Core Impurity Transport in Alcator C-Mod L-, I- and H-mode Plasmas

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with thanks to


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Motivation

Impurity accumulation unacceptable: radiation losses, dilution, disruptions

L-mode: turbulence dominates impurity transport, no problem

Plasmas with particle transport barriers: impurity transport approaches n-c, inward pinch increases with Z

Techniques to control inward pinch: electron heating, outward convection from gradT

I-mode has thermal barrier \((H^{98} \sim 1)\) with L-mode impurity confinement

Outline

Experimental setup

Impurity injection time histories in L-, I- and H-mode plasmas

Impurity confinement scalings with plasma parameters

Discussion
CaF₂ injection from multi-pulse laser blow-off system
N.T. Howard et al., Rev. Sci. Instrum. 82, 033512 (2011)

Imaging Johann spectrometer, spherically bent crystal with fast 2-D x-ray arrays

![Side View Diagram]

Impurity Injections into L-/I-mode Plasmas with ICRF Power Scan

Impurity transport anomalous
\[ D_{\text{eff}} \sim 0.3-0.5 \, \text{m}^2/\text{s} \]

‘unfavorable’ drift

Impurity confinement time decreases with total input power


C-Mod
Tore Supra and JET

Core impurity confinement time

Central electron temperature
Density Scan in Ohmic Discharges

Impurity Confinement Very Similar in LOC and SOC Plasmas

Energy confinement saturation and rotation reversal occur at critical $\nu_*$.

Core impurity transport similar in TEM and ITG dominant regimes.
L-mode Impurity Confinement Scaling with Current and Magnetic Field

$I_p$ scaling agrees with gk modeling at mid radius. Strong dependence on $I_p$ and weak dependence on $B_T$ suggest $q$ dependence is weak.


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**L-mode**

- Impurity confinement time
- $I_p$ scaling $^{0.31}$
- $I_p$ scaling $^{0.68}$
- Tore Supra and JET
- $n_e = 1 \times 10^{20}/m^3$
- $P_{ICRF} = 1$ MW

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**Ohmic**

- Impurity confinement time
- $B_T^{0.18}$
- C-Mod
- $n_e = 1 \times 10^{20}/m^3$
- $I_p = 0.8$ MA
Impurity Transport in I-mode Plasmas Very Similar to L-mode

Time histories and scaling with plasma current much like L-mode results.

**Graph**: 
- $W_p$: Poloidal stored energy, increasing over time before decreasing.
- $n_e$: Electron density, shows a peak.
- $T_e$: Electron temperature, fluctuates significantly.
- $P_{\text{ICRF}}$: ICRF power, near-constant.
- Ca$^{19+}$ brightness: spikes at specific times.

**Equation**: 
$$n_e = 1.5 \times 10^{20} \text{m}^{-3}$$

**Note**: Fast ion worry at low current.
Scalings with Background Ion and Impurity Mass in L- and I-mode

L-mode impurity transport independent of background ion mass.

I-mode impurity transport independent of impurity mass.

(Ohmic L-mode: E.S. Marmar et al., Nucl. Fusion 22 (1982) 1567.)
Impurity confinement times much longer than L- or I-mode, due to pinch driven by steep edge density gradient.

Apparent scaling with plasma current. (density and edge gradient not constant).
Global Impurity Confinement Time Scalings Across All Regimes

I-mode features L-mode impurity transport with H-mode energy confinement.

Impurity confinement time dominated by edge density gradient driven inward pinch.
Summary and Discussion

Impurity transport in L- and I-mode plasmas is anomalous, $D_{\text{eff}} = a^2/2.41^2 \tau \sim 0.4 \text{ m}^2/\text{s}$.

Impurity confinement similar in LOC and SOC plasmas.

Impurity confinement time decreases with ICRF power in L- and I-mode.

In L-mode, $\tau_I \sim I^{0.68} B^{0.18}$, so $q_{95}$ dependence is weak.

I-mode impurity transport similar to L-mode, scalings with current and independence on impurity mass.

Impurity confinement times much longer in H-mode.

Core impurity confinement time scales with edge density gradient in all regimes.
Flat Ca Density Profiles in the Core of I-mode and EDA H-mode Plasmas

Ca\textsuperscript{18+} emissivity profiles typically flat inside sawtooth radius. Total calcium density profiles determined from CR modeling. Flat Ca density profiles suggest absence of core impurity pinch.