Evolution of the turbulence radial wavenumber spectrum near the L-H transition in NSTX Ohmic discharges* EX-C

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The measurement of radially extended meso-scale structures such as zonal flows and streamers, as well as the underlying microinstabilities driving them, is critical for understanding turbulence-driven transport in plasma devices [1]. In particular, the shape and evolution of the radial wavenumber spectrum can indicate details of the nonlinear spectral energy transfer [2], the spreading of turbulence [3], as well as the formation of transport barriers [4]. In the National Spherical Torus Experiment (NSTX), the FMCW backscattering diagnostic [5] is used to simultaneously probe the radial wavenumber spectrum across the outboard minor radius in a range of (k_r=0-22 cm^{-1}). Here we report on measurements made near the formation of the edge transport barrier in Ohmic H-mode discharges.

Recent L- to H-mode transition studies have concentrated on the interplay between turbulence and zonal flows as an important component of the transition dynamics. In NSTX, zonal flow oscillations and associated quiet periods in the edge turbulence were observed with gas-puff imaging [6] in the L-mode phase of neutral beam-heated discharges, however the physical mechanism explaining the transition remains elusive.

Turbulence measurements are also routinely made with a conventional set of microwave and millimeter-wave reflectometers (FMCW, fixed-frequency, radial correlation), which observe predominantly low-k fluctuations. The response of these diagnostics to modifications of the turbulence by flow shear or flow oscillations is therefore relatively small. In order to probe the intermediate- and high-k_r regions of the radial wavenumber spectrum, the FMCW reflectometers were used to monitor electromagnetic waves backscattered by density fluctuations far from the cutoff layer. This technique is similar to conventional 180° collective backscattering, but with the advantage that the radial

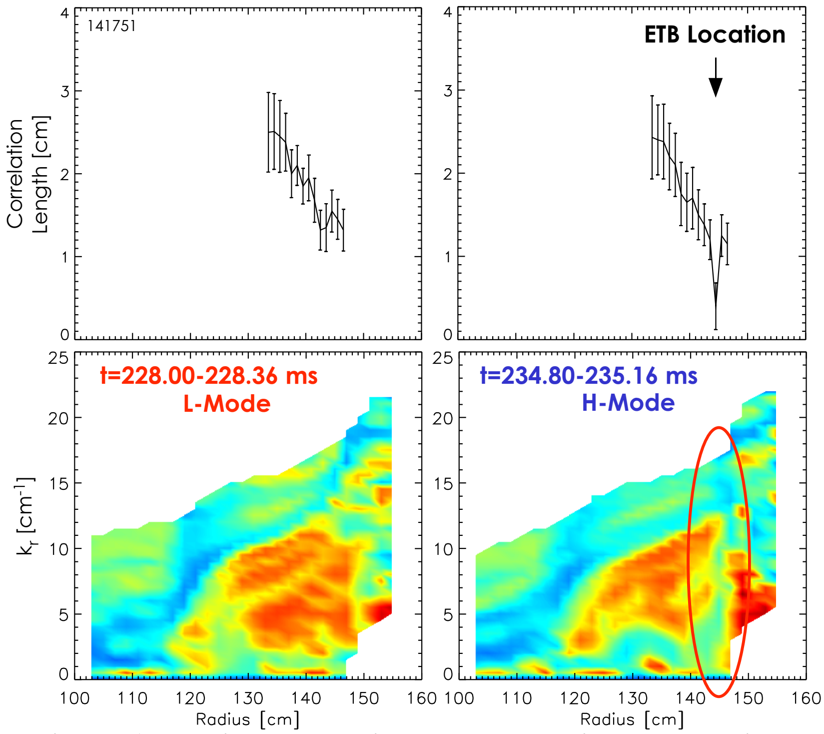

Figure 1: Radial correlation length and k_r spectrum in L-mode and immediately after the L-H transition.

location of the scattering volume can be determined from the time-of-flight. The probed wavenumber k_r is derived from the Bragg rule: k_r=2k_0μ(n_e(R),f), where k_0 is the vacuum wavenumber of the launched electromagnetic wave at frequency f, n_e(R) is the electron density profile, and μ(R,f) is the O-mode index of refraction. The radial wavenumber spectrum (k_r <22 cm^{-1}, f=13-53 GHz) across the entire outboard minor radius is accessible with high time and spatial resolution (Δt>10 μs, ΔR>1 cm).

Results are shown here for I_p=800 kA, B_T=3.5 kG, LSN, Ohmic H-mode discharges. Figure 1 shows measurements near the L-H transition; during L-mode, a broad spectral component (k_r~2-10 cm^{-1}) extends over a significant portion of the edge-core from R=120 to 155 cm (ρ=.4-0.95). At the L-H transition, turbulence is quenched across the measurable k_r range and the radial correlation drops from ~1.5 to 0.5 cm, but only at the ETB location. Once the barrier is formed (even transiently as described below), the evolution of the k_r spectrum diverges on either side of the barrier location. In the core-edge region interior to the ETB location, the spectral intensity decreases and the spectral width narrows (towards low-k), while in the edge region outside the ETB location, low-k turbulence disappears but at higher-k a broad spectral feature remains and increases in intensity. The fast time scales involved (tens of μs) in the evolution of the k_r spectrum in regions far from the ETB location, suggests that turbulence spreading may play a strong role.

Figure 2 shows the time evolution of the k_r spectral power and the density scale length at the ETB location. Close to the L-H transition the correlation between the two quantities increases; local steepening of the gradient occurs when the edge turbulence is quenched. The plasma oscillates through several cycles where the turbulence and edge gradients are "L-" or "H-mode-like" before entering the final transition to H-mode. While not a direct measurement of zonal flows, this phenomenon is not dis-similar to the predator-prey oscillations seen in dithering L-H transitions.

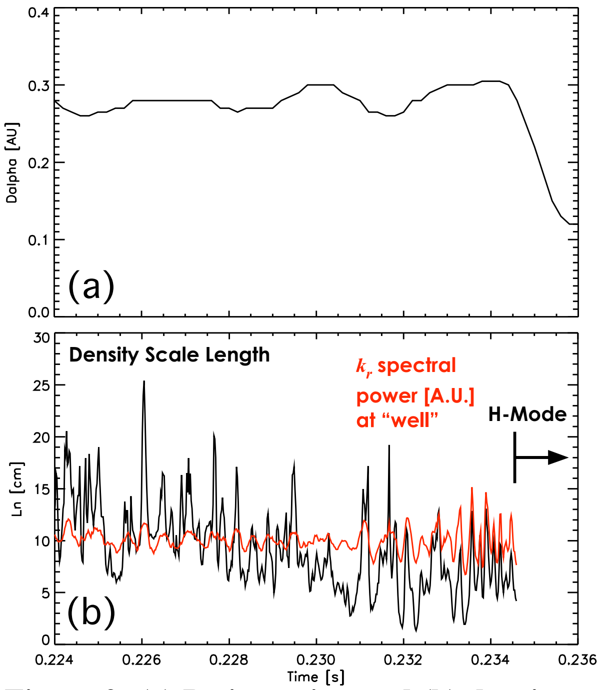

Figure 2: (a) D_α intensity, and (b) density scale length and k_r spectral power at the ETB location.

Finally, the edge dynamics described here seem to be fairly ubiquitous, as they are also observed in Ohmic discharges that stayed in L-mode; here the quenching of the k_r spectrum at the edge was far less frequent. Similar changes in the k_r spectrum are also seen near L-H transitions for neutral beam-heated discharges.

*This research was supported by the US Department of Energy, Contracts DE-FG02-99-ER54527 and DE-AC02-09CH11466.

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