Total Flow Vector in the C-Mod SOL

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Motivation and Goals

Measurements have revealed **high parallel flow velocities** in the High Field Side (HFS) SOL (approaching Mach 1)\(^1\) that appear to be driven by a strong ballooning-like transport asymmetry.

Goals of current investigation:

- Determine whether the measured parallel flows drive a net poloidal particle flux or are just part of toroidal rotation.
- Separate out transport and drift-driven components of poloidal flows.
- Identify mechanism for returning HFS poloidal particle flux to the core.

> Detailed measurements of the *total flow vector* are needed to address these goals

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Plasma Flow Diagnostics in the C-Mod SOL

- C-Mod is equipped with two pneumatic scanning probes on the low-field side (LFS): a LFS midplane probe and a vertical probe near the lower divertor.

- A key diagnostic is a new scanning probe located near the HFS midplane.

- All scanning probes can measure the total flow vector: $v_\parallel$, $v_\perp$, $E \times B$ and $v_r, \tilde{n}E_\theta$ (from fluctuation-induced particle flux).
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  - Has finite divergence
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We measure:

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

- A **favorable** drift direction flow pattern (Bx∇B towards x-point):
  \[ v_{\text{fav}} = v_{\text{transp}} + v_{\text{drift}} \]

- An **unfavorable** drift direction flow pattern (Bx∇B away from x-point):
  \[ v_{\text{unfav}} = v_{\text{transp}} - v_{\text{drift}} \]
Flow Components on LFS and HFS midplanes

- Flow components have been extracted from probe data at the LFS and HFS midplanes.
- Parallel, transport-driven flow is dominant on HFS.
- Drift-driven flows are dominant on LFS.
Drift-Driven Flow Component:

**HFS/LFS** comparison indicates divergence-free flow

- Total *drift-driven* flow is consistent with *divergence-free flow pattern* as expected from theory: similar profiles of $nv_\theta/B_\theta$ LFS to HFS.
Drift-Driven Flow Component: HFS/LFS comparison indicates divergence-free flow

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

- This calculation uses total fluid motion, not guiding center only; includes Parallel, ExB and Diamagnetic flow.
We can now unambiguously decompose the drift-driven parallel flow into Pfirsch-Schlüter and toroidal rotation components.
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Data confirm expectation that these components should cancel on closed field lines.
Transport-Driven Flow Component:
Should Agree with Measured Transport

- Model transport-driven poloidal particle flux as \( \sin(\theta) \) on LFS

\[ S = 0 \quad S = 1 \]

\( \Gamma_r \) LFS

\( n v_\theta / B_\theta \) Toward Inner Divertor

S: Normalized poloidal distance from outer to inner divertor
Transport-Driven Flow Component: Should Agree with Measured Transport

- Model transport-driven poloidal particle flux as $\sin(\theta)$ on LFS
- Constrain with measured value of poloidal flux on HFS

$S$: Normalized poloidal distance from outer to inner divertor

$n_{\theta}/B_{\theta}$ Toward Inner Divertor

$n_{\theta}$ [10^22 m^2 s^-1]

Depth into SOL [mm]
Transport-Driven Flow Component:
Should Agree with Measured Transport

- Model **transport-driven poloidal particle flux** as \( \sin(\theta) \) on LFS
- Constrain with measured value of **poloidal flux** on HFS
- Calculate **LFS radial particle flux** implied by HFS poloidal flux

\[
S = \frac{\text{normalized poloidal distance from outer to inner divertor}}{\text{HFS}}
\]

\[
\nu_r, \nu_\theta [10^{20} \text{m}^{-2} \text{s}^{-1}]
\]

**Graphs:**
- LFS: 
  - \( \nu_r \)
  - \( \nu_\theta \)
- HFS: 
  - \( \nu_\theta \)
Transport-Driven Flow Component:
Consistent with LFS fluctuation-induced radial flux data

- Model transport-driven poloidal particle flux as \( \sin(\theta) \) on LFS
- Constrain with measured value of poloidal flux on HFS
- Calculate LFS radial particle flux implied by HFS poloidal flux
- Result shows agreement with measurements of fluctuation-induced particle flux on the LFS through \( \bar{n}E_{i} \)
Sink for **Transport-Driven** Flow

- There must be an efficient particle sink on the HFS to sustain pressure gradients driving near-sonic **transport-driven** parallel flows.
- Could particles be returning to the core via a **HFS convective pinch**? This is a solution commonly employed by 2-D edge codes to explain HFS flows.\(^2\,3\,4\)

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

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Measurement of HFS Pinch Velocity

- HFS radial particle flux is robustly zero.
- Hint of pinch near LCFS from 2007 data was shown by improved statistics to be anomalous.
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Evidence that **Volume Recombination** Plays a Key Role in Closing Flow Loop

**USN, No MARFE**

![Image showing HFS Probe Location](image)

- **Electron Pressure**
  - $n_e T_e \times 10^{20} \text{ eV/m}^3$
  - LCFS
  - HFS
  - 0 [mm] into SOL to 10 [mm] into SOL

- **Parallel Mach #**
  - 0 [mm] into SOL to 10 [mm] into SOL
  - LCFS
  - HFS
  - To Divertor

Strong flow to partially-detached inner divertor
Evidence that **Volume Recombination** Plays a Key Role in Closing Flow Loop

**USN, No MARFE**

Strong flow to partially-detached inner divertor.

**USN, MARFE in Lower Chamber**

~ no plasma makes it around MARFE to populate **HFS**. Residual flow is towards MARFE (**recombination** zone).
Evidence that Volume Recombination Plays a Key Role in Closing Flow Loop

USN, No MARFE

USN, MARFE in Lower Chamber

MARFE closes the flow loop. Calls for careful modeling of inner divertor recycling / recombination effects.
Conclusions

- ExB flow data show that transport-driven parallel flows are responsible for net poloidal motion of HFS plasma toward active x-point.
- Measured drift-driven flows are divergence-free.
- Transport-driven poloidal particle flux is consistent with measured LFS fluctuation-induced radial particle flux.
- HFS particle pinch is zero; this is not the mechanism that closes the mass flow loop on the HFS.
- Recycling / recombination physics in inner divertor leg is a strong candidate to close mass flow loop.