Scrape-off layer flows, toroidal rotation and critical gradient phenomena in the tokamak edge

Presented by B. LaBombard

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J. Boedo
A. Graf
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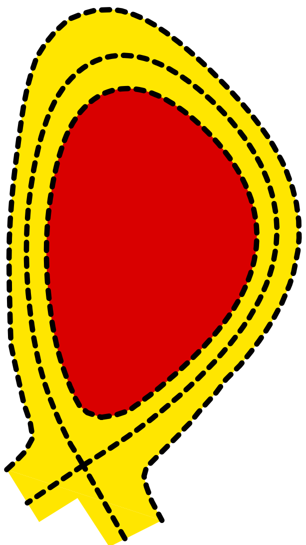
K. Marr
R. McDermott
M. Reinke
N. Smick
J.L. Terry
D.G. Whyte
S.J. Zweben
Alcator C-Mod Team
....

Edge Plasma Region -- interface between open and closed magnetic field lines; plays key role in tokamak performance...



- **Steep gradient region, L-mode and H-mode 'pedestals'**

  Plasma performance tied to pedestal height

- **Power and particle exhaust**

  Width of scrape-off layer sets divertor heat fluxes
  ELM phenomena, quasi-coherent modes, ...

- **Impurity control**

  Impurity 'screening', plasma flows, inward pinches, ...

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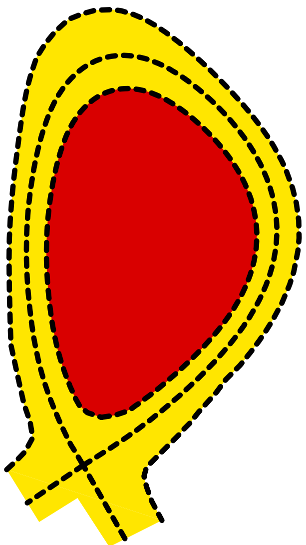

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- **Questions & Research Goals:**

  Underlying physics **that sets the transport levels, gradients, SOL widths?**

  Connections **among transport, plasma flows, magnetic topology, ...**
  (e.g. L-H power threshold)

  First-principles*, *predictive model **for edge plasma?**

  => *Some progress, but we have a long way to go...*

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Alcator C-Mod

...with evidence of close coupling among all parts

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- **Potential connection to the x-point dependence of the L-H power threshold:**
  - **Favorable Bx∇B => co-current SOL flows => co-current rotation => lower L-H power threshold**

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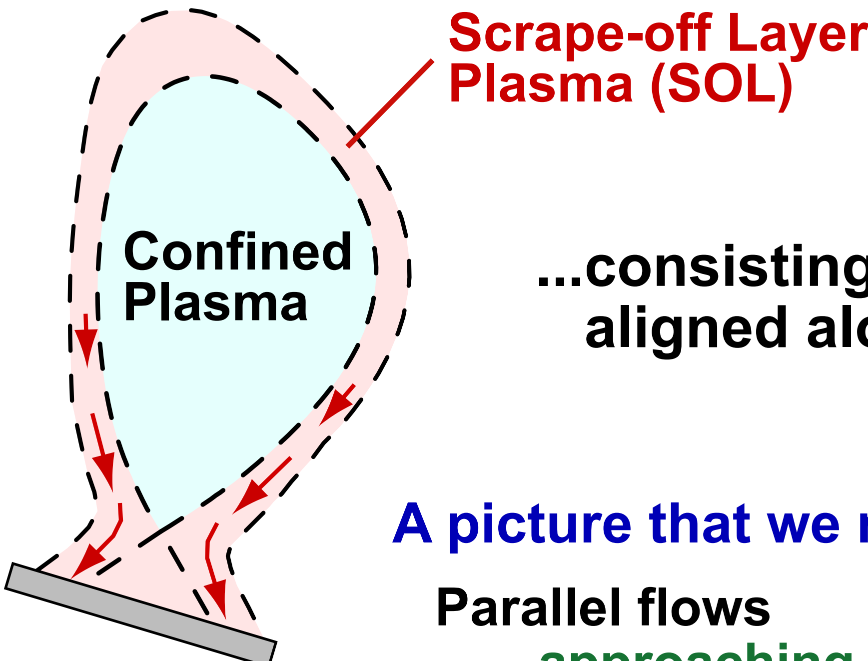
- **Interplay between 'critical gradient' behavior and SOL flows?**
  - L-mode: attainable value of α_{MHD} depends on Bx∇B direction
    - => edge flows, toroidal rotation are correspondingly different
  - ... a recurrent theme, consistent with L-H power threshold observations

Scrape-off Layer Flows

Scrape-off layer plasma flows.... a simple phenomenon... right?

- We expect some plasma flow on the open field-lines that surround a magnetically confined plasma volume



...consisting of flow components aligned along and across magnetic field lines

A picture that we might expect:

Parallel flows

- approaching sonic speed near material surfaces, $V_{//} \sim C_S$

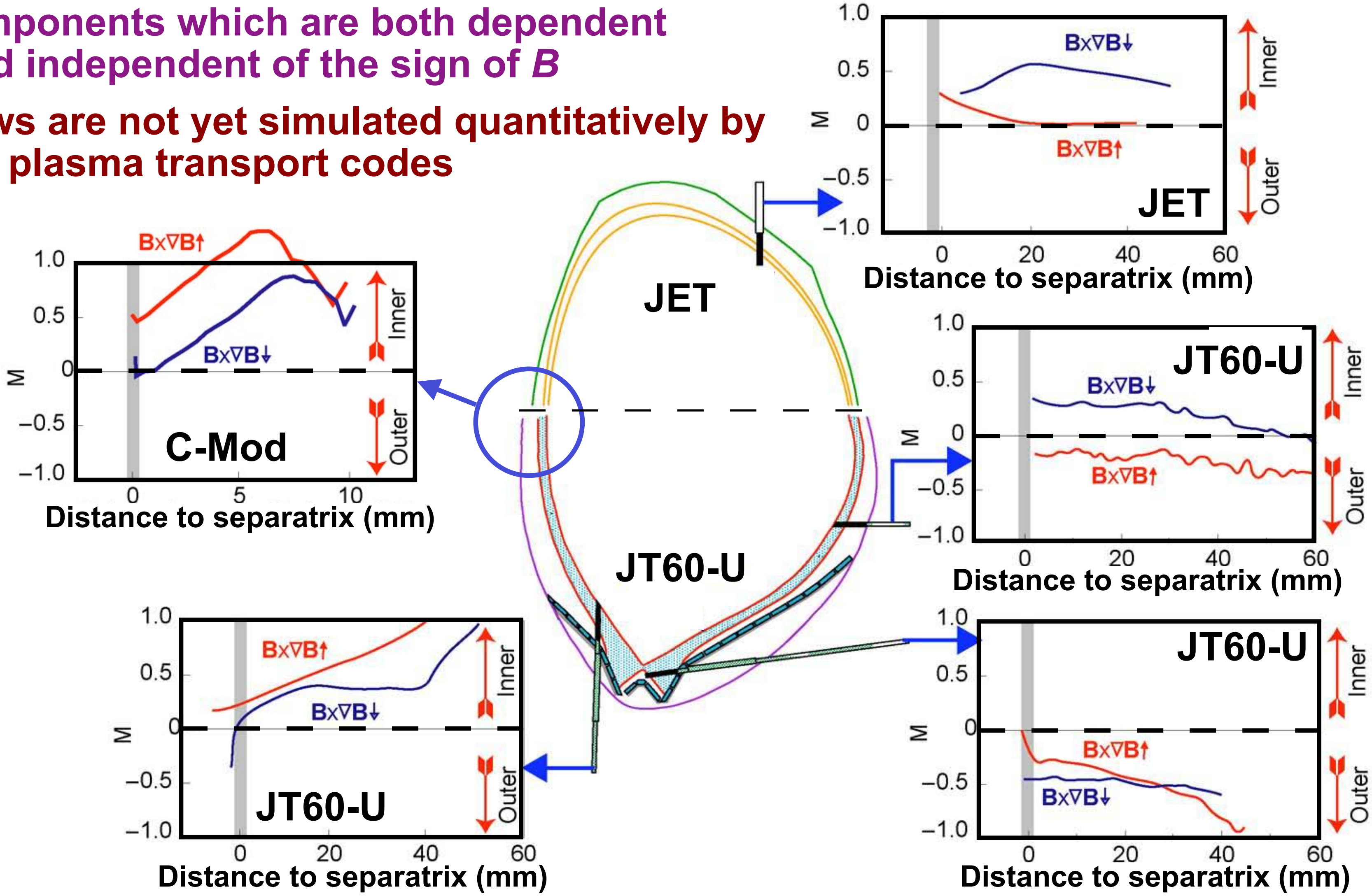
Cross-field (ExB) flows within magnetic flux surfaces

- $V_{\perp} \sim \nabla_{\perp} T_e / B$

Not Simple! Scrape-off layer flow patterns in a tokamak are complex - Near-sonic flow along field lines occurs *far from material surfaces*

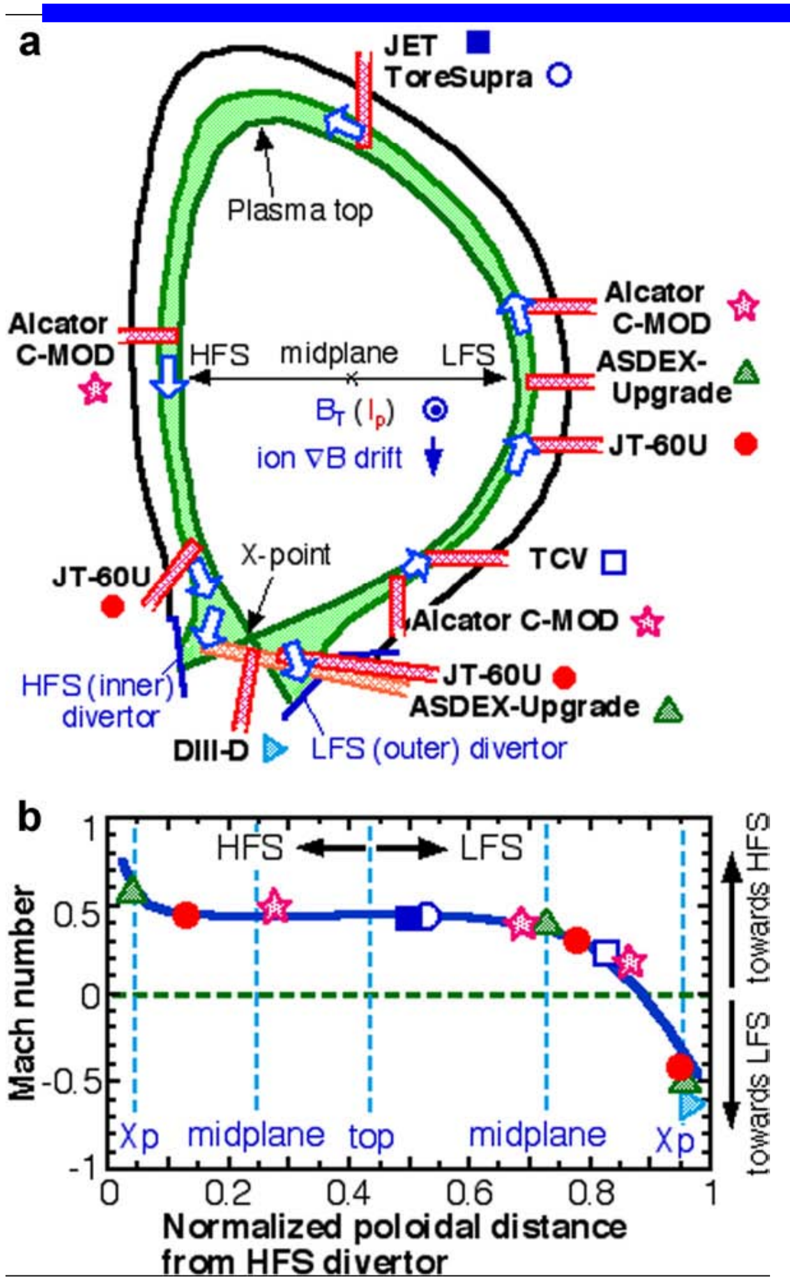
Representative composite of parallel flow data† from JT60-U, JET, C-Mod

- Strong flows along *B* ($M_{//}$ ~ 0.5)
- Components which are both dependent and independent of the sign of *B*
- Flows are not yet simulated quantitatively by 2-D plasma transport codes



†G. Matthews, J. Nucl. Mater. **137-139** (2005) 1.

Expanded composite picture from many tokamaks† paints consistent story -- Near-sonic parallel flows circulate around confined plasma

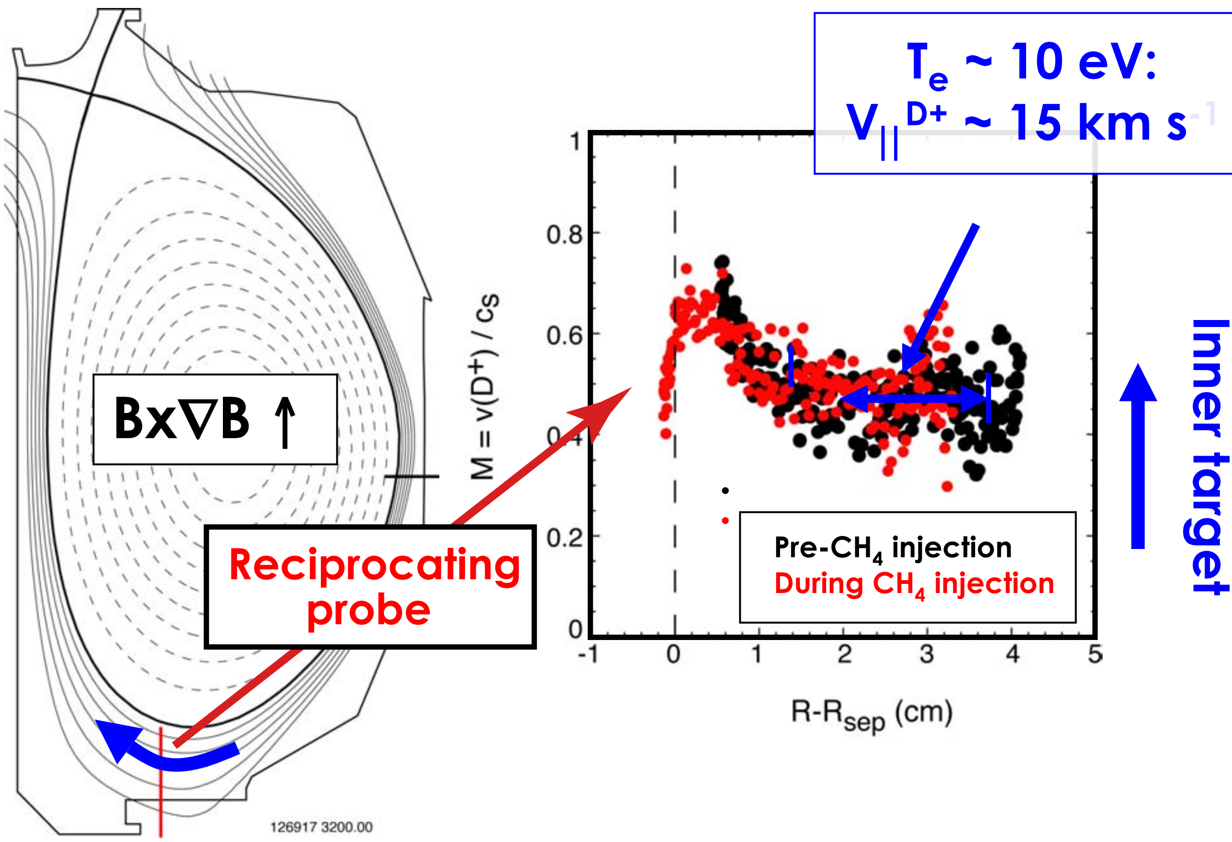


=> Parallel flow pattern is independent of the details of divertor/wall geometry

†N. Asakura, J. Nucl. Mater. **363-365** (2007) 41.

Strong parallel flows from low- to high-field SOL are also evident in DIII-D†, matching and extending original JET results

Reciprocating Mach probe: main ion flow in the crown is toward the inner divertor target at Mach ~ 0.5



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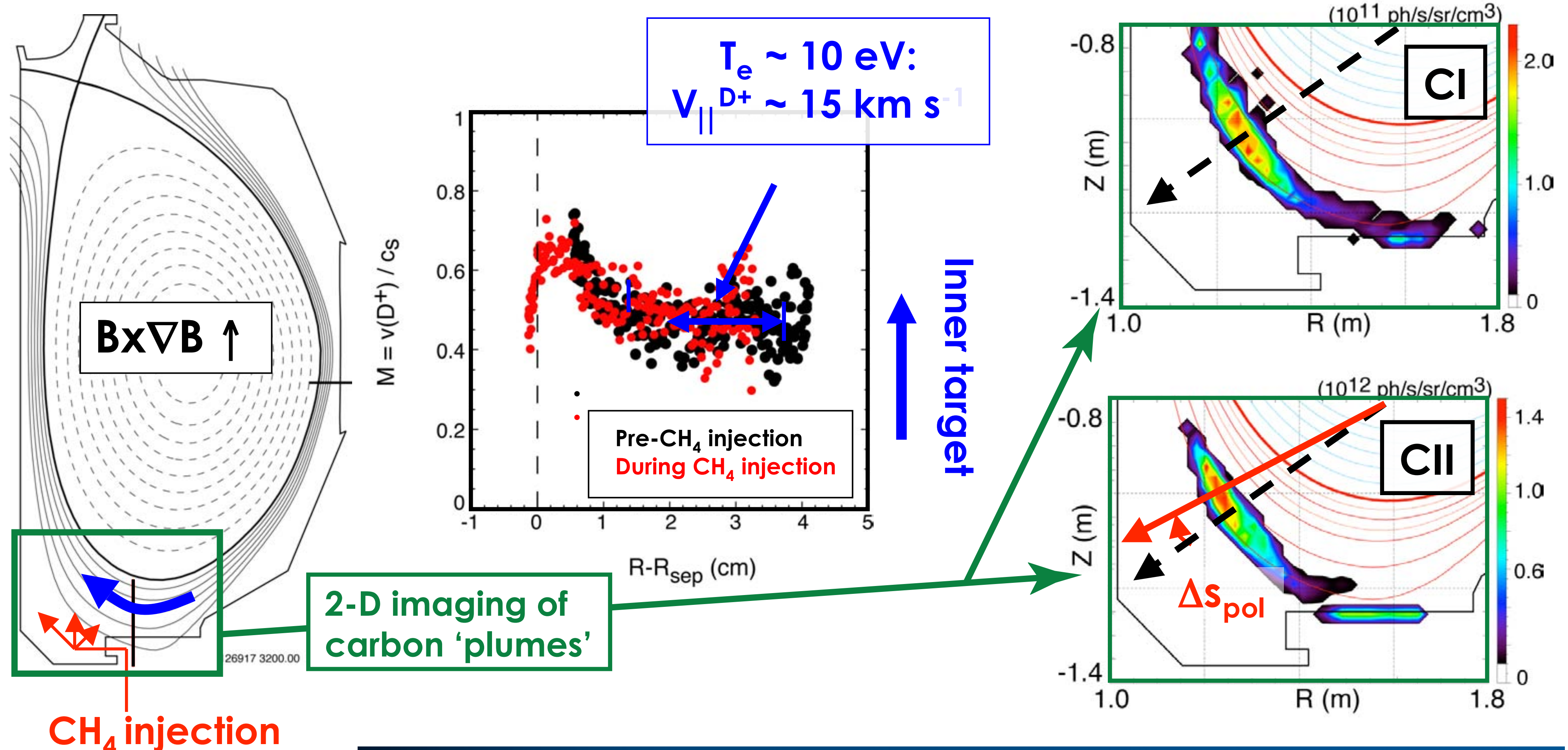

Poloidal shift of CII against CI emission and SOL plasma conditions put C^{1+} ion velocity at ~ 5-10 km/s

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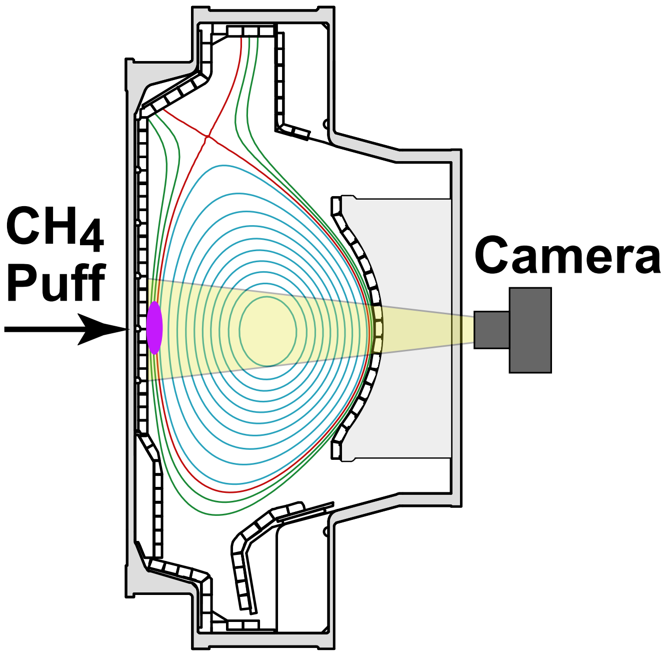
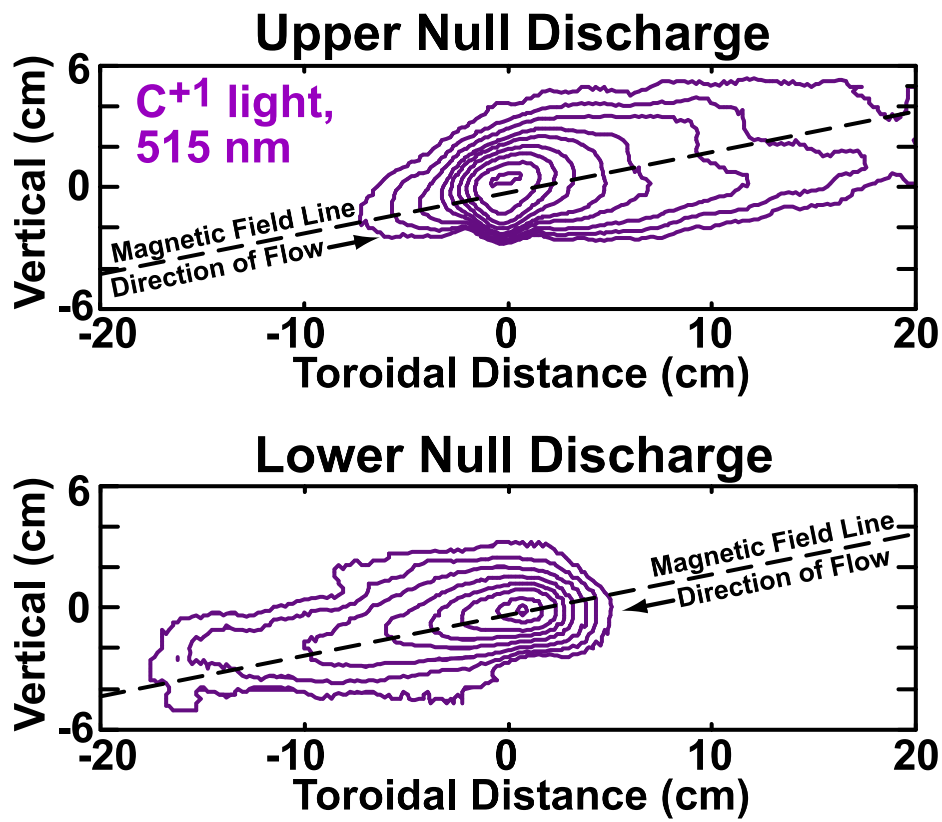
C-Mod Gas Injection Experiments: Strong High-field Side SOL Flows, Closely Aligned with Magnetic Field Lines

Alcator C-Mod

Data from C^{+1} "plumes" at inner midplane location†





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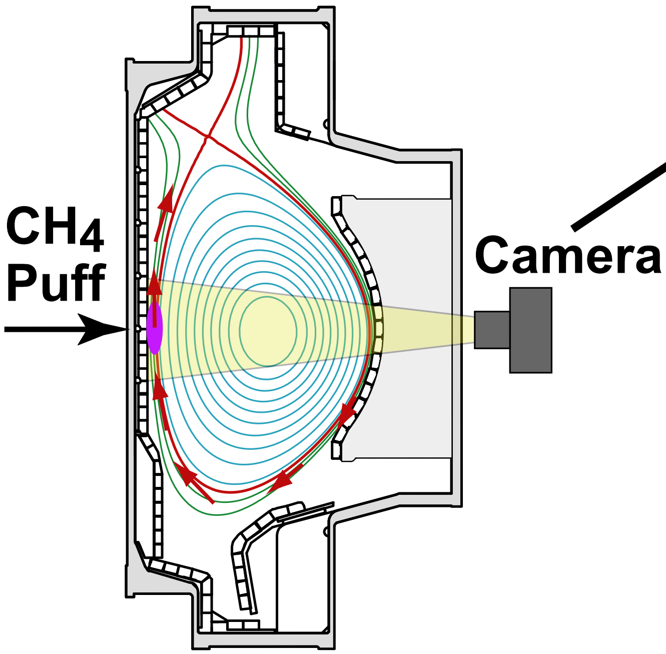

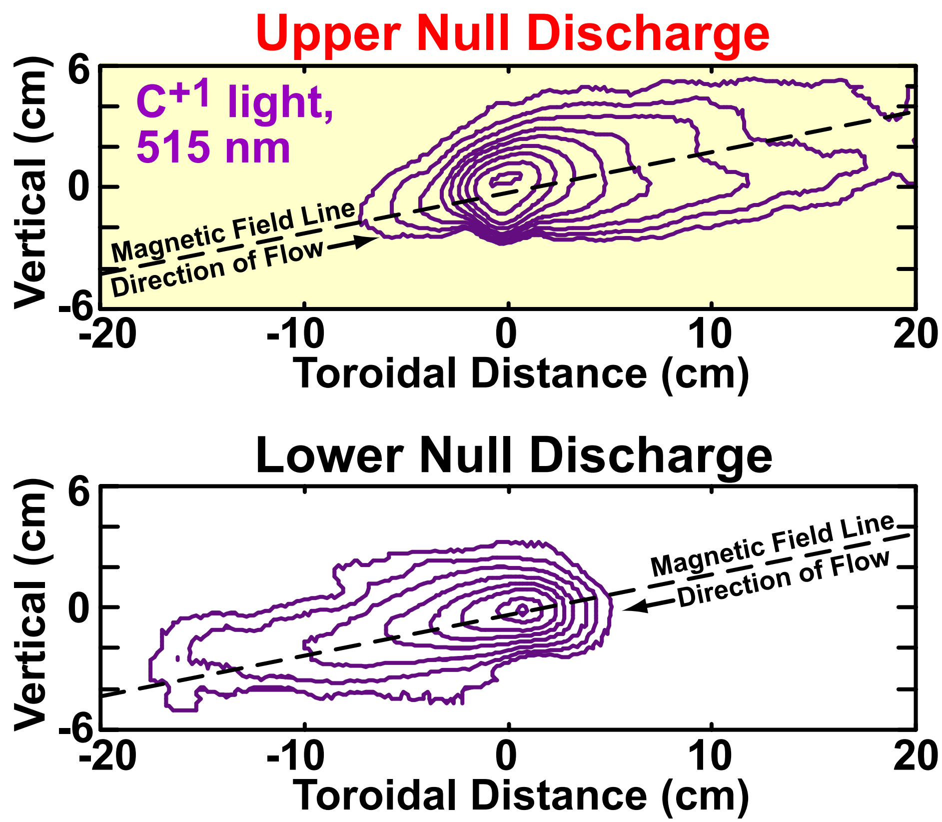

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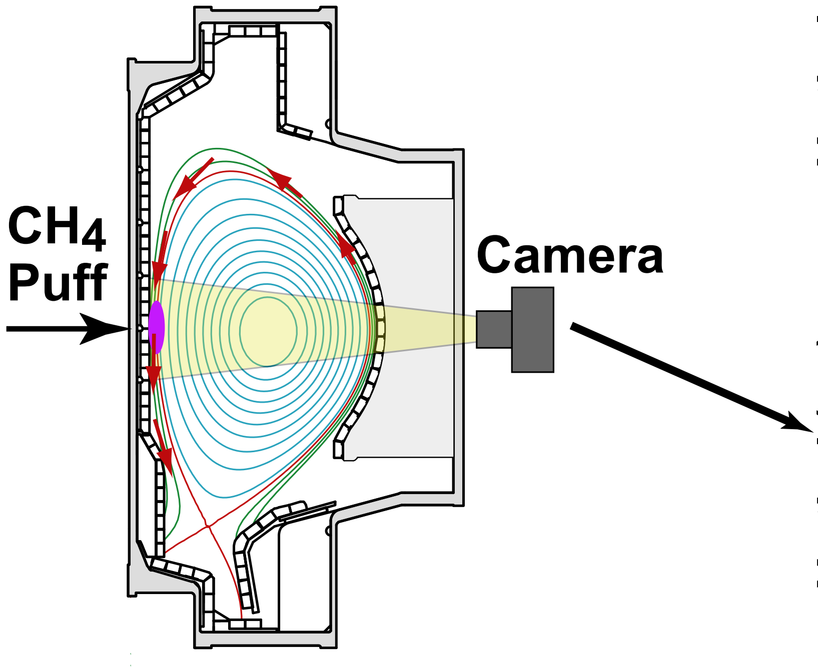

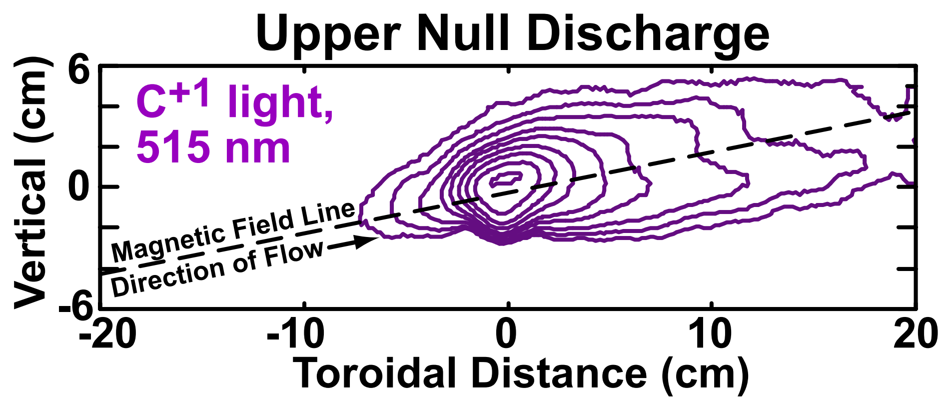

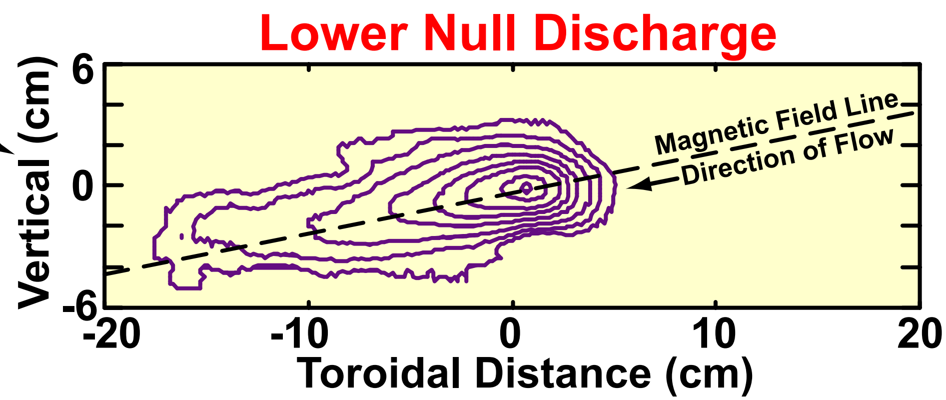

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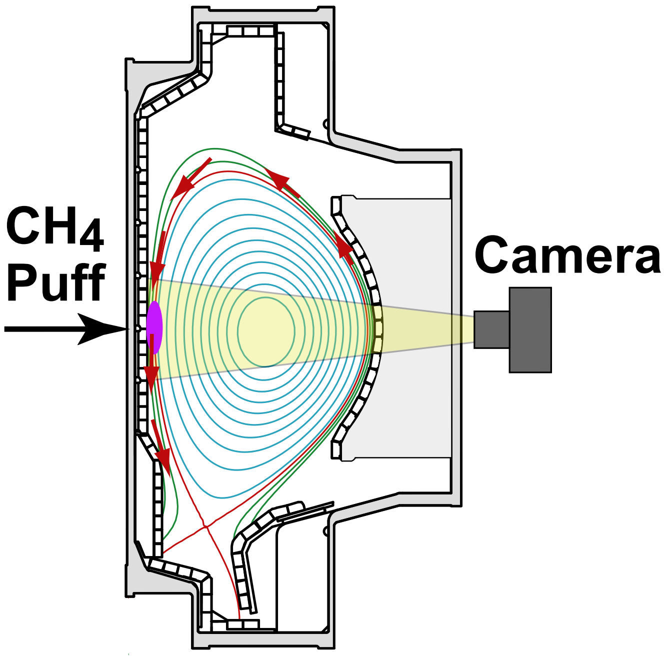

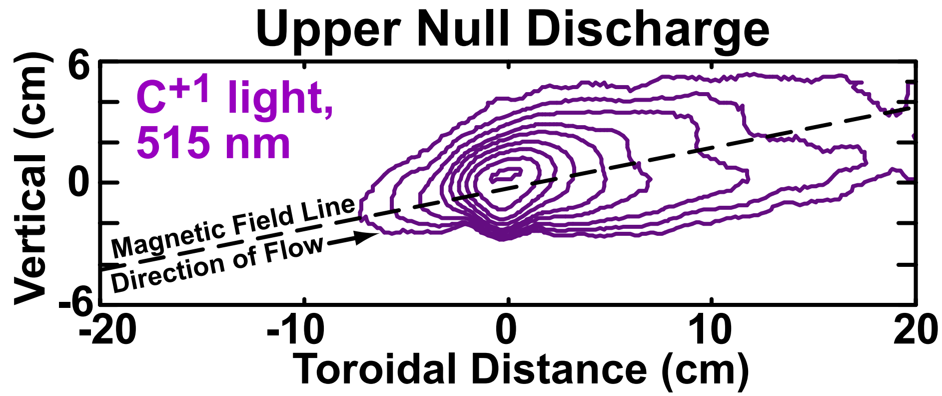

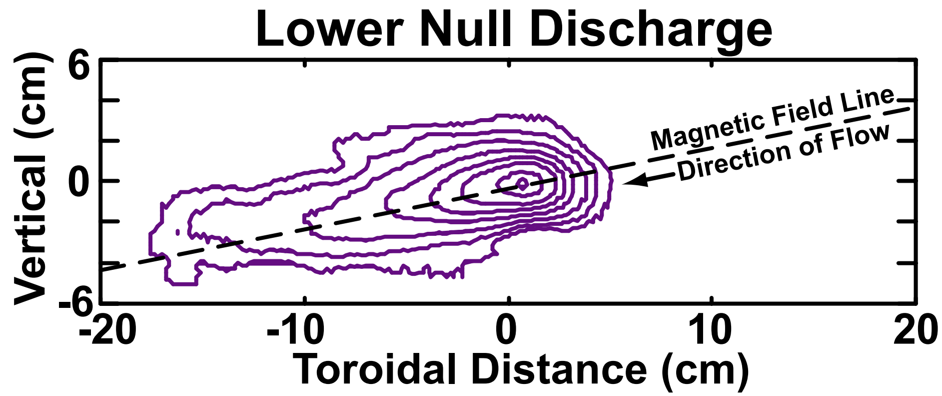

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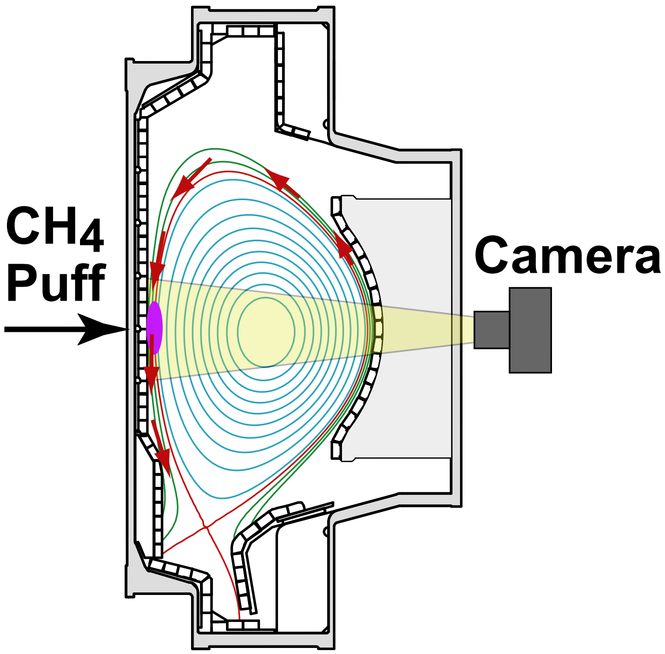
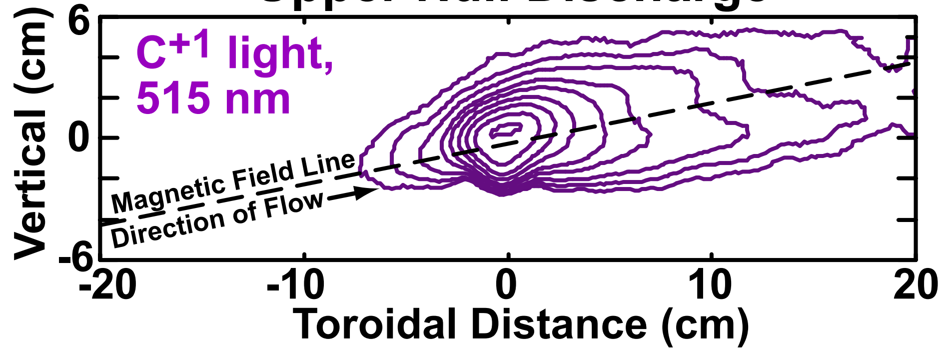
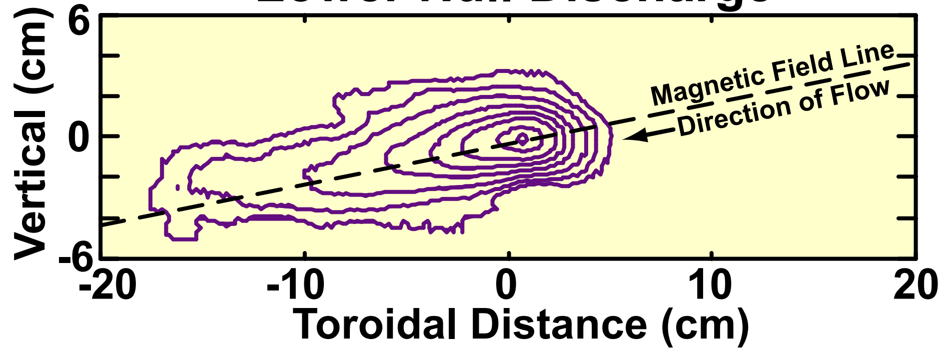


Upper Null Discharge



Lower Null Discharge



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Similar patterns of high-field side SOL flows are evident in other experiments:

JET: **Build up of inner div. carbon flakes, ^{13}C transport experiments**
DIII-D: **^{13}C transport experiments**

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Scrape-off Layer Flows

and connection to

Ballooning-like Radial Transport Asymmetries

Experiments indicate that Near-Sonic Flows in the High-Field SOL are largely driven by poloidal transport asymmetries...

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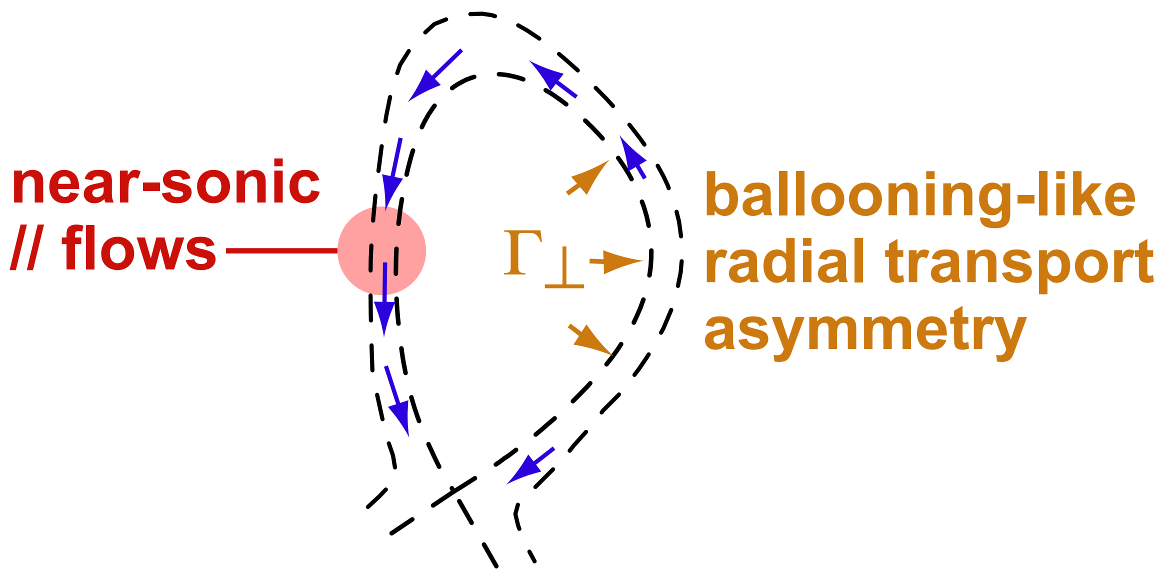

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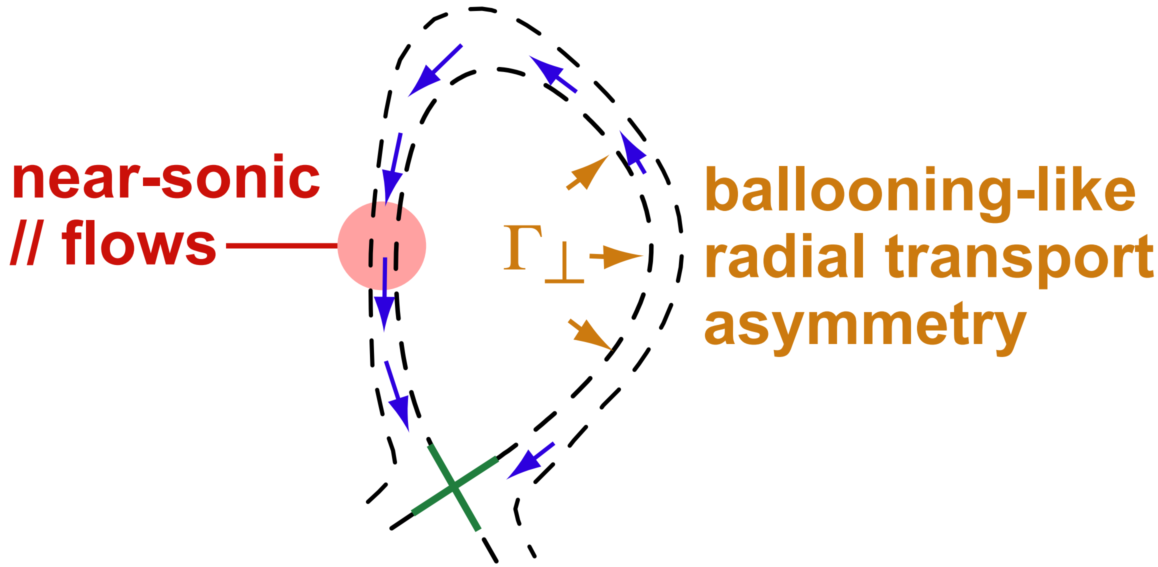

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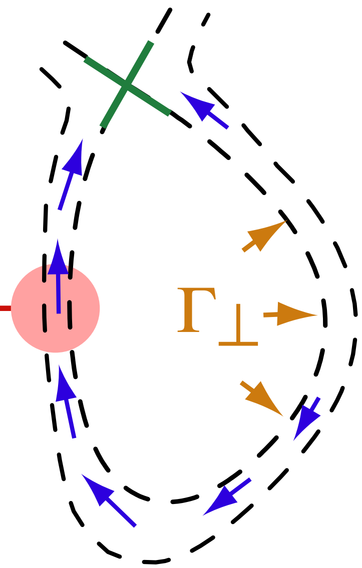

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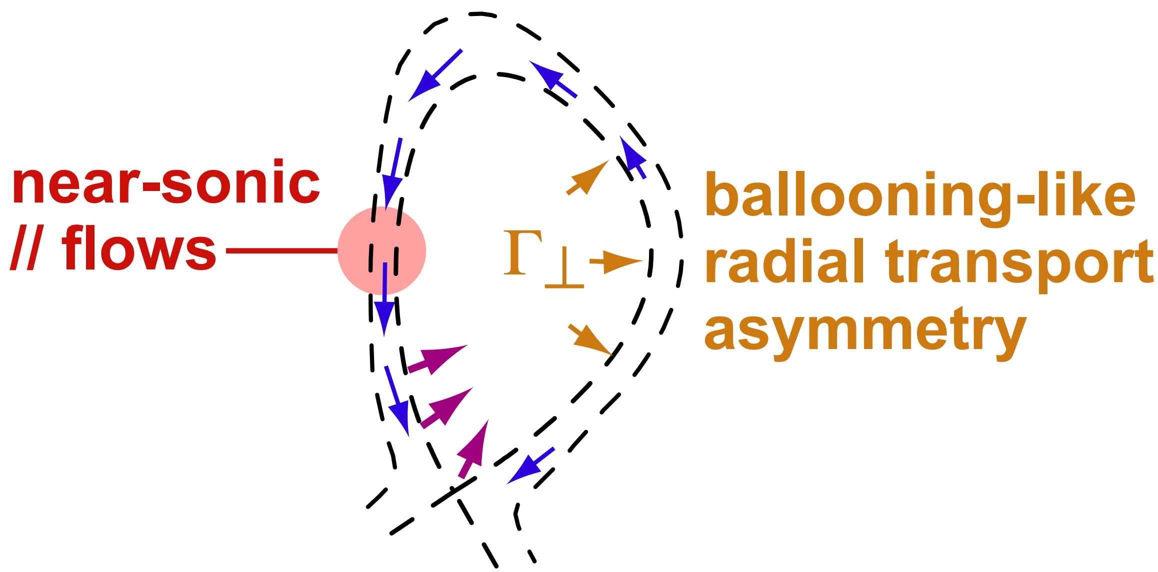


- Cross-field transport overpopulates flux tubes on low-field side, driving parallel flow
- These 'transport-driven' parallel flows circulate confined plasma in a helical pattern with direction that depends on X-point location
- The mechanism that 'closes the circulation loop' has not yet been revealed experimentally

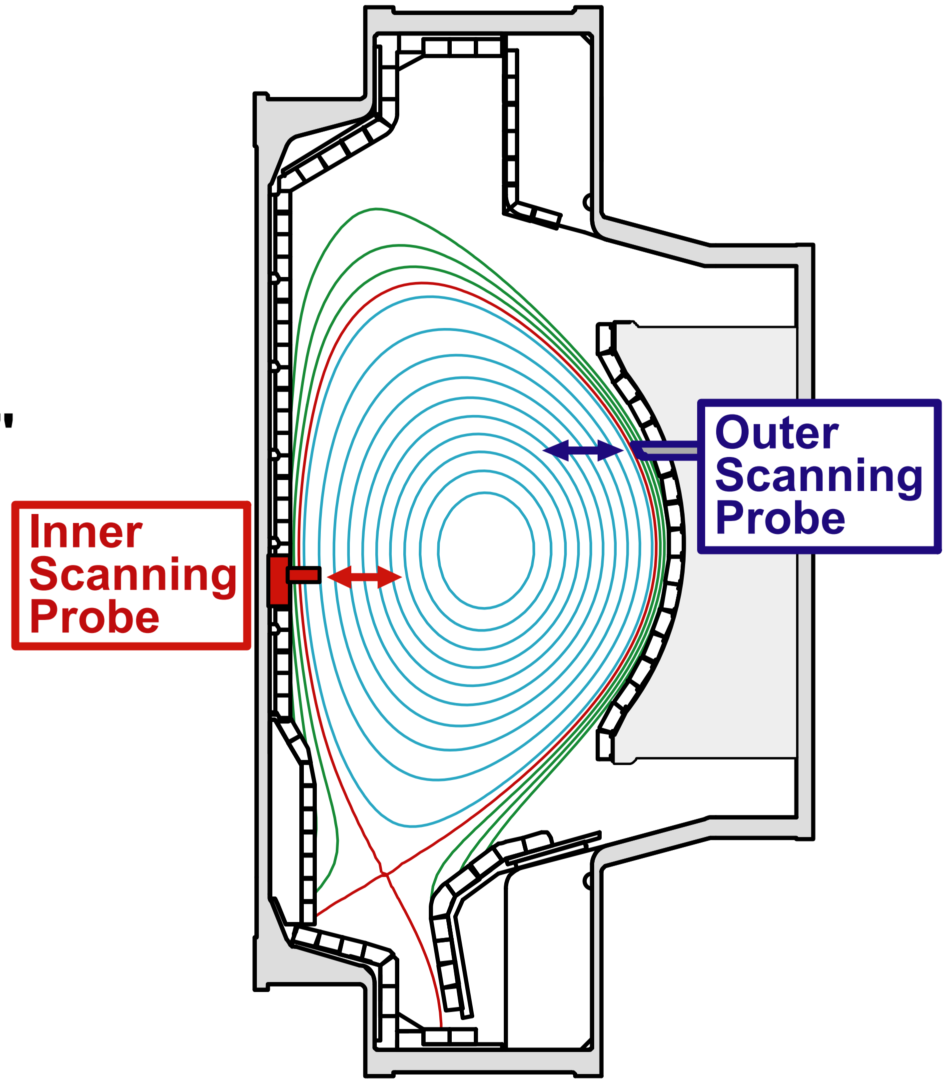
  Cross-field fueling and/or inward ⊥ transport near inner divertor?

Detailed experiments were performed on C-Mod to investigate the origins of SOL flows and their connections to magnetic topology†

Alcator C-Mod

- Fast-scanning Langmuir-Mach probes on High- and Low-field SOLs

"Inner"
or
"High-Field SOL"



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†Nuclear Fusion 44 (2004) 1047.

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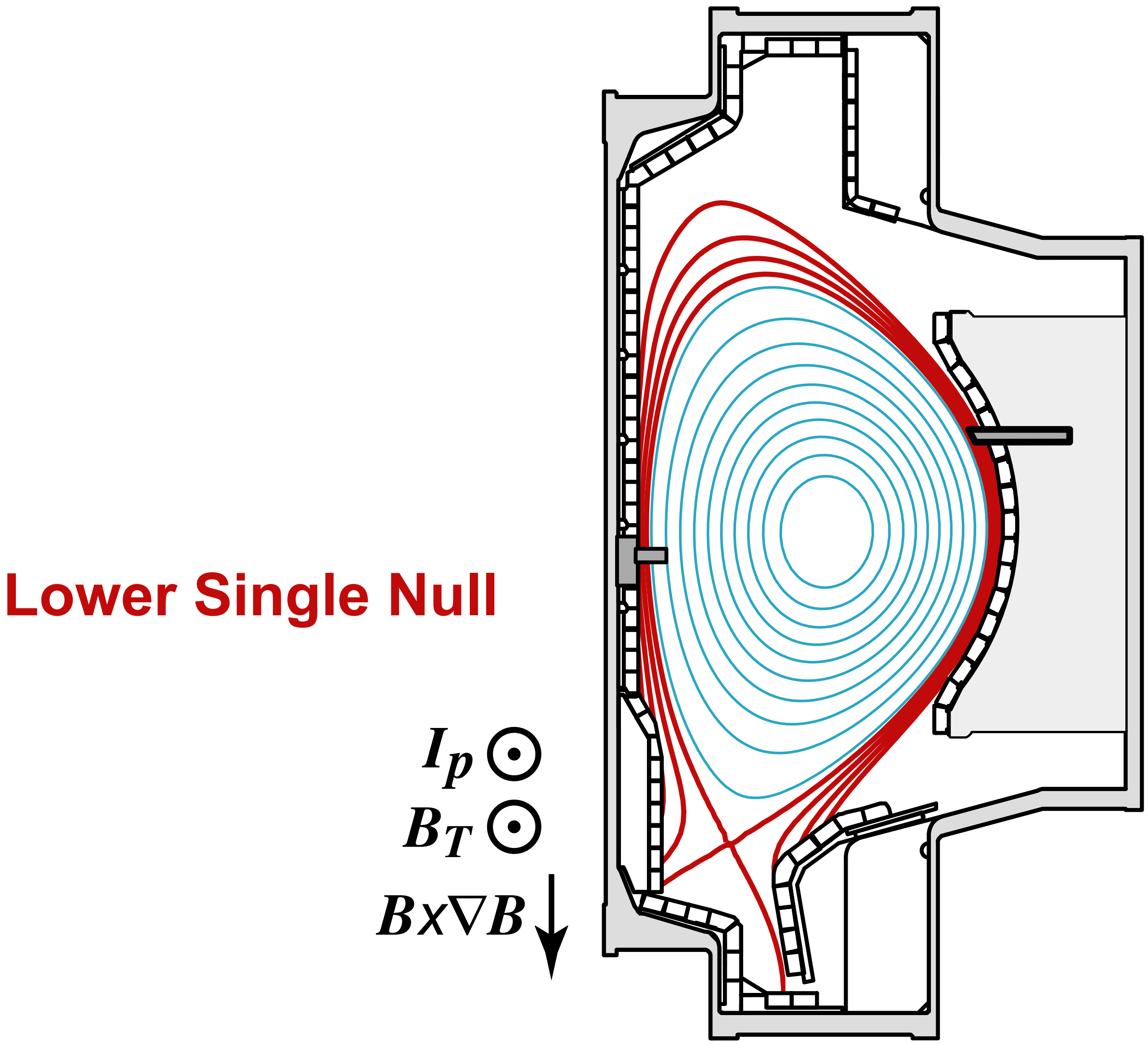

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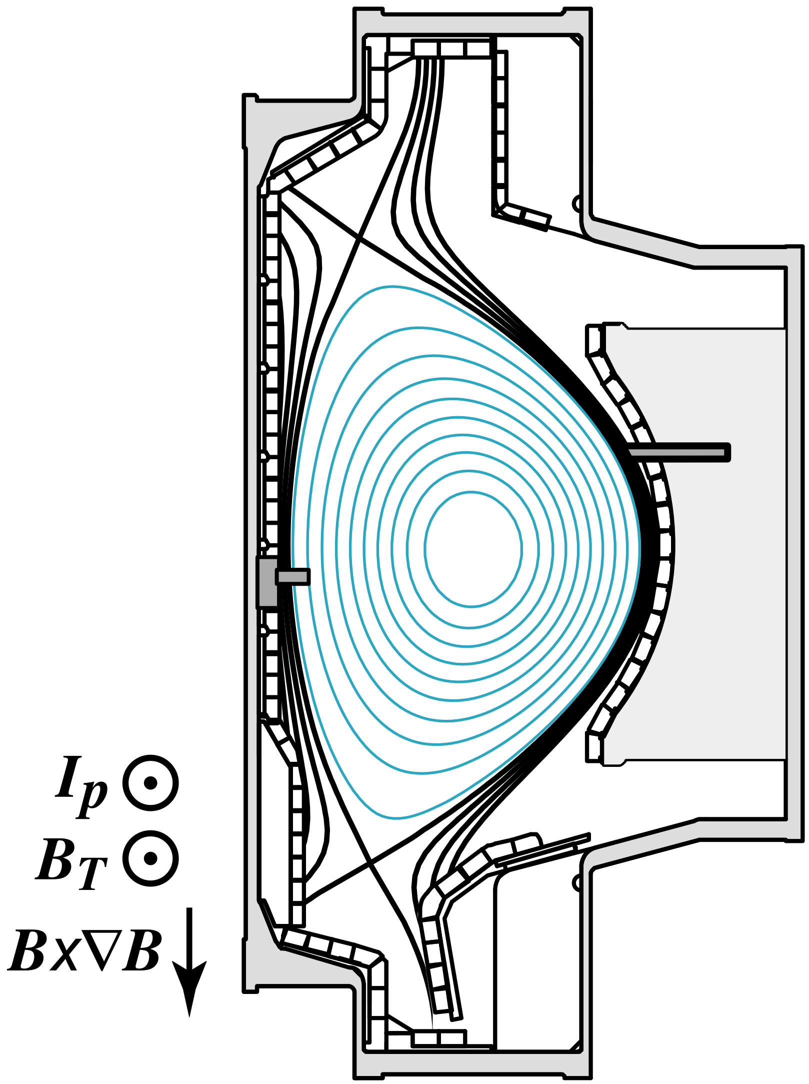

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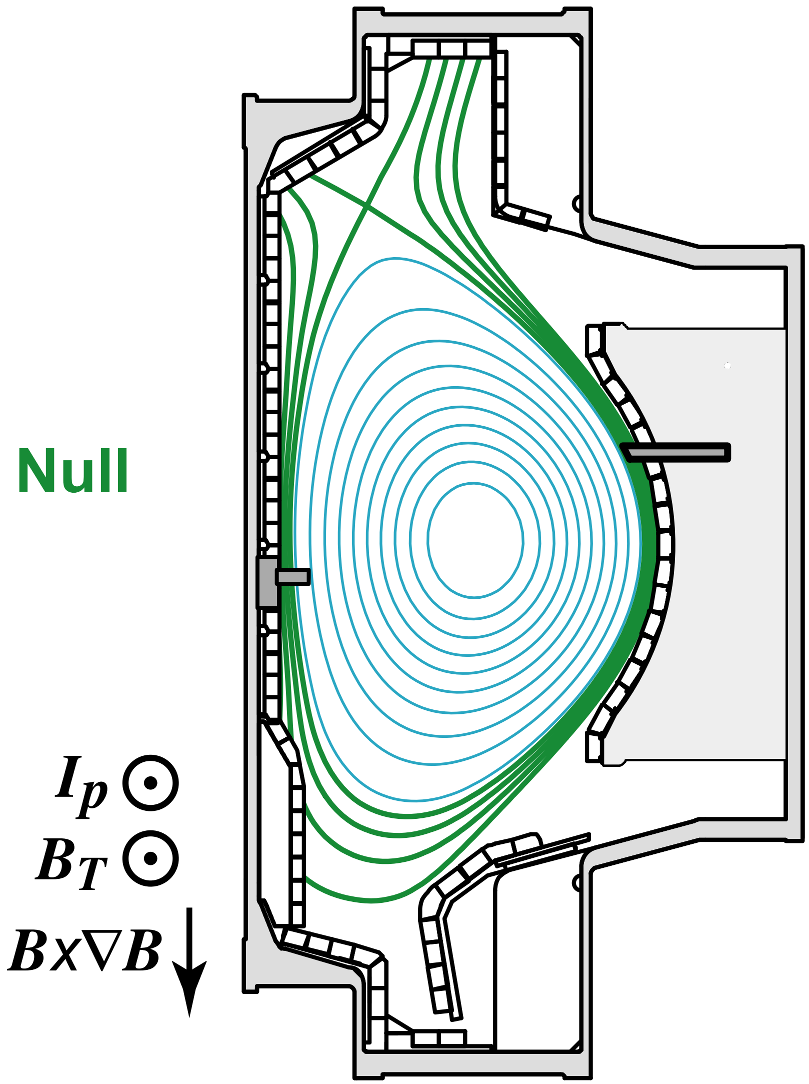

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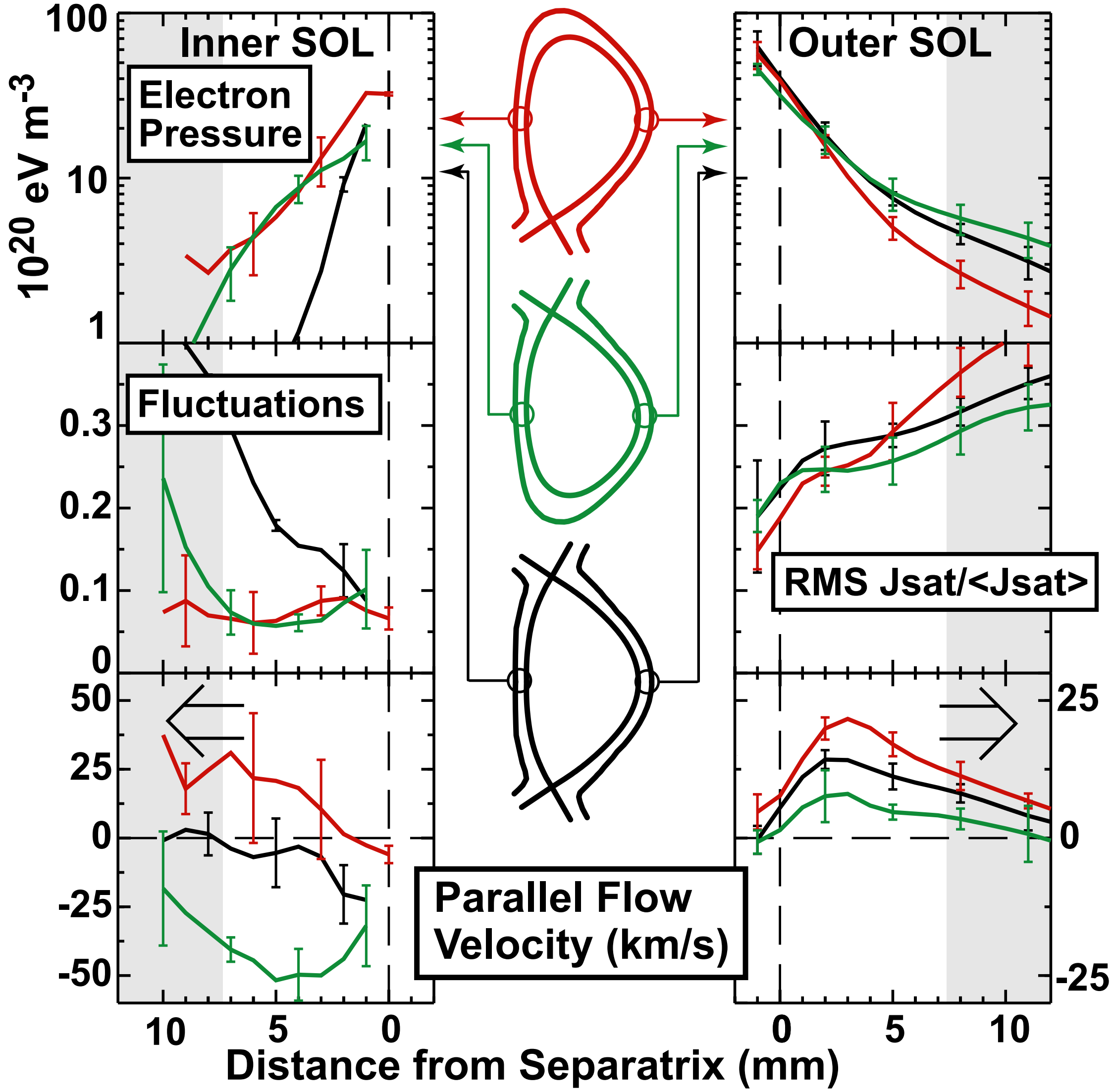
Evidence for Cross-field Transport Asymmetries....
...Driving Near-Sonic Flows in Inner SOL



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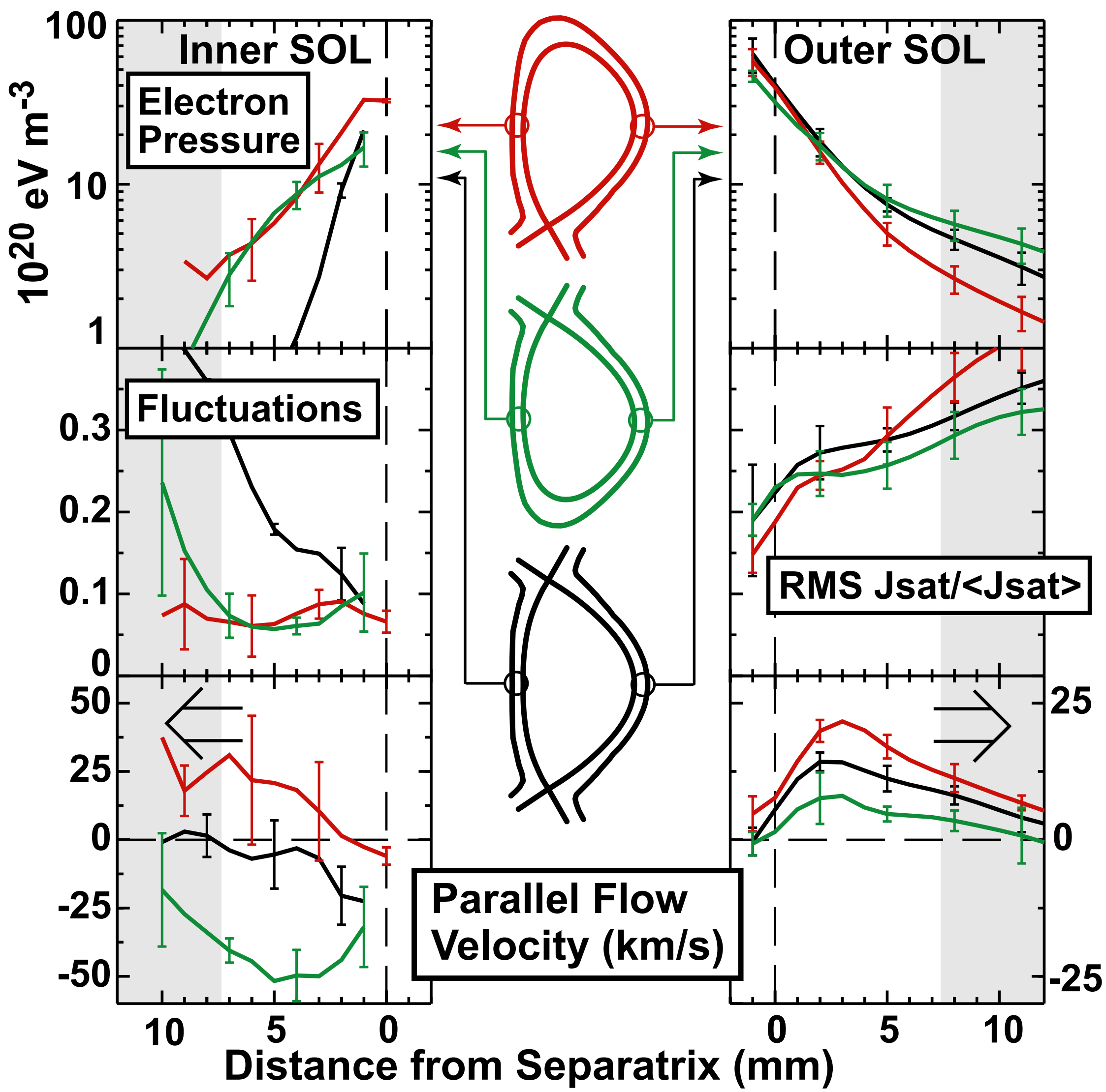
Inner SOL plasma 'disappears' in Double Null

L_{nT} reduced by factor of 4



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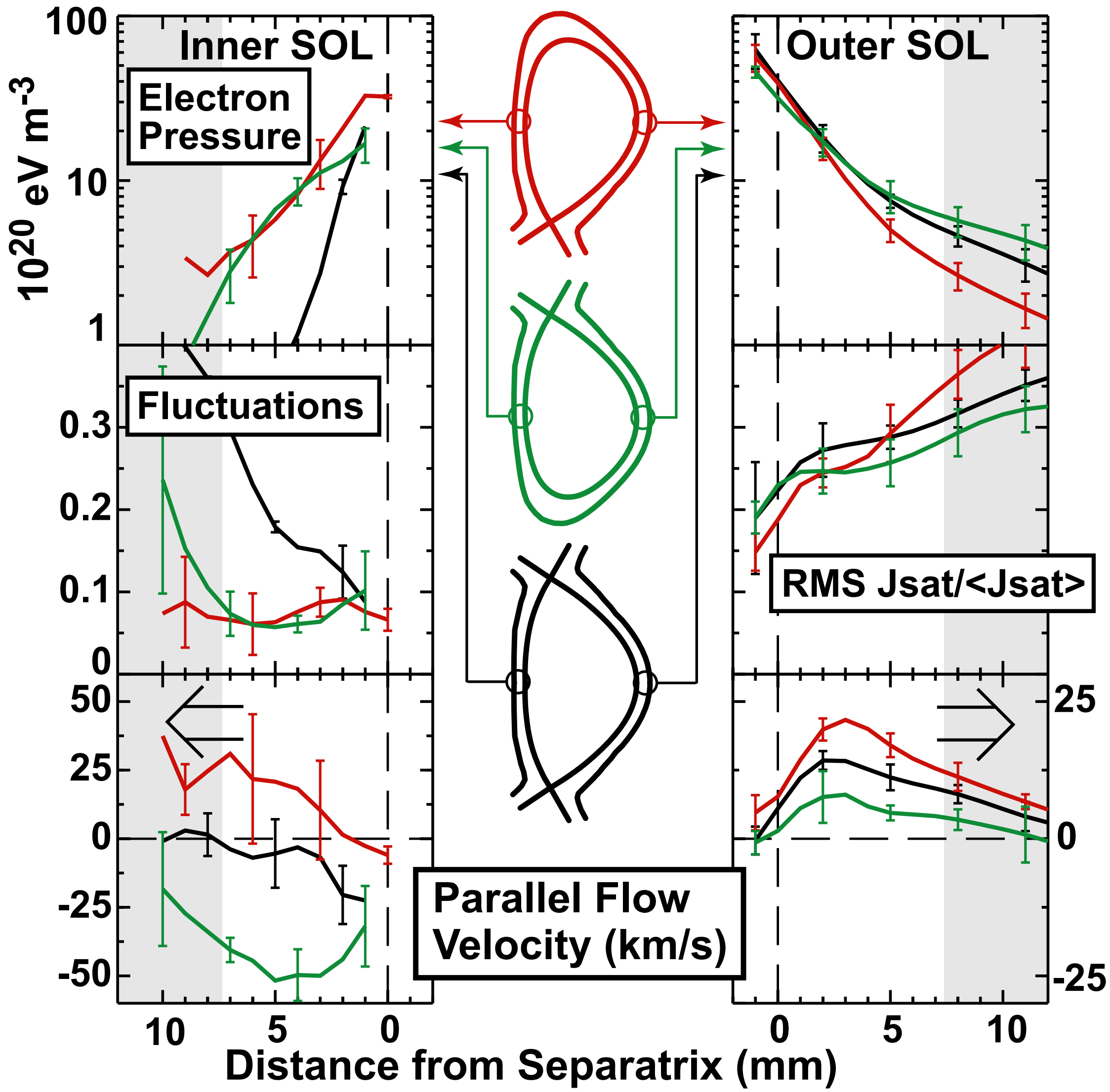
Consistent with low ⊥ transport in inner SOL



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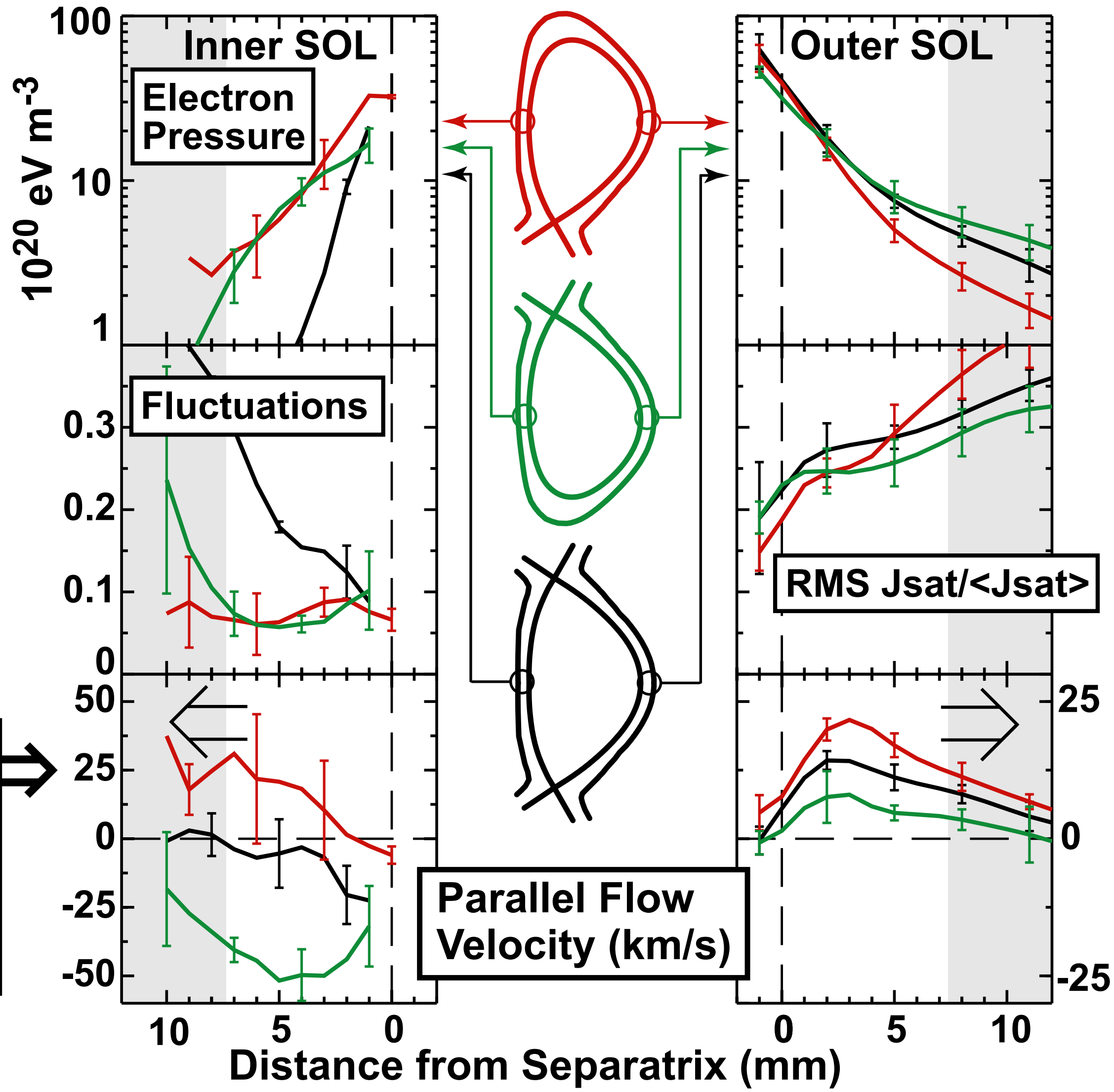
Always directed from outer to inner SOL in upper and lower-null, but ~stagnant in double-null



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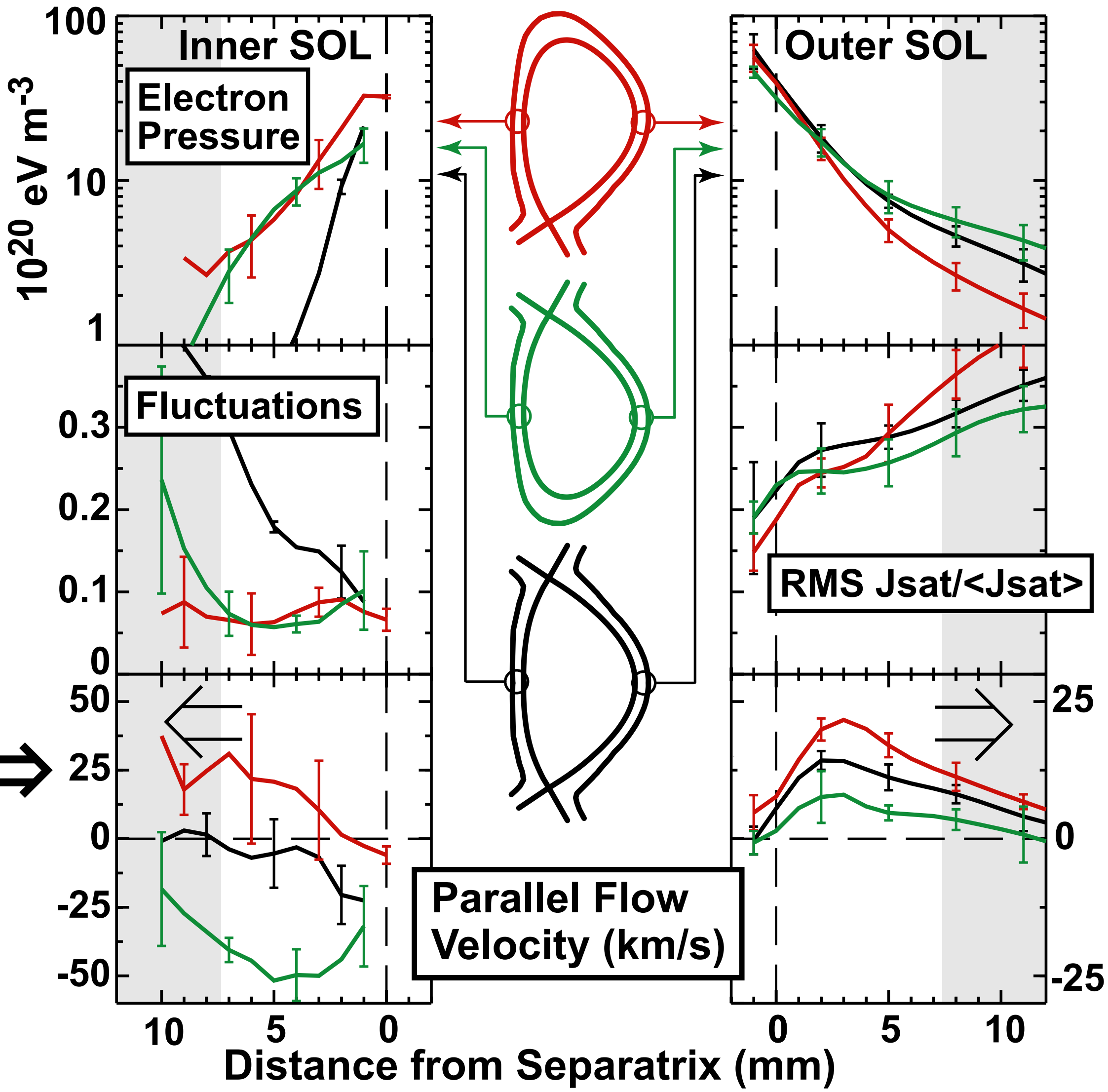

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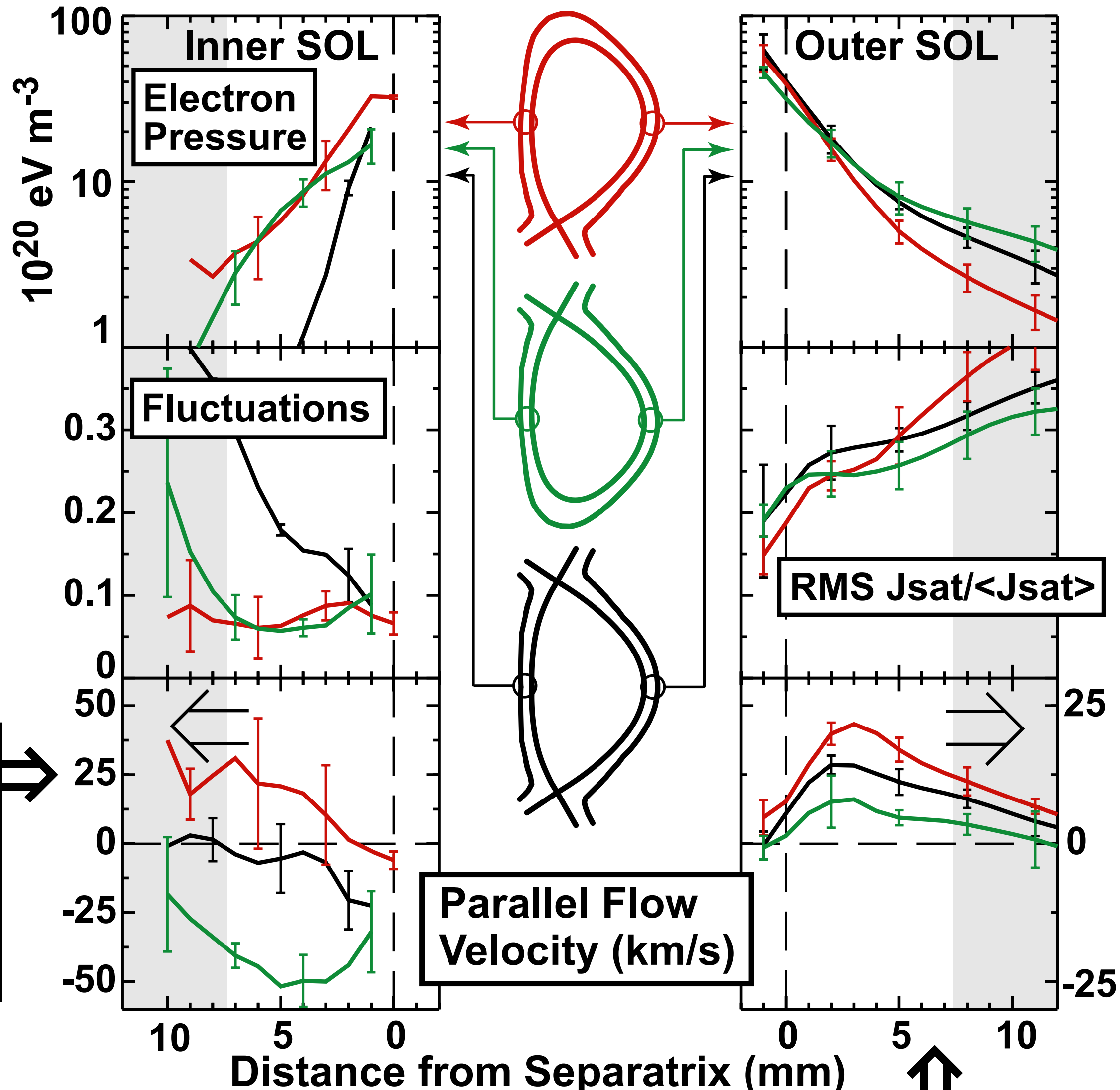
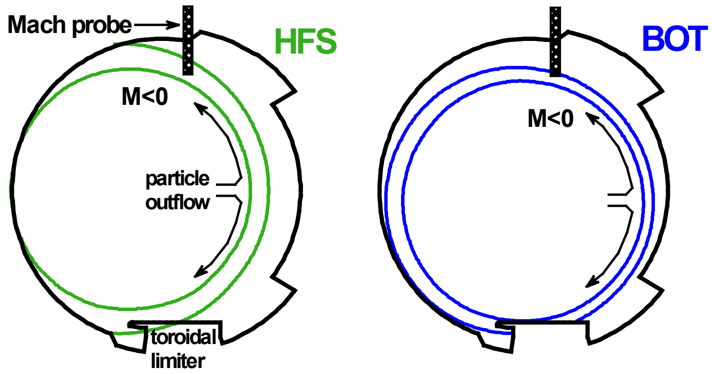


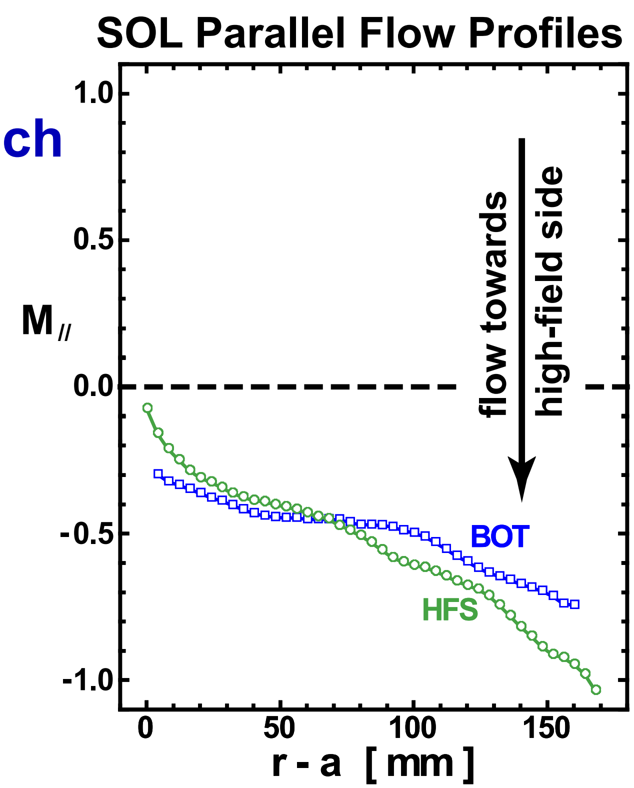
Outer SOL flows weaker, co-current, appear *modulated* by topology...

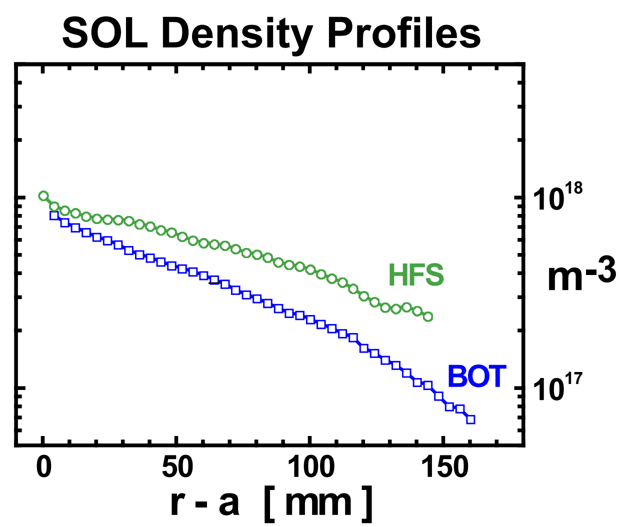
⇒ **Plasma exists on inner SOL *because it flows along field lines from outer SOL***

SOL flow and density profile measurements in Tore Supra reveal near-sonic flows driven by extreme ballooning-like radial transport asymmetry... without an x-point†



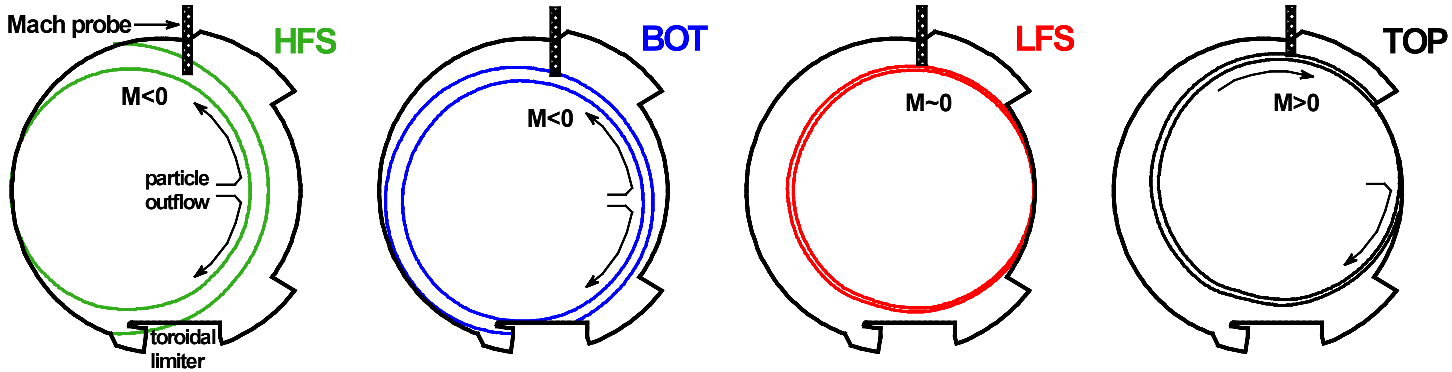
- Near-sonic // flow from low- to high-field side seen by Mach probe



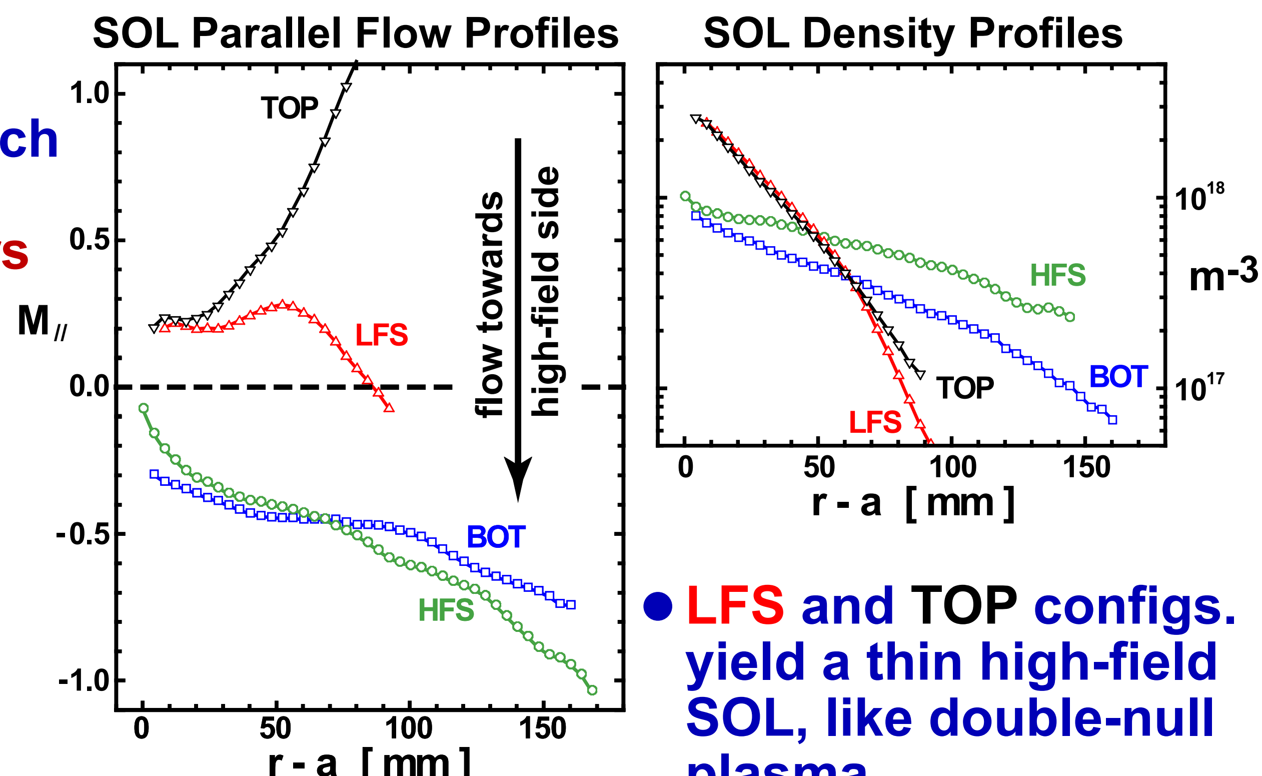


† J.P. Gunn, et al., J. Nucl. Mater. 363-365 (2007) 484.

SOL flow and density profile measurements in Tore Supra reveal near-sonic flows driven by extreme ballooning-like radial transport asymmetry... without an x-point†



- Near-sonic // flow from low- to high-field side seen by Mach probe, unless plasma is bumped against outer limiters



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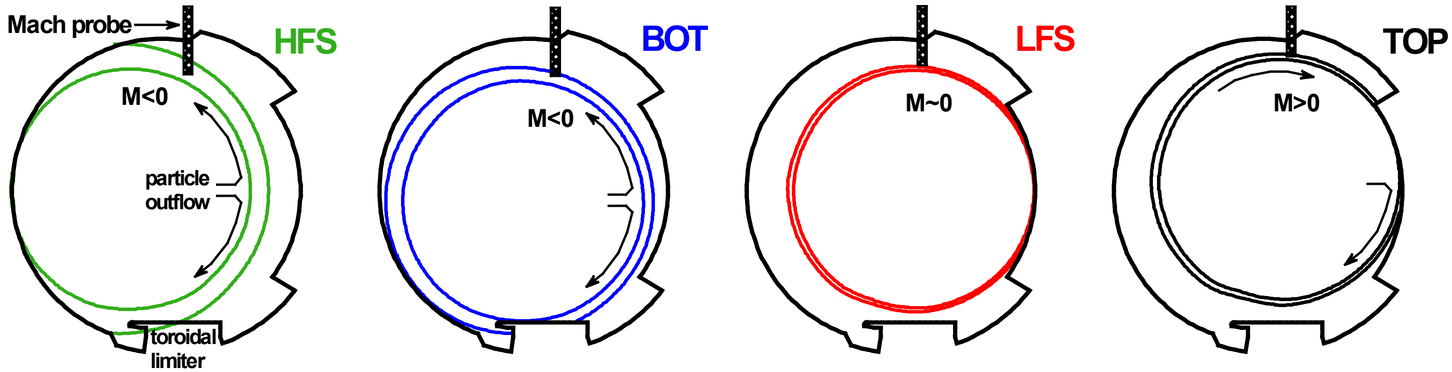
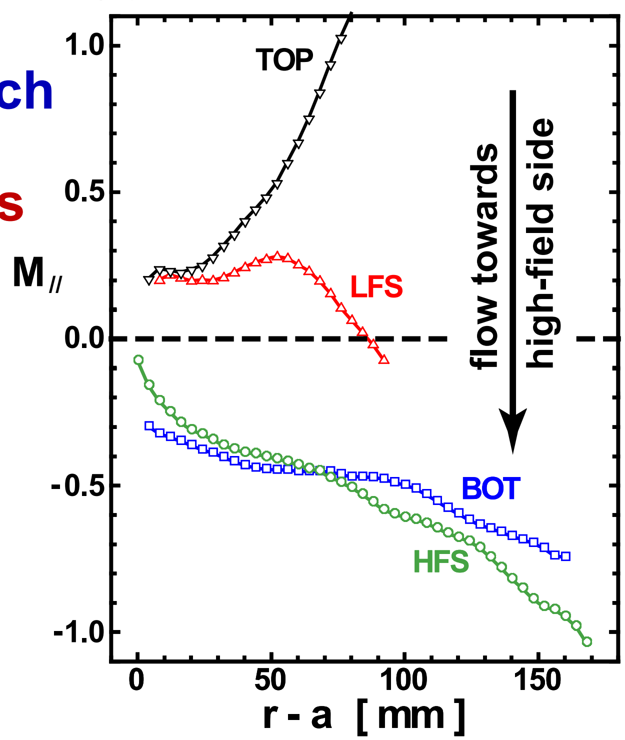
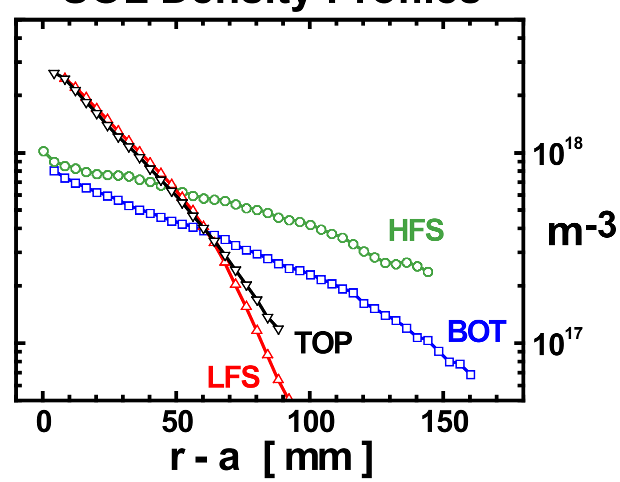


SOL Parallel Flow Profiles



SOL Density Profiles



- Near-sonic // flow from low- to high-field side seen by Mach probe, unless plasma is bumped against outer limiters

=> enhanced radial transport over ~30 degree poloidal extent, centered about the outer midplane

=> ratio of low-field side to high-field side effective diffusion coefficient ~ 200

- LFS and TOP configs. yield a thin high-field SOL, like double-null plasma

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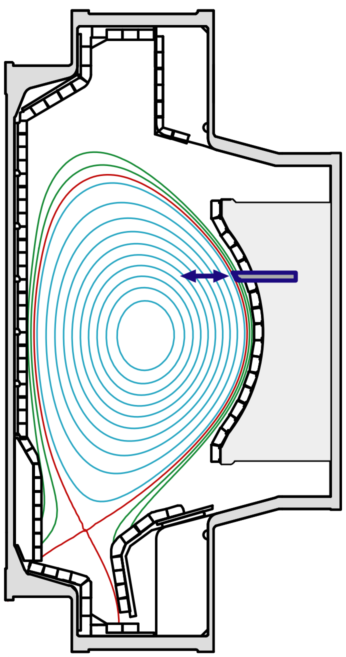
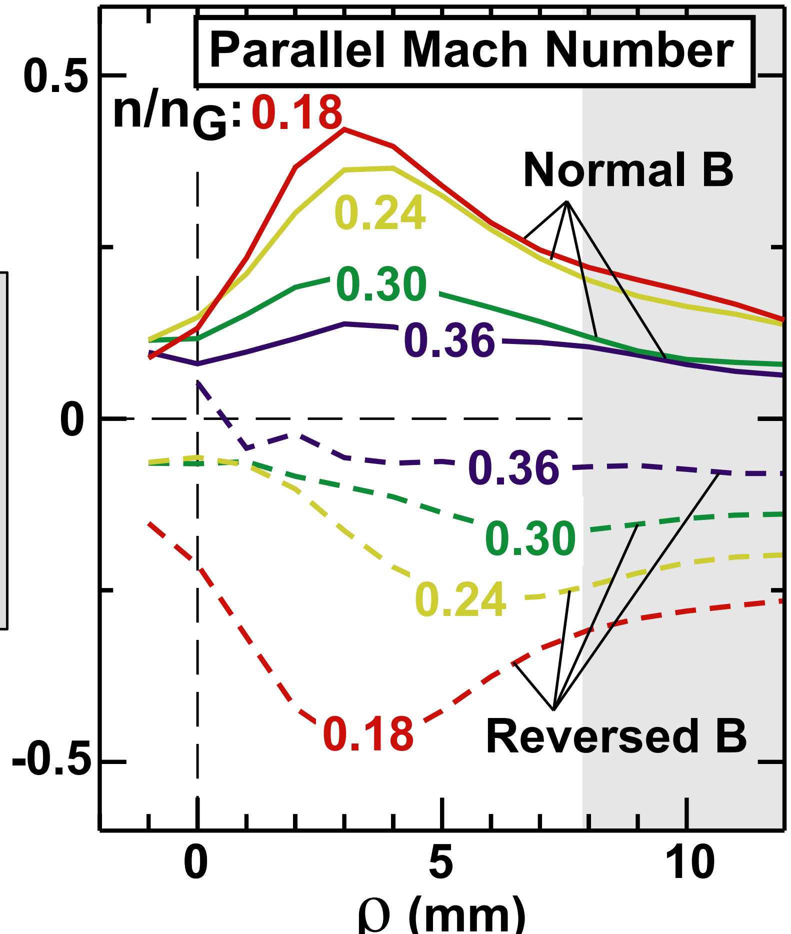
†J.P. Gunn, et al., J. Nucl. Mater. 363-365 (2007) 484.

Parallel Flows Near Outer Midplane:
Mostly Pfirsch-Schlüter Ion Flows† plus Toroidal Rotation...
...'transport-driven' component is relatively small

Alcator C-Mod

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 (*but not identical*)**

=> B-field sign dependence can be explained by Pfirsch-Schlüter plus co-current toroidal rotation contributions

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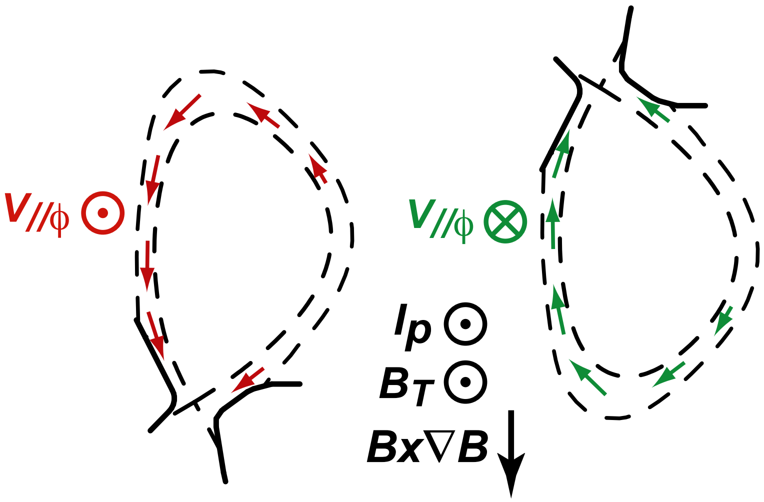
†See R.A. Pitts, et al., J. Nucl. Mater. 363-365 (2007) 505, also N. Asakura et al., Phys. Rev. Lett. 84 (2000) 3093.

Evidence that Scrape-off Layer Flows set a Toroidal Rotation Boundary Condition on the Confined Plasma

Experiments indicate that transport-driven SOL flows set a toroidal rotation boundary condition on the confined plasma

⊥ 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 (*Bx∇B* toward x-point), counter-current for upper null (*Bx∇B* away)**

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Alcator C-Mod

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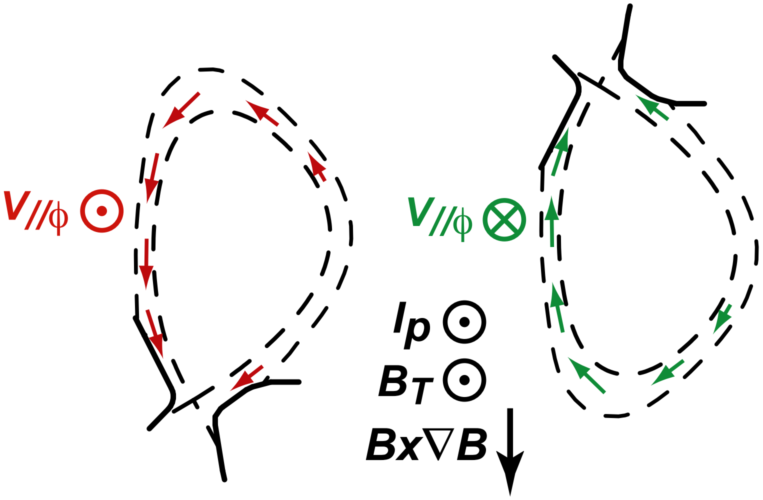

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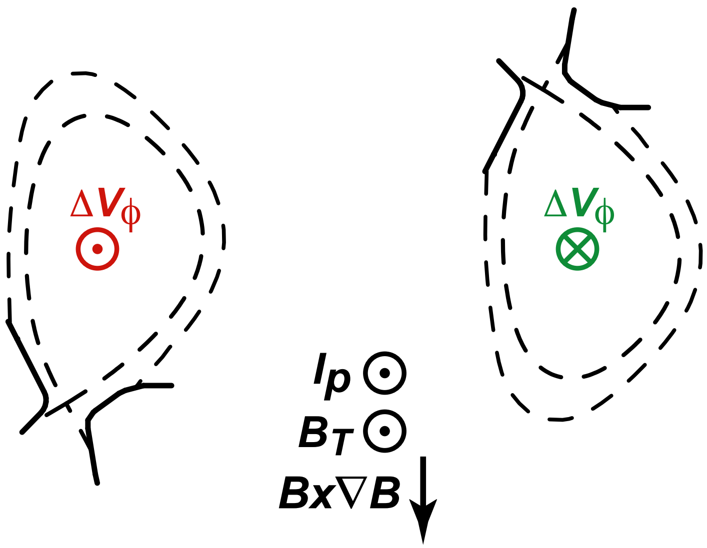
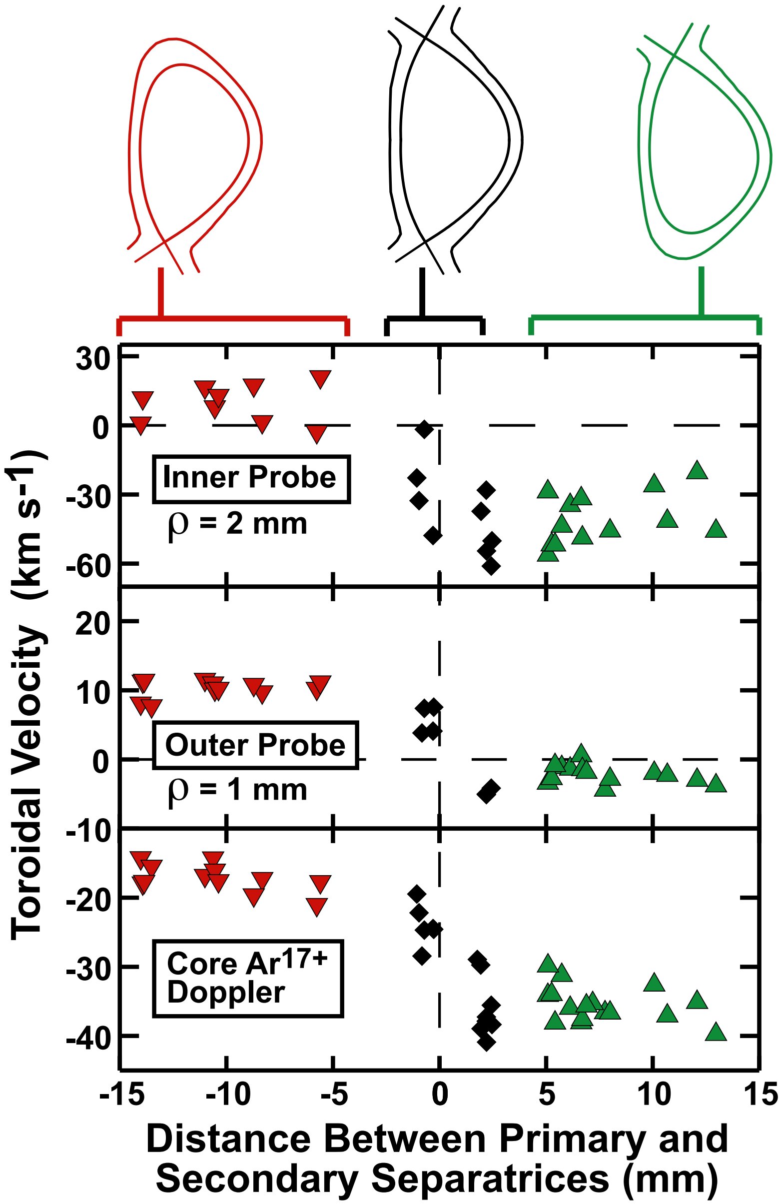
Influence on plasma rotation



- **Being free to rotate in the toroidal direction, the confined plasma can respond, acquiring a co-current or counter-current rotation increment**

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

Alcator C-Mod



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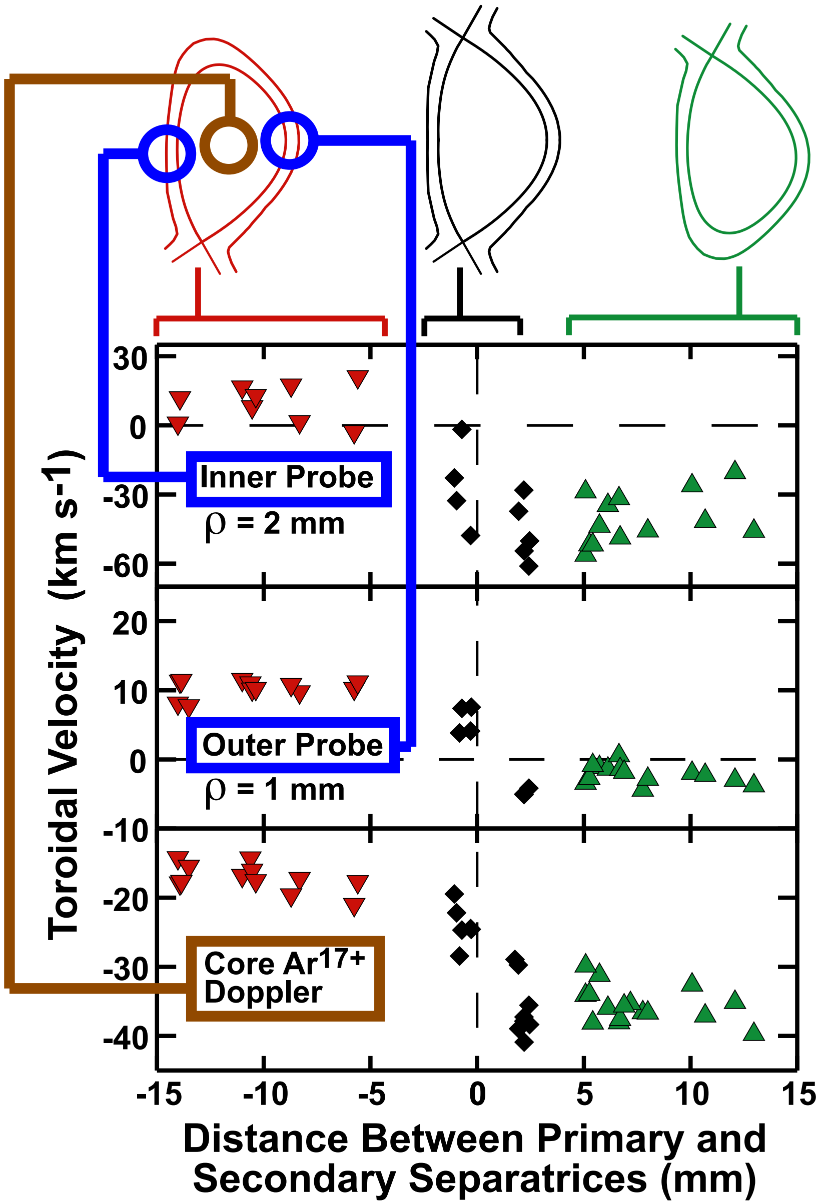

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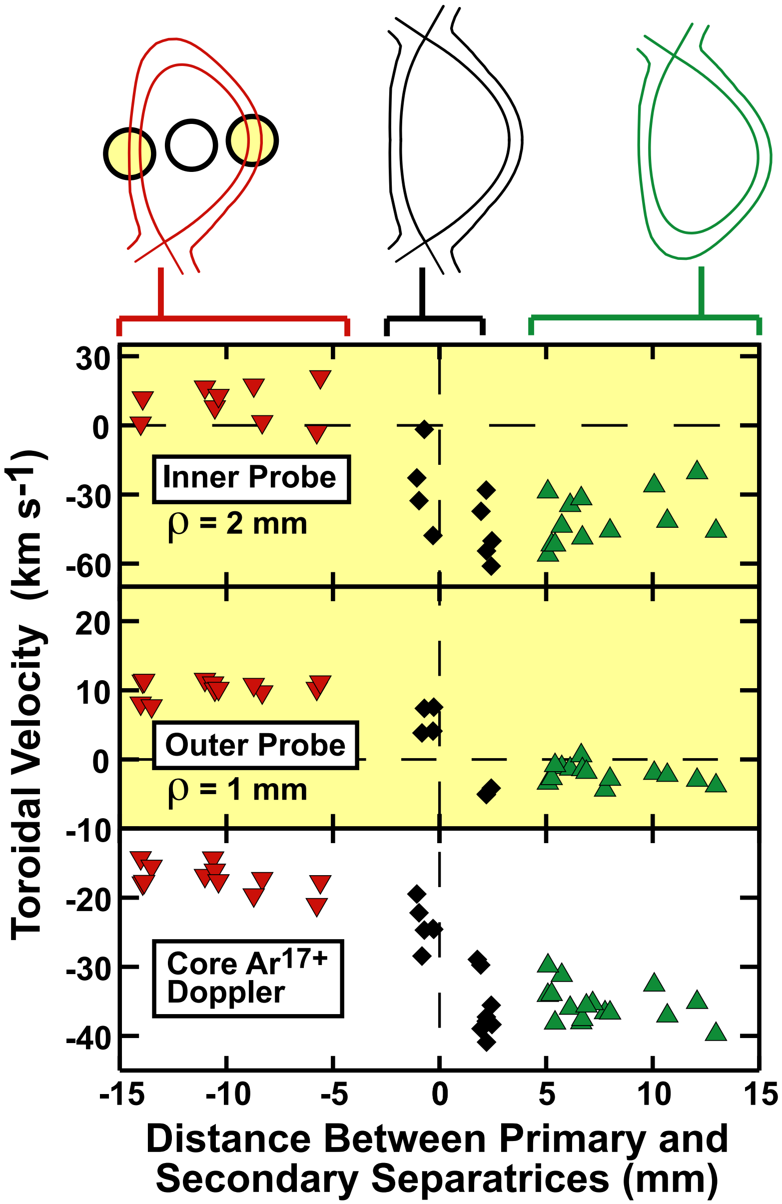

- **Toroidal projections of flows near separatrix shift toward counter-current in sequence:**
  lower => double => upper-null

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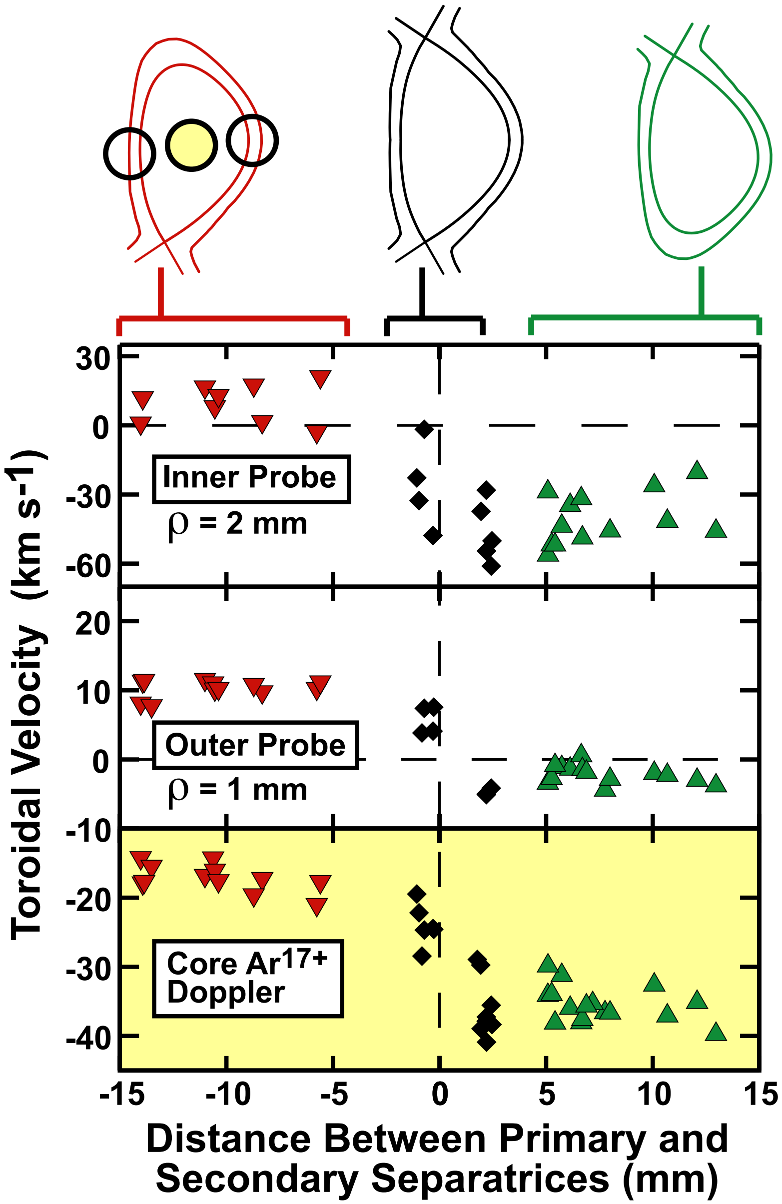

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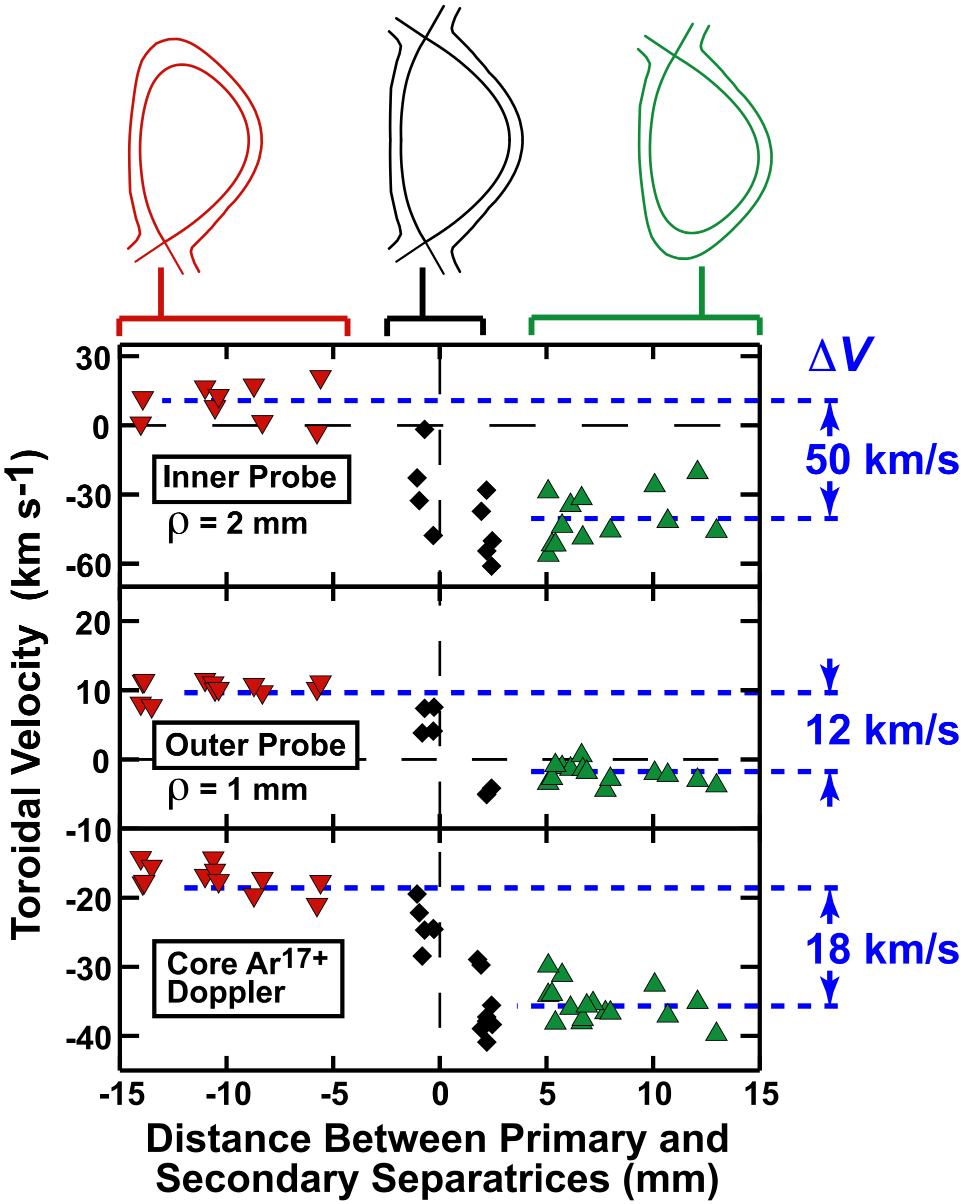

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  => suggests inner SOL flow is responsible for change in rotation of confined plasma

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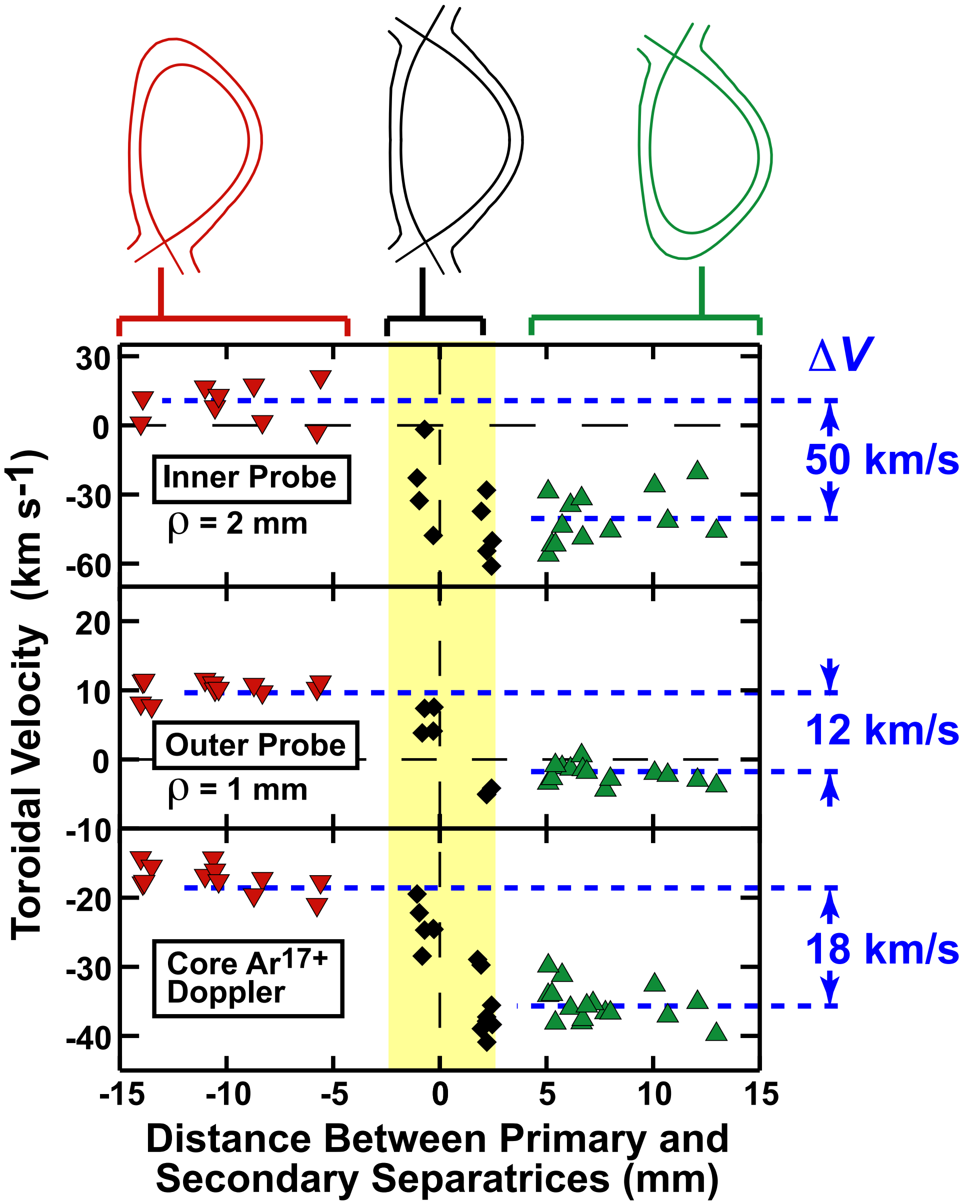

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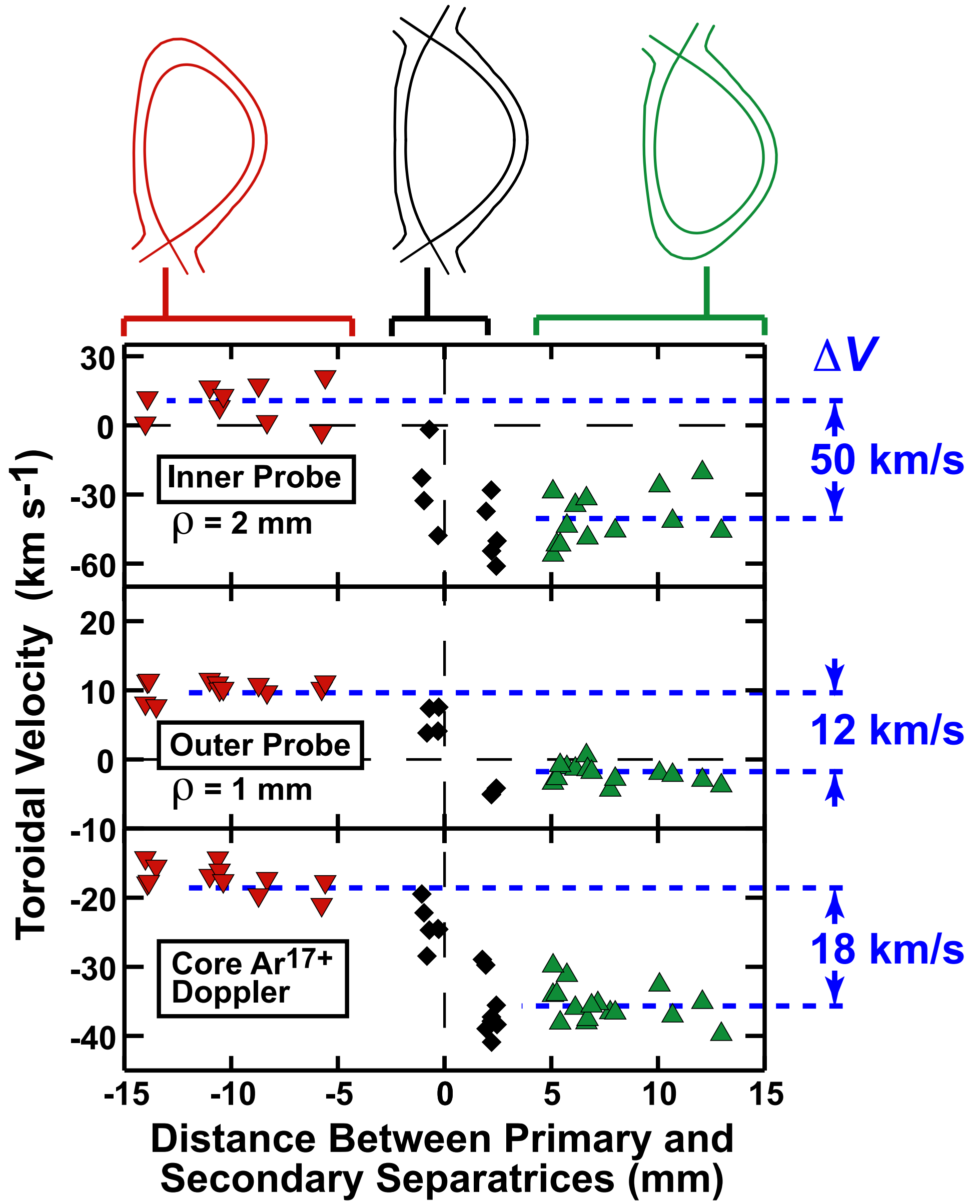

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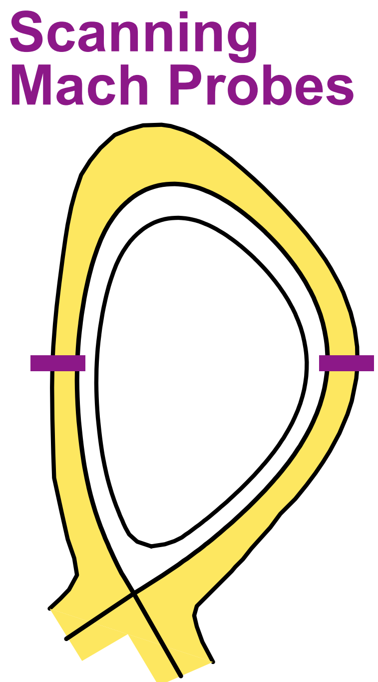
∴ Transport-driven SOL flows impose boundary conditions on confined plasma

New edge flow measurements with forward/reversed field support picture of SOL flows setting toroidal rotation BC†

Alcator C-Mod



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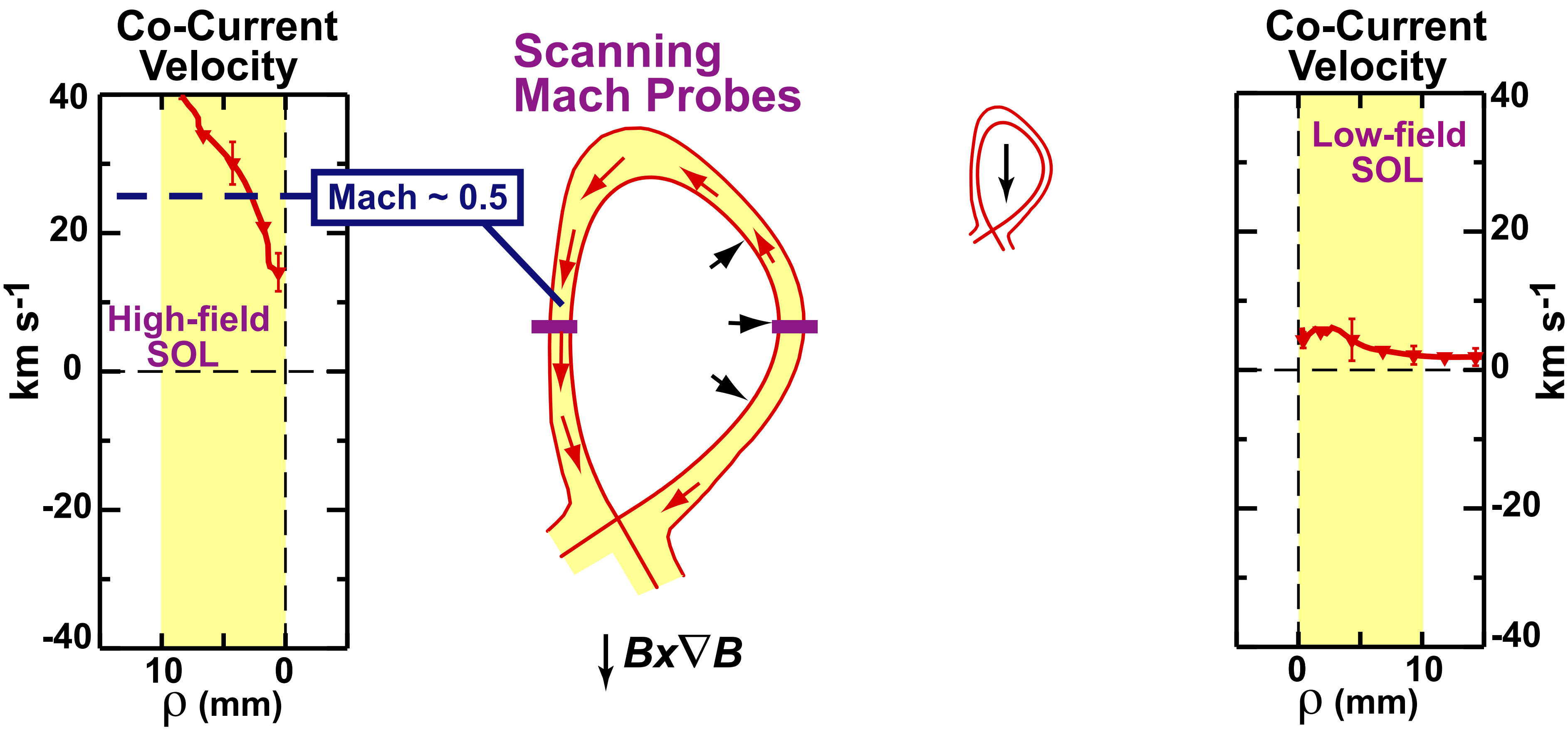

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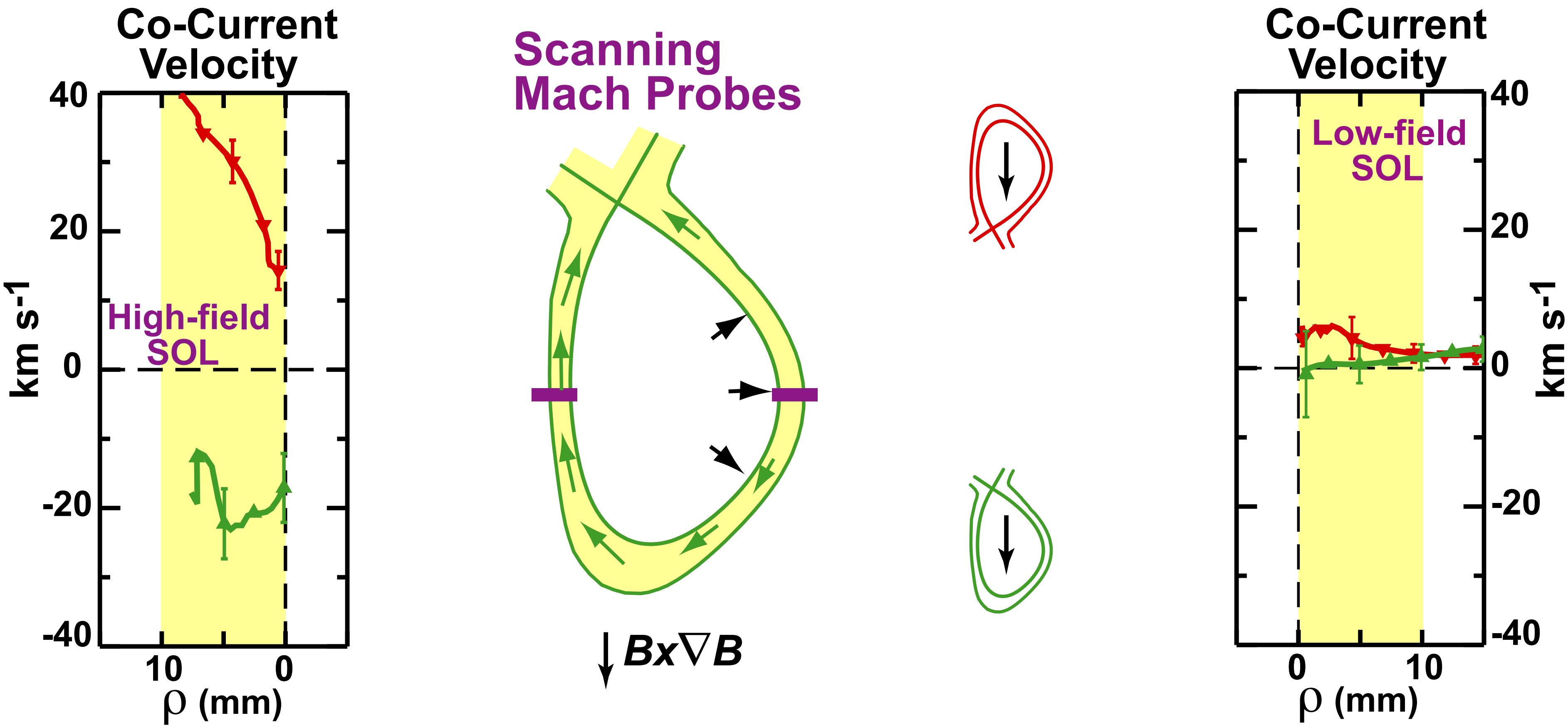

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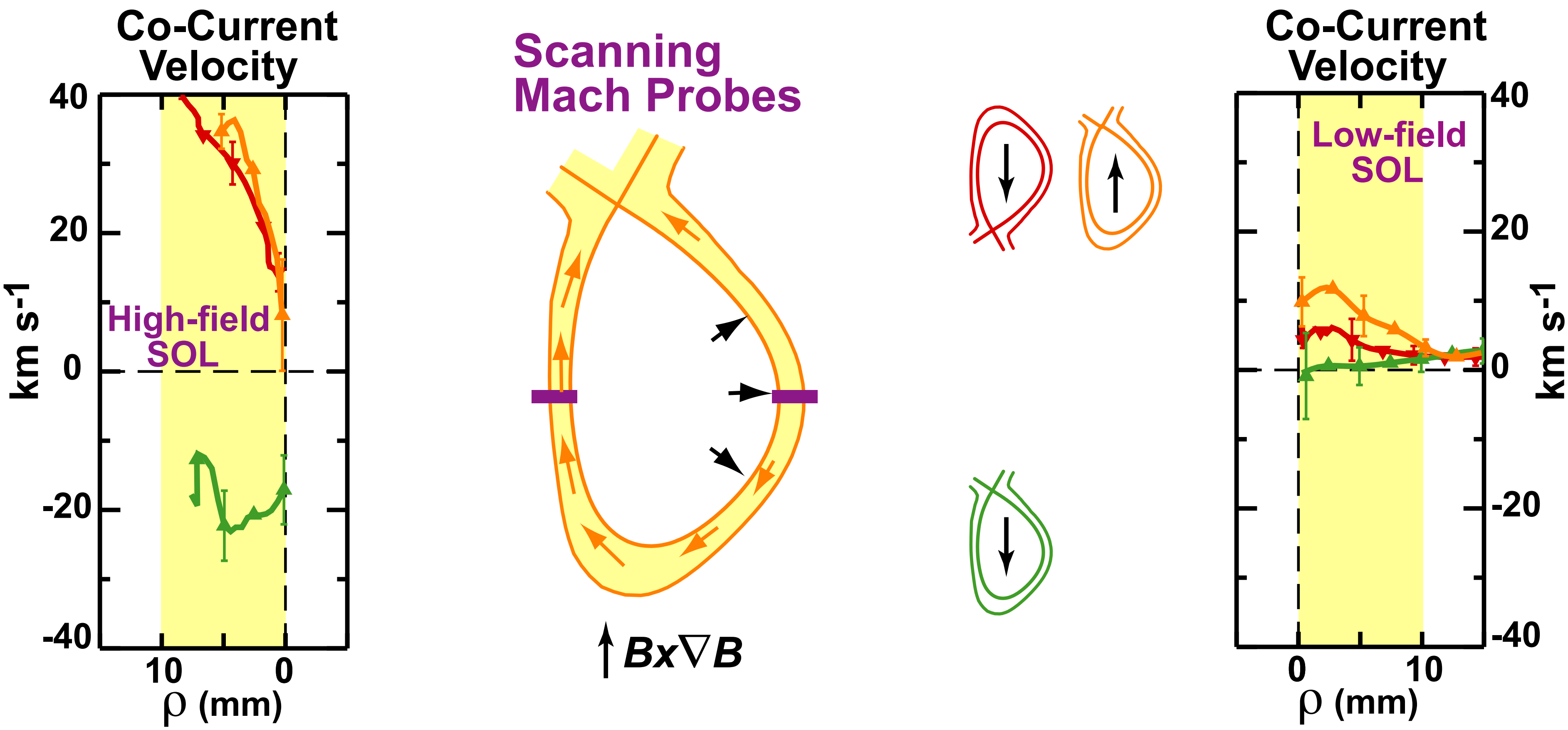

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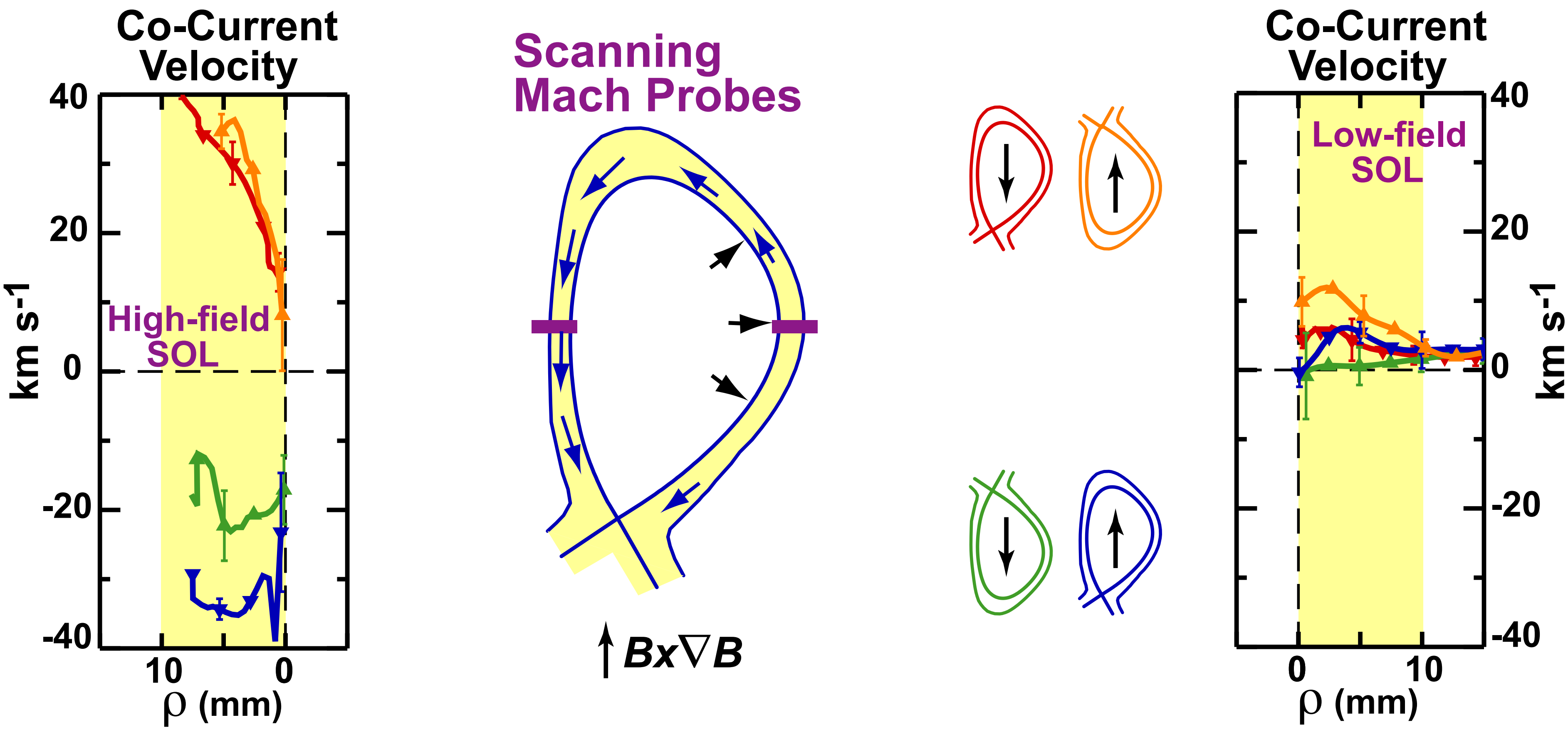

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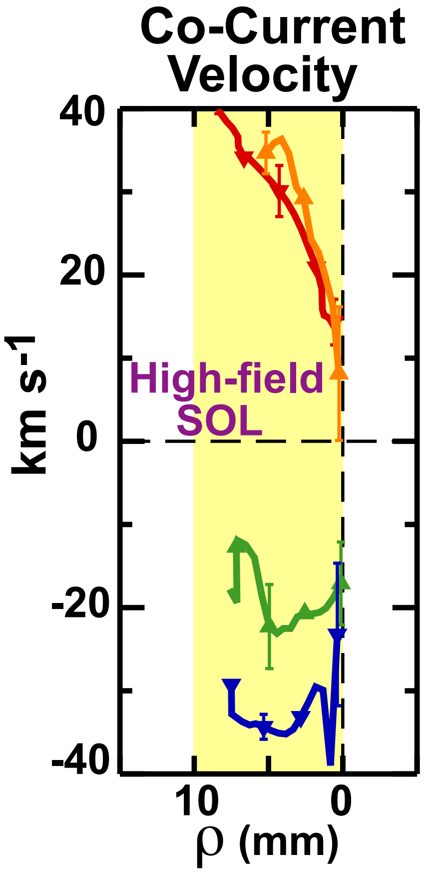

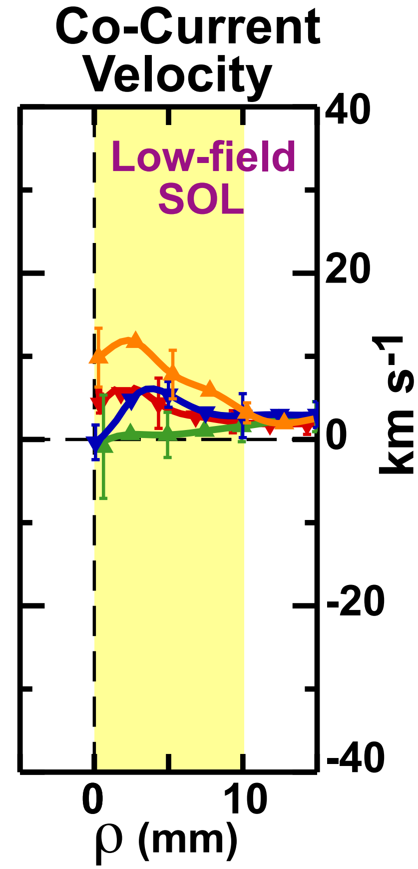

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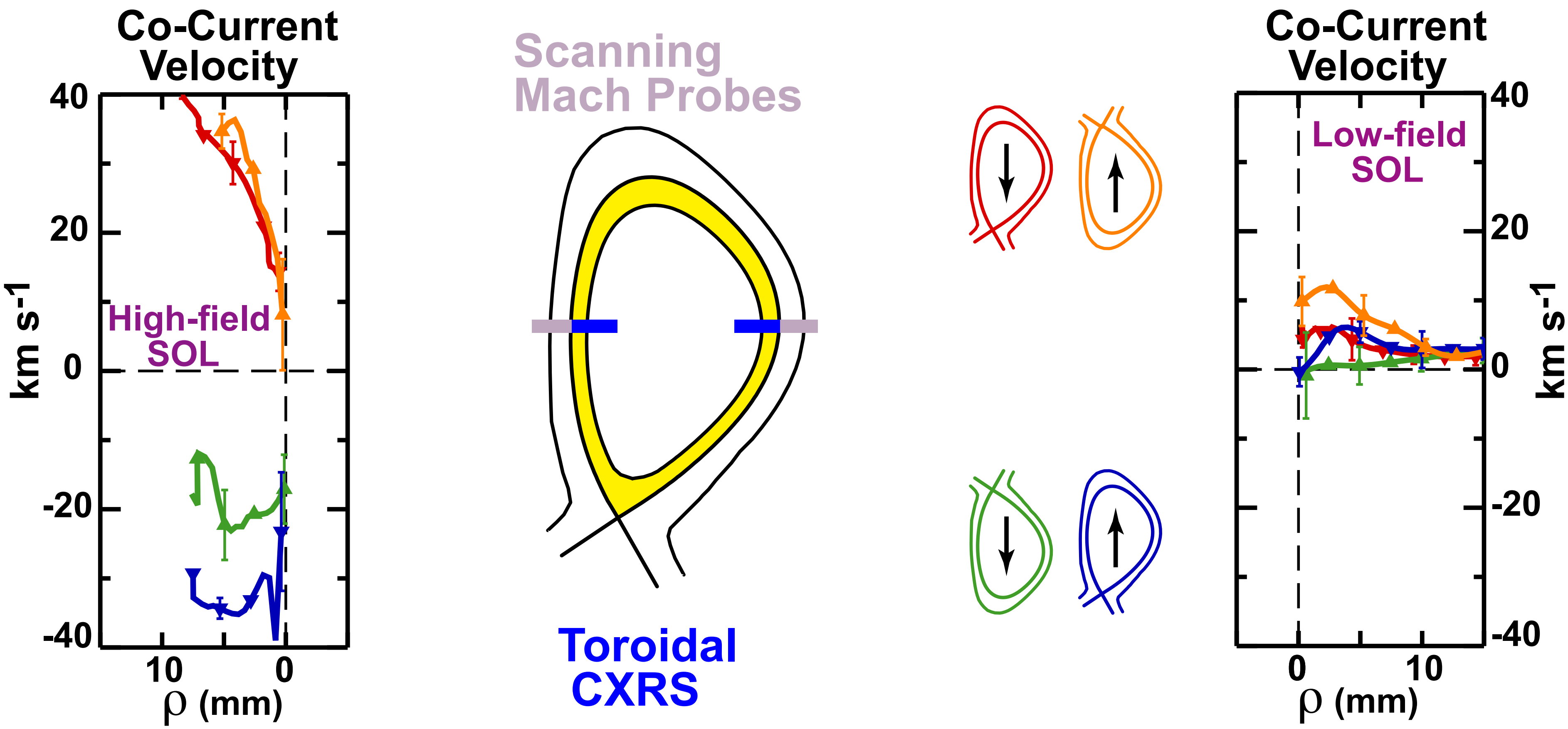

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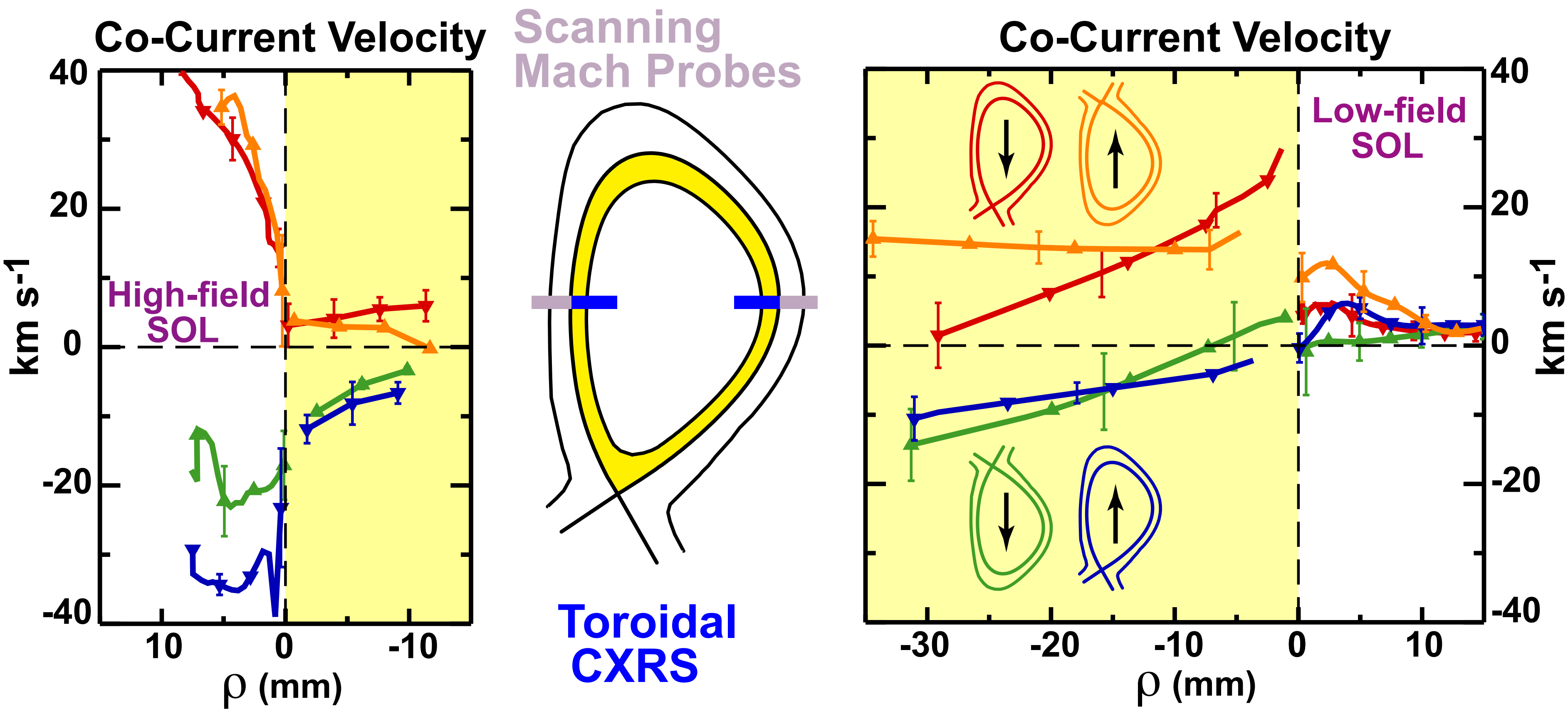

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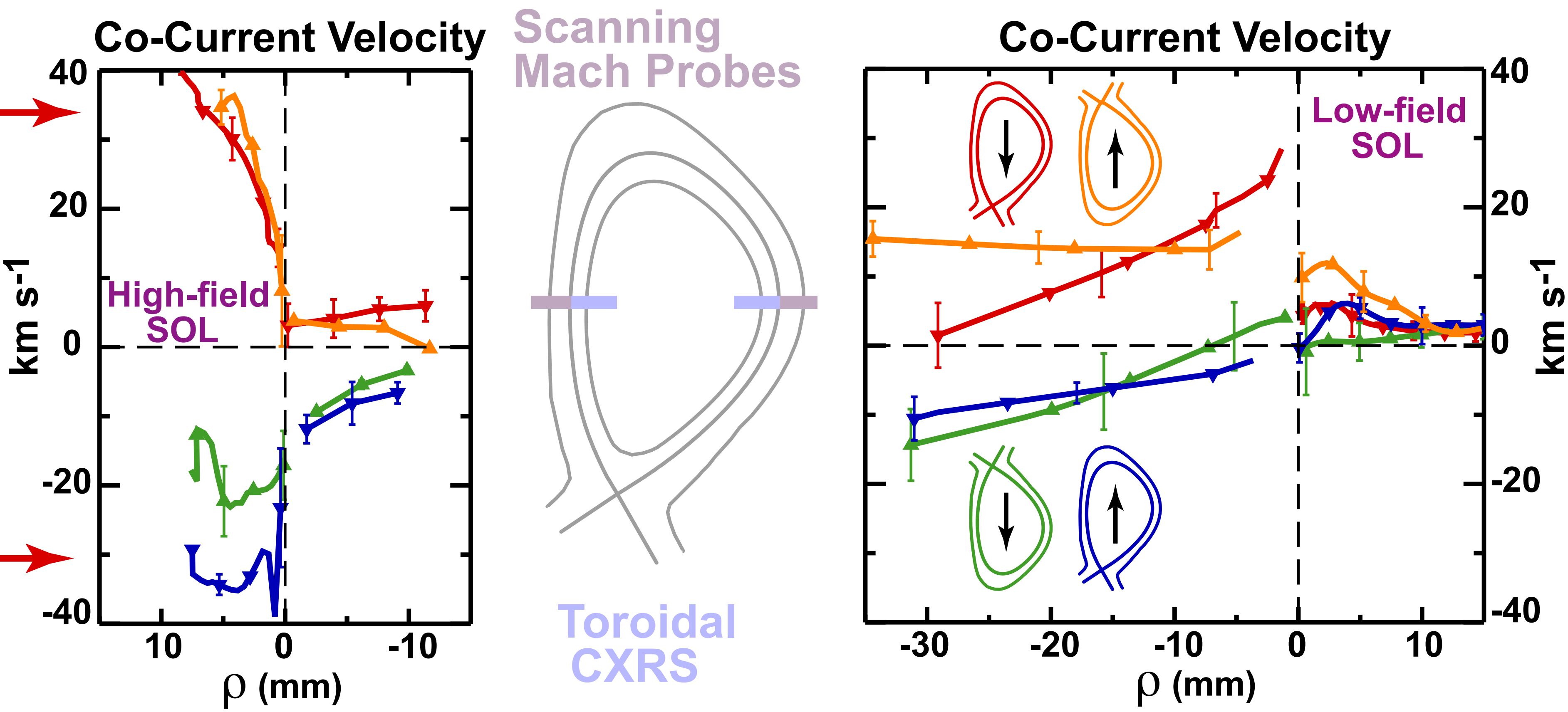

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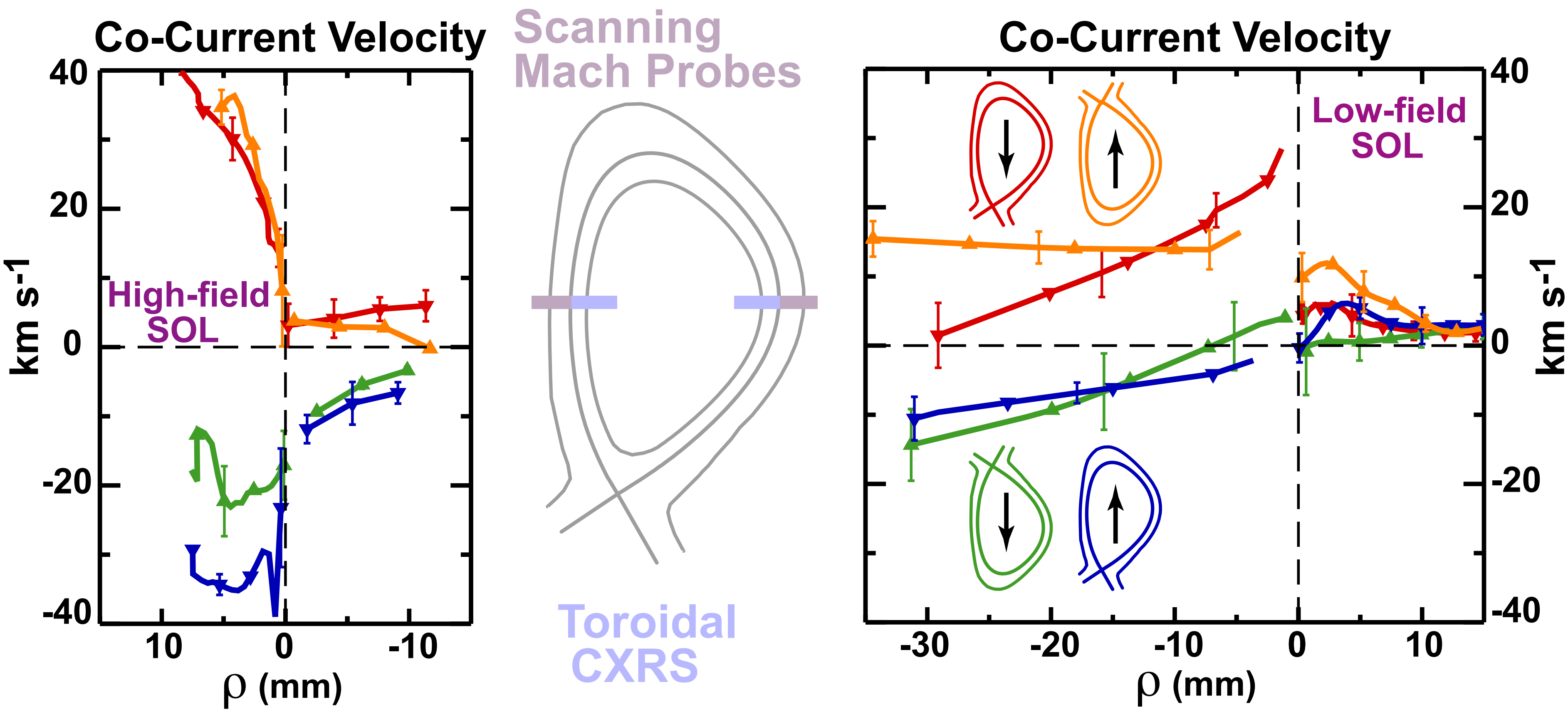

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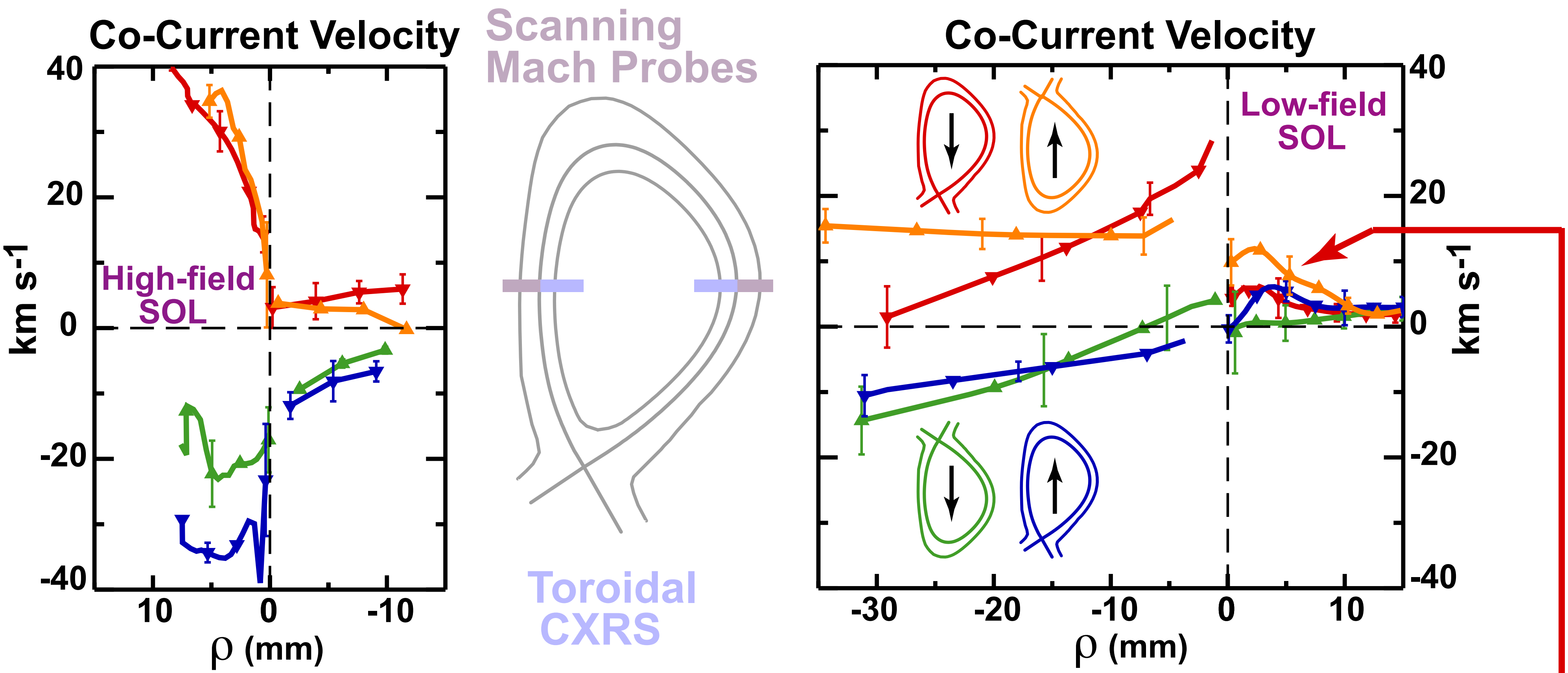

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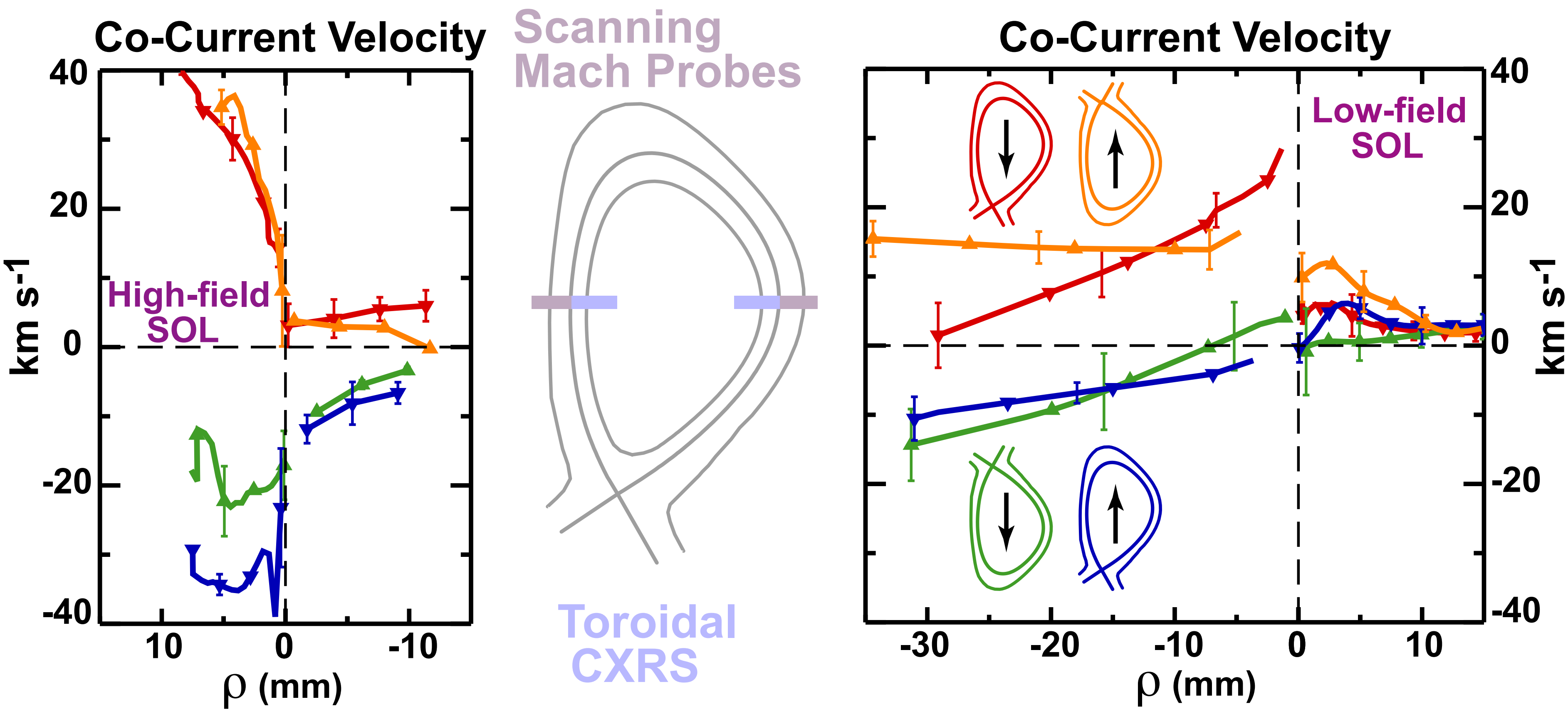

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- SOL flows set a flow 'boundary condition' on the confined plasma
  => tends to spin in the co-current direction for 'favorable' *Bx∇B*

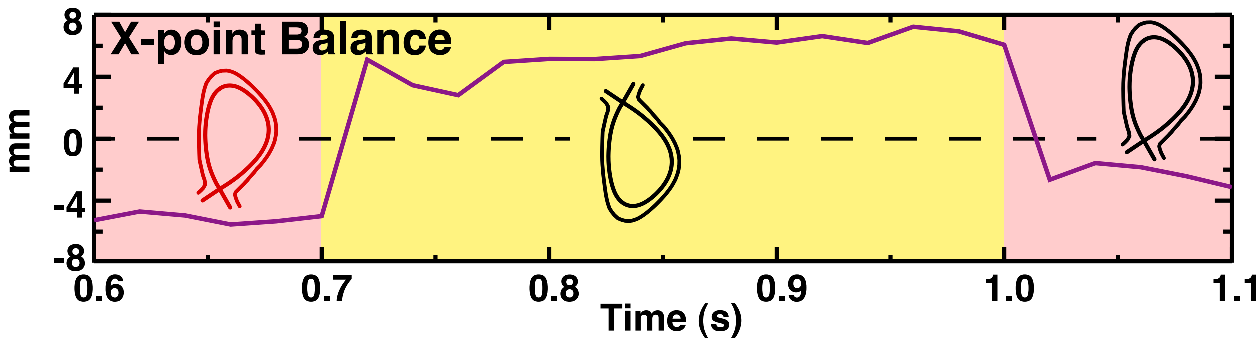
†Physics of Plasmas **15** (2008) 056106.

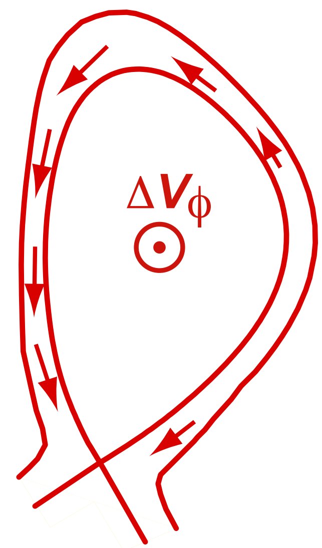
“X-point toggle” experiments in C-Mod† have begun to reveal toroidal momentum transport in L-mode plasmas

Alcator C-Mod

Idea:

- Switch quickly between LSN and USN





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†MP#537 - K. Marr, B. Lipschultz, A. Ince-Cushman, N. Smick, J. Hughes, J. Rice, B. Labombard, S. Wolfe
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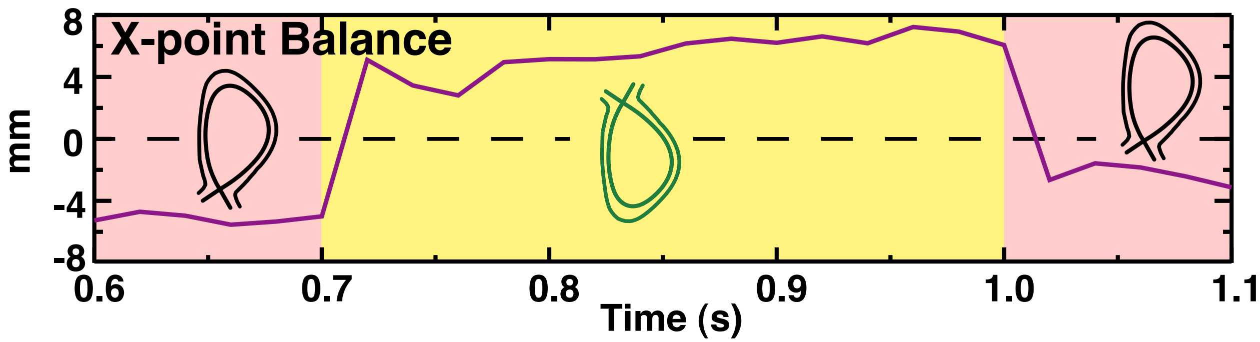

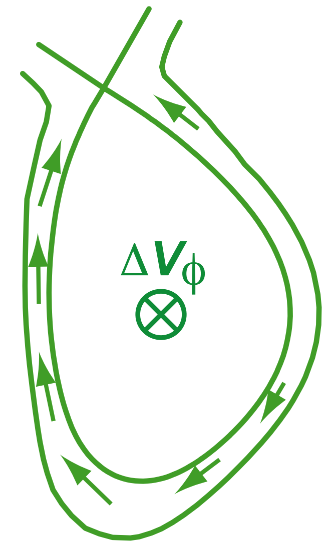

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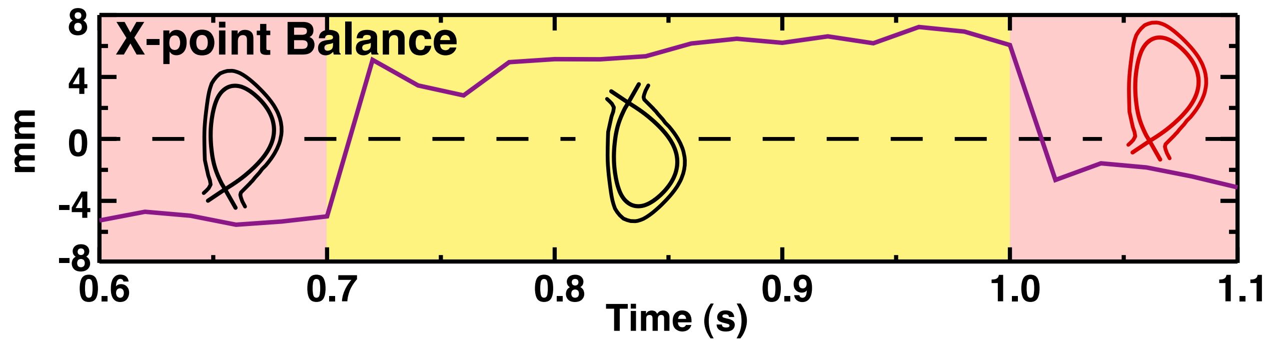

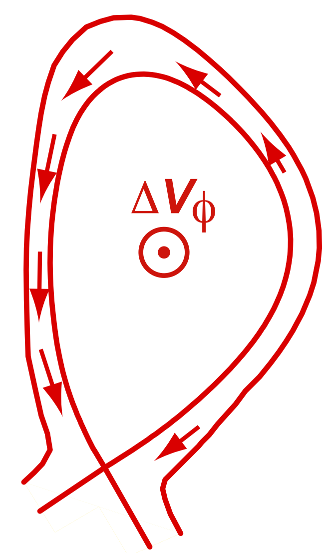

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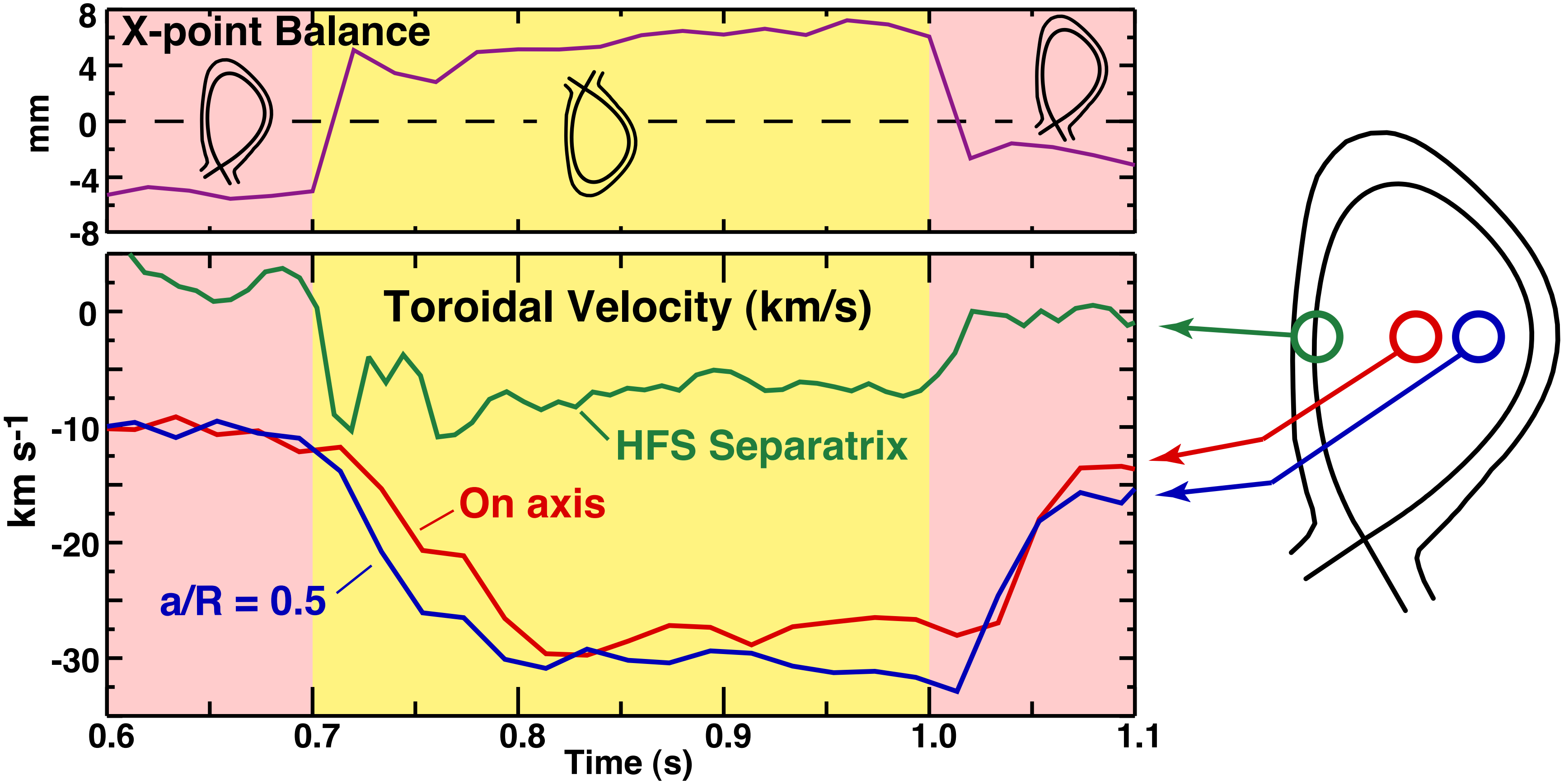

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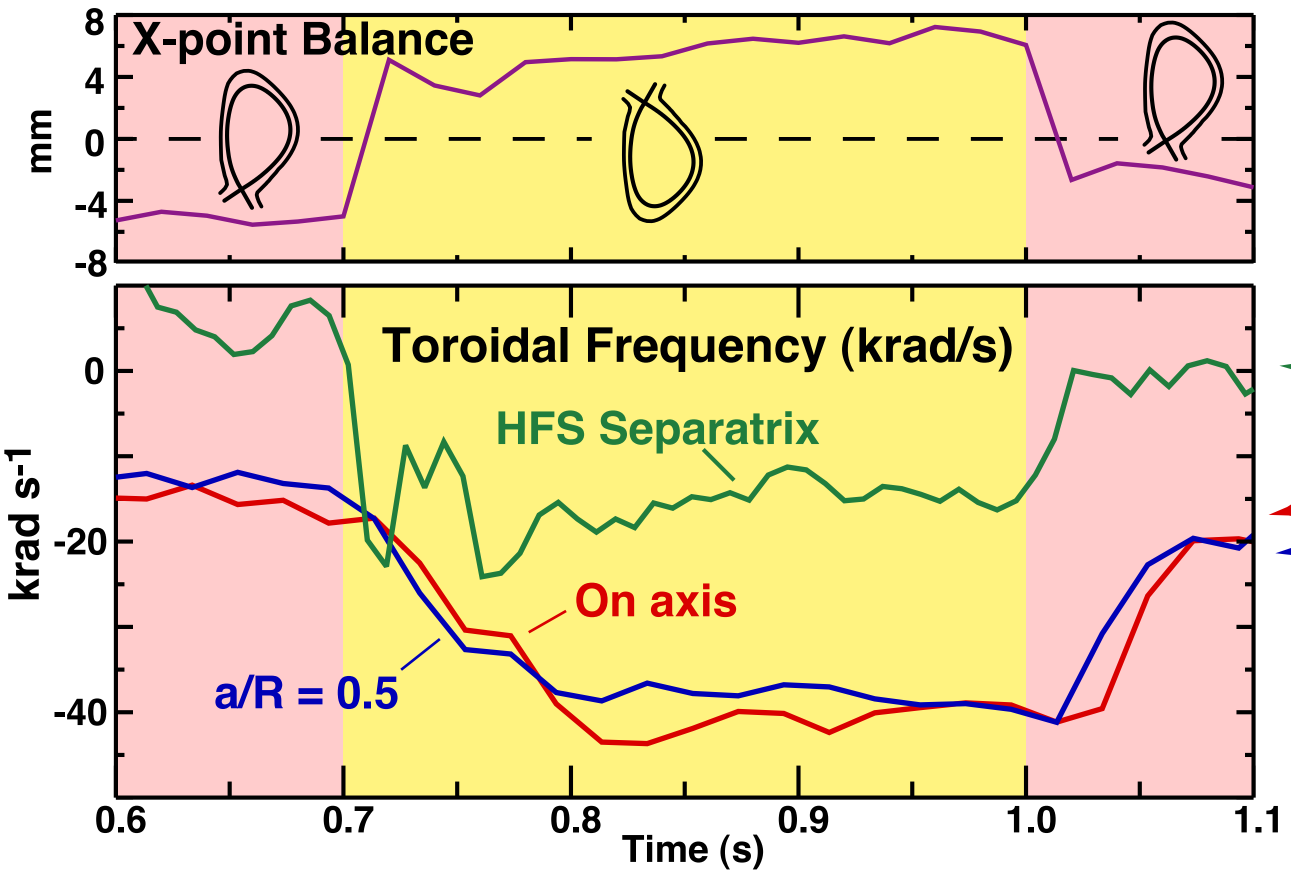

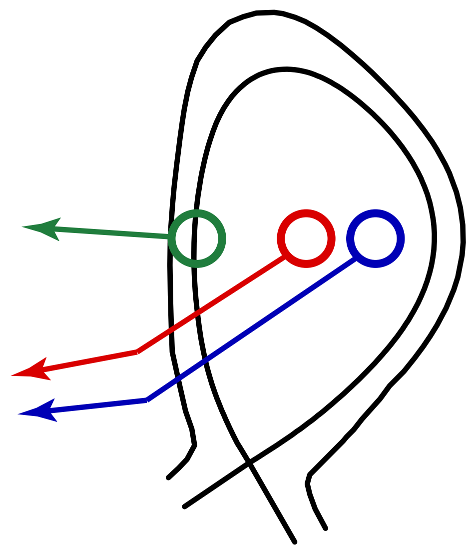

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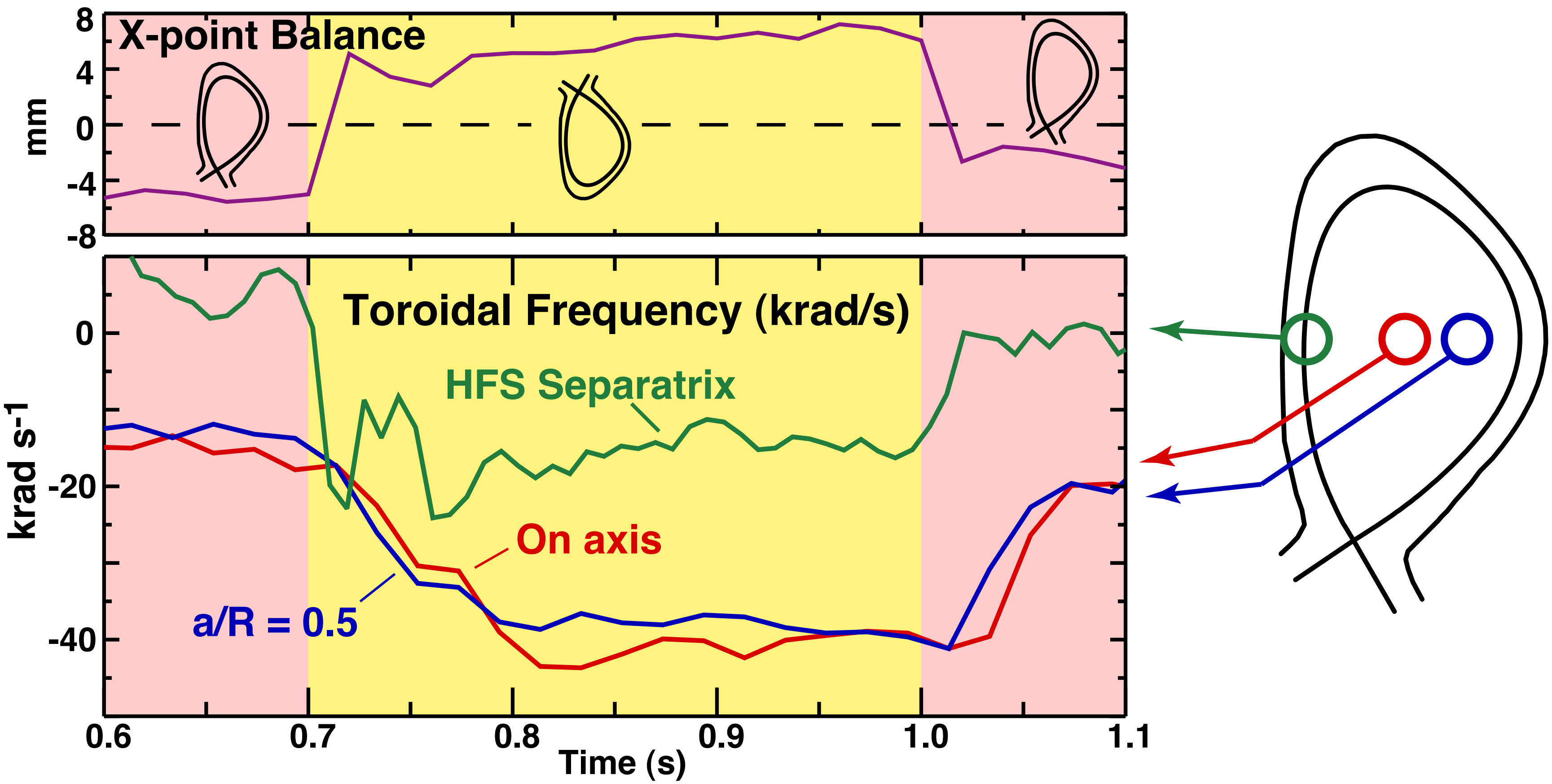

=> Direct evidence of x-point dependent SOL flow boundary condition

=> Allows momentum transport studies in L-mode ....

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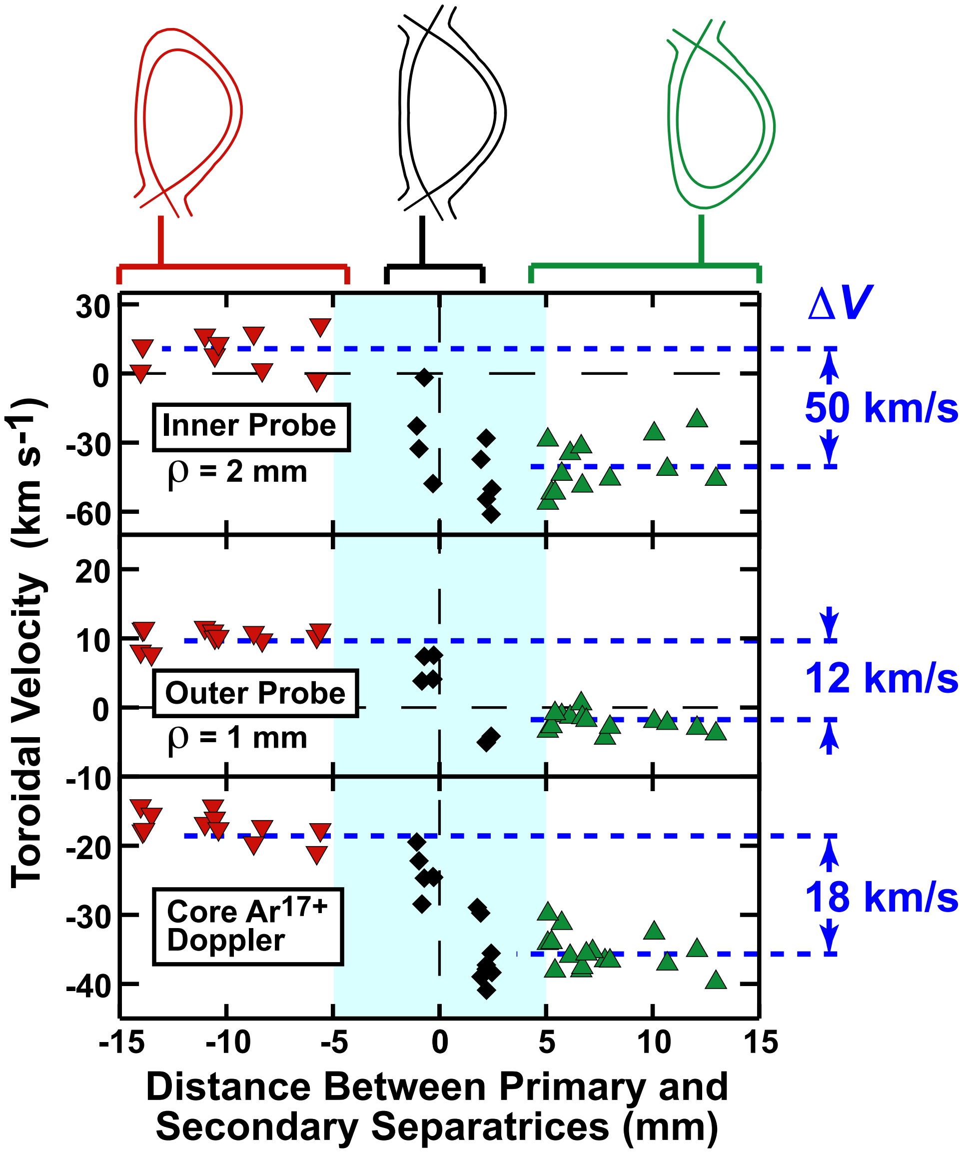
New insight on how $B \times \nabla B$ direction may lead to different L-H power thresholds†:
Magnetic topology => SOL flows => toroidal rotation



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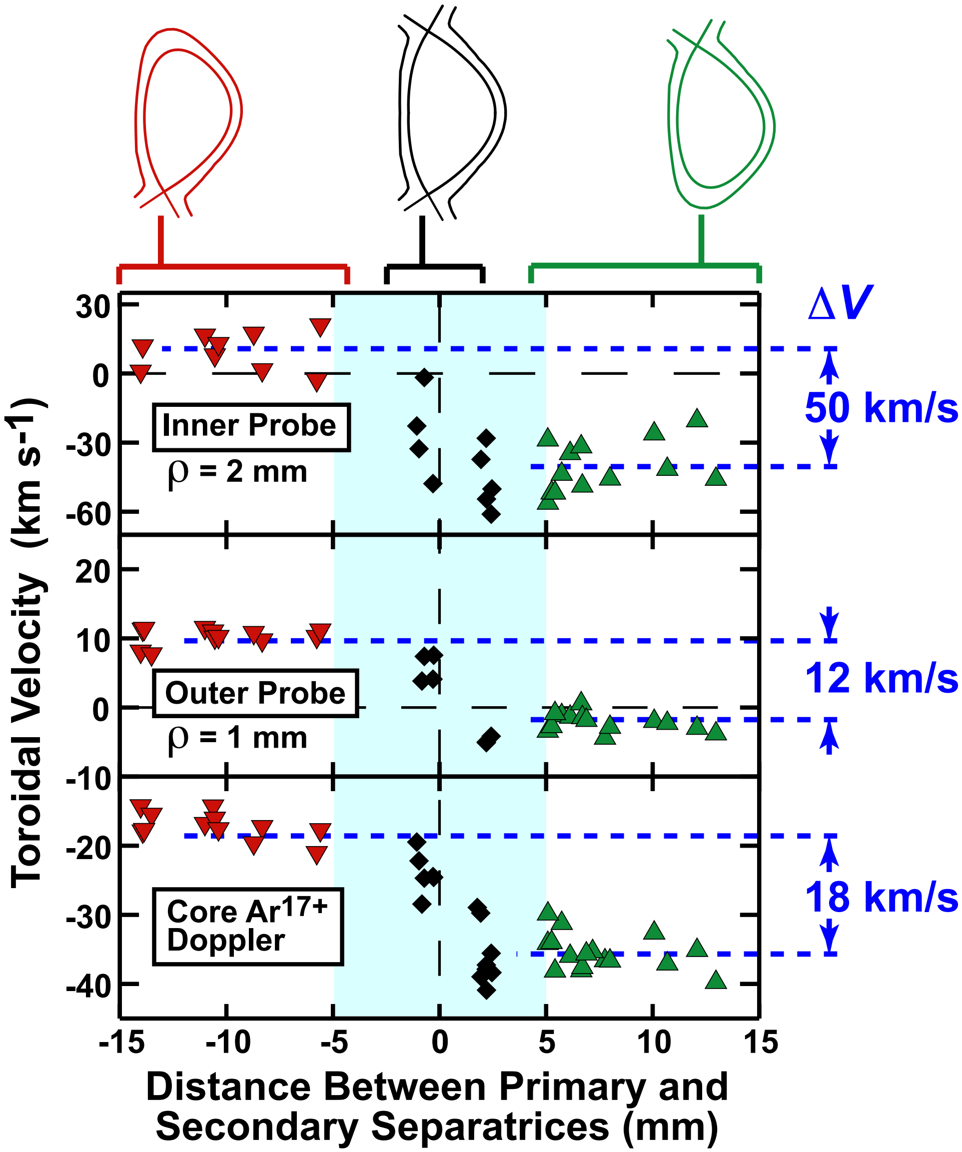

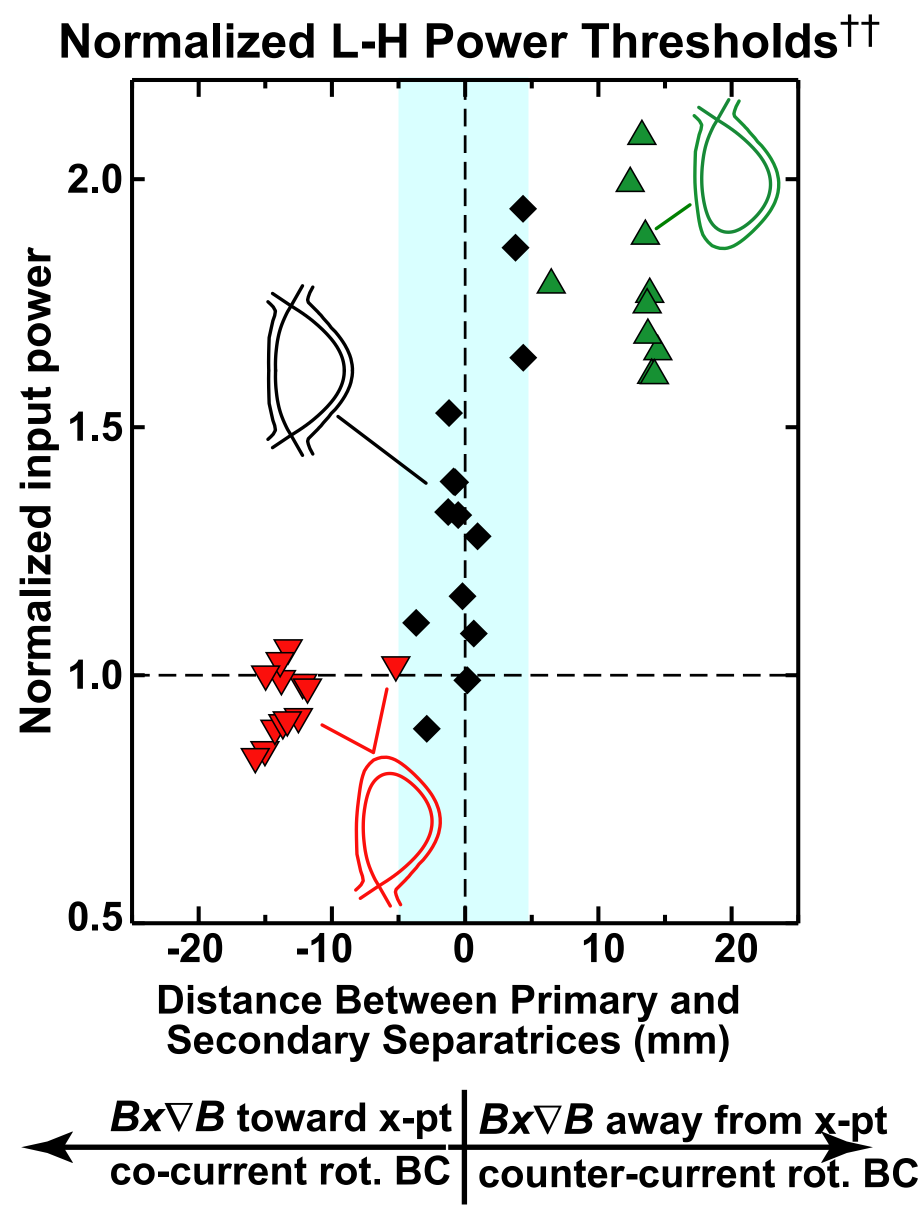

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††Power threshold scaling from Int. H-mode Threshold Database, J. Snipes, *et al.*, PPCF **42**, A299 (2000).

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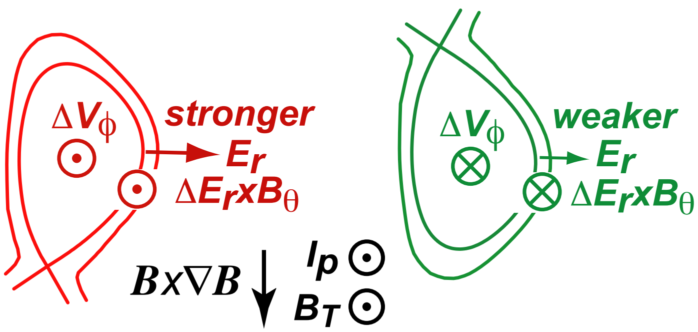
Magnetic topology => SOL flows => toroidal rotation

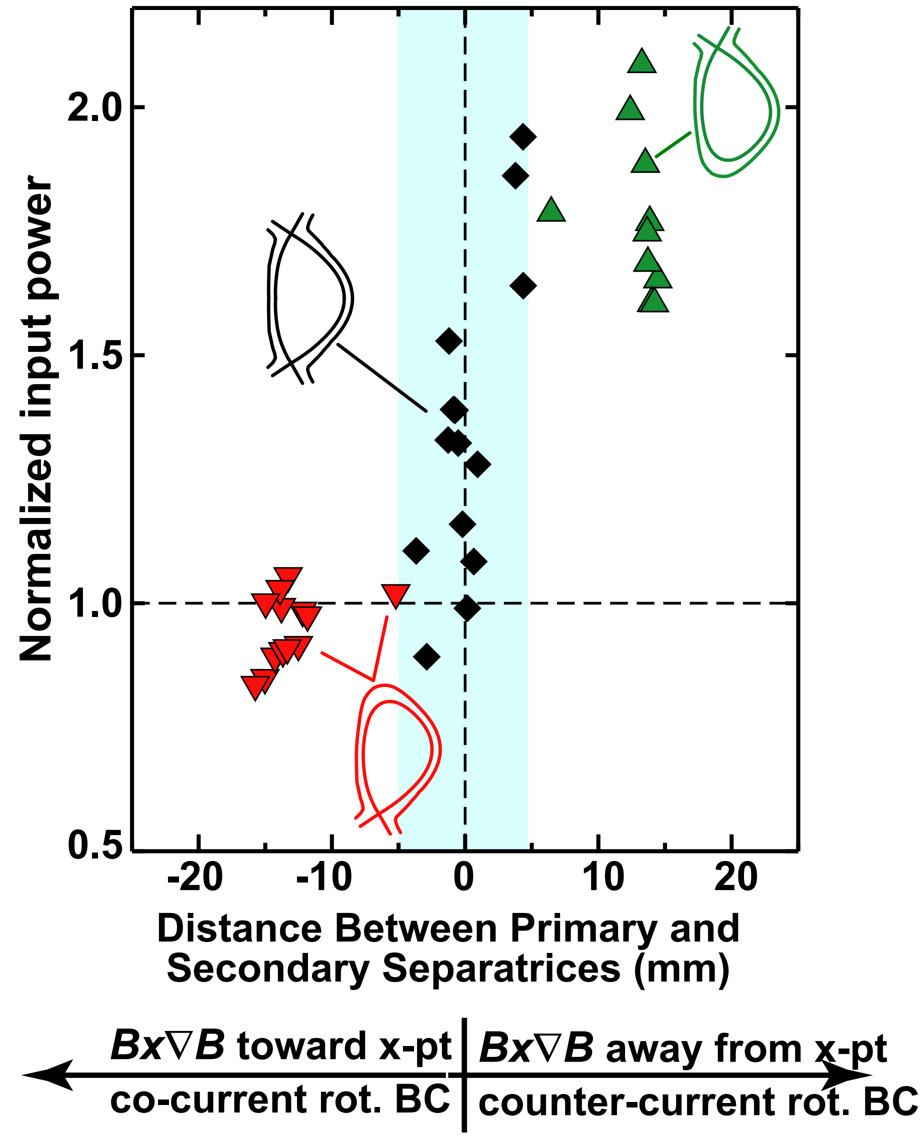
Conjecture:

Co-current rotation enhances E_r outside sep.†
...leading to more favorable (enhanced?) *ExB* shear layer?



- an area ripe for further investigation....
...shear measurements now starting in C-Mod

Normalized L-H Power Thresholds



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New insight on how $B \times \nabla B$ direction may lead to different L-H power thresholds:
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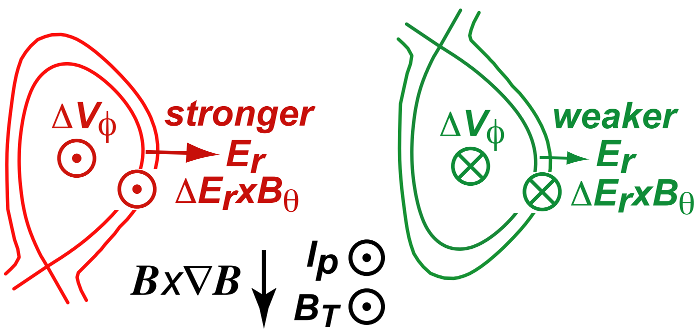

- an area ripe for further investigation....
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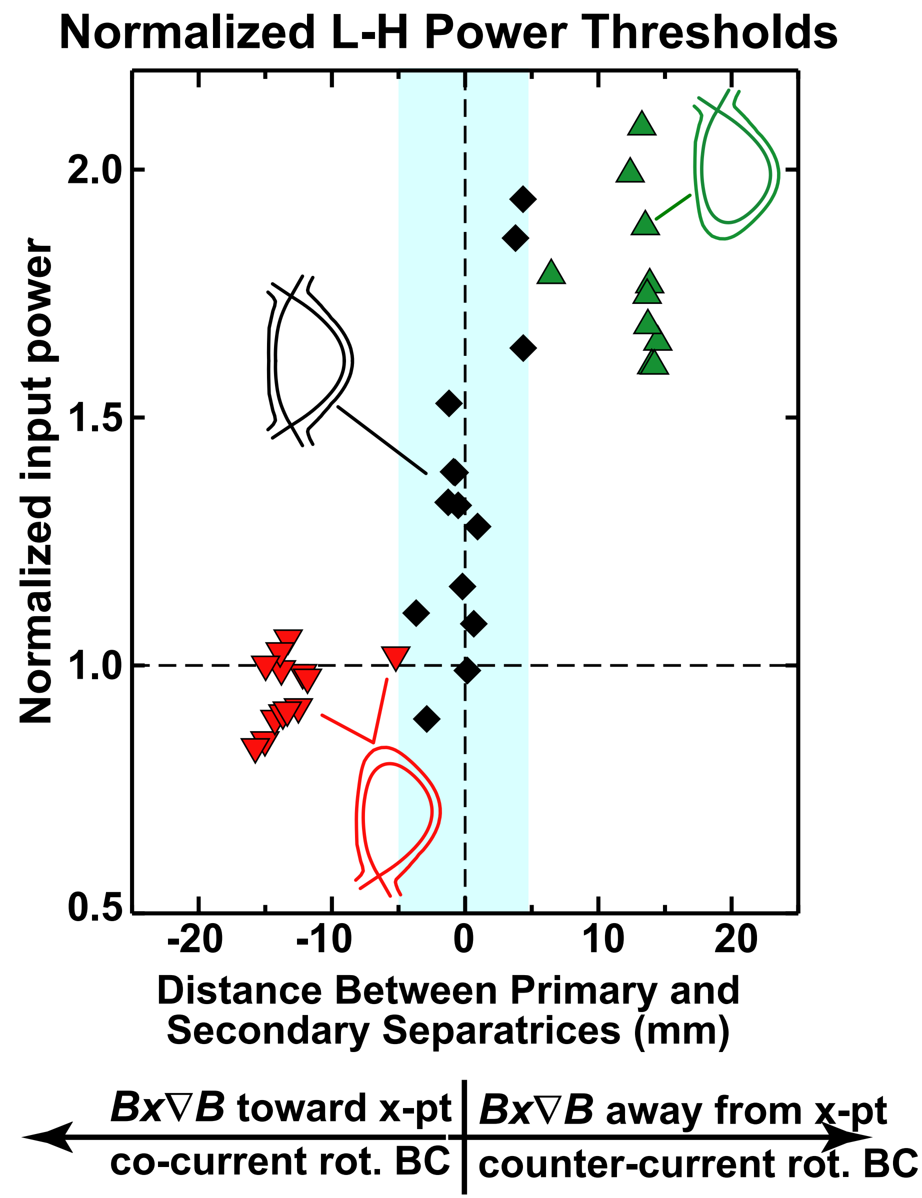
- **Recent DIII-D results (McKee, APS 2007) clearly show connections between beam-driven toroidal rotation, L-H power threshold and poloidal flow shear**
  - strengthens view that $B \times \nabla B$ dependence of L-H threshold involves similar physics



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Edge Plasma --

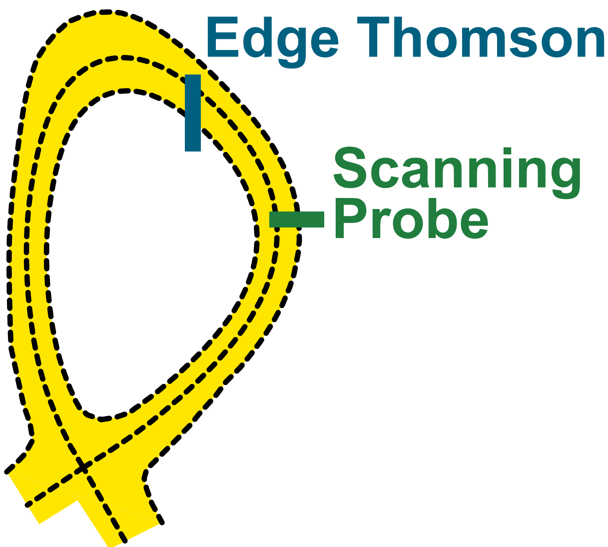
a system at ‘critical gradient’ near LCFS

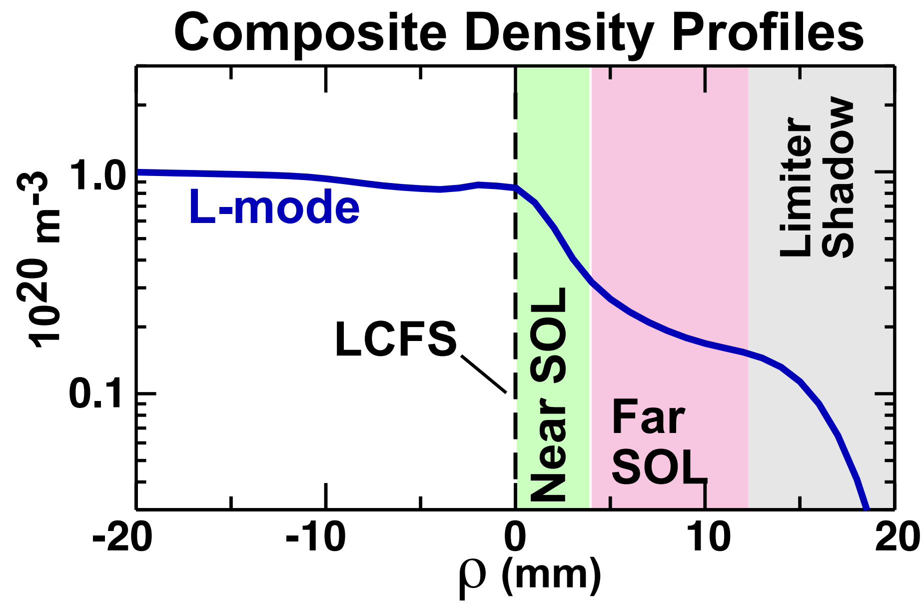
Edge Plasma ~ a system at 'critical gradient' near LCFS

Evidence from L-mode Plasmas:

(1) A weak pedestal in the "Near SOL" is seen

Diagnostics





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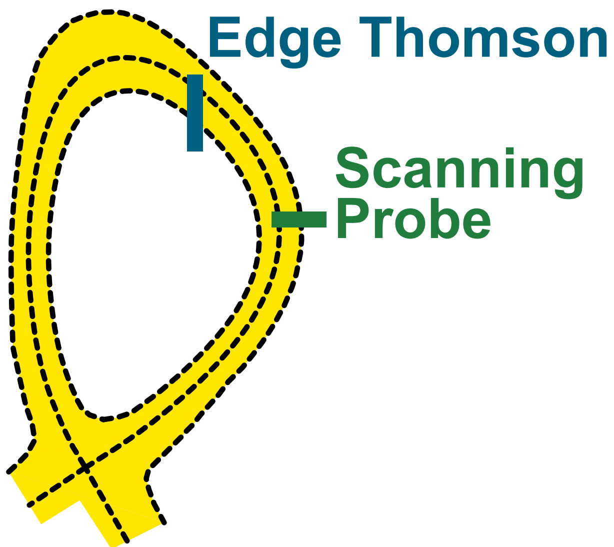

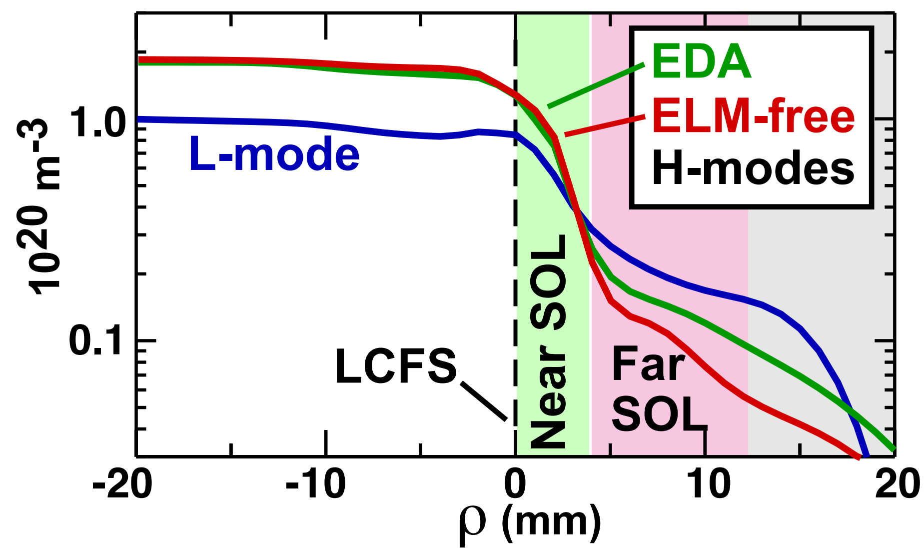

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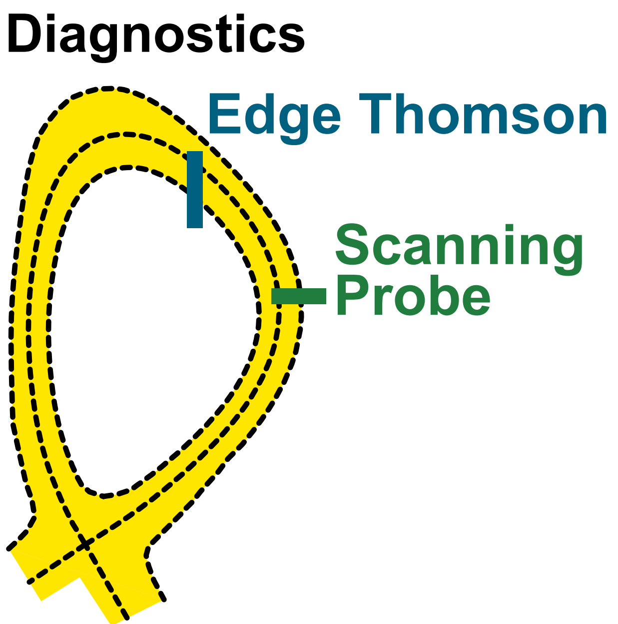

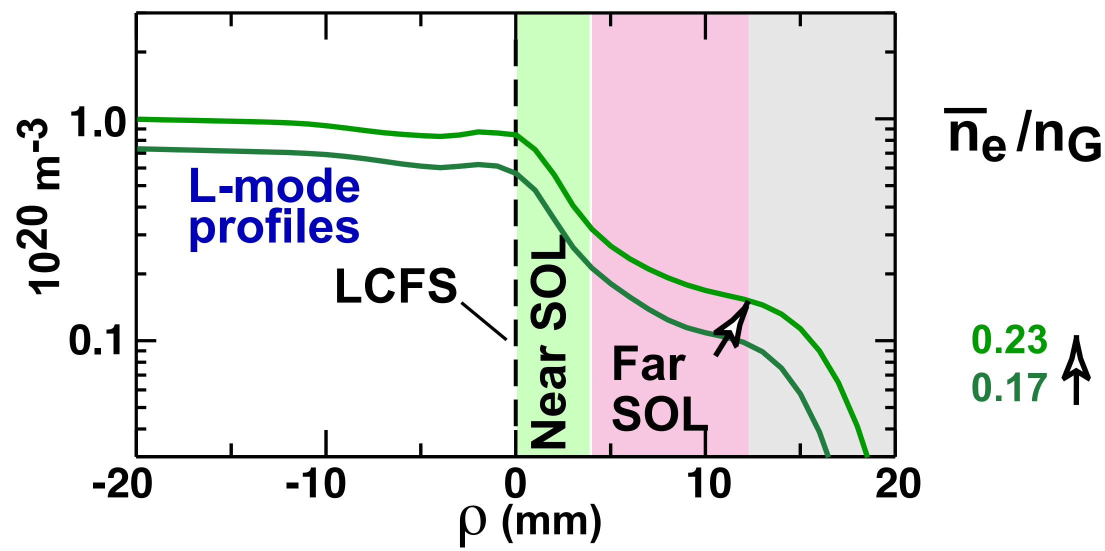

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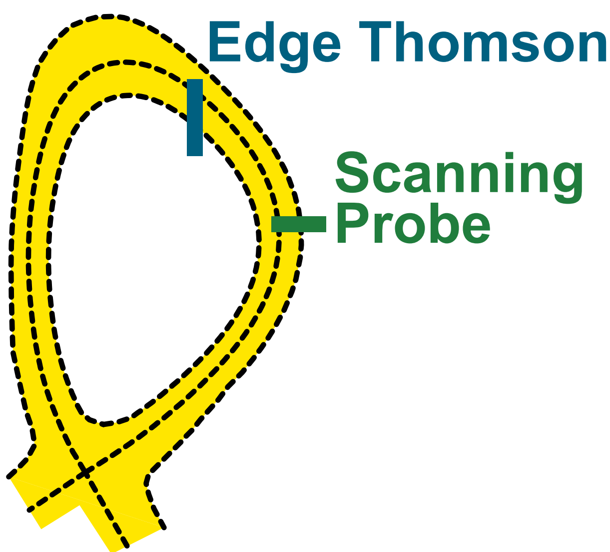

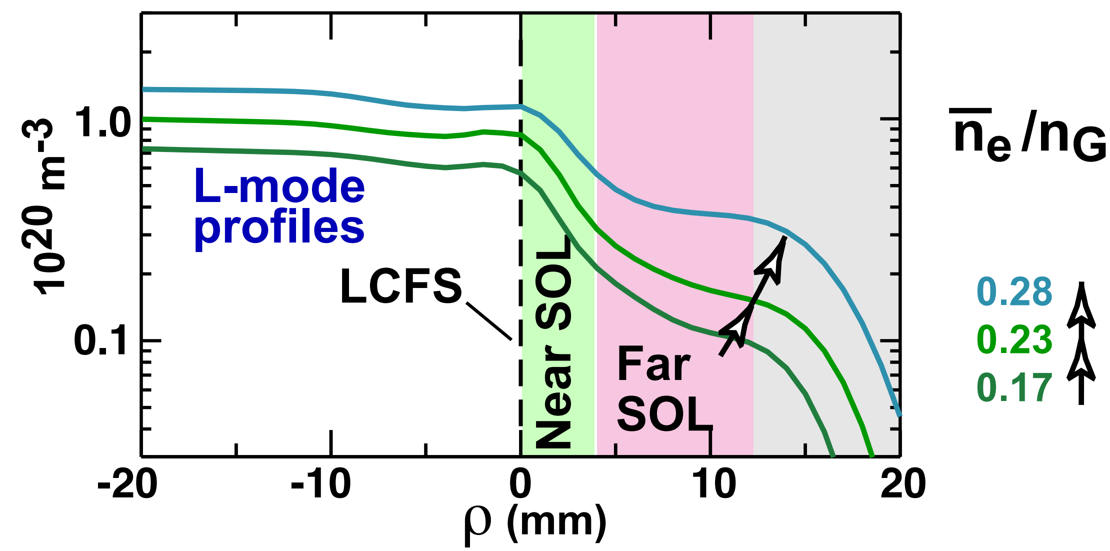

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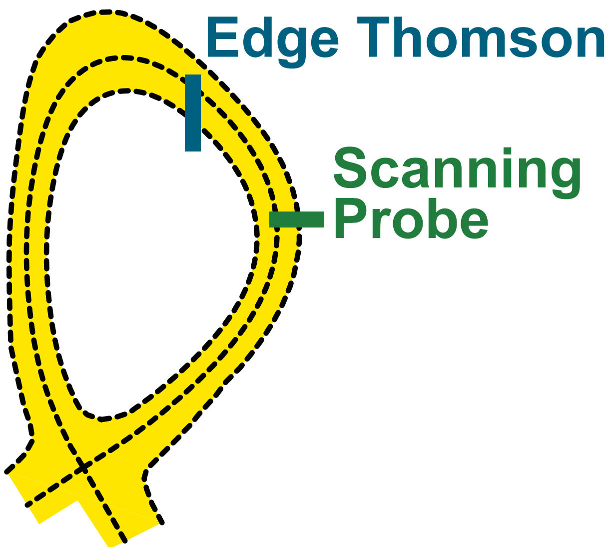

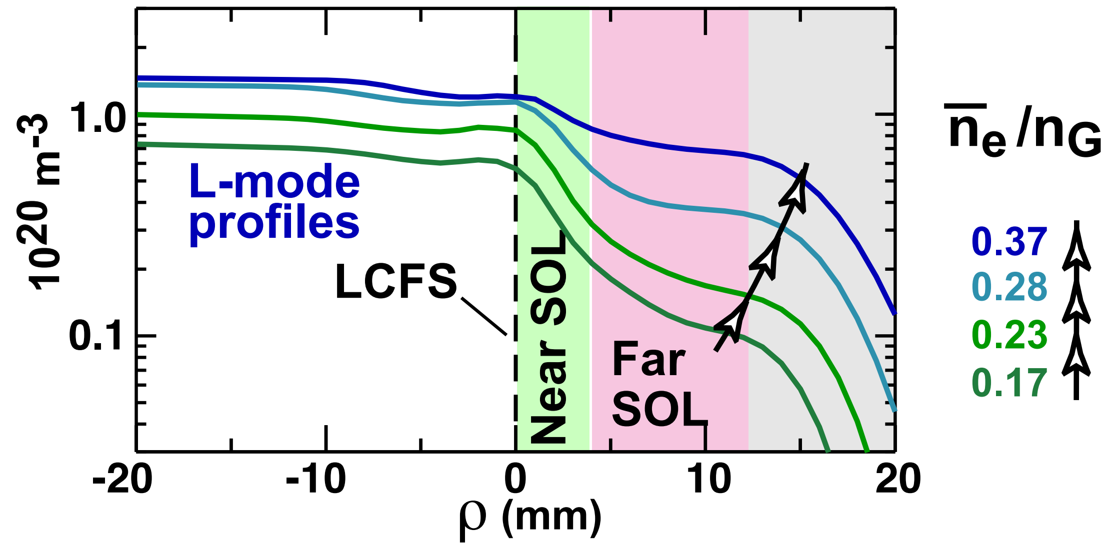

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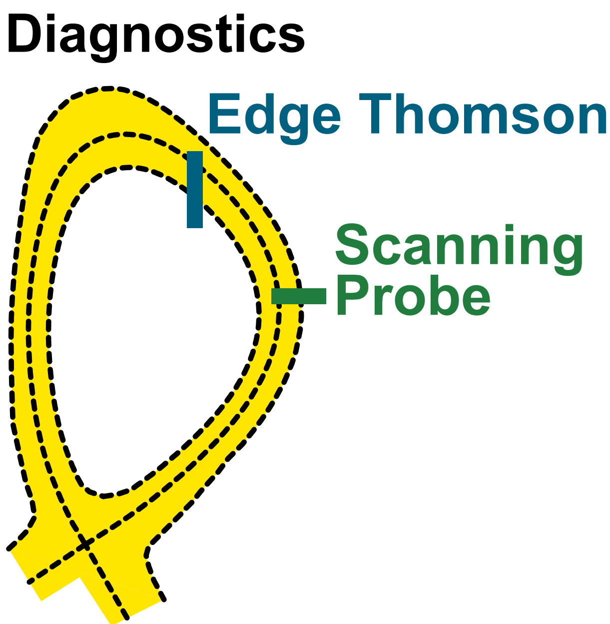

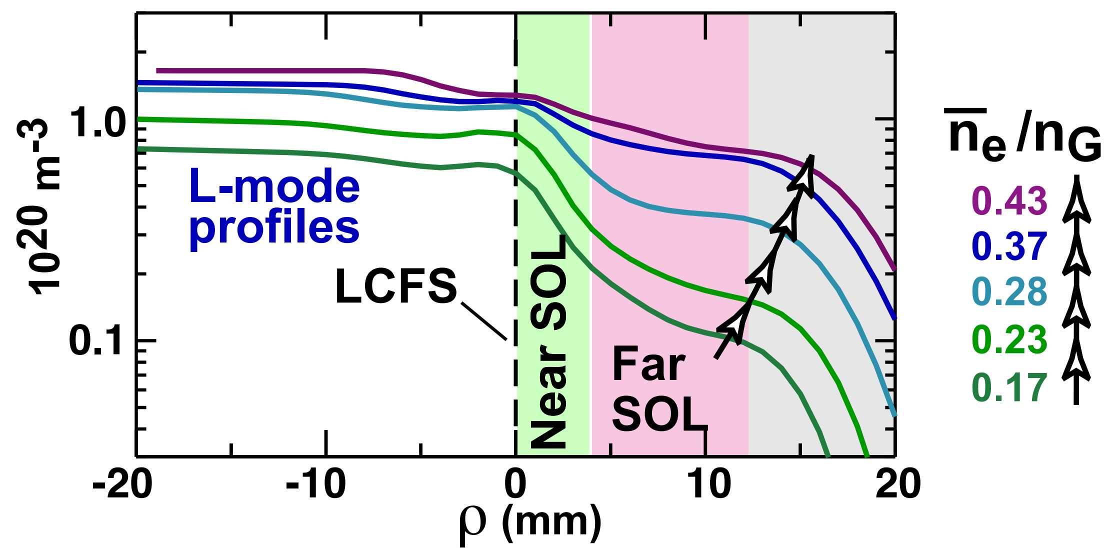

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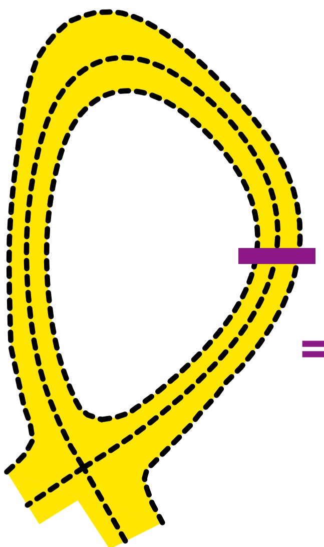
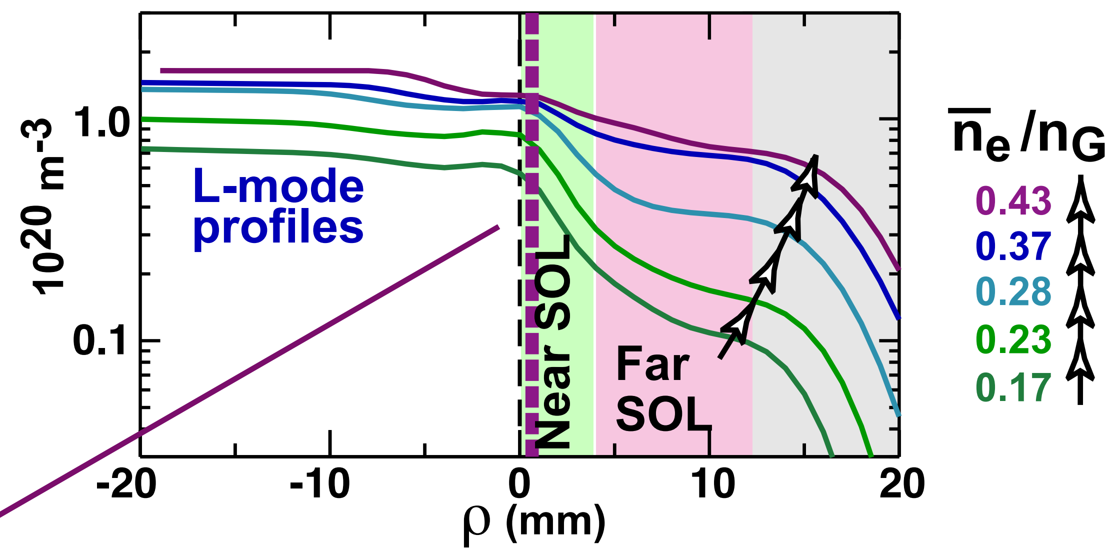


=> infer ionization profiles and cross-field fluxes in Near SOL



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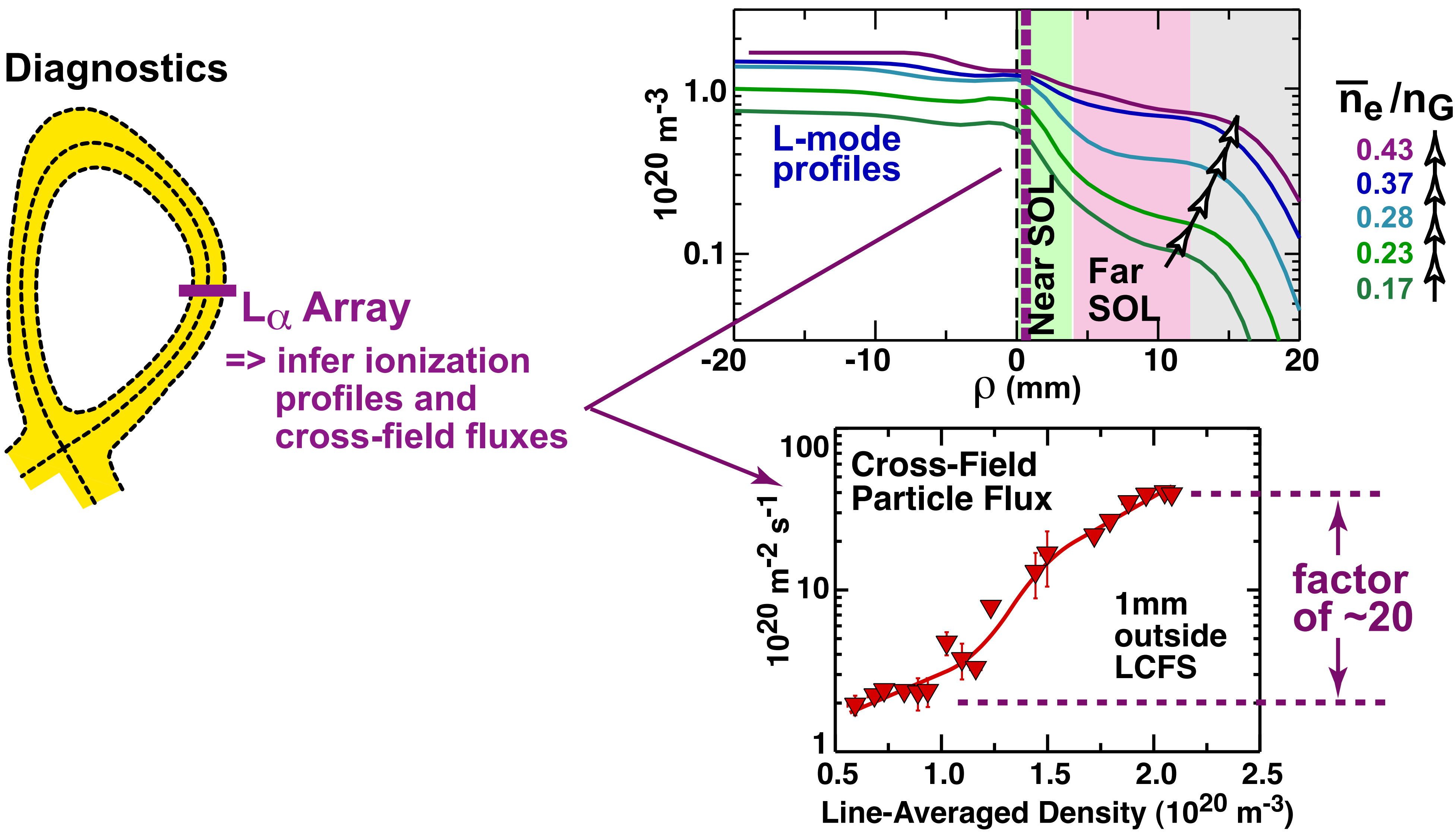

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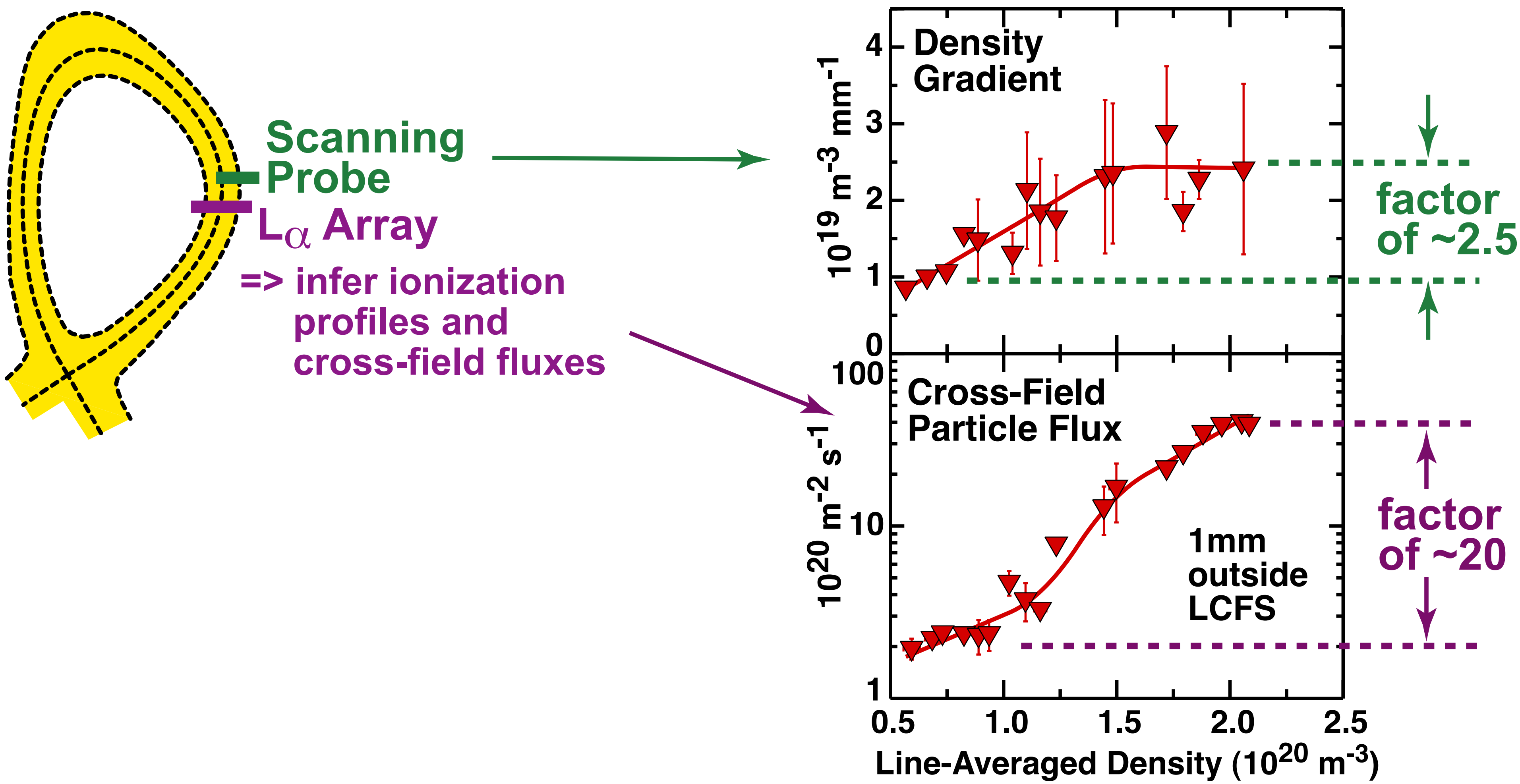

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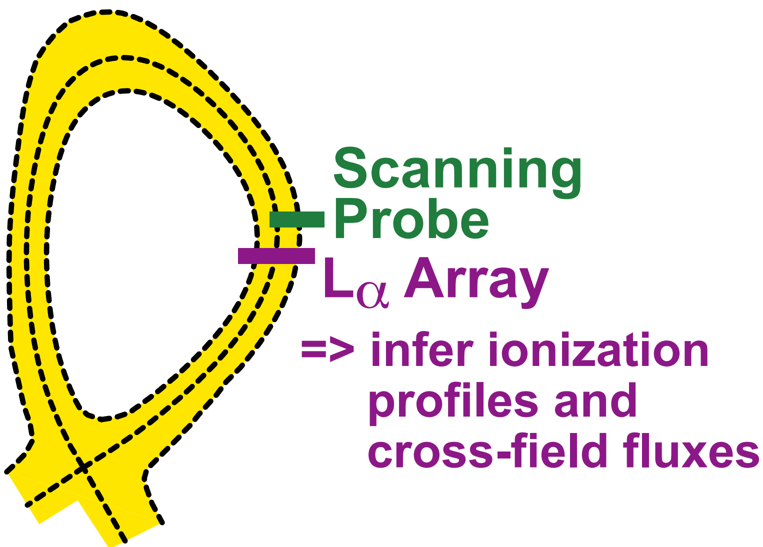

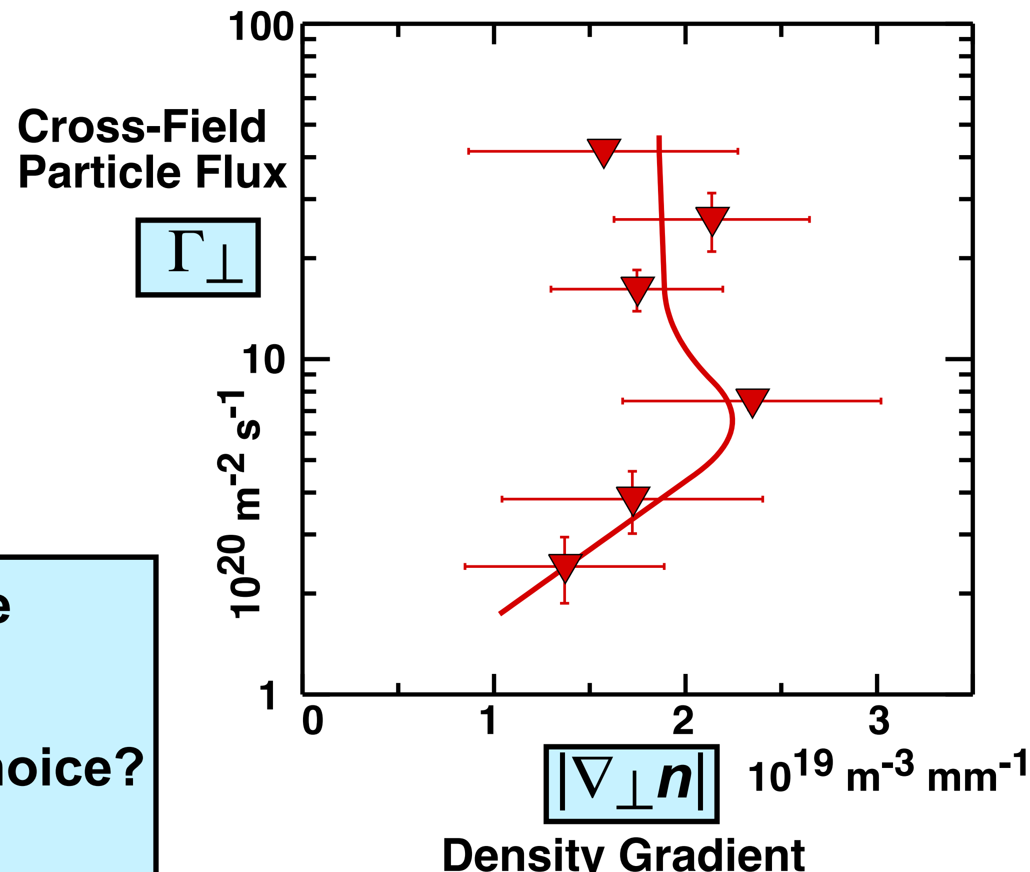

Flux-gradient model ~ a poor choice

$$\Gamma_\perp = -D_\perp \nabla_\perp n; \quad D_\perp = f(\ldots)$$

Critical-gradient model ~ a better choice?

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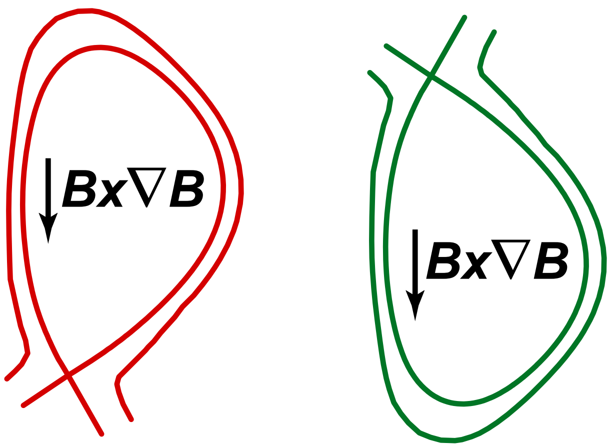
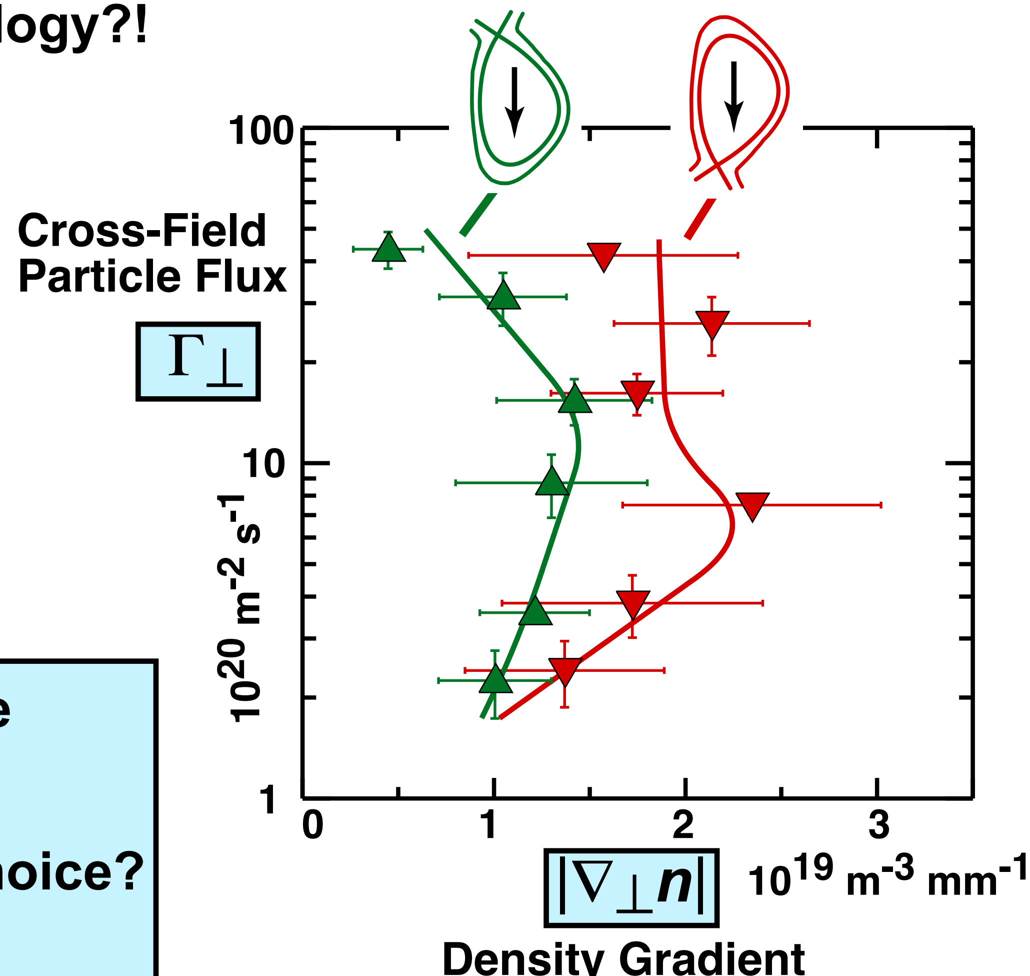
“Critical gradient” sensitive to topology?!

$|\nabla_\perp n|_{crit}$ reduced for “unfavorable” $B\times\nabla B$?





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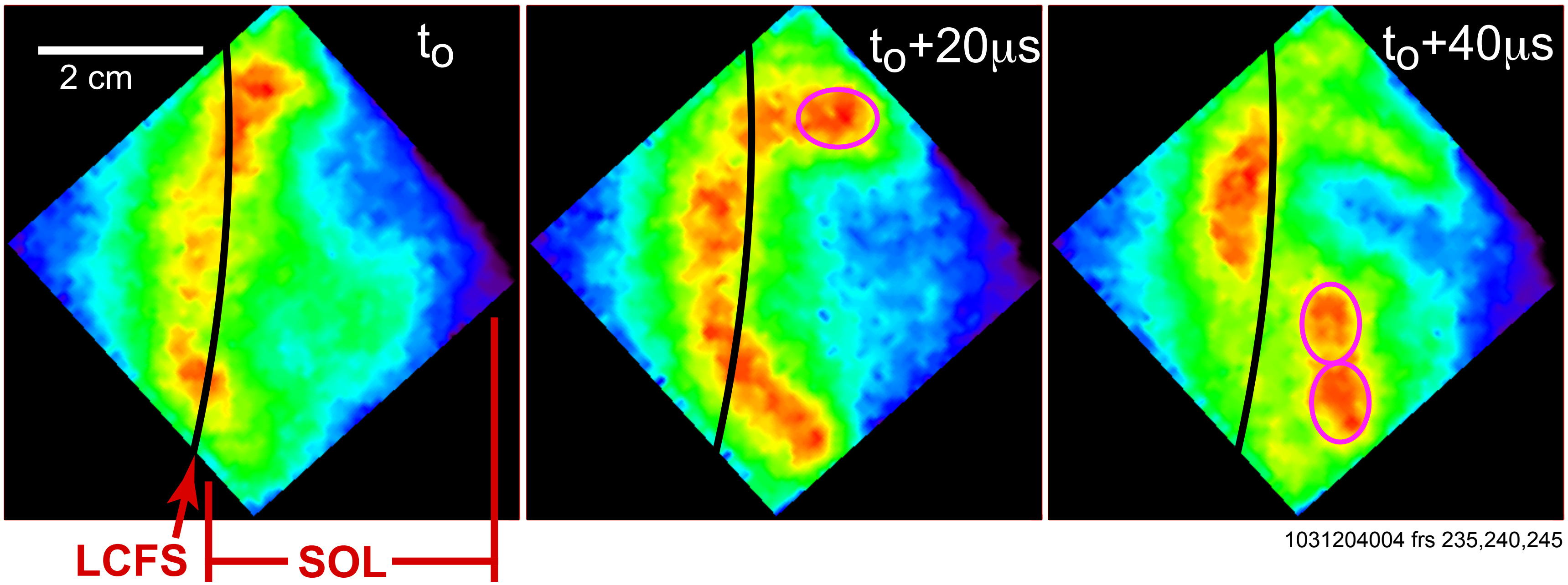

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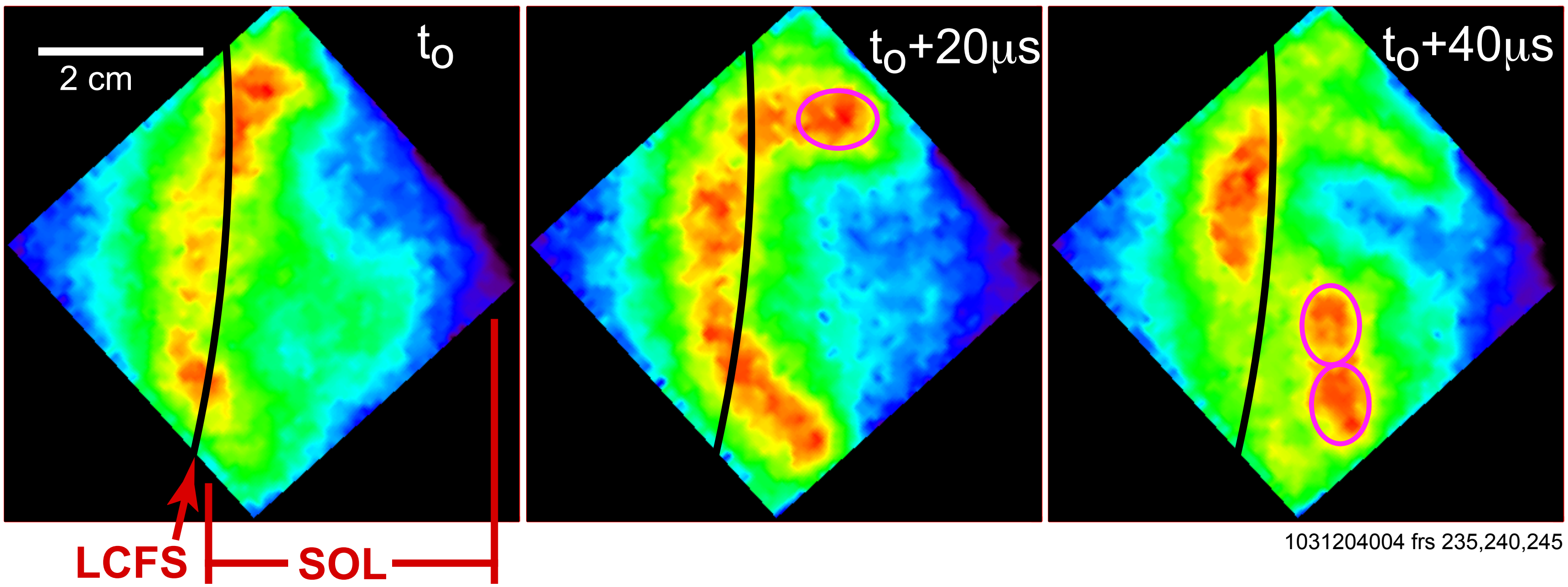

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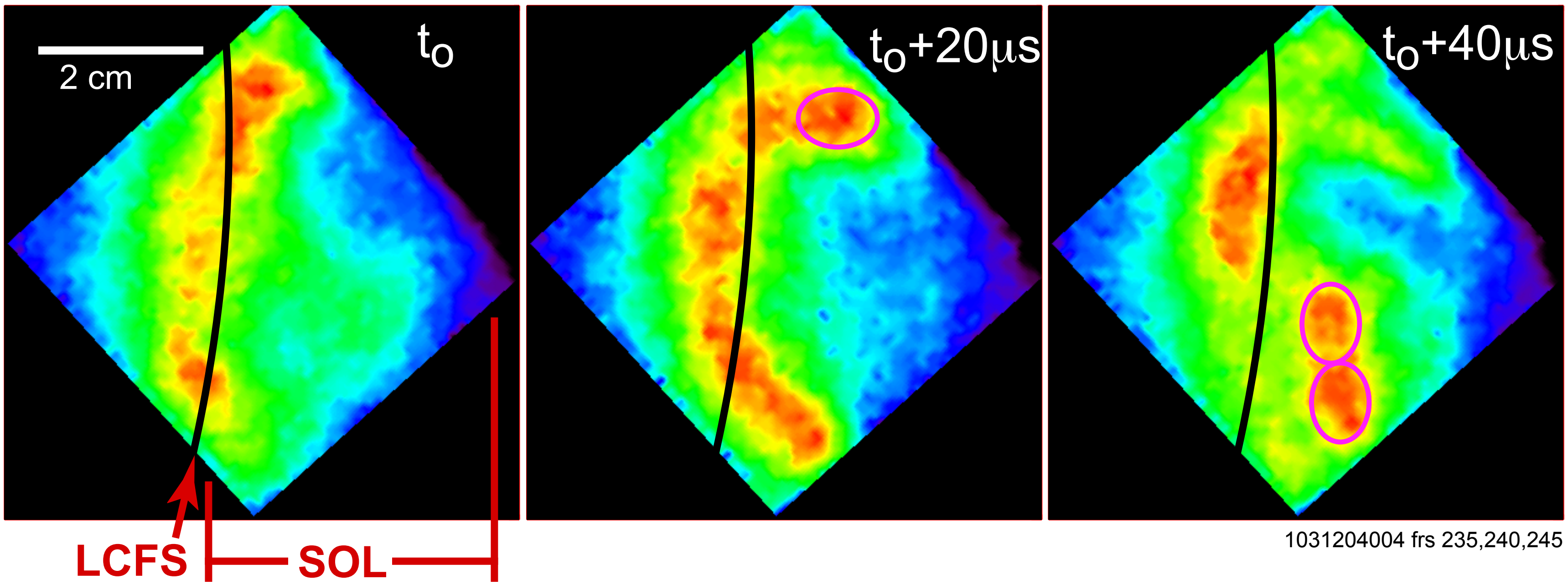

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=> Observations point to a 'critical gradient' phenomenon in Near SOL

H-mode physics: *Exceed peeling-ballooning boundary, get ELMs*

L-mode physics?

Evidence that Electromagnetic Plasma Turbulence sets ‘Critical Pressure Gradient’ Near LCFS

If first-principles 3-D transport simulations† are correct... ...physics of collisional edge plasma transport should involve Electromagnetic Fluid Drift Turbulence (EMFDT)

Alcator C-Mod

Physics:

ElectroMagnetic	parallel inductance, finite $\tilde{B}$, parallel resistivity,
Fluid (gyro-fluid) Drift	non-linear drift-wave, curvature,
3-D Turbulence	toroidal geometry, x-point effects

Turbulence character & transport level is affected by two key dimensionless parameters:

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

Inverse Collisionality Parameter $\Lambda = \frac{1}{q}\left(\frac{\lambda_{ei}}{R}\right)^{1/2}$

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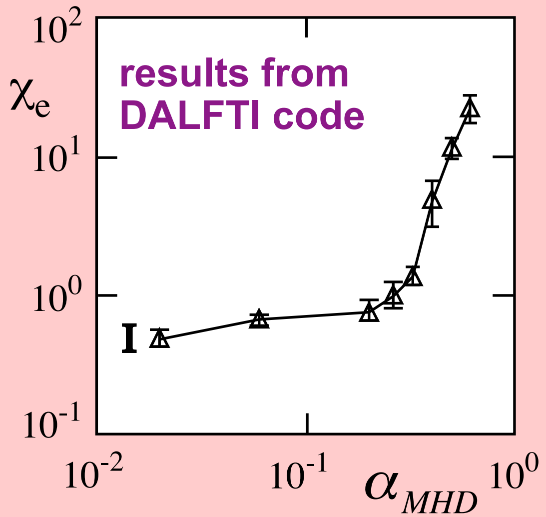

=> strong dependence on α_{MHD} for $\alpha_{MHD} > 0.2$

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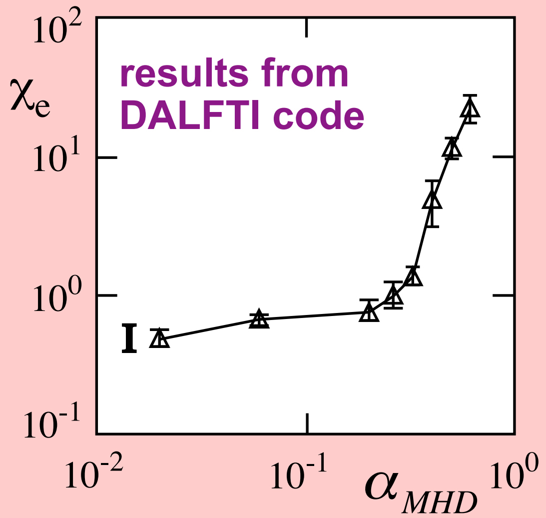

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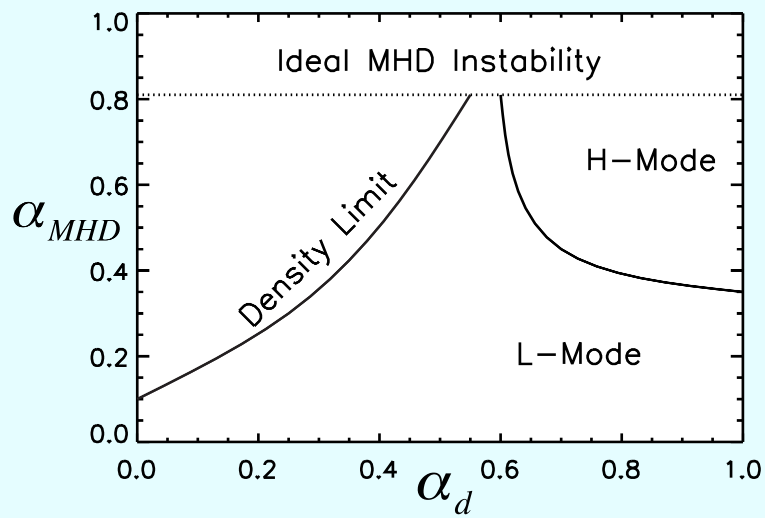
'Phase Space' of EMFDT [4]



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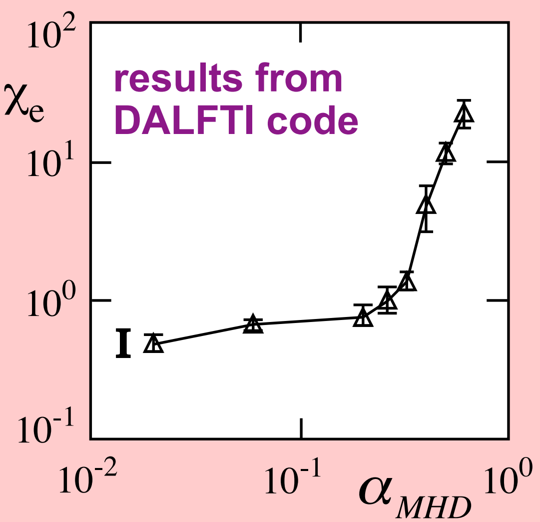

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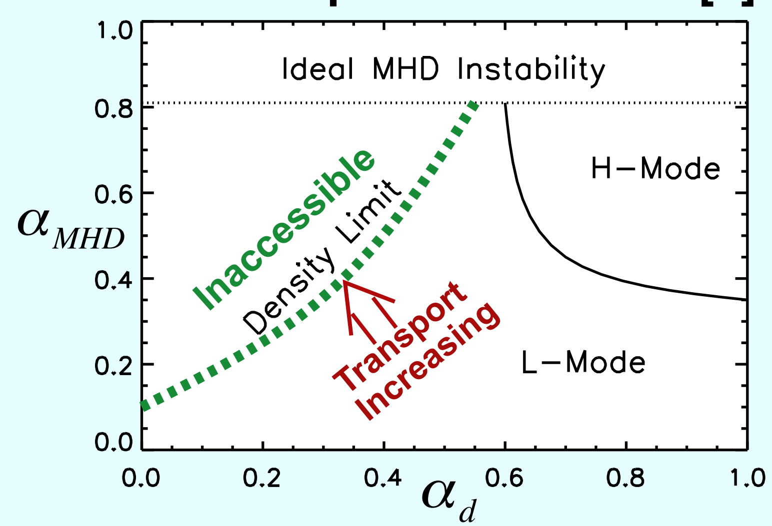

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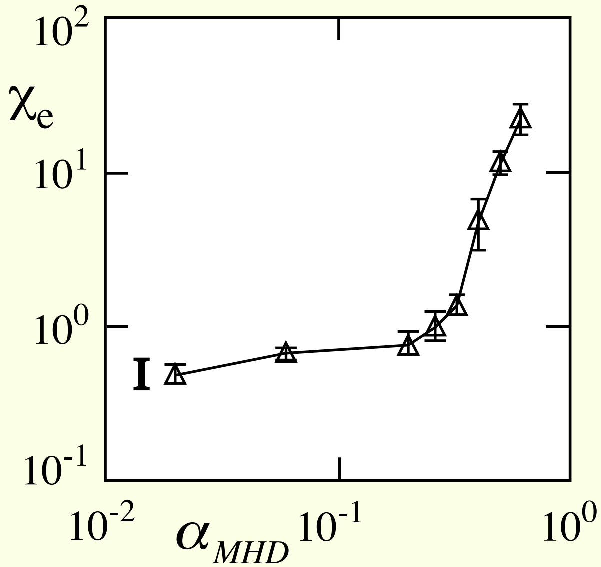

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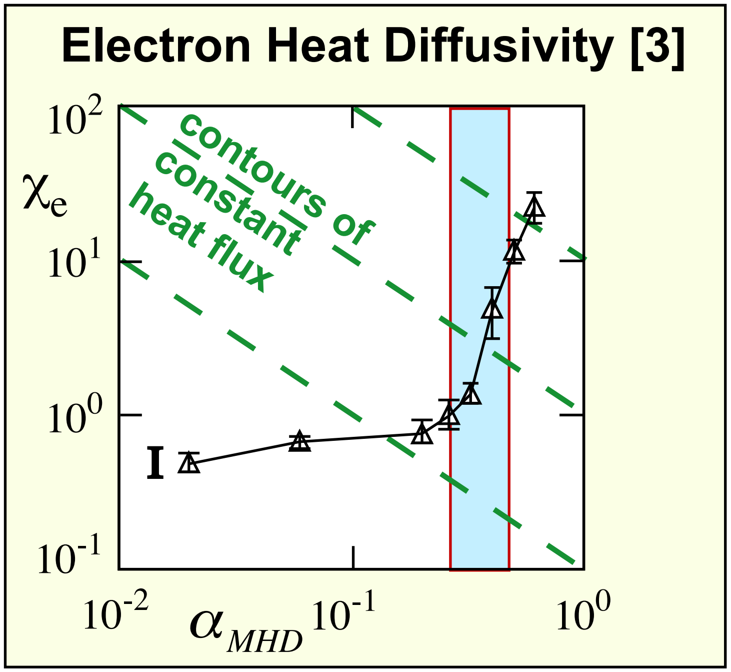

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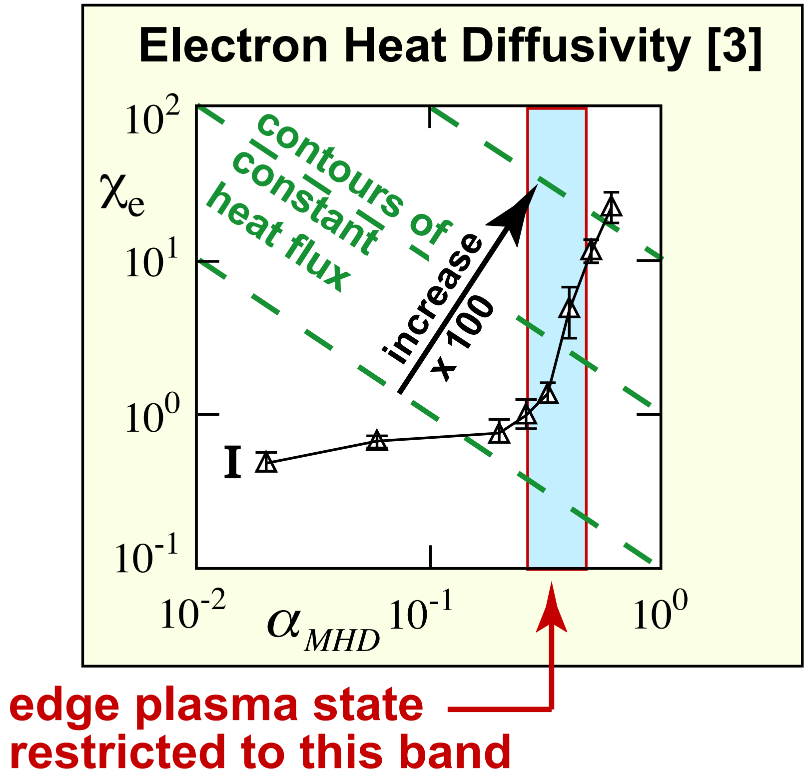

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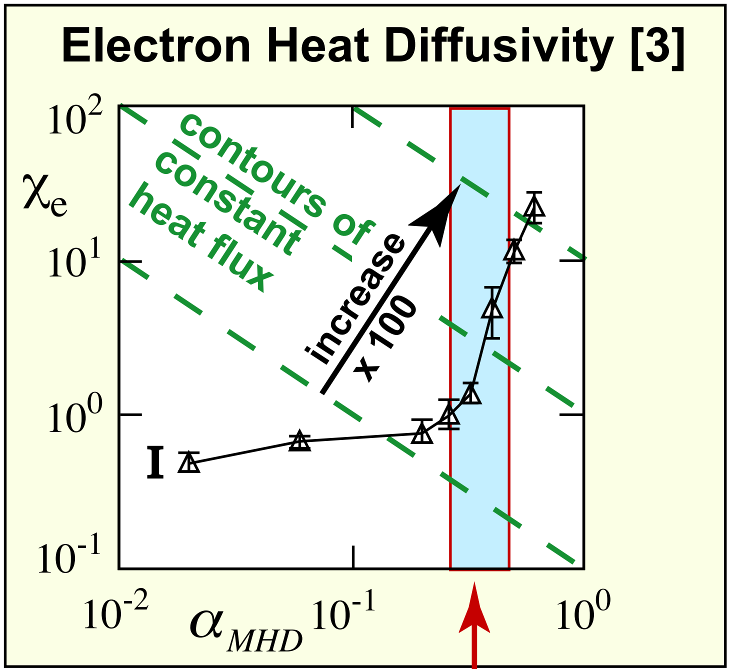

edge plasma state restricted to this band

"critical gradient"

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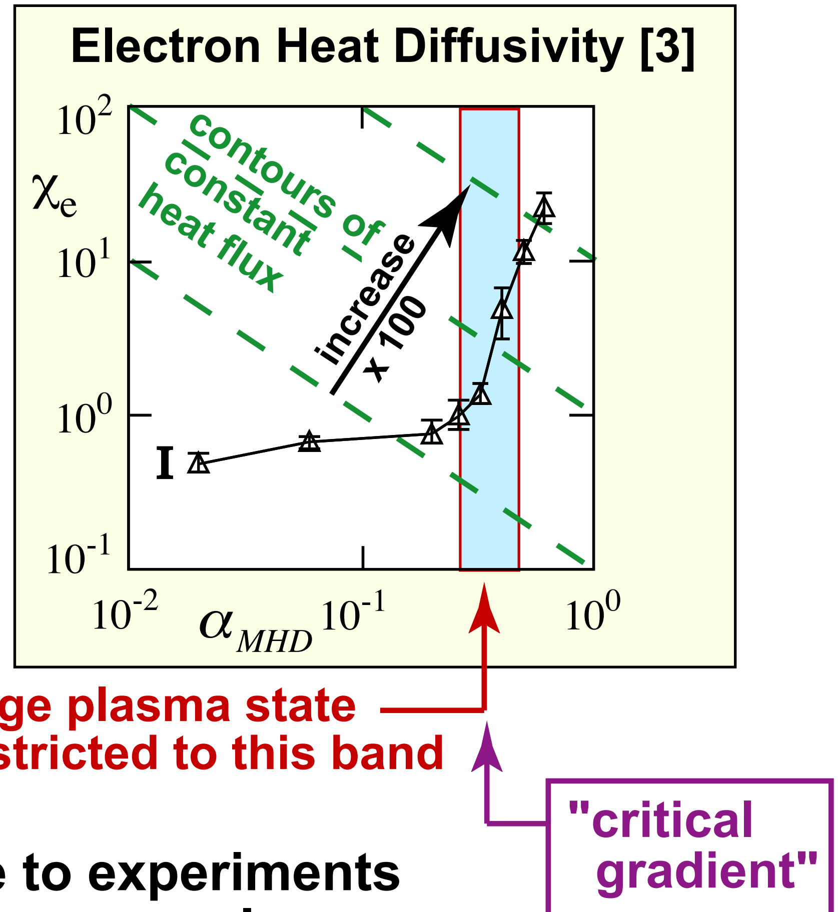


Experimental Test:

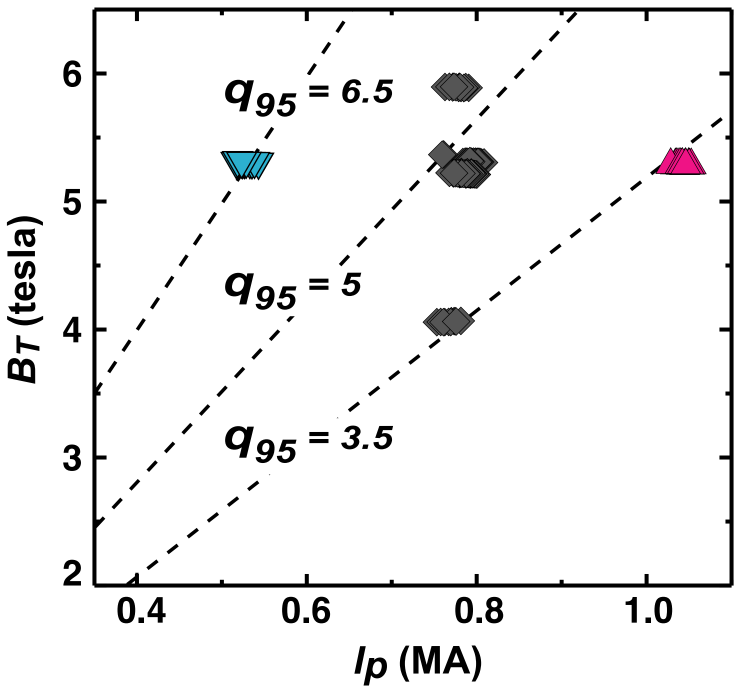
Edge plasma states that are accessible to experiments should ~map to the two-parameter 'phase-space',

$$\alpha_{MHD} \sim \boxed{q^2 R \frac{\nabla_\perp P}{B^2}} \quad ; \quad \Lambda = \boxed{\frac{1}{q}\left(\frac{\lambda_{ei}}{R}\right)^{1/2}}$$

<u>independent of dimensional parameters</u> (B_T, I_p, $\bar{n}_e$)

Plasma states near separatrix are indeed found to occupy a well-defined region in the phase space of EMFDT†

Discharges with different dimensional parameters: B_T, I_p, $\overline{n}_e$



Low-power Ohmic L-mode discharges

Density: $0.14 < n/n_G < 0.53$

Lower single-null

Forward I_p, B_T

---

†Nuclear Fusion 45 (2005) 1658.

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Alcator C-Mod

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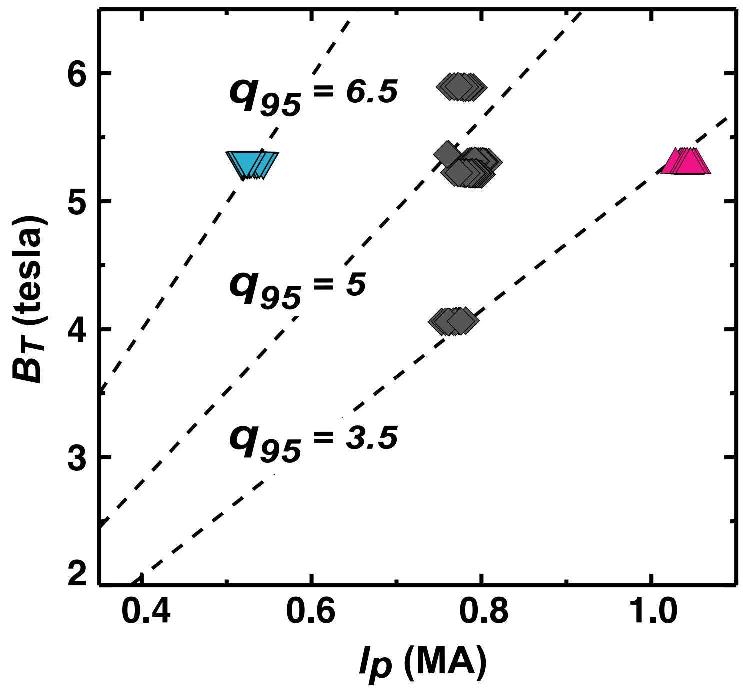

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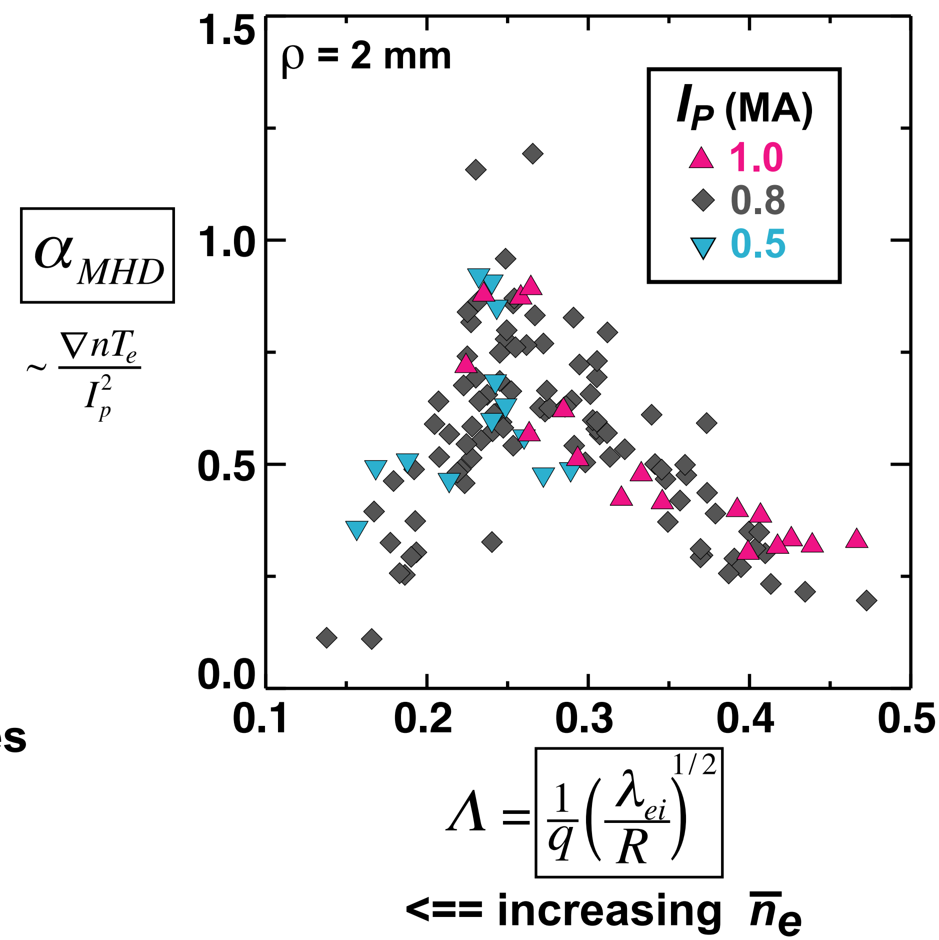
Lower single-null

Forward I_p, B_T

...occupy in a similar band in α_{MHD}, Λ space



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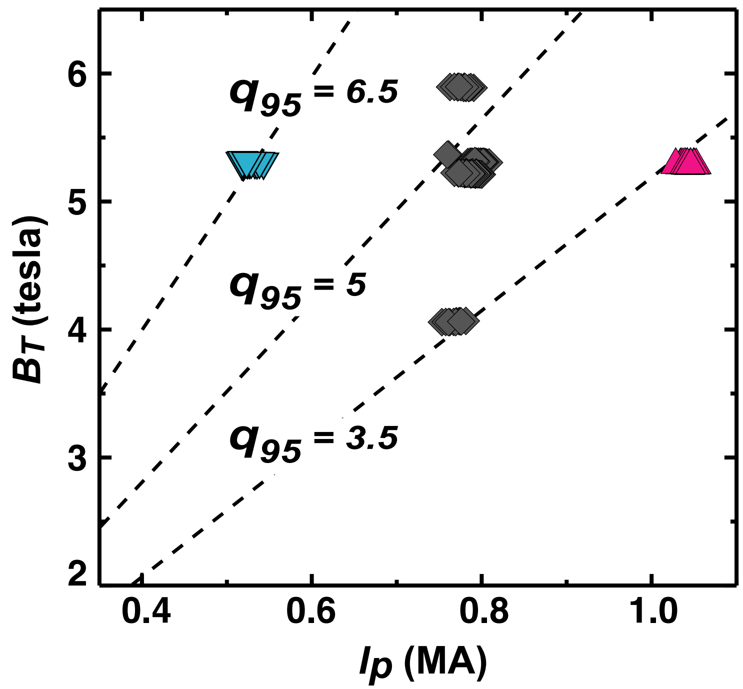

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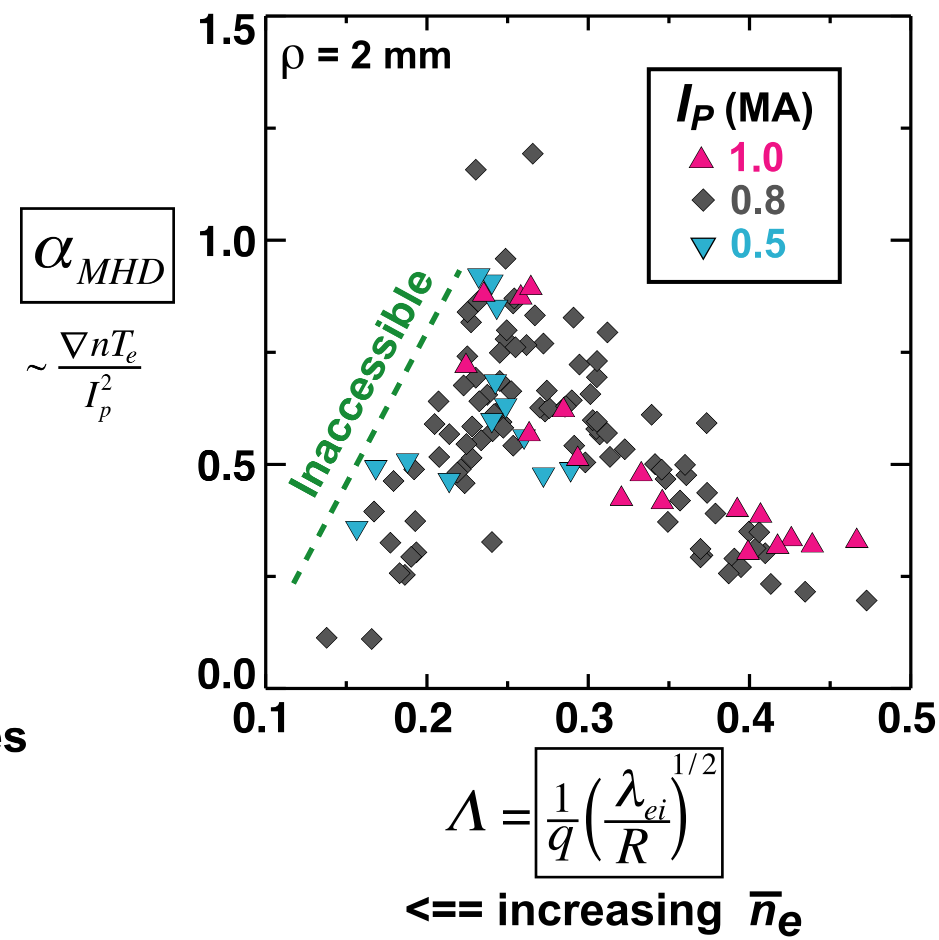

A region of high α_{MHD} at high density is inaccessible, owing to an explosive growth of cross-field transport

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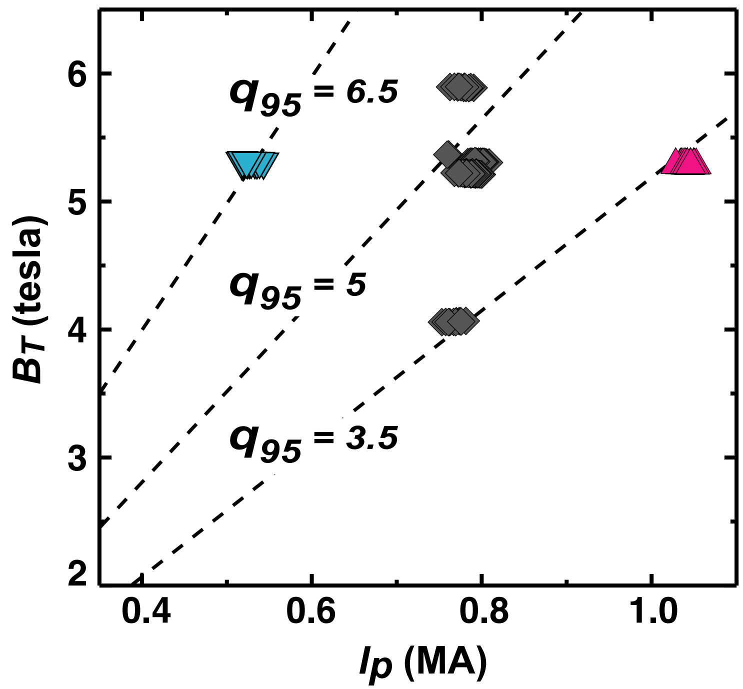

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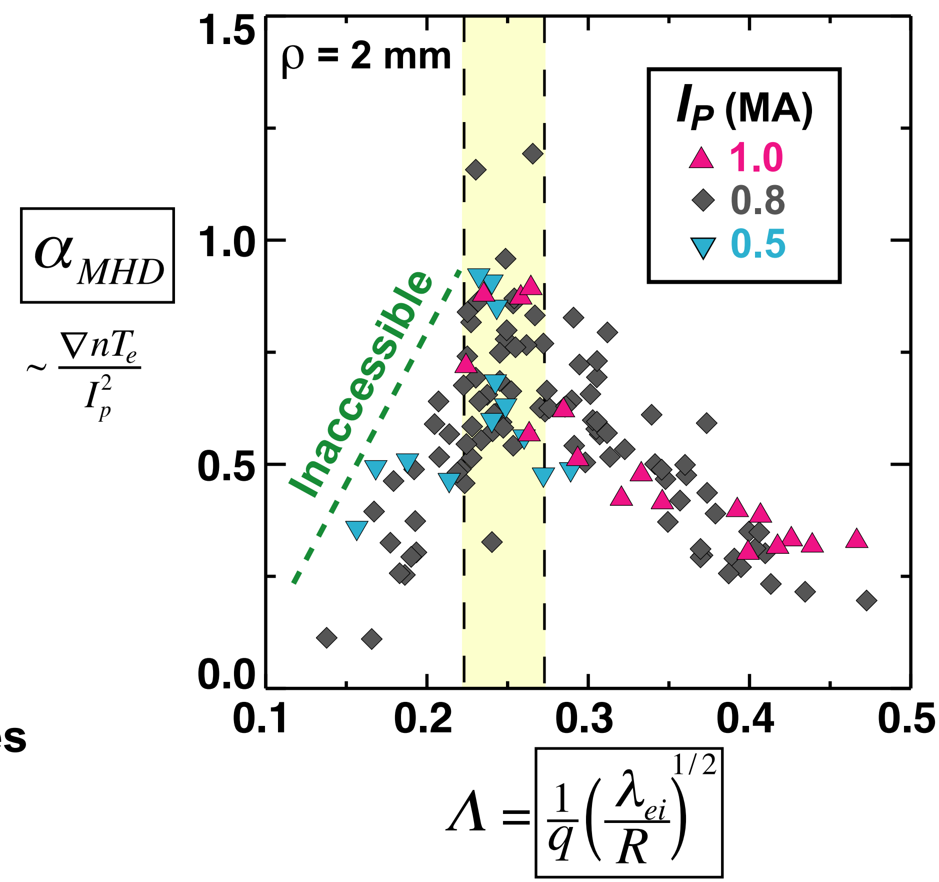


<== increasing $\bar{n}_e$

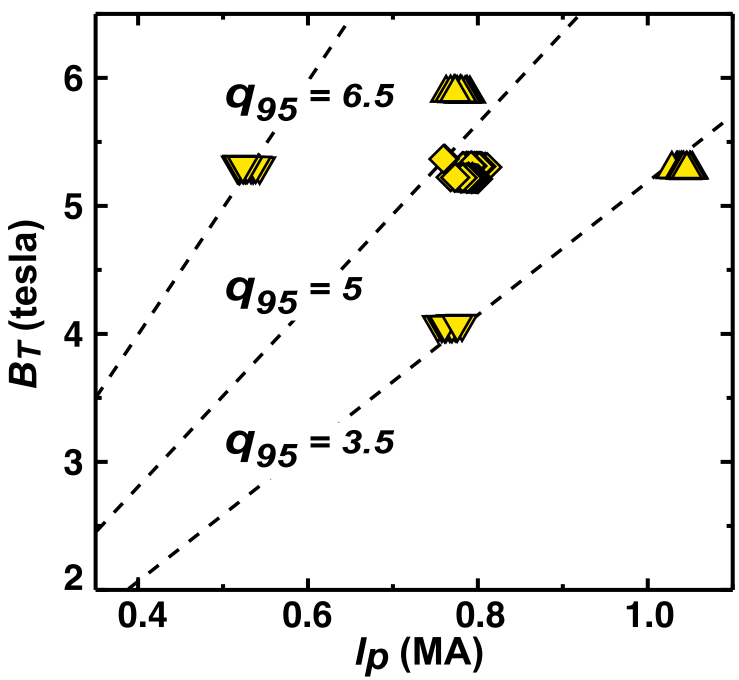
Next:
Examine SOL profiles at fixed Λ

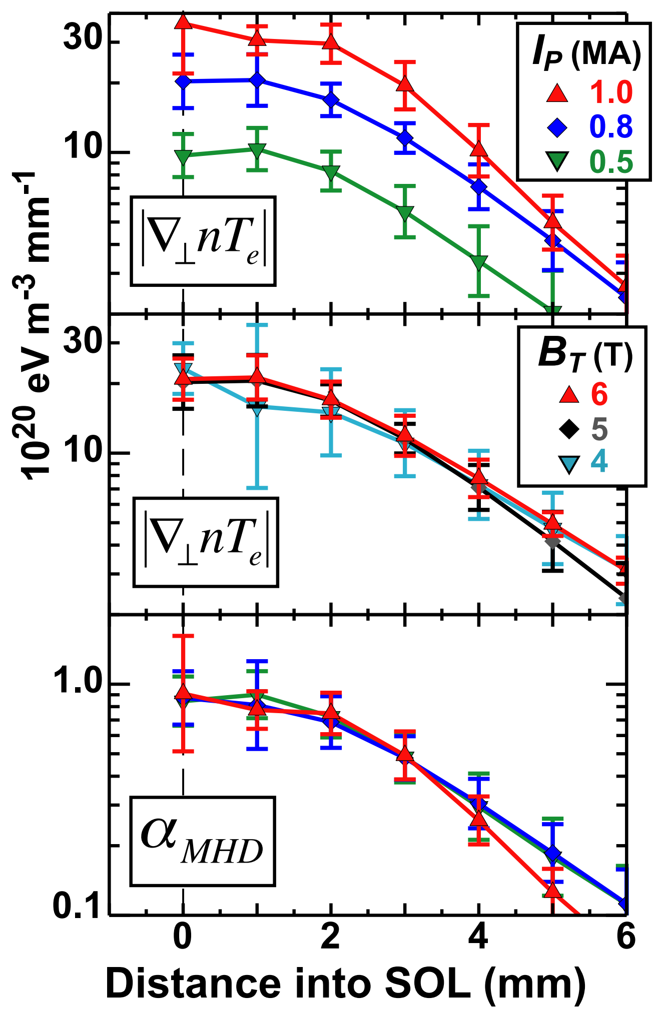
†Nuclear Fusion 45 (2005) 1658.

Pressure gradients near the separatrix appear to clamp at similar values of α_{MHD} when normalized collisionality is held fixed

Alcator C-Mod

Look at pressure profile data from discharges with Λ ~ 0.25, 2 mm from separatrix





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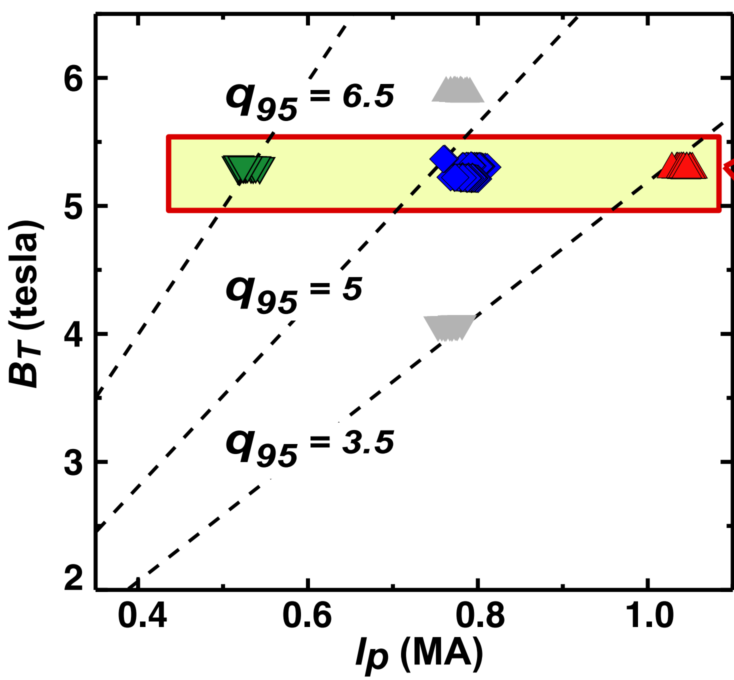

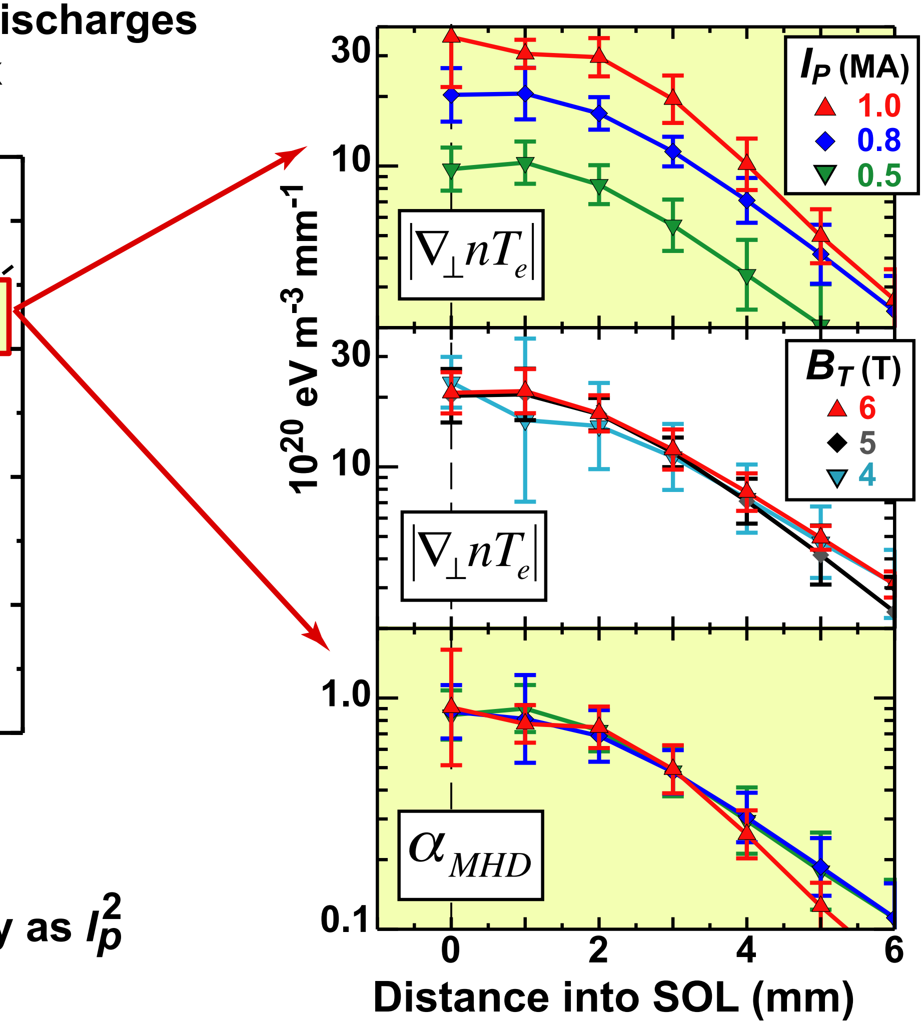

I_p Scan:

Pressure gradients scale roughly as I_p^2

=> similar α_{MHD}

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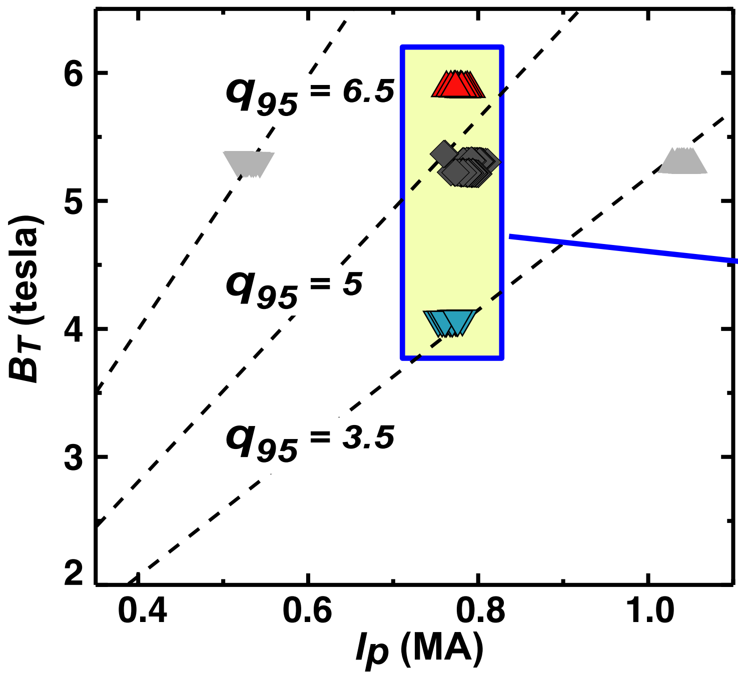

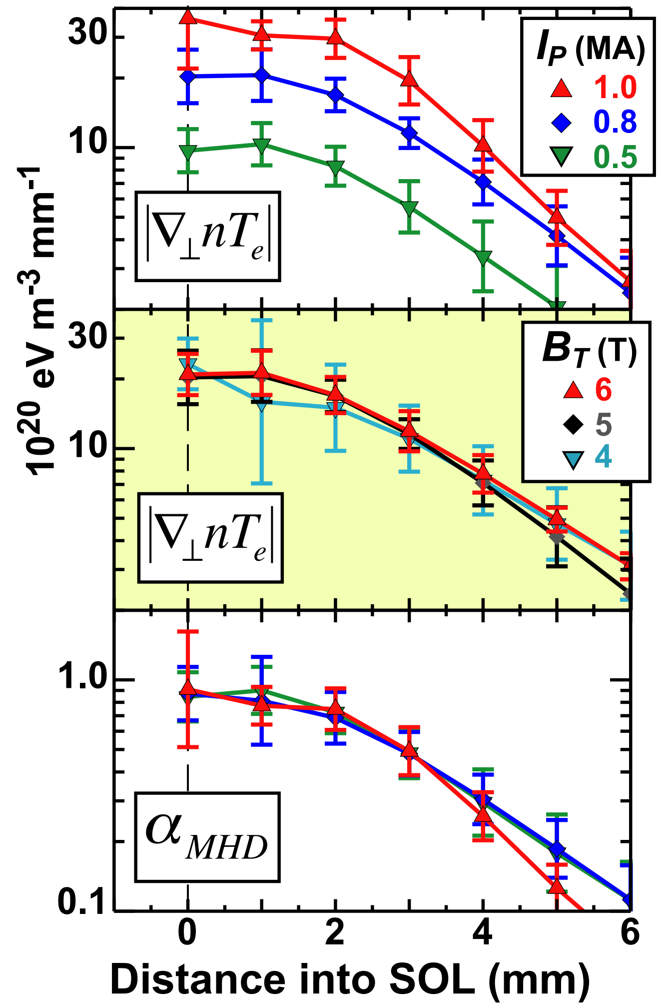

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No sensitivity to toroidal field

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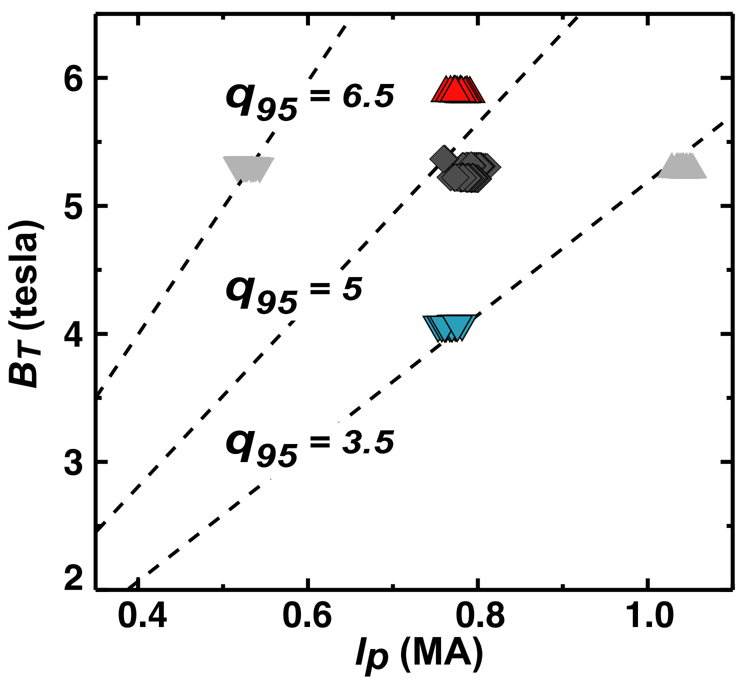
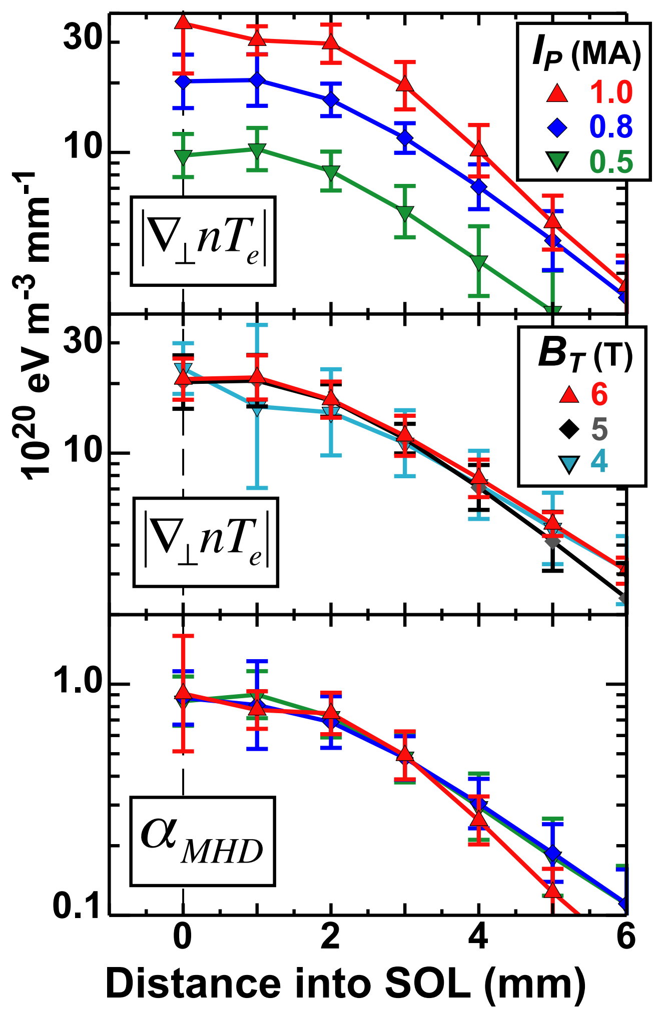




I_P Scan:

Pressure gradients scale roughly as I_P^2

=> similar α_{MHD}

B_T Scan:

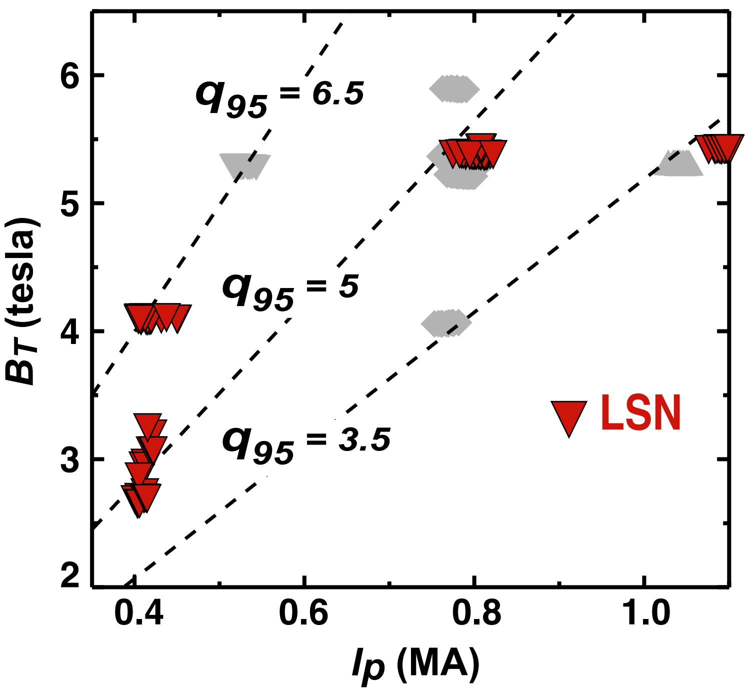
No sensitivity to toroidal field

=> Pressure gradient near separatrix set by a 'critical poloidal beta gradient'

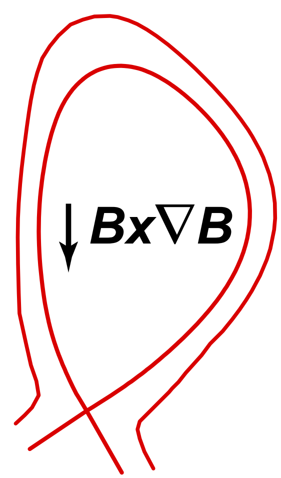
New Experiments -- Extended Range of Currents and Fields

Alcator C-Mod

Range of dimensional parameters: B_T, I_p



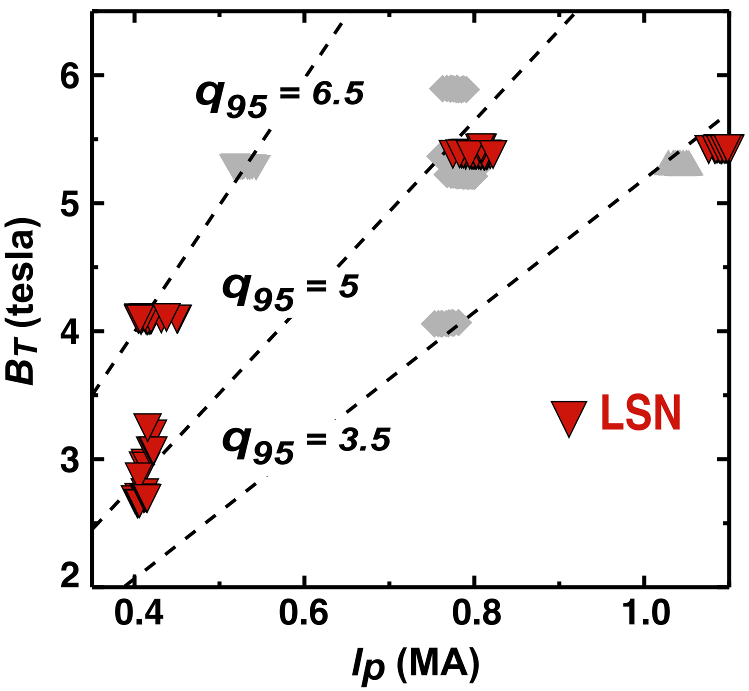
Lower single-null topology

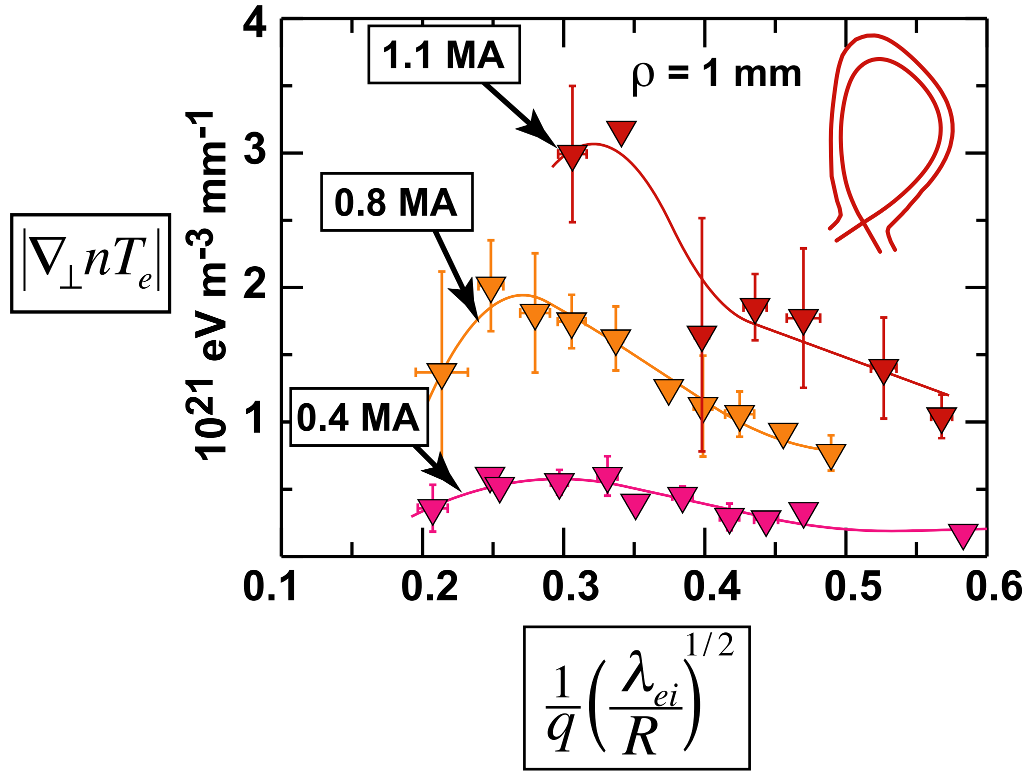


Density scans: $0.1 < n/n_G < 0.5$

New Experiments -- Extended Range of Currents and Fields
Pressure gradients near sep. consistently scale as I_p^2

Range of dimensional parameters: B_T, I_p





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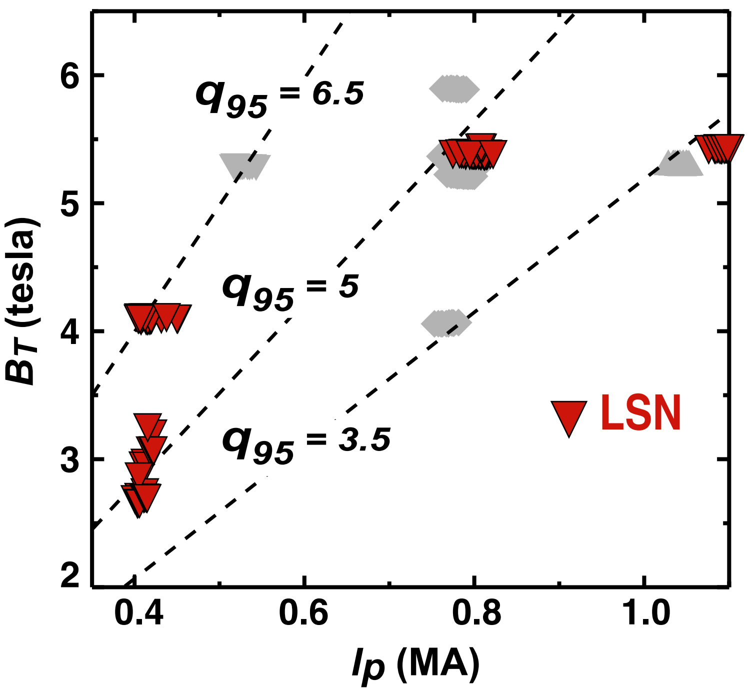

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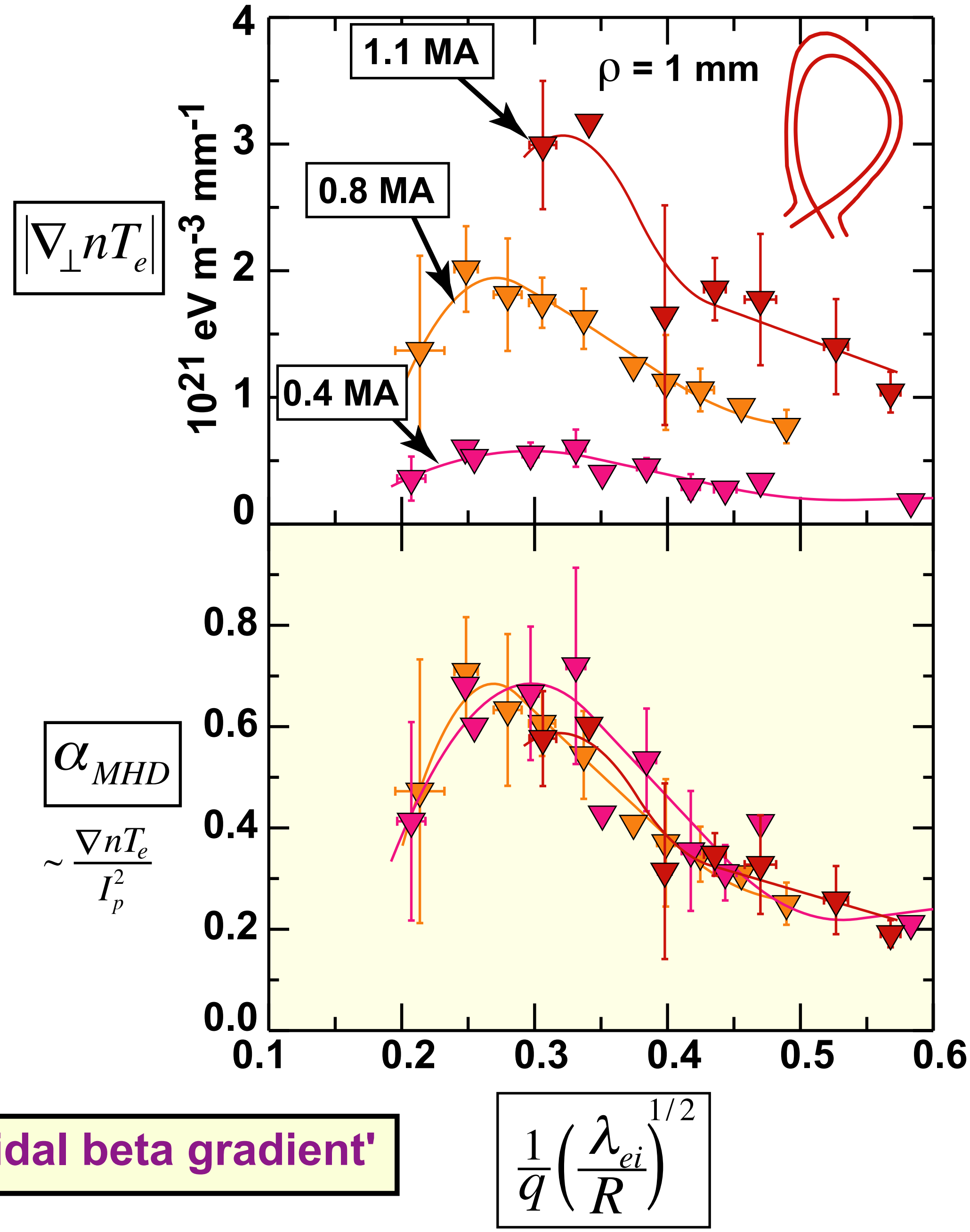
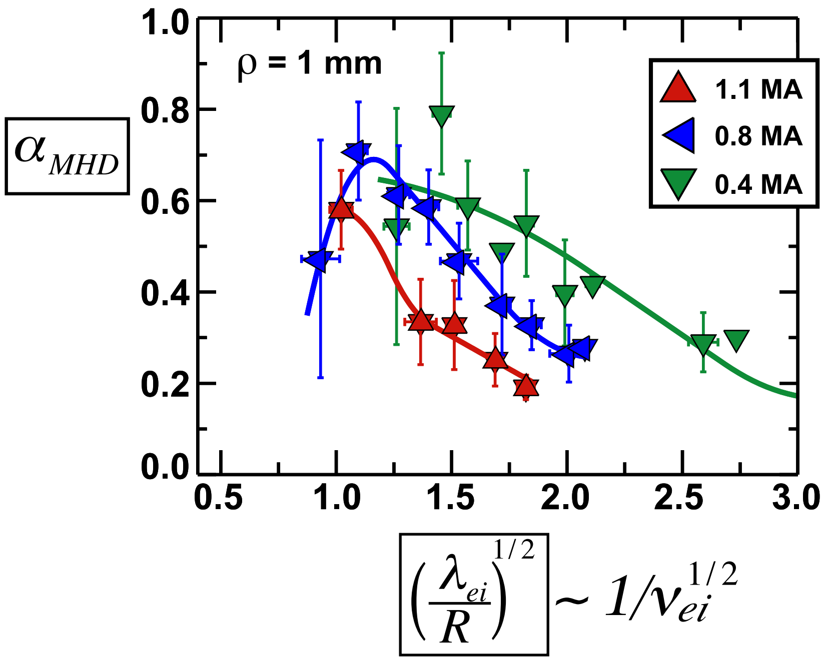


=> All discharges have same 'critical poloidal beta gradient'

EMFDT collisionality (Λ) contains 'correct' q_{95} normalization... edge states are ~invariant when mapped to (α_{MHD} , Λ) space

Alcator C-Mod

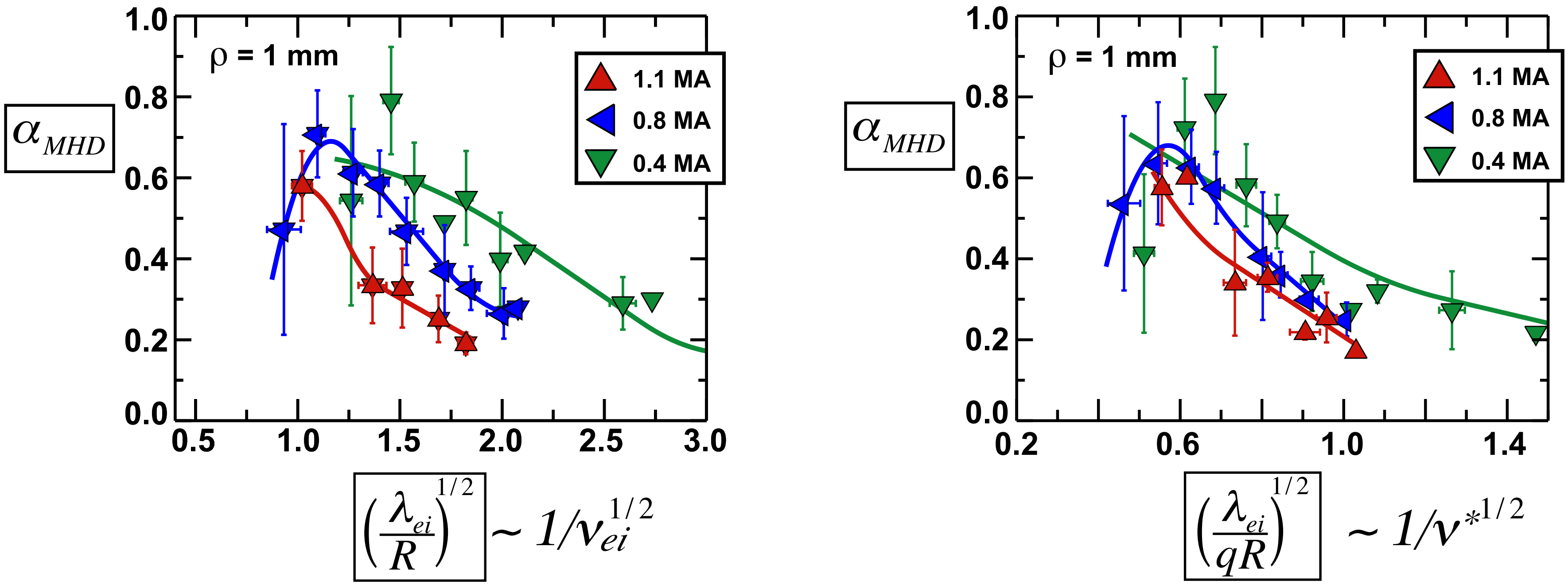


Plot versus inverse collision frequency

=> α_{MHD} values look like a function of I_p

EMFDT collisionality (Λ) contains 'correct' q_{95} normalization... edge states are ~invariant when mapped to (α_{MHD}, Λ) space

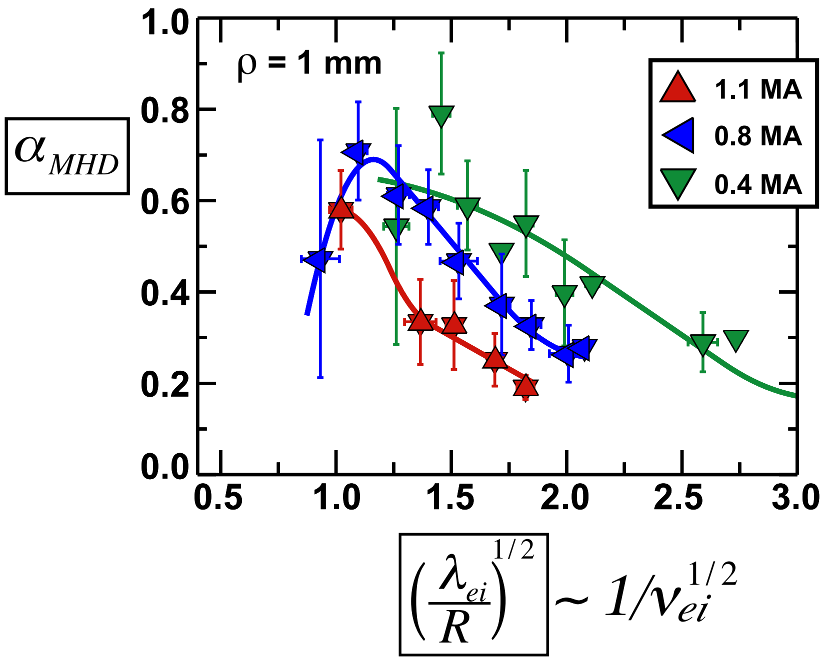
Alcator C-Mod

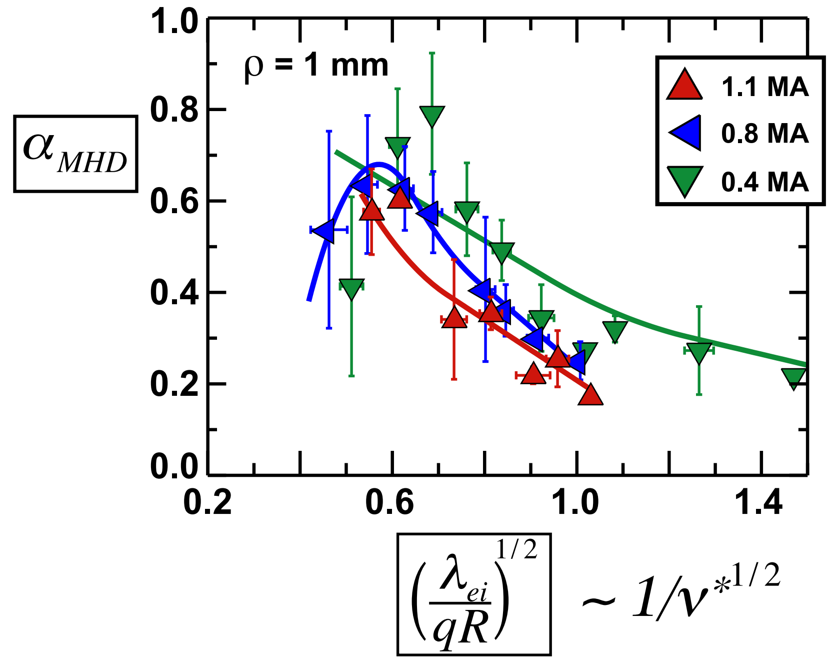


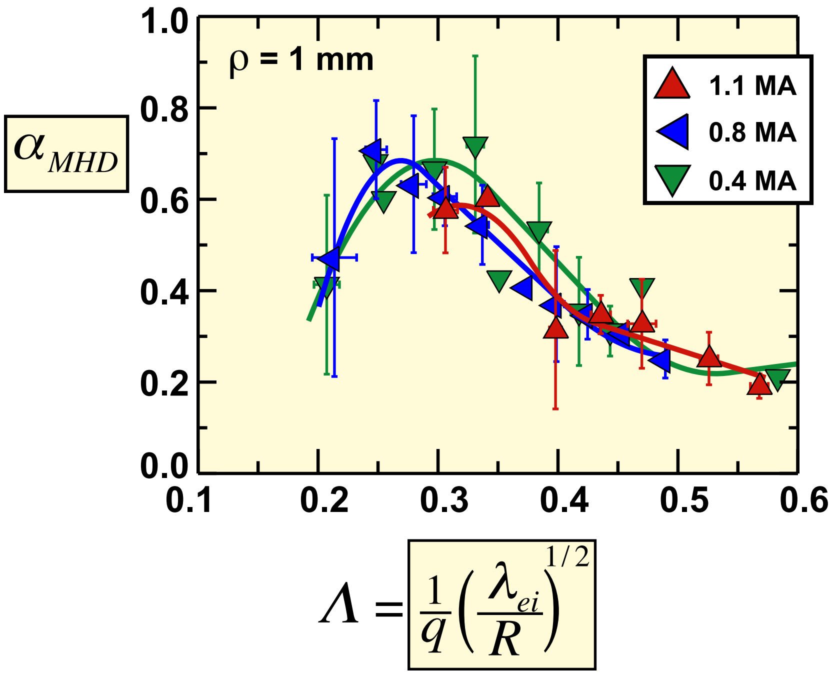
Plot versus inverse NC collision frequency

=> Better,... but α_{MHD} values still look like a function of I_p

EMFDT collisionality (Λ) contains 'correct' q_{95} normalization... edge states are ~invariant when mapped to (α_{MHD} , Λ) space







When described by local values of α_{MHD} and Λ, the 'plasma state' near the separatrix is seen to be invariant to machine parameters (B_T, I_p, $\bar{n}_e$)

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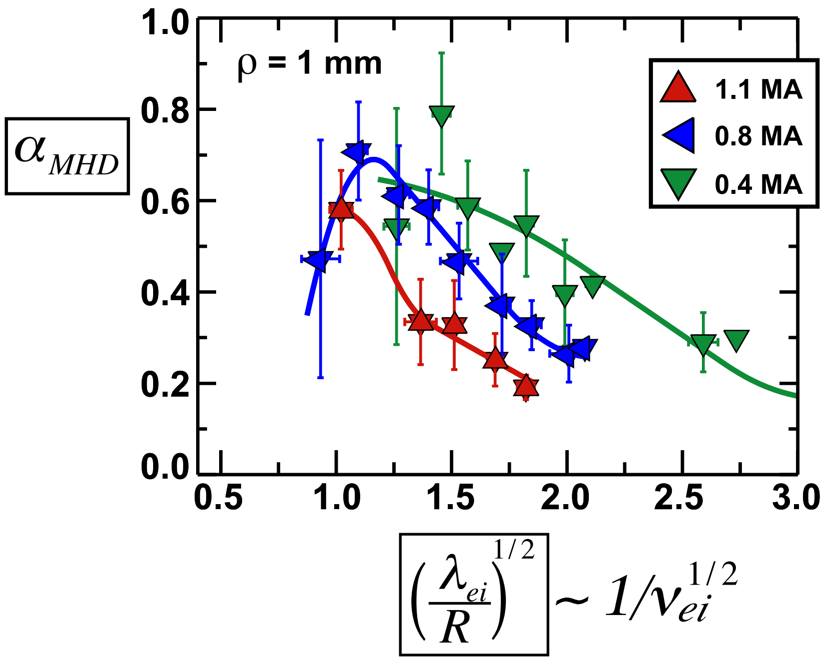
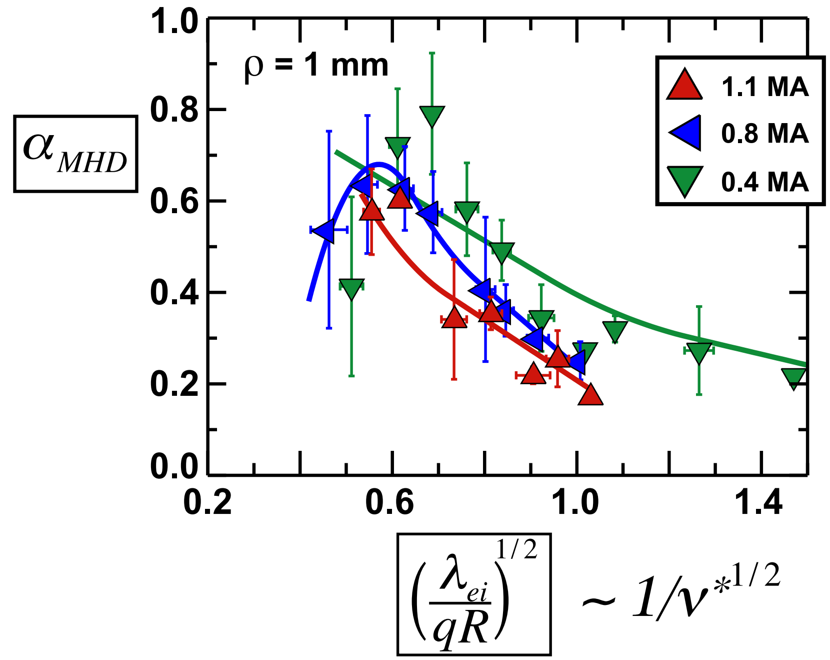
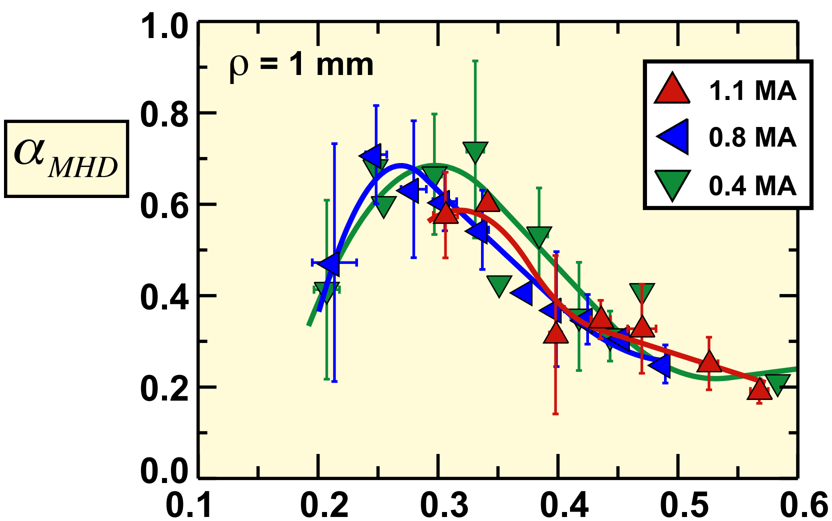
Alcator C-Mod







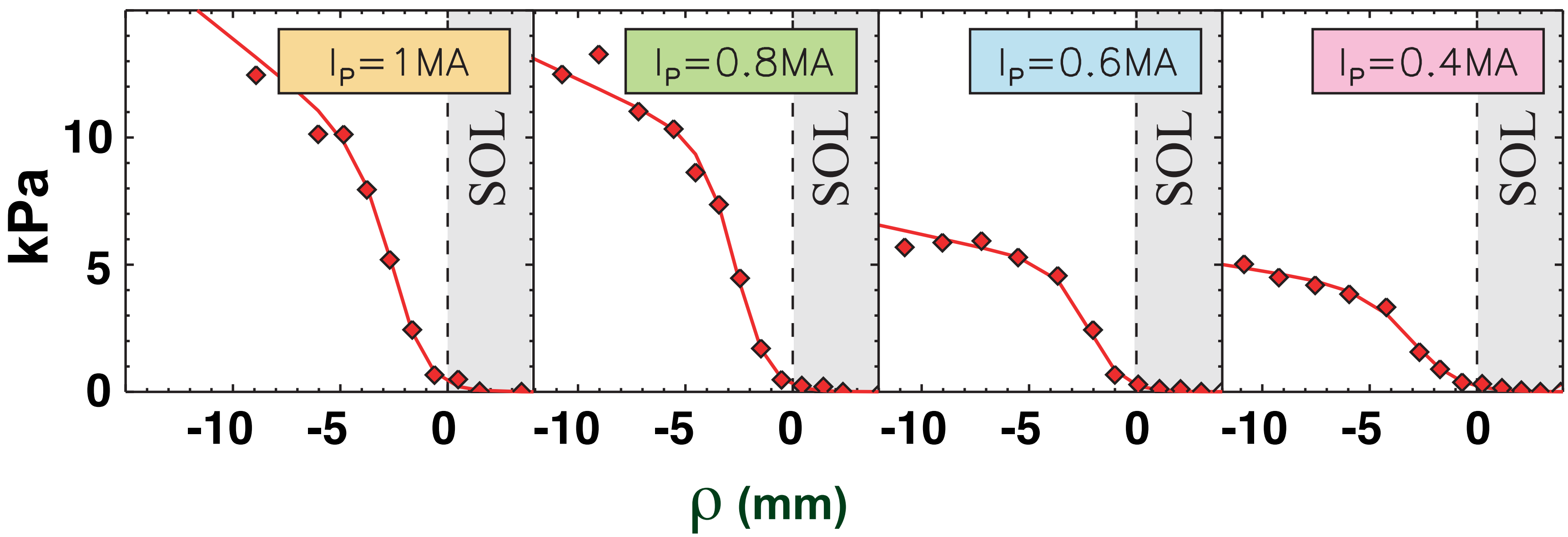
$$\Lambda = \frac{1}{q}\left(\frac{\lambda_{ei}}{R}\right)^{1/2}$$

When described by local values of α_{MHD} and Λ, the 'plasma state' near the separatrix is seen to be invariant to machine parameters (B_T, I_p, $\bar{n}_e$)

=> Strong evidence that EMFDT is setting the 'critical gradient' behavior seen in the Near SOL

H-mode pedestals show a similar 'critical gradient' behavior†...
...peak pressure gradients scale as I_p^2

Electron pressure profiles from EDA H-modes (no ELMs)



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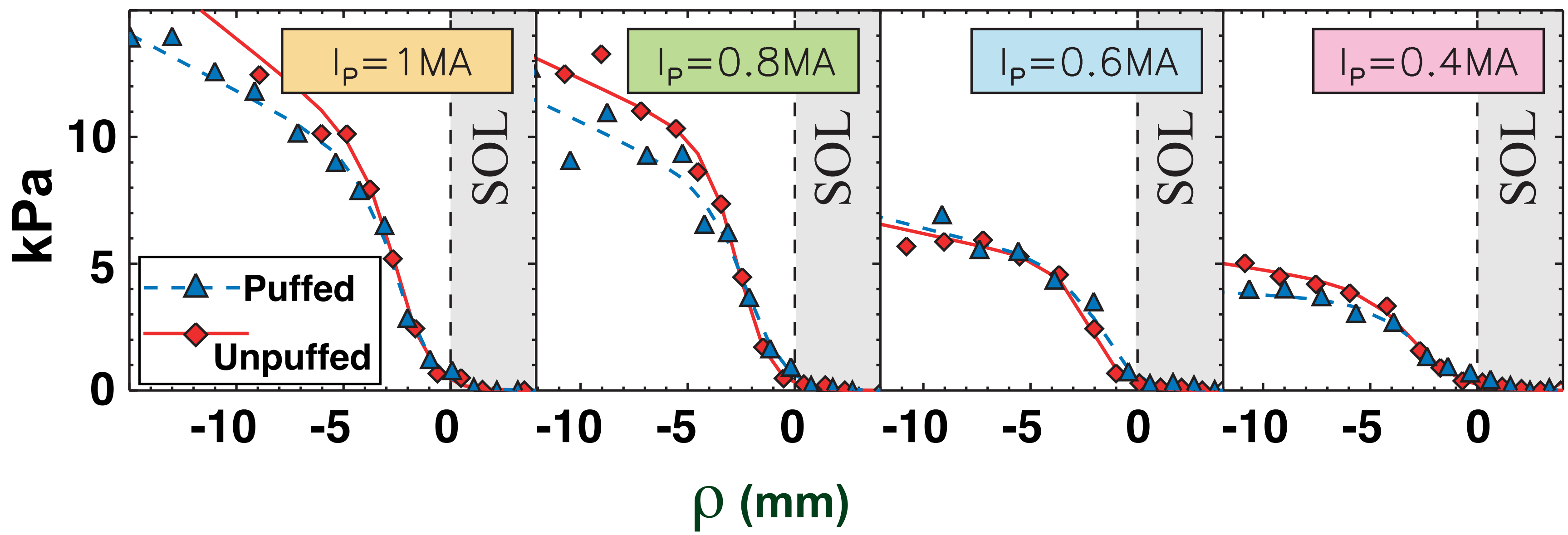

- **Pedestal gradients are 'stiff', unaffected by strong gas puffing or strong cryopumping**

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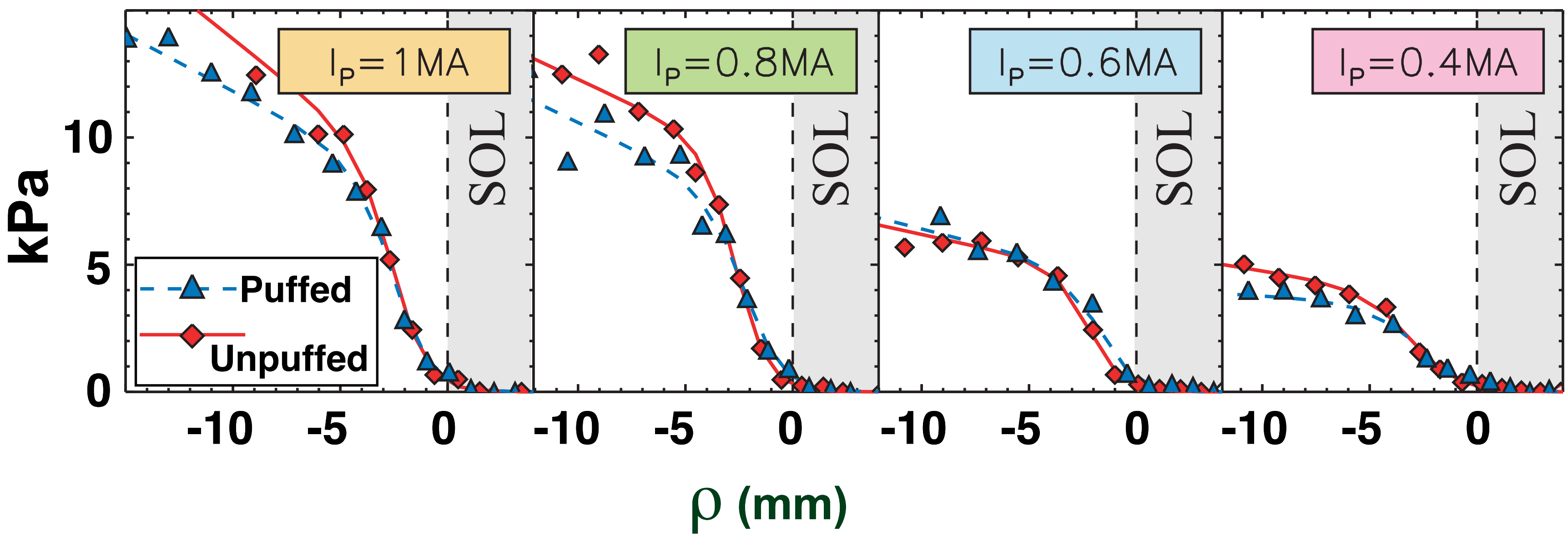

- Pedestal gradients are 'stiff', unaffected by strong gas puffing or strong cryopumping
- Despite absence of ELMs, peak pressure gradients scale as I_p^2, yielding similar values of α_{MHD} for the same edge collisionality

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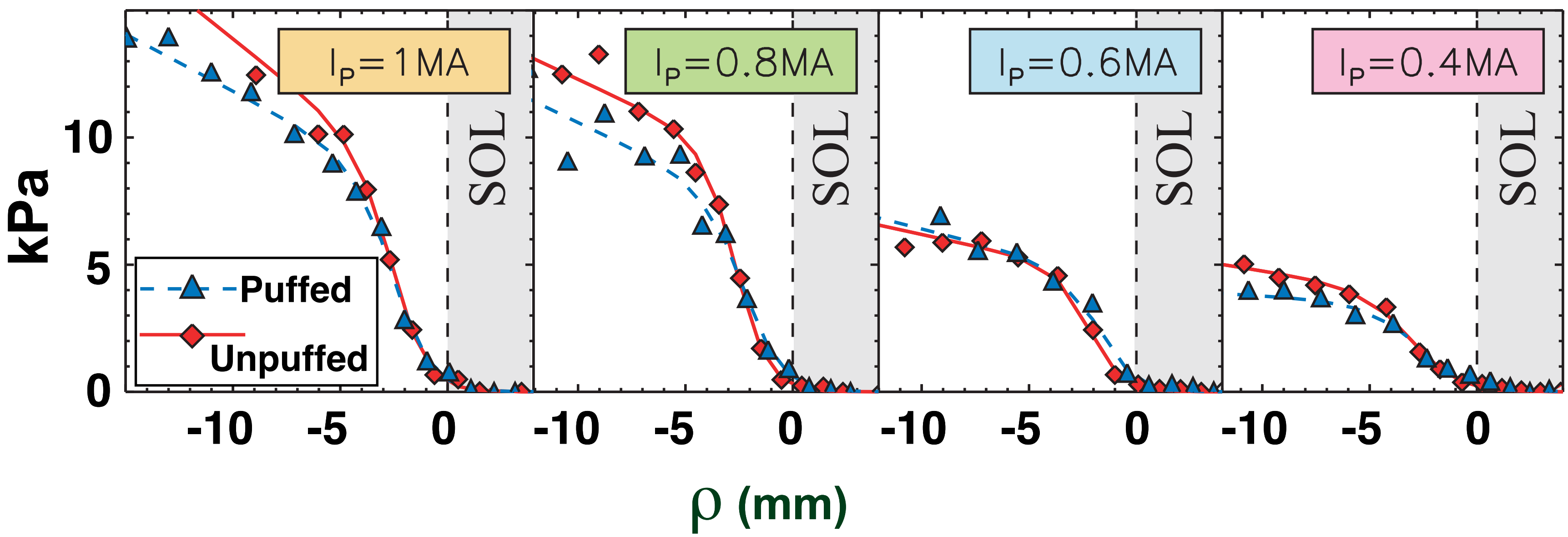

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=> Physics of L- and H-mode pedestals is linked
Electromagnetic plasma turbulence appears to be setting the 'critical gradients' in both regimes

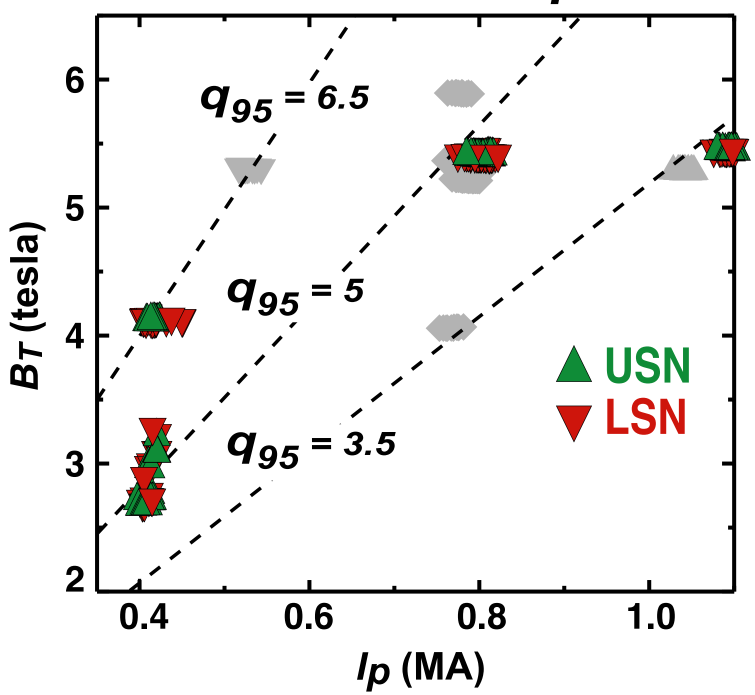
† [1] J. W. Hughes et al., Nucl. Fus. 47 (2007) 1057.

Evidence (?) that toroidal rotation affects ‘critical pressure gradients’ near LCFS in L-mode discharges

Magnetic x-point topology is found to affect 'critical gradient'

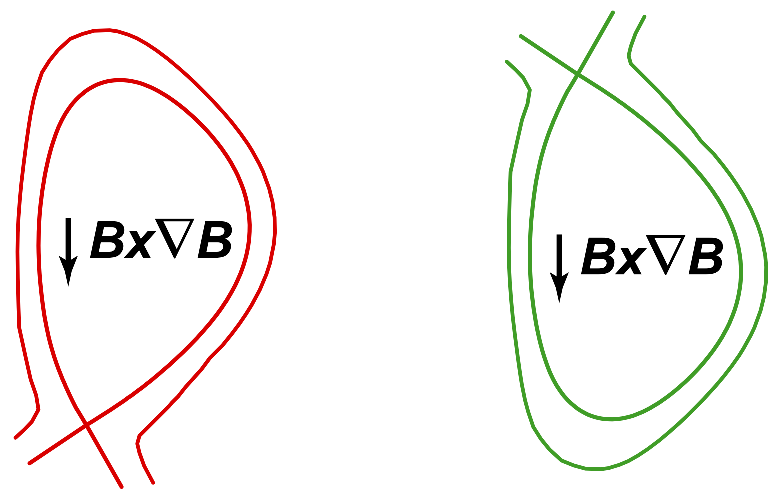
Alcator C-Mod

Range of dimensional parameters: B_T, I_p



Density scans: $0.1 < n/n_G < 0.5$

Lower and upper-null topologies



Magnetic x-point topology is found to affect 'critical gradient'
Pressure gradients near sep. consistently scale as I_p^2

Alcator C-Mod

... but value depends on lower / upper X-point topology

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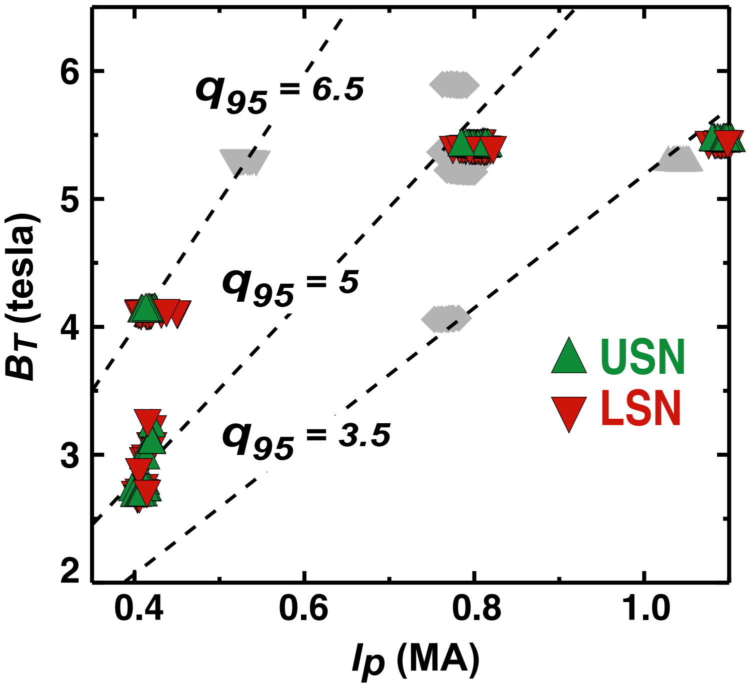

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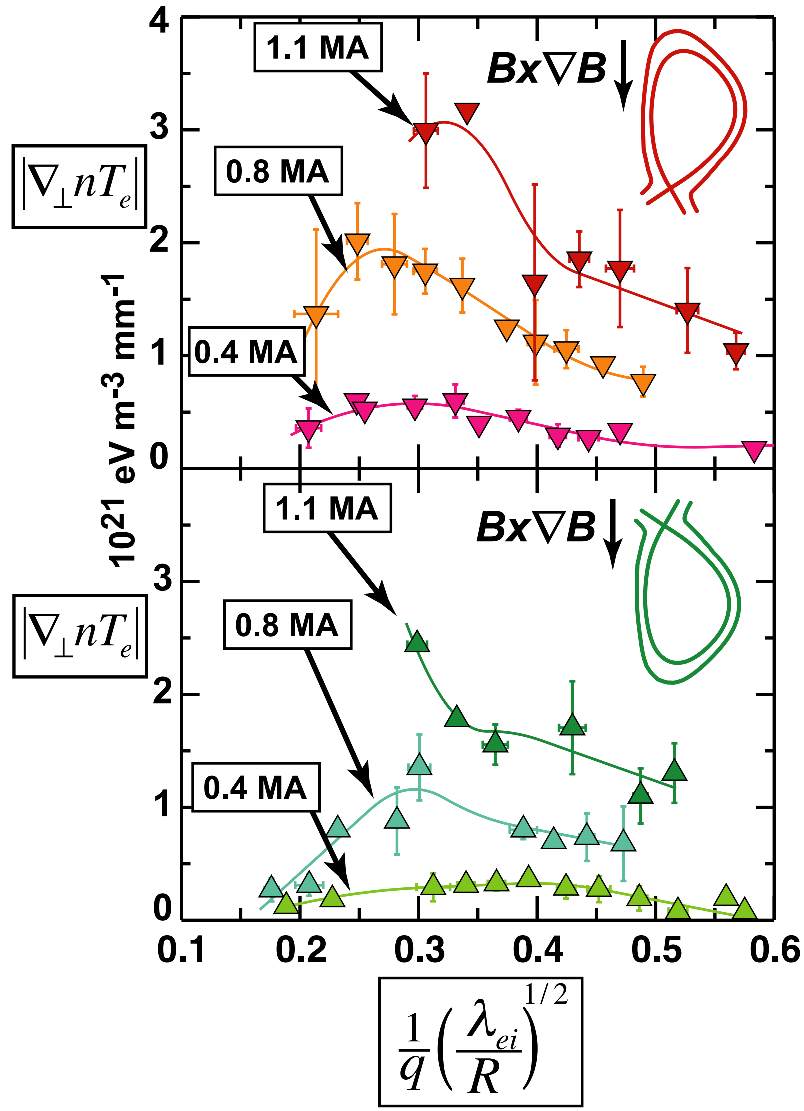

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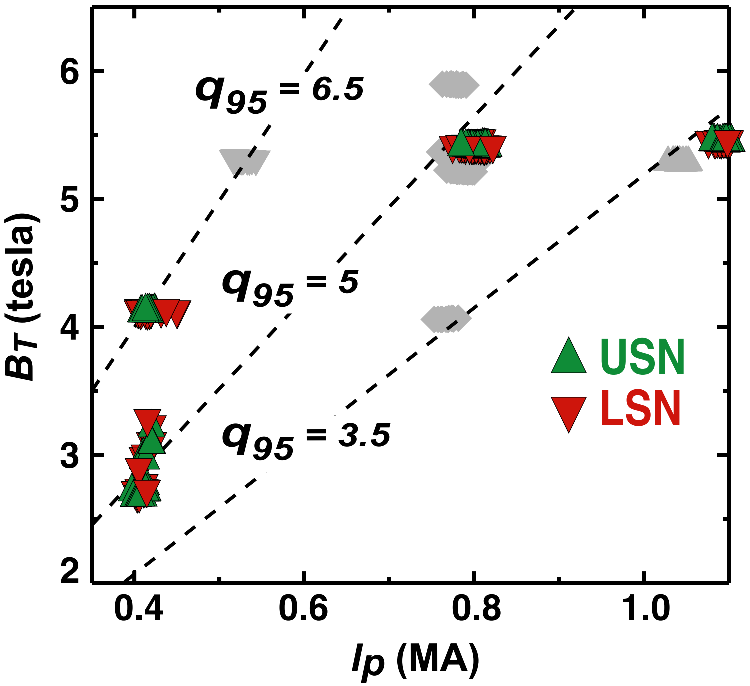

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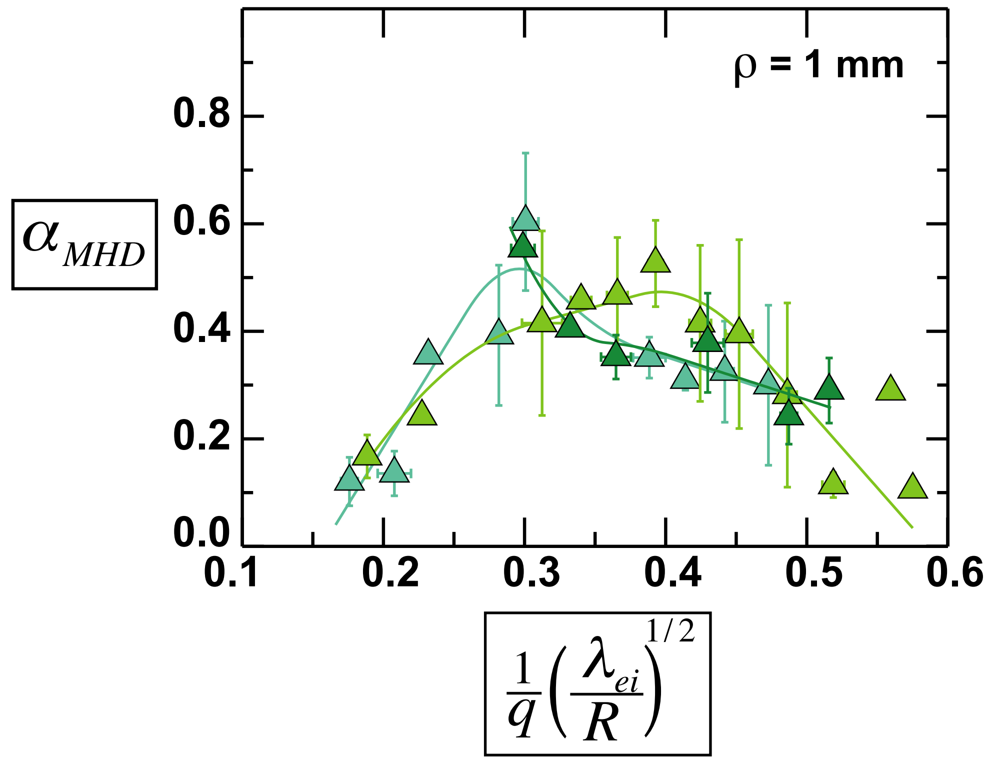
Edge plasma states again align in EMFDT phase-space, but in two bands



Lower null achieves higher values of α_{MHD} compared to upper null at high collisionality

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Alcator C-Mod

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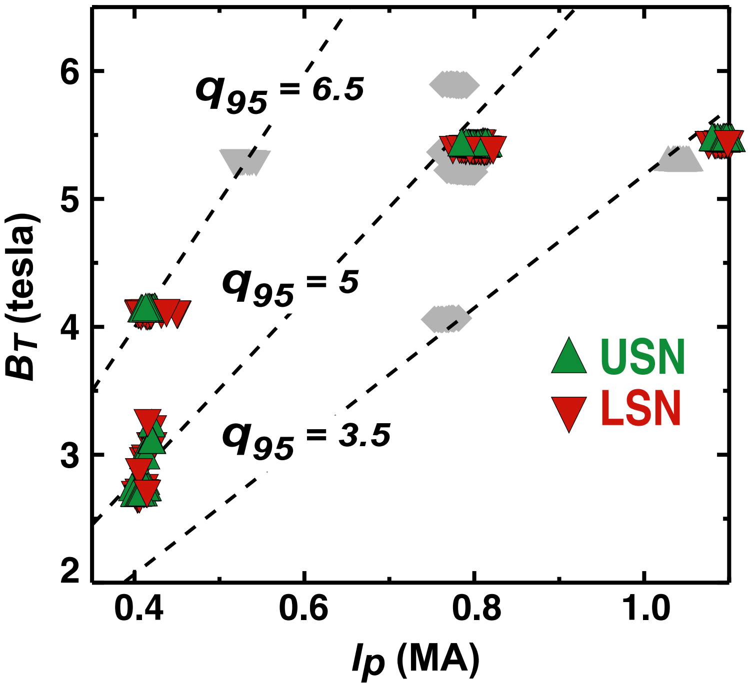

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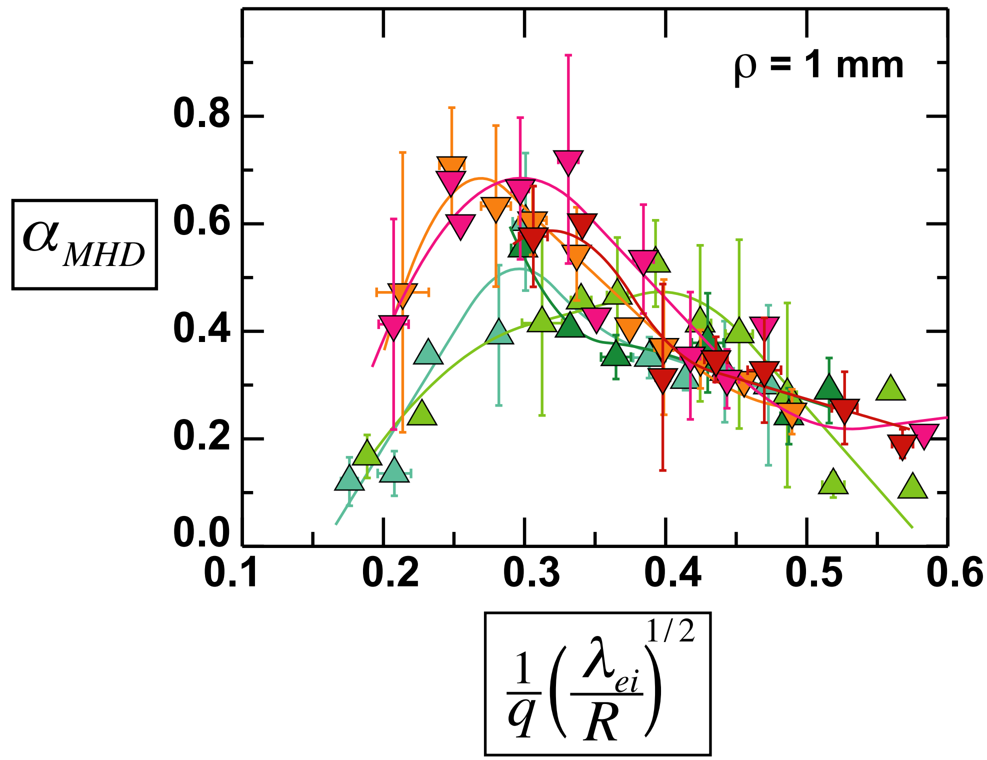

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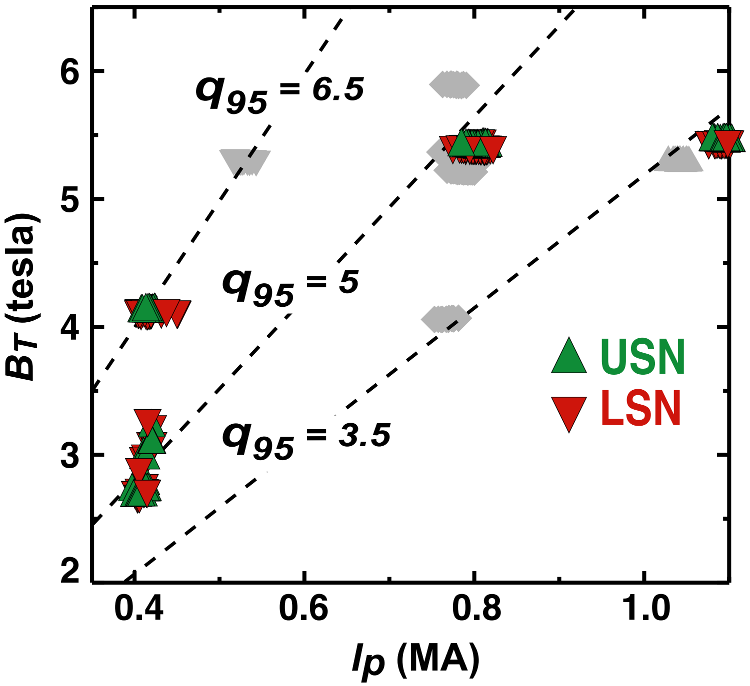

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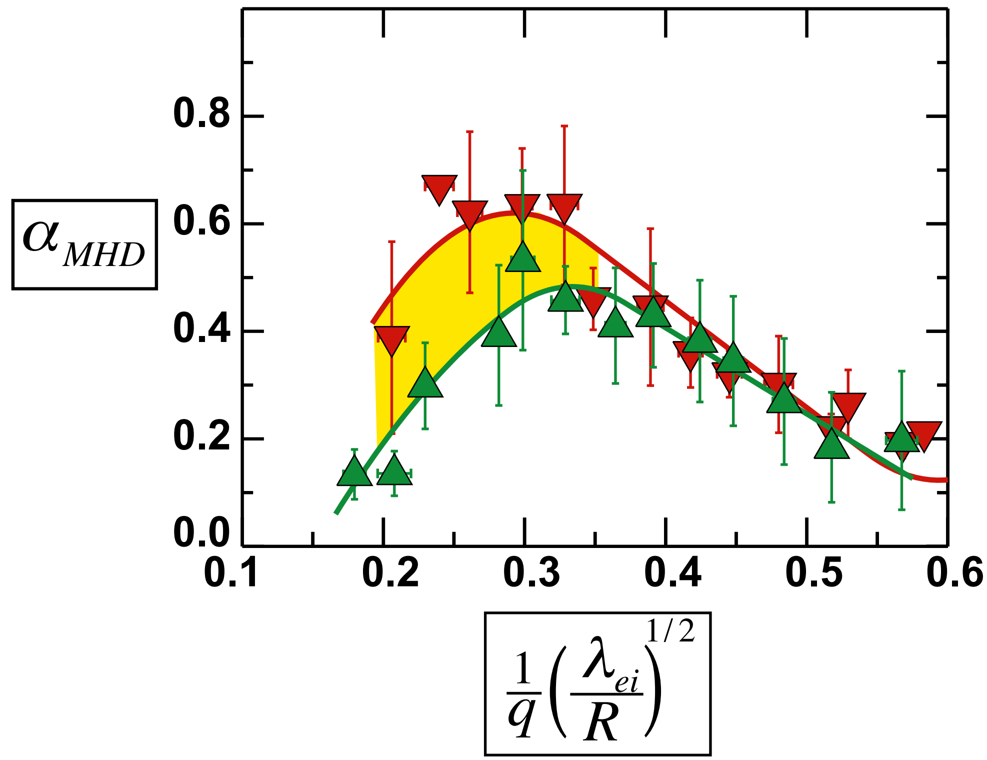
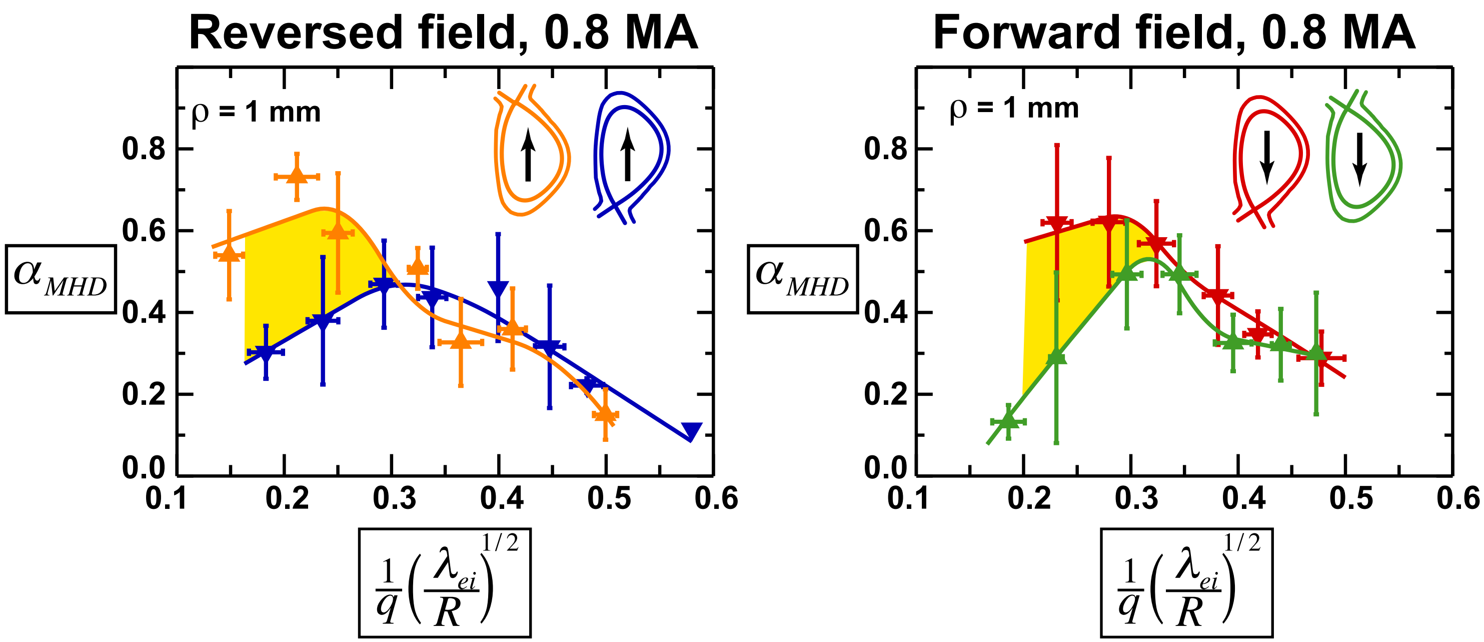


Lower null achieves higher values of α_{MHD} compared to upper null at high collisionality

Can SOL flows be causing the different 'critical gradients'?

Highest α_{MHD} are coincident with increased co-current flow... ...corresponding to 'favorable' $Bx\nabla B$ direction

Alcator C-Mod

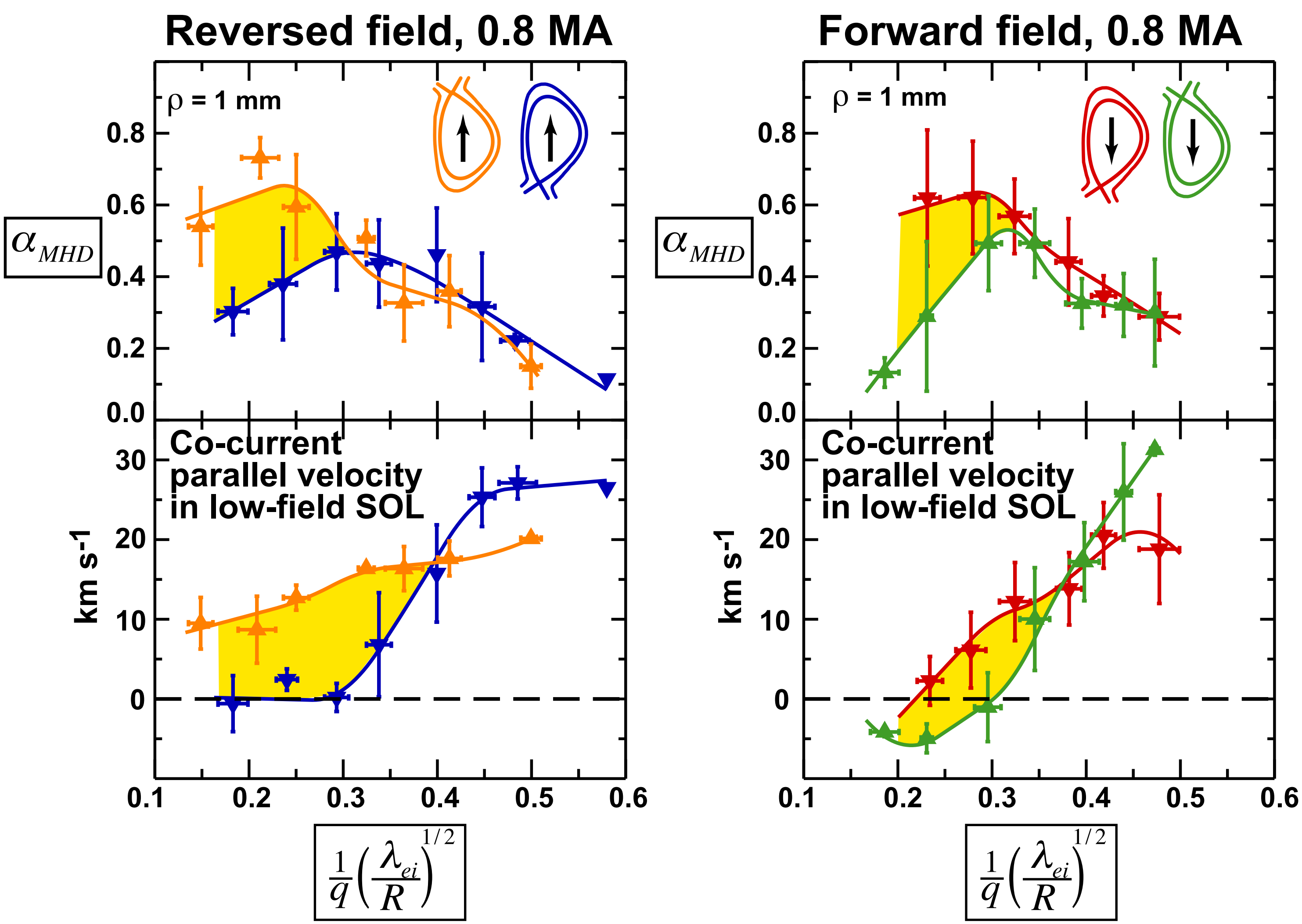


- Favorable $Bx\nabla B$ -- enhanced α_{MHD} at high collisionality

Independent of Forward/Reversed field

=> not a divertor/wall geometry effect

Highest α_{MHD} are coincident with increased co-current flow... ...corresponding to 'favorable' $Bx\nabla B$ direction



- Favorable $Bx\nabla B$ -- enhanced co-current flow/rotation at high collisionality

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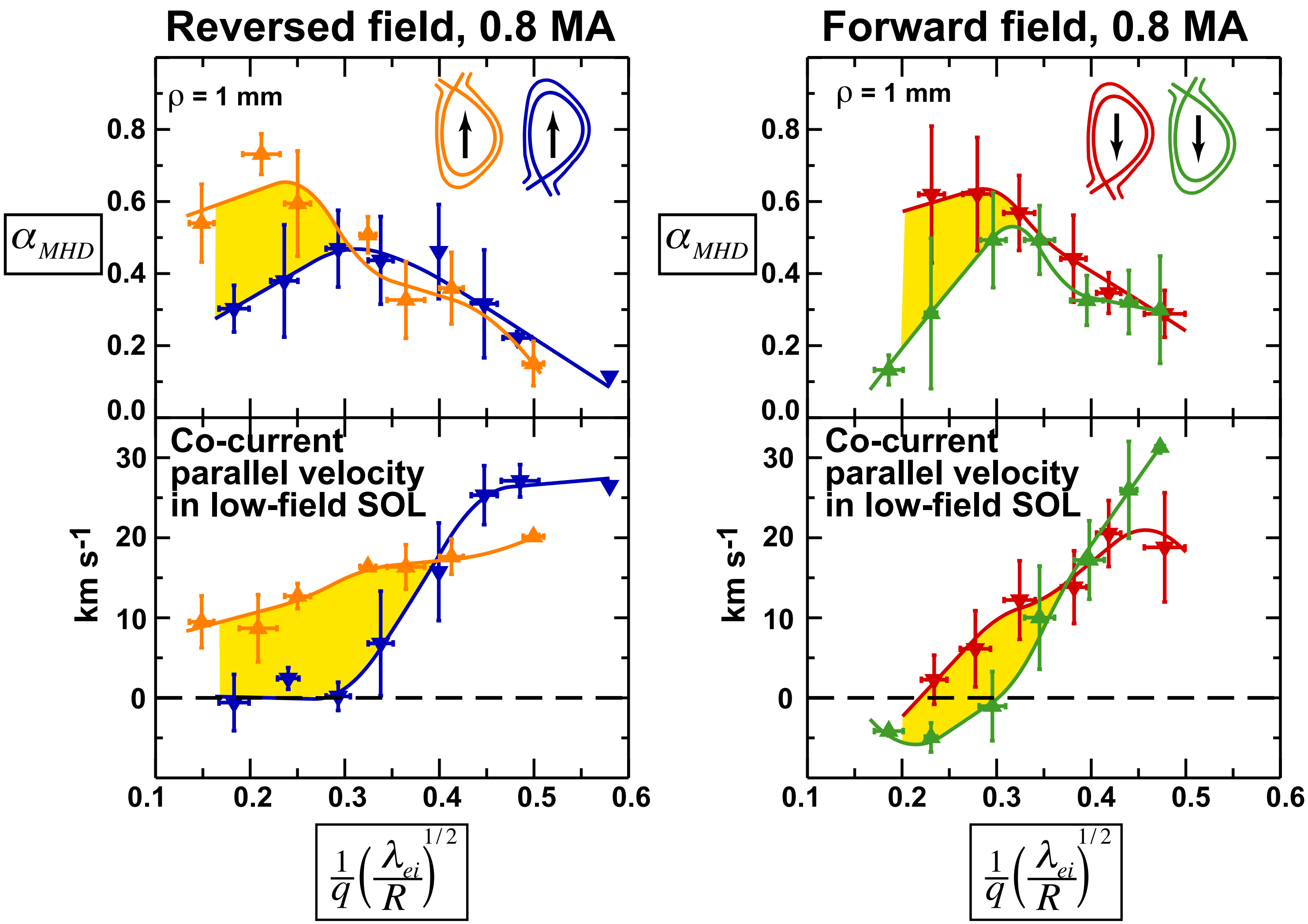

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=> *Connections*: transport-driven SOL flows, topology, gradients, L-H threshold†

†Phys. Plasmas 12 (2005) 056111.

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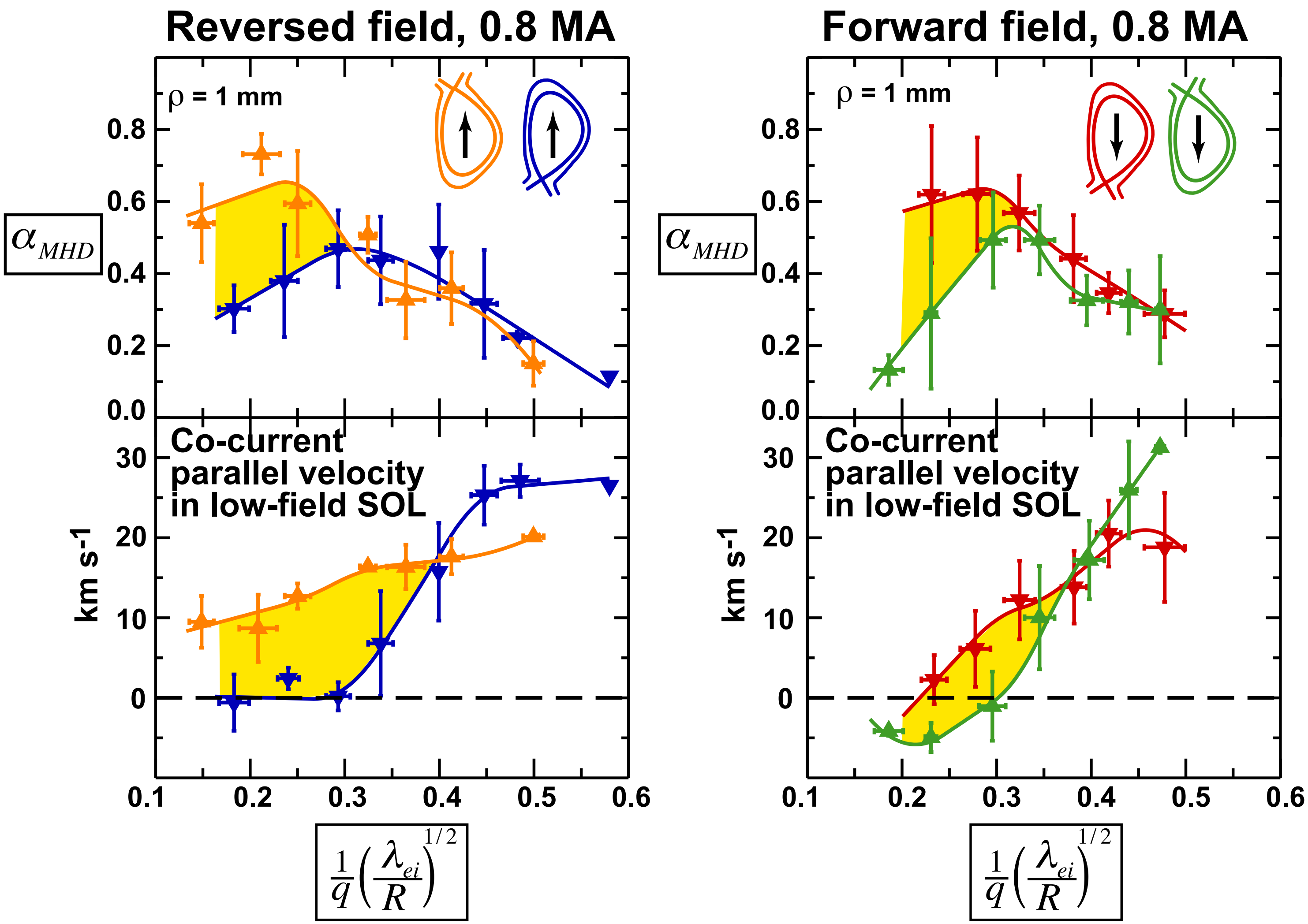

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Underlying physics not yet revealed: flow shear? collisionality dependence?

... a good area to focus further experimental investigations...

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Summary and Challenges Ahead

Alcator C-Mod

Tokamak experiments have revealed key attributes of edge transport phenomena, pointing towards underlying physical processes.

These observations challenge the development of first-principles models.

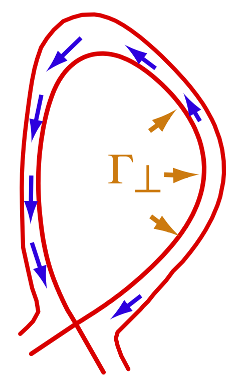
Summary and Challenges Ahead

Tokamak experiments have revealed key attributes of edge transport phenomena, pointing towards underlying physical processes.

These observations challenge the development of first-principles models.

Challenges for 2-D edge models and first-principles turbulence codes:

In order for codes/theories to be validated, they must accurately reproduce the observed edge transport phenomenology:



- **Extreme ballooning-like radial transport asymmetries**
- **Strong (near-sonic) plasma flows outside the LCFS with x-point topology setting parallel flow direction**
- **Toroidal rotation of confined plasma that depends on x-point topology**
  Linkage: magnetic topology <=> SOL flows <=> toroidal rotation

Summary and Challenges Ahead

Alcator C-Mod

Tokamak experiments have revealed key attributes of edge transport phenomena, pointing towards underlying physical processes.

These observations challenge the development of first-principles models.

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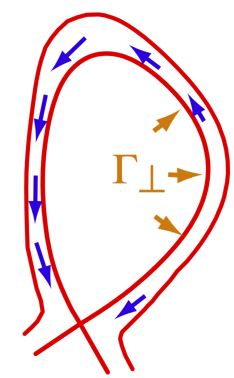

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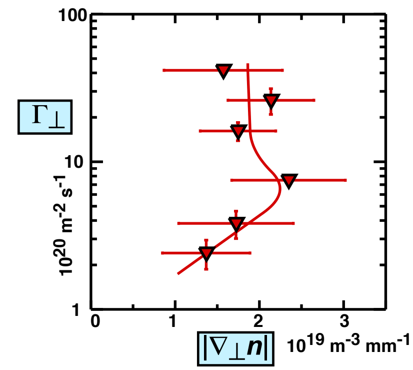
- **L-H transition, with x-point topology (rotation?) affecting threshold**

Summary and Challenges Ahead

Challenges for 2-D edge models and first-principles turbulence codes:

In order for codes/theories to be validated, they must accurately reproduce the observed edge transport phenomenology:

- **Edge plasma ~ a system at ‘critical gradient’ near LCFS**
  - **Intermittent, bursty transport in the ‘far SOL’**
  - **Small change in LCFS gradient => large change in fluxes**



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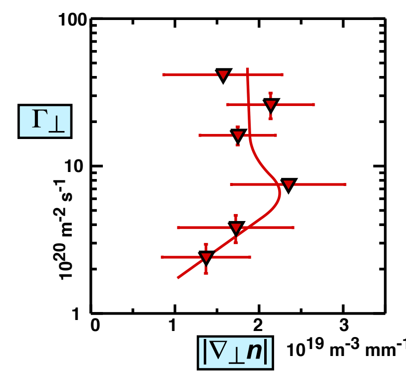

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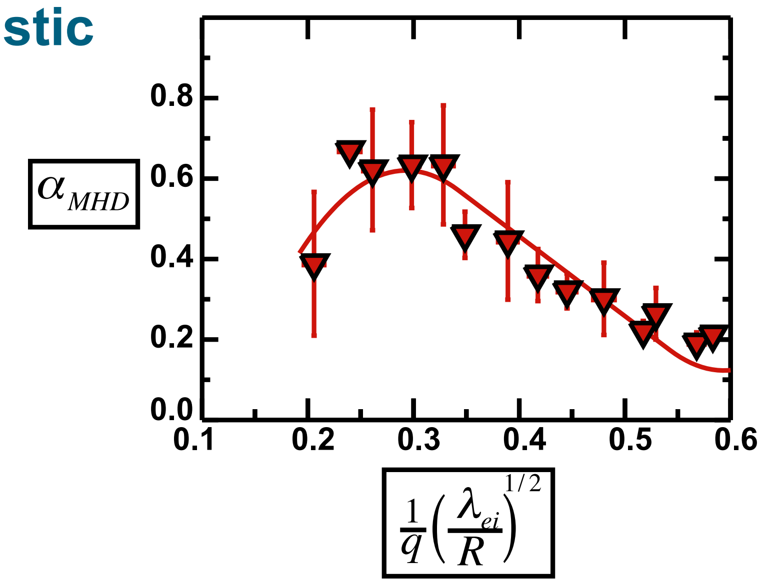

Summary and Challenges Ahead

Alcator C-Mod

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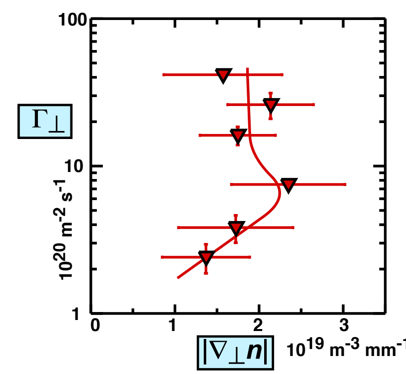

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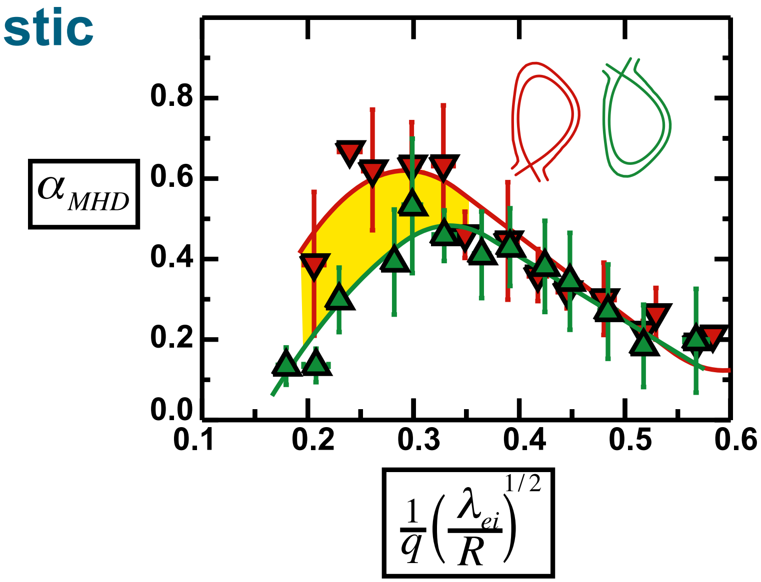


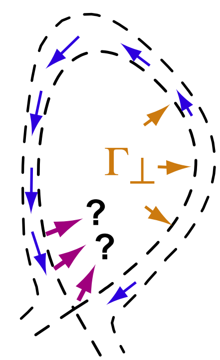
- **X-point topology (via plasma rotation?) affects characteristic α_{MHD} value**

Summary and Challenges Ahead

Alcator C-Mod

Challenges for experiments --

Continued experimental studies are clearly needed:



- **Reveal mechanism(s) that 'close the SOL circulation loop'**

- **Direct evidence that electromagnetic turbulence plays role near LCFS**
  - **Magnetic fluctuation levels, (ω, k) spectra -- comparison with EM codes**
  - **Phase relationships between $\tilde{P}$ and $\tilde{\Phi}$ -- comparison with EM codes**

- **Detailed studies of poloidal flow shear layer near LCFS**
  - **What sets shear layer magnitude? (ambipolar $\nabla\Phi$, Reynolds stress,...)**
  - **What role does SL play in affecting observed 'critical gradients'?**
  - **How does SL change (or not) with x-point, toroidal rotation, approach to L-H transition, ...**

- **...**