Response of Electron-scale Turbulence and Thermal Transport to Continuous ExB Shear Ramping-up in an NSTX L-mode Plasma

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Microturbulence is considered to be a major candidate in driving anomalous transport in fusion plasmas, and the equilibrium ExB shear generated by externally driven flow can be a powerful tool to control microturbulence [1] in future fusion devices such as FNSF and ITER. Thus, it is crucial to understand how the ExB shear simultaneously changes turbulence spectrum and plasma confinement using the state-of-art diagnostic in a controlled experimental setup. Here, using a high-k scattering system [2], we present the first experimental observation of a progressive change in electron-scale turbulence k spectrum and thermal confinement as the ExB shearing rate is continuously increased.

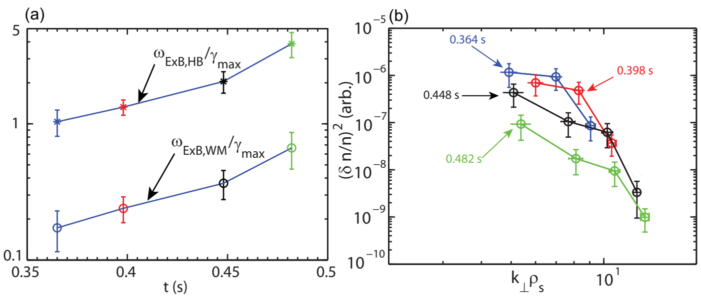

Figure 1 (a) The ratio between the ExB shear rate and the maximum linear growth rate for ITG instability (both the Hahm-Burrell ($\omega_{E\times B,HB}$) and Waltz-Miller ($\omega_{E\times B,WM}$) ExB shearing rates are shown); (b) $k_\perp$ spectra in arbitrary unit at the 4 time points shown in (a).

The observation was made in shot 141716, a NSTX NBI-heated L-mode plasma with toroidal field of 5.5 KG, plasma current of 900 kA. When 2 MW neutral beam power is re-injected from 335 ms after a first injection from 90 ms to 230 ms, the plasma spins up continuously, which leads to a simultaneous increase in the ExB shearing rate in the outer half of the plasma ($r/a \gtrsim 0.5$). The high-k scattering system is configured to measure the electron-scale turbulence from $k_\perp\rho_s$≈4 to about 14 at about R≈139 to 143 cm (r/a≈0.67-0.73). In Fig. 1 (a), $\omega_{E\times B}/\gamma_{max}$ averaged in the high-k measurement region is plotted as a function of time, where $\omega_{E\times B,HB}$ and $\omega_{E\times B,WM}$ are the ExB shearing rates using the Hahm-Burrell definition as used in Ref. [1] and the Waltz-Miller definition [3] (they differ by about a factor of 5 seen in Fig. 1 (a)) respectively, and γ_{max} is the maximum linear growth rate for the most unstable ion-scale instability (ITG modes) calculated with the GS2 code [4]. Note that the gradual increase of $\omega_{E\times B}/\gamma_{max}$ from t=0.36 to 0.45 s is due to the increase of $\omega_{E\times B}$, while the sharper increase of $\omega_{E\times B}/\gamma_{max}$ after t= 0.45 s is due to both the increase of $\omega_{E\times B}$ and decrease of γ_{max}. Figure 1(b) shows the measured $k_\perp$ spectra at time points used in Fig. 1(a). From t=0.364 to 0.398 s, the measured maximum spectral power (at $k_\perp\rho_s \approx 5$) decreases by about 40% while $\omega_{E\times B,WM}/\gamma_{max}$ increases from about 0.17 to 0.24. Meanwhile, the spectral power at larger wavenumbers ($k_\perp\rho_s \gtrsim 8$) has about a factor of 2 increase, and it appears that the slope of the spectra (at $k_\perp\rho_s \gtrsim 7$ for t=0.364 s and at $k_\perp\rho_s \gtrsim 8$ for t=0.398 s) is preserved. Larger decreases, about 60-80%, in spectral power at $k_{\perp}\rho_s \lesssim 10$ occur while $\omega_{E\times B,WM}/\gamma_{max}$ approaches 0.4 at t=0.448 s and 0.7 at t=0.482 s. We note that from t=0.398 to 0.448 s the k spectra preserve the shape at $k_{\perp}\rho_s \gtrsim 10$, and at t=0.482 s the spectral power at $k_{\perp}\rho_s \gtrsim 10$ also starts to decrease. This further decrease may be due to the large $\omega_{E\times B,WM}/\gamma_{max}$ (≈0.7) achieved at t=0.482 s. Since the maximum ETG growth rate in the high-k measurement region, $\gamma_{max} \sim 10-20C_s/a$ (C_s is the sound speed and a is the plasma minor radius), is much larger than the experimental ExB shearing rate ($(0.2-0.4)C_s/a$), we think that some of the observed electron-scale turbulence is nonlinearly driven by the ion-scale turbulence and its spectral power decreases as the ion-scale turbulence is progressively suppressed by the ExB shear. We also note that while the ExB shearing rate is varied by about a factor of 4 in the high-k measurement region, other relevant dimensionless parameters vary by no more than ~40% from t=0.364 to 0.482 s.

We would like to emphasize that the plasma confinement is also improved as the ExB shearing rate increases. In particular, the global confinement time normalized to ITER98Pby(2) prediction increases from 0.4 at t=0.364 to 1.1 at t=0.448 s. To show how individual transport channel changes, the ion and electron thermal diffusivity profiles at the times of interest used in Fig. 1 are plotted in Fig. 2. We can immediately see that the largest decrease in both χ_i and χ_e occurs at $R \gtrsim 130\ cm$ ($r/a \gtrsim 0.5$), which coincides well with where the ExB shear varies most. Figure 2 also shows that from t=0.364 to 0.398 s, χ_i and χ_e both decrease by about 35% in the high-k measurement region (the rectangular shaded regions in Fig. 2), and a larger decrease in χ_i and χ_e by about 50% occurs from t=0.398 to 0.448 s, which is anti-correlated with the changes in $\omega_{E\times B,WM}/\gamma_{max}$ shown in Fig. 1(a), i.e. about 40% increase from t=0.364 to 0.398 s and about 50% from t=0.398 to 0.448 s. We note that this reduction in both χ_i and χ_e with increased ExB shear is consistent with ExB shear stabilization of the ion-scale turbulence. However, we can see that χ_i is always anomalous since at its smallest at t=0.448 s, it only approaches to about a factor of 3 of the ion neo-classical thermal diffusivity, $\chi_{i,NC}$. Thus, at this time the ion-scale turbulence is likely not completely quenched. We also point out that χ_i becomes larger and χ_e remains essentially the same from t=0.448 to 0.482 s, even though $\omega_{E\times B,WM}/\gamma_{max}$ is almost doubled. This may be due to an n=1 MHD mode which starts to grow at about t=0.45 s when the stored energy also starts to saturate. This work was supported by the U.S. Department of Energy under Contracts No. DE-AC02-76CH03073, No. DE-FG03-95ER54295, and No. DE-FG03-99ER54518.

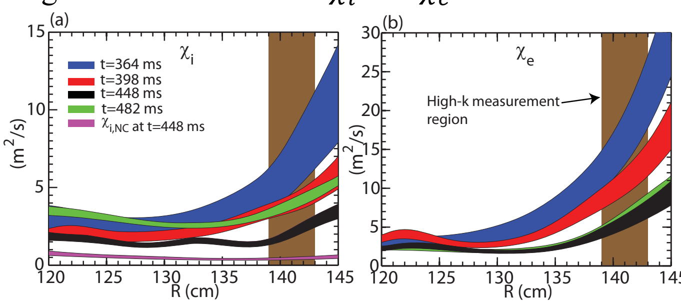

Figure 2 The radial profiles of Ion (a) and electron (b) thermal diffusivity at t=364 ms (blue), 398 ms (red), 448 ms (black), 482 ms (green) . The ion neo-classical thermal diffusivity, $\chi_{i,NC}$, (magenta) is also shown in (a). The vertical width of the colored bands denotes the experimental uncertainty mainly due to the uncertainty in ohmic heating and measured kinetic profiles (applicable to χ_i and χ_e). The rectangular shaded region denotes the high-k measurement region.

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