NSTX-U

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Investigations of pedestal turbulence and ELM bursts in NSTX H-mode plasmas

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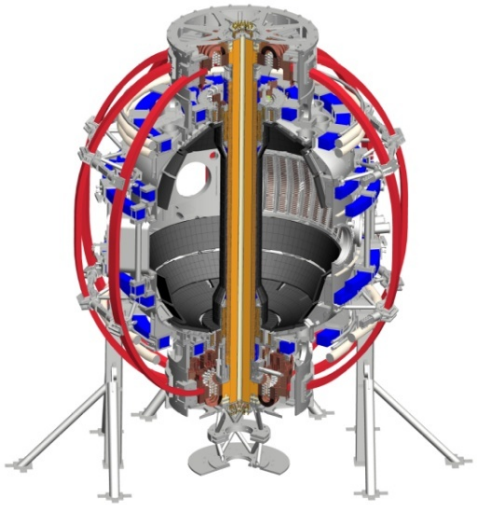

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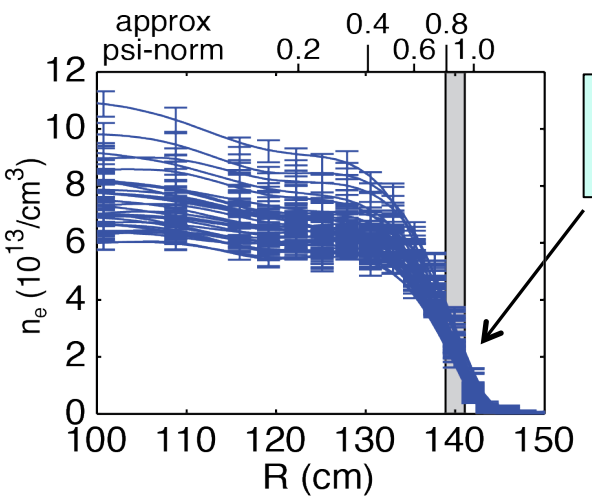
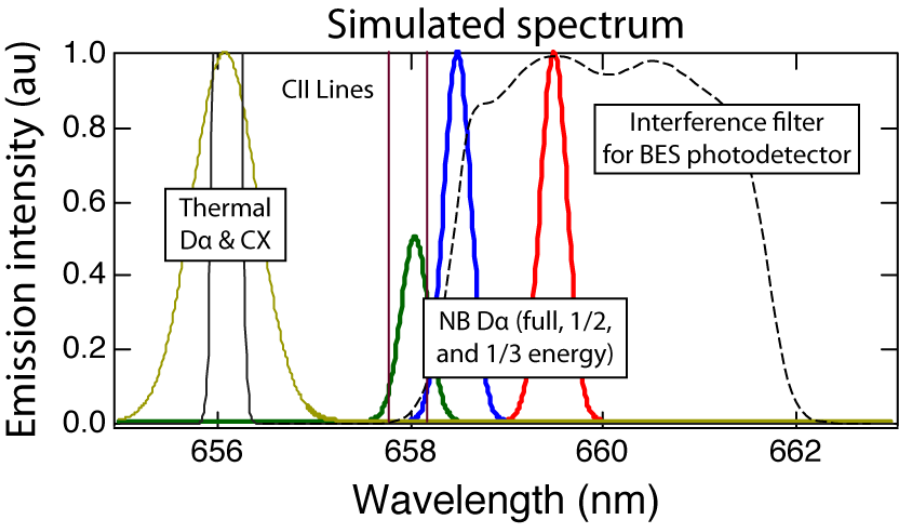
The pedestal sets boundary conditions for the core and ejects structures that damage plasma-facing components

- Projections for ITER depend on accurate pedestal models
  - **ST parameter regime** (large ρ^*, high β, shaping, beam-driven flow) is a challenging environment for pedestal simulations
- **Pedestal turbulence measurements** in NSTX H-mode plasmas during ELM-free, MHD quiescent periods
  - Identify **parametric dependencies** between turbulence quantities and transport-relevant plasma parameters
  - Compare to turbulence models → scalings point to TEM turbulence
  - Compare to pedestal turbulence **simulations**



Turbulence measurements in steep gradient region

Beam emission spectroscopy (BES) measures Doppler-shifted D_α emission from neutral beam particles

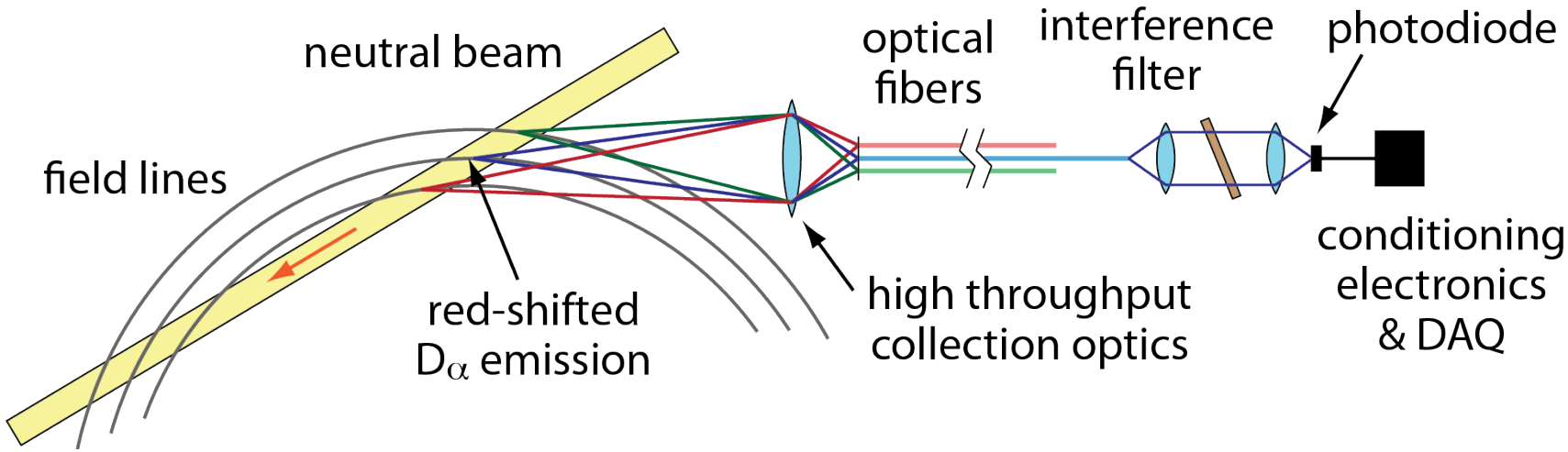


$$\frac{\delta I_{D\alpha}}{I_{D\alpha}} = \frac{\delta n}{n} \times C\left(E_{NB}, n, T_e, Z_{eff}\right)$$

neutral beam D_α emission

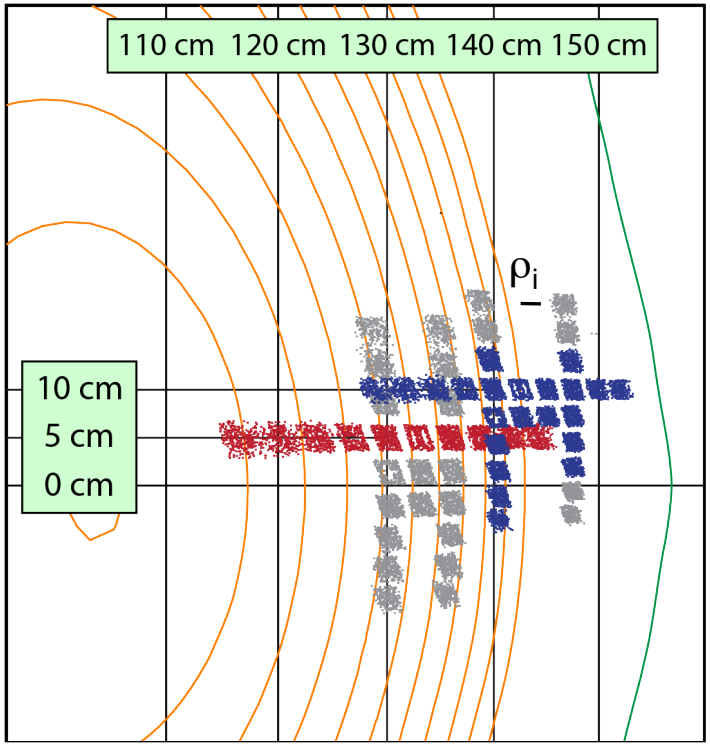
density fluctuation

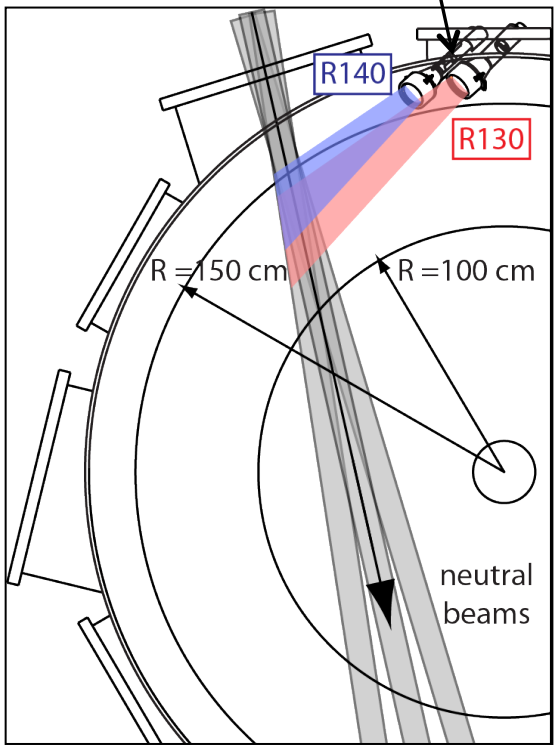
$C \approx 1/2$



The beam emission spectroscopy (BES) system on NSTX measures fluctuations on the ion gyroscale with $k_\perp \rho_i \leq 1.5$

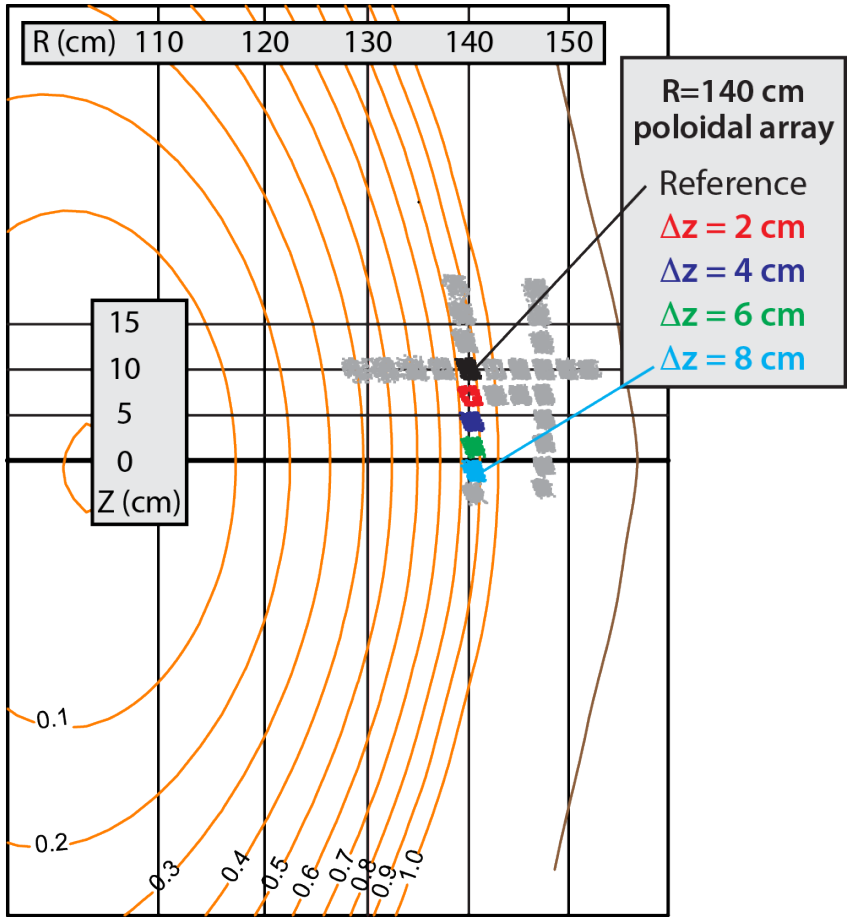
- Radial and poloidal arrays spanning core to SOL
- 32 detection channels
- **2-3 cm spot size and $k_\perp \rho_i \leq 1.5$**

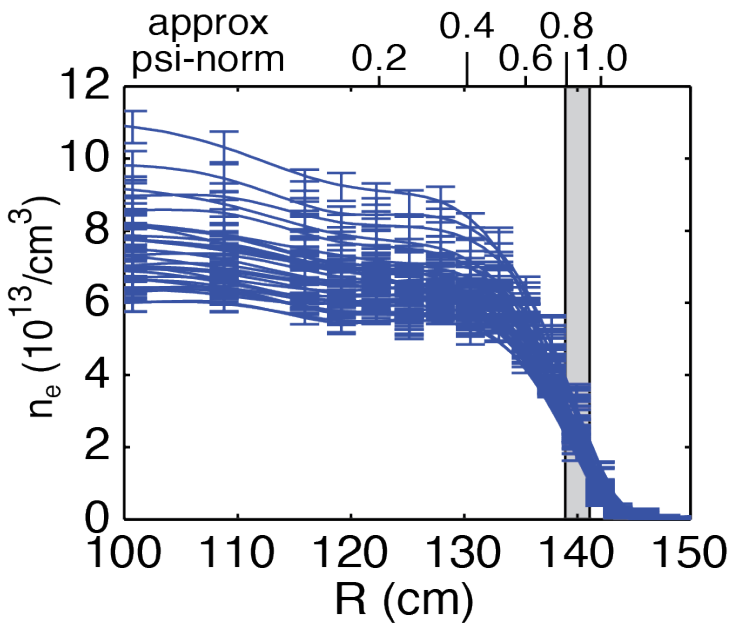




Pedestal turbulence measurements

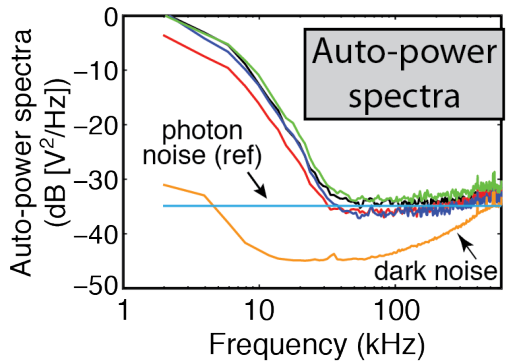
- ELM-free, MHD quiescent H-mode with Li conditioning
- $\Psi_N \approx 0.8 – 0.95$ in steep gradient region

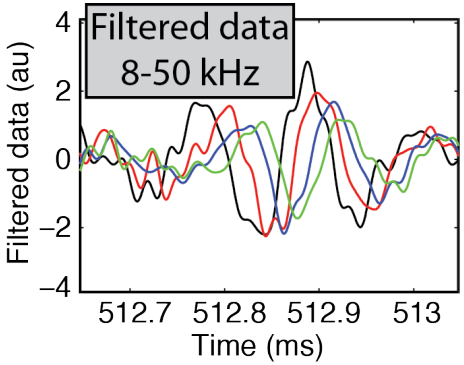




BES can measure poloidal correlation lengths (L_c), poloidal wavenumbers (k_θ), decorrelation times (τ_d), and amplitude ($\tilde{n}/n$)

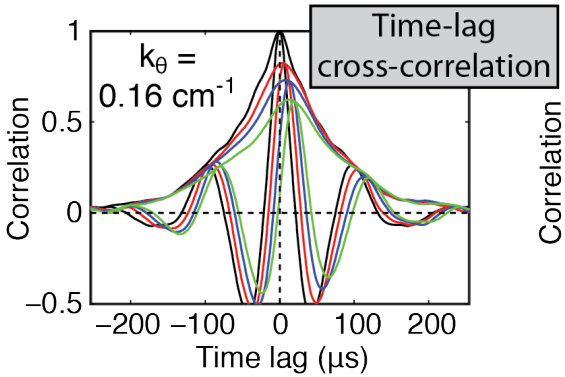
- Auto-power spectra show plasma turbulence signals above detector noise levels
- Filtered data (8-50 kHz) show eddies moving down BES array

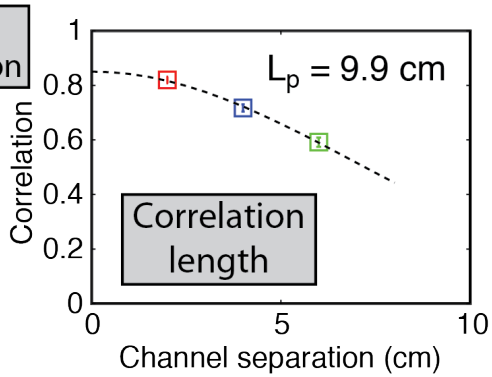


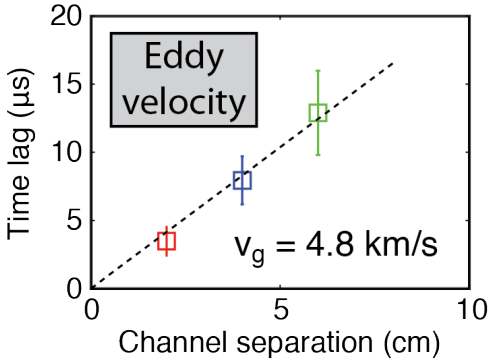


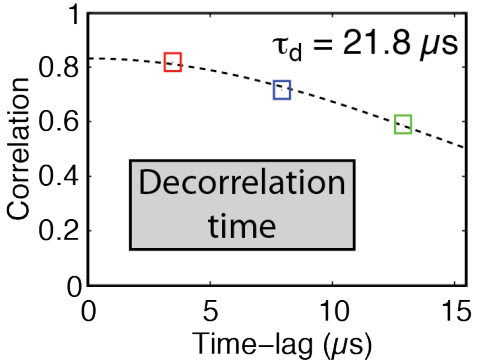
Time-lag cross-correlation gives:

- Correlation length $C(x,\tau=0)$
- Decorrelation time $C_{max}(\tau)$
- Eddy velocity $\Delta z/\Delta\tau_{lag}$
- Dominant wavenumber
  - Inferred from auto-correlation and eddy velocity





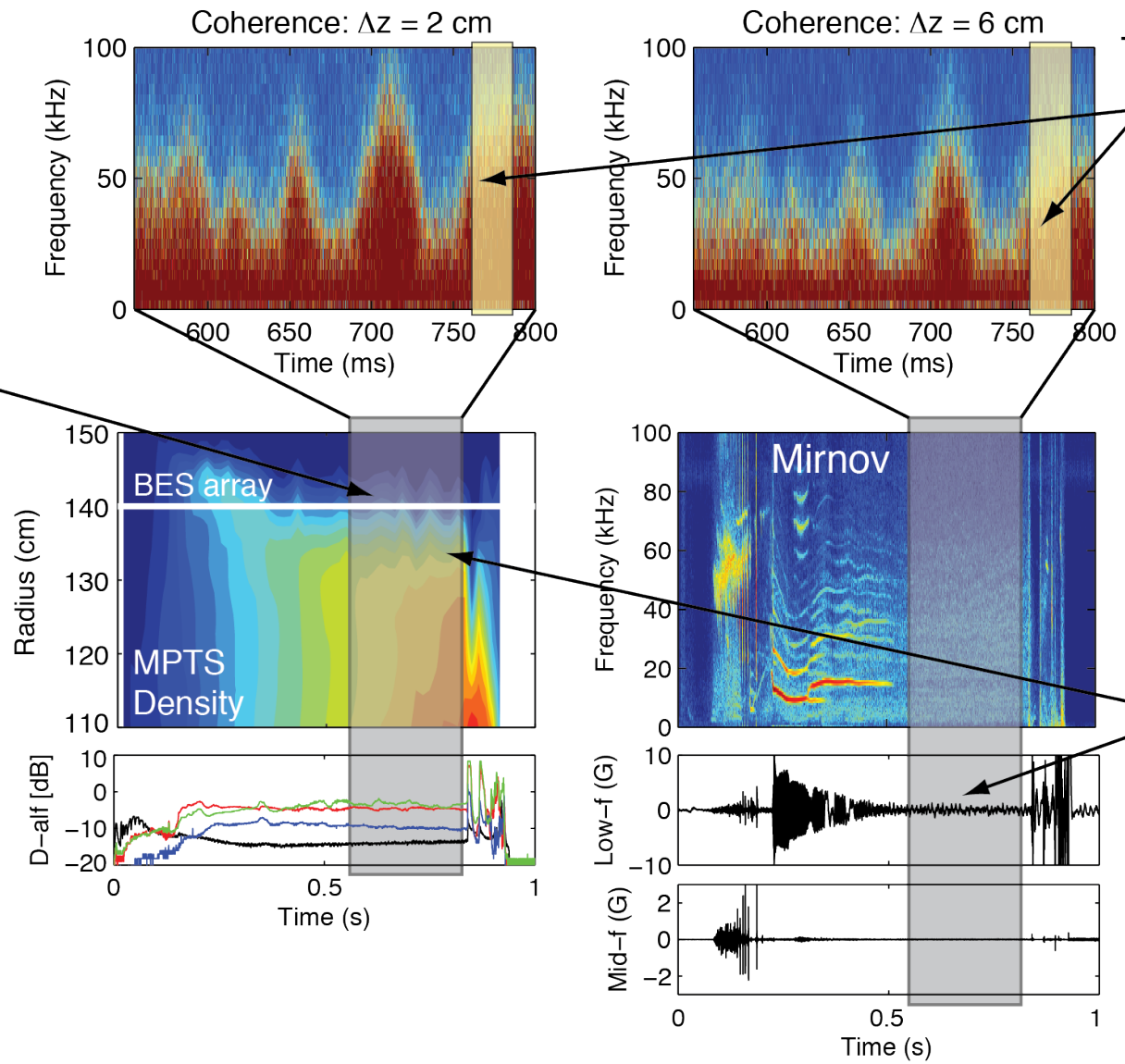




ELM-free, MHD quiescent periods > 150 ms were identified and partitioned into 15-40 ms bins for turbulence analysis

Coherence for BES poloidally-separated channels

Slow plasma motion allows BES to sample across pedestal

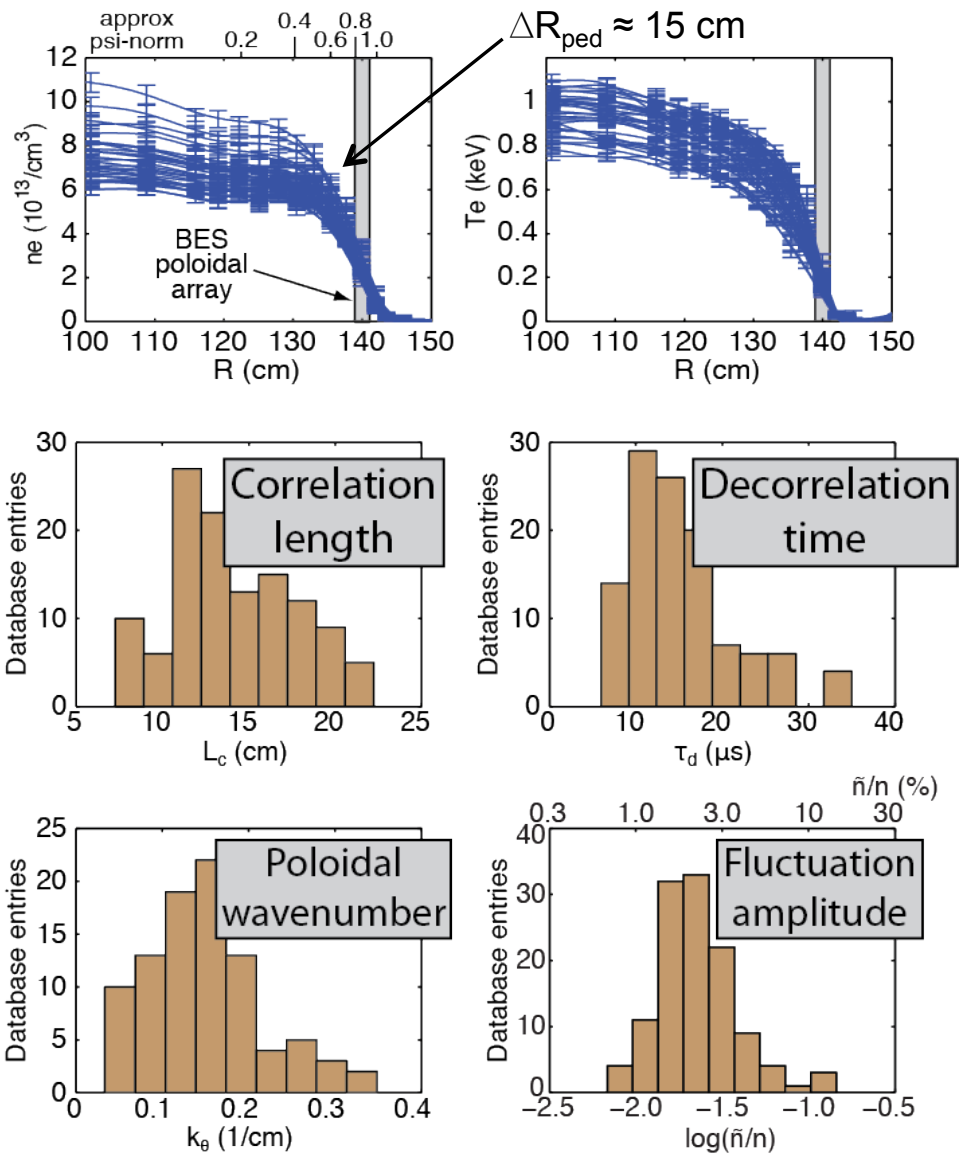


Typical binning for analysis (15-40 ms)

Sustained ELM-free, MHD-quiesent period

Populated database with pedestal turbulence measurements and transport-relevant plasma parameters

- Database with 129 observations from 29 discharges
  - B_{T0} = 4.5 kG
  - I_p = 700-900 kA
  - 15-45 ms averaging
- Turbulence quantities are consistent with **drift wave turbulence**
  - **$L_c/\rho_i \approx 8 - 18$**
  - **$k_\theta \rho_i \approx 0.07 - 0.31$**
  - **$\tau_d/(a/c_s) \approx 2.6 - 6.5$**
  - **$\tau_d \omega^*_{pi} \approx 0.04 - 0.28$**
  - **$\tilde{n}/n \approx 1\%-4\%$**
- Transport-relevant parameters
  - **n_e, ∇n_e, $1/L_{ne}$**, T_e, ∇T_e, $1/L_{Te}$, Ti, ∇T_i, $1/L_{Ti}$, v_t, ∇v_t, q, $\hat{s}$, ν_e, ν_i, β, β_e, n_{ped}, ΔR_{ped}, δ_r^{sep}
  - generally 50%-300% variation



A search algorithm identified many linear regression models among turbulence quantities and plasma parameters

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

turbulence quantities

scaling coefficient

plasma parameters

- **Many models exist** in high dimensional x_k space
  - Models are error local minima
- Screen models for good statistics
  - **High statistical significance**
    t-statistics → $P(H_0: \alpha_k=0) < 5\%$
  - **Low multicollinearity**
    Pair-wise corr. → $\max(|C_{jk}|) < 0.6$
    Var. inflation factor → $\max(VIF_k) < 5$
  - **Normally distributed residuals**
    $P(\varepsilon)$ → Skew and Ex. Kurt. within 2σ
    Studentized residuals → no outliers

6 representative models for L_c/ρ_s

Model R^2	α_k coefficients ∇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

Should we try to identify a single "best" model?

Not a good idea because…
- Highly subjective
- Each model contains only a few (3-4) plasma parameters

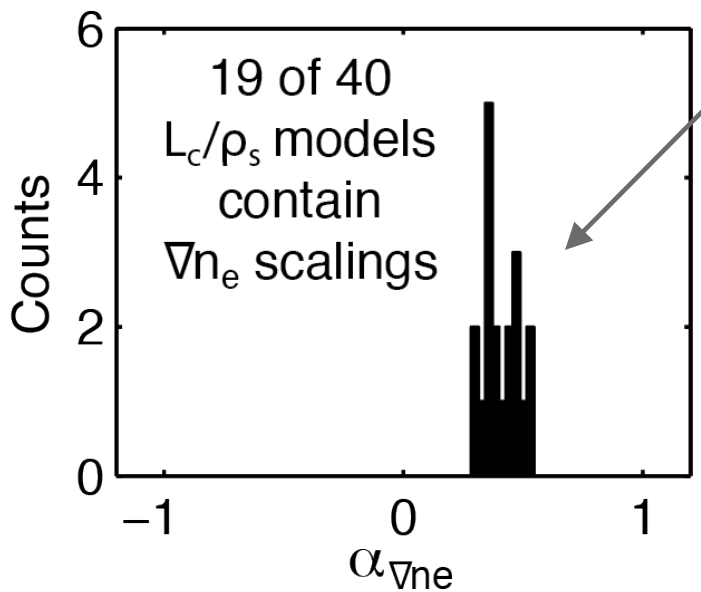
Is there a better method?

Model aggregation is helpful when assessing many potential predictor variables with complex interdependencies

Scalings are **robust** across models, regardless of number or combination of parameters in models

TABLE II: α_k coefficients for a subset of L_c/ρ_s models

Model	α_k coefficients						
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

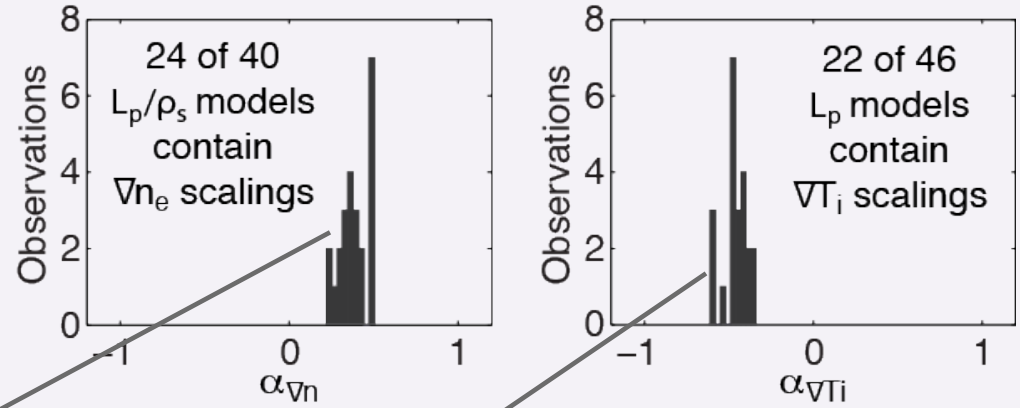


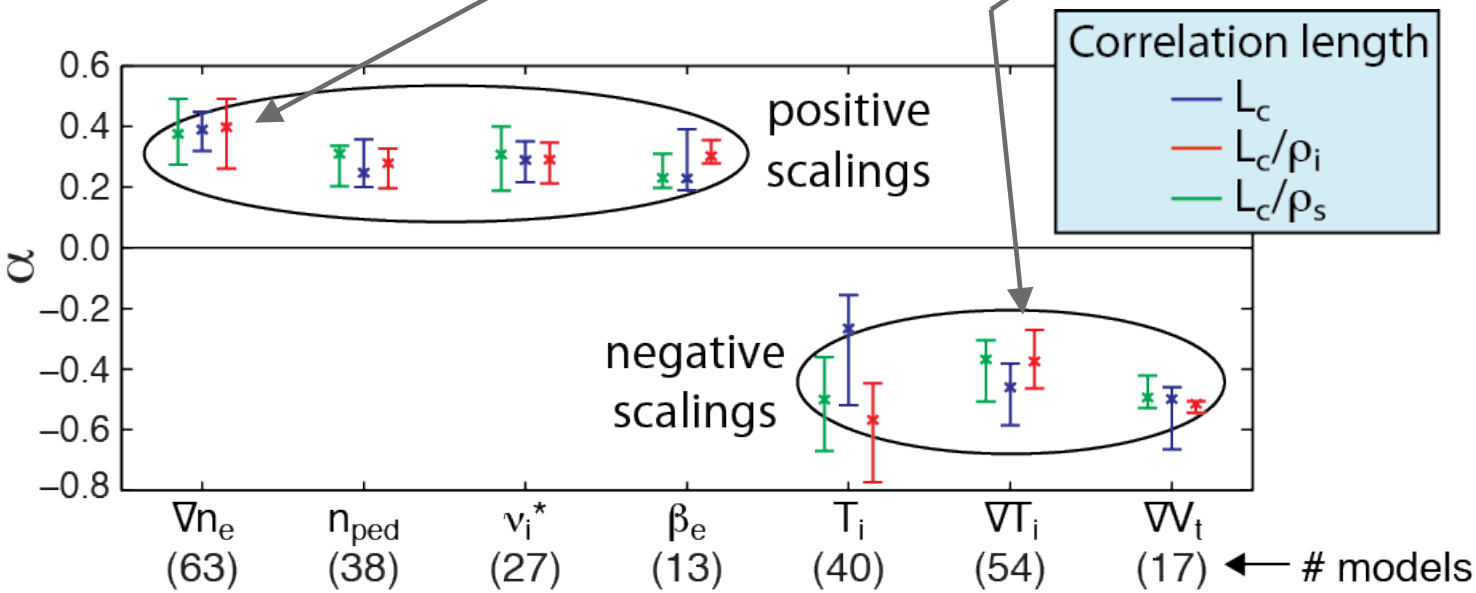
Model aggregation **advantages:**

- Identify more parameter scalings than single model
- Scalings are robust across different models

Model aggregation for L_c increases (α>0) with ∇n_e, ν, β_e, and n_{ped}; L_c decreases (α<0) with T_i, ∇T_i, and ∇V_t

Scalings are robust across models with different parameter combinations

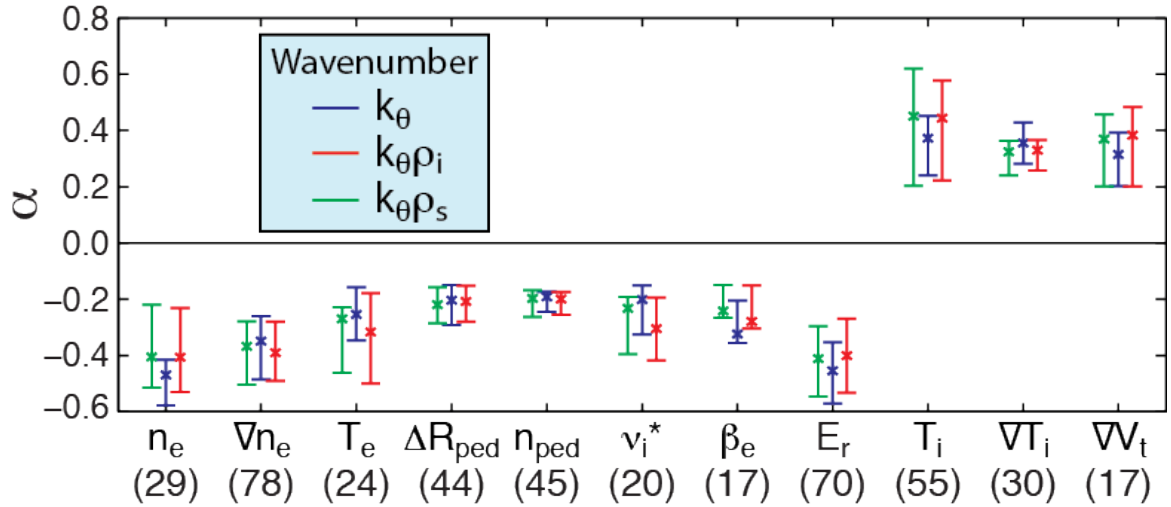


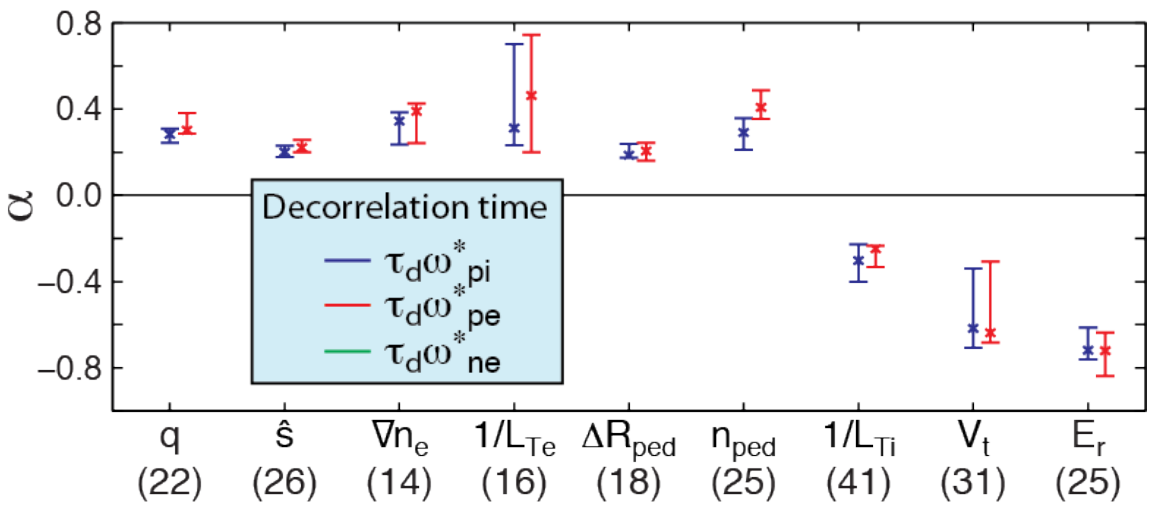


D. Smith et al, PoP 20, 055903 (2013)

Observed scalings can help identify turbulent modes

k_θ scalings are opposite to L_c scalings as expected ($k_\theta \sim 1/L_c$ for broadband turbulence)





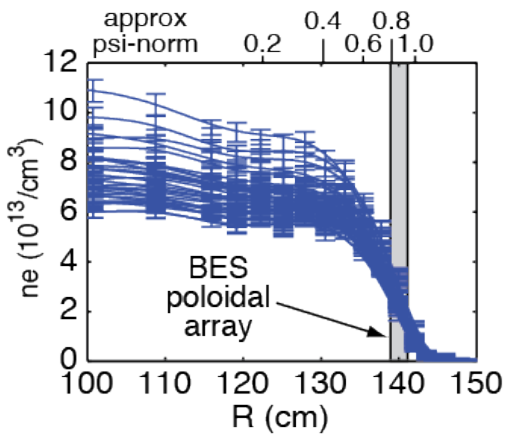
That's a lot of scalings, but what does it all mean?

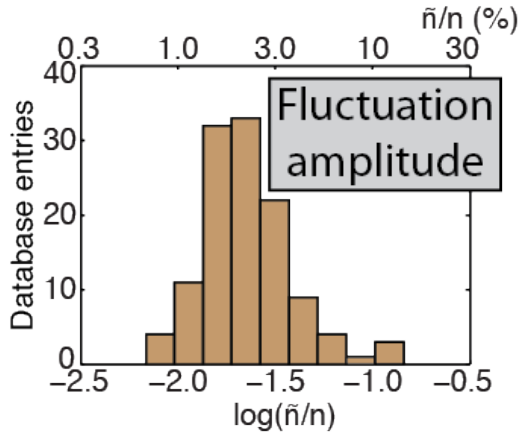
D. Smith et al, PoP 20, 055903 (2013)

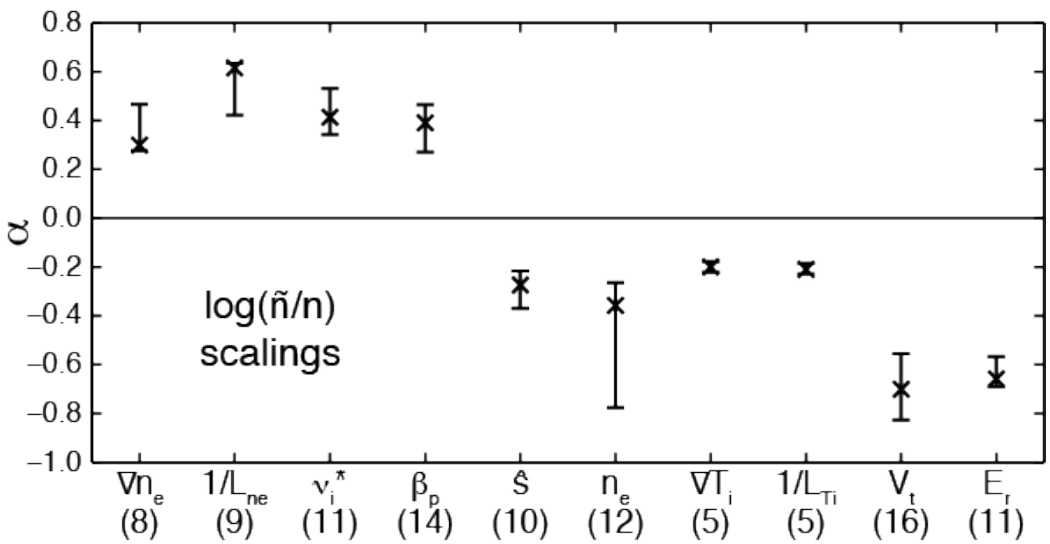
Turbulence reduction by equilibrium and zonal E×B flows can be inferred from observed scalings

- ∇v_t scalings for L_c and k_θ consistent with turbulence suppression by **equilibrium E×B flow shear**
  - L_c decreases and k_θ increases at higher ∇v_t
- E_r sclaings for τ_d are **consistent** with turbulence decorrelation by ExB flow shear
- Collisionality scalings **consistent** with collisionally-damped **zonal flows**
  - L_c increases at higher ν
- n_{ped} and ΔR_{ped} scalings **consistent** with empirical relationship between wider pedestals and larger turbulent structures (Z. Yan et al., PoP 18, 056117 (2011))

Recent ñ/n scalings bolster previous results







- Most consistent with **TEM**, **KBM**, and **MT** instabilities
- Least consistent with **ITG**
- Positive scalings with
  - ∇n_e and $1/L_{ne}$
  - ν_i^* (and other ν quantities)
  - β_p
- Negative scalings with
  - ∇T_i and $1/L_{Ti}$
  - $\hat{s}$
  - E_r and V_t
- Scalings consistent with equilibrium and zonal ExB turbulence suppression.
- Scalings consistent with larger ñ/n at edge.

D. Smith et al, NF 53, 113029 (2013)

Observed scalings point to TEM, KBM, or microtearing instabilities

Transport models (crude, but useful)

Random walk

$$D, \chi \approx \frac{L_r^2}{\tau_d} \approx \frac{L_p^2}{\tau_d}$$

Quasi-linear

$$D, \chi \approx \left(\frac{\gamma_l}{k_\theta^2} \right)_{\max \gamma}$$

Nonlinear mixing

$$D, \chi \approx \sum k_\theta \left| \Phi(k_\theta) \right|^2$$

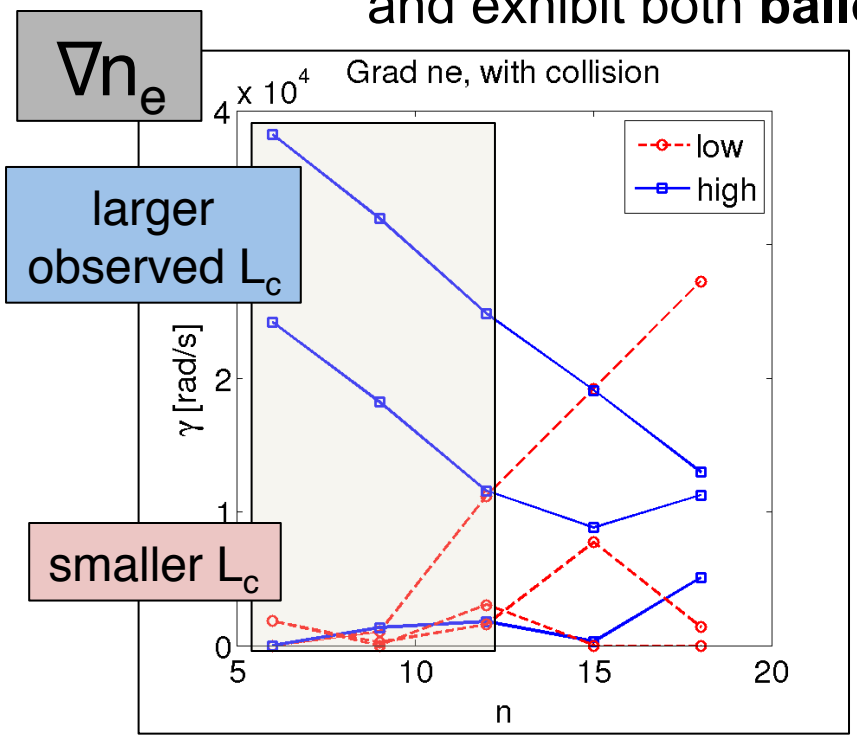
with $\left| \Phi(k_\theta) \right|^2 \propto k_\theta^{-\alpha}$ and $\alpha \approx 2 - 4$

- Microturbulence instabilities
  - ∇T_i, ∇n_e, and ν_i^* scalings are **inconsistent** with **ITG**-driven transport
  - ∇n_e, T_e, and T_i scalings are **consistent** with **TEM**-driven transport
  - β_e scalings are **consistent** with **KBM**-driven transport
  - ∇T_i, $1/L_{Te}$, and ∇n_e scalings show **mixed agreement** with **KBM**
  - β_e and ν scalings are **consistent** with **microtearing**-driven transport
  - $1/L_{Te}$ scalings τ_d are **inconsistent** with **microtearing**-driven transport

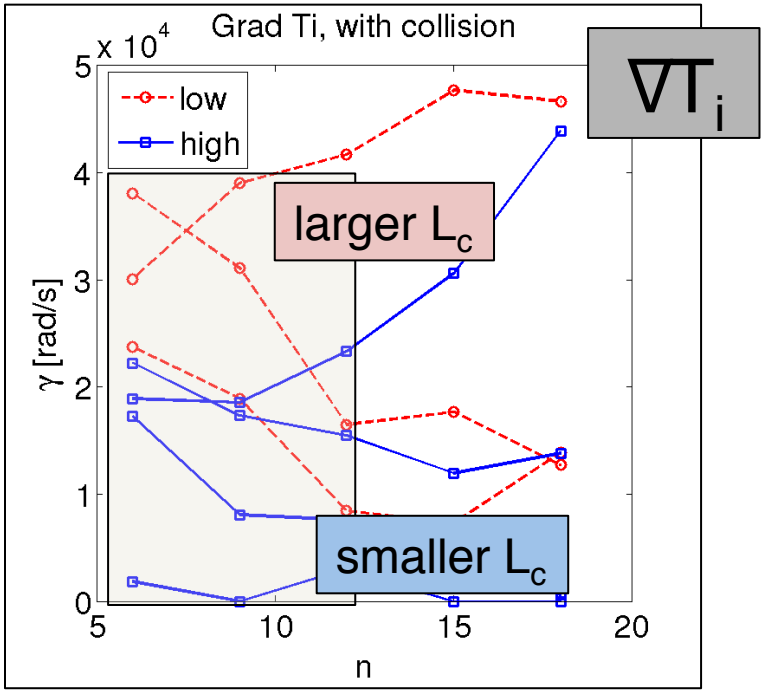
D. Smith et al, PoP 20, 055903 (2013) D. Smith et al, NF 53, 113029 (2013)

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

GEM* global (pedestal) simulations with $6 \le n \le 15$ 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



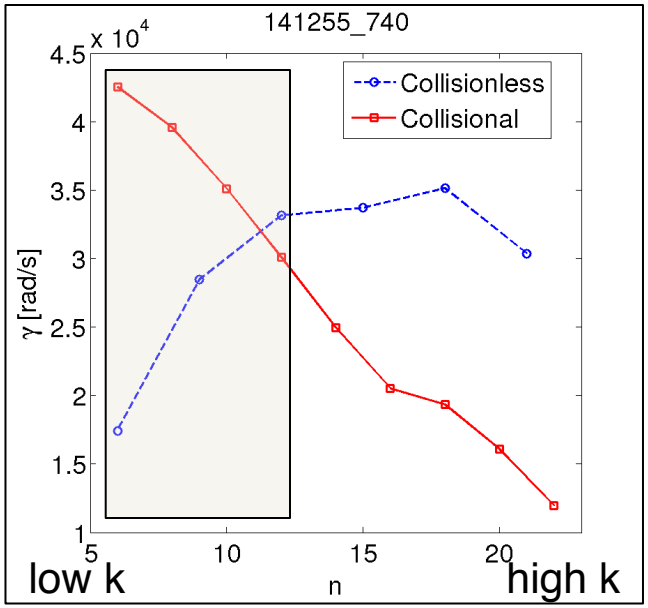
7 of 7 ∇T_i scenarios indicate low-n growth rates decrease at higher ∇T_i

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

* Y. Chen and S. Parker, J. Comp. Phys. 220, 839 (2007)

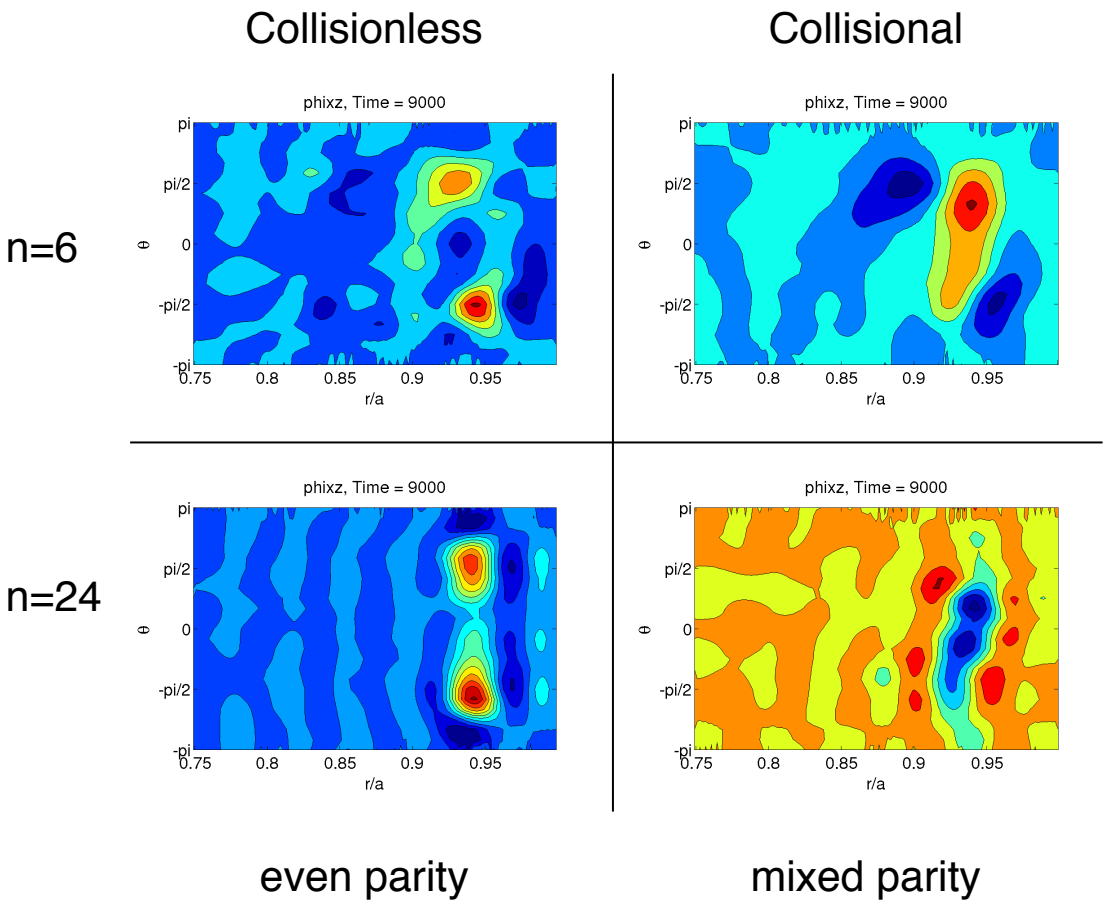
Linear GEM simulations point to mixed-parity modes and highlight the importance of collisions

Collisions increase γ at low-n (decrease γ at high-n)



Low-n modes consistent with observed scalings that show lower k_θ at higher ν

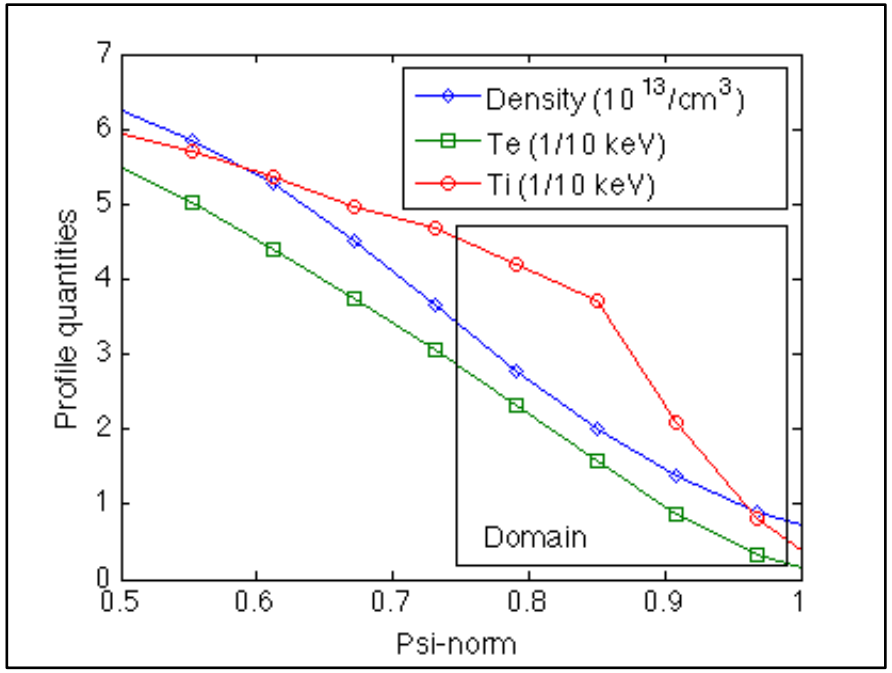
GEM ϕ contours in plane $\perp$ B (n=6)

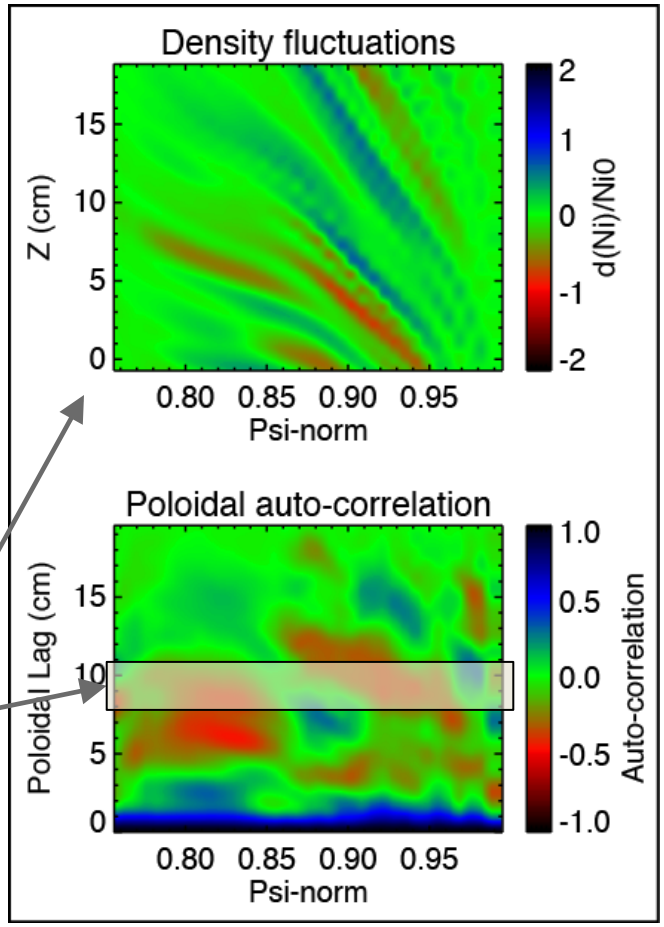


D. Smith et al, NF 53, 113029 (2013)

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

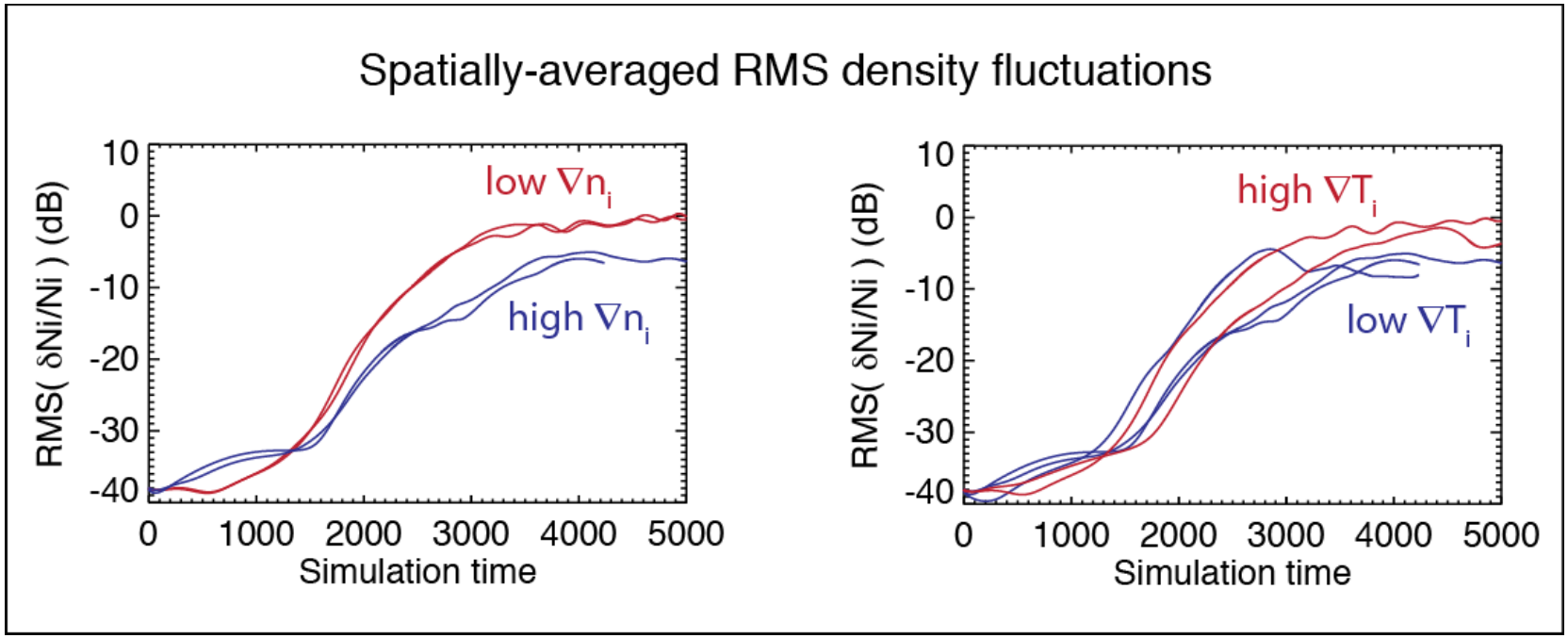
Initial value 3D Braginskii fluid simulations evolve n_i, ω, $j_{||}$, $A_{||}$, T_i, and T_e with collisionality, E×B advection, field line curvature, and drive terms for $j_{||}$ and ∇P. Simulations do not include toroidal rotation and parallel advection.





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

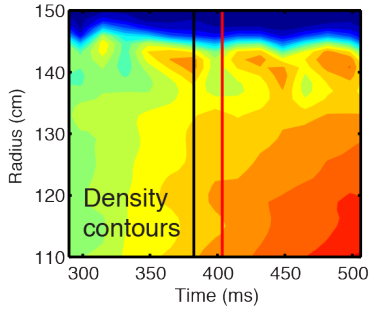
BOUT++ parameter scans point to larger fluctuation amplitudes at lower ∇n_i and higher ∇T_i

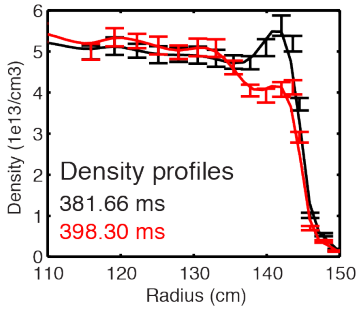


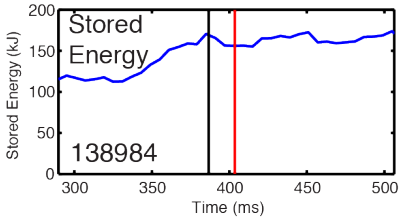
- ∇n_i and ∇T_i trends from Braginskii model do not reproduce observed scalings
  - Highlights the importance of **electron dynamics** for TEM and MT physics
  - Demonstrates that simple, order-of-magnitude comparisons (e.g. correlation length) can lead to erroneous inferences
  - Will benefit from BOUT++ **gyrofluid** model → X. Xu et al, in press, PoP (2013)

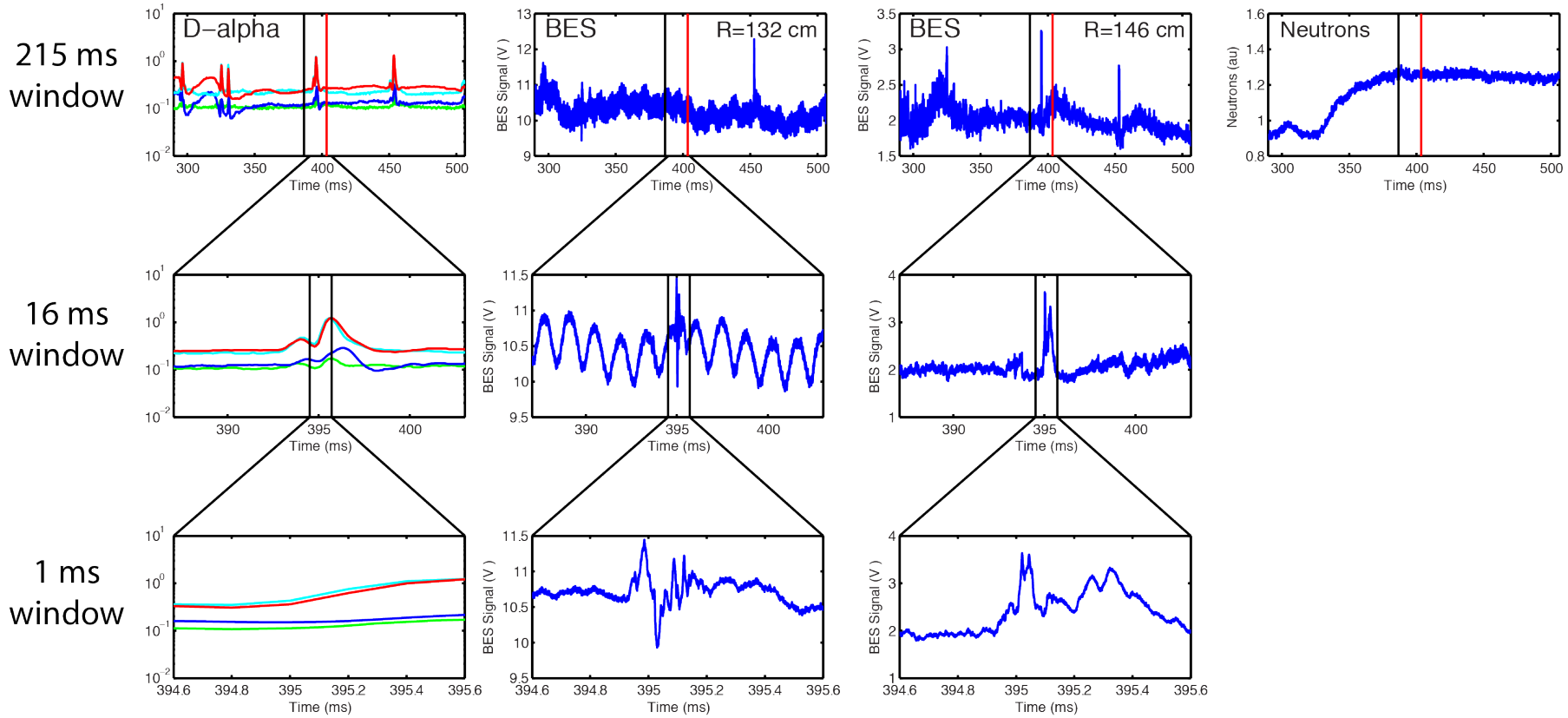
BES measurements with high time resolution show evolution and radial profile of ELM bursts

- Survey of 57 ELM bursts from 26 discharges
- Stored energy drops 1-16%
- Burst length 0.1-1.0 ms







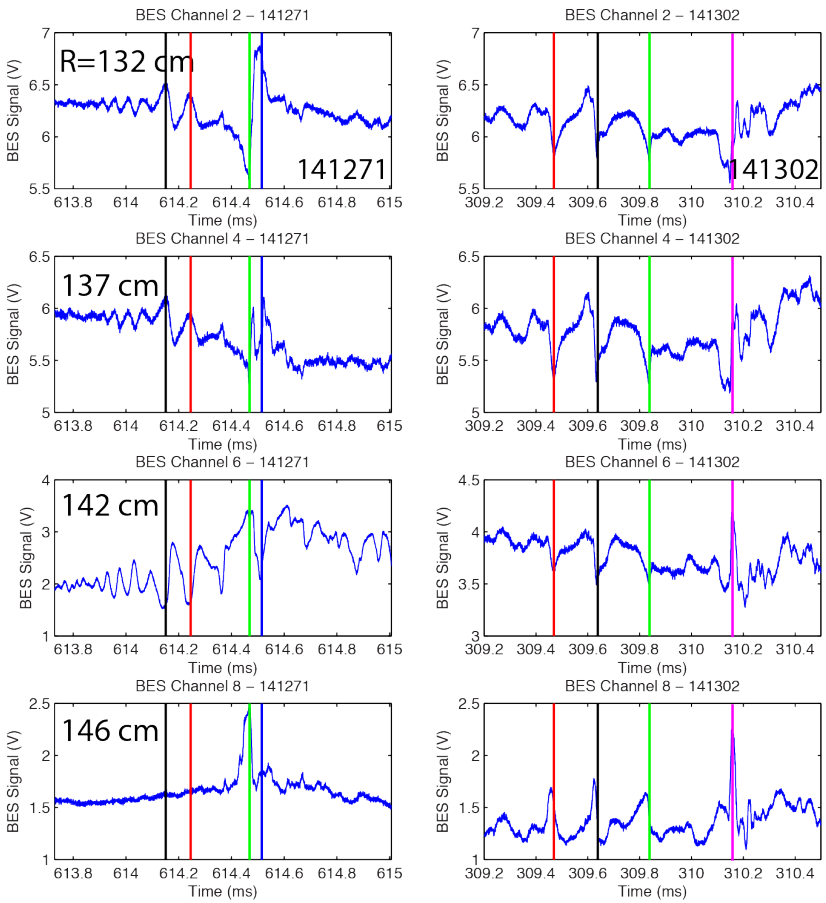


ELM bursts can show radial structure

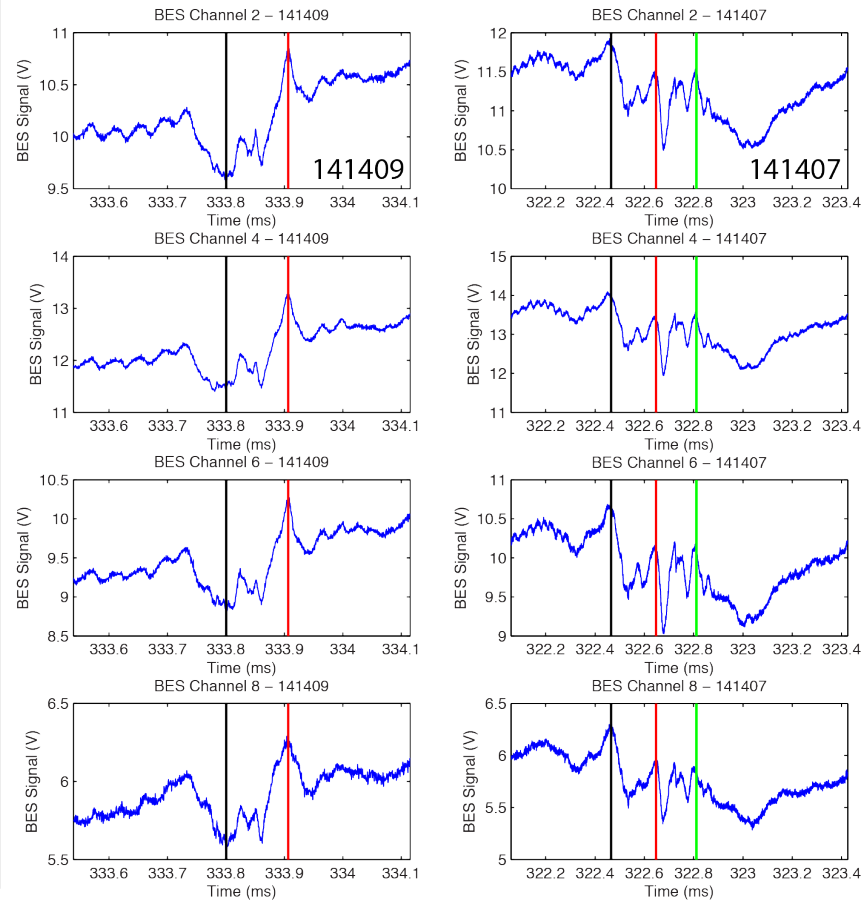
Pedestal Top

SOL

Strong radial variation

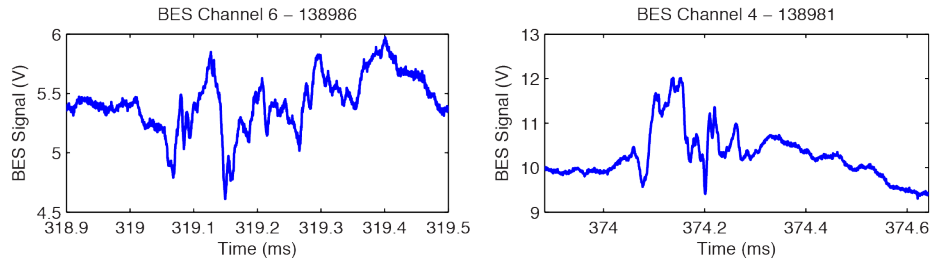


Radially uniform evolution

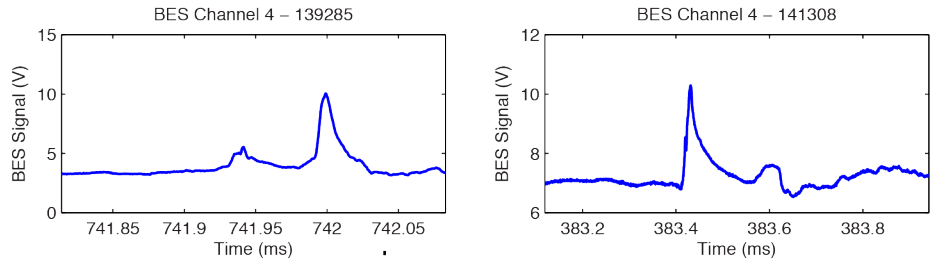


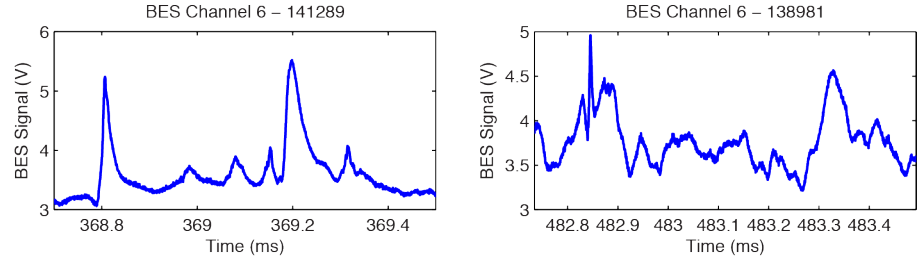
ELM bursts can also exhibit oscillations or multiple peaks

Oscillatory bursts →

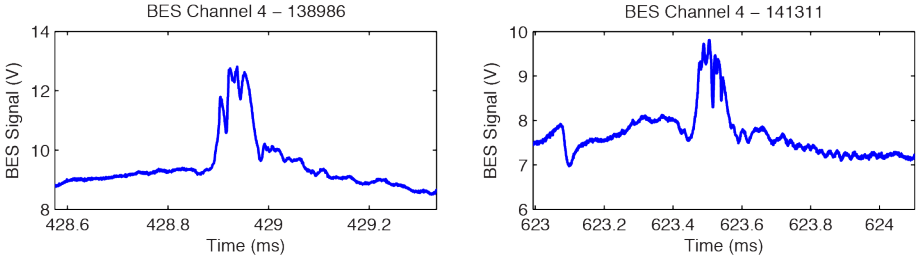


Non-oscillatory bursts →





← Multiple peaks



← Single peak

Summary (ELM burst survey)

- **Strong radial variation** is generally observed with **small ΔW**
  - ΔW < 7 kJ and ΔW/W < 5%
- Non-oscillatory bursts are generally short duration (< 300 μs) with **modest to large ΔW**
  - ΔW > 8 kJ and ΔW/W > 5%
- Single, isolated bursts are generally short duration (< 300 μs)
- Multi-peak bursts show **modest to large ΔW**
  - ΔW > 7 kJ and ΔW/W > 4%

Summary (Pedestal Turbulence)

- ST parameter regime can extend the parameter space and confidence in pedestal models
- We measured pedestal turbulence parameters in NSTX H-mode plasmas during ELM-free, MHD quiescent periods (with Li conditioning)
  - **$L_c/\rho_i \sim 12k_\theta\rho_i \sim 0.2$ $\tau_d/(a/c_s) \sim 5$ $\tilde{n}/n \sim 1\%\text{-}4\%$**
- Parametric dependencies for pedestal turbulence meas-urements are most consistent with **TEM turbulence** and partially consistent with **KBM and μ-tearing turbulence**
  - **GEM** gyrokinetic simulations show linear γ scalings **consistent** with measured L_c scalings for ∇n_e and ∇T_i