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The operational phase space of the edge plasma and its sensitivity to magnetic topology in Alcator C-Mod

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The range of ‘edge plasma states’ (i.e., the combination of densities, temperatures and gradients in the scrape-off layer near the separatrix) accessible to a tokamak are highly restricted. Experiments in Alcator C-Mod suggest that this restriction is a consequence of Electromagnetic Fluid Drift Turbulence (EMFDT), which sets the cross-field transport levels; plasma states are constrained to lie in a narrow region of EMFDT ‘phase-space’ defined by poloidal beta gradient (α_{MHD}) and normalized plasma collisionality. Recent experiments have investigated this behavior over an increased parameter range in lower- and upper-null (LSN/USN) discharges. L-mode edge pressure gradients are found to exhibit clear sensitivity to magnetic topology, favoring higher α_{MHD} for LSN compared to USN. These variations may be caused, in part, by the different edge plasma flow patterns in LSN versus USN. Such flows arise from a ballooning-like transport drive and can produce a topology-dependent modulation in the toroidal plasma rotation.

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1. Introduction and background

The edge plasma states accessible to magnetic fusion experiments are remarkably restricted; one can not ‘dial-up’ arbitrary plasma densities, temperatures and their gradients near the last closed flux surface. Instead, robust scrape-off layer (SOL) profiles are observed, which appear sensitive to plasma current (I_p) and line-averaged density ($\bar{n}_e$). In the far SOL, flattened profiles with intermittent transport fluxes are generally observed. In contrast, plasma near the last closed flux surface typically exhibits steep gradients, less intermittency and, in comparison to the far SOL, looks like a ‘transport barrier’ even in L-mode discharges. Moreover, the near SOL sets the cross-field width of the parallel heat flux into the divertor region. Thus, the underlying physics that determines the observed edge plasma states in the near SOL is of fundamental interest.

A leading theoretical framework for collisional plasma turbulence in the region near the separatrix is electromagnetic fluid drift turbulence theory (EMFDT), which is the basis for first-principles numerical simulations [1-3]. This work suggests that the magnitude of plasma transport should be controlled by two key parameters: poloidal beta gradient (i.e., the MHD ballooning parameter, α_{MHD}) and normalized collisionality (such as the ‘diamagnetic parameter’, α_d). In effect, these two parameters define a ($\alpha_{MHD} - \alpha_d$) ‘phase space’ for transport, including boundaries across which the transport level increases sharply. For example, the existence of one such boundary has been associated with a transport-defined tokamak density limit [2].

Recent C-Mod experiments [4] have uncovered clear connections between the observed operational space of the edge plasma and that expected from numerical simulations of EMFDT. Unlike simulations, heat and particle fluxes in real experiments are limited by input power and fueling. Thus, if EMFDT transport is a strong function of the ‘plasma state’ in ($\alpha_{MHD} - \alpha_d$) space, then only a restricted set of edge states (i.e. specific combinations of α_{MHD} and α_d) should be accessible to real plasmas. Indeed, at fixed values of normalized plasma collisionality, L-mode pressure gradients in C-Mod are found to increase with plasma current squared, holding the MHD ballooning parameter, α_{MHD}, unchanged. As a result, edge plasma states are found to populate only a narrow band within this two-parameter phase-space [4]. In essence, this is a critical gradient paradigm for the edge plasma profiles; the local gradient (α_{MHD}) need only change by a small amount in order for the transport fluxes (heat and particle) to balance the externally imposed input fluxes (power and fueling). Peak pedestal pressure gradients in Enhanced D_α H-mode (EDA) discharges (which are found stable to ideal MHD modes and have no ELMs) also scale with plasma current squared [5, 6], suggesting that both L and H-mode profiles are similarly controlled by a critical-gradient behavior.

Experiments on C-Mod have also uncovered clear connections between the magnetic x-point topology (upper single-null, USN; lower single-null, LSN) and edge plasma flows. Near-sonic parallel plasma flows are detected on the high-field side SOL, which are driven primarily by a ballooning-like cross-field transport asymmetry [7]. As a consequence, LSN discharges tend to exhibit a stronger co-current toroidal rotation near the separatrix compared to USN (for fixed magnetic field direction, $Bx\nabla B$ pointing down). In some cases, these SOL flows appear to impose a ‘flow boundary condition’, affecting the toroidal rotation of the confined plasma. It has been suggested that the different flow boundary conditions in LSN versus USN may explain the corresponding x-point dependence of the L-H power threshold in tokamaks [8].

Taken together, the above observations suggest an interesting interplay between cross-field SOL transport and plasma flows – an old but important idea that has received the attention of many researchers (e.g. [9]). Based on the C-Mod observations, the near SOL appears to self-organize towards a critical poloidal beta-gradient (α_{MHD}), but plasma flows (presumably flow shear) may affect the critical gradient for a given topology, perhaps even promoting a L-H transport bifurcation when the SOL flow pattern is most favorable (LSN).

With the aim of further investigating these ideas, we have begun a new series of experiments in Alcator C-Mod. Among the principal goals are to simply ‘map-out’ the edge plasma operational space over a wider parameter range and to systematically compare the edge plasma states in LSN and USN topologies. This paper highlights some recent results that address the following key questions for ohmic L-mode discharges: (1) Does the edge plasma continue to organize toward a critical poloidal beta-gradient over an expanded parameter range? (2) Does the edge state differ noticeably in LSN versus USN and (3) do these variations correlate in some way to the observed changes in equilibrium plasmas flows? In summary, the answer to all three questions is, yes; for fixed values of local normalized collisionality, higher values of α_{MHD} are indeed obtained in LSN compared to USN and this difference occurs when the equilibrium SOL flows in the low-field SOL are also observed to be different.

2. Experiment

The primary measurements are from two fast-scanning probes: “outer” and “inner” probes located respectively on low and high-field side SOL regions (see Fig. 1). These are Langmuir-Mach probes, recording parallel flows as well as density and electron temperature profiles three times in a discharge up to the separatrix [7]. A series of matched ohmic L-mode discharges (82 total) were run with upper (USN) or lower x-point (LSN) geometries. These discharges had four different combinations of plasma current and toroidal magnetic field (I_p, B_T): (0.4 MA, 2.7 T), (0.4 MA, 4.2 T), (0.8 MA, 5.4 T), and (1.1 MA, 5.4 T). For each current-field combination, a density scan was performed over a range of normalized line-averaged densities of roughly $0.07 < \bar{n}_e / n_G < 0.45$, where n_G is the Greenwald density [10]. In all cases, the direction of plasma current and magnetic field was held fixed, with $B \times \nabla B$ pointing down.

3. Cross-field plasma profiles and parallel flows

Representative measurements of electron pressure, temperature and plasma flow velocities are shown in Fig. 1. The curves represent averages over a number of matched LSN/USN discharges with plasma currents of 0.4 and 1.1 MA. Vertical bars indicate ±1 standard deviations, derived from repeated sampling of similar discharges. In addition, data in Fig. 1 are included from only those discharges which had normalized collisionalities near the separatrix in the range of $0.28 < \Lambda < 0.32$. Here Λ is an inverse collisionality parameter, $\Lambda \equiv \left(\lambda_{ei} / R\right)^{1/2} / q_{95}$, with electron-ion mean free path (λ_{ei}), major radius (R) and rotational transform at the 95% flux surface (q_{95}). λ_{ei} is evaluated at a location 1 mm outside the separatrix at the outer midplane. Λ captures the q normalizations contained in the 'diamagnetic parameter', α_d [2, 11], and the collisionality parameter C_0 in the work of Scott [1] (see details in [8]).

As the current is raised from 0.4 to 1.1 MA at fixed collisionality, electron pressure is seen to increase by a factor of ~5 in the inner and outer SOL with e-folding lengths near the separatrix increasing slightly. At both currents, USN discharges have reduced pressure gradients near the separatrix compared to LSN. Pressures tend to be lower in the inner SOL compared to the outer and a strong in/out asymmetry in electron temperature is evident, as reported earlier [7], but showing no significant differences in LSN versus USN discharges. Most importantly, near-sonic plasma flows are seen on the inner SOL, with direction dependent on x-point location. Flows in the outer SOL remain in the same direction (co-current), but are faster in LSN versus USN. The latter effect has been correlated with an increased toroidal rotation in the outer SOL [7]. A similar flow picture applies for both plasma currents.

4. Operational phase-space in LSN versus USN

The effects of changing plasma current and x-point topology on electron pressure gradients near the separatrix are shown in Figs. 2 and 3, where absolute and normalized gradients are plotted versus Λ. In both topologies, absolute pressure gradients increase roughly as I_p^2. As a result, a plot of α_{MHD} versus Λ tends to trace out a 'universal curve', which is independent of plasma current. (Note: Λ is evaluated assuming Z_{eff} = 1. Nevertheless, Z_{eff} varies systematically from 1.1 at low Λ to 3 at high Λ and is similar in otherwise identical LSN/USN discharges. As a result, Z_{eff}-corrected Λ values produce the same trend as seen here.) These observations strongly reinforce the conclusions drawn from the earlier 2000/2001 data set [4] – the operational space of the near SOL does indeed appear to be determined by the 'phase space' of EMFDT. However, values of α_{MHD} are noticeably lower in USN versus LSN discharges.

Figure 4 highlights a possible link between the lower α_{MHD} values in USN and the different equilibrium plasma flows. Independent of collisionality, Λ, the high-field side SOL shows a clear difference in parallel plasma flows, reversing sign (to counter-current) in USN versus LSN. The low-field side SOL also exhibits a trend towards lower velocity (i.e. towards counter-current direction) over the range $\Lambda < 0.35$. It is interesting to note that the range in Λ where α_{MHD} is reduced also corresponds to the range where the parallel flow on the low-field side is reduced (and correlated with a change toroidal rotation). While further analyses remain to be performed, these results suggest that the operational space of the edge plasma (apparently set by EMFDT) is indeed influenced by SOL plasma flows. Such flows are dramatically changed in upper versus lower x-point topologies.

Acknowledgments

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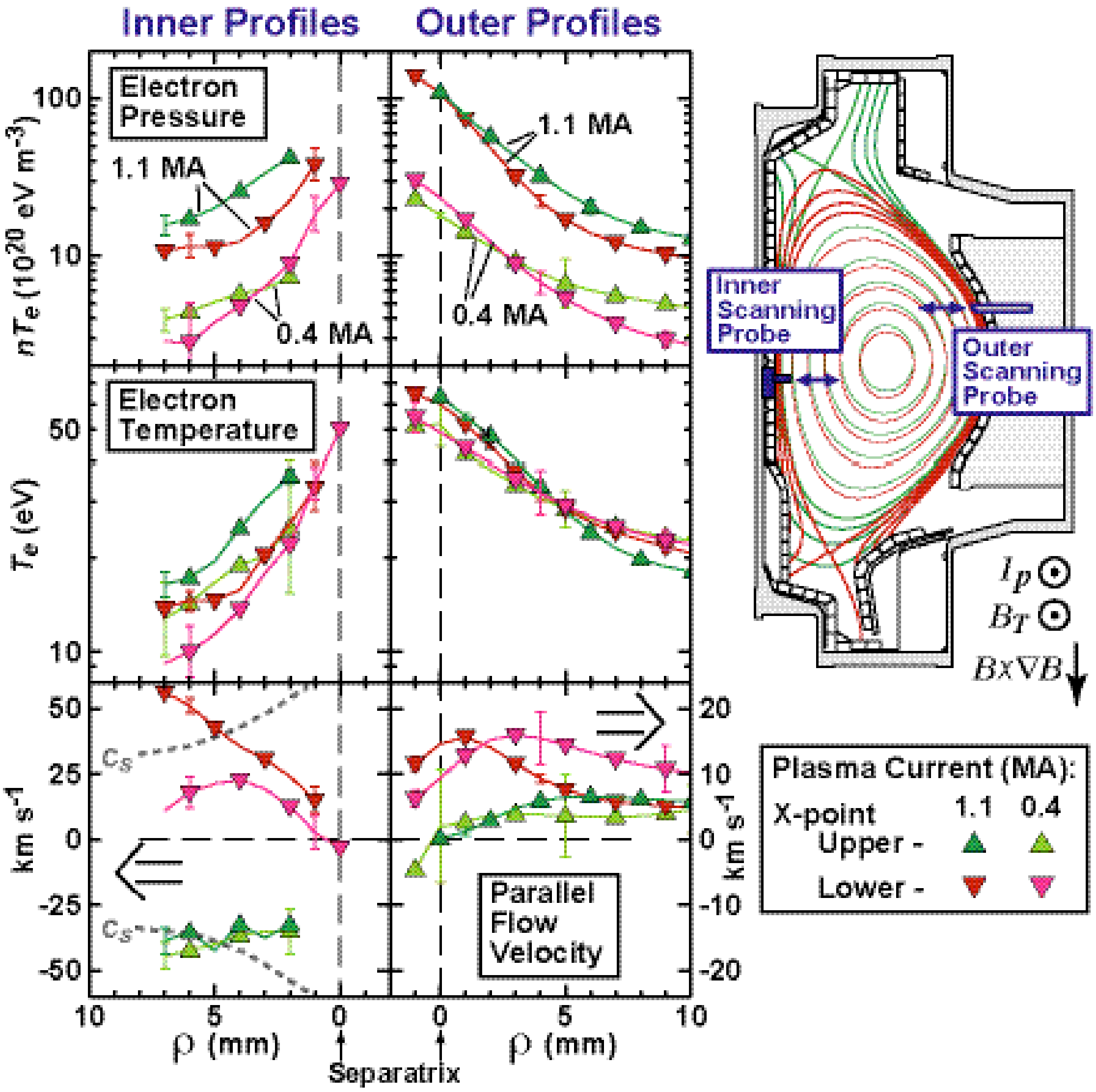

Fig. 1. Electron pressure, temperature and parallel plasma flow velocity profiles recorded from inner and outer scanning Langmuir-Mach probes for I_p = 1.1 and 0.4 MA and 0.28 < Λ < 0.32 in matched LSN and USN discharges. Horizontal axis (ρ) is distance outside the separatrix, mapped to the outer midplane. Positive velocities indicate a flow in the co-current direction; sound speed velocities (C_s) are shown for reference.

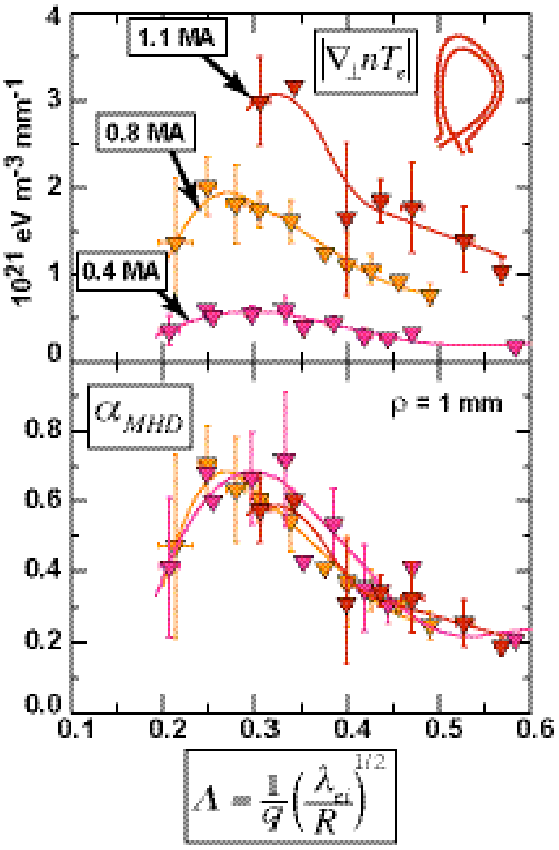

Fig. 2. Electron pressure gradients and α_{MHD} versus Λ evaluated at ρ =1 mm for LSN discharges. Data points represent average values from a number of probe scans; error bars indicate typical ±1 standard deviation in data sample.

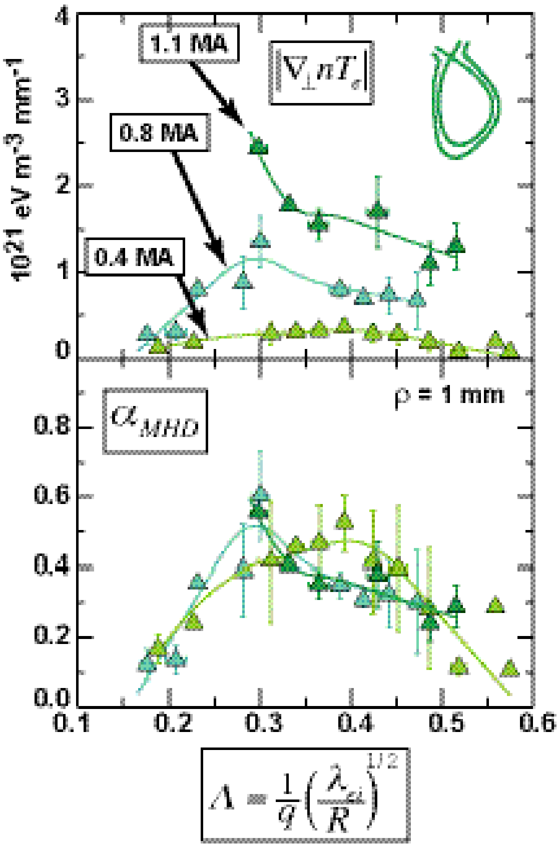

Fig. 3. Same quantities shown in Fig. 2. for USN discharges.

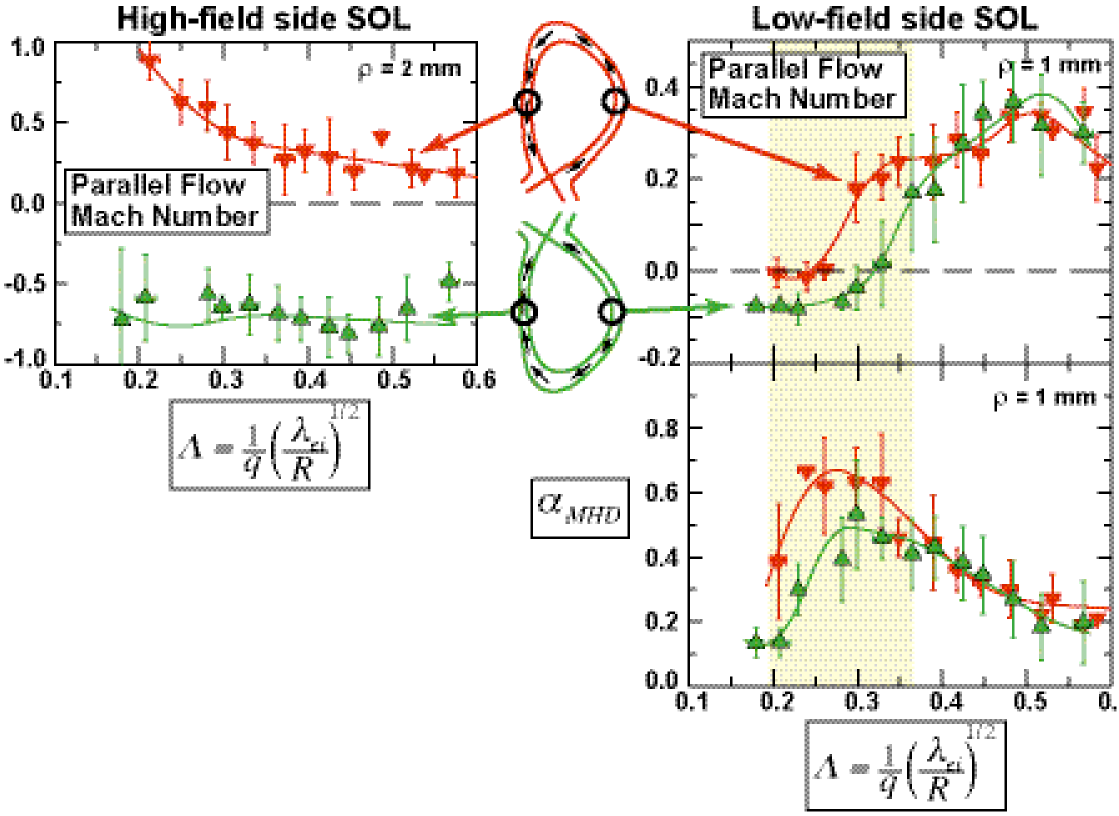

Fig. 4. Top left and right: Parallel Mach number on high (ρ =2 mm) and low-field side (ρ =1 mm) scrape-off layers as a function of Λ. Bottom right: α_{MHD} versus Λ, evaluated at ρ =1 mm. Data points represent averages over all data shown in Figs. 2 and 3. USN discharges are seen to have lower α_{MHD} values over range in Λ where flows in the low-field side SOL are also less co-current directed.