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MEASUREMENTS OF ELECTRONIC TEMPERATURE AND DENSITY FLUCTUATIONS AND COMPARISON TO GYROKINETIC SIMULATIONS

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Profiles $(0.3 < \rho < 0.9)$ of electron temperature and density fluctuations in a tokamak have been measured simultaneously and the results compared to nonlinear gyrokinetic simulations. Electron temperature and density fluctuations measured in neutral beam-heated, sawtooth-free L-mode plasmas in DIII-D are found to be similar in frequency and normalized amplitude, with amplitude increasing with radius. At $\rho = 0.5$, nonlinear gyrokinetic simulation results match experimental heat diffusivities and density fluctuation amplitude but overestimate electron temperature fluctuation amplitude and particle diffusivity. In contrast, the simulations at $\rho = 0.75$ do not match either the experimentally derived transport properties or the measured fluctuation levels.

1. Introduction

The cross-magnetic field transport of particles and energy in tokamak plasmas is higher than the expected levels based on neoclassical theory [1]. This is believed to be due in large part to the transport of particles and energy caused by micro-instabilities or turbulence. The linear modes of interest in typical DIII-D plasmas include the ion temperature gradient mode (ITG), the trapped electron mode (TEM), and the electron temperature gradient mode (ETG) mode. Independent of the underlying instability, the anomalous electron energy flux driven by electrostatic fluctuations can be expressed as [1]

$$Q_e = \frac{3}{2}\frac{nk_B T_e}{B_t}\left(\langle(\tilde{T}_e/T_e)\,\tilde{E}_\perp\rangle + \langle(\tilde{n}_e/n_e)\,\tilde{E}_\perp\rangle\right) \quad (1)$$

Here, T_e, n_e and B_t are the electron density, electron temperature, and toroidal magnetic field, respectively, and $\tilde{T}_e, \tilde{E}_\perp$, and $\tilde{n}_e$ are the fluctuation levels of electron temperature, perpendicular electric field, and density. As can be seen from equation (1), normalized fluctuation levels of electron temperature and density have the potential to contribute equally to the turbulence-driven energy flux. Long wavelength, core electron temperature fluctuations have been measured in stellarators [2] and tokamaks [3], and estimates for the fluctuation-driven electron energy flux were found consistent with the energy flux inferred from power balance [2,4], but there have been no comparisons of core electron temperature fluctuations with nonlinear gyrokinetic simulations. In addition, there are very few experimental studies that directly compare the characteristics of more than one fluctuating field [5]. This paper describes simultaneous measurements of electron temperature and density fluctuation profiles and comparisons to nonlinear gyrokinetic simulations.

2. The Correlation ECE Diagnostic at DIII-D

The correlation ECE (CECE) diagnostic on DIII-D employs a two-channel heterodyne correlation radiometer receiving 2nd harmonic X-mode cyclotron emission, with both channels viewing along the same line of sight, shown in Figure 1(a). A parabolic mirror located inside the vacuum collects radiation from the plasma at an angle of 7º to the tokamak midplane. The vertical and toroidal spatial resolution is determined by the 1/e^2 power diameter, 2w$_0$, of the Gaussian antenna pattern. The beam waist has been measured in the laboratory to be 2w$_0$ = 3.5 cm and the diameter is 2w < 4 cm across a 20 cm radial region. The CECE diagnostic is sensitive to local, long wavelength ($k_\perp < 2\pi/2w_0$ = 1.8 cm^{-1}) temperature fluctuations. The radiation is coupled to a dual-mode horn antenna [6] via a dielectric lens. The frequency bandwidth 92-106 GHz is admitted to the radiometer using a bandpass filter and is subsequently down-converted to the 6-18 GHz frequency range. Two tunable YIG bandpass filters (-20 dB bandwidth, B_{if} = 150 MHz) are used to detect two different frequencies of cyclotron emission. When the IF filters do not overlap in frequency, then the thermal noise components of the two channels will be completely incoherent [3]. With this method, the sensitivity to low amplitude fluctuations increases with the improved statistics of the correlation method,

$$(\tilde{T}_e/T_e)^2 > (B_{sig} / B_{if}) / \sqrt{N} \qquad (3)$$

where $N = 2B_{vid}\Delta t$ is the number of independent samples used to determine the correlation function [3]. The sensitivity also improves when the bandwidth of the signal of interest is less than the video bandwidth, $B_{sig} < B_{vid}$ [7]. By averaging over long data records, Δt = 400 ms, the sensitivity is roughly 0.2%, with B_{sig} = 400 kHz, B_{if} = 150 MHz and $N = 2 B_{vid} \Delta t$. When the non-overlapping filters are separated in real space by a distance less than the correlation length of the turbulence, the cross-correlation coefficient at zero time delay is directly related to the normalized radiation temperature fluctuation amplitude [2]. The rms amplitude is also obtained by integrating the cross-power spectrum over the frequency range of interest [3]. The local density fluctuation measurements are obtained with the beam emission spectroscopy (BES) diagnostic on DIII-D [8]. The CECE and BES diagnostics measure fluctuations simultaneously at the same radial location with their sample volumes vertically and toroidally separated, Figure 1(b).

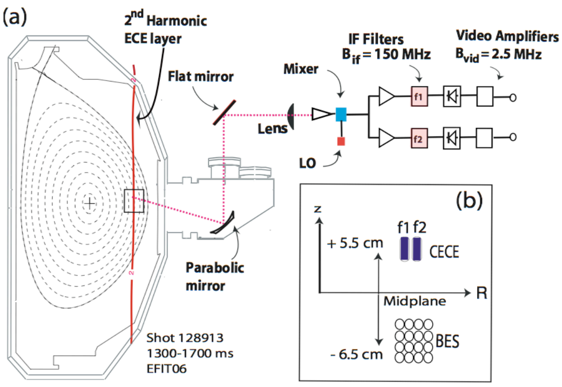

Figure 1. (a) CECE diagnostic layout (not to scale) (b) Relative BES and CECE measurement locations.

3. Plasma Parameters

A series of repeat discharges (128913-128919, 128923) is used to scan the BES and CECE diagnostics shot-by-shot to measure the radial profiles of the fluctuations. The plasmas are upper single-null with B_T = 2.1-2.14 T, I_p = 1 MA with a single co-injected neutral beam depositing 2.5 MW of power. Electron plasma density and temperature profiles averaged over the sawtooth-free L mode time period 1300-1700 ms are shown in Figure 2(a,b). The 2nd harmonic ECE is far above cut-off, Figure 2(c) and the plasma in the measurement region is optically thick, Figure 2(d). Under these conditions density fluctuations will not contribute to the measured temperature fluctuations [3].

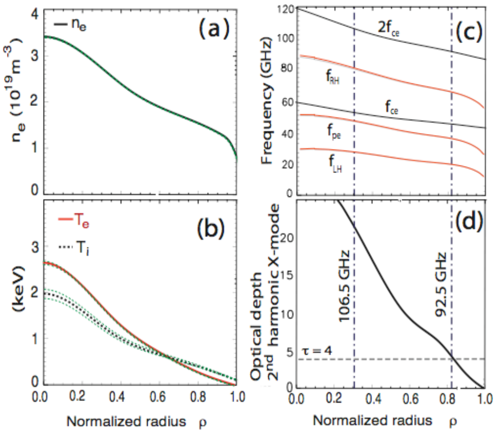

Figure 2: Profiles of electron density (a), electron and ion temperatures (b), plasma frequencies (c) and optical depth of the 2nd harmonic X-mode electron cyclotron

4. Comparison Between Electron Temperature and Density Fluctuations

Figure 3 shows the power spectrum of the temperature (a) and density fluctuations (b) measured at $\rho = 0.73$. The local fluctuations of the two fields are similar, both in frequency and in amplitude. The spectra of both are Doppler shifted by the E×B velocity. The fluctuation levels integrated from 40–400 kHz are $\tilde{T}_e/T_e \approx$ 1.5±0.2% from CECE and $\tilde{n}/n \approx$ 1.1±0.17% from BES. The spatial variation of the turbulence has been investigated by scanning the CECE and

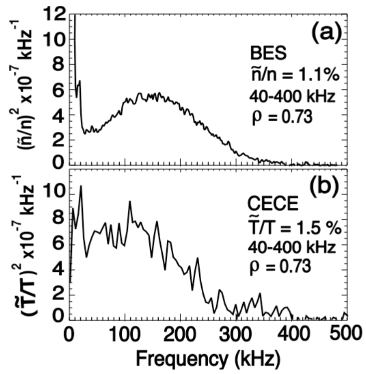

Figure 3: Fluctuation spectra of density fluctuations from BES data (a) and electron temperature fluctuations from CECE data (b)

BES diagnostics shot-by-shot between $0.3 < \rho < 0.9$. Figure 4 shows the rms amplitudes for the temperature and density fluctuations integrated over the same frequency range and plotted together as a function of normalized radius. The measured fluctuation levels are similar across the outer radius of the plasma, and fluctuation levels for both fields increase with radius. The "error" bars in Figure 4 represent the uncertainties in the measurements [9].

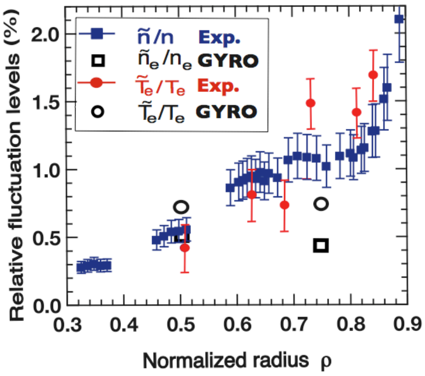

Figure 4: Experimental profiles of density and temperature fluctuations with GYRO results (density fluctuations - open squares, temperature fluctuations - open circles) at $\rho = 0.5$ and $\rho = 0.75$.

5. Comparison Between Experiment and Gyrokinetic Simulations

Simulations of discharge 128913 are performed using the fully nonlinear, electromagnetic global continuum code GYRO [10]. Local turbulence and transport properties are modeled using two separate, long-wavelength flux-tube simulations, centered at ρ = 0.5 and ρ = 0.75. The GYRO results for electron and ion thermal diffusivities and the electron particle diffusivity are compared to the experimentally inferred values from power balance analysis [ ]. Linear drift-wave stability analysis shows that the ITG mode is the dominant instability at the wavelengths resolved by the CECE and BES diagnostics.Synthetic diagnostics are used to analyze the GYRO results for comparison with experiment [9, 11]. The fluctuation levels (40-400 kHz) predicted by GYRO are shown in Figure 4 as open symbols. The experimental results are closed symbols.

At ρ=0.52, where the experimental and GYRO predicted heat diffusivities are in good agreement, the predicted density fluctuation level is $\tilde{n}_e/n_e$ = 0.50 %, compared with experiment, ñ/n = 0.55 ±0.075 % measured at ρ=0.52. The predicted temperature fluctuation level $\tilde{T}_e/T_e \approx 0.70\%$ is higher than the experimental value of $\tilde{T}_e/T_e = 0.4\pm0.2\%$. For the nonlinear simulation at $\rho = 0.75$ the simulation results underestimate both the temperature and density fluctuations, giving $\tilde{T}_e/T_e = 0.71\%$ and $\tilde{n}_e/n_e = 0.43\%$ compared to the experimental values of $\tilde{T}_e/T_e = 1.5\pm0.2\%$ and $\tilde{n}/n = 1.1\pm0.15\%$ at this radius. The disagreement between the GYRO predicted fluctuation levels and the experimental levels is consistent with the underestimate in the energy fluxes at this radius [9].

6. Conclusions

Experimentally the electron temperature and density fluctuations are found to be similar in amplitude and frequency, with normalized fluctuation levels increasing with radius. Nonlinear flux-tube simulations of the ITG/TEM unstable L-mode plasmas have been performed using the GYRO code. Synthetic diagnostics are used to compare the GYRO results to experimental fluctuation levels, and reasonable agreement with the spectral features can be obtained. At $\rho = 0.5$, the local simulation matches the experimental values of the electron and ion heat diffusivities and $\tilde{n}/n$ very well, but overestimates $\tilde{T}_e/T_e$. At $\rho = 0.75$, the local simulation underestimates both the transport and fluctuation levels and the discrepancy with experiment at this radial position cannot be resolved with variations of the input or synthetic diagnostics.

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