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1. THRESHOLD POWER DEPENDENCE ON INPUT TORQUE

The ability to produce high performance H-mode plasmas in future fusion 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. 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. Subsequently, this allowed H-mode transition studies with NBI at low or zero torque, which were then compared with ECH (i.e., zero torque) triggered H-mode transitions. 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.

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 edge safety factor, q_{95}, of around 5 and a range of line averaged densities in L-mode of 2.4–3.1 $\times 10^{19}$ 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 of which are directed in the opposite (i.e., clockwise) direction [2]. 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 were injected with their centerlines near the nominal midplane of the plasma. 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 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 so that 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 (80–90 ms) and beam ion slowing down times (~40 ms), 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. In this manner, a power scan could be obtained at a fixed value of applied torque. This allowed for a more accurate determination of the threshold power without any variation due to a changing beam torque during the scan. Power scans were started at a level well below the L-H 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 L-H transition. Power scans with ECH were also performed for cases of: (a) only applied ECH; (b) a combination of ECH plus co- or counter-NBI in order to investigate the influence pf ECH in the presence of applied 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 net threshold power is determined from the sum of the input power (NBI, ECH, ohmic) minus the core radiated power and the time derivative of the stored energy. The results of these scans are shown in figure 1. The H-mode power threshold exhibits a clear and

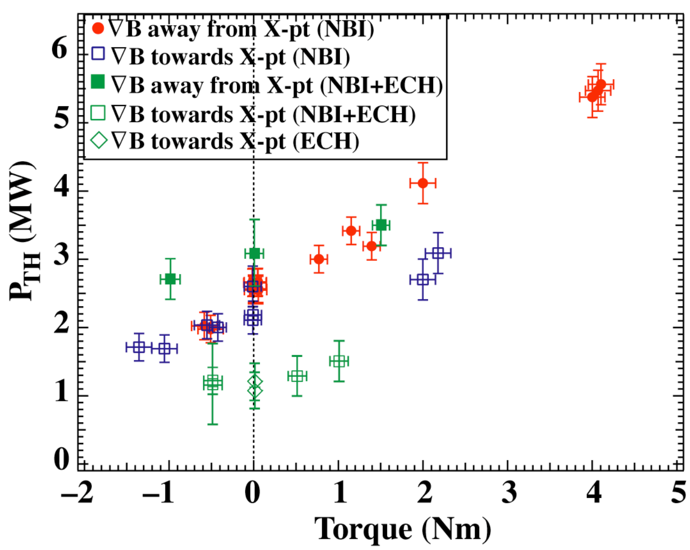

Figure 1. The H-mode threshold power as a function of the input torque from neutral beams. The dependence is shown for plasma discharges with the ion ∇B drift away from the X-point (USN) and for plasmas with the ion ∇B drive towards the X-point (LSN).

significant increase with the applied beam torque of nearly a factor of 3 for the USN discharges at $\bar{n}_e$ = 2.4 – 2.7 $\times 10^{19}$ m^{-3} (solid symbols) from about 2 MW with predominantly counter-injected beams (applied torque of –0.5 Nm) to about 5.5 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 at the same target densities (open symbols), but is less pronounced, showing an increase of nearly a factor of 2 from about 1.7 MW (applied torque of –1.3 Nm) to about 3.1 MW (at applied torque of 2 Nm). The threshold power is lower for the LSN discharges with applied ECH when compared with only NBI heated discharges. For both LSN and USN discharges, the ECH plus NBI heated discharges exhibit a slight increase in the threshold power with the input torque, but not as strong as the only NBI heated cases.

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

Given the strong correlation of the H-mode power threshold with the input torque, an attempt was made to induce the H-mode transition at power levels below the nominal threshold value (i.e., the threshold power with all co-NBI torque) 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 1 shows that the H-mode threshold power at 2 Nm of torque is about 4 MW. Subsequently, the NBI 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 2. The plasma clearly stays in L-mode during the time the net torque is in the co-direction. Then, as more counter-injected

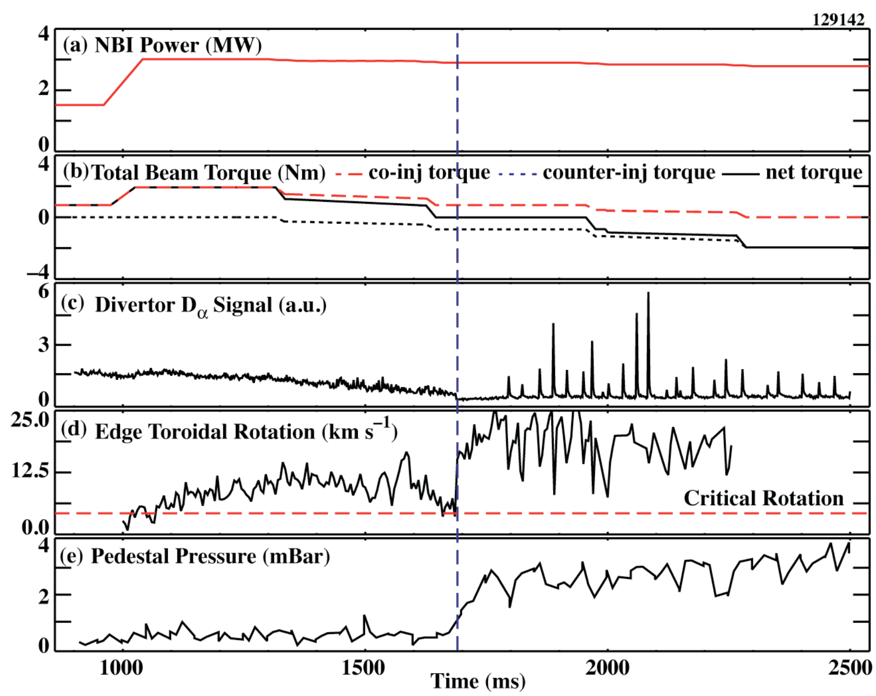

Figure 2. The time histories of various plasma quantities for an USN plasma discharge during the application of NBI at constant power and varying torque. (a) Total NBI power, (b) total beam torque together with co- and counter-injected torque components, (c) D_α signal from the divertor region, (d) toroidal 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.

beams are applied for the given power, the edge toroidal rotation decreases and the H-mode transition occurs at about 1687 ms. 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 input torque.

3. 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 [3]. 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 × 6 channel grid covering an approximately 4 × 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 [4]. 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 3. Figure 3(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 3(c) and (d) show the phase shift at $r/a = 0.9$ and $r/a = 1.0$, respectively, between two poloidally separated measurements ($\Delta Z = 1.2$ 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 velocity (fixed delay time between sensors at all frequencies) of the turbulent eddy structures as a result of $E \times B$ 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 $E \times B$ 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. 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.

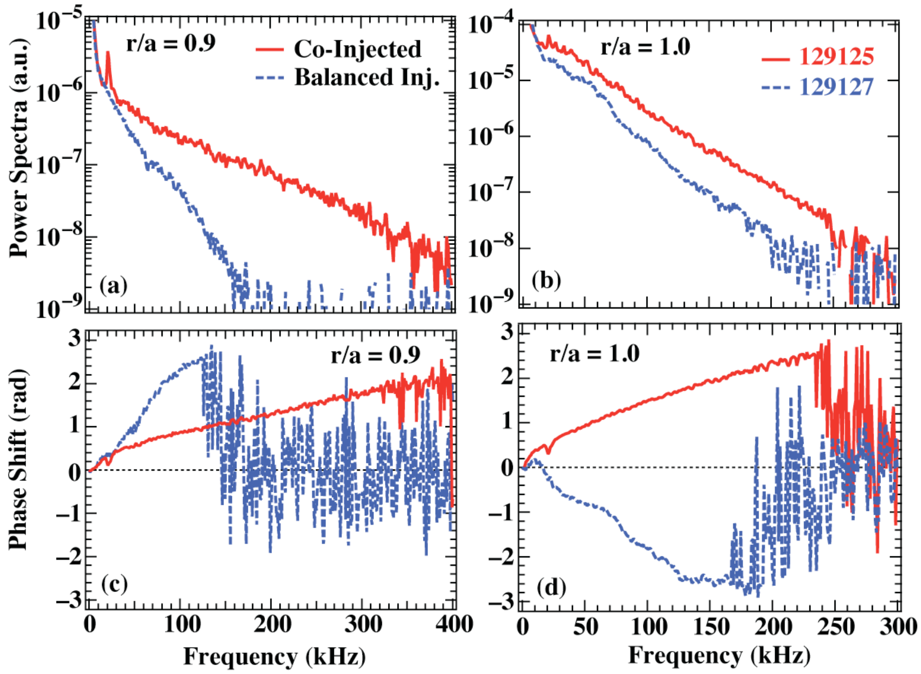

Figure 3. Density Fluctuation power spectra and phase for BES channels at two radial locations (r/a = 0.9 and 1.0). (a) and (b) Density fluctuation power spectra at r/a = 0.9 and 1.0, respectively, for an all co-injection USN discharge (129125) and for a balanced injection USN discharge (129127). (c) 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.

5. SUMMARY

The power required to induce the H-mode transition is dependent on the applied beam torque. For only NBI heated 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 to predominantly counter-injection. 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. 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 threshold power is lower for the LSN discharges with applied ECH when compared with only NBI heated discharges. For both LSN and USN discharges, the ECH plus NBI heated discharges exhibit a slight increase in the threshold power with the input torque, but not as strong as for the only NBI heated cases. 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 implications are favorable for ITER given the low plasma rotation expected. However, the assumptions and extrapolations of the H-mode threshold power scaling relations to ITER need to be re-examined in light of these torque and plasma rotation dependencies.

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