GA–A26777

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MAY 2010

GENERAL ATOMICS

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This is a preprint of a paper to be presented at the 16th Joint Workshop on Electron Cyclotron Emission and Electron Cyclotron Resonant Heating, April 12–15, 2010, in Sanya, China, and to be printed in the *Proceedings*.

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Work supported by
the U.S. Department of Energy under
DE-AC05-06OR23100, DE-FG03-08ER54984, DE-FG02-07ER54917,
DE-FC02-04ER54698, DE-FG02-89ER53296, and DE-FG02-08ER54999

GENERAL ATOMICS PROJECT 30200
MAY 2010

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This paper describes measurements of long wavelength, turbulent electron temperature fluctuations in the core plasma of the DIII-D tokamak made with a correlation electron cyclotron emission (CECE) radiometer-based diagnostic. Experimental and simulation results indicate that long wavelength electron temperature fluctuations (1) are similar in amplitude and spectrum to density fluctuations, (2) can be associated with both ITG and TEM turbulence, (3) exhibit changes in the relative fluctuation level that correlate with changes in electron thermal transport, and (4) are correlated, but out of phase, with density fluctuations measured simultaneously with reflectometry.

1. Introduction

The study of long wavelength turbulent electron temperature and density fluctuations is important for understanding the physics of turbulent driven transport. Advancements in nonlinear gyrokinetic turbulence simulations [1] and the development of synthetic diagnostics [2] have allowed for direct and quantitative comparisons between theory and experiment.

2. Experimental Set-Up

The correlation electron cyclotron emission (CECE) diagnostic at DIII-D allows for the measurement of long wavelength ($k_\theta \rho_s < 0.3$) electron temperature fluctuations associated with drift-wave type instabilities such as the ITG mode or TEM. The CECE diagnostic is a radiometer-based turbulence diagnostic, shown schematically in Fig. 1 [3]. The CECE diagnostic uses a spectral decorrelation method [4] to measure low amplitude (~1%), broadband ($0 < \Delta f < 800$ kHz) electron temperature fluctuations.

The CECE diagnostic can be used to measure temperature fluctuations at the same radial location as a beam emission spectroscopy (BES) diagnostic [5], although the sample volumes are separated poloidally and toroidally, with the poloidal separation of the CECE sample volumes and the 2-D BES array shown in the inset in Fig. 1.

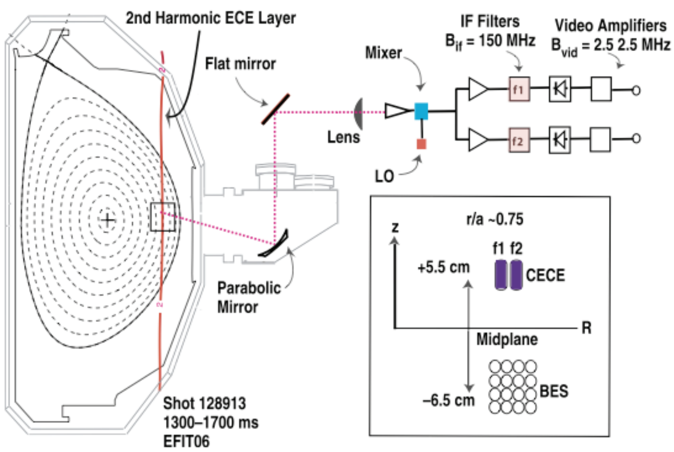

Figure 1. Diagram of the CECE system at DIII-D. Inset shows location of BES and CECE sample volumes.

Recently, the CECE diagnostic has been coupled with a multichannel X-mode heterodyne reflectometer [6] that measures long-wavelength density fluctuations. The CECE and reflectometer diagnostic share the same antenna and the same line of sight to the plasma. This allows for the poloidal and toroidal overlap of the sample volumes. The CECE and reflectometer radial viewing locations can be remotely tuned so that the sample volumes can be made to overlap radially as well. The CECE radiometer signals can then be correlated with the reflectometer signals using standard techniques [7], which allows for the coherency and cross-phase angle between temperature and density fluctuations to be measured.

3. Comparisons Between Electron Temperature Fluctuations, Density Fluctuations and Nonlinear GYRO Simulations

Temperature fluctuations have been measured with the CECE diagnostic in a variety of plasmas at DIII-D: Ohmic, L-mode, H-mode and QH-mode. In Ohmic and L-mode plasmas, electron temperature fluctuations have relative fluctuation levels between 0.5% and 2.0%, increasing with radius. During H-mode and QH-mode plasmas the amplitude of electron temperature fluctuations in the core is reduced by at least a factor of 5 to below the sensitivity level of the diagnostics, concomitant with the improved confinement during H-mode [8]. The profile of electron temperature fluctuations measured simultaneously with density fluctuations using BES during sawtooth-free beam heated L-mode plasma is shown in Fig. 2. The spectra of the two fluctuating fields are very similar, as seen in Fig. 3. These data in Figs 2 and 3 are from a 400 ms time average of the turbulence data during quasi-steady sawtooth-free L-mode plasmas, heated with 2.5 MW of co-injected neutral beam power, described in more detail in Ref. 9.

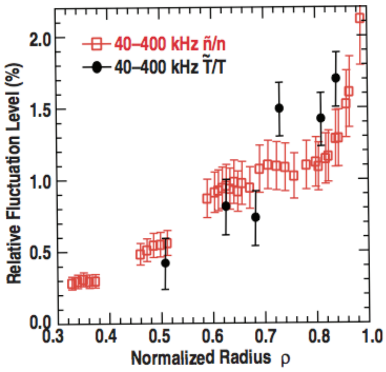

Figure 2. Profiles of turbulent electron temperature (circles) and density (squares) measured simultaneously with CECE and BES in L-mode plasmas.

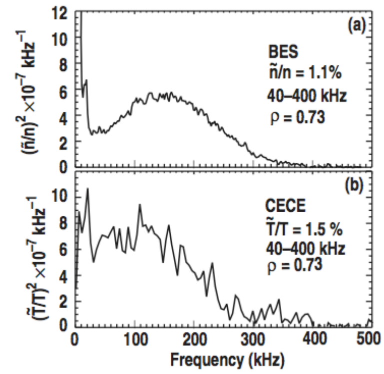

Figure 3. Spectra of density (a) and electron temperature fluctuations (b) at ρ = 0.73 in L-mode plasmas, corresponding to Fig. 2 profiles.

Linear stability analysis indicates that these plasmas are dominantly ITG unstable. Detailed comparisons of these fluctuation profile data with the nonlinear gyrokinetic turbulence transport code, GYRO, have been successful at matching both the fluctuation levels and transport deep in the core ($\rho = 0.5$) but at $\rho > 0.7$ in these plasmas GYRO consistently underpredicts [2,9] the transport and the fluctuation levels when the experimental equilibrium profiles are used as input in traditional simulation-experiment comparisons [10,11]. New, gyrokinetic transport modeling [12] has shown that the use of power-matching profiles can reproduce the experimentally observed trend that fluctuation level increases with radius. CECE data are playing an important role in these validation efforts [13] by providing a new constraint on the codes.

When electron cyclotron heating (ECH) (X-mode, 110 GHz, radial launch) is used to increase the electron temperature, the ratio T_e/T_i, and decrease the collisionality in these type of L-mode plasmas [14], there is a significant increase in electron thermal diffusivity and a significant increase in electron temperature fluctuations (Fig. 4). There is little to no change in density fluctuations measured simultaneously with BES. Linear stability analysis indicates that in these experiments, before the ECH is added, the plasma is dominantly ITG unstable, but after the ECH is added, the TEM growth rate increases. The increase in the ratio of the fluctuation levels is expected from driftwave theory to increase with the ratio $(\gamma_{TEM}/\gamma_{ITG})$ of the growth rates consistent with experimental observations.

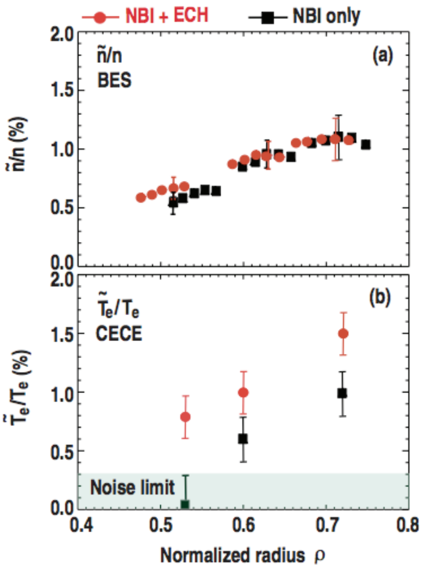

Figure 4. Profiles of density (a) and electron temperature fluctuations (b) measured with BES and CEE showing response to changes in profiles during ECH.

In a different experiment using similar beam-heated L-mode plasmas with and without ECH [15], the coherency and cross-phase angle between the density and electron temperature fluctuations were measured using the coupled CECE and reflectometry diagnostics. Before the experiment, the GYRO code was used to predict what (if any) change in the cross-phase angle would occur when the ECH was added, e.g. when the primary drive was changed from ITG to ITG mixed with strong contributions from the TEM. Linear and nonlinear GYRO results indicated that as the TEM drive increased, the phase angle should decrease towards zero for measurements made near half radius, ρ= 0.5.

Experimentally, a decrease towards zero in the cross-phase angle is observed at two of the core measurement locations in the plasmas with ECH – qualitatively consistent with predictions from GYRO. However, at the outer measurement location, there is no change in the phase angle during ECH (Fig. 5). Nonlinear GYRO simulations for ρ = 0.65 have been performed on the plasma with ECH plus neutral beams, and the phase angle is in good quantitative agreement with the measured value (Fig. 6). However, even though the measured turbulent phase angle between density and electron temperature fluctuations agrees well with the GYRO results, GYRO over-predicts the electron thermal flux by 50% and under-predicts the ion thermal flux by nearly a factor of 4 when the equilibrium experimental profiles were used as input to the simulations. The measured electron temperature fluctuation levels are in good agreement with the GYRO results, but the measured density fluctuation levels (BES) are 50% higher than the GYRO predicted levels [15].

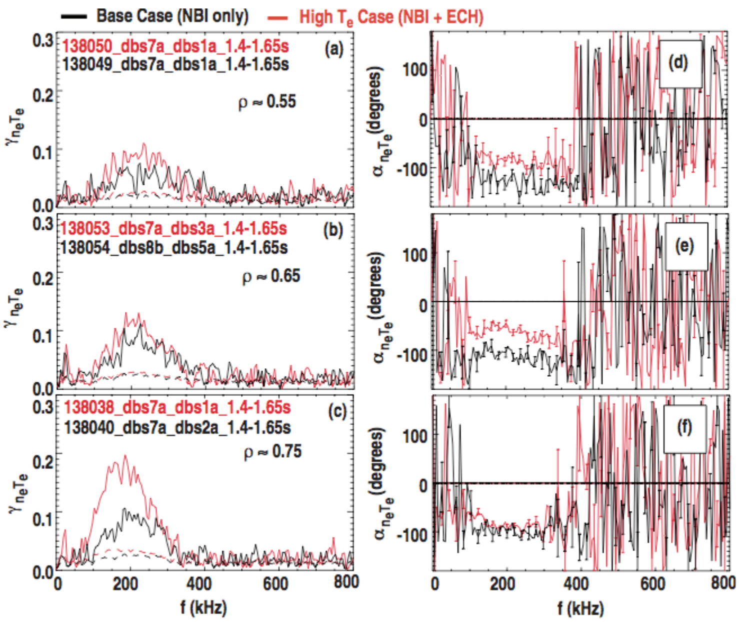

Figure 5. Coherency and cross-phase angle between density and electron temperature fluctuations measured with the coupled multichannel reflectometer and CECE diagnostics.

4. Conclusions

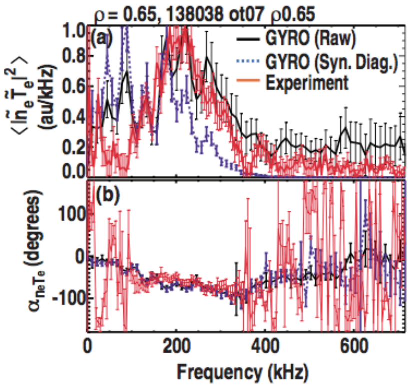

Figure 6. The measured cross-power spectrum (a) and phase angle (b) between density and electron temperature fluctuations (coupled reflectometer and CECE diagnostics) are compared with nonlinear GYRO results.

Measurements of long wavelength, turbulent electron temperature fluctuations in the core plasma of the DIII-D tokamak are made with a correlation electron cyclotron emission (CECE) radiometer-based diagnostic. Experimental and simulation results indicate that long wavelength electron temperature fluctuations (1) are similar in amplitude and spectrum to density fluctuations, (2) can be associated with both ITG and TEM turbulence, (3) exhibit changes in the relative fluctuation level that correlate strongly with changes in electron thermal transport, and (4) are correlated, but out of phase, with density fluctuations measured simultaneously with reflectometry. This paper has reviewed some key recent experimental observations and results from quantitative comparisons with the GYRO code using synthetic diagnostics. Comparisons between electron temperature fluctuations and nonlinear GYRO simulations are part of an ongoing validation research thrust at the DIII-D tokamak through Transport Model Validation taskforce. Data from the CECE diagnostic has played an important role in these efforts.

Acknowledgments

This research was supported by the U.S. Department of Energy under DE-AC05-06OR23100, DE-FG03-08ER54984, DE-FG02-07ER54917, DE-FG03-95ER54309, and DE-FC02-04ER54698. A.E.W is very grateful to the DIII-D team for their support of these experiments.

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