Lower L-H transition power threshold via enhanced turbulence Reynolds stress and flow shear in favorable magnetic geometry

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The L-H transition power threshold in favorable magnetic geometry (ion ∇B drift direction towards X-point) is found up to two to three times lower than in the unfavorable magnetic geometry (ion ∇B drift direction away from X-point) on multiple tokamaks [1, 2]. Experiments performed on DIII-D showed a significant increase of turbulence velocity shear driven by increased Reynolds stress prior to the L-H transition as the plasma magnetic equilibrium is moved from unfavorable to favorable divertor configuration at constant toroidal field, plasma current and input heating power. This increase appears to trigger the L-H transition and lower the transition power threshold in the favorable configuration compared to that in the unfavorable configuration.

The dedicated experiment was carried out in a Double Null (DN) plasma shape. The favorable or unfavorable direction of ion ∇B drift is changed by varying the parameter dRSEP, which is the radial distance between the upper and lower divertor separatrices at the outboard mid-plane. At normal B_t direction with positive dRSEP, the plasma is operated in the unfavorable configuration, and with negative dRSEP the plasma is operated in the favorable configuration. Fig.1 shows a plot of the time history of basic parameters across the L-H transition in this experiment. The plasma was heated by balanced torque neutral beam (NBI) injection. The dRSEP parameter was continuously reduced from +5 cm to -3 cm during a 2-second time window (Fig. 1(a)). During this time NBI power was kept constant at 4 MW (Fig. 1(b)), which is between the transition power threshold for favorable and unfavorable magnetic configuration. Toroidal field, plasma current and line-averaged density were also kept constant. The L-H transition occurred as dRSEP was reduced to 3 cm (at ~1980ms) as indicated by the sudden drop in the D_α signal (Fig. 1(c)). Fig. 2 is a zoom-in of the last ~300ms time window across the transition. A three-phase dynamic behavior is seen from D_α signal (Fig. 2(c)). During this three-phase time window, the ion ∇B drift direction is moving towards more favorable direction slowly (Fig.2 (a)). It is seen that at earlier time before

1790ms, D_α has few oscillations. In the middle time window ~1790-1890 ms larger periodic oscillations appear that are similar to limit cycle oscillations (LCO) observed previously [3]. At the last 150 ms before the transition, ~1890-1980 ms, oscillations in D_α increase in amplitude. Each large burst is separated by periods of smaller, higher frequency oscillations. During this

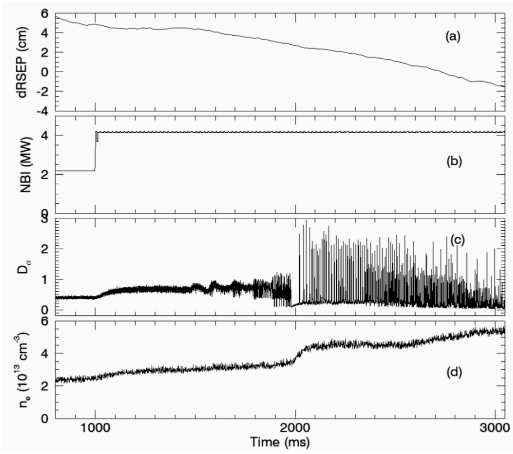

Fig. 1 Time history of (a) dRSEP; (b) NBI heating power; (c) D_α; and (d) line-averaged electron density

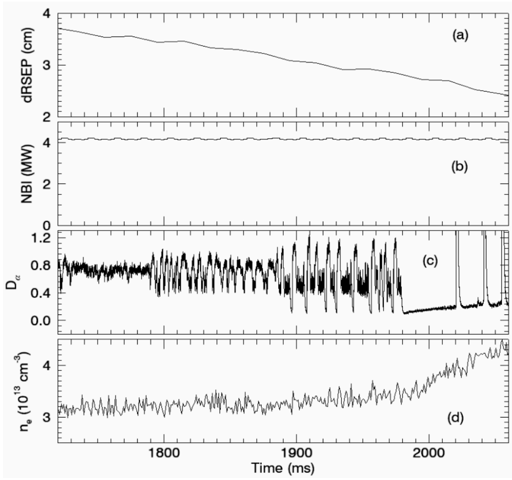

Fig. 2 Time history of (a) dRSEP; (b) NBI heating power; (c) D_α; and (d) line-averaged electron density

three-phase time window, electron temperature, ion temperature and density profiles remain similar at the plasma edge. The equilibrium radial electric field measured by charge exchange recombination spectroscopy (CER) is found to increase approaching the transition. Of note, the dRSEP parameter is still positive, +2 cm (unfavorable) at the time of transition, but the L-H power threshold has been reduced from that at dRSEP=+5 cm.

Detailed turbulence and flows during the three-phase time windows are measured by 2D Beam Emission Spectroscopy (BES) covering the plasma edge region. Fig. 3 is an example of the 2D 8x8 BES array overlaid on plasma equilibrium with spatial resolution of ~1 cm. Low-wavenumber normalized density fluctuation amplitudes are found to reduce substantially approaching the transition suggesting stronger turbulence suppression. This reduction in the turbulence level seems to not be related to the driving mechanism, as the gradients in the profiles at the plasma mid-plane are nearly unchanged. With the capability of 2D density fluctuation measurements from BES, the dynamics of the

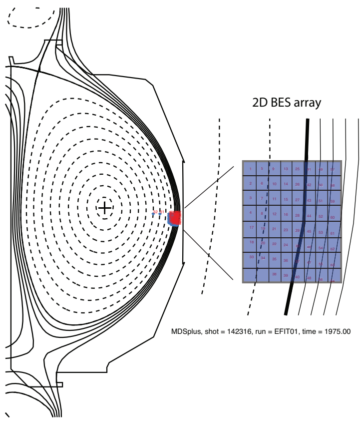

Fig.3 EFIT equilibrium of the plasma with 2D BES overlaid

turbulent eddies can be visualized by imaging the density fluctuations. The density fluctuation data are first frequency filtered to include the broadband turbulence. Instantaneous radial and poloidal velocity fields, $V_r(t)$ and $V_\theta(t)$, can then be obtained via the velocimetry technique [4] applied to the filtered density fluctuation imaging. The turbulence Reynolds stress (RS) is thus inferred as RS= $\langle V_r V_\theta \rangle$, which has been shown to drive the radially sheared poloidal velocity and flow shear. In this work a 20ms analysis time window is chosen from each time phase. Fig. 4(a)-(c) shows the time history of inferred RS for the three 20 ms time windows respectively at ψ~0.96. It is found that at the earlier time 1500-1520ms (Fig.4(a)), the RS is very stable. There is no oscillation seen in RS. During the middle time window, 1850-1870ms (Fig.4(b)), a few bursts appear in the RS. In the last 20ms prior to the L-H transition (Fig.4(c)), many more bursts with larger amplitude in the RS are observed. This suggests stronger drive for shear flow prior to the transition. This is indeed consistent with the flow measurements that are shown in Fig. 4(d)-(f). At the earliest time window, 1500-1520ms, the turbulence poloidal velocity field is nearly constant. Positive velocity means flow is in the ion diamagnetic direction, and negative velocity means the flow is in the electron diamagnetic direction. At the middle time phase, 1850-1870ms, there are a few rapid changes in the flow from ion diamagnetic direction to electron magnetic direction. Finally during the last 20ms prior to the transition, the dynamical changes in the flow become more vigorous with the flow changing frequently between ion diamagnetic direction and electron diamagnetic direction. These rapid changes in the flow are consistent with the dynamic evolution in the Reynolds stress. It is also found that both the

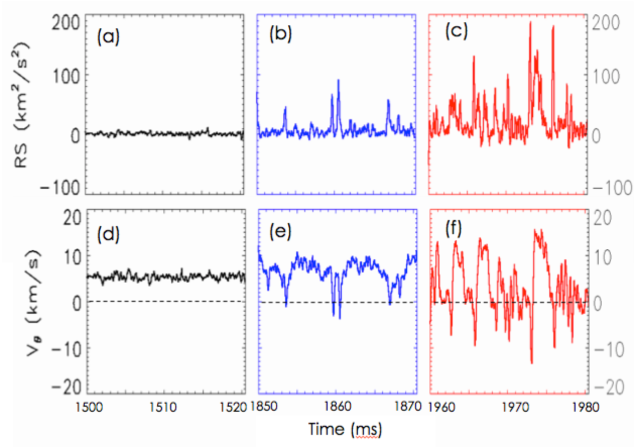

Fig.4 (a)-(c) Reynolds stress from BES measurements for three time windows; (d)-(f) Turbulence poloidal velocity fields for the same three time windows as RS at ψ =0.96.

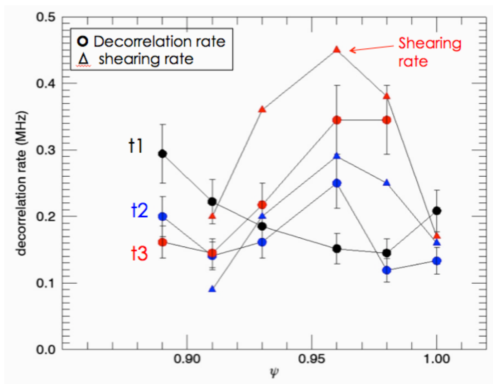

Fig.5 Profiles of flow shearing rate for 1960-1980ms just prior to the transition (diamond) and turbulence decorrelation rate (circle) for three time phases: t1:1500-1520ms (black), t2:1850-1870ms (blue) and t3:1960-1980ms (red).

changes in the RS and the turbulence poloidal flow field are localized in the plasma edge region ψ~0.95-1. The turbulence decorrelation rate is measured by poloidally separated BES channels and is compared with the flow shearing rate. Fig. 5 is a profile of the decorrelation rate for the three time phases. The turbulence decorrelation rate increases as the L-H transition is approached. At the last 20ms prior to the transition the increasing flow-shearing rate from the rapid changes in the flow dynamics shown in Fig. 4 exceeds the decorrelation rate, which can further suppress turbulence facilitating the transition [5]. At earlier times the decorrelation rate is more comparable with the shearing rate. These observations indicate that as plasma moves from unfavorable towards favorable configuration the local edge profiles near the plasma mid-plane is not a major player in the L-H transition; instead, the increasing amplitude of the flow shear driven by increased RS plays a critical role. However, it is unknown why turbulence and flow have this dynamical behavior when heating power and equilibrium parameters are all kept the same. One possibility is changes in the boundary and SOL drift [2].

In summary, a significant increase of turbulence poloidal flow shear driven by increased Reynolds stress is observed prior to the L-H transition as the plasma-operating regime moves from unfavorable to favorable configuration at constant toroidal field, plasma current and input heating power. This increase facilitates the transition and plays a critical role in lowering the L-H transition power threshold in the favorable configuration. Future work will focus on investigating the origin of these turbulence and flow dynamics preceding the transition.

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