Measurements of low-wavenumber turbulence in NSTX H-mode plasmas

David R. Smith, R. J. Fonck, G. R. McKee,
D. S. Thompson, and I. U. Uzun-Kaymak

University of Wisconsin-Madison

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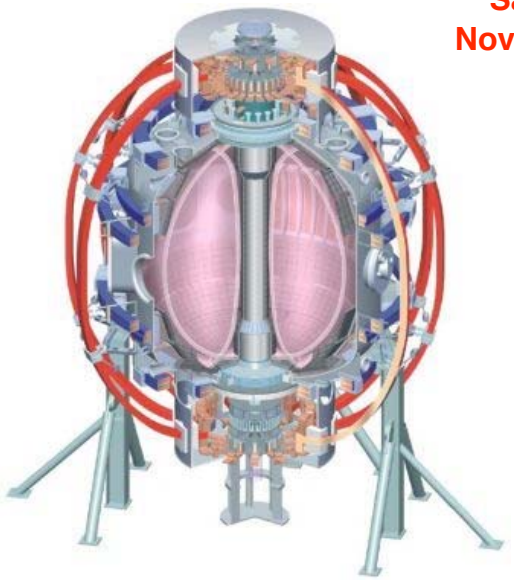

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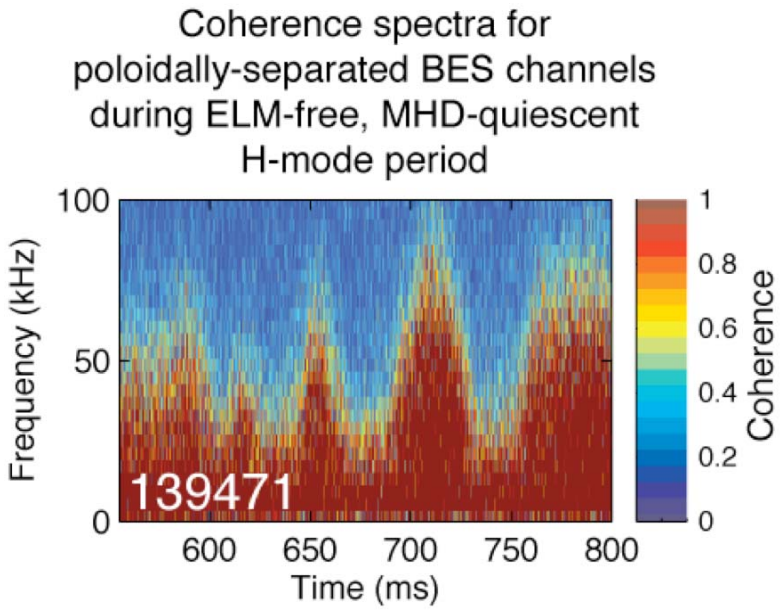
Overview

- Motivation
  - **Identify** the **low-k turbulence** modes in NSTX plasmas
  - **Validate** turbulence simulations
  - Assess impact on **transport**



- Outline
  - Beam emission spectroscopy **(BES)** diagnostic overview
  - **Poloidal correlation lengths** and parametric dependencies in ELM-free, MHD-quiescent **H-mode pedestals**
    - Correlation lengths in **pre-** and **post-LH transition** periods covered in **PP9.32** (D. Thompson et al., Wed PM)
    - Correlation lengths in the **ELM cycle** covered in **PI2.3** (A. Diallo et al., Wed PM)
  - Summary

BES observes D_α emission from collisionally-excited NB particles to measure localized density fluctuations

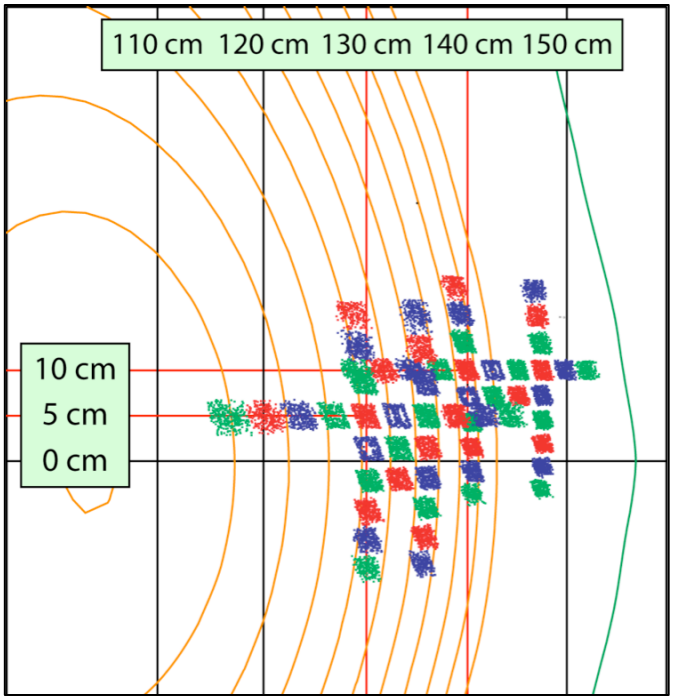
- Presently 32 detection channels
- 56 sightlines in radial and poloidal arrays spanning core to SOL
- 2 MHz sampling
- $k_\perp \rho_i \leq 1.5$ & 2-3 cm spot size
- Field-aligned optics with high throughput (etendue = 2.3 mm^2-ster)

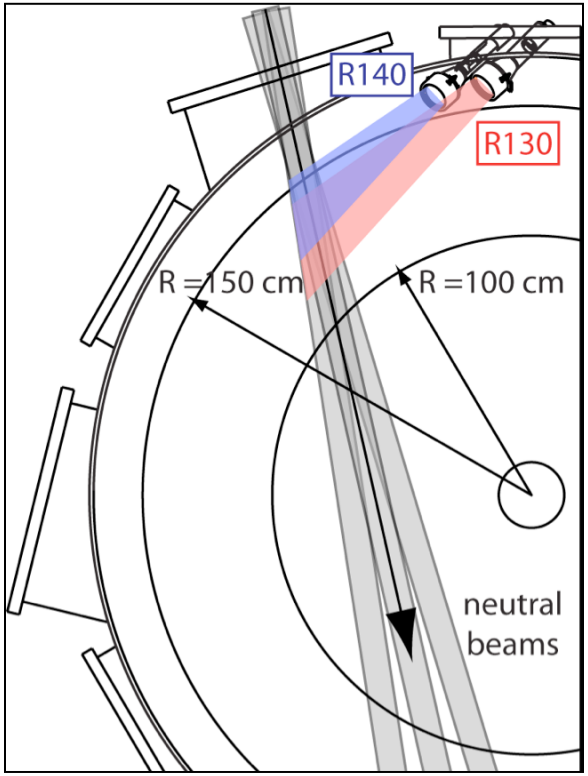
$$\frac{\delta I_{D\alpha}}{I_{D\alpha}} = \frac{\delta n}{n} \times C\left(E_{NB}, n, T_e, Z_{eff}\right)$$

neutral beam D_α emission

density fluctuation

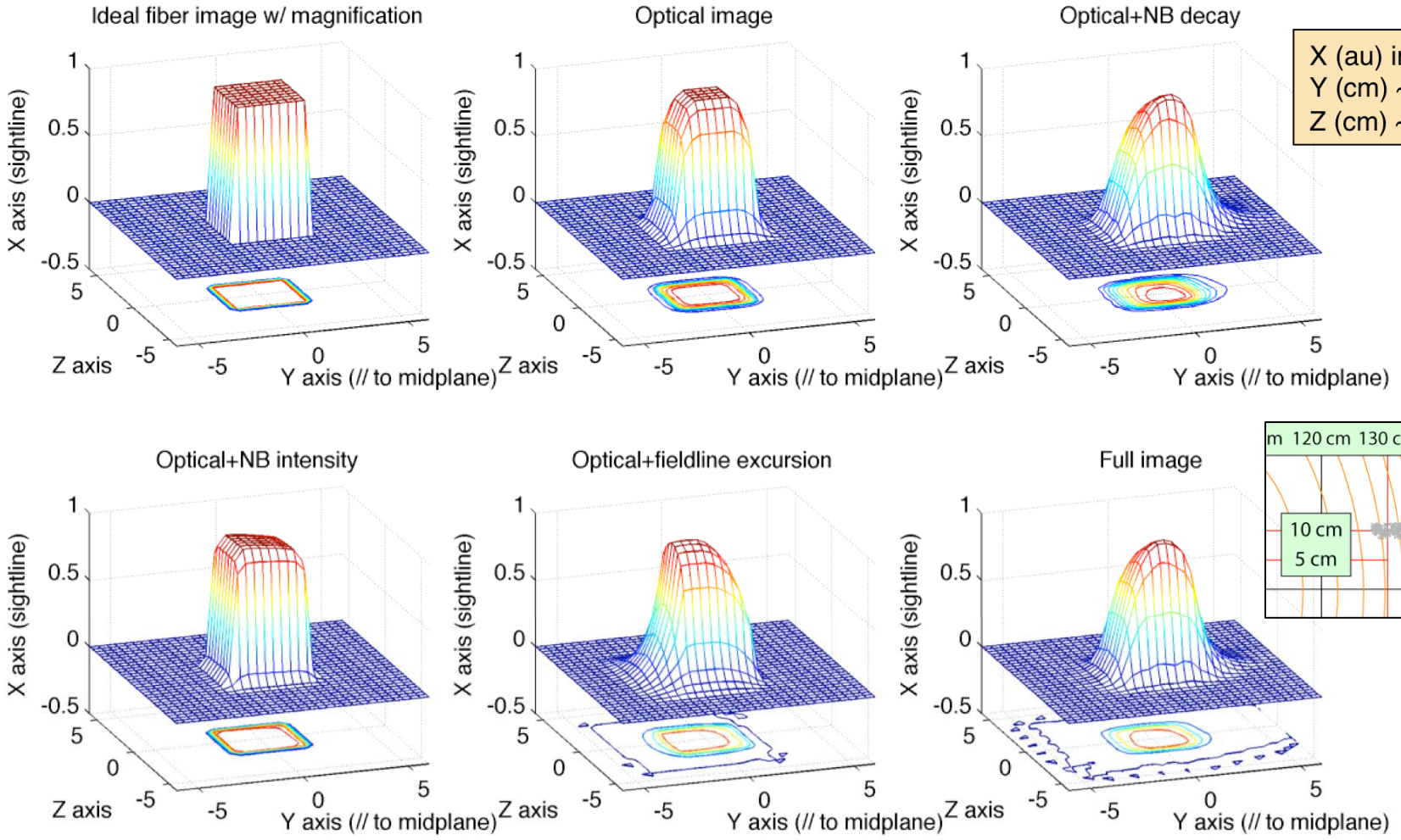
C ≈ 1/2





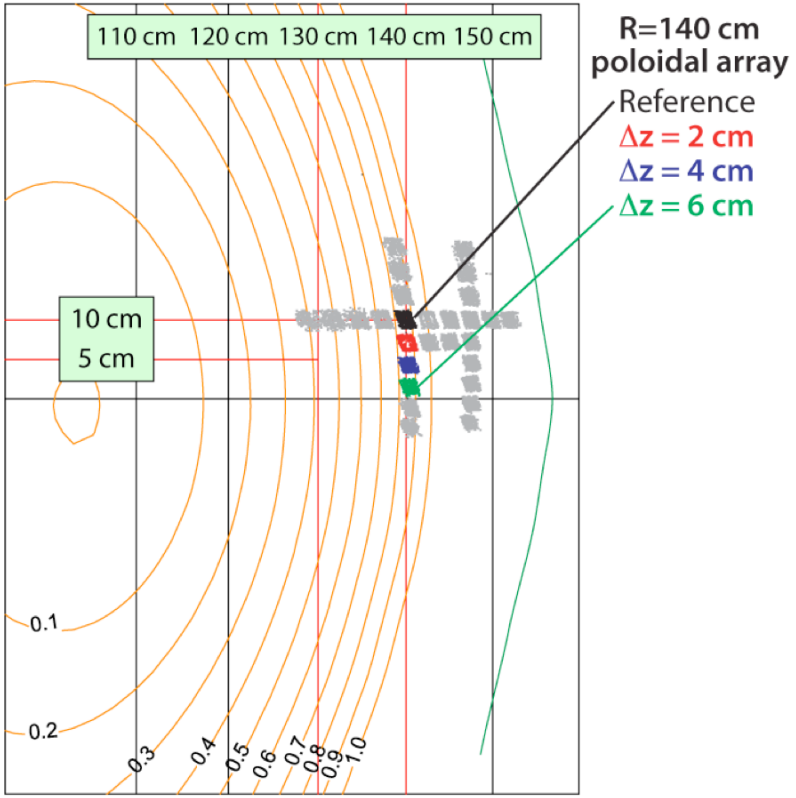
Point spread function calculations at r/a ~ 0.9 indicate NB excited state lifetimes and fieldline trajectory increase radial size by approx 40%

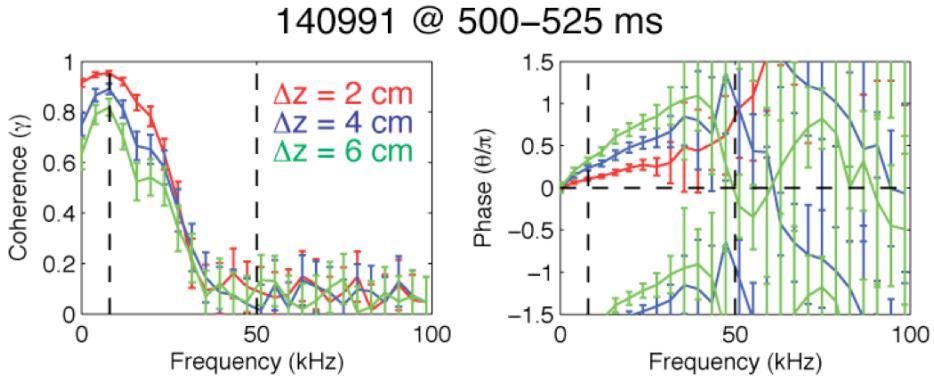
Model	Ideal fiber	Focusing optics	Optical+NB decay	Optical+NB intensity	Optical+fieldline excursion	All effects
Y $1/e^2$ width (cm)	3.2	4.0	4.4	3.2	4.4	4.4
Y displacement (cm)	0.0	0.0	0.5	0.0	-0.5	0.3

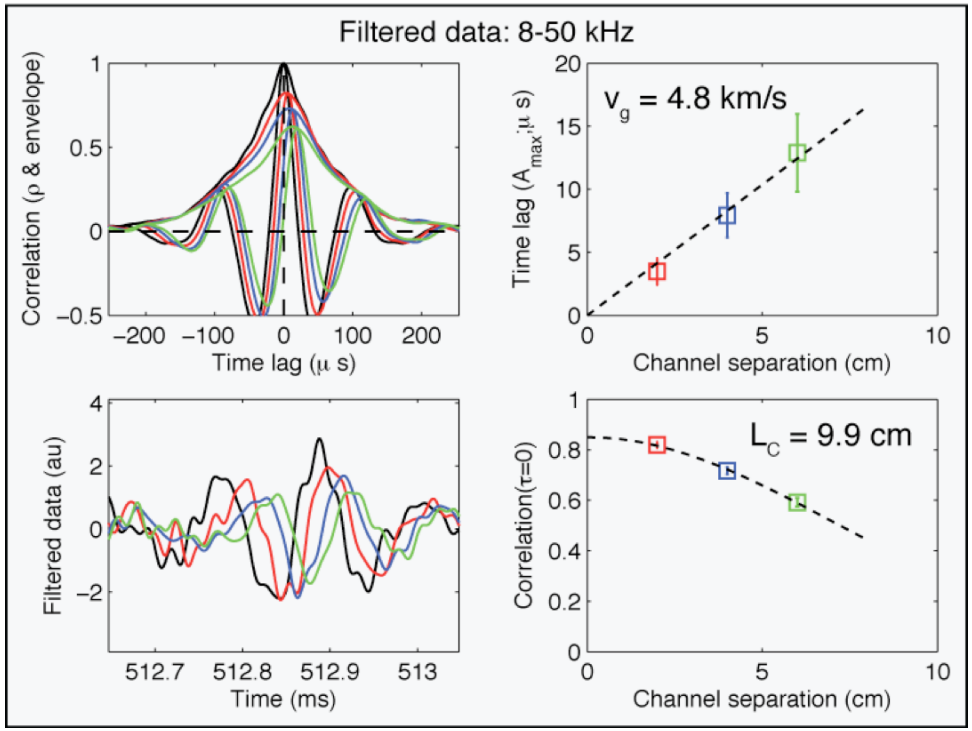


Poloidal L_c obtained from BES poloidal array at R=140 cm (r/a ≈ 0.8-0.95)

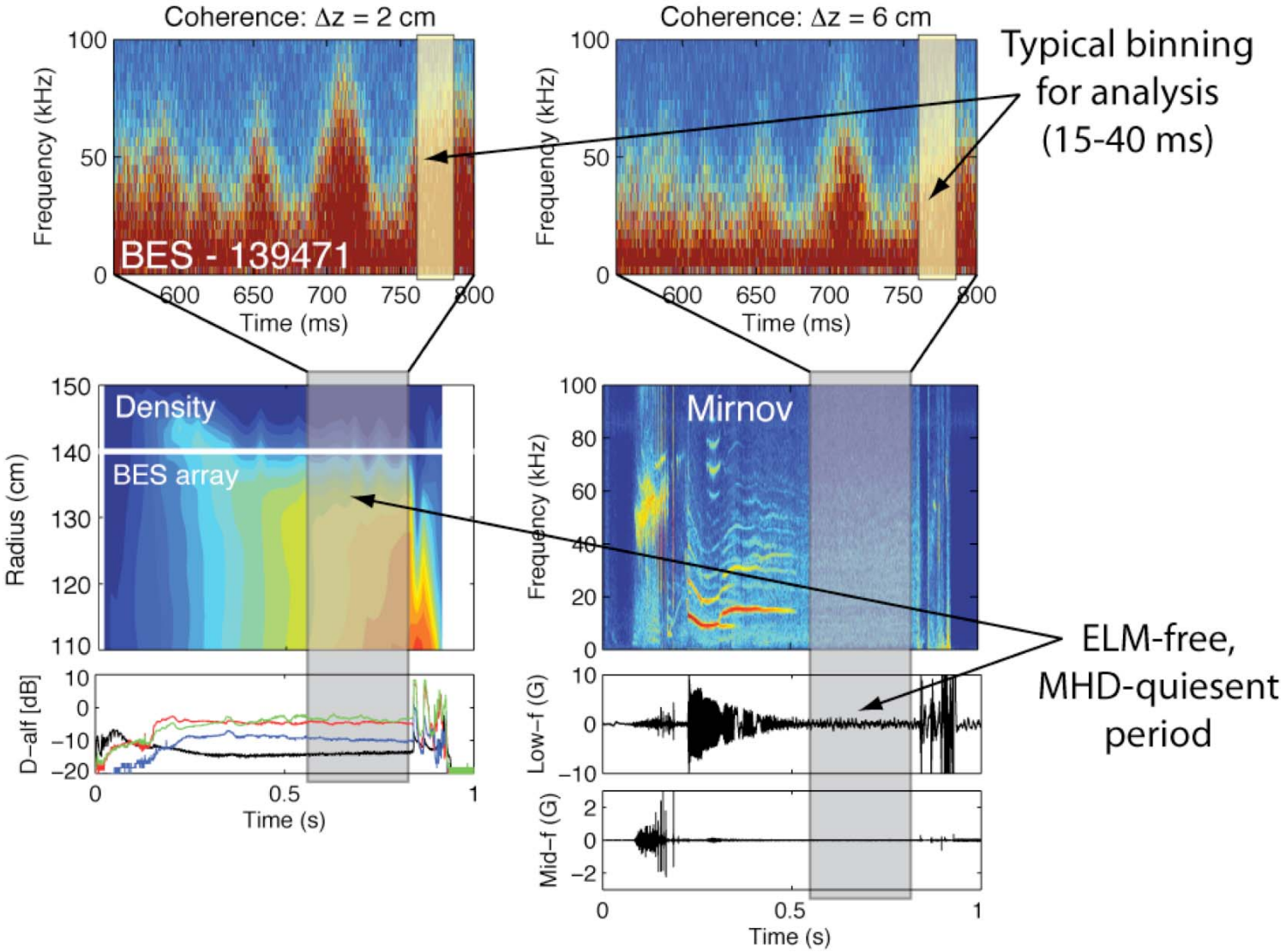
- Correlation functions and coherence spectra indicate:
  $k_\theta \approx 0.2\text{-}0.4\ cm^{-1}$ and **$k_\theta \rho_i \approx 0.1\text{-}0.25$**
- Cross-phase and time-lags show eddy advection in **ion diamagnetic direction**







BES coherence spectra can show complex activity during quiescent H-mode periods – possibly due to pedestal motion



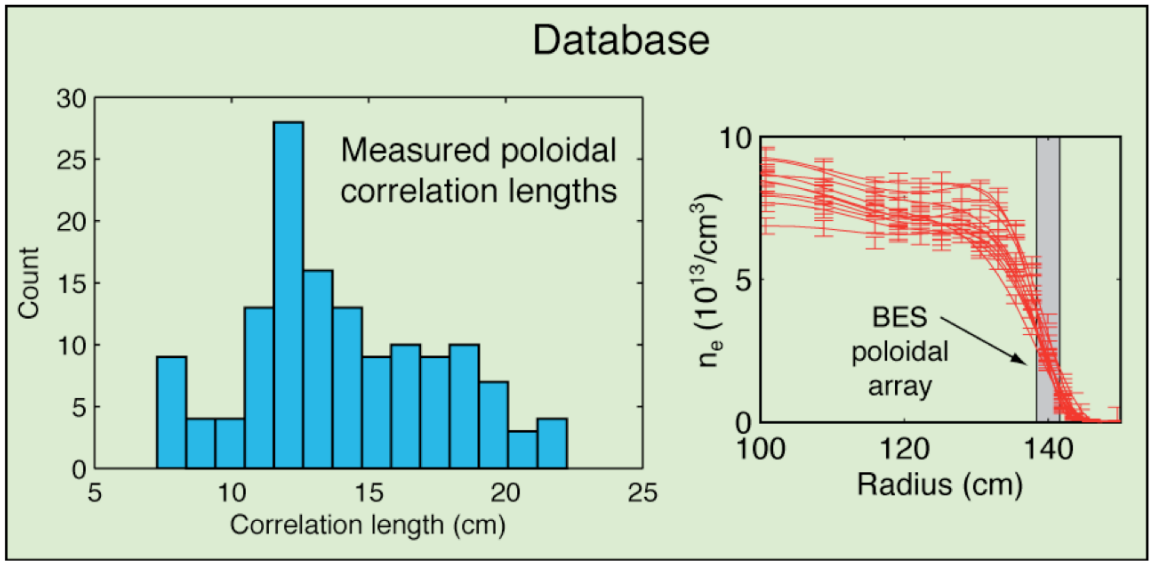
Poloidal L_C at r/a ≈ 0.8-0.95 are typically 7-22 cm; L_C scalings emerge from regression analysis

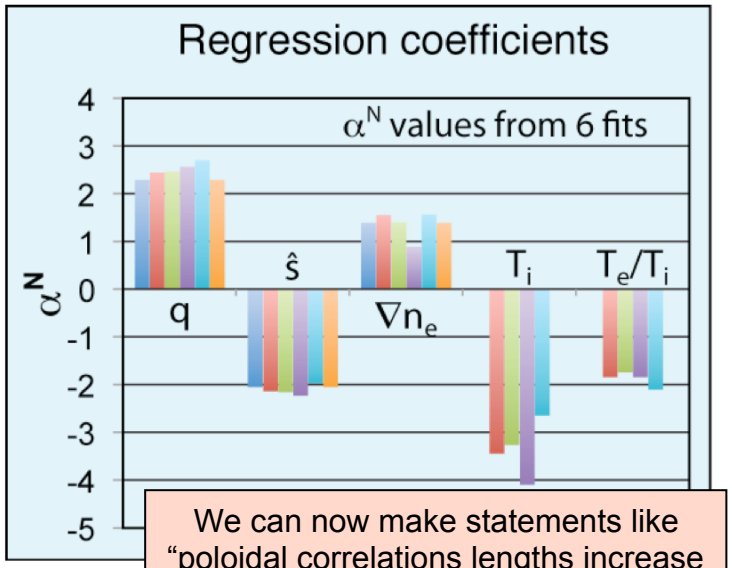
- Poloidal L_C database for ELM-free, MHD-quiescent H-mode contains 130 entries from 29 shots (fixed B_{T0} = 4.4 kG)
- Local plasma parameters include n_e, T_e, T_i, V_t, ∇X, $1/L_X$, q, ŝ, κ, δ_{bot}, ν, and β
- Stepwise multivariate regression initialized with every 2, 3, and 4 parameter combination to find multiple fits (30+) with RMSE local minima

$$L_C = \bar{L}_C + \sum \alpha_i^N \frac{x_i - \bar{x}_i}{\sigma_{xi}}$$

scaling coefficient

plasma parameters

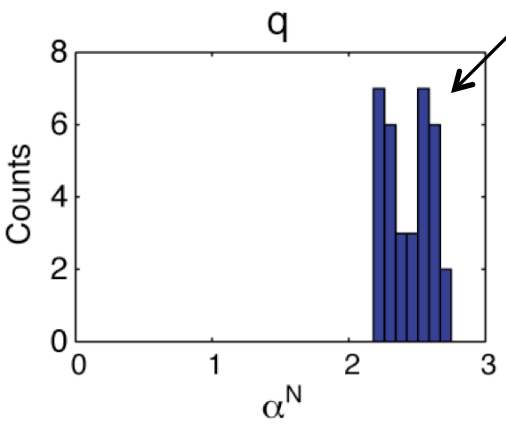


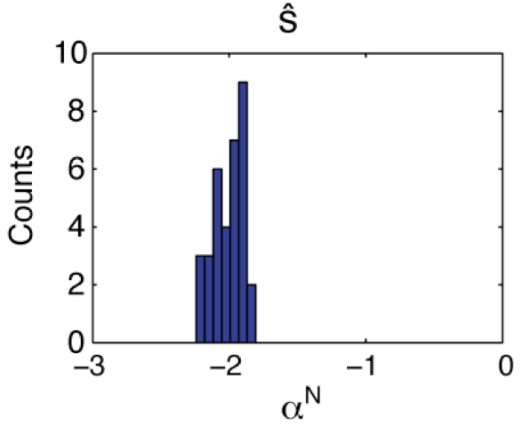


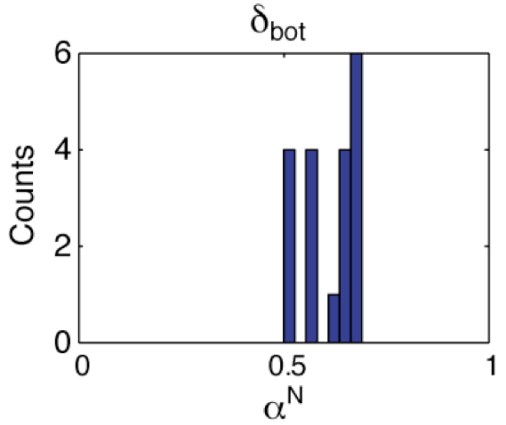
We can now make statements like "poloidal correlations lengths increase at higher q" with justification

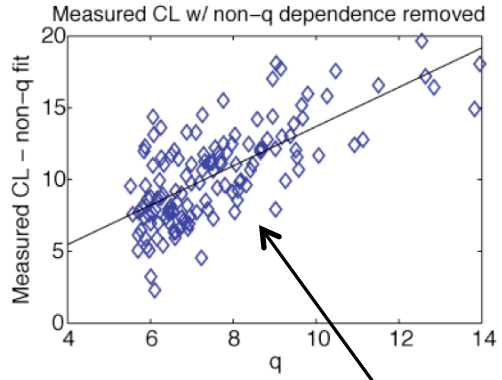
Among equilibrium parameters, analysis of L_C database indicates positive scalings for q and δ_{bot} and a negative scaling for ŝ

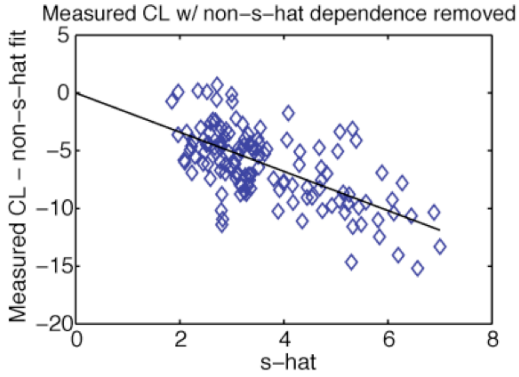
Distribution of α^N's among fits

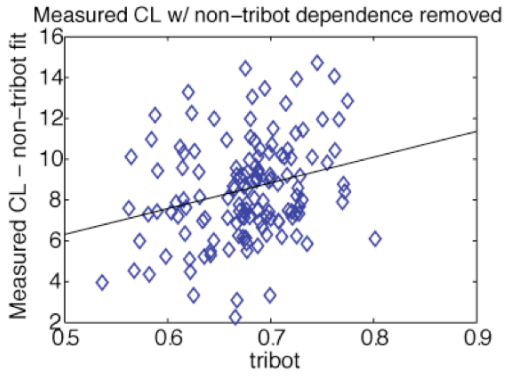






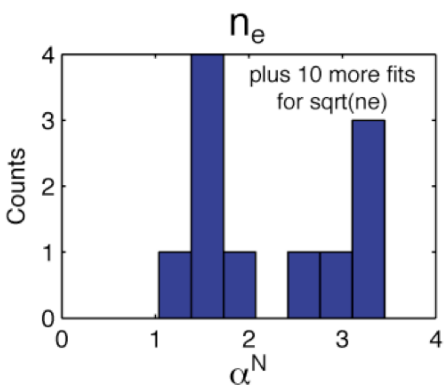


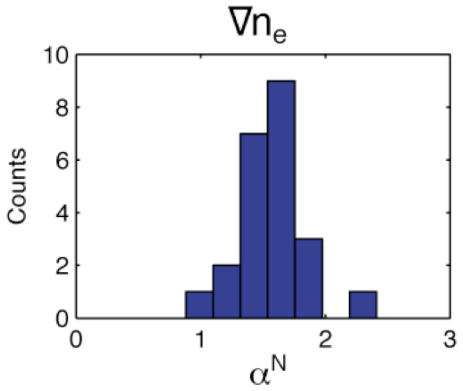


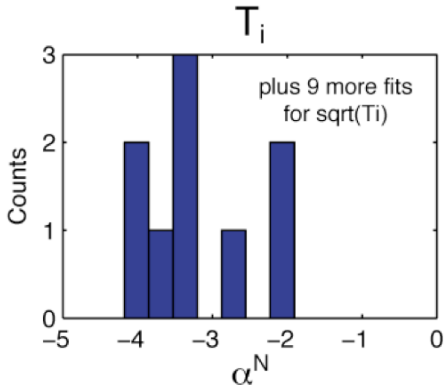


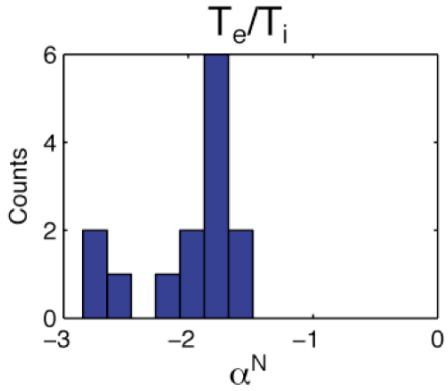
Residuals + parameter dependence (single fit)

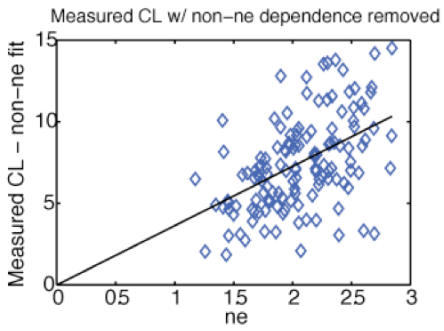
Among species parameters, analysis indicates positive scalings for n_e and ∇n_e, and negative scalings for T_i and T_e/T_i

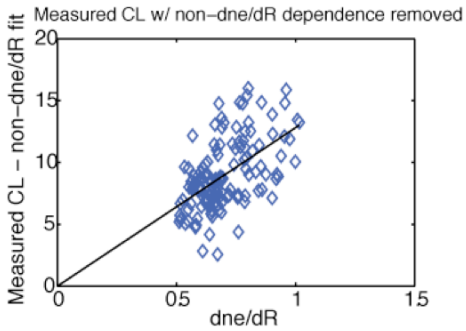


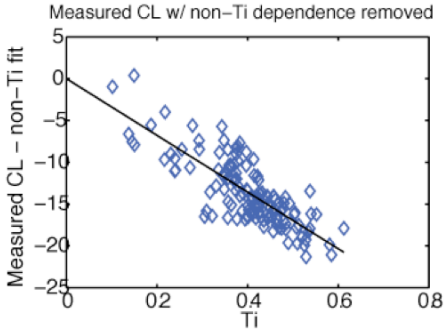


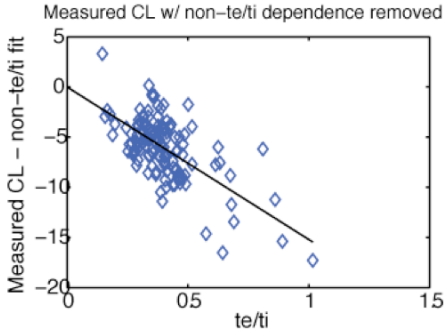












Other local quantities, such as ν, β, and V_t, do not explain data variation or improve regression fits with high confidence

Summary

- **Poloidal correlation lengths** are in the range L_C = 7-22 cm in ELM-free, MHD-quiescent H-mode pedestals (r/a ≈ 0.8-0.95)
  - $k_\theta \approx 0.2\text{-}0.4\ cm^{-1}$ and $k_\theta \rho_i \approx 0.1\text{-}0.25$
  - L_C **increases** at higher q, δ_{bot}, n_e, and ∇n_e
  - L_C **decreases** at higher $\hat{s}$, T_i, and T_e/T_i
- Initial PSF calculations indicate excited state lifetimes and fieldline trajectory increase the radial spot size by ~40% at R=140 cm
- For more information: **PP9.32** (Wed PM), D. S. Thompson et al.
- Future work
  - Expansion to 64 detection channels
  - Expanded 2D capability
  - High resolution edge/SOL channels

Backup

Poloidal L_C database includes many local and global parameters

- Constructed from 2010 BES data using R=140 poloidal array
- Quiescent periods in H-mode plasmas
  - ELM-free and MHD quiescent
- 130+ entries from 29 shots with B_T = 4.4 kG
- 15-40 ms periods capture slow BES signal evolution
- Local plasma parameters in database
  - q, ŝ, q/ŝ, n_e, T_e, T_i, V_t, sqrt(n_e, T_e, T_i), ∇(n_e, T_e, T_i, V_t), $1/L_{(ne,\ Te,\ Ti)}$, κ, δ_{bot}, T_e/T_i, β_e, β_t, ν_e, ν_i
- Global/engineering parameters in database
  - I_P, P_{NB}, peak quantities (e.g. n_e), LCFS geometry

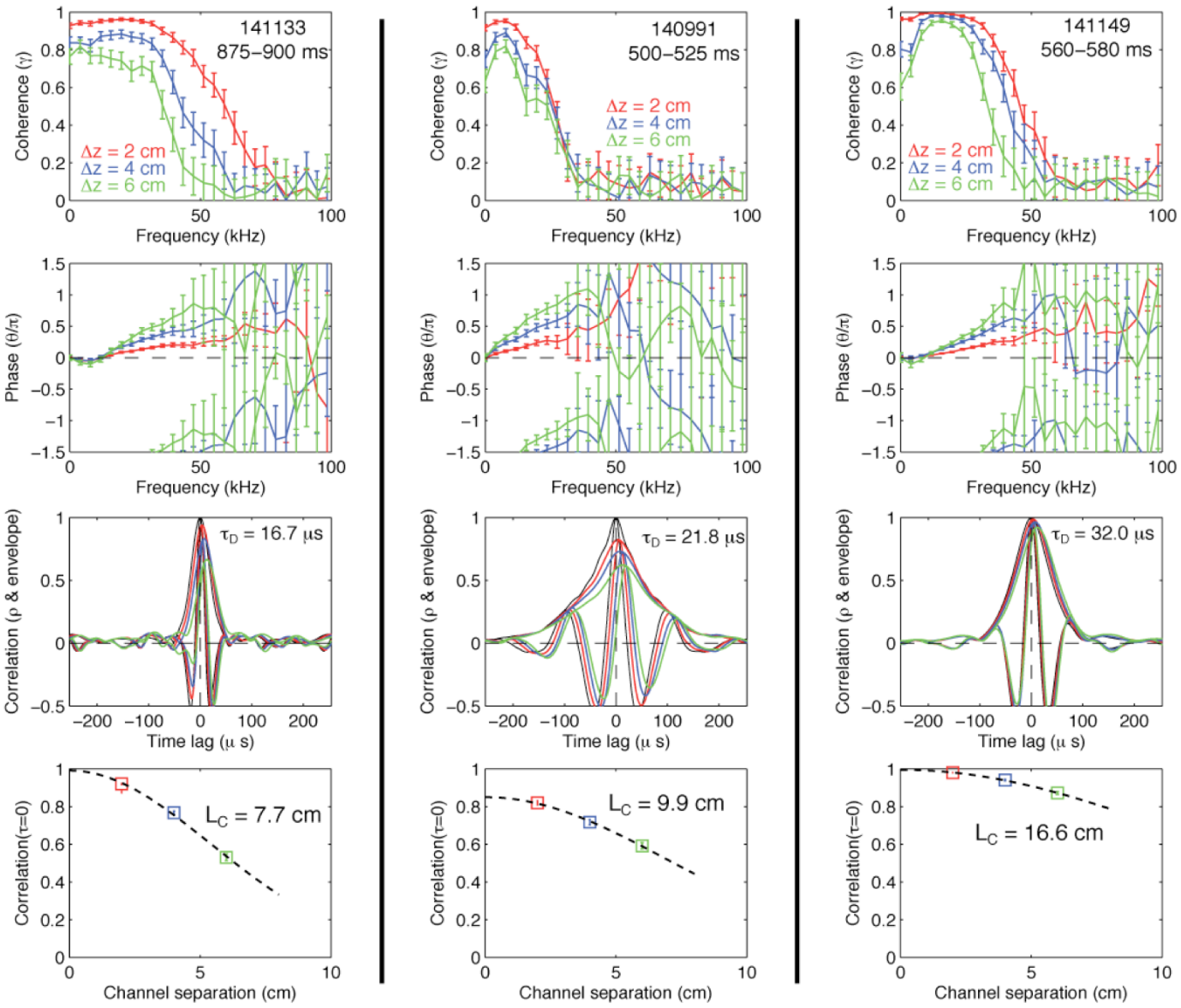
Poloidal L_C at r/a ≈ 0.8-0.95 are typically 5-20 cm and coherence spectra can extend up to 20-100 kHz

Coherence spectra

Cross-phase spectra

Time-lag cross-correlation (and envelope)

Correlation vs. channel separation



Regression analysis can identify parametric scalings in the L_C database

- Stepwise multivariate linear regression (normalized form)
  - Iteratively test additional parameters (x_i) for statistical significance and RMSE reduction
  - Only **local physics** parameters in this presentation (e.g. q, n_e, κ, T_e/T_i)

$$L_C = \bar{L}_C + \sum \beta_i^N \frac{x_i - \bar{x}_i}{\sigma_{xi}}$$

- Assessing regression fits and parameter scalings
  - Good fits exhibit large R^2 (amount of L_C variation captured by fit), small RMSE, small H_0 probability (null hypothesis: fit parameters do not explain L_C variation), and contain only **statistically significant** parameters
  - Good parameter scalings (e.g. β^N for n_e) appear in many fits with β_N values clustered around a typical value and comparable to or larger than fit RMSE

Future work

- Additional analysis of 2010 BES data
  - Extend regression analysis to
    - Global/engineering parameters
    - Decorrelation times and radial correlation lengths
  - Quantify **poloidal flow fluctuations** using time delay estimation (TDE) techniques
    - Identify zonal flows, if present
    - Assess predator-prey model of turbulence and flow shear
- Perform edge turbulence simulations
  - Complete PSF calculations for BES synthetic diagnostic
  - Validate simulations using analysis results from 2010 BES data
- Enhance BES measurement capabilities for NSTX-U
  - Expansion to 64 detection channels for better utilization
  - Expanded 2D imaging with high-resolution edge sightlines