TURBULENCE FLOW DYNAMICS AND MODE STRUCTURE IMPACTS ON THE L-H TRANSITION

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Abstract

Understanding the physics behind multiple parameters that affect the L-H transition power threshold but are not included in the current $P_{\text{LH}}$ scaling law is crucial for obtaining a physics-based L-H transition power threshold model for ITER/burning plasmas. Measurements of long wavelength ($k_{\perp} \rho_i < 1$) density fluctuations characteristics and flow dynamics in the edge of the plasmas on DIII-D have demonstrated that turbulence driven shear flow through Reynolds stress and the coexistence of multiple modes associated with different instabilities can lower the L-H transition power threshold across multiple parameters: $q_{95}$, ion VB drift direction, and plasmas with and without applied resonant magnetic perturbations (RMP). The L-H transition power threshold is found to be lower at higher $q_{95}$ near $n_e \sim 3 \times 10^{19}$ m$^{-3}$, which is near the $P_{\text{LH}}$ density minimum on DIII-D. Coexistence of two turbulence modes with opposite poloidal propagation direction is observed at higher $q_{95}$ where $P_{\text{LH}}$ is lower, which is associated with enhanced turbulence Reynolds stress and larger poloidal turbulence flow shear. Linear Gyrokinetic simulations show a transition from one mode to two modes as $q_{95}$ is increased, indicating that $T_i$ profiles strongly impact the ion mode growth rate, even in the pedestal region. As the ion VB drift direction is changed from unfavorable to favorable at constant toroidal field, plasma current and input power, turbulence Reynolds stress and turbulence flow shear are significantly increased approaching the transition. There is little change in the edge plasma profiles of density and temperature. Application of RMP at a magnitude required to suppress ELMs has been observed to raise the turbulence decorrelation rates and reduce Reynolds stress driven flow shear, disrupting the turbulence suppression mechanism, hence increasing the L-H transition power threshold. It also reduces the transient kinetic energy transfer from turbulence to the flow leading up to the transition. Taken together, these unifying experimental observations of the coexistence of multiple turbulence modes, enhanced Reynolds stress and flow shear across multiple parameters demonstrate the significance of turbulence and turbulence driven flow in lowering the L-H transition power threshold, and might lead to the development of methods to reduce the power threshold for ITER.

1. INTRODUCTION

Achieving reliable L-H transitions is of great importance for ITER operation, especially during the initial non-nuclear Hydrogen experimental phase when the available heating power is believed marginally enough to access H-mode. Understanding the physics of the L-H transition mechanism is critical to obtaining a physics model for predicting the transition power threshold ($P_{\text{LH}}$) for ITER, and could also open up prospects of lowering $P_{\text{LH}}$ on ITER. The current empirical scaling law for $P_{\text{LH}}$ [1] was derived without consideration of the full transition
physics in order to maintain simplicity. Several parameters that have been shown to affect the transition power threshold are not included in the scaling law [2-5], such as density minimum, $q_{95}$, ion VB drift direction, and Resonant Magnetic Perturbations (RMP). Previous studies have demonstrated turbulence-driven shear flow as an important player in triggering the L-H transition from both experiments [6-8] and modelling [9]. Increased heating flux drives stronger turbulence, which can drive higher shear flow through Reynolds stress with increased nonlinear energy transfer prior to the transition. Turbulence characteristics and internal mode structures have also been demonstrated to affect the L-H transition power threshold with Dual-frequency band modes observed in the plasmas with lower $P_{\text{ion}}$ in different conditions, such as in deuterium plasmas (which have lower power threshold than hydrogen plasmas) [10], in plasmas with favorable magnetic geometry (lower threshold than that in unfavorable geometry) [11], and in plasmas with lower toroidal rotation (lower threshold than higher toroidal rotation) [12].

In this paper we report results from several L-H transition experiments across multiple parameters on DIII-D: $q_{95}$, ion VB drift direction, plasmas with and without resonant magnetic perturbations (RMP). Several observations are made in these works: Coexistence of two turbulence modes with opposite poloidal propagation direction is observed at higher $q_{95}$ where $P_{\text{LH}}$ is lower, which is associated with enhanced turbulence, Reynolds stress and larger poloidal turbulence flow shear. As the ion VB drift changes direction from unfavorable to favorable at constant toroidal field, plasma current and input power, turbulence Reynolds stress and turbulence flow shear are significantly increased approaching the transition. Application of RMP at a magnitude required to suppress ELMs has been observed to raise the turbulence decorrelation rates and reduce Reynolds stress driven flow shear, disrupting the turbulence suppression mechanism, hence increasing the L-H transition power threshold. All these observations point to a key commonality that turbulence driven shear flow through Reynolds stress and the coexistence of multiple modes associated with different instabilities can lower the L-H transition power threshold.

2. EXPERIMENTAL SET UP

A set of L-H transition experiments were carried out on the DIII-D tokamak in ITER similar shape at $B_t=2T$ with varying $q_{95}$, changing ion VB drift direction and application of RMP at different amplitudes. In the experiments of varying $q_{95}$ and RMP amplitude, the plasmas are in favorable magnetic geometry (ion VB drift towards the X-point), with balanced co- and counter-current neutral beams injected tangentially at nearly zero net torque to keep rotation low for ITER relevance. In the $q_{95}$ scan, plasma current was operated at 1 MA, 1.2 MA, and 1.4 MA at fixed line-averaged density ($1.5\times10^{19}$ m$^{-3}$ and $3.2\times10^{19}$ m$^{-3}$) and toroidal field. Long-wavelength localized density fluctuations are measured with Beam Emission Spectroscopy (BES), which measures Doppler-shifted $H_\alpha$ & $D_\alpha$ emission from collisionally excited high-energy neutral beam atoms. The light intensity is related to the local density through the atomic physics of beam atom excitation [13, 14]. An $8 \times 8$ 2D array of BES channels, each channel imaging a 0.9 cm (radial)$\times$ 1.2 cm (poloidal) area is located at the plasma edge at the outboard mid-plane, providing two-dimensional measurements of the turbulence dynamics over multiple turbulence correlation lengths. An example of the 2D BES array overlaid on plasma equilibrium is shown in Fig. 1. Detailed results from different scans are described in the sections below.
3. TURBULENCE AND FLOW DYNAMICS APPROACHING L-H TRANSITION WITH VARYING q95

Previous work on ASDEX-U at medium and low densities has shown that $P_{\text{LH}}$ depends on plasma current [4], which is not included in the scaling law. In contrast no such dependence has been observed on C-Mod [15]. In this section we will describe the experiment done on DIII-D investigating turbulence and flow dynamics prior to the transition as plasma current ($q_{95}$) is varied. During the experiment, L-H transitions were achieved with beam power ramps with balanced torque neutral beam injection at different plasma current, 1MA, 1.2MA and 1.4MA ($q_{95}$ correspondingly varies from 4.9, 4.0, to 3.5). The transition power threshold is determined as $P_{\text{threshold}} = P_{\text{NBI}} + P_{\text{ohmic}} - dW/dt - P_{\text{radiated}}$, where $P_{\text{NBI}}$ is neutral beam injected power, $P_{\text{ohmic}}$ is Ohmic heating power, $dW/dt$ is the change of stored energy and $P_{\text{radiated}}$ is radiated power inside the separatrix. In the experiments presented here, the radiated power is a small fraction. Therefore, the power threshold does not change significantly whether or not one subtracts radiated power.

Fig. 2(a) shows the power threshold as a function of $q_{95}$ at line averaged density $n_e \sim 3.2 \times 10^{19} \text{m}^{-3}$, which is near the $P_{\text{LH}}$ density minimum on DIII-D. It is seen that L-H transition power threshold decreases by 40% with increasing $q_{95}$. Long wavelength density fluctuations are measured across the L-H transition with 2D BES spanning $0.85 < \rho < 1$. Turbulence amplitude is measurably higher at higher $q_{95} \sim 4.9$ at the plasma edge, suggesting the potential for higher Reynolds stress drive for shear flow at higher $q_{95} \sim 4.9$ than $q_{95} \sim 3.5$. Fig. 2(c) is the wavenumber spectrum of the fluctuations at $q_{95}=4.9$ for $\psi \sim 0.97$. The slope of the turbulence frequency vs $k_\theta$ has two directions: from upper-right to lower-left, indicating a mode propagating in the electron diamagnetic direction and from upper-left to lower-right, indicating a mode propagating in the ion diamagnetic direction in the lab frame. It is seen from Fig. 2(c) that a dual frequency mode with low frequency broadband (<10 kHz) propagating in the ion diamagnetic drift direction and a higher frequency band (>10 kHz) in the electron drift direction (labelled accordingly). The poloidal wave number of the ion mode peaks near about $k_\theta \sim 0.6 \text{cm}^{-1}$ ($k_\theta \rho_s \sim 0.04$) and of the electron mode peaks near $k_\theta \rho_s \sim 0.1$. Comparing with the $E \times B$ velocity, the two modes are propagating in opposite poloidal direction in the plasma frame [16]. As $q_{95}$ goes lower, the dual mode nature becomes less dominant. As is shown in Fig. 2(b) at $q_{95}=3.5$, only a single mode propagating in the electron diamagnetic direction is observed. The two modes observed at $\psi \sim 0.97$, $q_{95}=4.9$ appear to be associated with enhanced turbulence Reynolds stress and larger poloidal turbulence flow shear [16]. Linear gyro-kinetic CGYRO simulations with experimental profiles have shown a transition from one mode to two modes with opposite poloidal propagating directions as $q_{95}$ is increased consistent with the experimental observations. It is also found that $T_i$ profiles strongly impact the ion mode growth rate, even in the pedestal region. On ASDEX-U and C-Mod, a critical ion heat flux has been reported to be necessary for L-H transition [17, 18]. This critical ion heat flux may be related directly to the edge ion temperature gradient, which is observed here to strongly impact the ion mode.
3. TURBULENCE AND FLOW DYNAMICS EVOLUTION AS ION ∇B DRIFT DIRECTION CHANGES FROM UNFAVORABLE to FAVORABLE CONFIGURATION

L-H transition power threshold in favorable ion ∇B drift direction is up to a factor of two lower than in the unfavorable direction. The underlying physics is not understood yet. Previous work from C-MOD suggests it can be related to the scrape-off layer (SOL) flow \[19\]. In this section we will describe a dedicated experiment carried out on DIII-D in Double Null (DN) plasma shape with varying ion ∇B drift direction to investigate the physics behind the threshold dependence.

On DIII-D the favorable or unfavorable direction of ion ∇B drift is changed through varying the parameter dRSEP, which is the radial distance between the upper and lower divertor separatrix at the outboard mid-plane. At normal B_t direction with positive dRSEP, the plasma is operated in unfavorable configuration, and with negative dRSEP the plasma is operated in favorable configuration. Fig. 3 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. dRSEP parameter was continuously reduced from 5cm to -3cm in a 2 second time window (Fig. 3(a)). During this time NBI power was kept constant at 4MW (Fig. 3(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. L-H transition occurred as dRSEP was reduced to 3cm (at ~1980ms) as indicated by the sudden drop in the D_α signal (Fig. 3(c)). Fig. 4 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. 4(c)). During this three-phase time window, ion ∇B drift direction is moving towards more favorable direction slowly (Fig.4 (a)). It is seen that at earlier time before 1790ms, D_α has few oscillations. In the middle time window ~1790-1890ms larger periodic oscillations appear that are similar to limit cycle oscillation (LCO) observed previously \[20\]. At the last 150ms before the transition, ~1890-1980ms, oscillations in D_α become even stronger. Each big burst is separated by periods of smaller, higher frequency oscillations. During this three-phase time window, electron temperature, ion temperature and density profiles are found to have very little changes at the plasma edge. Equilibrium radial electric field measured by charge exchange recombination spectroscopy (CER) is found to increase approaching the transition.

Detailed turbulence and flows during the three-phase time windows are measured by 2D BES. Relative 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 plasma mid-plane are nearly unchanged. With the capability of 2D density fluctuation measurements from BES, the dynamics of the 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 [21] applied to the filtered density fluctuation imaging. The turbulence Reynolds stress (RS) is thus inferred as $RS = \langle V_r V_\theta \rangle$, which is thought to drive the turbulence eddy velocity and flow shear. In this work a 20ms analysis time window is chosen from each time phase. Fig. 5 (a)-(c) shows the time history of inferred RS for the three 20ms time window respectively at $\psi \sim 0.96$. It is found that at the earlier time 1500-1520ms, RS is very stable. There is no oscillation seen in RS. During the middle time window, 1850-1870ms, a few bursts appear in RS. In the last 20ms prior to the L-H transition, many more bursts with larger amplitude in 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. 5(d)-(f). At the earliest time window, 1500-1520ms, turbulence poloidal velocity field is nearly constant with time. The positive velocity means flow is in the ion diamagnetic direction, and the negative velocity means the flow is in the electron diamagnetic direction. At middle time phase, 1850-1870ms, there appear a few rapid changes in the flow from ion diamagnetic direction to electron magnetic direction. Finally at the last 20ms prior to the transition, the dynamical changes in the flow become more vigorous with flow changing frequently between ion diamagnetic direction and electron diamagnetic direction. These rapid changes in the flow are consistent with the dynamic evolution in RS. It is also found that both the changes in the RS and the turbulence poloidal flow field are localized in the plasma edge region $\psi \sim 0.95-1$. Turbulence decorrelation rate can also be measured by poloidally separated BES channels and is compared with the flow shearing rate. Fig. 6 is a profile of the decorrelation rate for three time phases. It is found that 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. 5 exceeds the decorrelation rate, which can further suppress turbulence facilitating the transition [6]. At earlier time the decorrelation rate seems to be more comparable with the shearing rate. These observations indicate that as plasma moves from unfavorable towards favorable configuration the local edge profile near the plasma mid-plane is not a major player in the L-H transition; instead, the increasing amplitude in the flow shear driven by increased RS plays a critical role. However, it is unknown why turbulence and flow have such dynamical behaviors when heating power and equilibrium parameters are all kept the same. One possibility could be related to the changes in the boundary and SOL drift. More dedicated experiments will be planned to investigate this in the future.

5. TURBULENCE AND FLOW DYNAMICS APPROACHING THE TRANSITION WITH RMP APPLICATION

Application of resonant magnetic perturbations (RMPs) has been demonstrated to be a leading technique for

![Fig.5 (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](image)

![Fig.6 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).](image)
ELM control [22-24]. In a reactor-scale tokamak to avoid the first ELM successfully, RMPs may need to be applied before the L-H transition. However this application raises the L-H transition power threshold inhibiting H-mode access. Several theories [25, 26] have predicted that RMPs effectively increase the zonal flow damping rate. In this section we will describe some key results from experimental investigations of the turbulence and flow dynamics approaching the transition with the application of magnetic perturbation, which show commonality in the observations made in the other parameter scans described in previous sections, i.e., $q_{95}$ and ion VB drift direction. More detailed results can be found in reference [27].

During the experiment magnetic perturbations were applied using the I-coil, which consists of two toroidal rows of six window-frame coils each. In this work only $n=3$ MPs were investigated. RMPs were generated by energizing the I-coil in even parity configuration, and non-resonant MPs (NRMPs) were generated with odd parity configuration [27]. The maximal amplitude of $\delta B/B=4.4\times10^{-4}$ with the applied RMPs corresponding to an I-coil current of 5.4kA. The plasma was initially held in L-mode by applying maximum RMP amplitude to increase $P_{LH}$ and using low auxiliary heating at 1.7MW NBI plus 1.2MW ECH. Then the RMP amplitude was reduced stepwise at constant heating power until a L-H transition occurred as shown in Fig. 7. The first and second transitions were at different constant ECH power level marked by dashed blue and red lines; the threshold power required to access H-mode at lower RMP current (second transition) was reduced by $\sim$250 kW.

Turbulence characteristics and flow dynamics approaching the transition are analyzed for three cases: no applied MPs, maximum RMPs and maximum NRMPs. The turbulence decorrelation rate ($\Delta\omega_D$) measured with BES is shown in Fig.8 (a) for the three cases. It is found that $\Delta\omega_D$ increases by 60% across plasma edge, $\rho$=0.9-1.0 when RMP is applied. This increase in the turbulence decorrelation rate suggests that more shear will be needed to suppress turbulence when RMP is applied, which is consistent with the higher power threshold with RMP application.

Turbulence Reynolds stress is inferred by velocimetry analysis of 2D BES data. The gradient of the Reynolds stress is a force on the mean flow, which is called the Reynolds force. Fig.8 (b) is the profile of Reynolds force for three cases. A large negatively directed Reynolds force is observed near $\rho$=0.93 when no MPs are applied. This force is greatly reduced when an RMP is applied throughout the edge region. The negative Reynolds force indicates the force is in the electron diamagnetic direction. Consistently a larger negative turbulence velocity well is observed as shown in Fig.8 (c) when no MPs are applied. Both the location and the direction of the velocity well are consistent with the peak value of Reynolds force. When RMPs are applied, the turbulence velocity field is substantially reduced. This demonstrates that RMPs greatly reduce Reynolds force over most of the edge region, and hence reduce the turbulence velocity and velocity shear, which increases the transition power threshold. This increase in $\Delta\omega_D$ and reduction in the flow shear rate disrupt the turbulence suppression.
mechanism. It is also found that the application of RMP reduces transient kinetic energy transfer from turbulence to the flow approaching the L-H transition [27]. When non-resonant MP is applied, little change in the decorrelation rate was observed, and the turbulence Reynolds stress and flow shear exhibit less reduction, which is consistent with the much reduced impact on the L-H transition power threshold with non-resonant MP compared with RMP.

6. SUMMARY AND DISCUSSIONS

We have investigated the detailed turbulence flow dynamics and turbulence characteristics of long wavelength density fluctuations across L-H transitions for various parameters, \( q_{95} \), ion \( \nabla B \) drift direction and RMP application. The lower \( P_{LH} \) observed at higher \( q_{95} \) is associated with the coexistence of two turbulence modes with opposite poloidal propagation direction and enhanced turbulence Reynolds stress and larger poloidal turbulence flow shear. Turbulence Reynolds stress and turbulence flow shear are significantly increased at constant input power as the ion \( \nabla B \) drift changes direction from unfavorable to favorable. Application of RMP at a magnitude required to suppress ELMs raises the turbulence decorrelation rates and reduces Reynolds stress drive for poloidal flow, disrupting the turbulence suppression mechanism, hence increasing the L-H transition power threshold. These observations demonstrate the important role of turbulence, turbulence driven flow and flow shear in modifying the L-H transition power threshold. They also suggest that it may be possible to reduce the required input power to trigger the transition near the density minimum on ITER by increasing Reynolds stress drive, for example if both ion and electron modes can be driven in the edge plasma. The work described here support current L-H transition theories [28] but suggest a complex behavior that can inform a more complete physics-based model of the L-H transition power threshold for ITER and beyond.

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