Internal transport barriers in the MAST spherical tokamak

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Internal transport barriers (ITBs), observed on many devices, are thought to originate from a suppression of turbulence arising from E_rxB shear, as well as favorable magnetic shear. Multiple mechanisms have been demonstrated in different machines in different scenarios. For example, ITBs can be triggered just before the occurrence of rational surfaces at q_{min}, consistent with explanations based on transport improvement due to reduction of the density of high order rationals [1]. On the other hand, fishbone induced fast ion losses create an E_rxB enhancing torque around the minimum magnetic shear region [2]. One of the major problems with ITB scenarios is their transient nature, as MHD instabilities such as (N)TMs, RWMs can be triggered as β increases.

The principle of the ITB scenario in MAST is similar to other tokamaks, with early heating for slowing current penetration, leading to reverse shear q profiles which is observed to favour formation of rotational shear and the ITB. One main exercise is to determine the extent to which rotation shear is important compared with magnetic shear [3]. To that degree, we choose to examine ITBs with co and counter injection, between which the torque to power ratio is different. Furthermore, there appear to be ITBs at multiple surfaces in counter-injected discharges. The profiles and TRANSP transport analysis, as well as normalized shearing & growth rates, for co discharge 24600 at t=0.25s, when the ion temperature is highest, is plotted in Figure 1. The ion thermal and momentum channels exhibit a transport barrier in this case. Additionally, recently analyzed carbon density profiles show a strong gradient in the ITB region [4]. The steep barrier region here is inside the q_{min} surface, where the ion thermal diffusivity reduces to the neoclassical value. The shearing rate ω_{se} (defined in the usual manner [5]), normalized to c_s/a, peaks in the barrier region. The ITG growth rate based on the formula in [6], valid for the low shear region where toroidal effects dominate, is well short of the ExB shearing rate in the barrier region. Outside r/a=0.6, the formula is not valid because normalized magnetic shear>1, however, ITG growth rates normally increase towards the edge. GS2 simulations are in process. Recent calculations [3] indicate that potentially the shearing rate needs to be several times the growth rate for turbulence suppression.

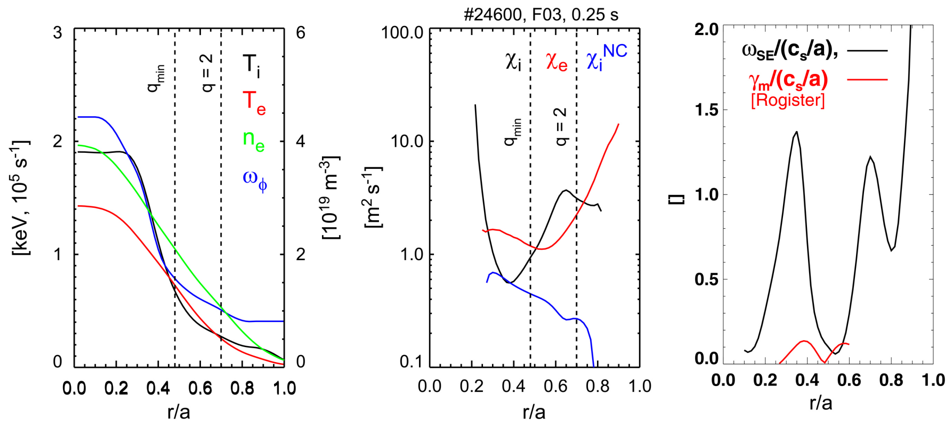

Figure 1: Profile quantities, thermal diffusivity and normalized shearing rates for co discharge at time near maximum Ti. Transport analysis in the deep core region (r/a<0.25) is problematic on account of shallow gradients and small mismatches in flux surface mapping.

Trigger and sustainment

The ITB identification criterion can be thought of as the formation of a radial region in which transport is strongly reduced. In the case of the ion thermal channel, the transport can reduce to neoclassical levels. In the particular analyzed co-injected discharge 24600, the time history of the TRANSP derived ion thermal conductivity reduced to neoclassical at t=0.1s. This can be considered the start of the ITB. However, at this time, the core ion temperature is not very high (~300eV). On the other hand, $\rho^*_{T,\omega}=\rho_s/L_{T,\omega}$, the Larmor radius normalized by either the scale length for a ion temperature or toroidal rotation, compared with the Mirnov spectrogram, is plotted in Figure 2, for both co and counter discharges. The values of $\rho^*_{T,\omega}$ are larger than conventional tokamaks, which from dimensional arguments implies that transport is already "improved". For co, at t=0.1s, ρ^*_T at the barrier reaches ~0.1. Early in the discharge, q is dropping rapidly, passing q=4 then q=3 as the ITB is formed, and a correlation with rational surface density as in [1] is not clear, though is not discounted as a small systematic error in q may significantly alter the deduced time of the rational surfaces. Additionally, ρ^*_ω in fact appears to have a region which is negative, for both co and counter cases - reflecting a non-monotonic shape to the profile, implying that there is a strong torque drive opposite to the injected torque (perhaps offset from other sources) just around the zero shear position (further out for the counter case). While the ρ^*_ω rotation shear (which, since it is $\sim 1/L_\omega$, is proportional to ω_{se}) is weak just inside the q_{min}, it is enhanced just inside. In the case of co-NBI, energetic particle instabilities are active around the ITB trigger time. Since an outward movement of fast ions should produce a counter torque, the onset of fast ion losses could be an ITB trigger, as observed in [2]. In the counter discharge, the enhancement of ρ^*_ω rotational shear is concomitant with a sudden quietening of the MHD spectrogram. The direction can be understood from the point of view that fast particle losses (which one assumes are correlated with activity on the Mirnov coils) are suddenly switched off, thus allowing the rotation to relax back towards the co-direction -- against the injection direction. Planned fast ion diagnostic improvements will help to investigate these phenomena in the future.

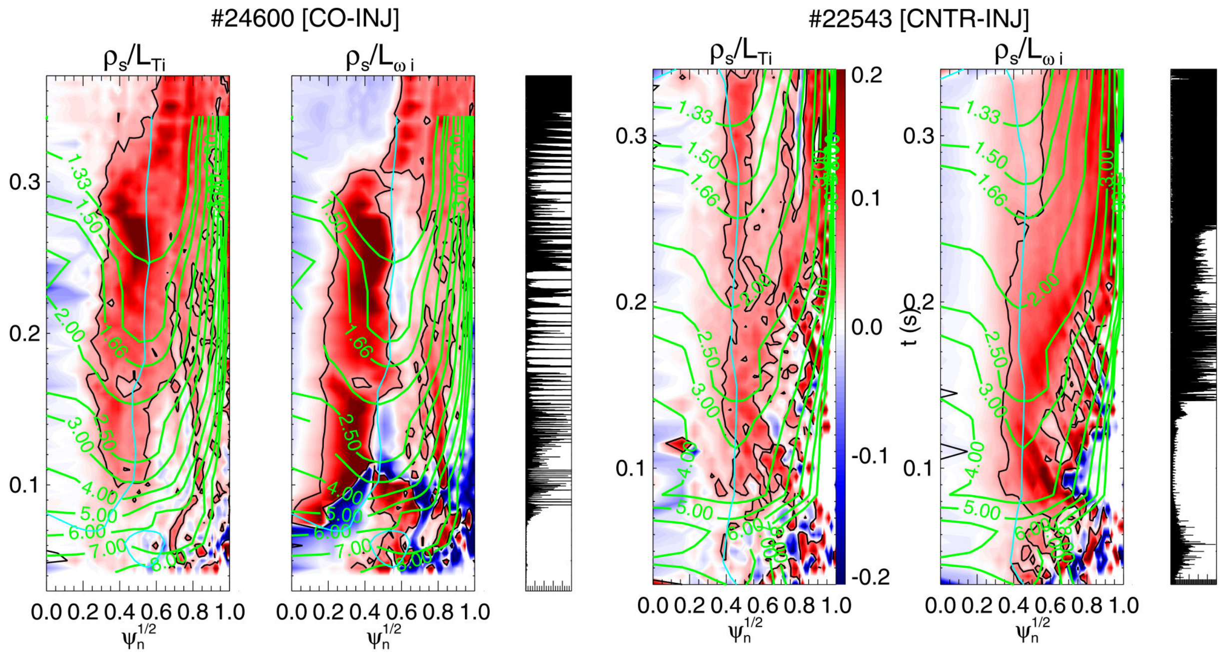

Figure 2: Time/space evolution of normalized temperature gradient, and toroidal rotation gradient, overlaid with q contours (green) and the q_{min} surface (cyan), in co (24600, left) and counter (22543, right) discharges. Mirnov signals, which may be correlated with fast ion losses, are plotted in the right hand strips. The direction of rotation here is relative to the injected beam.

The presence of counter torque at mid-radius is even seen clearly during an NBI modulation experiment #25009, where 1 beam is at steady power (for measurement) and another is modulated. When the modulated NBI switches on, rotation increases in the core, and decreases at mid radius, while when it switches off, the rotation relaxes in the opposite direction. The modulation which has 22 ms on/off allows repeat cycles to demonstrate the effect of the NBI. Viscous (diffusive) transport as well would not explain it as this would tend only to flatten the rotation, not reverse it. One possible explanation it could be related to fast ion losses.

In the co discharge, the ITB is formed in the vicinity of the q_{min} surface, then moves slightly over time. In counter, however, the region of high ρ^*_{Ti} and ρ^*_{ω} appears to track outwards significantly starting near the q=5/2 surface (again, experimental uncertainties prevent precise alignment). Additionally, another high ρ^*_{Ti} region (ITB) persists around q_{min}, increasing towards the end of the beam measurement time window. There is also a clear inversion in the electron and carbon density profiles between the inner and outer transport barriers. After ITB formation, rotational shear decreases at the q_{min} surface (and is even lower in another shot). It is therefore likely that the ExB shear is not the suppression mechanism in this case, rather, that the transport reduction is due favourable magnetic equilibrium properties (magnetic shear, for example), which has been shown in transport simulations, including similar discharges in MAST [3].

Termination due to MHD

Various MHD phenomena play a role on MAST, particularly the so called "long lived mode" (LLM), having properties consistent with a saturated ideal infernal mode [7], appearing as q_{min} approaches towards unity. The associated NTV braking modestly degrades rotation towards the end of the discharge, but does not terminate the ITB immediately. Almost all discharges above appear to be terminated by such a LLM. Additionally, tearing modes appear on rational surfaces and may be associated with island growth. When the resonance condition between two distinct flux surfaces (1,2) $n_1\ \omega_1 = n_2\ \omega_2$ is satisfied, the islands can lock to each other, dramatically reducing rotational shear. Generally, these tearing modes always appear, though may not persist for long. For example, at t=0.17s in co discharge 24600 (Fig. 2), the rotational shear at the barrier is transiently decreased around the position of q_{min}. The case of mode locking between a core n=3 mode localized near q=4/3 with an n=2 mode localized near $q=q_{min}=3/2$ is shown in Figure 3. The rotation frequencies, their rate of change and q profiles, all independent measurements are consistent here. The modes, which tend to flatten the core rotation, transfer velocity shear towards the outer region of the plasma. In fact, most H-mode discharges begin like the ITB discharge. A 2/1 mode decreases the velocity shear dramatically and destroys the ITB and after a time the ETB forms.

In summary, co and counter ITBs tend to build in the early phases of the discharge after favourable rotational shear profiles are established. Evidence was presented of the role of fast ion losses to generate this trigger torque. Two barriers are observed in counter discharges. Rotational shear was weak in the inner barrier. Ultimately, a LLM or tearing mode usually destroys the barrier.

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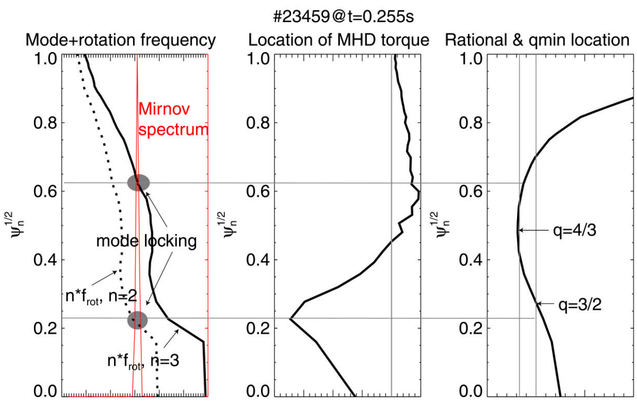

Figure 3: Mode frequency of 30kHz is localized to ρ=0.62 for n=2 and ρ=0.25 for n=3 modes, which are very close to the 4/3 and 3/2 surfaces where a torque is exerted (measured by change in rotation rate).