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ABSTRACT

Recent measurements from the DIII–D tokamak indicate that shear in the group velocity of the edge density fluctuations is at least partly responsible for the factor 2 change in the H–mode power threshold that is observed, when the direction of the ion ∇B drift relative to the X–point location is reversed. Spatially resolved edge density fluctuation measurements show a change in the poloidal group velocity of the fluctuations when the ∇B drift direction was changed, even though the edge profiles of density and temperature remained nearly the same. High (low) shear in the poloidal velocity is associated with a low (high) power threshold.

1. INTRODUCTION

The direction of the ion ∇B drift relative to the divertor X–point is well known to have a large effect on the H–mode power threshold, P_{TH} [1] When the ion ∇B drift is towards the X–point, P_{TH} is 2–3 times lower than when it is away from the X–point. We have exploited this fact to change the proximity of the plasma to the power threshold without changing the input power level. This allows us to compare plasmas near and far from the power threshold while maintaining other externally controlled parameters constant. In this way, we hope to uncover changes in the plasma that are related to the conditions necessary for the L-H transition and not just changes associated with changing the input power.

The effect of the ion ∇B drift direction on the L-H transition has been previously studied using a fixed X–point location and reversing the direction of B [2]. In that study it was found that the midplane edge profiles of ne, T_e, and T_i were invariant with the direction of B, but that the plasma near the X–point region and in the divertor showed substantial differences and the midplane edge radial electric field, E_r, changed direction. However, when the power was increased to obtain H–mode in the unfavorable ∇B drift case, neither the divertor conditions nor E_r changed in a way that resembled the conditions found in the favorable ∇B drift case. It was therefore difficult to assign a particular importance of the differences in the two cases to the conditions necessary for the L-H transition.

Fluctuation diagnostics on DIII–D now include beam emission spectroscopy [3], and poloidal correlation reflectometry. These diagnostics have recently measured shear in the edge poloidal group velocity of the density fluctuations, (shear = $dV_{\theta group}/dr$), that is present in the favorable ∇B drift case at low power but is not present in the unfavorable ∇B drift case at the same power level. In addition, when the power is increased in the unfavorable ∇B drift case, the magnitude of the shear increases to a value near that in the favorable ∇B drift case at low power.

A leading theory of improved edge confinement in H–mode is E×B flow shear stabilization of turbulence [4]. When the flow shear reaches a critical value, the turbulence is suppressed and radial transport is reduced. The results in this paper suggest that it may be the shear in the edge poloidal group velocity of the turbulent eddy flow field near the plasma edge that is important in determining the L-H transition and P_{TH}.

2. DESCRIPTION OF EXPERIMENT

In this study, the direction of the ion ∇B drift was fixed and the X–point location was changed from a lower single-null (LSN) divertor configuration to an upper single-null (USN) configuration, as shown in Fig. 1. This was done in order to compare the results with our previous study in which the X–point location was fixed and the ion ∇B drift direction was changed. Since the power threshold only depends on the relation between the ion ∇B drift direction and the X–point location, it is assumed that the physics important to the L-H transition will be similar in both cases.

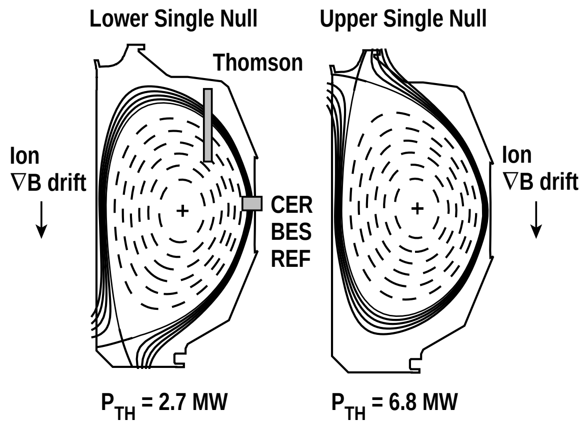

Fig. 1. Comparison of flux surface plots from EFIT for LSN and USN discharges. Also shown are the measurement locations for Thomson scattering (Thomson), charge exchange recombination spectroscopy (CER), beam emission spectroscopy (BES), and correlation refectometer (REF). The ion ∇B drift direction was down in all cases.

Operationally, all the plasma parameters were identical except for the X–point location; I_p = 1 MA, B_T = 2.1 T, $n_e = 2.5\times10^{19}$ m^{-3}, NBI = 1.8 MW, P_{ohmic} = 0.5 MW. There could be some differences in the divertor region, since the geometry of the divertors is different. We are not aware of any measurements that would indicate that the divertor geometry influenced the results of the comparison. Data was collected during steady portions of these discharges ranging from 0.3 to 1.0 s duration. Since the power level was often below one full neutral beam source, the beams were modulated at roughly 75% duty cycle with a period of 40 ms. This period was shorter than the global energy confinement time of 90 to 100 ms so that the power flow to the plasma edge was reasonably steady. No changes in edge temperature or recycling were correlated with the modulation. Repeat shots were taken with different neutral beam sources active in order to collect data from various diagnostics.

3. EDGE PROFILES

Comparisons at fixed heating power and density, but with opposite ∇B drift directions with respect to the X–point location, result in midplane edge profiles of density and temperature that are nearly identical. Figure 2(a-c) shows the edge profiles of n_e, T_e, and P_e measured by Thomson scattering and mapped to the plasma midplane on constant flux surfaces. The profiles are nearly identical with perhaps a slight (roughly 1 cm) inward shift of the USN data.

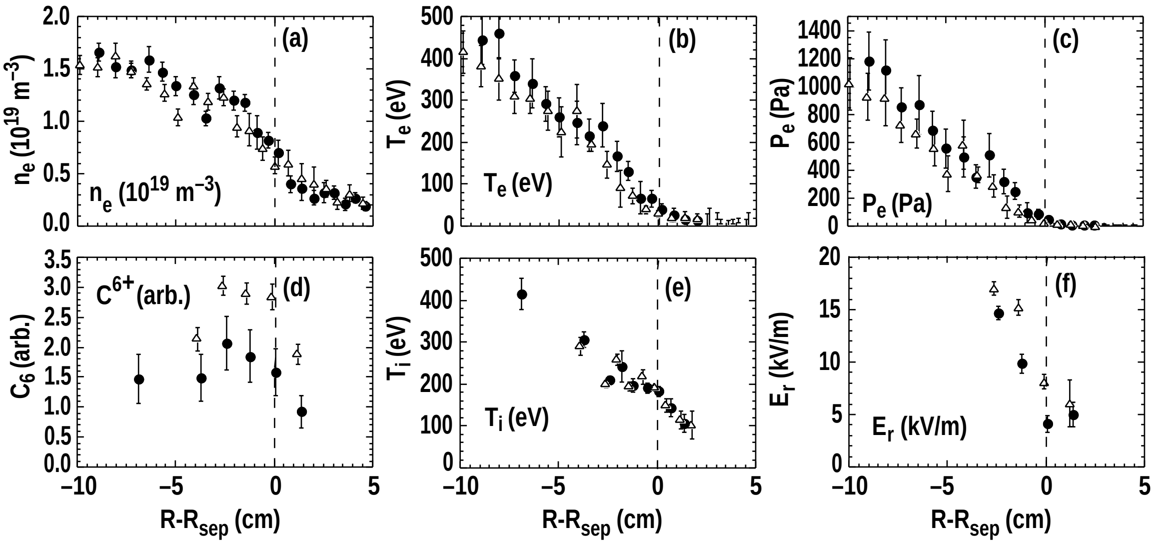

Fig. 2. Edge profiles of (a) n_e, (b) T_e, and (c) P_e measured by Thomson scattering, mapped to the plasma midplane, and (d) C^{6+}, (e) T_i and (f) E_r measured by CER. Closed symbols are for the LSN case and open symbols are for the USN case. The points represent an average of 16 Thomson and 8 CER measurements during a 200 ms steady portion of a single discharge and the error bars represent the standard deviation. The neutral beam power is 1.8 MW in both cases.

The origin of the shift is not known but two possibilities may contribute to it. Mapping errors related to errors in the determination of the separatrix position where the Thomson scattering measurement is made may contribute to uncertainties in the spatial position of the profiles. These errors are estimated to be ± 0.5 cm. Poloidal asymmetries in the density and temperature profiles may also cause a shift between the relative position of the profiles. In the LSN case, the measurement is made away from the X–point while in the USN case, the measurement is made closer to the X–point. Lower temperature or higher density near the X–point would be consistent with the measurements.

The C^{6+} density, ion temperature, and radial electric field, E_r measured by charge exchange recombination spectroscopy are shown in Fig. 2(d-f). E_r is calculated from radial force balance. The slightly higher carbon density in the USN case, may be due to the different divertor configurations. These carbon densities are low and small changes do not affect P_{TH}. In other experiments, the carbon density has changed significantly between boronizations of the DIII–D vessel without changing P_{TH}. The total radiated power was 0.9 MW in both cases. Therefore, we do not think this is a significant contribution to the 4.1 MW difference in P_{TH} for these discharges. The T_i profiles are nearly identical in both discharges and significantly higher than the T_e profiles. The fact that the edge profiles are so similar indicates that the specific values of edge temperature, beta, or their gradients are not playing key roles in determining P_{TH}.

4. EDGE E_r

As shown in Fig. 2(f), the USN plasma has a slightly higher E_r throughout the edge region than the LSN case. However, E_r is positive in both cases. This result differed from our previous result using a fixed X–point location and reversing the direction of B, where we found a negative E_r when the ion ∇B drift was towards the X–point [2].

To better diagnose E_r in this region, several repeat shots were averaged together as shown in Fig. 3. The increase in E_r for the USN case persists in this averaging and the gradient of E_r inside the separatrix has been fitted with a straight line. There is a modest increase of the shear in E_r for the low P_{TH}, LSN case, which corresponds to a shearing rate $\omega_{E\times B} = 3.4 \times 10^5\ s^{-1}$ compared to a rate of $2.5 \times 10^5\ s^{-1}$ for the USN case. The LSN case also shows a slight E_r well forming at the separatrix.

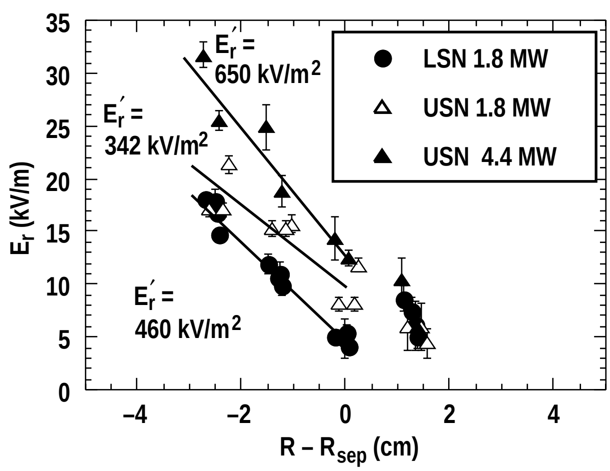

Fig. 3. Edge E_r profiles averaged over multiple discharges. The curves are a linear fit to the points inside the separatrix. The error bars represent the standard deviation of measurements on several discharges.

When the total input power is increased to 4.7 MW, (NBI = 4.4 MW, P_{OH} = 0.3 MW, shot 102017) closer to P_{TH} in the USN case, both E_r and its shear increase. The increase in E_r is due primarily to the increase in the toroidal rotation term of the force balance equation for C^{6+} caused by the momentum input from the neutral beams. The increase in E_r with increasing neutral beam power may help to explain the negative E_r observed in the previous study where the beam power was only 0.3 MW. The higher beam power used in this study, 1.8 MW, may have shifted E_r to more positive values. However, the difference between E_r for the two cases of the ion ∇B drift toward and away from the X–point was similar in the two studies.

These results weakly support the hypothesis of E×B flow shear stabilization of turbulence as the cause for the L-H transition. As more shear develops in the edge plasma, the plasma moves closer to a spontaneous L-H transition. However, the changes in E_r are modest and different configurations seem to have different critical values of E_r shear. As discussed in the next section, there appears to be additional mechanisms other than E×B which create shear in the poloidal group velocity of the density fluctuations near the edge of these plasmas.

5. POLOIDAL VELOCITY OF TURBULENCE

Recent measurements of spatially resolved edge density fluctuations, measured by beam emission spectroscopy (BES) and poloidal correlation reflectometry, show a large change in the poloidal group velocity of the fluctuations when the X–point location is changed. Figure 4 shows the poloidal group velocity of the edge density fluctuations measured by BES ($0.5 \leq k_\perp < 3.0\ \mathrm{cm}^{-1}$) using time delay correlation [5]. The LSN case shows a reversal in the propagation direction of the fluctuations in the region 2–3 cm inside the separatrix. The USN case does not show this reversal and the shear in the poloidal group velocity is weak in comparison to the LSN case.

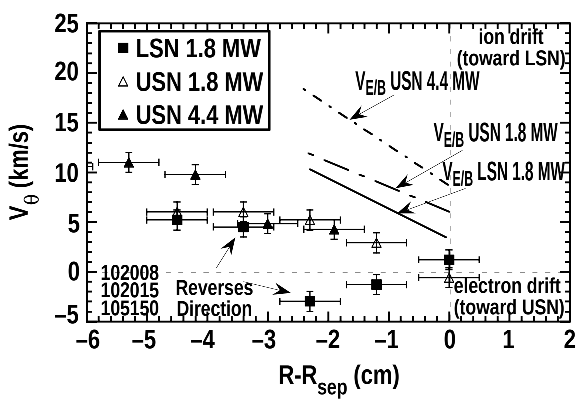

Fig. 4. Poloidal group velocity of the density fluctuations measured by BES. The curves represent the poloidal E×B velocity.

At power levels near the L-H transition the shearing rate of the density fluctuations measured by BES is close to the decorrelation rate as required for turbulence stabilization. The maximum shearing rate given by $dv_{\theta group}/dr$ is $7 \times 10^5\ s^{-1}$ for the LSN case and $3.5 \times 10^5\ s^{-1}$ for the USN case. This compares with measured decorrelation rates of $0.3–2 \times 10^5\ s^{-1}$ for LSN case and $0.4-1.4 \times 10^5\ s^{-1}$ for the USN case. The decorrelation rate is approximated by the inverse decorrelation time, which is calculated from time delay correlation of multipoint measurements [5]. As the power is increased to just below P_{TH} for the USN case, the maximum shear increases to roughly 6×10^5 s^{-1}. These results show that the shearing rate is close to the decorrelation rate as required for turbulence stabilization and that the shearing rate increases to comparable values just before the L-H transition, regardless of P_{TH}.

Of particular note is that the poloidal group velocity of the density fluctuations differs from the E×B velocity. Using E_r calculated from CER measurements, the poloidal E×B velocity is shown as the curves in Fig. 4. The reversal of the poloidal group velocity in the LSN BES data is not apparent in the E×B data. This result is in contrast to our usual result in the plasma core region where the fluctuation group velocity moves with the bulk E×B velocity.

Similar results are measured by poloidal correlation reflectometry as shown in Fig. 5. This instrument is sensitive to wavenumbers in the range $0 \le k_\theta \le 4$ cm^{-1}. Data are obtained from two poloidally separated reflectometer detection positions and analyzed using a two-point correlation technique [6] to extract the group or phase velocity of the fluctuations. The two point technique is used extensively in plasma physics, especially by Langmuir probes, to provide wavenumber, particle flux, phase velocities, etc. A limitation of this technique is that the value of the group velocity can be overestimated whenever counter-propagating modes of the same frequency are simultaneously present (e.g., the phase velocity goes to infinity when a pure standing wave is present). The data here do not appear to be affected by such effects since the measured fluctuation dispersion relation (ω versus k) is found to be well behaved with no sign of strong standing wave activity (i.e. ω varies nearly linearly with k).

A reversal in the propagation direction of the poloidal group velocity of the density fluctuations exists in the region 3–4 cm inside the separatrix for the LSN case, which is not present in the USN case. The horizontal error bars represent the uncertainty in the radial location of the measurement. The ± 1 cm is due in part to the requirement that the density profile is needed to determine the radial location of the fluctuations. The shear in the poloidal group velocity is weak in the USN case whereas it is significant in the LSN case. As the power is increased in the USN case, the group velocity 6–8 cm inside the separatrix increases while the edge group velocity remains the same, resulting in increased shear.

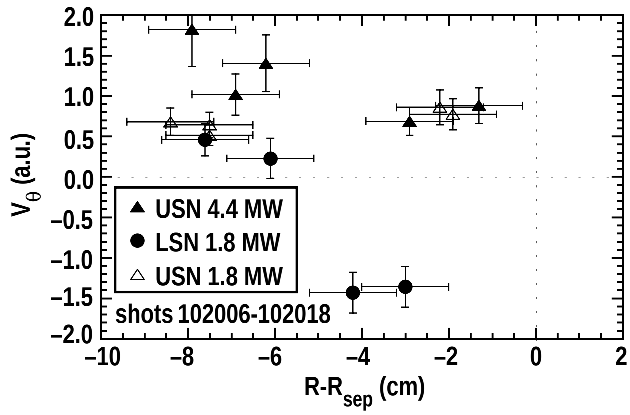

Fig. 5. Poloidal group velocity of the density fluctuations measured by correlation reflectometry.

High (low) shear in the poloidal group velocity of the density fluctuations is associated with the low (high) P_{TH}. We speculate that the naturally occurring shear in the LSN case brings the plasma close to the L-H transition and little additional power is required to increase the shear enough to stabilize the turbulence and initiate the L-H transition. In the USN case, the shear in the poloidal group velocity is weak and significantly more power is required to increase the shear to the point where the turbulence is suppressed and the L-H transition is initiated.

The cause of the naturally occurring high shear of the poloidal group velocity of the density fluctuations in the LSN case is unknown and is presently under investigation. It is possible that in the LSN case the dominant mode of the turbulence changes from an ion to an electron mode close to the plasma edge and diamagnetic flows carry the modes in opposite directions. In some cases, the BES data shows dual modes propagating in opposite directions: a low frequency (< 40 kHz) mode in the electron drift direction and a high frequency (> 50 kHz) mode in the ion drift direction. Non-linear effects between the modes could provide a mechanism for turbulence suppression but this remains to be investigated theoretically.

6. SUMMARY

Comparisons at fixed heating power and density, but with opposite ∇B drift directions with respect to the X–point location, resulted in midplane edge profiles of density and temperature, as well as amplitudes of density and potential fluctuations, that were nearly identical. This indicates that the specific values of midplane edge temperature, beta, or their gradients are not playing key roles in determining P_{TH}.

Spatially resolved edge density fluctuation measurements show a change in the poloidal group velocity of the fluctuations when ∇B drift direction was changed. High (low) shear in the poloidal group velocity is associated with the low (high) P_{TH}. A power scan shows that the poloidal group velocity shear increases with the heating power. It is also observed that the poloidal group velocity can differ from the $E_r \times B_T$ velocity near the plasma edge.

Together, these results suggest that shear in the edge poloidal group velocity of the turbulence is important for obtaining H–mode and in determining P_{TH}.

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