Parametric dependencies of low-k turbulence in NSTX H-mode pedestals (P7-18)

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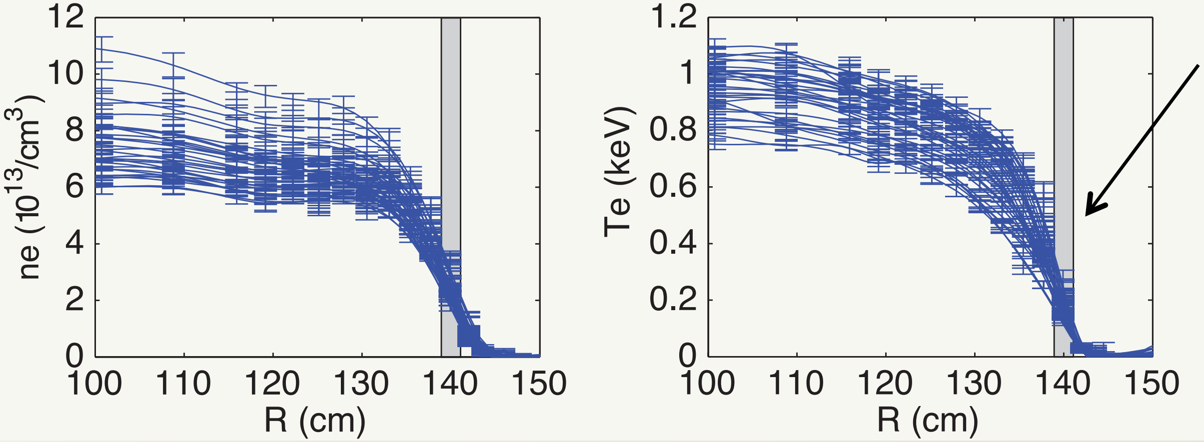
What are the characteristics and parametric dependencies of **pedestal turbulence** in NSTX? Can simulations reproduce the observations?

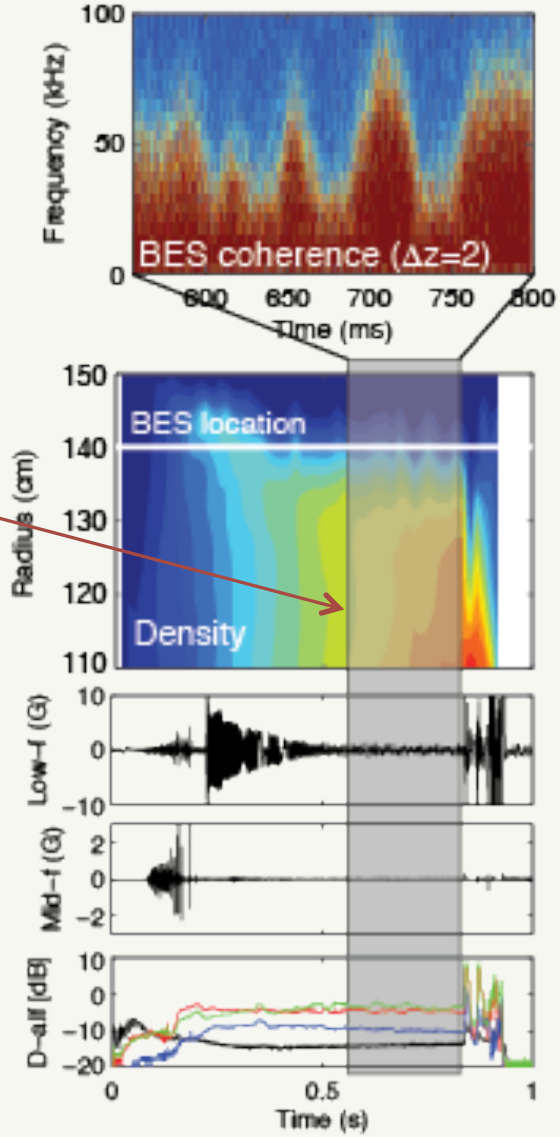
- Global confinement predictions for ITER depend upon accurate edge and pedestal models
  - ST edge parameters are among the most challenging regimes for plasma turbulence simulations: steep gradients, large ρ^*, high β, strong shaping, strong beam-driven flow
- We measure **pedestal turbulence** parameters 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)
- In addition, we compare measurements to **pedestal turbulence simulations** (GEM and BOUT++)



measurements from multiple discharges in outer region of pedestal

Outline

- Beam emission spectroscopy (BES) diagnostic on NSTX
- Pedestal turbulence measurements and parametric dependencies
  - ELM-free, MHD quiescent periods
- Fluid and gyrokinetic simulations of pedestal turbulence
- Future work and summary



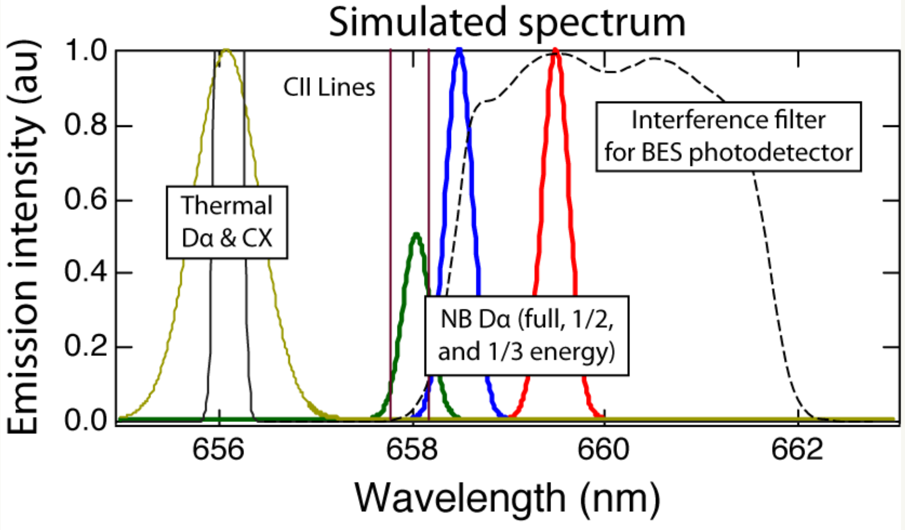
BES measures Doppler-shifted D_α emission (λ_0=656 nm) from neutral beam particles

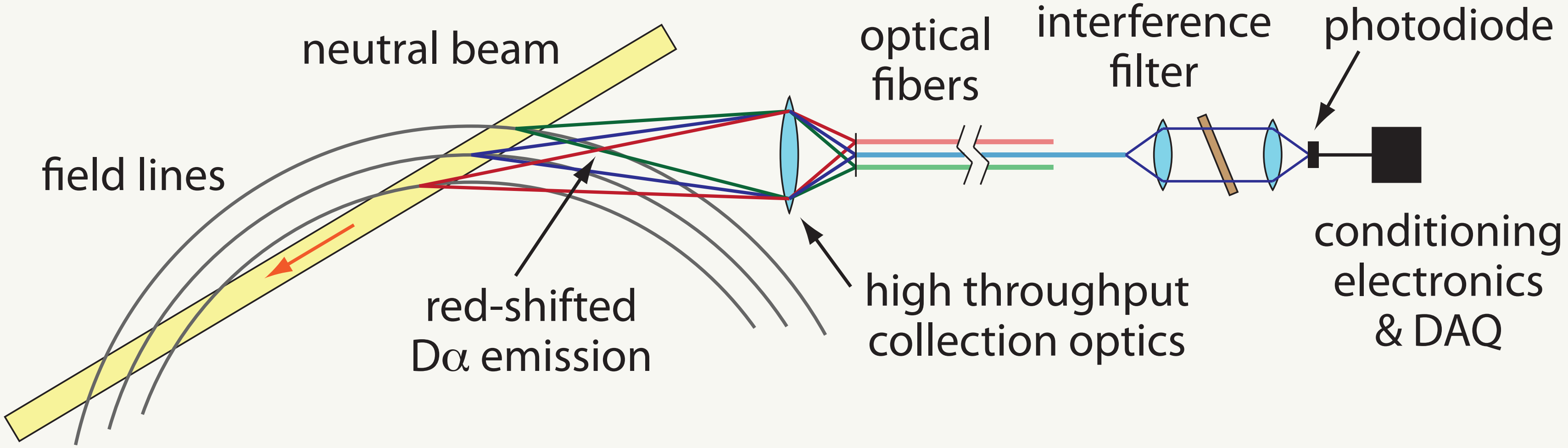
$$\frac{\delta I_{D\alpha}}{I_{D\alpha}} = \frac{\delta n}{n} \times C\left(E_{NB}, n, T_e, Z_{eff}\right)$$

neutral beam D_α emission

density fluctuation

C ≈ 1/2





neutral beam

field lines

red-shifted Dα emission

optical fibers

interference filter

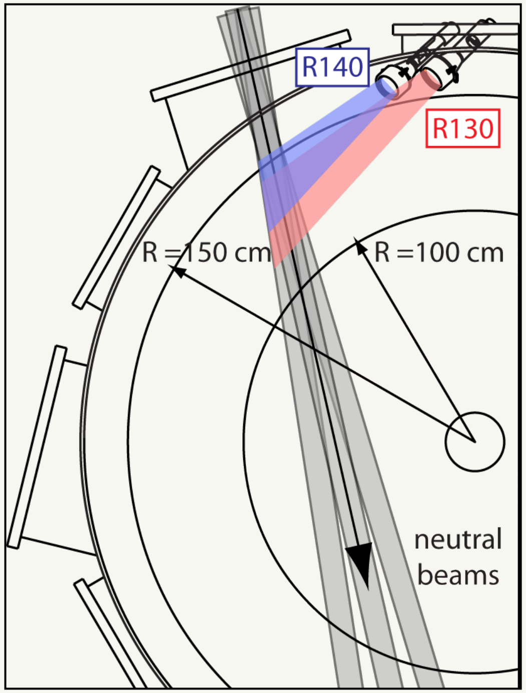
photodiode

high throughput collection optics

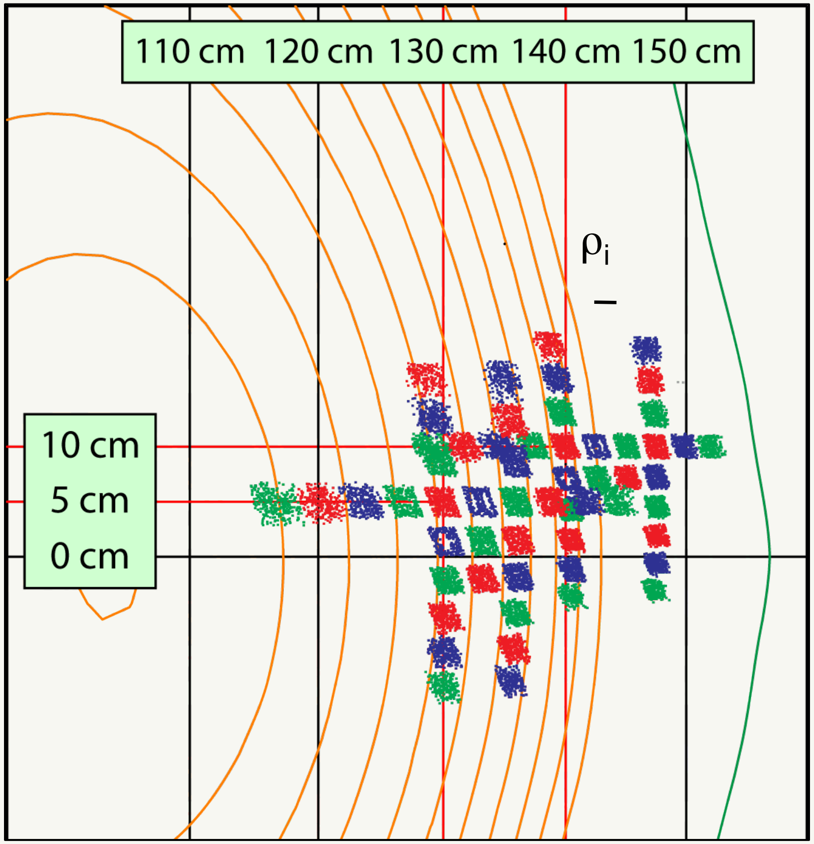
conditioning electronics & DAQ

The beam emission spectroscopy (BES) system on NSTX measures fluctuations on the ion gyroscale

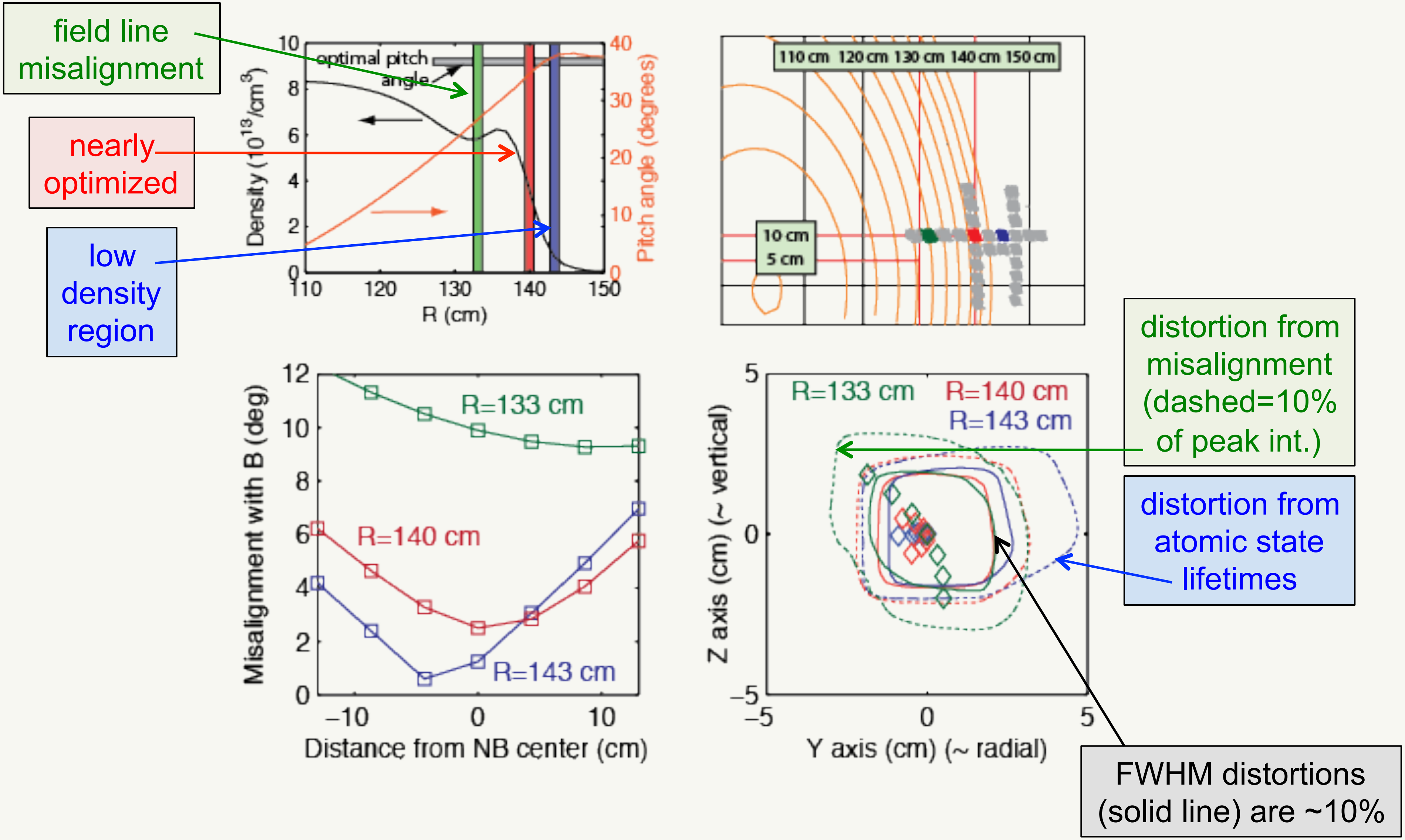
- Presently 32 detection channels
- 56 sightlines in radial and poloidal arrays spanning core to SOL
- 2 MHz sampling with digital AA filter
- $k_\perp \rho_i \leq 1.5$ & 2-3 cm spot size
- Field-aligned optics with high throughput (etendue = 2.3 mm^2-ster)



56 BES sightlines
in radial and poloidal arrays



Point spread function calculations indicate image distortion from atomic state lifetimes and field line geometry are negligible



field line misalignment

nearly optimized

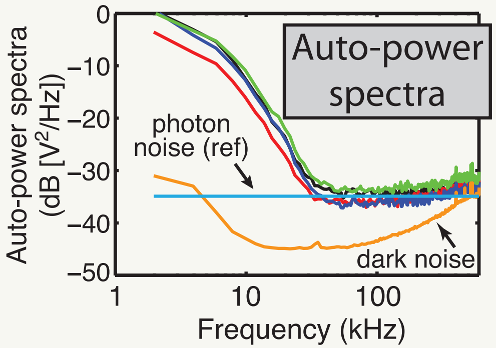
low density region

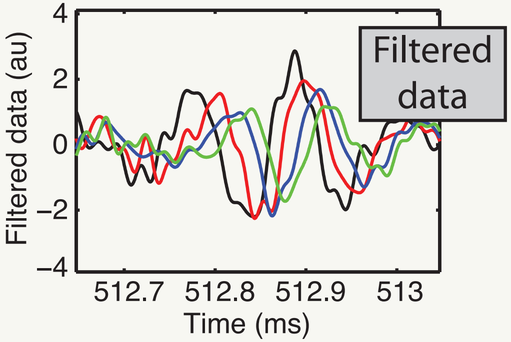
distortion from misalignment (dashed=10% of peak int.)

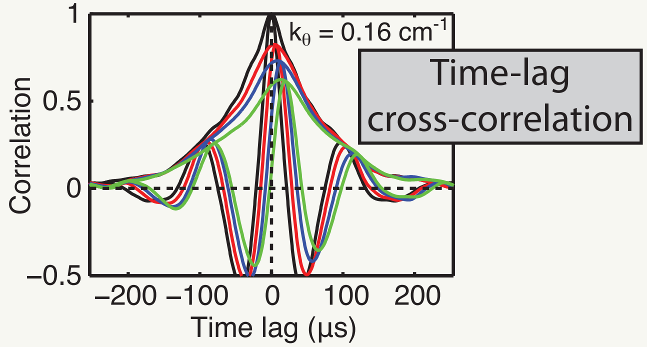
distortion from atomic state lifetimes

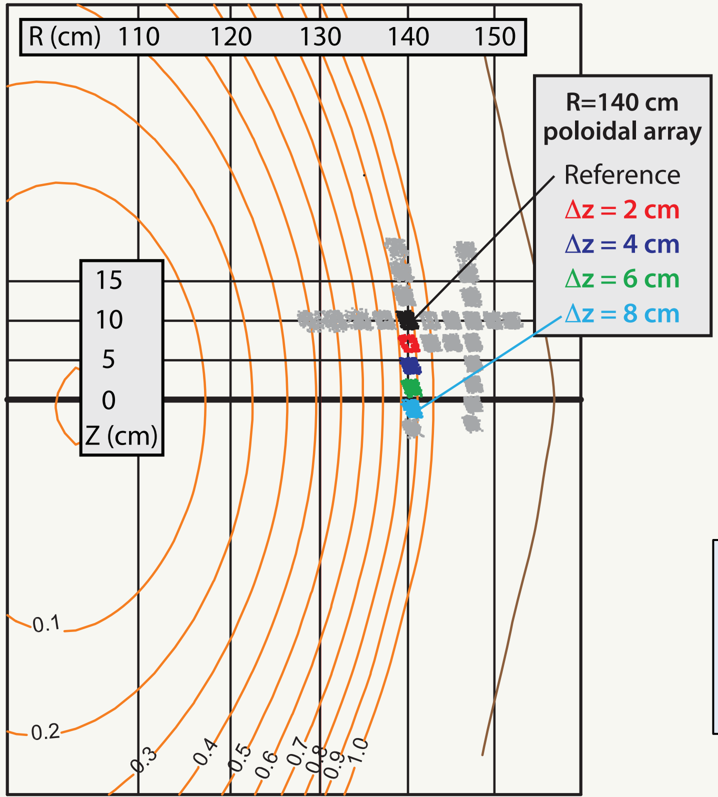
FWHM distortions (solid line) are ~10%

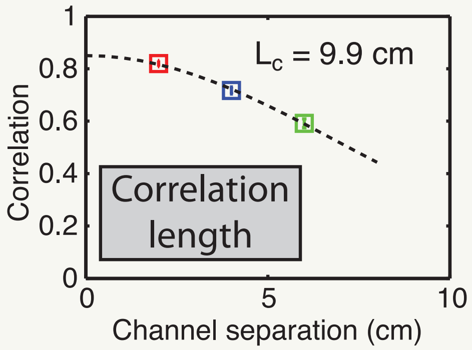
We measure poloidal correlation lengths (L_c), poloidal wavenumbers (k_θ), and decorrelation times (τ_d) with BES

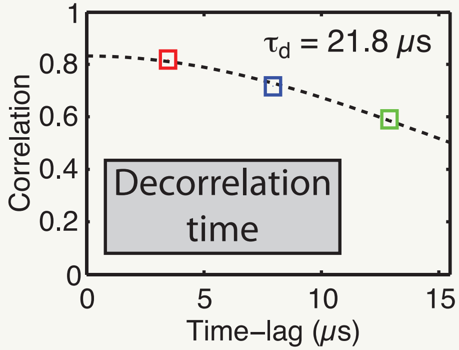






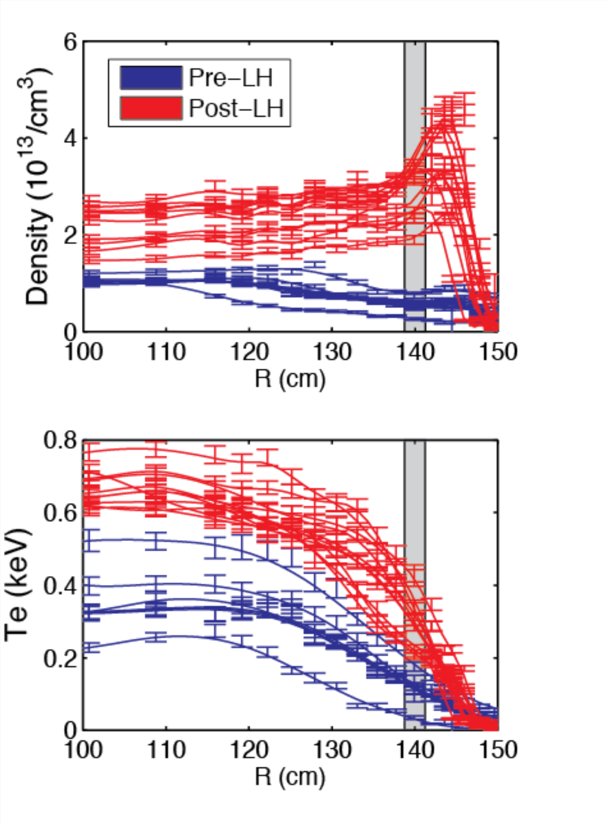


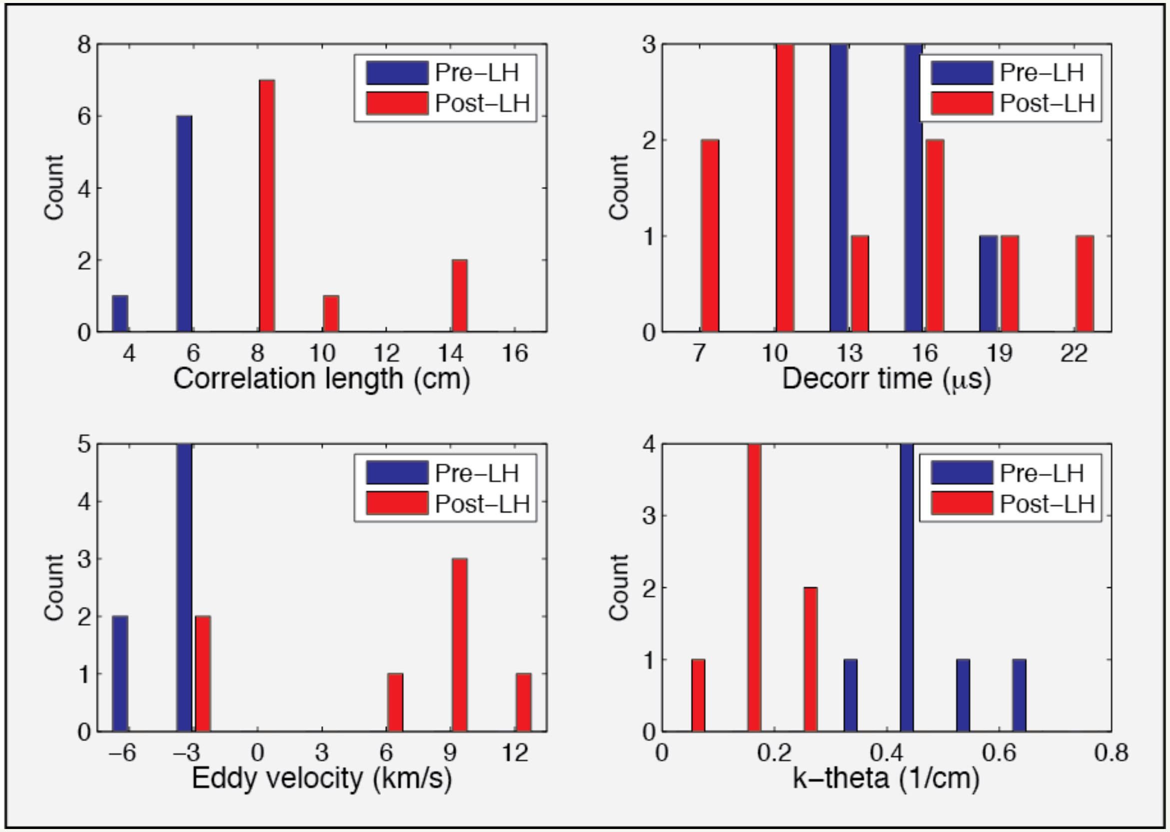




- Filtered data shows eddy propagation
- Turbulence quantities calculated from time-lag cross-correlations

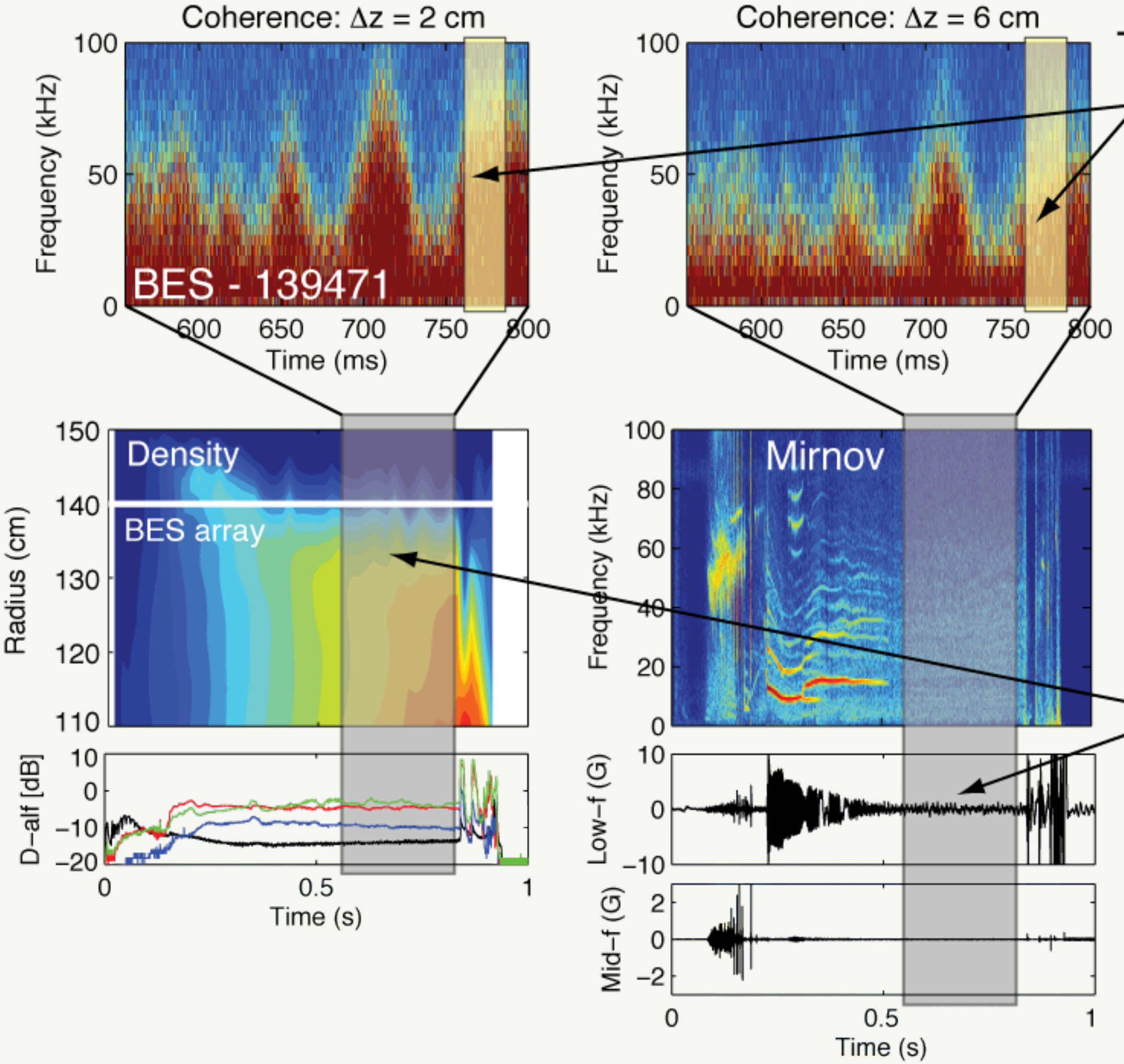
At the LH transition, L_{pol} increases and k_θ decreases





Also, measurements suggest eddy advection in lab frame shifts from *electron* to *ion* diamagnetic direction

Pedestal measurements show complex turbulence activity in H-mode during ELM-free, MHD quiescent periods



Typical binning
for analysis
(15-40 ms)

ELM-free,
MHD-quiesent
period

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?

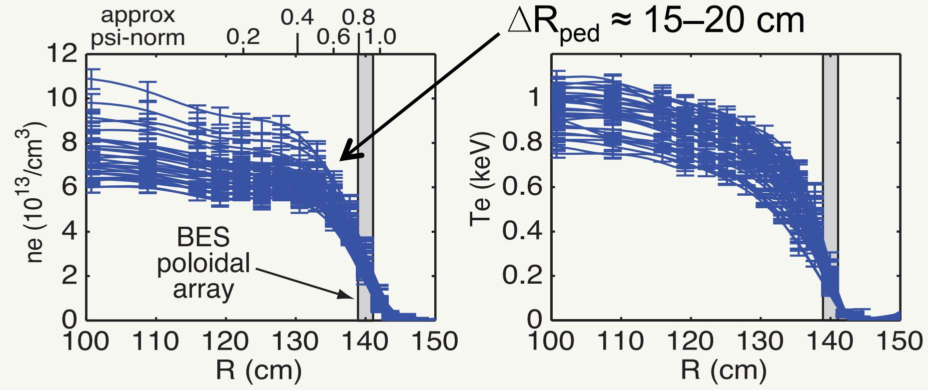
- How do L_c, k_θ, and τ_d change with plasma parameters?
  - ∇n_e, ∇T_i, $q/\hat{s}$, ν_e, β_e, n_{ped}, etc.

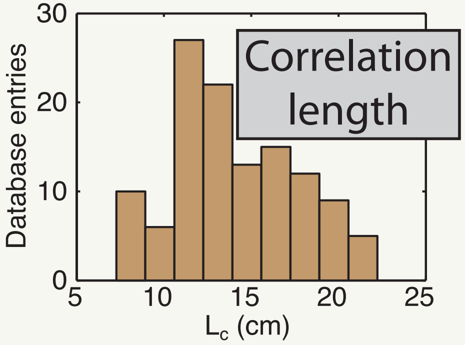
- Can we connect observations to edge turbulence simulations?
  - GEM, XGC1 or BOUT++?

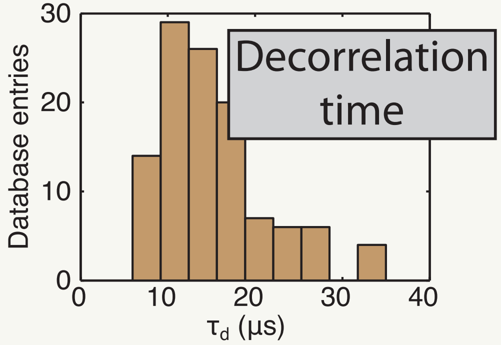
Pedestal turbulence measurements and plasma parameters from ELM-free, MHD quiescent H-modes were gathered in a database

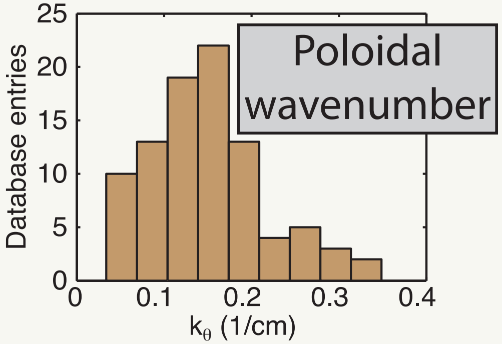
Database details

- 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}




Correlation length


Decorrelation time


Poloidal wavenumber

A search algorithm identifies regression models; models exhibit **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

scaling coefficient

plasma parameters

- Algorithm adds or removes x_k in model to find local minimum in model error

- **Many models (local minima) exist** in high dimensional x_k space

- Screen models to ensure high statistical quality
  - Statistical significance (α_k t-statistics)
  - Multicollinearity (variance inflation factor)
  - Error normality (Studentized residuals)

Regression models exhibit **similar scalings** despite different parameter compositions

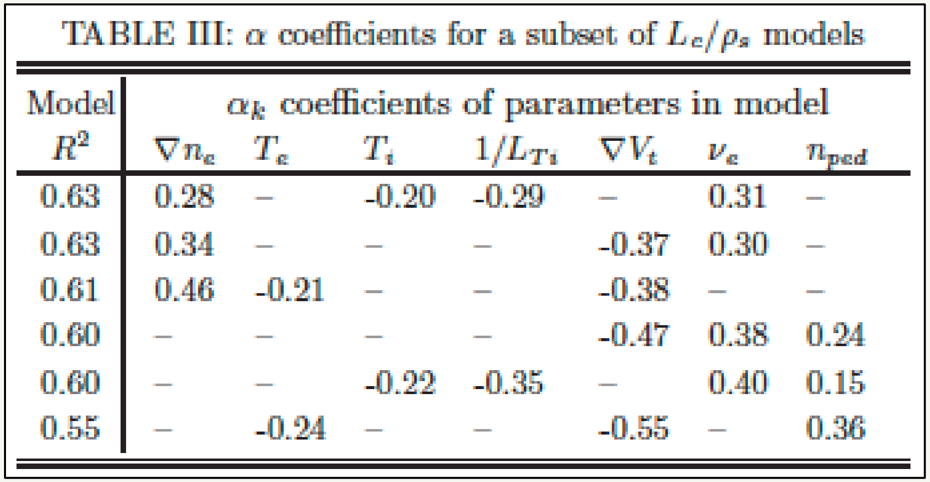
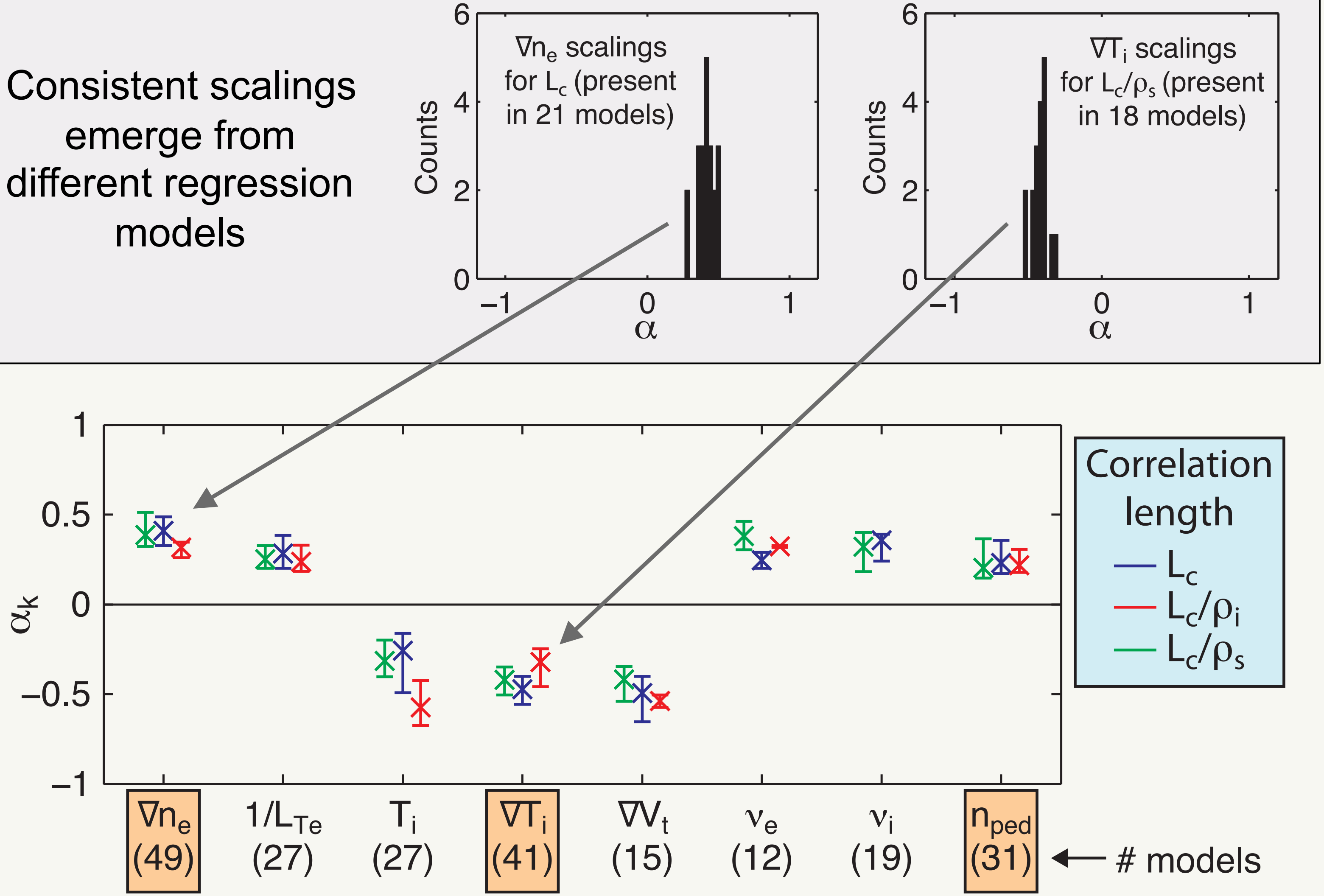


TABLE III: α coefficients for a subset of L_c/ρ_s models

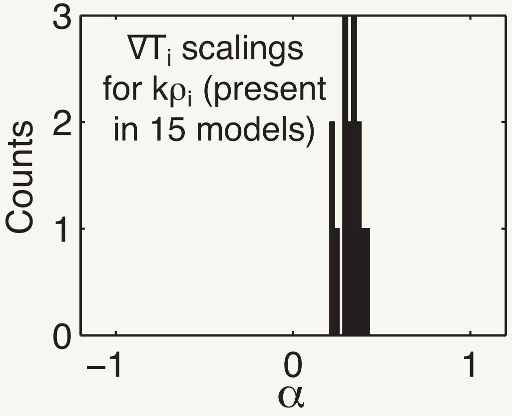
Model	α_k coefficients of parameters in model						
R^2	∇n_e	T_e	T_i	$1/L_{Ti}$	∇V_t	ν_e	n_{ped}
0.63	0.28	–	-0.20	-0.29	–	0.31	–
0.63	0.34	–	–	–	-0.37	0.30	–
0.61	0.46	-0.21	–	–	-0.38	–	–
0.60	–	–	–	–	-0.47	0.38	0.24
0.60	–	–	-0.22	-0.35	–	0.40	0.15
0.55	–	-0.24	–	–	-0.55	–	0.36

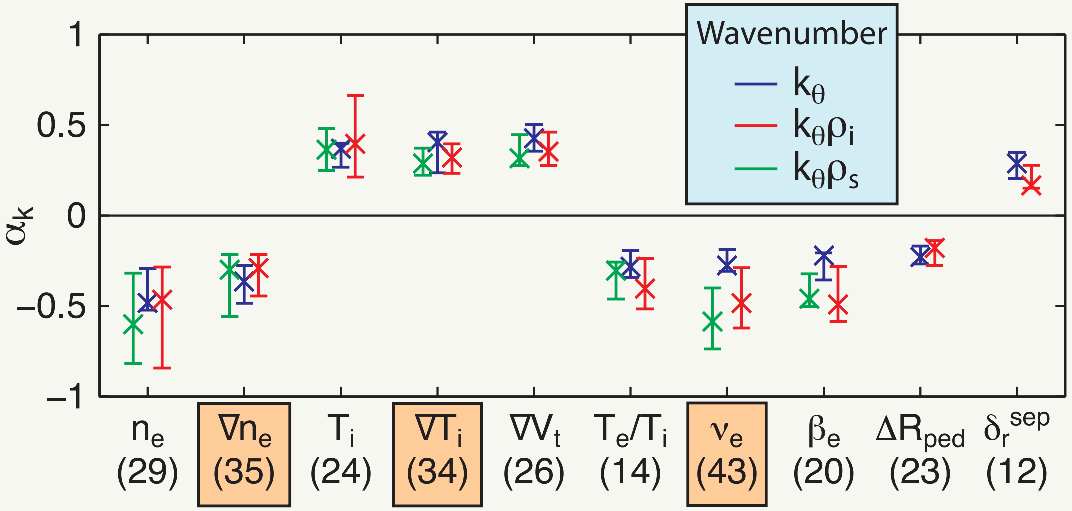
L_c increases at higher ∇n_e, $1/L_{Te}$, ν, and n_{ped}; decreases at higher T_i, ∇T_i, and ∇v_t

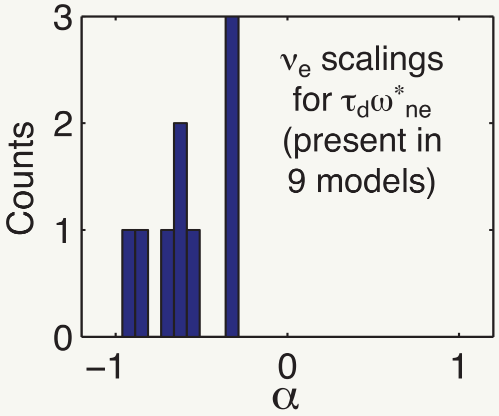
Consistent scalings emerge from different regression models

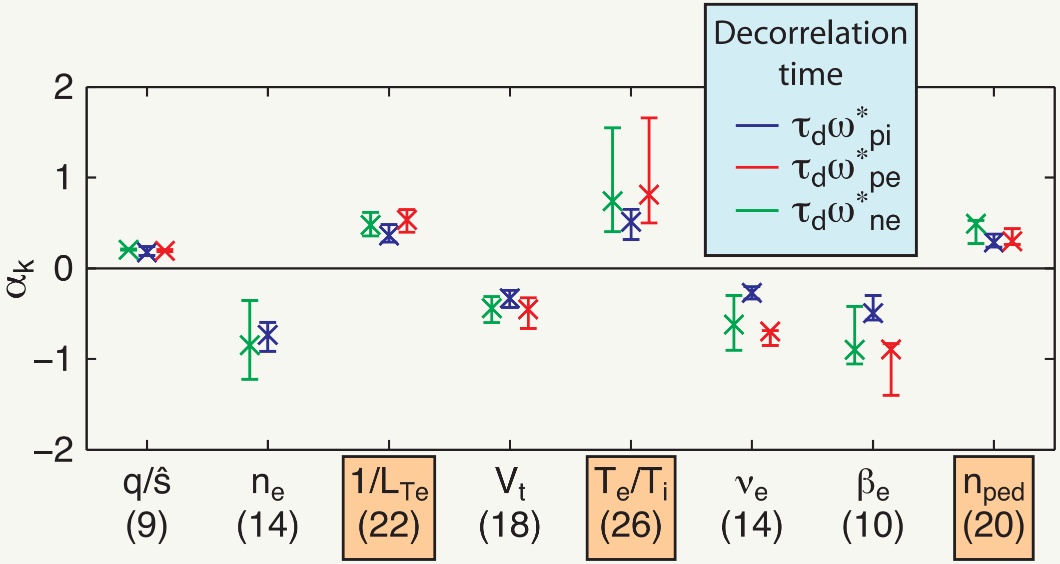


k_θ scalings consistent with L_c scalings; τ_d scalings provide additional insight









Parametric scalings point to **TEM turbulence** and possibly **KBM** or **μ-tearing turbulence** in NSTX H-mode pedestal

Parametric dependencies are …

most consistent with **TEM turbulence**

- ∇n_e (L_c and k_θ) and $1/L_{Te}$ (τ_d) scalings are consistent with TEM; Te/Ti and ν_e scalings show mixed agreement

partially consistent with **KBM turbulence**

- β_e scalings (k_θ and τ_d) are consistent with KBM; ∇n_e, ∇T_i, and $1/L_{Te}$ show mixed agreement

partially consistent with **μ-tearing turbulence***

- all β_e and ν_e scalings are consistent with μ-tearing, but $1/L_{Te}$ scaling for τ_d is inconsistent
- * NSTX core μ-tearing simulations indicate BES is not sensitive to μ-tearing, but pedestal simulations show tearing-parity instabilities

least consistent with **ITG turbulence**

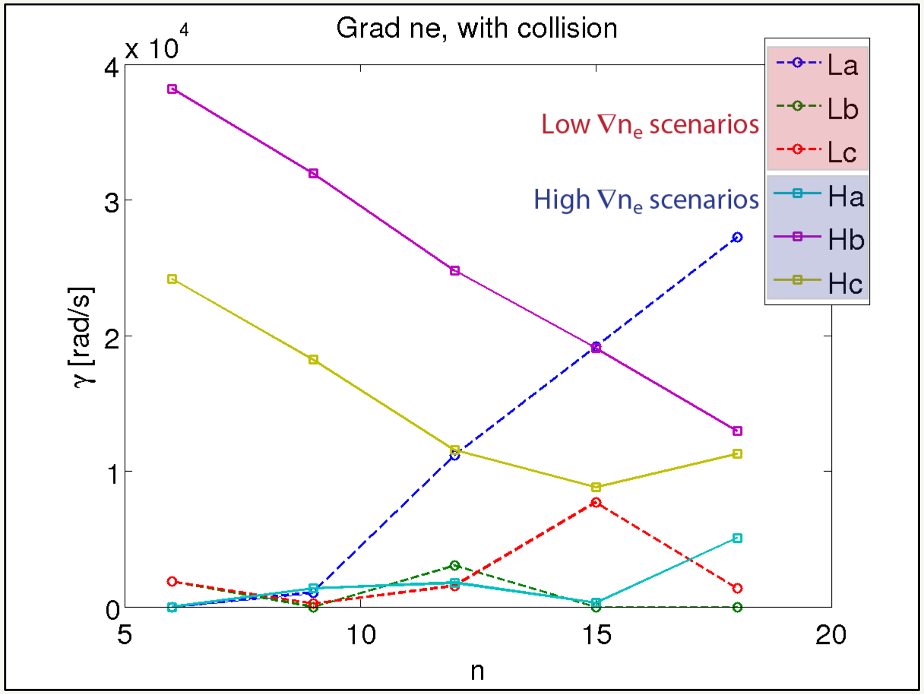
- ∇n_e and ∇T_i (L_c and k_θ) and all ν_e scalings are inconsistent with ITG; Te/Ti scalings (k_θ and τ_d) show mixed agreement

Parametric scalings also consistent with equilibrium and zonal E×B flows

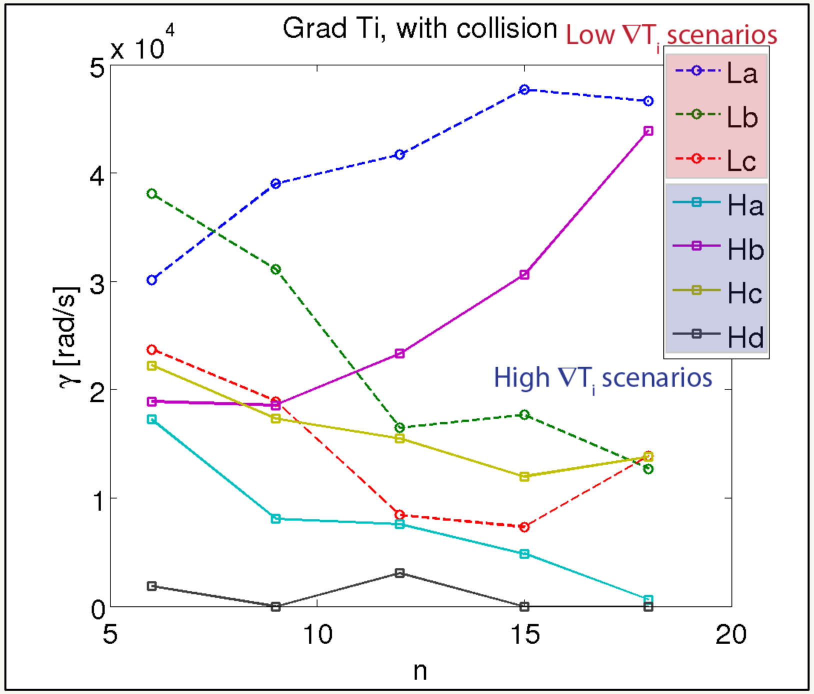
- ∇v_t scalings for L_c and k_θ point to turbulence suppression by **equilibrium E×B flow shear**
  - L_c decreases and k_θ increases at higher ∇v_t
- Collisionality scalings are consistent with turbulence reduction via **zonal flows**
  - τ_d decreases and L_c increases at higher ν
- **Pedestal height** (n_{ped}) increases at larger L_c and τ_d
  - Consistent with empirical relationship between wider pedestals and larger turbulent structures (Z. Yan et al., PoP 18, 056117 (2011))

Linear growth rates from GEM gyrokinetic simulations show scalings consistent with measured L_c scalings

GEM simulations with $6 \lesssim n \lesssim 15$ and $k_\theta \rho_s \sim 0.2$ indicate instabilities are **electromagnetic**, destabilized by **collisions**, and exhibit both **ballooning** and **tearing parity**



5 of 6 ∇n_e scenarios indicate low-n growth rates increase at higher ∇n_e

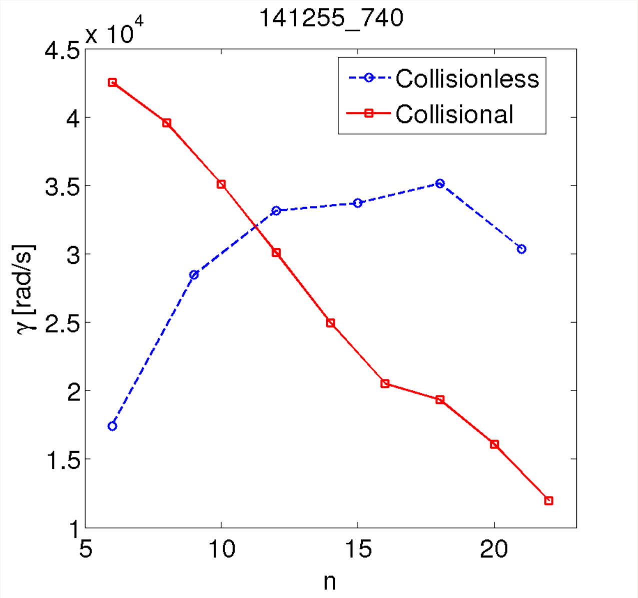


7 of 7 ∇T_i scenarios indicate low-n growth rates decrease at higher ∇T_i

GEM γ dependencies on ∇n_e and ∇T_i are consistent with measured L_c scalings

GEM simulations point to **tearing parity** mode structures and highlight the importance of **collisions**

With collisions, γ rises at low-n and drops at high-n



Consistent with measured scalings that show higher L_c and lower τ_d at higher ν

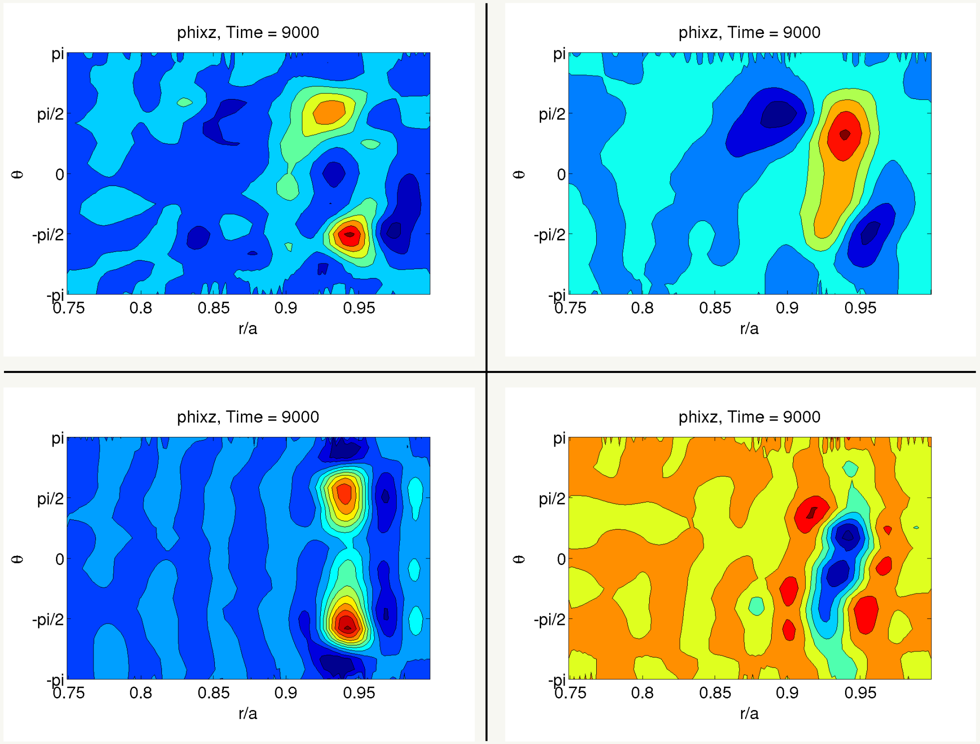
ϕ contours

Collisionless

Collisional

n=6

n=24

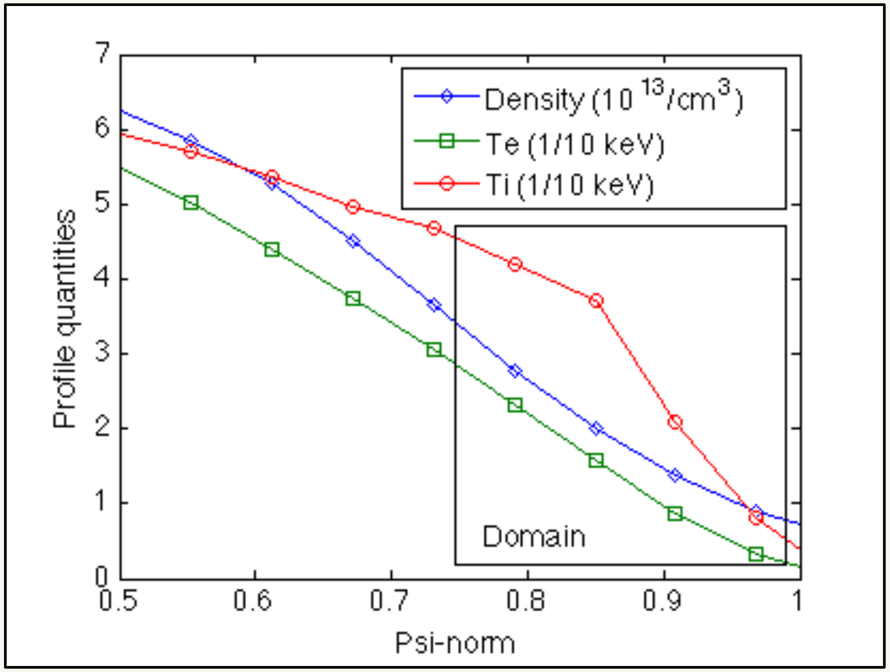


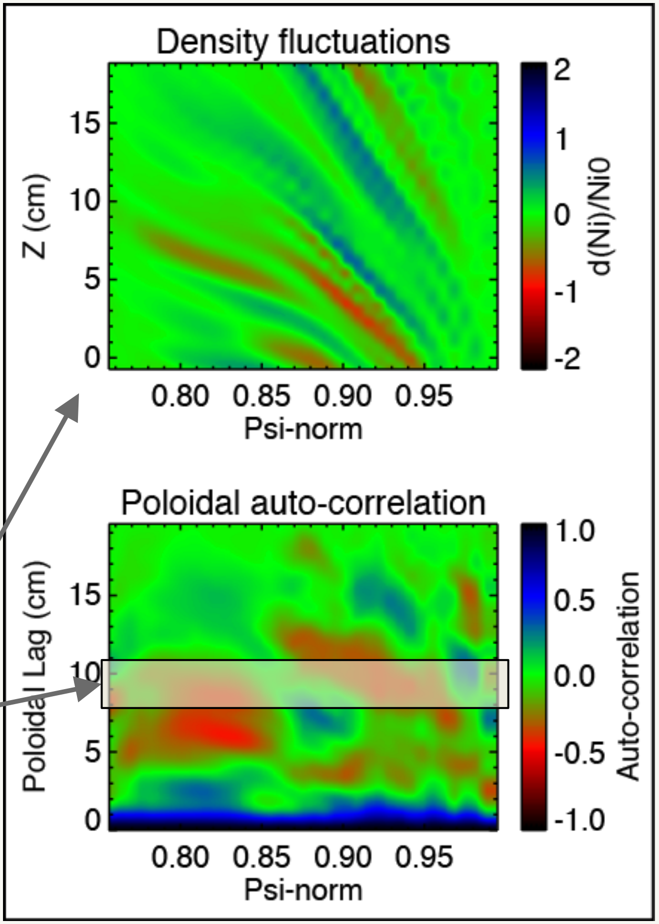
even parity

likely tearing parity

L_c and k_θ from BOUT++ pedestal simulations compare favorably with measurements

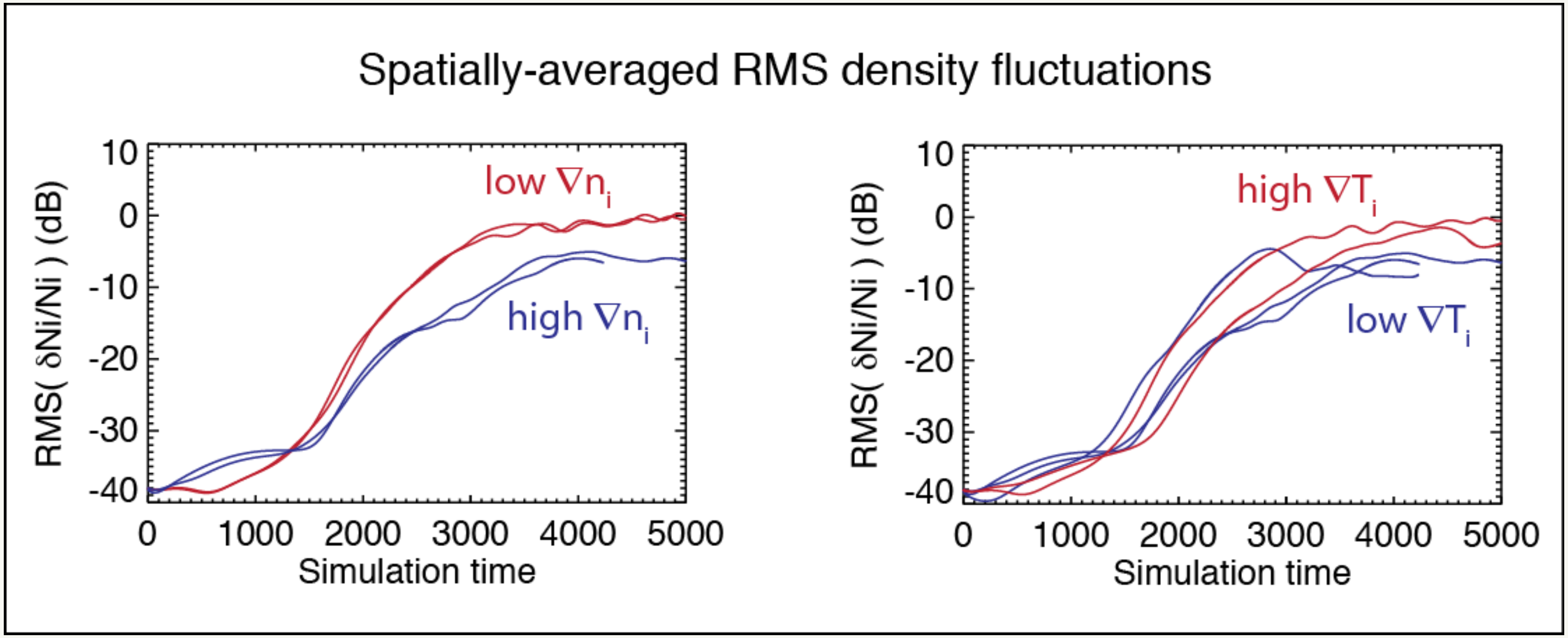
Initial value 3D Braginskii fluid simulations evolve n_i, ω, $j_{||}$, $A_{||}$, T_i, and T_e with collisionality, E×B advection, field line curvature, and drive terms for $j_{||}$ and ∇P. Simulations do not include toroidal rotation and parallel advection.





$L_c/\rho_i \sim 8$ is in line with measurements, but $k_\theta\rho_i \sim 0.7$-1.4 is higher than measurements

BOUT++ parameter scans point to larger fluctuation amplitudes at **lower** ∇n_i and **higher** ∇T_i



Note that measurements indicate L_c increases at **higher** ∇n_i and **low** ∇T_i

Future work

- Fluctuation amplitudes
  - Radial dependence
  - Parametric dependencies
- Radial correlation length analysis
- Radial and poloidal wavenumber spectra
- Flow fluctuations and time-delay estimation
  - Predator-prey model between flow fluctuations and turbulence parameters
- Fluid simulations with parallel advection and V_{tor}

Summary

- Pedestal model validation is critical for ITER, and ST edge parameters are among the most challenging regimes for turbulence simulations

- We measured pedestal turbulence parameters in NSTX H-mode plasmas during ELM-free, MHD quiescent periods
  - **$L_c/\rho_i \sim 12$ $k_\theta\rho_i \sim 0.2$ $\tau_d/(a/c_s) \sim 5$**

- Parametric dependencies for pedestal turbulence measurements are most consistent with **TEM turbulence** and partially consistent with **KBM and μ-tearing turbulence**

- **GEM** gyrokinetic simulations show higher γ at higher ∇n_e and lower ∇T_i → **consistent** with measured L_c
  - Collisions increase γ at low-n → **consistent** with measured scalings

- **BOUT++** Braginskii fluid simulations show **saturation amplitudes** that decrease with ∇n_i and increase with ∇T_i → not consistent with scalings

Pedestal turbulence measurements

Pedestal turbulence parametric dependencies in ELM-free, MHD quiescent H-modes

Preliminary pedestal turbulence simulations (gyrokinetic and Braginskii fluid)