NSTX

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H-mode Pedestal Evolution in ELMy and ELM-free Discharges in NSTX

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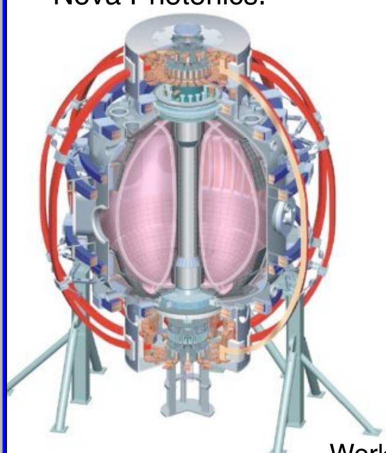

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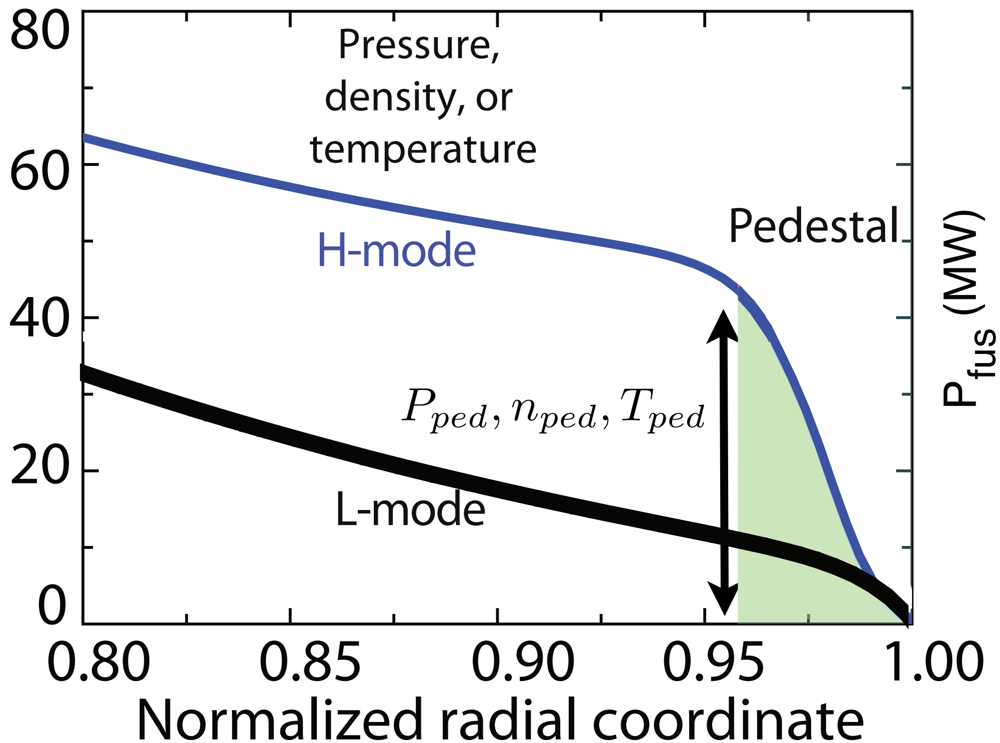
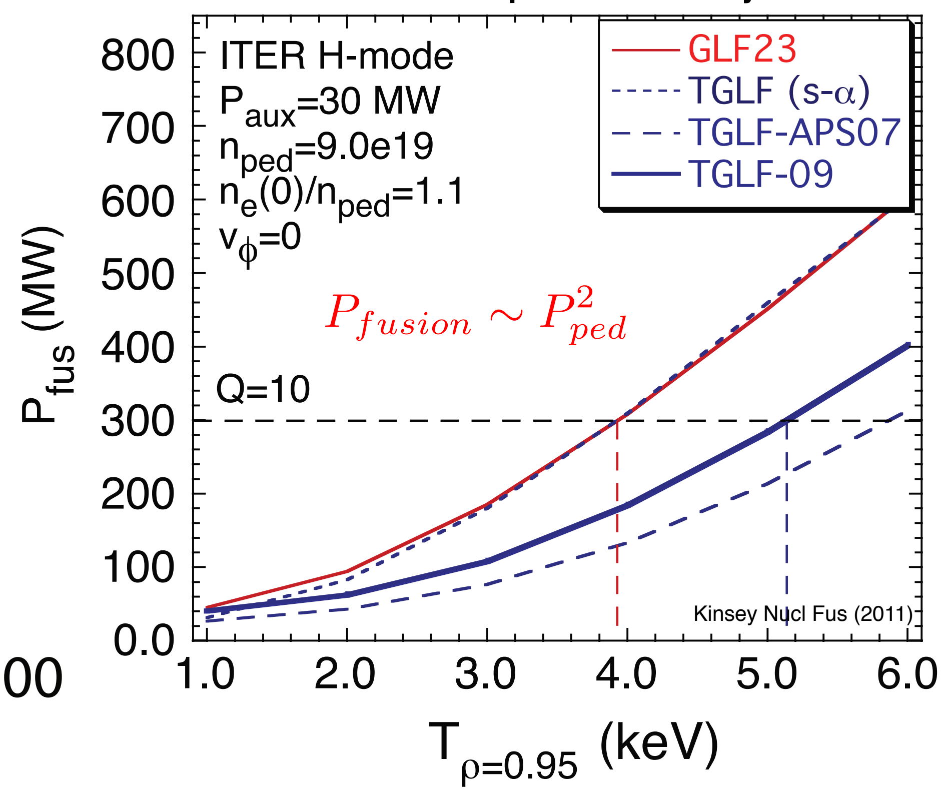
Understanding the pedestal structure is crucial for performance prediction of fusion devices

- **Pedestal is an edge transport barrier associated with high-confinement regime (H-mode)**

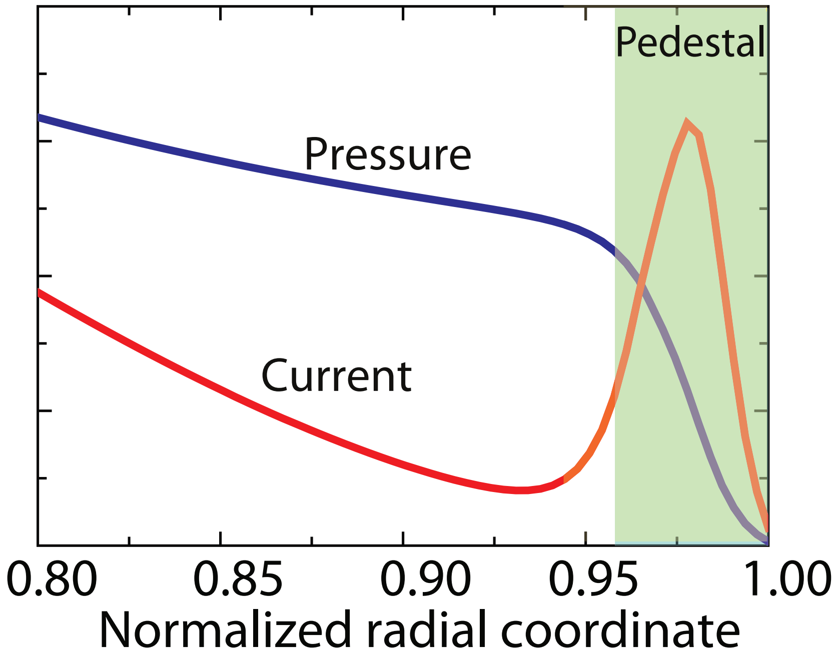
- **Predictive models indicate that the pedestal height plays a crucial role in fusion performance**

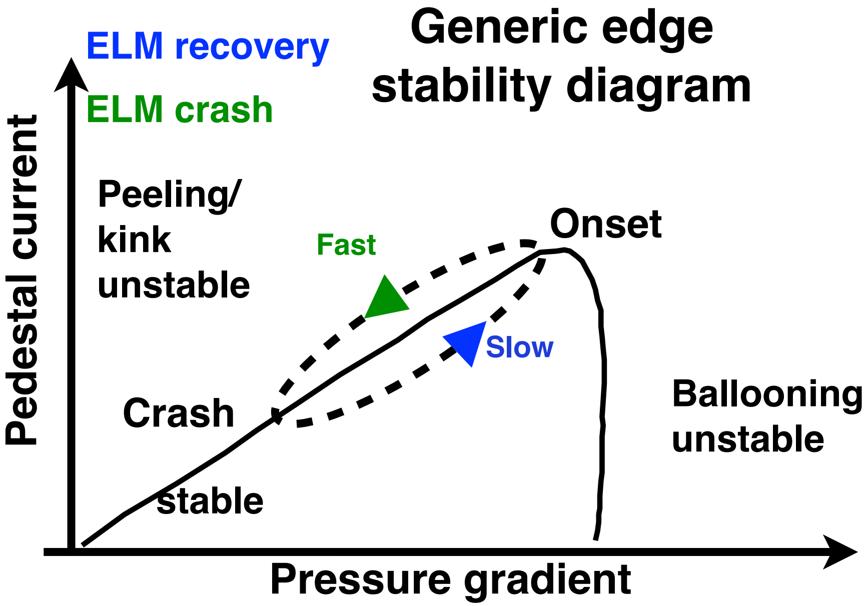


Predicted fusion power vs pedestal temperature at fixed pedestal density



Peeling ballooning theory is the leading model for explaining the the edge localized modes (ELM) cycle





Connor, PoP (1998)
Wilson, PoP (2002)
Snyder PoP (2002)

- It is hypothesized that ELMs are triggered when the plasma edge (current and/or pressure gradient) crosses the stability boundary

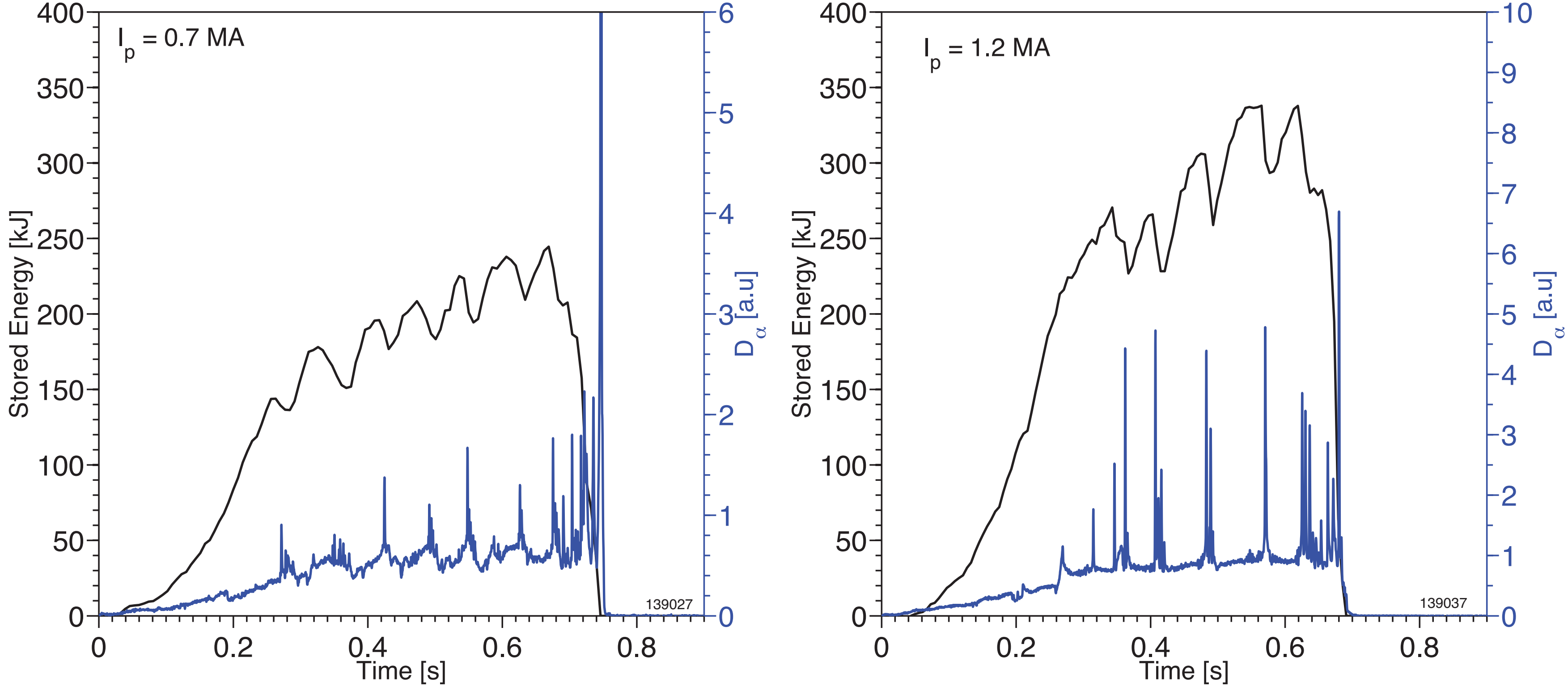
Continuing efforts for an experimental characterization of the pedestal dynamics during the inter-ELM phase

Outline

- Pedestal structure characterization in ELMy H-modes
  - Pedestal pressure height builds up and at times saturates late in the ELM cycle
  - Pedestal width increases during the inter-ELM phase
  - Peak pressure gradient is clamped early in the ELM cycle
- Maximizing the pedestal height and width
- Role of microturbulence during the inter-ELM phase
- Summary and future work

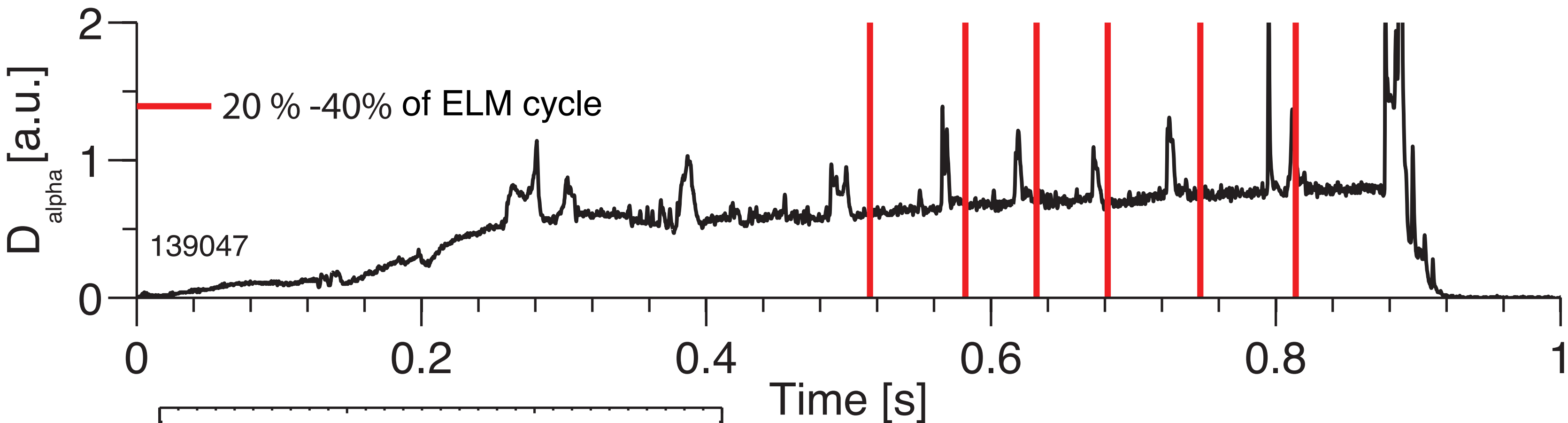
Dedicated experiments to vary the pedestal pressure height and width through I_p scans were performed on NSTX

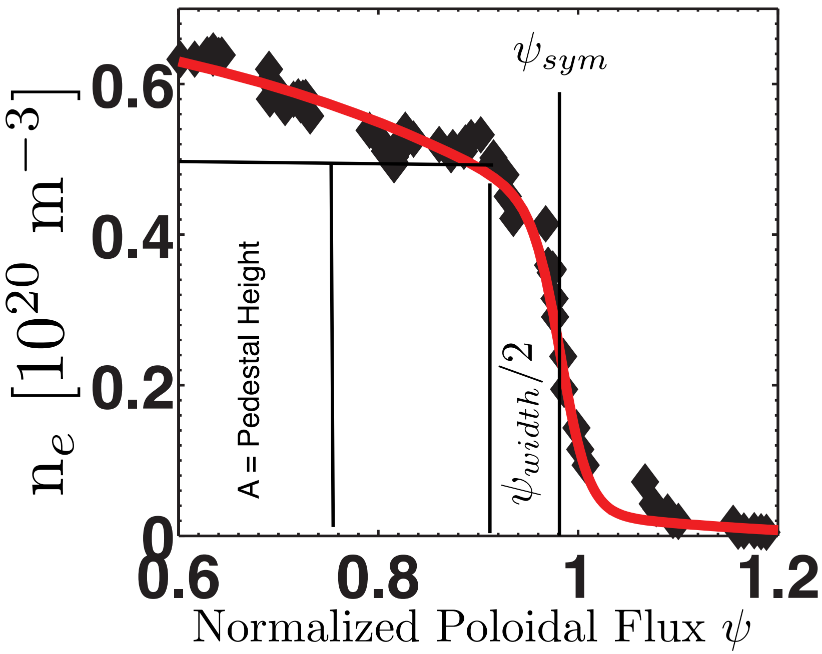
- Constant injected power (P_{NBI}) and magnetic field (B_T)
- Lower single null slightly downward and fixed high triangularity shaping.



- Large drop (up to 15%) of stored energy (W_{mhd}) after each ELM crash
  - Pedestal stored energy ~ 25% - 40% of W_{mhd}
- Discharges operated near stability boundary

Radial profiles of density, temperature and pressure are composite of times between multiple fraction of ELMs





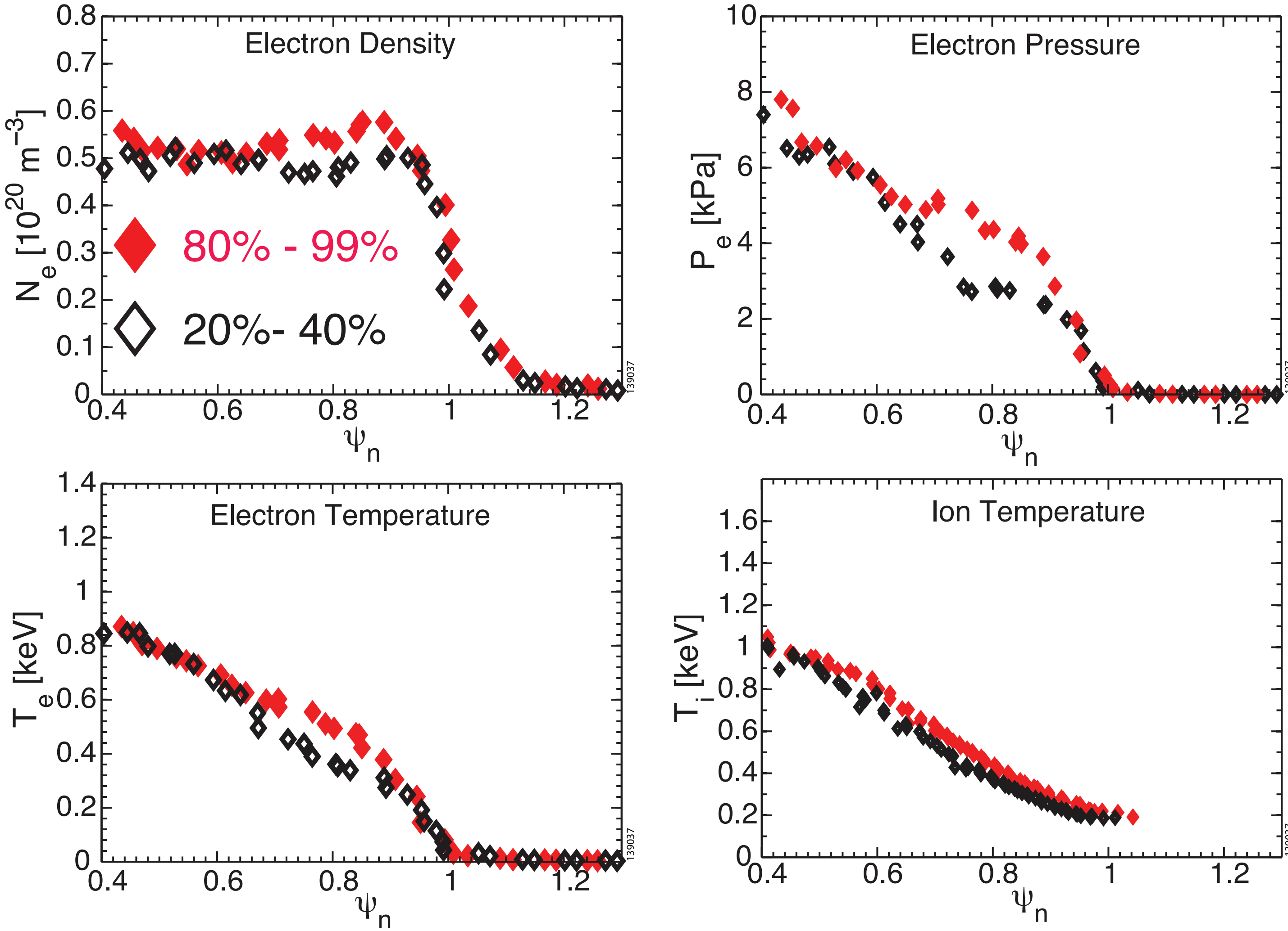
- Electrons edge radial profiles are systematically fitted during fraction of ELM cycle using a modified tanh function

$$N(\psi) = A \tanh\left(\frac{\psi_{sym} - \psi}{\psi_{width}}\right) + offset$$

R. Groebner and T. Osborne PoP (1998)

- Ion profiles are spline fitted

Observe increase of the pedestal pressure height prior to onset of ELM



Late in ELM cycle

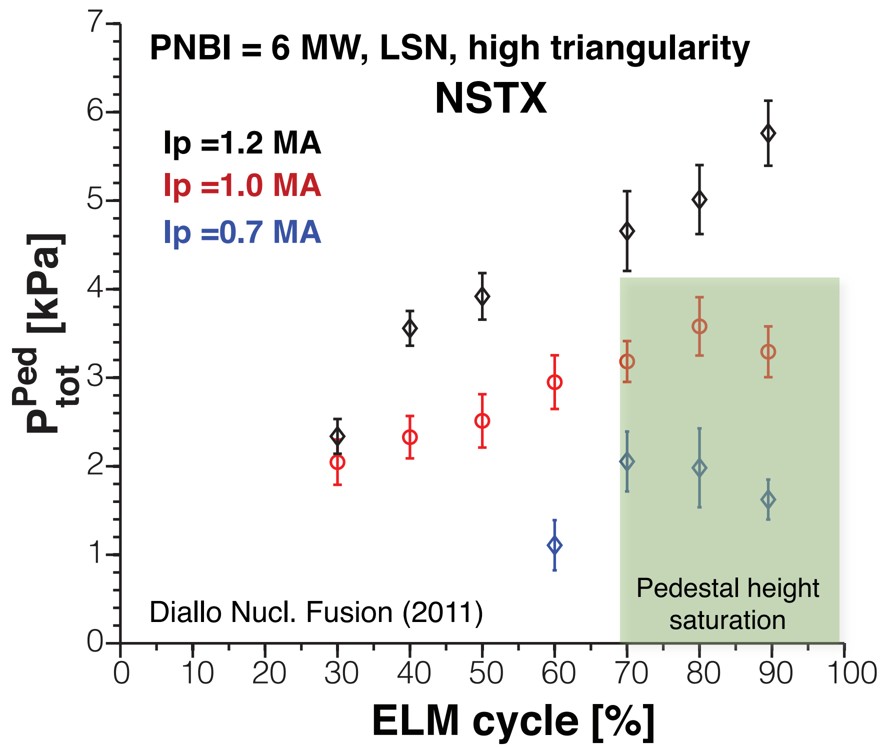
Early in ELM cycle

n_e,T_e at the pedestal top increase prior to the onset of ELM while T_i remains unchanged

Pedestal pressure height builds nearly continuous during the inter-ELM phase

- Pedestal height increases by a factor ≤ 3 before the ELM crash

- Pedestal height saturates prior to ELM crash at low and medium I_p

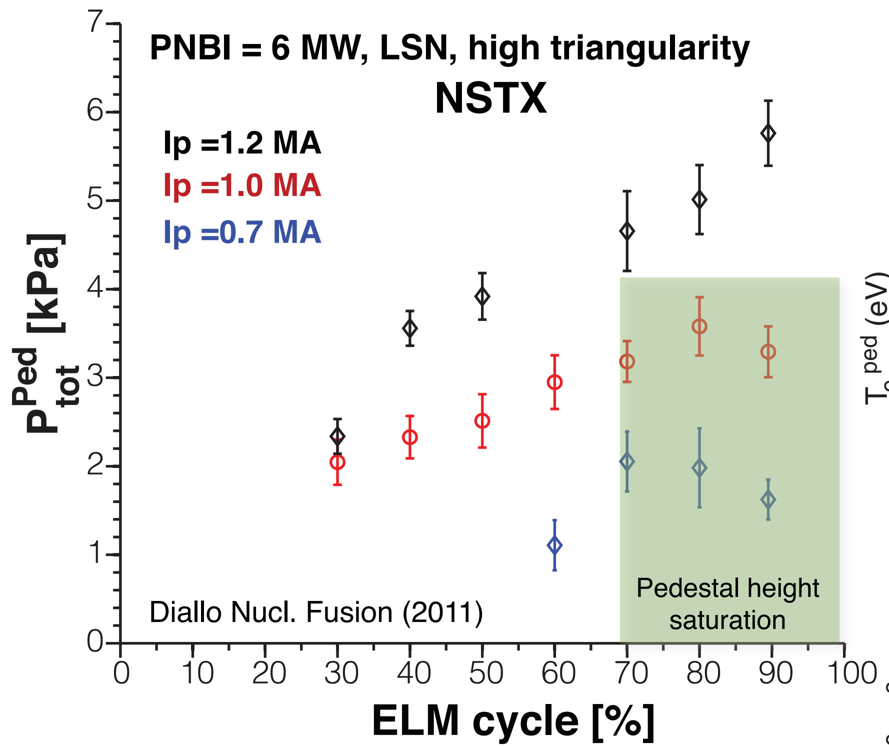


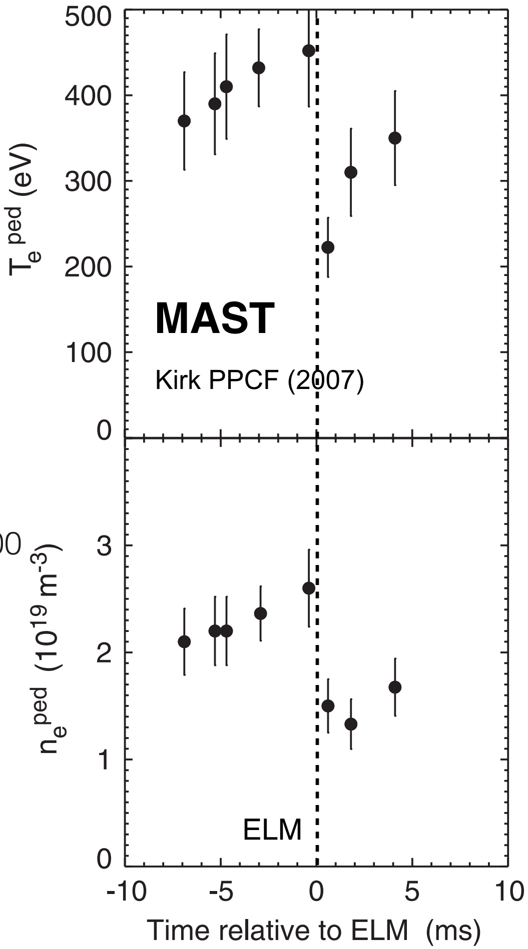
Pedestal pressure height builds nearly continuous during the inter-ELM phase

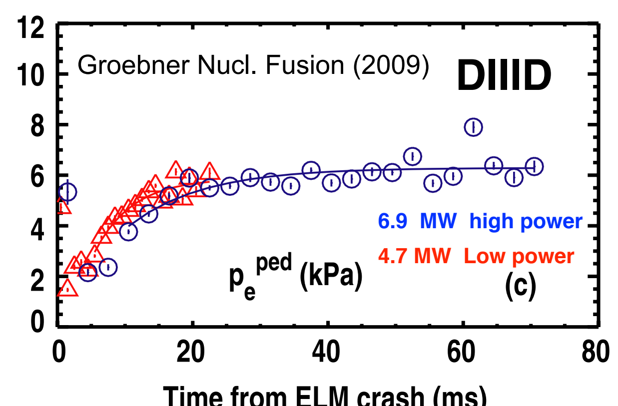
- Pedestal height increases by a factor ≤ 3 before the ELM crash

- Pedestal height saturates prior to ELM crash at low and medium I_p

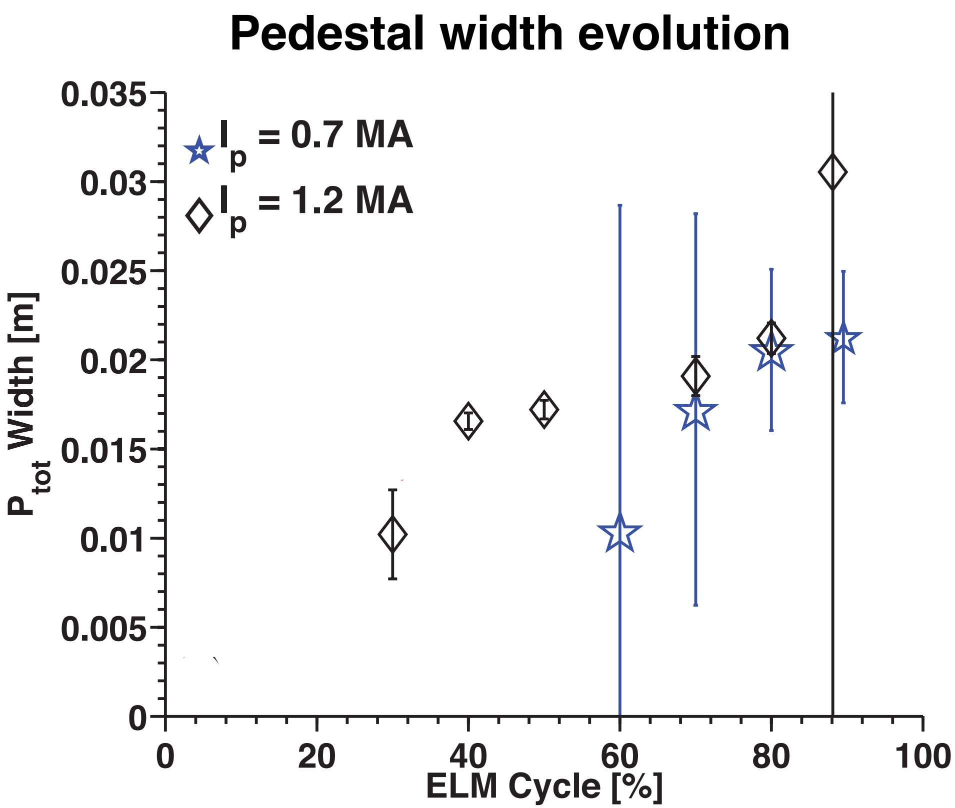
- Low aspect ratio tokamak (NSTX and MAST) pedestals do not necessarily saturate prior to ELM onset

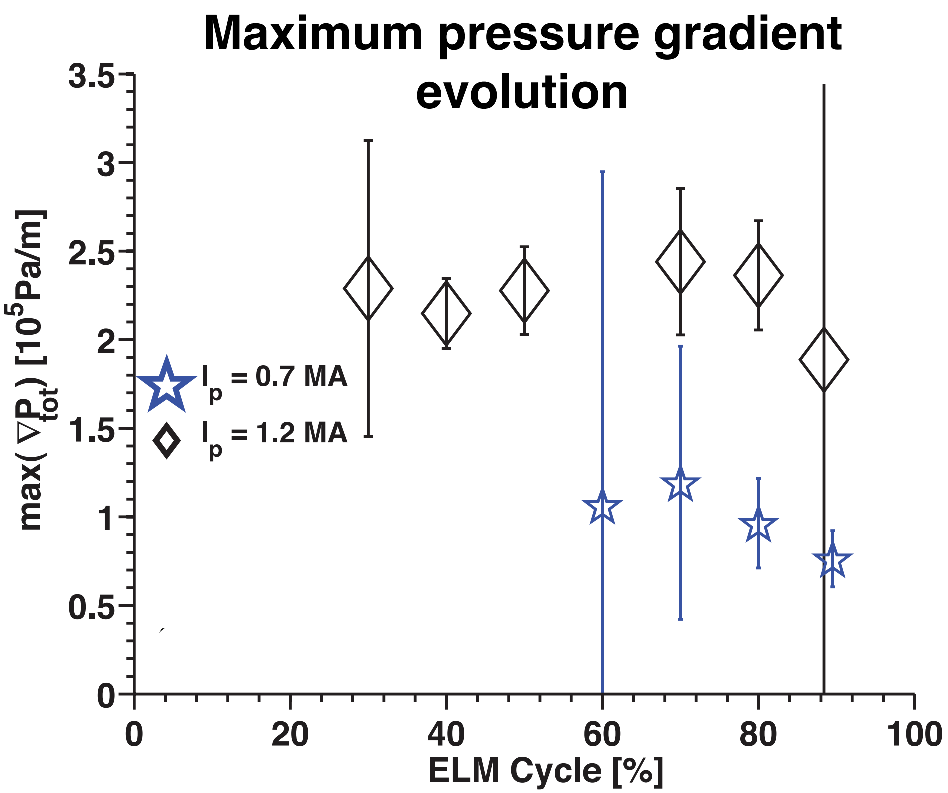






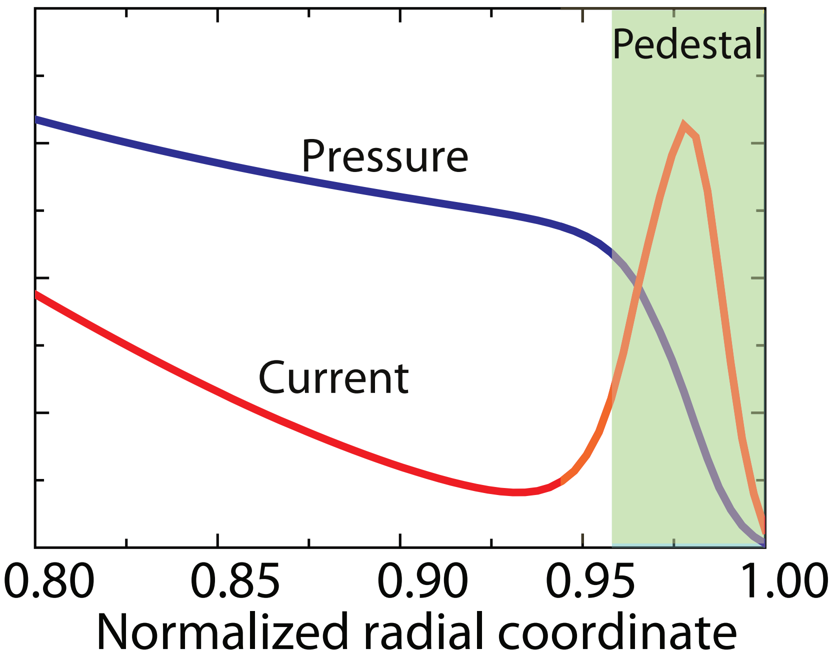
Pedestal width progressively increases during ELM cycle but the peak pressure gradient remains unchanged

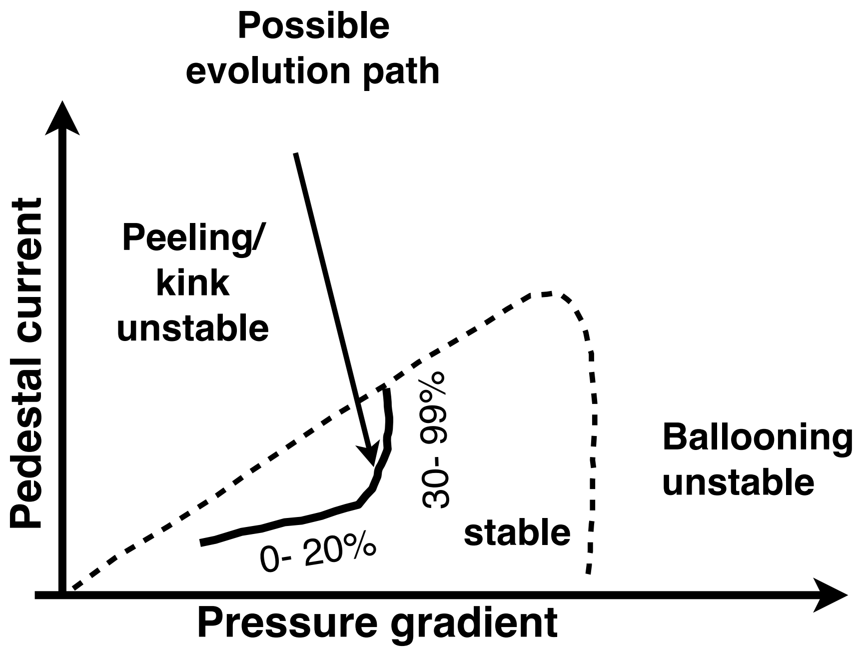




- Pedestal width increases during the inter-ELM phase independently of I_p
- Peak pressure gradient saturates early in the ELM cycle:
  - Peak pressure increases with I_p

Pedestal dynamic during the inter-ELM phase is indicative of the possible current and pressure gradient evolution in the stability diagram





Connor, PoP (2002)
Wilson, PPCF (2006)

- ELMs are triggered when the plasma edge (current and pressure gradient) crosses the stability boundary

Outline

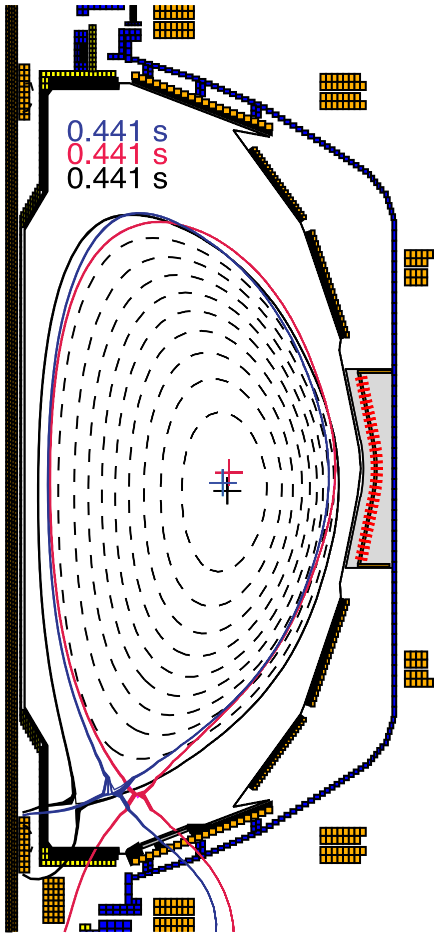
- Pedestal structure characterization in ELMy H-modes

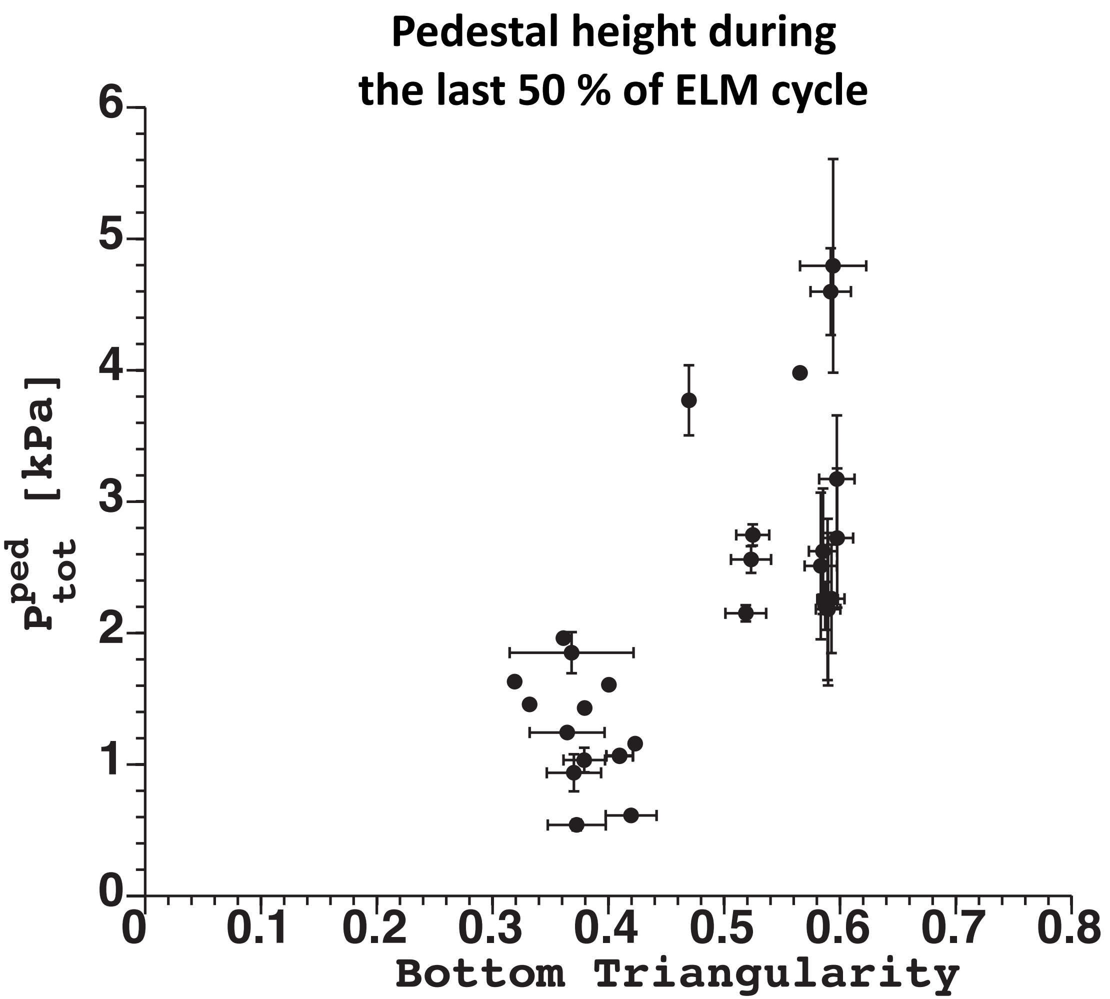
- Maximizing the pedestal height and width
  - Plasma shaping provides a knob for increasing the pedestal height
  - lithium wall coating modifies the pedestal structure, allowing access to larger pedestal widths and higher pedestal pressure
    - Evolution of the pedestal structure is consistent with NSTX discharges being close to the kink/peeling stability boundary

- Role of microturbulence during the inter-ELM phase

- Summary and future work

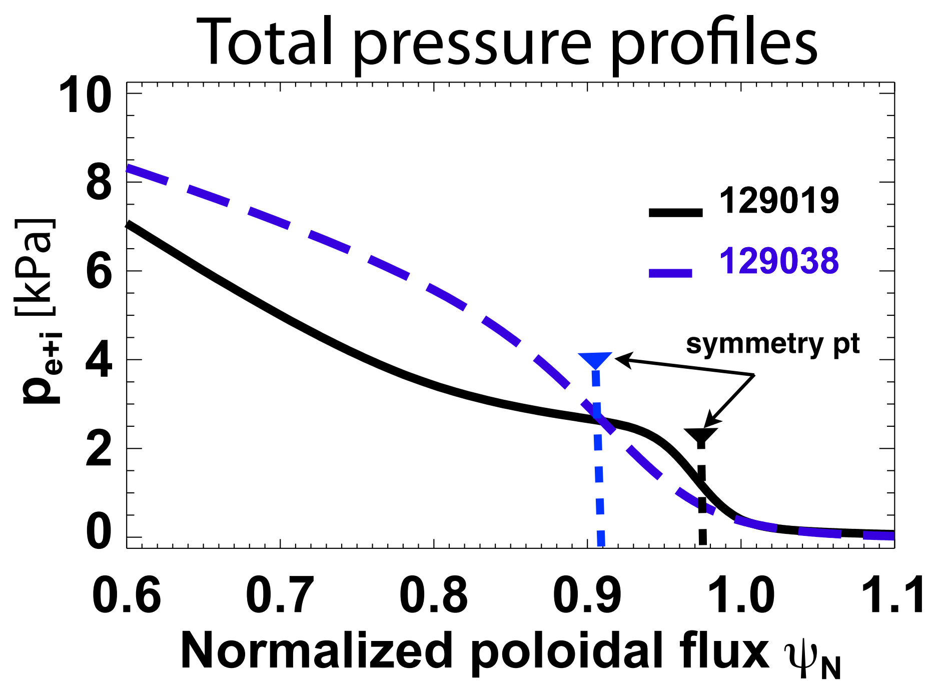
Pedestal pressure height increases with shaping (triangularity δ)

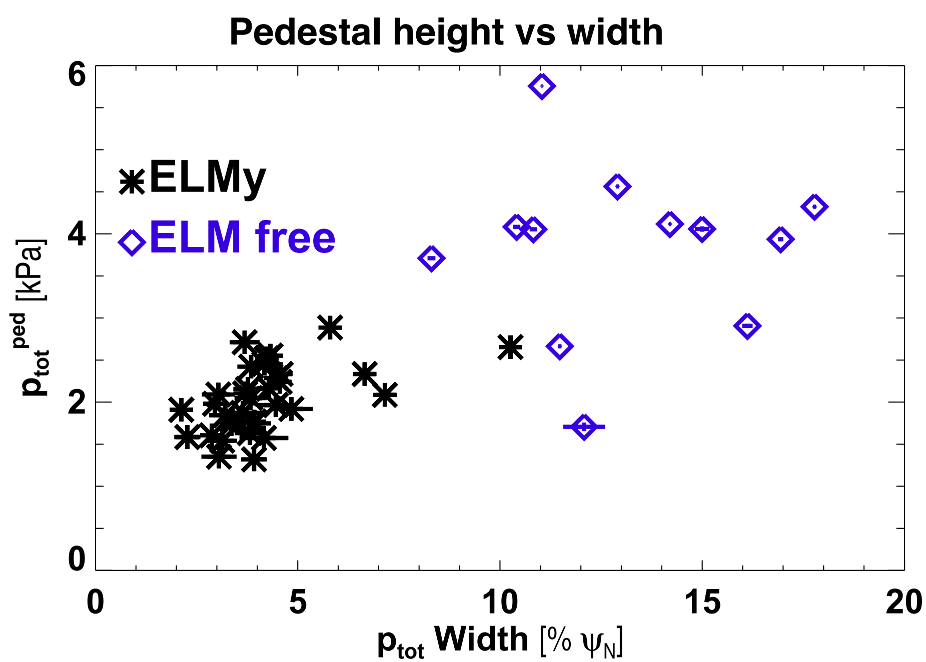




Increasing shaping leads to stability limits at higher P'_{ped}

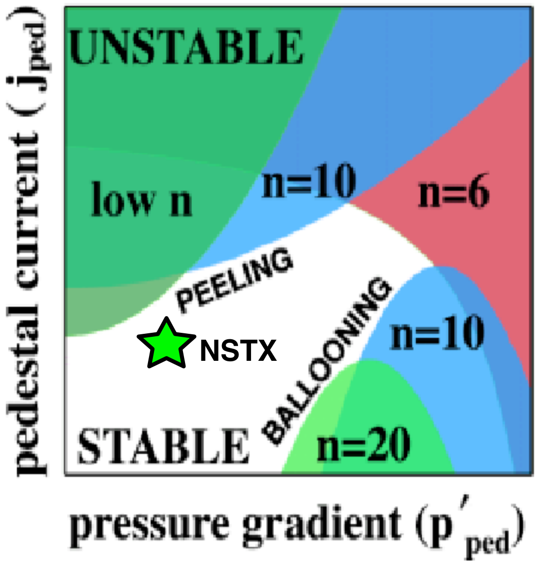
ELMy regimes transition to ELM-free regimes with the application of lithium on the divertor to access larger pedestal pressure and width





- ELM-free regimes exhibit a pedestal height and width larger than in ELMy cases
  - Application of lithium clearly modifies the edge pressure
- Inward shift of the peak pressure gradient

Stability diagram with and without lithium: Lithium cases are farther away from the kink/peeling boundary



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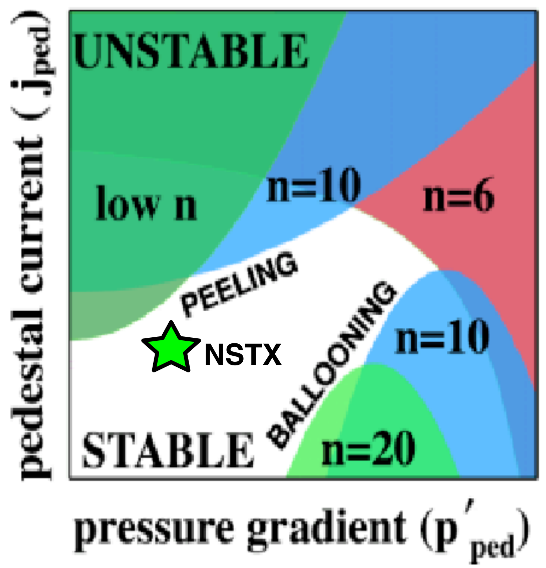
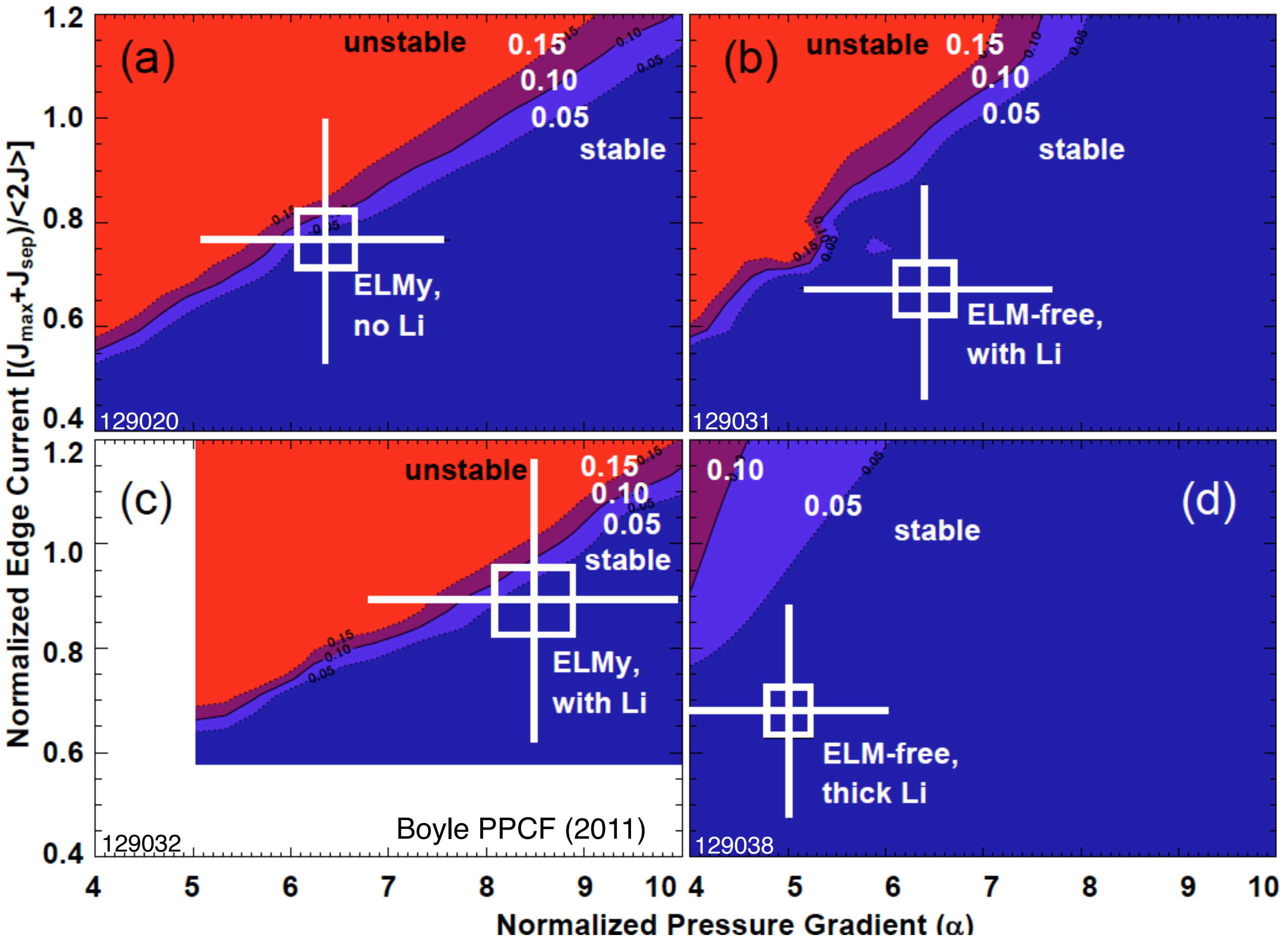
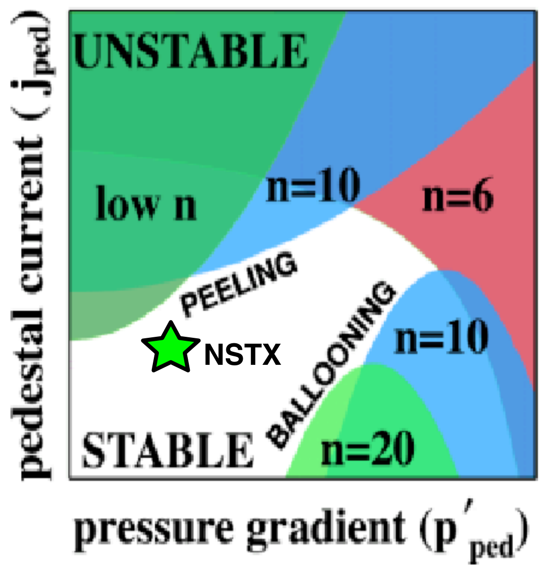


Consistent with NSTX close to the kink/peeling stability boundary

Lithium coatings are a useful tool for shifting peak pressure gradient inward and stabilizing kink/peeling modes.

Stability diagram with and without lithium: Lithium cases are farther away from the kink/peeling boundary





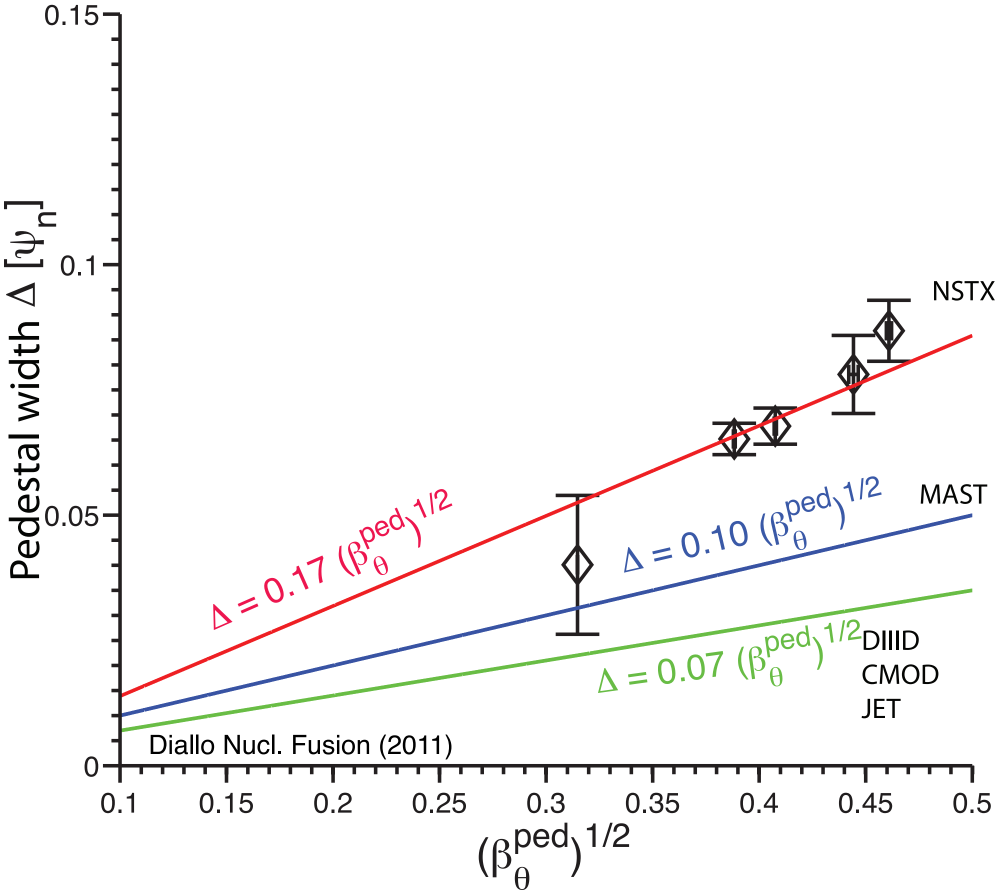
Consistent with NSTX close to the kink/peeling stability boundary

Lithium coatings are a useful tool for shifting peak pressure gradient inward and stabilizing kink/peeling modes.

Outline

- Pedestal structure characterization during the inter-ELM phase
- Maximizing the pedestal height and width
- Role of microturbulence during the inter-ELM phase
  - If the pressure gradient is limited by kinetic ballooning modes (KBM), it is expected that the pedestal width is proportional to the poloidal β
  - Correlation reflectometry probes radial correlation lengths
  - BES probes the poloidal correlation lengths and advection direction
  - Combination of both BES and reflectometer (< 50kHz) provides characterization of the microturbulence at play during the inter-ELM phase
- Summary and future work

Measured pedestal pressure width scales with $\sqrt{\beta_\theta}$



- Good description of the width scaling over multiple machines (DIIID, CMOD, JET, MAST)

Groebner, NF, (2009)
Kirk, PPCF, (2009)
Beurkens, PoP, (2011)

- In NSTX, the observed width is larger than conventional tokamaks
  - NSTX pedestal width is 1.7 and 2.4 larger than MAST and DIII-D respectively

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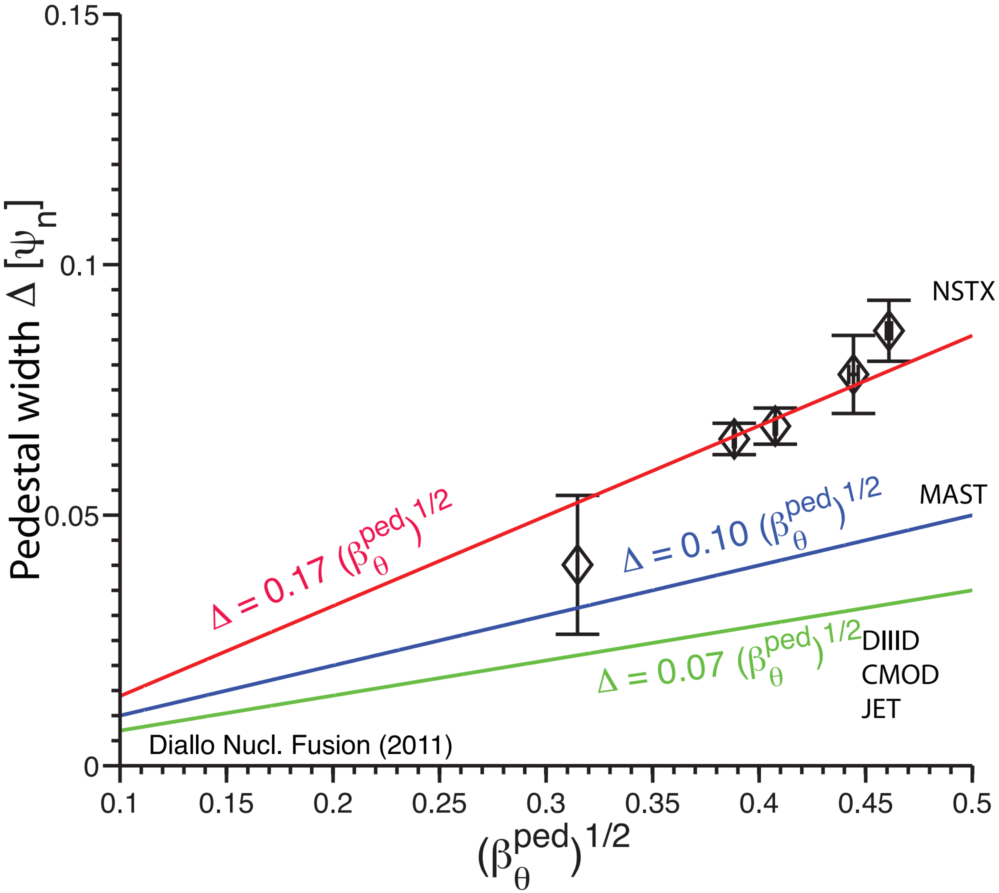

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- In NSTX, the observed width is larger than conventional tokamaks
  - NSTX pedestal width is 1.7 and 2.4 larger than MAST and DIII-D respectively

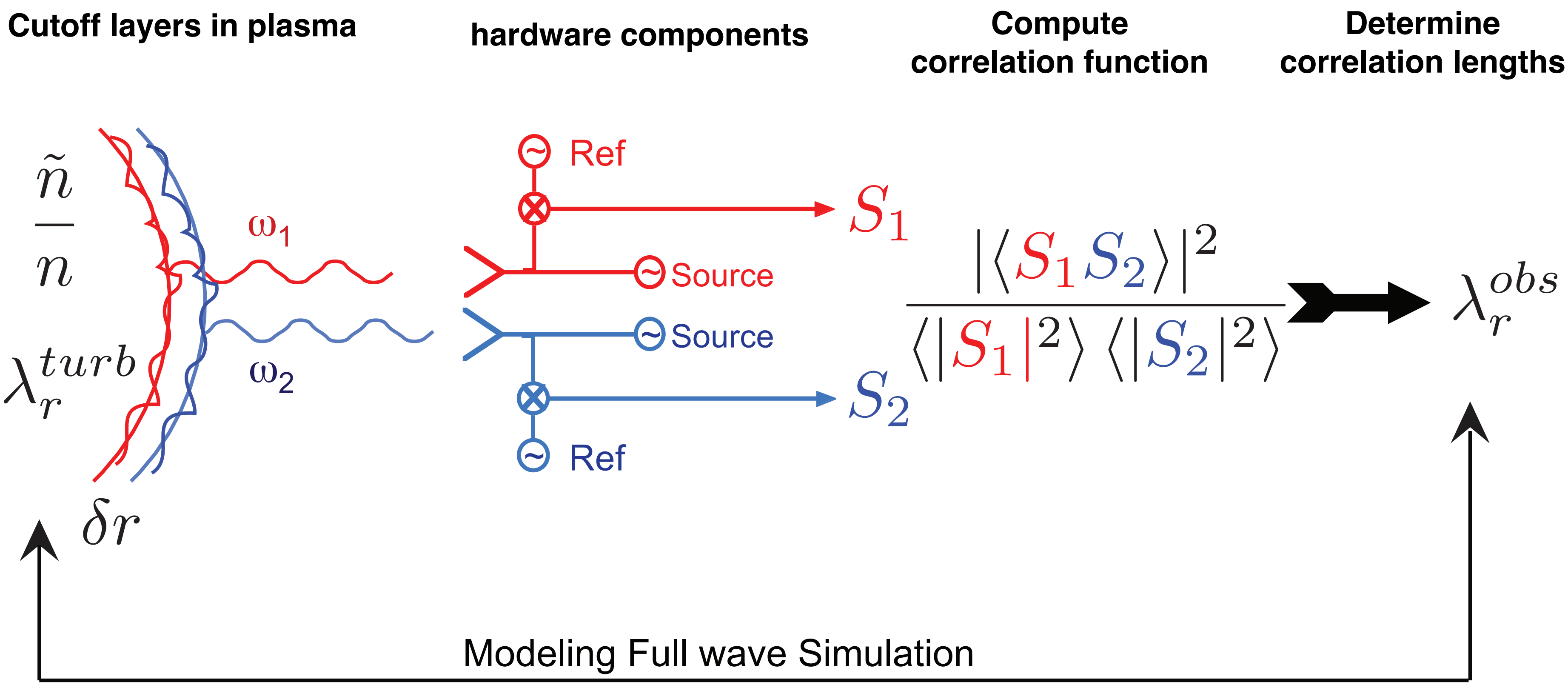
- Kinetic ballooning instability is the leading candidate for explaining the width scaling

Role of the edge density fluctuations on setting the pedestal structure during the inter-ELM phase

- Pedestal gradient has been predicted to be constrained by the onset of kinetic ballooning mode (KBM)* *Snyder PoP 9 (2002)
  - Recent DIIID work has shown observations of modes localized in the pedestal region with features similar to KBM Yan PRL 107 (2011)
  - KBM characterized by:
    - $k_{\perp}\rho_i < 1$
    - modes have radial scales of the order few cm in the pedestal region of NSTX
    - fast rising growth rate increasing with electron β
    - propagation in the ion diamagnetic direction.

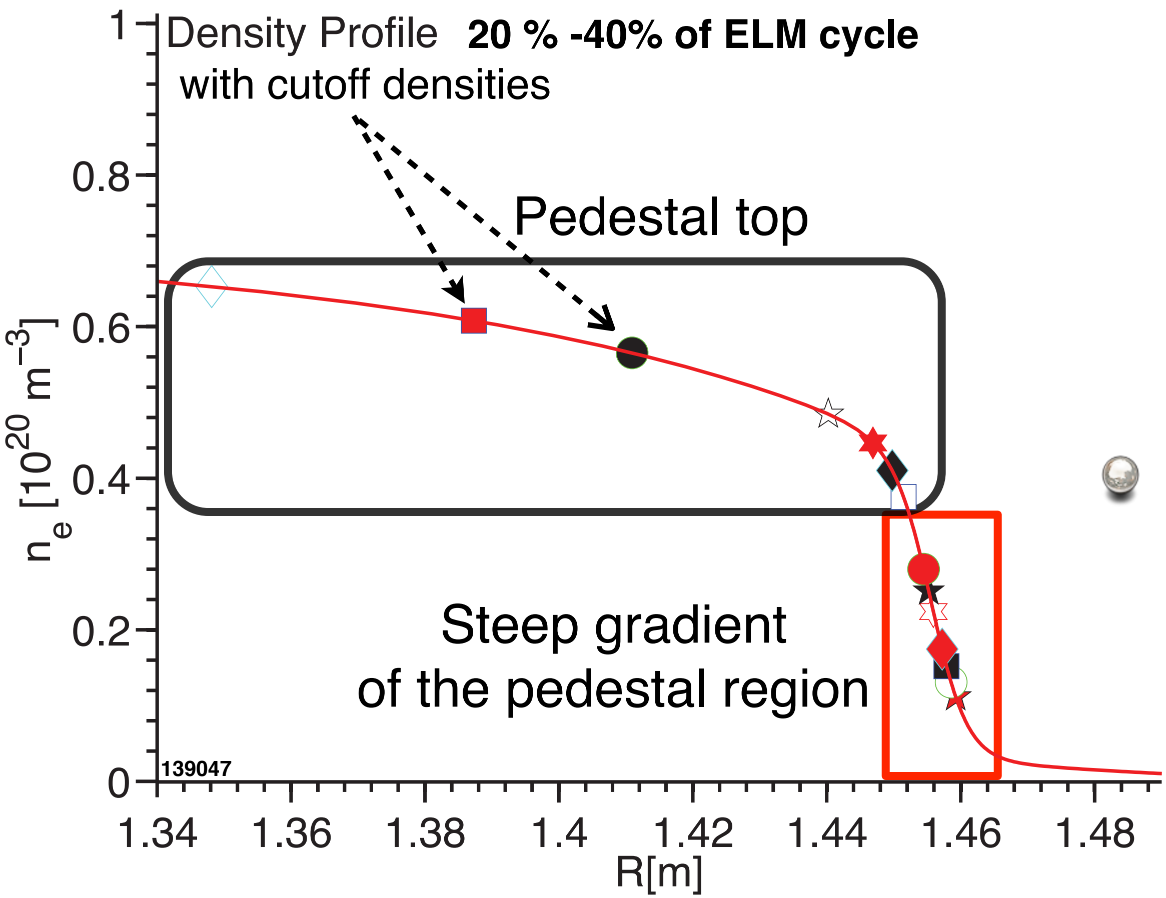
- NSTX: We look for evidence of pedestal-localized microinstabilities, and their correlation with the ELM cycle
  - Use both reflectometry and BES
  - Because it's hard to conclusively identify KBM, we characterize our instabilities in terms of radial scale, wave number, and propagation direction

Turbulent fluctuations during the inter-ELM dynamics determined using the correlation reflectometry (UCLA)



- Compare the correlation length measurements with 2D full wave simulations to remove potential instrument function $\lambda_r^{turb} \neq \lambda_r^{obs}$
  - density fluctuation level, equilibrium profiles, and turbulent correlation lengths.

Radial density correlation lengths at the pedestal top and steep gradient region

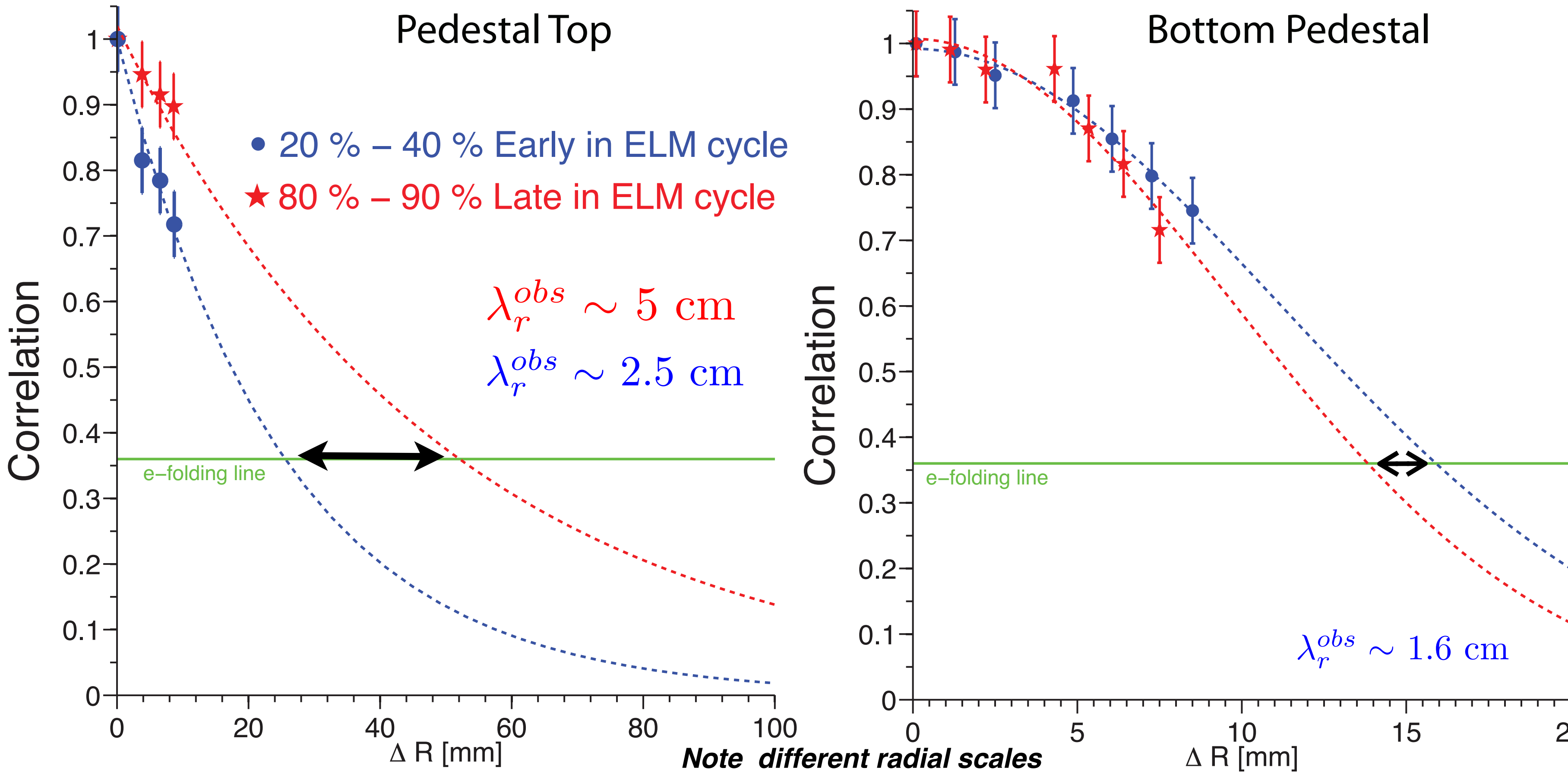


- The density fluctuations are measured using a 16-channel O-mode reflectometer

Crocker, PPCF (2011)

- Using two-point correlation the radial correlation function is determined.
  - tracks the equilibrium plasma motion

Correlation function at the pedestal top and steep gradient during the inter-ELM phase

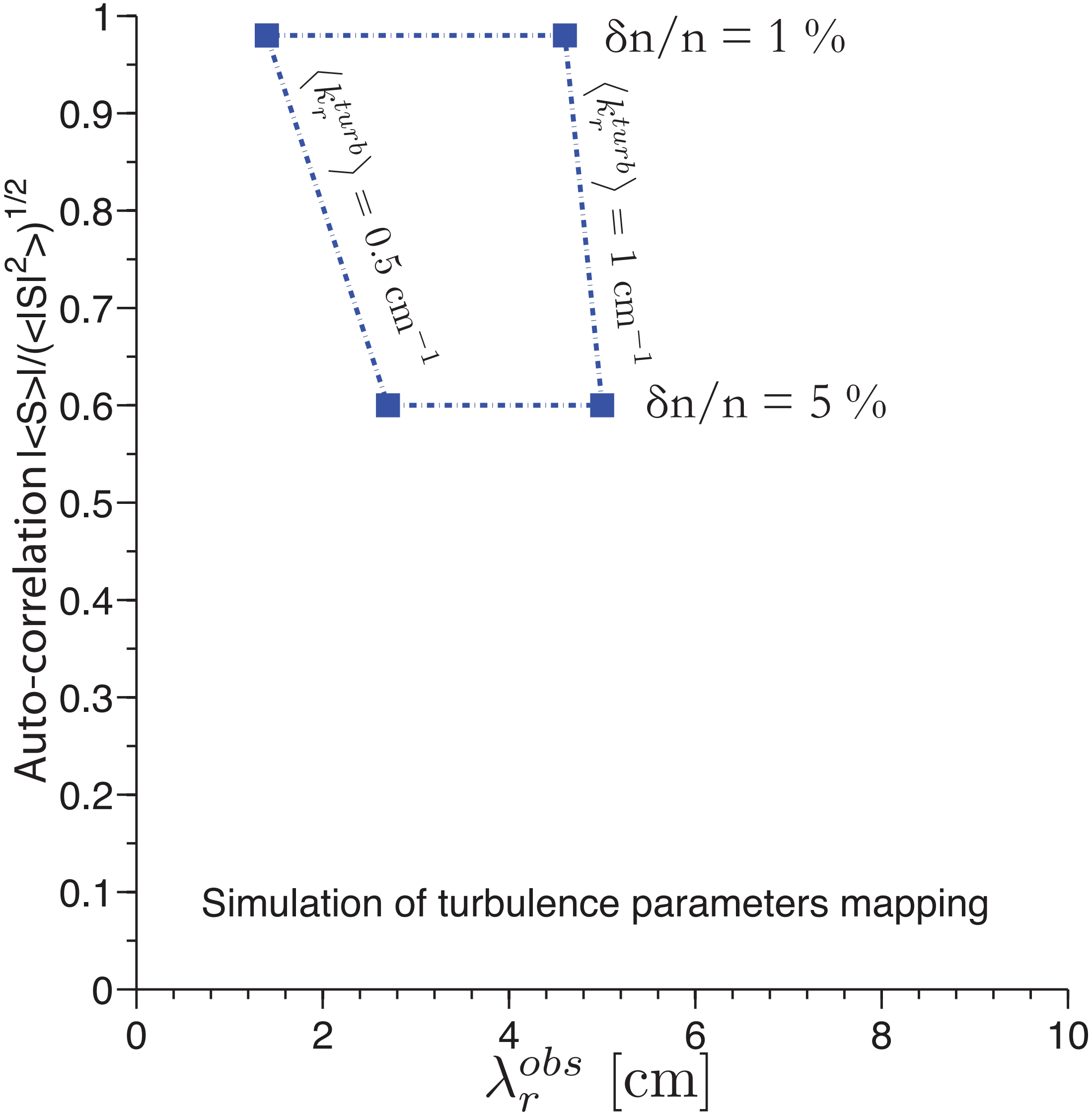


Note different radial scales

- Assuming an exponential decay of the edge fluctuations
- Pedestal top correlation length is larger than that of the region of steep density gradient

2D full wave modeling (FWR2D*) provides correspondence between observed quantities and turbulent parameters

*Valeo, PPCF (2002)

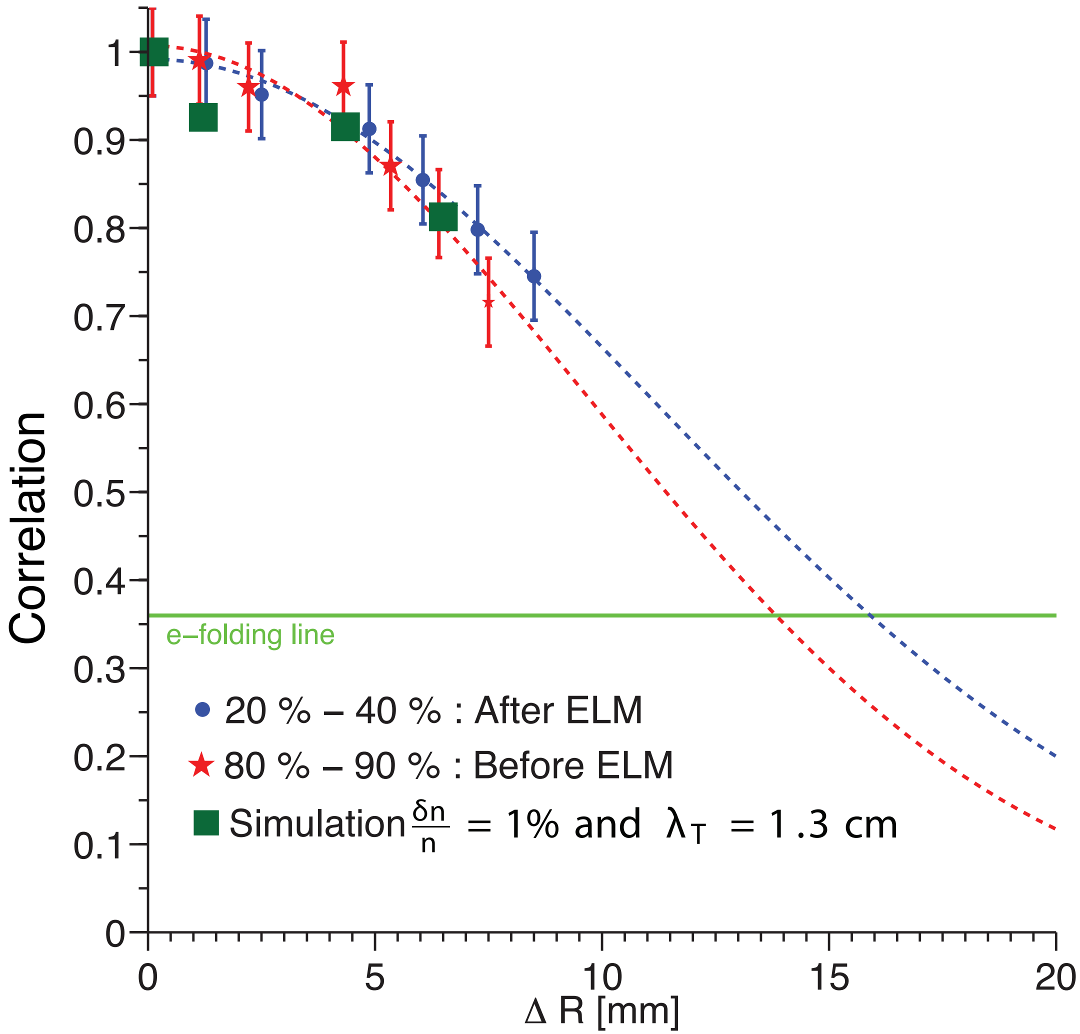


- Density fluctuations are generated using a model based gaussian distribution

Kramer RSI 74 (2003)

$$\left(\frac{\delta n}{n}\right)^2 e^{-\delta R^2/\lambda_{turb}^2}$$

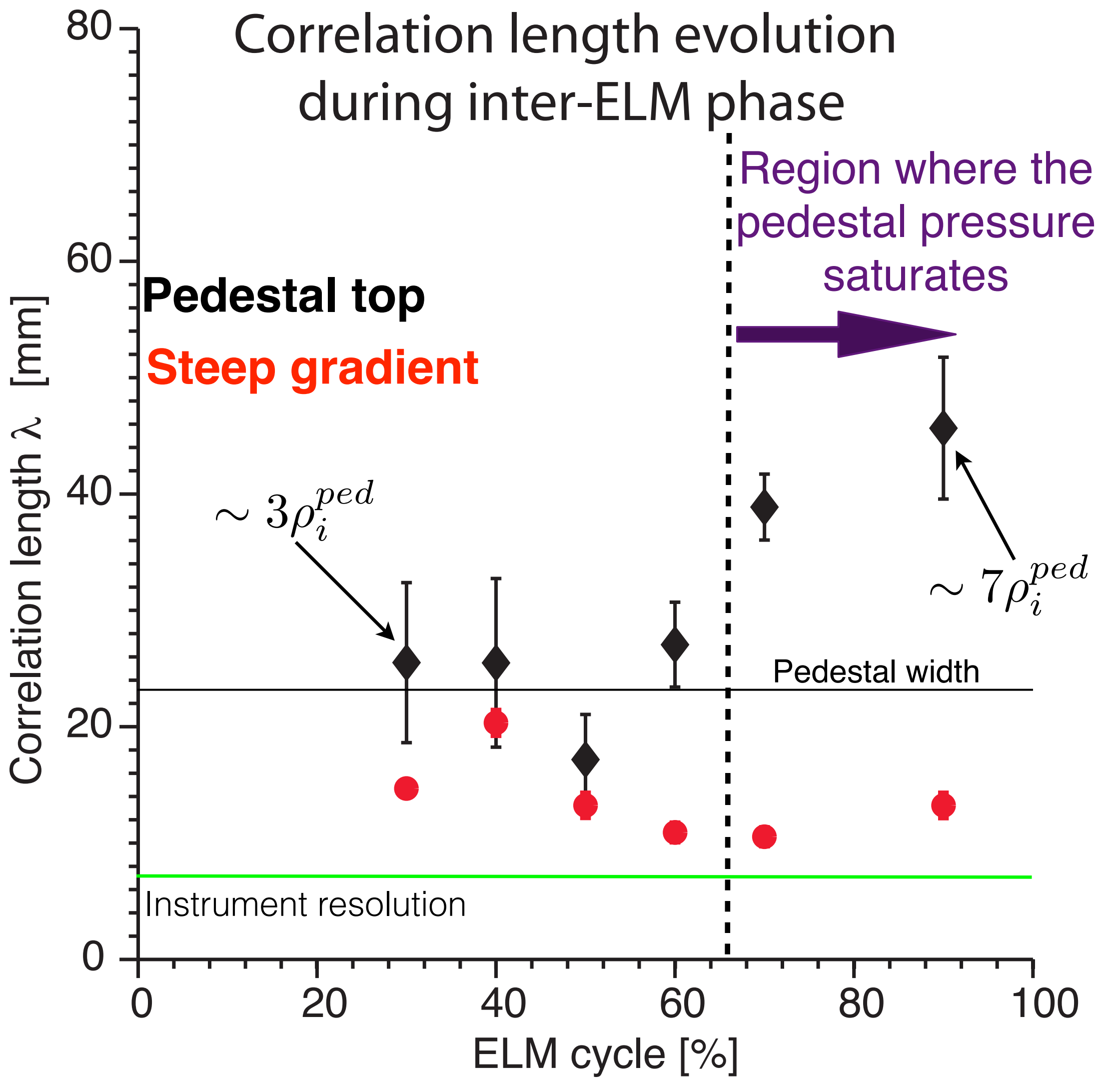
2D full wave simulation of correlation function inside pedestal region reproduces measurements



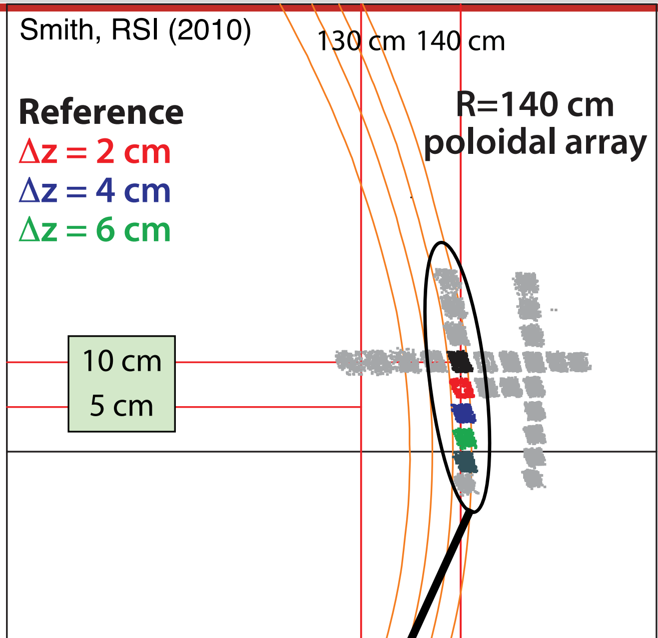
Observed correlation length corresponds to an average eddy size of ~ 1.3 cm with fluctuation level in the vicinity of 1% in the gradient region.

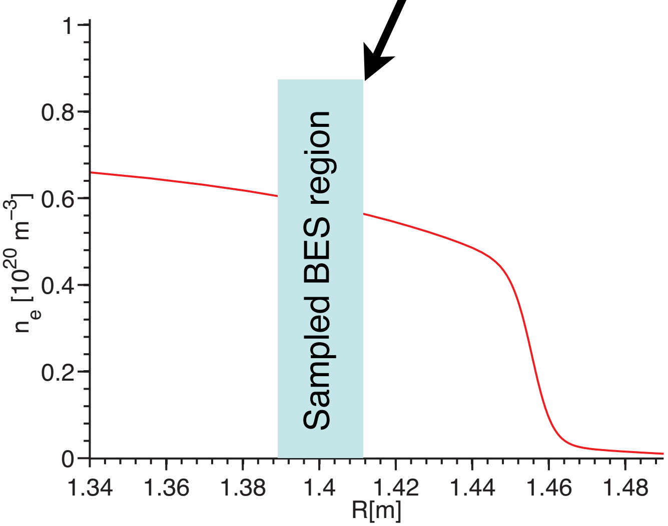
Radial correlation length evolution depends on location inside pedestal region

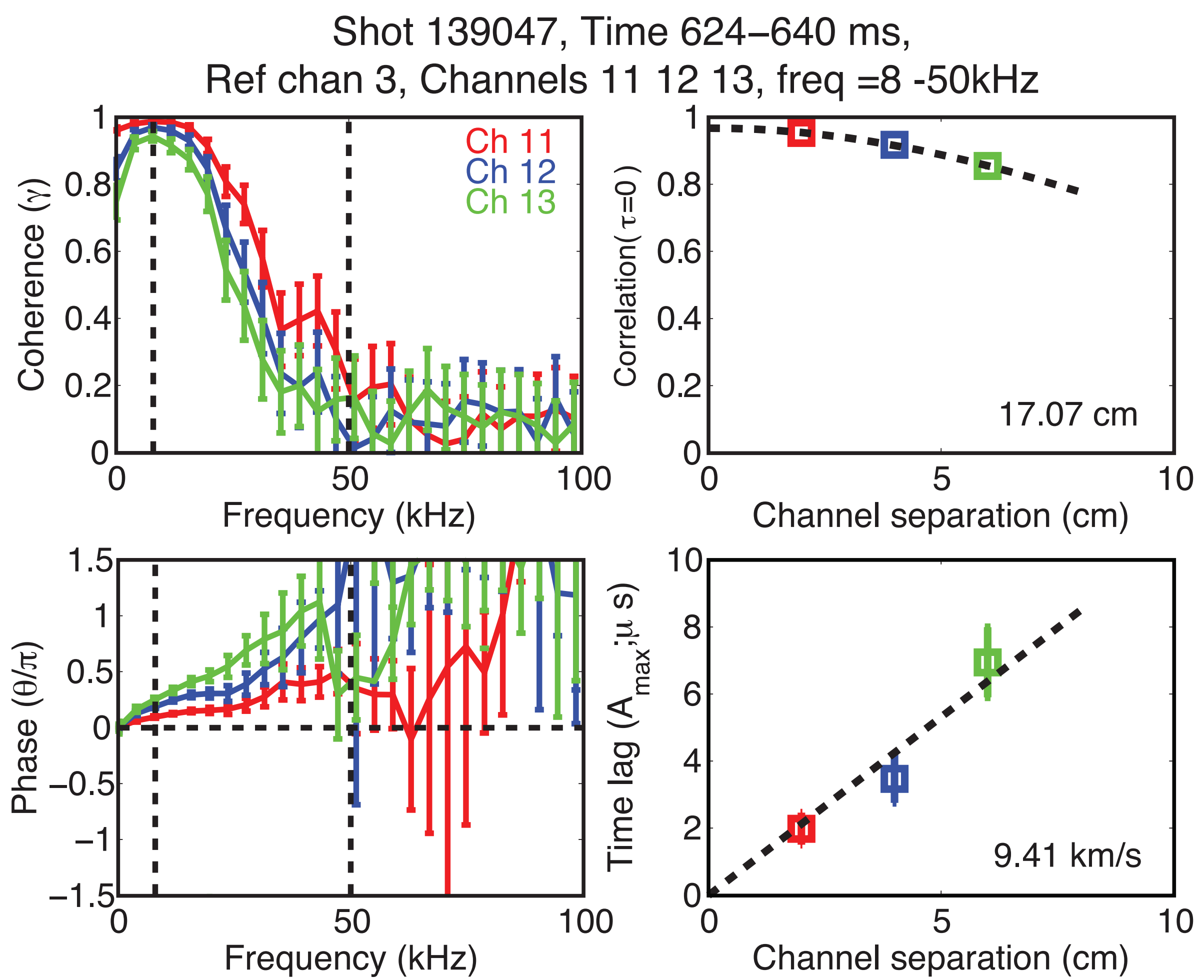
- Radial correlation length increases at the pedestal top
  - A factor of 2 increase during the last 50% of ELM cycle
- Steep gradient correlation length is unchanged
- Pedestal width is larger than eddy size in steep gradient region



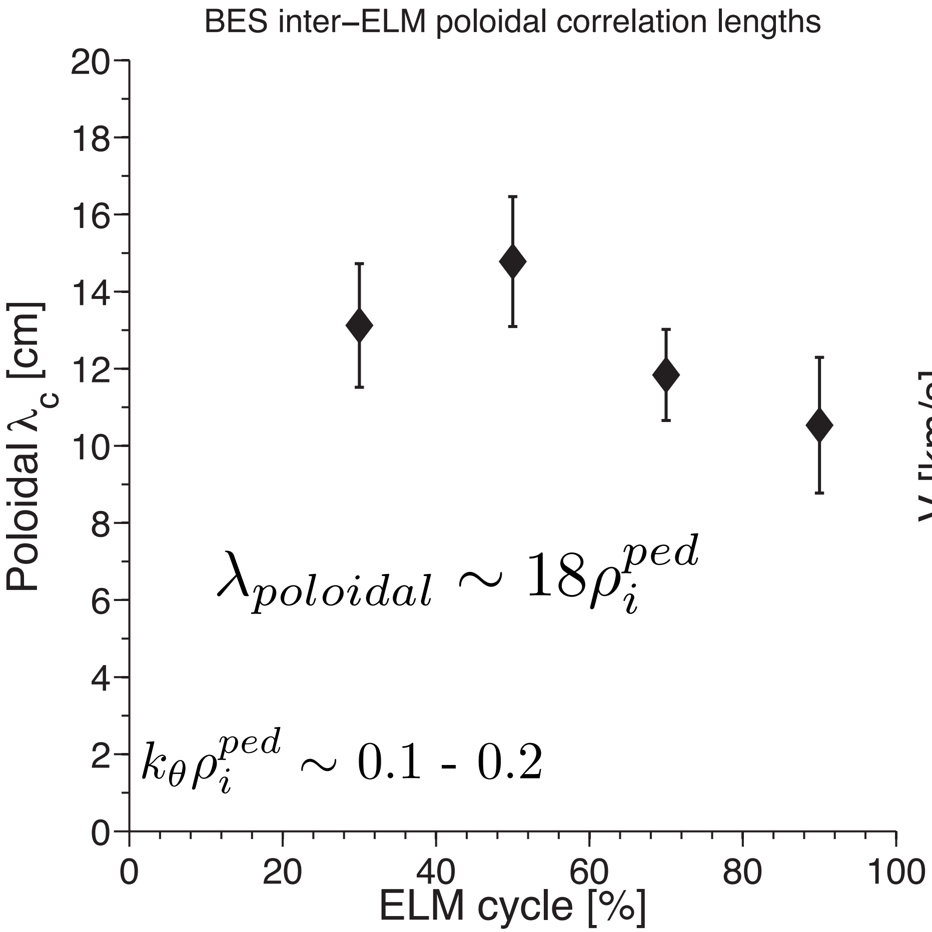
BES yields measurements of the poloidal correlation the top of the density pedestal

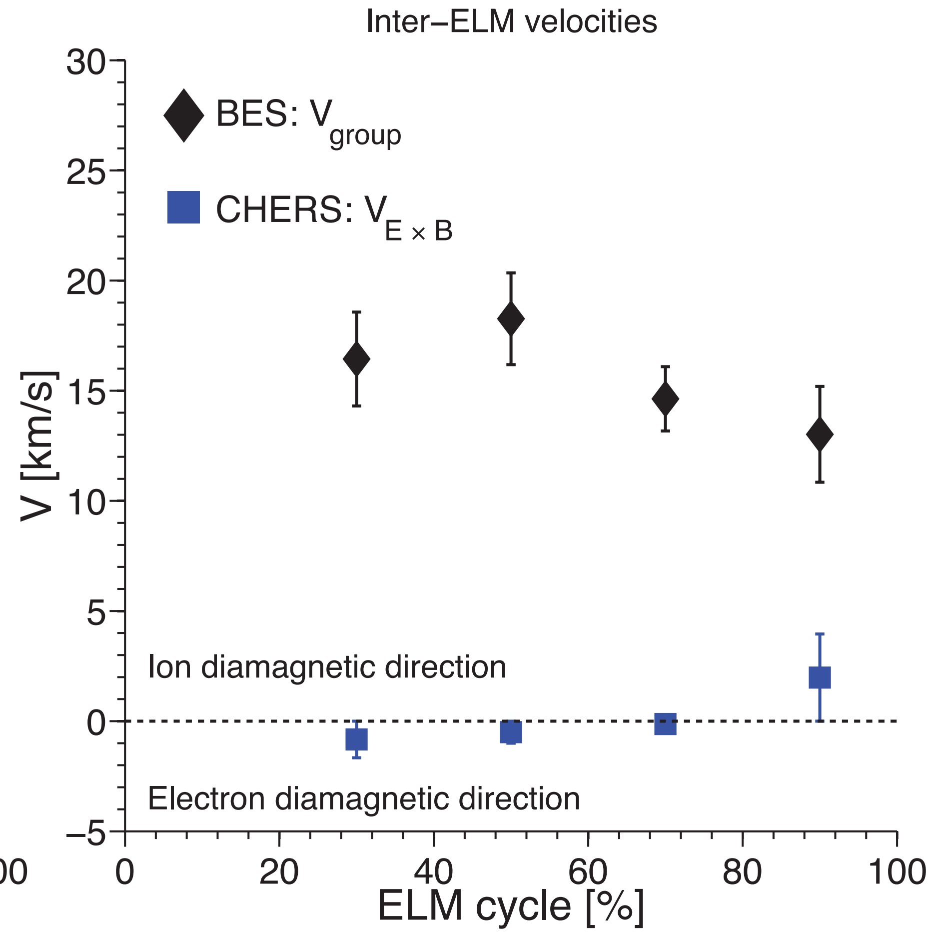






BES provides measurements of the poloidal correlation length and poloidal velocity

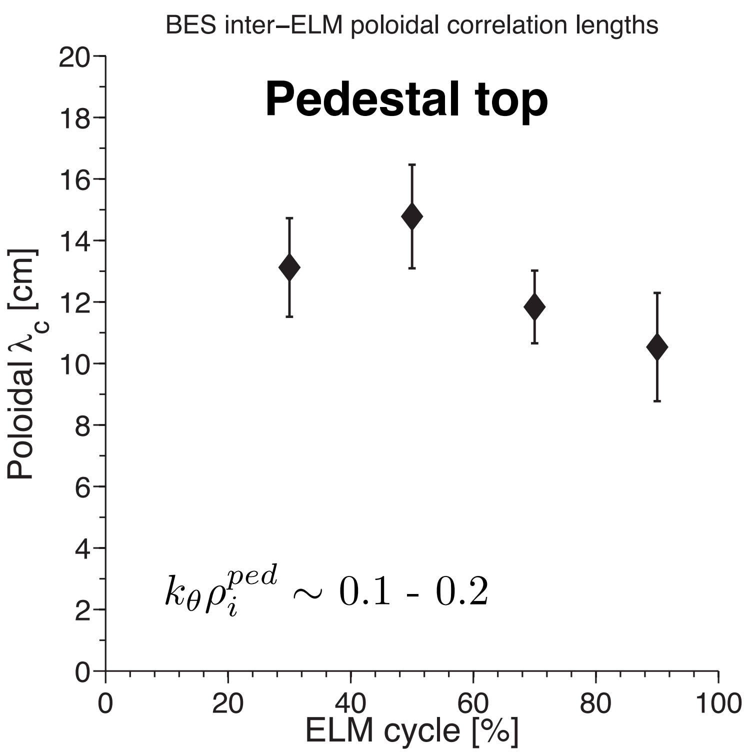


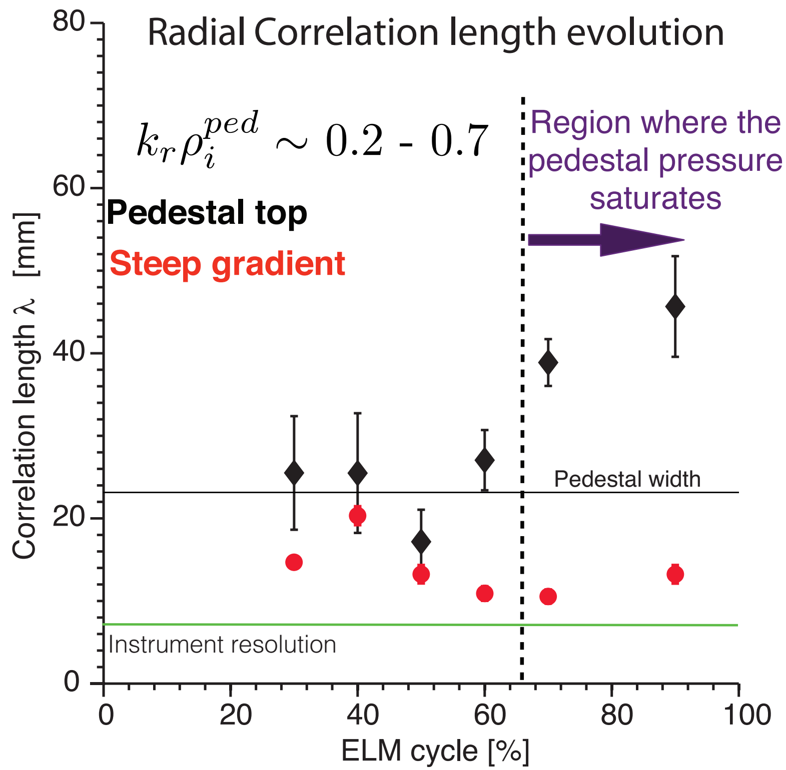


- Modest change in poloidal correlation length during the inter-ELM phase
  - Group velocity corrected for ExB indicates propagation in ion diamagnetic direction
  - Poloidal correlation length corresponds to toroidal mode number (rk_θ/q) n = 2 - 3

Using both BES and correlation reflectometry, the inter-ELM spatial structure of fluctuations exhibit ion-scale microturbulence

- Strong anisotropy of the turbulence is observed during the inter-ELM phase
- Turbulence data suggests microturbulence with $0.2 \leq k_\perp \rho_i \leq 0.7$ propagating in ion diamagnetic direction





Given turbulence measurements during the inter-ELM phase, what are the theoretical implications?

- Based on Jenko's ITG stability criteria*, $R/L_{TI} = 15 > 3 \times (R/L_{TI\_crit})$ over the pedestal top throughout the ELM cycle
  - ITG could be unstable

*Jenko PoP (2001)

- KBM could also be a key player due to the scales involved
  - MHD $\alpha = 4.4$ and remains constant during inter-ELM phase, but α_{crit} is not yet calculated.

$$\alpha = \frac{-2\partial_\psi V}{(2\pi)^2}\left(\frac{V}{2\pi^2 R_0}\right)^{1/2} \mu_0 \partial_\psi p$$

- At present we cannot distinguish between ITG and KBM
- Preliminary transport calculations (SOLPS and XGC0) show ion heat diffusivity is within neoclassical estimates in pedestal region
  - E x B must still be important
- So, presumably electron transport can be affected by ion scale turbulence which contributes to pedestal structure

Detailed gyrokinetic calculations at the pedestal top are needed and being pursued.

Summary

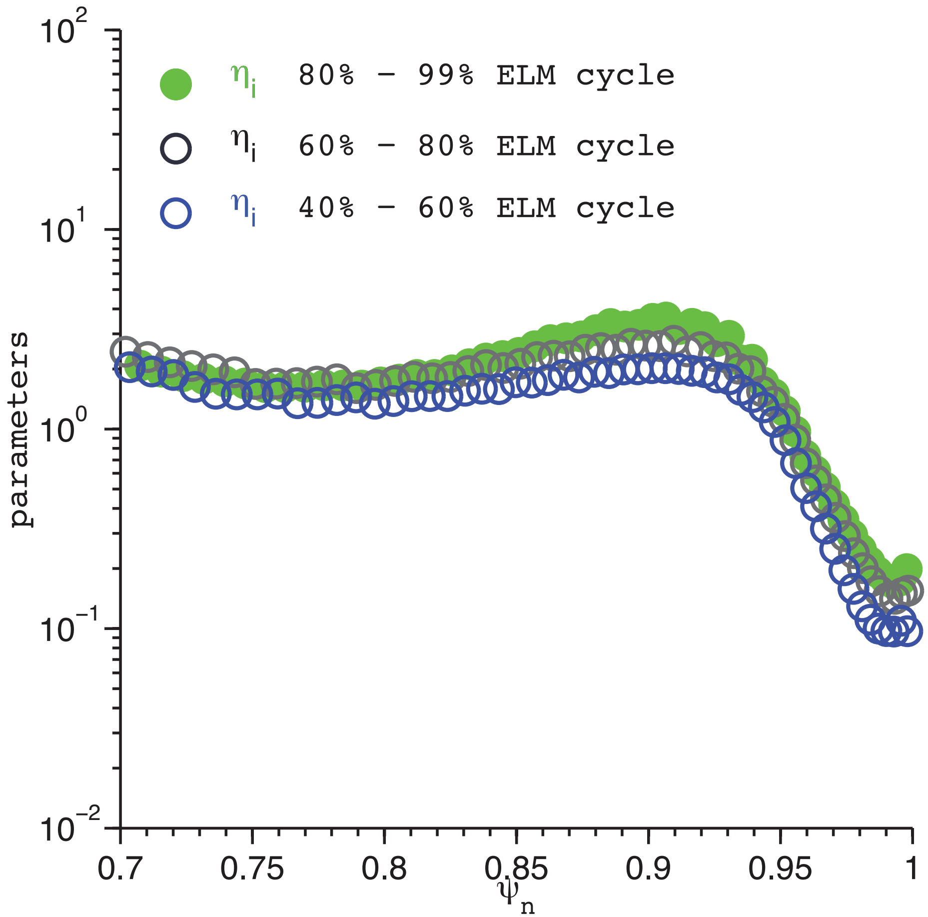
- Pedestal parameters are qualitatively consistent with kink/peeling model of the ELM cycle
  - Progressive expansion of the pedestal structure during the inter-ELM phase leading at times to saturation.
  - Lithium induced ELM-free regimes exhibit larger than ELMy discharges pedestals because edge boundary moves to a higher stability point
- During the inter-ELM phase, the turbulence diagnostics reveal:
  - $0.2 \leq k_\perp \rho_i \leq 0.7$ and propagation in ion diamagnetic direction suggesting

    microturbulence of the type ITG/TEM/KBM are present at the pedestal top during the inter-ELM phase
  - Strong anisotropy in microturbulence ($\lambda_\theta > \lambda_r$)
  - Due to lack of high-k measurements, we cannot rule out electron-scale turbulence
- Discussion and ongoing work:
  - Perform simulations of turbulence using XGC1 to compare with experimental results and determine effects on the pedestal structure.
  - Using gyrokinetic codes identify modes present at the pedestal top.

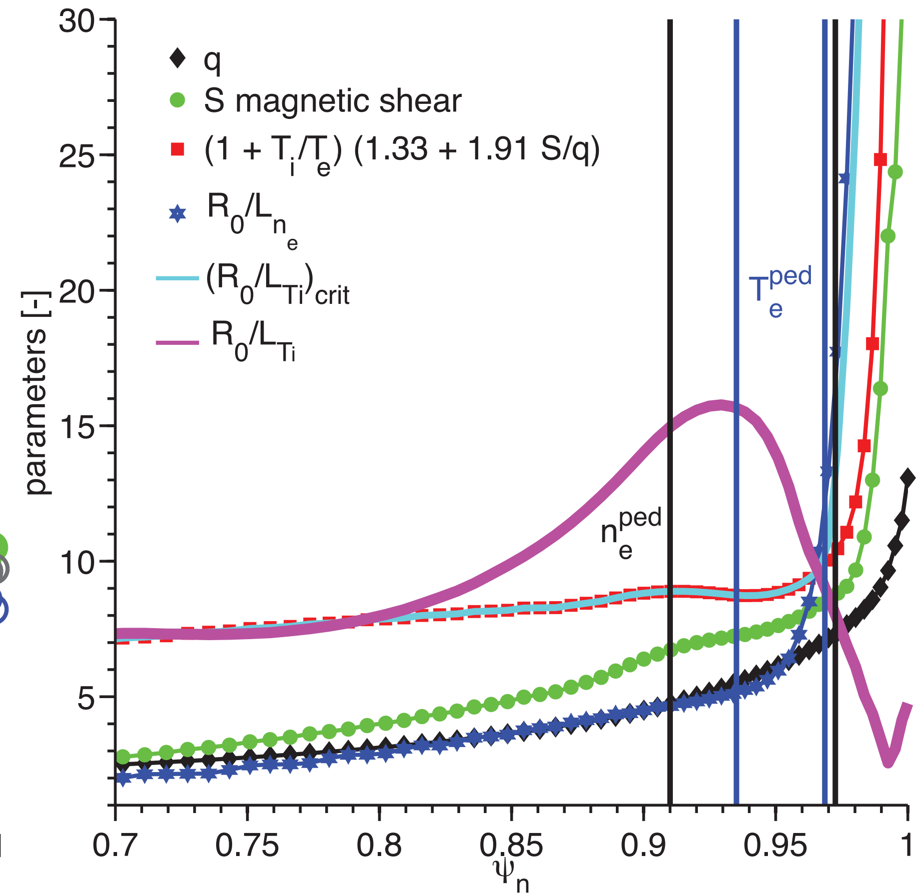
Backup

ITG drives peaks at the pedestal top and R/L_{TI} is larger than R/L_{TI_crit}

ITG drive during inter-ELM phase

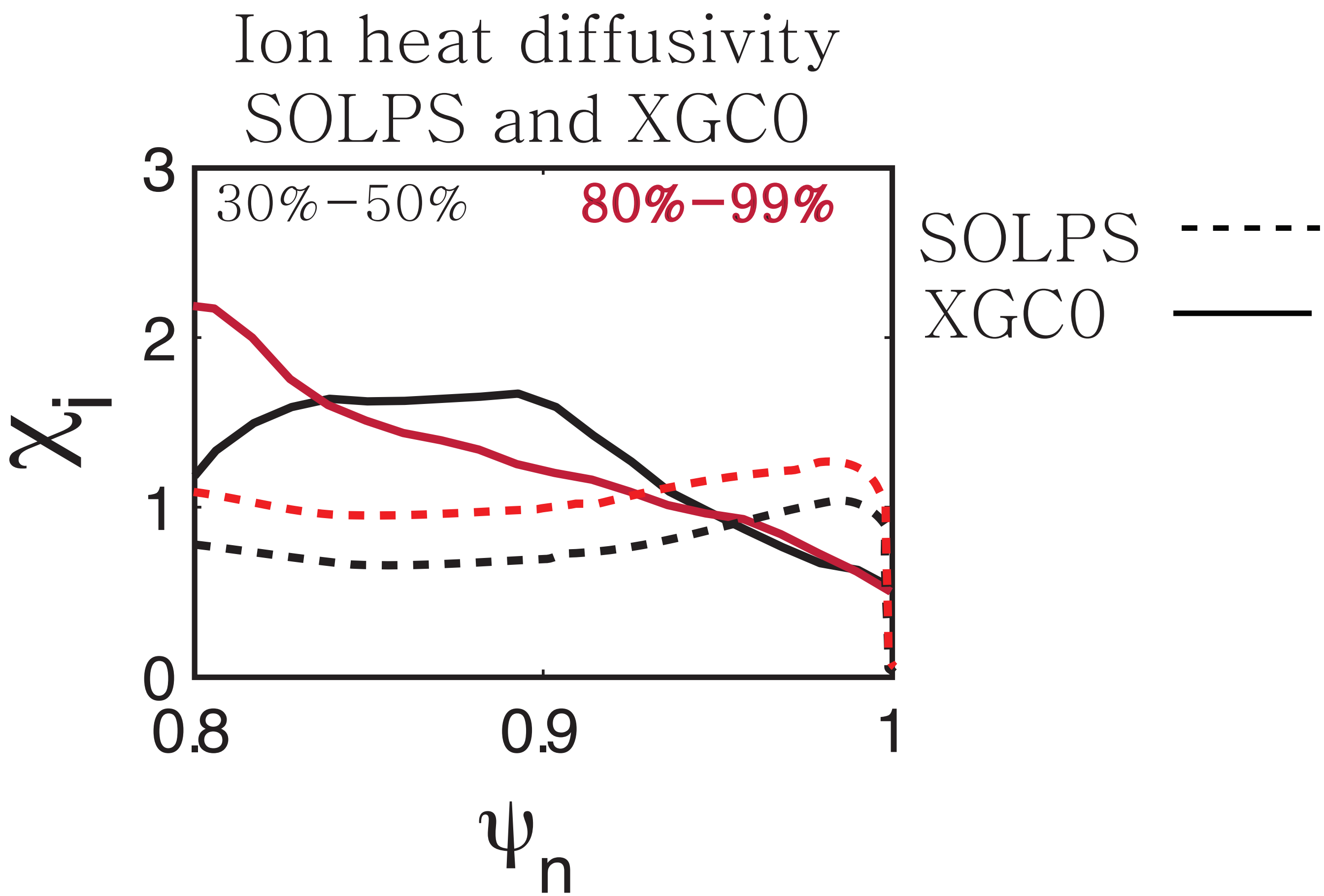


Critical ITG Gradient



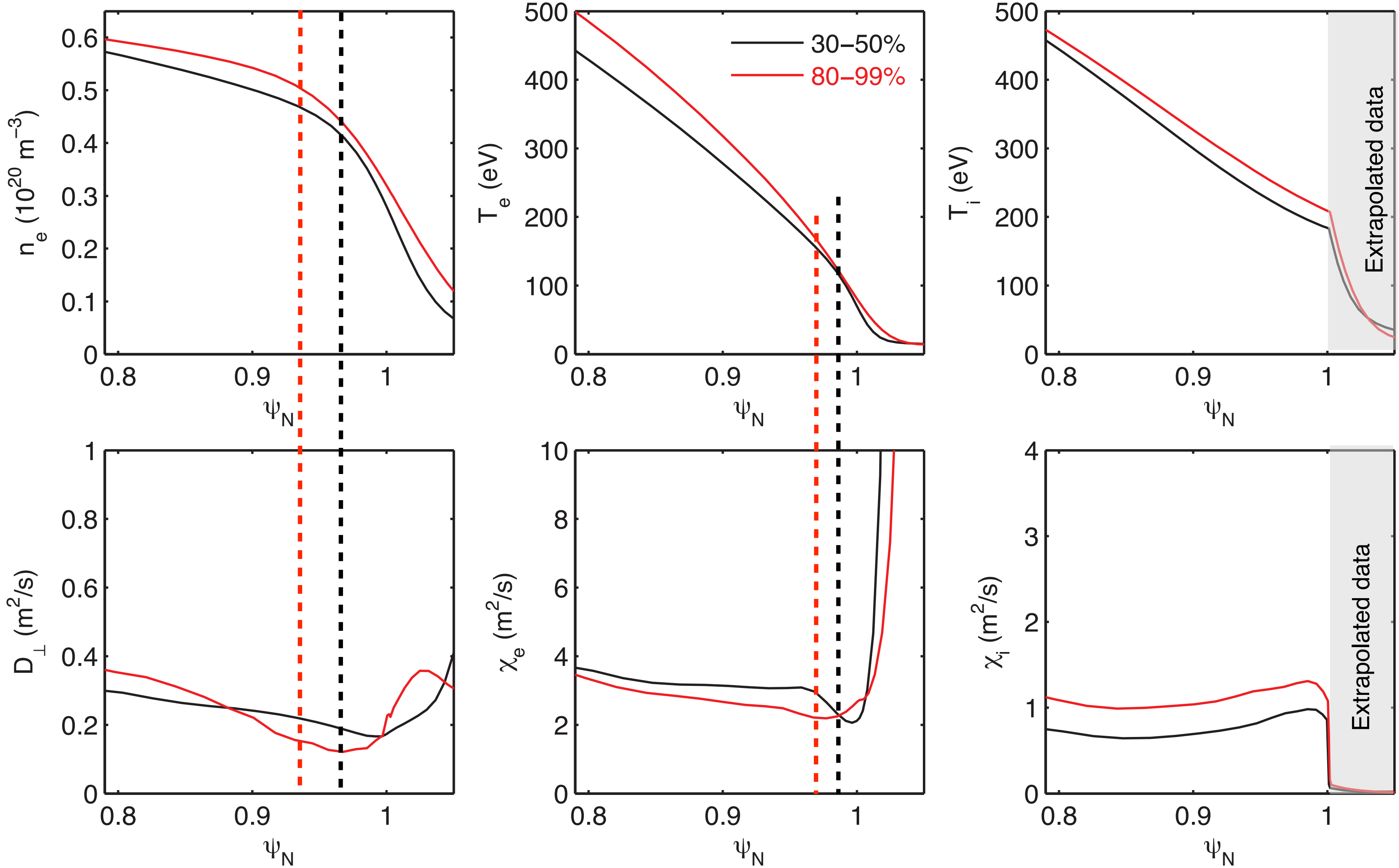
- Jenko's approximation suggests ITG could be unstable in the pedestal top.

Preliminary:ion heat diffusivity comparison: SOLPS and XGC0



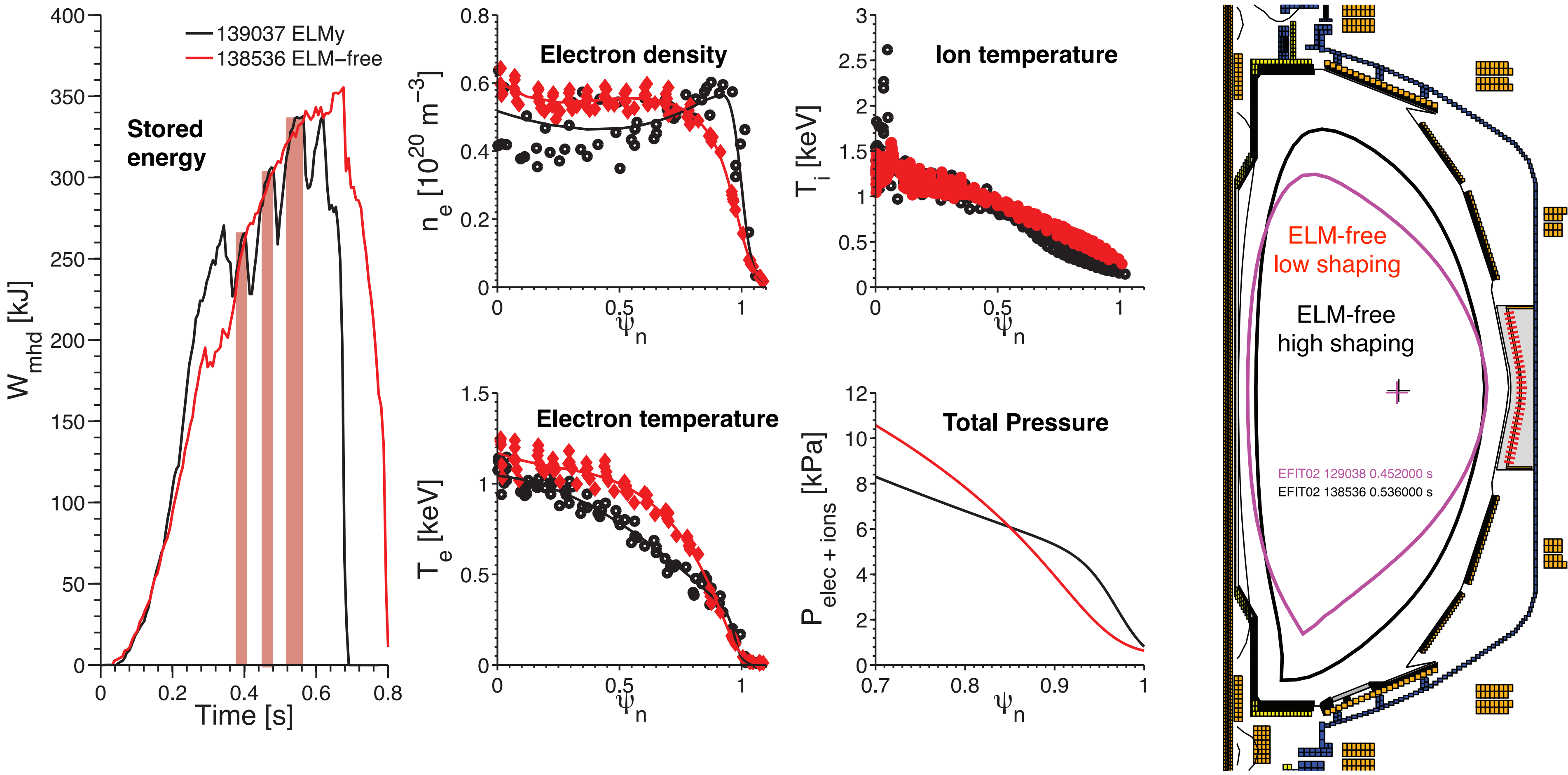
- Neoclassical ion diffusivity remains unchanged during the inter-ELM phase in the pedestal region
- In the pedestal region SOLPS show larger than neoclassical ion diffusivity

2D SOLPS modeling shows modest variations at the pedestal top of the transport parameters



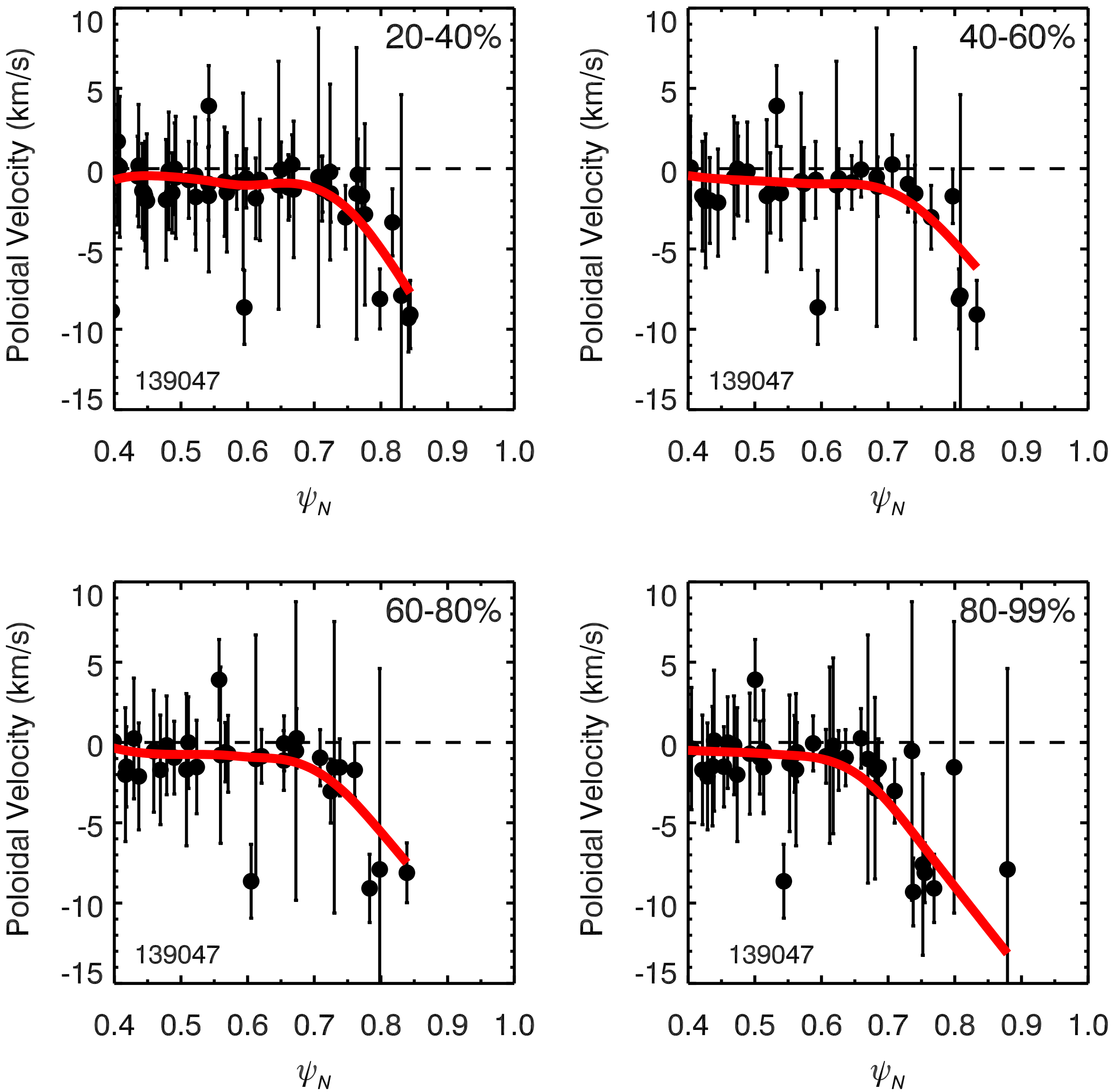
J. Canik

ELM-free pedestal structure feature persists through high performance discharges (i.e.,strong shaping - high triangularity)



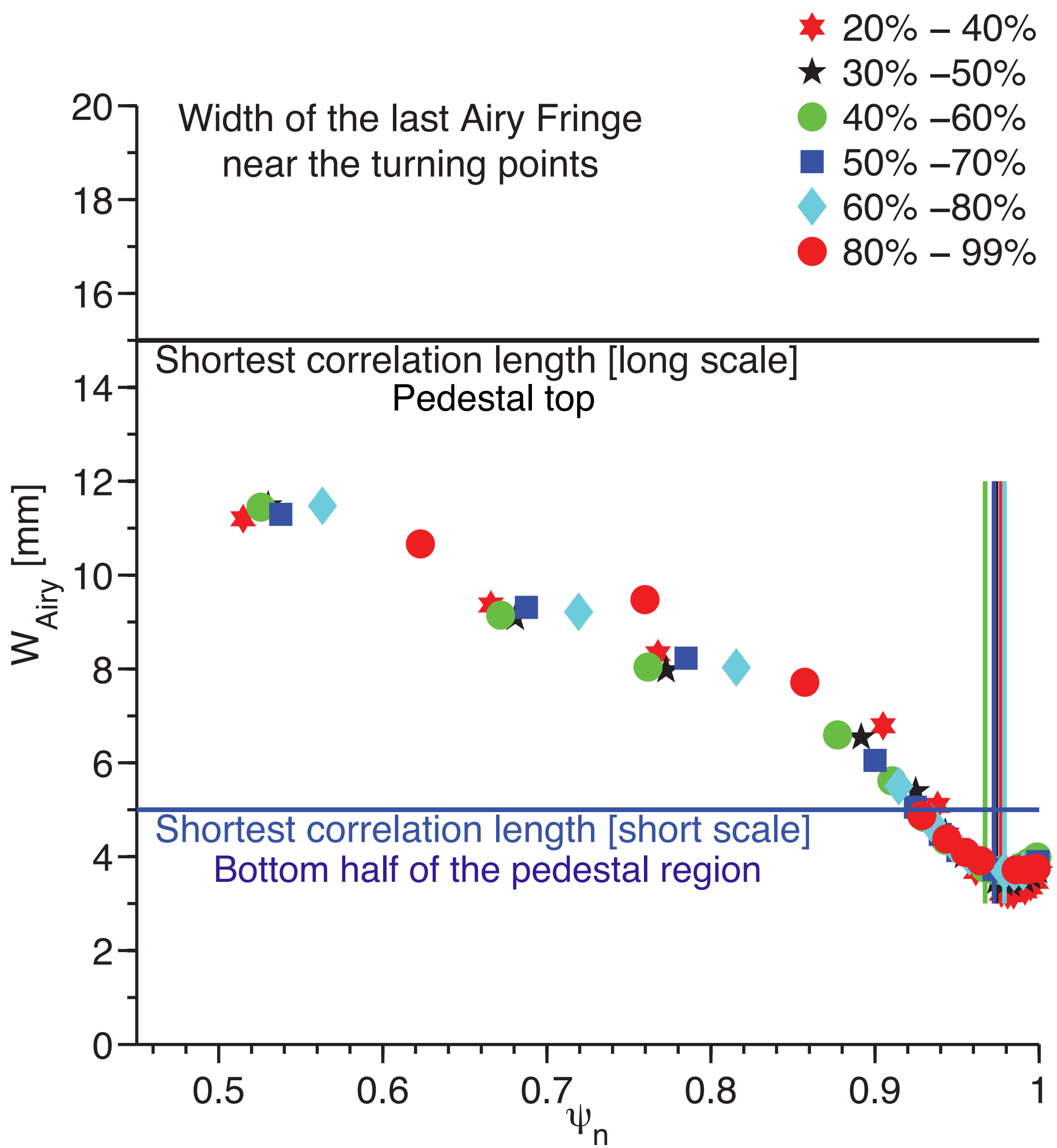
Pedestal structure continues to widen during high lithium deposition in high triangularity discharges at comparable stored energy.

CHERS poloidal flow are similar in magnitude with BES flow estimates

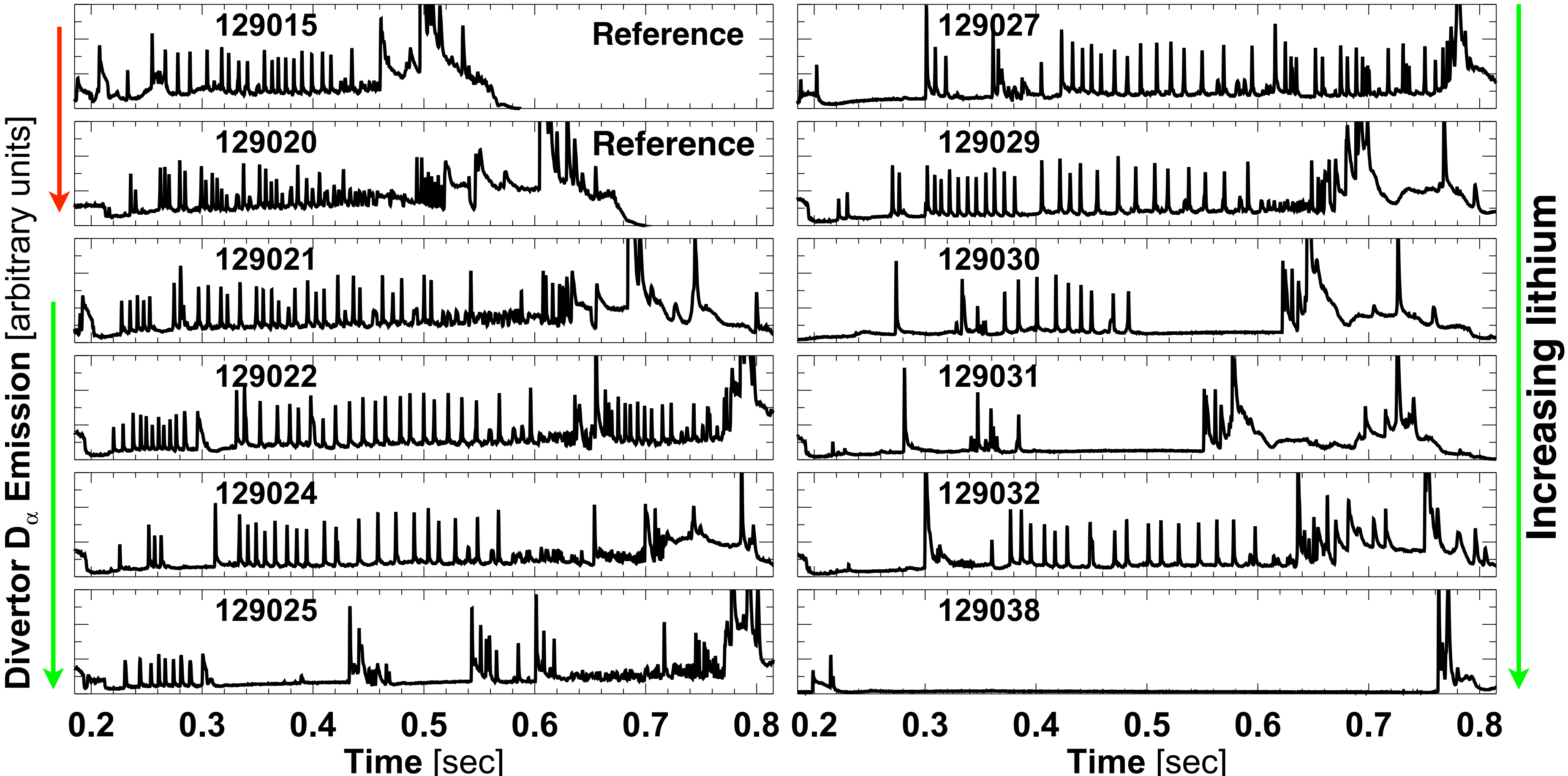


- Modest change of the poloidal flow near the pedestal top
- Impurity poloidal flows ~ 10 km/s at the pedestal top in the electrons diamagnetic direction.
  - in opposite direction to the main ion poloidal flow determined by BES.
- Mean poloidal flow prior to the onset ELM is not affected.

Reflectometry measurements are beyond the instrument resolution



NSTX has the unique capability to suppress ELMs using lithium coating on the divertor



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- Lithium coating on the bottom divertor modifies the edge stability boundary