# Turbulence characterization at the LH transition in NSTX

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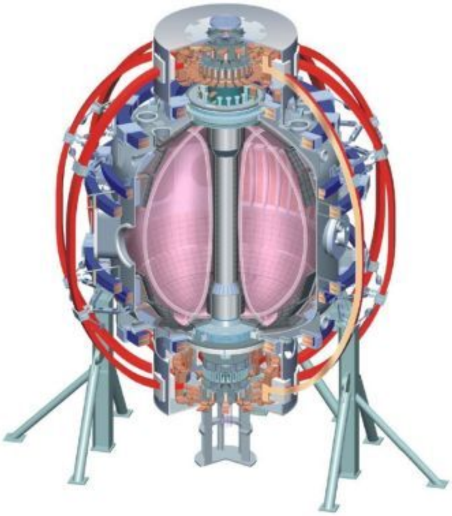

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# Abstract

Long-wavelength density fluctuations are suppressed at the LH transition in both the edge and core regions of National Spherical Torus Experiment (NSTX) plasmas. The magnitude of reduction varies among operational regimes. A beam emission spectroscopy (BES) system installed on NSTX measures these ion gyroscale fluctuations from *r*/*a* ~ 0.1 to the scrape off layer. The system includes four poloidal arrays and high throughput optics aligned to the magnetic field pitch angle at the neutral beam. Poloidal correlation lengths are measured near r/a ~ 0.85 across the LH transition and typically increase at the transition. These edge fluctuations have frequencies up to 100 kHz and radial and poloidal correlation lengths of approximately 10 cm.

# Overview

- Motivation
  - **Identify** the **low-k turbulence** modes in NSTX plasmas
  - Validate turbulence simulations
  - Assess impact on transport
- Beam emission spectroscopy (BES) diagnostic overview
- Poloidal correlation lengths, $L_C$, before and after LH transition
  - Poloidal correlation lengths and parametric dependencies in ELM-free, MHD quiescent H-mode pedestal covered in **BO4.2** (D. R. Smith et al., Mon AM)
- Regression analysis on poloidal correlation lengths
  - Identify parameters that impact measured quantities
- Future work and summary

# BES observes $D_\alpha$ emission from collisionally-excited NB particles to measure localized density fluctuations

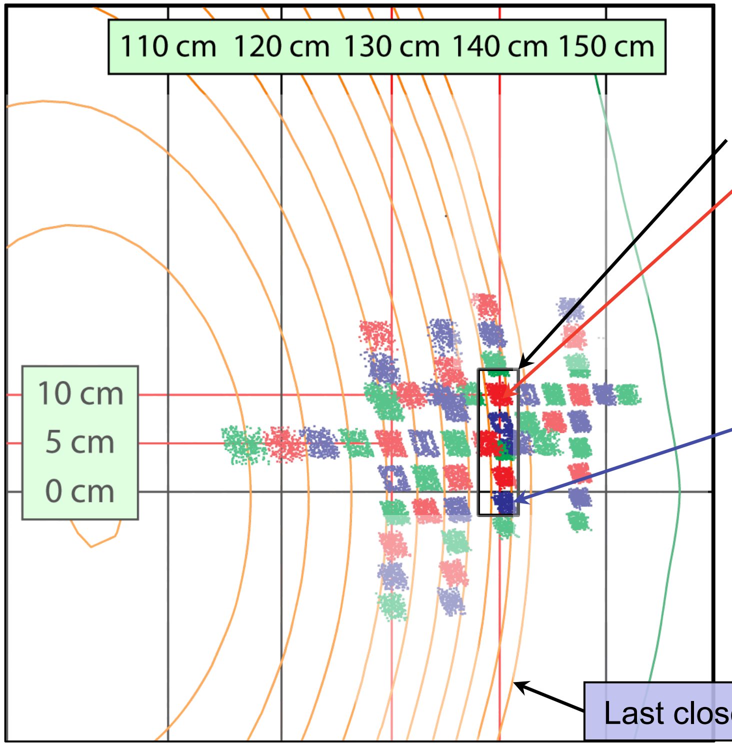
- Presently 32 detection channels
- 56 sightlines in radial and poloidal arrays spanning core to SOL
- 2 MHz sampling
- $k_\perp \rho_i \leq 1.5$ & 2-3 cm spot size
- Field-aligned optics with high throughput (etendue = 2.3 $mm^2$-ster)

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

neutral beam $D_\alpha$ emission

density fluctuation

C ≈ 1/2



R = 140 cm poloidal array

Reference

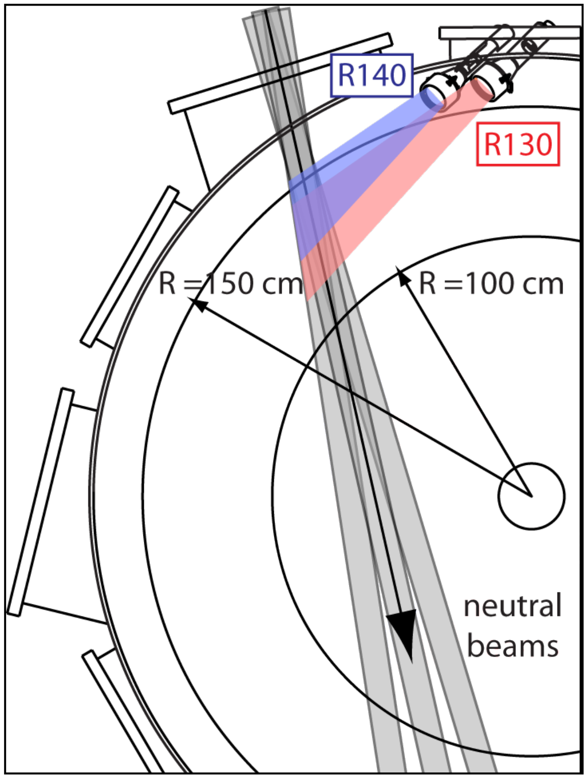
Δz = 2 cm

Δz = 4 cm

Δz = 6 cm

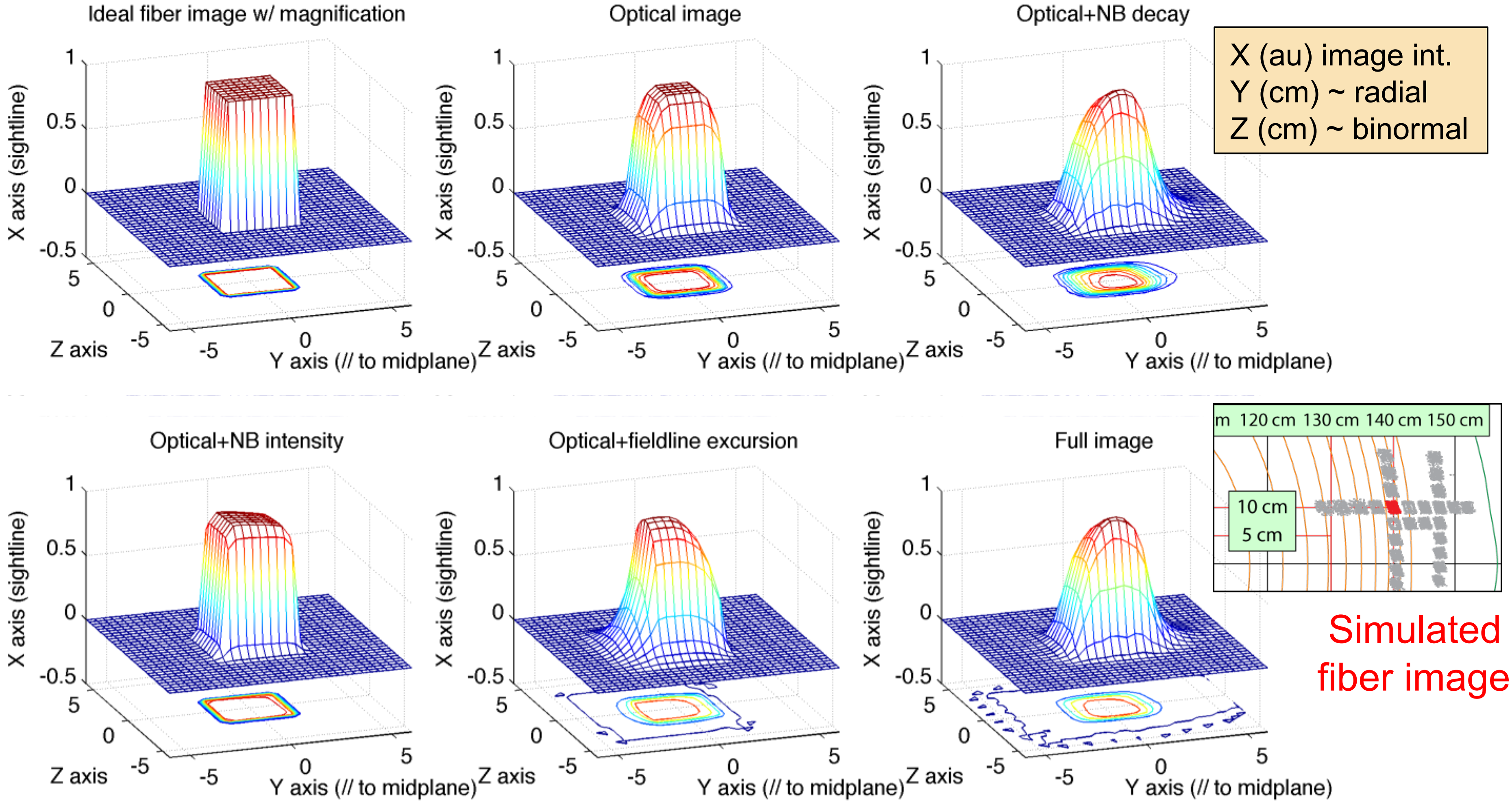
Δz = 8 cm

Last closed flux surface



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

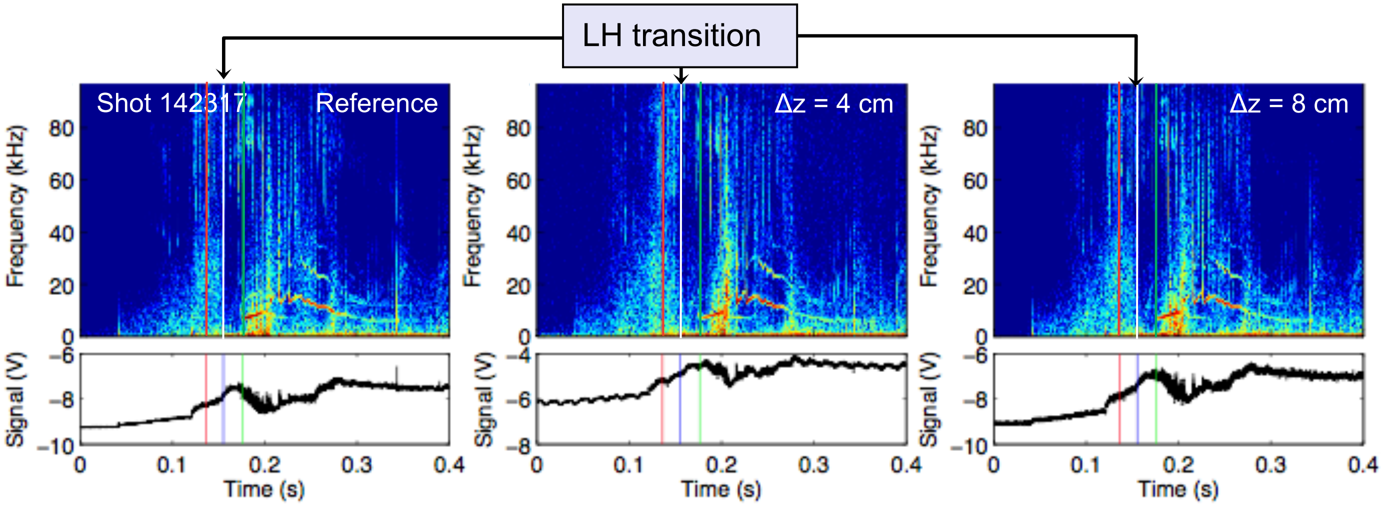
| Model | Ideal fiber | Focusing optics | Optical+NB decay | Optical+NB intensity | Optical+fieldline excursion | All effects |
|---|---|---|---|---|---|---|
| Y 1/e$^2$ width (cm) | 3.2 | 4.0 | 4.4 | 3.2 | 4.4 | 4.4 |
| Y displacement (cm) | 0.0 | 0.0 | 0.5 | 0.0 | -0.5 | 0.3 |



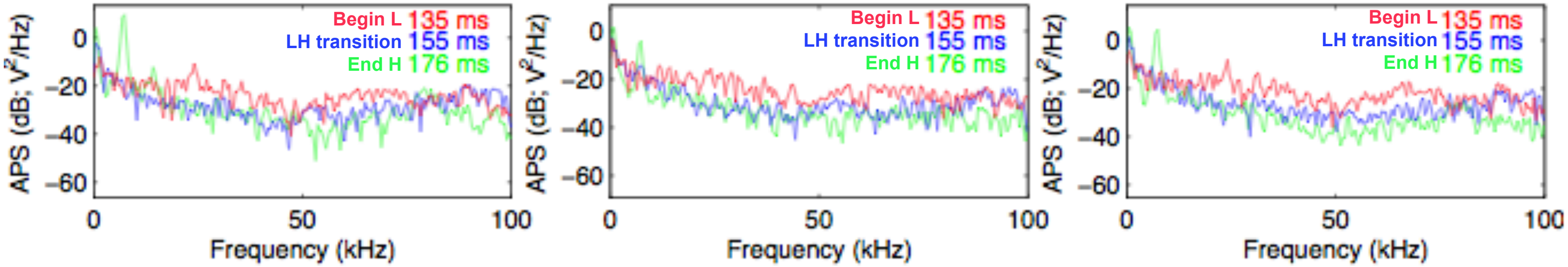
X (au) image int.
Y (cm) ~ radial
Z (cm) ~ binormal

Simulated fiber image

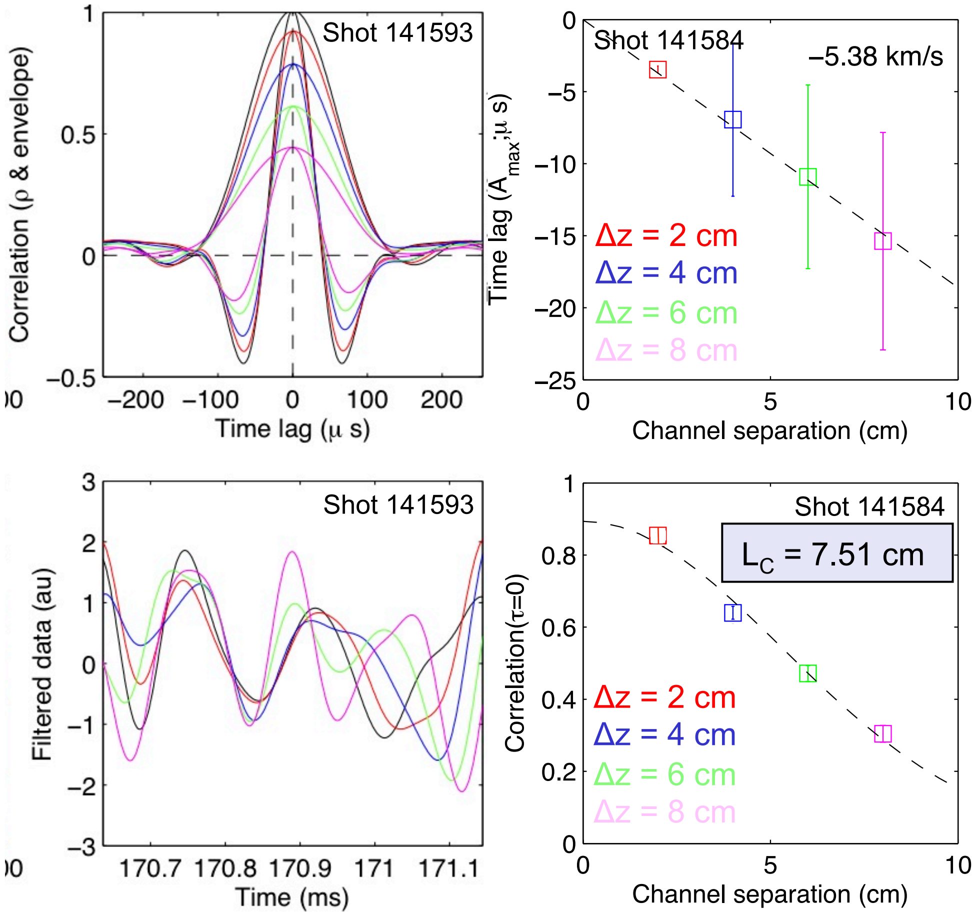
# BES observes a reduction in fluctuation amplitude following LH transition



The LH transition coincides with a reduction in intensity fluctuations, indicating turbulence suppression in early H-mode



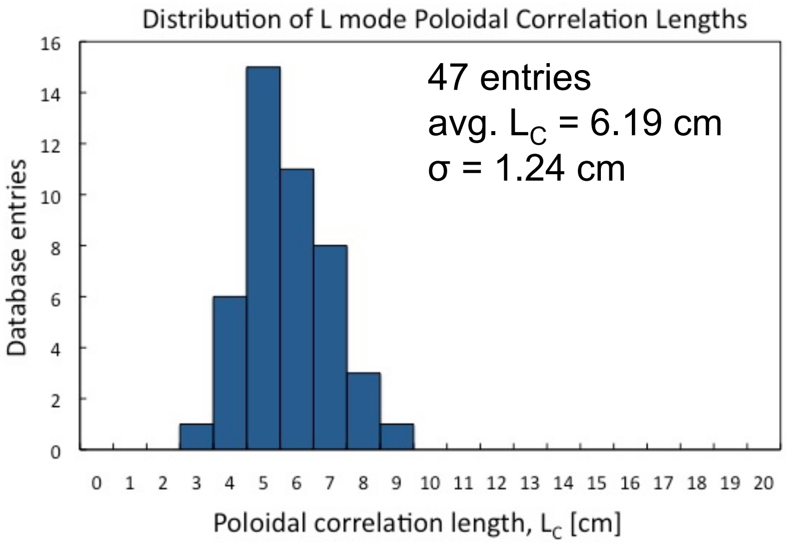
# Poloidal $L_C$ obtained from BES poloidal array at R=140 cm (r/a ≈ 0.8-0.95)



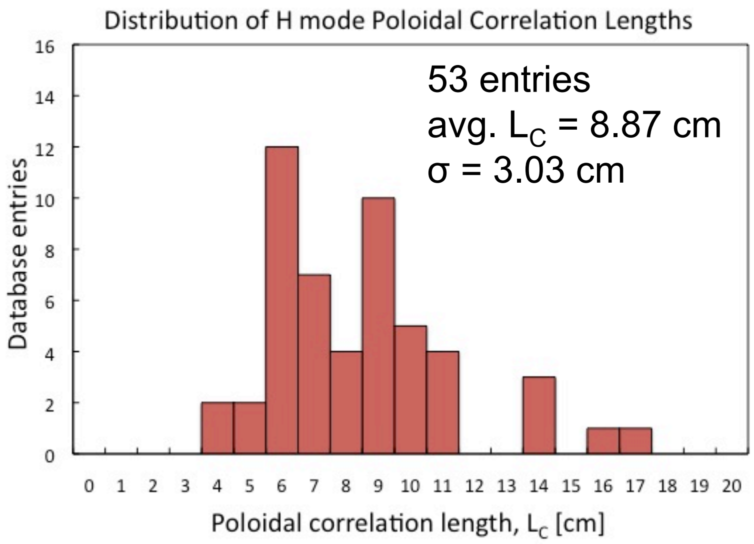
- $L_C$ calculated by a Gaussian fit to the correlation (Hilbert envelope) at zero time lag
- Shots with at least 3 channels (plus reference) of BES data were included

# Poloidal $L_C$ at r/a ≈ 0.8-0.95 are typically 3-18 cm; Larger average $L_C$ is observed after LH transition

- No dedicated BES experiment to test theoretical turbulence scaling has been conducted on NSTX
- In preparation for future experiments on NSTX-U, a database of intervals before and after the LH transition was filtered to include shots satisfying the following criteria
  - Free of neutral beam steps
  - Low low-frequency (< 3G) and mid-frequency (< 5G) MHD activity
  - Absence of ELMs and TAE modes
- Larger average $L_C$ observed after transition


Distribution of L mode Poloidal Correlation Lengths

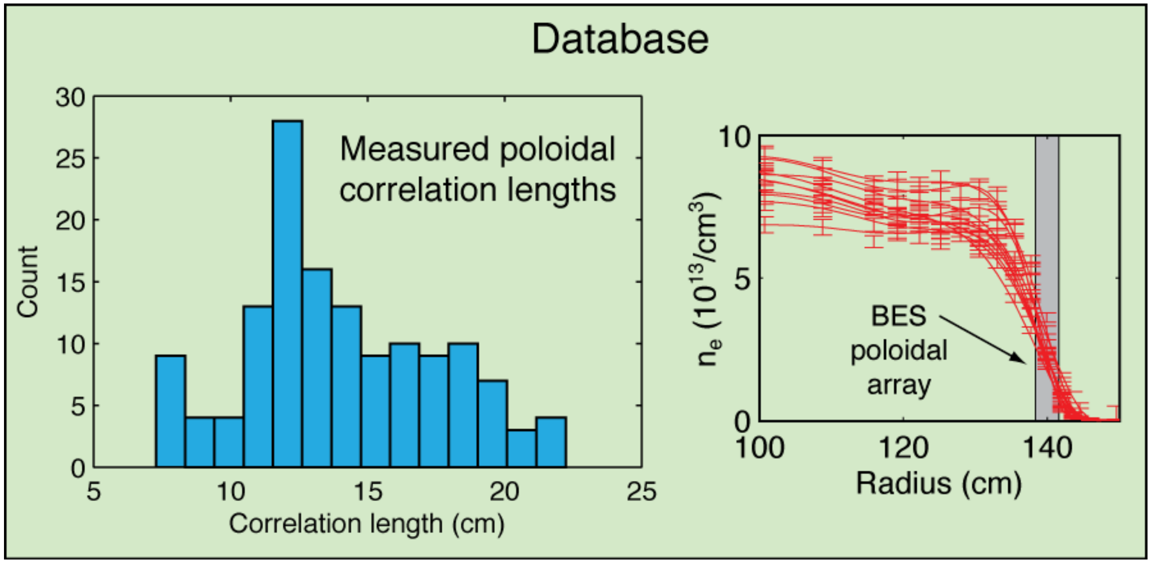
47 entries
avg. $L_C$ = 6.19 cm
σ = 1.24 cm

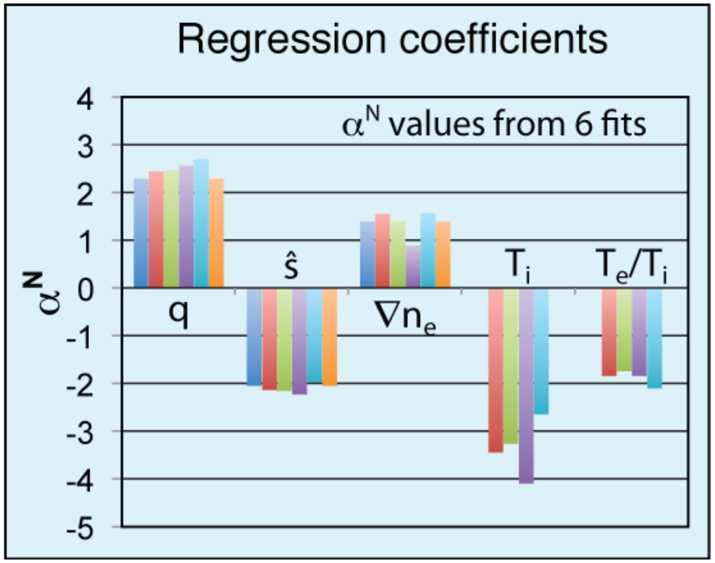

Distribution of H mode Poloidal Correlation Lengths

53 entries
avg. $L_C$ = 8.87 cm
σ = 3.03 cm

# 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)





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

# Stepwise multivariate linear regression analysis suggests sensitivity of $L_C$ to local plasma parameters

- In preparation for experiments anticipated for NSTX-U, stepwise multivariate linear regression analysis was applied to a database of intervals of BES data on both sides of the LH transition, and to ELM-free quiescent H-mode periods

- Iteratively test the following parameters ($x_i$) for statistical significance and MSE reduction:
  - $q$, $\hat{s}$, $q/\hat{s}$, $n_e$, $T_e$, $T_i$, $V_t$, sqrt($n_e$, $T_e$, $T_i$), $\nabla$($n_e$, $T_e$, $T_i$, $V_t$), $1/L_{(ne,\ Te,\ Ti)}$, $\kappa$, $\delta_{bot}$, $T_e/T_i$, $\beta_e$, $\beta_t$, $n_e$, $n_i$
  - Initialize search with every 2, 3, and 4-pair parameter combination to find multiple (30+) MSE local minima
  - $\alpha_i^N > 0$ indicates correlation. $\alpha_i^N < 0$ indicates anticorrelation.

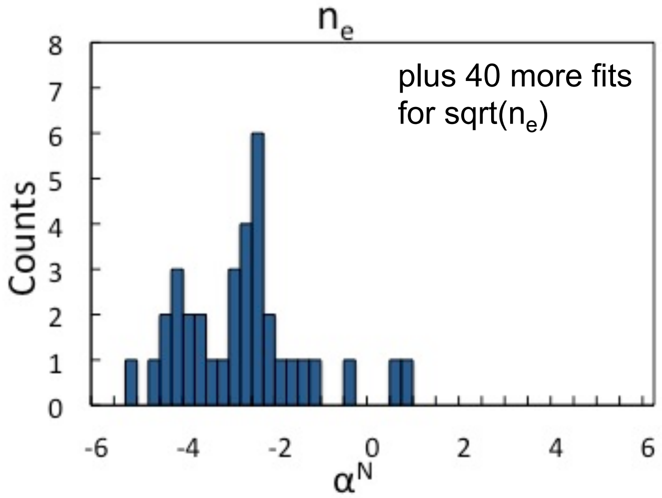
$$L_C = \overline{L}_C + \sum \alpha_i^N \frac{x_i - \overline{x}_i}{\sigma_{xi}}$$

plasma parameters

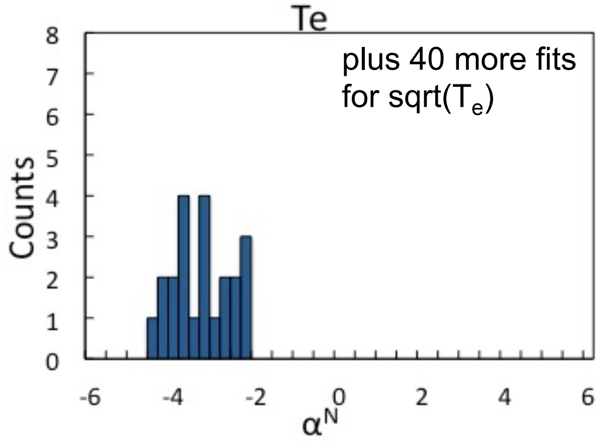
scaling coefficient

# Among local parameters, analysis of LH transition database suggests negative scaling for $n_e$, $T_e$, and $T_i$ in L-mode period before transition

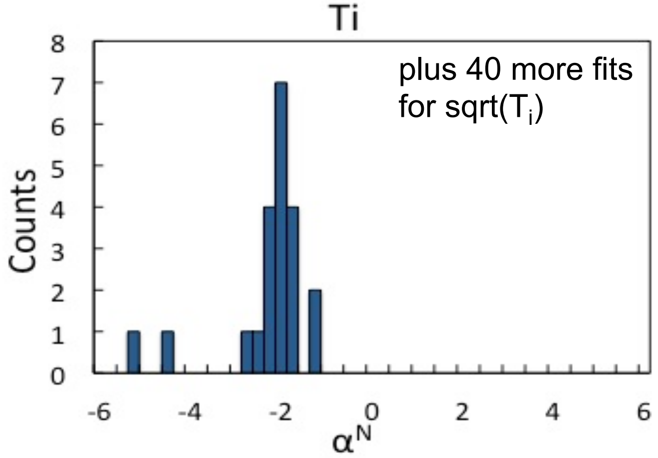
- $L_C$ **increases** at higher $T_e/T_i$
- $L_C$ **decreases** at higher $n_{e,}$ $T_e$, $T_i$, and sqrt($n_e$, $T_e$, $T_i$)



plus 40 more fits for sqrt($n_e$)



plus 40 more fits for sqrt($T_e$)

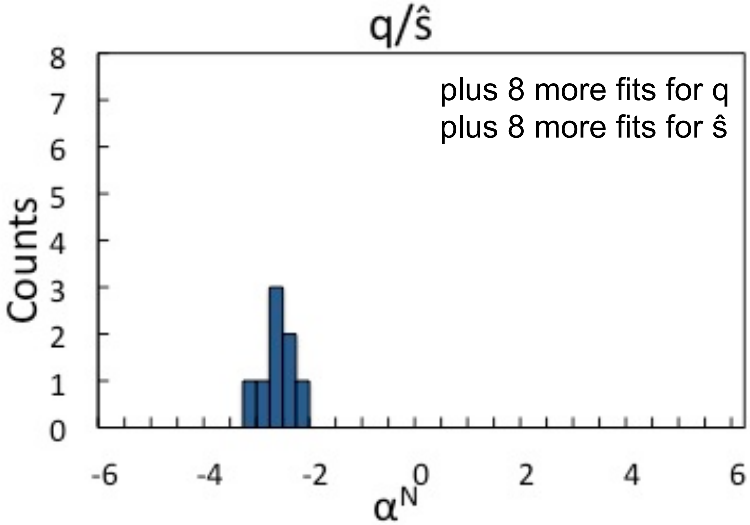


plus 40 more fits for sqrt($T_i$)

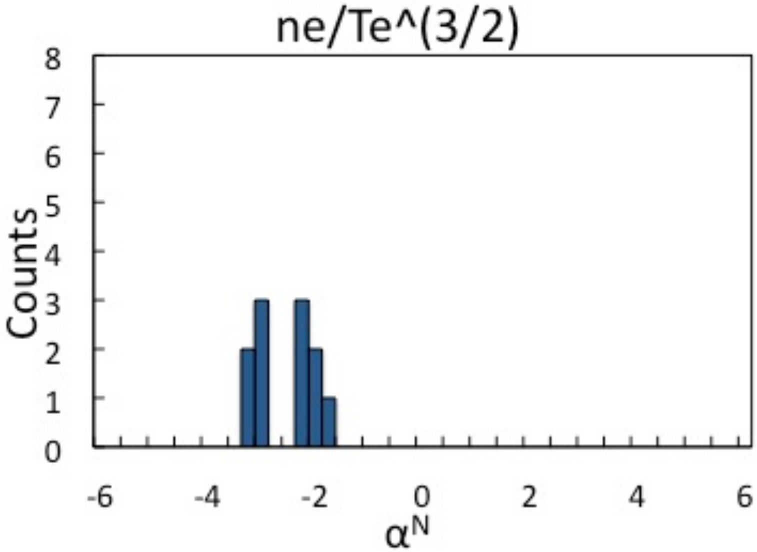
Other local quantities, such as $\nu$, $\beta$, and $V_t$, do not explain data variation or improve regression fits with high confidence

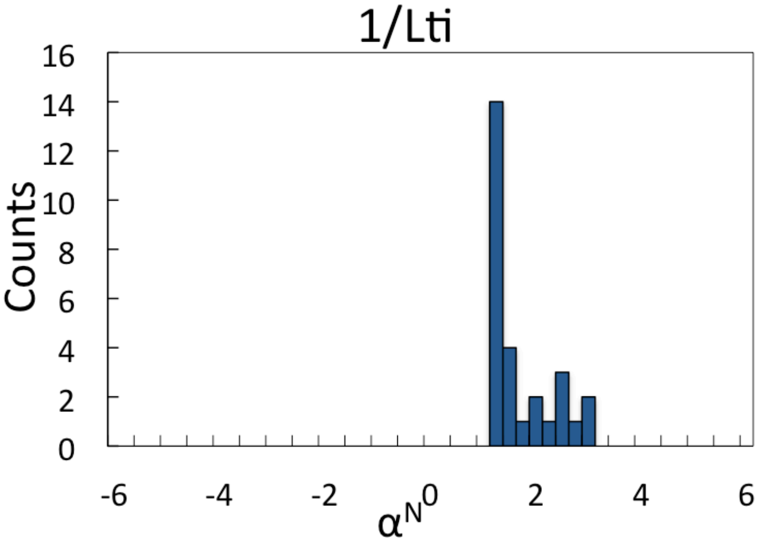
# Among local parameters, analysis of LH database suggests negative scaling for $n_e/T_e$^(3/2), and q/ŝ in H-mode period after transition; positive scaling for $1/L_{Ti}$

- $L_C$ **increases** at higher $1/L_{Ti}$ and q
  - $V_T$, $1/L_{Te}$, and $\delta_{bot}$ with lesser confidence
- $L_C$ **decreases** at higher ŝ, q/ŝ, and $n_e/T_e$^3/2
  - $\delta_{bot}$, and κ with lesser confidence

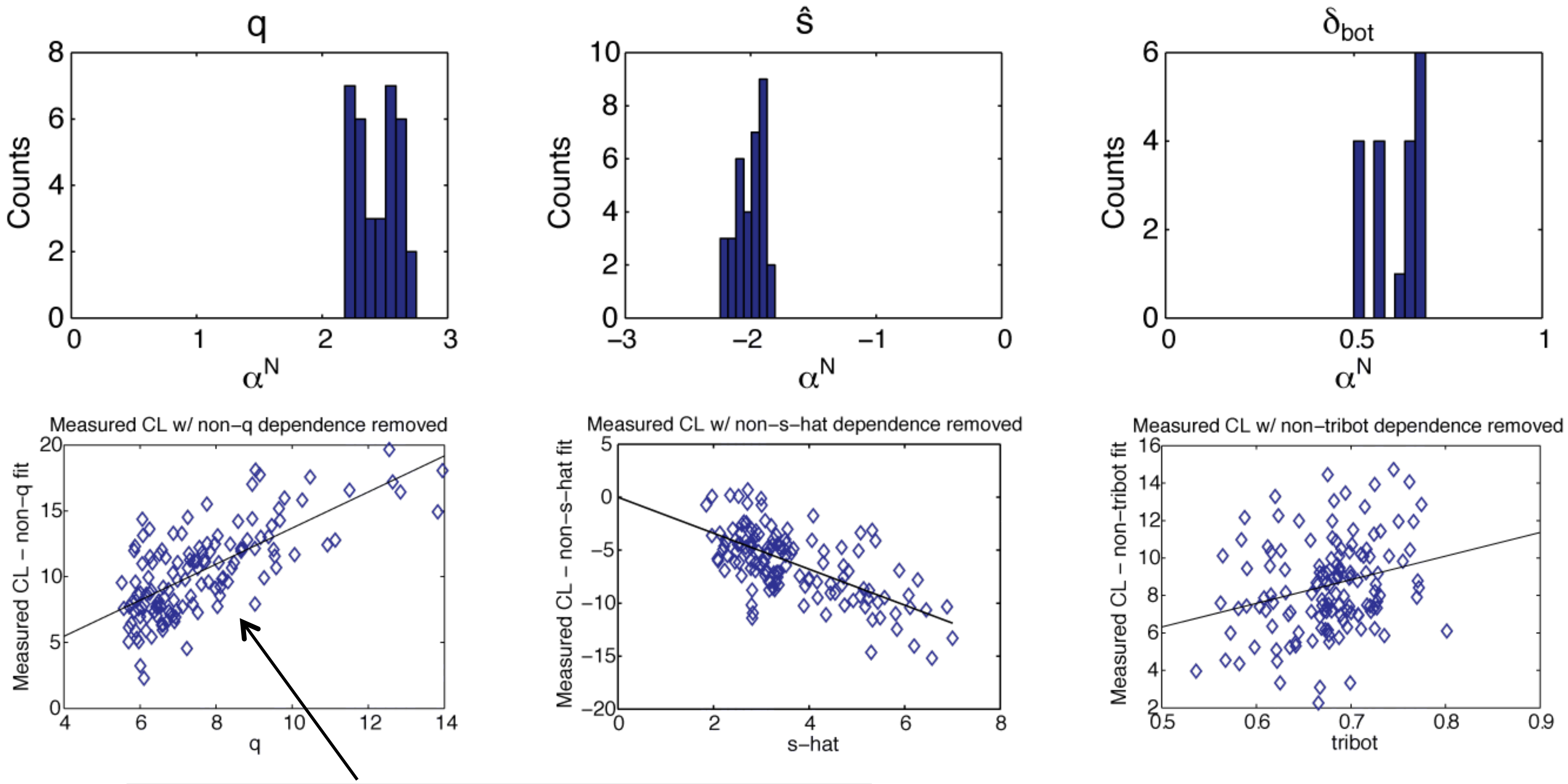


plus 8 more fits for q
plus 8 more fits for ŝ



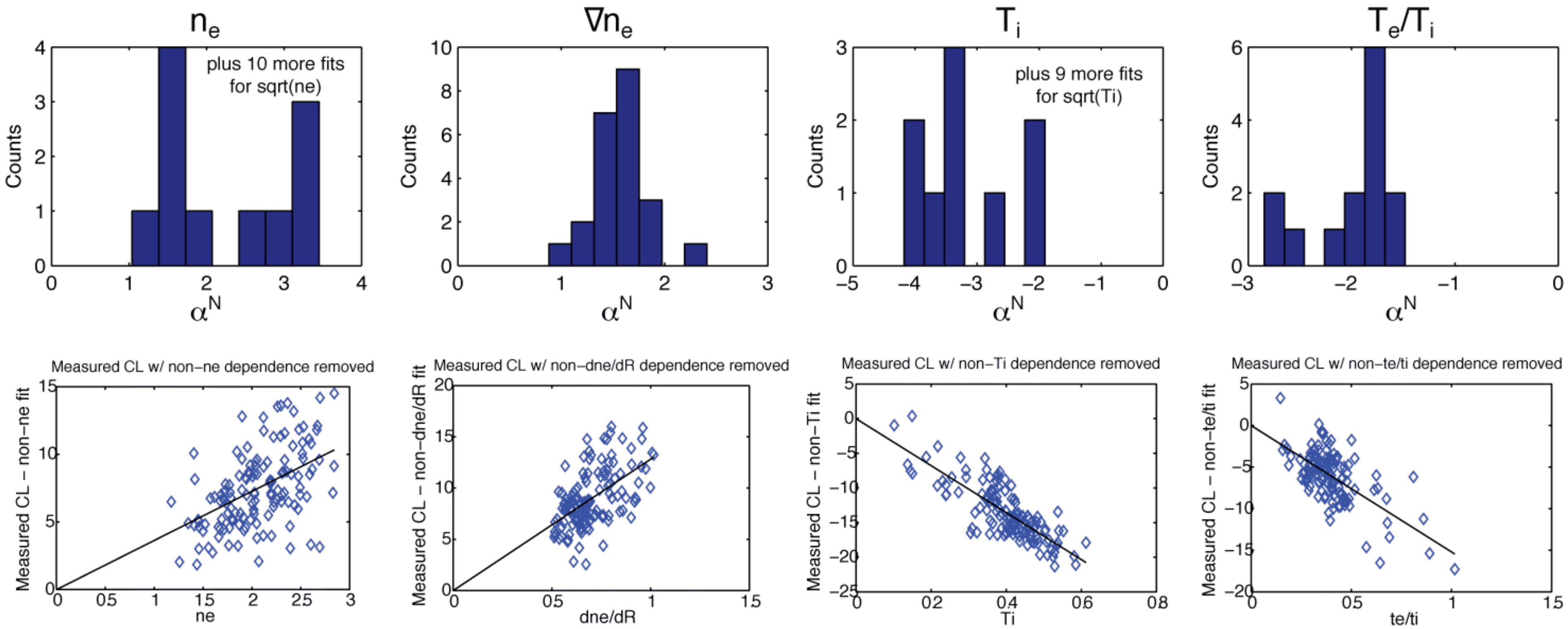


# Among equilibrium parameters, analysis of quiescent H-mode database indicates positive scaling for q and $\delta_{bot}$ and negative scaling for $\hat{s}$



Residuals + parameter dependence (single fit)

# Among species parameters, analysis indicates positive scaling for $n_e$ and $\nabla n_e$, and negative scaling for $T_i$ and $T_e/T_i$



# 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

# 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)
  - $k_\theta \approx 0.2\text{-}0.4\ \mathrm{cm}^{-1}$ and $k_\theta \rho_i \approx 0.1\text{-}0.25$
  - Radial correlation length calculations and TDE tools are under development
- Regression analysis of quiescent H-mode intervals suggests
  - $L_C$ **increases** at higher q, $\delta_{bot}$, $n_e$, and $\nabla n_e$
  - $L_C$ **decreases** at higher ŝ, $T_i$, and $T_e/T_i$

- Regression analysis of intervals before and after LH transition suggests
  - L-mode: $L_C$ **increases** at higher $T_e/T_i$
    $L_C$ **decreases** at higher $n_e$, $T_e$, $T_i$, and sqrt($n_e$, $T_e$, $T_i$)
  - H-mode: $L_C$ **increases** at higher $1/L_{Ti}$, q, $V_T$, $1/L_{Te}$, and $\delta_{bot}$
    $L_C$ **decreases** at higher ŝ, q/ŝ, $n_e/T_e$^3/2, $\delta_{bot}$, and κ