DEPENDENCE OF THE H-MODE POWER THRESHOLD ON TOROIDAL PLASMA ROTATION IN THE DIII–D TOKAMAK

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ABSTRACT

The power required to induce the transition from L-mode to H-mode plasmas (L-H transition) is dependent on the applied beam torque and the edge toroidal plasma rotation. For upper single null discharges in which the ion grad-B drift is away from the X-point, the L-H transition power threshold is reduced by nearly a factor of 3 by changing from predominantly co-injection (~6 MW) to predominantly counter-injection (~2.2 MW). A similar, but less prominent dependence is observed in lower single null discharges, in which the ion grad-B drift is towards the X-point, where the power threshold is reduced by nearly a factor of 2. Over a similar torque range of 2.0 Nm to –0.5 Nm, the USN discharges exhibit a reduction in threshold power of over 50% and the LSN cases show a power reduction of about 30%. The threshold power decreases with decreasing edge toroidal rotation and, at low edge toroidal rotation, large changes in the shear of the poloidal velocity of the edge turbulent eddies are observed prior to the L-H transition that may be strong enough to induce the transition. For the first time, the L-H transition has been induced at constant input power below the nominal threshold power by reducing the input torque from all co-beams to balanced beams. The variation in threshold power with applied torque is not found to be dependent on the ion orbit losses in the plasma.

1. INTRODUCTION

Understanding the influence of the plasma rotation and its shear on the physics of H-mode plasmas is important for increasing the performance of these plasmas. This is of particular relevance to future fusion devices, such as ITER, for which operational and performance predictions are being extrapolated and scaled from present day experimental results. The ability to produce high performance H-mode plasmas in these future devices will depend on knowledge of how the H-mode power threshold varies as a function of various plasma parameters and configurations [1]. Investigations in this area have been advanced at DIII-D following major modifications to the neutral beam injection (NBI) system to allow for simultaneous NBI in both the co and counter directions to the direction of the plasma current. Subsequently, it is possible to vary the input NBI power to the plasma for fixed applied beam torque and, conversely, vary the applied NBI torque at constant input power. The present experiments at DIII-D have been performed for plasma configurations in which the ion grad-B drift direction is away from the dominant X-point in the plasma and also for cases in which the ion grad-B drift direction is towards the dominant X-point. This is because studies have shown that the direction of the ion grad-B drift with respect to the X-point affects the H-mode power threshold [2]. It should be noted that the H-mode power threshold scaling formulae derived to date for the most favourable ion grad B drift case (i.e. towards the X-point) involve global plasma parameters [1,3]. However, H-mode plasmas are the result of the formation of a transport barrier at the edge of the plasma, which is susceptible to and affected by the local conditions at the plasma edge, especially with regard to quantities such as the edge radial electric field [4,5]. The experiments described in this paper have focussed on detailed measurements of plasma edge quantities in order to resolve the physics behind the H-mode power threshold behaviour. In particular, these include high spatially resolved measurements of the edge toroidal and poloidal rotation, the radial electric field and the edge plasma turbulence.

In the present experiments, the power required to induce the transition from L-mode to H-mode plasmas is found to be dependent on the applied beam torque and the edge toroidal plasma rotation. For upper single null discharges in which the ion grad-B drift is away from the X-point, the L-H transition power threshold is reduced by nearly a factor of 3 by changing from predominantly co-injection (~6 MW) to predominantly counter-injection (~2.2 MW). A similar, but less prominent dependence is observed in lower single null discharges, in which the ion grad-B drift is towards the X-point, where the power threshold is reduced by nearly a factor of 2, from ~3 MW with predominantly co-injected beams to ~1.7 MW with counter-injected beams. Further, at low plasma rotation, edge turbulence measurements indicate the presence of a significant shear in the poloidal rotation of the edge turbulent eddies in the L-mode, which may facilitate the transition to H-mode at low power values. These experiments also investigated the hypothesis that fast ion orbit differences

between co and counter injected beams may account for the observed differences in power threshold. Ions born from co-current beams are better confined and localized more towards the core compared with counter-current beam ions. This can lead to changes in the edge potential and electric field, which may facilitate the H-mode transition at low power levels with counter beam injection. However, the experimental results show that prompt ion orbit losses do not affect the H-mode threshold power. Overall, the above results pose significant implications for the low toroidal rotating plasmas expected in ITER for which the assumptions and extrapolations for H-mode threshold power need to be re-examined in light of these torque and plasma rotation dependencies.

This paper describes experiments in which the H-mode threshold power has been measured for different values of the applied beam torque and for different plasma configurations. Section 2 describes details of how the H-mode threshold power varies with the applied beam torque and the edge toroidal rotation. Section 3 describes experiments in which, for the first time, the H-mode transition has been induced by performing a scan in the applied beam torque at constant input power. Section 4 contains details on how the plasma turbulence is affected as a function of the input torque and section five describes the effects of fast ion losses on the transition. The summary and conclusions are presented in Section 6.

2. THRESHOLD POWER DEPENDENCE ON EDGE TOROIDAL ROTATION

These experiments were performed in deuterium plasmas with a plasma current, I_p, of 1.0 MA, a toroidal magnetic field, B_T, of 2.0 T, an elongation, κ, of 1.7, an edge safety factor, q_{95}, of around 5 and a line averaged density in L-mode of 2.4x 10^{19} m^{-3}. The plasma configurations used were upper single null (USN) and lower single null (LSN) diverted plasmas in which the magnetic geometry has a null at both vertical ends, but with the plasma biased upwards or downwards by +/–>5 cm, so making the upper or lower null active, respectively. In this manner, these plasmas could be described as unbalanced double-null discharges with either a dominant upper null or lower null. The ion grad-B drift remained in the same direction (i.e. downwards) for both configurations (USN and LSN). Correspondingly, the USN discharges had the ion grad-B drift away from the active null or X-point and the LSN discharges had the ion grad-B drift towards the X-point. The plasma configurations were not optimized to make use of the divertor cryopumps.

The present NBI system on DIII-D consists of seven horizontal beams, five of which are injected in the counter-clockwise direction (when viewed from above), and two beams which are directed in the opposite (i.e. clockwise) direction [6]. For the normal counter-clockwise direction of the plasma current in DIII-D, this meant that the five co-directed sources were in the same direction as the plasma current and two beams were injected counter to the plasma current. All of the beams are injected with their centerlines being near the nominal midplane of the plasma. Four of the beams (3 co and 1 counter) are injected at 47 degrees to the tangential plane of the magnetic axis of the plasma at the point of intersection and shall be referred to as tangential beams in the rest of the paper. Three of the beams (2 co and 1 counter) are injected at 63 degrees to the tangential plane and will be referred to as perpendicular beams. The beam acceleration voltages were varied from 81 kV to 60 kV during the experiments (between shots) so that the power per beam could be changed if less power was required.

The initial set of conditions investigated were with USN plasmas, which have higher L-H power thresholds compared to LSN plasmas at similar conditions [7,8]. The total beam power was increased in incremental steps of 0.25 of a beam source, i.e., between 400–700 kW/step, depending on the beam voltage settings. Note that ion orbit losses were not taken into account in the NBI power estimations and the quoted NBI powers are the values entering the vessel. The power steps were achieved by modulating the beams at various duty cycles of maximum cycle time of 40 ms, so that each 0.25 step corresponded to an additional 10 ms within the 40 ms cycle window. This modulation time scale is less than the fast-ion slowing-down time and so any instantaneous variation of the beam power is averaged out over a longer time scale by the plasma. The duration of each power step was 320 ms, which was many confinement times, so allowing the plasma to respond to the time-averaged power

increases. This also allowed enough time for high-quality fluctuation measurements to be obtained. The power steps were applied whilst maintaining a given value of plasma torque. This was achieved by balancing out the torque from a co beam by injecting the same (but opposite) torque from a counter beam. Increases in tangential co beams were balanced out by the same increase in counter tangential beams and similarly for the perpendicular beams. In this manner, a power scan could be started at a given value of applied torque, which was then maintained during successive increasing steps in the beam power. This allowed for a more accurate determination of the threshold power without any variation due to a changing beam torque during the scan. The uncertainty in the torque estimations was around 10%. For the cases with all co-NBI or all counter-NBI, it was necessary to ramp the power and torque steps together since the two quantities are not independent. Power scans were started at a level well below the LH power threshold in the quasi-stationary phase of the discharge and then the power was ramped up, at constant torque, in 320 ms steps to trigger the LH transition.

The H-mode power threshold with the highest torque input was determined by injecting all co-beams into an USN plasma. Figure 1 shows the time histories of various plasma quantities as the beam power input is stepped up. The edge toroidal rotation, at a location of 1 cm inside the separatrix, slowly increases as the power is increased in L-mode until the H-mode transition occurs at 2150 ms with an input power of 5.9 MW and an injected torque of just over 4 Nm, as calculated from the beam geometry and the beam deposition calibrations. The co-injected beams in this case were applied with an accelerating voltage of mostly 75 kV. The edge toroidal rotation is determined from charge exchange recombination (CER) spectroscopic measurements performed on the emission from the C VI ion ($\lambda=5290.5$ A), which is produced as a result of charge exchange between heating beam atoms and fully stripped carbon atoms [9]. At the plasma edge in DIII-D, the spatial resolution of the toroidal rotation measurements (as well as poloidal rotation measurements from vertically viewing chords) is about 6 mm. Figure 1 shows that both the beam power and the beam torque continue to increase, since only co-injected beams are used and there are no counter beams to balance out any increases in torque due to the increasing the co-injected power. The transition, as indicated by the sudden drop in the edge recycling D_α signal, occurs at an edge toroidal rotation of about 25 km s^{-1}. Figure 2 shows the H-mode transition for the case of increased applied power at constant input torque. The power is slowly increased at near zero applied torque [figure 2(b)] from 1200 ms until the transition occurs at 1506 ms. Both sets of beams (co-injected and counter-injected) in this case were operated at 60 kV. The H-mode transition at zero torque occurs at about 3 MW. Note that the edge toroidal rotation measured about 1 cm inside the separatrix is much lower than the all co-injected case and is around 5 km s^{-1}.
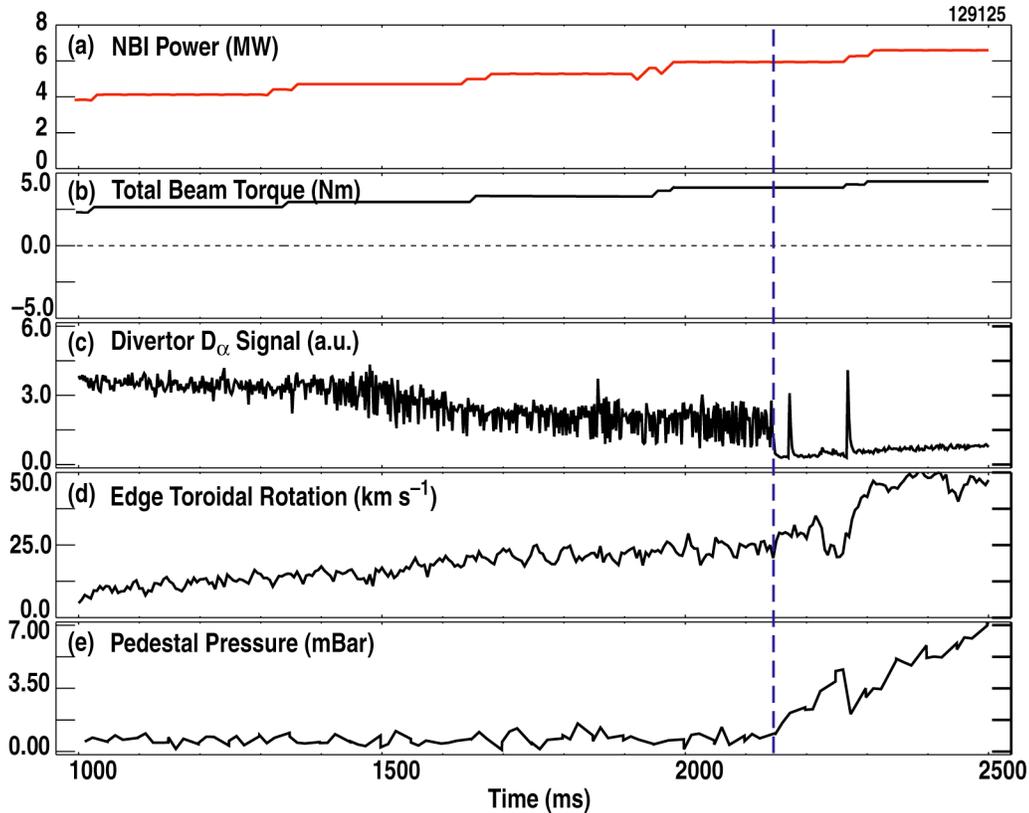
Fig. 1. Time histories of various plasma quantities for a plasma discharge during the application of all co-current neutral beams. (a) Total NBI power, (b) total beam torque, (c) D_α signal from the divertor region, (d) toroidal rotation of a CER chord located 1 cm inside the separatrix, (e) electron pressure at the location of the pedestal. The time of the L-H transition is marked by the dashed vertical line.

Note that he target plasmas (i.e. before the application of beams) for this cases were repeat discharges at the same operational parameters (i.e. Ip, Bt, target density, etc). The only conditions that were varied were the parameters for the NB input, such as power and torque. The Da signals for these repeat discharges were identical before the time of first beam application. Then any variation in the Da signal from discharge to discharge is the result of the combination of beams used and the affect of the applied power and torque.

The H-mode power threshold was obtained for many cases with increasing power steps at constant applied beam torque, but with different starting torques for the same set of plasma parameters and conditions. Only the plasma configuration was changed from USN to LSN plasmas. The results of these scans are shown in figure 3. The H-mode power threshold exhibits a clear and significant increase with the applied beam torque of nearly a factor of 3 from about 2.2 MW with predominantly counter-injected beams (applied torque of –0.5 Nm) to about 6 MW with all co-injected beams (applied torque of about 4.1 Nm). An increase in threshold power with applied beam torque is also observed in LSN plasmas, but is less profound showing an increase of nearly a factor of 2 from about 1.8 MW (applied torque of –1.3 Nm) to about 3.3 MW (at applied torque of 2 Nm).
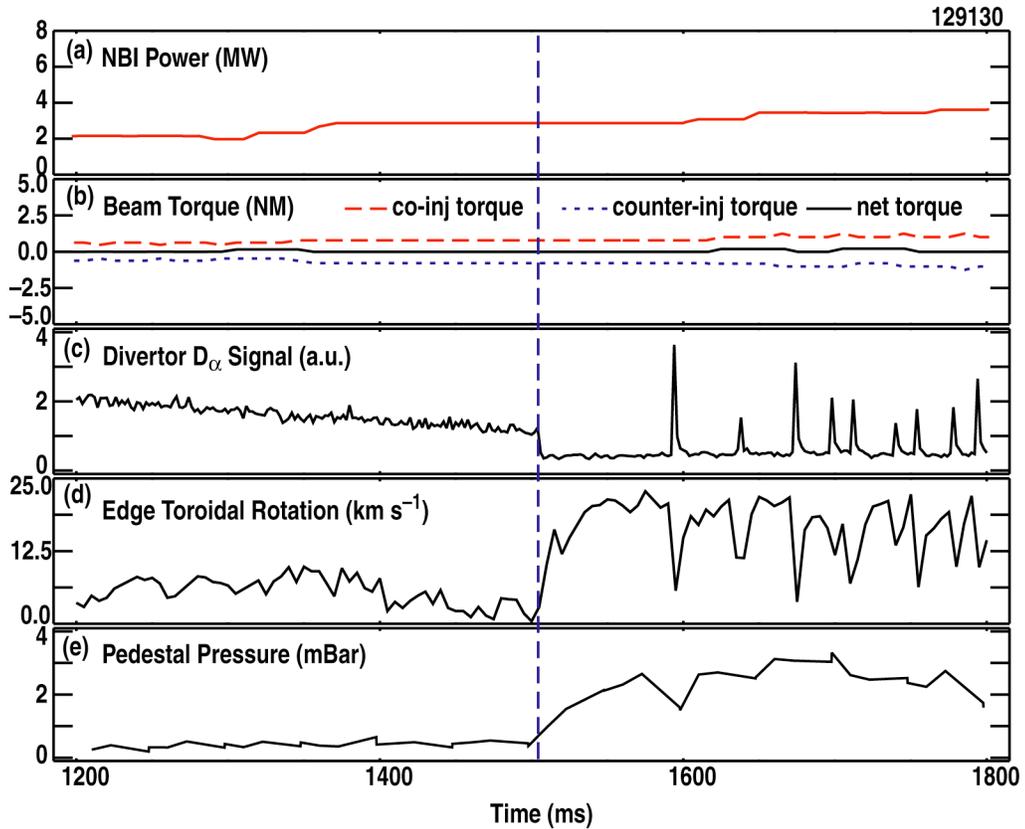
Fig. 2. Time histories of various plasma quantities for a plasma discharge during the application of NBI power at net zero torque. (a) Total NBI power, (b) total beam torque together with the co- and counter-injected torque components, (c) D_α signal from the divertor region, (d) toroidal rotation of a CER chord located 1 cm inside the separatrix, (e) electron pressure at the location of the pedestal. The time of the L-H transition is marked by the dashed vertical line.
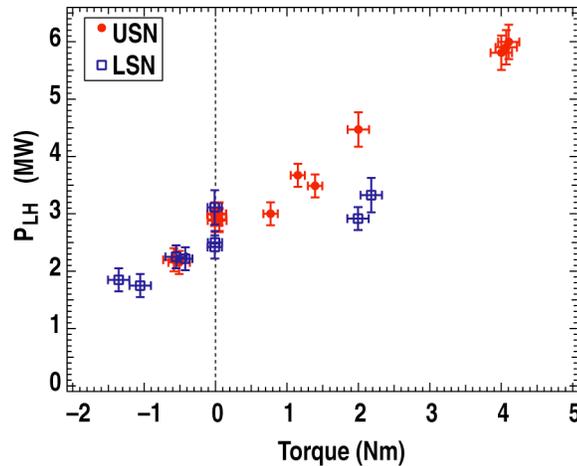

Fig. 3. The H-mode threshold power as a function of the input torque from neutral beams. The dependence is shown for plasma discharges biased in the upwards direction (USN) and for plasmas biased downwards (LSN).

The results shown in figure 3 clearly indicate a dependence of the H-mode power threshold on the applied beam torque. However, they do not, in themselves, reveal the important plasma quantity that may be influencing the threshold power behavior. In order to determine the role of any edge quantity, a detailed analysis of various quantities at the plasma edge was performed for the many (a total of 9) scans performed for figure 3. Such quantities included the evolution of the electron and ion temperatures and densities, the toroidal and poloidal rotation and the edge electron pressure in the L-mode prior to the H-mode transition. A key edge quantity that showed a clear correlation with the threshold power was the edge toroidal rotation. Figure 4 shows the dependence of the power threshold on the toroidal plasma rotation measured 1 cm inside the location of the separatrix in the L-mode phase just before the H-mode transition. The toroidal rotation is not simply determined for one CER chord for all the cases, but is instead determined from the actual profile of the toroidal rotation at the plasma edge, from which the rotation value is taken at the location of 1 cm from the separatrix. Figure 5 shows the edge toroidal rotation profiles measured for 2 USN cases at 4 Nm and 0 Nm input torque. There appears to be a near monotonic increase in the H-mode power threshold with edge rotation at low to medium rotation values (for both the USN and LSN discharges). A flattening off in the dependence is observed at high rotation values. Note that the edge rotation is still positive for the cases with negative torque input because there is some intrinsic positive rotation in the plasma even without any beam input which is larger than the rotation induced by the negative torque. It may be said that a dependence on the toroidal rotation may not be surprising given that the main driver is the applied beam torque, which directly affects the toroidal rotation. The H-mode transport barrier is an edge barrier and the edge rotation measured 1 cm from the separatrix in the L-mode phase appears to be clearly correlated with the formation of this barrier.
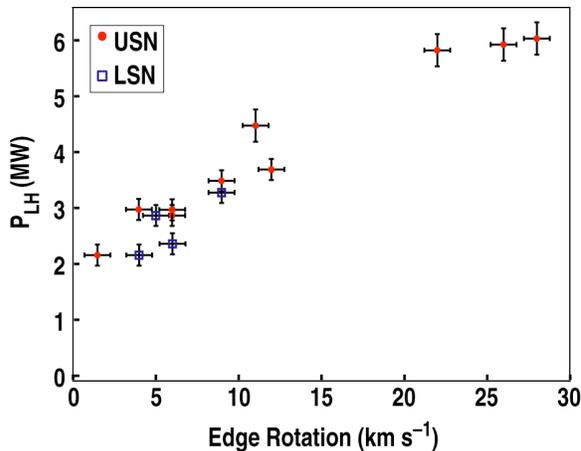

Fig. 4. The H-mode threshold power as a function of edge toroidal rotation. The toroidal rotation is measured 1 cm from the separatrix, inside the plasma. The dependence is shown for both USN and LSN plasmas.
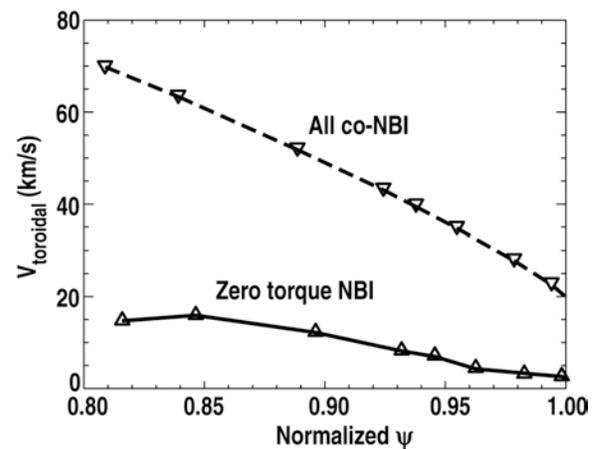
Fig. 5. Edge toroidal rotation profiles just before the H-mode transition for USN discharges shown in figures 1 and 2. The location of 1 cm inside the separatrix corresponds to approximately normalized $\psi = 0.98$.

3. H-MODE TRANSITION INDUCED BY TORQUE SCAN AT CONSTANT POWER

Given the strong correlation of the H-mode power threshold with the edge toroidal rotation, an attempt was made to induce the H-mode transition at power levels below the nominal threshold value by changing the applied torque during the discharge. This experiment was performed with an USN plasma, in which the power was injected into a co-rotating discharge below its power threshold i.e. in L-mode. Figure 3 shows that the H-mode threshold power at 2 Nm is about 4.5 MW. Subsequently, the total power was kept at a constant level below this value (i.e. at 3 MW) whilst the applied beam torque was changed. The initial beam configuration consisted of all co-injected beams with a total power of about 3 MW and applied torque of about 2 Nm. The applied torque was then varied during the discharge by successively applying increased counter torque (with counter-injected beams), whilst simultaneously reducing the co-injected torque (by reducing the amount of co-injected beams) and also maintaining a near constant total beam power by careful selection of the co and counter beams used. The time histories of the applied beam power and torque can be seen in figure 6. There is a very small droop in the total beam power over the time of interest
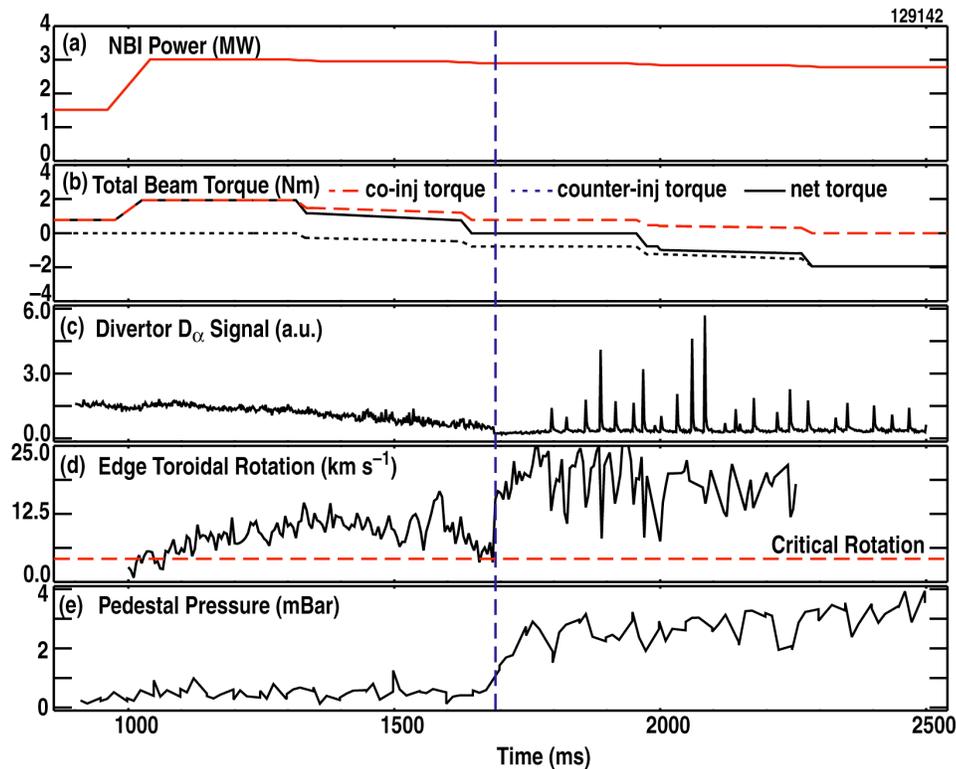
Fig. 6. The time histories of various plasma quantities for a plasma discharge during the application of NBI at constant power and varying torque. (a) Total NBI power, (b) total beam torque together with co- and counter-injected torque components, (c) D_α signal from the divertor region, (d) toroidal rotation of a CER chord located 0.7 cm inside the separatrix, and (e) electron pressure at the pedestal location. The time of the L-H transition is marked by the dashed vertical line.

as a result of a small mismatch in the net power from the various individual beams. The plasma clearly stays in L-mode during the time the net torque is in the co-direction. Then, as more counter-injected beams are applied for the given power, the edge toroidal rotation decreases and the H-mode transition occurs at about 1687 ms, at the point when the edge toroidal rotation is close to the critical rotation for the H-mode as determined from figure 4. Note that the values shown in figure 4 were determined from power scans at constant torque, whereas the rotation value at the H-mode transition shown in figure 6 is obtained through a different approach by which the rotation is varied at constant power. This result marks the first occurrence in which an H-mode transition has been produced at constant power, below the nominal threshold power, by changing the edge rotation.

A clearer understanding of the physics behind the H-mode transition described in figure 6 was obtained by more detailed analysis of the toroidal rotation in L-mode just prior to the L-H transition. Figure 7 shows an expanded time scale of figure 6, just before the H-mode transition, showing the time histories of the toroidal rotation for several CER spatial chords at various locations inside the separatrix. At the start time of figure 7, the gradient in the edge toroidal rotation, as determined by the separation between the various toroidal chords [figure 7(c)], is small. However, the gradient in toroidal rotation increases with time, as can be seen by the increasing separation between the chords at –0.7 and –2.6 cm. This, in turn, leads to an increased shear (i.e. gradient) in the edge radial electric field, E_r, as can be seen in the increased separation of E_r between locations (c.f. at –1.0 cm and –2.3 cm) for the E_r measurements at the plasma edge [figure 7(d)]. The E_r values were determined from CER spectroscopic measurements of the edge pressure gradient and the edge toroidal and poloidal rotation velocities. The increased shear E_r in due to changes in the edge toroidal rotation may be sufficient to then cause the H-mode transition observed at 1687 ms.

A working hypothesis on the increased shear in E_r as the edge rotation is reduced is as follows: at low edge rotation, the relative influence of changes in the pressure gradient term (i.e., diamagnetic contribution) and/or poloidal flow variations are more significant to E_r and its shear than for an E_r profile dominated by a large toroidal rotation contribution. This behavior would be consistent with the decrease in the H-mode power threshold with decreasing edge rotation.
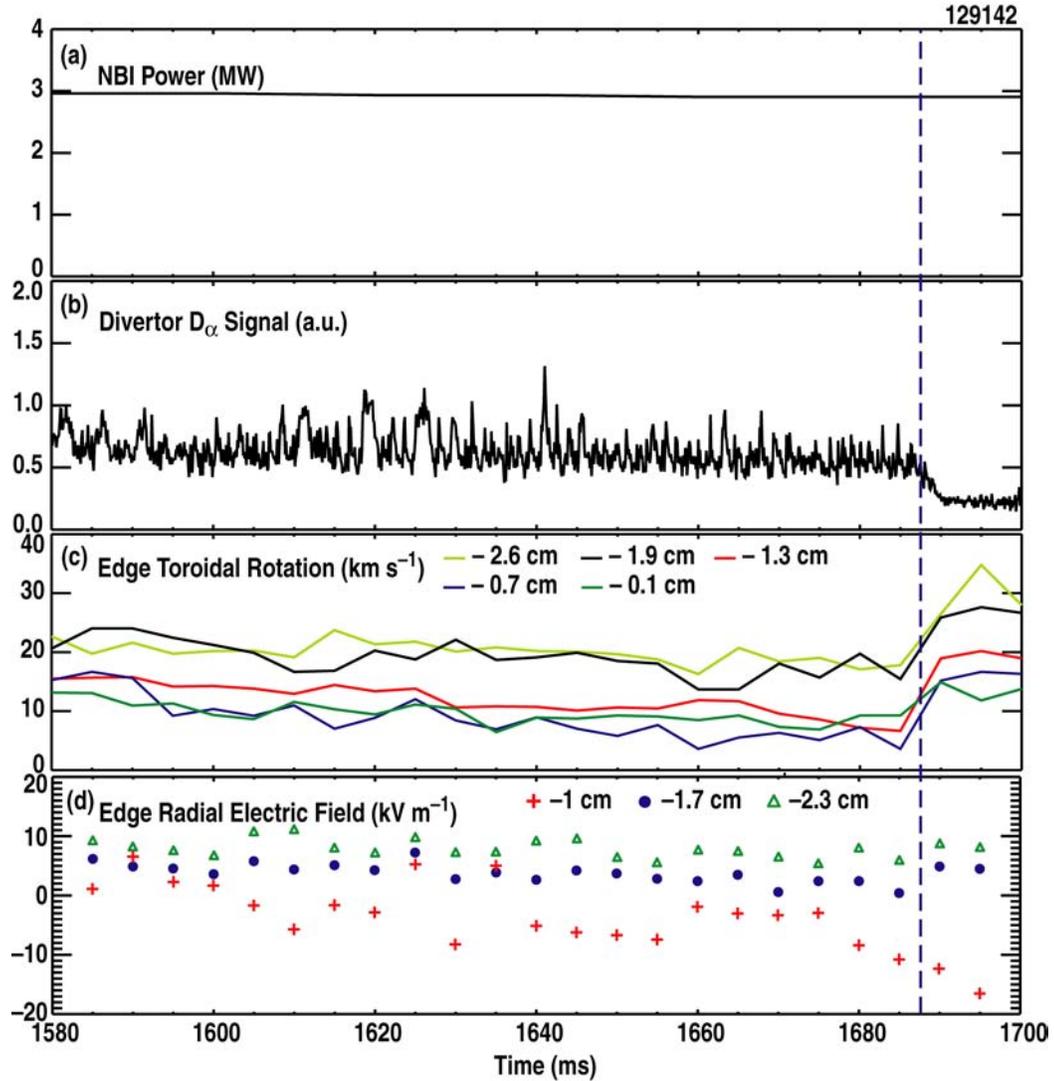
Fig. 7. The time histories of various plasma quantities for the plasma discharge shown in figure 6, but with an expanded time scale. (a) The total NBI power, (b) the D_α signal from the divertor region, (c) the toroidal rotation of multiple, successive CER chords located at varying distances inside the separatrix, (d) the radial electric field as measured by successive CER chords inside the separatrix. The time of the L-H transition is marked by the dashed vertical line.

4. PLASMA FLUCTUATION MEASUREMENTS FROM BEAM EMISSION SPECTROSCOPY

Two-dimensional measurements of the density fluctuation spectra and spatial phase relationships were obtained near the outboard midplane in these discharges with the upgraded Beam Emission Spectroscopy diagnostic [10]. BES observes localized long-wavelength ($k_\perp \rho_I$ < 1) density fluctuations by measuring the Doppler-shifted D_α beam emission intensity that is excited by collisions between beam atoms and plasma ions and electrons. Measurements were obtained with a 5 x 6 channel grid covering an approximately 4 x 7 cm region near 0.9 < r/a < 1.0 at a spatial resolution of approximately 1 cm in the radial and 1.2 cm in the poloidal direction [11]. These time-resolved 2D measurements allow for detailed examination of turbulence and turbulence flows during the time leading up to and across the L-H transition.

The power spectra and poloidal phase relationships are shown in figure 8. Figure 8(a) and (b) show the density fluctuation power spectra at r/a=0.9 and r/a=1.0 for a co-injected and balanced discharge, while figure 8(c) and (d) show the phase shift at r/a=0.9 and r/a=1.0, respectively, between two poloidally separated measurements (ΔZ=1.2 cm) for the same two discharges. In each case, these measurements are averaged over a 100 ms period in the L-mode phase just prior to the L-H transition. These measurements show a dramatic difference in the edge turbulence and turbulence flow patterns for these two plasma rotation conditions. In the co-rotating discharge (solid line), the spectra extend out to higher frequency, primarily due to the increased Doppler-shift for these lab-frame measurements. The frequency-integrated fluctuation amplitude is seen to be larger in the co-injection case. This is consistent with the significantly higher power level injected into this discharge in this phase just before the L-H transition.

The phase measurements show a dramatic difference between the two plasma rotation conditions. In the co-injected discharge, the phase shift is seen to be monotonically increasing with frequency, reflecting the approximately uniform motion of the turbulent eddy structures as a result of ExB and diamagnetic drifts. The smaller phase shift at r/a=0.9 in the co-injected discharge compared with that at r/a=1.0 results from a higher poloidal turbulence flow velocity at the interior location. A positive phase shift indicates flow in the ion diamagnetic drift direction in the lab frame that is the same as the usual ExB direction for co-injected plasmas on DIII-D. In the case of the balanced injection discharge, the phase shift changes from positive at r/a=0.9 to negative at r/a=1.0. This indicates that the turbulence undergoes a complete flow reversal near this edge region of the plasma in the balanced-injection case. This also indicates a significant poloidal flow shear between these two radial locations.
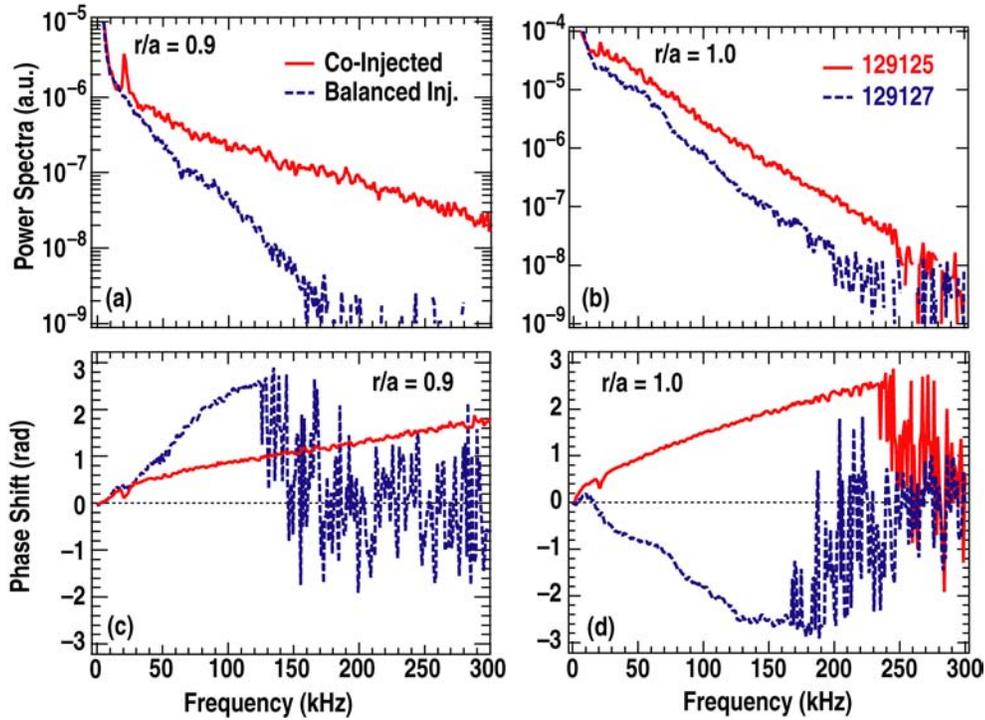
Fig. 8. Density Fluctuation power spectra and phase for BES channels at two radial locations (r/a=0.9 and 1.0). (a) and (b) Density fluctuation power spectra at r/a=0.9 and 1.0, respectively, for an all co-injection USN discharge and for a balanced injection USN discharge. (c) and (d) Phase shift at r/a=0.9 and 1.0, respectively, between two poloidally separated measurements (ΔZ=1.2 cm) for the same two discharges.

The large difference in edge turbulence poloidal flow and in particular the large flow shear observed in the balanced injection plasma at significantly lower injection power may facilitate the L-H transition and would be consistent with the developing shear in E_r in the L-mode observed by the CER system at low toroidal rotation [see figure 7(d)]. Further analysis is underway to compare the ExB shearing rates and decorrelation rates for these plasmas.

5. EFFECTS OF FAST ION ORBIT LOSSES

One hypothesis for the reduced H-mode power threshold with decreasing torque may be the variations in the fast ion orbit loss as a result of the different mixes of co and counter beams used. Co-current beam ions are better confined and localized more towards the plasma core compared with counter-current beam ions. For example, the fast ion confinement time can be roughly 40% greater for the co tangential injection than for the counter tangential injection from analysis using a plasma transport code [12]. Furthermore, the counter tangential beams have greater ion orbit losses than the counter perpendicular beams. Altogether, this can lead to changes in the potential and electric field and consequently the rotation profiles, independent of, or in addition to that induced by the total torque. This issue was resolved by performing experiments in which the beam power was scanned for various configurations (i.e. mixes) of co- and counter-injected beams. These experiments consisted of varying the total beam power at a fixed torque value for the following cases: (a) using the counter perpendicular beam as the baseline beam with additional power steps at net zero torque (i.e. with balanced co and counter tangential beams); (b) repeating the power scan, but now using the counter tangential beam as the baseline beam with additional power steps at zero torque (i.e. with balanced co and counter perpendicular beams); (c) performing a power scan at net zero torque throughout by using only a combination of the counter perpendicular beam with a co- perpendicular source (i.e. net zero torque) or increasing the power using only a combination of the counter tangential beam with a co tangential beam (i.e. net zero torque) will vary the injection into the loss cone. The relative losses between the perpendicular and tangential beam pairings are between 10–15%.

The results from the above scans are summarized in Table 1, which shows the power required to produce the H-mode transition as well as the time of the transition for different scans and different combinations of tangential beams (co and counter) and perpendicular beams (co and counter). If there is an influence from the fast ion losses as a result of using the tangential beams compared to the perpendicular beams, then this effect would show up in a reduced power for the tangential beams compared to the perpendicular beams and also in an earlier time for the transition given that the times of the power steps were the same for both the tangential and perpendicular beams. However, as can be clearly seen in Table 1, it appears that there is no significant difference in the H-mode power threshold or the timing of the transition (of roughly 100 ms) between the tangential and perpendicular beams. Furthermore, detailed analysis of the radial electric field at the plasma edge revealed no clear differences between the different sets of beams for the various scans performed for Table 1. Therefore, the variation in the threshold power with applied torque appears not to be dependent on the ion orbit losses in the plasma.

Table 1. **The L-H transition power and time for various neutral beam configurations. The various scans consist of power scans at constant torque (for both USN and LSN discharges) and a torque scan at constant power (USN discharge). The tangential beams are a combination of co- and counter-injected tangential beams and the perpendicular beams represent a combination of co- and counter-injected perpendicular beams.**

Experiment	Tangential Beams		Perpendicular Beams	
	L-H Transition Power (MW)	L-H Transition Time (ms)	L-H Transition Power (MW)	L-H Transition Time (ms)
Power scan at near zero torque (USN)	2.9	1460	3.0	1484
Power scan at near zero torque (LSN)	2.4	1616	2.4	1684
Power scan at torque –0.6 Nm (USN)	2.2	1826	2.2	1719
Power scan at torque –0.5 Nm (LSN)	2.2	1721	2.2	1747
Torque scan at power 3 MW (USN)	3.0	1694	2.9	1687

6. SUMMARY

The power required to induce the H-mode transition is dependent on the applied beam torque and, more specifically, the edge toroidal plasma rotation. For upper single null discharges in which the ion grad-B drift is away from the X-point, the L-H transition power threshold is reduced by nearly a factor of 3 by changing from predominantly co-injection (~6 MW) to predominantly counter-injection (~2.2 MW). A similar, but less prominent dependence is observed in lower single null discharges, in which the ion grad-B drift is towards the X-point, where the power threshold is reduced by nearly a factor of 2. The threshold power decreases with decreasing edge toroidal rotation. For the first time, the L-H transition has been induced at constant input power below the nominal threshold power by reducing the input torque from all co-beams to balanced beams. At low toroidal rotation, a shear in E_r develops in the L-mode as a result of an increased gradient in the toroidal rotation just prior to the L-H transition and large changes in the poloidal velocity shear of the edge turbulent eddies are observed prior to the L-H transition that may be strong enough to induce the transition. The variation in threshold power with applied torque is not found to be dependent on the ion orbit losses in the plasma. The implications for ITER are favourable given the low rotation plasmas expected in ITER. However, the assumptions and extrapolations of the H-mode threshold power scaling laws to ITER need to be re-examined in light of these torque and plasma rotation dependencies. An important aspect of these experiments is to consider how these results compare to auxiliary heating methods that have no torque inputs such as RF heating. This will be especially relevant for ITER, which will have a significant amount of its total auxiliary heating power been applied through RF heating. Future experiments at DIII-D will be aimed at comparing these results with predominantly RF heated discharges for the formation of the H-mode barrier.

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