Experimental and Gyrokinetic Investigations of Impurity Transport on Alcator C-Mod

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Measured Changes in Impurity Confinement May Be Explained by Turbulent Transport

- Plasma confinement increases with $I_p$.

- Increased impurity confinement degrades fusion performance.

- All impurity confinement scaling laws to date demonstrate an $I_p$ dependence.
  - Alcator A, Alcator C, JET/Tore Supra, and Alcator C-Mod

- Neoclassical levels of impurity transport are insufficient for explaining experiment. [E. Marmar et al. PRL 1980, M.E. Puiatti, PoP 2006]

- New measurements of impurity transport in L-mode plasmas will be compared to global, nonlinear GYRO simulations of plasma turbulence to better understand the observed current scaling.

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A Unique Set of Experimental Tools are Available for Studying Impurity Transport on Alcator C-Mod

- The Multi-Pulse Laser Blow-off System
  - Introduces trace amounts of non-recycling impurity
  - Effectively a delta function in time
  - CaF$_2$ was used for these experiments

- High Resolution X-ray Spectrometer
  - Measures the full, time evolving profile of Ca$^{18+}$

- STRAHL*
  - Determines impurity transport, models atomic physics, and line emission


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An Experimental $I_p$ Scan: Modification of $q$ and the Turbulence Drive Term, $a/L_{Te}$

- $I_p = 0.6$ to $1.2$ MA
- $n_e(0) \sim 1.4 \times 10^{20}$
- $T_e(0) \sim 3.0$ KeV
- $P_{ICRF} = 1$ MW

During the $I_p$ scan, changes are observed in $a/L_{Te}$ and $q$ (therefore $\hat{S}$).
Experimental Values of D and V are Determined Using STRAHL

- The impurity transport code, STRAHL is used to simulate the coupled continuity equations.

\[ \frac{\partial n_{i,z}}{\partial t} = \nabla \cdot \Gamma + Q_{i,z} \]

- The flux is assumed to be of the form:

\[ \Gamma_{imp} = -D \nabla n + Vn \]

- Ionization, recombination, and line emission are modeled using data from ADAS

- Sawteeth are modeled and transport between crashes is determined.

- D and V are determined through $\chi^2$ minimization.

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Where Outside of Error bars, the Magnitude of D and V Decrease with $I_p$

- Error bars are generated by 50 STRAHL runs with variations of the background profiles.

- In the region $r/a \sim [.3, .5]$ a significant decrease in the inward velocity is observed with increasing current.
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GYRO Simulations Can Model the Effects of \( q \) and \( a/L_{Te} \) Individually

- A global, nonlinear GYRO simulation of the reference case (.8 MA in the \( I_p \) scan) was performed

- \( r/a \sim [.3 \rightarrow .5] \)
- \( k_\theta \rho_s \sim [0 \rightarrow 1.25] \)
- 16 toroidal modes
- kinetic electrons
- small amounts of impurities (.001 \( n_e \))
- no ExB effects

- Ti profiles were unavailable. The simulation profile matched GYRO \( Q_e + Q_i \) to corresponding power balance value.
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**a/L_{Te} and q profile modification**

- Starting from the reference case, both the $q$ profile and $a/L_{Te}$ were modified to match the .6 MA case. This approach was then repeated for the 1.2 MA case.
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\(a/L_{Te}\) modification

- Starting from the reference case, the \(a/L_{Te}\) only was modified to match the .6 MA case. This was then repeated, changing only \(a/L_{Te}\) to match the 1.2 MA case.

- \(D\) and \(V\) are inferred from GYRO's impurity flux:
  - Quantitative agreement might not be expected due to a reduced physics model (no ExB) and unmeasured \(T_i\) profiles.
GYRO Simulations Can Model the Effects of q and $a/L_{Te}$ Individually

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**q profile modification**

- Starting from the reference case, the q profile only was modified to match the .6 MA case. This was then repeated, changing only the q profile to match the 1.2 MA case.

- D and V are inferred from GYRO’s impurity flux:

\[
\frac{\Gamma_{GYRO}}{n_{imp}} = -D \frac{\nabla n_{imp}}{n_{imp}} + V
\]

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The Combined Effects of $q$ Profile and $a/L_{Te}$ Changes Reproduce the Experimental Trend of the Convective Velocity

Changing $a/L_{Te}$ and $q$ profile

- Trend in the convective velocity is well reproduced
- How important are the individual $a/L_{Te}$ or $q$ changes?

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Changing $q$ profile only

The trend of reduced inward convection with current is recovered with only changes in the $q$ profile.
- It was observed that impurity confinement increases with plasma current.

  • Performing a scan of $I_p$ at approximately fixed $n_e$, $T_e$, and $P_{icrf}$ showed an increase in $a/L_{Te}$ and $q$ with current.

  • The magnitude of experimentally determined values of $D$ and $V$ were demonstrated to decrease with current.

  • GYRO simulations reproduce the experimental decrease in the inward convection.
    - $a/L_{Te}$ changes are unimportant
    - Modification of the $q$ profile is responsible for reproduction of the trend

  • Discrepancy in the diffusion coefficient can be investigated later through full physics simulations and STRAHL simulation of the GYRO output

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