Turbulent Particle Transport in the Tokamak Edge Plasma & Its Implications

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Collaborators
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And many more from the DIII-D and Alcator C-Mod teams
Motivation

• Particle transport in edge plasmas of tokamaks is critical to success of fusion energy research (e.g. ITER)
  ➢ Particle control, particularly the radioactive & mobile Tritium fuel.
  ➢ Impurity control for burning plasmas.
  ➢ Erosion lifetimes for materials.

• Our record of understanding these subjects in present tokamaks?
  ➢ Global particle balance is usually not even measured, let alone understood.
  ➢ The density/ Greenwald limit remains an empirical observation.
  ➢ Tritium isotopes are retained at a 10-50% level, about 1,000-5000 times too large for a D-T reactor.
  ➢ The originating source & control of core plasma impurities is unknown.
  ➢ Net erosion rates of materials (rarely measured) are ~100 times too large.
Why such a poor record on particles in present experiments?

- Joules are expensive, particles are cheap!

Fig. 2-13  Negative ion neutral particle injector installed in the JT-60 hall
Why such a poor record on particles in present experiments?

- Joules are expensive, particles are cheap! *

* But NOT in a D-T fusion experiment/reactor:
  Tritium “costs” ~ $50M / kg & ~ 1 kg in-vessel safety limit.
It has long been recognized that “edge” particle transport is turbulent...

- > 30% $n_e$ fluctuations.
- Approximately consistent with drift wave instability.
- “Anomalous” high diffusion coefficients inferred.

...so why has progress has been slow on understanding & controlling effects?

- Difficult 2-D or 3-D geometry of Scrape-Off Layer (SOL).
- Gradient scale lengths $\sim \Delta R_{\text{SOL}}$
- Complex, strong local sources (ionization) and sinks (walls, recombination).

- As a result, divertor design and operations have not taken turbulent transport into account:
  - e.g. ITER divertor is designed through combination of empirical “rules-of-thumb” and time-averaged fluid codes.
Goal of this work is to place edge turbulence in a broader context: Cross-field particle transport in the “far SOL” to the wall surfaces

• **Innovation**: Diagnostic techniques for “routine” measurement of local (turbulent) and global (time-averaged) particle flux to all surfaces in a divertor tokamak.

• **Leads to important constraints on interpretation of turbulence…**
  - Extrapolation of locally measured turbulent-driven flux.
  - Information on edge turbulent structures.
  - Variation with background plasma (collisionality, etc.)

• **& Implications**
  - Impurity sources.
  - Fueling control.
  - Erosion & Tritium retention.
  - Power balance
  - Density limits.
Outline

• Plasma flux to walls in DIII-D.
  ➢ The “window-pane” technique

• Intermittent, convective particle transport.
  ➢ Self-consistent diagnosis.

• Implications.
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Measuring plasma flux to main-wall surfaces in a divertor tokamak: the “Window-pane”
Measuring plasma flux to main-wall surfaces in a divertor tokamak: the “Window-pane”

\[ j_{\text{wall}} = \Gamma_\perp = 1.22(n_e c_s)_{\text{window-pane}} \cdot \lambda_{\text{shadow}} \frac{B_p}{B_t} \cdot \frac{1}{L_{\text{pol}}} \]

\[ I_{\text{wall}} = j_{\text{wall}} \cdot \text{Area}_{\text{plasma}} = j_{\text{wall}} \cdot 2\pi R \cdot L_{\text{pol}} \]
LFS window-pane on DIII-D covers >60% of plasma area

Diagnostics

- $I_{\text{wall}}$: window-pane
- $I_{\text{div}}$: probe-array
- $I_{\text{rec}}$: $D-\gamma$
- $D$ recycling: $D-\alpha$
- Fluctuations:
  - B.E.S.
  - $D-\alpha$ array
  - Scanning probe
Window-pane with realistic geometry and diagnostics

- Particles stepping through primary window-pane experience sudden decrease in connection length to surfaces and are no longer connected to divertor phenomena...they are lost to the “main-wall”.
- Secondary window-panes exist at each non axisymmetric surfaces.
Plasma flux to wall is directly confirmed with embedded probe

L-mode density scan
$\Delta R_{\text{sep}}$: 70 mm

H-mode density scan
$\Delta R_{\text{sep}}$: 50 mm

Measured $\Gamma_{i,\parallel}$ from embedded nose probe in main wall limiter ($10^{23}$ s$^{-1}$m$^{-2}$)

Predicted $\Gamma_{i,\parallel}$ from shadow plasma ($10^{23}$ s$^{-1}$m$^{-2}$)

#101559
#105194
Use density scans to examine flux behavior in edge

- Exploits $\Gamma \propto n_e^{2-3}$
- Constant power and energy confinement.
- $T_e \sim$ fixed by parallel heat conduction ($\propto q_{///}^{2/7}$).
- SOL density becomes increasingly flat.
- Shadow profiles:
  - $T_e \sim$5-10 eV
  - Clear break in $n_e$. 

SOL <profiles>
(First) Global particle balance: 
Surprisingly high plasma flux to main-wall.

- $I_{\text{div}}$ rolls-over from detachment.
- $I_{\text{wall}}$ increases strongly with $\langle n \rangle$.
- Shadow transport $\sim$ constant.
- Main-wall and divertor particle sinks/sources $\sim$ equal!
During H-Mode, ELMs send large plasma flux to main-wall

- ELM (Edge Localized Mode) MHD-event cause intermittent plasma bursts.
- Excellent correlation between main-wall flux & recycling in all confinement modes and during ELMs.
- Lack of profiles ($\lambda_{\text{shadow}}$) inhibits accurate $I_{\text{wall}}$ with type-I ELM.
  - Window-frame probe array will provide routine $I_{\text{wall},\text{ELM}}$.
Density scan in high-δ H-Mode results nearly identical to L-mode

- Small rapid ELMs allow shadow plasma diagnosis.
Recycling & refueling in the main-chamber is controlled by $I_{\text{wall}}$, not divertor leakage.

Attempts to determine $I_{\text{wall}}$ from main-wall recycling are highly uncertain.
Power balance validation of $I_{wall}$

Plasma flux to main-wall carries little energy

![Graph showing power balance validation]

- $P_{NBI}$
- $P_{ohmic}$
- $P_{rad}$
- $Q_{wall}$
- $Q_{div}$

**Power (MW)**

**line averaged density ($10^{19}$ m$^{-3}$)**

**Note:**
- $P_{rad}$
- $Q_{wall}$
- $Q_{div}$
- $P_{rad} + Q_{wall} + Q_{div}$
Transport analysis of $\lambda_{\text{shadow}}$ suggests convective ansatz with $v_{\text{eff}} \sim 100 \text{ m/s}$

**Simple-SOL model**

\[ D_{\text{eff}} \approx \frac{2 \lambda_{\text{shadow}}^2 c_s}{L_{\parallel}} \]

\[ v_{\text{eff}} \approx \frac{2 \lambda_{\text{shadow}} c_s}{L_{\parallel}} \]

<table>
<thead>
<tr>
<th>Case</th>
<th>$L_{\parallel}$ m</th>
<th>$\lambda_{\text{shadow}}$ mm</th>
<th>$D_{\text{eff}}$ m$^2$ s$^{-1}$</th>
<th>$D_{\text{Bohm}}$ m$^2$ s$^{-1}$</th>
<th>$v_{\text{eff}}$ m s$^{-1}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>L-Mode</td>
<td>14</td>
<td>30-40</td>
<td>3-6</td>
<td>0.2</td>
<td>110-140</td>
</tr>
<tr>
<td>H-Mode</td>
<td>20</td>
<td>40-60</td>
<td>4-9</td>
<td>0.2</td>
<td>100-150</td>
</tr>
</tbody>
</table>

Table 1  Summary of transport analysis based on $\lambda_{\text{shadow}}$. 
Outline

• Plasma flux to walls in DIII-D.
  ➢ The “window-pane” technique

• Intermittent, convective particle transport.
  ➢ Self-consistent diagnosis.

• Implications.
We will examine how “turbulent” convective plasma transport to wall is linked to ExB propagation of plasma filaments.

- High density & pressure plasma filament or “blob” is born at the separatrix.
  - First experimentally identified by Endler & Zweben (late 80’s).

- The filament propagates radially to the outer wall due to $\nabla B$ plasma polarization and associated $E_\theta \times B$ drift.

- Model by Krasheninnikov relies on sheath resistivity at divertor plate to close current paths in filament.

$S. \text{ Krasheninnikov}$

BES movie shows an example of a single filament propagating through the SOL

- B.E.S. (beam emission spectroscopy) measures local $n_e$ fluctuation level.

- Unfortunately, DIII-D BES rarely setup for far SOL studies.
Midplane D-α array:

Density spikes associated w/ filaments originate at separatrix & propagate across entire SOL

- Tangentially views SOL with 1 cm spatial resolution -- *routine diagnostic*.

- Frequency regime:
  - 100 kHz sampling rate.
  - 50 Hz - 20 kHz noise floor.

- Conditional averaging: picks out and “tracks” single-event, large amplitude fluctuations through SOL.

- Intrinsic SOL D-α emission is best described as a measurement of ionization...f (T_e, n_e, n_D)
  - But origin at separatrix (T_e > 50 eV) rules out T_e fluctuation as cause.
  - Neutrals too fast.
  - Best described as n_e fluctuations.
Key observations

- Net outward radial propagation.
- \(\Delta r \sim 20-30\) mm.
- Point of origin: separatrix.
- Filaments remain coherent propagating across SOL & must be greatly extended in parallel direction: \(L_{//} > 5\) m \(\sim M c_s \tan \theta \tau_{\text{SOL}}\)
- Filaments reaching the window-pane: \(v_{\text{poloidal}} < v_{\text{radial}}\)
Ensemble-average D-α fluctuations show radially outward propagation at ~ 100 m/s

Time-lag Correlation Over ~ 1 second

$v_r = 100 \text{ m/s}$

$n_e \sim 0.45 \, n_{Gr}$
Our detailed filament information allows us to calculate turbulent particle flux density in SOL

**Filament flux density**

\[
\sum_{N_y} \# = n_{fil} \, v_{radial} \, \Delta t \, \Delta y \, \Delta z \cdot N_y
\]

\[
\Gamma_{radial} = \frac{\sum_{N_y} \#}{\Delta t \cdot \text{Area}} = \frac{\sum_{N_y} \#}{\Delta t \cdot Y \cdot \Delta z} = n_{fil} \, v_{radial} \left( \frac{\Delta y \, N_y}{Y} \right)
\]

\[
\delta n = n_{fil} \left( \frac{\Delta y \, N_y}{Y} \right)
\]

\[
\Gamma_{radial} = \delta n \, v_{radial} = \left( \frac{\delta n}{n} \right) n \, v_{radial}
\]
SOL fluctuations & correlation are measured independently.

SOL <profiles>

SOL Fluctuations
SOL fluctuations & correlation are measured independently.

- Norm. fluctuation level increases through SOL
- Norm. fluctuation independent of core density.
- TS shows peak $\delta n - \delta Te$ at separatrix, consistent with filaments radial origin, but poloidally far from midplane.
Remarkably consistent $v_{\text{eff}}(r)$ profiles → Increasing radial flux with increasing $n_e,\text{SOL}$

\[ \Gamma_{\text{radial}} = \delta n \; v_{\text{radial}} = \left( \frac{\delta n}{n} \right) n \; v_{\text{radial}} \]

(a) Ensemble averaging

(b) Conditional averaging

(c) Cross-field Convective Flux density
Filament transport through window-pane explains >50% of the magnitude and matches trend of plasma flux to the main-wall.

- Filament transport consistent with ExB propagation:
  - Probe measures $E_{\text{poloidal}} \times B$ fluctuation flux at window-pane.

- For the first time we have linked turbulent-driven edge particle flux to a “global” parameter.
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The far SOL transport is resilient: \( v_{\text{eff}} \sim 100 \text{ m/s} \) invariant with density/collisionality or energy confinement!

- Supported by multiple diagnostics on DIII-D:
  - \( \lambda_{\text{shadow}} \text{ analysis: } v_{\text{eff}} \sim 100-150 \text{ m/s} \)
  - \( D-\alpha \text{ fluctuations: } v_{\text{radial}} \times (\delta n_e/n_e) \sim 70-100 \text{ m/s} \)
  - \( \text{BES: } v_{\text{radial}} \times (\delta n_e/n_e) \sim 150-200 \text{ m/s}. \)
  - \( \text{Langmuir probes: } v_{\text{radial}} \times (\delta n_e/n_e) \sim 100 \text{ m/s}. \)
  - \( \text{Particle balance.} \)
- Suggests strong de-coupling from transport barrier near separatrix.
Dimensionless SOL comparison also shows consistent $v_{\text{eff}} \sim 100$ m/s between DIII-D and compact high-field Alcator C-Mod.

- Flux density analysis based on measured, time-averaged ionizations in SOL, particle balance and $I_{\text{wall}}$. 
Energy and particle balance model of filament indicate consistent behavior with experiments

- Measured radial propagation velocities imposed.

- \( n_f(r) \): competition between volumetric ionization sources within the filament (~\( n_f n_D S_{ion} \)) and parallel “sonic” particle losses out the ends of the filament (~\( n_f c_s / L \))

**Energy Balance**

\[
Q_{\parallel, cond} = \kappa_o T_{f, \parallel}^{-5/2} \nabla T_{\parallel} A_{\parallel} \sim \kappa_o T_f^{-5/2} \left( \frac{T_f - T_{div}}{L_{\parallel}} \right) r_f^2
\]

\[
Q_{ion} = n_f n_D S_{ion} (T_e) kE_{ion} V_f \sim n_f n_D S_{ion} (T_e) kE_{ion} r_f^2 L_{\parallel}
\]
Energy and particle balance model of filament indicate consistent behavior with experiments.
Understanding filaments in the context of ionization sources shows us that they create a fuelling loop that competes with the divertor.

- Filaments bring plasma to main-wall that must recycle.
- Ionizations occur near window-frames: i.e. filaments must extend along LFS poloidal side.
- Loop 2 is difficult to measure but…
  - Divertor flux amplification ~5-10.
  - $I_{\text{drain}} \sim I_{\text{wall}}$ at $3.5 \times 10^{19} \text{ m}^{-3}$. 
Understanding filaments in the context of ionization sources also informs us about the validity of particle transport diagnosis.

- Cross-field flux density from probe (ExB) strongly diverges from flux balance and D-α diagnosis near separatrix…causes?
  1. Probe body induces transport (LaBombard) also violates global power balance.
  2. Comparison of auto-power spectra and radial/poloidal propagation (BES vs. D-α) suggest SOL transport is split into two distinct regions
    - **Near SOL**: high frequency (missed by D-α) with \( v_{\text{poloidal}} \sim v_{\text{diamag}} \)
    - **Far SOL**: low frequency (0.1-10 kHz) with \( v_{\text{poloidal}} \sim 0 \) and \( v_{\text{radial}} \sim 300-500 \text{ m/s} \).
Self-fuelling “density” limit induced by SOL with convective transport

- “Know” $v_{\text{eff}} \sim 50$ m/s.
- “Fit” $\tau_p \sim 75$ ms $\sim \tau_E$ for data.

- Insight: SOL opacity + convective transport prohibits raising density.
- Result:
  - Max. allowed $n_{e,\text{core}} \sim 6.5 \times 10^{19}$ m$^{-3}$
Turbulent plasma transport to the wall can also control core impurity levels

- Carbon source \( \propto \Gamma_i \)
  - Carbon erosion has weak energy dependence due to chemical sputtering.

- Methane trace experiments show relative penetration of methane to core:
  \[ P_{\text{wall}} \geq 10 \times P_{\text{div}} \]
  \[ (I_{\text{wall}}/I_{\text{div}}) \times (P_{\text{wall}}/P_{\text{div}}) > 1 \]
  \[ \therefore \text{main-wall carbon source dominate at all densities.} \]

- Confirmed with wall-gap scans.

### Upper baffle knee gap scan

- Core plasma
- Incident ion flux (s^{-1} m^{-2})
- Brightness (ph s^{-1} m^{-2} sr^{-1})
- Fraction carbon \( f_{\text{carbon}} \)

\( n/n_{\text{Greenwald}} \): 0.25, 0.35, 0.45, 0.55

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Turbulent plasma transport to the wall can also control divertor deposition & T retention
This should be the beginning of a better predictive design capability for edge & divertor in burning plasmas.

- Window-pane geometry & convective transport ansatz can be easily included in existing 2-D fluid codes.
  - Optimize wall-plasma gaps.
  - Control impurity erosion and T retention.
  - Plasma operation near density limit.

- Use time-dependent codes to understand dynamical impact of intermittent density bursts interacting with wall.
  - Impurity and fuel recycling.
  - Effect of transient events like ELMS.

- Use combination of local and global fluctuation diagnosis to obtain better fundamental understanding on cause and effects of edge turbulence.