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Dependence of the C-Mod L-H Threshold on Magnetic Configuration and Relation to Scrape-off-layer Flows*

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Introduction

It is well known that the power threshold for the transition from the low confinement (L-mode) to High Confinement (H-Mode) can have a strong dependence on magnetic topology. Thresholds are generally higher for divertor discharges with the ion $B\times\nabla B$ drift direction away from rather than towards the active divertor, and with limited than diverted configurations[1]. On C-Mod, comparisons of discharges with forward and reversed field showed that both the power, and the edge T_e, at transition were approximately twice as high with unfavourable drifts[2]. Similar results have been obtained on DIII-D[3] and on ASDEX Upgrade[4], though JET reports little difference between thresholds[5]. However, there is not yet a clear and consistent explanation for the dependence on magnetic topology. We report here on recent C-Mod experiments which find strong, topology-dependent flows in the inner SOL, and evidence that these likely cause the differences in threshold between configurations.

Experimental Description and L-H Power Threshold

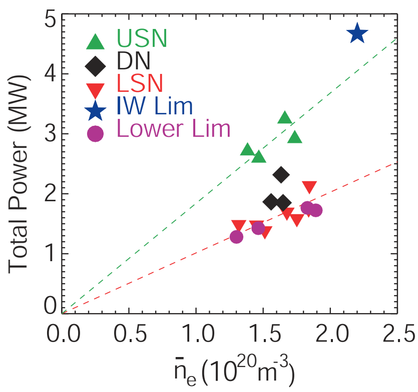

Figure 1. L-H threshold power vs $\bar{n}_e$ for a set of 5.4 T, 0.8 MA discharges with different configurations.

A series of dedicated experiments was carried out in the Alcator C-Mod tokamak (R=0.68 m, a=0.21 m, $I_p \leq 2$ MA, $B_T \leq 8.0$ T). The results reported here were at B_T=5.4 T and I_p=0.8 MA, with I_p and B_T in the same direction and oriented such that the ion $B\times\nabla B$ drift direction is always down. Lower single null diverted (LSN) discharges thus have favourable drift. C-Mod is well suited to study thresholds and the effects of flows and rotation since it uses ICRF heating (here at 80 MHz, up to 5.2 MW), which has continuously variable power, imparts no direct momentum input and avoids complications of beam ion orbit losses. Five magnetic configurations were studied; LSN, upper single null (USN), double null (DN), with small separation S_{sep} of upper and lower X-points when mapped to the outer midplane, inner wall limited (IWL) and a 'lower limited' configuration in which the

LCFS touched the vacuum vessel at the 'nose' just above the lower divertor. Power threshold results are summarized in Figure 1. P_{thresh} is computed including ohmic power and assuming 80% RF absorption efficiency. As expected, the LSN discharges have the lowest power threshold, with P/nBS averaging 0.025 $\times10^{-20}$ MW m T^{-1}. USN discharges average 1.8 times higher P_{thresh}. DN discharges have P_{thresh} intermediate between LSN and USN. A fine scan of S_{sep} revealed extreme sensitivity of P_{thresh}, which doubled from S_{sep}=-3 mm to +2mm. Only a single, weak L-H transition was obtained at this I_p and B_T in an IWL discharge. Surprisingly, the threshold in the 'lower limited' configuration was nearly identical to that in LSN; this indicates that magnetic topology, and not simply material contact, affects the threshold.

Measurements of edge profiles, flows and core rotation

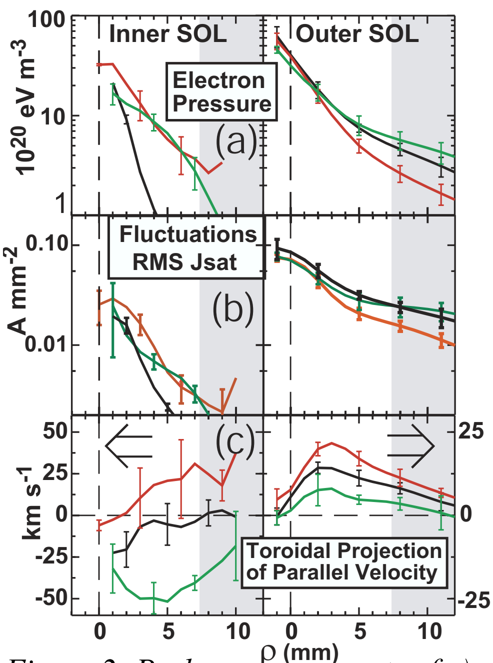

Figure 2: Probe measurements of a) P_e, b) J_{sat} fluctations and c) $V_{//tor}$, for inner and outer SOL in LSN (red), DN(black) and USN (green).

An important clue to the origin of the topology dependence is revealed through recent measurements using scanning Langmuir probes, including a unique new inner wall probe, of near sonic flows in the inner scrape-off layer (SOL) which reverse direction depending on X-pt location[6]. Typical results in ohmic discharges with LSN, USN and DN are compared in Fig. 2. Electron pressure profiles (a) at the outer midplane SOL (right column) are similar in all cases. For LSN and USN discharges, they are also comparable in the inner SOL, but for balanced DN the pressure in the inner SOL drops sharply. Fluctuation levels (b) are much higher in the outer than the inner SOL, indicating higher turbulent transport at the outer midplane. Most dramatically, the toroidal projection of the parallel velocity, $V_{//,tor}$ (c) in the inner SOL changes sign between LSN (+25 km/s) and USN (-50 km/s); these correspond to Mach numbers approaching one. For DN, $V_{//,tor}$ drops to near zero. Together, these observations indicate that the primary particle flux is to the outer midplane and that for LSN or USN discharges, it then flows along field lines toward the active X-point, 'filling in' p_e in the inner SOL. $V_{//,tor}$ is co-current for LSN and counter-current for USN. For DN, the flows and flux to the inner SOL are blocked. Flux tube particle balance analysis supports this interpretation[6].

The strong sensitivity of ohmic SOL flows to S_{sep} is shown in Fig. 3 (a,b). Strikingly,

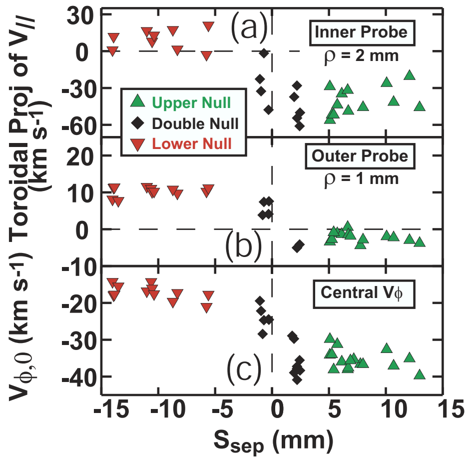

Figure 3: Variation with S_{sep} of toroidal projection of $V_{//}$ at a) inner SOL, b) outer SOL and c) plasma center, for ohmic plasmas.

a very similar dependence is seen on the *central* toroidal velocity, Vϕ (c), measured by x-ray Doppler spectroscopy. The change in rotation is largest (~50 km/s) in the inner SOL, indicating that these flows set the boundary condition for rotation and that momentum is partially coupled across the separatrix to the core plasma. The variation in velocities mirrors the dependence seen in P_{thresh}. This can be understood in the context of a separate effect, the observed dependence of core rotation plasma stored energy, W. As W increases due to increased power input and/or τ_E (eg the L-H transition), rotation consistently increments in the *co-current* direction, independent of magnetic topology[7]. While not fully understood, the time dependence of radial channels indicates momentum is transported from the edge[8]. A co-current increment with power in L-mode has also been seen on SOL flows, though this has been less extensively studied.

The combined effect of the two components of rotation, and the apparent connection to the L-H transition threshold, is illustrated in Fig. 4, which shows three otherwise similar discharges in the LSN (red), DN (black) and USN (green) topologies. RF power (b) has been adjusted to the minimum level required to produce an L-H transition, and the time axes shifted so that the transition is at t=0. Before RF, the only significant difference is in the core Vϕ (e), which is near-zero in LSN and counter- current (-50 km/s) in USN. Vϕ increases during RF, most rapidly for the higher power USN case[8]. It is striking that the rotation reaches about the same value in all three cases, at the time of the L-H transition. Edge flows showed a similar trend, though probe measurements were not possible at the highest power. It appears that the counter- current rotation sets an initial condition which is further away from that needed for the L-H transition. More input power, and a larger increase in edge

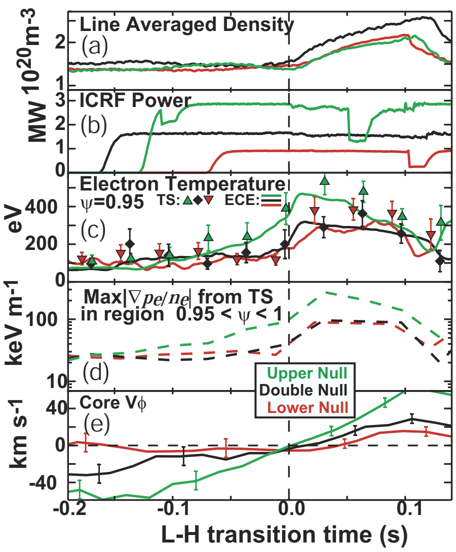

Figure 4: Comparison of rotation and edge parameters at L-H threshold in LSN, DN and USN configurations.

parameters such as T_e (c) and $\nabla p_e / n_e$ (d) are then required to compensate; n_e and ∇n_e are similar in the three cases. While core rotation is easiest to measure routinely, the actual responsible variable is presumably in the edge, for example E_r or $E \times B$ flow shear. However, we lack measurements of the rotation terms in E_r in the pedestal region. It is not yet known whether the same Vϕ would be seen at the L-H transition under other plasma conditions.

Previous studies on C-Mod, and elsewhere, of LSN plasmas have found that, for given global parameters, edge T_e or a closely related quantity is in a narrow range at the L-H transition[2]. Reasonable agreement was found with a criterion for $T_e / \sqrt{n}$ by Guzdar[9,10]. However, the systematically higher T_e in USN than LSN, seen in Fig. 4(c), cannot be simply explained by this or other local profile threshold criteria. This suggests that a complete model of the L-H transition would have to include mean flows and E_r shear as well as locally generated zonal flows.

Conclusions

Studies of the L-H threshold on C-Mod have shown that, as on most other tokamaks, P_{thresh} is nearly twice as high with $B \times \nabla B$ drift away from rather than towards the active X-point, and is very sensitively dependent on the magnetic balance. New measurements in the inner SOL reveal near-sonic flows which reverse direction with x-point location and are believed to result from ballooning particle transport. These SOL flows correlate with core rotation, indicating that they set a key boundary condition. Flows and rotation also correlate with P_{thresh}; discharges which are more strongly counter-rotating in the ohmic phase have higher thresholds. This strongly suggests that the SOL flows are an important factor which can affect the L-H transition; while they are not believed in themselves to cause the L-H bifurcation they may well be responsible for the *differences* in threshold with magnetic configuration. Improved measurements of edge E_r profiles are needed to understand these effects, which also need to be incorporated in models of the L-H transition.

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