Light Impurity Transport at an Internal Transport Barrier in Alcator C-Mod

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Internal transport barriers have peaked main-ion profiles and higher core reactivity

Peaked impurity profiles increase radiation losses and dilute the fuel

All profiles for C-Mod are measured except for light impurities and we know that there are sometimes differences between light and heavy impurities

This data will complete the particle profiles set for C-Mod

Outline

- Light impurity profiles compared to plasma profiles
- Transport
  » Profile analysis
  » Numerical simulation
- Neoclassical comparison
- Conclusions and future work
Boron Profiles Steepen During ITB

- $B^{+5} = \text{total boron density, } \rho < 0.8$
- $B^{+4} \text{ IP} = 340 \text{ eV}$
- Boron profile steepens in the ITB
- Hollow profiles: future research
Plasma Shape, Heating Location, and ITB Location

RF resonances

ITB region

Grad B drift is in the favorable direction
Comparison to Other Plasma Profiles

Comparison graphs showing plasma profiles with different parameters such as $B^5$, $p$, $n_e$, $T_i$, and $T_e$. The graphs illustrate changes over time with labels for $\Delta t = 0.30\ s$, $\Delta t = 0.12\ s$, and $\Delta t = 0.0\ s$. The plots depict density and temperature variations with respect to position ($\rho$).
Impurity Transport Profile Analysis

\[ \frac{\partial n_j^z}{\partial t} + \nabla \cdot \Gamma_j^z = S_j^z \]

\[ \Gamma_j^z = -D \frac{\partial n_j^z}{\partial t} + v n_j^z \]

\[ \frac{\partial n_j^z}{\partial t} = 0 \]

\[ (L_z)^{-1} = \frac{1}{n_j^z} \frac{\partial n_j^z}{\partial r} = \frac{v}{D} \]

\[ \Delta t = 0.0 \text{ s} \]

\[ \Delta t = 0.30 \text{ s} \]

\[ (L_{\text{Zneocrit}^{-1}} - L_z^{-1})/10 \]
Simulation of Impurity Transport

Review

$$\frac{\partial n_j^z}{\partial t} + \nabla \cdot \Gamma_j^z = S_j^z$$

fixed background

$$n_e(r,t), n_i(r,t), T_e(r,t), T_i(r,t)$$

$$\Gamma = -D \frac{\partial n_j^z}{\partial r} + n_z v$$

$$S_j^z = -I_j^zn_j^zn_e + I_{j-1}^zn_{j-1}^zn_e +$$

$$\alpha_{j+1}^zn_{j+1}^zn_e - \alpha_j^zn_j^zn_e + S_B^z$$

$A_{impurity \ species}$

$A_{ionization \ stage}$

Results

impurity density (x10^{12} cm^{-3})

$v/D_s\_\text{sim}$

$B^{+4}$

$B^{+5}$
Prediction for Impurity Transport

\[ \Gamma_z = \Gamma_{Anom} + \Gamma_{coll} \]

- \( \Gamma_{coll} \), neoclassical transport
  collisions of particles in a toroidal magnetic field
- \( \Gamma_{anom} \), turbulent transport
  convection of density fluctuations by fluctuating E\(\times\)B drift velocity
- For neoclassical transport and for turbulent transport within quasilinear theory

\[ \Gamma_z = -D \frac{\partial n_z}{\partial r} + v_z n_z \]

\[ v_z = v_{Anom} + v_{coll} \]

\[ D_z = D_{Anom} + D_{coll} \]
Neoclassical Predictions for $v/D$

benchmark confinement

$$\left( \frac{v_{neo}}{D_{neo}} \right) = \frac{Z_I}{Z_D} \left( \frac{1}{n_D} \frac{dn_D}{dr} + K \frac{1}{T_D} \frac{dT_D}{dr} \right)$$

$\varepsilon^\frac{3}{2} < v_*$ \hspace{1cm} Pfirsch-Schulter $K = -0.5$; Ar, Mo

$1 < v_* < \varepsilon^\frac{3}{2}$ \hspace{1cm} banana-plateau $K = 1.5$; B

$$\left( \frac{v_{neo}}{D_{neo}} \right) < 0$$ \hspace{1cm} pinch

$$\left( \frac{v_{neo}}{D_{neo}} \right) > 0$$ \hspace{1cm} screening -- or small
Impurity Transport
Neoclassical Comparison

\[
\left( \frac{v_{neo}}{D_{neo}} \right) = \left( L_{Zneo}^{-1} \right)
\]
More Predictions for v/D

\[ \Gamma_z = -D \frac{\partial n_z}{\partial r} + v_z n_z \]

examples of turbulent v/D

<table>
<thead>
<tr>
<th>pinch name</th>
<th>dependence</th>
<th>direction</th>
<th>charge dependence</th>
<th>mass dependence</th>
<th>refs</th>
</tr>
</thead>
<tbody>
<tr>
<td>curvature</td>
<td>( \propto \frac{1}{q} \frac{\partial q}{\partial r} )</td>
<td>( \frac{\partial q}{\partial r} &gt; 0 )</td>
<td>( \neq f(Z) )</td>
<td>( \neq f(A) )</td>
<td>1,2,3,4,5</td>
</tr>
<tr>
<td>thermodiffusion</td>
<td>( \propto \frac{1}{T} \frac{\partial T}{\partial r} )</td>
<td>TEM ( \Rightarrow ) inward</td>
<td>ITG ( \Rightarrow ) outward</td>
<td>( \frac{1}{Z} )</td>
<td>( \neq f(A) )</td>
</tr>
<tr>
<td>parallel compression</td>
<td>TEM ( \Rightarrow ) outward</td>
<td>ITG ( \Rightarrow ) inward</td>
<td>( \frac{Z}{A} )</td>
<td>( \frac{Z}{A} )</td>
<td>1,2,3</td>
</tr>
</tbody>
</table>

2 Dubuit, N., et al., 2007 Phys. Plasmas 14 042301
5 Baker D R and Rosenbluth M N 1998 Phys. Plasmas 5 2936
Next Step: Hollow Profiles?

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<td>$\frac{Z}{A}$</td>
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Conclusions

- In the region of an ITB in Alcator C-Mod, boron peaks. The hollow or flat profile observed in L-mode and early H-mode evolves to one in which the local boron density exceeds that in the plasma region outside the ITB.
- Boron accumulates in the ITB region. This follows from the comparison of main ion and impurity gradient.
- Inward convection increases relative to the diffusion.
- Comparisons with neoclassical transport indicate that anomalous transport is reduced in the ITB, but for these discharges, neoclassical transport does not predict the impurity peaking or scale length of the gradients.
- For the Alcator C-Mod ITB, light impurity transport shares with heavy impurity transport, both peaking and increased inward convection.