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Studies of Density Fluctuation Dynamics in L-H Transitions and Pedestal Formation in DIII-D Using Beam Emission Spectroscopy

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I. Introduction

In this paper, we report on studies of density fluctuation dynamics across the edge and pedestal region in DIII–D, during and beyond the L-H transition, measured with a newly upgraded beam emission spectroscopy (BES) diagnostic [1]. It is found that in the pedestal region, the turbulence is rapidly suppressed at the transition, but then begins to grow in amplitude as the pedestal height increases and the E_r well evolves, but always remains below L-mode intensity levels until edge localized modes (ELMs) begin. We present here the first direct experimental measurements of nonlinear energy transfer of internal energy mediated by a geodesic acoustic mode (GAM) in a tokamak. Initial results indicate that the advection of density fluctuations by the geodesic acoustic mode leads to significant "forward cascade" of internal energy, as expected from theories of shear-flow suppression of turbulence.

II. Studies of Edge Fluctuation Dynamics Across the L-H Transition

Using the upgraded BES diagnostic, the dynamics of density fluctuations in the pedestal region were measured across an L-H transition at multiple spatial points; the results are shown in Fig. 1. The spatial profiles of the radial electric field, electron density, and fluctuation emission intensity (proportional to the density fluctuation intensity) were averaged over 100 ms windows, with the different colored curves corresponding to window centers indicated by the correspondingly colored vertical lines on the line-averaged density plot; the dashed vertical lines indicate the window centers for the radial electric field (which is on a slightly different timebase than the Thompson scattering diagnostic used to measure electron density). As in previous studies [2], the intensity of density fluctuations (proportional to the emission intensity shown in the bottom plot of Fig. 1) drops rapidly (within a few milliseconds) at the L-H transition which occurs at roughly 1570 ms, and a strong E_r well forms. As the pedestal develops, the E_r well relaxes slightly and the fluctuation intensity exhibits a small increase in the region of strong density gradient formation, but always remains significantly below L-mode levels until 2100 ms when ELMs begin. Investigation of auto-and cross-correlations of density fluctuations at different radial locations suggests that both the correlation time and radial correlation length of

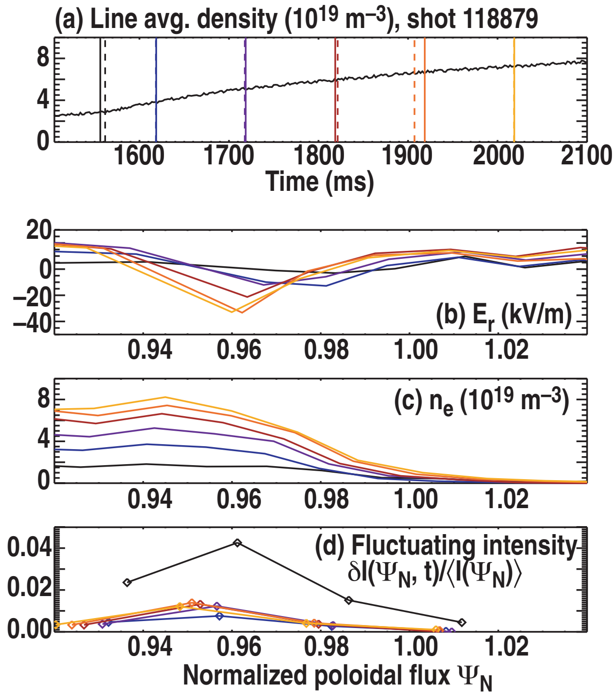

Fig. 1. Evolution of the (a) line average density vs. time (top), and spatial profiles of (b) E_r, (c) electron density, and (d) fluctuating emission intensity (measured by BES).

the turbulence are significantly decreased, and the radial correlation function becomes highly anisotropic (i.e $\langle \tilde{n}(r,t)\tilde{n}(r+\Delta r,t)\rangle \neq \langle \tilde{n}(r,t)\tilde{n}(r-\Delta r,t)\rangle$). At the top of the pedestal and closer to the core, the equilibrium density gradient is very weak, and BES measurements indicate that the density fluctuation intensity is less than one percent.

III. Measuring Nonlinear Energy Transfer in Experiment

In addition to turbulent suppression by large-scale equilibrium shear flows in H-mode (which are self-consistently supported by the strong pressure gradients), the regulation of turbulence by smaller scale (ion gyro_radius), nonlinearly generated shear flows is an important problem for understanding turbulence saturation levels in L-mode, or in the absence of the large-scale shear flows [3]. One such class of nonlinearly generated shear flows is the geodesic acoustic mode which is believed to be important near the tokamak edge. These flows have been measured in the edge of L-mode discharges via the use of time-delay estimation (TDE) techniques [4]. To quantify the effect of GAMs on density fluctuations, one can begin by calculating the rate of nonlinear energy transfer due to GAM advection. Starting from the continuity equation, it is straightforward to show

$$\frac{1}{2}\frac{\partial\langle|\tilde{n}|^2\rangle}{\partial t} \approx -\langle\Gamma_x(f)\rangle\frac{d\langle n\rangle}{dx} + \sum_{f'} T_n^X(f,f') + \sum_{f'} T_n^Y(f,f') \tag{1}$$

$$T_n^R(f,f') = -\,\mathrm{Re}\left\langle \tilde{n}^*(f) V_R(f-f') \frac{\partial \tilde{n}}{\partial R}(f') \right\rangle , \quad R = x \text{ or } y \quad . \tag{2}$$

The brackets denote a time-average, V_R is the radial ($R = x$) or poloidal ($R = y$) velocity, f and f' denote frequencies, $\tilde{n} = n - \langle n \rangle$, $\Gamma_x(f)$ is the turbulent density flux, and the quantities $T_n^{X/Y}(f,f')$ measure the transfer of energy from density *gradient* fluctuations at frequency f' into density fluctuations at frequency f at a specific spatial location, due to radial (x)/poloidal (y) advection, respectively. Note that as BES gives spatially resolved measurements, all of the data needed to directly calculate $T_n^Y(f,f')$ at a specific spatial location is available: by taking two measurements separated poloidially by a distance Δy, we have $n(r,t) = (n_1 + n_2)/2$, $\partial n/\partial y(r,t) = (n_1 - n_2)/\Delta y$, and obtain $V_y(r,t)$ by applying the TDE procedure to n_1 and n_2. It is then straightforward to calculate $T_n^Y(f,f')$, which was done using 700 ms of steady-state L-mode data to ensure that the estimate of $T_n^Y(f,f')$ is converged; the results are shown in Fig. 2. $T_n^Y(f,f')$ exhibits a clear positive feature along the curve of $f = f' + 15$ kHz, and an equal and opposite curve along $f = f' - 15$ kHz; examination of the velocity spectrum (not shown) clearly exhibits the existence of a GAM at 15 kHz, similar to previous investigations [4]. These findings are therefore consistent with the idea of a forward cascade (i.e. to higher frequencies and smaller scales) of internal energy ($|\tilde{n}|^2$) driven by GAM advection. Internal energy at $f' - f_{GAM}$ is nonlinearly transferred by GAM advection into density gradient fluctuations at f', and then back into density fluctuations at $f' + f_{GAM}$, and so on. Note this is also consistent with the idea of shear suppression of turbulence, where the shear flow rips apart eddies and transfers them to smaller spatial scales

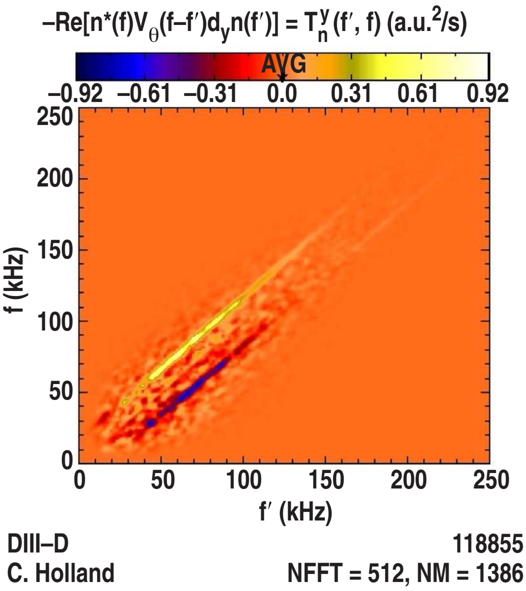

Fig. 2. $T_n^Y(f,f')$, measuring the rate at which energy is transferred into (yellow) or out of (blue) density fluctuations at frequency f from density *gradient* fluctuations at f' during L-mode.

(which correspond to higher frequencies). Finally, we note that here the energy transfer has been measured directly, as opposed to previous studies [5] which relied on a single field quantity and then used a lengthy fitting process to estimate growth rates and coupling coefficients.

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