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

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In collaboration with
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Main points/Highlights: New and unique measurements shed light on inter-ELM thermal 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 observed estimated heat fluxes**

- **Modes are identified based on their theoretically expected dependencies on background T_i/T_e and ∇n_e**

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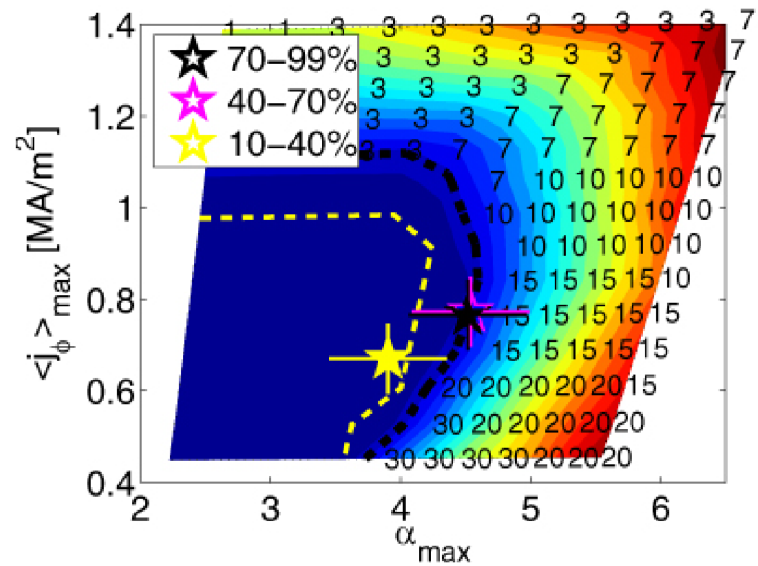
Complete understanding of all transport mechanisms is necessary to improve prediction of pedestal evolution

- **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 saturated pedestal height and width**
  - **KBM driven transport constrains $\nabla P_{e,ped}$ until P-B modes excite an ELM**
  - **Drift wave turbulence is shear suppressed**
  - **In this work we will show clear evidence of inter-ELM drift wave like turbulence that is not completely shear suppressed**
- **Improved and validated models can impact pedestal thermal flux predictions for ITER and future fusion devices.**



Saarelma et al, PPCF (2013)

[1]Snyder et al, NF (2011)

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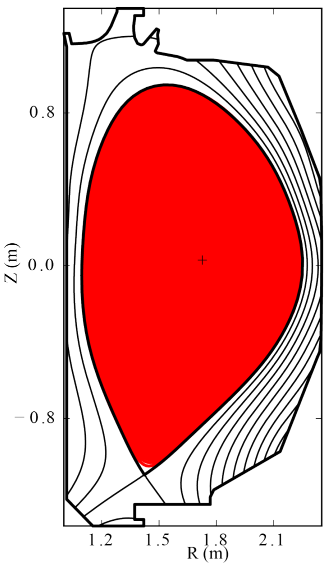
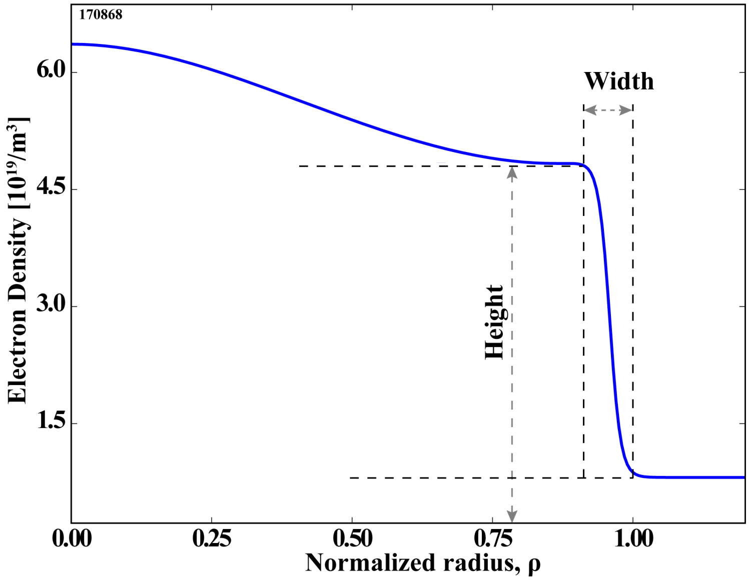
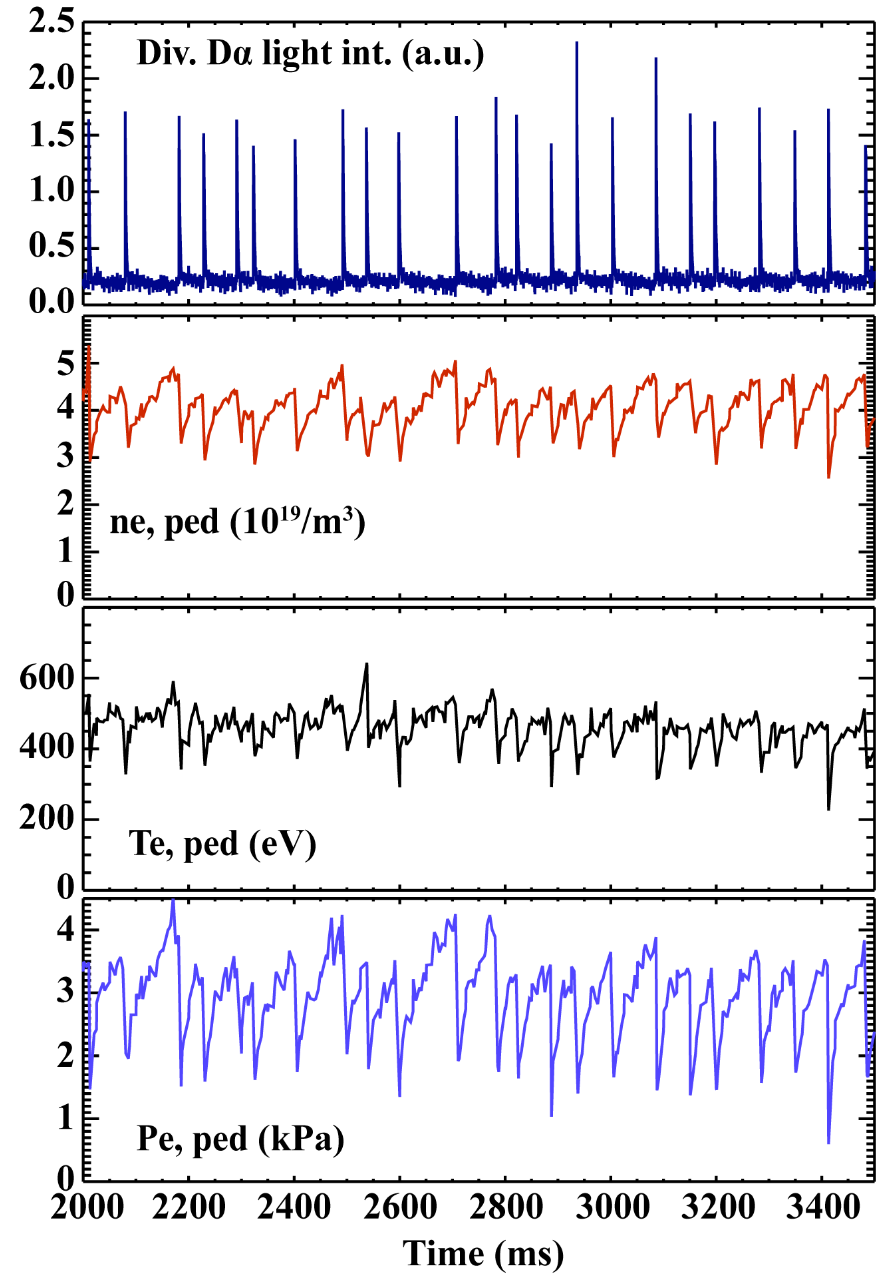
Experiments are performed in Lower Single Null shape H-mode plasmas with low frequency type-I ELMs







Ip~1 MA, Bt~2.1 T, Power close to $P_{L\text{-}H}$, P_{NBI}~2.3 MW, $\bar{n}_e$ ~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.**
- **Pedestal gradients are calculated from measured heights and widths.**

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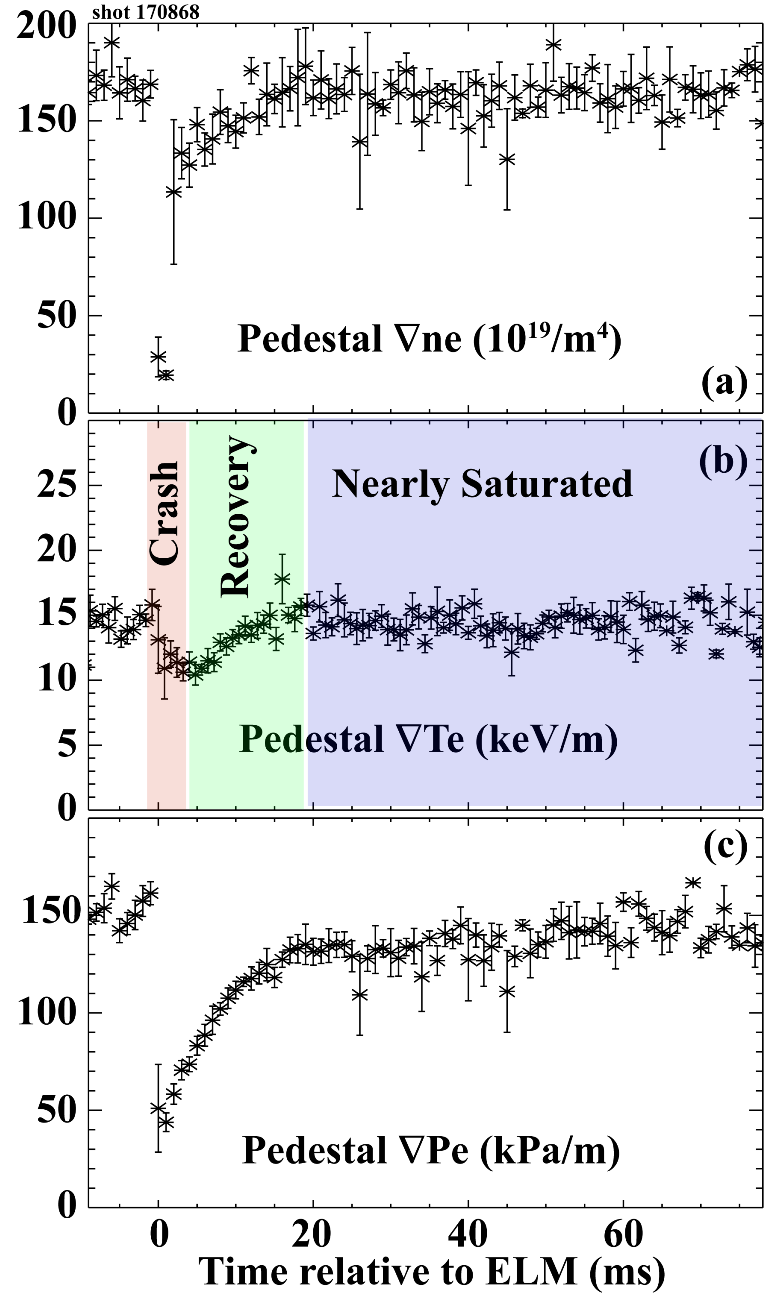
Electron Pedestal Gradients remain nearly saturated for most of the inter-ELM period

- ELM synchronized analysis with ~42 inter-ELM periods
- Three distinct phases: Relaxation/crash, recovery, and near saturation
- During gradient recovery: Height increases and width decreases
- In gradient saturation phase: Both height and width increase
- Gradients of pedestal density, temperature, and pressure stay saturated for nearly 75% of the inter-ELM period



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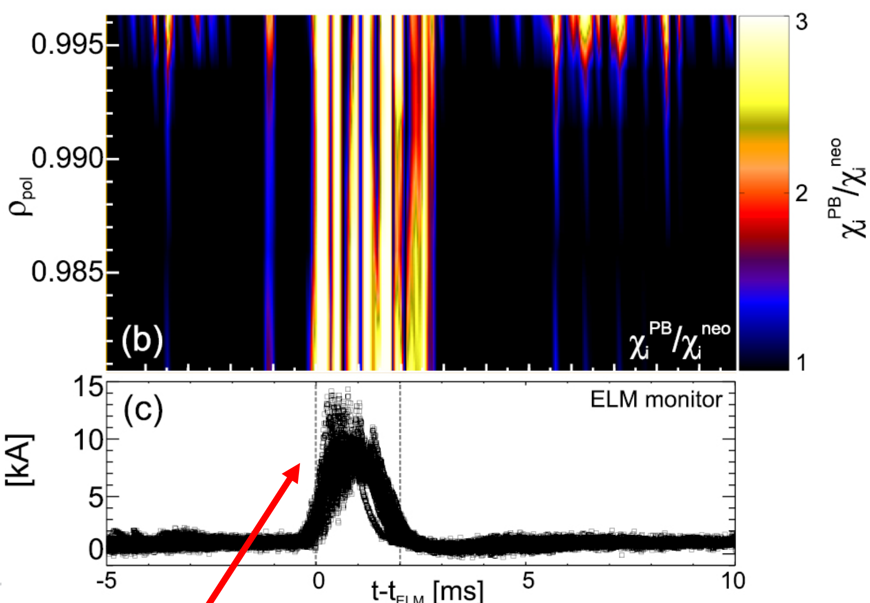
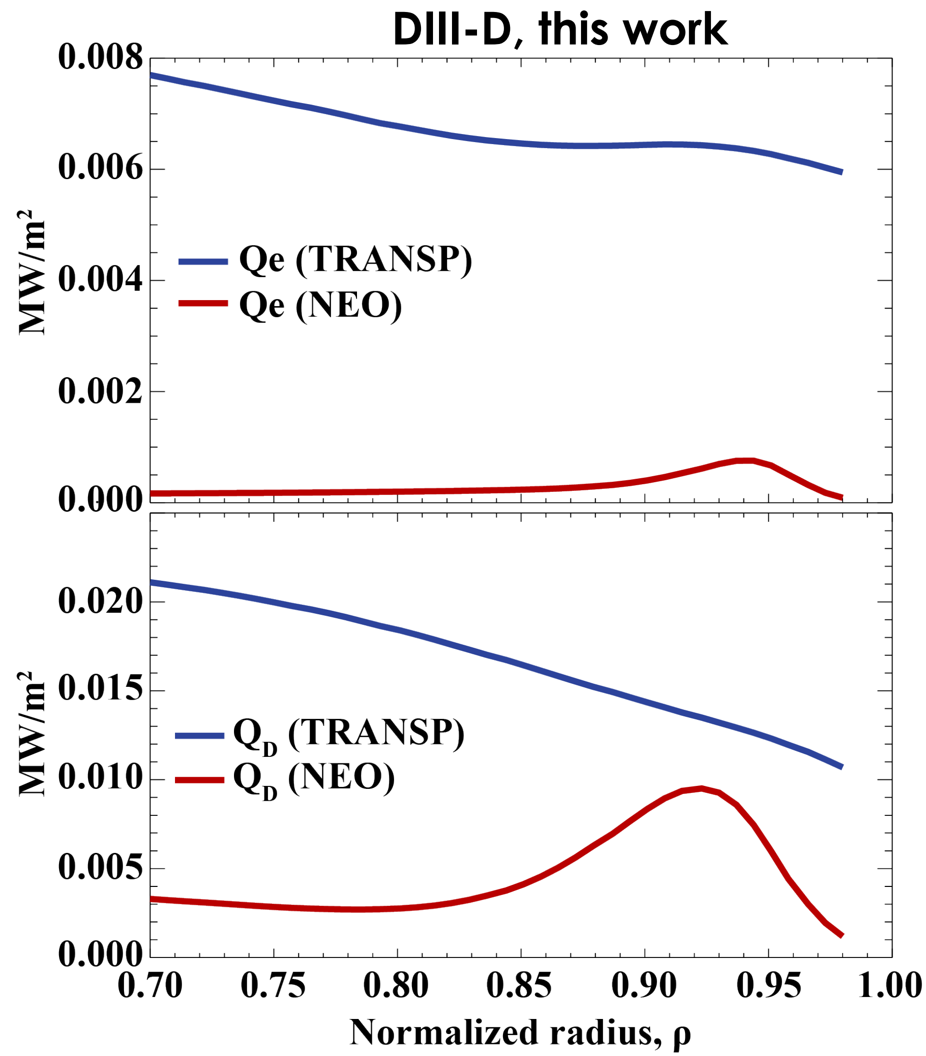
Main ion heat flux is close to neoclassical (NC) and electron heat flux is anomalous in the nearly saturated phase

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

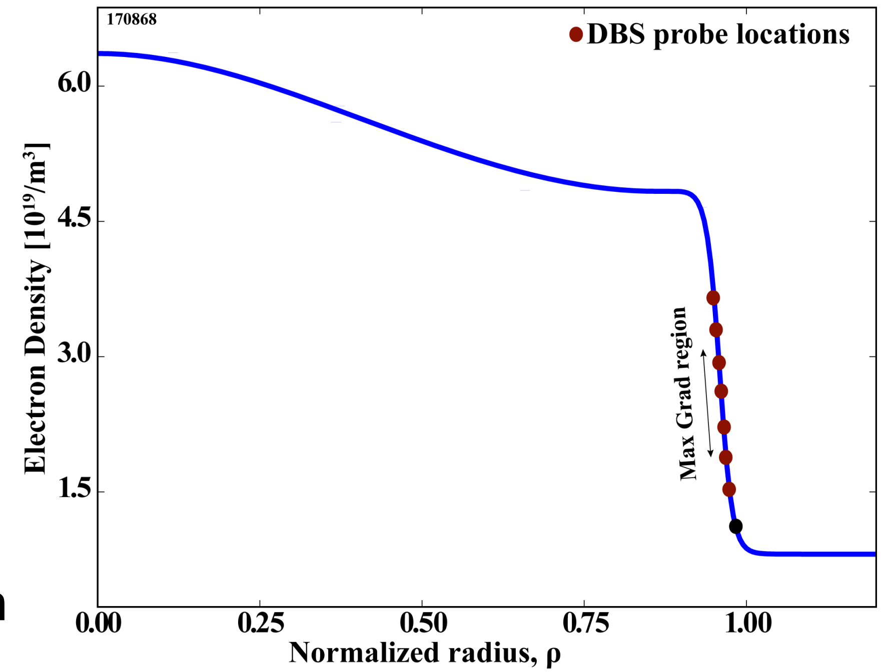


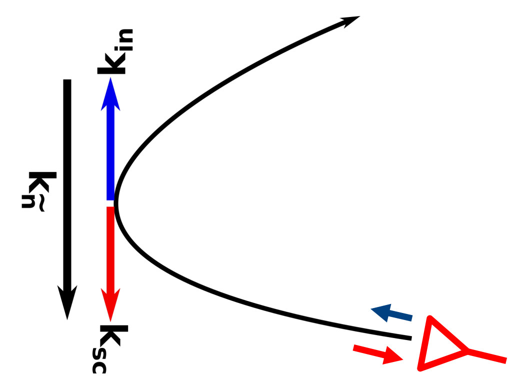
ASDEX-U E. Viezzer et al., Nucl. Fusion (2017)



ITG and TEM-scale ñ in the pedestal are measured by Doppler Backscattering (DBS) 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.**
- **Local ExB velocity shear is calculated from estimated $v_{E\times B}$ at different probe radii**
- **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.**





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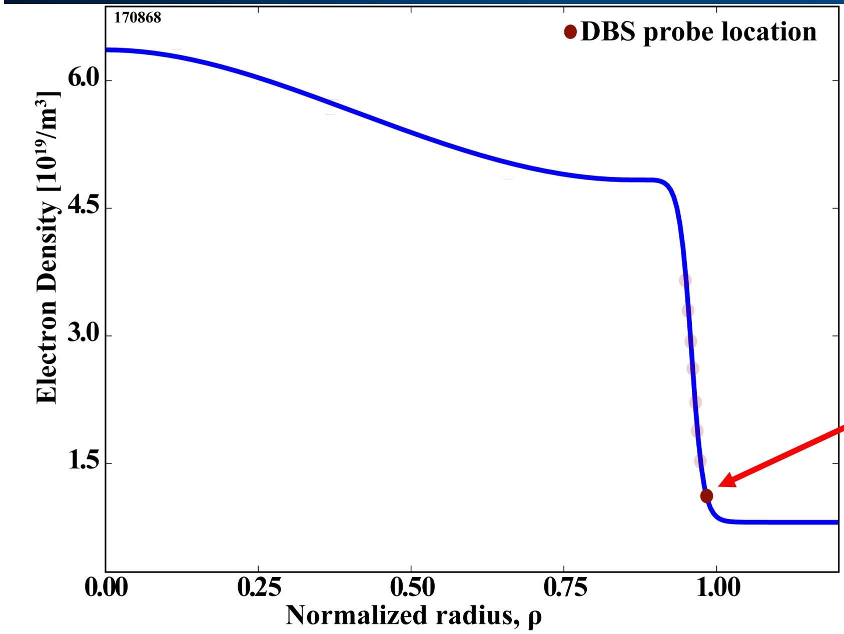
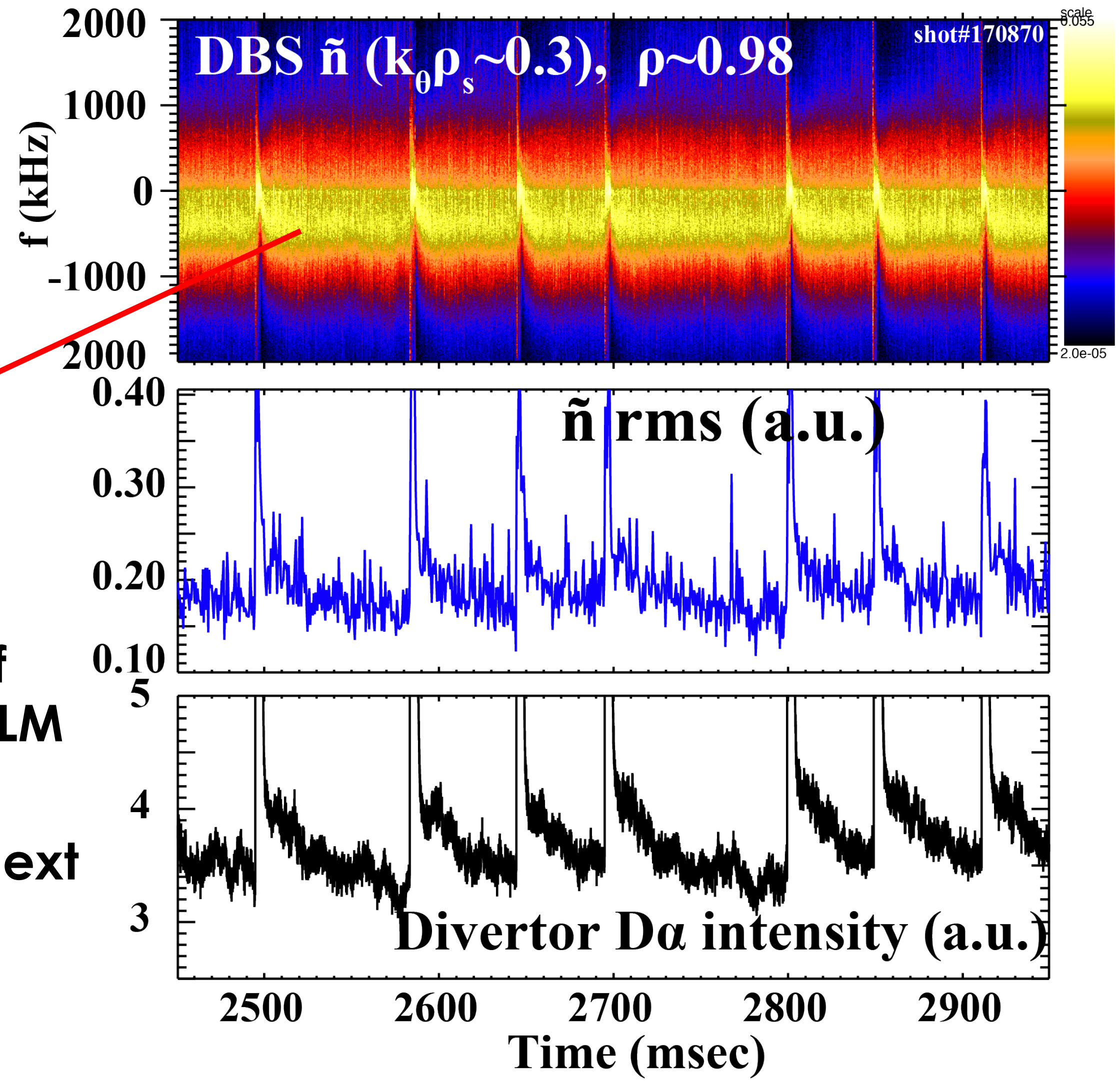
ITG-Scale ñ near pedestal foot increases right after ELM and is subsequently suppressed until the next ELM





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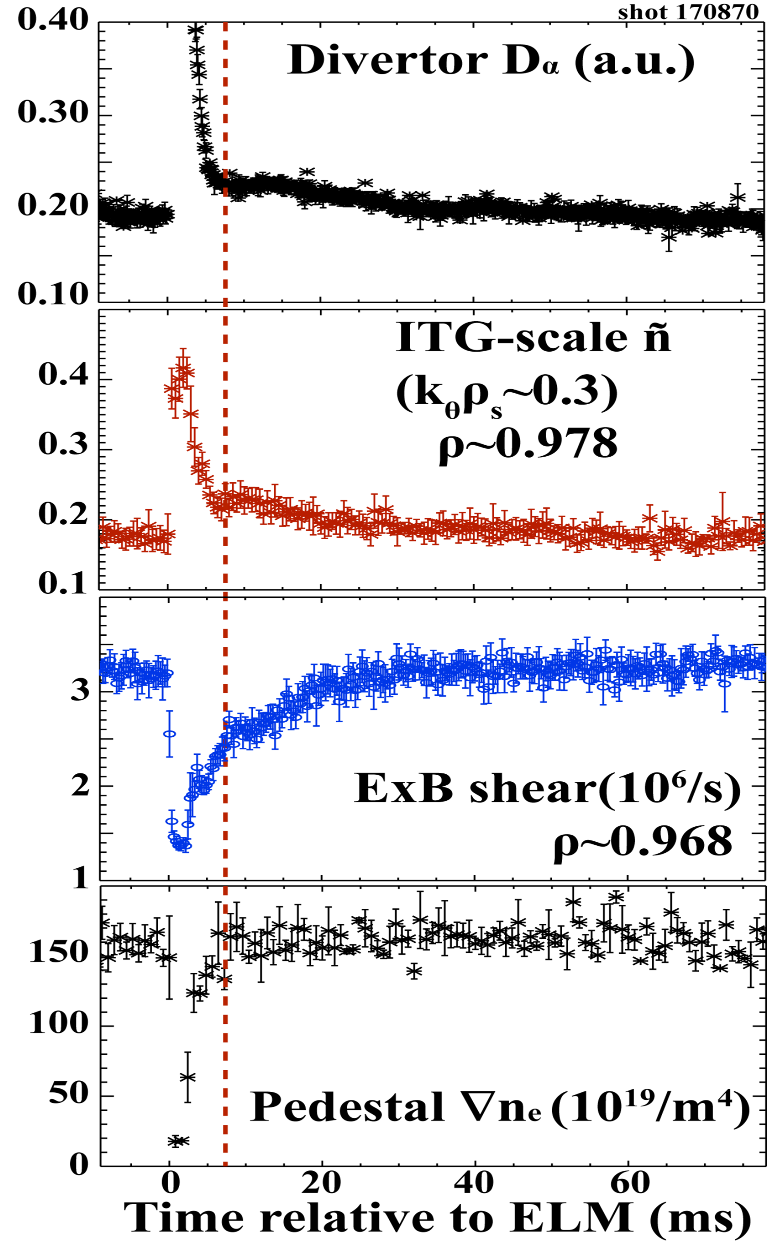
Suppression of ITG-scale turbulence correlates with ExB shear evolution and increase in pedestal ∇n_e

- 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
- Further increase in local ExB shear leads to further but small decrease in ITG−scale ñ but not complete suppression



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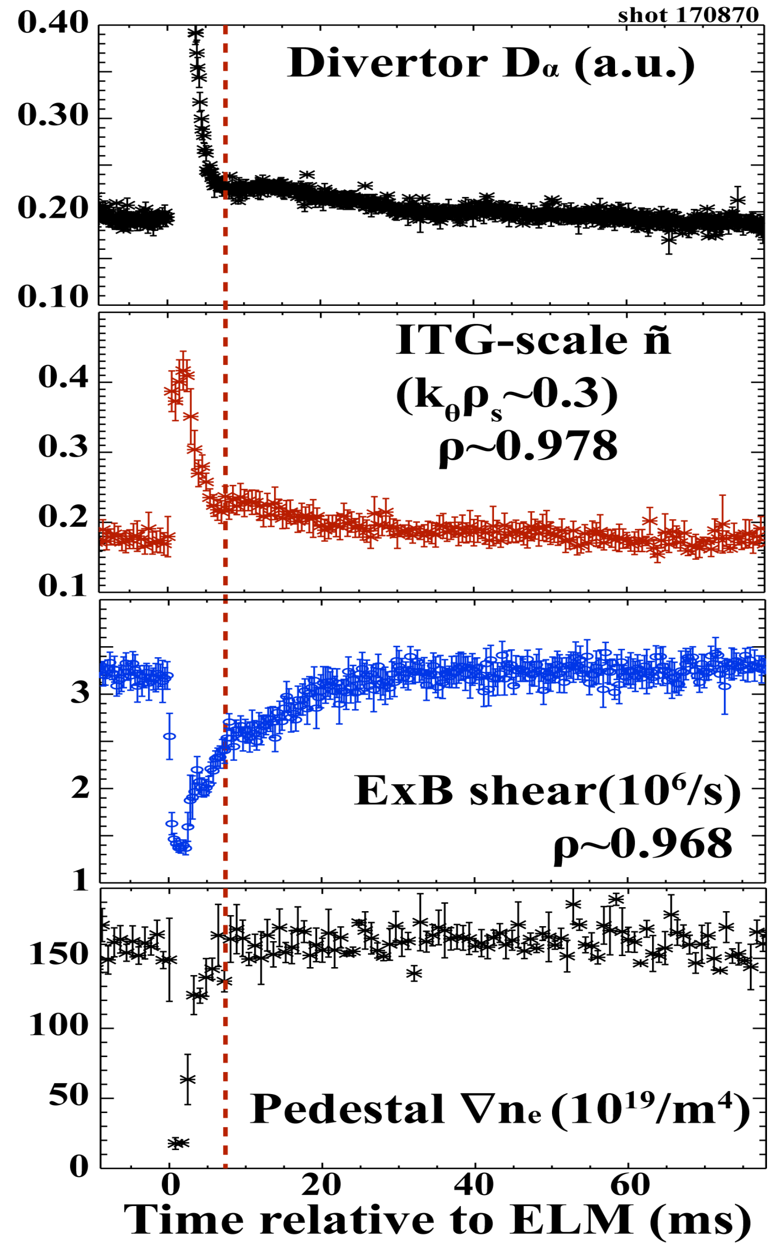
Suppression of ITG-scale turbulence correlates with ExB shear evolution and increase in pedestal ∇n_e

- **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**
- **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 Qi evolution reported* from ASDEX−U**
    - **Q_i anomalous right after ELM and then decreases and becomes close to NC values in the gradient saturation phase**
- **$\nabla n_{e,\,ped}$ increase is correlated with ITG-scale ñ suppression**



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

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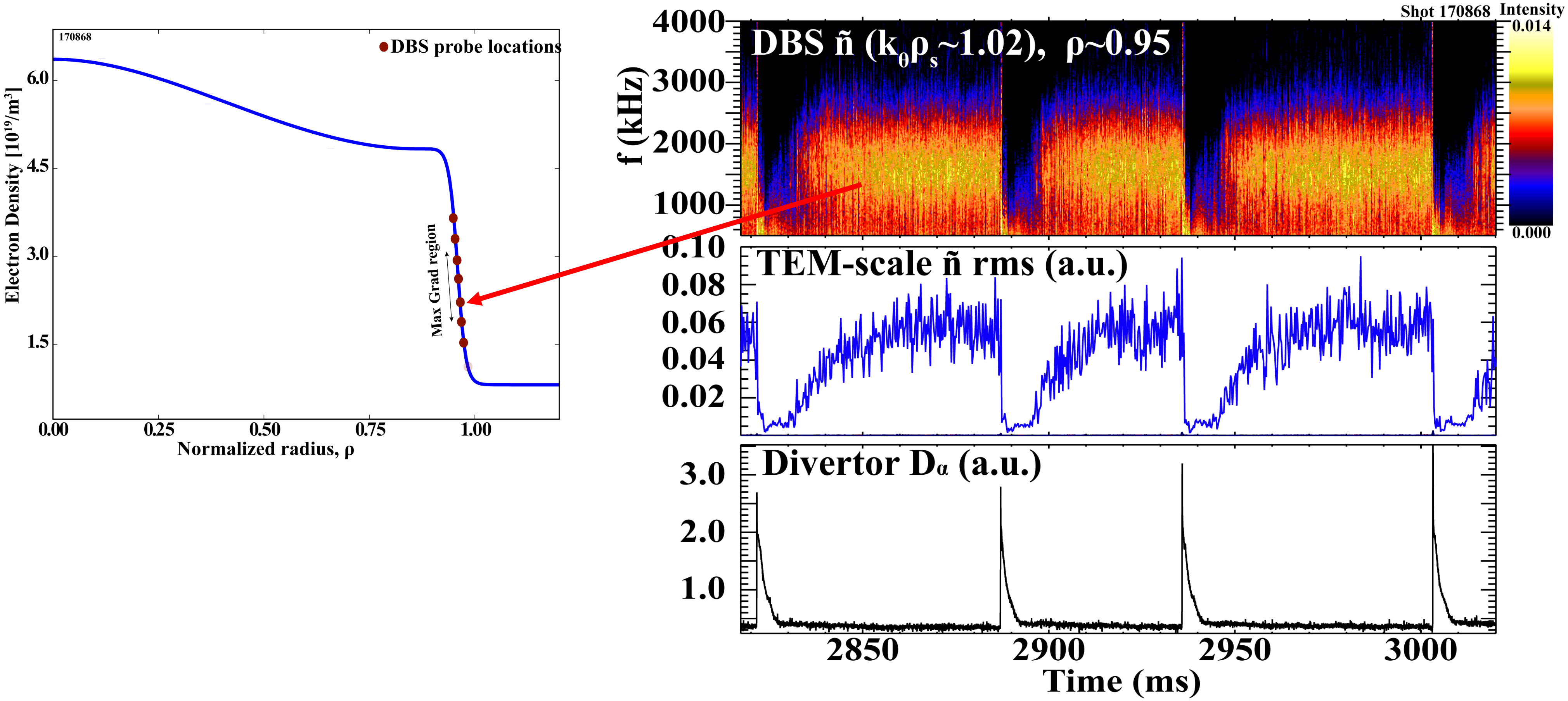
TEM-scale $\tilde{n}_{DBS}$ in the steep gradient region increases after a time delay from the ELM onset



- 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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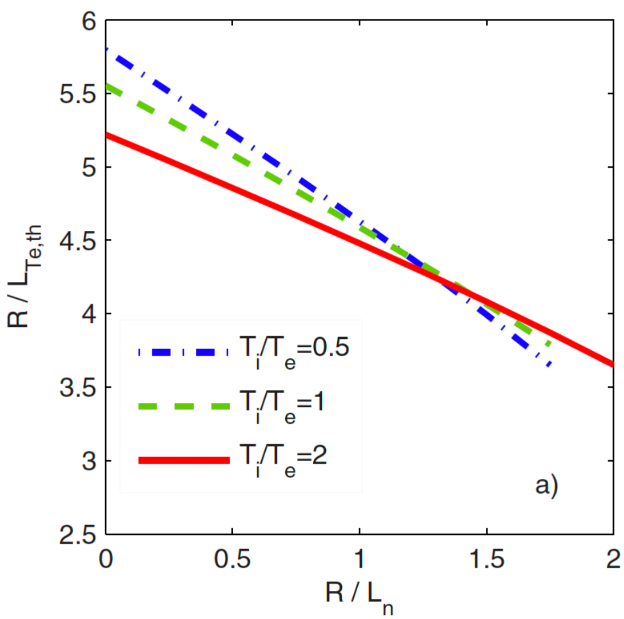
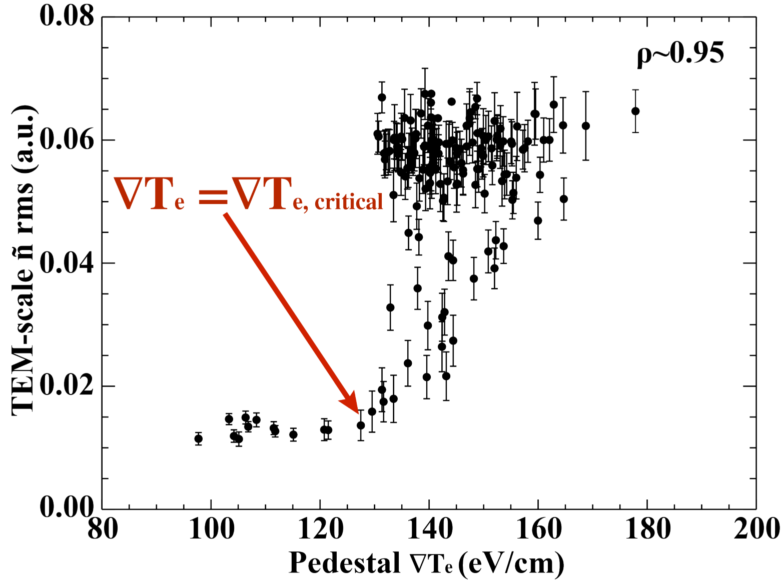
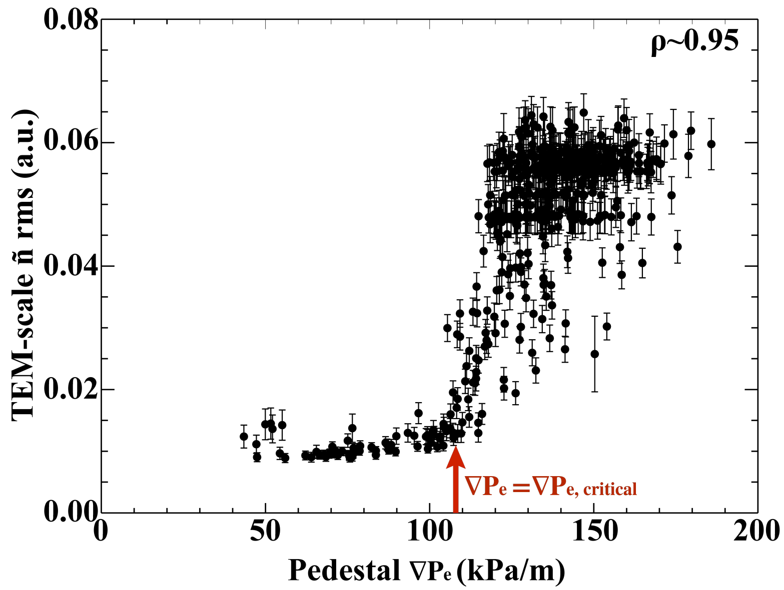
Steep gradient localized TEM ñ shows a critical ∇T_e behavior

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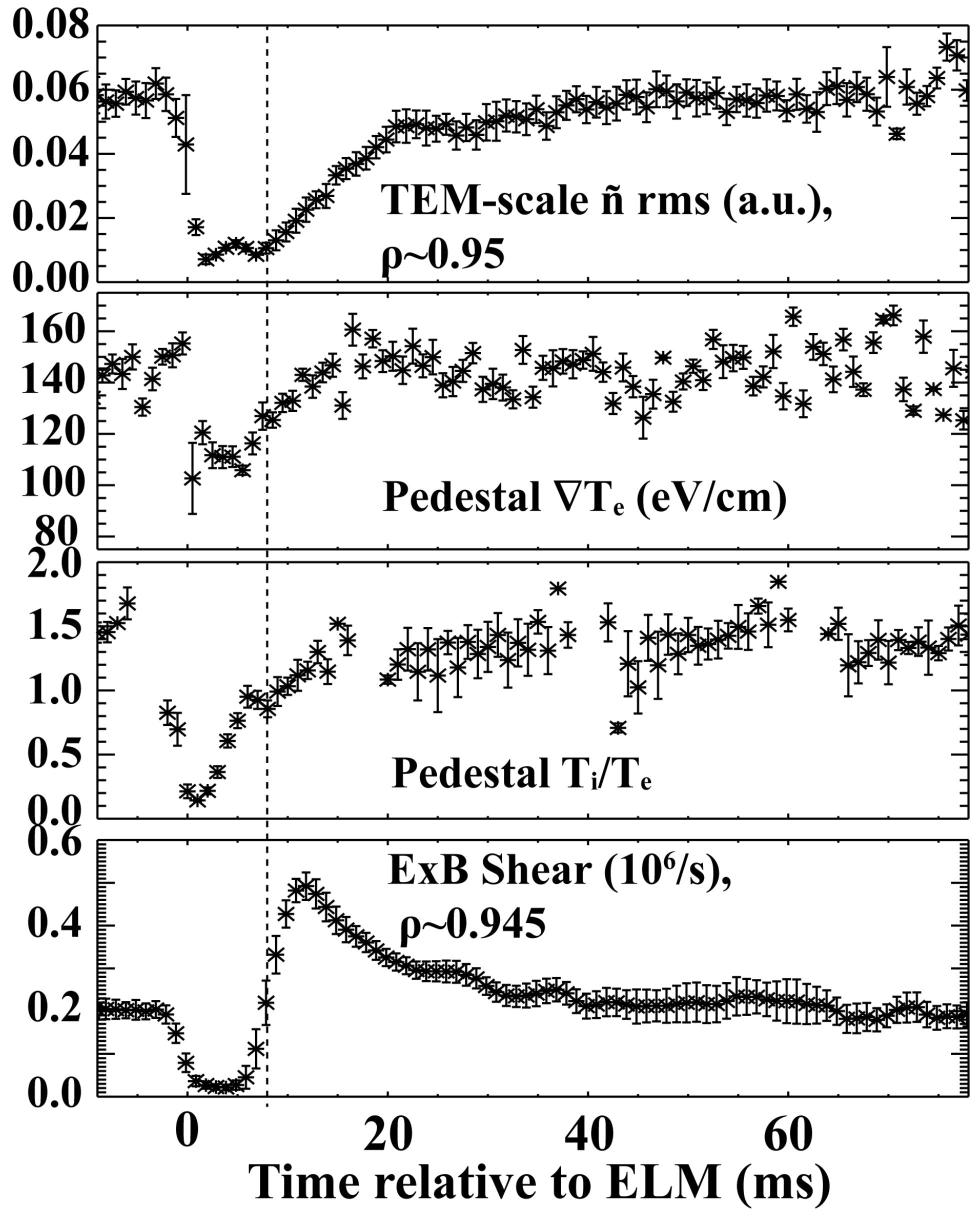
TEM-scale ñ increases with ∇T_e supported by presence of increased background T_i/T_e and ∇n_e

- At critical ∇T_e, TEM-scale ñ increases supported by presence of 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
- This TEM-scale ñ has potential to drive electron heat transport and may contribute to the inferred anomalous Q_e in the saturated phase



Identification of the observed modes are attempted by varying $\nabla T_{e,ped}$ and background T_i/T_e and $\nabla n_{e,ped}$. This is done by ECH at ρ~0.5.

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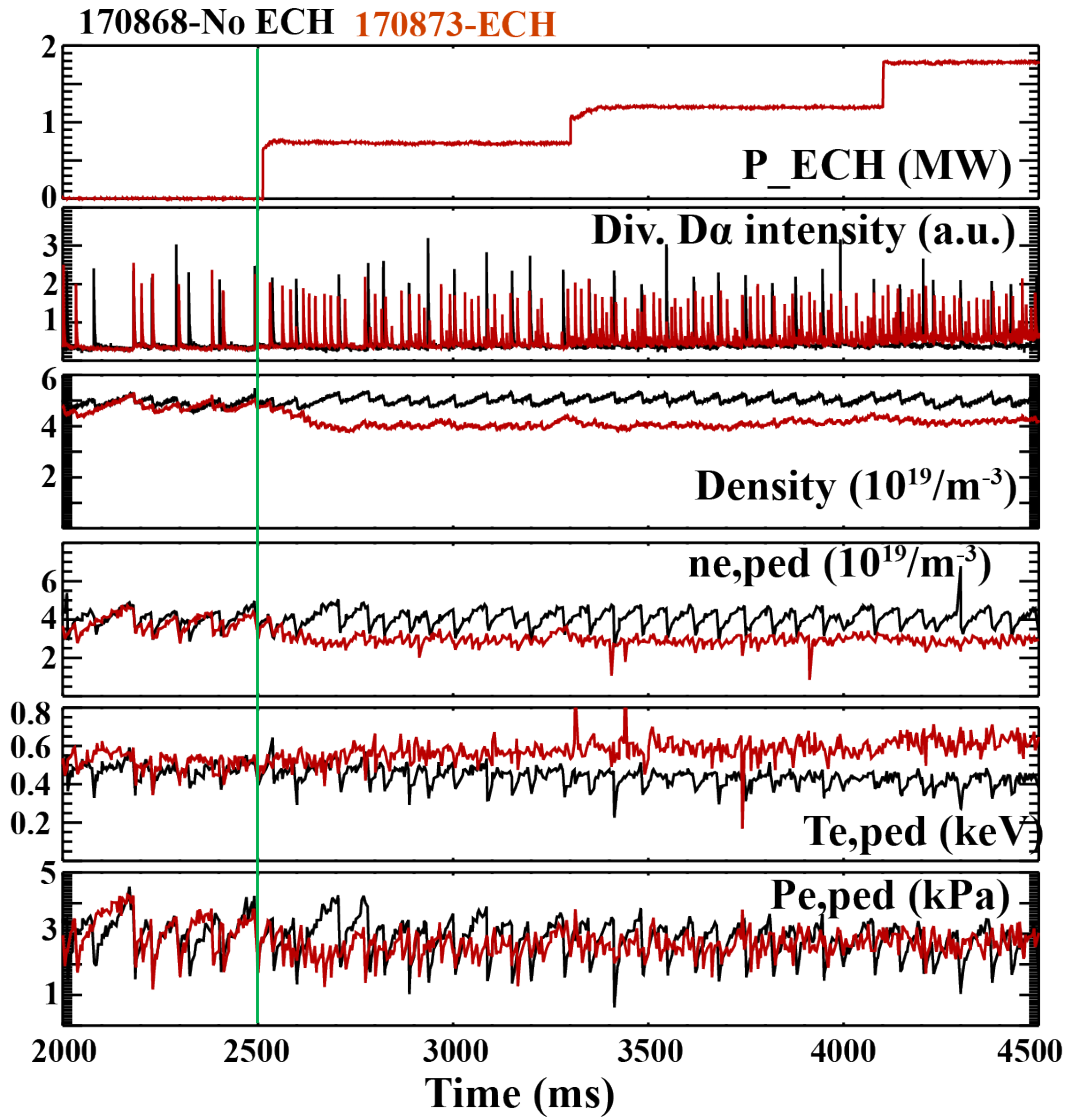
With ECH, $T_{e,ped}$ increases and $n_{e,ped}$ decreases whereas $P_{e,ped}$ does not change much

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



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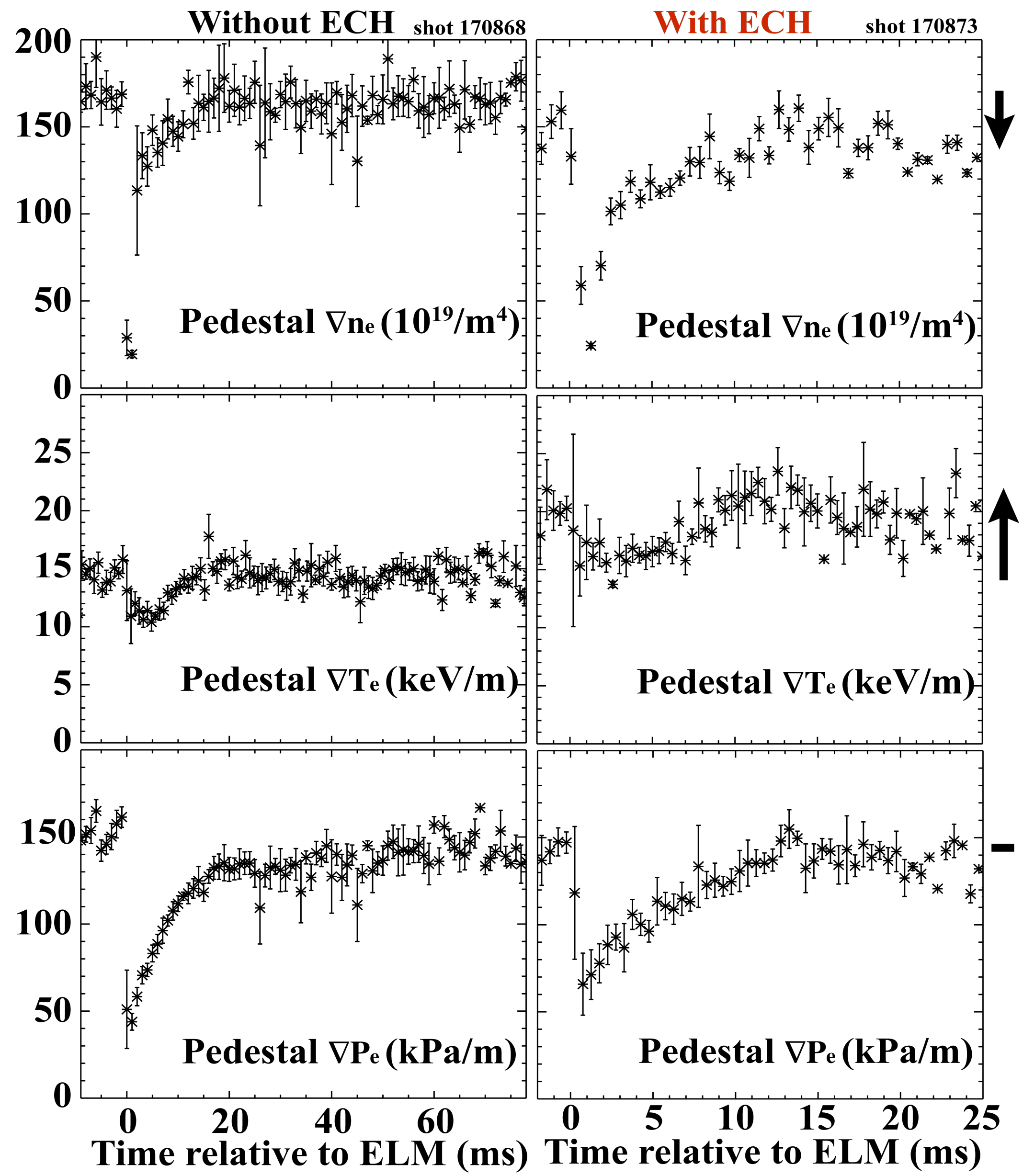
With ECH, $\nabla n_{e,ped}$ decreases and $\nabla T_{e,ped}$ increases but $\nabla P_{e,ped}$ attains the same level as pure NBI case

With additional ECH:

- 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
- How these above changes affect ITG-scale and TEM-scale ñ?



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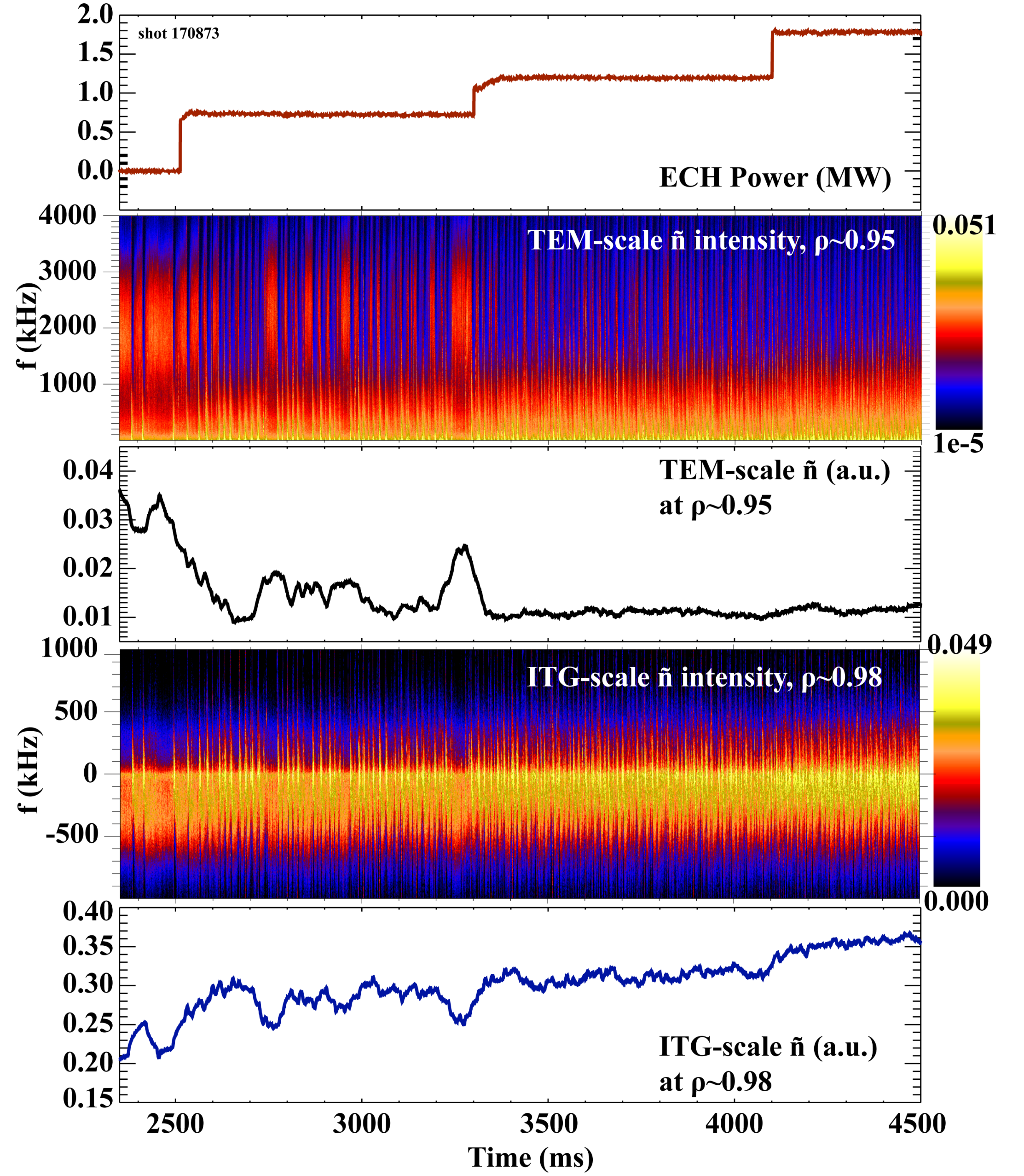
At lower T_i/T_e and lower ∇n_e, TEM-scale ñ decreases and ITG-scale ñ increases consistent with theoretical predictions

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

- TEM ñ stabilization with ECH consistent with theoretical predictions[1] 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[1] which suggests a lower ∇T_i threshold



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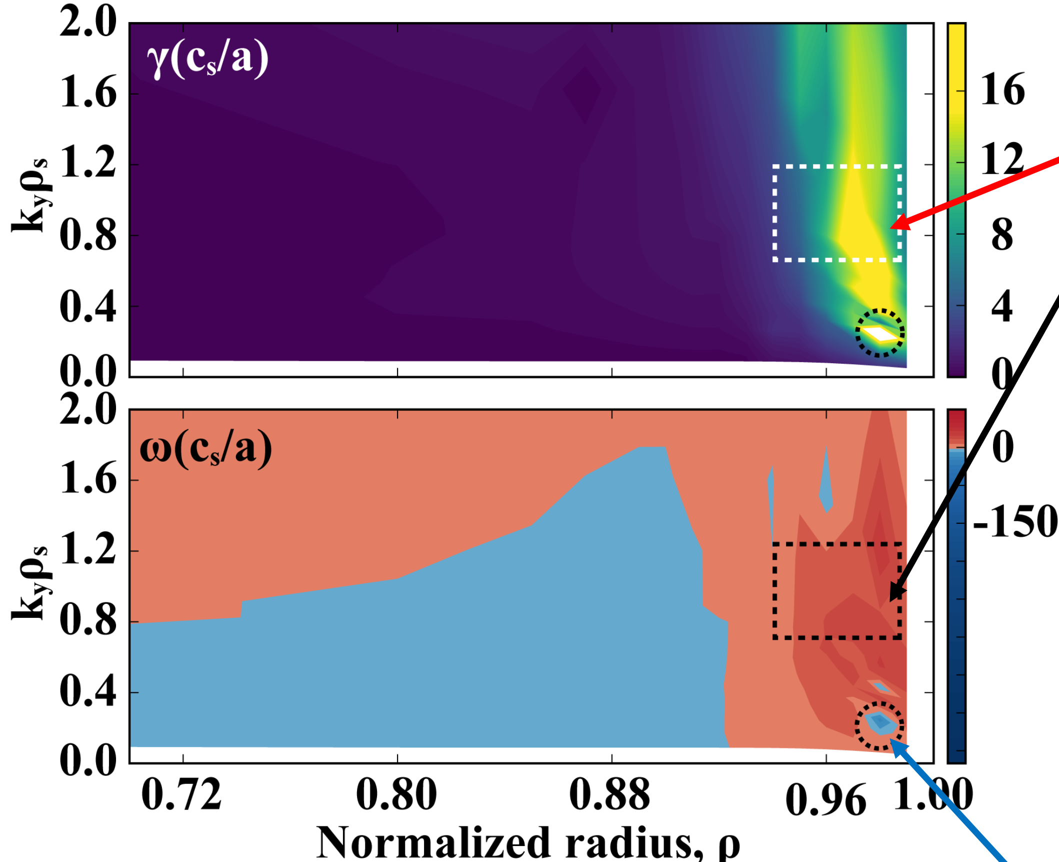
[1]A. Casati, et al, PoP (2008)

Initial TGLF simulations in saturated phase suggest TEM-scale fluctuations are unstable in the steep gradient region



DBS measurement range in $k_\theta \rho_s$-ρ space in dashed rectangle

Linear TGLF simulations shows in the steep gradient region, the most unstable modes

- have similar $k_\theta \rho_s$ of TEM-scale ñ measured in experiment
- propagating in electron diamagnetic drift direction in plasma frame

and near pedestal foot an unstable mode

- propagating in ion diamagnetic drift direction at ρ~0.98
- with $k_\theta \rho_s$~0.2, close to the ITG-scale ñ observed in experiment

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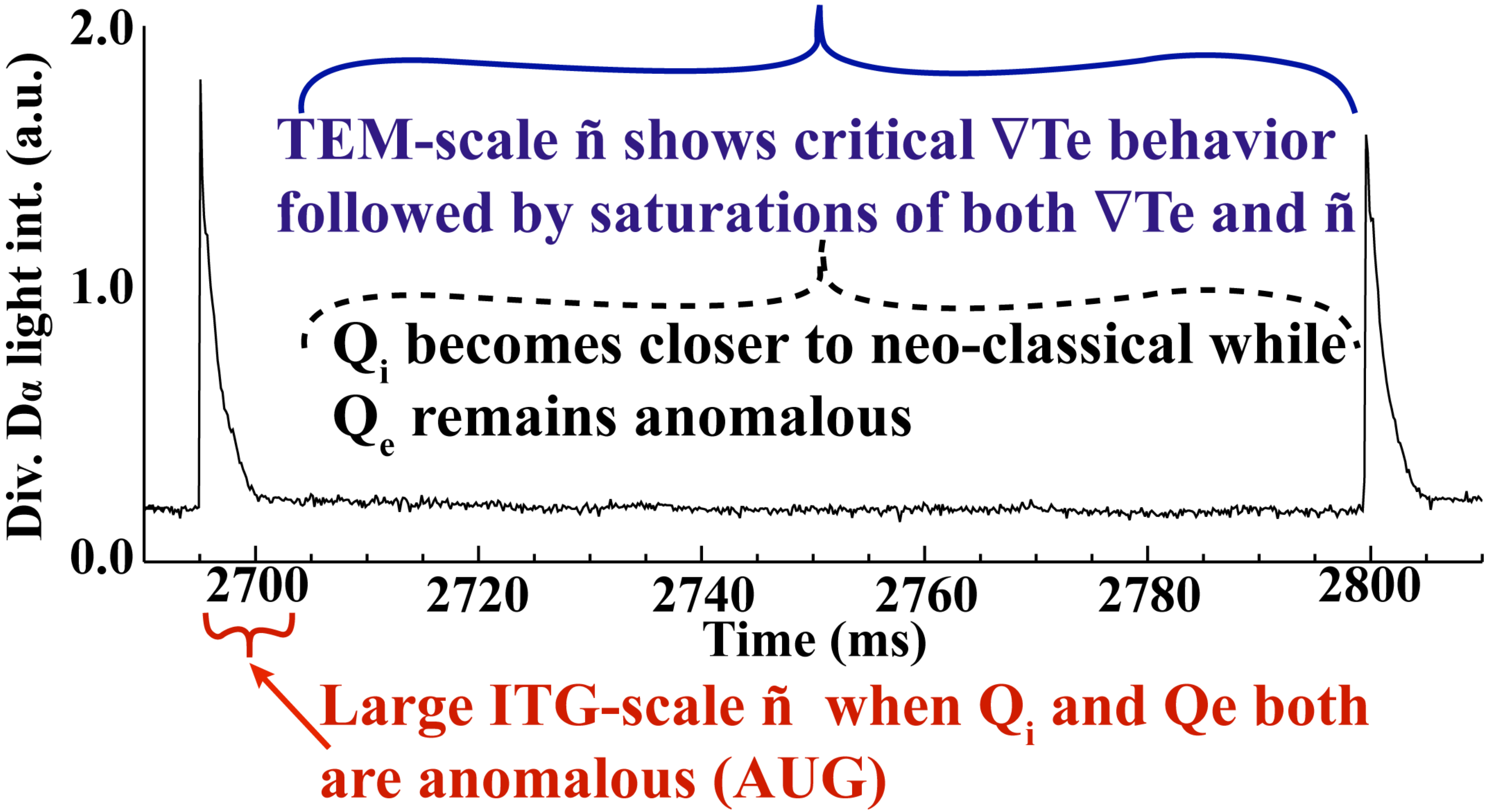
These observations can improve our pedestal evolution predictions by explaining some of the inter-ELM Q_e and Q_i



Thank you