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Scrape-off layer flows, magnetic topology and influence on the L-H threshold in a tokamak

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The dependence of L-H power threshold on magnetic topology (upper-, lower-null) in a tokamak is linked to near-sonic plasma flows in the high-field side scrape-off layer. Scrape-off layer flow momentum, coupling across the separatrix, imparts a topology-dependent increment to edge and core toroidal rotation (counter-, co-current). In all topologies, rotation increases in the co-current direction with input power: the L-H transition is seen when co-rotation achieves a characteristic level. Correspondingly, higher power is required to attain H-modes in upper- versus lower-null (with $Bx\nabla B$ down).

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H-mode energy confinement [1] has proved essential for optimizing tokamak performance; reactor concepts typically project to ignition conditions based on achieving this regime. It is therefore extremely important to understand the physical mechanisms that control access to H-modes in a tokamak. The transition from low to high confinement mode (L-H) is thought to involve ExB velocity shear [2-5], leading to a bifurcation in plasma transport characteristics near the vicinity of the separatrix [6].

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While this physics may explain observations of an L-H power threshold, no compelling explanation has been advanced to account for the higher powers required when $Bx\nabla B$ points away from rather than toward the active x-point [7]. Edge conditions associated with the threshold (e.g., critical temperature or its gradient) are also found to change substantially; a factor of ~2 increase in edge temperature accompanies a factor of ~2 higher power threshold in Alcator C-Mod [8] and elsewhere [9]. Most notably, when topology alone is changed (at fixed power levels), no differences in the L-mode edge profiles are evident (e.g. [10]) while some unexplained changes in edge velocity shear have been seen [11], offering few clues about the physics that causes differences in H-mode accessibility. Nevertheless, the pervasive sensitivity of power threshold to topology suggests that there must be a correspondingly robust explanation – something that might involve the time-averaged 'equilibrium' plasma state, an equilibrium that is necessarily constrained by the underlying micro-turbulence which regulates transport.

Based on recent experiments in Alcator C-Mod, we claim in this Letter that the equilibrium is indeed fundamentally different in L-mode discharges with upper versus lower x-point topologies. The key experimental observations are: strong plasma flows in the scrape-off layer (SOL), a clear dependence of these flows on the magnetic topology, and the coupling of the flow momentum into the confined plasma to yield a toroidal rotation velocity (V_ϕ) that depends on topology. The origin of the flow appears to be related to the ballooning-like nature of edge plasma micro-turbulence, a robust, ubiquitous drive mechanism. A connection between this flow drive and the differences seen in the L-H threshold power comes through the observation that V_ϕ exhibits a characteristic value at the L-H transition which is *independent* of topology in otherwise similar discharges. Since the radial electric field near the separatrix (E_r) is coupled to V_ϕ [12], these observations potentially connect to an underlying ExB velocity-shear turbulence-suppression paradigm. Thus the dependence of L-H threshold power on topology may be understood, once the topology-dependent plasma flow boundary conditions on the confined plasma are taken into consideration.

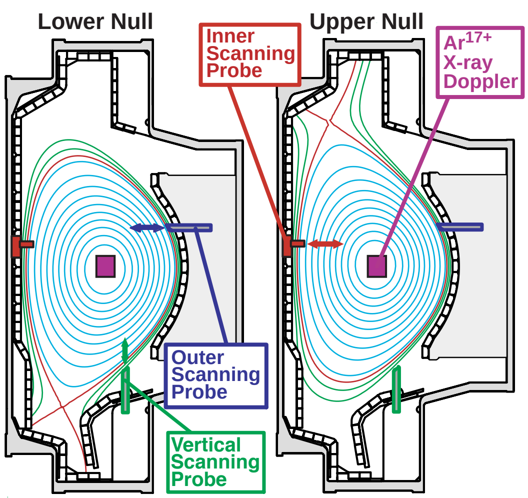

FIG. 1. Lower single-null and upper single-null magnetic equilibria and locations of probe and core x-ray doppler flow measurements.

Key plasma flow measurement locations in Alcator C-Mod are shown in Fig. 1: three scanning Langmuir-Mach probes, and an x-ray crystal spectrometer, measuring central toroidal rotation of Ar^{17+} ions from Doppler-shifts [13]. Important new information on electron pressure profiles, plasma flow profiles, fluctuations, and their sensitivities to magnetic topology is revealed here, utilizing a unique inner-wall scanning Langmuir-Mach probe. Plasma flows along field lines are inferred by comparing upstream and downstream ion-saturation current densities [14]. Doppler-shifts of He^{1+} line spectra on the inner midplane corroborate probe-derived flow velocities. Electron temperature (T_e) and pressure (p_e) profiles inside the separatrix are measured by electron cyclotron emission (ECE) and high resolution edge Thomson scattering (TS).

Inner and outer midplane SOL profile data are compared in Fig. 2 for different topologies: lower single-null (LSN), near balanced double-null (DN) and upper single-null (USN). Discharge conditions are: plasma current of 0.8 MA, toroidal field of 5.4 tesla (aligned co-current with $Bx\nabla B$ pointing down), and line-averaged electron density ($\overline{n}_e$) between 1.2 and 1.6x10 ^{20} m^{-3} in ohmic L-mode. The curves represent averages of profile data taken from more than 10 probe scans. Vertical bars indicate ±1 standard deviation. The flux-surface coordinate, ρ, is the distance into the SOL, mapped to the outer midplane. Small shifts in the ρ-axis (up to 2 mm) have been applied to some probe data, using SOL power balance as a constraint.

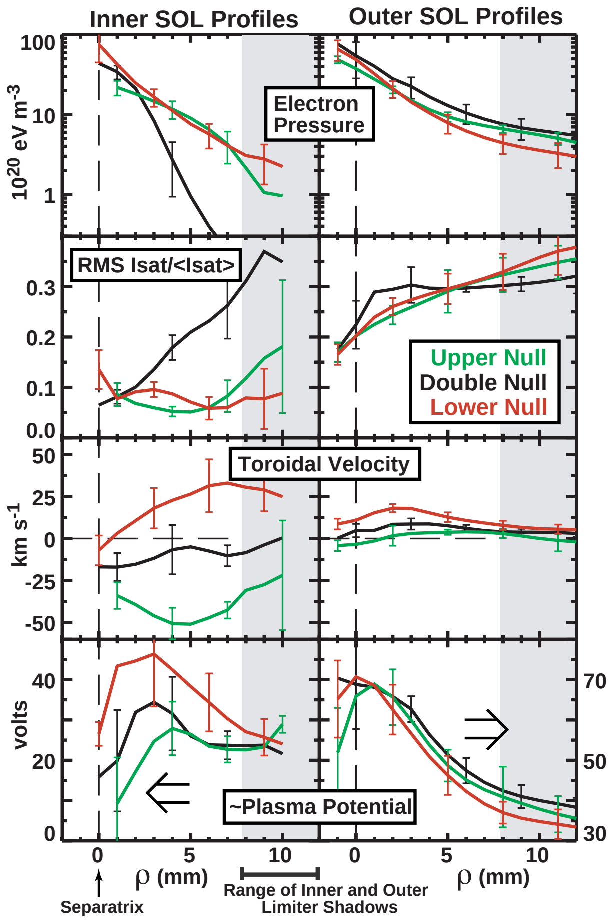

FIG. 2. Profiles of electron pressure, normalized RMS ion current fluctuation, toroidal projection of parallel plasma flow (positive is co-current) and estimated plasma potential from inner and outer scanning probes.

Dramatic changes occur in the inner SOL as magnetic topology changes. While pressure approximately maps between inner and outer SOLs in SN plasmas, it clearly does not in DN plasmas; pressure e-folding lengths in the inner SOL decrease from ~3 mm to ~1 mm as a result of breaking the magnetic connection. Regardless of topology, absolute ion saturation current fluctuation levels are lower in the inner SOL. Factors of ~3 to ~5 in/out asymmetry in this quantity persist in SN. These data indicate a strong poloidal asymmetry in the cross-field transport. Without communication along field lines between inner and outer SOLs (DN), little plasma exists in the inner SOL. Yet, the effect of a magnetic connection (SN) is not to increase the fluctuations in the inner SOL (and by implication, is not to increase the local cross-field transport levels). Therefore it appears that plasma must be flowing along field lines in SN discharges and 'filling in' the inner SOL.

The plasma flow data independently support this picture. The inner SOL exhibits the highest flow magnitudes in SN. Peak flows occur away from the separatrix, indicating that the drive mechanism is located within the SOL. For comparison, the plasma sound speed is ~50 km s^{-1} for $T_e = T_i = 25$ eV in deuterium. Therefore, the inner SOL flows are at about the maximum level that can arise from pressure variation along a field line. LSN yields a co-current directed flow, USN counter-current, and DN a reduced flow magnitude. Near DN, the magnitude and direction of the inner SOL flow are found to be remarkably sensitive to small deviations in magnetic flux balance. These responses are consistent with plasma streaming from low- to high-field regions when field lines connect between the two. Evidently, the near-sonic flows in the inner SOL are driven primarily by strong poloidal asymmetries in cross-field transport, similar to that detected in the limiter shadows of Alcator C [15].

Secondary flows which involve other drive mechanisms are also present. For example, the outer SOL tends to exhibit weaker but persistently co-current directed flows, independent of topology. Co-current V_ϕ may explain in part this tendency at the outer midplane [16]. Co-rotation is expected on open field lines since parallel electron mobility links the plasma potential (Φ) to T_e resulting in a positive E_r [12]. Other possible contributions to the flow include Pfirsch-Schlüter ion current [17, 18], which changes its direction in the inner/outer SOLs (counter/co-current) and may explain some of the differences in flow magnitudes near the separatrix.

Both inner and outer parallel flow velocities near the separatrix exhibit a systematic increase towards the co-current direction in the sequence: USN, DN, LSN. Evidently, this region acquires a corresponding component of co-current V_ϕ. Since there is no external momentum input, such a response cannot be simply explained. Yet, regardless of cause, an increased co-rotation implies an increased E_r near the separatrix which in turn implies a more positive Φ near the separatrix. To explore this tendency, we show estimated Φ profiles in Fig. 2, computed from the probes' sheath potential drops. Although this estimate is found to be uncertain, particularly with regard to computing E_r [16], we expect its change with topology to indicate changes in the true Φ. The data indeed suggest that Φ increases near the separatrix in going from USN to LSN, particularly for the inner SOL. While changes in Φ might be explained in terms of changes in T_e, no such correlation is observed. We suggest a more direct explanation: SOL flow momentum couples across the separatrix and causes a toroidal rotation of the confined plasma. The cross-field velocity gradients seen in the inner SOL are consistent with such a momentum transfer; particles exchanging their parallel velocities across the separatrix would carry co-current (counter-current) toroidal momentum into the plasma in LSN (USN) discharges.

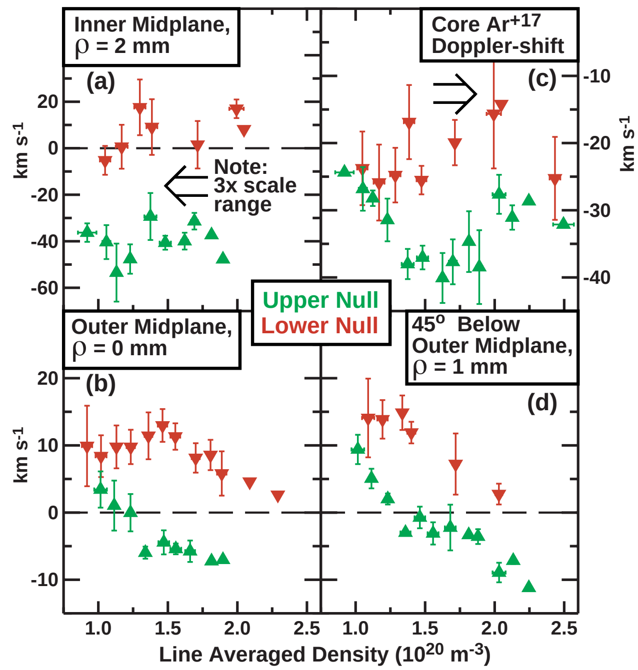

FIG. 3. Toroidal flow velocities (positive is co-current) measured near the separatrix by probes (a, b, d) and in the plasma center by x-ray spectroscopy (c). Bars indicate ±1 standard deviation.

Recent experiments in C-Mod demonstrate that toroidal momentum rapidly transports into the core plasma in response to changes in V_ϕ near the edge [13, 19]. Therefore, if topology-dependent SOL flow momentum is responsible for 'spinning' the plasma near the separatrix, one might expect the core plasma to respond similarly. As shown in Fig. 3, this is indeed found to be the case. Measurements of the toroidal component of parallel flow at three locations near the separatrix and in the plasma center are plotted for a series of discharges with different $\overline{n}_e$. All other conditions are identical to those in Fig. 2. A co-current increase in V_ϕ near the separatrix (~15 km s^{-1}) [panels (b) and (d)] in changing from USN to LSN is matched by a similar quantitative change in core V_ϕ [panel (c)]. The topology-induced change in V_ϕ also exhibits a sensitivity to $\overline{n}_e$

which roughly tracks at these three measurement locations. Changes in V_ϕ near the separatrix at the inner midplane [panel (a)] are a factor of ~3 larger than elsewhere and show no sensitivity to $\bar{n}_e$. These observations again point to inner SOL plasma flow as the primary drive for the V_ϕ changes seen in the confined plasma. Apparently, the transport of inner SOL flow momentum across the separatrix varies with discharge conditions (e.g. $\bar{n}_e$).

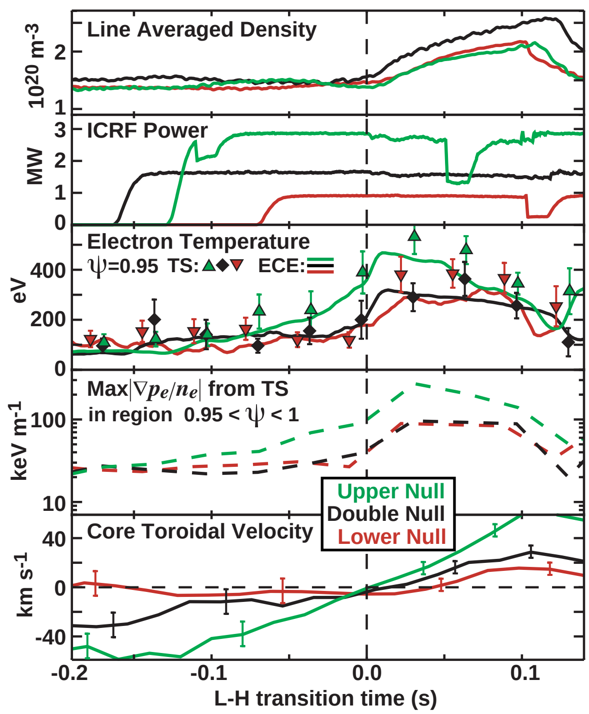

FIG. 4. Time traces for three plasmas with L-H transitions at threshold power levels. Ohmic L-mode conditions are identical to those in Fig. 2. The time axis is offset, placing zero at the time of L-H transition.

In auxiliary heated L-mode plasmas, core and separatrix V_ϕ are found to be affected not only by topology but also something related to stored plasma energy, leading to a co-current increase with increased input power. Similar findings were reported previously [20]. Figure 4 illustrates these relationships for three plasmas (USN, DN, LSN) with otherwise identical initial conditions. In the ohmic phases, the familiar offsets in core V_ϕ are present, becoming more co-current directed in the sequence: USN, DN, LSN. Ion-cyclotron range of frequency (ICRF) heating power is applied at levels close to the L-H threshold (0.9, 1.6, 2.9 MW) to induce a transition later in time. Note that this heating method imparts no momentum to the plasma. Also note that the DN threshold power is approximate; it is found to be sensitive to small deviations in magnetic flux balance, reminiscent of the SOL flows. After the ICRF turn-on but prior to the L-H transition, the edge T_e and p_e gradients are seen to evolve slowly, with larger increases corresponding to the higher power levels. The core V_ϕ also evolves, ramping towards the co-current direction fastest in USN (highest input power). At the time of L-H transition, T_e at the 95% poloidal magnetic flux surface (ψ = 0.95) is a factor of ~2 higher in USN versus LSN discharges, similar to differences seen with forward versus reversed magnetic field and fixed x-point location [8]. Although causal links between edge profiles and V_ϕ are not yet clear, the resultant magnitude of V_ϕ appears to be closely associated with the threshold physics: the L-H transition is seen to occur when core V_ϕ achieves roughly the same value, *independent of magnetic topology*.

Figure 5 shows that core and separatrix V_ϕ are closely coupled in the L-mode phase, exhibiting a co-current shift with increasing total input power, ~14 km s^{-1} MW^{-1} in the core and ~8 km s^{-1} MW^{-1} 2 mm outside the separatrix. Unfortunately, the probes were able to scan only during modest input power levels and only to ρ = 2 mm. The velocity changes at the separatrix may be larger. Nevertheless, these data demonstrate that topology and input power changes combine in an additive fashion during the L-mode phase to affect V_ϕ of the entire confined plasma. By inference, the core V_ϕ measurement can be considered a crude measure of E_r near the separatrix in the L-mode phase (with offsets that may include rotation profile effects).

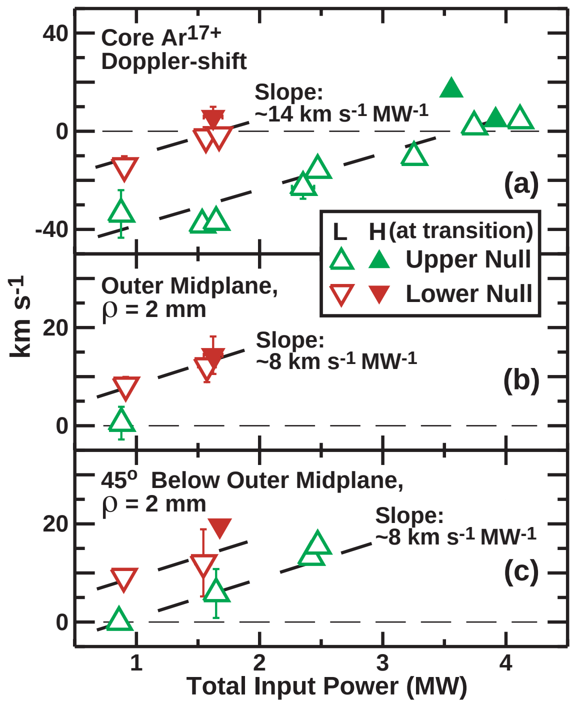

FIG. 5. Toroidal velocities in the core and 2 mm into the SOL as a function of total input power. L-mode target plasma conditions are identical to those in Fig. 2.

In summary, we find V_ϕ, and by implication E_r near the separatrix, as a unifying theme in the L-H transition. Co-current V_ϕ is impeded in USN but enhanced in LSN topologies (with $Bx\nabla B$ down). The underlying mechanism is traced to SOL flows, driven by ballooning-like transport, which couples momentum into the confined plasma. V_ϕ is also found to change with plasma pressure; co-current V_ϕ is enhanced with increasing input power (its underlying mechanism is not investigated here). The L-H transition is seen when co-rotation achieves a characteristic value, independent of magnetic topology, when all other external control parameters (apart from auxiliary input power) are held fixed. In USN discharges, this requires a higher input power level. Thus, the dependence of the L-H power threshold on magnetic topology may be understood in terms of toroidal rotation, E_r near the separatrix, and the topology-dependent plasma flow boundary conditions imposed by the scrape-off layer.

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[1] F. Wagner *et al.*, Phys. Rev. Lett. **49**, 1408 (1982).
[2] H. Biglari, P. H. Diamond, and P. W. Terry, Phys. Fluids **2**, 1 (1990).
[3] R. J. Groebner, K. H. Burrell, and R. P. Seraydarian, Phys. Rev. Lett. **64**, 3015 (1990).
[4] K. H. Burrell, Phys. Plasmas **4**, 1499 (1997).
[5] P. W. Terry, Rev. Mod. Phys. **72**, 109 (2000).
[6] J. W. Connor and H. R. Wilson, Plasma Phys. Control. Fusion **42**, 1 (2000).
[7] F. Ryter *et al.*, Nucl. Fusion **36**, 1217 (1996).
[8] A. E. Hubbard *et al.*, Plasma Phys. Control. Fusion **40**, 689 (1998).
[9] F. Ryter *et al.*, Plasma Phys. Control. Fusion **40**, 725 (1998).
[10] T. N. Carlstrom *et al.*, Nucl. Fusion **39**, 1941 (1999).
[11] T. N. Carlstrom *et al.*, Plasma Phys. Control. Fusion **44**, A333 (2002).
[12] V. Rozhansky *et al.,* Nucl. Fusion **42**, 1110 (2002).
[13] J. E. Rice *et al.*, Nucl. Fusion (to be published).
[14] I. H. Hutchinson, Phys. Rev. A **37**, 4358 (1988).
[15] B. LaBombard and B. Lipschultz, Nucl. Fusion **27**, 81 (1987).
[16] B. LaBombard *et al.*, J. Nucl. Mater. **313-316**, 995 (2003).
[17] N. Asakura *et al.*, Phys. Rev. Lett. **84**, 3093 (2000).
[18] S. K. Erents *et al.*, Plasma Phys. Control. Fusion **42**, 905 (2000).
[19] W. D. Lee *et al.*, Phys. Rev. Lett. **91**, 205003 (2003).
[20] J. E. Rice *et al.*, Nucl. Fusion **41**, 277 (2001).