New understandings of inter-ELM pedestal turbulence, transport, and gradient behavior in the DIII-D tokamak

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with
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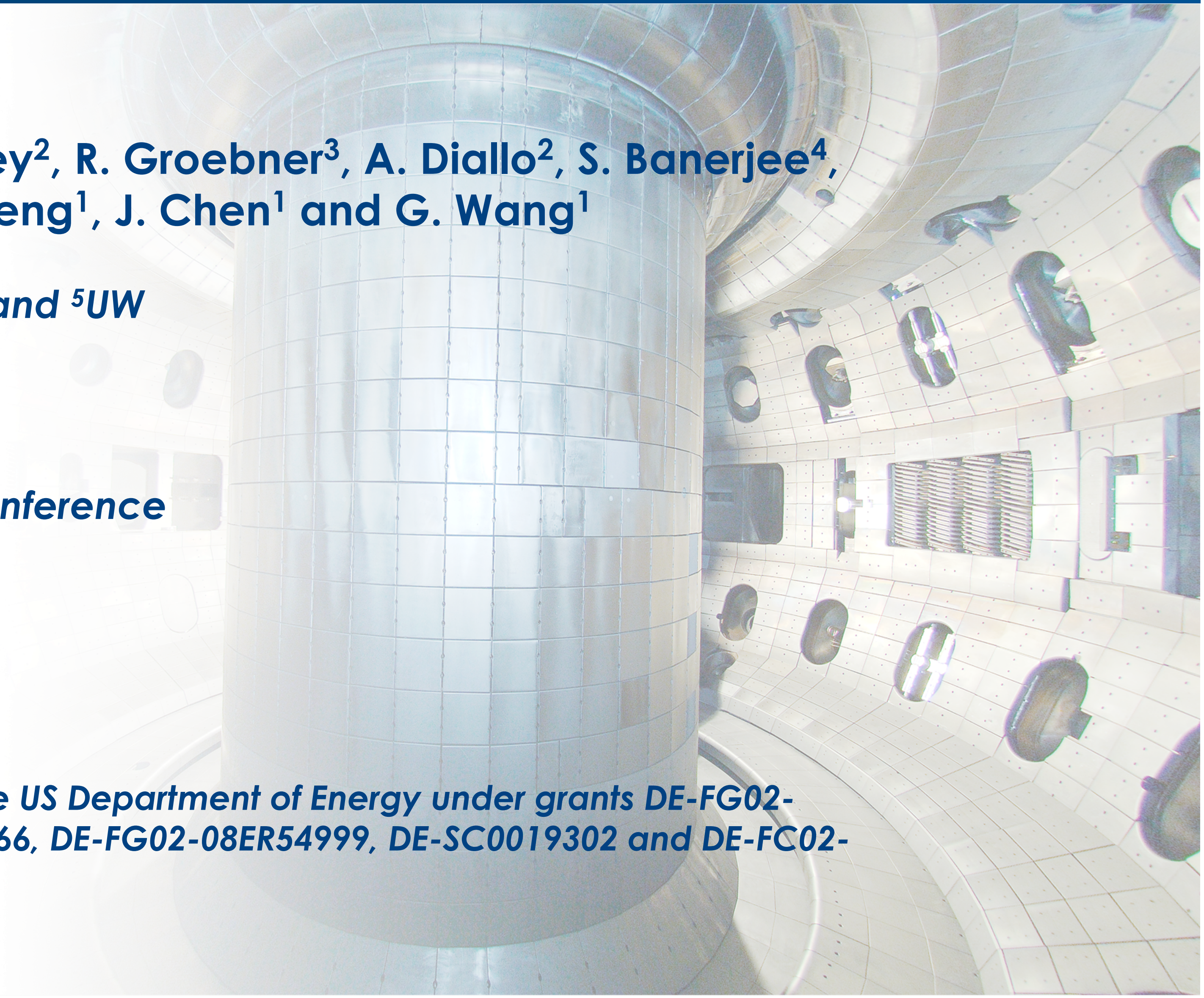
Presented at the
28th IAEA Fusion Energy Conference
10th-15th May 2021

This work was supported by the US Department of Energy under grants DE-FG02-08ER54984, DE-AC02-09CH11466, DE-FG02-08ER54999, DE-SC0019302 and DE-FC02-04ER54698.



Main points/Highlights: New and unique measurements shed light on inter-ELM transport

- **Clear evidence of inter-ELM ITG-scale and TEM-scale turbulence with drive and damping mechanisms**
- **This measured multiscale turbulence is consistent with the inter-ELM evolution of the estimated heat fluxes**

Note: Although ETG and MTM modes are thought/predicted to explain some of the Q_e in this work ETG-scale ñ are not measured and the identification of MTM like modes are not conclusive.

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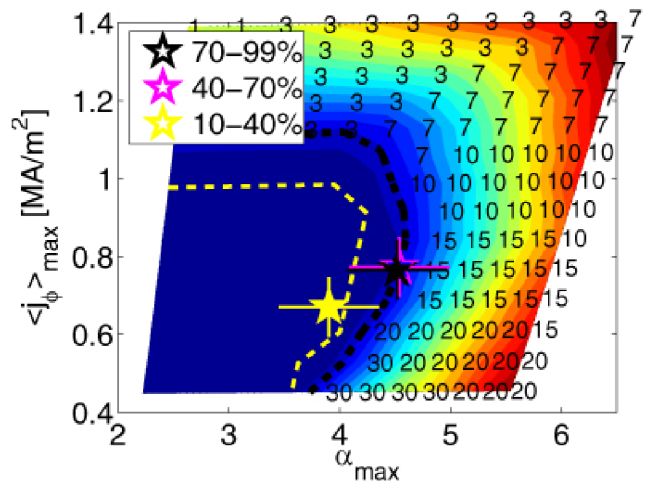
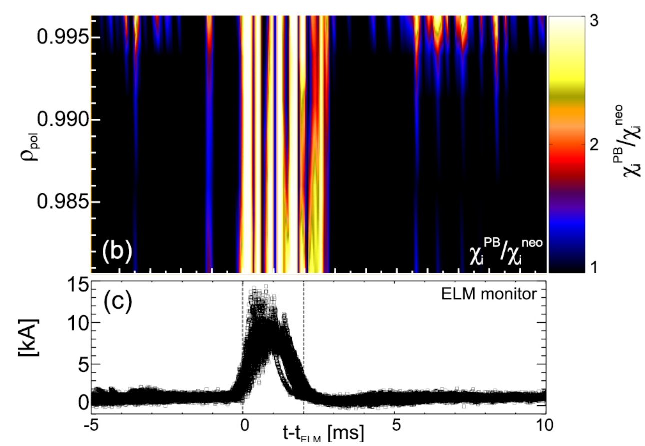
Complete understanding of all transport mechanisms is necessary to improve prediction of pedestal evolution

- **Pedestal can remain close to the Peeling-Ballooning (P-B) stability boundary for a significant amount of inter-ELM period**
- **EPED[1] model had many successes in predicting pedestal height and width**
  - **KBM driven transport constrains $\nabla P_{e,ped}$ until P-B**
  - **Drift wave turbulence is shear suppressed**
  - **In this work will show you clear evidence of inter-ELM drift wave like turbulence that is not completely shear suppressed.**
- **Improved and validated models impact pedestal thermal flux predictions for ITER and future fusion devices.**



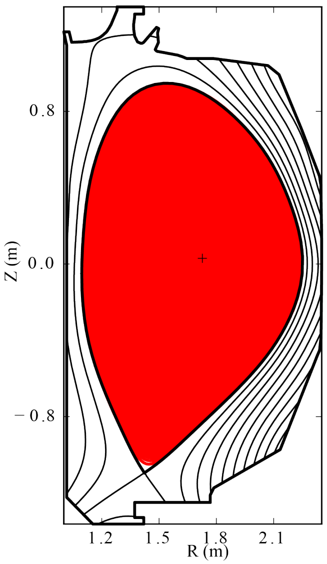
Saarelma et al, PPCF (2013)

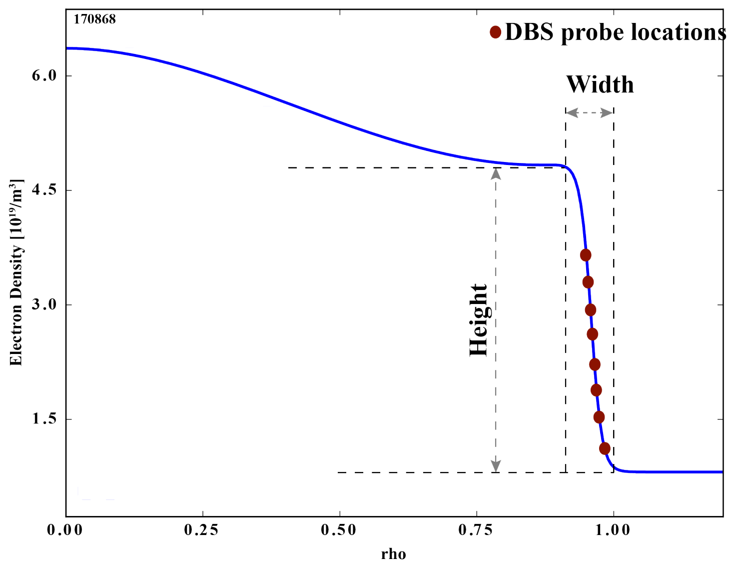


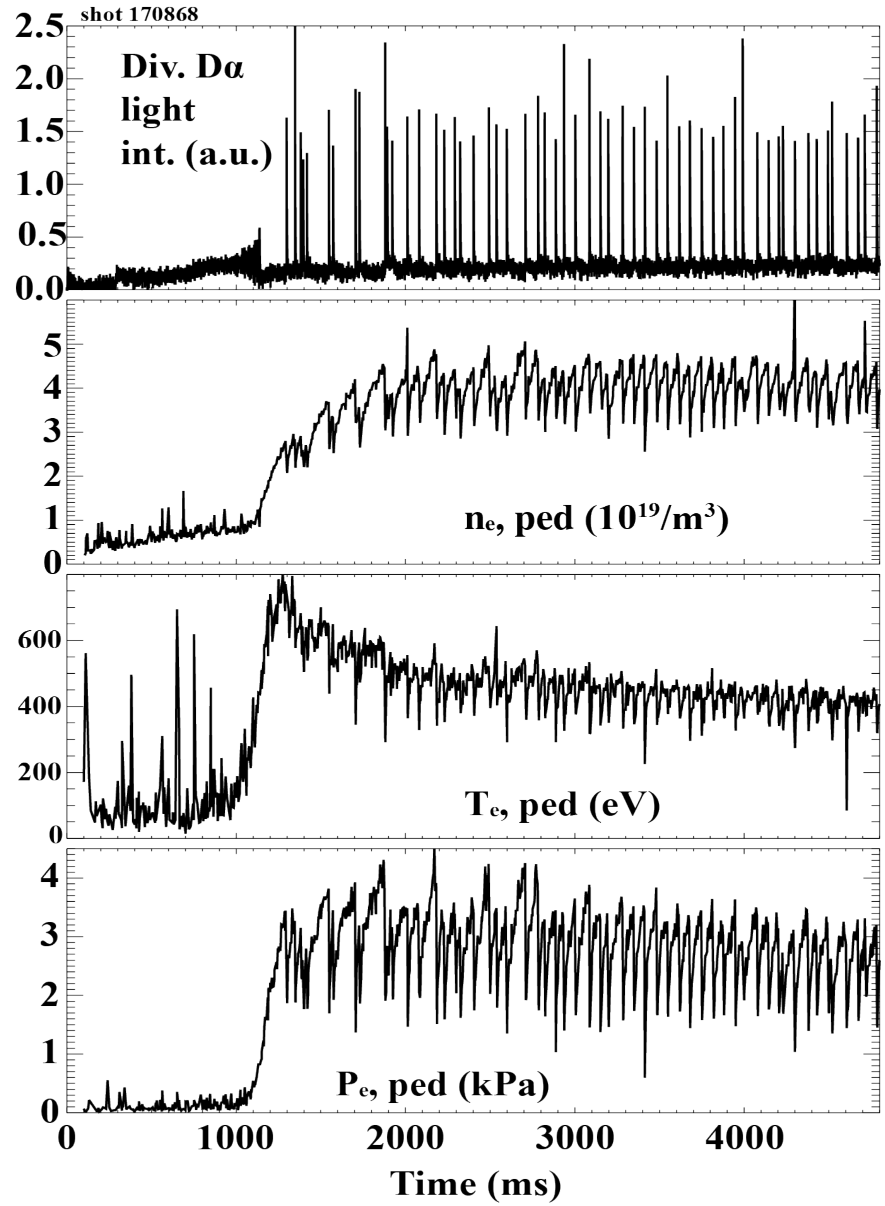
Viezzer et al, NF (2018)

[1]Snyder et al, NF (2011)

Experiments are performed in Lower Single Null shape H-mode plasmas with low frequency type-I ELMs





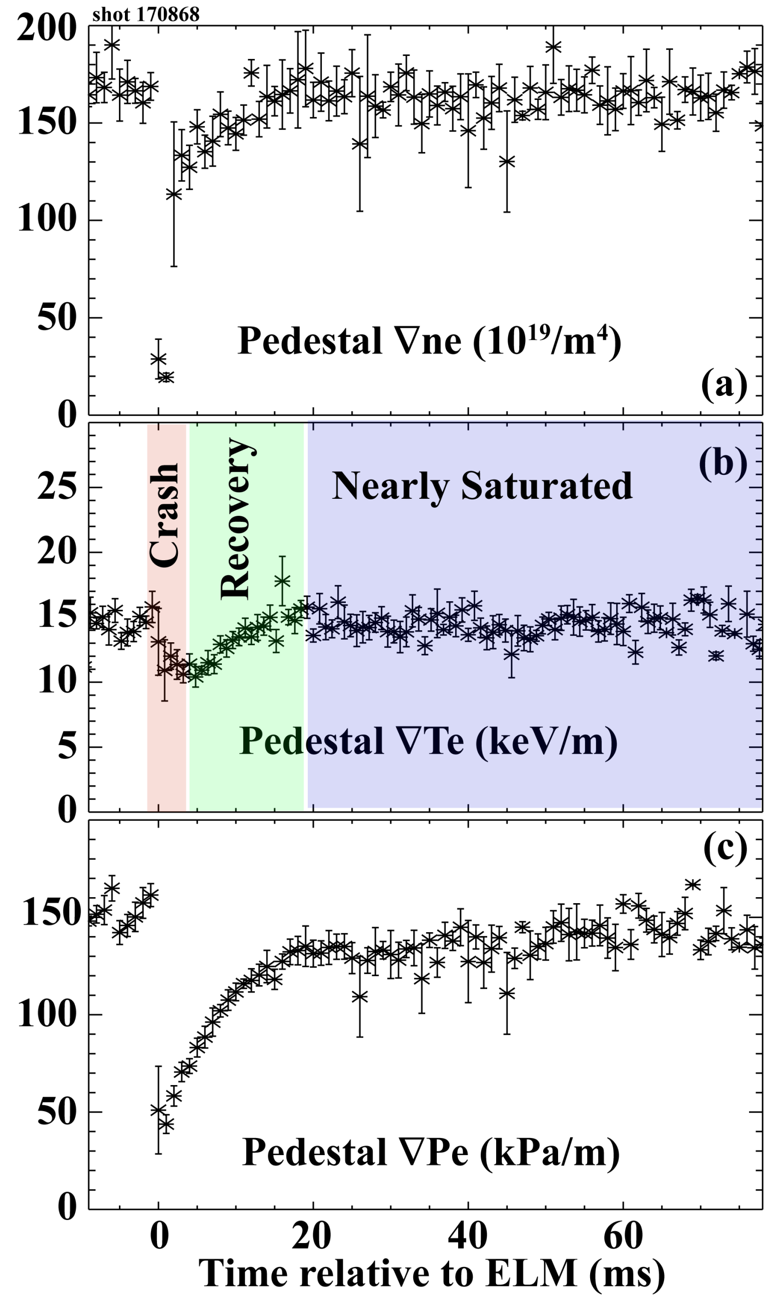


Ip~1 MA, Bt~2.1 T, Power close to $P_{L\text{-}H,}$
P_{NBI}~2.3 MW, $\overline{n}_e$ ~5.1x10^{19}/m^3

- Longer inter-ELM periods offer better statistics for ELM synchronized analysis
- Height and widths of n_e, T_e, and P_e pedestal are estimated from tanh fits to Thomson measured profiles.

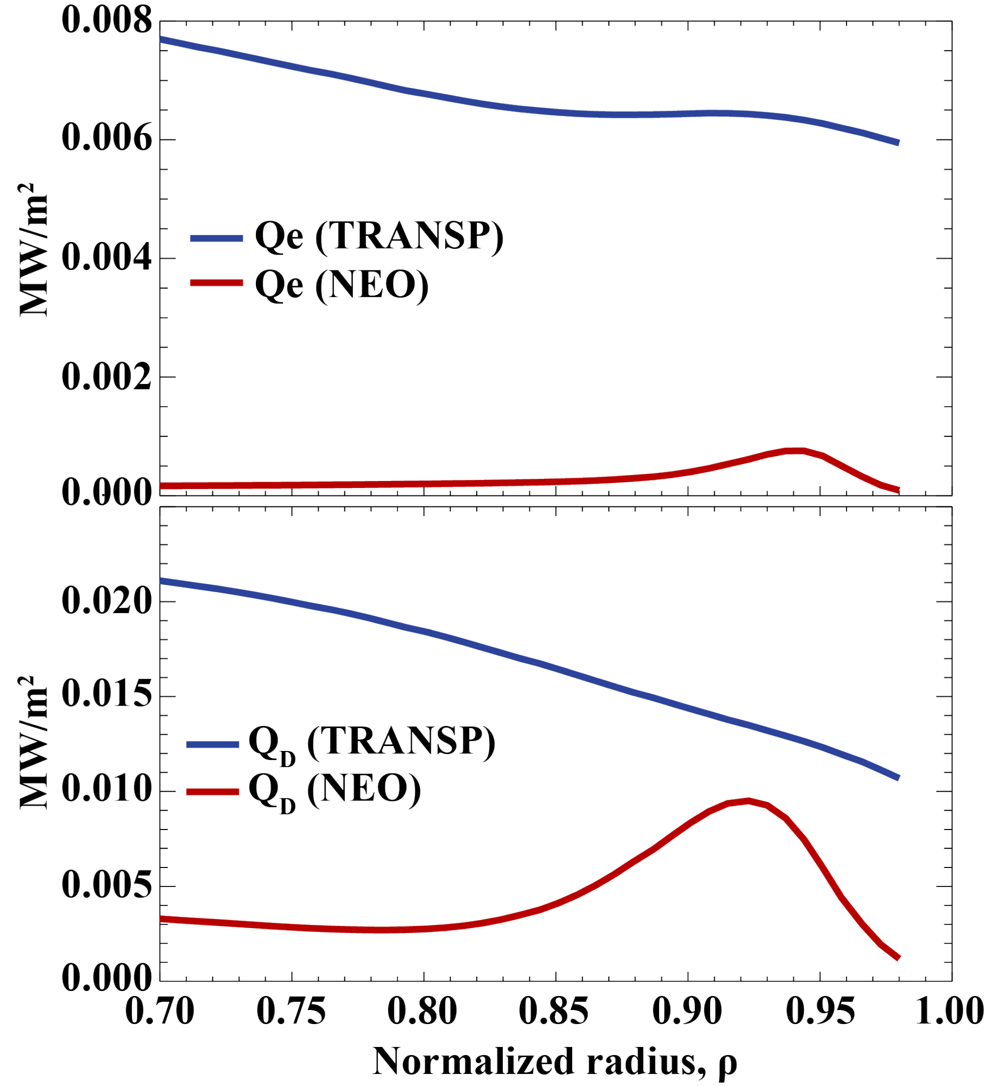
Electron Pedestal Gradients remain nearly saturated for most of the inter-ELM period

- **Gradients of pedestal density, temperature, and pressure stay saturated for nearly 75% of the inter-ELM period.**
- **During gradient recovery: Height increases and width decreases.**
- **In gradient saturation phase: Both height and width increase.**



Main ion heat flux is close to neoclassical (NC) and electron heat flux is anomalous in the nearly saturated phase

- **Power balance estimated Q_i is close to NC values calculated from experimental gradients whereas Q_e is anomalous (ν_i^*~0.74)**
- **NC heat flux contribution to total heat flux changes at different radii**
- **Decreasing ν_i^*, difference between estimated and neoclassical Q_i increases (Haskey et al, IAEA 2020)**



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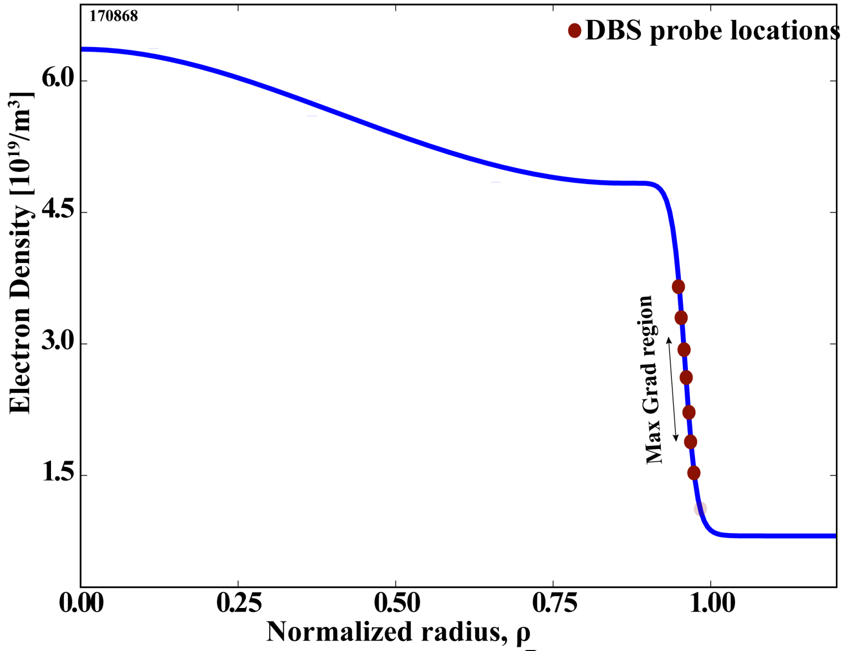
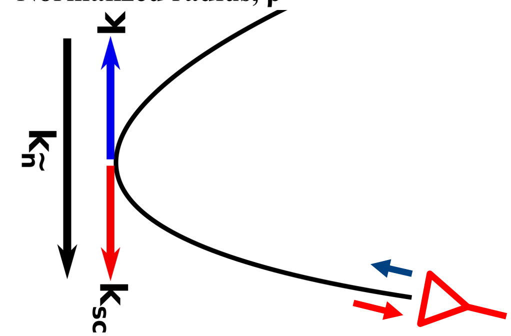
ITG and TEM-scale ñ in the pedestal are measured by Doppler Backscattering Diagnostics

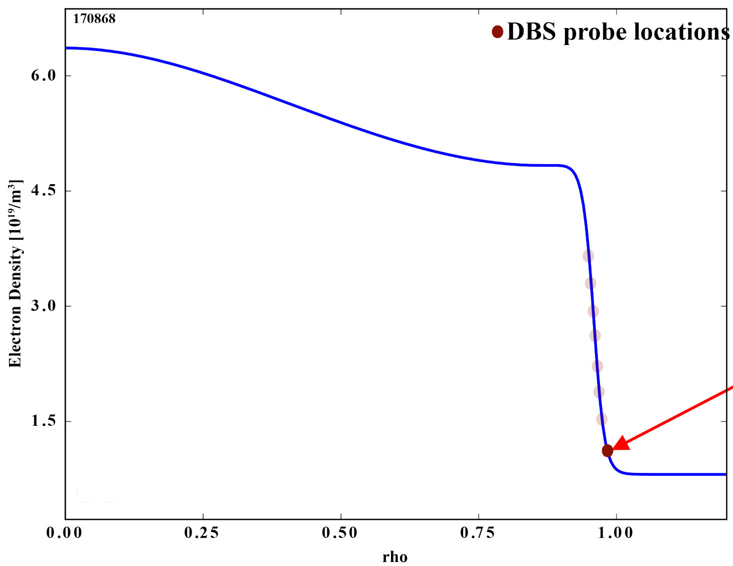
- **Spatially, temporally, and wave number resolved ñ amplitude and its lab frame perpendicular velocity, $v_\perp$ are measured.**
- **The 180° backscattered signal is Doppler shifted w.r.t incident wave ($f_D = k_{\tilde{n}} v_\perp / 2\pi$, $v_\perp = v_{E\times B} + v_{ph}$) and the intensity of the received signal is proportional to ñ.**
- **ITG-scale ($k_\theta \rho_s \sim 0.3$) ñ is measured near the foot of the pedestal whereas TEM-scale ($k_\theta \rho_s \sim 0.7$-1.2) ñ is measured in the steep gradient region of the pedestal.**

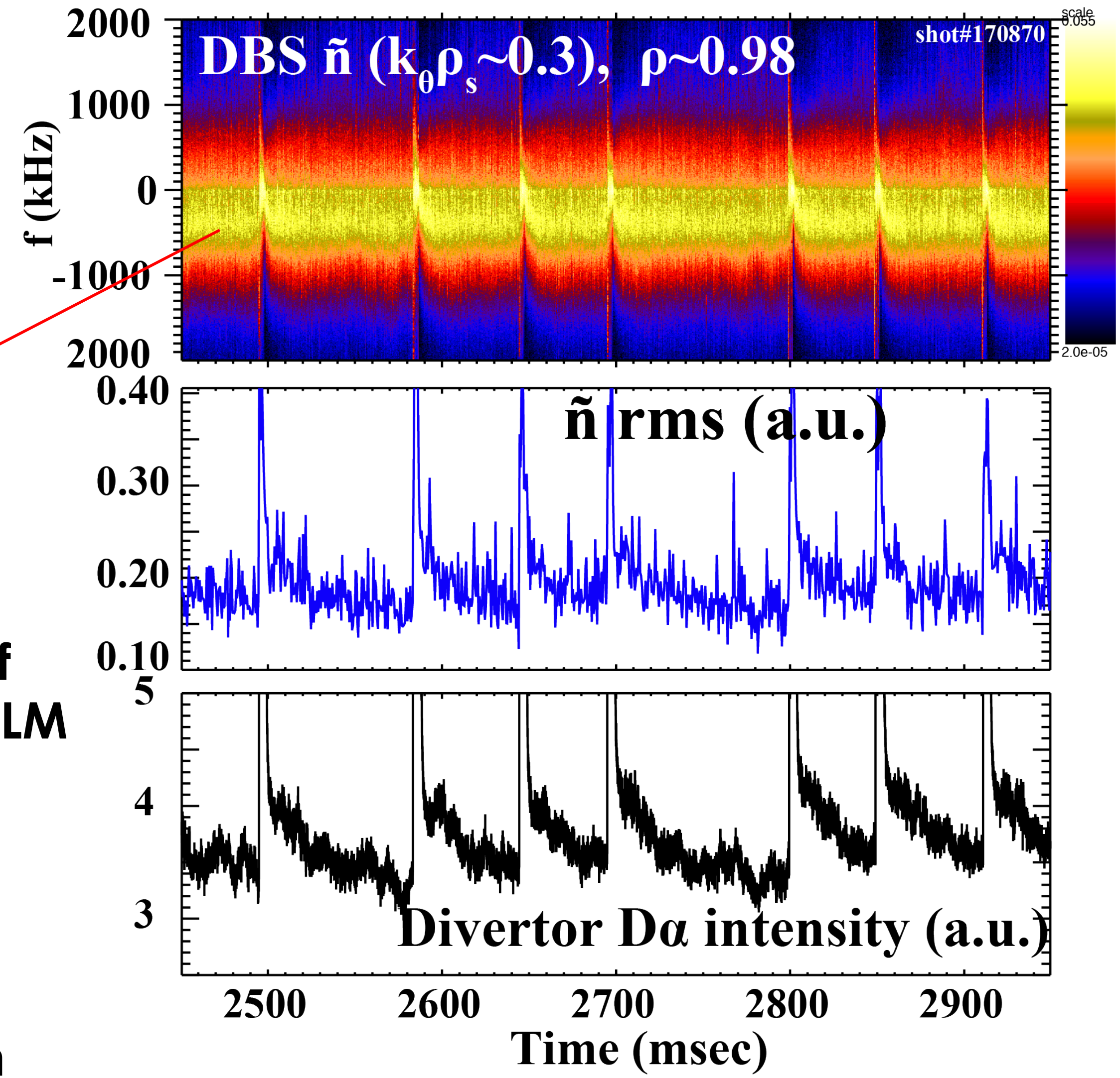




$k_{\tilde{n}} = 2k_{in}\sin(\theta/2)$

ITG-Scale ñ near pedestal foot increases right after ELM and is subsequently suppressed until the next ELM





- ITG scale ñ measured near foot of the pedestal increases just after ELM event
  - Reduced progressively until next ELM but not completely suppressed
  - Has temporal correlation with Divertor D_α emission intensity

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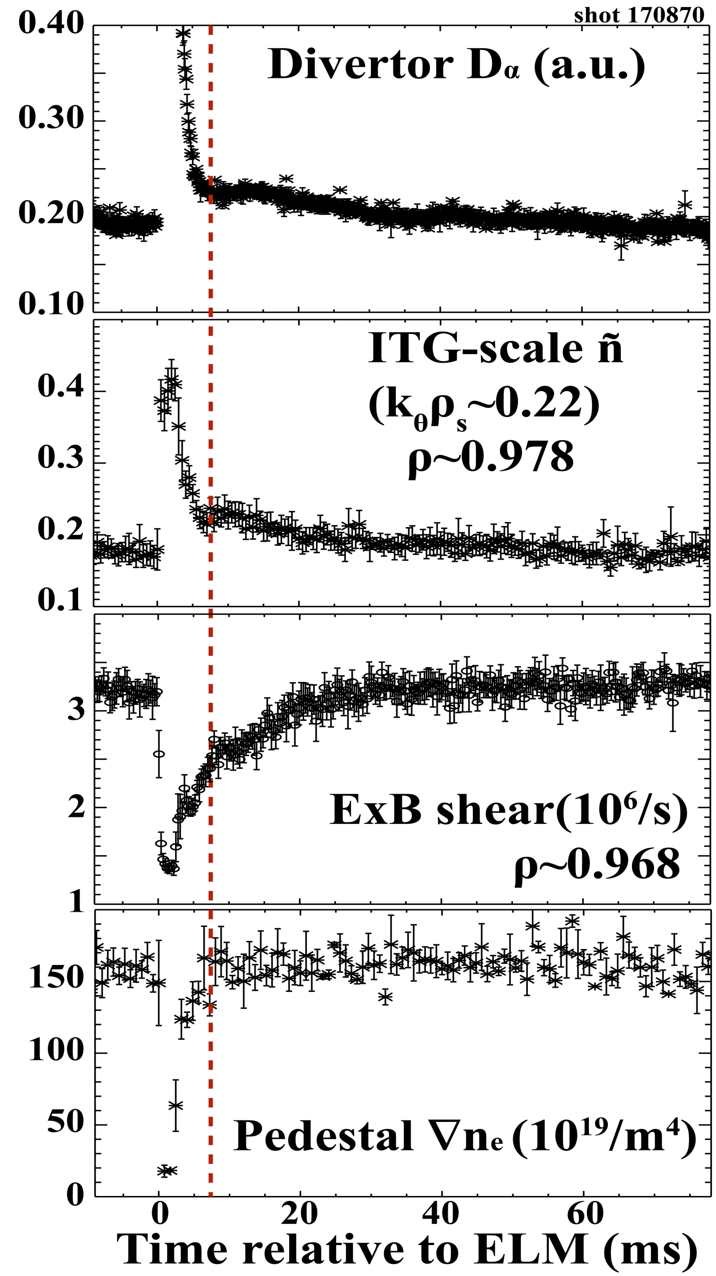
Suppression of ITG-scale turbulence correlates with ExB shear evolution and increase in pedestal ∇n_e

- ExB shear near pedestal foot drops right after ELM crash and ITG scale ñ increases.
- Within few ms, local ExB shear increases and ITG-scale ñ is suppressed.
- $\nabla n_{e,\,ped}$ increase is correlated with ITG-scale ñ suppression.
- Further increase in local ExB shear leads to further but small decrease in ITG-scale ñ but not complete suppression.
- ITG-scale ñ evolution is consistent with Q_i evolution reported* from ASDEX-U
    - Q_i anomalous right after ELM and then becomes close to NC values in the gradient saturation phase.



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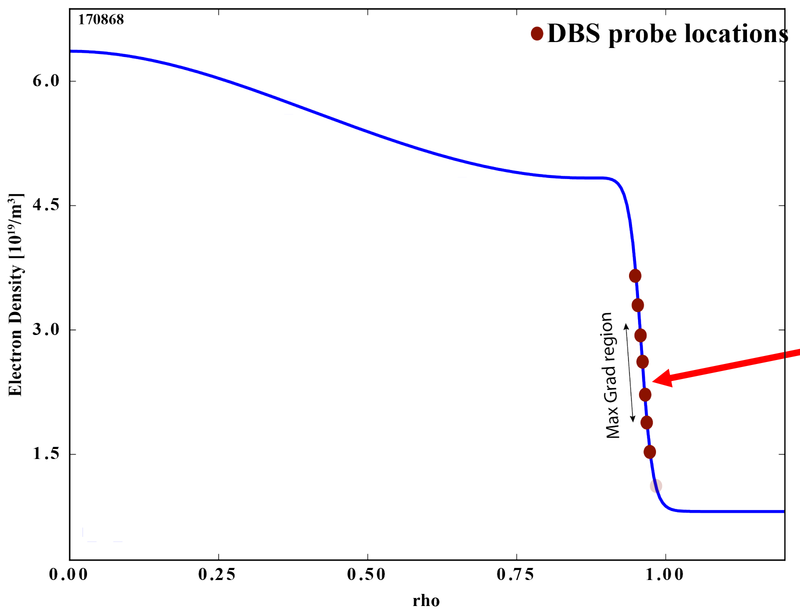
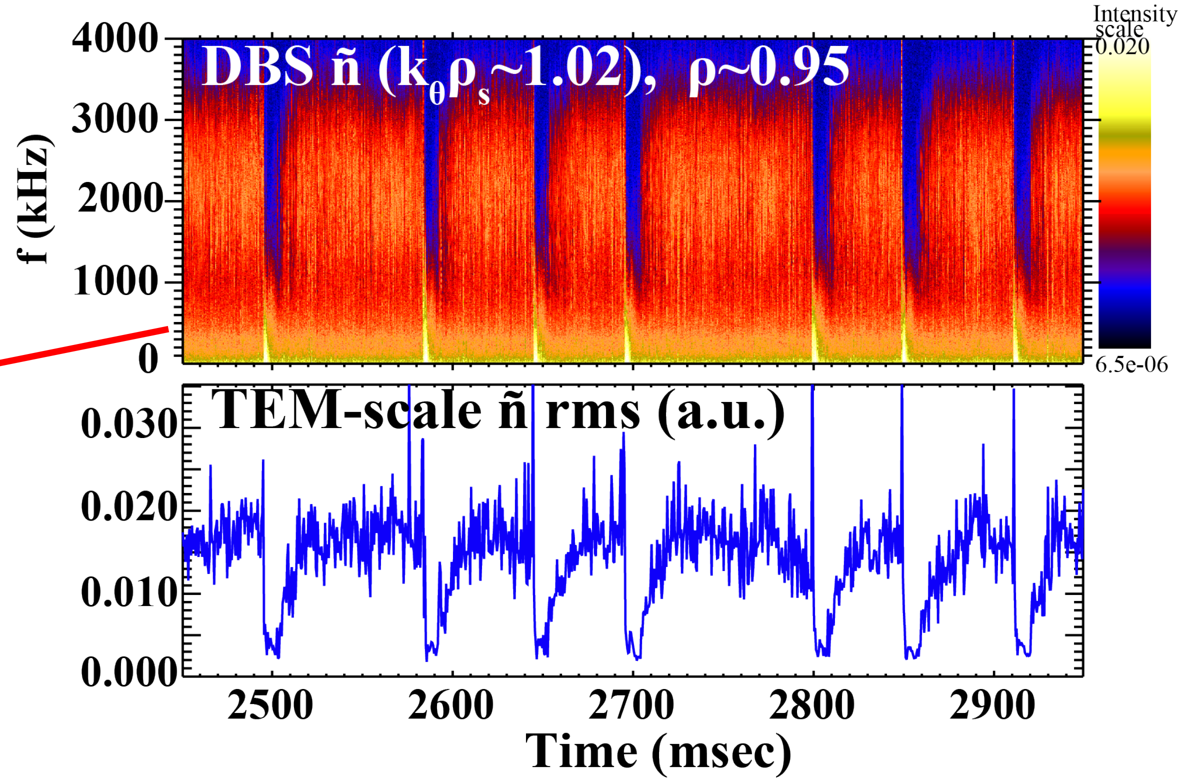
*E. Viezzer et al., Nucl. Fusion 57, 022020 (2017)

TEM-scale $\tilde{n}_{DBS}$ in the steep gradient region increases after a time delay from the ELM onset





- **Intermediate-k (TEM-scale) ñ propagating in electron diamagnetic direction (in the lab frame) with $k_\theta \rho_s \sim 0.7$-1.2 measured in the steep gradient region**
- **TEM-scale ñ increases after a time delay and the same delay has been observed in all steep gradient localized probed locations.**

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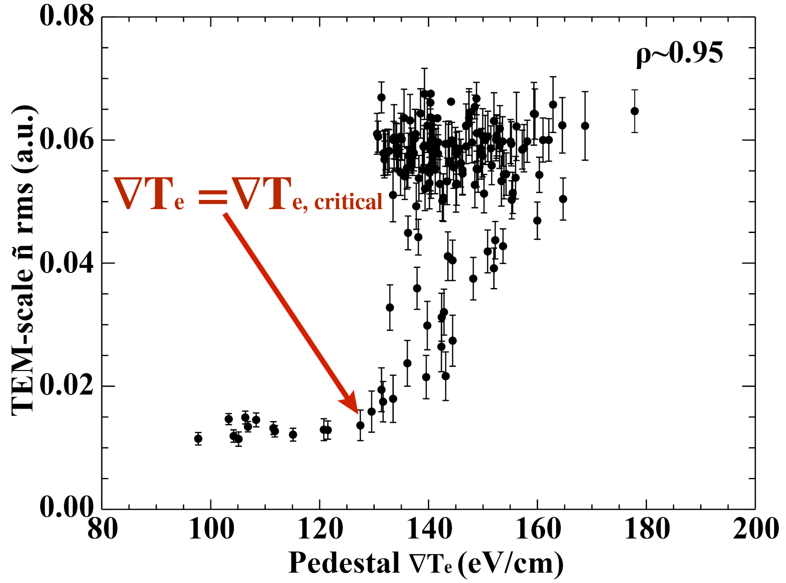
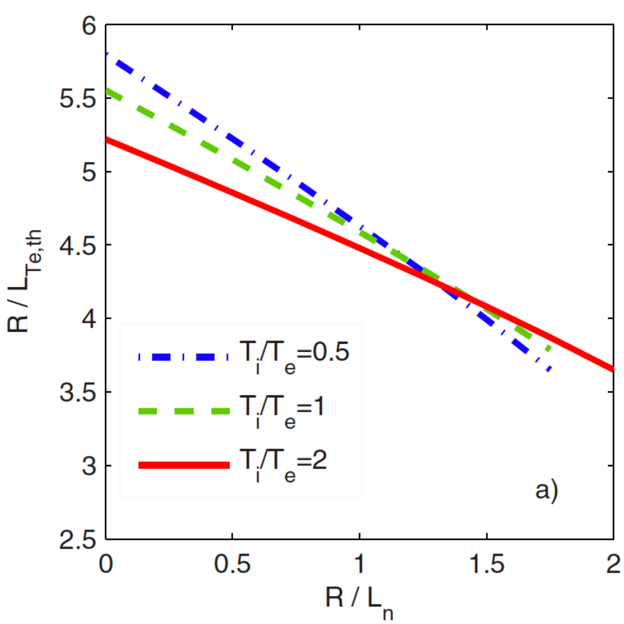
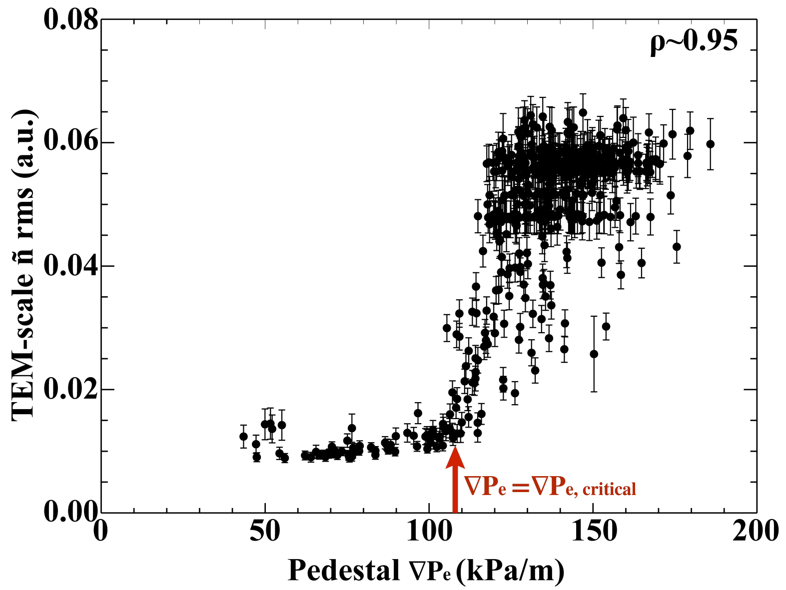
Steep gradient localized TEM ñ shows a critical ∇T_e behavior

- In the steep gradient region, TEM scale ñ increases by nearly 3-5 times when a critical ∇T_e is recached in the inter-ELM period. $\nabla T_e = \nabla T_{e,critical}$~ 130 eV/cm.
- TEM turbulence can be driven by ∇T_e but the threshold depends on background T_i/T_e and ∇n_e [Casati et al, PoP (2008)]







A. Casati, et al, PoP (2008)

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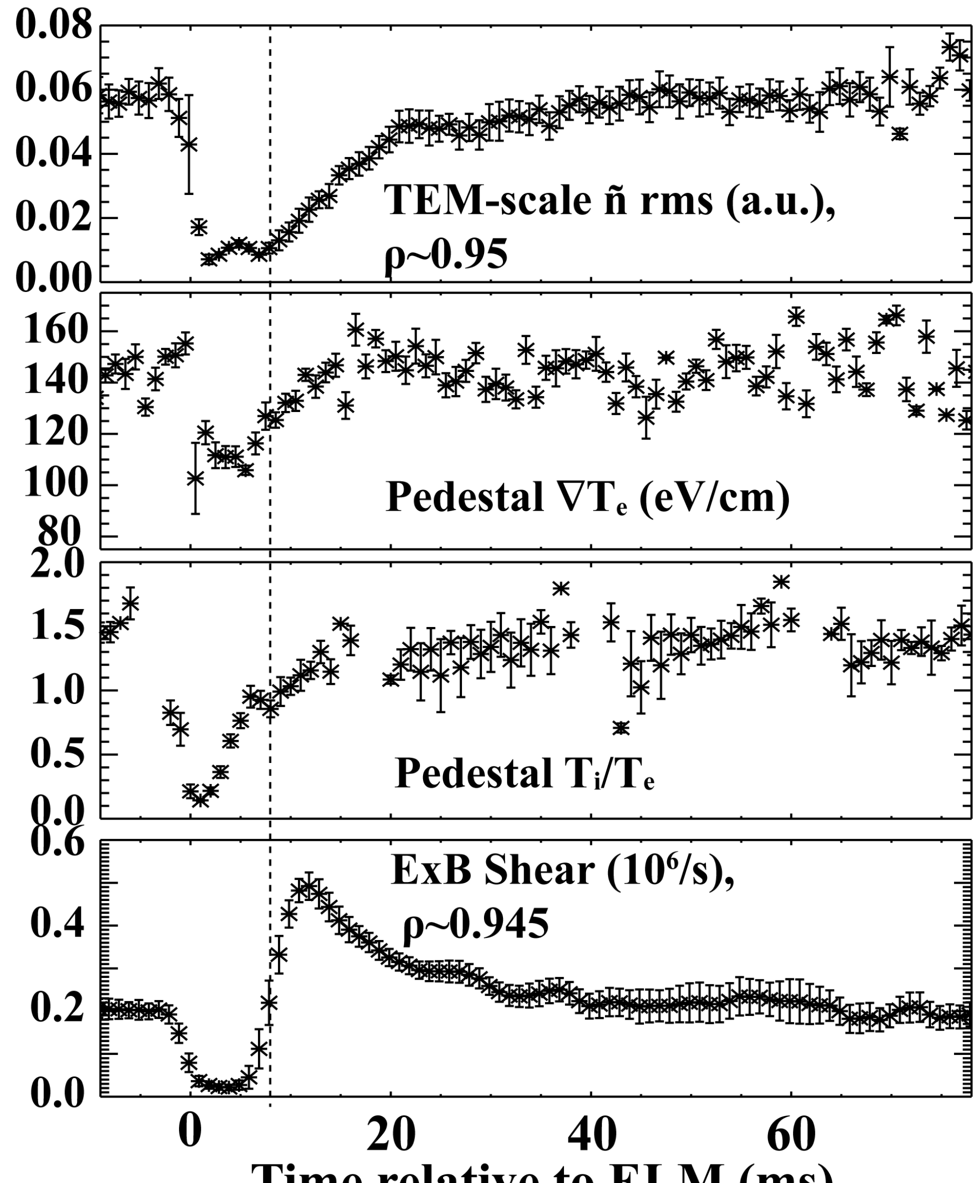
TEM-scale ñ increases with ∇T_e supported by presence of increased background T_i/T_e and ∇n_e

- At critical ∇T_e, TEM-scale ñ increases supported by increased background T_i/T_e and ∇n_e.
- TEM-scale ñ is nearly saturated with nearly saturated ∇T_e and background T_i/T_e and ∇n_e in the presence of higher ExB shear.



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Identification of the observed modes attempted by varying ∇T_e and background T_i/T_e and ∇n_e. This is done by adding ECH at ρ~0.5

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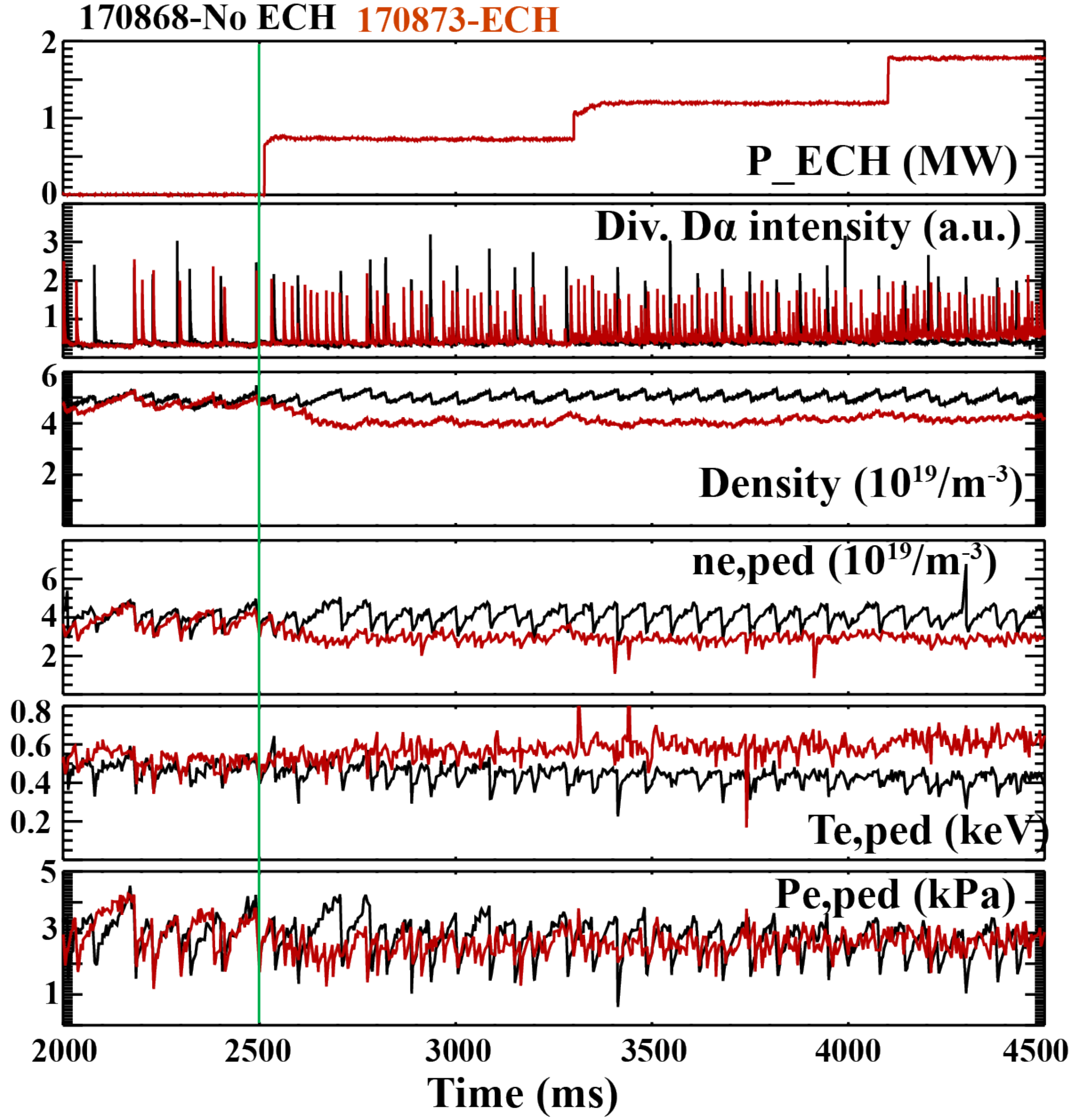
With ECH, $T_{e,ped}$ increases and $n_{e,ped}$ decreases whereas $P_{e,ped}$ does not change much

- ECH at ρ~0.5 added to beam heated discharge
- Smaller and higher frequency ELMs replace larger low frequency ELMs
- Next: How different gradients change with electron heating?



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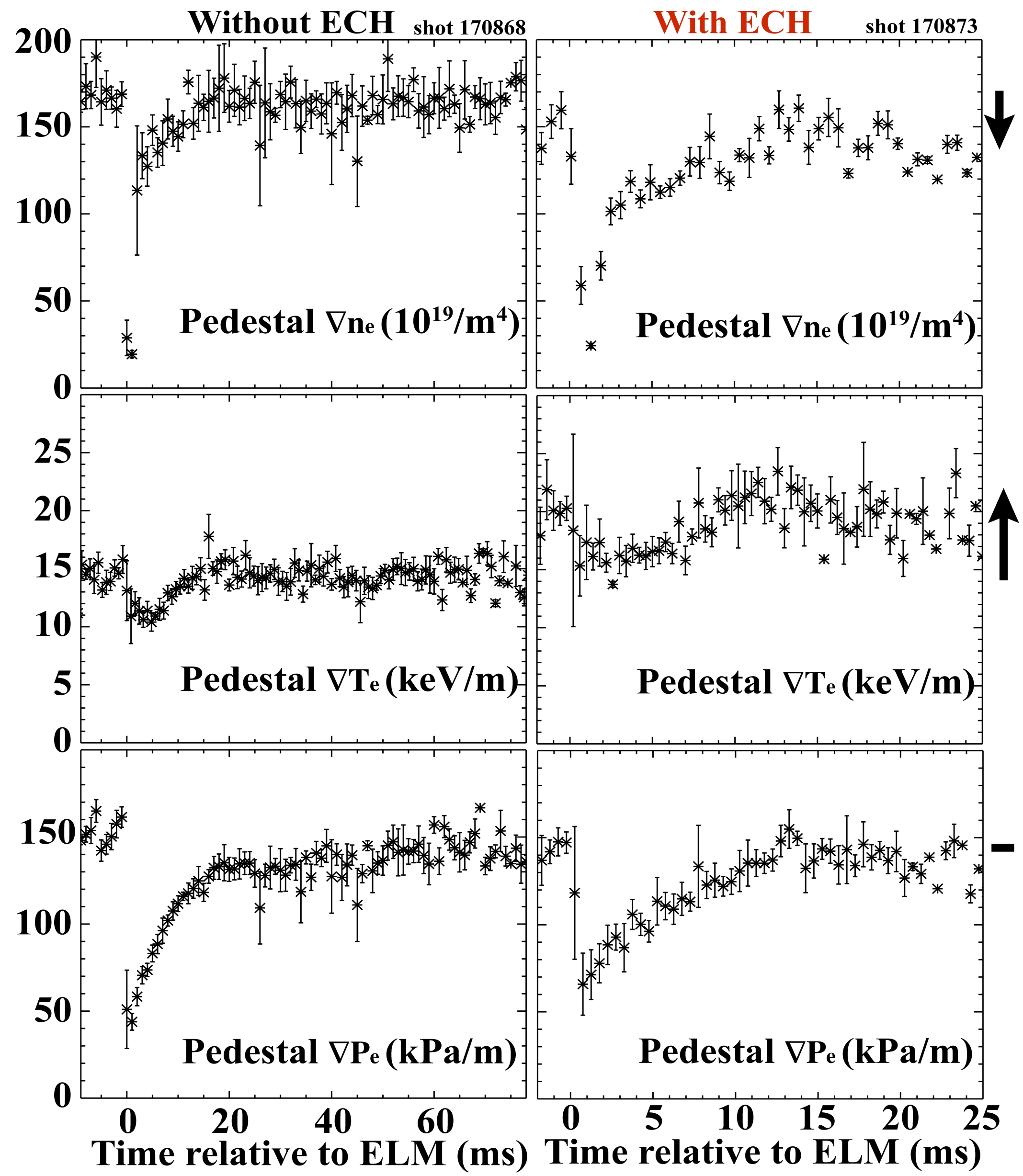
With ECH, $\nabla n_{e,ped}$ decreases and $\nabla T_{e,ped}$ increases but $\nabla P_{e,ped}$ attains the same level as pure NBI case

With additional ECH (1.2 MW):

- Lower pedestal ∇n_e and higher ∇T_e
- Pedestal ∇T_e is always higher than pure NBI case.
- Pedestal ∇P_e increases nearly to same level as no ECH case before ELM crash.
- T_i/T_e decreases by a factor of 2 in the pedestal
- Next: How these above changes affect ITG-scale and TEM-scale ñ?



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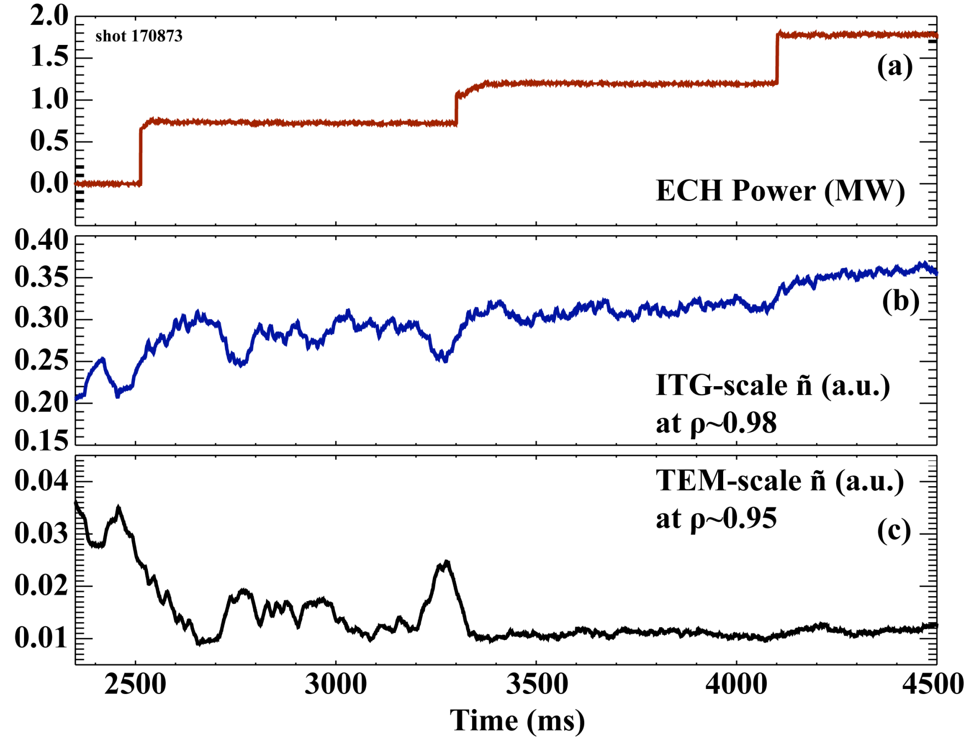
At lower T_i/T_e and lower ∇n_e, TEM-scale ñ decreases and ITG-scale ñ increases consistent with theoretical predictions

- ITG-scale ñ increases ~50%
- TEM-scale ñ decreases ~66%



- TEM ñ stabilization with ECH consistent with theoretical predictions of increased ∇T_e threshold for lower T_i/T_e and lower ∇n_e
- ITG-scale ñ increase is also consistent with this theory
- Increased ITG-scale ñ also consistent with main heat flux differing from NC values at lower ν_i^* (S. Haskey, IAEA 2020)

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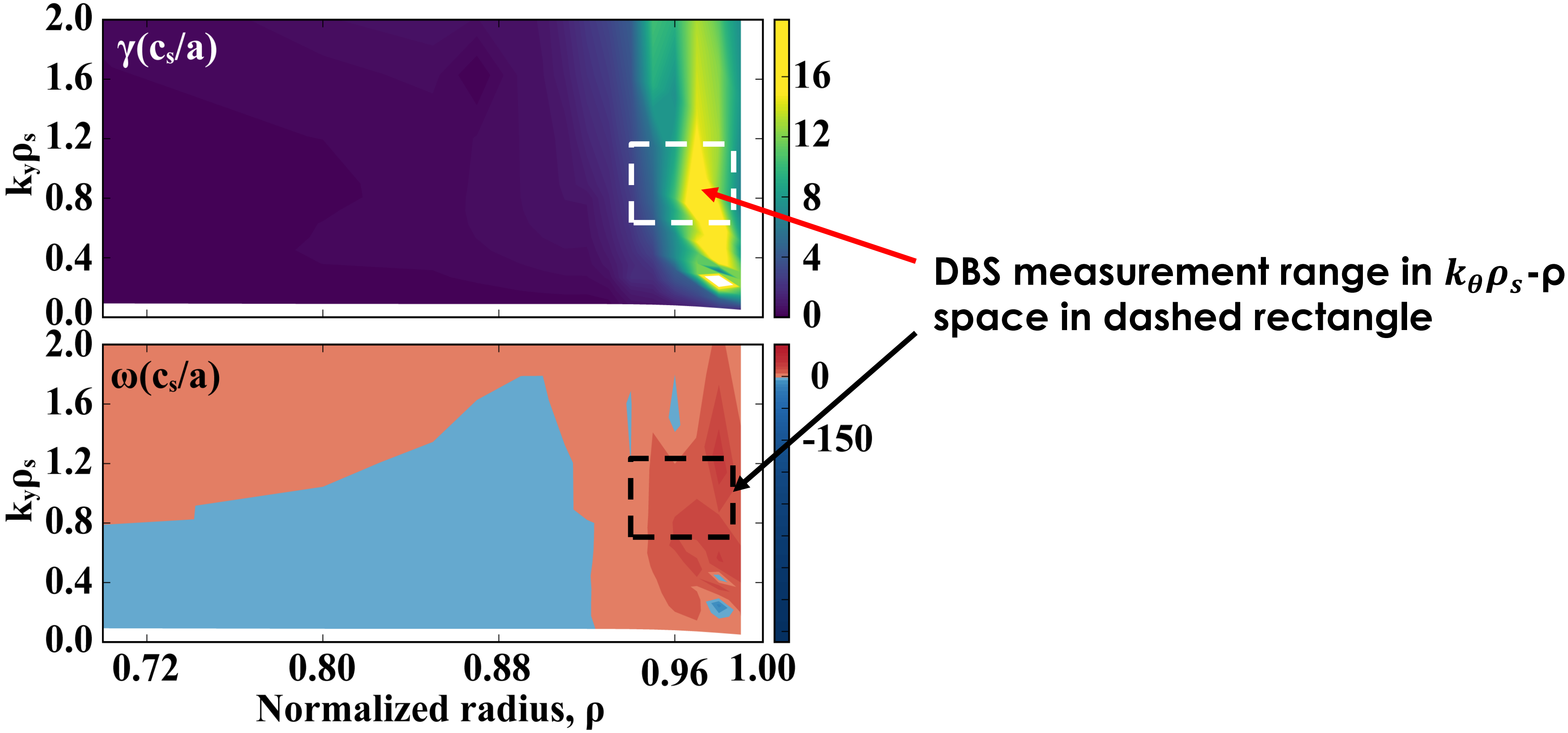
Initial TGLF simulations suggest TEM-scale fluctuations in the saturated phase of the inter-ELM period



- Linear TGLF simulations using kinetic equilibrium and profiles shows
- Most unstable modes having similar $k_\theta \rho_s$ and propagating in electron diamagnetic drift direction
- An unstable mode propagating in ion diamagnetic drift direction at ρ~0.98 with $k_\theta \rho_s$~0.2, similar to observed in experiment using DBS

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Summary

- New and unique measurements shed light on inter-ELM thermal transport by drift wave like turbulence
- Evolution of ITG-scale turbulence regulated by ExB shear consistent with Q_i decreasing from being anomalous to closer to NC
- TEM-scale ñ increases at critical ∇T_e and can be responsible for anomalous Q_e inferred from experiments
- ITG and TEM-scale ñ evolutions are consistent with theoretical predictions of these being ITG and TEM instabilities respectively

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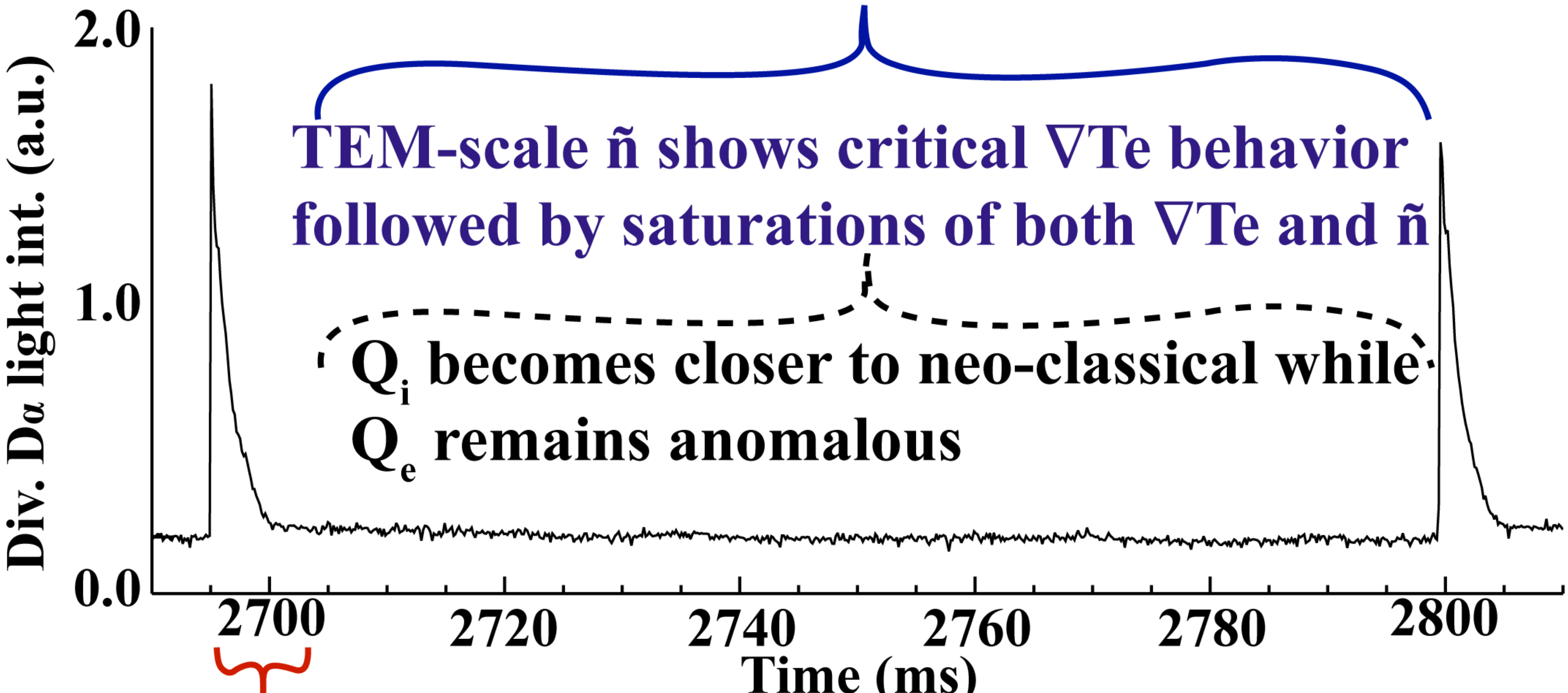
These observations can improve our pedestal evolution predictions by explaining some of the inter-ELM Q_e and Q_i



Large ITG-scale ñ when Q_i and Qe both are anomalous (AUG)

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