Drift-Driven and Transport-Driven Plasma Flow Components in the Alcator C-Mod Boundary Layer

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Motivation for boundary flow studies

- Boundary flows move particles poloidally around the plasma to the divertors.
- Poloidal motion of entrained impurities $\rightarrow$ macroscopic erosion and redeposition of divertor surfaces $\rightarrow$ co-deposition of tritium.
- It is difficult to produce a theoretical description of these flows because they are driven in part by anomalous transport.

Other reasons for Boundary flow studies:
- Impurity screening
- Flow-shear turbulence suppression
- Core rotation boundary condition
- Topology-Dependence of H-Mode power threshold
Strong, poloidally asymmetric plasma flows are observed in tokamak boundaries

- Near-sonic (M ~ 0.5) parallel flow is persistently observed in the High Field Side (HFS) SOL (C-Mod [1], JET [2], JT60-U [3]).

- Parallel flow data from Tore Supra imply a strong ballooning-like transport asymmetry, localized within a 30° sector at the low-field side (LFS) midplane [4].

- What are the contributions of different drive mechanisms?
  - Strong ballooning-like transport asymmetry (transport-driven)
  - Neo-classical Pfirsch-Schlüter flows (drift-driven)
  - Toroidal Rotation (drift-driven)

- Mechanism that closes flow loop?

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C-Mod’s unique array of scanning Langmuir probes provide three localized measurements of total flow vector:

- Parallel flow from Mach probes, \( v_\parallel \)
- Perpendicular flow from potential gradients, \( v_\perp, E \times B \)
- Radial flow from fluctuation-induced fluxes, \( v_r, \nabla E_\theta \)
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- Net poloidal particle flux can be compared with divertor probes.
Outline of talk

Flow measurements:
- Parallel ($V_\parallel$)
- Perpendicular ($V_\perp \mathbf{E}_B$, $V_\perp \mathbf{v}_P$)
- Radial ($V_r \mathbf{n}_\theta$)

Compare upper / lower null discharges

Drift-driven components
- Consistency check: $\nabla \cdot V_\theta = 0$?
- $V_\parallel$ Pfirsch-Schlüter
- $V_\parallel$ Toroidal rotation

Transport-driven components
- Consistency check: $\nabla \cdot V_\theta + \nabla \cdot V_r = 0$?
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Closure of flow loop?
- Recycling from HFS divertor
- HFS turbulent inward pinch
- Volume recombination zone
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We measure:

- A **favorable** drift direction flow pattern \((B_x \nabla B \text{ towards } x\text{-point})\):
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- A **favorable** drift direction flow pattern ($B_x \nabla B$ towards $x$-point):
  $$v_{\text{fav}} = v_{\text{transp}} + v_{\text{drift}}$$

- An **unfavorable** drift direction flow pattern ($B_x \nabla B$ away from $x$-point):
  $$v_{\text{unfav}} = v_{\text{transp}} - v_{\text{drift}}$$
Transport-driven flow is dominant on HFS; drift-driven flows are dominant on LFS.

- Parallel, **transport-driven** flow is dominant on HFS.
  - Quantitative analysis shows significant heat convection to inner divertor.
- **Drift-driven** flows are dominant on LFS.

L-mode, $0.8 < \langle n_e \rangle [10^{20} m^{-3}] < 1.6.$
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Drift-driven flow component:
HFS/LFS comparison confirms divergence-free flow

- Calculate total poloidal fluid motion, not guiding center only; includes **Parallel**
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- Calculate total poloidal fluid motion, not guiding center only; includes **Parallel, ExB**

<table>
<thead>
<tr>
<th>HFS</th>
<th>LFS</th>
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<tbody>
<tr>
<td>Drift-Driven Flow [km/s]</td>
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<tr>
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![Drift-Driven Component Diagram]
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- Calculate total poloidal fluid motion, not guiding center only; includes **Parallel**, **ExB** and **Diamagnetic** flow.

- Total **drift-driven** flow is consistent with **divergence-free flow pattern** as expected from theory: similar profiles of $n\nu_\theta/B_\theta$ to **LFS** to **HFS**.

→ Measurements confirm $\nabla \cdot (\text{Drift-Driven Flow}) = 0$
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- Model transport-driven poloidal particle flux as $\sin(\theta)$ on LFS.

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- Constrain with measured value of poloidal flux on HFS.
- Calculate LFS radial particle flux implied by HFS poloidal flux using continuity.
- Result shows agreement with measurements of fluctuation-induced particle flux on the LFS through $\tilde{n}\tilde{E}_\theta$.
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• KN1D simulations [5, 6] indicate that neutral penetration to core/private zone from inner divertor is <10% due to short neutral MFP.

• Thus, continuity requires that some other mechanism is diverting particles from the HFS SOL.

→ Inner divertor recycling does not explain closure of flow loop.


Could particles be returning to the core via a **HFS turbulent pinch**? This is a solution commonly employed by 2-D edge codes to explain HFS flows. [7, 8, 9]

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• Caveat: Particle pinch at other locations along the inner divertor leg cannot be ruled out
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Hypothesis: Volume recombination closes flow loop

Could a **volume recombination** zone be present in the far SOL of the inner divertor leg, returning particles to the core as neutrals? [10]

- KN1D modeling indicates recombining plasma would have to impinge on closed field lines to allow sufficient neutral penetration to close loop.
- This is inconsistent with observation of partially attached inner divertor.
- Neutral penetration from volume recombination zone does not close mass flow loop.

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Future work: Other candidates for closing mass flow loop must be investigated

Having eliminated the most obvious closure mechanisms for the poloidal flow loop, we must look to other candidates:

- Radial convection ($E_\theta \times B$)
- X-point specific physics
- Pinch or diffusion into private flux zone
Conclusions

- Total flow vector has been measured and shown to be consistent with physical expectations.
  - Measured drift-driven flows are divergence-free.
  - Transport-driven poloidal particle flux is consistent with measured LFS fluctuation-induced radial particle flux.
  - Pfirsch-Schlüter, toroidal rotation and and transport-driven contributions to parallel flow are uniquely identified.

- Transport-driven parallel flows dominate HFS poloidal particle flux, carrying plasma toward active X-point.
  - Convection is important in HFS poloidal heat transport.

- Closure mechanism for transport driven flow loop:
  - Divertor recycling cannot account for transport-driven poloidal particle flux.
  - HFS midplane turbulent particle pinch is zero.
  - KN1D simulations show that direct neutral penetration from recombining plasma zone does not close the flow loop.
References