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H-mode optimization using magnetic topology variation in Alcator C-Mod

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Regulation of the edge transport barrier (ETB) in H-mode has been examined on the Alcator C-Mod tokamak in a series of recent experiments intended to characterize the ETB, or edge pedestal, structure, as well as associated edge relaxation mechanisms. Extensive prior work [1,2] determined a number of robust scaling laws for the pedestal in high-recycling plasmas with single null geometry and with the ion ∇B drift directed towards the active x-point. Current experiments address modification of the edge pedestal and global confinement that can be obtained when tools such as neutral particle control and shaping variation are invoked. The main operational goal is to use these tools to reduce core particle inventory to explore high-performance operation at reduced density and/or collisionality ν^*. The H-modes under study, which are often maintained in steady state for periods much longer than the energy confinement time τ_E, generally do not exhibit large edge-localized modes (ELMs). Typical edge relaxation mechanisms are the quasi-coherent mode (QCM) associated with enhanced D_α (EDA) discharges [1] and, under the right operational conditions, small ELMs. Pedestal measurements presented here are from mm-resolution edge Thomson scattering; comparisons with charge exchange recombination spectroscopy measurements, when available, demonstrate near equality of T_e and T_I over a wide range of discharges.

C-Mod plasmas are fuelled entirely from the edge, and H-mode density control tends to be challenging, in part due to high neutral opacity in the scrape-off layer (SOL) and pedestal region. Previous H-mode fuelling studies with gas puffing only [2,3] showed that pedestal density n_{ped} and pedestal ∇n are modified only modestly by changes in neutral source, suggesting a dominant role for plasma transport in defining the edge profile structure. In addition to

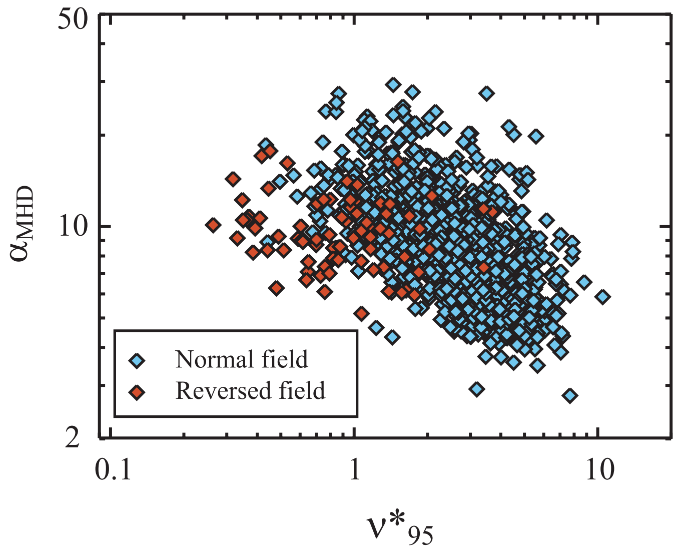

Figure 1. Normalized pressure gradient α_{MHD} *vs.* pedestal collisionality ν^*_{95} in LSN H-modes with normal B_T direction (blue, 2.6<B_T[T]<7.9, 0.4<I_P[MA]<1.7) and with B_T reversed (red, 5.4T, 0.9MA).

setting n_{ped}, plasma transport also governs edge pressure such that the poloidal beta gradient ($\propto \nabla p / I_P^2$) is a decreasing function of ν^*_{ped}, [2], a result which holds even across H-mode regimes with no ELMs. The blue data points in Figure 1 show this trend for lower single null (LSN) discharges with $B \times \nabla B$ pointing down, over a wide range of field and current. Here the pressure gradient is normalized as: $\alpha_{MHD} = (2\mu_0 q^2 R / B^2)\nabla p$.

In upper single null (USN) or near double null (DN) magnetic equilibria, the use of an upper divertor cryopump effectively reduces main chamber neutral pressure far from the gas puff as well as SOL plasma density; core particle inventory can be substantially reduced in ohmic and L-mode plasmas. Density pedestal reduction in H-mode is more modest, suggesting a similar stiffness to that demonstrated with aggressive gas puffing [2]. Pumping raises pedestal temperature T_{ped}, helping to reduce significantly edge collisionality, ν^*_{ped}, and to increase global confinement. Figure 2 shows the effect of the cryopump on pedestal parameters in USN discharges, the topology of which maximizes recycling at the upper divertor pumping slots, allowing for optimal neutral pumping. The simultaneous decrease in collisionality and boost in edge pressure (and thus global confinement) that is obtained generally is consistent with the trend demonstrated in Figure 1.

Because magnetic topology plays a critical role in the effectiveness of the cryopump, it is important to distinguish differences in intrinsic pedestal structure in LSN and USN discharges, as well in near DN configurations. Prior research on C-Mod has demonstrated that for single null (SN) discharges with similar engineering parameters, substantial reduction of n_{ped} and ν^*_{ped} is observed in the case of ion ∇B drift direction directed away from the active x-point [4]. Figure 1, for example, suggests a reduction in ν^* for a given

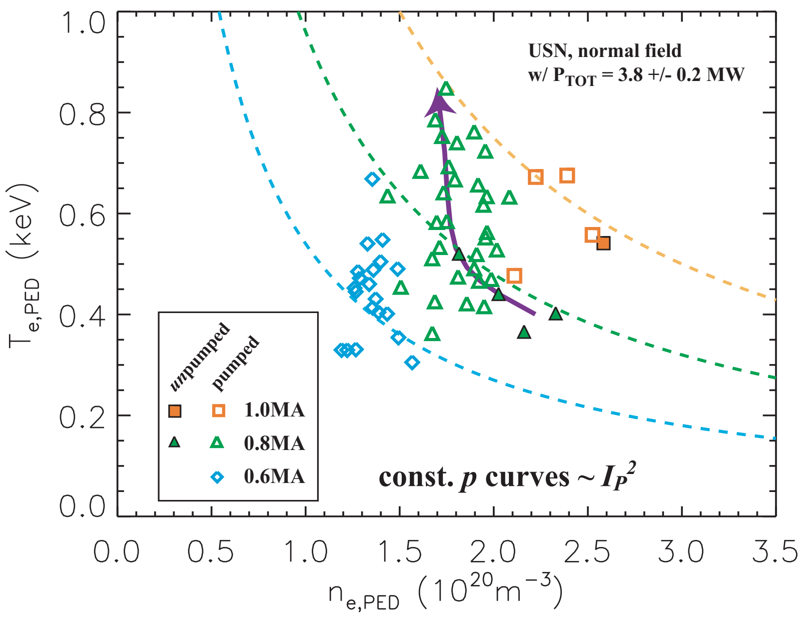

Figure 2. Comparison of H-mode pedestals in 5.4T USN discharges, with (open symbols) and without (closed symbols) cryopumping

value of normalized ∇p when switching from favourable to unfavourable drift direction. Magnetic balance is known to affect a number of phenomena in tokamaks such as the direction of bulk SOL flows, intrinsic core rotation and input power threshold for obtaining H-mode [5]. Furthermore, these quantities can show very sensitive variation with magnetic balance about DN. Thus motivated to explore the sensitivity of the H-mode pedestal to magnetic balance, we designed experiments to vary the topology in near DN configurations. Target discharges were nominally EDA H-modes (5.4T, 800kA) and were not actively pumped. The magnetic balance was quantified by the outboard midplane separation between the two separatrices, Δ_{sep}, as reported by the EFIT equilibrium reconstruction code, with the convention such that $\Delta_{sep}<0(>0)$ corresponds to LSN(USN). This signal was found to be accurate to within 1—2mm based on examination of flux to probes in the upper and lower divertors, as well as neutral gas pressures measured in the upper and lower vessel chambers.

H-modes were initiated using auxiliary ICRF heating and maintained steadily during sweeps of Δ_{sep} through balanced DN. Pedestal structure and confinement indeed were found to vary significantly for $|\Delta_{sep}| < 1$cm. Figure 3(a) demonstrates a repeatable ~30% drop in n_{ped} observed when discharges became biased slightly USN, trending downward toward the nominal values of n_{ped} expected for similar conditions in a fully USN equilibrium. A similar result has been reported for bias in the unfavourable drift direction on the DIII-D tokamak [6]. Also similar to DIII-D, we observe a reduction in energy confinement for slight USN bias, as indicated by the drop in $T_{e,ped}$ for a given amount of net power flowing into the SOL.

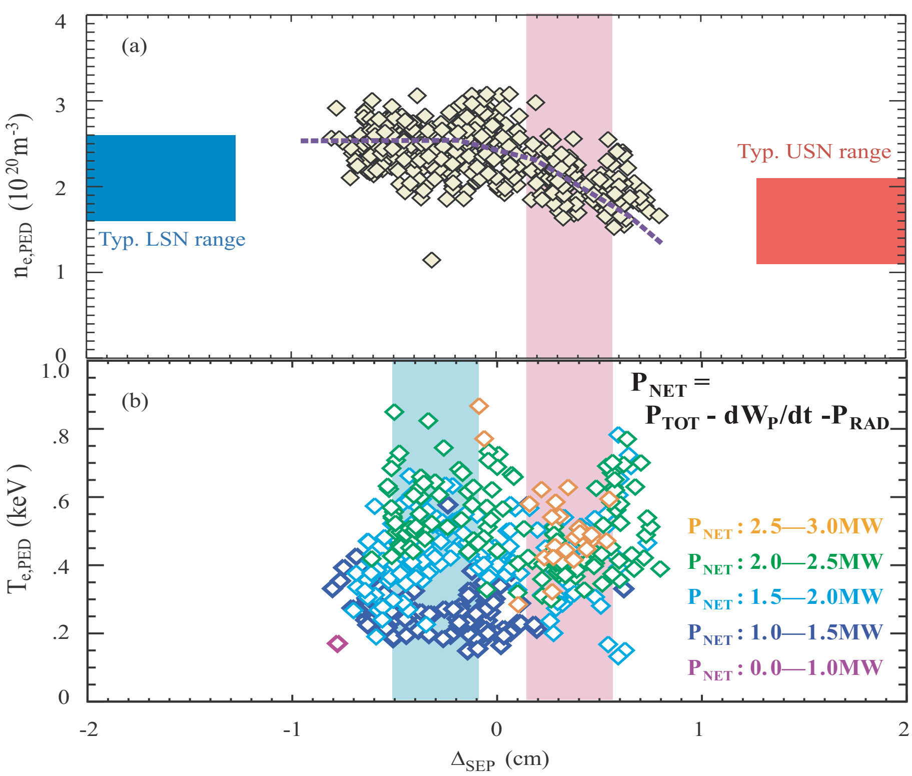

Figure 3. Variation of pedestal electron density and temperature as magnetic balance is varied.

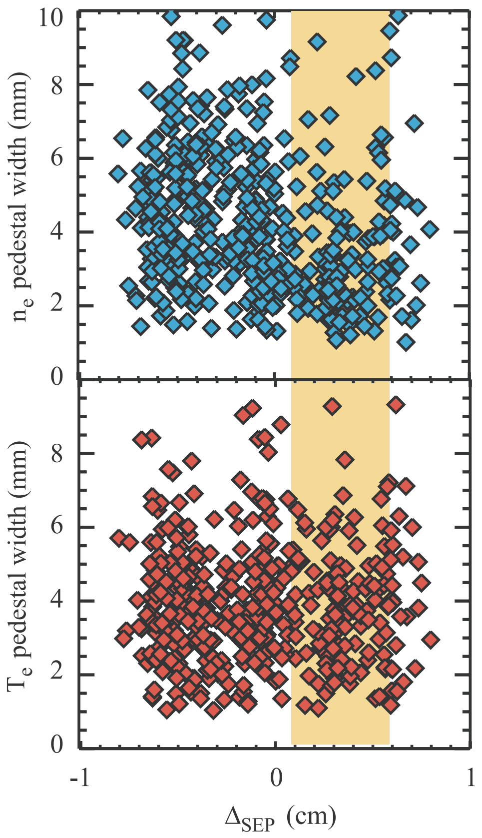

Figure 4. Pedestal widths in Δ_{SEP} scans

Pedestal widths obtained by automated fitting of measured profiles with a modified *tanh* function [1] suggest a narrowing of the density pedestal in the region of $0<\Delta_{sep}<1$cm, as shown in Figure 4. The highest levels of confinement ($H_{98}>1$) are observed for slightly LSN configurations, in which pedestal pressure gradients and temperature were higher even than in the standard LSN configurations. In the absence of heavily radiating impurities, H-modes in this configuration could be maintained for several confinement times, and exhibited small ELMs with fairly modest amounts of ICRF heating (~3MW). The ν* in these discharges can be further lowered, and H_{98} improved, if cryopumping is used.

In short, we observe a strong variation in pedestal and confinement properties when $|\Delta_{sep}|$ approaches a value characteristic of the pedestal width. This result is very interesting, given that ITER is likely to operate in a nearly DN geometry, and suggests further exploration of magnetic balance effects on current devices. For H-mode operation on C-Mod, the results have been useful in developing both high-confinement discharges for small ELM research and low-n_e, moderate-confinement discharges for advanced scenario and lower hybrid (LH) current drive experiments. Future work will continue exploring means of regulating the pedestal parameters with particle control and more aggressive shaping changes. External pedestal relaxation will also be explored; in particular, we will pursue a promising result of n_{ped} depression with no observed confinement degradation when LH waves are launched into H-mode discharges of suitably low density [7].

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