Experimental studies of plasma and neutral particle transport in the Alcator C-Mod plasma edge

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Abstract

Details of interactions between plasma and neutral atomic species at the tokamak plasma edge are crucial to the assessment of local transport and the consequent profiles of plasma temperature and density. Since edge quantities directly affect core plasma confinement, it is important to evaluate the influence of these edge neutral-plasma interactions. On Alcator C-Mod, edge electron density and temperature profiles are measured with millimeter resolution edge Thomson scattering (TS) and with the use of scanning Langmuir probes. A kinetic neutral code (KN1D) supplied with TS and probe data, is used to model radial profiles of molecular and atomic deuterium, along with resulting ionization sources. Based on this modeling, we can evaluate neutral fueling rates and effective plasma diffusion coefficients in various regimes of edge transport (i.e. L-mode, EDA and ELM-free H-mode). We examine the roles played by atomic physics and plasma physics in determining the characteristic shape of edge plasma profiles. Particularly helpful in this analysis are dedicated experiments in which plasma density was systematically varied in both L-mode and H-mode discharges.
Outline

• H-mode pedestal characteristics on Alcator C-Mod
• Scaling of pedestal width with density, influence of neutral fueling
• Kinetic neutral calculations using KN1D
• Comparison of neutral penetration, ionization source, and pedestal scale length in various regimes
• Attempts to change fueling characteristics by puffing into H-mode
• What we can say about neutrals and pedestals
Motivation

- Tokamak edge conditions strongly influence core energy confinement\textsuperscript{6,7}
- The high confinement regime (H-mode)\textsuperscript{8} of operation is associated with large particle, temperature gradients near the last closed flux surface (LCFS); local elevation of $T_e$, $n_e$ results in an edge pedestal
- Confinement predictions for large next-step devices require accurate extrapolations of the H-mode pedestal; understanding must be had of the physics determining pedestal heights, widths, and gradients
- Neutral fueling of the plasma edge: what impact does it have on the pedestal characteristic shape?
Poloidal locations of selected edge diagnostics on Alcator C-Mod

**Edge Thomson scattering (TS)**
- 22 spatial channels
- ~1mm radial resolution at midplane
- Optimal for plasmas with $T_e$ of 30—1000 eV, $n_e$: 0.3—5x10$^{20}$ m$^{-3}$

**Scanning Langmuir probe**
- Several cm above outboard midplane
- Sub-mm resolution scans of $T_e$, $n_e$ in scrape-off layer (SOL) over a ~100ms reciprocating stroke
- Capable of brief penetrations past the last closed flux surface (LCFS)
- Limited use in ICRF heated plasmas

**Lyman-α photodiode array**
- Several cm below outboard midplane
- 20 channels filtered for Lyman-α giving Abel-inverted profiles of emissivity with 2 mm resolution

Profiles from diagnostics are mapped to machine midplane along surfaces of constant flux from EFIT equilibrium reconstruction code.
Edge transport barrier routinely observed in high confinement (H-mode) regime

• Transport barrier associated with high $T_e$, $n_e$ gradients, localized to narrow pedestal region

• Typical pedestals are 2—6 mm in width

• On average the $T_e$ pedestal is wider and is located slightly inside the $n_e$ pedestal

• Profiles are fit to a modified tanh function\textsuperscript{12} for ease of analysis:

$$f = b + \frac{h}{2} [\tanh(\frac{R_0 - R}{\delta}) + 1] - m (R - R_0 + \delta) H(-R + R_0 - \delta)$$

from Ref. 5
Density pedestal width in Enhanced $D_{\alpha}$ (EDA)$^{13}$ H-modes has been seen to increase with $n_{e,PED}$, $1/q_{95}$.

- Simple theoretical considerations$^4$ suggest a $\Delta_n$ characteristic of the neutral atomic penetration length at the edge.
- Result would be a width scaling with inverse of $n_{e,PED}$.
- Previous analysis indicated the opposite trend on C-Mod in Enhanced $D_{\alpha}$ (EDA)$^{13}$ H-modes roughly constant $n_e$ gradient over a range of plasma currents (0.6—1.2 MA)
  - $\Delta_n$ scaled equally well with $1/q_{95}$
  - Raising $I_p$ both lowers $q$ and raises $n_{e,PED}$.
  - Needed to scan $n_e$ at fixed current to isolate density effect.

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![Graph showing the relationship between $\Delta_n$ and $n_{e,PED}$ with fixed target density, varied current.](from Ref. 5)

![Graph showing the relationship between $\Delta_n$ and $q_{95}^{-1}$ with fixed target density, varied field and current.](from Ref. 5)
At fixed field, current and magnetic geometry, density pedestal was varied by changing L-mode target density.

\[ I_p = 0.8 \text{MA}, \quad B_T = 5.4 \text{T} \]

\[ \kappa = 1.7, \quad \delta_U = 0.35, \quad \delta_L = 0.5 \]

\[ T_{e,\text{PED}} \approx 300 \text{eV} \]

No clear trend observed in pedestal width.
Neutral population distributions computed with \text{KN1D}^3

\text{KN1D}

\text{Kinetic Neutral 1-D Transport Code}

1-D space, 2-D velocity, kinetic transport code for molecular and atomic hydrogen (written in IDL)

Input
- Plasma Background (Core, SOL, limiter shadow), 'midplane' neutral pressure, 1D geometry

Boundary Conditions
- Zero mass flux onto 'wall' and 'limiter' sides, limiter recycling, RT molecules from wall, 'Black' core plasma

Output
- Self-consistent velocity space distributions $[f_{H_2}(v_r,v_x,x), f_{H}(v_r,v_x,x)]$, molecular dissociation, fluid moments, molecular ion density and temperature profiles.

Options Included
- Self collisions, cross-collisions: $D^+$, $D_2$, $D_0$, $D_2^+$ collisions with 'limiter sides'

from: B. LaBombard, PSFC Research Report RR-01-03, “KN1D: A 1-D Space, 2-D Velocity, Kinetic Transport Algorithm For Atomic and Molecular Hydrogen In an Ionizing Plasma”
Example of neutral density profile and ionization source computation using KN1D

- Inputs to KN1D include $n_e$, $T_e$ as determined from edge TS and scanning probes
- Assume $T_i = T_e$
- Neutral D$_2$ launched from behind limiter at $T_{\text{wall}}$; dissociation yields atomic D$_0$ source
- Charge-exchange, elastic scattering, electron impact ionization included in computation of neutral penetration
- Molecular source scaled in order to match magnitude of calculated Lyman-emissivity with that inferred from edge measurements
Inferred profile scale lengths, diffusion coefficient for the L-mode, EDA H-mode

- Neutral penetration ($L_D$), plasma density ($L_n$) scale lengths compared directly
- Inward neutral flux calculated, giving plasma flux and effective diffusion coefficient $D_{\text{eff}}$

\[
L_D = \left| \frac{n_D}{\nabla n_D} \right|
\]

\[
L_n = \left| \frac{n_e}{\nabla n_e} \right|
\]

\[
\Gamma_i = -\Gamma_D
\]

\[
D_{\text{eff}} = -\frac{\Gamma_{e,i}}{\nabla n_e}
\]
General observations on neutral penetration calculations

- Neutral penetration length $L_D$ decreases with increasing $n_e$
- $S_{ion}$ tends to be peaked locally near middle or foot of $n_e$ pedestal
- Relatively large values of $S_{ion}$, Lyman-$\alpha$ emissivity calculated in SOL
- $D_{eff}$ drops sharply in the pedestal region during H-mode, demonstrating values similar to neoclassical
- Difficulties in interpretation
  - Placement of separatrix by EFIT accurate to only 3 mm, making it difficult to relate measured and computed profiles to LCFS
  - TS and probe profiles must connect smoothly in order to produce sensible KN1D inputs
  - Lyman-$\alpha$ profile measurements usually cannot be well matched everywhere in $R_{mid}$
    - Brightness signals often noisy
    - High densities measured by probes sometimes imply larger emissivity in SOL and behind limiter than are measured
  - Uncertainty in the required neutral source leads to factors of perhaps ~2-3 uncertainty in $S_{ion}$, $D_{eff}$
KN1D analysis performed on experimental data from density scans at both 0.6, 0.8 MA

- Hybrid TS/probe profiles fit to \( \tanh \) function to obtain \( n_{e,PED}, n_{e,SOL}, \Delta_n \)
- At a given current, a higher density is required for obtaining EDA H-mode\(^{14}\); enhanced particle transport in EDA gives substantial SOL density
- Ionization mean free path \( \lambda_{ion} = v_D/n_e <\sigma v>_{ion} \)
  calculated using pedestal \( n_e \)
  and average \( T_e, T_D \) in the pedestal region
- The KN1D calculated \( n_D \) profile has an e-folding length \( \lambda_{D,PED} \), which is roughly \( \frac{1}{5} \lambda_{ion} \)

Pedestal width \( \Delta_n \) is of the same order as \( \lambda_{D,PED} \).
Ref. 4 predicts \( \Delta_n \sim (2/E)\lambda_{ion} \), where \( E \) is a flux expansion factor. For this model to describe C-Mod to leading order, the physical distance between flux surfaces would have to be \( \sim 10 \times \) greater at the main location of fueling than at the midplane.
At a given plasma current, $\Delta_n$ shows no clear indication of a trend with neutral penetration.

- Available data show $\Delta_n > \lambda_{D,PED}$ in most cases, with no obvious trend with pedestal $n_e$.
- However, the set of low density pedestals (@0.6MA) are wider on average than those from the initial experiment (@0.8MA).
  - Previously determined scalings would have predicted narrower pedestals at lower current, since $q_{95}$ is increased (from <5 to >6).
  - However, plasma shaping is slightly different in these two experiments; triangularity has been shown to have a potentially strong effect on the density pedestal width.\(^5\)
EDA, ELM-free H-modes show differences in neutral penetration, ionization profiles

ELM-free pedestal widths may be more closely related to neutral penetration lengths than EDA
What relationship exists between neutral fueling and pedestal shape?

• Pedestal density and operational regime (L-mode, EDA or ELM-free H-mode) impact the distribution of $S_{\text{ion}}$

• Models for pedestal structure suggest a balance between plasma diffusion and ionization of incoming neutrals in generating $n_e$ pedestal $\Delta n \sim L_D \sim 1/n_e$

• C-Mod data suggest a $n_e$ pedestal determined less by neutral penetration than by plasma physics
  – In EDA H-mode, $n_e$ pedestal height is most easily affected by varying plasma current; it rises, and in general, so does the width
  – Varying target density in a given discharge has small effect on pedestal height, no strong effect on width

• Yet it is difficult to rule out the significance of neutrals in determining the pedestal
  – $\lambda_D$ is of the same order as $\Delta n$
  – The known effect of plasma shaping on the pedestal could be related to changes in the 2-D fueling distribution
Active gas puffing was applied during H-mode to change fueling characteristics.

- Increase in core density
- Edge $T_e$ depression
- Drop in stored energy and radiated power
- Increased noise on $D_\alpha$ trace

$D_2$ gas puff is applied from 0.8 to 1.3 seconds after H-mode pedestal becomes fully developed.
Pedestal response to aggressive puffing

- Typical profiles from H-mode discharges before (squares) and after (diamonds) gas puffing are shown at right
  - $I_p=0.8\text{MA}$
  - $B_T=5.4\text{T}$
  - $n_e L=1.2\times10^{20} \text{ m}^{-3}$
  - Nominal $P_{\text{ICRF}}=2.7\text{MW}$

- For both outer wall and inner wall localized gas puffs, the $n_e$ pedestal height and width are essentially unchanged, but position is *shifted outboard*.

- $T_{e,\text{PED}}$ is markedly lower, reducing plasma stored energy
Edge effects of outer wall gas puffing

- Scanning probe measures elevated $n_e$ in SOL during inboard and outboard gas puffing.
- Increased Lyman-$\alpha$ emissivity also observed, with a peak shifted in the outboard direction.

Inner wall gas puff yields similar profiles.
KN1D analysis of EDA with and without outer wall gas puff

- **Density pedestal** height and width change very little under aggressive gas puffing, while SOL \( n_e \) rises
- We see slightly enhanced rate of fueling during gas puffing into H-modes, and note an apparent increase in \( S_{\text{ion}} \) inside the LCFS
- **Neutral density** in pedestal is higher during puff, but characteristic penetration length remains similar to pedestal width
Discussion of gas puffing results

- Profiles in edge plasma are changed considerably during gas puffing, demonstrating importance of neutral-plasma interactions to pedestal structure
  - SOL density, ionization rates driven up during puff
  - $T_e$ pedestal shifts more inboard of $n_e$ pedestal
  - Increased neutral population appears to remove power from plasma edge, leading to poorer energy confinement

- However, $n_e$ pedestal height not easily changed by attempts to alter the fueling source after H-mode already developed

- Pedestal shape likely determined from a combination of plasma physics and neutral-plasma interactions in the ionizing region
Ongoing and future improvements to this work

- Extend modeling and computation to radial thermal transport
- Obtain improved emissivity profiles, using Dα imaging camera, then calculate nD and Sion profiles using the technique of Ref. 10; some data already exist
- Extend measurements and modeling poloidally: 2-D examination of neutral fueling
- Benchmarking of KN1D against the DEGAS 2 neutral code has been initiated
- Want to understand why C-Mod does not demonstrate a clear relationship between ne pedestal width and neutral fueling
  - Plasma physics dominant?
  - At fixed plasma parameters, not enough range in ne,PED to draw a conclusion?
Improved experimental measurements of neutral emissivity can aid analysis

- $D_\alpha$ emissivity profile can be determined with ~2mm spatial resolution.
- Using well resolved edge profiles of $n_e$, $T_e$, profiles of $n_D$ and $S_{ion}$ can be inferred, compared with KN1D predictions.
- At right, model $n_e$, $T_e$ inputs to KN1D adjusted to give match to experiment.
Summary

- Profile data, along with kinetic computation of neutral profiles, allow us to better diagnose the pedestal region.
- Experimental evidence suggests neutral transport normally does not play a dominant role in determining C-Mod $n_e$ pedestal structure.
- Neutral-plasma interactions may be more important under certain regimes of operation.
- Results depend heavily on correct modeling of neutral penetration and ionization source.
  - Improved emissivity measurements will allow experimental derivation of neutral penetration.
  - Reliable $D_\alpha$ profiles can guide modeling as well.
References