Observation of a Critical Gradient Threshold for Electron Temperature Fluctuations in the DIII-D Tokamak

Presented by

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Motivation: Validation of the critical gradient paradigm for turbulence driven transport

- Gyroradius-scale mode becomes linearly unstable, explosive growth leads to large macroscopic change in heat fluxes and diffusivities
- Threshold can be up-shifted non-linearly, e.g. Dimits shift
Motivation: Validation of the critical gradient paradigm for turbulence driven transport

- Direct validation of this picture requires systematic measurements of the turbulent fluctuations driven unstable by the new mode, which cause the increased transport
  - Previous work restricted to indirect studies
Motivation: Critical gradient leads to stiff transport

Many previous studies of critical gradients and stiffness:
- B. Coppi and N. Sharky, Nucl. Fusion 21, 1363 (1981)
and lots more

- **Local stiffness parameterizes incremental change in flux for incremental change in gradient:**
  \[ S = \frac{VT_e}{Q_e} \frac{\partial Q_e}{\partial (VT_e)} \]

- **Global stiffness (i.e. profile resilience):** little change to profiles with additional heating, strongly diminishing returns
Summary of results

• First direct, systematic observation of a critical gradient in a locally measured fluctuating turbulent quantity in a tokamak
  – Critical gradient observed for both electron thermal transport and electron temperature fluctuations

\[ Q_e, \frac{\delta T_e}{T_e} \]

• Evidence identifies threshold with \( \nabla T_e \) driven trapped electron mode turbulence

\( \nabla T_e \)-TEM

• Supported by linear & non-linear calculations
  – Linear gyrofluid calculations with TGLF
  – Nonlinear gyrokinetic simulations with GYRO
L-mode target discharge

- **Upper single null, diverted**
  - \( I_p = 0.8 \text{ MA} \)
  - \( B_T = -2 \text{ T} \)
  - \( <n_e> \approx 2 \times 10^{13} \text{ cm}^{-3} \)
  - \( R \approx 1.7 \text{ m}, a \approx 0.6 \text{ m} \)

- **ECH-only and NBI+ECH shots**
  - Rotation scan at fixed power
  - \( P_{ECH} \approx 3 \text{ MW}, 1 \text{ gyrotron modulated} \)
  - \( P_{NBI} \approx 2 \text{ MW} \)

- **Turbulence measurements:**
  - \( T_e \) fluctuations, 2 radii per shot (CECE)
  - \( nT \) crossphase (CECE + reflectometry)
  - Density fluctuations (BES, DBS)
Steady-state time periods used to average profile and turbulence data

- Highly reproducible, stationary discharges
- 3 time periods per shot: ECH-only, ECH+Co-NBI, and either ECH+Bal-NBI or ECH+Ctr-NBI
Local electron temperature gradient and rotation systematically varied in repeated L-mode discharges

- ECH deposition locations modified shot-to-shot to locally scan $\nabla T_e$ at $\rho=0.6$

- Fluctuation measurements acquired near $\rho=0.6$ during ~500-800 ms steady-state periods

- Rotation (and flow shear) varied by changing NBI mix at fixed power

- Other profiles:
  - For ECH only $T_i$ lower everywhere, $T_e$ lower in core ($\rho<0.5$)
  - Density feedback controlled, well-matched
  - $Z_{\text{eff}}$ higher with Ctr-NBI
Long wavelength electron temperature fluctuations increase with $1/L_{Te}$

ECH+Bal-NBI $Te$ fluctuation power spectra

- $1/L_{Te} = 3.01 \, m^{-1}$  $\delta T_e/T_e \approx 1.5 \pm 0.2 \%$
- $1/L_{Te} = 3.70 \, m^{-1}$  $\delta T_e/T_e \approx 1.8 \pm 0.2 \%$
- $1/L_{Te} = 3.84 \, m^{-1}$  $\delta T_e/T_e \approx 2.0 \pm 0.2 \%$

$k_\theta \rho_s \leq 0.4$
Rho=0.6
$T_e$ fluctuations show critical gradient threshold in $1/L_{Te}$

\[ \frac{\delta T_e}{T_e} \]

$\tilde{Q}_e = \frac{3 n_e T_e}{2B} k_\theta \left( \frac{|\tilde{n}_e|}{n_e} |\tilde{\varphi}| n_{e,\varphi} \sin \alpha_{n_e,\varphi} + \frac{|\tilde{T}_e|}{T_e} |\tilde{\varphi}| T_{e,\varphi} \sin \alpha_{T_e,\varphi} \right) \]

$\eta \leq 0.4$

$\rho \approx 0.55$ and $\rho \approx 0.61$

Power balance inferred flux increases non-linearly with $1/L_{Te}$, limited rotation dependence

- Electron heat flux similar to results from F. Ryter et al. Phys. Rev. Lett. 95, 085001 (2005), but also shows little rotation dependence

- Further transport and stiffness analysis reported in J.C. DeBoo et al., Phys. Plasmas 19, 082518 (2012)
Simultaneous increase in $T_e$ fluctuations and heat flux with little sensitivity to rotation or flow shear

$$\bar{Q}_e = \frac{3n_e T_e}{2B} k_\theta \left( \left| \frac{n_e}{n_e} \right| \left| \bar{\phi} \right| \gamma_{n_e,\varphi} \sin \alpha_{n_e,\varphi} + \left| \frac{T_e}{T_e} \right| \left| \bar{\phi} \right| \gamma_{T_e,\varphi} \sin \alpha_{T_e,\varphi} \right)$$

- $\delta T_e/T_e$ can only partially account for $Q_e$ increase
  - $Q_e$ increase $>10x$, $\delta T_e/T_e \sim 2x$
  - Changes to transport crossphases, High-k (ETG) possible
Fit to model equation quantifies critical gradient value and uncertainty estimate


• Data varied within uncertainties; mean and standard deviation of fits to:

\[
\frac{\delta T_e}{T_e} \Big|_{\text{crit}} = 2.8 \pm 0.4 \text{ m}^{-1}
\]

\[
\chi_e \propto \frac{\delta T_e^2}{T_e^2} = c_0 + c_1 (L_{T_e}^{-1} - L_{T_e}^{-1}|_{\text{crit}})^\ell H (L_{T_e}^{-1} - L_{T_e}^{-1}|_{\text{crit}})
\]

\[
\rho = 0.55 \text{ and } \rho = 0.61
\]
Heat pulse analysis shows critical gradient; stiffness parameter increased above threshold

- ECH-only threshold at $1/L_{\text{crit}} = 3.0 \pm 0.2 \text{ m}^{-1}$, within uncertainties of temperature fluctuation threshold at $2.8 \pm 0.4 \text{ m}^{-1}$

- See C. C. Petty NO4.00009 Wednesday for additional heat pulse analysis
Threshold identified

- First direct, systematic observation of a critical gradient in a locally measured fluctuating turbulent quantity in a tokamak
  - Critical gradient observed for both electron thermal transport and electron temperature fluctuations
  - Electron temperature fluctuations threshold
  - Electron thermal diffusivity threshold
    - Increase in local stiffness above threshold
  - Nonlinear increase in electron heat flux
- Evidence identifies threshold with $\nabla T_e$ driven trapped electron mode turbulence

\[ Q_e, \frac{\delta T_e}{T_e} \]

- Supported by linear & non-linear calculations
  - Linear gyrofluid calculations with TGLF
  - Nonlinear gyrokinetic simulations with GYRO
What trends and characteristics can be observed in the turbulence measurements?

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$\nabla T_e$ - TEM

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Density fluctuations show little change with $1/L_{Te}$, The ratio $(\delta T_e/T_e)/(\delta n_e/n_e)$ increases at low-$k$

- $1/L_{Te}$ threshold & $(\delta T_e/T_e)/(\delta n_e/n_e)$ trend consistent with transition to $\nabla T_e$-TEM turbulence
- Intermediate-$k$ fluctuations higher with NBI
Changes to intermediate-k density fluctuation spectra consistent with new mode being driven at high $1/L_{Te}$

- Frequency-localized increase in DBS spectrum with $1/L_{Te}$ in ECH+Bal-NBI plasmas
  - Electron diamagnetic direction is negative direction
  - Increase on electron diamagnetic side of spectrum consistent with $vT_e$-TEM
- Different behavior below critical gradient with the various NBI configurations
The crossphase angle between fluctuating quantities is a fundamental characteristic of plasmas instabilities

- **Crossphase measurements:**
  - Changes imply changes to dominant mode driving transport
  - Changes give reason to consider changes to transport crossphases
  - Strong, multi-field constraint for comparison to simulations

- **Coherency between electron temperature and density fluctuations increases with $1/L_{Te}$**
  - Coherent frequency range varies with rotation, consistent with a Doppler shift

- **Measured crossphase changes with $1/L_{Te}$**
nT crossphase changes with $a/L_{Te}$, implying change in dominant instability driving turbulent transport

- ECH+Co-NBI and ECH+Bal-NBI quantitatively similar to previous results (White PoP 2010, Rhodes NF 2011, Wang PoP 2011), where changes to $T_e/T_i$ and collisionality (with comparatively little $1/L_{Te}$ change) were attributed to ITG to TEM transition
Predicted linear nT crossphase from TGLF consistent with interpretation of measurements in ECH+Co-NBI as transition from predominantly ITG to TEM

- nT crossphase shows little trend with $\alpha/L_{Te}$ for each mode independently
  - Interpretation: measured crossphase is weighted average

- Crossphase measurements changed from $-149^\circ \pm 15^\circ$ to $-86^\circ \pm 7^\circ$; trend consistent with ITG below threshold in ECH+Co-NBI plasmas
ECH-only plasmas exhibit different behavior, implying different instability below threshold.

- Measurement implies different instability behavior below threshold, current conjecture for ECH-only is $\nabla n_e$-TEM.
Different instability behavior also implied for ECH+Ctr-NBI by nT crossphase measurements

- Significantly different behavior for ECH+Ctr-NBI at low $1/L_{Te}$
  - Radial dependence: positive values both from inner location
All cases converge at high $1/L_{Te}$, implying common mode present in all four
Accumulated evidence strongly constrains identification of $\nabla T_e$ -TEM

- First direct, systematic observation of a critical gradient in a locally measured fluctuating turbulent quantity in a tokamak
  - Critical gradient observed for both electron thermal transport and electron temperature fluctuations
- **Accumulated evidence identifies threshold with $\nabla T_e$ driven trapped electron mode turbulence**
  - $1/L_T$ threshold
  - The ratio $(\delta T_e/T_0)/(\delta n_e/n_e)$ increases for low-k fluctuations
  - $nT$ crossphase
    - Measurements imply common mode above threshold
    - Measured crossphase moves from ITG toward TEM in linear predictions
  - Spectral changes consistent with TEM
- **Supported by linear & non-linear calculations**
  - Linear gyrofluid calculations with TGLF
  - Nonlinear gyrokinetic simulations with GYRO
How to experimental results compare to linear and nonlinear predictions?

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- Evidence identifies threshold with $\nabla T_e$ driven trapped electron mode turbulence
  - $1/L_{Te}$ threshold
  - The ratio $(\delta T_e/T_e)/(\delta n_e/n_e)$ increases
  - nT crossphase
    - Common mode above threshold
    - Measured crossphase moves from ITG toward TEM in linear predictions
  - Spectral changes consistent with TEM

- **Supported by linear & non-linear calculations**
  - Linear gyrofluid calculations with TGLF
  - Nonlinear gyrokinetic simulations with GYRO
Growth rate spectrum of fastest growing linear modes propagating in electron diamagnetic direction generally increases with $1/L_{Te}$

- The Trapped-Gyro-Landau-Fluid (TGLF) code used for linear stability analysis
  - Experimental profiles used as inputs
- TEM growth rates consistent with experimental critical gradient

Other measures ($\gamma(k), \langle \gamma \rangle, \gamma/k^2$) similar

Range for experimental threshold

$2.8 \pm 0.4 \text{ m}^{-1}$

$k_\theta \rho_s \approx 0.3$

$\rho = 0.6$

Other measures ($\gamma(k), \langle \gamma \rangle, \gamma/k^2$) similar
Density gradient affects linear stability calculations, instability above $\eta_e = L_{n_e}/L_{T_e} \sim 2$

- No large non-linear upshift of threshold ("Dimits shift") observed
  - If an upshift exists, it’s impact is smaller than the $\sim 10\%$ variations in other parameters that lead to scatter in the growth rate calculations
  - Consistent with simulations of with $\nabla T_e$-TEM showing weak impact of zonal flows (Dannert PoP 2005, Ernst PoP 2009); opposite seen in simulations for $\nabla n_e$-TEM (Ernst PoP 2004), ITG (Dimits PoP 2000), see also following talk

\[ \frac{\delta T_e}{T_e} \]

\[ \langle \gamma_{\text{electron}}/(c_s/a) \rangle \]

Mean $(0.0 \leq k_\parallel \rho_s \leq 0.4)$ linear gyrofluid growth rates at $\rho=0.6$
Nonlinear GYRO prediction for $Q_e$ close to experimental values in ECH-only plasmas at low $a/L_{Te}$, but a shortfall exists at high $a/L_{Te}$

- **Global nonlinear gyrokinetic simulations with GYRO**
  - Electrostatic, with 3 kinetic species (electrons, deuterium, and carbon)
  - Wavenumbers up to $k_{\theta}\rho_s \sim 1.3$ included; box widths $\sim 100 \rho_s$

- **Ion heat flux systematically under-predicted**
GYRO under-predicts $\delta Te/Te$, but shows similar trend with $a/L_{Te}$

- Synthetic CECE diagnostic used on GYRO output (Holland PoP 2009)
- Even though $Q_e$ is matched reasonably well at low $a/L_{Te}$, electron temperature fluctuations are under-predicted
- See S.P. Smith TP8.00004 Thursday for more GYRO, TGLF, and TGYRO results
Principle result

- Critical gradient observed for both electron thermal transport and electron temperature fluctuations

\[ \mathcal{Q}_e = \frac{3 n_e T_e}{2B} k_\theta \left( \left| \frac{n_e}{n_e} \right| \gamma_{n_e,\varphi} \sin \alpha_{n_e,\varphi} + \left| \frac{T_e}{T_e} \right| \gamma_{T_e,\varphi} \sin \alpha_{T_e,\varphi} \right) \]

\[ \frac{Q_e}{Q_{GB}} = \frac{Q_e}{n_e T_e c_s (\rho_s / a)^2} \]
Summary of results

• Observed effect of critical gradient threshold in multiple parameters
  – \( \Delta T_e/T_e \), heat pulse analysis of \( \chi_e \), experimental power balance \( Q_e \), local stiffness, linear growth rates

• \( \nabla T_e \)-TEM identified as instability responsible for threshold
  – \( 1/L_{Te} \) threshold, \( (\Delta T_e/T_e)/(\Delta n_e/n_e) \), \( nT \) crossphase, spectral changes

• Characteristics of \( \nabla T_e \)-TEM:
  – Low-k (ITG-scale) if driven strongly (not strictly intermediate-k)
  – At low-k, \( \Delta T_e/T_e \) steadily increases above threshold, \( \Delta n_e/n_e \) does not
  – No significant non-linear upshift observed

• Nonlinear GYRO predictions reproduce trends in \( Q_e \) and \( \Delta T_e/T_e \)
  – \( Q_e \) in reasonable agreement at low \( 1/L_{Te} \), shortfall at high \( 1/L_{Te} \)
  – \( \Delta T_e/T_e \) under-predicted for all \( 1/L_{Te} \)
  – Further synthetic diagnostic comparisons ongoing