TURBULENCE AND FLOW DYNAMICS APPROACHING THE DENSITY LIMIT IN L-MODE PLASMAS AT DIII-D

Z. Yan[1], F. Khabanov[1], G.R. McKee[1], P. Diamond[2], G. Tynan[2], R. Hong[3], and L. Schmitz[3]

[1]University of Wisconsin - Madison, Madison, Wisconsin 53706, USA
[2]University of California - San Diego, San Diego, California, 92037, USA
[3]University of California - Los Angeles, Los Angeles, California, 90095, USA
e-mail: zyan5@wisc.edu

Measurements of long wavelength density fluctuations and turbulence poloidal flow at the edge of L-mode plasmas on DIII-D operating near the Greenwald density limit ($n_G=I_p/(\pi a)^2$) have revealed important dynamic properties and the role of turbulent transport leading to the density limit. An abrupt increase in turbulence amplitude and a reduction in poloidal velocity shear were observed as density increased, prior to the drop in edge electron temperature. These observations are consistent with the theoretical prediction that shear flow collapse at high density leads to density limit disruptions. Experiments involving ramping down the plasma current (i.e., reducing the Greenwald density limit) at constant electron density and power showed similar dynamics: an increase in edge density fluctuations and a reduction of edge toroidal rotation were followed by edge cooling and development of the multifaceted asymmetric radiation from the edge (MARFE), which then expanded to the high field side (HFS) and led to a disruption. In recent years, with advances in both experiments and related theories, it is suggested that density limits depend on more parameters and edge dynamics rather than simply the plasma current [1]. Therefore, the experimental observations of edge turbulence and flow dynamics near the density limit help to provide key insights into the underlying physical mechanisms, which are critical to developing new models that can be extrapolated to ITER and future burning plasmas, potentially enabling the operational limit to be increased to higher densities, thereby increasing fusion power production.

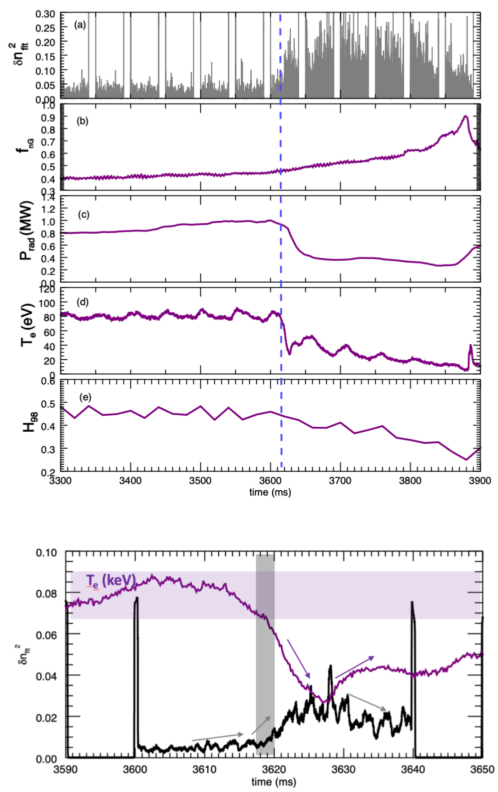

Fig. 1 **Top**: Time history of (a) the square of density fluctuation amplitude; (b) Greenwald density fraction; (c) radiation power at lower divertor; (d) electron temperature near separatrix; (e) H_{98}; **Bottom**: A Zoom-in view of the time window across blue dashed vertical line. Black line is the fluctuations in (a) after 0.5 ms smooth is applied. Purple line is electron temperature near separatrix, same as in (b). The purple-shaded region indicates the T_e oscillation range and grey-shaded region indicates the start of the rapid increase of fluctuations. Shot number is 191787

A dedicated experiment investigating density limit physics was conducted in L-mode plasmas on DIII-D with an unfavorable ion ∇B drift direction in Lower Signal Null (LSN) shape. The Greenwald limit was approached in two different ways: by increasing the density through gas puffing while maintaining constant power and current, and by reducing the plasma current while keeping the density and power constant. Long-wavelength density fluctuations were measured using an 8×8 array of Beam Emission Spectroscopy (BES) throughout the entire time history, covering a radial range of $0.9<\psi<1.04$. The gas puff was increased linearly to raise density at constant power. As shown in Fig. 1Top(b), the Greenwald density fraction initially increased slowly. Around 3618 ms, as indicated by the blue dashed vertical line, several rapid changes were observed: the density fluctuations measured at $\psi\sim0.95$ increased significantly and quickly (Fig.1 Top(a), a Zoom-in view of the time is shown in Fig.1 Bottom), and the rate of increase of Greenwald density fraction became larger. Additionally, the electron temperature near separatrix (Fig.1 Top(d)) and H_{98} factor (Fig.1 Top(e)) began to drop, and the plasma detached, as evidenced by the drop in the radiation power at lower divertor (Fig.1 Top(c)). After 3620 ms, the density continued to increase until the Greenwald fraction reached nearly 0.9, leading to a disruption around 3890 ms.

Fig. 2 shows the profile of the relative density fluctuation amplitude at different times as density is increased. A small change of density fluctuations occurred initially just near the separatrix. Shortly after 3605 ms, the fluctuation amplitude increased significantly across the region inside the separatrix, peaking around ψ~0.95. At the same time, the electron density decreased near ψ~0.95 before increasing later, while it continued to rise in the SOL region. The electron temperature decreased significantly near ψ~0.95 as the turbulence amplitude increased. The skewness of the electron density fluctuation, $\tilde{n}^3/(\tilde{n}^2)^{1.5}$, was also calculated. The skewness profile shifted inwards after the rapid increase in turbulence amplitude, with the zero value of the skewness moving from the separatrix to near ψ~0.95. This suggests that the location of the blob generation moves inwards to ψ~0.95, which is consistent with the location of the maximal increase in the turbulence amplitude.

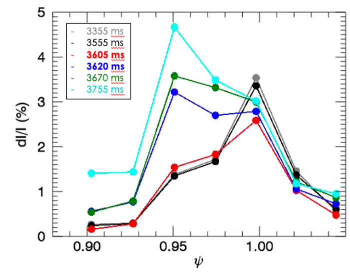

Fig. 2 The profile of relative density fluctuation amplitude at different times with increasing density

Turbulence velocity fluctuations were measured with a velocimetry technique applied to the 2D BES density fluctuation imaging. The profile of the turbulence velocity field is shown in Fig. 3 for the same times. It was found that the velocity well shifted inwards from ψ~0.98 to ψ~0.95 after 3605 ms. The reduction of the velocity shear near ψ~0.95 is consistent with the initial rapid increase of the turbulence amplitude at that location. The outward turbulent particle flux, calculated as $<\tilde{n}\tilde{v}_r>$, began to increase significantly near ψ~0.95 when the rapid increase of turbulence occurred. The adiabaticity parameter, $\boldsymbol{\alpha = k_{\parallel} v_{the}^2/\omega v_{ei}}$, was estimated and shown in Fig. 4. It is predicted to be a key parameter for shear layer collapse. It was found that α dropped from near unity to well below unity after 3610 ms as the density fluctuation increased rapidly. This observation seems to be consistent with theoretical predictions in [2]. In a separate scan, plasma current was ramped down with a fixed toroidal field (increasing q_{95}) and with a decreasing toroidal field (fixed q_{95}). The Greenwald density fraction reached approximately 0.7 with increasing q_{95} but reached higher values of approximately 0.8-0.9 with fixed q_{95}. Turbulence characteristics have been found to strongly depend on q_{95}, with higher turbulence amplitude at higher q_{95}. The higher amplitude of turbulence at higher q_{95} appears consistent with the lower achievable Greenwald density fraction.

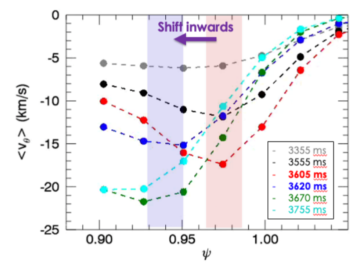

Fig. 3 The profiles of turbulence poloidal velocity field at different times with increasing density

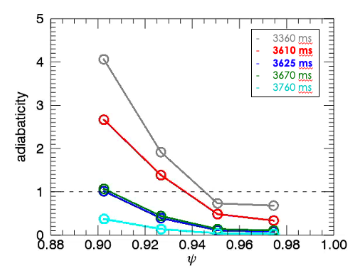

Fig. 4 The profile of the adiabaticity parameter, $\boldsymbol{\alpha = k_{\parallel} v_{the}^2/\omega v_{ei}}$, at different times with increasing density

Detailed spatial and time-resolved analyses of electron density fluctuations and the resulting flow dynamics have revealed the important roles of turbulent transport and shear flow leading to the density limit. This indicates that enhancing edge flow shear can potentially push the operational limit to higher densities in ITER and beyond.

ACKNOWLEDGEMENTS

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