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Progress in understanding turbulence on the ion and electron gyroscales in NSTX plasmas

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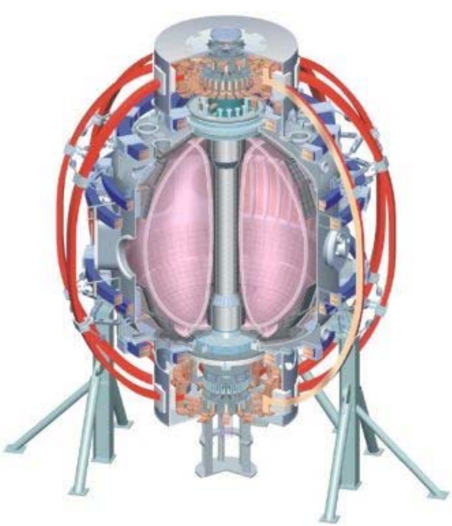
Experimental Seminar, PPPL
March 22, 2011



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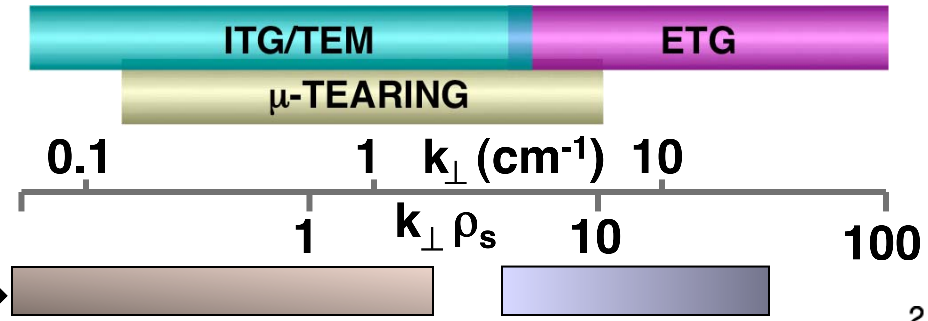
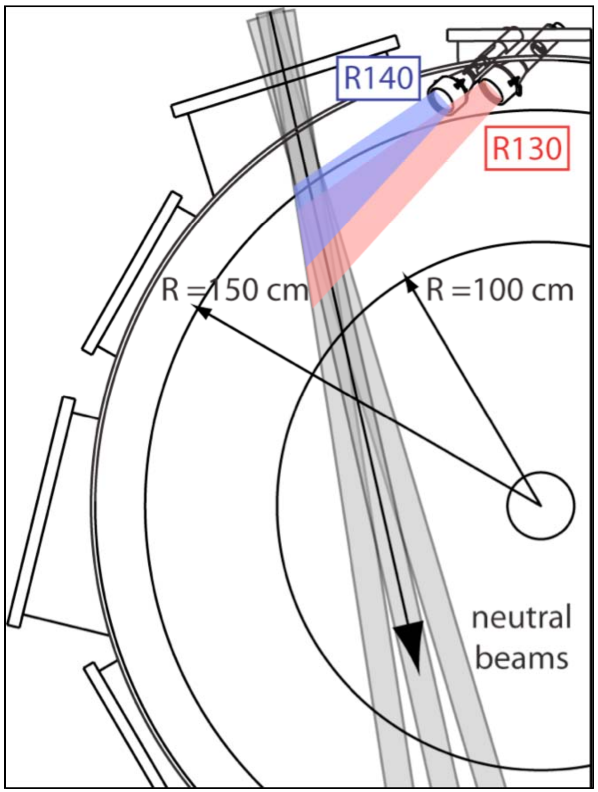
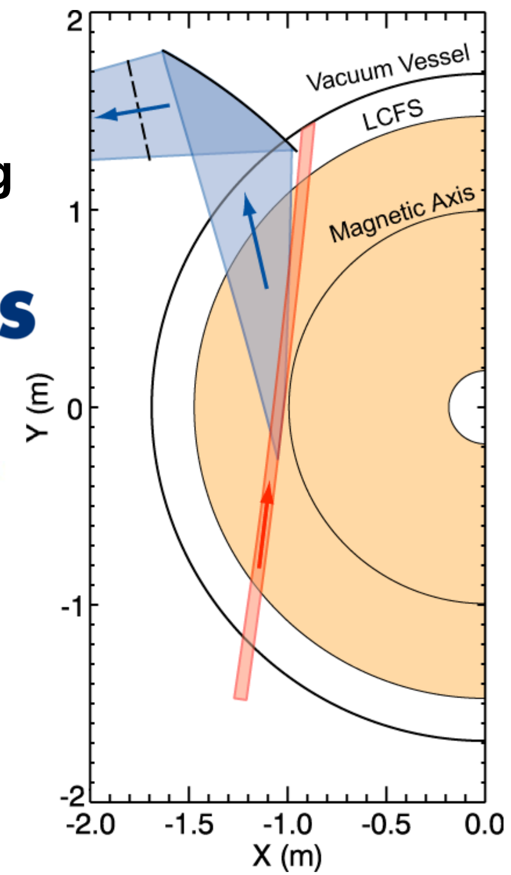
Beam emission spectroscopy (BES) and high-k scattering provide turbulence measurements spanning the ion to electron gyroscales



Low-k BES →

↑ High-k Scattering





Outline

- BES diagnostic overview and preliminary results
  - Reversal of eddy poloidal motion in pedestal across LH transition
  - Preliminary |B| scaling for poloidal correlation lengths
  - Post-ELM harmonic features (~50-150 kHz) localized at top of pedestal
- Review of high-k scattering measurements and ETG turbulence results
  - Is ETG turbulence anisotropic in k_θ-k_r plane as predicted by GK simulations?
- Identification of high-k microtearing modes
  - Comparison to ETG modes, ITG/TEM modes, and conventional microtearing modes
- Low coherence backscattering
  - Novel plasma fluctuation measurement (1-D profile and 2-D imaging) that uses low coherence radiation
  - Inspired by a biomedical imaging technique
- Summary

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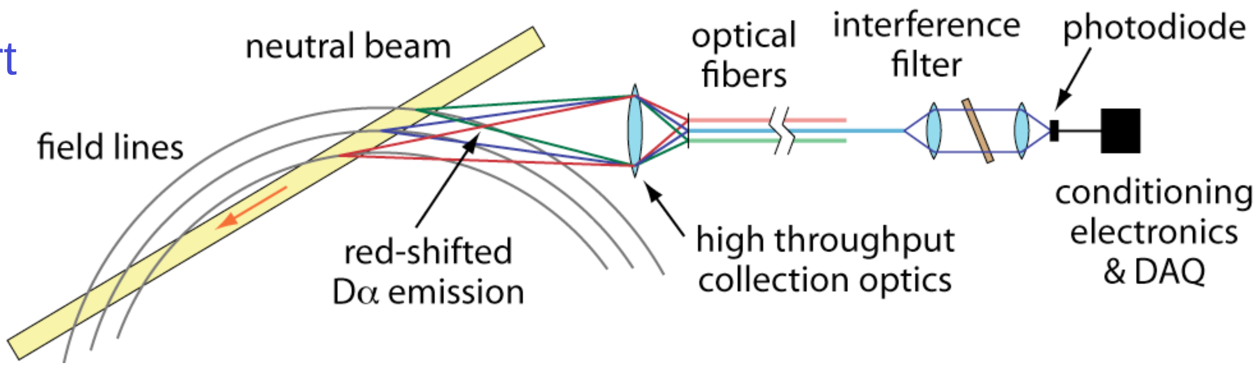
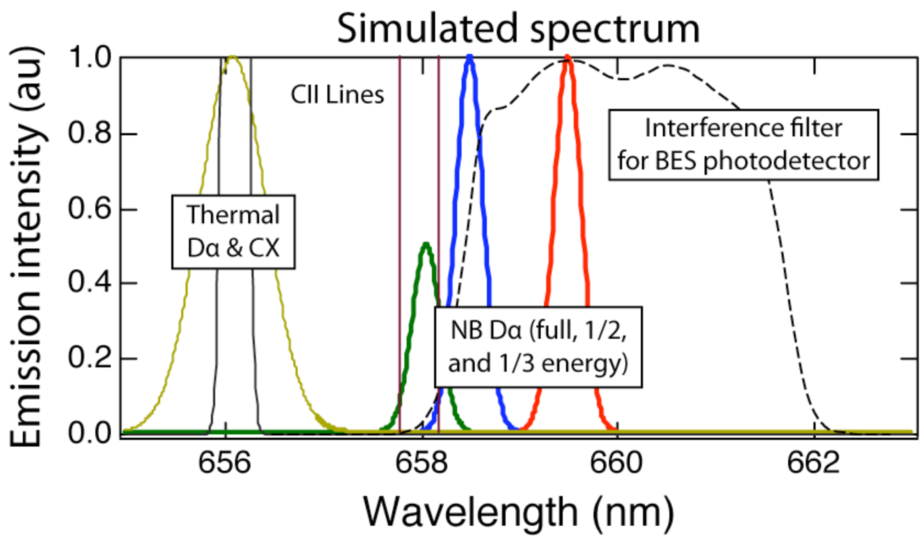
Beam emission spectroscopy provides localized, long-wavelength fluctuation measurements with $k_\perp \rho_i < 1$

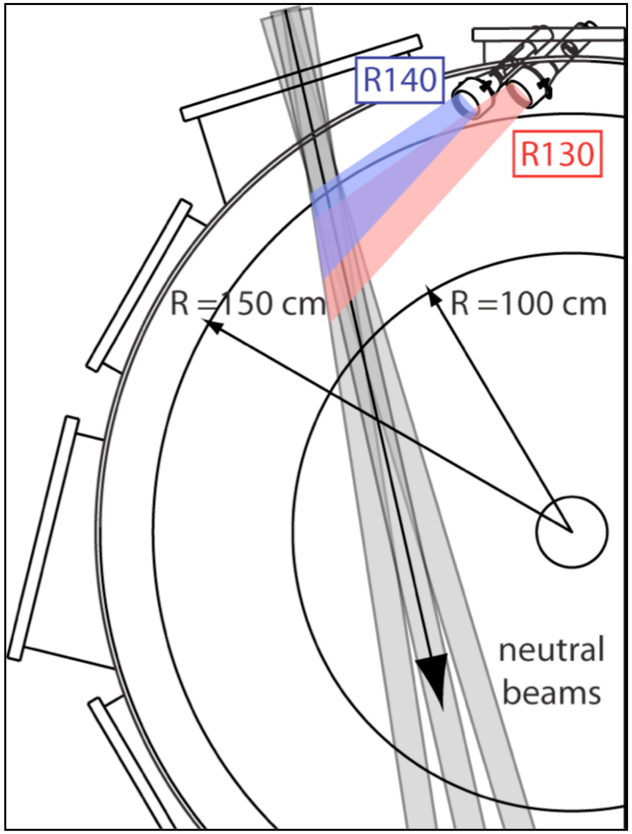
- BES measurements contribute to several NSTX research areas
  - Turbulence and transport
    - ITG/TEM turbulence
    - ZFs and GAMs
    - Flow fluctuations
  - Boundary physics
    - LH transition
    - Pedestal & SOL fluctuations
    - ELMs and EHOs
  - Waves-particle interactions
    - TAE/EP/GAE modes
    - Mode coupling





The NSTX BES system was commissioned in 2010

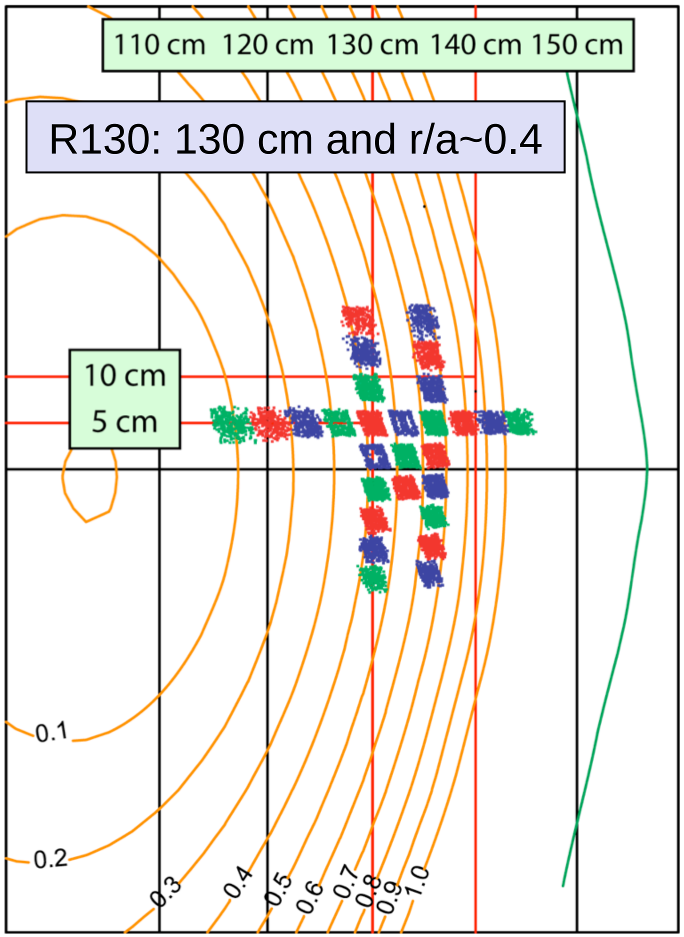
- Doppler shift and optical filter isolate NB D_α emission from thermal D_α
- Two optical views are aligned to steep pitch angles in NSTX plasmas

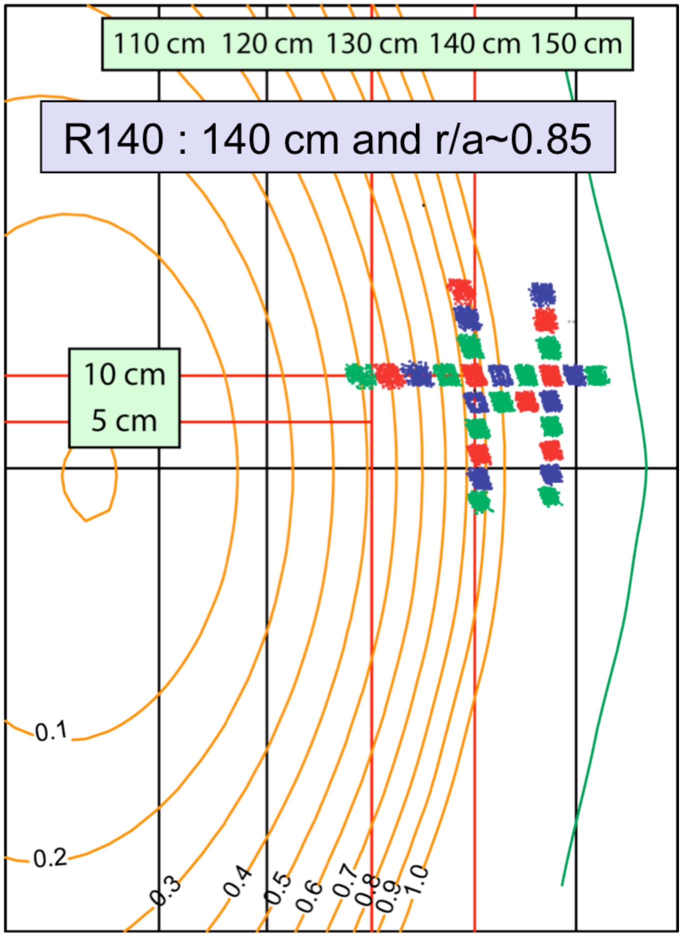


D. R. Smith et al, **RSI** 81, 10D717 (2011)

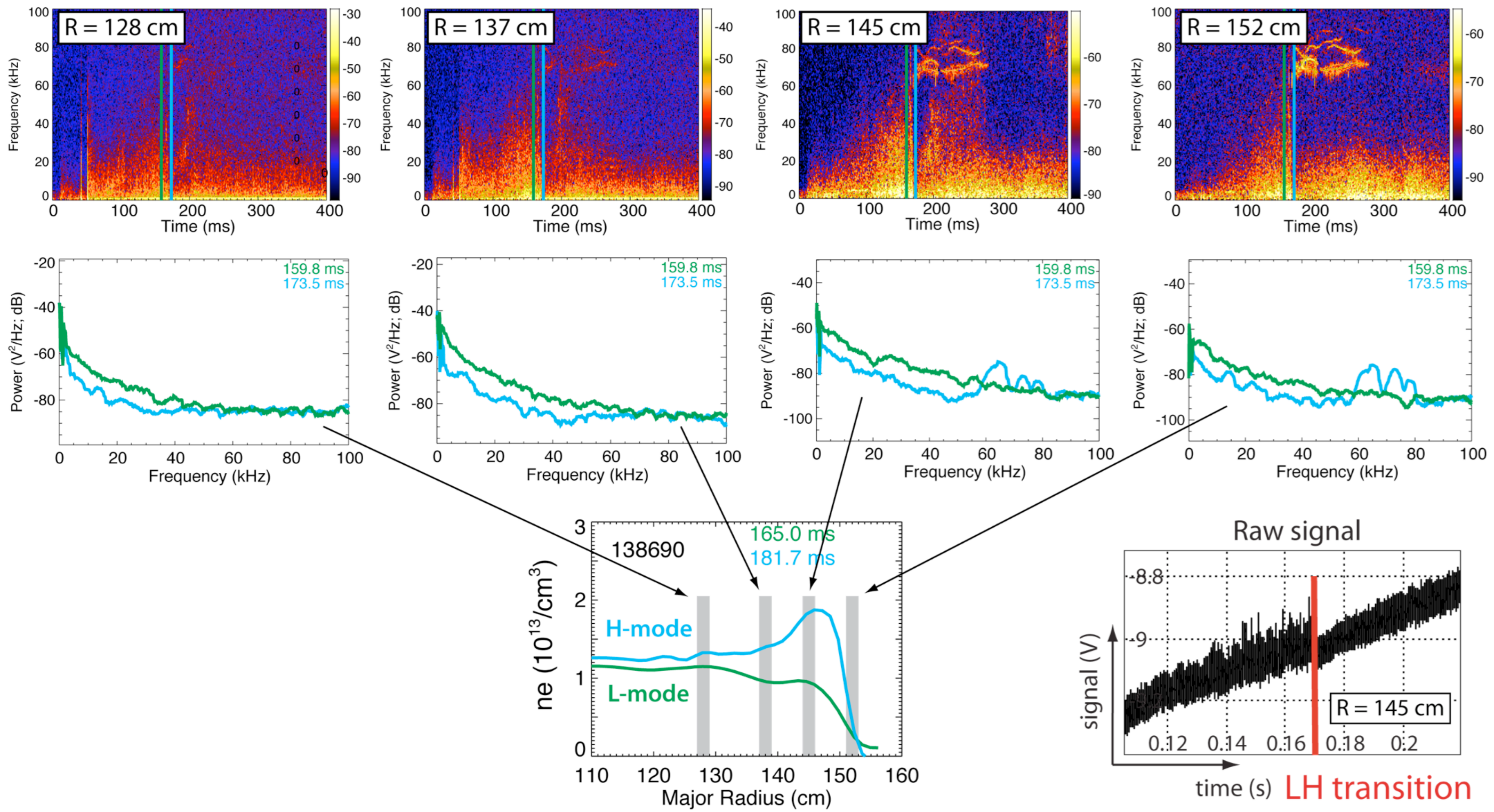
Two optical views with 56 fiber bundles provide radial coverage from r/a ≈ 0.1 to SOL with 2-3 cm spot sizes

Image patterns provide radial and poloidal correlation lengths, k-spectra, and flow fluctuations



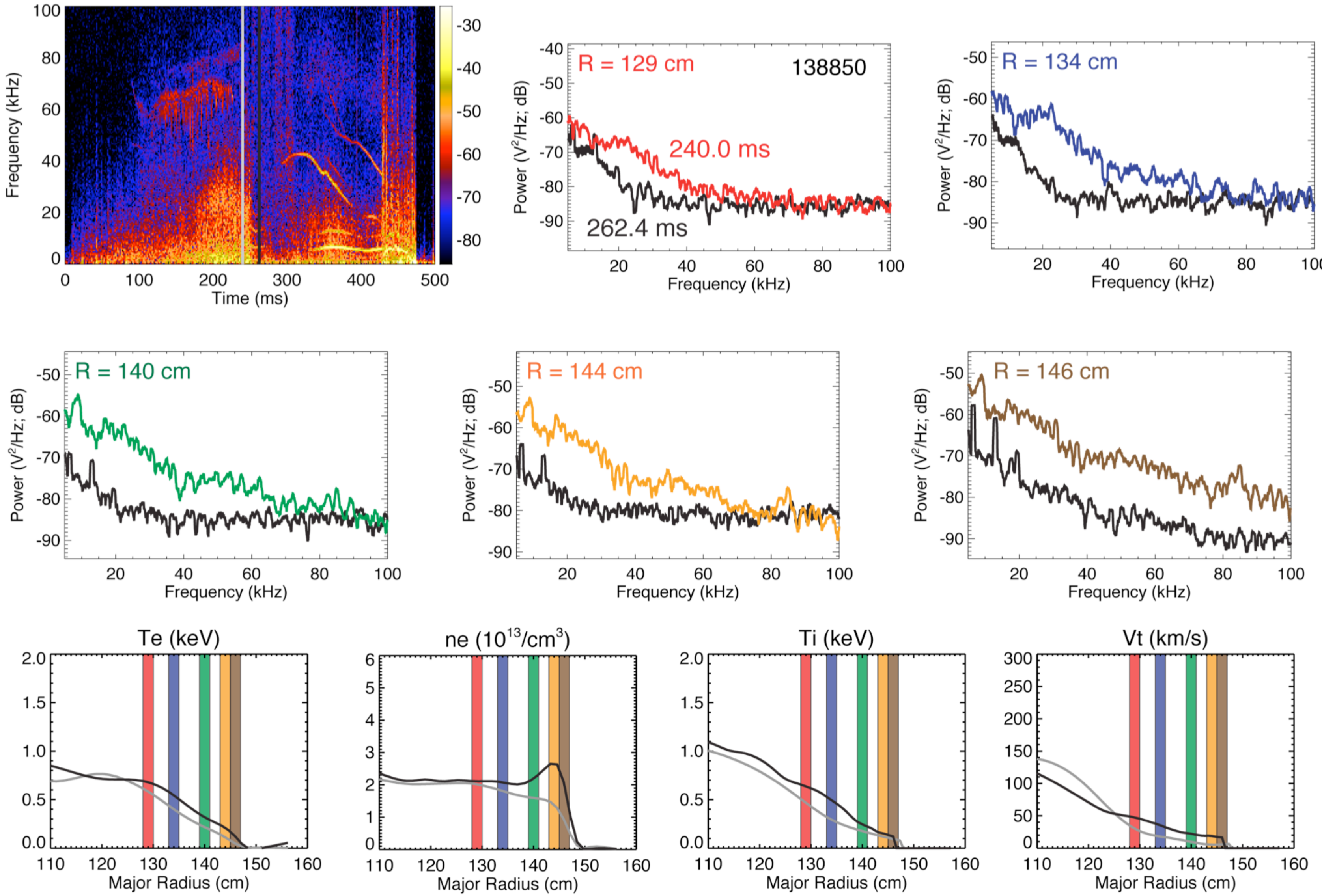


Decrease in fluctuations at LH transition observed from edge to core in some discharges



Also, some HL back-transitions have exhibited an increase in fluctuations

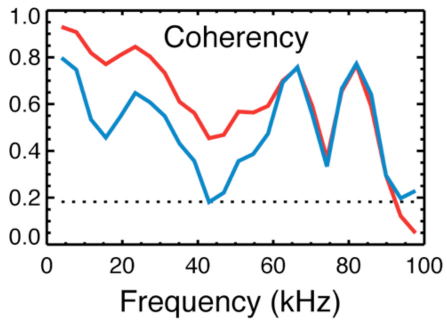
Decrease in fluctuations at LH transition observed from edge to core in some discharges

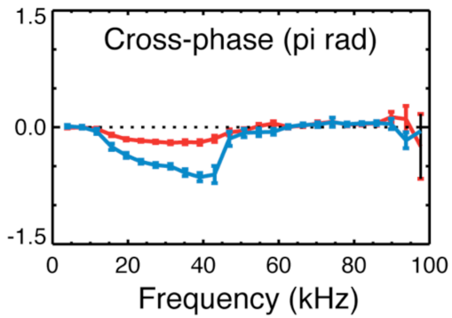


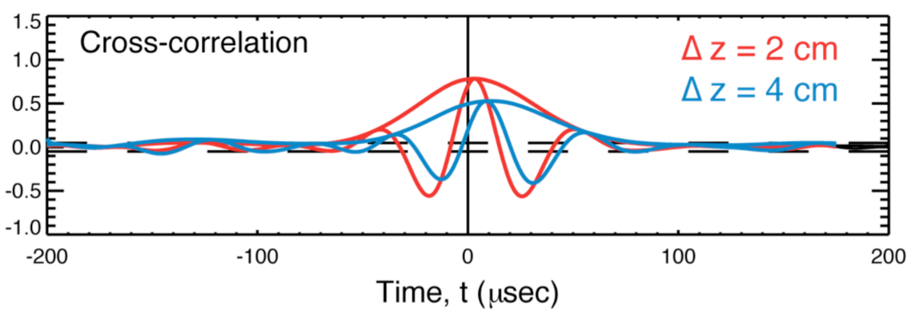
Correlation analysis indicates the apparent motion of eddies changes from up to down at the LH transition

Poloidal coherency/correlation in 138850 at R = 140 cm

L-mode phase: 219-249 ms

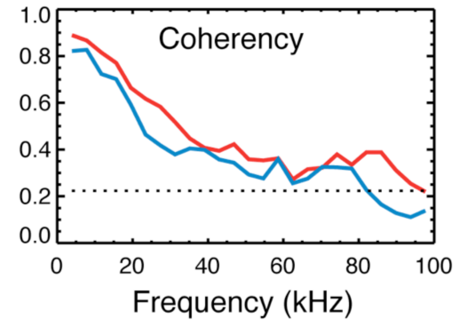


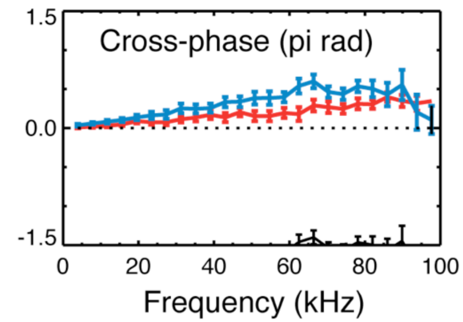


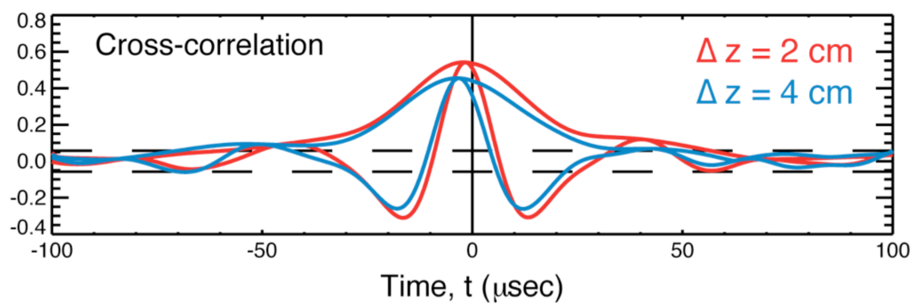


Time lag indicates upward motion
(electron drift direction)

H-mode phase: 266-287 ms



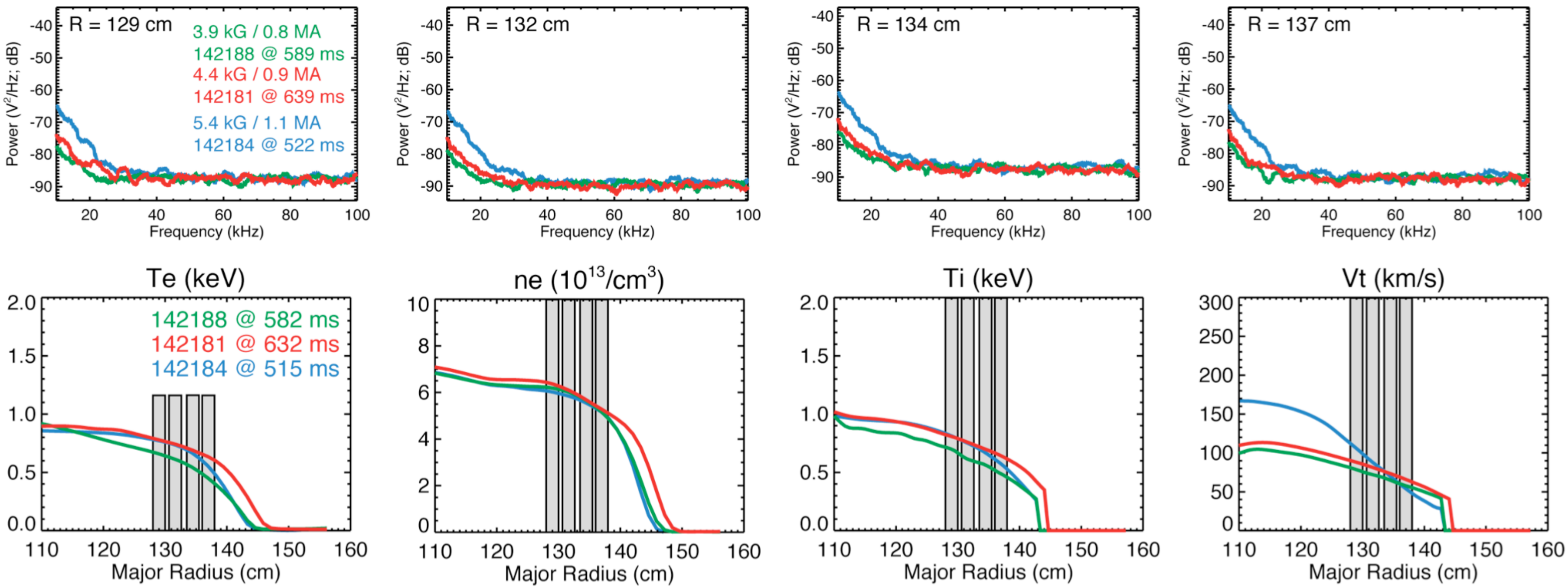




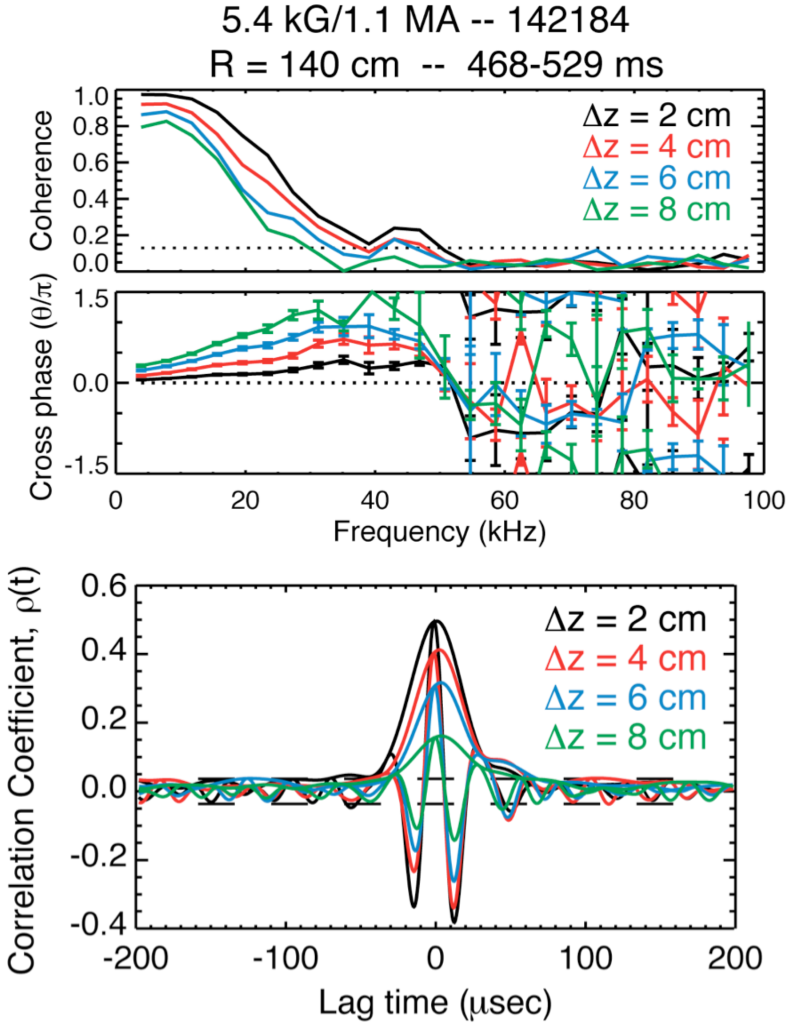
Time lag indicates downward motion
(ion drift direction)
Er increases at LH, so greater ExB
in ion drift direction

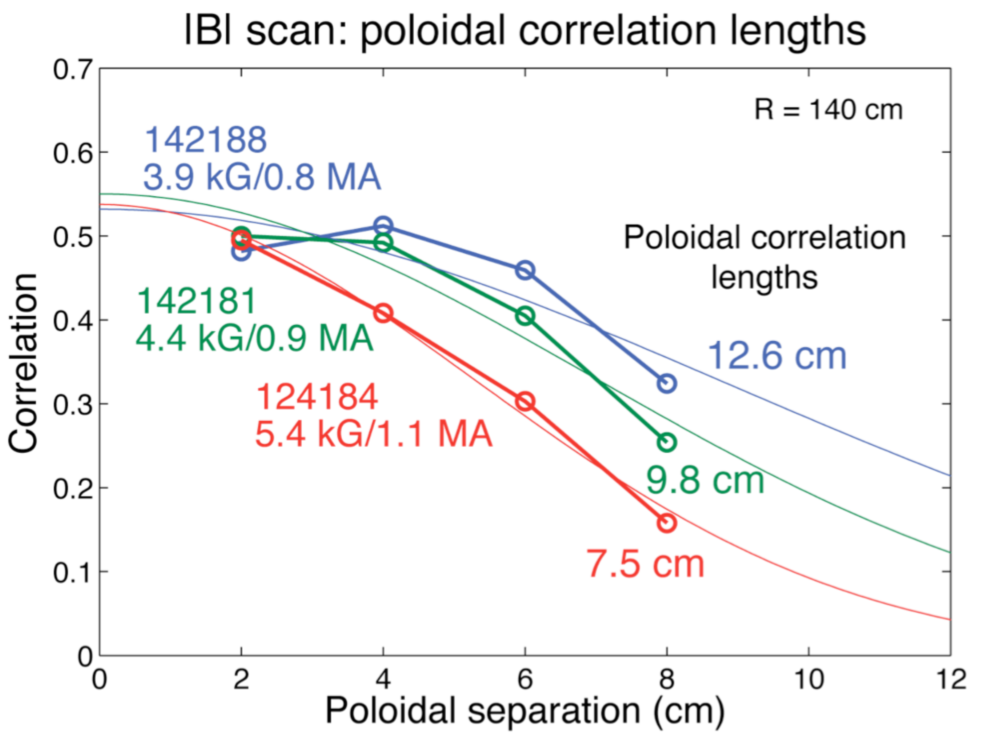
|B| scan: BES auto-power spectra do not exhibit a trend

NSTX confinement scaling (Kaye et al, NF (2007)): $\tau_e \sim B_T \sqrt{I_P}$



|B| scan: Cross-correlation analysis indicates poloidal correlation lengths decrease at higher |B|

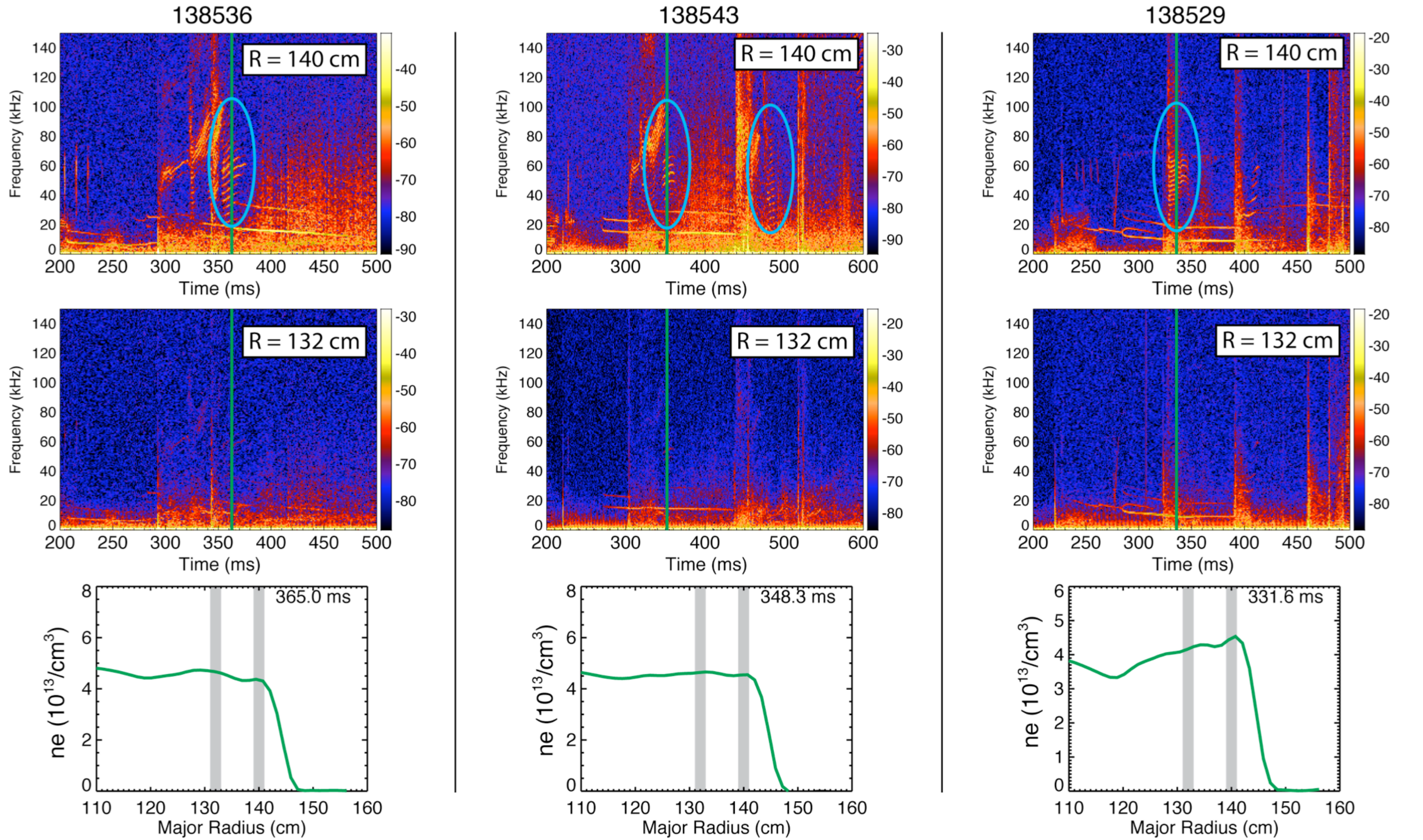




Intuitively consistent with NSTX scaling:

$$\tau_e \sim B_T \sqrt{I_P}$$

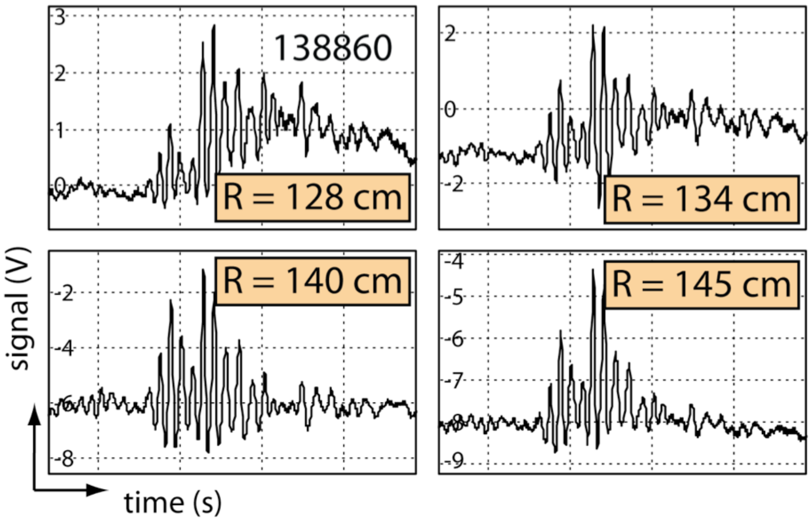
Post-ELM harmonic features at 50-100 kHz are localized at the top of the pedestal

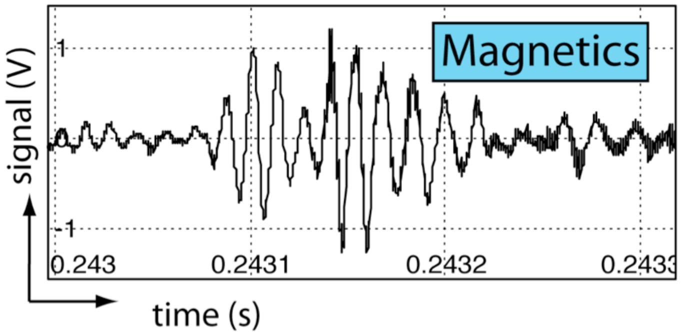


Harmonic features are either absent from or weakly present in magnetic spectra

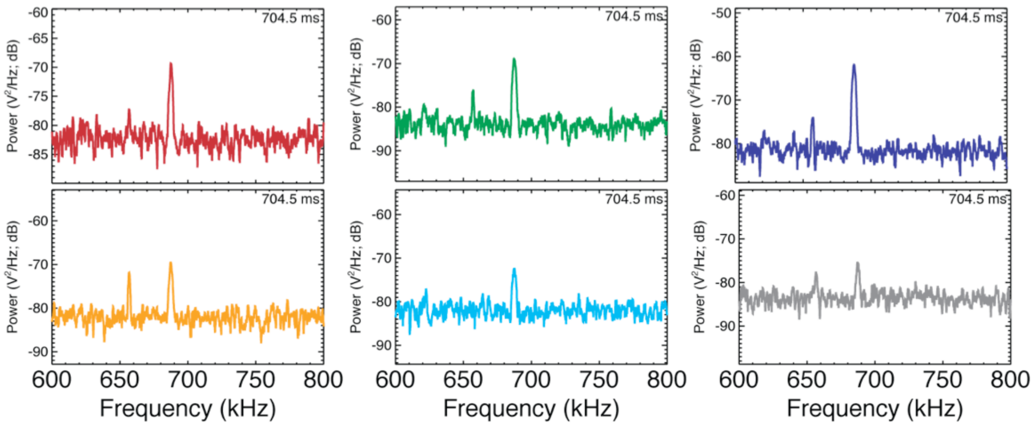
TAEs and GAEs have been observed in extended radial regions

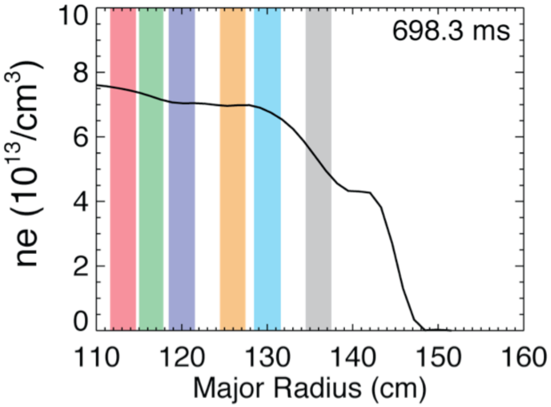
TAE burst





GAE mode





Heidbrink, CO4

Tritz, PI2

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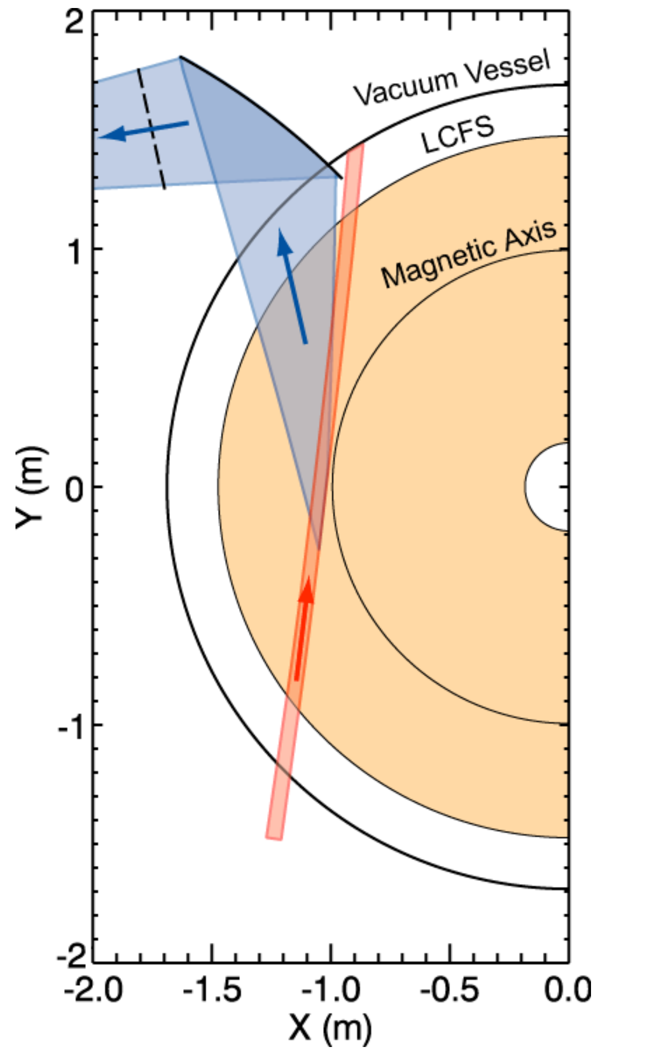
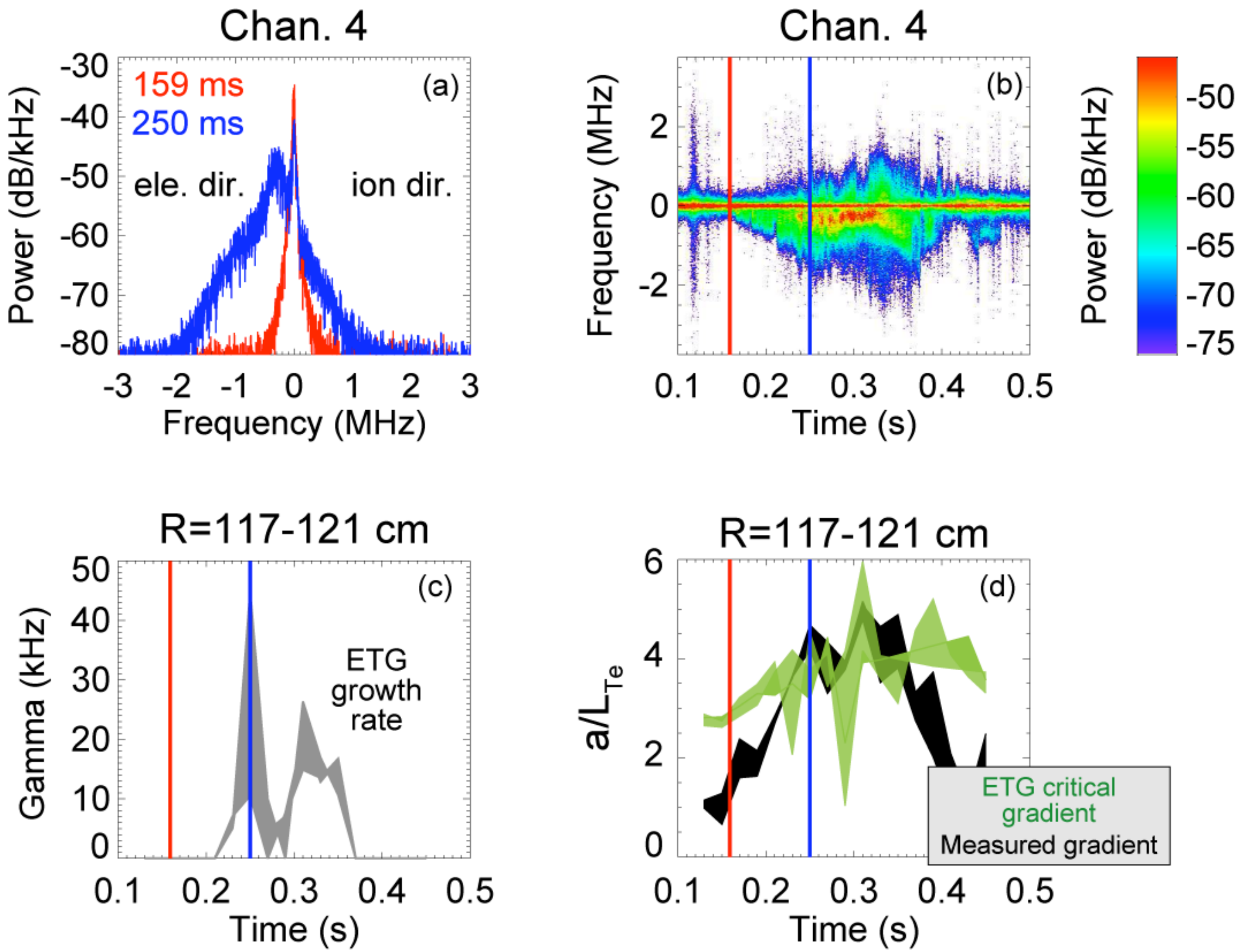
The NSTX high-k scattering system measures fluctuations up to $k_\perp \rho_e < 0.6$

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



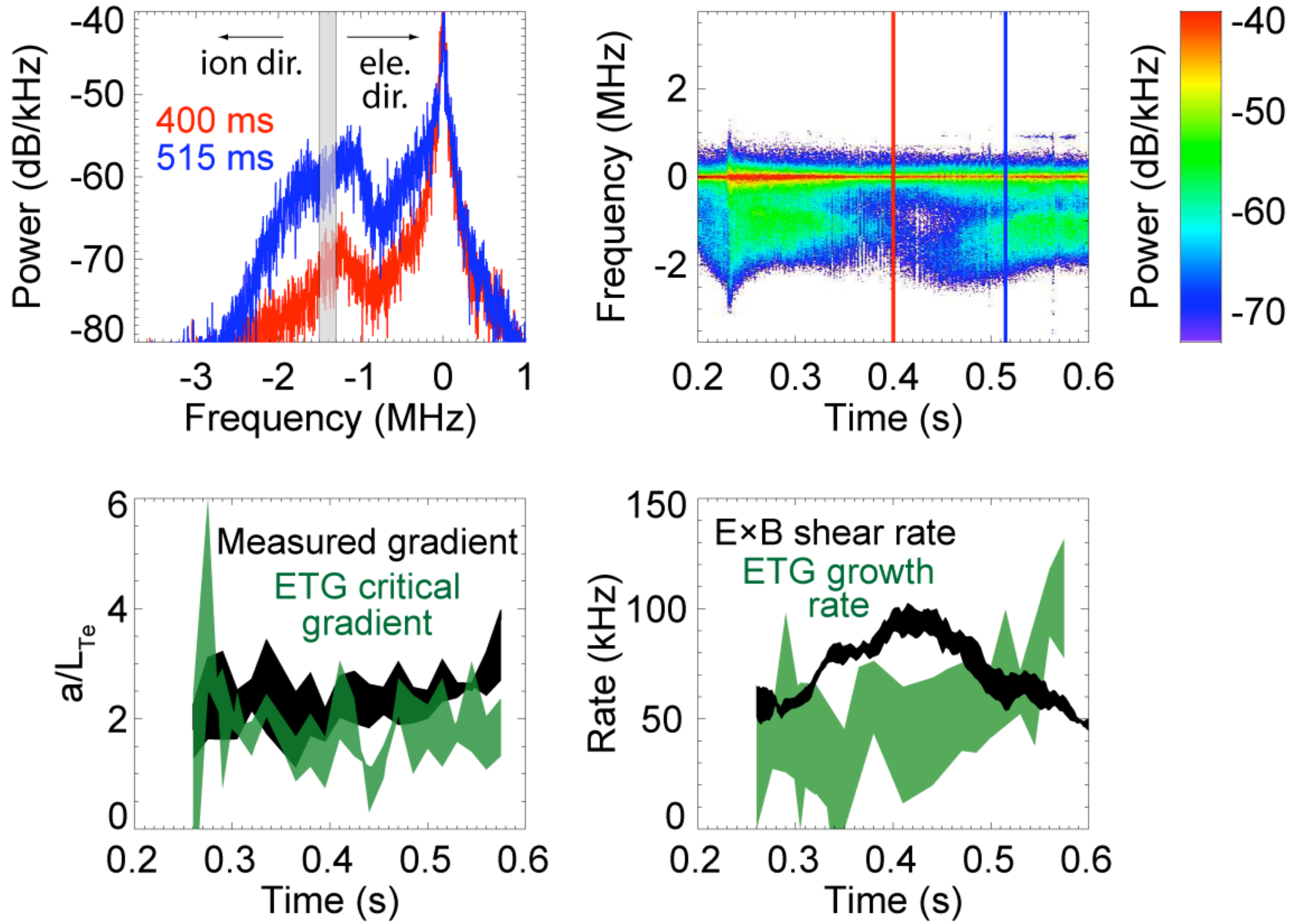
D. R. Smith et al, **RSI** 79, 123501 (2008)

Measurements show enhanced ETG-scale fluctuations when ∇T_e is comparable to the ETG critical ∇T_e



E. Mazzucato, D. R. Smith, et al, **PRL** 101, 075001 (2008)
D. R. Smith, Ph.D. thesis (2009)

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



D. R. Smith et al, **PRL** 102, 225005 (2009)
D. R. Smith, Ph.D. thesis (2009)

Recent high-k/ETG results and upcoming experiments

- Additional high-k/ETG results including fluctuation k-spectra
  - D. R. Smith et al., **PoP** 16, 112507 (2009)
- Recent high-k/ETG results
  - Reverse shear stabilization of ETG: H. Yuh et al, **PRL** 106 (2010)
  - Density gradient stabilization of ETG: Y. Ren et al., in press in **PRL** (2011)
- GK simulations predict ETG-driven electron thermal transport is associated with anisotropic ETG turbulence in the k_r-k_θ plane.

  Question: Are high-k scattering measurements of ETG turbulence isotropic or anisotropic in the k_r-k_θ plane?

  NSTX experiments (D. Smith and Y. Ren) are investigating this question.

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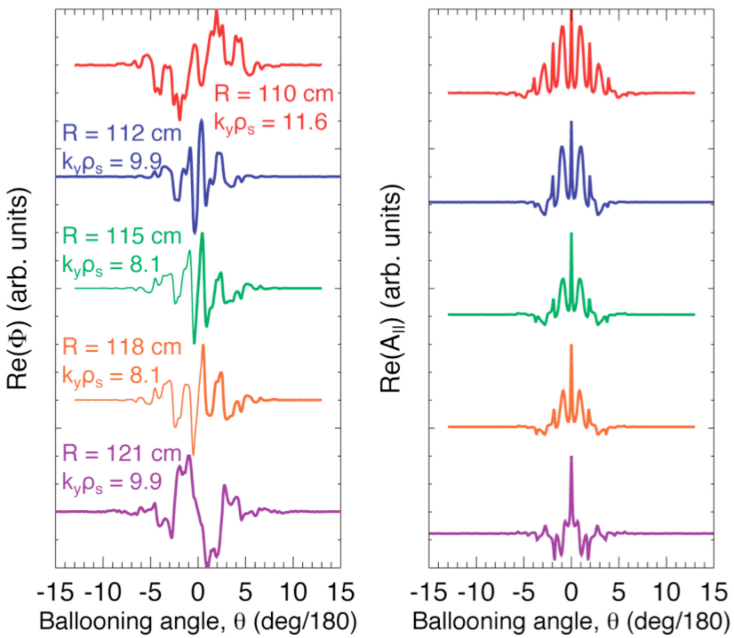
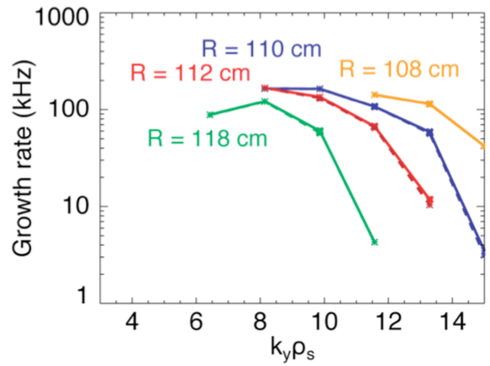
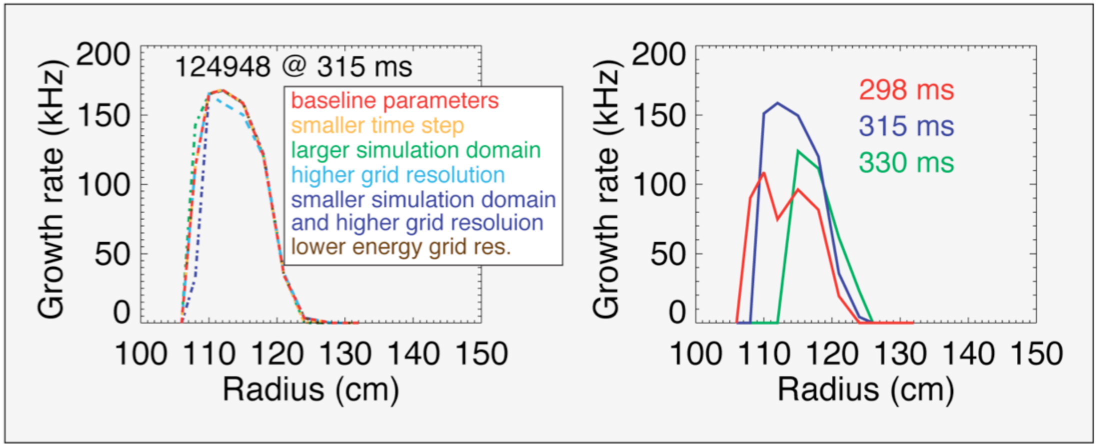
Microtearing modes below the ion gyroscale can be linearly unstable near the core of a NSTX plasma



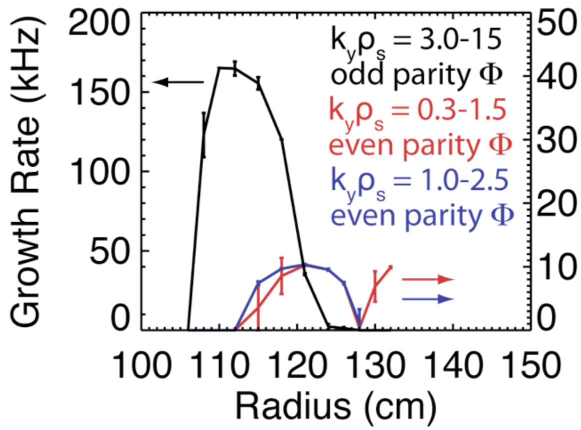


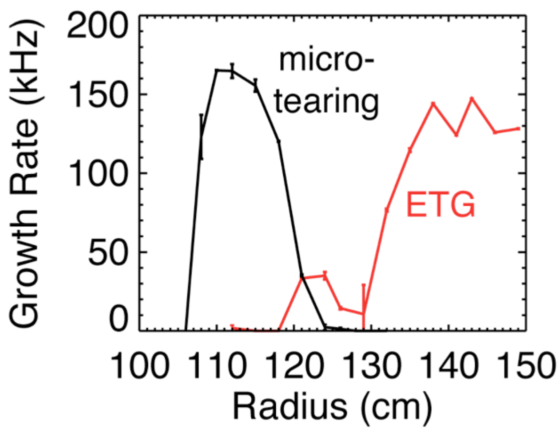


- Narrower Φ and broader $A_{||}$ mode structures
- Toroidal n ≈ 50 is comparable to conventional microtearing modes
- High-k microtearing modes near the magnetic axis are consistent with conventional microtearing modes with large ρ_s/r values

D. R. Smith et al, **PPCF** 53, 035013 (2011)

High-k microtearing growth rates can be greater than low-k DW growth rates and comparable to ETG growth rates





- High-k microtearing growth rates are greater than low-k drift-wave growth rates and located deeper in the core

- High-k microtearing growth rates are comparable to ETG growth rates
- High-k microtearing modes are located in the core, but ETG modes are located in the outer plasma

D. R. Smith et al, **PPCF** 53, 035013 (2011)

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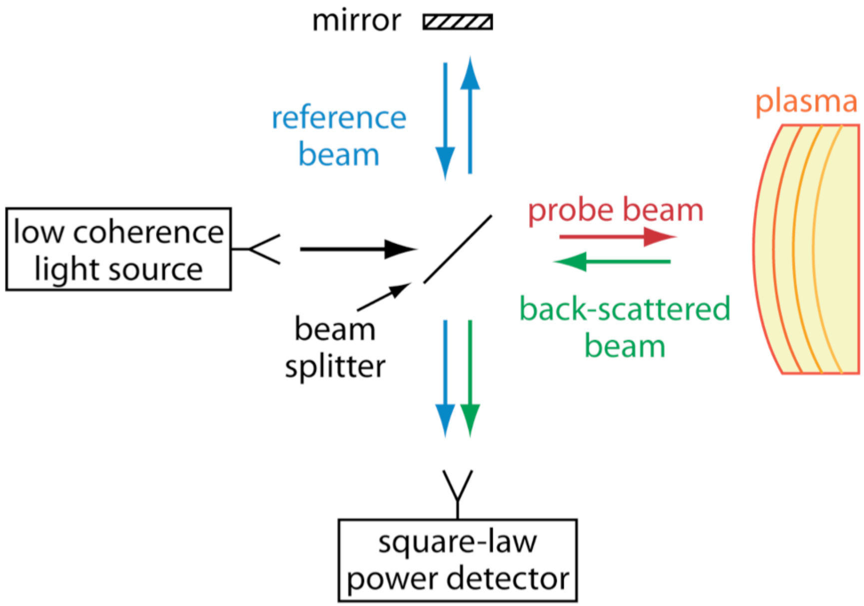
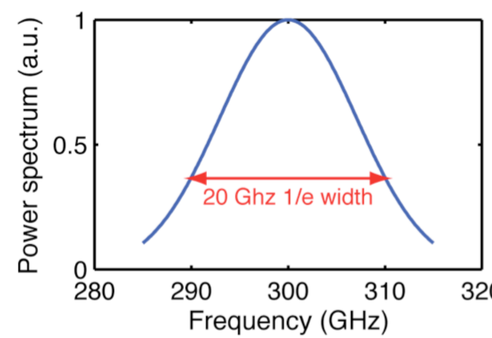
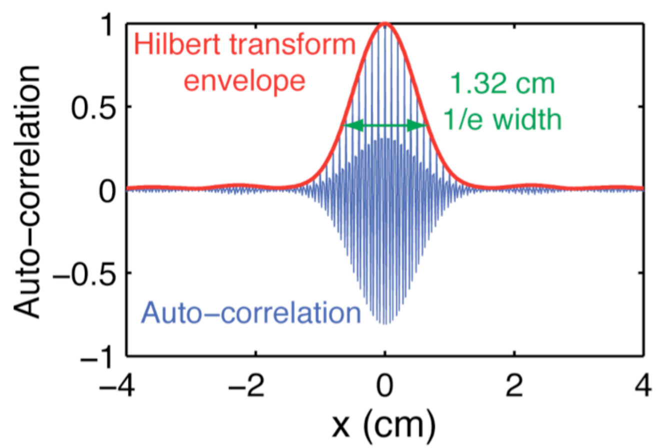
Low coherence radiation provides a mechanism for achieving spatial localization along a probe beam

- Low coherence back-scattering (LCBS)
- Adapted from optical coherence tomography, a biomedical imaging technique that constructs images from depth scans in tissue
- Mirror location for reference beam fixes the measurement location
- Scalable for 1-D profile measurements and 2-D imaging
- Spatial localization:

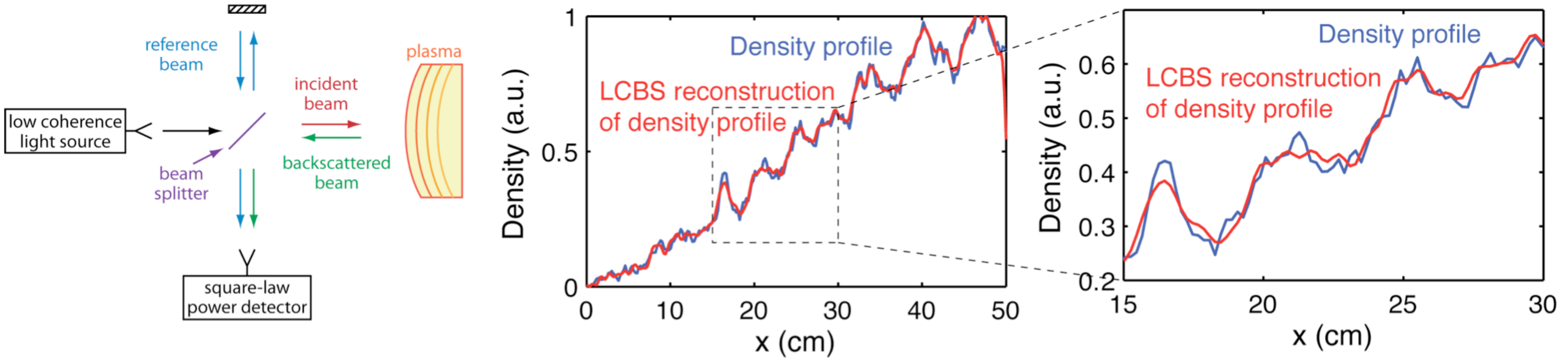
$$\Delta x \approx \frac{\bar{\lambda}^2}{2\Delta\lambda} = \frac{c}{2\Delta f}$$







LCBS measurements can reconstruct a 1-D density profile using a single probe beam



- Interferometry measurements are line-averaged, but LCBS measurements are spatially localized
- Scattering measurements are plagued by spurious reflections, but LCBS is immune to spurious reflections
- Reflectometry measurements are hindered by irregular wave-fronts at the cut-off layer, but LCBS frequencies exceed cut-off frequencies
- Reflectometry measurements can not measure density minima, but LCBS can measure any density profile
- BES measurements require a neutral beam, but LCBS measurements are possible without a neutral beam

D. R. Smith, patent pending (2011)

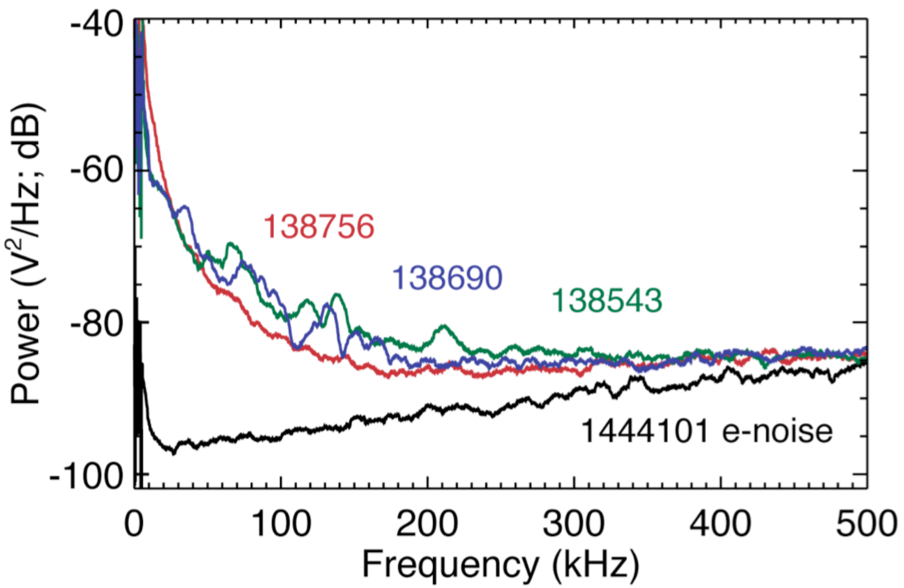
Summary

- BES and high-k scattering diagnostics are valuable tools for studying turbulence spanning the ion and electron gyroscales in NSTX plasmas
- High-k scattering measurements
  - Strong evidence for the existence of ETG turbulence
  - Demonstration of E×B flow shear suppression of ETG turbulence
- BES measurements
  - Preliminary results indicate poloidal correlation lengths are on the order of 10 cm and decrease at higher |B|
  - Flow reversal at LH transition and post-ELM harmonic features point to intriguing pedestal dynamics
- Microtearing modes below the ion gyroscale can be linearly unstable near the core of NSTX plasmas
  - Growth rates comparable to ETG growth rates, but core localized
- Low coherence back-scattering
  - Novel plasma fluctuation measurement technique for 1-D profiles or 2-D imaging using low coherence radiation
  - Adapted from a biomedical imaging technique

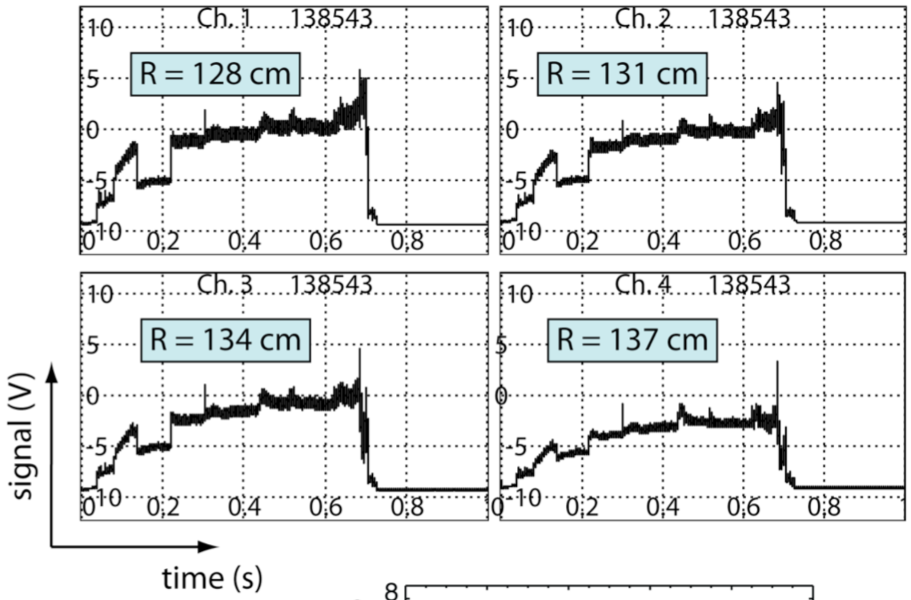
Backup

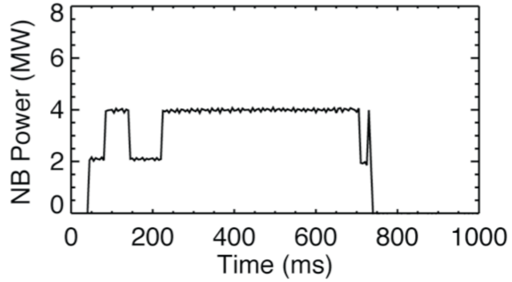
Measured spectra exceed e-noise and signal amplitudes correspond to NB power

Measured spectra exceed e-noise



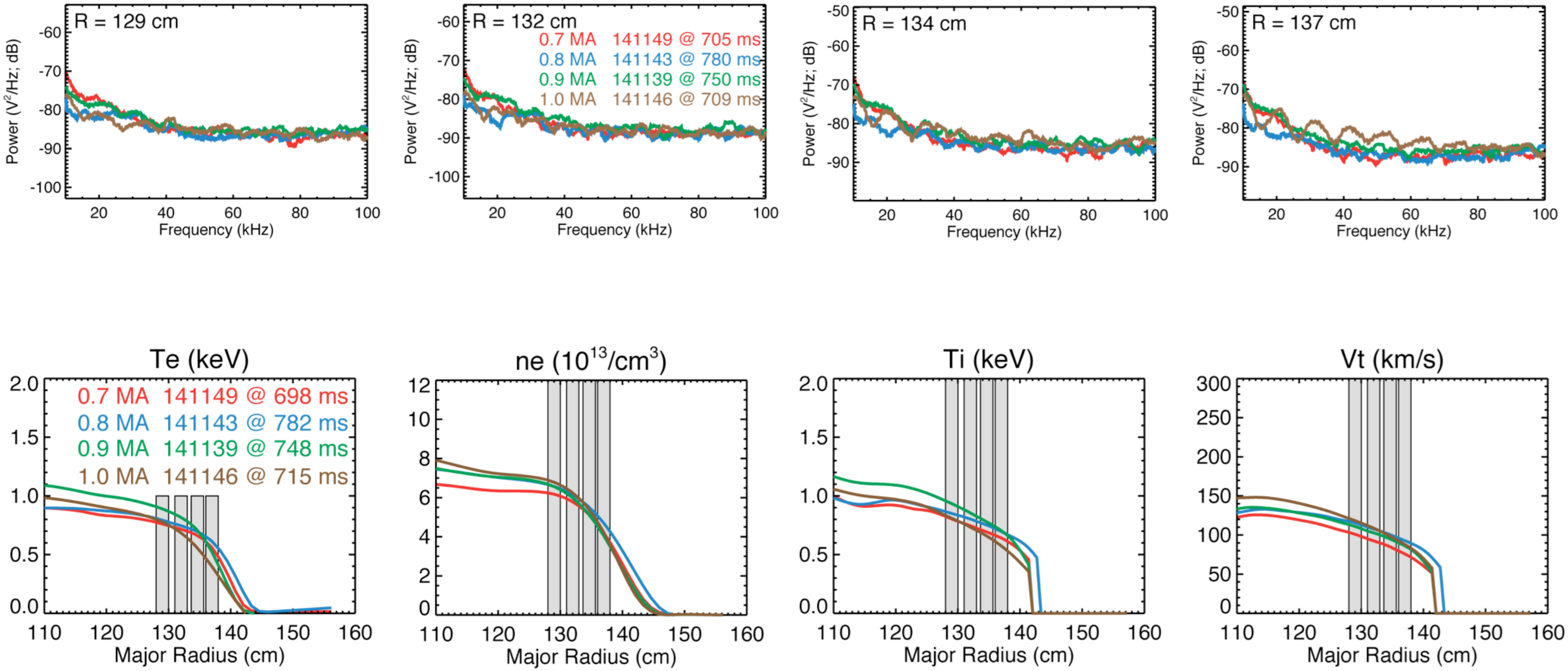
DC signals correspond to NB power



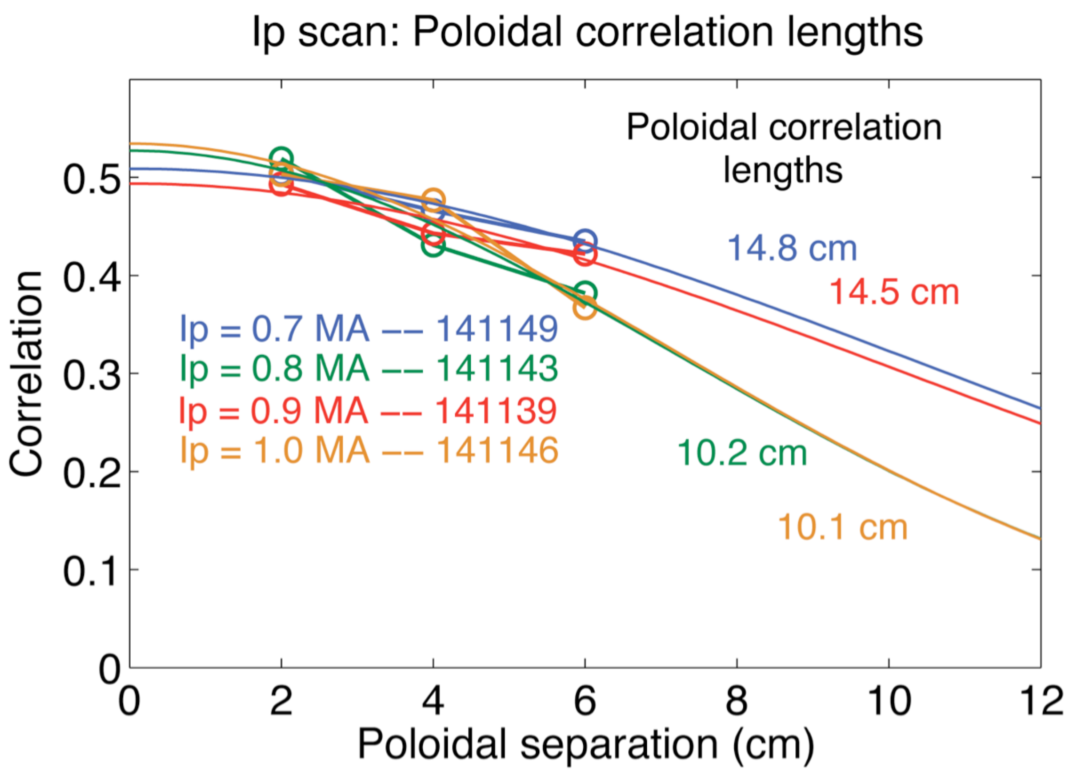


E-noise and photon noise must be removed from measured spectra to isolate plasma fluctuation spectra

Ip scan: Auto-power spectra do not exhibit a trend

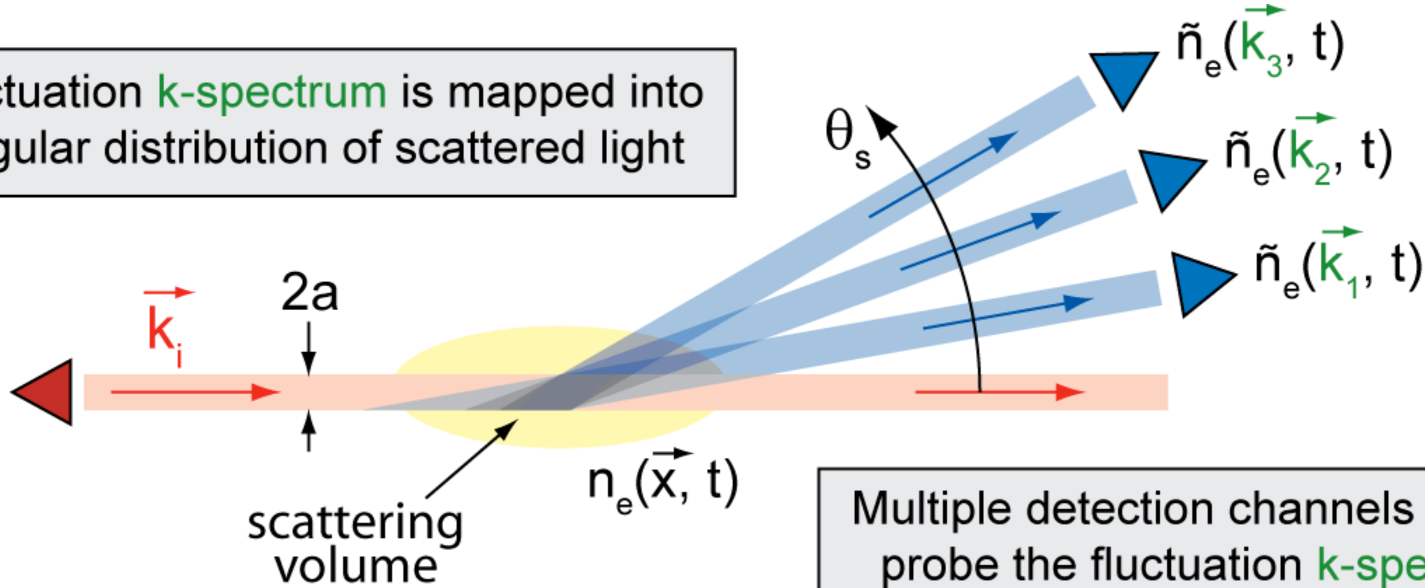


Ip scan: Poloidal correlation lengths do not show a clear trend



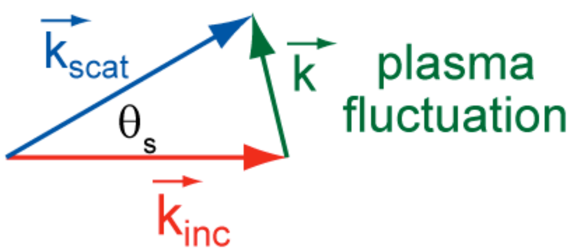
Collective scattering provides density fluctuation measurements with spatial and k-space localization

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



Multiple detection channels directly probe the fluctuation k-spectrum

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: $\omega_i, \omega_s >> \omega$