Poloidal Transport Asymmetries, Edge Plasma Flows and Toroidal Rotation in Alcator C-Mod


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Motivation: Strong parallel flows ($M_{//} \sim 0.5$) have been seen in the SOLs of many tokamaks, far from material surfaces...

....yet, the underlying physics has not been fully resolved

Questions:

Do these flows impact SOL impurity transport & screening from core?  
...balance of material erosion/deposition in divertor legs (e.g. JET)?

Are SOL flows just a passive, local response?  
Or, do they couple to flows in the confined plasma in any significant way?

Focus of this talk:

SOL plasma flow experiments in Alcator C-Mod  
- plasma flow pattern  
- underlying drive mechanisms
Key Results: A remarkable interplay between ballooning-like transport, parallel plasma flows and toroidal rotation

- A cross field transport-driven plasma circulation loop is evident in C-Mod
  - ballooning-like transport
  - x-point topology sets // flow direction
  - promotes main-chamber impurity migration toward inner divertor

- SOL flows set flow boundary conditions for confined plasma
  - x-point dependent toroidal rotation of core!
  => x-point dependent toroidal rotation of SOL

Surprising result:

- Topology-dependent SOL flow boundary condition may explain sensitivity of L-H power threshold on upper/lower x-point topology!
Outline of Talk

- Profiles & Parallel Flows in High and Low-Field Side SOLs
- Cross-Field Flow Information
- Flux-Tube Particle Balance Analysis
- X-point Dependent Flow Boundary Conditions Imposed on Confined Plasma
- Connection to L-H Power Thresholds & Topology

Diagnostics:

Inner Scanning Probe

Outer Scanning Probe

Inner Wall Probe: N. Smick, P1-56
Inner Wall Doppler: K. Marr, P2-42
Scrape-off Layer Profiles Reveal Transport Asymmetries and Topology-Dependent Near-Sonic Parallel Plasma Flows

**Independent of Topology**
- Lower average $T_e$, higher average density on high-field side (inner) SOL
- Lowest $T_e$ are detected by inner probe when facing inner strike-point

**Dependent on Topology**
- Inner SOL: Near-sonic parallel flow is co-current directed (+) in LSN, counter-current directed (-) in USN
- Outer SOL: Stronger co-current flow in LSN, weaker in USN
Near-Sonic Inner SOL Flows are Connected to Cross-field Transport Asymmetries

$B \times B$

Electron Pressure

RMS $J_{sat}/\langle J_{sat} \rangle$

Toroidal Projection of Parallel Velocity
Near-Sonic Inner SOL Flows are Connected to Cross-field Transport Asymmetries

Inner SOL plasma 'disappears' in Double Null! $L_{nT}$ reduced by factor of 4!
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- Fluctuation levels persistently lower on inner SOL
  - (See: J. Terry, O-9)
  - Consistent with low $\parallel$ transport in inner SOL
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Inner SOL // flows are always directed from outer to inner SOL in upper and lower-null, but ~stagnant in double-null
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Plasma exists on inner SOL because it flows along field lines from outer SOL!
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- Fluctuation levels persistently lower on inner SOL
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  **Consistent with low transport in inner SOL**

- Outer SOL flows weaker, co-current, appear *modulated* by topology
  (Location is near poloidal flow stagnation point)

- Inner SOL // flows are always directed from outer to inner SOL in upper and lower-null, but ~stagnant in double-null

⇒ Plasma exists on inner SOL *because it flows along field lines from outer SOL!*
Near-sonic parallel flows, $V_{//}$, on inner SOL appear to be transport-driven, i.e., driven by ballooning-like cross-field transport asymmetries:

$V_{//}$ includes cross-field fluid drift, $V^\perp$:

$\Rightarrow$ link between Inner SOL flow direction/magnitude and magnetic topology

However, total plasma flow vector, $V$, includes cross-field fluid drift, $V^\perp$:

$\Rightarrow$ Need to examine cross-field flow information
Plasma flow direction depends on Upper/Lower Null topology, identical to that seen by Inner Mach Probe

Impurity dispersal pattern is closely aligned with magnetic field line

**Inner SOL flows dominated by parallel flow component**

**Direct evidence of wall-source impurity migration toward inner divertor leg**

Outer SOL Plasma Flows: Largely Toroidal Rotation and/or Pfirsch-Schlüter Flow

Outer probe data from matched discharges with normal and reversed $I_p$ & $B_T$

- Parallel Mach numbers reverse direction when $I_p$ & $B_T$ reverse
- Similar reduction in flow as normalized density is increased

$\Rightarrow$ Consistent with parallel flow arising from co-current toroidal rotation and/or Pfirsch-Schlüter contributions

Case of pure toroidal rotation:

$V_∥ = E_r/B_∥$

Normal $B$:

Reversed $B$:

$V_∥$ reverses with $B$
Outline of Talk

• Profiles & Parallel Flows in High and Low-Field Side SOLs

• Cross-Field Flow Information

• **Flux-Tube Particle Balance Analysis**

• X-point Topology-Dependent Flow Boundary Conditions Imposed on Confined Plasma

• Connection to L-H Power Thresholds & Topology
Data can be Mapped to a "Flux-Tube Coordinate", $S$, Revealing Transport-Driven Component of Parallel Flow
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Definition of flux-tube coordinate, S

Data from matched Lower-Null and Upper-Null discharges

![Diagram showing flux-tube coordinate and data points for Electron Pressure, nTe, Mach Number, M//, and nTe(1+ M//^2/2).]
Data can be Mapped to a "Flux-Tube Coordinate", $S$, Revealing Transport-Driven Component of Parallel Flow

Definition of flux-tube coordinate, $S$

- Lower $nT_e$ on Inner SOL

Data from matched Lower-Null and Upper-Null discharges
Data can be Mapped to a "Flux-Tube Coordinate", S, Revealing Transport-Driven Component of Parallel Flow

- Lower $nT_e$ on Inner SOL
- Transport-driven parallel flow from Outer to Inner SOL

Toroidal rotation, Pfirsch-Schlüter flows, ... ...appear as offsets to average of ▼ + ▲
Data can be Mapped to a "Flux-Tube Coordinate", S, Revealing Transport-Driven Component of Parallel Flow

Definition of flux-tube coordinate, S

- Lower Null
- Upper Null

- Lower $nT_e$ on Inner SOL
- Transport-driven parallel flow from Outer to Inner SOL
  Toroidal rotation, Pfirsch-Schlüter flows, ...
  ...appear as offsets to average of ▼ + ▲
- Thermal + flow energy ~constant

Data from matched Lower-Null and Upper-Null discharges

Mach Number, $M_{//}$

Electron Pressure, $nT_e$

$nT_e(1 + M_{//}^2/2)$

Normalized distance along field line, S
Data can be Mapped to a "Flux-Tube Coordinate", $S$, Revealing Transport-Driven Component of Parallel Flow

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  Toroidal rotation, Pfirsch-Schlüter flows, ...
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- Thermal + flow energy $\sim$constant

Net flow of plasma out ends of flux tube requires a net particle source into (□) flux tube

Data from matched Lower-Null and Upper-Null discharges

$\Box = 4$ mm

- Electron Pressure, $nT_e$
- Mach Number, $M_{//}$
- $nT_e(1 + M_{//}^2/2)$

Normalized distance along field line, $S$
Flux-Tube Particle Balance Analysis: Net Particle Source Profiles Exhibit Ballooning Asymmetry

Probe Data:
- Upper Null
- Lower Null

Model:
- Parallel Mach Number
- Net Particle Source

...conserving particles & \parallel momentum
Flux-Tube Particle Balance Analysis:
Net Particle Source Profiles Exhibit Ballooning Asymmetry

Probe Data:
- ▲ Upper Null
- ▼ Lower Null

Model:
- Parallel Mach Number
- Net Particle Source
  - ...conserving particles & // momentum

A transport-driven plasma circulation loop is implied!

- Cross-field transport overpopulates flux tubes on the low-field side, driving parallel flow
- The resultant circulation loop likely closes via cross-field fueling near the inner divertor region
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Flux-tube coordinate, S

Parallel Mach Number

Outer SOL  Inner SOL

Note: A separate set of radial fluxes associated with main-chamber recycling and ionization can be superimposed
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Diagnostics:

- Ar\textsuperscript{17+} X-ray Doppler
- Inner Scanning Probe
- Outer Scanning Probe
- Vertical Scanning Probe
X-point Topology Sets Magnitude and Direction of Transport-Driven SOL Flows => Core Plasma Rotation is Affected

Distance Between Primary and Secondary Separatrix (mm)

- Toroidal Projection of Parallel Velocity (km s⁻¹)
- Toroidal Velocity (km s⁻¹)

- Inner Probe □ = 2 mm
- Outer Probe □ = 1 mm
- Core Ar¹⁷⁺ Doppler

- Upper Null
- Double Null
- Lower Null

Ip ⊗ BT ⊗

BxB
X-point Topology Sets Magnitude and Direction of Transport-Driven SOL Flows => Core Plasma Rotation is Affected

- Toroidal projections of flows near separatrix shift toward counter-current in sequence: lower => double => upper-null
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- Central plasma toroidal rotation correspondingly shifts more toward counter-current direction
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- Toroidal velocity change is largest on inner SOL => suggests inner SOL flow is responsible for change in rotation of confined plasma!

Transport-driven SOL flows impose boundary conditions on confined plasma
If Transport-Driven SOL Flow/Rotation Paradigm is Correct, Radial Electric Fields in SOL Should Depend on X-point Topology

- transport-driven parallel SOL flows

• Ballooning-like transport leads to a helical flow component in the SOL with *net volume-averaged toroidal momentum*: co-current for lower null, counter-current for upper null
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- Being free to rotate only in the toroidal direction, the confined plasma acquires a corresponding **co-current** or **counter-current** rotation increment

Influence on plasma rotation
If Transport-Driven SOL Flow/Rotation Paradigm is Correct, Radial Electric Fields in SOL Should Depend on X-point Topology

- transport-driven parallel SOL flows

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Influence on plasma rotation

• Via momentum coupling across separatrix, a topology-dependent toroidal rotation component, $E_r/B$, should appear in the SOL

  => Stronger $E_r$ in SOL for lower null
  => Weaker $E_r$ in SOL for upper null
Plasma Potentials Near Separatrix Systematically Increase in the Sequence: **Upper, Double, Lower-Null**

- More positive $E_r$ in SOL near separatrix in **Lower-Null**
  - $E_r/B_\parallel \sim 5$ km/s, a significant fraction of measured change in parallel flow

=> Consistent with an increased co-current plasma rotation in lower-null, arising from transport-driven SOL plasma flows!
Transport-driven SOL flows lead to topology-dependent toroidal plasma rotation (and $E_r$) near separatrix.

- SOL widths are unchanged; Toroidal rotation $\neq 0$ near wall.
  
  => Implies **toroidal velocity shear** ($E_r \times B$ shear) near separatrix is:

  stronger  |  weaker

$L-H$ transition is thought to involve velocity shear suppression of plasma turbulence.

=> May explain why the L-H power threshold is *lower when $B \times B$ is pointing toward the x-point!*
L-H Transition Coincides with Plasma Rotation Attaining Roughly the Same Value, Independent of Topology

Input power level to attain L→H depends on x-point topology

Ohmic+ICRF => no momentum input
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- Input power level to attain L→H depends on x-point topology
  - Ohmic+ICRF => no momentum input

- Edge \(T_e\) and electron pressure gradients at L→H transition also different

- But ramps toward co-current as pressure gradients build up

- Plasma rotation during ohmic phase starts out counter-current in USN....

--- SOL flow boundary condition!
**L-H Transition Coincides with Plasma Rotation Attaining Roughly the Same Value, Independent of Topology**

- **Line Averaged Density**
- **ICRF Power**
- **Electron Temperature**
- **Max $\frac{p_e}{n_e}$ from TS**
- **$\text{Ar}^{17+}$ Toroidal Velocity**

**Input power level to attain L$\rightarrow$H depends on x-point topology**

**Ohmic+ICRF => no momentum input**

**Edge $T_e$ and electron pressure gradients at L$\rightarrow$H transition also different**

**...but ramps toward co-current as pressure gradients build up**

**Similar rotation at the L$\rightarrow$H transition!**

**Plasma rotation during ohmic phase starts out counter-current in USN...**

--- SOL flow boundary condition!

**=> Potential explanation for x-point topology dependence of L-H power threshold**
Summary

- A cross field transport-driven plasma circulation loop is evident in C-Mod ballooning-like transport
  x-point topology sets // flow direction promotes main-chamber impurity migration toward inner divertor

- SOL flows set toroidal rotation boundary conditions for confined plasma x-point topology and toroidal rotation near separatrix are linked!
Summary

- Possible explanation for the x-point dependence of L-H power threshold

\[ \text{SOL flows + topology influence flow shear near separatrix} \]

L-H threshold studies with different x-point topologies support hypothesis

L-H transition is coincident with toroidal rotation achieving similar level, independent of x-point topology

SOL flows impede co-current rotation with upper x-point

Correspondingly, more input power (which promotes co-rotation) is required