Impurity expulsion in an RFP plasma and the role of temperature screening

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Impurity sources

- Plasma-wall interaction
- Radiative edge
Impurity sources

- Plasma-wall interaction
- Radiative edge

Global observations

- Impurity accumulation
  \[
  \frac{n_z(r)}{n_z(0)} = \left[ \frac{n_i(r)}{n_i(0)} \right]^Z
  \]

- Transport generally anomalous, but close to neo-classical for high confinement modes
Introduction: Impurities in fusion plasma

**Impurity sources**

- Plasma-wall interaction
- Radiative edge

**Global observations**

- Impurity accumulation
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  \]
- Transport generally anomalous, but close to neo-classical for high confinement modes

**Detrimental effects**

- Fuel dilution - reduction of fusion power
- Radiation loss - line radiation (edge) Bremsstrahlung (core)
- Radiative collapse
- Contribution to resistivity - shaping current density profile
Impurity sources in the Madison Symmetric Torus
Aluminum wall, graphite limiters, boronization

- 5 cm thick aluminum wall
- Graphite limiters
- Ceramic tiles
- Recent boronization efforts

Intrinsic impurities are Al, C, O, B
Improved confinement deuterium discharges

\( I_p \sim 400 \text{ kA}, \quad n_e \leq 1 \times 10^{19}/\text{m}^3 \)

**Time Evolution**

- **Plasma Current**
  - kA vs. Time (s)
  - \( I_p \) peaks at \( \sim 400 \text{ kA} \)

- **Electron Density**
  - \( n_e \) in \( \times 10^{19}/\text{m}^3 \)
  - \( n_e \) drops as \( I_p \) decreases

- **Magnetic fluctuations**
  - Gauss over Time (s)
  - Improved confinement indicated by lower fluctuations

**Radial Profiles**

- **\( n_e \)**
  - Electron density profile over \( \rho \)
  - Smooth profile indicative of improved confinement

- **\( T_e \)**
  - Electron temperature profile over \( \rho \)
  - Decreasing temperature as \( \rho \) increases

- **\( T_i (C^+6) \)**
  - Ion temperature profile over \( \rho \)
  - Similar to \( T_e \) trend
CHarge Exchange Recombination Spectroscopy (CHERS)

- CVI emission at 343.4 nm
- Simultaneous background measurement enables high temporal resolution (up to 100 kHz)
- Spectrometer calibrated for radiant sensitivity

[Diagram showing experimental setup with MST vessel, 50 keV H beam, CVI emission at 343.4 nm, and beam views.]
Radial profile and time evolution of $C^{+6}$ density hollow profile, sharp edge gradient, expulsion from the core

- Slow decay of core impurity density concurrent with slow increase at the outer region

- Sharp $C^{+6}$ gradient consistent with $T_e$ gradient - barrier formation?
Impurity transport is governed by

\[ \frac{\partial n_z}{\partial t} + \nabla \cdot \Gamma = S \]

For improved confinement,

\[ \nabla \cdot \Gamma = -\frac{\partial n_z}{\partial t} \]

Radial impurity flux,

\[ \Gamma_r = -D \frac{\partial n_z}{\partial r} + v_r n_z \]

\[ \frac{\partial n_z}{\partial r} = \frac{v_r}{D} n_z + \frac{\Gamma_r}{D} \]
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- \( \tau_{c+6} \sim 31 \text{ms at } \rho \sim 0.016 \)
- \( \sim 41 \text{ ms at } \rho \sim 0.371 \)
- \( D \sim 1.6 \text{ m}^2/\text{s} \) (close to classical)
- \( v_r \sim 1.0 \text{ m/s} \) (Positive, Outward)
$^{\alpha+6}$ ions are highly collisional in MST

- Radial impurity flux $\rightarrow$ Classical $+$ Pfirsch-Schlüter contributions
1. Classical

\[ \Gamma_{cl} = \frac{\nu_i \rho_i^2 n_i}{2Z} \left[ \frac{\partial \ln P_i}{\partial r} - \frac{\partial \ln P_z}{Z \partial r} - \frac{3\partial \ln T_i}{2\partial r} \right] \]

2. Pfirsch-Schlüter

\[ \Gamma_{PS} = \frac{q^2 \nu_i \rho_i^2 n_i}{Z} \left[ K \left( \frac{\partial \ln n_i}{\partial r} - \frac{\partial \ln n_z}{Z \partial r} \right) + H \left( \frac{\partial \ln T_i}{\partial r} \right) \right] \]

- \( K \) and \( H \) depends on impurity concentration and main ion collisionality. Typical values are 1 and -0.5 respectively.
Equilibrium impurity density profile

1. Classical

\[
\frac{n_z(r)}{n_z(0)} = \left[ \frac{n_i(r)}{n_i(0)} \right]^Z \left[ \frac{T_i(r)}{T_i(0)} \right]^\frac{-Z}{2} - 1
\]

- \( \nabla n_i \) leads to accumulation, \( \nabla T_i \) leads to expulsion ("screening")

2. Total (P-S + Classical)

\[
\frac{n_z(r)}{n_z(0)} = \left[ \frac{n_i(r)}{n_i(0)} \right]^Z \left[ \frac{T_i(r)}{T_i(0)} \right] \gamma
\]

\[
\gamma = \frac{-Z - 2 + 4q^2 HZ}{2 + 4q^2 K}
\]
Excellent matching with experimental profile
Transport dominated by classical flux

• Impurity concentrations (Al, C, B, N, O) scaled to get $Z_{eff}(0) \sim 4.5$

• Temperature equilibration assumed

• $n_i$ self-consistently calculated starting from $n_e$ & impurity profiles

• Pfirsch-Schlüter contribution is negligible as expected

Impurity profile is determined by the temperature gradient -

“Temperature screening effect"
Summary

- Radial profile of impurities is clearly hollow in the improved confinement discharges in MST
- Impurity expulsion from the core of the plasma is observed
- Radial profile well explained by classical transport: Temperature screening responsible for the hollow profile, as \( n_i \) profile is flat

First experimental observation of classical impurity ion confinement in the RFP