Poloidal Variation of High-Z Impurity Density in ICRF-Heated Alcator C-Mod Plasmas


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Density of High-Z Impurities Varies Poloidally

poloidal flux-surface variations in $n_z$ are regularly observed even when low-Z & main-ions are poloidally symmetric

the same physics is weighted differently

- large mass enhances inertial effects
- large charge amplifies electrostatic effects
- enhanced i-Z friction (unlike collisions)

this research describes advancements in theory and experiments to better understand parallel high-Z impurity transport in ICRF-heated plasmas

Measured LFS peaking of molybdenum in Alcator C-Mod
Recent theory indicates $n_z(\theta)$ to be important for flux-surface averaged turbulent transport [Mollen PoP 2012, Casson PoP 2010].

**E×B** drift due to *poloidal* electric fields predicted to be important in ITG-driven radial impurity flux.

(A. Mollen, *et al.* PoP 19 052307 (2012))

(l. Pustzai BP8.00165)
Presentation Overview

- Neoclassical parallel impurity transport physics
  - qualitative & quantitative explanation of asymmetry drives
- C-Mod diagnostics and examples of strong in/out high-Z impurity asymmetries on C-Mod
- Combined effect of an in/out asymmetry due to fast ion poloidal electric fields and centrifugal force
  - experimental evidence for asymmetry link to ICRH non-thermals
  - agreement between asymmetry measurements and analytical theory predictions
- Up/down asymmetries in C-Mod EDA H-modes
  - disagreement with theory and implications for $n_z(θ)$, $v_{z,θ}$ physics
• for a tor. rotating plasma, centrifugal force pushes ions to the low-field side (LFS) of a flux-surface

• in $v_i/v_{th,i} = M_i \sim 1$ plasmas, impacts main ions (MAST, NSTX)

• effect scales as $m_z \omega^2 R^2 / T_z$ but since $T_z \sim T_i$, scales with $M_i^2 (m_z/m_i)$

• heavy impurities can vary on a flux surface, $\bar{n}_z(\theta)/\langle n_z \rangle \sim 0.3$, even in when the main ions are nominally flux surface symmetric, $\bar{n}_i(\theta)/\langle n_i \rangle << 1$
LFS Accumulation in Soft X-rays

- first observed on ASDEX
- JET has observed and studied LFS accumulation of impurities [Gianella 1992, Alper 1996, Ingesson 98, 2000, Chen 2000]
- first quantitative comparison to theory (JET) Ni LBO w/ \( v_z/v_{th,z} \sim 4 \) in hot-ion H-mode
- very important consideration for recent JET ILW plasmas [Putterich – IAEA 2012]
- recent C-Mod observations show centrifugal effects driven by \textit{intrinsic rotation}

FIG. 4. Ni density derived from the soft x-ray emissivity at \( t=6.72 \) s (cross) and calculated Ni density at the same time (line).

Fast-Particle Driven Poloidal Elec. Fields

- the high charge of imp. leads to sensitivity to poloidal variation of electrostatic potential

\[ \frac{n_z}{\langle n_z \rangle} = \exp[-Ze\Phi(\theta)/T_z] \]

- first exp. observation in ICRF-heated Ni LBO shots on JET [Ingesson – 2000]

- should also be an effect from neutral beam ions and ECRH electrons

INBOARD ACCUMULATION
electric field from rf-heated minority ions \( \nabla \parallel \Phi(\theta) \) moves impurities to HFS

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scanning D(H) resonance layer modifies minority trapping adjusting the balance of asymmetry due to inertia & electrostatic pot.

\[ n_z(\psi, \theta) = \langle n_z(\psi) \rangle + n_{z,\cos}(\psi) \cos \theta \]
Analytical Theory for ICRH + Inertia

\[
\frac{m_2 n_2 \omega^2}{2} \nabla_{\parallel} R^2 + Z n_2 e \nabla_{\parallel} \Phi + T_z \nabla_{\parallel} n_z = R_{z,\parallel}
\]

**THERMALIZED IONS**

\[
n_a = \langle n_a \rangle \exp \left[ -\frac{Z_a e \tilde{\Phi}}{T_a} + \frac{m_a \omega^2}{2T_a} \left( R^2 - \langle R^2 \rangle \right) \right]
\]

**ELECTRONS**

\[
n_e = \langle n_e \rangle \exp \left( \frac{e \tilde{\Phi}}{T_e} \right)
\]

Use quasi-neutrality to find the \( \Phi(\theta) \)

\[
Z_m n_m + \sum_{j \neq m} Z_j n_j - n_e = 0
\]

for details see: Reinke PPCF 54 045004 (2012)

**Model the fast-ion using a bi-Maxwellian dist. w/ \( \eta=\left( \frac{T_{\perp}}{T_{\parallel}} \right)^{-1} \)**

\[
\frac{n_m}{\langle n_m \rangle} = \left( \frac{1}{B^n} \right)^{-1} \frac{1}{B^n} \exp \left( -\frac{Z_m \tilde{\Phi}}{T_{m,\parallel}} \right)
\]

Kazakov PPCF 54 105010 (2012) has shown a more detailed computation

\[
\frac{n_z}{\langle n_z \rangle} = 1 + \frac{m_z \omega^2}{2T_i} \left( 1 - \frac{Z_{m_i}}{m_z} \frac{Z_{\text{eff} T_e}}{T_i + Z_{\text{eff} T_e}} \right) \left( R^2 - \langle R^2 \rangle \right) - Z f_m \frac{T_e}{T_i + Z_{\text{eff} T_e}} \left( \left( \frac{1}{B^n} \right)^{-1} \frac{1}{B^n} - 1 \right)
\]

**inertia (centrifugal)**

**electrostatic (ICRH)**

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i-Z Friction Asym. Links $n_z(\theta)$ and $v_\theta$

assuming ion/impurity collisions drives $v_{z,||}$ towards $v_{i,||}$ has effect of HFS impurity accumulation

\[
\frac{n_z}{n_i} = \frac{K_z/K_i B^2}{B^2 + \frac{3}{f_c} \frac{\nabla \ln p_i}{\nabla \ln T_i} \langle B^2 \rangle}
\]

Comparing with NCLASS assumes $n_z$ doesn’t vary on a flux surface

Friction also drives an up/down (sin) asymmetry

\[
(1 + \alpha_z n) \frac{\partial n}{\partial \theta} = g \left[ n + \gamma \left( n - \frac{K_z}{\langle n_z \rangle u_i} \right) b^2 \right] + \frac{\partial M^2}{\partial \theta} n
\]


• 1D equation for $n=n_z(\theta)/\langle n_z \rangle$ using B.C. $n(0)=n(2\pi)$ defines $K_z$

• poloidal rotation, $v_\theta(R,Z)=[K_z(\psi)/n_z(\psi,\theta)]B$, sensitive to $n_z$

Comparing with NCLASS assumes $n_z$ doesn’t vary on a flux surface

NEO has inertia, need to verify friction and include $\Phi(\theta)$ effects

Churchill - BO7.00008
Marr PPCF 2010, Putterich NF 2012
investigate the 2-D radiation in C-Mod plasmas with significant molybdenum contamination

use multiple, horizontally viewing pinhole cameras at different heights

measure \( B(R,Z_o) \), invert each to get \( \varepsilon(R,Z_o) \) \([\text{in/out asymmetry}]\)

combine all cameras to find low-order poloidal variation \([\text{in/out & up/down}]\)

standard poloidal tomography difficult

- divertor radiation, inner-wall MARFE
- poor HFS/vertical diagnostic access

\( T_e, n_e \) Thomson/ECE, \( T_i, \omega_\phi \) – XICS and \( T_\perp/T_\parallel \) using TRANSP
Symmetric Emission in Ohmic Plasmas

EXAMPLE DATA FROM MIDPLANE ARRAYS

BRIGHTNESS PROFILE

EMISSION MAPPED TO MINOR RADIUS

EMISSION PROFILE

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LFS Accumulation in EDA H-mode

EXAMPLE DATA FROM MIDPLANE ARRAYS

BRIGHTNESS PROFILE

EMISSIVITY MAPPED TO MINOR RADIUS

EMISSIVITY PROFILE

HFS  LFS

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HFS Accumulation in ICRH L-mode

EXAMPLE DATA FROM MIDPLANE ARRAYS

BRIGHTNESS PROFILE

EMISSION MAPPED TO MINOR RADIUS

EMISSION PROFILE

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HFS Linked to ICRH Dynamically: $P_{RF}$ Drop

Off-axis (LFS) RF power is ramped down between 1.40 and 1.42 sec.

Little change in background plasma in 10s of ms but longer time scale drop in rotation, temp. and dens.

Prompt change in the in/out asymmetry with measurements moving to the inertial modeling (----).

Pitch angle scattering reduces minority ions $T_\perp/T_\parallel$.

Also observe drop in HFS peaking as $n_e$ rises at fixed $P_{RF}$. 

\begin{align*}
\rho/a &= 0.75 \\
\rho/a &= 0.51
\end{align*}
\[
\frac{n_z}{\langle n_z \rangle} = 1 + \frac{m_z \omega^2}{2T_i} \left( 1 - \frac{Zm_i}{m_z} \frac{Z_{\text{eff}}T_e}{T_i + Z_{\text{eff}}T_e} \right) \left( R^2 - \langle R^2 \rangle \right) - Zf_m \frac{T_e}{T_i + Z_{\text{eff}}T_e} \left( \left\langle \frac{1}{B^n} \right\rangle^{-1} \frac{1}{B^n} - 1 \right)
\]

\[
\frac{n_{z,\cos}}{\langle n_z \rangle} = 2 \frac{r}{R_o} \left[ \frac{m_z \omega^2 R_o^2}{2T_i} \left( 1 - \frac{Zm_i}{m_z} \frac{Z_{\text{eff}}T_e}{Z_{\text{eff}}T_e + T_i} \right) - Zf_m \frac{T_e}{Z_{\text{eff}}T_e + T_i} \left( \frac{T_\perp}{T_\parallel} - 1 \right) \right]
\]

LFS accumulation due to centrifugal force

HFS accumulation due to minority anisotropy

\( n_z \text{,cos} / \langle n_z \rangle \)

\( 0.4 \)

\( 0.2 \)

\( 0.0 \)

\( -0.2 \)

\( 0.0 \)

\( 0.2 \)

\( 0.4 \)

\( 0.6 \)

\( 0.8 \)

\( 1.0 \)

\( r/a \)

\( n_z \text{,cos} / \langle n_z \rangle \)

\( 0.0 \)

\( 0.2 \)

\( 0.4 \)

\( 0.6 \)

\( 0.8 \)

\( 1.0 \)

\( r/a \)

**INERTIA ONLY**

**MEASUREMENT**

**THEORY**

**INERTIA+ICRH**
\[
\frac{n_z}{\langle n_z \rangle} = 1 + \frac{m_z \omega^2}{2T_i} \left( 1 - \frac{Z m_i}{m_z} \frac{Z_{\text{eff}} T_e}{T_i + Z_{\text{eff}} T_e} \right) \left( R^2 - \langle R^2 \rangle \right) - Z f m \frac{T_e}{T_i + Z_{\text{eff}} T_e} \left( \left\langle \frac{1}{B^n} \right\rangle^{-1} \frac{1}{B^n} - 1 \right)
\]

no peaking in \( n_z(\theta) \) profile around the resonance layer
Using the Asymmetry as a Diagnostic

- measuring $E_\theta$ using parallel force balance
- tool to study fast-ion physics (sawtooth induced transport)
- identify when inertial or anisotropic pressure effects should be included in EFIT
- avoid the use of SXR emissivity contours as an EFIT constraint

\[
E_\theta = \hat{b} \cdot \nabla \theta \frac{T_z}{e} \left( \frac{1}{Zn_z} \frac{\partial n_z}{\partial \theta} - \frac{m_z \omega_z^2}{2ZT_z} \frac{\partial R^2}{\partial \theta} \right)
\]

very small, ~1%, poloidal potential variations are resolvable
ICRF-heated EDA H-mode

- solve 1-D parallel force balance with all forces included (inertia, friction and ICRH effects) and kinetic EFIT reconstruction
- assume a trace high-Z impurity
- in/out asymmetry matches well, mostly inertia, small corrections due to on-axis heating and friction
- large differences for the up/down asymmetry

$n_z, \sin < 0$ predicted
$n_z, \sin > 0$ measured
Disagreement Seen Over All EDA H-modes

- compare measurements for circular up/down asym. theories
Brau\(\text{a}\) model: \(n_z(\theta)/\langle n_z \rangle = 1 + \eta q_f \sin(\theta)\)  
FH: Fülöp\(\text{b}\) (m=1) exp.

- both predicted similar trend that disagrees with measurement

obs. \(\to 0\) for large predicted asym.

10% asym. obs. as prediction \(\to 0\)

\(\text{a}\)K. Brau, \textit{et al.} Nucl. Fusion 23 1657 (1983)  
Explore Link to Main Ion Flow

- friction asym. have been calculated in the trace limit
- when $n_{z}Z^{2} \sim n_{i}$, the ion-impurity friction affects the main-ion poloidal flow ($v_{\theta,i}$), impacting $n_{z}(\theta)$
- when $Z_{\text{eff}} \sim 2$, **trace-limit theory is not valid** even if the asym. being studied is due to a trace $n_{z}$

a more advanced treatment of the 1-D impurity transport is needed, coupling multiple impurity species
*(need to verify friction-based asym. physics in codes)*

study effect of changes in $v_{\theta,i}$ artificially in current code computing $n_{z}(\theta)$ based on experimental data
To Match Asym. Over-Predicts $v_{\theta,z}$

define $u_i/u_{i,\text{NC}}$ and compare results of asym. and imp. $v_{\theta}$

$$u_{i,\text{NC}} = -\frac{f_c}{3} \frac{I}{e\langle B^2 \rangle} \frac{\partial T_i}{\partial \psi}$$

- for $u_i/u_{i,\text{NC}} = 10$ the modeled up/down and in/out asym. agree with measurement
- this forces $v_{\theta,z}$ to disagree with XICS observations, which find $|v_{\theta,z}| < 1.5 \text{ km/s}$

demonstrates link between direction and magnitude of asymmetries and the poloidal flow
Summary

- Poloidal variation of high-Z impurities can be large, 0th order, in intrinsically rotating, auxiliary-heated tokamak plasmas
  - The centrifugal force leads to strong LFS accumulation
  - Impurities respond to $E_\theta$ driven by non-thermal particles
- C-Mod has a mature program for dedicated asymmetry studies
- In/out asymmetries in molybdenum density agree with new theory based on combined ICRH and inertial effects
- Up/down asymmetries do not agree with trace-limit theory
- Parallel impurity transport physics links $n_z(\theta)$ and $v_\theta$, providing a more strict test of neoclassical theory

Continuing work will focus establishing the impact of these asymmetries on the flux-surface averaged radial transport