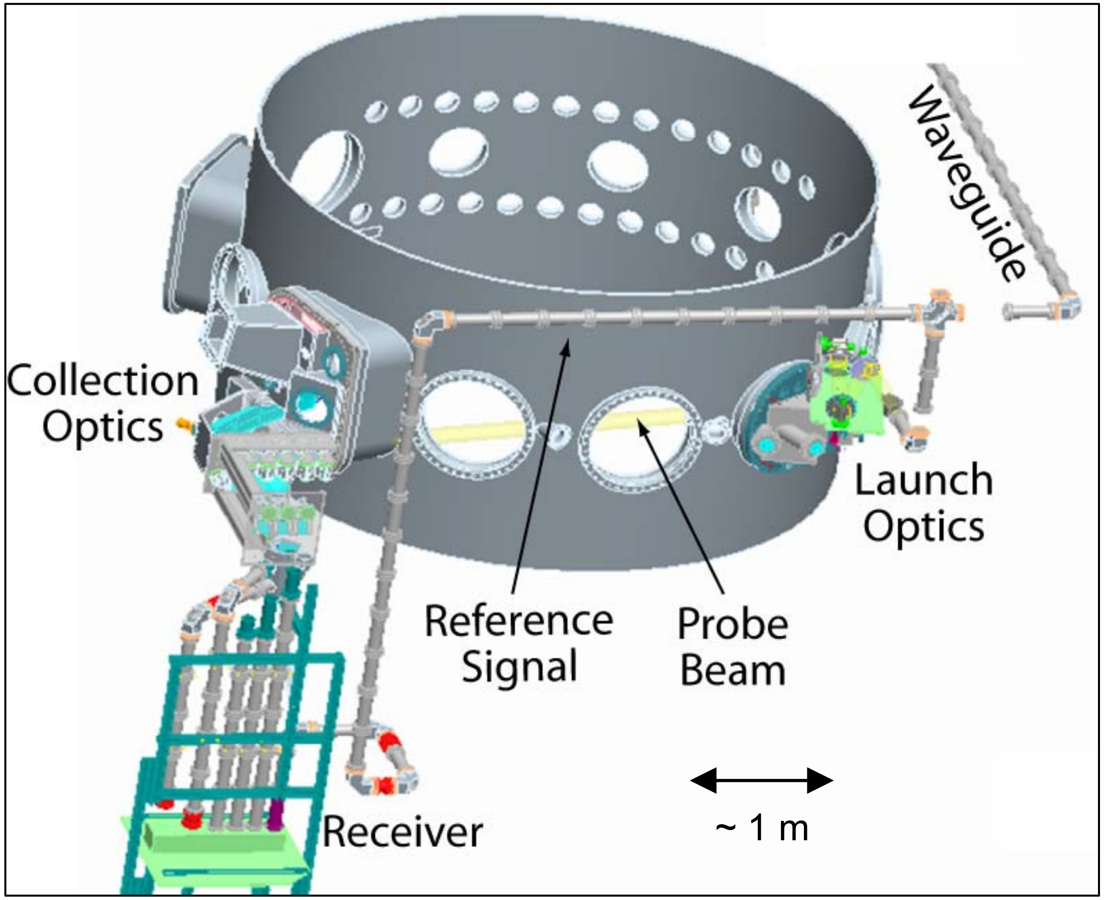


Large toroidal curvature imposes an instrument selectivity function that constricts the scattering volume within the overlap volume along the probe beam.



E. Mazzucato, PoP, 2003
E. Mazzucato, PPCF, 2006

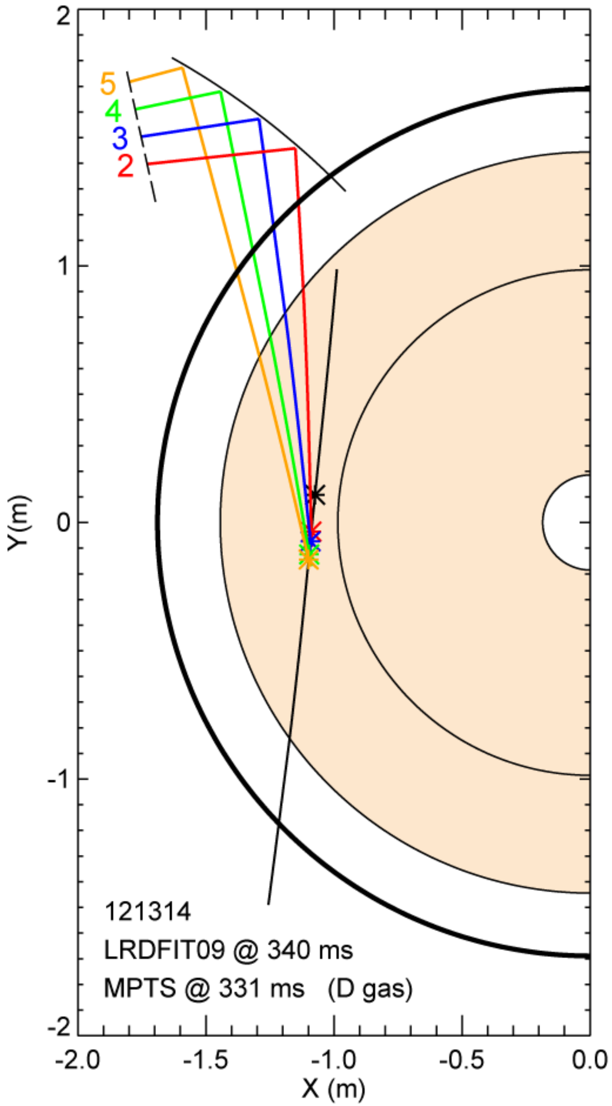
Scattering system hardware



- 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

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
$k_{\|\|}$ (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

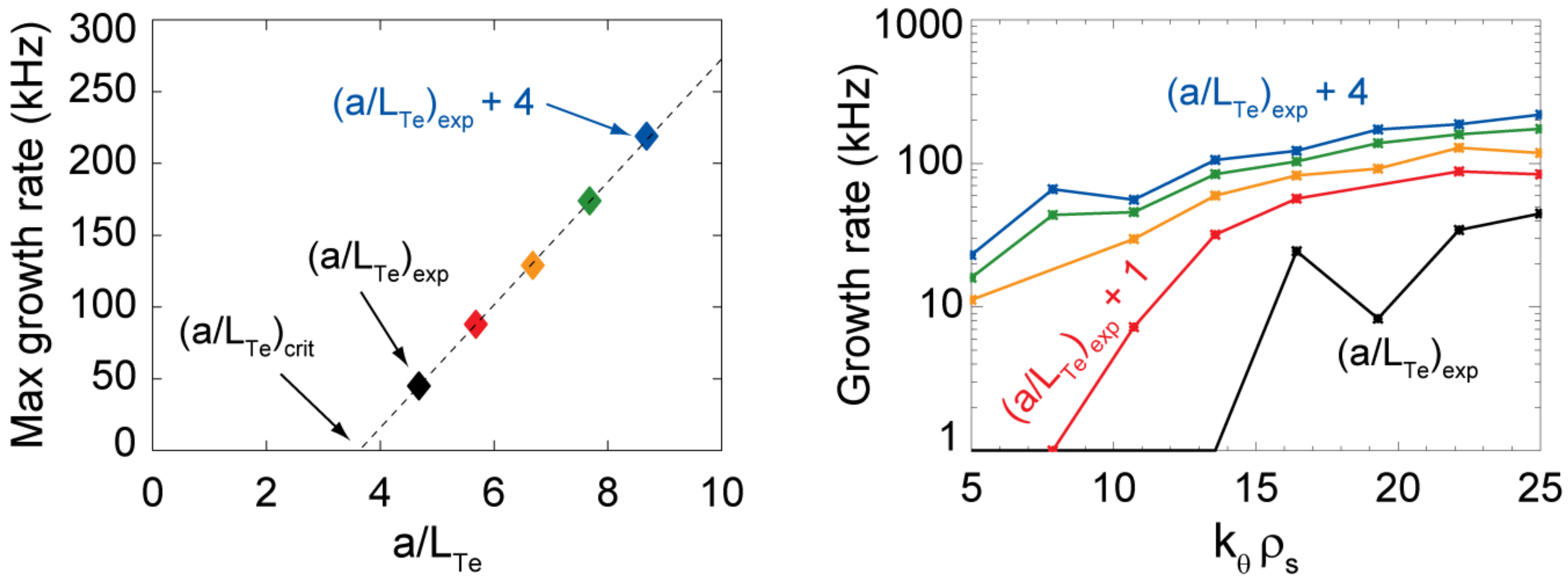
ETG scale

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



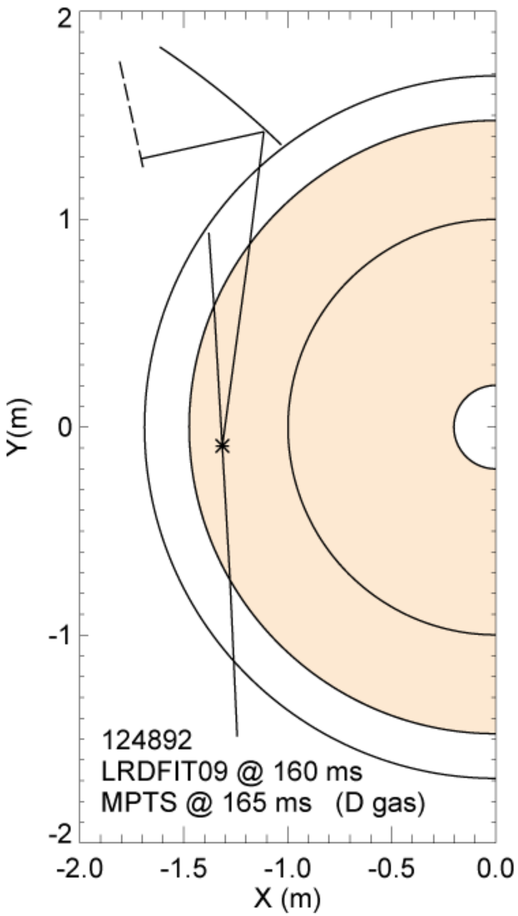
$$\left(\frac{R}{L_{Te}}\right)_{crit} \propto \left(1+\frac{Z_{eff}T_e}{T_i}\right)\left(1.33+1.91\frac{\hat{s}}{q}\right)$$

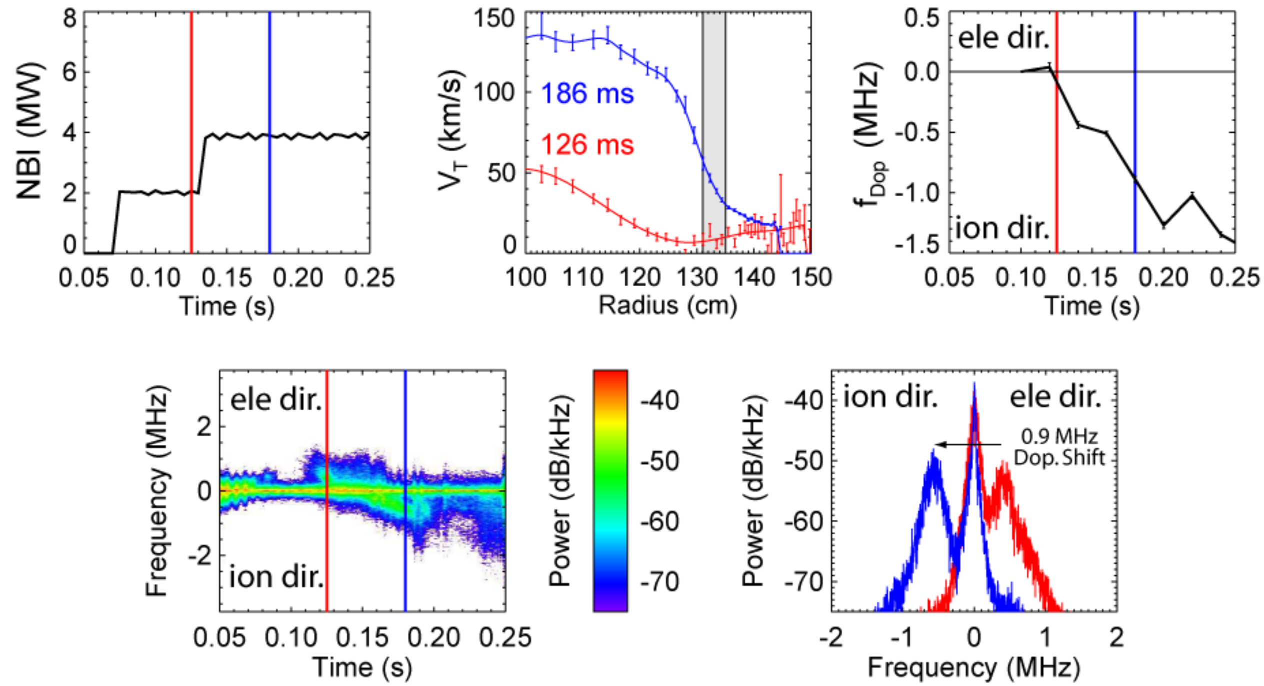
F. Jenko, Comp Phys Comm 2000

F. Jenko et al, PoP 2001

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

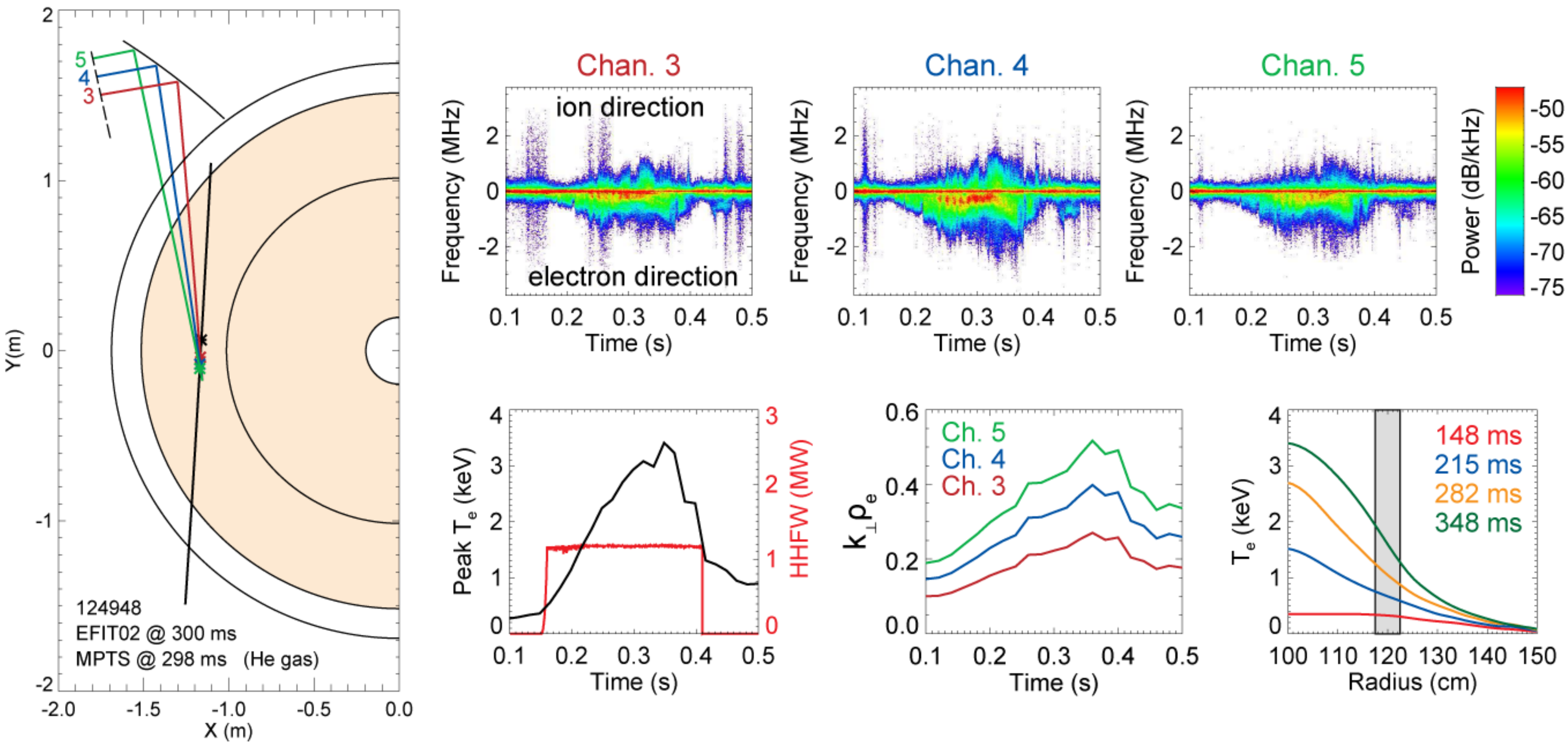
3.5 kG, 700 kA, 4 MW NBI, R=133 cm, r/a≈0.55



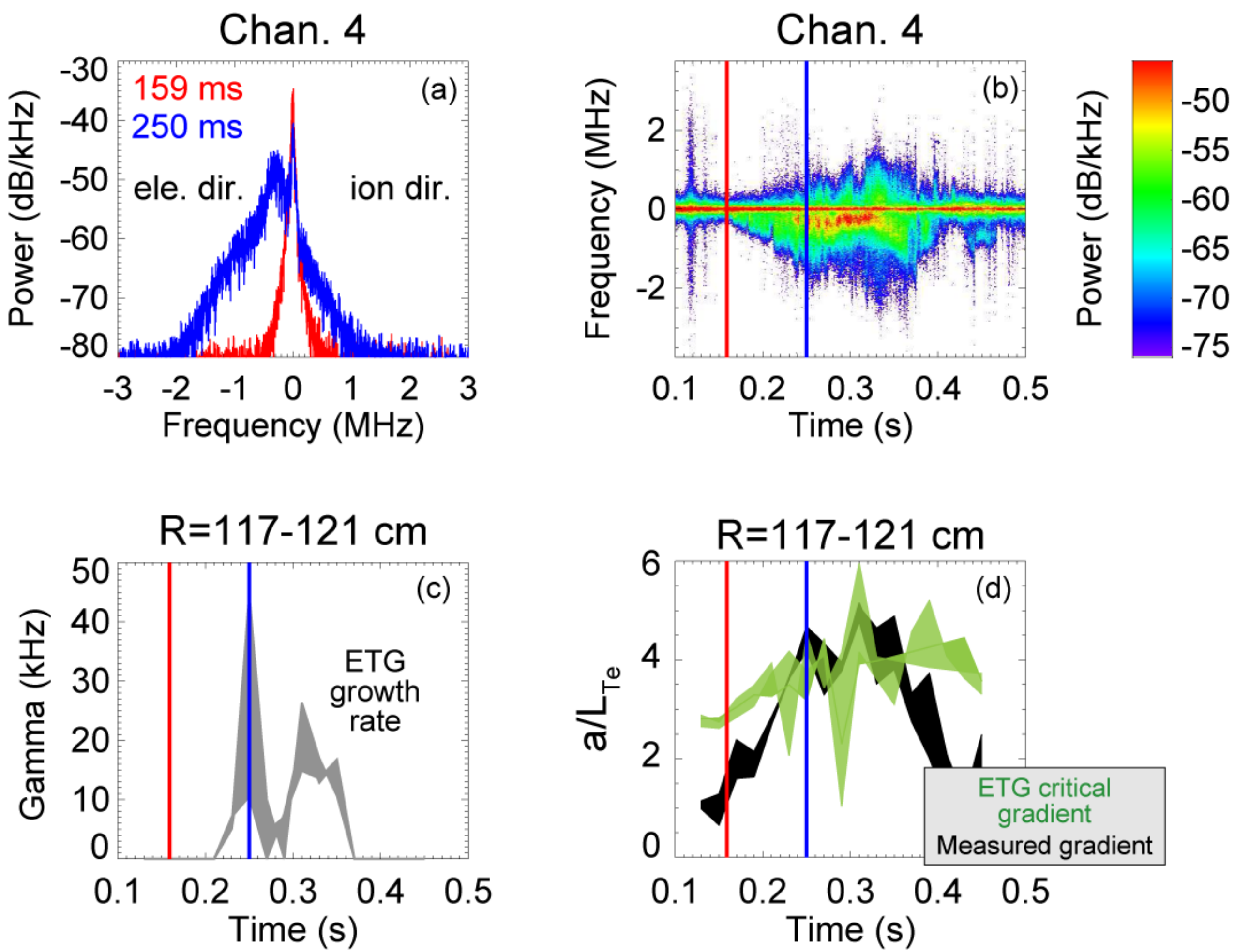


Spurious reflections of the probe beam produce the ubiquitous interferometric signal at 0 Hz.

5.5 kG, 600 kA, 1.2 MW HHFW, R=119 cm, r/a≈0.28



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

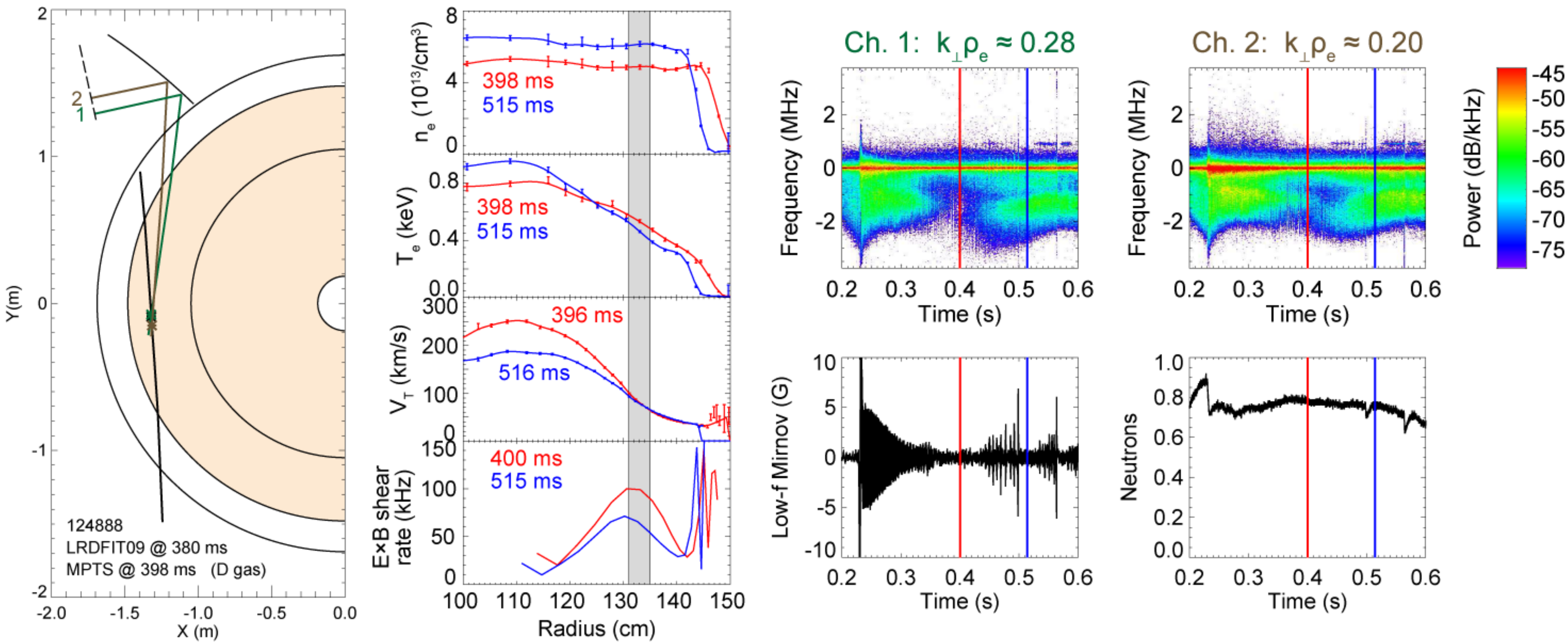


Similar observation at R=134±2 cm

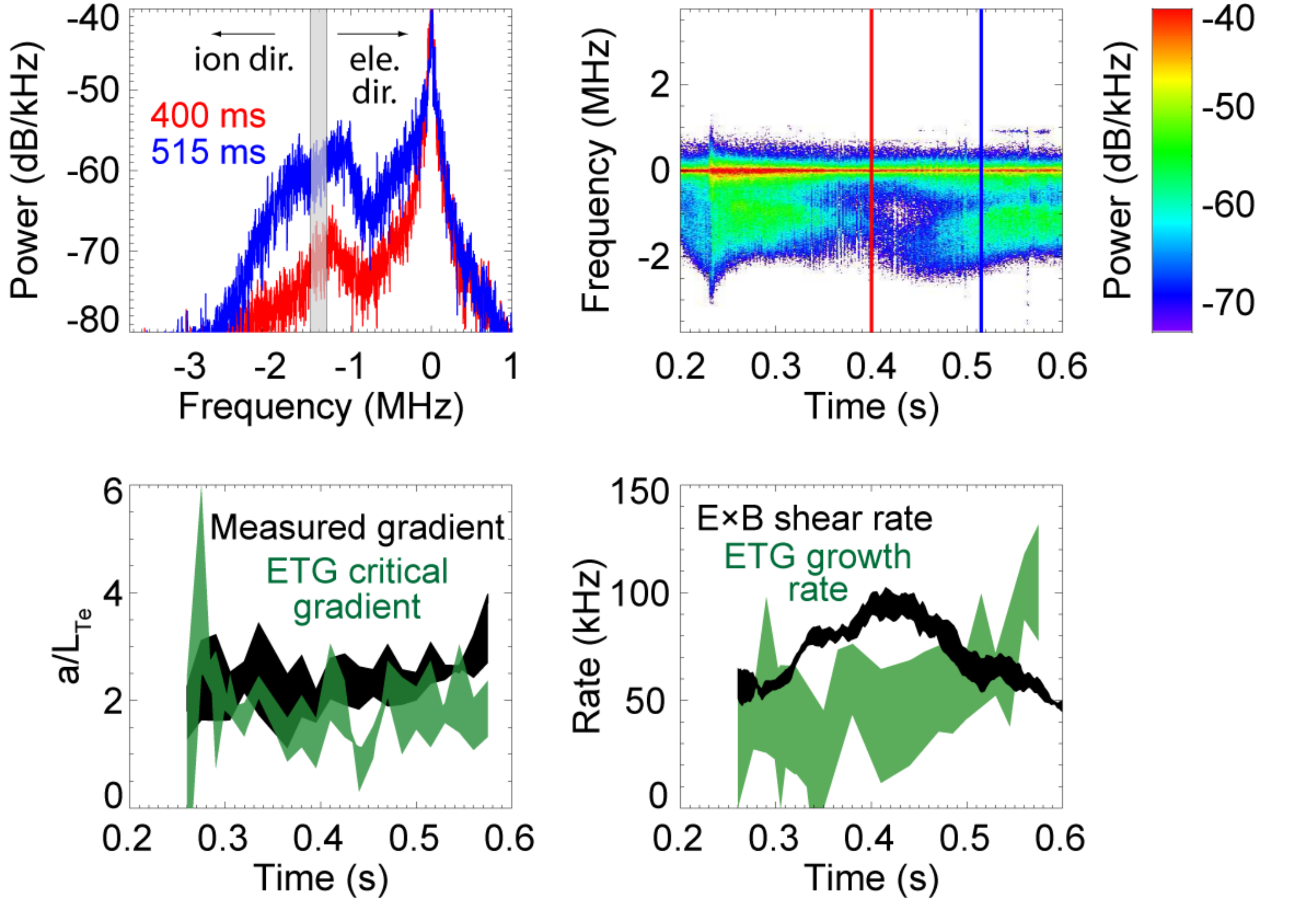
Mazzucato, Smith, et al, PRL, 2008

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

4.5 kG, 700 kA, 4 MW NBI, R=133 cm, r/a≈0.55



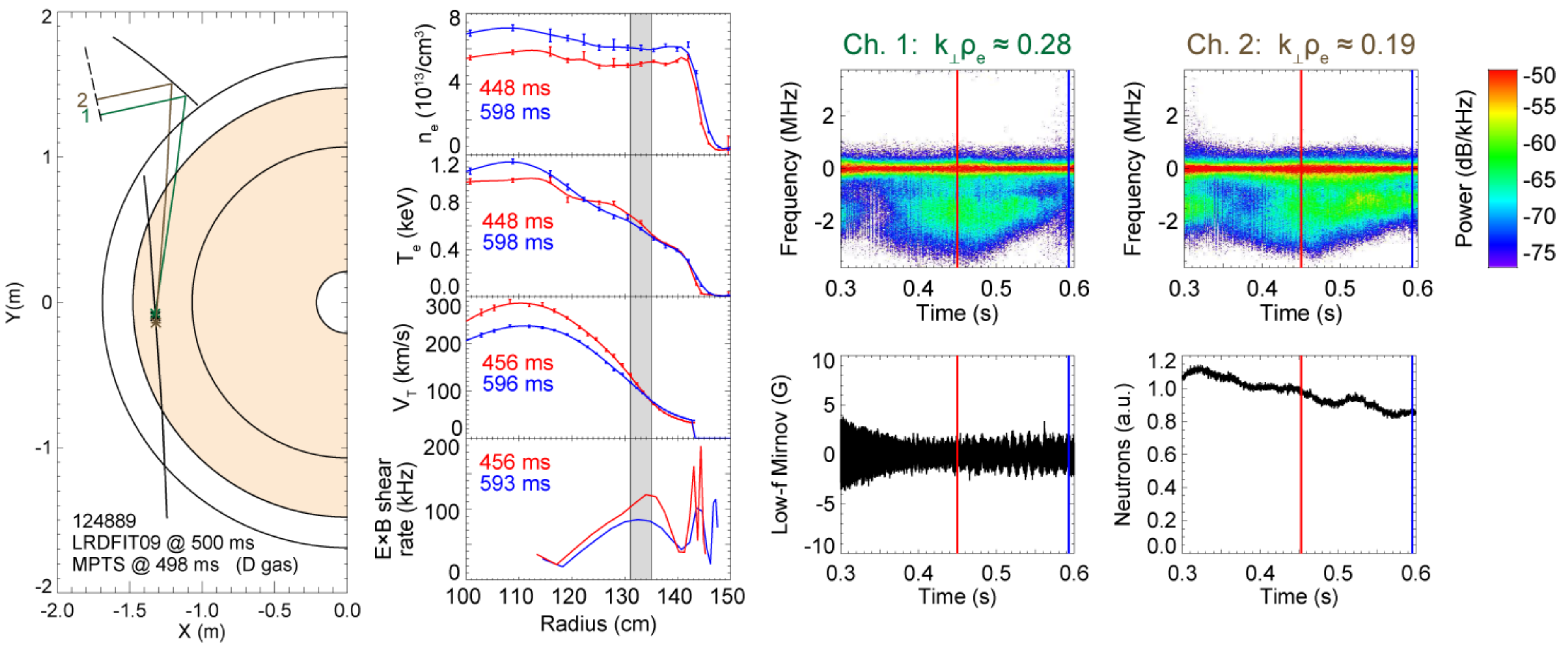
Near ETG marginal stability, fluctuation amplitudes decrease when the E×B shear rate exceeds the ETG growth rate



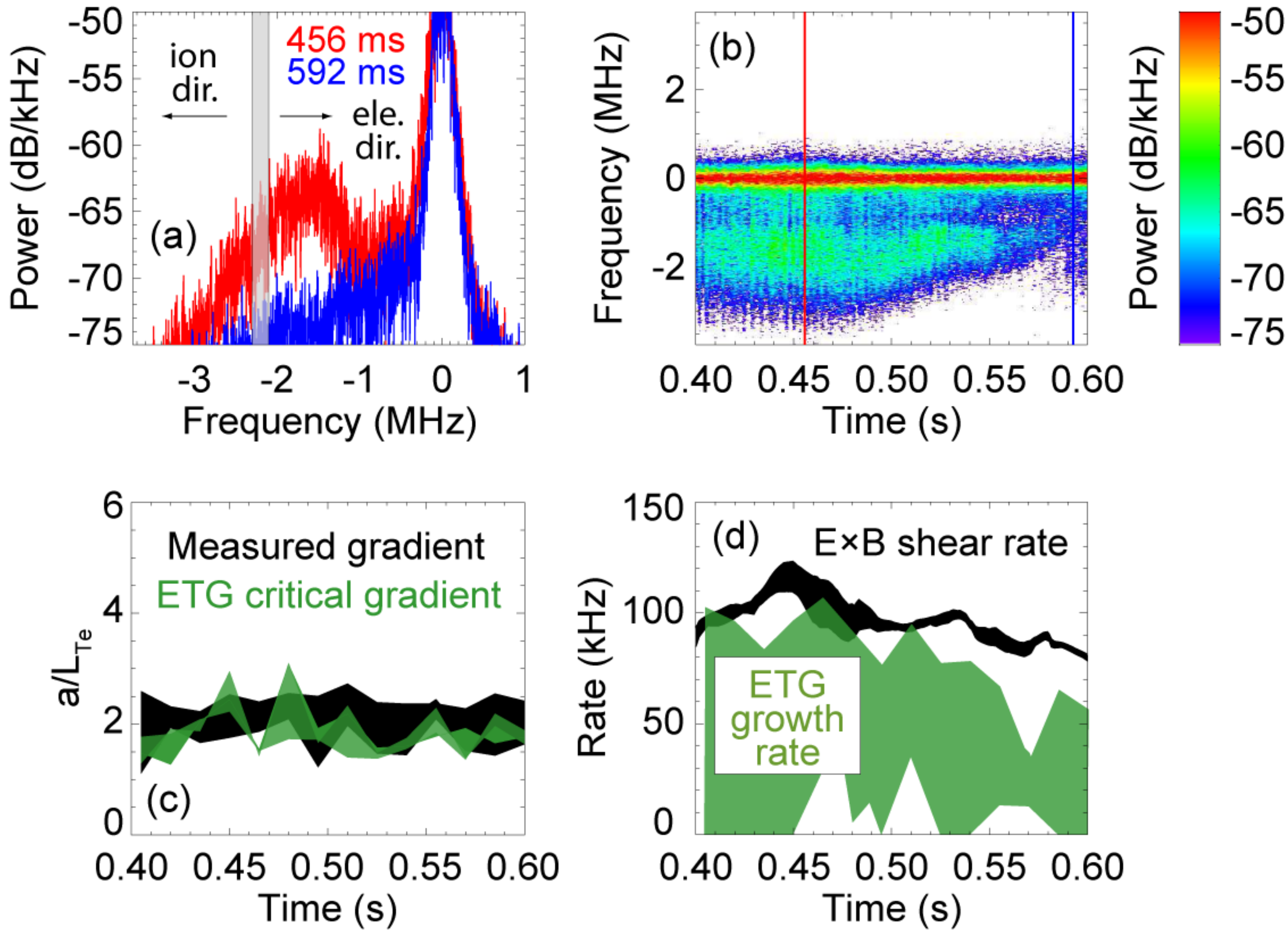
D. R. Smith et al, submitted to PRL

E×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 cm, r/a≈0.55

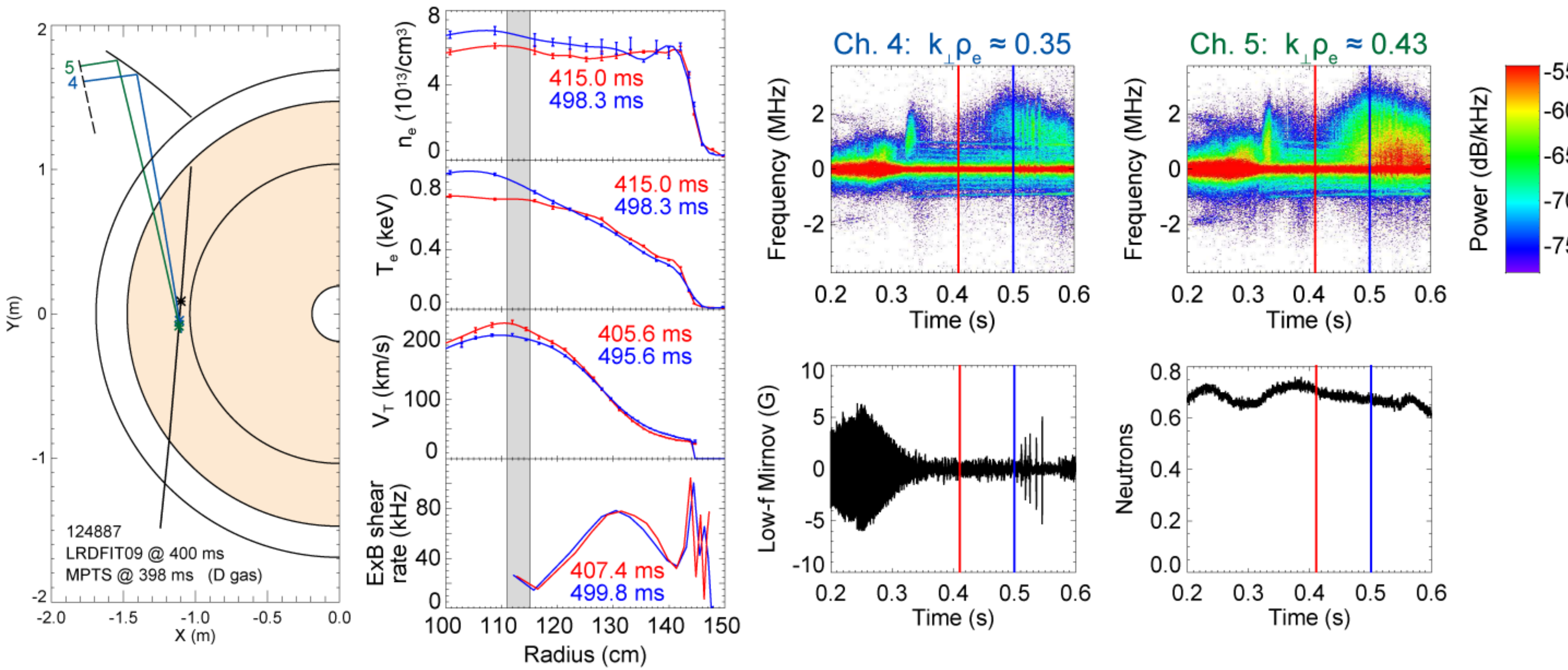


Near ETG marginal stability, fluctuation amplitudes decrease when the ETG growth rate drops below the E×B shear rate

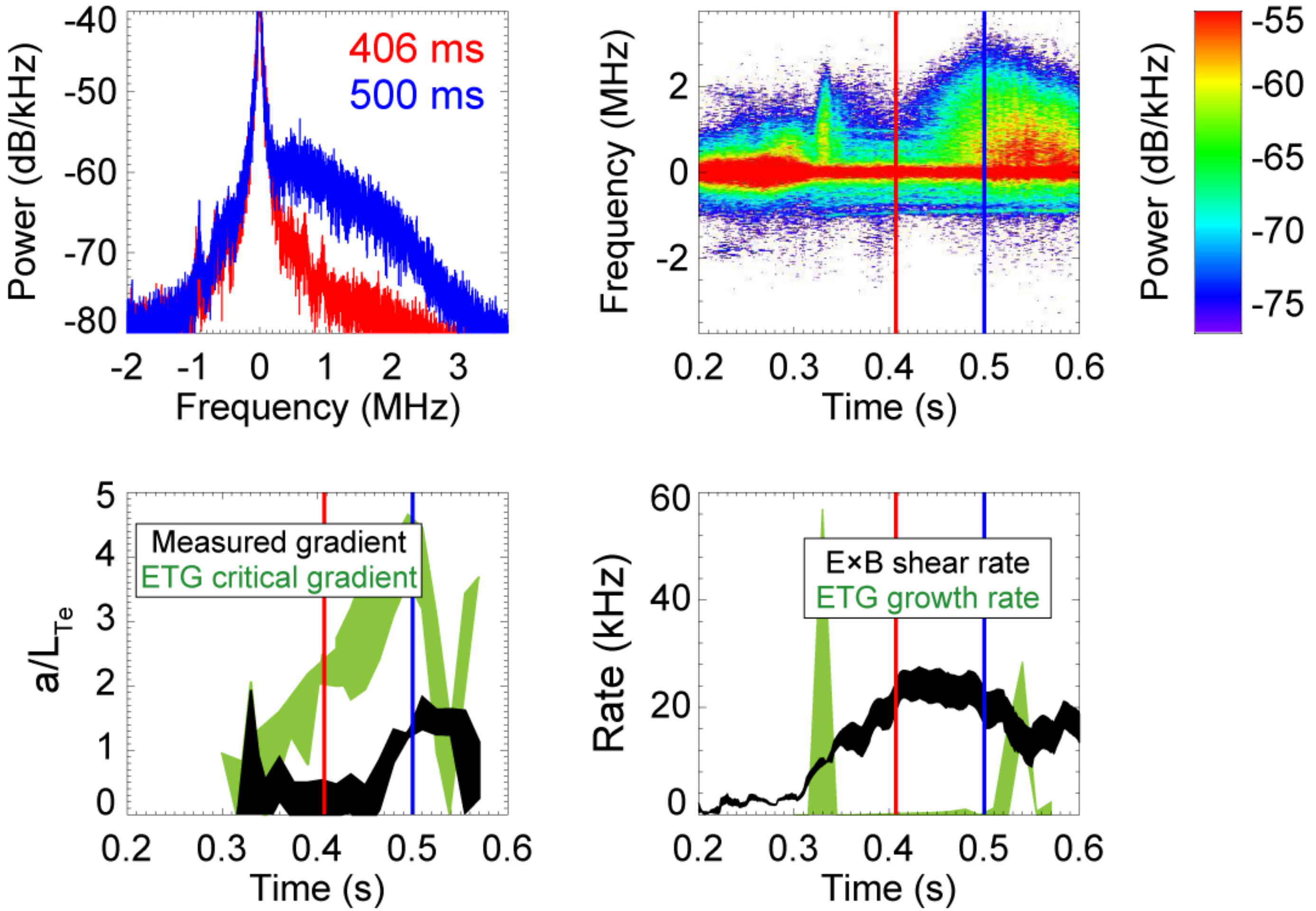


Enhanced fluctuations observed near magnetic axis in NBI-heated H-mode plasma

4.5 kG, 700 kA, 4 MW NBI, R=113 cm, r/a≈0.15

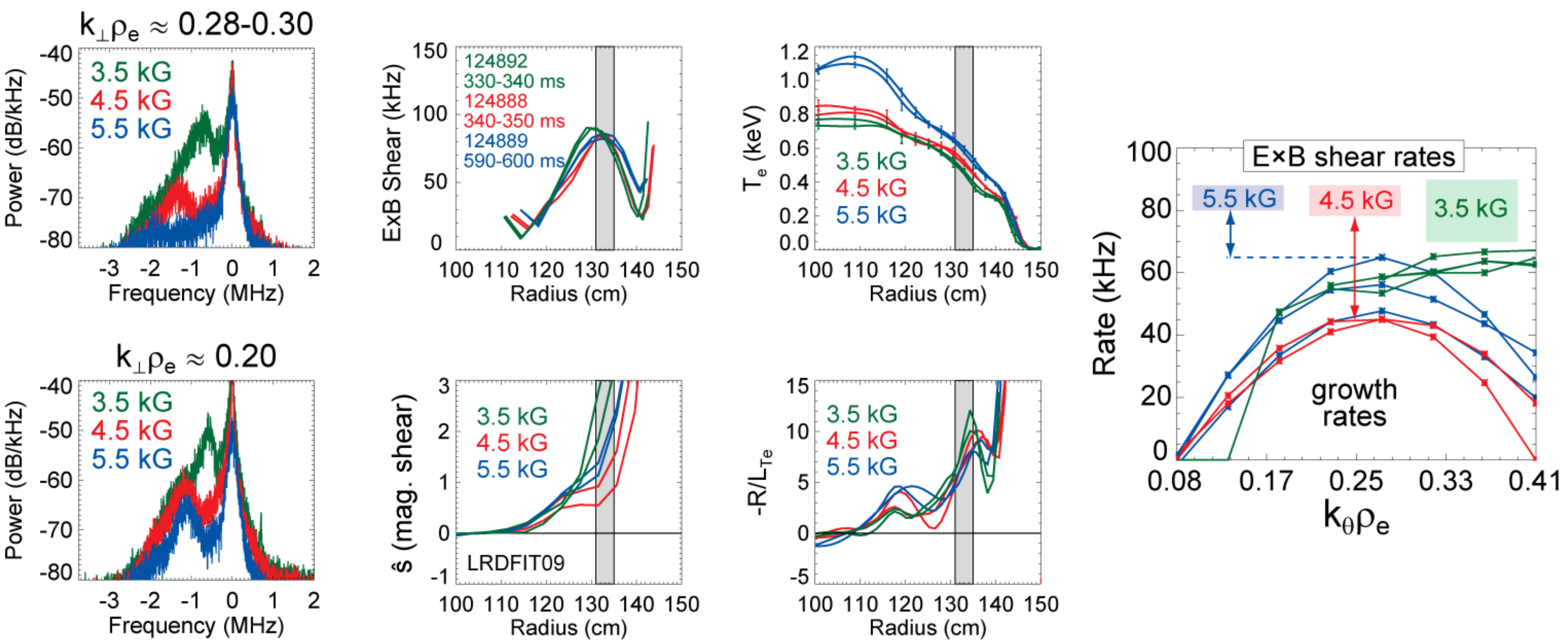


Enhanced fluctuations occur while the ETG mode is linearly stable



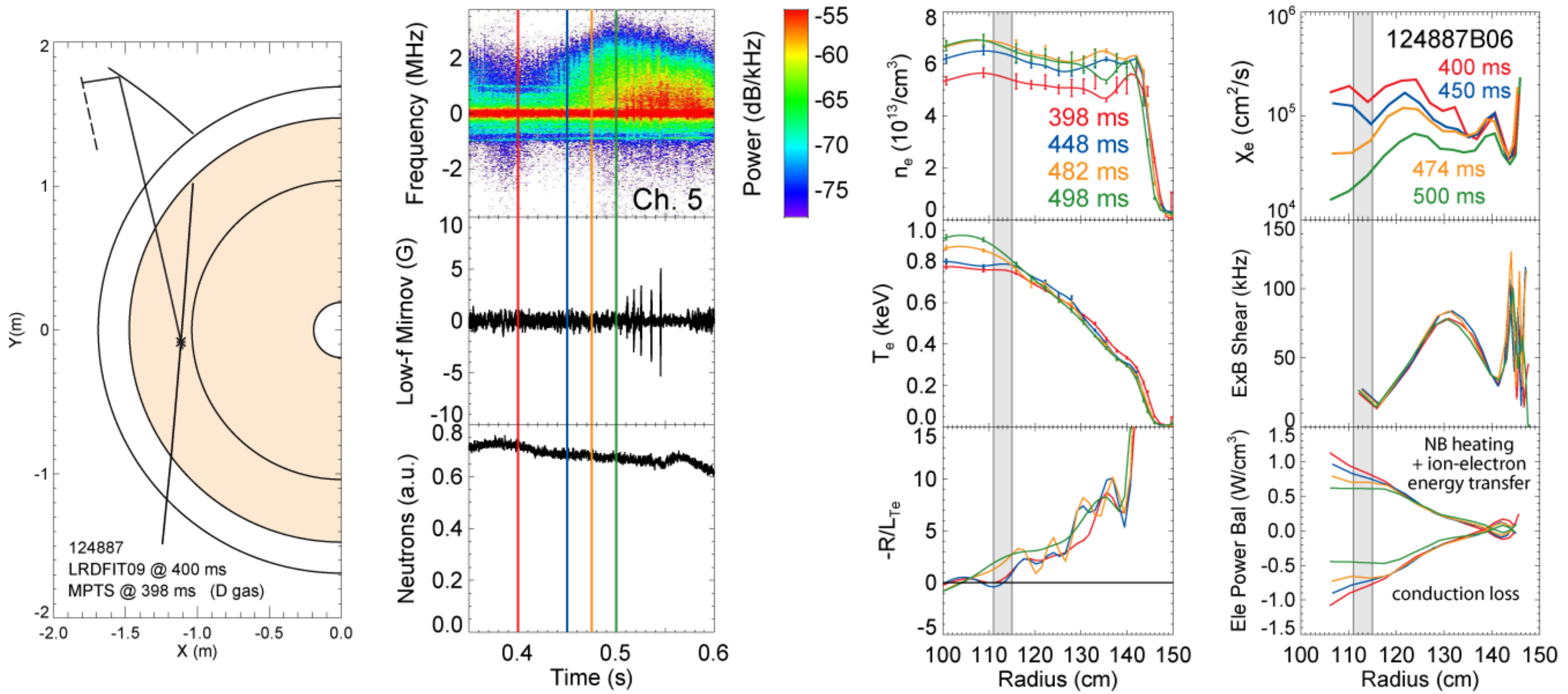
Turbulence spreading from outer plasma to core?

Fluctuation amplitudes decrease at higher B_T with similar E×B shear rates, ETG growth rates, and ∇Te



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

Electron thermal diffusivity decreases when fluctuation amplitudes increase



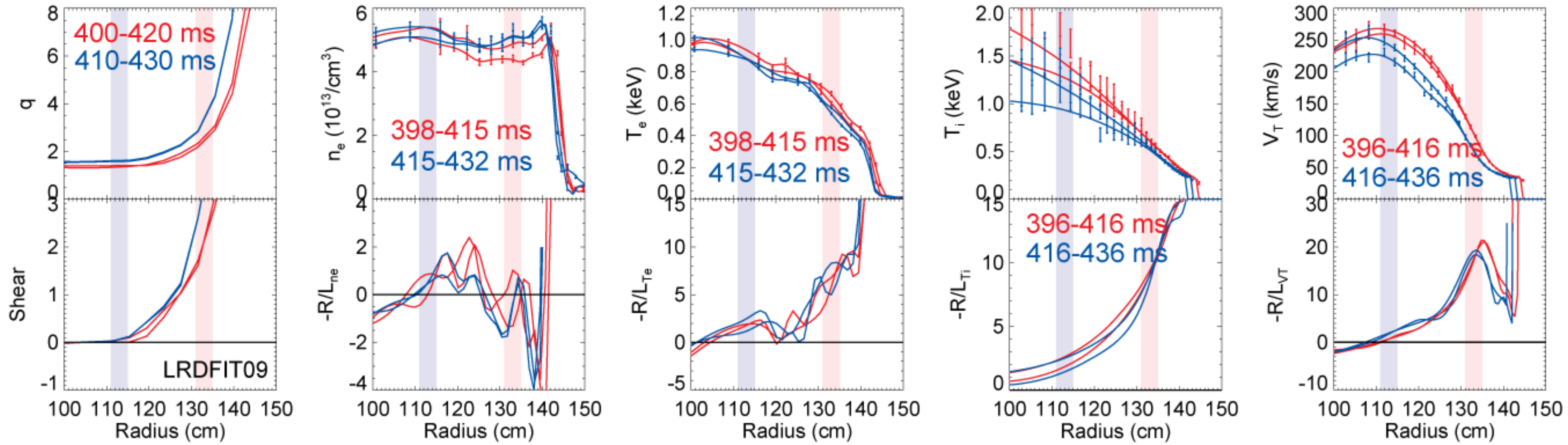
Observation suggests fluctuations simply respond to local plasma conditions without generating transport

Fluctuation magnitudes and wavenumber spectral exponents

5.5 kG discharges

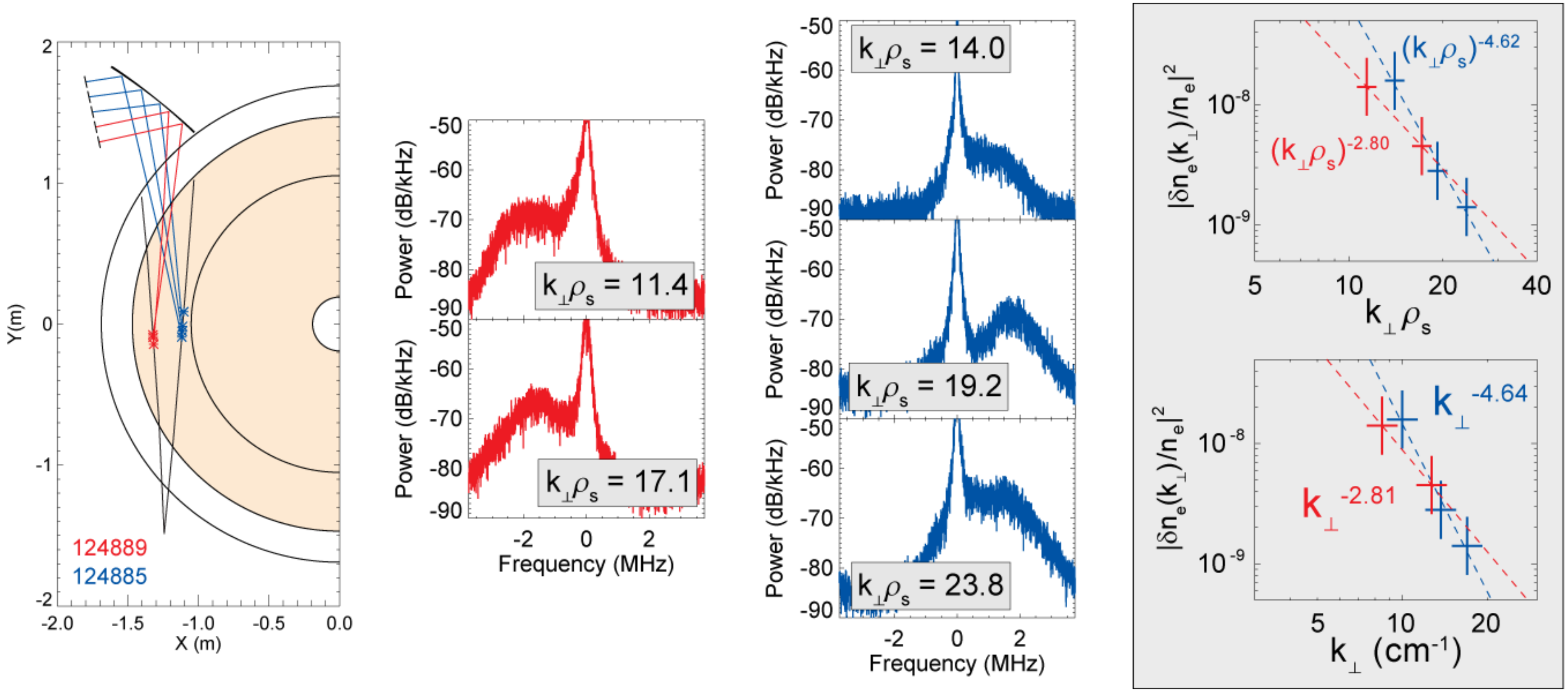
124885 @ R=111-115 cm

124889 @ R=131-135 cm



$$\text{k-spectrum:} \quad |\delta n_e(k_r)/n_e|^2 \propto k_r^{-\alpha}$$

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



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

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; XP submitted 2/23/09
- 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

Contributions to the NSTX program

- Contributions to the design, fabrication, and installation of the NSTX collective scattering system
  - Quasi-optical design
  - Waveguide and mirror placement
  - Steerable exit window mirrors
- Extensive alignment and calibration activities
  - Alignment mappings with FaroArm measurements
  - Power and frequency response calibrations
- Computational tools used by other NSTX team members
  - Ray tracing code
  - GS2 tools (~16k linear GS2 runs, ~400k CPU-hrs, ~50 CPU-yrs)
- Key role in meeting NSTX milestones
  - R(06-1) in FY06 and R(07-1) in FY07
- 3 invited talks, 2 RSI papers, 1 PRL submitted, and 1 APS-DPP invited paper in prep for PoP
  - plus contributions to invited talks and papers by Ernesto and Howard

Summary of physics results

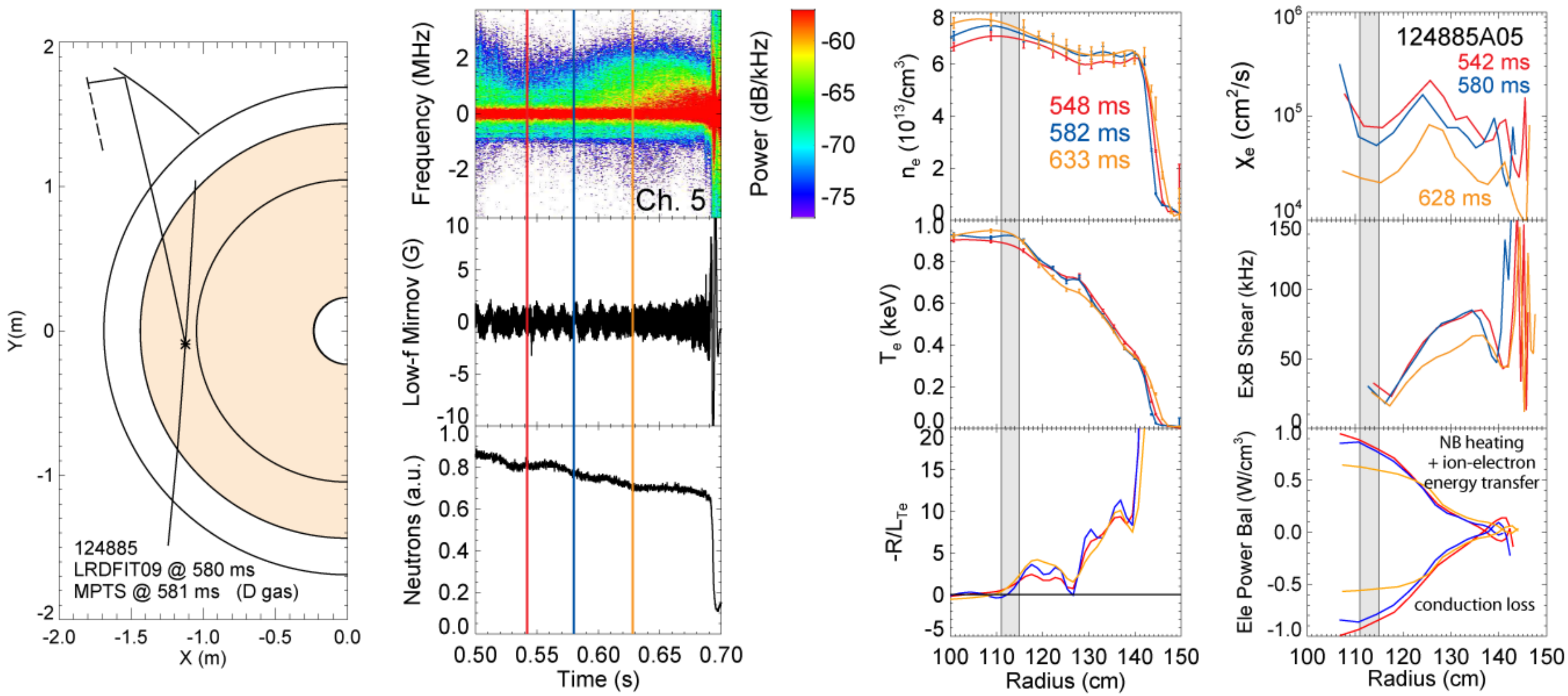
- In L-mode plasmas, enhanced fluctuation amplitudes occur when ∇T_e is comparable to or exceeds the ETG critical gradient
- At mid-radii in H-mode plasmas with large toroidal rotation, fluctuation amplitudes decrease when the E×B shear rate exceeds the ETG growth rate
- Near the magnetic axis in H-mode plasmas, enhanced fluctuations were observed without unstable ETG modes
- 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
- Transport analysis fails to establish a correlation between larger fluctuation amplitudes and higher electron thermal diffusivity
- Fluctuation magnitudes, $|\delta n_e(k_r)/n_e|^2 \approx 10^{-9} - 10^{-8}$, 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

Acknowledgements

Ernesto Mazzucato (advisor), Hyeon Park (prior co-advisor), Woochang Lee, Cynthia Phillips, Stan Kaye, Dave Mikkelson, Howard Yuh, Ron Bell, Ben LeBlanc, Bob Kaita, Greg Hammett, Phil Efthimion, Mike Bell, Russ Feder, John Trafalski, Barbara Sarfaty, Jon Menard, Masa Ono, Luc Peterson, Mark Normberg, and many others

Backup slides

Again, electron thermal diffusivity decreases when fluctuation amplitudes increase



Similar magnitudes and exponents at lower TF

4.5 kG discharges

124887 @ R=111-115 cm

124888 @ R=131-135 cm