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

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Plasma turbulence plays a major role in redistributing energy in a broad array of physical systems, such as astrophysical [1], processing [2], and laboratory plasmas [3], including the hot, confined plasmas used for fusion energy research. This is particularly true for magnetic confinement fusion devices, where the transport of particles, momentum, and heat across the magnetic field by gyroradius-scale turbulence is a major issue. This turbulence is widely thought to arise due to linear instabilities, differing from neutral fluid dynamics, where turbulence arises while the system is linearly stable [4]. Many of these gyroradius-scale modes are expected to exhibit a threshold in the equilibrium gradient providing free energy for the instability, where the mode is linearly stable below the threshold and unstable above [5]. Direct, systematic observation of instability has been related to critical gradient criteria in linear experiments [6–8]; however, no previous work exists in the core of a confined high-temperature plasma. Indirect evidence supporting the existence of critical gradients has been reported in tokamaks for both electron and ion thermal transport [9–13]. Many experiments in tokamaks have related fluctuation levels monotonically to driving gradients or input power or have investigated transient measurements [3], but controlled, steady-state observations directly demonstrating a threshold for a gradient in a systematic experiment have proven elusive due to the combination of plasma conditions, localized heating, and diagnostic capabilities necessary to isolate and directly observe the critical gradient behavior. A generic attribute of gradient-driven turbulence is that the system tends to be constrained nearby the marginal value for the critical gradient. The dynamics of this process have been studied, for instance, within the context of self-organized criticality [14] for plasma turbulence [15]. We present observations of how linear stability, measured fluctuations, and heat flux are related as a critical gradient is surpassed in a toroidal, high-temperature plasma.

A phenomenon related to critical gradients is stiff transport. Qualitatively, stiffness locally parametrizes the incremental change in flux for an incremental change in gradient. A consequence of globally stiff transport (i.e., high stiffness at all radii) is little change to equilibrium profiles with additional source input. Since fusion power in a magnetically confined plasma is proportional to pressure squared, the diminishing returns enforced by stiff heat transport could present an issue for the efficiency of future reactors [16]. The observations presented here relate to electron temperature fluctuations and local profile stiffness, which is relevant to scenarios with strong electron heating, such as would be expected by alpha particles in burning plasmas.

In this Letter, for the first time, we present direct, systematic evidence of a critical gradient threshold in a locally measured turbulence characteristic in the core of a tokamak. As illustrated in Fig. 1(a), we observe a threshold in $L_T^{-1} = [\nabla T_e]/T_e$ [17] above which electron temperature fluctuations, $\delta T_e/T_e$, steadily increase. A critical gradient was simultaneously observed for electron thermal transport, the effect of which can be seen in Fig. 1(b). In contrast, measurements of the density fluctuation level have no definite threshold.

The experiment was performed in the DIII-D tokamak [19] and was designed to investigate critical gradients and electron profile stiffness [18]. Plasmas were in $L$-mode (no edge transport barrier); MHD quiescent (no equilibrium-scale instabilities impacted the presented measurements); upper single null diverted (magnetic geometry with a single magnetic X-point, at the top of the plasma), with...
The change in $L_{Te}^{-1}$ was predominantly due to $\nabla T_e$; $T_e$ also increased but was restricted to the range of 0.7 to 0.9 keV at $\rho = 0.6$. The local value of $L_{Te}^{-1}$ from data as in Fig. 2 provides the abscissa value for each $\delta T_e/T_e$ measurement in Fig. 1. There are $\sim 25\%$ uncertainties in plotted values of $L_{Te}^{-1}$.

The $n_e$ profiles and $T_e$ profiles for $\rho > 0.5$ were well matched (to each other) for all conditions, although the minimum value of $L_{Te}^{-1}$ for cases with NBI was higher. The $T_i$ profiles were well matched for cases with NBI but were uniformly lower for ECH-only. The effective ionic charge at $\rho = 0.6$ for most of the discharges was $Z_{\text{eff}} \approx 2.3$–2.8 but was systematically higher for shots with ECH + Ctr – NBI, where $Z_{\text{eff}} = 2.9$–3.2. The main ion species was deuterium, and the dominant impurity was carbon. The presented results indicate little sensitivity to toroidal rotation and flow shear changes.

Simultaneous measurements of $\delta T_e/T_e$ and the cross phase, $\alpha_{n_e,T_e}$, between electron temperature and density fluctuations were acquired with a coupled correlation electron cyclotron emission (CECE) radiometer and reflectometer [20–22]. The CECE system [23] acquired...
$$\Delta T_e/T_e$$ at two radial locations, $\rho = 0.55$ and $\rho = 0.61$; the plasma was optically thick ($\tau > 5$) for the ECE measurements. A reflectometer array [24] overlapped the CECE channels at $\rho = 0.61$; most shots also showed significant, although lower, coherency with CECE channels at $\rho = 0.55$. Due to small density profile variations, there existed some mismatch in the radial location of the closest CECE and reflectometer channels; however, this would be expected to only change the measured coherency, not the existence of some mismatch in the radial location of the closest CECE and reflectometer channels. All reported turbulence measurements are long wavelength ($k_{\phi} \rho_s \leq 0.5$; $\rho_s$ is the ion sound gyroradius, and $k_{\phi}$ is the poloidal wave number).

The principal result is shown in Fig. 1, where both the local electron heat flux and $\Delta T_e/T_e$ increase rapidly above a critical value of $L_{T_e}^{-1}$. Figure 1(a) shows $\Delta T_e/T_e$ measurements: a threshold value is observed at $L_{T_e}^{-1} \approx 3 \text{ m}^{-1}$, below which $\Delta T_e/T_e$ is constant (within uncertainties that are given by the detection limit of the diagnostic [21,26]) and above which it steadily increases by a factor of $\sim 2$. This observation is consistent with the trapped electron mode (TEM) instability [27] that is characterized by growth rates proportional to $L_{T_e}^{-1}$. The normalized electron collision frequency, $\nu^* = \nu_{ei}/(c_s/a)$ ($\nu_{ei}$ is the electron-ion collision frequency), is $\sim 0.1$ at the measurement locations, and $\beta$ (the ratio of plasma pressure to magnetic field pressure) is $< 0.5\%$, which places the experiment in a TEM relevant regime. The electron heat flux from the power balance analysis for the data set is plotted in Fig. 1(b), normalized to the gyro-Bohm flux (the expected scale size of the flux from dimensional analysis), $Q_{GB} = n_e T_e c_s (\rho_s/a)^2$, where $c_s = \sqrt{T_e/m_i}$. The heat flux increases nonlinearly with $L_{T_e}^{-1}$, similar to Ref. [11]. The electron heat flux inferred by power balance transport analysis is heavily constrained by the heat sources; varying input profiles within uncertainties yield an estimated random error of $\sim 5\%$ or less. Systematic errors would be expected to be highly correlated and should not affect interpretations of results. For further transport analysis and equilibrium information, including quantification of stiffness, see Ref. [18].

Measurements of $\delta n/n$ from beam emission spectroscopy, depicted in Fig. 1(a), at $\rho = 0.58$ in the ECH + CO – NBI scan, show a $\sim 25\%$ increase from the minimum $L_{T_e}^{-1}$ to the next lowest value, above which $\delta n/n$ shows little change. The increase in the ratio ($\delta T_e/T_e$)/($\delta n/n$) is consistent with a transition to predominantly TEM turbulence [28].

Model fits were performed to quantify the threshold value. Taking the electron thermal diffusivity, $\chi_e$, to be proportional to $(\Delta T_e/T_e)^2$ and using a functional form similar to Ref. [29], the $(\Delta T_e/T_e)^2$ data were fit to

$$c_0 + c_1 (L_{T_e}^{-1} - L_{T_e}^{-1}) H(L_{T_e}^{-1} - L_{T_e}^{-1}) \text{crit},$$

where $H(x)$ is the Heaviside function and $c_0$, $c_1$, $l$, and $L_{T_e}^{-1} \text{crit}$ are the fit parameters. By varying $(\Delta T_e/T_e)^2$ within uncertainties, the average and standard deviation of an ensemble of fits resulted in $L_{T_e}^{-1} \text{crit} = 2.8 \pm 0.4 \text{ m}^{-1}$. The average fit is shown with a solid line in Fig. 1(a). Several functional forms were used, with Eq. (1) yielding the smallest average goodness-of-fit parameter, $\chi^2$, for the ensemble.

A critical gradient for $\chi_e$ was also found for ECH-only plasmas using transient heat pulse analysis [18] at $L_{T_e}^{-1} \text{crit} = 3.0 \pm 0.2 \text{ m}^{-1}$, which is within uncertainties of the critical value for $\Delta T_e/T_e$. Above the threshold, stiffness locally increased, as is reflected in Fig. 1(b).

It has been argued in previous work that zonal flows have little influence on $\nabla T_e$-TEM turbulence, with little expected nonlinear upshift of the critical gradient [30,31]. The experimental results are therefore compared to linear predictions, and we defer detailed comparison to nonlinear simulations to future work. Figure 3(a) shows linear gyrofluid results from the code TGFL [32] that use experimental profiles for inputs. Globally, density profiles were well matched from shot to shot, but small variations in the local density gradient appear to be significant. Plotted is the mean growth rate over $0.0 \leq k_{\phi} \rho_s \leq 0.4$ of the fastest growing mode propagating in the electron diamagnetic direction, $(\gamma_e/(c_s/a))$, where the upper bound was chosen to approximate the CECE diagnostic. The remaining scatter in the data is attributed to additional dependencies beyond $\chi_e$. A rapid increase begins at $\eta_e = 2$, consistent with critical gradient behavior. Figure 3(b) shows the

FIG. 3 (color online). (a) Linear gyrofluid growth rates of the fastest growing modes propagating in the electron diamagnetic direction averaged over $0.0 \leq k_{\phi} \rho_s \leq 0.4$ and (b) electron temperature fluctuations as a function of $\eta_e = L_{n_e}/L_{T_e}$. There are dashed vertical lines for reference at $\eta_e = 2$. 

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data in Fig. 1(b) plotted as a function of $\dot{e}$; a sharp increase occurs at $\dot{e}$.

Figure 4(a) shows measured power spectra in the ECH + Bal − NBI case: the measured fluctuation level increases with $L_1$. Values for $\dot{e}$ plotted in Fig. 1 are determined by integration of the $\dot{e}$ power spectra between 0–400 kHz. The peaks at $\approx 20$ kHz in Fig. 4(a) appear to be related to a geodesic acoustic mode. Figure 4(b) shows the coherency between electron temperature fluctuations; note that, since thermal noise determined by the equilibrium value of $\dot{e}$ dominates the autopower spectrum of a single ECE channel, one would expect the coherency to increase if $\dot{e}$ increases, with all else the same. A large number of records are used, $\approx 2k–4k$ from the long steady-state periods, so even coherency values of $\gamma_{n,\dot{e}} \approx 0.05–0.10$ are significant. For the other conditions in the rotation scan, the peak in the spectra that occurs at $\approx 80$ kHz in Fig. 4(b) shifts, consistent with a Doppler shift due to the equilibrium $E \times B$ drift, which is dominated by toroidal rotation. Figure 4(c) shows the cross

FIG. 4 (color online). (a) Electron temperature fluctuation power spectra. (b) Coherency and (c) cross phase between CECE and reflectometry for ECH + Bal − NBI at $\rho = 0.6$. The legend indicates local values of $L_1$ for the measurements and integrated (0–400 kHz) values of $\dot{e}$. The approximate coherency noise floor is shown by a dashed horizontal line in (b).

$\dot{e}$ data in Fig. 1(b) plotted as a function of $\eta_e$; a sharp increase occurs at $\eta_e = 1.9$.

Figure 4(a) shows measured power spectra in the ECH + Bal − NBI case: the measured fluctuation level increases with $L_1$. Values for $\dot{e}$ plotted in Fig. 1 are determined by integration of the $\dot{e}$ power spectra between 0–400 kHz. The peaks at $\approx 20$ kHz in Fig. 4(a) appear to be related to a geodesic acoustic mode. Figure 4(b) shows the coherency between electron temperature and density fluctuations; note that, since thermal noise determined by the equilibrium value of $\dot{e}$ dominates the autopower spectrum of a single ECE channel, one would expect the coherency to increase if $\dot{e}$ increases, with all else the same. A large number of records are used, $\approx 2k–4k$ from the long steady-state periods, so even coherency values of $\gamma_{n,\dot{e}} \approx 0.05–0.10$ are significant. For the other conditions in the rotation scan, the peak in the spectra that occurs at $\approx 80$ kHz in Fig. 4(b) shifts, consistent with a Doppler shift due to the equilibrium $E \times B$ drift, which is dominated by toroidal rotation. Figure 4(c) shows the cross

\[ \alpha_{n,\dot{e}} \] increases ($\dot{n}_e$ and $\dot{\dot{e}}$ are more in phase; $\dot{n}_e$ leads $\dot{\dot{e}}$) with $L_1$. A relatively constant cross phase is measured over frequencies with sufficiently high coherency.

Values for $\alpha_{n,\dot{e}}$ are plotted in Fig. 5, averaged over the frequency range where $\gamma_{n,\dot{e}} \geq 80\%$ of the maximum coherency. Within each NBI configuration, $\alpha_{n,\dot{e}}$ changes with $L_1$ while rotation and flow shear did not vary significantly. Additionally, different rotation and shear values correspond to several of the same $\alpha_{n,\dot{e}}$ values. This shows that $\alpha_{n,\dot{e}}$ is not directly dependent on rotation or flow shear in this experiment; similar reasoning applies to the $\dot{e}$ measurements.

For the $L_1$ scans in ECH + Co − NBI and ECH + Bal − NBI, the trends and values in the cross phase are remarkably similar to previous experiments [21,22,33,34]; there, it was concluded that the trend in the cross phase was associated with a change in the dominant instability, from ion temperature gradient or mixed ion temperature gradient and TEM at low (more negative) values of $\alpha_{n,\dot{e}}$ to TEM at higher values. In those experiments, ECH was added near the axis of Ohmic and NBI-heated $L$-mode plasmas, which had large effects on $\dot{e}$ and collisionality but caused a comparatively small change to $L_1$. Here, with targeted off-axis ECH, large changes to $L_1$ were induced. Either set of parameter changes would be expected to favor TEM instability.

Three direct measurements of turbulence characteristics are individually consistent with $\dot{e}$-driven trapped electron modes at high $L_1$: the $L_1$ threshold, the

FIG. 5 (color online). Cross phase angle between electron density and temperature fluctuations.
convergence of $\alpha_{n,T_e}$ at high $L_T^{-1}$, and the $(\delta T_e/T_e)/(\delta n/n)$ trend. The collisionality and $\beta$ reside in a TEM relevant regime. Both the mean linear growth rates and $\delta T_e/T_e$ showing a sharp increase at $\eta_T = 2$ further support the $\nabla T_e$-TEM interpretation. In sensitivity studies, the growth rates for the electron direction propagating modes in Fig. 3(a) increase with $L_T^{-1}$ and are stabilized by increasing $\nu_T/(c_s/a)$, which identifies the modes in the calculation as $\nabla T_e$-TEM. The accumulated evidence strongly enforces the identification of the experimentally observed threshold with $\nabla T_e$-TEM turbulence.

It is notable that, while $\tilde{Q}_e/(n_e T_e)$ increases by more than $10 \times$, $\delta T_e/T_e$ only increases by $\sim 2 \times$. The electrostatic turbulent cross-field electron heat flux can be written as [35]

$$
\tilde{Q}_e = \frac{3n_e T_e}{2B} \sum_{k} k_q \left( \frac{\delta n}{n_e} \right) \frac{\delta \varphi}{\gamma_{n,e} \sin \alpha_{n,e}} + \frac{\delta T_e}{T_e} \left( \frac{\delta \varphi}{\gamma_{T,e} \sin \alpha_{T,e}} \right),
$$

(2)

where the sum is taken over the fluctuations associated with each $k_q$ and $\varphi$ is the electrostatic potential (which is not measured). Nonlinear gyrokinetic simulations of similar plasmas found that the conductive term $(\delta T_e, \delta \varphi)$ dominated, accounting for $\sim 90\%$ of $\tilde{Q}_e$ [36]. The $\alpha_{n,T_e}$ measurements indicate a more subtle picture than the $\delta T_e/T_e$ measurements alone. Changes to $\alpha_{n,T_e}$ give reason to consider that the transport related cross phases, $\alpha_{n,T_e}$ and $\alpha_{T,e}$, might also change in such a way that the turbulent heat flux increases. Other possibilities include additional transport from higher $k_q$'s than are measured (in past work from DIII-D, high-$k$ density fluctuations, $k_r \sim 35$ cm$^{-1}$, did increase [34] and intermediate-$k$ density fluctuations, $k_q \sim 4$ and $8$ cm$^{-1}$, did change [37]), a modification to the average wave number of the low-$k$ fluctuations, and nonlocal transport.

Two plausibility checks on the role of cross phase modifications can be accomplished briefly (taking high-$k$ and other contributions to be negligible). First, by contradiction, if one assesses only the conductive term and assumes that the coherency and cross phases between fluctuations do not change, then $\tilde{Q}_e$ would have to increase by $\sim 5 \times$. One would expect such a change to be reflected in the particle transport (unless $\sin \alpha_{n,e} = 0$), which was not the case. Second, the required potential fluctuations to drive the observed $\tilde{Q}_e/(n_e T_e)$ can be assessed. At high $L_T^{-1}$, $\tilde{Q}_e/(n_e T_e) = 45$ m/s and $\delta T_e/T_e = 2\%$. To set a bound, take $\gamma_{T,e} = 1$, and $\alpha_{T,e} = 90^\circ$. Also take the average poloidal wave number to be $(k_q) = 1.5$ cm$^{-1}$ ($k_q \rho_T = 0.3$). One then finds that, for the conductive term to account for $\tilde{Q}_e/(n_e T_e) = 45$ m/s at low-$k$, it would require $e \tilde{Q}_e/T_e = 2.5\%$, a level similar to the measured $\delta T_e/T_e$—the conclusion being that it is indeed plausible.

We have reported the first observation of a critical gradient threshold for a measured turbulent fluctuation level in the core of a tokamak. Both analysis of electron thermal transport and measurements of electron temperature fluctuations show a critical threshold in $L_T^{-1}$ and little sensitivity to rotation or rotation shear. Measurements and supporting calculations strongly constrain identifying the mode responsible for the observed critical gradient threshold to the $\nabla T_e$-TEM instability. The clear inference is that the $\delta T_e/T_e$ increase from $\nabla T_e$-driven TEM turbulence plays a causal role for the increased transport and stiffness.

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[17] For consistency with Ref. [18], the definition used for all scale lengths is $L_T^{-1} = \rho_{m}\sqrt{\frac{1}{\pi}} \frac{\partial \phi}{\partial \rho}$; the radial coordinate, $\rho$, is the square root of the normalized toroidal flux, and $\rho_{m} = \sqrt{\Phi}/(\pi B_0)$, where $\Phi$ is the toroidal flux within the last closed flux surface. For the plasmas reported on here, $\rho_{m} \approx 79$ cm.