Poloidal Structure of Impurity Density and Flows in the Pedestal Region of Alcator C-Mod

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Outline

- HFS Parallel Flow Discrepancy
  
- Gas Puff-CXRS Diagnostic
  
- In-Out Impurity Density Comparisons
  
- Explanations for Impurity Asymmetries

Prior observations
Measuring $n_z$, $T_z$, and $V_z$ at the LFS and HFS
Results in L-, I-, and H-mode
Possible mechanisms driving asymmetries
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Inferred Parallel HFS Flow Overpredicts Measurements by >3x

- $V_{z,\parallel,HFS}$ calculated[1] from LFS flow measurements and general flow eqn
  \[ V_z = \frac{k_z(\psi)}{n_z} B + \omega_z(\psi) R \hat{\phi} \]
  - Assumed $n_z \approx n_z(\psi)$

- Discrepancy also observed on ASDEX Upgrade[2]

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$V_z = \frac{k_z(\psi)}{n_z} B + \omega_z(\psi) R\phi$

**Valid in Pedestal?**
- Sources?
- Radial transport?

**Poloidally varying $n_z$?**

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Explanations for Impurity Asymmetries
Gas Puff CXRS System on Alcator C-Mod

- Diagnostic expanded:
  - LFS and HFS gas puffs
  - Poloidal and Parallel views

- New diagnostic technique developed to measure impurity density using Gas Puff-CXRS [3]

Complete set of LFS and HFS measurements of $n_z$, $T_z$, $V_{z\theta}$, $V_{z//}$, $E_r$

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In-Out Boron Density Asymmetry in H-mode, absent in L- and I-mode

No asymmetry in plasmas with low $\nabla n_e$ (L-mode, I-mode)

<table>
<thead>
<tr>
<th></th>
<th>$n_e$ Pedestal</th>
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<th>$n_z$ Asymmetry</th>
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<tbody>
<tr>
<td>L-mode</td>
<td>✗</td>
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In-Out Boron Density Asymmetry in H-mode, absent in L- and I-mode

H-mode

Peak asymmetry (>10) is larger than maximum allowed by conventional neoclassical theory (~4) [4,5]

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Conventional Neoclassical Transport Can’t Explain LFS Midplane Impurity Density

- Simulated, 1D radial impurity transport with neoclassical transport coefficients predicts impurity density profiles close to measured C-Mod HFS $n_{B5^+}$.

- In contrast to ASDEX-U, where “conventional” ($\rho_{\theta,i} << L_{ni}, L_{Ti}$) neoclassical transport reproduces LFS impurity density profiles [6].


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Inboard $n_z$ Pedestal Fixed
Outboard $n_z$ Pedestal Varies

- In-out $n_{B_{5+}}$ asymmetry in H-mode increases with $q_{95}$
  - LFS $n_{B_{5+}}$ pedestal shifts inwards and widens
  - HFS $n_{B_{5+}}$ pedestal remains $\sim$fixed in position and width

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Possible mechanisms driving asymmetries
Fluctuations Driving Asymmetry?

- Poloidally asymmetric radial transport a candidate for \( n_{B5+} \) asymmetry

- Quasi-coherent (QC) mode in EDA H-mode
  - Bad curvature driven (LFS only)
  - Measured \( \langle \tilde{E}_\theta \tilde{n}_e \rangle \) directed outward [7]

- ELM-free H-mode shows:
  - No coherent mode
  - Reduction in \( \tilde{n} \) fluctuation power


Figure from I. Cziegler, PoP, 2010

but \( n_{B5+} \) asymmetry still present!

Suggestive that other physics at play...
Radial Transport Can Become Important in the Pedestal

- Radial transport time can be comparable to or faster than parallel transport time in H-mode

- Non-local neoclassical calculations (PERFECT) show radial transport important in the pedestal [8]

- Large radial transport will break $k_z(\psi)$, $\omega_z(\psi)$ flux functions

$$V_z = \frac{k_z(\psi)}{n_z} B + \omega_z(\psi) R \dot{\phi}$$

**Test experimentally**

Density Asymmetry Compared to that Predicted by Poloidal Velocity

- Poloidal velocities **underpredict** impurity density asymmetry

\[ n_{z,HFS} = \frac{B_\theta}{V_\theta} |_{HFS} \quad \frac{V_\theta n_z}{B_\theta} |_{LFS} \]

\[ V_{\theta,HFS} = \frac{B_\theta}{n_z} |_{HFS} \quad \frac{V_\theta n_z}{B_\theta} |_{LFS} \]

Radial transport important

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Conclusions

- Direct **boron density** measurements demonstrate:
  - Impurity density *symmetric* in low $n_e$ gradient plasmas (L- and I-mode)
  - Impurity density *asymmetric* in H-modes
    - Peak asymmetry (>10) larger than allowed by conventional neoclassical theory (~4)
    - LFS pedestal shifts inwards and widens as Ip ↓
- Fluctuation driven transport low in ELM-free H-modes
  - Suggestive that other physics driving impurity density asymmetry
- Gradient driven, collisional radial transport appears to be primary driver in the impurity density asymmetry
  - Supported by breaking of flux functions $k(\psi), \omega(\psi)$
End Presentation
H-mode Flux Functions

- Measured $k_Z(\psi)$ and $\omega_Z(\psi)$ at the LFS and HFS
  - Reasonable in magnitude
  - Shift present

$$k_Z(\psi) = \frac{n_Z}{B_\theta} V_{Z\theta}$$

$$\omega_Z(\psi) = \frac{1}{\cos \gamma} V_{Z/\|} - V_{Z\theta} \left[ \frac{\sin \gamma}{\cos \gamma} + \frac{B_\phi}{B_\theta} \right]$$
Sources Backup Slide Here

- Really interesting plot
Ion-Impurity Friction Can Cause Impurity Density Asymmetries

- Helander-Fülöp-Landreman [5-7] developed theory for in-out impurity density asymmetry
  - Neoclassical (no anomalous transport)
  - Driven by ion-impurity friction in all collisionality regimes
- Theory not strictly valid in the pedestal, since pedestal transport non-local ($\rho_{\theta i} \sim L_{ni}, L_{Ti}$) → GUIDE ONLY

\[
\frac{n_{Z,HFS}}{n_{Z,LFS}} = \frac{B_{HFS}^2}{B_{LFS}^2} \frac{1 + \gamma b_{LFS}^2}{1 + \gamma b_{HFS}^2}
\]

where
\[
b = \frac{B}{\langle B^2 \rangle^{\frac{1}{2}}}
\]
\[
\gamma = \begin{cases} 
0.33 f_c \frac{L_{Ti}}{L_{ni}} \frac{1}{\nu^* - \frac{1}{2}} & \text{banana} \ (\nu^* < 1) \\
2.8 \frac{L_{ni}}{L_{Ti}} & \text{Pfirsch-Schlüter} \ (\nu^* > \varepsilon^{-3/2})
\end{cases}
\]

**LIMITS**
\[
\frac{L_{ni}}{L_{Ti}} \rightarrow 0, \quad \frac{n_{Z,HFS}}{n_{Z,LFS}} = \frac{B_{HFS}^2}{B_{LFS}^2} \sim 4
\]
\[
L_{ni}, L_{Ti} \rightarrow \infty, \quad \frac{n_{Z,HFS}}{n_{Z,LFS}} = 1
\]


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Comparison with High-Energy Beam CXRS

- LFS GP-CXRS profiles match well profiles from LFS NBI-CXRS profiles (50keV, 7A diagnostic neutral beam)

- Higher signal in pedestal a major advantage for GP-CXRS on C-Mod
Pedestal Characteristics: Comparing Boron and Fluorine in H-mode

- **In-out** boron ($B^{5+}$) density pedestal shifts quantitatively agree with **up-out** fluorine ($F^{8+}$) emissivity pedestal shifts [Pedersen, PoP, 2002]

**Soft X-Ray Views**

![Soft X-Ray Views](image-url)
In-Out Impurity Density Asymmetry Develops During ELM-free H-mode

- $n_{B^5^+}$ asymmetry develops during H-mode phase, disappears during L-mode-like radiative collapses.
Poloidal Variation in $n_e$, $n_i$, $\Phi$

Given $n_z$ and Assuming $T=T(\psi)$

\[ n_e(\psi, \theta) = \frac{Z - 1}{2} [n_z - n_{z0}] + n_{e0} \]
\[ n_i(\psi, \theta) = -\frac{Z + 1}{2} \left[ n_z + \frac{Z - 1}{Z + 1} n_{z0} \right] + n_{e0} \]
\[ \Phi(\psi, \theta) = \Phi_0 + \frac{T(\psi)}{e} \ln \left( \frac{Z - 1}{2} \frac{n_z - n_{z0}}{n_{e0}} + 1 \right) \]

“0”: Parameter at specific poloidal angle $\theta_0$

Poloidal Variation
- <6% of $n_e$, $n_i$
- <10V of $\Phi$

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**H-mode Flux Functions**

- Nonlocal treatment of neoclassical transport ($\rho_{\theta i} \sim L_{ni}, \rho_{\theta i} << L_{Ti}$) shows significant poloidal variation in $k$ [Landreman PPCF 2012]
  - Due to non-divergent radial particle flux

- For C-Mod case, full nonlocal treatment ($\rho_{\theta i} \sim L_{ni}, \rho_{\theta i} \sim L_{Ti}$) needed, from e.g. XGC0

*Figure from M. Landreman, PPCF, 2012*