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NSTX-U

Parametric dependencies of low-k pedestal turbulence in NSTX H-mode plasmas

David R. Smith[1]

with R. Fonck[1], G. McKee[1], D. Thompson[1], I. Uzun-Kaymak[1],
A. Diallo[2], and B. Stratton[2]

[1]University of Wisconsin-Madison
[2]Princeton Plasma Physics Lab

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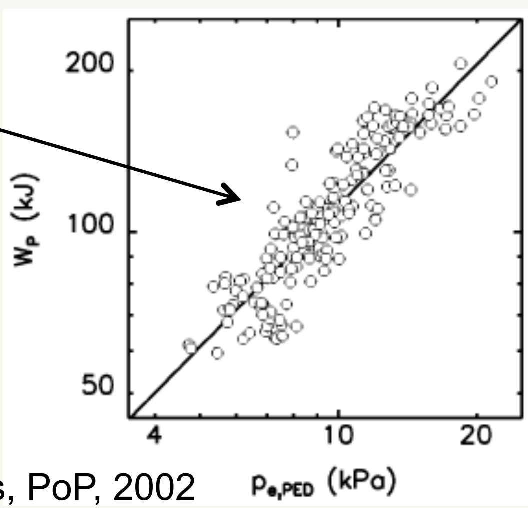
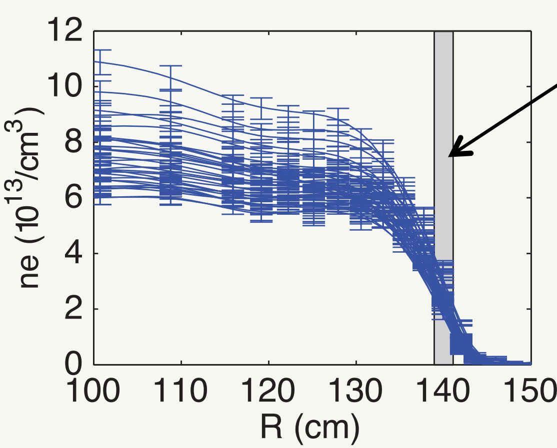
What are the characteristics and parametric dependencies of pedestal turbulence in NSTX?

- ITER and next-step devices need accurate models of pedestal dynamics
  - Global confinement predictions
  - Diverter heat flux and first-wall lifetime predictions
  - ST edge parameters are among the most challenging regimes for turbulence simulations (steep gradients, high β, large ρ_i/a, strong shaping)
- Here, we measure **pedestal turbulence** parameters in NSTX H-mode plasmas during **ELM-free, MHD quiescent** periods
  - Poloidal correlation length, wavenumber, and decorrelation time
  - Identify parametric dependencies (∇n_e, ∇T_i, etc)

C-Mod: stored energy increases with pedestal height



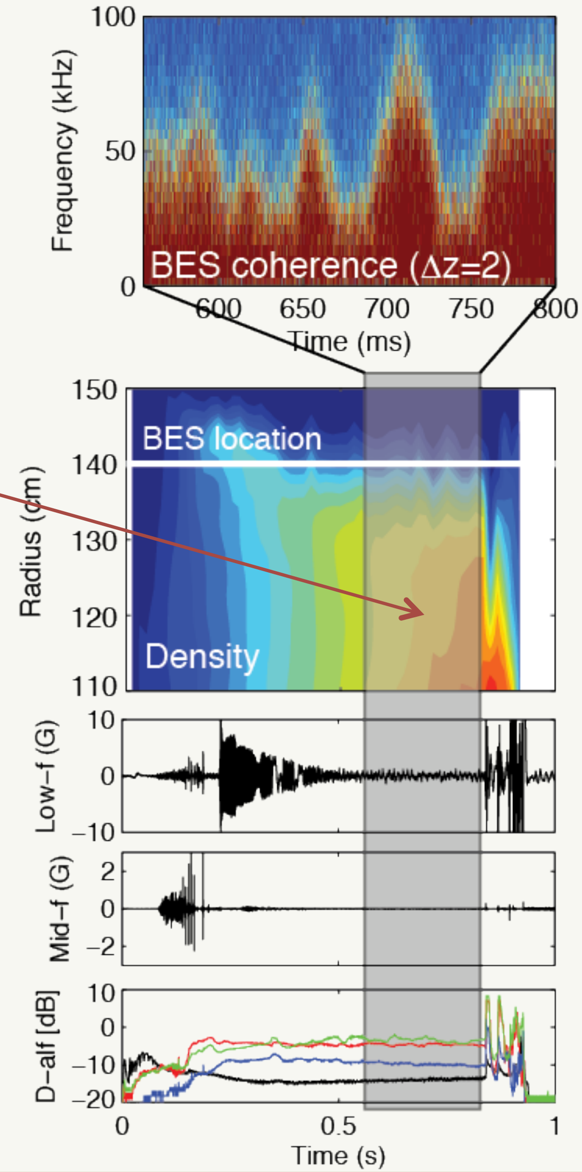
Hughes, PoP, 2002



NSTX: BES measurements from multiple discharges in steep gradient region

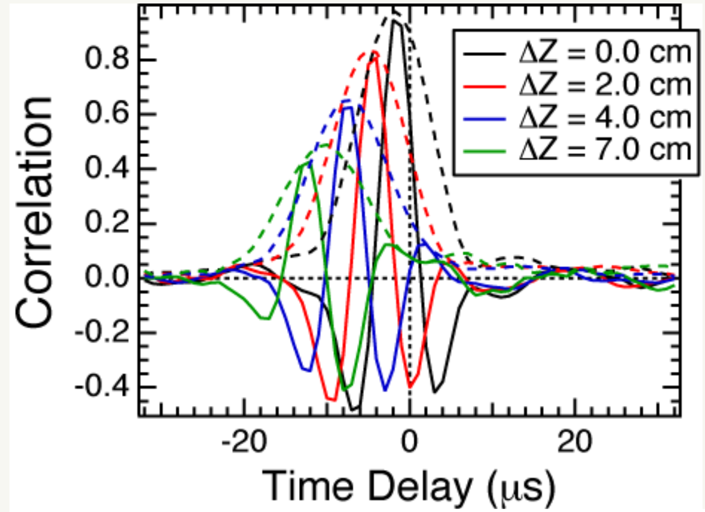
Outline

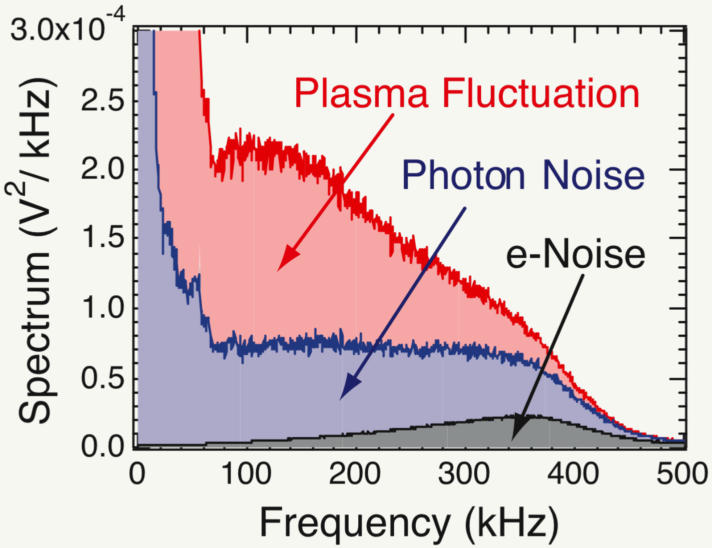
- Beam emission spectroscopy (BES) diagnostic overview
- Pedestal turbulence measurements
  - LH transition
  - ELM-free, MHD quiescent periods
  - Parametric scalings
- Correlation length during the ELM cycle
  - Initial theory/experiment comparison
- Other BES observations
  - Post-ELM harmonic features
  - TAE and GAE mode structures
- Future work and summary

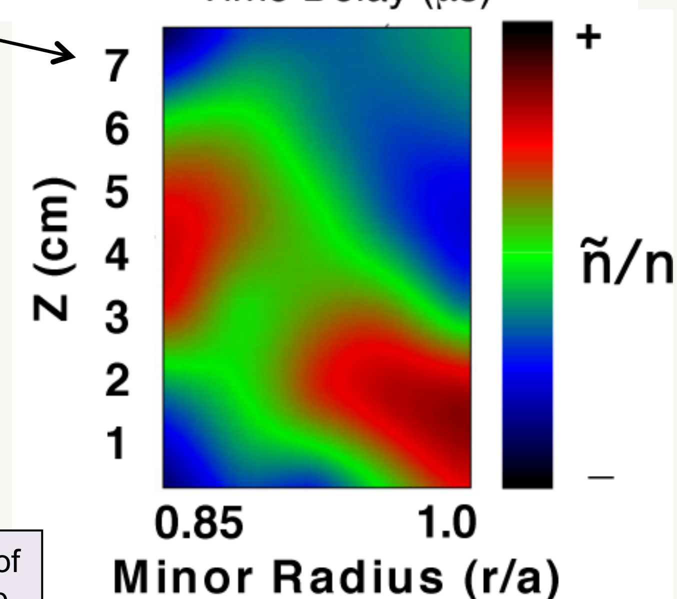


Beam emission spectroscopy (BES) is a diagnostic technique for measuring ion gyroscale ($k\rho_i < 1$) density fluctuations

- Measured & derived quantities
  - Fluctuation amplitudes
  - **Frequency spectra**
  - Radial and **poloidal correlation lengths**
  - **Decorrelation times**
  - Poloidal flow, flow fluctuations, flow shear, and 2D flow fields
  - 2D fluctuation imaging
  - 3-wave bispectral analysis
  - Particle flux







Figures courtesy of DIII-D BES group

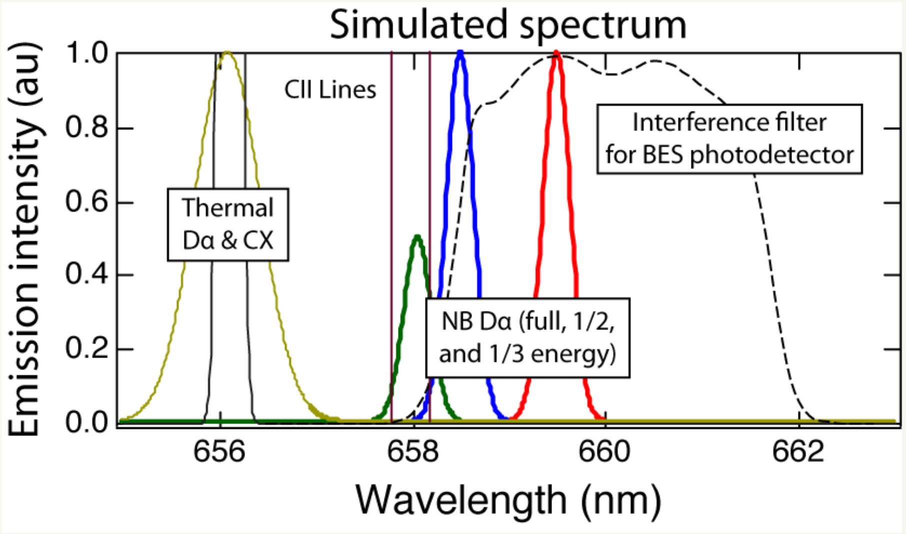
BES measures Doppler-shifted D_α emission (λ_0=656 nm) from neutral beam particles

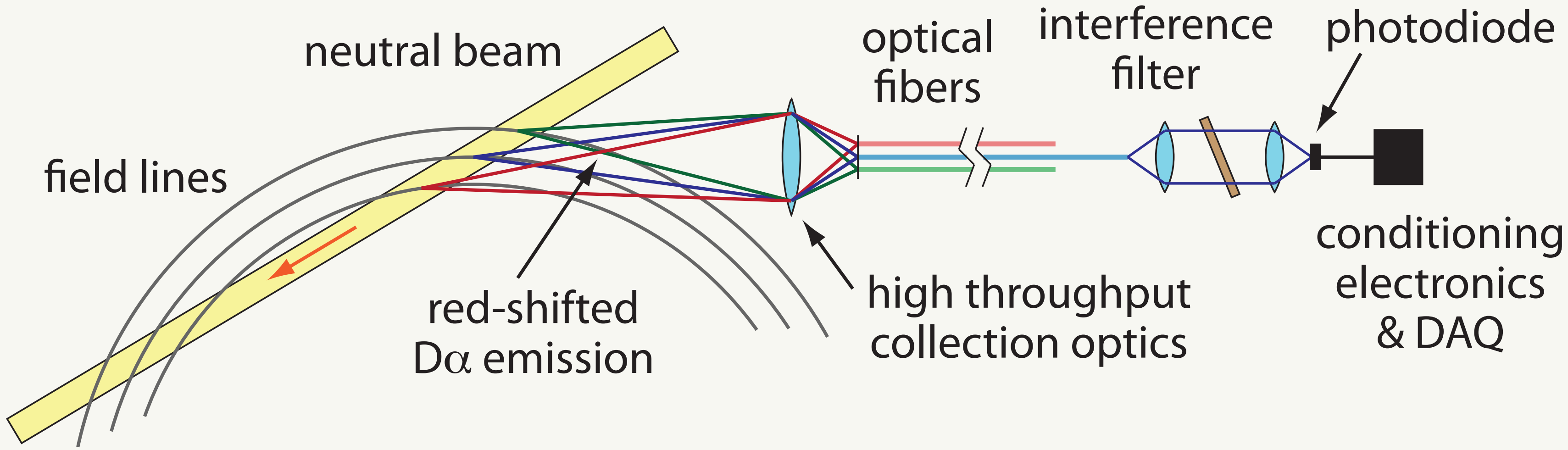
$$\frac{\delta I_{D\alpha}}{I_{D\alpha}} = \frac{\delta n}{n} \times C\left(E_{NB}, n, T_e, Z_{eff}\right)$$

neutral beam D_α emission

density fluctuation

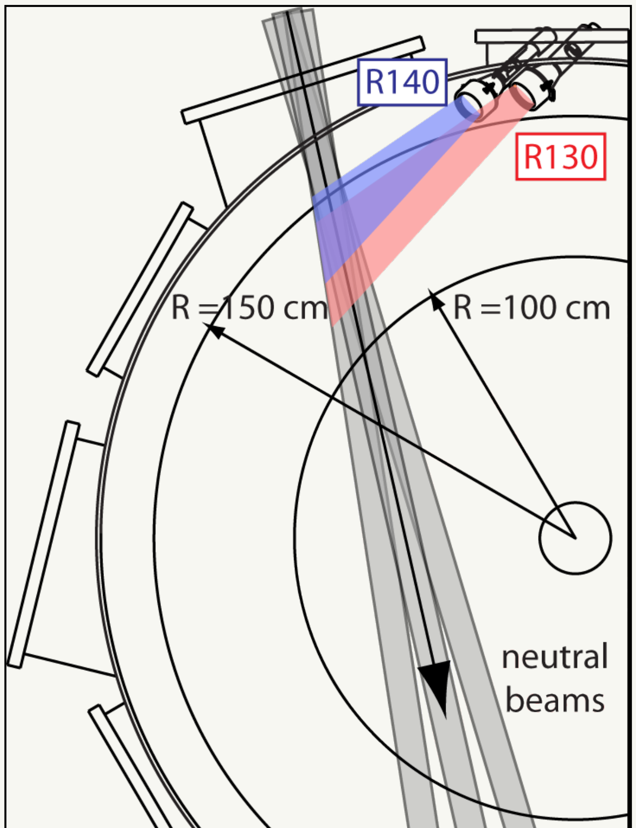
C ≈ 1/2

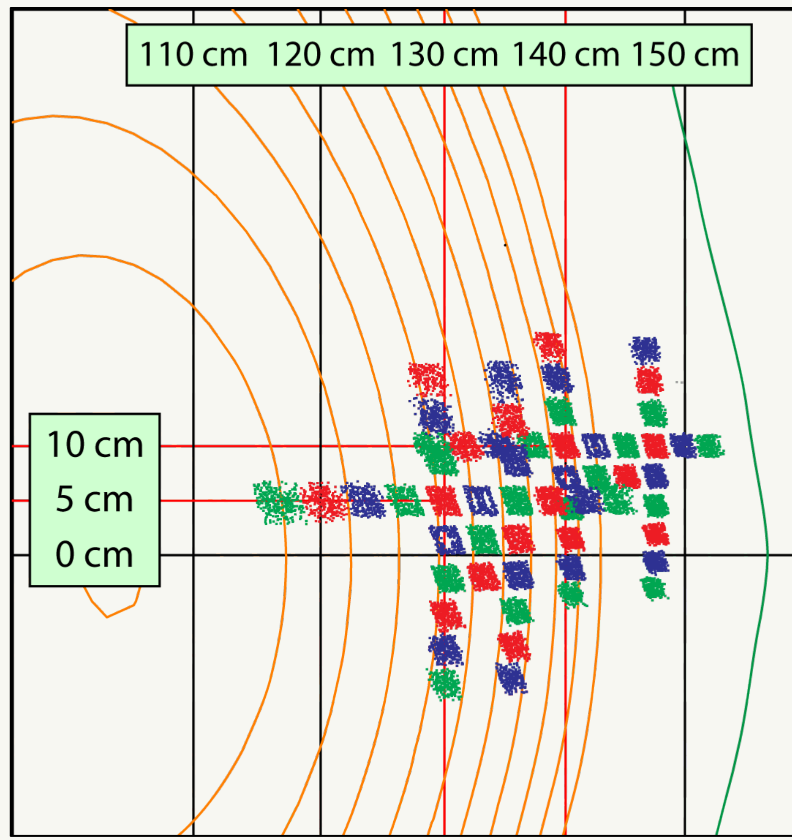




NSTX BES system includes 56 sightlines in radial and poloidal arrays spanning core to SOL

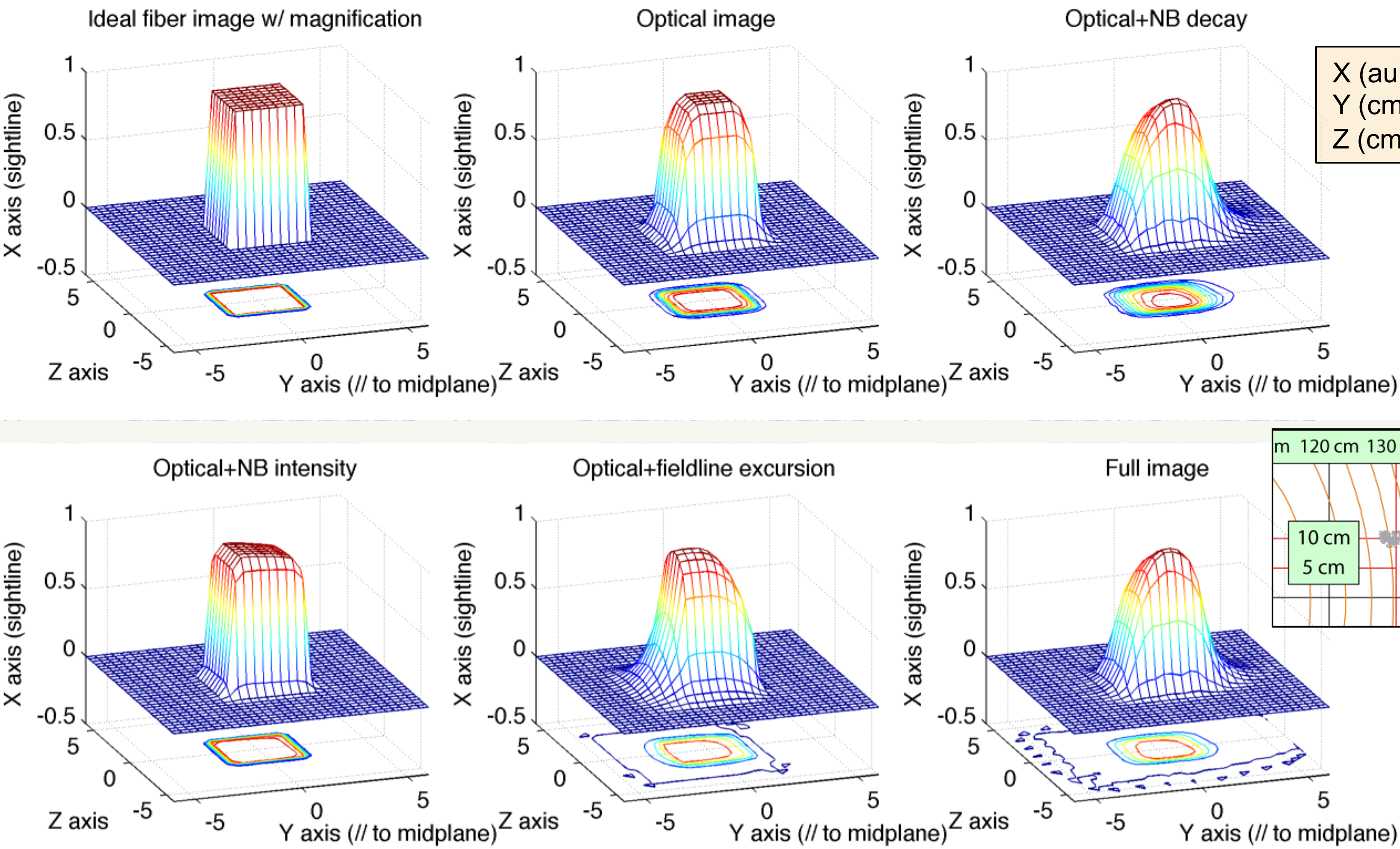
- 32 detection channels; expansion planned for NSTX-U
- 2 MHz sampling with digital anti-alias filter
- 2-3 cm image size and sensitive to $\tilde{n}$ with $k_{\perp}\rho_i \leq 1.5$
- Field-aligned optics with high throughput (etendue = 2.3 mm^2-ster)



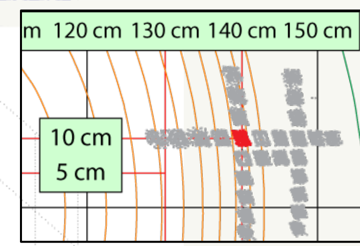


Point spread functions

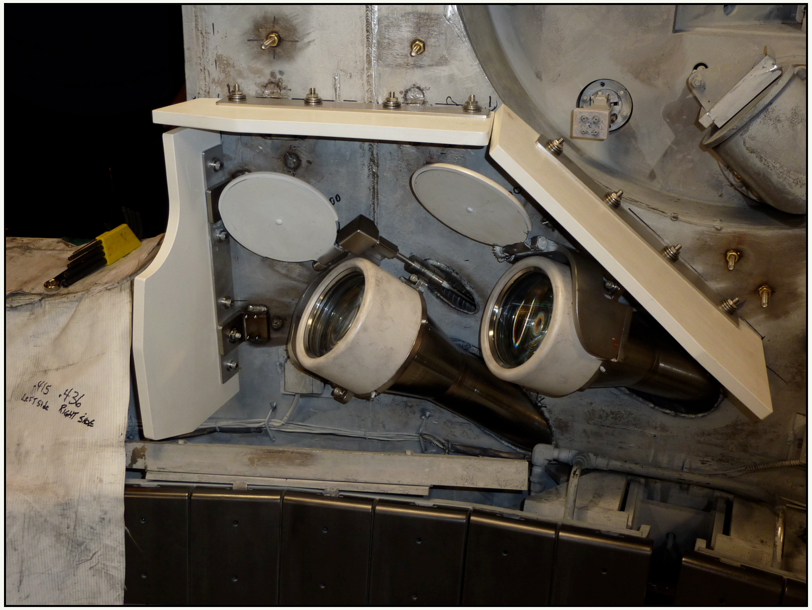
Model	Ideal fiber	Focusing optics	Optical+NB decay	Optical+NB intensity	Optical+fieldline excursion	All effects
Y 1/e^2 width (cm)	3.2	4.0	4.4	3.2	4.4	4.4
Y displacement (cm)	0.0	0.0	0.5	0.0	-0.5	0.3

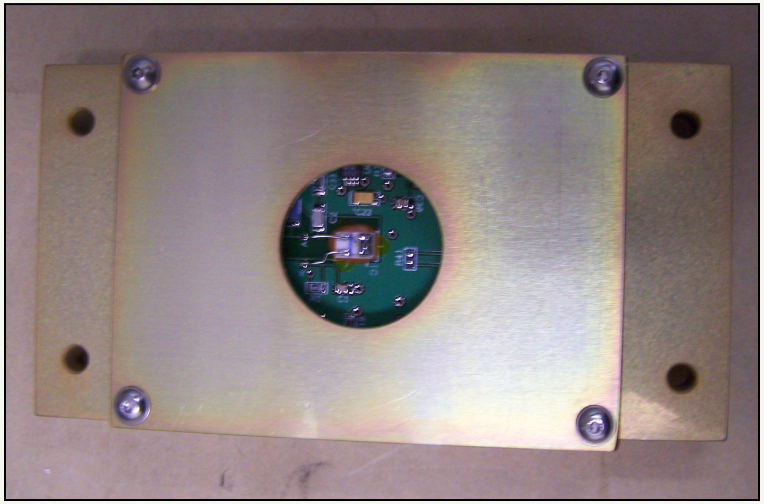


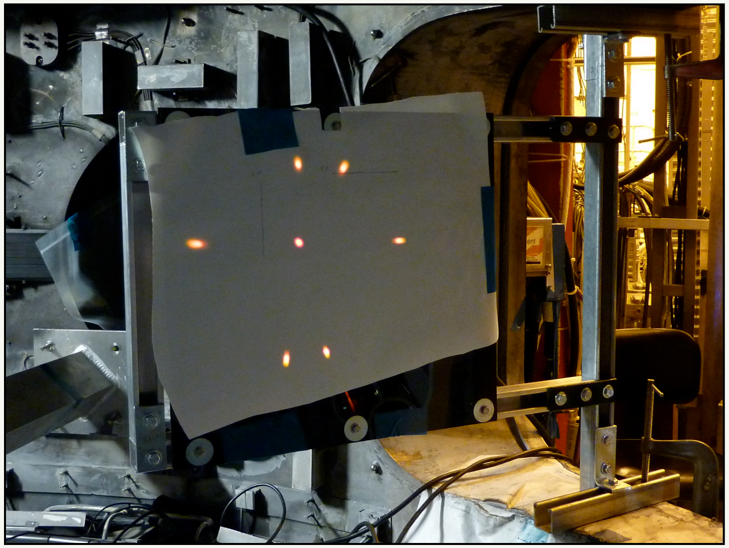
X (au) image int.
Y (cm) ~ radial
Z (cm) ~ binormal



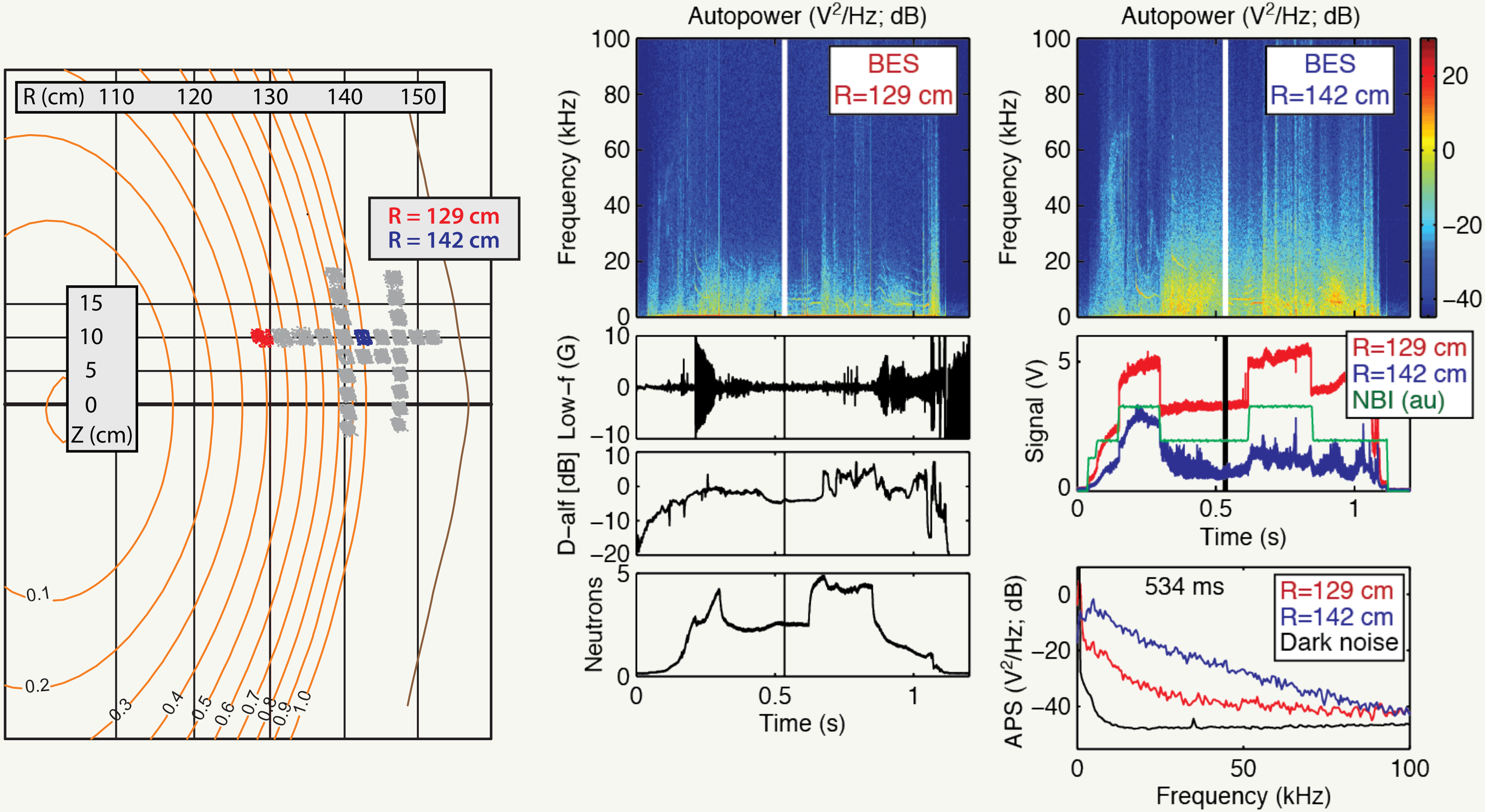
NSTX BES system commissioned in 2010



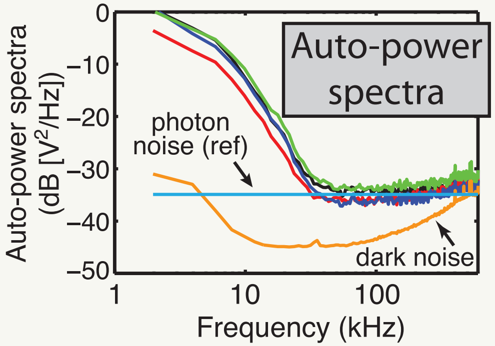


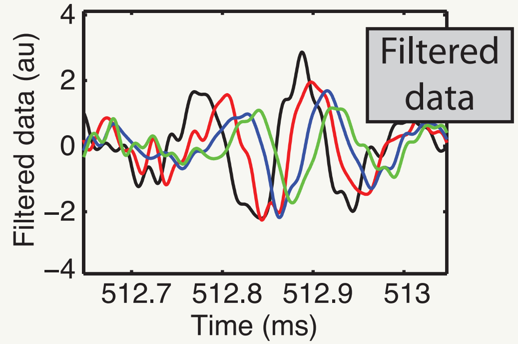


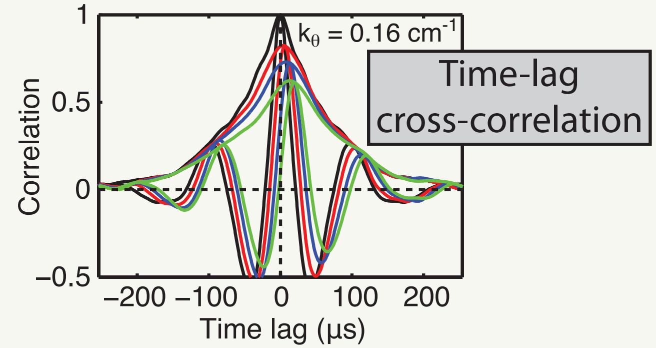
BES measurements show radially-localized response to NB emission and high signal-to-noise ratio

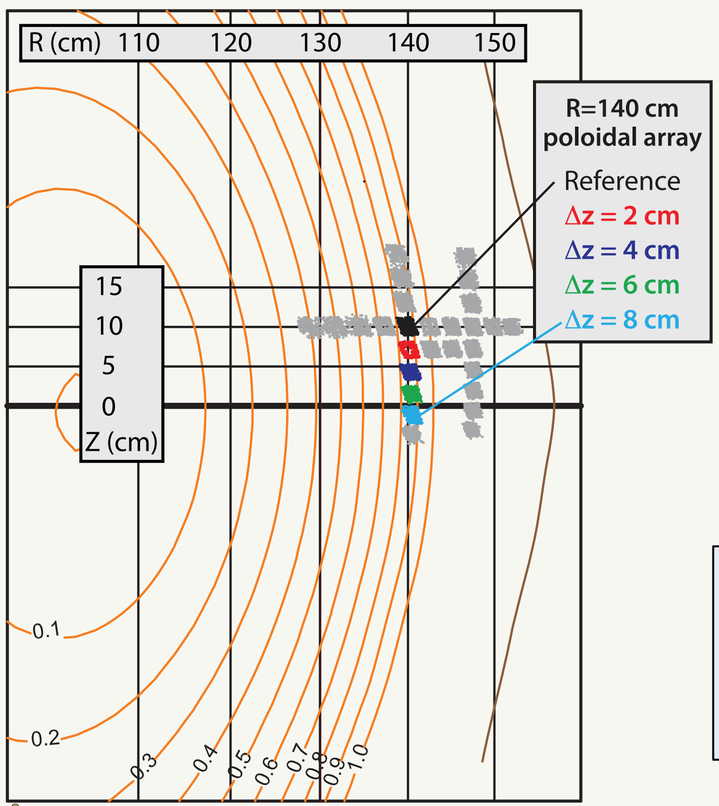


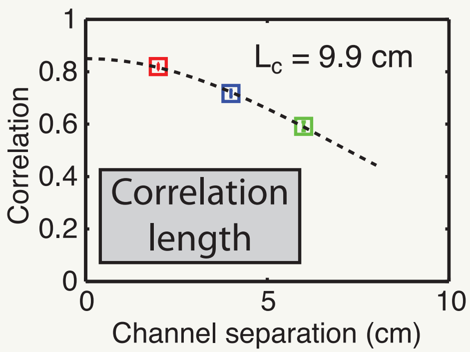
BES measurements provide poloidal correlation lengths (L_c), poloidal wavenumbers (k_θ), and decorrelation times (τ_d) in the pedestal

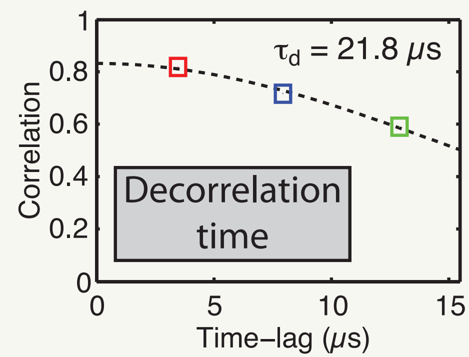






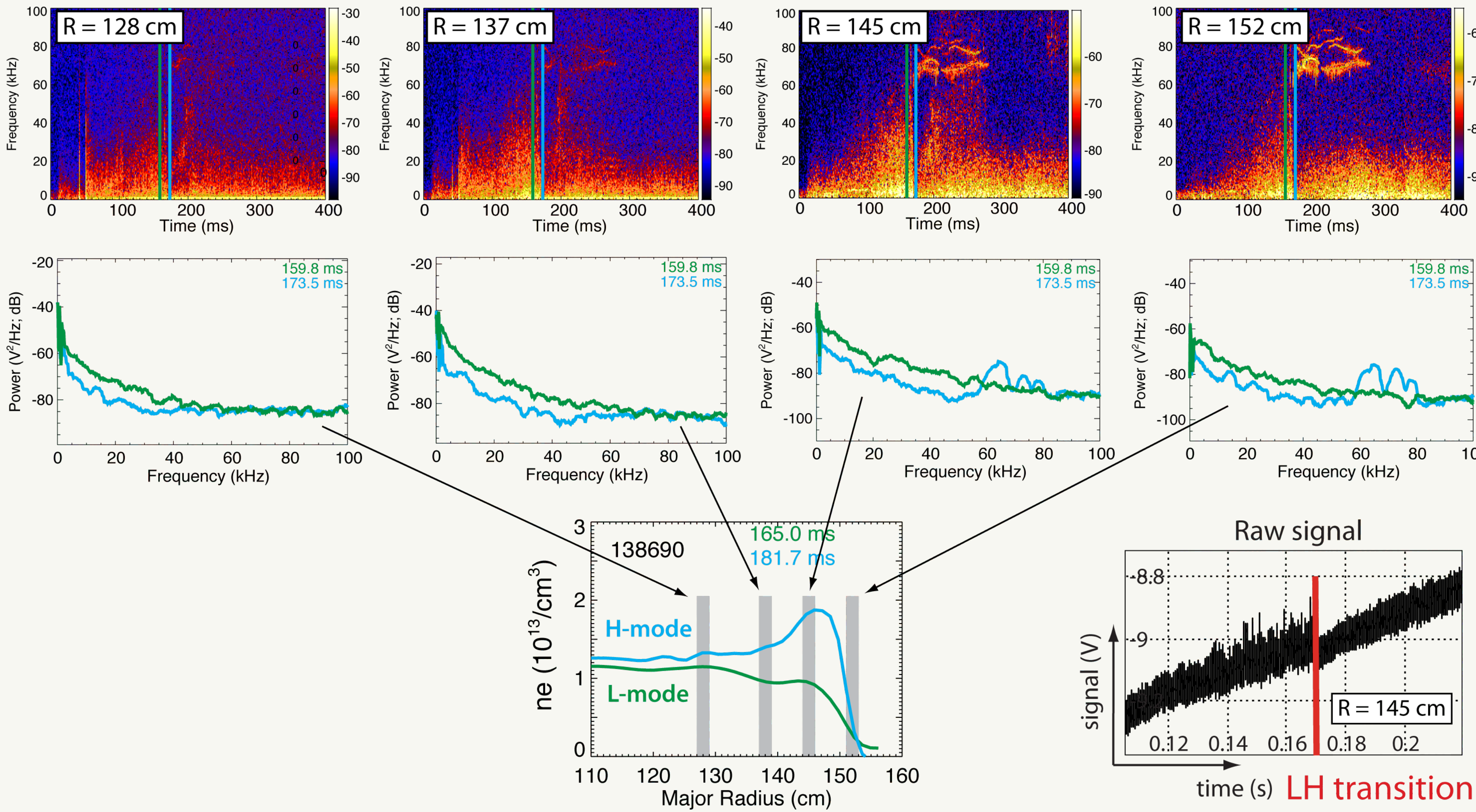






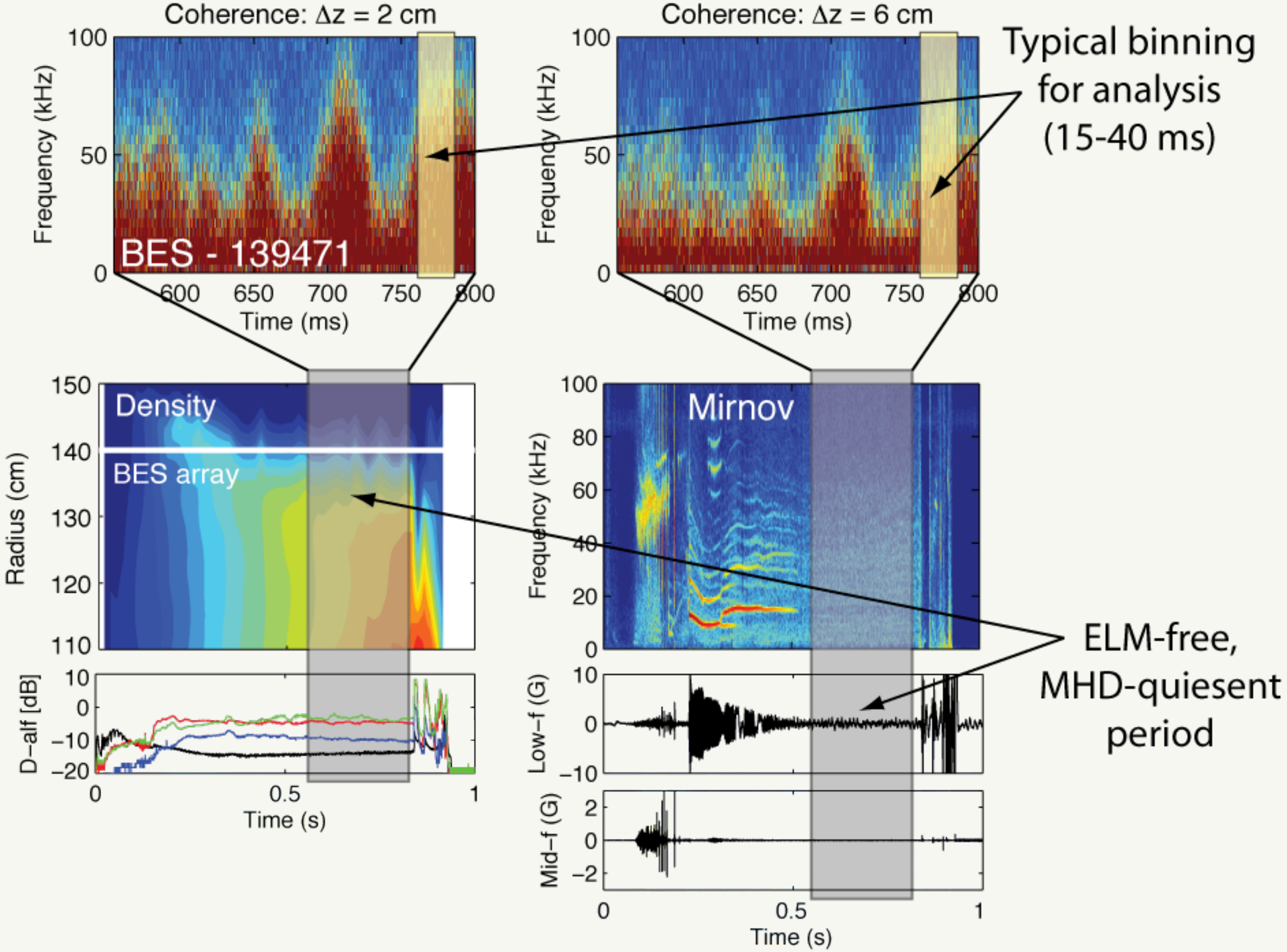
- Filtered data shows eddy propagation
- Turbulence quantities calculated from time-lag cross-correlations

Decrease in fluctuations at LH transition observed from edge to core regions



Similar increase in fluctuations observed at HL back-transitions

BES shows complex turbulence activity in pedestal during quiescent H-mode periods



Questions about pedestal turbulence to ask and answer with BES measurements

- What are typical L_c, k_θ, and τ_d values in the H-mode pedestal during ELM-free, MHD quiescent periods?

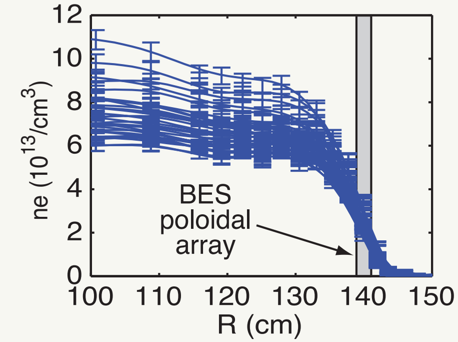
- How do L_c, k_θ, and τ_d change with plasma parameters?
  - ∇n_e, ∇T_i, $q/\hat{s}$, ν_e, β_e, n_{ped}, etc.

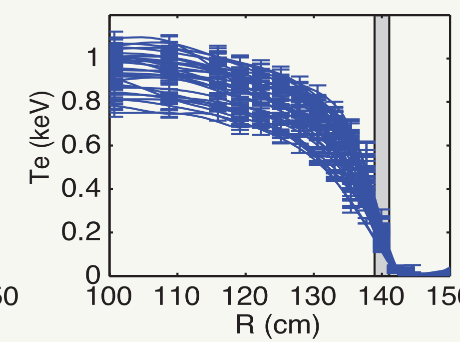
- Can we connect observations to edge turbulence simulations?
  - XGC1 or BOUT++?

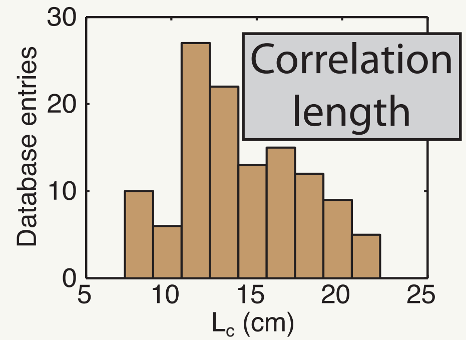
Pedestal turbulence measurements and plasma parameters from ELM-free, MHD quiescent H-modes were gathered in a database

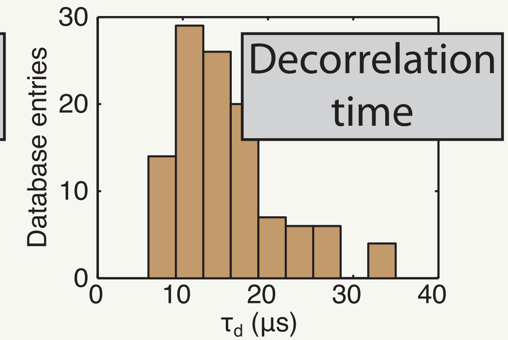
Database details

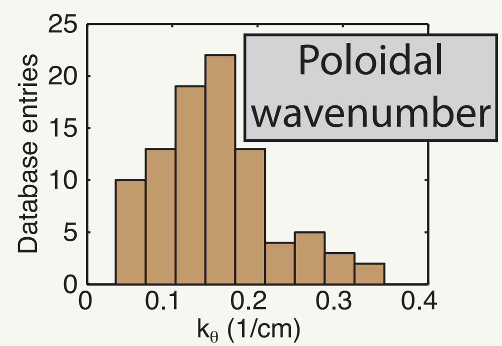
- 129 entries from 29 discharges
  - B_{T0} = 4.5 kG
  - I_p = 700-900 kA
  - 15-45 ms averaging
- Turbulence parameters
  - $L_c/\rho_i \sim 12$
  - $k_\theta \rho_i \sim 0.2$
  - $\tau_d/(a/c_s) \sim 5$
  - $\tau_d \omega^*_{pi} \sim 0.15$
- Plasma parameters
  - generally 50%-300% variation
  - n_e, ∇n_e, T_e, ∇T_e, Ti, ∇T_i, v_t, ∇v_t, q, $\hat{s}$, ν_e, ν_i, β, β_e, n_{ped}, ΔR_{ped}, δ_r^{sep}











A search algorithm identified linear regression models that show similar scalings despite different parameter compositions

$$\frac{\hat{y} - \bar{y}}{\sigma_y} = \sum \alpha_k \frac{x_k - \bar{x}_k}{\sigma_{xk}}$$

turbulence parameters ($\hat{y}$) · scaling coefficient (α_k) · plasma parameters (x_k)

- Search algorithm minimizes regression model's squared sum of errors (SSE) by adding or removing x_k in model
- **Many SSE local minima exist** in high dimensional x_k space
- Objective: find **many** models and screen for statistical quality
  - Statistical significance (α_k t-statistics)
  - Multicollinearity (variance inflation factor)
  - Error normality (Studentized residuals)

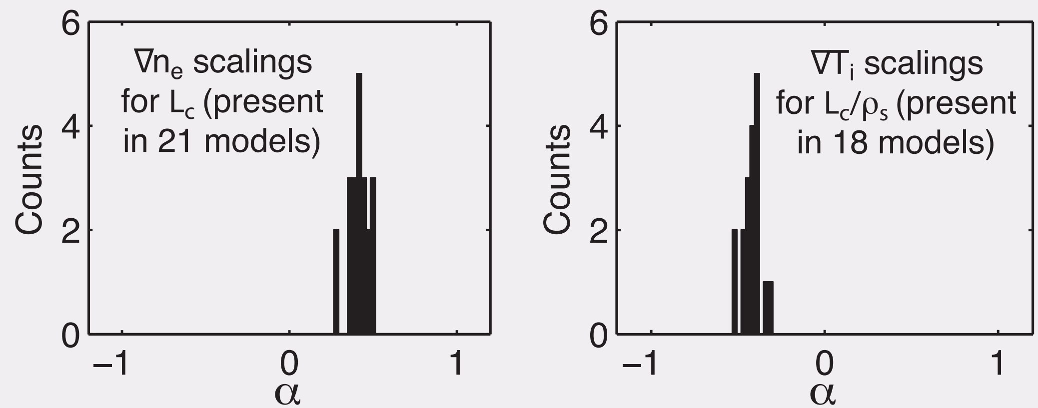
Linear regression models exhibit **similar scalings** despite different parameter compositions

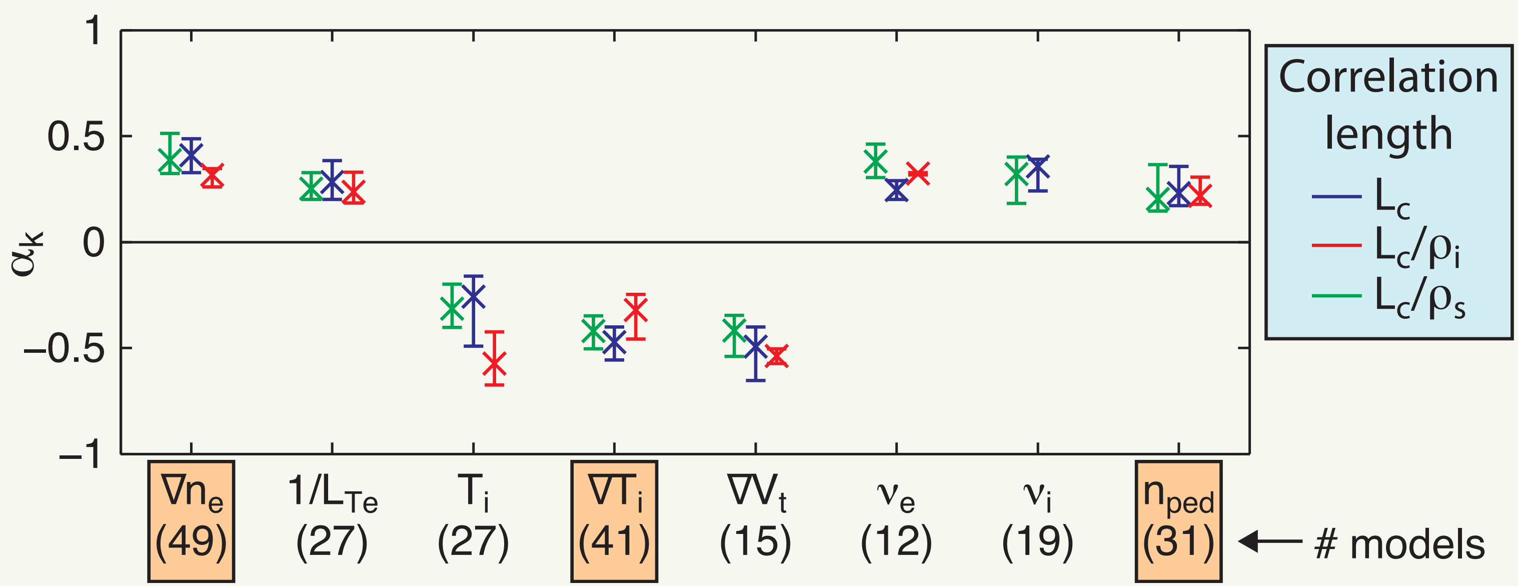
TABLE III: α coefficients for a subset of L_c/ρ_s models

Model	α_k coefficients of parameters in model						
R^2	∇n_e	T_e	T_i	$1/L_{T_i}$	∇V_t	ν_e	n_{ped}
0.63	0.28	–	-0.20	-0.29	–	0.31	–
0.63	0.34	–	–	–	-0.37	0.30	–
0.61	0.46	-0.21	–	–	-0.38	–	–
0.60	–	–	–	–	-0.47	0.38	0.24
0.60	–	–	-0.22	-0.35	–	0.40	0.15
0.55	–	-0.24	–	–	-0.55	–	0.36

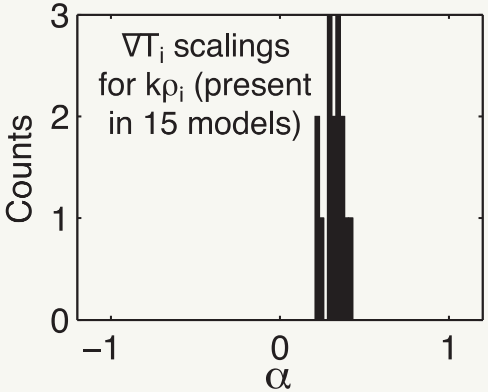
L_c increases at higher ∇n_e, $1/L_{Te}$, ν, and n_{ped}; decreases at higher T_i, ∇T_i, and ∇v_t

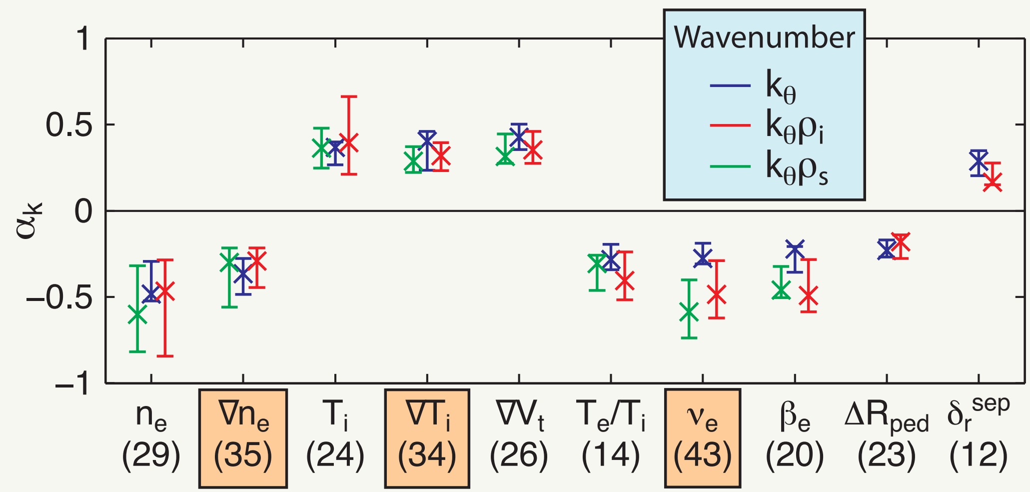
Consistent scalings emerge from different regression models

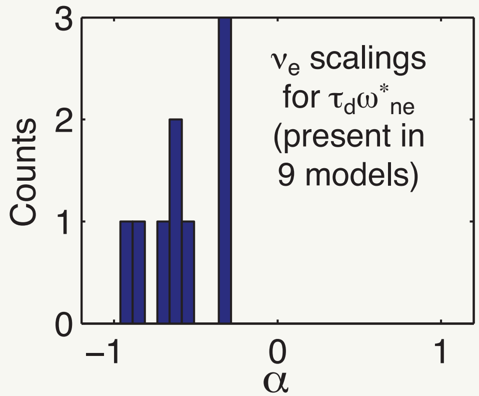


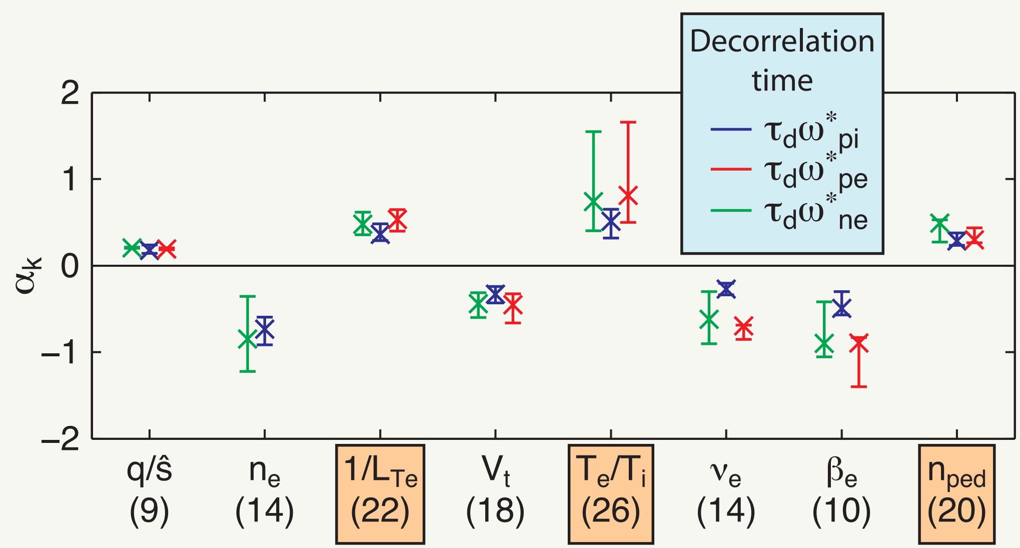


k_θ scalings consistent with L_c scalings; τ_d scalings provide additional insight





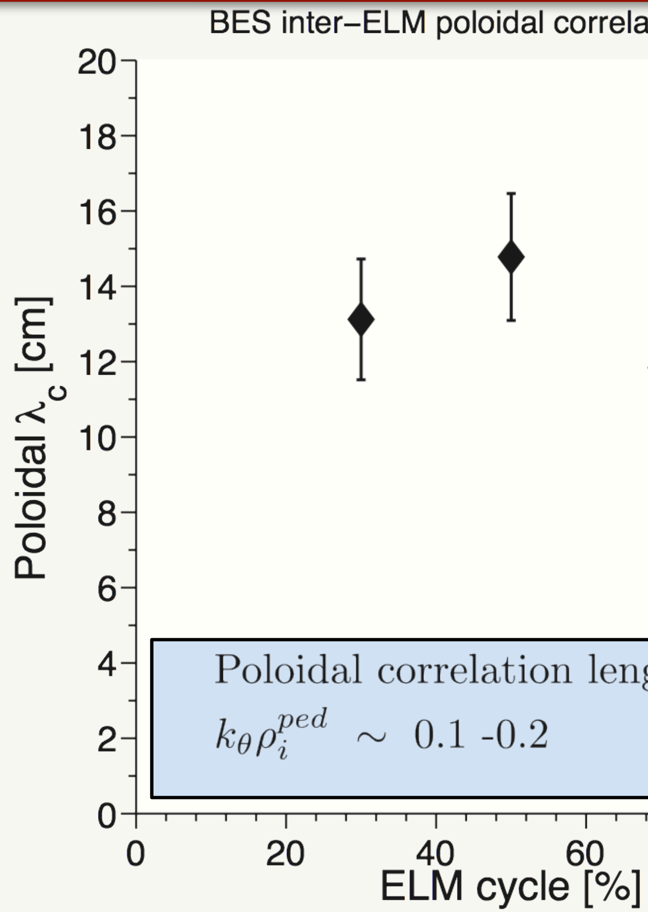


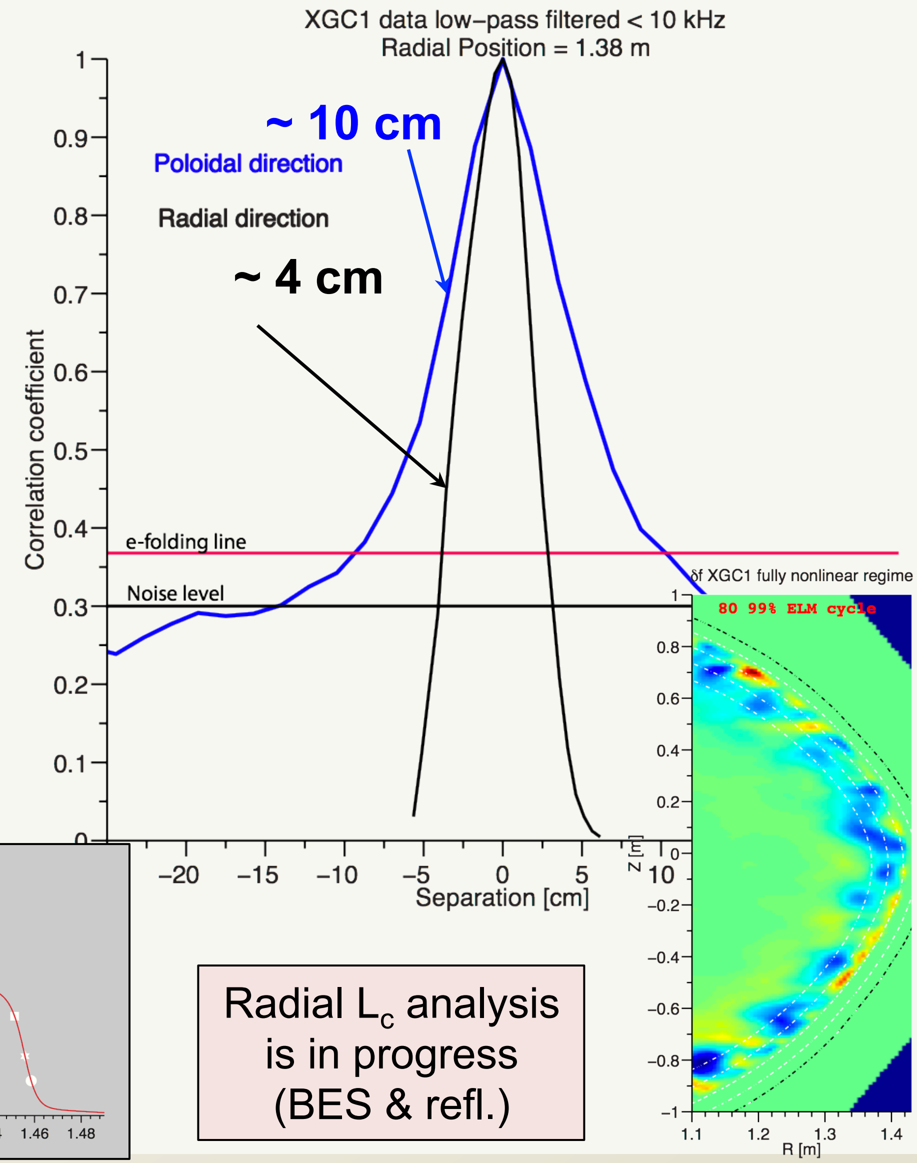


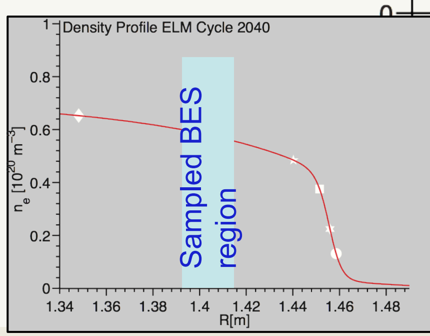
Scalings point to a variety of turbulence mechanisms

- Parametric scalings point to enhanced turbulence structures (larger L_c and τ_d) at higher ∇n_e and $1/L_{Te}$
  - Possibly **TEM** turbulence
- ∇v_t scalings for L_c and k_θ point to turbulence suppression
  - Equilibrium E×B flow shear
- ν_e and ν_i scalings for L_c and k_θ are consistent with **zonal flows**
  - τ_d decreases with ν_e
- **Pedestal height** (n_{ped}) increases at larger L_c and τ_d
  - Consistent with larger structures and wider pedestals

Poloidal correlation lengths during inter-ELM cycle are consistent with XGC1 simulation

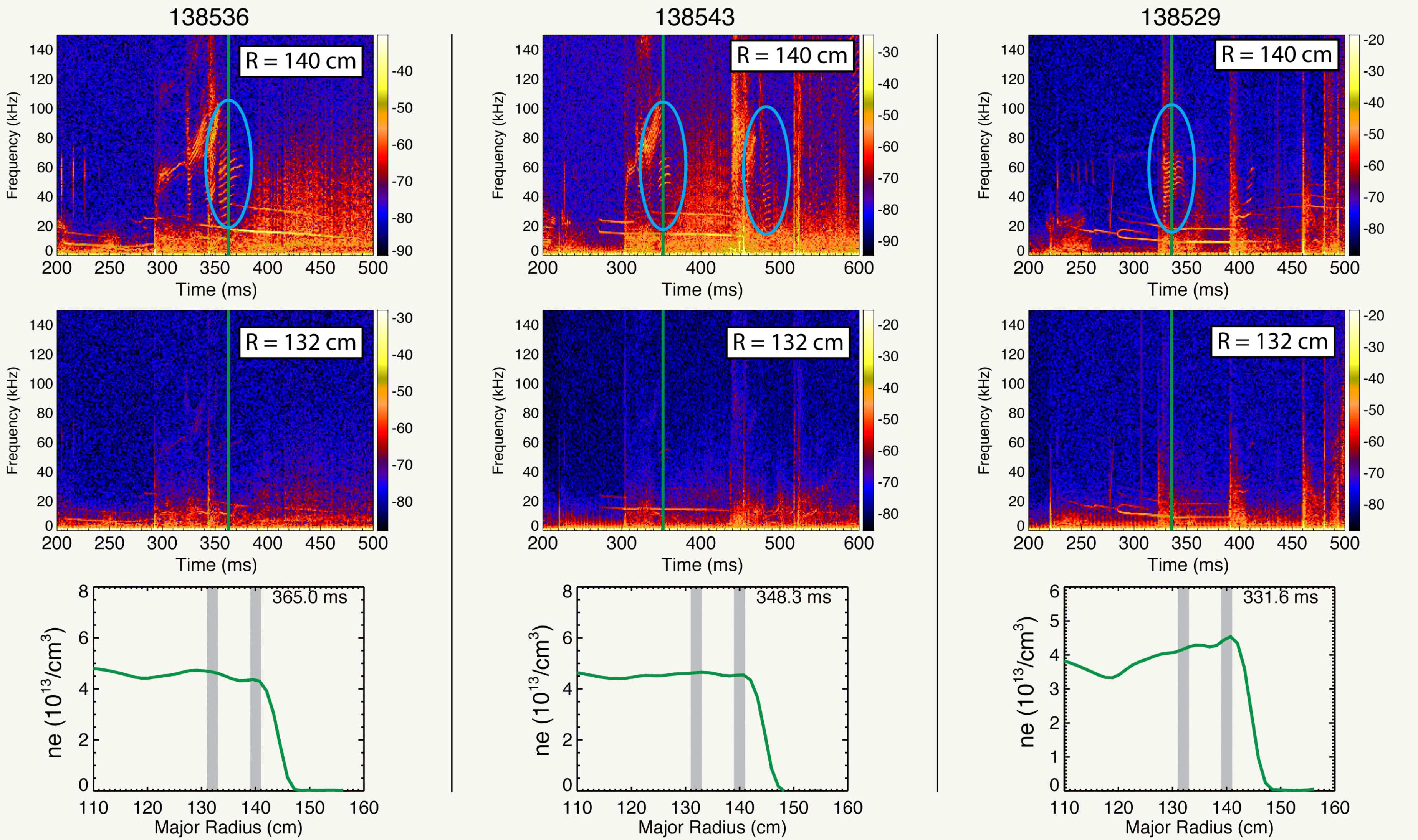






Radial L_c analysis is in progress (BES & refl.)

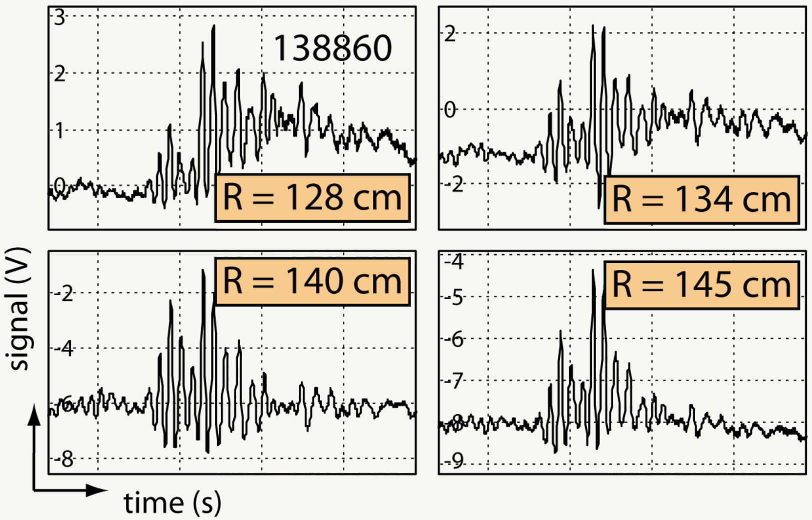
Post-ELM harmonic features at 50-100 kHz are localized at the top of the pedestal

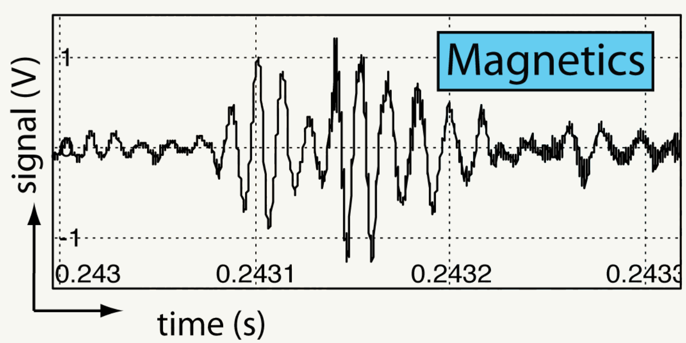


Harmonic features are either absent from or weakly present in magnetic spectra

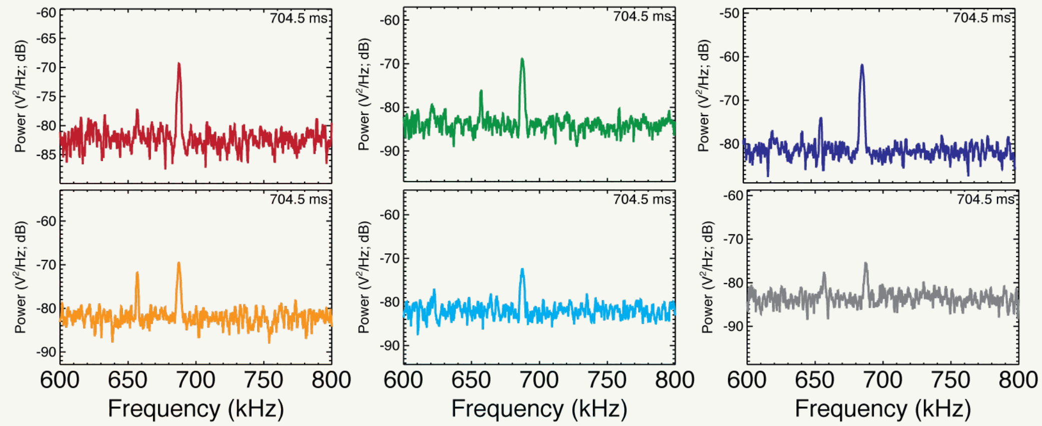
TAE and GAE mode structures have been observed in extended radial regions

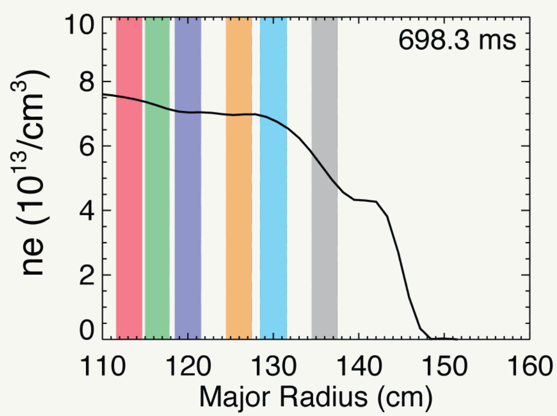
TAE burst





GAE mode





Directions for future work

- Quantify fluctuation amplitudes
- Quantify radial correlation length
- Study pre- and post-LH transition
- Measure flow fluctuations and flow shear
  - Study flow fluctuations and shear across LH transition
- Identify post-ELM harmonic oscillations
  - Captured by peeling-ballooning model?
  - Connect to DIII-D observations

Summary: We measured pedestal turbulence quantities and identified parametric dependencies in ELM-free, MHD quiescent H-mode plasmas

- ST edge parameters are among the most challenging regimes for simulations
- The BES system on NSTX can measure poloidal correlation length, wavenumber, and decorrelation time of pedestal turbulence
- Regression models identify parametric scalings that point to a variety of turbulence mechanisms
  - Enhanced turbulence structures at higher ∇n_e and $1/L_{Te}$
  - ∇v_t scalings point to E×B turbulence suppression
  - Collisionality scalings for L_c and k_θ are consistent with zonal flows
  - Pedestal height increases at longer L_c and τ_d
- Other observations
  - Initial experiment/theory comparison for inter-ELM measurements
  - Reduced turbulence at LH transition
  - Post-ELM harmonic oscillations
  - TAE and GAE mode structure