Role of Density Gradient Driven Trapped Electron Mode Turbulence in the H-mode Inner Core with Electron Heating


1MIT Plasma Science and Fusion Center, Cambridge, MA 02139
2General Atomics, PO Box 85608, San Diego, CA 92186
3Princeton Plasma Physics Laboratory, PO Box 451, Princeton, NJ 08543
4University of California Los Angeles, PO Box 957099, Los Angeles, CA 90095
5Lawrence Livermore National Laboratory, P.O. Box 808, Livermore, CA 94551
6Fourth State Research, 503 Lockhart Drive, Austin, TX 78704
7University of California San Diego, 9500 Gilman Dr., La Jolla, CA 92039
8University of Wisconsin - Madison, 1500 Engineering Dr., Madison, WI 53706 and
9University of Colorado, DUAN F827, Boulder, CO 80309-0390

May 2016

Plasma Science and Fusion Center
Massachusetts Institute of Technology
Cambridge  MA  02139  USA

This work was supported by the U.S. Department of Energy, Grant No. DE-FC02-08ER54966, DE-FC02-04ER54698, DE-AC02-09CH11466, DE-FG02-08ER54984, DE-SC-0006957, DE-FG02-08ER54999 and DE-AC02-05CH11231. Reproduction, translation, publication, use and disposal, in whole or in part, by or for the United States government is permitted.
Role of Density Gradient Driven Trapped Electron Mode Turbulence in the H-mode Inner Core with Electron Heating

D. R. Ernst¹, K. H. Burrell², W. Guttenfelder³, T. L. Rhodes⁴, A. M. Dimitς, R. Bravenec⁶, B. A. Grierson⁴, C. Holland⁷, J. Lohr², A. Marinoni¹, G. R. McKee⁵, C. C. Petty², J. C. Rost¹, L. Schmitz⁴, G. Wang⁴, S. Zemedkun⁹, L. Zeng⁴, and the DIII-D Team

¹MIT Plasma Science and Fusion Center, Cambridge, MA 02139
²General Atomic, PO Box 85608, San Diego, CA 92186
³Princeton Plasma Physics Laboratory, PO Box 451, Princeton, NJ 08543
⁴University of California Los Angeles, PO Box 957099, Los Angeles, CA 90095
⁵Lawrence Livermore National Laboratory, P.O. Box 808, Livermore, CA 94551
⁶Fourth State Research, 503 Lockhart Drive, Austin, TX 78704
⁷University of California San Diego, 9500 Gilman Dr., La Jolla, CA 92093
⁸University of Wisconsin - Madison, 1500 Engineering Dr., Madison, WI 53706
⁹University of Colorado, DUAN F827, Boulder, CO 80309-0390

(Dated: December, 2015)

A series of DIII-D [J. L. Luxon, Nucl. Fusion 42 614 (2002)] low torque quiescent H-mode experiments show that density gradient driven trapped electron mode (DGTEM) turbulence dominates the inner core of H-Mode plasmas during strong electron cyclotron heating (ECH). Adding 3.4 MW ECH doubles $T_e/T_i$ from 0.5 to 1.0, which halves the linear DGTEM critical density gradient, locally reducing density peaking, while transport in all channels displays extreme stiffness in the density gradient. This suggests fusion $\alpha$-heating may degrade inner core confinement in H-Mode plasmas with moderate density peaking and low collisionality, with equal electron and ion temperatures, key conditions expected in burning plasmas. Gyrokinetic simulations using GYRO [J. Candy and R. E. Waltz, J. Comp. Phys. 186 545 (2003)] and GENIE [F. Jenko et al., Phys. Plasmas 7, 1904 (2000)] closely match not only particle, energy, and momentum fluxes, but also density fluctuation spectra from Doppler Backscattering (DBS), with and without ECH. Inner core DBS density fluctuations display discrete frequencies with adjacent toroidal mode numbers, which we identify as DGTEMs. GS2 [W. Dorland et al., Phys. Rev. Lett. 85 5579 (2000)] predictions show the DGTEM can be suppressed, to avoid degradation with electron heating, by broadening the current density profile to attain $g_0 > g_{\text{min}} > 1$.

Keywords: TEM, fluctuations, turbulence, ECH, tokamak, gyrokinetic

I. INTRODUCTION

Future burning plasmas will operate at low core collisionality, with simultaneously high temperatures and densities, nearly equal electron and ion temperatures, and little if any external momentum input. Fusion self-heating in deuterium-tritium plasmas by slowing-down $\alpha$-particles heats primarily electrons. Neutral beams, on other hand, are typically injected at energies near or below the critical energy $14.8 Z_{\text{eff}} T_e / T_i$ [2] (where $Z_{\text{eff}}$ is the effective ion charge for the electron-ion collision frequency, and $T_e$ is the electron temperature), so that slowing down deuterium beam ions heat mainly ions rather than electrons. This often results in ion temperatures $T_i \sim (2 - 3) T_e$, particularly at lower densities. Neutral beams are preferentially injected in the direction of the plasma current so that ion orbits move radially to the inside of their ionization locations, reducing beam ion orbit losses. Significant toroidal beam torque then drives toroidal rotation. Both $T_i/T_e > 1$ and sheared toroidal rotation (if not too strong), as well as dilution by energetic beam ions, generally improve core confinement by reducing turbulent transport [3–5]. However, with the strong electron heating and low rotation expected in burning plasmas, these benefits diminish. To optimize fusion yield, it is essential to develop a detailed understanding of the underlying turbulent transport mechanisms in these more relevant conditions. In this work, we add strong electron heating to neutral beam heated H-Mode plasmas with peaked density profiles. We show this results in profile evolution toward conditions characteristic of burning plasmas, while density gradient driven trapped electron mode turbulence emerges to determine inner core confinement. In our case, inner core transport increases in all channels with strong electron heating. In other studies, it has been found that turbulent transport can also change favorably, resulting in density peaking that can help improve or recover fusion gain in ITER relative to the flat density profile presently assumed [6–8].

We have carried out dedicated experiments in the steady state quiescent (ELM)-free H-Mode regime [9–11] in DIII-D to study transport degradation and fluctuations associated with density gradient driven TEM turbulence, which intensifies during strong electron heating. We fo-
focus on the inner core, where nearly all fusion power would be produced. In the absence of electron cyclotron heating (ECH), these plasmas attain steady conditions for durations exceeding ten to twenty energy confinement times, and do not exhibit sawteeth, core magnetohydrodynamic or Alfvénic activity, or significant edge localized modes. During strong electron heating, the experiments have dominant thermal loss borne by electrons, and an inner core operating at ITER collisionality. Neutral beam torque is sufficiently low that sheared parallel flows do not influence confinement. The neutral beam density is negligible, and electron and ion temperatures are nearly equal. Coupling between transport channels plays an important role in the approach to burning plasma conditions. For example, increased momentum transport is coupled with increased particle, ion thermal, and electron thermal energy transport, diminishing the role of rotation and reducing the ion temperature gradient. Similar inner core responses to strong electron heating in H-Mode plasmas have been observed previously. These prior studies, with one exception, used approximate quasi-linear or reduced models to identify possible mechanisms. To develop a quantitative and validated understanding of turbulent transport in the H-Mode inner core as burning plasma conditions are approached, we compare pure neutral beam heating with neutral beam and electron cyclotron heating, using detailed transport analysis and linear and nonlinear gyrokinetic simulations, including direct comparison with measured fluctuation spectra.

Our work continues a line of research beginning with Ref. 12, which showed that density gradient driven TEM turbulence in the inner core of Alcator C-Mod H-Modes, with strongly peaked density profiles, provides the mechanism for the local control of the density peaking and impurity accumulation with minority ICRH electron heating. This initial work described the first nonlinear gyrokinetic simulations of pure TEM turbulence, where a new nonlinear upshift of the TEM critical density gradient, associated with zonal flow dominated states, was discovered. This nonlinear upshift increases strongly with collisionality. In Alcator C-Mod ITB experiments, the density gradient is effectively limited by this TEM non-linear critical density gradient during on-axis ICRF electron heating, which arrests density peaking and metallic impurity accumulation. In the C-Mod experiments, the nonlinear TEM critical density gradient exceeds the linear critical density gradient by a factor of 1.7. The DIII-D experiments presented here explore the role of TEM turbulence at an order of magnitude lower collisionality, with a correspondingly lower nonlinear threshold, while varying $T_e/T_i$. Because the nonlinear TEM critical density gradient is reduced at lower collisionality and with increasing $T_e/T_i \sim 1$, the density gradient driven TEM can become dominant in H-Mode plasma cores with relatively modest density peaking.

The increased particle transport during radio frequency electron heating is often characterized as "density pumpout". In some cases the reduction in density may be partly a pedestal or edge effect propagated to the core by profile stiffness, but is more commonly a local reduction in density peaking in the core. In other studies of H-Mode density pumpout, particularly in ASDEX-U, the addition of ECH to the inner core is thought to change the dominant instability from an ion temperature gradient (ITG) driven mode to a temperature gradient driven TEM, which reverses quasilinear thermo-diffusion (driven by the electron temperature gradient) at lower collisionality from inward to outward. In our case, the density gradient driven TEM is the sole instability in the inner core prior to ECH. During ECH, the critical density gradient for onset of this mode is reduced by a factor of two, causing TEM turbulent transport to increase strongly until the density gradient closely follows changes in the effective critical density gradient. Ion temperature gradient driven modes, temperature gradient driven TEMs, and ETG modes remain stable in the inner core. Thermodiffusion remains outward, and the diagonal diffusion term driven by the density gradient is at least 2.7 times stronger than thermodiffusion, based on nonlinear gyrokinetic simulations. Using quasilinear arguments, it has been suggested that the density peaking will decrease (increase) with ECH if the dominant linear mode frequency moves away from (toward) zero. While we are in a regime where quasilinear theory does not apply, the real frequency remains in the electron direction and moves further away from zero during ECH, in apparent consistency with this notion.

In this work, we have directly observed density gradient driven TEMs with discrete, adjacent toroidal mode numbers for the first time, and connected them with the confinement degradation with strong electron heating. Gyrokinetic simulations using GYRO and GENE closely match not only particle, ion and electron thermal energy, and momentum fluxes, but also density fluctuation spectra measured by Doppler Backscattering, with and without ECH. This simultaneous agreement is achieved using local fixed-profile nonlinear gyrokinetic simulations without adjustments to measured profiles. In these experiments, gyrokinetic stability analysis was used to predict target conditions where density gradient driven TEMs would be solely unstable in the inner core. Between shots linear GYRO simulations were developed and used as a guide to destabilize inner core TEMs, and to determine the desired Doppler Backscattering launch angle (wavenumber) and cutoff location.

Other recent studies of QH-Mode core transport in DIII-D have focused on the outer half-radius, and utilized lower density operation. Lower density QH-Modes typically have large beam densities, bringing the core closer to marginal stability, where comparisons with gyrokinetic simulations are subject to larger uncertainties, and the dominant instabilities are different. These studies did not address transport in the inner core with nonlinear gyrokinetic simulations or compare with fluctuation measurements.

The remainder of the paper begins with an overview
of the experiments (Sec. II), followed by gyrokinetic linear stability analysis (Sec. III), which shows the density gradient driven TEM is solely unstable in the inner half-radius. We then compare nonlinear gyrokinetic simulations with transport fluxes of particles, electron and ion thermal energy, toroidal angular momentum, and impurities (Sec. IV). Next, we discuss experiments which vary the ECH heating radius in the inner core to vary the electron temperature gradient, demonstrating extreme stiffness in the density profile (Sec. V). Finally, we discuss the comparison of the measured fluctuation spectra with gyrokinetic simulations using a synthetic diagnostic (Sec. VI).

II. OVERVIEW OF EXPERIMENTS

A. Experimental Setup

These dedicated quiescent H-Mode experiments, carried out as part of the DIII-D National Fusion Science Campaign, allow us to study the effect of ECH on inner core transport under controlled conditions without ELMs, core MHD activity, Alfvén eigenmodes, or sawteeth ($q_{\text{min}} > 1.5$). We chose a near double-null shape with very high upper and lower triangularity, $\delta_U \sim \delta_l \sim 0.65$ to avoid peeling-ballooning modes (ELMs) during ECH at the higher densities we desired. Obtaining good QH-Modes without extensive conditioning requires a boronization immediately prior, and the plasma current was set up in the reversed configuration.

The power and duration of ECH pulses was limited by ELM onset, which appears to be related to slowing of the toroidal rotation during ECH. In these experiments, the ECH pulse duration was limited to 100 ms, with 200 ms between pulses, using the full 3.4 MW of ECH available (six gyrotrons). The low toroidal mode number edge harmonic oscillations (EHO) which regulate the QH-Mode pedestal are thought to be peeling instabilities driven partially by toroidal rotation (or its shear). The pedestal density (hence core density) can be increased by reducing the tangential neutral beam torque, reducing part of the drive for the EHO.

Neutral beam heating power was held constant from 1.0 s to 5.0 s. To avoid large fast ion densities, which make comparison with gyrokinetic simulations more difficult, we transitioned during the discharge from counter-current dominated 5.7 N-m neutral beam torque to a lower 4 N-m torque to raise the density. The local fast ion density in these cases from ONETWO/NUBEAM and TRANSP is less than 12% of the electron density at $\rho = 0.3$. After transitioning to the low counter-current torque phase at 2.5 s, conditions were held steady from 3.0 to 5.0 s, during which modulated ECH was applied, 100 ms on and 200 ms off, maintaining the beam power at 5.5 MW. Profiles with and without ECH are shown in Fig. 1, at 2980 ms immediately prior to the first 3.4 MW ECH pulse, and at 3080 ms, near the end of the first ECH pulse, which was applied from 3000 to 3100 ms. The plasma current was -1.2 MA, and the magnetic field on-axis was -2.05 T, with negative signs signifying the clockwise direction viewed from above the tokamak.

![Graph showing profile changes induced by 3.4 MW ECH heating aimed at $\rho = 0.22$. (a) Density, (b) Toroidal rotation velocity at outboard midplane, (c) electron temperature, (d) ion temperature, and (e) carbon impurity density.]

B. Profile and fluctuation measurements

As shown in Fig. 1, the effect of ECH, injected at $\rho = 0.22$, is to raise the electron temperature 47% from $0.5 T_i$ to $T_i$ in the inner core, locally reduce the density gradient for $\rho < 0.4$, slow the toroidal rotation over the whole profile including the pedestal, and modestly
FIG. 2. Time dependent changes induced by ECH heating beginning at 3000 ms. Steady state conditions are achieved at the two analysis times, 2980 ms and 3080 ms, indicated by blue and red vertical lines, respectively. The ECH does not significantly affect the electron density, beam density, ion temperature, or toroidal rotation in the outer half-radius. A small isolated ELM occurs near 3042 ms, with a small effect on the electron temperature, pedestal ion temperature and rotation, but little effect on the density. When the ELM relaxes the pedestal profiles slightly, the coherent EHO becomes more broadband in character, but the change appears to have little effect on the profiles. Changes in radiated power and safety factor are minimal.

reduce the inner core ion temperature and its gradient. Profile uncertainties, obtained from an ensemble of Monte Carlo spline profile fits which vary individual data points within their uncertainties, are shown as green bands. Density profiles are measured by swept frequency microwave reflectometry\(^{39}\), with full profile coverage for \(\rho > 0.1\). Density profiles were calculated directly from profile reflectometer phase data, without fitting, significant smoothing, or other processing for \(\rho > 0.1\), preserving their 2 – 4 mm radial accuracy and 10% uncertainty in the inverse scale length \(a/L_n\). Electron temperature profiles from ECE and Thomson scattering were used in the core, with Thomson scattering for the pedestal. Ion temperature and carbon toroidal rotation were measured by charge exchange spectroscopy. The carbon toroidal rotation was corrected for the energy dependence of the charge exchange cross-section\(^{40}\). Magnetic equilibria were calculated by kinetic EFIT\(^\dagger\) with \(q\)-profiles constrained by Motional Stark Effect measurements, including corrections for the equilibrium radial electric field.
The temporal evolution, together with the spectral analysis of the magnetics signals showing the EHO, is shown in Fig. 2. Steady state conditions are achieved at the two analysis times, 2980 ms and 3080 ms, indicated by blue and red vertical lines, respectively. The density at all radii has reached steady state within approximately 60 ms after the start of ECH. The neutral beam density from TRANSP at $\rho = 0.30$ remains a small fraction of the electron density, and increases very slightly during ECH. The beam density as a fraction of the electron density increases from 10% (before) to 15% (during) ECH. A significant increase in beam density would reduce turbulent transport by increasing dilution. In this case it is clear that changes in the beam density cannot account for the observed changes in electron density. The electron temperature on-axis, as measured by ECE, also reaches steady state by the end of the ECH pulse. Radiated power increases approximately 20% during ECH, reaching steady state by the analysis time, 3080 ms. The ion temperature and toroidal rotation slowly decrease during steady state by the analysis time, 3080 ms. The ion temperature comes to steady state before the analysis time, 3080 ms, the toroidal rotation continues to slow throughout the ECH pulse. The ECH does not significantly affect the electron density, beam density, ion temperature, or toroidal rotation in the outer half-radius.

As shown in the right hand column of Fig. 2, the EHO is dominated by toroidal mode number $n = 1$, which bursts quasi-periodically every $\sim 100$ ms, with relatively steady subdominant $n = 2, 3, 4$ components. This bursting does not appear to affect the density profile significantly, including near the pedestal top at $\rho = 0.90$. During ECH, the EHO amplitude is larger, with additional harmonics $n = 5, 6$ also visible in the spectrum. A small isolated ELM occurs near 3042 ms, causing a small perturbation in the electron temperature, pedestal ion temperature, and rotation, but has little effect on the density. When the ELM relaxes the pedestal profiles slightly, the coherent EHO becomes more broadband in character, but the change appears to have little effect on the profiles. The ECH launchers were aimed radially, so that no significant current density was driven. The minimum value of the safety factor $q_{\text{min}}$ decreases only slightly during the ECH pulse, and remains above 1.5, so that there are no sawteeth or $m/n = 2/1$ or $3/2$ tearing modes.

Density fluctuations are measured locally by Doppler backscattering (DBS) using the electron cyclotron wave ordinary mode (O-Mode) polarization, with selectable radius and wavenumber. Data were carefully acquired by all available fluctuation diagnostics, but inner core ($\rho < 0.5$) fluctuations fell below the noise floor for beam emission spectroscopy and correlation electron cyclotron emission. The coherent fluctuations were seen only on DBS. Usable data was acquired by electron cyclotron emission imaging at $\rho = 0.3$ and several other locations, and is being analyzed. Phase Contrast Imaging data, to be analyzed further using synthetic diagnostics, shows possible indications of kinetic ballooning mode (KBM) activity in the case without ECH, which is marginally stable to KBMs as discussed in Sec. IV. No high frequency coherent fluctuations were seen in CO$_2$ laser interferometer fluctuation data.

III. GYROKINETIC LINEAR STABILITY ANALYSIS

The density gradient driven TEM is the sole instability in the inner core for $\rho < 0.4$, where $\rho$ is the normalized square root of toroidal magnetic flux, as shown by both GS2$^{43}$ in Fig. 3, and by the GYRO$^{28}$ eigensolver, in Fig. 4. Moving out in radius in Fig. 4, a shorter wavelength tail in the growth rate spectrum becomes increasingly important, signifying the onset of temperature gradient driven TEMs and ETG modes. The radial profile of the maximum linear growth rate from GS2, neglecting sheared flows, is shown in Fig. 3, separating ion and electron scale modes. The ETG maximum linear growth rate in the region $0.4 < \rho < 0.8$ is relatively weak due to the strong density gradient. The ETG growth rate is only 10 times the maximum linear growth rate of the density gradient driven TEM, which is not sufficient to compensate for its $\sqrt{m_e/m_i}$ smaller wavelength. A simple mixing length estimate of the ETG transport, with an ad-hoc $5\times$ increase to estimate the reduced role of zonal flows in ETG turbulence$^{29,43}$ (i.e., the presence of radially elongated “streamers”), suggests that transport from ETG turbulence will be of order 20 times lower than that from density gradient driven TEM turbulence in this outer region. Nevertheless, we find possible evidence of ETG fluctuations near $\rho = 0.43$, which intensify during ECH, as shown later in Fig. 15(b).

![Max. Linear Growth Rate Profiles (GS2)](image)

FIG. 3. GS2 radial profiles of maximum linear growth rate, during ECH, neglecting sheared flows. For $\rho < 0.4$, the density gradient driven TEM with $k \rho_s < 1$ is the sole instability. Moving out in radius, ETG modes are also weakly unstable for $\rho > 0.4$, but produce negligible transport.

The mechanism leading to the increased inner core particle transport with ECH is the following: ECH eventually increases $T_e$ from $0.5 T_i$ to $T_i$, leading to $T_e \simeq T_i$ in
the inner core, which reduces the TEM linear critical density gradient by half. The concomitant reduction in the gradients of ion temperature and toroidal velocity, which occur as a result of increased TEM turbulent transport, nonlinearly enhance this $T_e/T_i$ dependence. The sensitivity of the TEM critical density gradient to parameters which change significantly during ECH is shown in Fig. 5, where the linear TEM critical density gradient, $a/L_n^{\text{crit}}$, is computed from GS2 simulations excluding sheared flows. Each point shown is derived from a scan of the inner core, which reduces the TEM linear critical density gradient, $a/L_n^{\text{crit}}$, by half. The concomitant reduction in the gradients of ion temperature and toroidal velocity, which occur as a result of increased TEM turbulent transport, nonlinearly enhance this $T_e/T_i$ dependence.

The evolution of local gradients and the TEM threshold are shown at $\rho = 0.30$ for shot 155161 in Fig. 6(a-c). As $T_e/T_i$ increases and $a/L_{Ti}$ decreases, immediately following the start of ECH, the TEM critical density gradient $a/L_n^{\text{crit}}$ drops precipitously, as shown by the solid black line in Fig. 6(a). The filled circles at 2980 ms and 3080 ms represent the same result obtained from the GYRO eigensolver, using only input data taken at the two times. The measured $a/L_n$ from the reflectometer closely tracks the evolution of the calculated GS2 critical density gradient, $a/L_n^{\text{crit}}$, which is itself independent of $a/L_n$. The electron collision frequency was varied consistently with $T_e$ in this scan. The TEM critical density gradient also increases strongly with the normalized ion temperature gradient, $a/L_{Ti}$, as shown in Fig. 5(b). Here the threshold was taken to be the value of $a/L_n$ at which the frequency changed to the electron direction. Finally, the TEM critical density gradient decreases only weakly with the normalized electron temperature gradient, $a/L_{Te}$, as shown in Fig. 5(c).

The TEM critical density gradient $a/L_n^{\text{crit}} = a/L_n^{\text{crit}}(T_e/T_i, a/L_{Ti}, a/L_{Te})$ was obtained as a continuous function by interpolating these results.

The evolution of local gradients and the TEM threshold are shown at $\rho = 0.30$ for shot 155161 in Fig. 6(a-c). As $T_e/T_i$ increases and $a/L_{Ti}$ decreases, immediately following the start of ECH, the TEM critical density gradient $a/L_n^{\text{crit}}$ drops precipitously, as shown by the solid black line in Fig. 6(a). The filled circles at 2980 ms and 3080 ms represent the same result obtained from the GYRO eigensolver, using only input data taken at the two times. The measured $a/L_n$ from the reflectometer closely tracks the evolution of the calculated GS2 critical density gradient, $a/L_n^{\text{crit}}$, which is itself independent of $a/L_n$. The electron collision frequency was varied consistently with $T_e$ in this scan. The TEM critical density gradient also increases strongly with the normalized ion temperature gradient, $a/L_{Ti}$, as shown in Fig. 5(b). Here the threshold was taken to be the value of $a/L_n$ at which the frequency changed to the electron direction. Finally, the TEM critical density gradient decreases only weakly with the normalized electron temperature gradient, $a/L_{Te}$, as shown in Fig. 5(c).

The TEM critical density gradient $a/L_n^{\text{crit}} = a/L_n^{\text{crit}}(T_e/T_i, a/L_{Ti}, a/L_{Te})$ was obtained as a continuous function by interpolating these results.
the change in diffusivity due to DGTEM turbulence is much more rapid, and the analysis remains valid.

As shown in Fig. 7 using the GYRO eigenmode solver, the destabilizing effect of parallel flow shear in the no ECH case more than doubles the growth rate over the entire TEM range of wavenumbers. Without sheared parallel flow or ECH, the inner core would be stabilized entirely by $E \times B$ shear and exhibit no transport. During ECH, the effect of sheared parallel flow drive is seen mainly at shorter wavelengths, and does not affect the transport fluxes or their dependence on the density gradient, as shown later in Sec. IV. The nonlinear GYRO simulations of TEM turbulence in the ECH case show that the effect of $E \times B$ shear on the energy and particle fluxes closely matches a scaling $^{14}$ for the linear quench rule, $\alpha_E(\kappa, \varepsilon) = 0.71(\kappa/1.5)(R_0/3a)(0.60) = 0.68$ from simulations of ITG turbulence, which reduces fluxes by the factor 0.4.

FIG. 6. Time-dependent changes at $\rho = 0.3$ associated with the application of 3.4 MW of ECH beginning at 3000 ms: (a) Density gradient measured by reflectometry, $a/L_n$, compared with TEM linear critical density gradient computed by GS2, interpolating the results shown in Fig. 5 to account for dependence on $T_i/T_e$, $a/L_T$, and $a/L_n$, compared with GYRO results at the analysis times 2980 and 3080 ms, (b) changes in $a/L_T$, $a/L_n$, $T_e/T_i$, and toroidal angular velocity, (c) $T_i$ and $T_e$, and (d) TRANSP analysis of particle balance, showing the time-dependent term has become negligible by 3080 ms, the beam and volume ionization sources do not change with ECH, while the increase in wall ionization source following the ELM shown in Fig. 2 makes a very small contribution.

FIG. 7. Effect of sheared flows in GYRO simulations. (a) Effect of shear in parallel flow ($\gamma_{p}$) and Mach number ($Ma$) on linear growth rate, (b) and on frequency, (c) effective linear growth rate, subtracting $E \times B$ shear rate, with and without parallel flow shear (PFS), (d) including the effect of $E \times B$ shear reduces the electron thermal flux by a factor of two to match experiment, in nonlinear GYRO simulation of the ECH case at 3080 ms. All data from GYRO simulations at $\rho = 0.3$ for shot 155161.

Analysis in the remainder of this paper focuses on the inner core radius $\rho = 0.30$ where the density gradient driven TEM is solely unstable. Scans of $a/L_T$, $a/L_n$, and other parameters including parallel and $E \times B$ flow shear, as well as the growth rate spectrum and frequency spectrum confirm that the instability for $k_{p}p_{Te} < 1$ is a TEM driven primarily by the density gradient, as shown
FIG. 8. Comparison of fluxes inferred from TRANSP and ONETWO, with and without ECH, with gyrokinetic simulations from GYRO and GENE, at \( \rho = 0.30 \). The neoclassical fluxes from NEO have been subtracted. The inverse density gradient scale length \( a/L_n \) is varied in the simulations while holding all other parameters fixed, including the magnetic equilibrium. Uncertainty shown in \( a/L_n \) is purely statistical. Shown are (a) Particle flux, (b) toroidal angular moment flux, (c) electron heat flux, (d) ion heat flux, and (e) carbon impurity flux.

later in Sec. V. Focusing on \( \rho = 0.30 \) where ETG modes are stable avoids the need for multiscale simulations, which may be required to treat \( \rho > 0.5 \) accurately.

IV. NONLINEAR GYROKINETIC SIMULATIONS AND TRANSPORT ANALYSIS

Detailed transport, equilibrium, and profile analysis was carried out using three iterations of ONETWO, NUBEAM, and kinetic EFIT\(^{41}\) constrained by \( E_r \)-corrected MSE \( q \)-profiles, and with TRANSP. The MSE measurements show the \( q \)-profile reaches near-equilibrium during the steady state phase of the discharge. However, the TRANSP self-consistent evolution of the equilibrium, using neoclassical calculations of the bootstrap current and resistivity, along with the beam driven current from NUBEAM Monte-Carlo simulations, resulted in current density diffusion throughout the discharge duration, i.e., \( q_{\text{min}} \) decreasing with time. We resolved this by using the EFIT equilibrium directly in TRANSP, so that MSE measurements constrained the safety factor profile. Full kinetic EFITs proved unnecessary, and introduced spline artifacts within EFIT which exceeded the desired correction. Using the TRANSP pressure profile as a constraint in EFIT did not result in significant changes in the core equilibrium (we note kinetic EFITs including a bootstrap current calculation would be required for analysis of the pedestal).

A breakdown of the TRANSP particle balance, Fig. 6(d), shows the temporal evolution of fluxes at \( \rho = 0.30 \). The particle source is dominated by beams and volume ionization, which are unaffected by ECH. The time derivative of the density increases steadily from the start of the ECH pulse at 3000 ms to approximately 3060 ms, then falling sharply to become negligible at the analysis time 3080 ms. This further shows that steady state conditions in the particle balance are attained at both analysis times, 2980 ms and 3080 ms. A transient increase in wall ionization source following the small ELM at 3042 ms makes a negligible contribution.

Figure 8 compares the transport fluxes with gyrokinetic simulations at two times 2980 ms (no ECH) and 3080 ms (ECH) for shot 155161 at \( \rho = 0.30 \). The TRANSP and ONETWO analysis shows that the addition of 3.4 MW of ECH centered at \( \rho = 0.22 \) increases the electron heat flux by an order of magnitude to 3.3 MW, doubles the ion heat flux to 0.8 MW, and does not significantly change the particle or momentum flux. Consistent with the factor of two reduction in density gradient, TRANSP shows the effective total particle diffusivity doubles with ECH. The two times chosen correspond to quasi-steady equilibrium in most channels with the exception of impurity particle transport, which is characterized by longer timescales. Note that time dependence, while not significant, is not included in ONETWO, but is accounted for in the TRANSP results by including all partial time derivatives when inferring the fluxes. Our
The inverse density gradient scale length $\rho$ of flux, and (d) ion heat flux. radial flux of toroidal angular momentum, (c) electron heat in times of order $\sim 30$. The inverse density gradient scale length $a/L_n$ is varied in the JRO as sheared parallel flow drive, there would be no turbulent transport in the no-ECH case. In the ECH case, however, the toroidal rotation has slowed significantly, so that sheared parallel flow has no significant effect, consistent with the approach to burning-plasma-like conditions. The slowing of toroidal rotation with ECH can result from a bifurcation induced by the increased momentum transport with ECH, resulting from the dependence of momentum diffusivity on the velocity gradient, which leads to multiple solutions for rotation at the same applied torque. The role of sheared parallel flows is quite interesting and will be explored in detail in a separate publication. The role of sheared parallel flow in the TEM nonlinear threshold is also included in a first-principles predator-prey model of the zonal flow dominated TEM system that we have recently developed. This model reproduces the scaling of nonlinear upshift of the TEM critical density gradient with collisionality and other parameters, as obtained from GS2 nonlinear simulations that these experiments were designed to test.

We find that shear in the parallel flow velocity in the no-ECH case strongly reduces the effective nonlinear TEM critical density gradient by roughly 45%, from $a/L_{n_{\text{crit}}}$ = 1.6 to 1.1, as shown in Fig. 9. Without sheared parallel flow drive, there would be no turbulent transport in the no-ECH case. In the ECH case, however, the toroidal rotation has slowed significantly, so that sheared parallel flow has no significant effect, consistent with the approach to burning-plasma-like conditions. The slowing of toroidal rotation with ECH can result from a bifurcation induced by the increased momentum transport with ECH, resulting from the dependence of momentum diffusivity on the velocity gradient, which leads to multiple solutions for rotation at the same applied torque. The role of sheared parallel flows is quite interesting and will be explored in detail in a separate publication. The role of sheared parallel flow in the TEM nonlinear threshold is also included in a first-principles predator-prey model of the zonal flow dominated TEM system that we have recently developed. This model reproduces the scaling of nonlinear upshift of the TEM critical density gradient with collisionality and other parameters, as obtained from GS2 nonlinear simulations. Future work will compare the scalings predicted by this model with those obtained here and in our C-Mod experiments, and will explore the impact of the exact linearized gyrokinetic collision operator.

Significant core impurity concentrations dilute the fuel and can affect core confinement (sometimes favorably) as well as reducing fusion yield. Peaked density profiles can result in a strong turbulent impurity inflow. It is important to understand changes in impurity transport and core impurity accumulation as burning plasma like conditions are approached. In these experiments, carbon is the dominant impurity, but there are also finite metallic impurity concentrations. During ECH, the inner core impurity concentrations of both carbon and metallic impurities (not shown) are reduced, consistent with the increased outward impurity transport driven by DGTEM turbulence. Because there is no core impurity source (at least for carbon, which is fully ionized), the carbon density profile is determined by condition that the turbulent carbon flux must balance the neoclassical carbon flux, along with any correction for the partial time deriv-
tive of the carbon density. This balance is well-satisfied in the no ECH case, but not in the ECH case, where periodic bursting of the $n = 1$ edge harmonic oscillations modulates the carbon density. On average, there is a clear decrease in inner core carbon density during ECH, as shown in Fig. 1(e).

During ECH, the operating point is marginally stable to the Kinetic Ballooning Mode at $\rho = 0.30$, as shown in Fig. 10. A scan of $\beta = \beta_e \sum (n_j/n_e)(T_j/T_e)$ in GYRO, with other parameters held fixed, is carried out by varying $\beta_e$. During ECH, only the electron temperature gradient increased, while all density and ion temperature gradients decreased. The same results as a function of the MHD ballooning stability parameter $\alpha_{\text{MHD}} = \sqrt{(R/a)} \beta_e \sum (n_j/n_e)(T_j/T_e) (a/L_{n_j} + a/L_{T_j})$ show that while $\beta_e$ increased during ECH slightly, $\alpha_{\text{MHD}}$ decreased by 25%, largely as a result of the decrease in safety factor. At the same time, $\alpha_{\text{MHD}}$ increased 50%, perhaps as a result of a 40% increase in magnetic shear, and possibly other parameter changes including increasing $T_e/T_i$ and decreasing rotation.

As a result of this marginally stable KBM initial attempt to simulate the no-ECH case with GYRO suffered wild oscillations in fluxes, resulting in values greatly exceeding experiment. Extensive convergence tests were carried out to attempt to resolve the issue, but improved resolution and larger box sizes only delayed the onset of the large oscillations. The large Mach number in this case exacerbated the problem, which was seen only in electromagnetic cases, apparently leading to artificial amplification of the KBM oscillations. Certain missing terms in the field equations in GYRO, which appear in the Sugama first order gyrokinetic formulation may be responsible, and numerical issues are not entirely ruled out. Because the finite Mach number implementation in nearly all gyrokinetic codes is presently incomplete, and the Mach number in the present ordering should not have a large physical impact, we chose to set it to zero in both GYRO and GENE (while retaining both $E \times B$ and sheared parallel flows). This produced the well-converged results shown in Fig. 8. The agreement between GYRO and GENE in the fluxes of particles, momentum, and electron and ion thermal energy is extremely good, as shown. The challenge to simulations in this case is clear from the fact that $E \times B$ shear and electromagnetic effects combine to reduce the electron thermal flux (and the other fluxes consistently) about equally, overall by an order of magnitude. Once sheared parallel flows, $E \times B$ shear, and electromagnetic effects are included, the fluxes from GENE and GYRO closely match those inferred from TRANSP.

Because our results suggest that $\alpha$-heating in future burning plasmas will tend to self-regulate by reducing density peaking, it is of interest to find ways to avoid this. Figure 11(a) shows a scan of magnetic shear for the ECH case 155161 at $\rho = 0.3$, holding all other parameters fixed. The trapped electron precession drift frequency reverses for an increasing fraction of barely trapped electrons as the magnetic shear $\dot{s} = (\rho/q)dq/d\rho$ becomes more negative. This implies that fewer trapped electrons are resonant with the instability, weakening its drive, a well-known result. Weak or negative magnetic shear in the inner core will suppress TEMs and may avoid the confinement degradation associated with...
strong electron heating. This mechanism was previously suggested\textsuperscript{12} as an explanation of early JT60-U results\textsuperscript{51} which showed inner core confinement degradation with electron cyclotron current drive (ECCD), which reduced the degree of reversed magnetic shear. Our estimates for DIII-D suggest that the beam driven current can be optimized through the timing of the torus reduction during QH-Mode evolution, while off-axis ECCD can contribute a comparable localized current density to broaden the safety factor profile. The weak or slightly reversed shear inner core sketched in Fig. 11(b) should be sufficient to suppress the DGTEM and prevent degradation with ECCH.

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{density_gradient_tem}
\caption{(a) GS2 maximum linear growth rate as function of magnetic shear, for the ECC case at $\rho = 0.3$, with all other quantities held fixed. The density gradient driven TEM is stabilized by both reversed magnetic shear, and by $\dot{s} > 0.65$ for the parameters corresponding to $\rho = 0.3$. (b) Example of modification to yield TEM-stable safety factor profile (red).}
\end{figure}

\section{Density Profile Stiffness}

To obtain more direct empirical evidence that inner core transport is mainly driven by the density gradient, we conducted an additional experiment in the same regime to vary the electron temperature gradient in the inner core by varying the ECH heating location. Figure 12 shows the electron temperature profiles and density profiles from this scan. The ECH was aimed along the vertical resonance location at $\rho = 0.35, 0.25, 0.15, 0.24$, and $0.35$ in a shot by shot scan at constant power, starting at the outermost location. Profiles shown are averaged over a one second steady phase. The electron temperature profiles are obtained from spline fits to ECE data, showing good reproducibility. The scan resulted in a large variation in $a/L_T$, from approximately 0 to 2. However, no significant change in the reflectometer density profile was observed, as shown in Fig. 12(b). The electron temperature near $\rho = 0.30$ varied less than 20% over the scan.

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{density_scan}
\caption{Profile response to inner core ECH location scan shows density profile unaffected by large changes in electron temperature gradient at $\rho = 0.3$, when electron temperature is held constant to within 20%. (a) Electron temperature and its inverse scale length, $a/L_T$, and (b) corresponding electron density profiles and ECH location.}
\end{figure}

Figure 13 shows the sensitivity of particle, momentum, ion thermal and electron thermal fluxes to changes in $a/L_{ne}$, $a/L_T$, and $a/L_{Ti}$ about the nominal operating point for the ECH case in GYRO simulations. Again there is much less stiffness in $a/L_T$ than $a/L_{ne}$, and increasing $a/L_{Ti}$ actually reduces the fluxes (with the exception of the momentum flux), consistent with expectations for density gradient driven TEM turbulence\textsuperscript{12}. These results show that thermodiffusion\textsuperscript{22} is a factor of 2.7 smaller than the diagonal diffusive transport driven by the density gradient. Onsager symmetry implies an electron thermal pinch driven by the density gradient with a magnitude equal to the particle pinch driven by the electron temperature gradient (thermodiffusion)\textsuperscript{52}. In this case, the electron heat flux driven by the density gradient is apparently outward, as shown in Fig. 13(c), suggesting that thermodiffusion is also outward, as shown in Fig. 13(a).
The fact that the density profile did not change measurably, with constant beam fueling but with large variations in $a/L_{Te}$, shows extreme stiffness in particle transport with respect to $a/L_{ne}$, consistent with the results shown in Fig. 8. If $a/L_{Te}$ were to affect transport in the inner core, the density gradient would have changed consistently and significantly. This is corroborated by Fig. 14, which shows the linear growth rate from GYRO as a function of $a/L_{ne}$ and $a/L_{Te}$, both with and without ECH. The linear growth rate is extremely sensitive to changes in $a/L_{ne}$, but much less sensitive to changes in $a/L_{Te}$ near the operating point.

![Graph showing linear growth rate as a function of a/Lne and a/LTe](image)

**Fig. 13.** Stiffness in driving gradients $a/L_{ne}$, $a/L_{Te}$, $a/L_{Ti}$ from GYRO nonlinear scans, for the ECH case at 3080 ms, $\rho = 0.3$: (a) Particle flux, (b) radial flux of toroidal angular momentum, (c) electron heat flux, (d) ion heat flux.

**VI. DBS FLUCTUATION SPECTRUM COMPARISON WITH GYROKINETIC SIMULATIONS**

Doppler backscattering measurements\(^{42,53,54}\) for these experiments have revealed new coherent density fluctuations (or discrete modes) accompanied by broadband turbulence. The new coherent modes have wavenumbers $k_y \rho_s \approx 0.5$ in the DGTEM range. These density fluctuations intensify during ECH, together with the broadband turbulence, shown in Fig. 15(a). The laboratory frame frequency interval between the coherent modes appears to be uniform and matches the Doppler shift computed from the radial electric field, which is primarily determined by the measured carbon toroidal rotation, with a small correction from the neoclassical poloidal rotation and carbon pressure gradient. The plasma frame frequency $\omega_r$, found in our linear gyrokinetic simulations is much smaller than this Doppler shift. In fact, the frequency of the DGTEM, $\omega_r$, is generally small and comparable to the magnetic drift frequency $\omega_{De}$ as shown in Fig. 6 of Ref. 12. The measured lab frame frequencies of the modes correspond to $n \Omega + \omega_r$, where $\omega_r \ll \Omega$. Here $n$ is the toroidal mode number in the Fourier decomposition made possible by $2\pi$ toroidal periodicity, and $\Omega$ is the toroidal angular velocity. The peak in the spectrum occurs near $n \sim 19$. This implies that the coherent modes correspond to adjacent toroidal mode numbers.

We infer that these coherent fluctuations are density gradient driven TEMs, consistent with the results of stability analysis showing they are the sole instability, as well as their wavenumbers, frequencies, parameter scalings, and the consistency of nonlinear fluxes in all channels with experiment\(^{20}\). Slightly farther out in radius, near $\rho = 0.43$, a strong increase in spectral power is seen at shorter wavelengths, $k_y \rho_s \approx 3.5$ [Fig. 15(b)], also in the electron diamagnetic direction in the lab frame. ETG modes become increasingly unstable beyond $\rho > 0.35$ during ECH in GYRO simulations, as shown earlier in Fig. 4.

![Graph showing GYRO linear TEM growth rate at k_y rho_s = 0.4, near its spectral peak, as a function of driving gradients a/Lne and a/LTe, for the ECH (3080 ms) and no-ECH (2980 ms) cases, at $\rho = 0.3$.](image)

The large Doppler shift spreads out the toroidal mode numbers in frequency in the laboratory frame so that they appear to be coherent. The spectral line widths of the modes in the laboratory frame are given by $n \delta \Omega + \delta \omega_r$, where $\delta \Omega$ represents the variation in flow velocity over the DBS effective spot size. We estimate $\delta \Omega \sim 2$ krad/s using the measured velocity gradient and DBS radial width of $\sim 0.4$ cm. The plasma frame frequency interval between adjacent toroidal modes from the simulations is typically 6 krad/s, which we take as an upper bound on $\delta \omega_r$. Both are negligible relative to $\Omega_c \sim 125$ krad/s, so the modes appear to be well-separated in frequency when observed in the laboratory frame.
Low frequency edge harmonic oscillations (EHO) are also observed at frequencies up to 70 kHz on DBS, magnetics, and the CO2 laser interferometer, but their frequencies do not follow the core toroidal rotation, and their 8.5 kHz frequency interval is much smaller than the 20-30 kHz interval seen at higher frequencies. One may ask whether the the band of coherent modes observed correspond to amplitude (AM) or frequency modulation (FM) of a single high frequency “carrier” mode, possibly a high mode number EHO, by the low mode number EHO. Absent a plausible nonlinear interaction, these possibilities can be excluded by considering the relevant frequencies observed and their temporal evolution, together with the fact that EHO mode numbers above \( n = 8 \) are not seen on DBS at \( \rho = 0.30 \). Further, the EHO changes to broadband fluctuations after the small ELM, which occurs before the ECH analysis time, 3080 ms, as shown in Fig. 2. In contrast, the coherent high frequency fluctuations intensify. In the case of AM, only two sidebands would appear, separated from the carrier by \( \pm 8.5 \) kHz, the interval between EHO harmonics. However, the observed interval between harmonics is 20-30 kHz, much larger than this. This suggests that the band of equally spaced harmonics does not result from a nonlinear interaction of high and low mode number EHO’s. The spectrum shown does resemble one resulting from FM, where equally spaced harmonics appear with a frequency interval equal to the frequency of the modulating signal. The carrier frequency would need to be in the 250 kHz range, and the modulating signal in the 20-30 kHz range. Consider the hypothetical case where an \( n = 3 \) EHO modulates the toroidal rotation at a frequency of 26 kHz in proportion to its amplitude. If an \( n = 19 \) fluctuation having a very small plasma frame phase velocity were present and observed by DBS with the Doppler shifted frequency, then a spectrum similar to that observed could result from FM by the \( n = 3 \) EHO. However, the interval between the high frequency coherent modes decreases markedly as the toroidal rotation slows during ECH, but the EHO frequencies increase. This would increase the interval between coherent modes during ECH in an FM scenario. Further, the \( n=1 \) EHO dominates over the required \( n=3 \) EHO, and a mixture of EHO’s modulating the rotation would result in interstitial frequencies which are not observed in the 20-30 kHz interval between the coherent modes. It is not clear in this scenario where the high frequency carrier would originate.

The DBS measurements are most sensitive to a binormal (\( \sim \)poloidal) wavenumber \( k_y \approx 1 \) cm\(^{-1}\), with a negligible radial component. Full-wave simulations in 2D\(^5\) suggest a Gaussian response function for power spectral density, with estimated half-width \( \Delta k \approx 0.94 \) cm\(^{-1}\). DBS is therefore sensitive to a band of toroidal mode numbers \( n \) determined by \( k_y = nq(\rho, \theta)/r_\rho(\rho, \theta) \), where \( q(\rho, \theta) \) is the local poloidally varying safety factor with average value \( q(\rho) \), and \( r_\rho(\rho, \theta) \) is the local cylindrical minor radius at the DBS cutoff location, with response \( R(n) = \exp(-(n-n_0)^2/(\Delta n)^2) \), where \( n_0 \approx 19 \) and \( \Delta n \approx 18 \) at 2980 ms.

After demonstrating quantitative agreement with gyrokinetic simulations in all transport channels, we now show close agreement with measured density fluctuation spectra with and without strong electron heating, establishing a direct link between coherent TEM fluctuations and inner core transport.

We have developed a new GYRO synthetic diagnostic for DBS that accurately accounts for flux surface shaping with analytical forms for geometric quantities, and extends previous work\(^5,56\) using a similar methodology, to allow detailed comparison with measured frequency spectra. The DBS response is taken to be Gaussian in \( k_y \), and only the \( k_z = 0 \) component is selected. For the DBS launch angles and O-Mode cutoff location in this experiment, the DBS response was centered at \( k_y \rho_s \sim 0.50 \), and the Gaussian half-width was calculated to be \( \Delta k_y \rho_s \approx 0.45 \) (these parameters are only slightly different for the no-ECH case). At these smaller wavenumbers, the width of the response function is comparable to the mean, \( \Delta k_y \approx k_y \). This broad response, combined with the very wide dynamic range and nano-Watt sensitivity of DBS, reveals the band of adjacent toroidal mode numbers in the DBS frequency spectrum discussed above.

Figure 16 shows the comparison between the measured DBS frequency spectra and nonlinear GYRO simulations for the same discharge, radius, and times as in Sec. IV. The DBS data shown in Fig. 16(a), as well as the GYRO results were binned in frequency to average over the coherent fluctuations so that the overall shapes of the spectra could be compared. The frequency spectrum from nonlinear GYRO simulations during ECH (155161, \( \rho=0.30, 3080 \) ms) closely reproduces the shape of the DBS frequency spectrum, as does that at 2980 ms prior to ECH. Because DBS is not absolutely
FIG. 16. Comparison of density fluctuation spectra from nonlinear gyrokinetic simulations (GYRO) with Doppler backscattering measurements (DBS), with and without ECH. The vertical scale is from the simulations. DBS is normalized to GYRO using the same factor for both ECH and no-ECH cases.

calibrated, we have normalized it to match the spectral peak amplitude from GYRO for the ECH case. The same constant normalization factor for DBS relative to GYRO was used for both 2980 ms and 3080 ms, so that GYRO closely reproduces both the shape of the DBS spectrum and the change in shape and intensity with ECH. The shape of the DBS frequency spectrum prior to ECH at 2980 ms is much broader and attains roughly half the power spectral density as the ECH case. GYRO closely matches the shape of the DBS spectrum over four orders of magnitude on a log scale (not shown).

This change in DBS spectral shape with ECH is also qualitatively reproduced by the net GYRO linear growth rate (details discussed above) including sheared parallel flow, when weighted by the DBS wavenumber response. Nonlinearly the GYRO spectrum peaks at \( k_p \rho_s = 0.3 \) at 3080 ms (corresponding to a Doppler shifted frequency 153 kHz), which is downshifted from the wavenumber of maximum linear growth rate, \( k_p \rho_s = 0.85 \). The linear growth rate spectra resemble Fig. 16, but are shifted upward in frequency. This nonlinear downshift in the spectrum is not accounted for in quasilinear approaches. With much less frequency smoothing, the GYRO simulations also reproduce the individual coherent modes seen on DBS as well as the overall spectral shape.

VII. CONCLUSIONS

Density gradient driven trapped electron modes are found to dominate inner core transport in QH-mode plasmas in DIII-D, allowing local control of density peaking with electron heating. Their critical density gradient threshold decreases with \( T_e/T_i \), so that in plasmas with nearly equal ion and electron temperatures, density gradient driven TEMs can become the dominant instability, even with moderate density peaking. They produce strong transport in all channels, and are destabilized by increasing density gradients, \( T_e/T_i \) (which are both stabilizing for shorter wavelength ETG modes), and decreasing ion temperature gradients. These opposite scalings relative to ITG and ETG modes can lead to equilibria in which density gradient driven TEMs become the sole limiting instability when the density profile is sufficiently peaked, \( T_e \sim T_i \), the collisionality is low, and the magnetic shear is positive.

Gyrokinetic simulations reproduce the particle, momentum, electron thermal, and ion thermal energy fluxes in the experiments within measurement uncertainty. Newly discovered coherent core density fluctuations in DIII-D intensify during ECH and are consistent with density gradient driven trapped electron modes\(^{20} \). Nonlinear gyrokinetic simulations, using a synthetic DBS diagnostic in DIII-D, closely reproduce the measured frequency spectrum of broadband density fluctuations with and without ECH, while simultaneously matching transport in all channels. This simultaneous agreement in both fluctuation spectra and transport fluxes is demonstrated for the first time in H-Mode plasmas, without adjustments to measured parameter values, both with and without strong electron heating. These results are made possible through careful design of the experiments to isolate a single instability (the DGTEM), combined with accurate measurements of the main driving gradient for that instability (\( a/L_n \)), and local fluctuation measurements at the radius where the instability is strongest. The nonlinear upshift in the TEM critical density gradient\(^{12,18,20} \) is confirmed to be reduced at low collisionality, but still significant. This work illustrates a potential mechanism for the self-regulation of fusion power in self-heated fusion plasmas and improves quantitative predictions of transport in the inner core under the relevant conditions.

Prior QH-Mode studies with ECH have focused on the outer half-radius and lower density operation. Recent initial gyrokinetic simulations were carried out at \( \rho = 0.6 \) in low-density beam-heated QH-mode plasmas\(^{30} \), where large beam densities (~25% of the electron density), result in transport suppression that is more pronounced nonlinearly than linearly\(^{57} \). This motivated initial simulations of a higher density QH-mode discharge 131920, which had only 5% beam density (at \( \rho = 0.6 \)). These initial simulations yielded essentially no transport, but did not have the benefit of density profile reflectometer data, which is necessary for accurate gyrokinetic simulations. This high density near double-null case was the initial target discharge for our experiments.

The experiments in Ref. 17 also examined the effect of ECH on turbulence in QH-Mode plasmas, at lower density (\( n_{i0}^{\text{med}} \sim 1.5, n_{e0} \sim 4 \times 10^{19} \text{ m}^{-3} \)), and at much higher temperatures \( T_{i0} \sim 10 \) (8.5) keV and \( T_{e0} \sim 5 \) (12) keV without (with) ECH. Using TGLF to calculate growth rates, the core of these plasmas is initially ITG dominated, but marginal to the temperature gradient driven TEM. The increase in \( T_e/T_i \) due to ECH lowers the
ITG threshold to increase ion thermal and momentum transport, reducing the ion temperature gradient, leaving the temperature gradient driven TEM dominant during ECH. The electron temperature profile remains close to the TEM critical temperature gradient in the outer half-radius. In these studies of the outer core, the density gradient lies well below the stability limit for density gradient driven TEMs, as computed by TGLF.

Other researchers have recently associated core TEMs with “Quasi-Coherent” features in the fluctuation spectrum on the basis of various linear growth rate calculations based on simplified models. The features appear as spectrally symmetric bumps of width ~100 kHz in the reflectometer spectrum at frequencies ~ ±100 kHz \({\rho_L}^{58,59}\), and are observed in T-10, JET, TEXTOR, and TORE-Supra reflectometry data. The evidence that the features are TEMs appears to be based on linear growth rate calculations showing electron modes dominate for \(r/a < 0.2\) (in TORE Supra) as \(R/L_{Te}\) is increased with ECH. No nonlinear simulations or comparisons with synthetic diagnostics have been shown. With the exception of vertical reflectometry measurements on TEXTOR, the measurements are taken at the outboard midplane with radially propagating waves, and thus sensitive only to the radially varying part of the fluctuations.

The first comparison of measured wavelength spectra with nonlinear gyrokinetic simulations using a synthetic diagnostic \(^{18}\) was carried out for pure density gradient driven TEM turbulence, providing further evidence of the role of density gradient driven TEMs during strong central electron heating in the H-Mode inner core. Recent studies of ITG dominated H-Mode plasmas \((\rho_{pol} > 0.6)\) with ECH \(^{60,61}\) have not been able to simultaneously match relative changes in fluctuation levels with ECH while reproducing transport in one or more channels. Other recent work comparing DBS spectra with gyrokinetic simulations has been carried out in Ohmic or L-Mode plasmas \(^{62-65}\). To the best of our knowledge, all other work aimed at identifying TEM turbulence in fluctuation measurements, or which studies TEM turbulence with RF electron heating, has focused on temperature gradient driven TEMs in the outer half-radius in L-Mode plasmas \(^{30,66-71}\), where gyrokinetic simulations are unable to match transport fluxes. In very recent work, spatially coherent structures have been observed in 2D electron temperature fluctuations measured by ECE Imaging in DIII-D \(^{71}\), in the outer half-radius of L-Mode plasmas. The structures are seen using a narrow bandpass filter in frequency, where temperature gradient driven TEMs are found to be marginally stable in linear gyrokinetic simulations.

In other studies of the role of TEMs in experiments based on linear stability analysis, measured electron temperature gradients in ASDEX-U and DIII-D were consistent with the linear TEM critical temperature gradient \(^{15,17,31}\). Separate nonlinear gyrokinetic simulation work focused on electron temperature gradient driven TEMs, considering electron channel dominated parameters, \(R/L_{Te} = 6, R/L_n = 3, and R/L_{Ti} = 0\), with \(T_e = 3T_i\). We emphasize that trapped electron mode turbulence driven by electron temperature gradients differs qualitatively from that driven by the density gradient, as a result of contrasting linear stability properties \(^{24}\). Density gradient driven TEMs have linear growth rate spectra typically falling in the same wavelength range \(k_y \rho_s < 1\) as toroidal ITG modes (often extending to \(k_y \rho_s \sim 4\) via a non-resonant ion diamagnetically-directed “ubiquitous” mode). On the other hand, temperature gradient driven TEMs have maximum growth rates at shorter wavelengths \(k_y \rho_s > 1\), often connecting seamlessly with toroidal Electron Temperature Gradient (ETG) modes. This leads to different zonal flow behaviors. Zonal flows play a strong role in density gradient driven TEM turbulence, producing a significant nonlinear upshift in the TEM critical density gradient \(^{12}\), but play a negligible role in temperature gradient driven TEM turbulence \(^{32,33}\). In work bridging the two extremes \(^{24}\), the role of zonal flows was found to diminish with increasing \(\eta_e\), so that zonal flows become unimportant for \(\eta_e \gtrsim 1\) (with \(T_i = T_e\); the boundary may depend on other parameters). Accurate treatment of electron temperature gradient driven TEM turbulence would generally require multiscale simulations spanning wavenumbers below \(k_y \rho_s\) to above \(k_y \rho_{Te}\), if toroidal ETG modes are simultaneously unstable \(^{34}\). However, in our case at \(\rho = 0.30\), ETG modes are stabilized by the density gradient at \(T_e \simeq T_i\), so that multiscale simulations are not required.

Finally, the suggestion that α-heating may limit or reduce density peaking to self-regulate fusion power in burning plasmas is predicated on having moderately peaked H-Mode density profiles. In the case we have shown, the particle flux from density gradient driven TEM turbulence balances the central beam fueling source. In a burning plasma without central fueling, shorter wavelength modes may be simultaneously unstable, with an associated particle pinch \(^{8,72}\) involving low energy particles. This short wavelength pinch, driven by the electron temperature gradient, would then replace the beam source to balance the longer wavelength outflow driven by the density gradient. It is not clear how the inflow and outflow depend on magnetic shear. Fusion performance may be improved by driving current off-axis (via bootstrap current) to create an inner core with weak positive or weakly reversed magnetic shear, reducing the outflow relative to the inflow. Future work will investigate whether peaked density profiles persist under these conditions.

**ACKNOWLEDGMENTS**

This material is based upon work supported in part by the US Department of Energy Office of Fusion Energy Sciences, using the DIII-D National Fusion Facility, a DOE Office of Science user facility, under Awards...
TABLE I. GYRO reference parameters at $\rho = 0.30$ for shot 155161 (note that $\beta_c$, $c_s$ and $\rho_s$ are not local physics parameters). Here $n_e$ is the electron density; $n_b$ is the beam density; $k_\psi$ is the wavenumber normal to a flux surface; $k_\phi$ is the binormal wavenumber in the electron density perpendicular to the magnetic field and tangent to the flux surface; $N_\phi, \Lambda, \kappa$ are the numbers of parallel grid points, velocity pitch angles, and energies, respectively; $n_e$ and $n_b$ are the effective numbers of radial and binormal grid points; $\nu_{ei}$ is the electron-ion collision frequency; $\beta_e$ is the electron beta using the magnetic field $B_{\text{unit}} = (1/r) d\Psi / dr$, where $\Psi$ is the toroidal flux; $q$ is the safety factor; and $s$, $\kappa$, $\delta$, $dR/dr$, and $R_0/a$ are the local Miller equilibrium parameters describing the local magnetic shear, ellipticity, triangularity, Shafranov shift, and the aspect ratio of the last closed flux surface. Here the radial coordinate $r$ is the half-diameter of the flux surface at the midplane.

<table>
<thead>
<tr>
<th>Time (ms)</th>
<th>$L_s \times L_p$</th>
<th>$\Delta n$</th>
<th>$n_e \times n_b$</th>
<th>$k_{\min} \rho_s$</th>
<th>$k^{\max} \rho_s$</th>
<th>$k^{\max} \rho_s$</th>
<th>$N_\phi$</th>
<th>$N_\Lambda$</th>
<th>$N_\kappa$</th>
</tr>
</thead>
<tbody>
<tr>
<td>2980</td>
<td>136 x 126</td>
<td>2</td>
<td>128 x 32</td>
<td>0.046</td>
<td>1.48</td>
<td>0.050</td>
<td>1.542</td>
<td>14 x 2</td>
<td>8</td>
</tr>
<tr>
<td>3080</td>
<td>109 x 114</td>
<td>2</td>
<td>128 x 32</td>
<td>0.058</td>
<td>1.84</td>
<td>0.055</td>
<td>1.71</td>
<td>14 x 2</td>
<td>8</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Time (ms)</th>
<th>$n_e (10^{19} \text{ m}^{-3})$</th>
<th>$n_b/n_e$</th>
<th>$T_e/T_i$</th>
<th>$Z_{eq}$</th>
<th>$a/L_{De}$</th>
<th>$a/L_{De}$</th>
<th>$a/L_{De}$</th>
<th>$10^3 \nu_{ei} \alpha_{ce}$</th>
<th>$\beta_e$ (%)</th>
<th>$R_0 \Omega/c_\mu$</th>
<th>$\gamma_P / c_s$</th>
<th>$\gamma_R / c_s$</th>
<th>$10^3 \rho_s / a$</th>
</tr>
</thead>
<tbody>
<tr>
<td>2980</td>
<td>3.68</td>
<td>0.10</td>
<td>3.55</td>
<td>0.55</td>
<td>3.21</td>
<td>1.23</td>
<td>1.22</td>
<td>1.27</td>
<td>15.4</td>
<td>0.55</td>
<td>0.11</td>
<td>0.077</td>
<td>4.87</td>
</tr>
<tr>
<td>3080</td>
<td>3.39</td>
<td>0.15</td>
<td>5.13</td>
<td>0.93</td>
<td>3.08</td>
<td>0.77</td>
<td>1.67</td>
<td>0.94</td>
<td>7.06</td>
<td>0.81</td>
<td>0.30</td>
<td>0.663</td>
<td>0.049</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Time (ms)</th>
<th>$r/a$</th>
<th>$R_0/a$</th>
<th>$q$</th>
<th>$\kappa$</th>
<th>$\delta$</th>
<th>$dR/dr$</th>
<th>$a$ (cm)</th>
<th>$\rho_s$ (cm)</th>
<th>$c_a / (10^7 / s)$</th>
<th>$B_{\text{unit}} (T)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>2980</td>
<td>0.33</td>
<td>2.95</td>
<td>1.70</td>
<td>0.15</td>
<td>1.48</td>
<td>0.038</td>
<td>-0.057</td>
<td>58</td>
<td>0.48</td>
<td>7.15</td>
</tr>
<tr>
<td>3080</td>
<td>0.33</td>
<td>2.95</td>
<td>1.72</td>
<td>0.21</td>
<td>1.43</td>
<td>0.034</td>
<td>-0.062</td>
<td>58</td>
<td>0.56</td>
<td>8.59</td>
</tr>
</tbody>
</table>

DE-FC02-08ER54966, DE-FC02-04ER54968, DE-AC02-09CH11466, DE-FC02-08ER54984, DE-SC-0006957, DE-FC02-08ER54999 and DE-AC02-05CH11231. DIII-D data shown in this paper can be obtained in digital format by following the links at https://fusion.gat.com/global/D3D_DMP. We acknowledge J. Candy (General Atomics) for developing and maintaining the GYRO code, and F. Jenko (UCLA) and T. Gérler (IPP-Garching) for developing and maintaining the GENE code. We express our appreciation to G. Staebler (General Atomics) for important discussions leading to credible electromagnetic simulations of the no ECH case. We gratefully acknowledge R. J. Buttery (General Atomics) for valuable guidance at all stages of this work. DRE, WG and AMD acknowledge an Advanced Leadership Computing Challenge Award atNERSC from the Office of Advanced Scientific Computing Research.

VIII. APPENDIX I: SIMULATION PARAMETERS

Nonlinear GYRO simulations included 3 kinetic species (deuterium, carbon, electrons) and neutral beams were treated as a diluting species (density gradient scans were carried out with kinetic beams and produced no significant differences in fluxes). Transverse magnetic fluctuations due to fluctuating $A_{\parallel}$ were included. Sheared parallel flows and sheared $E \times B$ flows were included, but the mean flow was set to zero. Electron and ion collisions were included with the Lorentz model. Increased radial resolution and compressional magnetic fluctuations $B_{\parallel}$ revealed no significant changes. Simulation input parameters are given in Table I.
