H-mode pedestal and threshold studies over an expanded operating space on Alcator C-Mod

Presented by Amanda Hubbard

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OUTLINE

• Introduction
  – Overview of H-mode regimes and prior pedestal results

• Influence of magnetic field B on
  – L-H threshold
  – Pedestal scalings
  – H-mode operating space, regimes

• Role of field and current direction
  – Review of results on configuration dependence
  – Flows and L-H thresholds with reversed field, current
  – Edge profile evolution in L-mode
  – Pedestals with reversed field

• Summary

Motivation:
H-mode profiles are ‘stiff’; Stored energy $W$ proportional to $p_{e,ped}$ across all the operating space discussed.
Several H-mode regimes obtained on C-Mod

**ELM-free H-mode**
- Low particle transport, transient H-modes.

**Enhanced D-Alpha (EDA)**
- Quasicoherent mode leads to steady $n_e$.
- Favored by higher $q$, $\nu^*$.  

**Small ("Type II"?) ELMs**
- Small ELMs on top of high $D_\alpha$.
- Occurs at higher pressure than EDA.
- Also gives steady $n_e$.

**Discrete ELMs**
- Recent observation, will be focus of talk by J. Terry, this session.
High-resolution diagnostics measure pedestal electron profiles and ionization rates

- Key diagnostic is Edge TS
  - Top view, 1.5 mm δR, 16 ms δt.
  - ECE used for faster $T_e$.
- SOL profiles from scanning probes.
- $D_\alpha$ profiles from camera enable derivation of neutral and ionization rate profiles, key to fueling and $n_e$ pedestal.
  - Find $L_D \leq L_{ne} < \lambda_{ion}, \lambda_{CX}$
- Diffusivity $D_{eff}$ derived from source, $n_e$ profiles.
  - Find $D_{eff}$ “well” in pedestal, decreasing with higher $I_p$. 

![Diagram of diagnostics and profiles](image-url)
Key prior pedestal scalings (mainly at B=5.4 T)

- **Strong correlation of $n_{\text{ped}}$ with $I_p$, weaker dependence on neutral source.**
  - Gas puffing has little effect in strong barriers, i.e., high $I_p$ H-modes.
  - SOL largely opaque to neutrals in these cases.
- **Narrow $n_e$, $T_e$, $p_e$ pedestal widths ($\Delta \sim 2$-5 mm).**
  - Little systematic variation with $I_p$, $n_e$ etc.
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- **Narrow** $n_e$, $T_e$, $p_e$ pedestal widths ($\Delta \sim 2-5$ mm).
  - Little systematic variation with $I_p$, $n_e$ etc.
- $p_{\text{ped}}$, $\nabla p_e$ scale with $I_p^2$.
  - Soft limit with higher $\alpha_{\text{MHD}}$ at lower $\nu^*$.
  - Suggests **critical gradient behaviour in pedestal** as in SOL.

Hughes, PoP 2006, IAEA 2006
2005-6 campaigns expanded H-mode parameter space

- C-Mod uses exclusively RF heating, primarily 6 MW ICRF.
- $B_T$ range for near-central heating constrained by $f_{RF}$.
- $2.6 < B_T < 8 \, \text{T}$ enabled by variable $f_{RF}$ (50-80 MHz), and D(He$^3$) as well as D(H) heating.
- $0.4 < I_p < 1.7 \, \text{MA}, \ 2.6 < q_{95} < 9.5$
  - Can now better separate $I_p$, $q$ dependences.

- Also a 2006 mini-campaign with reversed $I_p$, $B_T$ at 5.4 T, 0.8 MA.
As expected, L-H thresholds increase with $B_T$

- **Total power thresholds** for L-H transition are 2.7-5 MW for 8 T, vs typically 1-2 MW for 5.4 T.

- **Edge $T_e$** is also substantially higher at transition, ~300-450 eV vs 100-200 eV.
  - Higher edge $T_e$, lower $\nu^*$ at L-H transition likely affects the n-T trajectory of the following high field H-modes.
Extended scalings confirm pedestal widths are insensitive to $B_T$, $I_p$.

- Bulk of pressure width data $\sim$2-5 mm over 2.6-8 T, 0.4-1.7 MA.
  - Rules out $\rho_{pol}$, $\rho_{tor}$ scalings of pedestal width.

- Exception is at lowest $I_p$ (and $n_{ped}$) where $\Delta$ increases.
  - Correlated with deeper neutral penetration depth $L_D$ and may represent a fueling effect as on lower $n$ devices.
High B H-modes have same pedestal pressure as lower field cases, but higher $T_{\text{ped}}$

- **At given $I_p$, pressure pedestal profiles are independent of B**, ie. $\alpha_{\text{MHD}} \sim \text{const.}$ (even though most discharges do not have evident MHD).
- Stored energy, $\tau_E$ are also the same, since profiles remain “stiff”.
- **Balance between $T$, $n$ shifts.**
  - High $T_e$ at L-H may contribute.

\[
\begin{align*}
\text{Density Pedestal} (10^{20} \text{ m}^{-3}) & \quad \text{vs} \quad T_e \text{ pedestal (eV)} \\
0 & \quad 0 \quad 1 \quad 2 \quad 3 \quad 4 \quad 5 \quad 6 \\
5.4T, 1.2 \text{ MA} & \quad 7.9T, 1.2 \text{ MA} \\
\end{align*}
\]

\[
\begin{align*}
\text{High B n}_{\text{ped}} \text{ lower} & \quad \text{T}_{\text{ped}} \text{ higher} \\
p_e(r) \sim \text{same} \\
\end{align*}
\]
Higher B discharges therefore have lower $\nu^{*}_{\text{ped}}$

- 7.9 T H-modes tend to be shorter, with $n_e$ rising.
- Most to date are ELM-free, not EDA.
  - These cases had lower $\nu^*$ and/or lower $\alpha_{\text{MHD}}$ than typical EDA.
- Some discharges at high $\alpha$, $q_{95}$ had weak quasi-coherent modes, but not steady $n_e$.
  - These have low $\nu^*$ but higher $\alpha_{\text{MHD}}$, continuing prior trends and extending EDA operation space.

$\nu^{*}_{\text{ped}}$ computed taking $Z_{\text{eff}}=1$, lower bound
$n_{ped}$ is still linked to current. But, at high B, scales better with $q_{95}$.
**n\textsubscript{ped}** is still linked to current.  
But, at high B, scales better with q\textsubscript{95}.

The key result in all B ranges is that for high n and strong transport barriers, **n\textsubscript{ped} is not an easily controlled independent variable**.

- Largely determined by target plasma n, I, B.
- Target n is constrained when available power is near P\textsubscript{thresh}.
- Low gas fueling efficiency, related to opaque SOL.
- Transport sets n\textsubscript{e} gradient.
- **Potential issues for ITER H-mode scenarios.**
Influence of Magnetic Field Direction and Configuration
SOL flows appear linked to the changes in L-H threshold with configuration

- Well-known that L-H power threshold is \( \sim 2x \) HIGHER with \( B_x \nabla B \) drift away from active x-point. \( T_{\text{edge}} \) is also higher.

- Prior C-Mod experiments found strong parallel flows in inner SOL, reversing with USN vs LSN configuration. These affect core toroidal rotation \( V_{\text{tor}}(0) \).

- In unfavorable (USN) case, starts with more counter-current rotation, apparently further from L-H threshold conditions.
  - In all cases, flows and \( V_{\text{tor}} \) increment co-current with increasing power and pressure. \( \text{(no ext torque)} \)

- L-H transition occurs at similar rotation values in each case, but requires more power in USN than LSN.
  - Likely linked to differences in \( E_r \), shear.

Results consistent with SOL flows causing the differences in \( P_{\text{thresh}} \) with configuration (not necessarily the transition itself).
Reversing B and \( I_p \) removes ambiguities in comparing different magnetic configurations.

**C-Mod has only one (lower) “divertor” structure.** This means:

- Upper tile configuration is more open than lower, not designed for high heat flux.
- LSN and USN shapes were not exactly symmetric.

Do these effects contribute to the observed differences in SOL, flows/rotation, profiles, threshold?

**To find out, reversed I and B to compare in SAME configuration:**

“Reverse B” has ion \( B \times \nabla B \) drift **upward**.

“Normal B” has drift **downward**.
Key results confirmed by field reversal:
Inner SOL flows are unaffected by I, B direction

Parallel Flow in High-Field Side SOL
2 mm outside separatrix

- Flow direction depends only on X-point location, NOT Bx∇B.
  Consistent with transport-driven flux. Similar Mach No. in forward, reversed B.

Details in LaBombard talk JO1/4 Tues pm.
Key results confirmed by field reversal:

**Inner SOL flows are unaffected by I, B direction**

- Flow direction depends only on X-point location, NOT Bx∇B. Consistent with transport-driven flux. Similar Mach No. in forward, reversed B.

- But, since I_p is also reversed, flows are *counter*-I_p when Bx∇B is away from the X-point (‘unfavorable’), *co-*I_p in favorable cases.

Details in LaBombard talk JO1/4 Tues pm.
Key results confirmed by field reversal:
L-H Thresholds higher in Reversed B LSN

- **Ohmic core rotation is more counter-\(I_p\) in reversed field LSN.**
  - \(I_p\) increment when power, pressure increase.

- **LSN power thresholds** are much higher (2.7-3.7 MW) - “unfavorable”
  - Usual variability with wall conditions.

- **Threshold temperatures and gradients are also much higher** (>400 eV), particularly near low \(n_e\) limit.
  - Limit varies between campaigns.
Edge $T_e(r)$ with unfavorable drift shows interesting evolution before L-H transition

- Edge $T_e$ profiles evolve on a slow time scale, $3-4 \tau_E$.
- Often a “break-in-slope” in $T_e(t)$, $\nabla T \sim 40$ ms before L-H.
  - Two-phase H-mode transition?
- Steep $T_e$ gradients develop, before changes in $\nabla n_e$ & $D_\alpha$ (the classic “L-H”) transition.

- $V_{tor}(0)$ steadily reduces.
  - Smaller change in edge $V_{pol}$.

- Stored energy $W$, H-factor also increase gradually, $H_{89P}$ to 1.6 in L-mode.

- This L-mode evolution is NOT seen in favorable drift direction, even with high L-H thresholds (eg, 8 T).
- It is similar to behavior seen in AUG ‘Improved L-mode’ with unfavorable drifts. (Ryter, PPCF 1998).

![Graph showing various plasma parameters during ICRF on, P=3.4 MW](image-url)
“Pedestal” in $T_e$ develops prior to L-H transition

- $T_e$, $p_e$ gradients develop before L-H over a narrower region (~2 mm) than in later H-mode.
  - $\nabla p_e/n_e$ up to 200 keV/m!

- Preliminary measurements from ambient B$^{+4}$ spectroscopy near top of pedestal indicate that total $E_r$ does not change substantially until the L-H transition.
  - However, do not resolve the region of steepest $\nabla T_e$.

CX details in Bespamyatnov, QP1/56, McDermott QP1/57 Wed pm
Steady decrease in edge $\chi_{\text{eff}}$ is accompanied by changes in turbulent fluctuations

- Gradual decrease in magnetic fluctuations at outboard side, strongest in ~50-100 kHz band, accompanies 60% drop in edge $\chi_{\text{eff}}$ from power balance. Also a broadening, fluctuation increase at $f>150$ kHz;
  - Net decrease in integrated $\tilde{B}$ (5-250 kHz) during evolution is ~46%
  - Upshift but little change in net $n_e$ fluctuations by PCI (top view).
- Further sharp decreases in all fluctuations, and in $\chi_{\text{eff}}$, at L-H transition.

\[ \chi_{\text{eff}} = \frac{P_{\text{cond}}}{2kn_e\nabla T_{\text{eff}}} \]

0.97 $< \psi < 1.0$
Pre-LH evolution is consistent with a “soft” transition

- Edge flux-gradient plot shows gradual increase in $\nabla T$ with near-constant $Q$, $n_e$, after ‘break-in-slope’,
  - Appears to be a ‘soft’, second order transition, as would result from $-$ve dependence of $\chi$ on $T$ or $\nabla T$.
  - Contrasts with L-H transition, which is a rapid first order bifurcation.
  - Consistent with the gradual decrease in turbulence.
- Regime may help identify which modes contribute to edge transport.
- Transport phenomenon has globally similar features to the ‘Intermediate Mode’ regime seen on DIII-D but no evidence of “bursty” fluctuations or fluxes. (Colchin, PRL 2002).

- More similar to ‘Improved L-mode’ on AUG with unfavorable drifts.
- Regime might be attractive as starting point for advanced scenarios: $H \sim 1.6$, but low density.
H-mode pedestals in unfavorable configuration have lower $n_{\text{ped}}$, $\nu^*$

- In fully developed H-mode, pedestals in Reverse B LSN (unfavorable drift) tend to have lower $n$, higher $T$ (up to 900 eV) than Forward B LSN with similar $I$, $B$, target $n_e$. Pedestal widths, pressures are similar.
  - This leads to lower collisionality pedestals, $0.25 < \nu^*_{\text{ped}} < 2.5$

- Dimensionless pedestal space ($\alpha_{\text{MHD}}$ vs $\nu^*_{\text{ped}}$) is quite similar to Forward B 8 T H-modes. Common feature in both cases is a high power and temperature (lower $\nu^*$) at the L-H threshold. Is the initial condition determining the final operating point?

Pedestal details in Hughes QP1/44 Wed pm
QC Mode details in Cziegler talk JO1/7 Tues pm, Lin QP1/63.
Summary: H-mode studies over expanded operating space on Alcator C-Mod

- C-Mod H-modes studies have been extended to high field (7.9 T) and to reversed (unfavorable) field and current direction.
- In both cases, power and edge $T_e$ H-mode thresholds are increased.
  - Pedestal widths, pressure limits, confinement ~ same.

- With strong barrier and opaque SOL, pedestal density is largely set by target $I$, $B$, $n$. Target $n$ is constrained when $P_{\text{thresh}}$ high. *ITER may well be similar in these regards.* Parameters at the L-H threshold affect the final H-mode.
  - $T_{\text{ped}}$ is higher and $n_{\text{ped}}$ lower at high $B$ and Reversed $B$. $\Rightarrow$ Lower $\nu^*$. 

- Reversed field results are consistent with SOL flows affecting threshold.
- In unfavorable case, strong gradients in $T_e$ develop well before L-H transition in particle confinement. Gradual decrease in $\chi$ is accompanied by changes in fluctuations.
  - Regime of interest for edge transport physics, and perhaps for future use in advanced scenarios.

- 2007 experiments will exploit new cryopump to expand low $\nu^*$ operation, and extend high field H-modes to higher $I_p$ and $P_{RF}$. 