Poloidal Variation of Impurity Density and Flows in the Pedestal Region

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Impurity Asymmetries Contribute to Understanding Pedestal Impurity Transport

- Impurity control necessary to prevent radiative cooling and main ion fuel dilution
- Pedestal performance will set overall plasma performance in ITER and next-step fusion reactors

**GOAL:** Understand impurity transport in the strong $n_i$, $T_i$ gradients of the pedestal region

- Novel CXRS diagnostics installed on C-Mod to make first ever direct measurements of in-out impurity density in the pedestal region


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Theory: Ion-Impurity Friction Drives In-Out Impurity Density Asymmetry

Large radial gradients in $n_i$, $T_i$

| Ion-impurity friction | Parallel pressure gradient | Poloidal density asymmetry |

Helander-Fülöp-Landreman [2-4] 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 ($\rho_\theta \sim L_{ni}, L_{ti}$) → 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

\[
b = \frac{B}{\langle B^2 \rangle^{1/2}}
\]

\[
\gamma = \begin{cases} 
0.33 f_c \frac{L_{T_i}}{L_{n_i}} - \frac{1}{2} & \text{banana} \\
2.8 \frac{L_{n_i}}{L_{T_i}} & \text{Pfirsch-Schlüter} 
\end{cases} (\nu^* < 1)
\]

\[
\frac{L_{n_i}}{L_{T_i}} \rightarrow 0, \quad \frac{n_{Z,HFS}}{n_{Z,LFS}} = \frac{B_{HFS}^2}{B_{LFS}^2} \sim 4
\]

\[
L_{n_i}, L_{T_i} \rightarrow \infty, \quad \frac{n_{Z,HFS}}{n_{Z,LFS}} = 1
\]

• Impurity velocity measurements on Alcator C-Mod indicated an in-out impurity density asymmetry [5]
  – assumed divergence-free flow

• Measurements on ASDEX Upgrade gave similar results, emphasized need to measure density directly [6]

Diagnostic: Measuring Impurities using CXRS with Deuterium Gas Puff

- CXRS measurements made at pedestal/edge (r/a=0.85-1.0):
  - Measure impurity (B\textsuperscript{5+}) density, temperature, velocity E\textsubscript{r} [7]
  - Both the low-field side (LFS) and high-field side (HFS)
  - Neutral source: Thermal gas puff [7]

- Boron density (n\textsubscript{B\textsuperscript{5+}}) measured using parallel CXRS and D\textalpha views. Equation consists of:
  - Atomic physics pre-factor (f)
  - Ratio of CXRS to D\textalpha radiance (I\textsubscript{CX}/I\textsubscript{D\alpha})

\[
\begin{align*}
  n_{B^{5+}} &= \frac{E_{32} A_{21}}{\langle \sigma v \rangle_{2}} \frac{P E C_{32}}{P E C_{21}} \frac{E_{X C}}{I_{D\alpha}} I_{CX} \\
  &= f(n_e, T_e, T_i) \frac{I_{CX}}{I_{D\alpha}}
\end{align*}
\]

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H-mode in Pfirsch-Schlüter (PS) regime: In-Out B$^{5+}$ Density Asymmetry Observed

- Plasma characteristics:
  - EDA H-mode (1 MA, 5.4 T)
  - $v^*_{\text{ped}} \sim 13.7$
  - QC-mode present in pedestal

- Buildup of boron density on the HFS

- Similar boron density profile shapes

- Quasi-coherent (QC) mode correlated with impurity regulation [8]

- All data ($n_e$, $T_e$, $T_{B^{5+}}$, $I_{\text{CX}}$, $I_{\text{D} \alpha}$) shifted so that $T_e = T_{B^{5+},\text{LFS}} = T_{B^{5+},\text{HFS}}$

H-mode in Plateau regime: In-Out B^{5+} Density Asymmetry Observed

- Plasma characteristics:
  - EDA H-mode (600kA, 5.4T)
  - $\nu_{\text{ped}}^* \sim 4.5$
  - QC-mode present in pedestal

- Buildup of boron density still on the HFS

- LFS and HFS boron density profile shapes are distinctly different
H-mode in **Banana**→**Plateau** regime: 
In-Out B\(^{5+}\) Density Asymmetry Observed

- Plasma characteristics:
  - ELMy H-mode (900kA, 5.6T)
  - \(v^*_{\text{ped}} \sim 0.9 - 3.5\)
  - No benevolent fluctuations (QC, WCM)
I-mode: No observed impurity density asymmetry

- Plasma characteristics:
  - I-mode (1 MA, 5.5T)
  - $\nu^*_{\text{ped}} \sim 0.7$
  - WCM present in pedestal
- In-out impurity density asymmetry NOT observed
  - Inconsistent with analytical model predictions (full profile analysis needed)
- No $n_e$ pedestal in I-modes (large $L_n$)
- Weakly Coherent Mode (WCM) correlated with impurity regulation [9]

Conclusions

- Direct boron density measurements demonstrate a clear in-out asymmetry in impurity density in H-modes, with a buildup on the high-field side (HFS)
  - Asymmetry observed across all collisionality regimes
  - In qualitative agreement with current analytical models

- No in-out asymmetry in impurity density observed in I-modes
  - Inconsistent with analytical model predictions (full profile analysis needed)

<table>
<thead>
<tr>
<th>Confinement Mode</th>
<th>$\nu^*$</th>
<th>Asymmetry?</th>
<th>Particle Regulator?</th>
</tr>
</thead>
<tbody>
<tr>
<td>H-mode</td>
<td>13.7</td>
<td>Yes</td>
<td>QC</td>
</tr>
<tr>
<td>H-mode</td>
<td>4.5</td>
<td>Yes</td>
<td>QC</td>
</tr>
<tr>
<td>H-mode</td>
<td>0.9</td>
<td>Yes</td>
<td>ELMs</td>
</tr>
<tr>
<td>I-mode</td>
<td>0.7</td>
<td>No</td>
<td>WCM</td>
</tr>
</tbody>
</table>
• END PRESENTATION
EDA H-mode 600kA with Error Bars
(this one’s for Matt)

- Errorbars shown here do not include:
  - Rate coefficient error bars
  - PEC coefficient error bars