Particle Transport in the Scrape-off Layer and Relationship to Discharge Density Limit in Alcator C-Mod

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Invited talk BI1.006
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Motivation: Cross-field particle transport ($\Gamma_{\perp}$) in SOL and its dependence on discharge conditions impacts tokamak operation & design

- $\Gamma_{\perp}$ determines level of plasma/wall interaction in main-chamber
  neutral pressures ($\Rightarrow$ confinement)
  impurity sources
  $\Rightarrow$ impacts divertor design

Q: What will be operating regime in a reactor?

- Heat convection across separatrix and its scaling may play role in tokamak density limit

Goals:
Characterize and understand $\Gamma_{\perp}$:
- empirical scalings
- underlying turbulence
- relationship to tokamak density limit
Outline of Talk

- Main-Chamber Recycling
- Effective Cross-Field Particle Diffusivities ($D_{\text{eff}}$) & Scalings
- Cross-Field Heat Convection
- Fluctuations
- Behavior Near Discharge Density Limit

Diagnostics:
- Vertical Scanning Probe
- Horizontal Scanning Probe
- Midplane $D_\alpha$
- Divertor Probes
Scrape-off Layer Density Profiles Exhibit a "Two-Exponential" Decay

**Near SOL:** steep decay, $\lambda_n \sim 2$ to $8$ mm

**Far SOL:** shallow decay, $\lambda_n \sim 8$ to $> 100$ mm

- At low $\bar{n}_e$, density at limiter edge is less than $\sim 1/10$ of separatrix density

- Density at limiter edge increases sharply with increasing $\bar{n}_e$

=> Always some level of main-chamber (limiter) recycling
Main Chamber Recycling Regime (MCR) persists over wide parameter range

Recycling in Main Chamber SOL is primarily balance by fluxes onto main-chamber walls†

Poloidal flows to divertor/baffle are weak

Main-Chamber Recycling Regime (MCR) persists over wide parameter range

A New View of Particle Transport Processes in SOL

Old Paradigm:
- SOL density decays "exponentially" because... plasma drains along field lines towards divertor/baffle

![Diagram showing old paradigm](Image)

New Paradigm:
- SOL density decays "exponentially" because... cross-field transport velocity increases across SOL, maintaining cross-field flux towards wall

![Diagram showing new paradigm](Image)
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In MCR Regime, Cross-Field Diffusion Coefficient Profiles ($D_{\text{eff}}$) can be Inferred Directly from Profile Measurements†

- Density
  - $\overline{n_e}/n_G$
    - 0.43
    - 0.27
    - 0.19

- Ionization Source (from $\text{Ly}_\alpha$ profiles)

- Cross-Field Flux Profile

- Effective Diffusion Coefficient: $D_{\text{eff}} = -\Gamma_\perp/\nabla n$

- Persistent trend of $D_{\text{eff}}$ increasing by $\sim 10$ or more with distance from separatrix‡‡
  => variation in $D_{\text{eff}}$ reflects variation in $\nabla n$

- $D_{\text{eff}}$ increases with discharge density
  => $\Gamma_\perp$ gets larger, $\nabla n$ gets smaller

† Method benchmarked against UEDGE modeling
‡‡ $D_{\text{eff}} (\chi_{\text{eff}})$ increasing seen before: ASDEX, JT-60, JET, ...
Magnitude of $Deff$ in Near SOL is Correlated with Collisionality in Near SOL

64 Ohmic L-Mode Datapoints:

- $0.8 < \bar{n}_e < 2.5 \times 10^{20} \text{ m}^{-3}$
- $0.6 < I_p < 1.0 \text{ MA}$
- $4 < B_T < 6 \text{ tesla}$
- $0.14 < \bar{n}_e/n_G < 0.47$

4 Parameter Regression:

$\Rightarrow$ Suggests $(B_T/I_p)$, $q$, or $L$ dependence

1 Parameter Regression:

$\Rightarrow$ Statistics point to $(\lambda_{ei}/L)$ as most relevant parameter

$Deff$ correlates with local collisionality:

$Deff \sim (\lambda_{ei}/L)^{-1.7}$

Trend: $n_e/n_G \uparrow \Rightarrow \lambda_{ei}/L \downarrow \Rightarrow Deff \uparrow$ near sep.
Cross-Field Heat Convection to Limiter/Wall Competes with Parallel Conduction Losses to Divertor at Moderate $\bar{n}_e/n_G$

Finite $T_e$ on open field lines
$\Rightarrow$ power conducted to divertor: $Q_{div} \propto \int_0^\infty \rho T_e^{7/2}/L \delta \rho'$

Cross-field particle fluxes ($\Gamma_{\perp}$)
$\Rightarrow$ power convected: $Q_{conv} \sim 5 T_e \Gamma_{\perp} A_{sep}$

- At low density, heat losses in Near SOL are dominated by parallel conduction to Divertor
- At moderate density, cross-field heat convection to Limiter/Wall exceeds conduction losses to Divertor/Baffle over entire SOL
A New View of Heat Transport Processes in SOL

(in absence of a "radiating mantle")

Old Paradigm:

- Parallel e⁻ conduction to divertor dominates heat losses in Near SOL region

\[ T_{sep} \propto \left( \frac{P_{sol}}{\lambda_{Te}} \right)^{2/7} \]

Modified Paradigm:

- Parallel e⁻ conduction and cross-field heat convection contribute to heat losses in Near SOL region

(Charge exchange also can contribute)

At low collisionality, parallel conduction regulates \( T_{sep} \):

\[ T_{sep} \propto \left( \frac{P_{sol}}{\lambda_{Te}} \right)^{2/7} \]

At high collisionality, heat convection becomes large, \( T_{sep} \) is reduced and is no longer "regulated" by this law!
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- Cross-Field Heat Convection

Diagnostics:

- Fluctuations
- Behavior Near Discharge Density Limit
Fluctuations Exhibit Different Character in *Near* and *Far* SOL Regions

**Near SOL** (steep n profile):
- moderate amplitude, "random" fluctuations

**Far SOL** (flatter n profile):
- large amplitude, intermittent $I_{sat}$ "bursts"

$\Rightarrow$ Consistent with $D_{eff}$ $\uparrow$ with distance into SOL
2-D Turbulence Imaging: Intermittent, ~1 cm Scale "Blobs" of Emission Extend into Far SOL

Turbulence Imaging:
- 2-D Images of Dα emission, looking along field lines at a "plume" from D2 gas nozzle
- ~1 mm spatial resolution
- 2 μs exposure times
- 17 ms between exposures

- ~1 cm scale blobs intermittently occupy Far SOL zone, and extend to Limiter Shadow

- Intermittent "Blobs" (2-D imaging) and "Bursts" (probes) are consistent with large density and temperature (?) perturbations rapidly transporting particles and energy to Limiter/Walls

More on 2-D edge turbulence Imaging:
S.J. Zweben - oral JO1.005 Tuesday PM
J.L. Terry - poster UP1.116 Thursday AM
Collisionality at the Separatrix and \(\perp\) Heat Convection to Limiter/Wall Increases as Discharge Density Limit is Approached

As density limit is approached:
- \(\lambda_{ei/L}\) near separatrix drops dramatically
- Radiation and \(\perp\) Convection to Limiter/Wall are comparable and mostly account for input power

Near density limit:
- Radiation + \(\perp\) Convection to Walls \(~\) Input Power
Near density limit:

- SOL n & T<sub>e</sub> profiles become flat, T<sub>sep</sub> low ~ 25 eV!
- Fluctuations characteristic of "Far SOL" now occur everywhere, even across the separatrix

=> Consistent with large \(\downarrow\) Convection Losses
Summary

- SOL density profiles exhibit a "two-exponential" decay: Near and Far SOL
- Yet, Main-chamber plasma exhausts primarily onto Limiter/Wall surfaces!

=> New Particle Transport Paradigm:
- Density "decays exponentially" because ... cross-field transport ($D_{\text{eff}}$) increases rapidly with distance into SOL
  ... not because parallel flows "drain" SOL plasma

\[ D_{\text{eff}} \sim (\lambda_{ei} / L)^{-1.7} \]

=> Heat Transport Paradigm Modified:
- At moderate collisionality ($n_e/n_G \sim 0.5$), cross-field heat convection exceeds conduction losses

\[ T_{\text{sep}} \text{ no longer regulated by "conduction law":} \]

\[ T_{\text{sep}} \propto (P_{\text{sol}} / \lambda_{Te})^{2/7} \]
Summary (page 2)

• Fluctuation behavior supports picture of particle & energy transport increasing with distance into SOL

Near SOL: (steep density profile) low amplitude "random" fluctuations

Far SOL: (flat density profile) large amplitude intermittent "bursts" in $I_{\text{sat}}$ and $\sim 1 \text{ cm} "\text{blobs}"$ in $D_\alpha$, extending into Limiter Shadow

=> New Insight on Density Limit Physics:

• As density limit is approached, $\lambda_{ei}/L$ near separatrix drops and transport across the SOL increases dramatically

  ⊥ Heat Convection to Limiter/Wall becomes large fraction of input power

"Bursty" fluctuations (large transport) occur over entire SOL and begins to attack plasma on closed flux surfaces

~ at limit:

Radiation + Convection to Wall ~ Input Power

Rapid increase of ⊥ Heat Convection as edge plasma cools may play role in thermal instability leading to disruption