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PROGRESS TOWARDS SUSTAINMENT OF INTERNAL TRANSPORT BARRIERS IN DIII–D*

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1. Introduction

Neutral beam heated discharges with internal transport barriers (ITB) have been observed in most of the world's major tokamaks including DIII–D [1,2], TFTR [3], JT-60U [4] and JET [5]. Improved core confinement has been observed over a range of q profiles, including negative central magnetic shear (NCS) and weak positive shear. In discharges with an L-mode edge, the duration of ITBs is generally limited to a few energy confinement times (τ_e) by low-n MHD activity driven by the steep core pressure gradient or by q_{min} passing through low-order rational values. In order for ITBs to be useful in achieving a more compact advanced tokamak, the radius of the ITB must be expanded and the pressure gradient must be controlled in order to optimize β_N and the bootstrap alignment. In this paper, we discuss the results of recent experiments on DIII–D to produce and sustain ITBs for longer pulse lengths. Three techniques are evaluated: 1) reduction of neutral beam power (P_{NBI}) and plasma current to form a "weaker" ITB which can be sustained; 2) use of an ELMing H–mode edge to help broaden the pressure profile and improve MHD instability; 3) modification of the plasma shape (squareness) to achieve smaller ELMs with a lower density pedestal at the edge.

2. Effect of P_{NBI} and I_p on ITB Formation With L–mode Edge

The formation of transport barriers in NCS plasmas on DIII–D tends to proceed in two phases. When P_{NBI} exceeds a certain threshold, which depends on density but is typically ~5 MW, T_i and toroidal rotation begin to peak in the core; at higher powers, there is a second power threshold at which the density begins to peak. In general, once the density begins to peak, the core pressure becomes difficult to control and tends to "run away". As the pressure peaks, a fast growing (γ^{-1} ~ 0.1–0.5 ms) n=1 mode leads to a complete collapse of the ITB and in many cases a complete disruption[6].

Lowering P_{NBI} and I_p is one technique for achieving some control over the pressure peaking allowing sustainment of the ITB for longer durations. In Figs. 1 and 2, we compare three discharges with varying P_{NBI} and I_p. All three discharges have H_{ITER89p}~1.8–2.4, indicating the improved core confinement. Discharge 84682 (solid curve) [2], is a classic example of ITB formation with strong peaking of both the density and ion temperature as shown in Fig. 1(d) and 1(e). The discharge survives only 400 ms at full power before MHD activity causes a complete collapse of the ITB. By reducing both the early and late beam power (92691, dotted lines), weaker NCS and a weaker ITB are formed, allowing the ITB to be sustained for ~ 1 s. However, the discharge still terminates due to pressure peaking. Although the central-most Thomson scattering channel at a normalized radius of ρ~0.3 in

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Fig. 1(d) indicates less density peaking in 92691 compared with 84682, we see from the profile fits in Fig. 2(b), that the on-axis density is equal in these two cases just before termination. The broader profiles allow 84682 to reach β_N =2.3 before the collapse compared with β_N =1.5 for the narrower ITB in 92691. While the value of q_{min} does have an effect on the stability and beta limits, creating local minima in the stability limit near low-order rational values, the core pressure gradient is still the most important factor in limiting β_N.

In discharge 94777 (dashed), through a combination of lower I_p, lower P_{NBI}, and lower density, a transport barrier in T_i is observed and sustained for 5 s, the duration of P_{NBI}. In this case the ITB is weaker [Fig. 2(a)] and there is only slight peaking of the density [Fig. 2(b)]. The q profile is monotonic in this case with q_0~1.8 and is in a near steady-state equilibrium due to higher β_p, and bootstrap fraction obtained at this low current. We note that Alfvén eigenmodes were also observed in this discharge, which may have the beneficial effect of reducing pressure peaking by distributing fast ions to a larger minor radius.

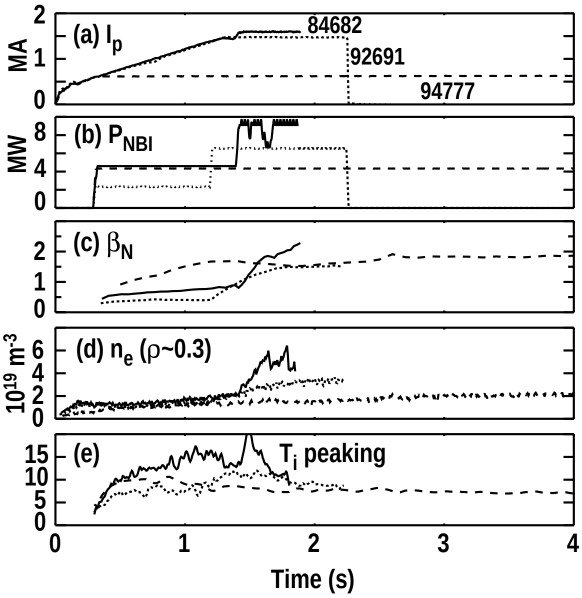

Fig. 1. Time evolution of a) plasma current, b) neutral beam power, c) normalized β, d) core density (at ρ~0.3), e) T_i peaking (defined as $T_i(0)/T_i(\rho\sim0.75)$) for three discharges with an ITB. Solid = 84682, dotted=92691, dashed=94777.

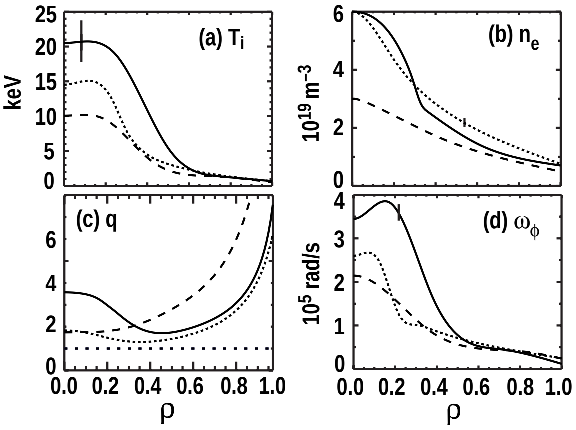

Fig. 2. Profiles of (a) T_i,, (b) density, (c) q, and (d) toroidal rotation for the discharges in Fig. 1. Solid=84682 at 1.625 s, dotted=92691 at 2.2 s, dashed = 94777 at 4 s.

3. ITB Formation in ELMing H–mode

Combining an ITB with an ELMing H–mode edge is one attractive possibility for achieving improved confinement and stability in discharges with a steady-state ELMing edge. In general, it has proven difficult to produce and sustain ITBs with type-I ELMs as shown in Fig. 3. Here an H–mode transition is programmed at 0.5 s by shifting the dominant plasma X–point from upper to lower (towards the ∇B×B drift direction). The hotter H–mode edge slows the diffusion of current during the I_p ramp resulting in low ℓ_i [Fig 3(b)], high q_{min}, and a very broad current density profile. Variation of the H-mode transition time has proven to be a useful tool for manipulating the current profile shape compared to the usual method of using an L–mode edge during the I_p ramp.

There are two phases of interest in Fig. 3. First, an H–L transition occurs at 1 s followed by the formation of NCS and a strong ITB as seen in Fig. 4 (solid lines). The edge density is low and the profile is peaked at this time. Second, a transition back to ELMing H–mode occurs at 1.9 s. The reverse shear q profile is maintained during H–mode, but the ITB is no longer observed (Fig. 4,dashed lines). The absence of an ITB during ELMing H–mode could be a consequence of the weaker NCS observed at this time, but we do not believe this is the case.It has been repeatedly demonstrated on DIII–D that ITBs can be formed with weak shear *q* profiles such as that shown for discharge 94777 in Fig. 2(c). Furthermore, the *q* profile inversion earlier in the H–mode period at 1.7 s [Fig. 3(c)] is similar to the L–mode phase, yet $T_i(0)$ has already begun to drop.

The loss of the ITB during the ELMing phase probably results from the higher density due to the improved particle confinement observed in H–mode as seen in Figs. 3(d) and 4(b). The basic paradigm for the formation of ITBs is the stabilization of turbulence from ITG and electrostatic drift modes when the $E\times B$ shearing rate exceeds the maximum linear growth rate of unstable modes, $\omega_{E\times B} > \gamma_{max}$ [7]. Higher density reduces $\omega_{E\times B}$ because the beam injected momentum per particle is reduced and toroidal rotation is the largest contributor to E_r in DIII-D. The large type-I ELMs also lead to reductions in $\omega_{E\times B}$, even in the plasma core. The higher density also can increase γ_{max}. Gyrokinetic simulations [8] indicate that large T_i/T_e, fast ion dilution, central beta, and Shafranov shift are all favorable for reducing γ_{max}. At high density all of these quantities are significantly reduced leading to increased γ_{max}.

As a final point, it is clear from Fig. 3(c) that the formation of an ITB significantly affects the evolution of the *q* profile through feedback of the bootstrap current. The quantity q_0-q_{min} increases during the L–mode phase with an ITB and decreases during the H–mode phase without an ITB.

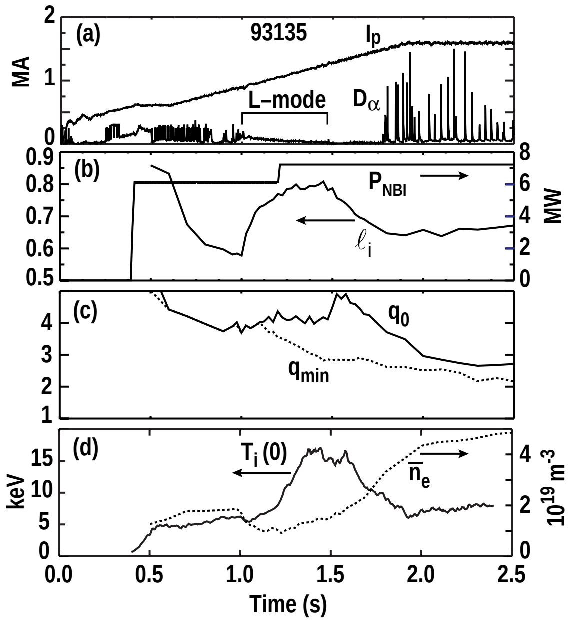

Fig. 3. Time evolution of NCS discharge 93135.

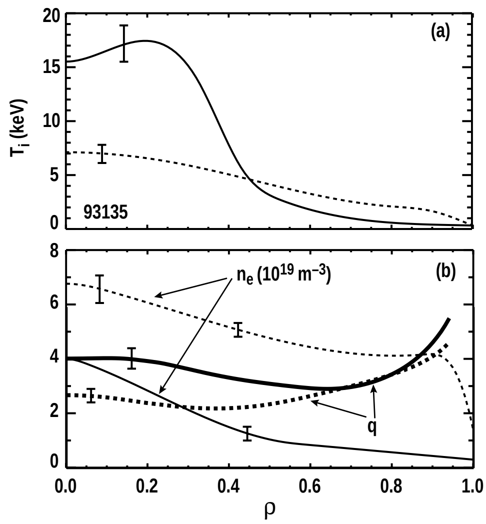

Fig. 4. Profiles of a) T_i, b) n_e and q for discharge 93135 in Fig. 3. Solid curves represent the L–mode phase at 1.425 s and dashed curves represent the ELMing H–mode phase at 2.3 s.

4. High Squareness Shapes

To achieve ITBs in ELMing H–mode, it is important to control and reduce the edge density and reduce the impact of large type I ELMs. Towards this end, we have undertaken a study of the effect of plasma shape on the ELM behavior and the formation of ITBs. It has been shown theoretically [9] that by increasing or decreasing the plasma squareness (from the normal D shape), one can eliminate 2nd stable access to ballooning modes at the edge and reduce the 1st stability pressure gradient limit, which should result in smaller more-frequent ELMs and a lower edge density pedestal height.

These predictions have been verified in recent high-squareness discharges on DIII–D as shown in Fig. 5. In this plasma shape, the L-H transition is barely visible on the D_α trace, the ELMs are very small and high frequency, and the edge pressure gradient is reduced. The jump in edge T_e confirms that the plasma is indeed going into H–mode.

Early beam injection was used to produce the NCS q profile and ITB shown in Fig. 5(c). A comparison of the L–mode phase with the H–mode phase for this discharge demonstrates that the ITB can be sustained in ELMing H–mode provided the density remains low and the ELMs are small. This discharge disrupted shortly after 2 s due to a rapidly growing n=1 mode, similar to most NCS discharges with an L–mode edge, indicating that core pressure profile is peaking. We note that the edge density in Fig. 5(b) is comparable to the edge density recently reported in the JT-60U reverse shear ELMing H–modes with an ITB [10] and that it is much lower than standard DIII–D H–mode edge densities as seen in Fig. 4(b).

In conclusion, it has been demonstrated that ITBs in NCS or weak positive shear discharges can be sustained for longer pulse lengths by reducing the central density peaking and hence core pressure gradient. ITBs are not observed in standard ELMing H–modes on DIII–D due to the high edge density, reduced beam penetration, and the effect of large type-I ELMs. By changing the plasma squareness, ELMing H–mode discharges with a lower density pedestal and smaller ELMs have been observed. Under these conditions, the ITB is maintained during the ELMing H–mode phase. The development of localized heating, current drive, and momentum drive sources to control the location and steepness of internal transport barriers to optimize stability remains a high priority for future work.

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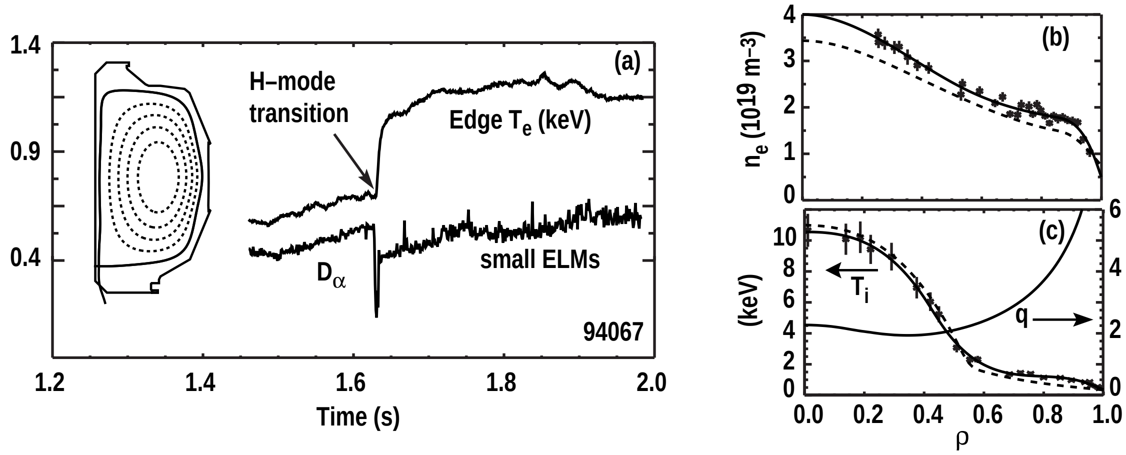

Fig. 5. a) Time evolution of edge T_e and D_α during the L-H transition of a high-squareness discharge. Profiles of b) n_e and c) T_i and q for the L–mode phase at 1.6 s (dashed) and the ELMing H–mode phase at 1.9 s (solid).