Plasma flows and critical gradient phenomena near the last-closed flux surface

B. LaBombard
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  - Connection to magnetic topology (LSN/USN)
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L-H threshold power: lower with 'favorable' SOL flows (LSN or lower-limited)
Transport-driven plasma flows in the SOL
Scrape-off layer flow patterns in a tokamak are complex - Near-sonic flow along field lines occurs *far from material surfaces*

Representative composite of parallel flow data† from JT60-U, JET, C-Mod

- Strong flows along $B$ ($M_{||} \sim 0.5$)
- Components which are both dependent and independent of the sign of $B$

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...Driving Near-Sonic Flows in Inner SOL
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Inner SOL plasma 'disappears' in Double Null

$\ln T$ reduced by factor of 4
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Consistent with low transport in inner SOL
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Outer SOL flows weaker, co-current, appear modulated by topology...

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

Distance Between Primary and Secondary Separatrices (mm)
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- Toroidal projections of flows near separatrix shift toward counter-current in sequence: lower => double => upper-null
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  => suggests inner SOL flow is responsible for change in rotation of confined plasma
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Transport-driven SOL flows impose boundary conditions on confined plasma
Transport-Driven SOL Flows: a mechanism for plasma near the separatrix to 'spin-up' toroidally, depending 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 can acquire a corresponding co-current or counter-current rotation increment.

Influence on plasma rotation.
Transport-Driven SOL Flows: a mechanism for plasma near the separatrix to 'spin-up' toroidally, depending on x-point topology

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- Via momentum coupling across separatrix, a topology-dependent toroidal rotation component, \( E_r/B_\parallel \), should appear in the SOL

\[ \Rightarrow \text{Stronger } E_r \text{ in SOL for lower null} \]
\[ \Rightarrow \text{Weaker } E_r \text{ in SOL for upper null} \]
Plasma Potentials Near Separatrix Systematically Increase in the Sequence: **Upper**, **Double**, **Lower-Null**

Plasma potential profiles estimated from sheath potential drop

Caution: Accuracy of potential profile shape is uncertain!

- More positive $E_r$ in SOL near separatrix in **Lower-Null**

$|E_r/B| \sim 8 \text{ km/s}$, $\sim$consistent with measured change in parallel (toroidal) flow in SOL
Critical gradient phenomena near the separatrix
'Critical Gradient' transport behavior is suggested in first-principles 3-D Electromagnetic Fluid Diffusion turbulence simulations†

Turbulence character & transport level determined primarily by two dimensionless parameters

Poloidal Beta Gradient $\nabla_{MHD} \sim q^2 R \frac{P}{B^2}$

Inverse Collisionality Parameter $\nabla_d \sim \frac{1}{q} \left( \frac{\nabla_{el}}{R} \right)^{1/2} \left( \frac{R}{L_n} \right)^{1/4}$

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Electron Heat Diffusivity [3]

$\Box_e \sim \frac{10^0 \Box_{MHD}}{10^0}$

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Electron Heat Diffusivity [3]

edge plasma state restricted to this band

"critical gradient"

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*Phase Space* of EMFDT

- Increasing collisionality transport depends on location in \((\Box_{MHD}, \Box_d)\) 'phase-space'.

---

[3] B. Scott
Results from 2000 campaign:†
Plasma states near separatrix are indeed found to occupy a well-defined region in the phase space of EMFDT

Discharges with different machine parameters: $B_T, I_p, \overline{n_e}$

Low-power Ohmic L-mode discharges
Density: $0.14 < \frac{n}{n_G} < 0.53$
Lower single-null
Forward $I_p, B_T$

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Discharges with different machine parameters: \( B_T, I_p, \bar{n}_e \)

...occupy in a similar band in \( B_{MHD}, \bar{d} \) space

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Lower single-null
Forward \( I_p, B_T \)

A region of high \( B_{MHD} \) at high density is inaccessible, owing to an explosive growth of cross-field transport

\[ \bar{d} \sim \frac{1}{q} \frac{n_e}{q R} \frac{1}{2} \frac{R}{L_n} \]

\[ \bar{n}_e \sim \frac{1}{q} \frac{n_e}{q R} \frac{1}{4} \frac{R}{L_n} \]

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Ohmic H-modes evolve from L-modes at the low collisionality boundary, increasing in $\square_{MHD}$

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Pressure gradients near the separatrix appear to clamp at similar values of \( q_{95} \) when normalized collisionality is held fixed.

Look at pressure profile data from discharges with \( d \sim 0.35 \), 2 mm from separatrix.
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$I_P$ Scan:
Pressure gradients scale roughly as $I_P^2$ => similar $I_{P, MHD}$.
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$I_p$ Scan:
Pressure gradients scale roughly as $I_p^2$ => similar $MHD$

$B_T$ Scan:
No sensitivity to toroidal field

$=>$ Pressure gradient near separatrix set by a 'critical poloidal beta gradient'
Coupling between flows and critical gradient?
Is there any evidence that edge plasma flows affect the 'critical gradient' (\( \nabla_{MHD} \)) seen near the separatrix?

New experiments (2005 & 2006)

Extended range of \( I_p, B_T \)

Density scans: 0.1 < \( n/n_G < 0.5 \)
with lower currents (0.4 MA)
and fields (4, 3.2=>2.7 tesla)

Improved scanning probe diagnostics
New experiments (2005 & 2006)

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![Graph showing extended range of \(I_p\) and \(B_T\) with different \(q_{95}\) values: \(q_{95} = 6.5\), \(q_{95} = 5\), and \(q_{95} = 3.5\).]

Density scans: \(0.1 < n/n_G < 0.5\) with lower currents (0.4 MA) and fields (4, 3.2\(\rightarrow\)2.7 tesla)

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Lower vs upper-null topologies

SOL flows change dramatically with X-point location

What is influence on SOL 'phase-space'?

=> Run matched discharges with upper and lower null
New Results (2005 & 2006) -
Pressure gradients near sep. consistently scale as $I_p^2$

... but value depends on lower / upper X-point topology
New Results (2005 & 2006) - Alcator C-Mod

Pressure gradients near sep. consistently scale as $I_p^2$

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Edge plasma states again align in EMFDT phase-space, but in two bands

Lower null achieves higher values of $\Box_{MHD}$ compared to upper null at high collisionality
Plasma flows in the SOL are dramatically different in Lower vs Upper null topologies... perhaps affecting the attainable values of $\square_{MHD}$.

- Plasma flows from low to high-field side (ballooning-like transport drive)
Plasma flows in the SOL are dramatically different in Lower vs Upper null topologies

... perhaps affecting the attainable values of $\mathcal{M}_{MHD}$

- Plasma flows from low to high-field side (ballooning-like transport drive)
- Low-field side flows near sep. are affected (~toroidal rotation)
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- Low-field side flows near sep. are affected (~toroidal rotation)

- Highest $\Omega_{MHD}$ is achieved when flow is positive (co-current) on low-field side
  => favors lower null topology

(Note: lower null also has lowest L-H threshold power)
Summary

Key plasma phenomena in edge/pedestal region

- Strong 'transport-driven' plasma flows exist just outside the LCFS
  Ballooning-like transport drive, x-point (and limiter) dependent flow pattern, a flow boundary condition for the confined plasma

- Plasma near the separatrix exhibits a 'critical gradient' \( (\theta_{MHD}) \) behavior
  Accessible L-mode edge states map to a \( (\theta_{MHD}, \theta_d) \) 'phase space'
  Mapping is invariant of machine parameters for fixed magnetic topology:
  \( 0.4 < I_p < 1 \text{ MA}, \ 2.7 < B_T < 6 \text{T}, \ 0.1 < \frac{n_e}{n_G} < 0.5 \)
  Broadly consistent with behavior in EMFDT simulations

- **Lower null** topology leads to higher \( \theta_{MHD} \) than **Upper null**
  when equilibrium plasma flows near the separatrix are different
  Co-current plasma flows in the SOL are associated with higher \( \theta_{MHD} \)
  => Flow is another phase space parameter (\( \theta_{MHD}, \theta_d, M,... \))