Density Limit and Cross-Field Edge Transport Scaling in Alcator C-Mod

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Motivation/Background

- Tokamak density limit is observed to follow Greenwald empirical scaling law, yet satisfactory physics-based understanding is lacking\(^1\)
  
  \[\text{=> Extrapolation to untested reactor-regimes is uncertain}\]

- Recent C-Mod experiments indicate that a number of edge plasma phenomena is tightly linked:
  
  - Two-zone scrape-off layer profiles
  - Non-diffusive, "bursty" edge transport
  - Main-chamber recycling
  - Onset of divertor detachment

  \[\text{Key element => cross-field particle transport and its strong increase with plasma collisionality}\]

- Observations further suggest that cross-field particle and heat transport physics plays a direct role in setting the tokamak density limit

  \[\text{=> Key physics behind empirical scaling law may lie in "scrape-off layer transport" mechanisms}\]

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Outline of Talk

- Edge Plasma Profiles and Fluctuations
- Cross-Field Particle Transport and Scalings
- Cross-Field Heat Convection
- Behavior Near Discharge Density Limit

Diagnostics:
- Horizontal Scanning Probe
- Fast Photo-Diode Array
- Turbulence Imaging
Scrape-off Layer Density Profiles Exhibit a "Two-Exponential" Decay and Strong Sensitivity to Discharge Density

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

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

- Density at limiter ($n_L$) increases nonlinearly with increasing $\bar{n}_e$, $n_L \sim (\bar{n}_e)^2$

  $=>$ Particle flux onto main-chamber wall (limiter) increases sharply with $\bar{n}_e$

† 'shoulders’ on SOL profiles are prevalent in the literature: ASDEX, ASDEX-U, JT-60U, TEXT-U, ...
Fluctuations Exhibit Different Character in Near and Far SOL Regions, Consistent with Rapid Transport in Far SOL

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

Far SOL (flatter n profile):
-> large amplitude, intermittent $I_{\text{sat}}$ "bursts"
Fluctuation Probability Distributions Indicate Non-Diffusive Transport in \textit{Far SOL}†

\begin{itemize}
\item \textbf{Near SOL:} \sim \text{Gaussian}
\item \textbf{Far SOL:} Non-Gaussian
\end{itemize}

±Bursty, SOC-like behavior is universally seen in SOL plasmas, including non-tokamak devices.
2-D Turbulence Imaging: Intermittent, ~1 cm Scale "Blobs" of Emission Propagate Towards Limiter in Far SOL Zone

Observations suggest:
- Plasma intermittently "peels away" from steep-gradient Near SOL region and ~freely propagates to wall
=> Level of particle fluxes set by Near SOL physics

\[ \text{\textsuperscript{\dag}} \text{see J.L. Terry et al., paper EX/P5-10} \]
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Magnitude of $D_{\text{eff}}$ in Near SOL is Correlated with Collisionality in Near SOL

127 Ohmic L-Mode Datapoints:
- $0.8 < \bar{n}_e < 3.0 \times 10^{20} \text{ m}^{-3}$
- $0.5 < I_p < 1.0 \text{ MA}$
- $4 < B_T < 6 \text{ tesla}$
- $0.15 < \bar{n}_e/n_G < 0.53$

4 Parameter Regression:
- $\Rightarrow$ Suggests $(B_T/I_p)$, $q$, or $L$ (// connection length) dependence

1 Parameter Regression:
- $\Rightarrow$ Statistics point to $(\lambda_{ei}/L)$ as a well-correlated parameter

Regression Analysis of $D_{\text{eff}}$ ($= -\Gamma_\perp /\nabla n$), 2 mm into SOL

$\propto T_e^{-4.5} n^{1.1} I_p^{-2.0} B_T^{2.4}$

$\propto (\lambda_{ei}/L)^{-1.5}$

$D_{\text{eff}}$ correlates with local collisionality:

$D_{\text{eff}} \sim (\lambda_{ei}/L)^{-1.5}$

- $D_{\text{eff}}$ has no explicit $B_T$ dependence†
- $D_{\text{eff}}$ is clearly not $D_{\text{Bohm}}$!

† $\chi_{\text{eff}}$ independent of $B_T$ was reported before for C-Mod and JET
For a fixed $\bar{n}_e/n_G$, the plasma chooses an "operating point" within a narrow range of $\lambda_{ei}/L$

$\Rightarrow$ results in $D_{eff}$ & $V_{eff}$ correlating well with $\bar{n}_e/n_G$

$\Rightarrow$ particle flux increases nonlinearly with $\bar{n}_e/n_G$
Primary SOL Power Loss Shifts from Parallel Conduction into Divertor to Cross-Field Convection onto Walls with Increasing $\bar{n}_e/n_G$

- Data indicates an ordered changeover in SOL plasma transport losses with increasing $\bar{n}_e/n_G$:
  1. Parallel conduction to divertor dominates
  2. Cross-field convection to walls ~ comparable to parallel conduction to divertor
     \[ \rightarrow \text{Outer divertor detaches} \]
  3. Cross-field convection to walls dominates\textsuperscript{†}

\textsuperscript{†} Modeling shows Charge-Exchange losses to be small
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Diagnostics:

- Behavior Near Discharge Density Limit
As $\bar{n}_e$ is Raised Near to Limit, Large Amplitude, Long Correlation-Time Fluctuations Move Inside Separatrix

Data from Deep Probe-Scan

SOL Profiles

Electron Temperature

Auto-Correlation Times ($V_f$ data)

RMS $I_{sat}/<I_{sat}>

$\bar{n}_e/n_G$

- 0.7
- 0.4
- 0.3

Near density limit:

SOL $n$ & $T_e$ profiles very flat, $T_{sep}$ low ~ 25 eV!

Fluctuations characteristic of "Far SOL" appear to cross the separatrix
Summary  (page 1 of 2)

An ordered progression in SOL transport is observed with increasing $\bar{n}_e/n_G$, suggesting that the tokamak Density Limit involves "SOL transport physics":

<table>
<thead>
<tr>
<th>$\bar{n}_e/n_G$</th>
<th>parallel conduction dominates SOL</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low</td>
<td>cross-field convection competes/dominates divertor detaches</td>
</tr>
<tr>
<td>High</td>
<td>&quot;SOL transport&quot; moves inside LCFS</td>
</tr>
<tr>
<td></td>
<td>operational density limit is reached</td>
</tr>
</tbody>
</table>

• At low and moderate $\bar{n}_e/n_G$, a two-zone SOL is observed:

**Far SOL:** flat profiles, non-gaussian PDFs, bursty, rapid transport to walls

=> main chamber recycling phenomenon

**Near SOL:** steep profiles, near-gaussian PDFs. Camera movies of "blobs" peeling away from Near SOL are recorded.

=> suggests transport level is set by Near SOL
Summary (page 2 of 2)

- Cross-field particle ($D_{eff}$) and heat convection near separatrix increases with collisionality

- $\bar{n}_e/n_G$ is seen as an effective "proxy" for $L/\lambda_{ei}$
  => particle flux increases much faster than $\bar{n}_e$

At high $\bar{n}_e/n_G (L/\lambda_{ei})$, the parallel conduction "thermostat" that regulates $T_{sep}$ is overcome by cross-field convection.

Convection increasing with collisionality↑
+ Radiation increasing with $T_e$↓ and $n$↑

... can naturally lead to regime where there exists no stable "operating point" for SOL transport/profiles,
  i.e., an operational density limit