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

K. Barada

In collaboration with

1University of California, Los Angeles, CA, USA
2Princeton Plasma Physics Laboratory, Princeton, NJ, USA
3General Atomics, San Diego, CA, USA
4College of William and Mary, Williamsburg, VA, USA
5University of Wisconsin, Madison, WI, USA

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 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 $\nabla n_e$

Note: Although ETG and MTM modes are thought/predicted to explain some of the $Q_e$, in this work ETG-scale $\tilde{n}$ are not measured and the identification of MTM like modes are not conclusive.
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 \( \nabla P_{e\text{,ped}} \) 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.

\(^1\) Snyder et al, NF (2011)
Experiments are performed in Lower Single Null shape H-mode plasmas with low frequency type-I ELMs

\[ I_p \approx 1 \, \text{MA}, \quad B_t \approx 2.1 \, \text{T}, \quad \text{Power close to } P_{L-H}, \quad P_{\text{NBI}} \approx 2.3 \, \text{MW}, \quad n_e \approx 5.1 \times 10^{19}/\text{m}^3 \]

- 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.
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
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 $\nu_i^* \sim 0.74$)
- NC ion heat flux contribution to total ion heat flux changes at different radii
- Decreasing $\nu_i^*$, difference between estimated and neoclassical $Q_i$ increases (Haskey et al, IAEA 2020)
ITG and TEM-scale $\tilde{n}$ in the pedestal are measured by Doppler Backscattering (DBS) Diagnostics

- Spatially, temporally, and wave number resolved $\tilde{n}$ 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 $\tilde{n}$.
- Local ExB velocity shear is calculated from estimated $v_{E\times B}$ at different probe radii
- ITG-scale ($k_\theta \rho_s \sim 0.3$) $\tilde{n}$ is measured near the foot of the pedestal whereas TEM-scale ($k_\theta \rho_s \sim 0.7-1.2$) $\tilde{n}$ is measured in the steep gradient region of the pedestal.
ITG-Scale $\tilde{n}$ near pedestal foot increases right after ELM and is subsequently suppressed until the next ELM.

- ITG scale $\tilde{n}$ 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 $D\alpha$ emission intensity
Suppression of ITG-scale turbulence correlates with ExB shear evolution and increase in pedestal $\nabla n_e$

- ExB shear near pedestal foot drops right after ELM crash and ITG scale $\tilde{n}$ increases
- Within few ms, local ExB shear increases and ITG-scale $\tilde{n}$ is suppressed
- Further increase in local ExB shear leads to further but small decrease in ITG-scale $\tilde{n}$ but not complete suppression
Suppression of ITG-scale turbulence correlates with ExB shear evolution and increase in pedestal $\nabla n_e$

- ExB shear near pedestal foot drops right after ELM crash and ITG scale $\bar{n}$ increases
- Within few ms, local ExB shear increases and ITG-scale $\bar{n}$ is suppressed
- Further increase in local ExB shear leads to further but small decrease in ITG-scale $\bar{n}$ but not complete suppression
- ITG-scale $\bar{n}$ evolution is consistent with $Q_i$ 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
- $\nabla n_{e,\text{ped}}$ increase is correlated with ITG-scale $\bar{n}$ suppression

*E. Viezzer et al., Nucl. Fusion (2017)
TEM-scale $\tilde{n}_{DBS}$ in the steep gradient region increases after a time delay from the ELM onset

- TEM-scale $\tilde{n}$ 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 $\tilde{n}$ increases after a time delay and the same delay has been observed in all steep gradient localized probed locations.
Steep gradient localized TEM $\vec{n}$ shows a critical $\nabla T_e$ behavior

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

TEM-scale $\tilde{n}$ increases with $\nabla T_e$ supported by presence of increased background $T_i/T_e$ and $\nabla n_e$

- At critical $\nabla T_e$, TEM-scale $\tilde{n}$ increases supported by presence of increased background $T_i/T_e$ and $\nabla n_e$
- TEM-scale $\tilde{n}$ is nearly saturated with nearly saturated $\nabla T_e$ and background $T_i/T_e$ and $\nabla n_e$ in the presence of higher ExB shear
- This TEM-scale $\tilde{n}$ 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 $\rho \sim 0.5$. 
With ECH, $T_{e,ped}$ increases and $n_{e,ped}$ decreases whereas $P_{e,ped}$ does not change much.

- ECH at $\rho \sim 0.5$ added to beam heated discharge
- Smaller and higher frequency ELMs replace larger low frequency ELMs
- How different gradients change with electron heating?
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 $\nabla n_e$ and higher $\nabla T_e$
- Pedestal $\nabla T_e$ is always higher than pure NBI case.
- Pedestal $\nabla P_e$ 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 $\bar{n}$?
At lower $T_i/T_e$ and lower $\nabla n_e$, TEM-scale $\bar{n}$ decreases and ITG-scale $\bar{n}$ increases consistent with theoretical predictions

Time averaged
- ITG-scale $\bar{n}$ increases $\sim$50%
- TEM-scale $\bar{n}$ decreases $\sim$66%

- TEM $\bar{n}$ stabilization with ECH consistent with theoretical predictions$^1$ of increased $\nabla T_e$ threshold for lower $T_i/T_e$ and lower $\nabla n_e$
- ITG-scale $\bar{n}$ increase is also consistent with this theory$^1$ which suggests a lower $\nabla T_i$ threshold

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

Linear TGLF simulations show in the steep gradient region, the most unstable modes:
- have similar $k_\theta \rho_s$ of TEM-scale $\tilde{n}$ 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 $\rho \sim 0.98$
- with $k_\theta \rho_s \sim 0.2$, close to the ITG-scale $\tilde{n}$ observed in experiment
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 $\tilde{n}$ increases at critical $\nabla T_e$ and can be responsible for anomalous $Q_e$ inferred from experiments

• ITG and TEM-scale $\tilde{n}$ evolutions are consistent with theoretical predictions of these being ITG and TEM instabilities respectively
These observations can improve our pedestal evolution predictions by explaining some of the inter-ELM $Q_e$ and $Q_i$.

TEM-scale $\tilde{n}$ shows critical $\nabla T_e$ behavior followed by saturations of both $\nabla T_e$ and $\tilde{n}$.

$Q_i$ becomes closer to neo-classical while $Q_e$ remains anomalous.

Large ITG-scale $\tilde{n}$ when $Q_i$ and $Q_e$ both are anomalous (AUG).

Thank you