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In recent experiments in the DIII–D tokamak, the previously reported enhanced performance regime with negative central magnetic shear (NCS)[1,2] has been extended to further improve fusion performance. This was done by using controlled L–H transitions to further broaden the pressure profile, thereby delaying the onset of MHD activity which would lead to the termination of the high performance phase.[3] Such discharges have achieved record parameters for DIII-D, including D–D fusion power up to 28 kW and stored energy in excess of 4 MJ.

Discharge Evolution

As in the earlier discharges, the core magnetic shear is reversed by use of low power neutral beam injection during the plasma current ramp. This has the effect of heating the core region, thereby “freezing in” the hollow current density profile peaked off-axis. By varying the early beam power, we can alter the degree of inversion of the current profile.

These discharges frequently undergo a transition to a regime of high performance. This transition typically involves formation of an internal transport barrier, developing in the region of negative central shear, as indicated by peaking of the ion temperature and rotation velocity (and with sufficient power, the electron density and temperature) profiles. These L–mode plasmas with peaked profiles have exhibited high fusion performance in DIII-D, but are frequently unstable, often resulting in disruption at relatively low normalized beta.

In recent experiments (Fig. 1), a double–null divertor configuration was biased toward the top of the vessel, in order to direct the ∇B drift away from the primary (upper) X–point and suppress the L–H transition.[4] Shortly before the plasma would otherwise reach the stability limit, the plasma is shifted downwards to make the lower null the controlling null, thereby reducing the H–mode power threshold and triggering a transition to H–mode. This has the effect of broadening the profiles (Fig. 2), and delaying the onset of detrimental MHD activity.

With these broadened profiles, the plasma continues to evolve, with increasing confinement time, beta and reactivity, until the regime of high performance terminates with MHD activity similar to the VH–mode termination.[5] During these experiments, such a procedure resulted in record performance in DIII-D.

Transport

The recent discharges (Fig. 1) were typically produced using somewhat lower beam power during the early phase, resulting in current profiles with weak negative (or neutral) shear (WNS).[6] Although local magnetic shear in the core is much weaker than in the NCS regime, the region with low shear extends over more of the plasma (to $\rho \le 0.7$ instead of $\rho \le 0.5$).

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At the internal transport barrier formation, fluctuation diagnostics including beam emission spectroscopy (BES)[7] and far infrared (FIR)[8] scattering indicate reductions in turbulence to below the minimum detectable level ($\tilde{n}/n \le 0.1\%$, Fig. 3) in regions of weak or negative magnetic shear. This effect is seen regardless of the strength of the magnetic shear in this region, as long as the shear is not strongly positive. The volume in which the transport barrier develops is typically larger for WNS than NCS plasmas. At the H–mode transition, this region extends to cover the entire plasma.

A pair of discharges was selected for detailed transport analysis, each with $I_P = 2.1$ MA, B_T = 2.1 T and P_{NBI} = 20.5 MW (during the full power phase of the discharge). The main difference between these two discharges is that one (87937) had weak central magnetic shear (WNS, P_{NBI} = 3.5 MW in the early phase) and the other (87953) negative central shear (NCS, P_{NBI} = 5.5 MW in the early phase) at the time of application of full beam power (Fig. 2). The NCS discharge clearly reaches stability limits earlier in its evolution, limiting the peak performance achieved in the discharge.[6] Prior to the termination of the high performance phase in the NCS discharge, the two behave similarly, with nearly identical evolution. We will focus on a comparison of transport analysis between the two discharges.

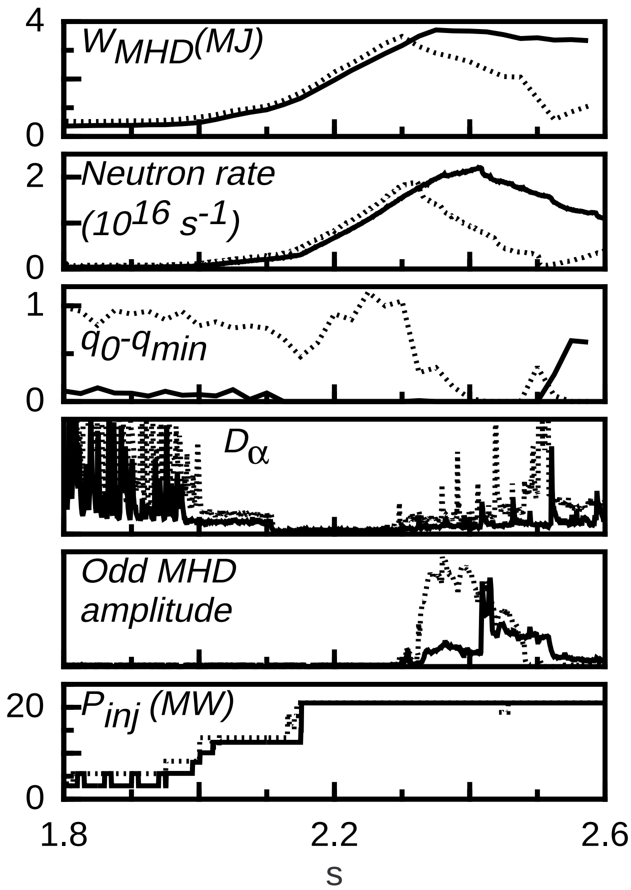

Fig. 1. Time traces for a pair of high performance discharges with weak (87937, solid lines) and negative (87953, dotted lines) magnetic shear and a controlled L–H mode transition. The high power neutral beams are applied at 2.0 s, with an L–H transition occurring at 2.106 s following a downward shift of the plasma.

During the L–mode phase, the formation of an internal transport barrier becomes evident in the ion temperature profiles (Fig. 2). After an L–H transition at 2.106 s, the identifiable transport barrier vanishes, with steep gradients now extending over the entire ion temperature profile. During this period, the second largest term in the core power balance (Fig. 4) after the applied heating power is dW/dt. In other words, the plasma core at this time acts as an integrator of the applied power. As a result, there is little power available to be diffusively conducted away from the core. In both discharges, these calculations suggest ion diffusivities consistently below Chang–Hinton neoclassical (Fig. 5). This implies that diffusive transport is not an important term in the core power balance in these discharges during H–mode.

Based on the transport analysis, during the H–mode phase, these discharges behave essentially the same. The difference between NCS and WNS discharges appears to be mainly in stability, with the NCS discharge reaching peak values ~100 ms sooner and at lower levels of β_N and reactivity.

High Performance

The discharges exhibit levels of fusion performance (D-D reactivity) a factor of 4 above the highest seen in DIII–D VH–modes,[9] and a factor of 3 above the highest observed in DIII–D NCS discharges prior to the introduction of the controlled L–H transition as a profile control “knob” (Table 1).

We used the TRANSP[10] code to simulate the discharge with the highest Q_{DD} (87977, I_P = 2.25 MA, B_T = 2.1 T and P_{NBI} =17.75 MW, $S_N = 2.2 \times 10^{16}$ s^{-1}, $Q_{DD} = 1.46 \times 10^{-3}$ in conditions where a portion of the deuterium injected by the neutral beams is replaced by tritium. In this numerical experiment, the density, temperature and impurity rotation profiles are all held fixed in the DT plasma as measured in the DD plasma. No correction is made for differences in transport due to isotope effects, other than the poorer penetration of the tritium neutral beams.

Under conditions where TRANSP computes roughly equal amounts of deuterium and tritium in the plasma core, we calculate a power multiplier (P_{DT}/P_{DD}) of 220. Applying this to $Q_{DD} = 1.46 \times 10^{-3}$ measured in the best discharge yields $Q_{DT}^{equivalent} \approx 0.32$. We note that this multiplier is higher than published predicted multipliers for TFTR Supershots made using a similar procedure.[11] This is not unreasonable given the differences between the DIII–D NCS/WNS and Supershot regimes. The higher central ion temperatures in Supershots (~35 keV vs. ≤20 keV in NCS/WNS) result in a considerably lower ratio $<\sigma v>_{DT}/<\sigma v>_{DD}$ (by about 25% on axis), and therefore of the thermonuclear reactivity multiplier. The higher neutral beam voltages in TFTR (110 kV vs. 80 kV in DIII–D) lead to a reduction of about 10% in the ratio σ_{DT}/σ_{DD} and therefore of the beam–plasma reactivity multiplier.

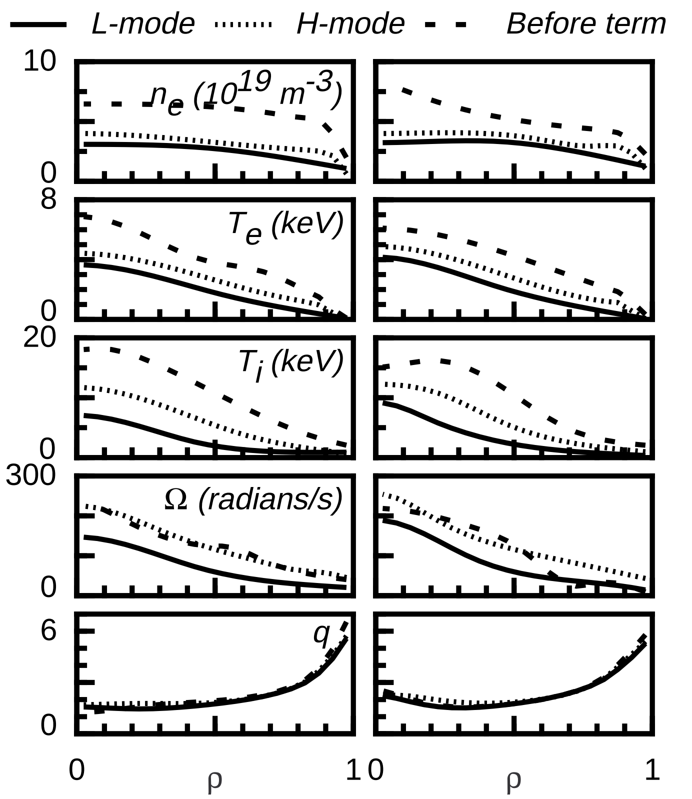

Fig. 2. Profile evolution of two similar discharges with weak (87937, left) and negative (87953, right) magnetic shear. Profiles shown in L–mode (2.05 s), H–mode (2.15 s) and prior to the termination of high performance (2.3 s for 87953 and 2.4 s for 87937).

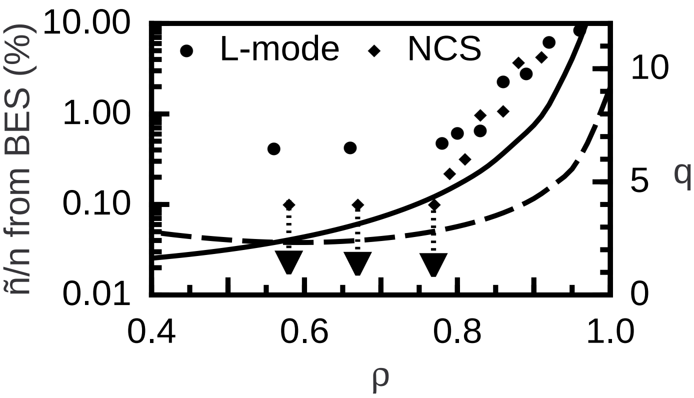

Fig. 3. Data from BES indicates that turbulence is suppressed by even weak shear in the current profile as compared to standard L–mode.

Summary

The high performance obtained in NCS and WNS plasmas in DIII–D has been further enhanced by application of controlled L–H transitions as a means of profile control. These discharges exhibit characteristics of a transport barrier (steep gradients, suppressed turbulence and low calculated energy flows) extending over nearly the entire plasma resulting in DIII–D record levels of fusion reactivity.The crude profile control employed gives a hint of the possibilities open to us in future experiments where we expect to have more toolsavailable, including radio frequency power (fast wave and electron cyclotron), density control via the pumped high triangularity divertor and pellet injection (deuterium and lithium).

Table 1. Highest parameters achieved in H–mode NCS/WNS plasmas in DIII–D (not simultaneously achieved)

Neutron rate S_N	2.4×10^{16} s^{-1}
Fusion power P_{DD}	28 kW
Fusion power efficiency Q_{DD}	1.46×10^{-3}
Equivalent DT efficiency Q_{DT}	0.32
Stored energy W_{MHD}	4.4 MJ
β_N	4.3
Confinement time τ_E	0.5 s (at P_{NBI} =17.75 MW)
Normalized confinement time H	4.8

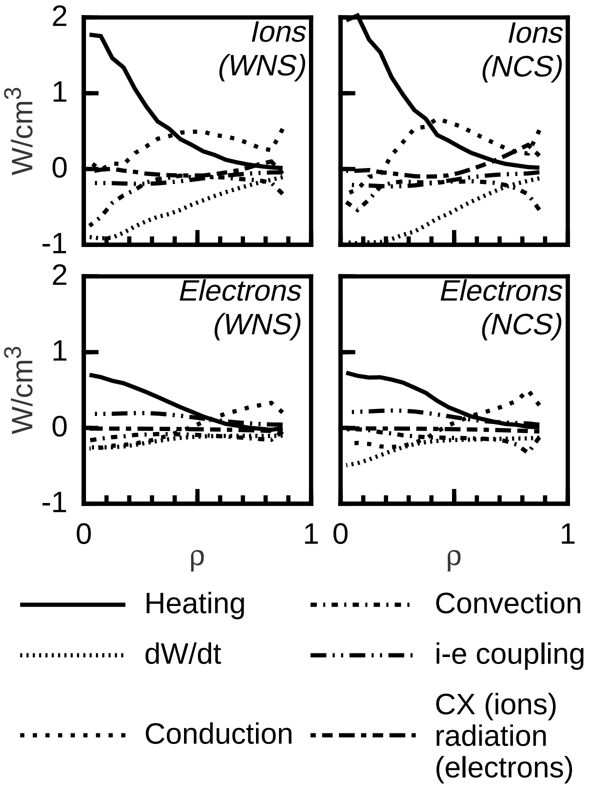

Fig. 4. Power balance for both discharges during H-mode phase (2.150 s).

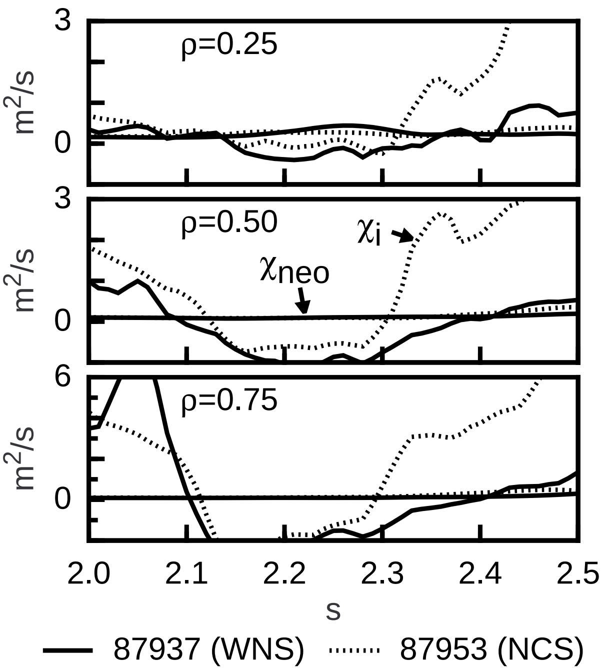

Fig. 5. Ion diffusivities vs. time for ρ= 0.25, 0.50 and 0.75 in both discharges.

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