MULTI-FIELD TURBULENCE AND TRANSPORT BARRIER MEASUREMENTS AND VALIDATING PREDICTIVE CODES FOR HIGH-PERFORMANCE, NEGATIVE TRIANGULARITY ELM-FREE DIII-D PLASMAS

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New multi-field turbulence and flow measurements shed light on how ELM-free, high-performance Negative Triangularity (NT) [1] DIII-D plasmas are formed, how they might be controlled, and our ability to predict them. Measurements of temperature ($\tilde{T}_e$) and density ($\tilde{n}$) turbulence, radial correlation lengths, and poloidal velocity profiles show clear evidence of an edge transport barrier, velocity well, and turbulence reduction (Fig. 1). In addition, simulations (TGLF [2]) show a transition from dominant ITG-like to TEM-like instabilities at the top of the pedestal where they are coincident with the observed peaking in $\tilde{n}$ and $\tilde{T}_e$ (Fig. 2). These significant results allow continued and improved testing of both linear and soon to follow non-linear simulations.

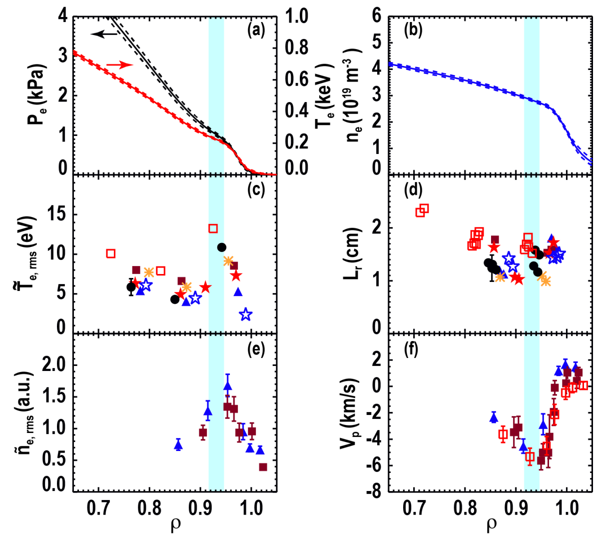

Figure 1 Radial profiles of (a) electron pressure (in black) and T_e (in red), (b) density, (c) T_e turbulence RMS level, (d) radial correlation length of the T_e turbulence, (e) density turbulence RMS level, and (f) poloidal density turbulence phase velocity. The shaded region marks the rough location where the T_e turbulence RMS level peaks. The studied plasmas [3] are ELM-free and have high performance with an average triangularity~-0.5, $H_{98y,2}$~1.2, β_N~2.1. The plasmas were NBI-heated with ~ 5 MW power, line averaged density $\bar{n}_e$~4.6x10^{19} m^{-3}, B_t~2 T, I_p~0.6 MA, and q_{95}~4.4.

The electron temperature (T_e), pressure (P_e), and density (n_e) profiles are plotted in Figs. 1(a) and 1(b) for these high performance NT plasmas [3]. As shown in Fig. 1(a), modest T_e and P_e pedestals are formed at the edge, with the steep gradients at similar radial locations, ρ~0.98. The density profile in Fig. 1(b), however, displays a fast falloff near the last closed flux surface, ρ~1. Similar edge pedestals are observed in H-mode positive triangularity (PT) plasmas but with ELMs believed to be driven by the steep gradients in the profiles. The T_e RMS fluctuating level measured by correlation electron cyclotron emission (CECE) radiometer is plotted in Fig. 1(c), where different symbols represent data from different but similar shots. It demonstrates a peaking profile with the shaded region marking the approximate location of the peak. This peaking location coincides with the T_e/P_e pedestal top as shown in Fig. 1(a) but slightly more inward in relation to the the pedestal top of the density profile (Fig. 1(b)). This peaking feature is also observed in the density RMS fluctuating level measured by Doppler backscattering (DBS) diagnostic (Fig. 1(e)). Figure 1(f) plots the radial profile of the poloidal density turbulence phase velocity (V_p) measured by DBS, showing a well near the location of the T_e/P_e pedestal top, and velocity shears on both sides of this well. Similar V_p profiles have been observed in the H-mode PT plasmas. In the velocity shear region outside this well, the reduction of T_e and n_e RMS fluctuating levels are observed (Figs. 1(c-e)), implying the formation of a transport barrier which leads to the edge pedestals. This observation is consistent with turbulence suppression by ExB shear, which has been universally observed in PT plasmas.

Initial comparisons to the TGLF linear instability code indicate ITG-like dominated turbulence in the core transitioning to TEM-like near the T_e/P_e pedestal top. Figure 2 plots the linear growth rate of the most unstable mode from TGLF turbulence simulations using experimental profiles. Positive and negative growth rates indicate modes propagating in the electron and ion diamagnetic directions respectively. It shows a change from ITG-like ion mode to TEM-like electron mode at T_e turbulence measurement wavenumber scales of CECE ($k_y\rho_s$ <~2 in the plots) near the T_e/P_e pedestal top.

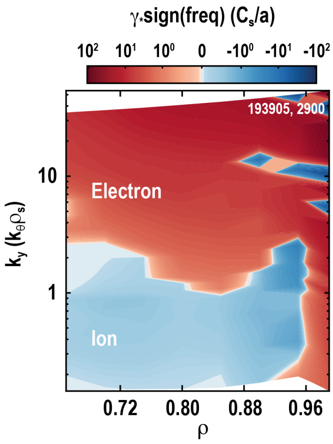

Figure 2 Linear growth rate of the most unstable mode from TGLF as a function of normalized radius ρ and wavenumber ($k_y\rho_s$). Positive and negative growth rates indicate modes propagating in the electron and ion diamagnetic directions respectively. The T_e turbulence measured with correlation ECE in this experiment has wavenumber sensitivity in $k_y\rho_s$ <~2 in the plot.

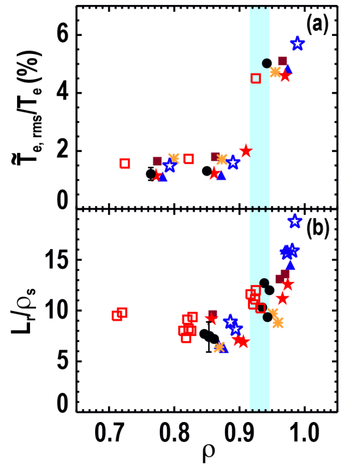

Figure 3 Radial profiles of (a) relative T_e turbulence amplitude, and (b) normalized radial correlation length of the T_e turbulence. The shaded region is the same as in Fig. 1.

Figure 3 illustrates the relative electron temperature turbulence amplitude and normalized radial correlation length for comparisons with simulations which often use normalized quantities. Figure 3(a) plots the radial profile of the normalized electron temperature turbulence amplitude $\tilde{T}_{e,rms}/T_e$. It shows a relatively flat profile from core to ρ~0.92, then there is a significant increase, and the location of the start of this increase is near the T_e/P_e pedestal top. Note that the $\tilde{T}_{e,rms}/T_e$ in this region and outward is generally much larger than the H-mode PT plasmas (typically $\tilde{T}_{e,rms}/T_e$<0.5% in PT plasmas) and comparable to the L-mode PT plasmas, which may be related to a weaker edge pedestal than H-mode PT plasmas. The normalized radial correlation length of T_e turbulence (L_r/ρ_s) also has a similar behavior as $\tilde{T}_{e,rms}/T_e$, as plotted in Fig. 3(b). It follows a scaling of L_r/ρ_s ~ 5-10 from core to ρ~0.92, similar to previously observed in L-mode PT plasmas [4-5], while increasing towards edge starting from the T_e/P_e pedestal top, i.e. L_r/ρ_s is larger than the L-mode PT plasmas in this shaded region and outward.

In summary, new measurements of temperature and density turbulence, radial correlation lengths, and poloidal velocity profiles are presented at edge of the ELM-free, high-performance DIII-D plasmas with a strong NT shaping. Data demonstrated clear evidence of an edge transport barrier, velocity well, and turbulence reduction, similar to the ELMing H-mode PT plasmas. TGLF simulation shows a transition from dominant ITG-like to TEM-like instabilities at the top of the pedestal where they are coincident with the observed peaking in $\tilde{n}$ and $\tilde{T}_e$. The relative T_e turbulence amplitude and normalized radial correlation length increases significantly near the pedestal top, with values generally much larger than the H-mode PT plasmas and comparable to the L-mode PT plasmas. Taking together, these results are a significant advance in our understanding of what controls the edge of these NT plasmas, providing quantitative measurements for advanced testing of linear and non-linear predictions of this important scenario.

ACKNOWLEDGEMENTS

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REFERENCES

[1] CAMENEN, Y., et al., Nucl. Fusion **47** (2007) 510.

[2] STAEBLER, G.M., KINSEY, J.E., and WALTZ, R.E., Phys. Plasmas **14** (2007) 055909.

[3] THOME, K.E., et al., Plasma Phys. Control. Fusion 66 (2024) 105018.

[4] RHODES, T.L., et al., Phys. Plasmas **9** (2002) 2141.

[5] WANG, G., RHODES, T.L., and PEEBLES, W.A., Rev. Sci. Instrum. **93** (2022) 113511.