Poloidal variation of Ar$^{17+}$ impurity density in Alcator C-Mod

M.L. Reinke, I.H. Hutchinson, J.E. Rice and J.L. Terry
MIT Plasma Science and Fusion Center

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OVERVIEW

- background/motivation
- diagnostic description and example profiles
- qualitative comparison to neoclassical theory
Motivation

Tokamaks have routinely observed that $n_z$ can be up/down asymmetric on a flux surface on the order of inverse aspect ratio, $\epsilon$

Alcator-A, PLT, PDX, ASDEX, JET, Compass-C, Phaedrus-T, Alcator C-Mod, TdeV

While ion-impurity friction has been shown to play a role in this asymmetry, a complete theory of neoclassical parallel impurity momentum balance has not been experimentally verified

A quantitative understanding of parallel impurity transport is important for:

- calculating main ion velocities from impurity measurements
- deducing local data from line-integrated measurements
- calculating the neoclassical $<\Gamma_{z,r}>$ where applicable

Here we discuss measurements of the up/down asymmetry of $\text{Ar}^{17+}$ line emission as part of a wider investigation of parallel $n_z$ transport

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Parallel Momentum Balance\textsuperscript{a,b}

\[ n_z e \nabla \parallel \Phi_1 + T_i \nabla \parallel n_z = R_z, \parallel \]

poloidal variation of ion-impurity friction can sustain a density gradient along the field

\[ \frac{n_z}{\langle n_z \rangle} = 1 + n_c \cos(\theta) + n_s \sin(\theta) \]

solving this equation in the circular, $\epsilon \ll 1$ limit gives

$1^{\text{st}}$ order up/down ($n_s$) and in/out ($n_c$) asymmetries

\[ n_s = \frac{2 \epsilon g}{1 + (1 + \gamma)^2 g} \]
\[ n_c = \frac{2 \epsilon (1 + \gamma) g^2}{1 + (1 + \gamma)^2 g^2} \]

radial gradients drive the asymmetry differently depending on the main-ion collisionality, with

\[ \gamma \sim L_{\perp,n} / L_{\perp,T} \]

\[ g_B = - \frac{Z^2 m_i I(\psi)}{\tau_{ii} \langle B \cdot \nabla \theta \rangle} \left( \frac{d \ln(p_i)}{d \psi} - \frac{3}{2} \frac{d \ln(T_i)}{d \psi} \right) \]
\[ g_{PS} = - \frac{Z^2 m_i I(\psi)}{\tau_{ii} \langle B \cdot \nabla \theta \rangle} \left( \frac{d \ln(n_i)}{d \psi} \right) \]

\textsuperscript{a}P. Helander, PoP 5 3999 (1998) \quad \textsuperscript{b}T. Fülöp, P. Helander, PoP 8 3305 (2001)
**Ar^{17+} From X-Ray Spectroscopy**

- spherical crystal spectrometer allows imaging of full plasma profile
- measure the 1s^2-1s2s “forbidden line” in He-like Ar
- for large r_i/a where \( T_e \ll E_\gamma \) recombination populates the 2s state
- line emissivity \( \sim \) H-like Ar density (Ar^{17+})

viewing geometry averages over \( n_c \) term and comparison of chords above and below the midplane give \( n_s \)

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Up/Down Symmetric in Core

- brightness profiles plotted vs. normalized tangency radius
- profiles are shown to be symmetric inside of $r_t/a \sim 0.6$
- $n_e$ scanned at fixed shape $I_p = 800$ [kA], $B_t=5.4$ [T]

$\overline{n_e} \sim 1.2 \times 10^{20}$ [m$^{-3}$]

$\overline{n_e} \sim 0.8 \times 10^{20}$

$\overline{n_e} \sim 0.3 \times 10^{20}$
Up/Down Symmetric in Core

- brightness profiles plotted vs. normalized tangency radius
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- $n_e$ scanned at fixed shape \( I_p = 800 \text{ [kA]}, B_t = 5.4 \text{ [T]} \)

Zoom in on profiles in the outer $\frac{1}{4}$ of of plasmas

\[ \bar{n}_e \sim 1.2 \times 10^{20} [\text{m}^{-3}] \]

\[ \bar{n}_e \sim 0.8 \times 10^{20} \]

\[ \bar{n}_e \sim 0.3 \times 10^{20} \]
Asymmetric Near the Edge

- brightness profiles plotted vs. normalized tangency radius, \( r_t/a \)
- profiles are shown to be symmetric inside of \( r_t/a \sim 0.6 \)
- \( n_e \) scanned at fixed shape with \( I_p = 800 \, [kA] \), \( B_t = 5.4 \, [T] \)
- up/down brightness ratio decreases and even inverts as \( n_e \) drops

characterize the up/down brightness ratio at \( r_t/a = 0.85 \)
vs. Ohmic plasma parameters
Ratio Varies With Density

ratio vs. $n_e$ at fixed $I_p$ for various magnetic configurations

- region of strong $n_e$ dependence
- independence of active x-point
- ratio reversal with $\nabla B$ drift direction

asymmetry direction consistent with theory for PS main ions

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**Ratio Varies With Density**

ratio vs. $n_e$ at fixed $I_p$ for various magnetic configurations

- region of strong $n_e$ dependence
- independence of active x-point
- ratio reversal with $\nabla B$ drift direction

**NEW OBSERVATIONS**
- ratio reverses at low density

![Graph showing ratio vs. $n_e$ at fixed $I_p$ for various magnetic configurations.](image)

**Ratio Varies With Density**

- LSN $\nabla B$ down
- USN $\nabla B$ down
- USN $\nabla B$ up

**Graph Details:**
- Ratio at $r/a = 0.85$
- All at $I_p = 0.8$ MA
- $n_e$ range: $10^{20} \text{ m}^{-3}$
- Brightness Ratio (up/down)
Ratio Varies With Density

**ratio vs. n_e at fixed I_p for various magnetic configurations**

- region of strong n_e dependance
- independence of active x-point
- ratio reversal with \( \nabla B \) drift direction
- **NEW OBSERVATIONS**
  - ratio reverses at low density
  - ratio eventually loses n_e correlation

**Chart:**
- LSN \( \nabla B \) ↓
- USN \( \nabla B \) ↓
- USN \( \nabla B \) ↑
- ratio at \( r_t/a = 0.85 \)
- all @ \( I_p = 0.8 \) MA

**Graph:**
- Brightness Ratio (up/down) vs. \( \bar{n}_e \) [10^{20} m^{-3}]
- Data points indicate ratio varies with density.
Ratio Reversal Linked to $\nu^*$

reversal of up/down asymmetry observed primarily for small $\nu^*$

- for high collisionality theory predicts $n_{s,PS}$ reversal **only** for change in $\nabla B$ drift direction
- at lower collisionality, $n_{s,B}$ is allowed to change sign depending on $T_i$ and $n_i$ gradient scale lengths

\[ n_{s,B} \sim \left( \frac{d \ln(p_i)}{d \psi} - \frac{3}{2} \frac{d \ln(T_i)}{d \psi} \right) \]

\[ n_{s,PS} \sim \left( \frac{d \ln(n_i)}{d \psi} \right) \]
Inverse $I_p$ Dependence Observed

LSN, Ohmic plasmas shows inverse scaling with plasma current

in contrast, Fülöp, Helander and earlier theories\textsuperscript{a,b} predict a $\sim I_p^{-2}$ scaling

to be consistent with theory other parameters in $n_s$ must vary like $I_p$

\textsuperscript{a}K. Brau, et al. Nucl. Fusion. 23 1657 (1983)  \hspace{2cm} \textsuperscript{b}K. B. Burrell, et al. Nucl. Fusion. 19 1571 (1979)
Summary

- Diagnostic upgrades have allowed for extended analysis of the observed poloidal asymmetry of Ar$^{17+}$ density on Alcator C-Mod.
- Brightness profiles shown to be up/down asymmetric at $r_t/a \sim 0.85$ and sensitive to $n_e$ and $\nabla B$ drift direction, consistent with previous observations.
- The brightness ratio is shown to reverse at low density ($v^* < 1$) which theory predicts only for collisionless main ions.
- The brightness ratio observed to vary like $1/I_p$ in contrast to theories with explicit $\sim 1/I_p^2$ dependance.

Future work will make use of the local $T_z(r)$ and $v_z(r)$ measurements for quantitative comparisons to neoclassical theories of parallel impurity transport.