Advances in measurement and modeling of the H-mode pedestal on the Alcator C-Mod tokamak

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Motivation: Pedestal physics a critical issue for tokamak performance

- High confinement (H-mode) associated with edge transport barriers (ETBs)
  - Localized region of steep $n_e, T_e$ gradients give pedestal at edge $\rightarrow$ B.C. for core profiles
  - Stiffness of core profiles leads to robust scaling of stored energy with pressure pedestal
- Physics determining pedestal structure incompletely understood
- Open questions touched on in this talk:
  - Pressure gradient limits
  - Impact of plasma operational parameters on H-mode edge transport
  - Influence of neutral fueling on density pedestal

Alcator C-Mod stored energy vs. electron pressure pedestal


Outline

• Pedestal characterization on C-Mod
• Experimental scaling studies
• Empirical diagnosis of particle transport in pedestal
• Kinetic neutral modeling
• Recent pedestal fueling experiments
• Conclusions
Edge Thomson scattering (ETS)\[^1\] mainly used for $T_e$, $n_e$ characterization in pedestal region

### Modified $tanh$-function

The modified $tanh$-function is fitted to H-mode pedestal data:

$$f(R) = b + \frac{\hbar}{2} \left[ \tanh \left( \frac{R_0 - R}{d} \right) + 1 \right] + m(R_0 - R - d) \times H(R_0 - R - d)$$

- **Widths** $\Delta_T$, $\Delta_n$ usually 2—6mm
- **$T_{e,PED}$** typically 200—800 eV
- **$n_{e,PED}$** can be 1—5x$10^{20}$ m$^{-3}$
- Typically assume $T_i = T_e$, due to high collisionality
- Measurements of edge $T_i$ from CXRS, when available, in reasonable agreement with Thomson $T_e$

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**Ion temperature:** Marr, Wed. AM (KP1.17)

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\[^1\] Rev. Sci. Instrum. 72, 1107 (2001)
Enhanced $D_\alpha$ (EDA) H-mode arrests density, impurity accumulation without large ELMs

EDA allows steady state H-mode operation by increasing particle transport through the edge, reducing impurity buildup and radiated power.

EDA associated with quasi-coherent mode (QCM), localized to pedestal region ($f\sim 100\text{kHz}$)

Line-integrated $n_e$

Radiated power

Edge $D_\alpha$

Edge $n_e$ fluctuation spectrum

ICRF power

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Pressure profiles exhibit a ballooning-like scaling in H-mode and L-mode

- Dominating the pressure pedestal is an $I_p^2$ scaling, suggesting a critical $\alpha$ limit
- But, edge is found stable to ideal MHD modes
- $I_p^2$-limit is “soft”; $|\nabla p_e|$ scales weakly with power
- Probe measurements in near SOL of ohmic plasmas \(^1\) also shows $|\nabla p_e| \sim I_p^2$

\[^1\] B. LaBombard, et al., to be published in Nucl. Fusion

Edge phase space:
LaBombard, Thurs. PM (RO3.8)
Dimensionless scaling for H-mode pressure gradient?

- Near SOL data (~2mm outside LCFS) show evidence of edge plasma state controlled by electromagnetic fluid drift turbulence[^1]
- Demonstrates apparent critical gradient behavior, with $\alpha_{\text{MHD}}$ determined as a function of a collisional-like parameter
- Near SOL becomes foot of pedestal in H-mode. Could similar physical mechanisms play a role in scaling of pedestal $|\nabla p_e|$?
- Pedestal data set can be recast in terms of dimensionless quantities ($\alpha_{\text{MHD}}$, collisionality $\nu^*$)
- Possible relation to QCM formation criteria[^3] should be explored

[^2]: B. LaBombard, *et al.*, to be published in *Nucl. Fusion*.
Density pedestal shows positive scalings with current, target density

- Recent extensions to pedestal scaling studies show $n_{e,\text{PED}} \propto I_P$ over nearly 4x current variation, in all types of H-mode
- $n_{e,\text{PED}}$ shows a weaker dependence on target density (available particle source) at typical C-Mod operational parameters
- Suggestive of an interplay of plasma physics and neutral fueling in determining density pedestal

Pedestal scalings: Biewer, Thursday PM (RO3.00007)
Impact of neutral source on pedestal appears to differ between tokamaks

- 1D fluid neutral modeling\(^1\) for edge fueling makes predictions for pedestal scalings
  - \( \Delta n \sim \lambda_{\text{ion}} \sim 1/n_{e,\text{PED}} \)
  - \( \nabla n \sim n_{e,\text{PED}}^2 \)

- Model assumptions:
  - Flux balance: \( \Gamma_i = -\Gamma_n \)
  - Diffusive plasma transport: \( \Gamma_i = -D_{\text{eff}} \nabla n_i \)
  - Ionization \( \rightarrow \) plasma source, neutral sink
  - Constant neutral temperature, drift velocity

- Results from puffing, pumping experiments on DIII-D consistent with model\(^2\)

- Experience on C-Mod generally different
  - Puffing into H-mode yields little density rise (more later)
  - Recall, C-mod \( n_{e,\text{PED}} \) set largely by \( I_p \)
  - Raising \( n_{e,L} \) at fixed \( I_p \) yields no systematic change in \( \Delta n \), though \( \lambda_{\text{ion}} \) drops significantly

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Wider than normal density pedestal observed as $I_P$ is made unusually low

- Vary $n_{e,\text{PED}}$ by varying $I_P$
- At $I_P < 600\,\text{kA}$, $n_e$ pedestal becomes significantly wider, with $\nabla n_e$ near L-mode levels
  - Trend of $\Delta n$ vs. $n_{e,\text{PED}}$ resembles more closely DIII-D results
  - *But*, width variation at a given current is still uncorrelated with total density
- Edge $q$ changing significantly, with corresponding changes in character of QCM
  - Mode weaker at low $q$ (high $I_P$)
  - Broader in $\omega$-space at high $q$ (low $I_P$)
- Both plasma transport (increasing with $q$) and neutral penetration characteristics ($\lambda_{\text{MFP}} \sim 1/n_e$) are expected to change over this range

Can we diagnose the relative plasma and neutral transport experimentally?
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Diagnosis of $n_D$ in pedestal shows very short penetration scale length

- At low $I_p$ (high $q$), highest SOL $n_e$, $D_\alpha$ observed $\Rightarrow$ enhanced plasma transport and high recycling
- Lower $n_{e,PED}$ at low $I_p$:
  - broader $S_{ion}$ profile inside pedestal region
  - Increased average neutral penetration scale length $<L_D>$

Measured $<L_D>$ less than average $\Delta n$, and much less than characteristic neutral MFPs: $\lambda_{ion}, \lambda_{CX}$

Experimentally observed particle diffusivity a strong function of $I_P$

- Particle transport variation in pedestals can be expressed using effective transport coefficient
- Diffusive form for transport assumed: $\Gamma_i = -D_{\text{eff}} \nabla n_i$, with $n_i = n_e$
- $D_{\text{eff}}$ well is clearly present in the pedestal region
  - Width on the order of $\Delta n$
  - Higher $D_{\text{eff}}$ at lower $I_P$, correlated with lower $n_{e,\text{PED}}$
- The dependence of pedestal density appears strongly linked to plasma transport
- What can we say about the neutral source?
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Neutral penetration is simulated using fully kinetic calculation

• Modeling neutrals in a 1D fluid manner allows for simple analytic scalings of pedestal with neutral source
• Kinetic solution allows for more sophisticated treatment
  – Neutral drift velocity
  – Temperature equilibration with ions → strong coupling in high $n_i$ regime
  – Valid when $\lambda_{MFP} > L_n$, the condition demonstrated experimentally on C-Mod
• KN1D: a kinetic solver for neutrals in slab geometry
  – Key inputs: $n_e$, $T_e$ profiles, neutral pressure at wall
  – Includes ionization, CX, elastic scattering
  – Outputs molecular and atomic distribution functions → $n_n$, $T_n$, $v_n$
• KN1D includes no plasma physics and must be coupled with a model for the plasma transport
Modeling fixed plasma transport and variable neutral source results in a stiff $n_i$ pedestal

- Simple model: assume fixed $T_e=T_i$, $D_{eff}$ profile
- Find neutral source $N$ consistent with experiment and scale it by 1.50, 1.25, 0.75 and 0.50
- $n_{e,\text{PED}}$ scales roughly as $N^{0.5}$: similar to experimental scaling with target density
- Radial position of pedestal shows little change (diamonds)
- Neutral penetration decreases with $n_e$ rise
- Pedestal gradient scale length $L_n$ varies little, indicating stiff $n_i$ profiles
- Density pile-up and peaked ionization profile evident in pedestal
- Pedestal is largely self-screening to neutrals
Modeling pedestal more typical of DIII-D yields less stiff $n_i$ profile

- Lower absolute densities $\rightarrow$ Longer neutral penetration lengths
- Pedestal narrows slightly at higher density
- Resulting $n_i$ gradient scale lengths exhibit more variability as neutral source is changed
- Flatter ionization profile
- Qualitatively more consistent with DIII-D experimental results at low density, and with fluid model predictions
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D$_2$ puffing into H-mode used to examine response of $n_{e,\text{PED}}, \nabla n_e$

- Fueling gas puffs intended to provide additional neutral source for H-mode pedestal
- D$_2$ delivered through a capillary, usually on inner wall
- Puffing affects discharge
  - Enhances vessel particle inventory
  - SOL $n_e$, ionization rise
  - Lower $T_{e,\text{PED}}$ within 50ms of D$_2$ entering vessel
  - Edge cooling results in total stored energy decline, suppressed radiated power
H-mode gas puff fuels pedestal more readily in low $I_P$, $n_e$ discharges

- Low-$I_P$ H-mode responds to gas puff, showing seemingly stiff $n_e$ pedestal
  - Qualitatively like perturbed density profiles in model
  - Excessive fueling leads to H-mode termination in ~60ms
- “Standard” 0.8MA pedestal shifts outward while $n_{e,\text{PED}}$ stays constant → pedestal screening appears greater than in model
  - Plasma transport changing?
  - SOL density, flows playing a stronger role at higher $I_P$?

Profiles averaged over these windows

Conclusions

- Experimental studies give insight into pedestal physics
  - Ballooning-like scaling of the pressure pedestal may have links to edge turbulence rather than ideal MHD
  - Density scaling \((I_p n_e L^{1/2})\) suggestive of a \(n_e\) pedestal influenced by both plasma transport and neutral fueling
  - Empirical diagnosis of \(D_{\text{eff}}\) demonstrates strong inverse dependence on \(I_p\)
  - Large puffs produce relatively little pedestal fueling in typical H-modes
- Kinetic neutral treatment used to model neutral fueling in the pedestal
  - Simulated C-Mod pedestals with fixed plasma transport largely self-screening to neutals
  - Qualitative behavior of C-Mod \(n_e\) pedestal reproduced by model
  - Simulated DIII-D-like profiles show less profile stiffness, much as in experiment and more consistent with fluid modeling results
- Gas puffing into H-mode pedestals explicitly demonstrates screening effects
  - Screening increases at higher with \(I_p (n_e)\)
  - Resistance to H-mode gas puffing is worth thinking about; possible implications for ITER fueling
- More opportunities for understanding here: SOL opacity, flows, 2D, 3D effects etc. More complete modeling needed for the future!
Edge and pedestal studies: upcoming presentations related to C-Mod

• Wednesday morning:
  – H-mode power threshold: Rice KP1.10
  – Edge ion temperature, velocity measurements: Rowan, Bespamyatnov, McDermott, Ince-Cushman, Marr KP1.10—12, 16, 17
  – Scanning probe development: Smick KP1.19
  – Reflectometry upgrades: Dominguez KP1.23

• Thursday afternoon:
  – Pedestal scaling studies: Biewer RO3.7
  – Edge plasma phase space: LaBombard RO3.8
  – ELMs: Terry RO3.9
Questions? Reprints?

Reprint available at:

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