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# Ion Transport Barrier Formation with Low Injected Torque in JET

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In many present theories of internal transport barrier (ITB) formation, **E**×**B** shear is invoked to stabilise turbulence. Tangential neutral beam injection (NBI) is a significant source of plasma toroidal momentum and shear in this flow can establish high levels of **E**×**B** shear. In the experiment reported here we aimed to establish ion ITBs using ICRH ion minority heating, without momentum injection, and to study the effect of varying the applied torque.

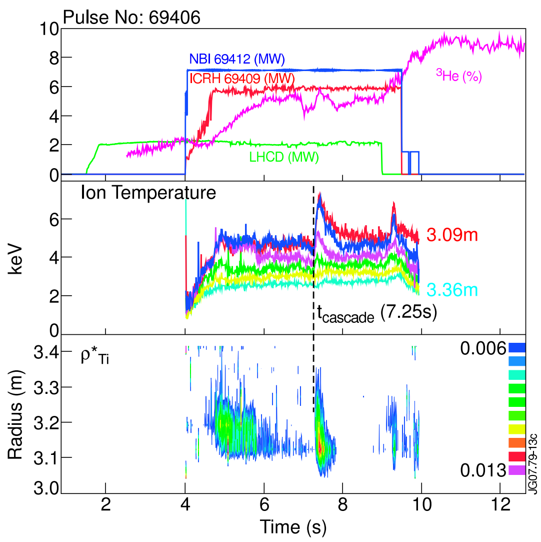


Figure 1: *Typical waveforms for the experiment. ICRH ranged from 0—6 MW and NBI from 1.5—7 MW, combined power kept at 7 MW. The contour plot shows $\rho^*_{Ti} = \rho_i/L_{T_i}$, where $\rho_i$ is the ion gyroradius and $L_{T_i}$ the ion temperature gradient scale length. $\rho^*_{Ti}$ ranges from 0.006 to 0.012.*

In these discharges RF heating at 37 MHz coupled to a $^3$He minority was used at 3.45 T to provide ion heating at R=2.84 m, close to the magnetic axis (R=2.98 m), with no excitation of H minority or D majority species (the 'isolated resonance' condition). Calculations with the TORIC code [1] predict that above about 8% $^3$He mode-conversion of the RF begins and causes electron heating. The ratio of ion/electron heating was measured by modulating the RF with a 6 Hz square waveform at the end of the discharge. A $^3$He concentration which maximised this ratio was established experimentally at about 7% and this level held constant during the shot sequence using feedback control based on visible spectroscopy signals. Discharges were run

*See Appendix of M. L. Watkins, *et al.*, Fusion Energy 2006 (Proc. 21st Int. Conf. Chengdu) IAEA (2006) with a varying mixture of ICRH and NBI heating, to alter the toroidal momentum deposited in the plasma, whilst keeping the total power constant. A single ion source from the NBI system was operated in all discharges of the torque scan in order to obtain charge-exchange (CXRS) $T_i$ data. In discharges with higher levels of NBI heating it was possible to also run the sources needed for poloidal rotation and MSE measurements. Typical waveforms for the experiment are shown in figure 1. The calculated ICRH ion power deposition profiles, shown in figure 2(a), are broadly consistent with the deposition profiles inferred from a Fourier analysis of the $T_i$ response during ICRH modulation, figure 2(b).

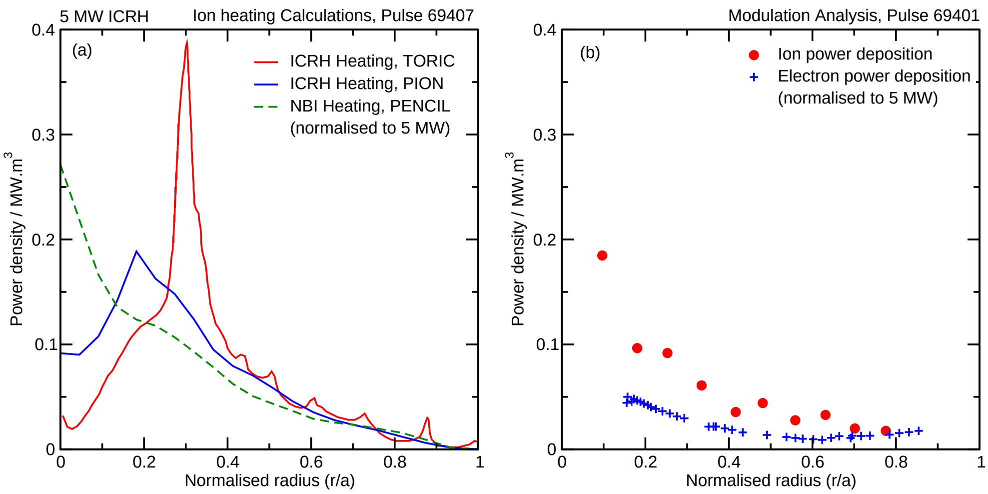


Figure 2: *(a)—Calculated ICRH ion heating powers, TORIC and PION [2] compared to NBI heating power, PENCIL (normalised to the same power). (b)—Measured ICRH ion and electron heating from modulation data in similar plasma conditions and normalised to the ICRH power in (a).*

Using predominantly ICRH heating in these experiments the total available heating power was limited to 7 MW. To optimise conditions for ITB formation a shear-reversed target $q$-profile was established by allowing an initially current-hole profile to relax. Transport barriers in $T_i$ were formed when $q_{min}$ crossed $q = 3$ and $q = 2$ during the main heating phase, changes in $T_e$ were barely detectable, while $n_e$ fell with the rise in $T_i$. MSE-derived $q$-profile measurements, figure 3, indicate the degree of shear reversal, but can underestimate the absolute value of $q$. However, the timing of Alfvén cascades indicates that the ITBs are triggered at integer $q$ values. In all cases the plasma remained in L-mode.

**Results: ITB Characteristics**

Transport barrier events were obtained in all discharges of the torque scan, including those with the lowest torque, with just one NBI source (1.5 MW). The events are clearly indicated by an increase in $T_i$ for channels inboard of 3.2 m in figure 1. The $\rho^*_{Ti}$ plotted at the bottom of figure 1 shows an increase from 0.005 to 0.012, which is below the level normally considered a clear ITB in JET [3]. However, there is a clear indication of a steepening of the temperature gradient, indicating a local reduction of transport. In this paper we classify these as 'weak' barriers (or 'trigger' events) compared to the steeper gradients and longer durations achieved with higher power (>10 MW) combined heating [4]. The ITB radius in these discharges is small, with the radius of maximum $T_i$ gradient at 3.2 m ($r/a = 0.2$) and a foot point (where the gradient relaxes) at 3.3 m. The barriers do not show a clear expansion in radius after formation. The radial coverage of the poloidal rotation diagnostic extends from the outboard edge of the plasma into approximately the ITB radius, so, although no poloidal rotation is detected in these ITBs we cannot be certain of the value of poloidal rotation inside the ITB radius. Measurements of poloidal rotation in JET for ITBs of wider radius have found that the rotation is small before the ITB develops. Consequently calculations of the $\mathbf{E}\times\mathbf{B}$ shearing rate have been made, using neoclassical predictions for $v_{\rm pol}$ with measured profiles of toroidal rotation and $T_i$, using the JETTO code [5]. In the lowest-torque case the ratio of shearing rate to growth rate, $\omega_{\mathbf{E}\times\mathbf{B}}/\gamma_{\rm ITG}$, remains less than 0.1 during the period of steepest $T_i$ gradient.

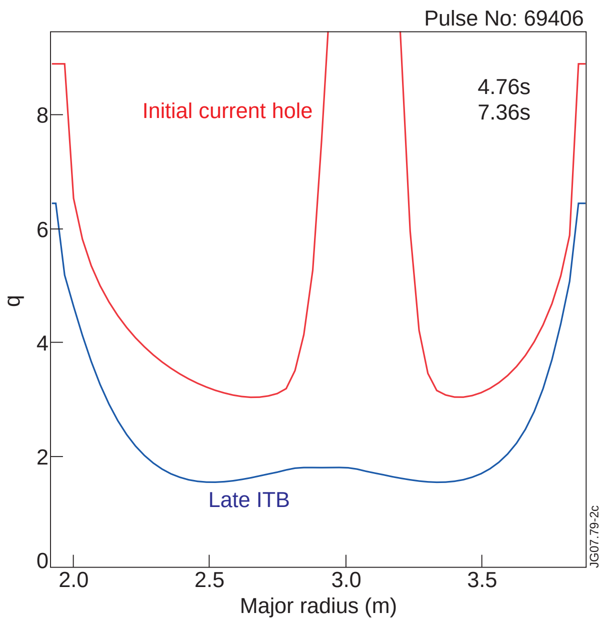


Figure 3: *Indicative typical q-profiles: initially current hole during the first ITB, then weak shear reversal at the times of the later ITB.*

In the discharges with higher NBI applied torque, the formation of the ITB in $T_i$ is accompanied by a barrier in toroidal rotation. The formation of this barrier is coincident (to less than 50 ms) with that of the $T_i$ ITB, it does not precede it. The peak in $\Omega'$ is established at a smaller radius (one channel spacing—about 6 cm—inboard) compared to the peak in $T_i'$.

Figure 4 plots the ITB strength (the global maximum $T_i$ gradient) as a function of axis rotation speed for shots in the torque scan. A trend is evident with the strength of the $q$=2 ITB becoming weaker at higher rotation. This trend argues against toroidal rotation shear being beneficial to the ITB formation. The timings of the $q$=2 and $q$=3 ITBs become later as the rotation is increased. TRANSP [6] simulations indicate that the $q$-profile is modified (a slight flattening at $q_{min}$) by an inductive reaction current at the $q_{min}$ radius due to the on-axis NBI current drive. For the circled point, the $q$=3 ITB occurs so early that the auxiliary heating has not reached full power, others of the $q$=3 points are also affected, but less severely. Bearing in mind this ambiguity, we argue that the trend in the $q$=2 ITB strength is also likely to be present in the $q$=3 cases.

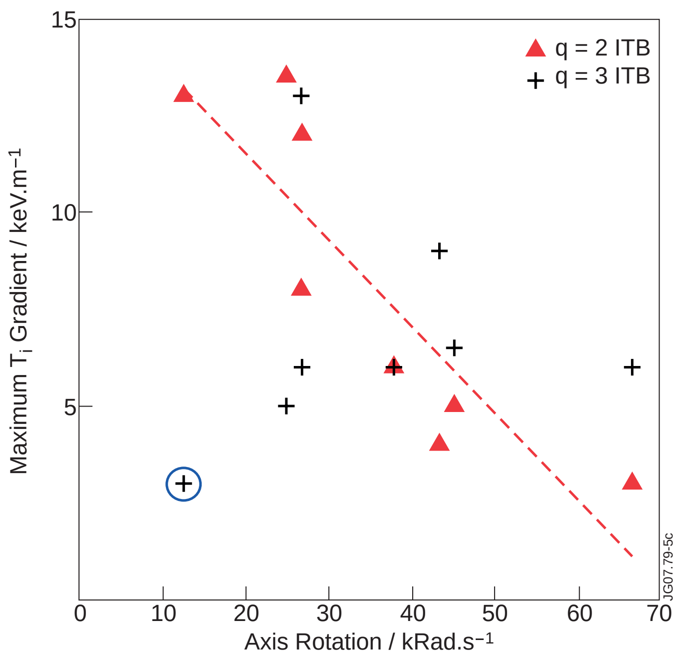


Figure 4: *Variation of ITB 'strength' (global maximum $T_i$ gradient) with axis rotation.*

For the $q$=2 ITBs it may be argued that the $q$-profile is so close to becoming monotonic that even small modifications to the profile could have a large effect on the ITB strength. Thus the apparent trend in figure 4 may instead be due to $q$-profile effects, rather than the changing torque.

In many cases a drop in $T_i$ (and its gradient) is seen to precede the rise in $T_i$ at the ITB formation, (the same feature is seen in $v_{tor}$.) The timing of the grand Alfvén cascade is associated with the rise in $T_i$, not the preceding drop. This behaviour has also been observed on DIII–D and has been attributed to the rarefaction of rationals in the proximity of integer-$q$ [7]. The drop in $T_i$ is more pronounced in the high torque $q$=2 cases—which may be connected with the trend seen in figure 4.

**Summary**

Ion temperature ITB trigger events have been provoked on JET with very low levels of injected torque using a $^3$He minority ion heating scheme. The evidence indicates that $\mathbf{E}\times\mathbf{B}$ shear driven by toroidal rotation is not important in these ITB triggers, however the ITBs which form are weak and short lived. Evidence from other experiments [4], suggests that higher torque is necessary to establish and maintain strong ITBs. Future experiments with the increased RF power of the new JET ICRH antenna will be made to explore whether 'strong' ITBs can be created at high power and low applied torque.

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