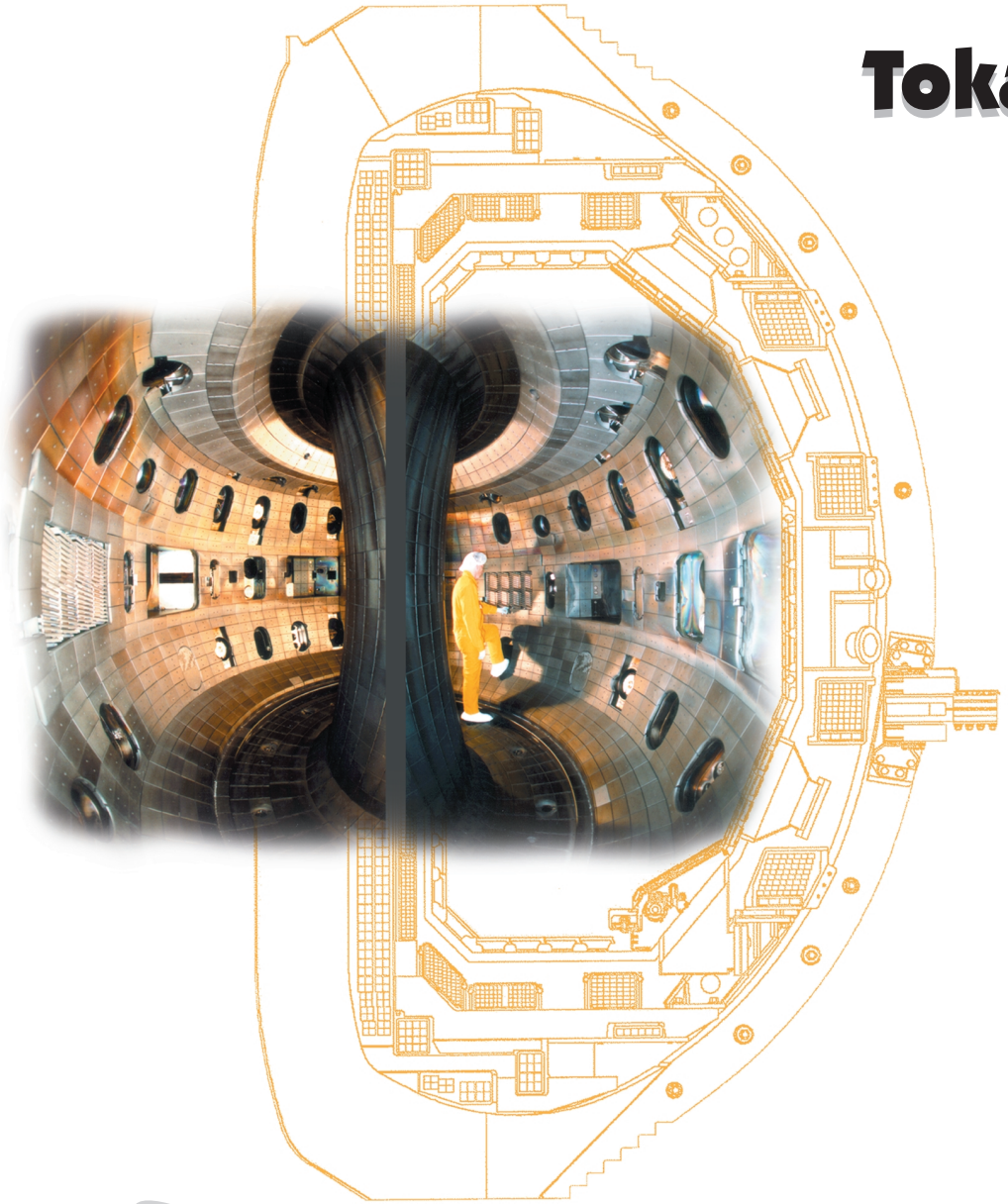
ExB Circulation at the Tokamak Divertor X–Point



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ExB CIRCULATION AT THE TOKAMAK DIVERTOR X–POINT

By

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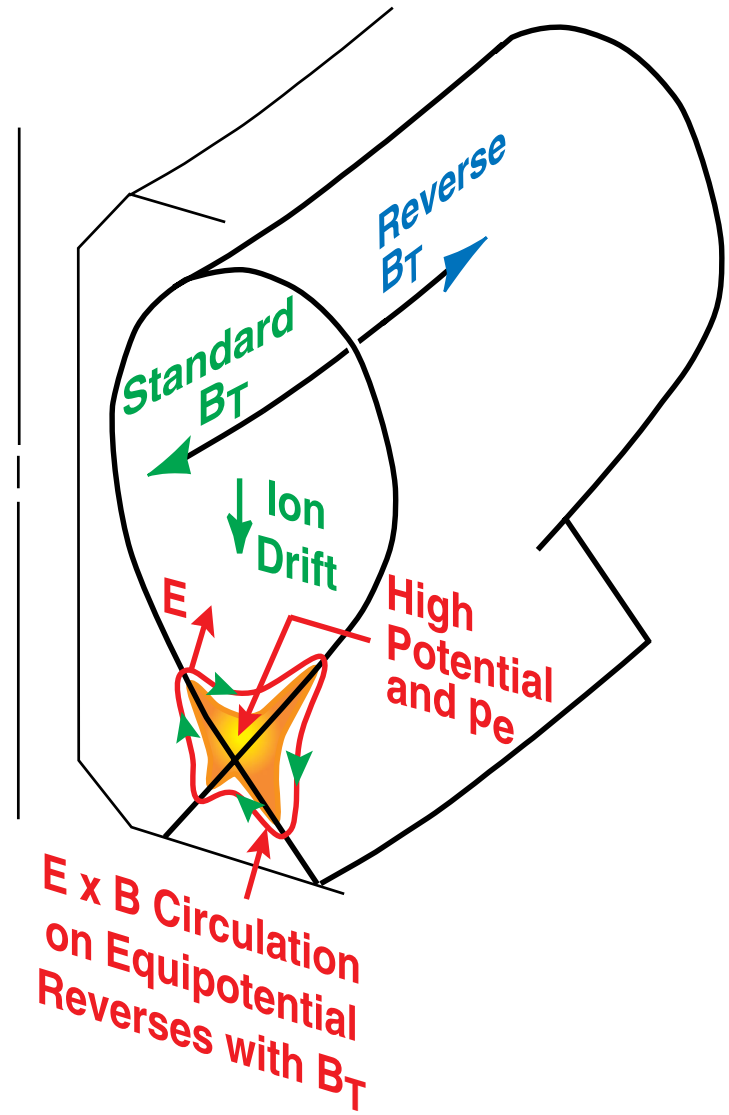
GENERAL ATOMICS

MAIN RESULT: A LOCAL ELECTRIC POTENTIAL HILL DRIVES ExB PLASMA CIRCULATION AROUND THE DIVERTOR X–POINT

- Potential (Φ) and electron pressure (p_e) hills found near X–point in L–mode.
  - Experiment and 2D transport (UEDGE).
- Electric field drives ExB_T poloidal flow around X–point.
  - Flow direction depends on B_T direction.
- Poloidally nonuniform edge boundary layer, even on closed magnetic surfaces.
- ExB flow mixes particles, energy and momentum among confinement, SOL and private regions.
- ExB and ∇B drifts enrich physics at the tokamak edge.



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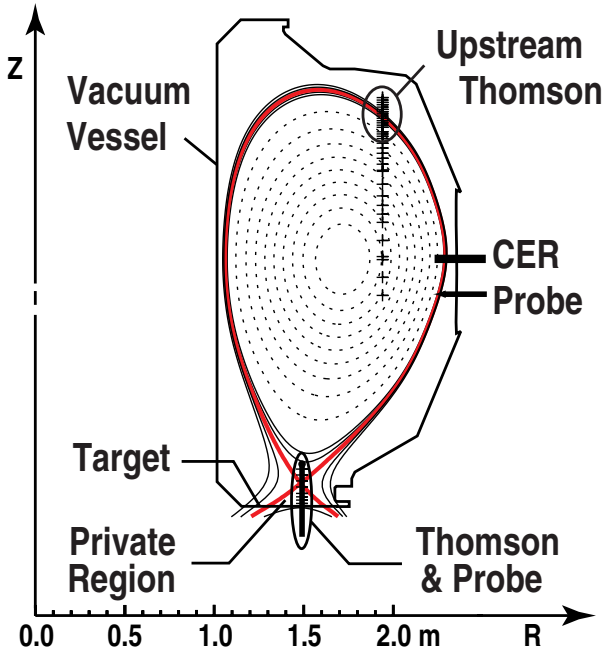
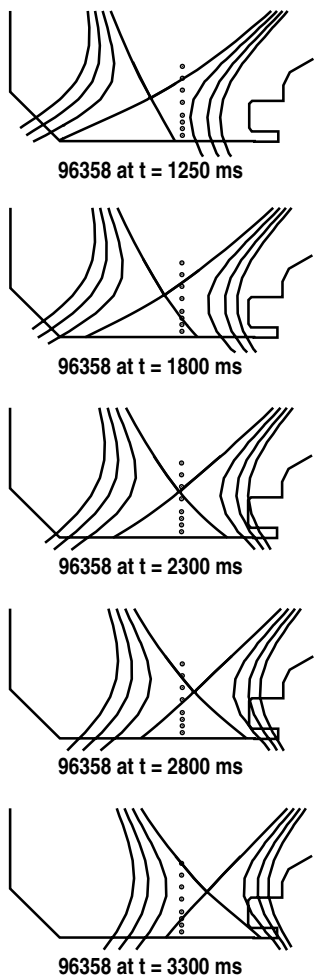
EXPERIMENTS

DIAGNOSTICS VIEW BOTH DIVERTOR AND UPSTREAM REGIONS. MOST DATA ARE FROM LOW-POWER L–MODE PLASMAS.

- Thomson scattering:
  - Divertor and Top
- Scanning Langmuir probe arrays:
  - Divertor and Outer Mid
- Charge Exchange Recombination Spectroscopy (CER):
  - Outer Mid



Thomson scattering and divertor geometries



Plasma Conditions:

DIII–D tokamak

L–mode

2.1 T toroidal magnetic field

1.0 MA plasma current

0.3 MW NB, 0.6 MW OH

$2.5 \cdot 10^{19}$ m^{-3} line-average density

Single–null diverted

Detached at inner divertor

Almost detached at outer divertor

Both B_T directions:
Ion ∇ B drift toward and away from X–point

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UPSTREAM n_e, T_e AND T_i ARE TYPICAL OF LOW POWER L–MODE

- Mapped onto magnetic flux calculated by EFIT code.
  - Normalized Poloidal Flux:

    Magnetic axis = 0

    Separatrix = 1

    SOL > 1

- T_i >> T_e near separatrix.

- At Separatrix:

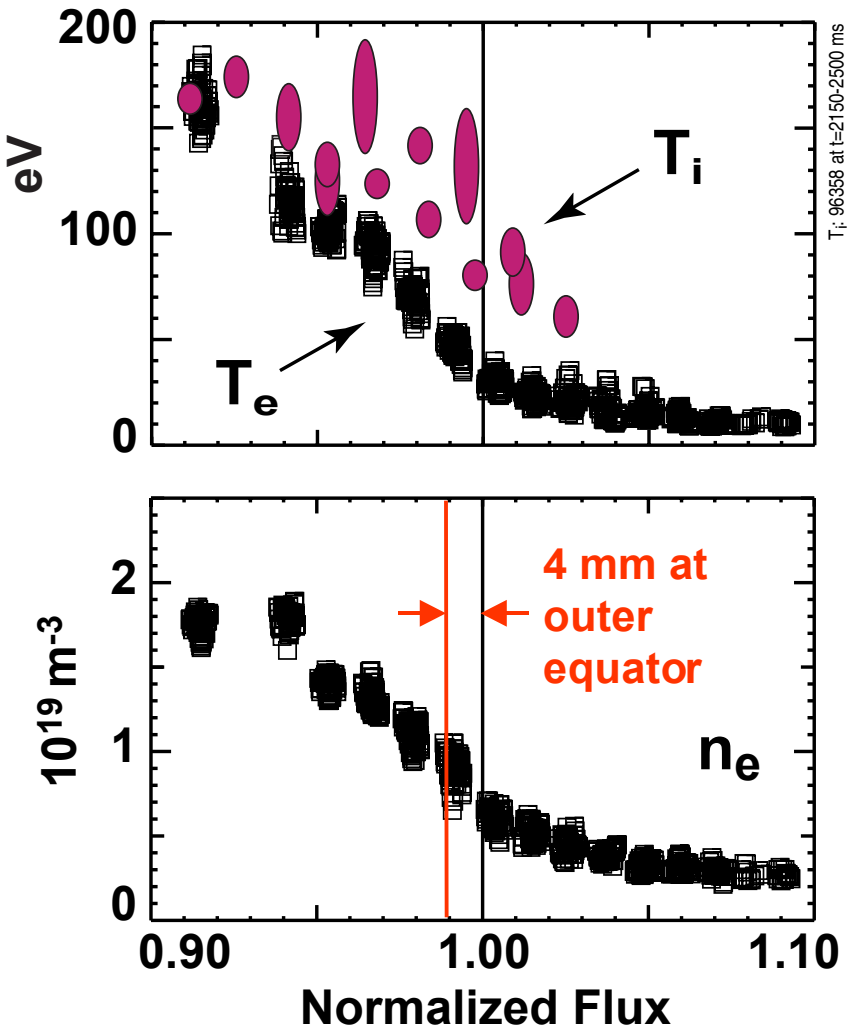
  $n_e \approx 0.7 \cdot 10^{19}\ m^{-3}$

  $T_e \approx 40$ eV

  $T_i \approx 125$ eV

  $p_e \approx 45$ Pa

  $p_i \approx 150$ Pa >> p_e



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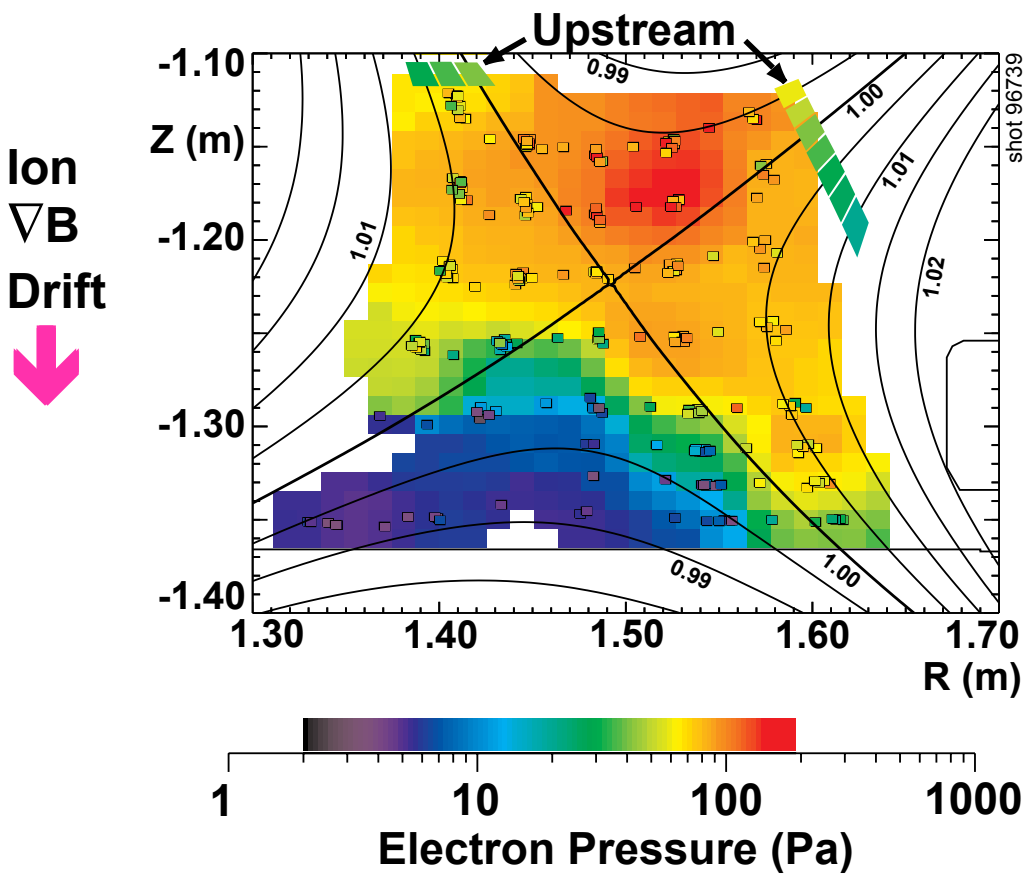
p_e IS LARGER NEAR X–POINT THAN UPSTREAM ON SAME SURFACE

L–mode



- Local p_e hill on closed and SOL surfaces near X–point, relative to upstream on the same surface upstream.
  - Not the expected uniform or monotonic p_e.
- p_e hills for both ion ∇B_T drift directions, ↓ and ↑ .
  - Persist in higher power L–mode (drift ↑).
- p_e hills also seen in Ohmic and perhaps H–mode with type–3 ELMs.
- No p_e hill so far in H–mode (ELM-free and type–1 'giant' ELMing).

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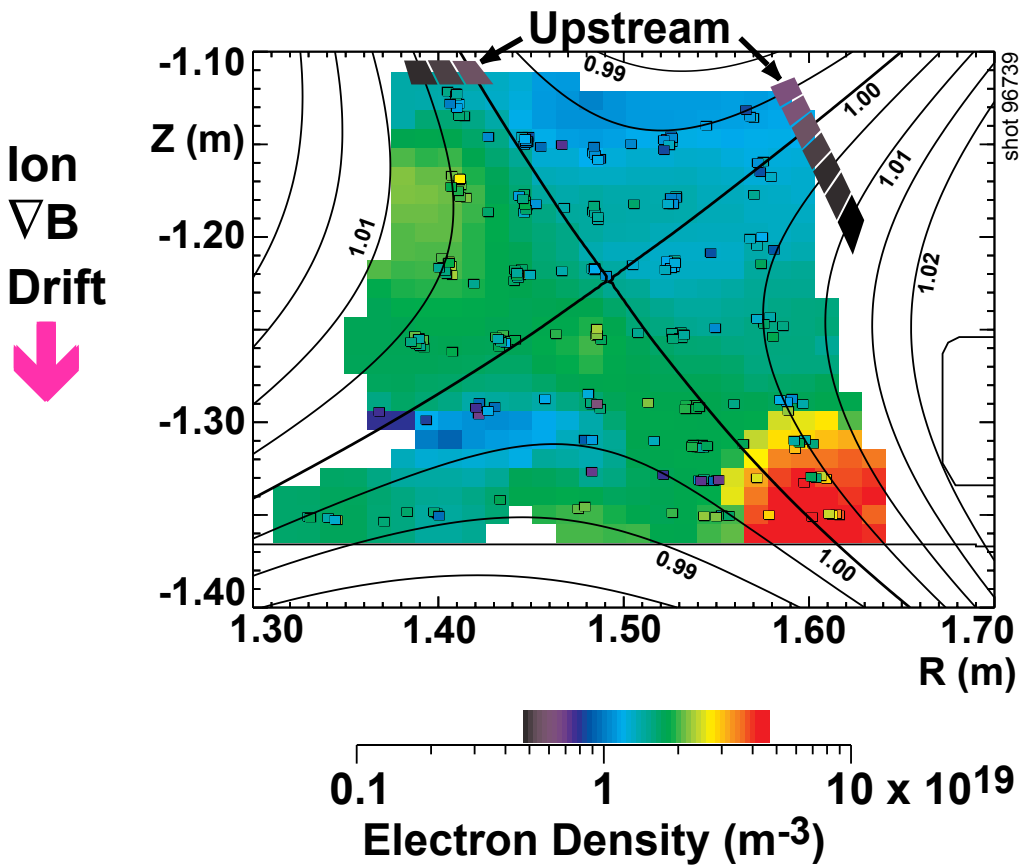
n_e IS LARGER NEAR X–POINT THAN UPSTREAM ON SAME SURFACE

L–mode



- Density is greater on closed and SOL surfaces near X–point than on the same surfaces upstream.
  - (High density at target is the usual divertor recycling.)
- High X–point density goes with the high p_e, since T_e is fairly uniform on a surface.
- n_e hills for both ion ∇B_T drift directions, ↓ and ↑ .

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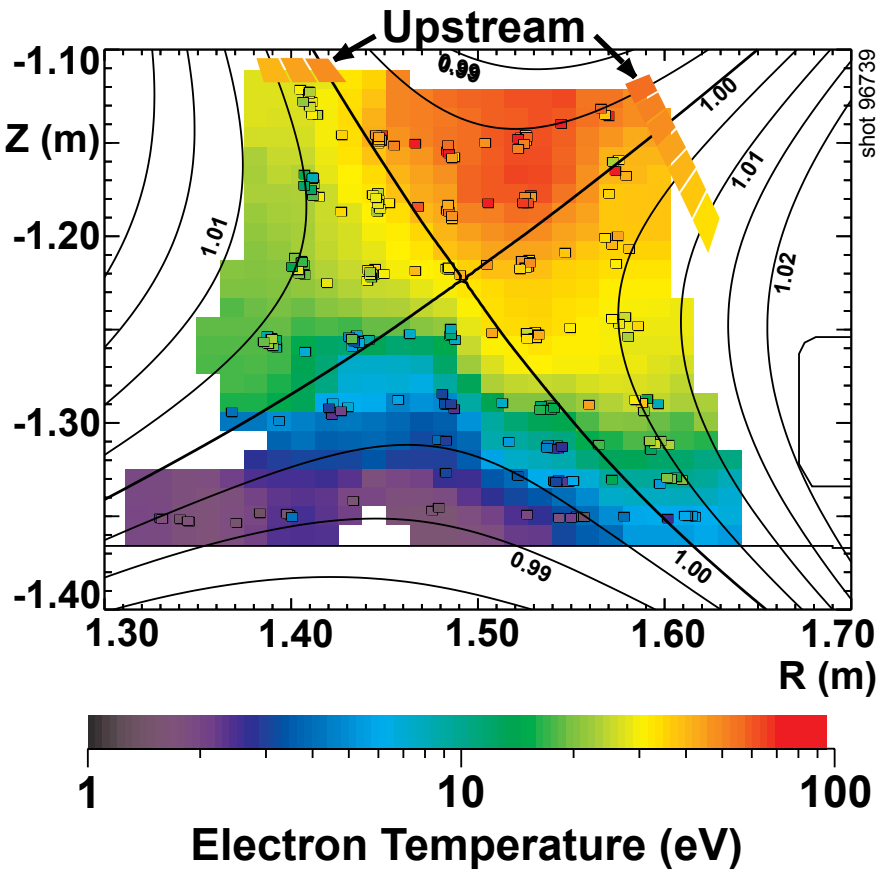
T_e IS APPROXIMATELY CONSTANT ON A SURFACE

L–mode

Ion
∇B
Drift



- T_e uniformity is expected,.
  - Large e^- parallel thermal conductivity.
- However, T_e is sometimes greater on closed surfaces near X–point than on same surfaces upstream.
  - Puzzling result, but it survives many checks.
  - Mainly for reversed B_T direction (↑).

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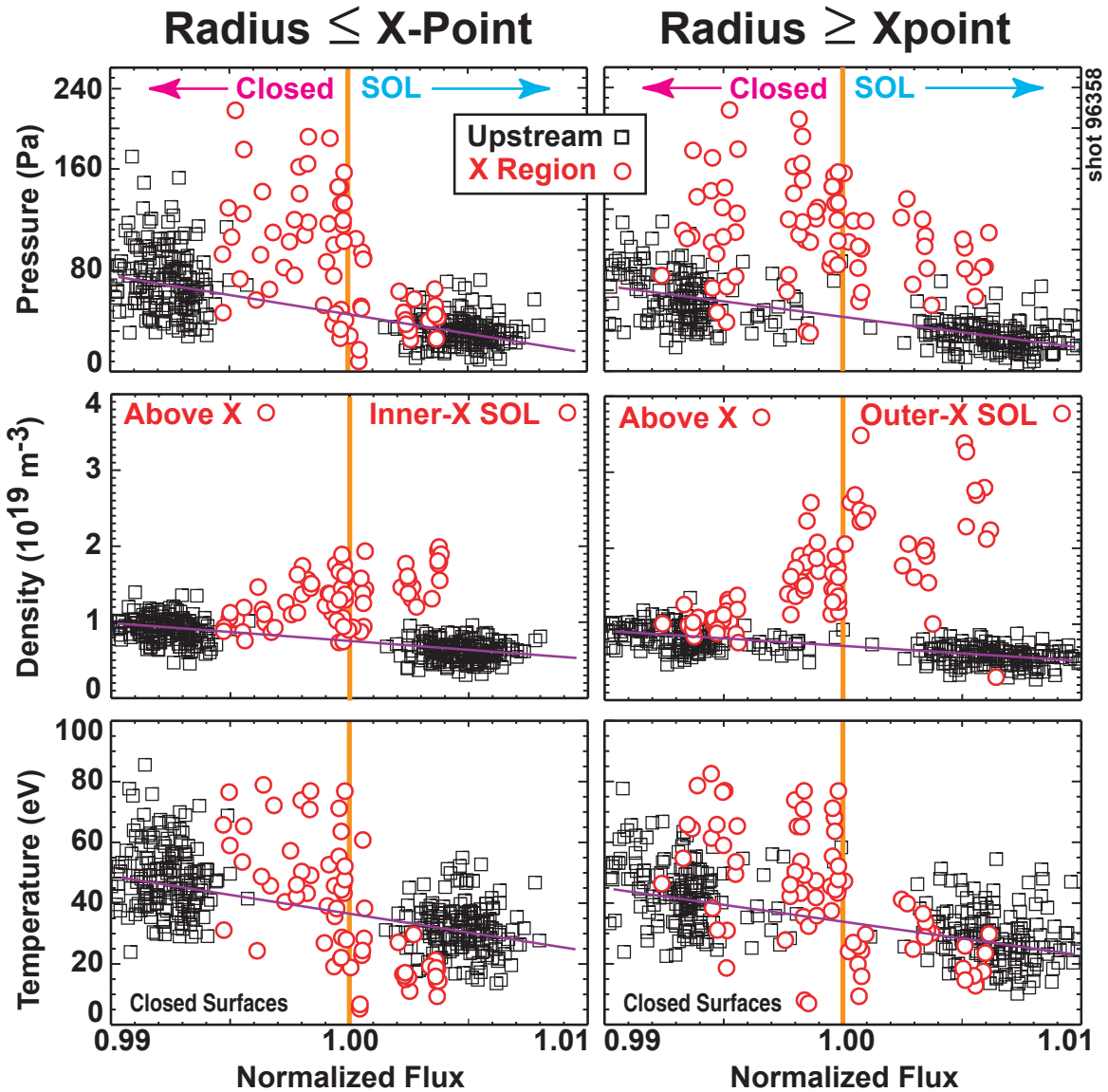
THOMSON SCATTERING SHOWS p_e, n_e and T_e LARGER NEAR X–POINT THAN UPSTREAM ON THE SAME MAGNETIC SURFACE

Ion ∇B Drift ↑

- X–region p_e is higher on closed surfaces and outer SOL than upstream.
- X–region n_e is higher than upstream.
- X–region T_e is higher on closed surfaces than upstream.
  - Fluctuations are large.
  - Probes agree with Thomson scattering T_e.



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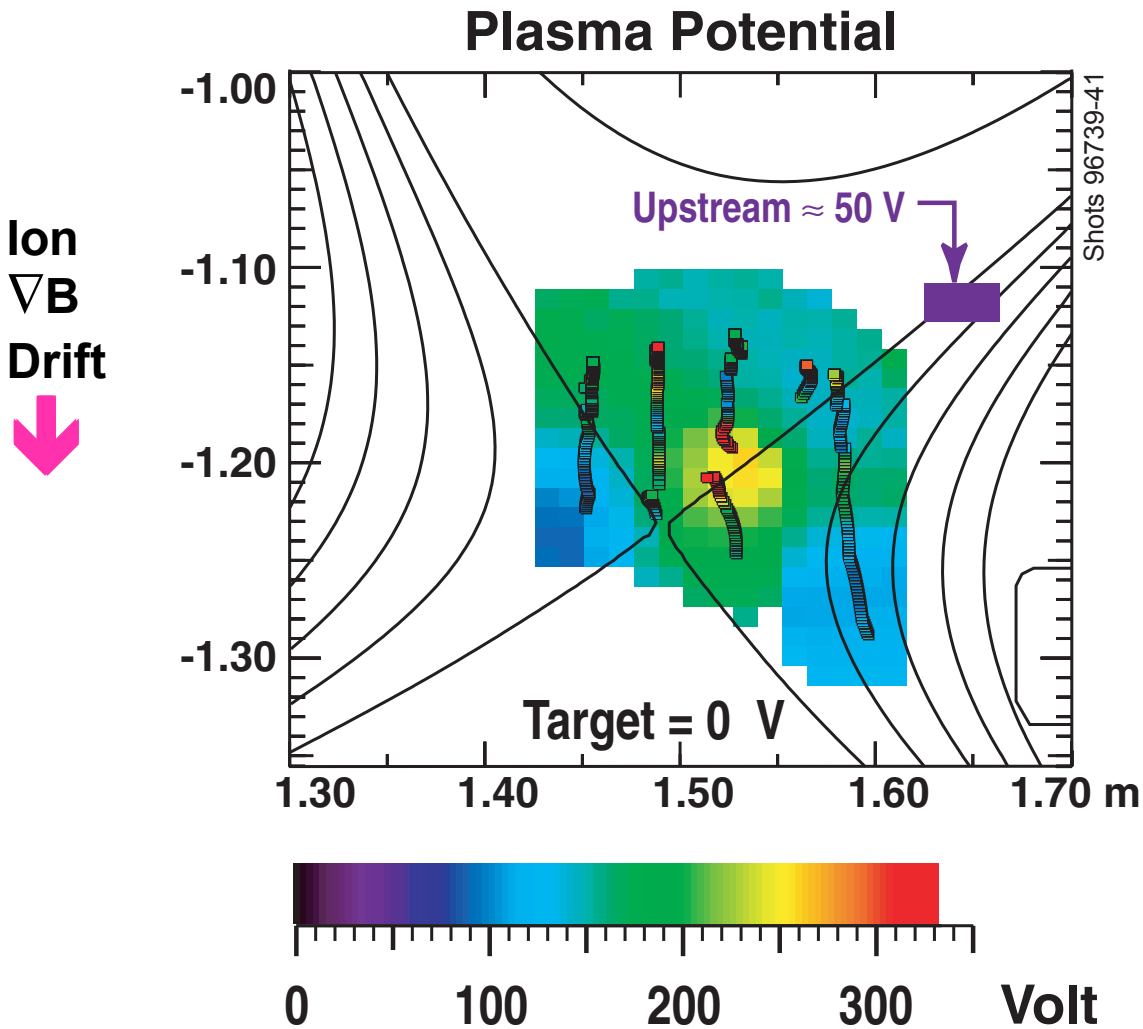
ELECTRIC POTENTIAL IS HIGHER NEAR X–POINT THAN UPSTREAM



- 2D potential field.
- High potential near X on closed surfaces (Moyer).
- High potential on divertor leg and into private region is common (Boedo).

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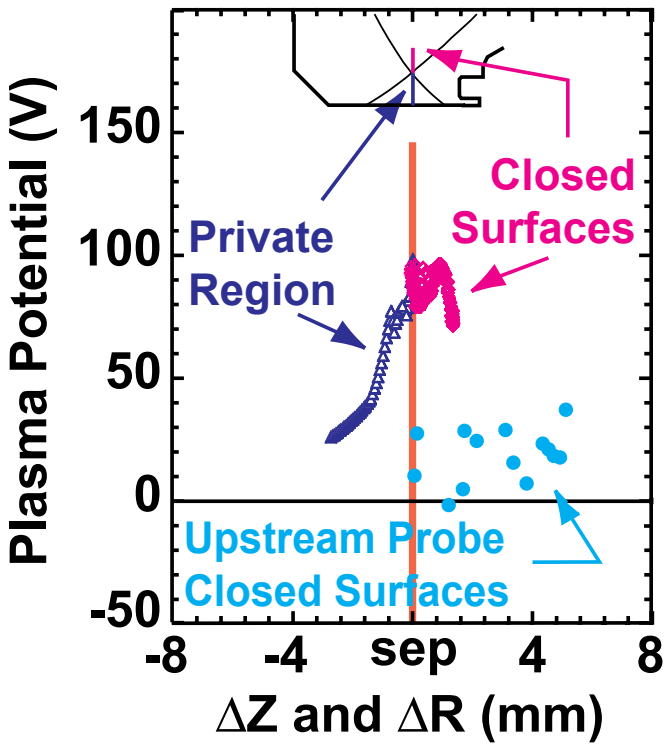
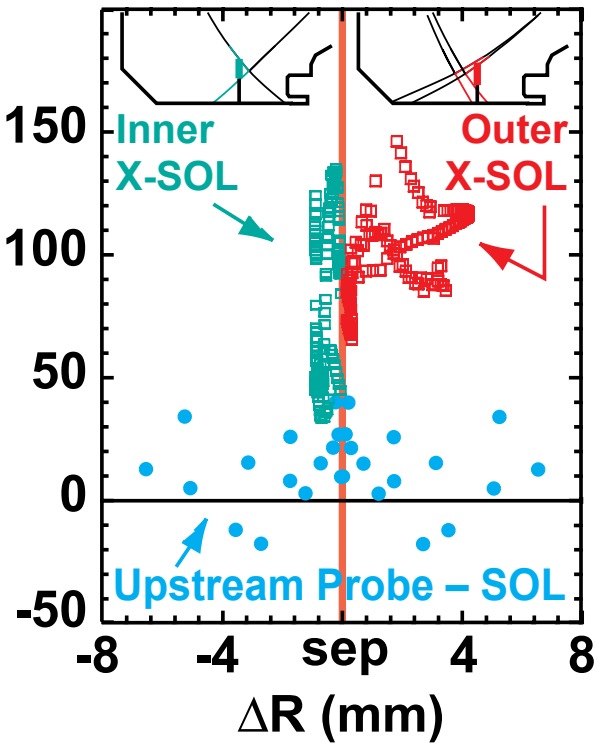
+ Moyer (GP1.129), Boedo (GP1.137)

ELECTRIC POTENTIAL IS HIGHER NEAR X–POINT THAN UPSTREAM

Probe Results

Ion
∇B
Drift





Mapped as Midplane ΔR from Separatrix

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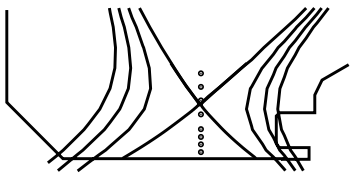
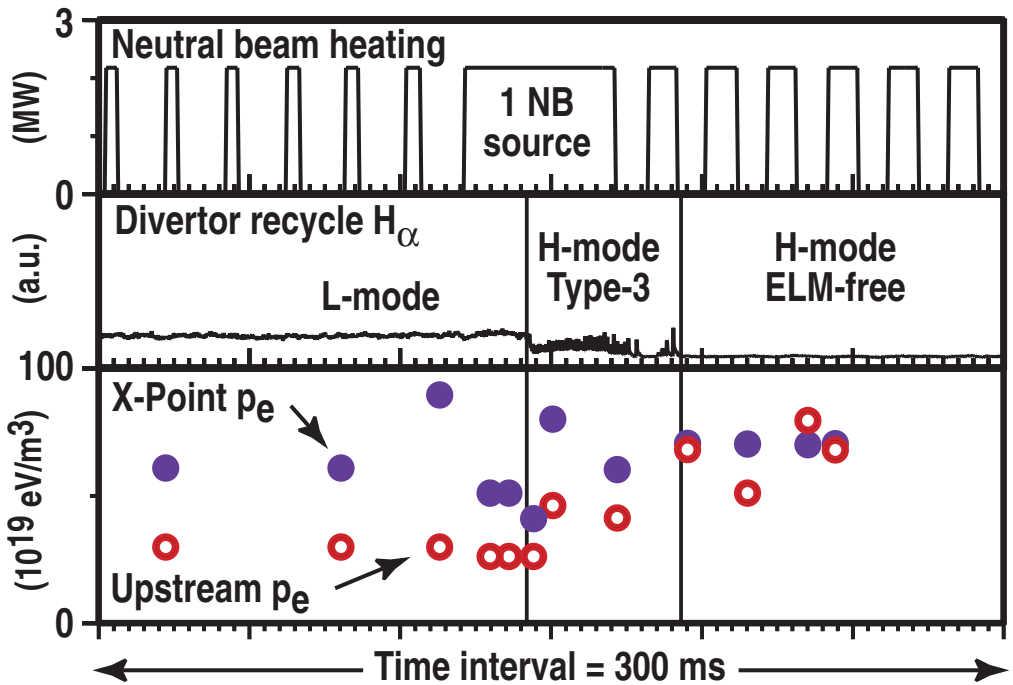
+ Moyer GP 1.129

X–POINT p_e MAXIMUM EXISTS in L–MODE and maybe in H–MODE WITH TYPE-3 ELMs. ABSENT in ELM-free H–MODE.

- Preliminary Experiment:
  - Thomson data through L→H.
  - Fixed X–point



  - Ion B drift ↓ toward X.
  - Low power, slow transition.
  - Seven transitions; few data.
- Showing p_e data from 0.5% inside separatrix.



- Preliminary Conclusions:
  - X–point p_e hill in L–mode and maybe in H–mode with Type 3 ELMs.
  - p_e seems uniform in ELM-free H–mode.
  - Implies ExB circulation is common in low confinement or low temperature edge, absent at higher confinement.

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MODELING AND INTERPRETATION

MODEL: POTENTIAL VARIATION ALONG A MAGNETIC FLUX TUBE AT LOW POWER EXPLAINED BY LOW T_i AT X–POINT (p.1)

- Assume total pressure uniform on a surface: $p_e + p_i = p \uparrow$ constant.
- Parallel Ohm's law (electron momentum equation) governs electric potential Φ along magnetic lines, whether open or closed:

$$e\nabla_{||}\Phi = -eE_{||} = \frac{\nabla_{||}p_e}{n_e} + 0.7k_B\,\nabla_{||}T_e$$

$$= \frac{\nabla_{||}(p - p_i)}{n_e} + 0.7k_B\,\nabla_{||}T_e$$

- High X potential is driven by high local p_e, or equivalently, low p_i.
  - Calculated X–region 45 V more positive than equatorial.
  - High n_e on closed surfaces is from pressure equilibrium.
    - No need to invoke an X–region particle source.

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MODEL: POTENTIAL VARIATION ALONG A MAGNETIC FLUX TUBE AT LOW POWER EXPLAINED BY LOW T_i AT X–POINT (p.2)

Upstream, Just Inside Separatrix

$n = 0.6\ e19\ m^{-3}$

$T_e = 45$ eV

$p_e = 43$ Pa

$T_i = 125$ eV

$p_i = 120$ Pa

$p = 163$ Pa

X–Point, Just Inside Separatrix

$n = 1.5\ e19\ m^{-3}$

$T_e = 45$ eV

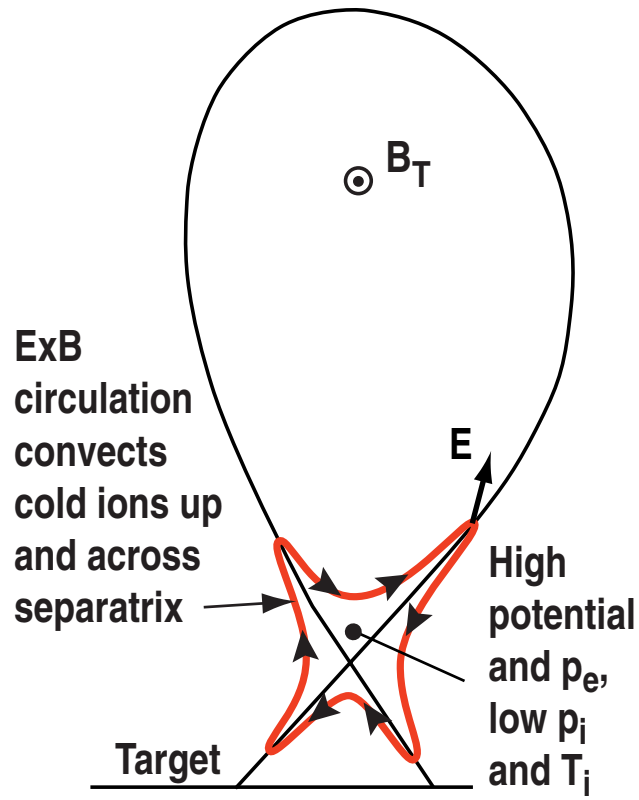
$p_e = 108$ Pa

$T_i = 23$ eV

$p_i = 55$ Pa

$p = 163$ Pa

- T_i is not measured at the X–point, so calculate for constant p.
- Cold ions ExB drift up from the target, and cool X–point ions.
  - Ion conduction, etc. are small.



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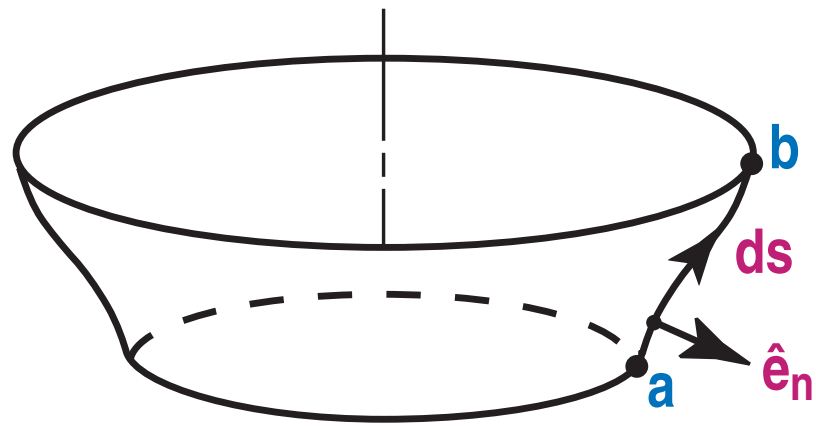
+ Zaniol (Post Deadline)

ExB CONVECTION ACROSS SEPARATRIX IS IMPORTANT TO KNOW. HERE IS HOW WE CALCULATE IT.

Number of particles convected by E x B drift, where $-\vec{E} = \nabla\Phi$, is

$$
\begin{aligned}
N &= \int_a^b n \frac{\vec{E}\times\vec{B}}{B^2}\cdot \hat{e}_n \, 2\pi R \, ds \\
&= \int_a^b 2\pi R \, n \frac{B_\phi}{B^2}\left(-\vec{E}\cdot ds\right) \\
&\approx \int_a^b 2\pi R \, n \frac{1}{B_\phi} \, d\Phi \\
&= \frac{2\pi}{R_0 B_0}\left\langle R^2 n\right\rangle\left(\Phi_b - \Phi_a\right)
\end{aligned}
$$



- Depends on average density along ab and potential difference.
  - Similarly for convected energy (5/2 p) and toroidal angular momentum ($m\, n\, \Omega\, R^2$).

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X–POINT ExB CONVECTIVE MIXING IS IMPORTANT

	ExB Mixing	Total Transport Across Separatrix
• Particles	$3 \times 10^{21}\ s^{-1}$	$5 \times 10^{21}\ s^{-1}$
• Energy	0.14 MW	0.7 MW
• Toroidal Angular Momentum	0.14 N·m	0.165 N·m (NB injected)
• Exchange Rate	$3000\ s^{-1}$	$300\ s^{-1}$ (charge exchange*)

*Charge exchange rate iscalculated using the neutral density measured by Colchin et al., Nucl. Fusion 40 (2000) 175.

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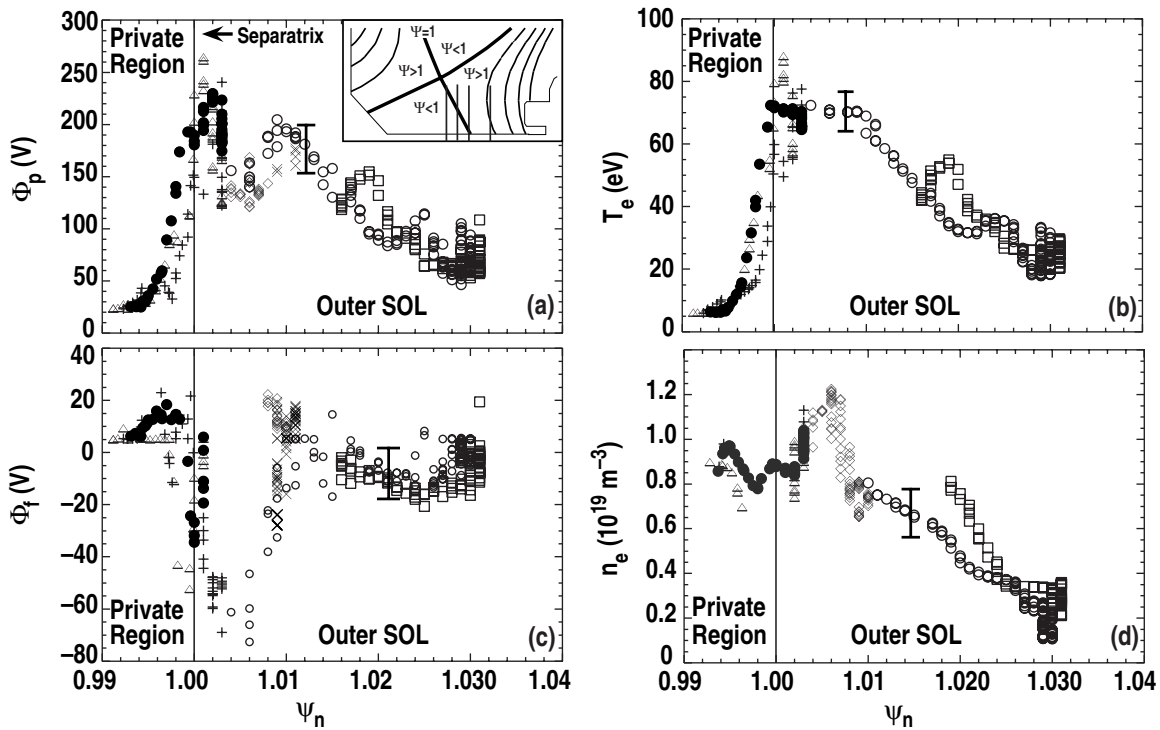
+ Owen (GP1.130), Colchin (MO1.012)

HIGH POTENTIAL IN DIVERTOR YIELDS LARGE POLOIDAL ExB FLOW, ESPECIALLY IN PRIVATE REGION

- Ion ∇B drift ↓ toward X
- ELMy H–mode
- 1.4 MA, 3.5 MW NBI

- Potential is insensitive to B_T sign.
- Private ExB flow convects
  ≈ $1 \cdot 10^{22}$ ions /s
  from one target to the other.
  cf. total target ion current
  ≈ $3 \cdot 10^{22}$ ions /s.



- These measurements (Boedo et al., Phys. Plasma 7 (2000) 1075) support the conclusion from UEDGE code run with drift terms, that **Private ExB flow is the principal factor governing the B_T direction sensitivity of the target power and particle flux distributions.**

(Rognlien et al., 13th PSI)

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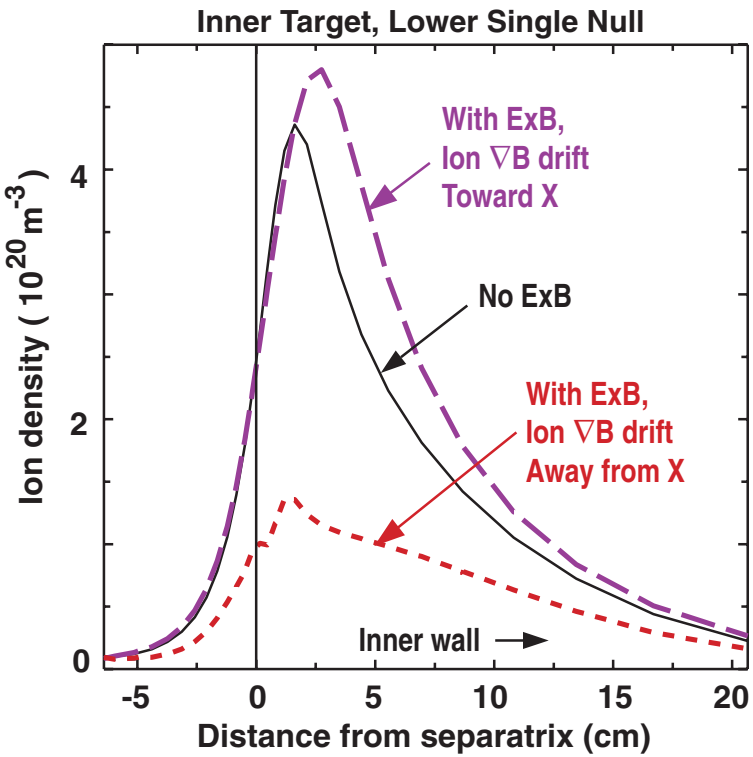
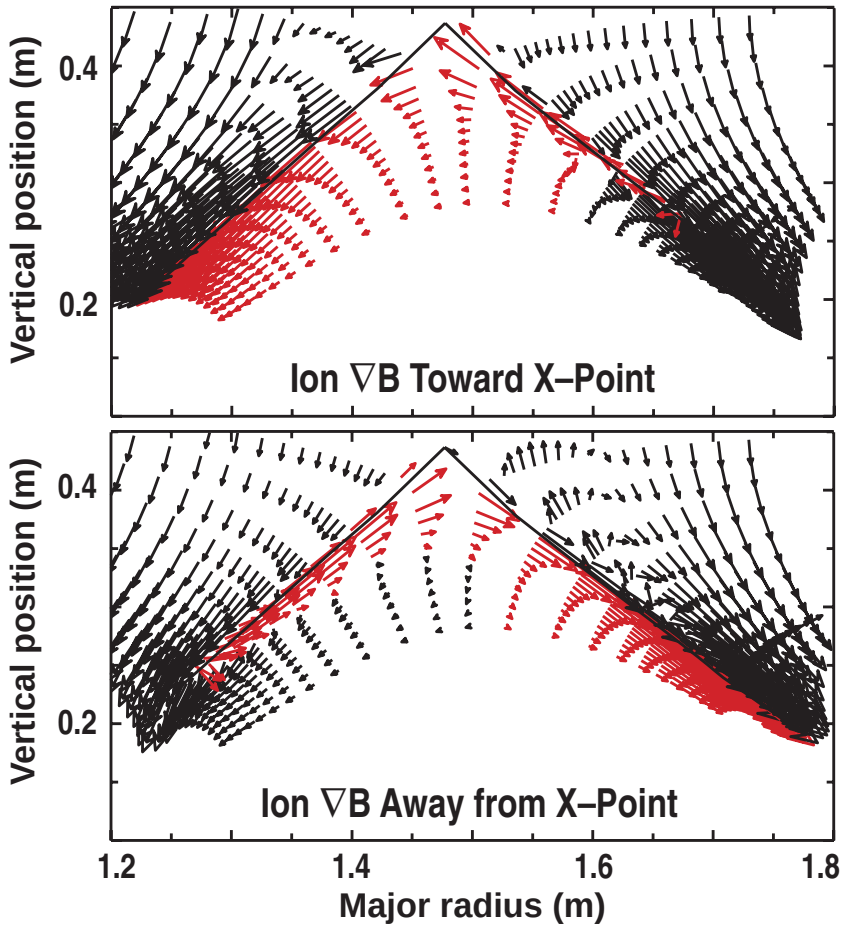
Rognlien et al: ExB PRIVATE FLOW BETWEEN STRIKE POINTS IS THE MAIN FACTOR IN B_T DIRECTION SENSITIVITY OF DIVERTOR PLASMAS

- **UEDGE simulations of a generic DIII–D plasma with self–consistent drifts:**
  - **ExB more important than ∇B in divertor.**
  - **UEDGE private ion ExB flow ≈ $0.7 \cdot 10^{22}$ ion /s is close to DIII–D ≈ $1.0 \cdot 10^{22}$ ion /s.**

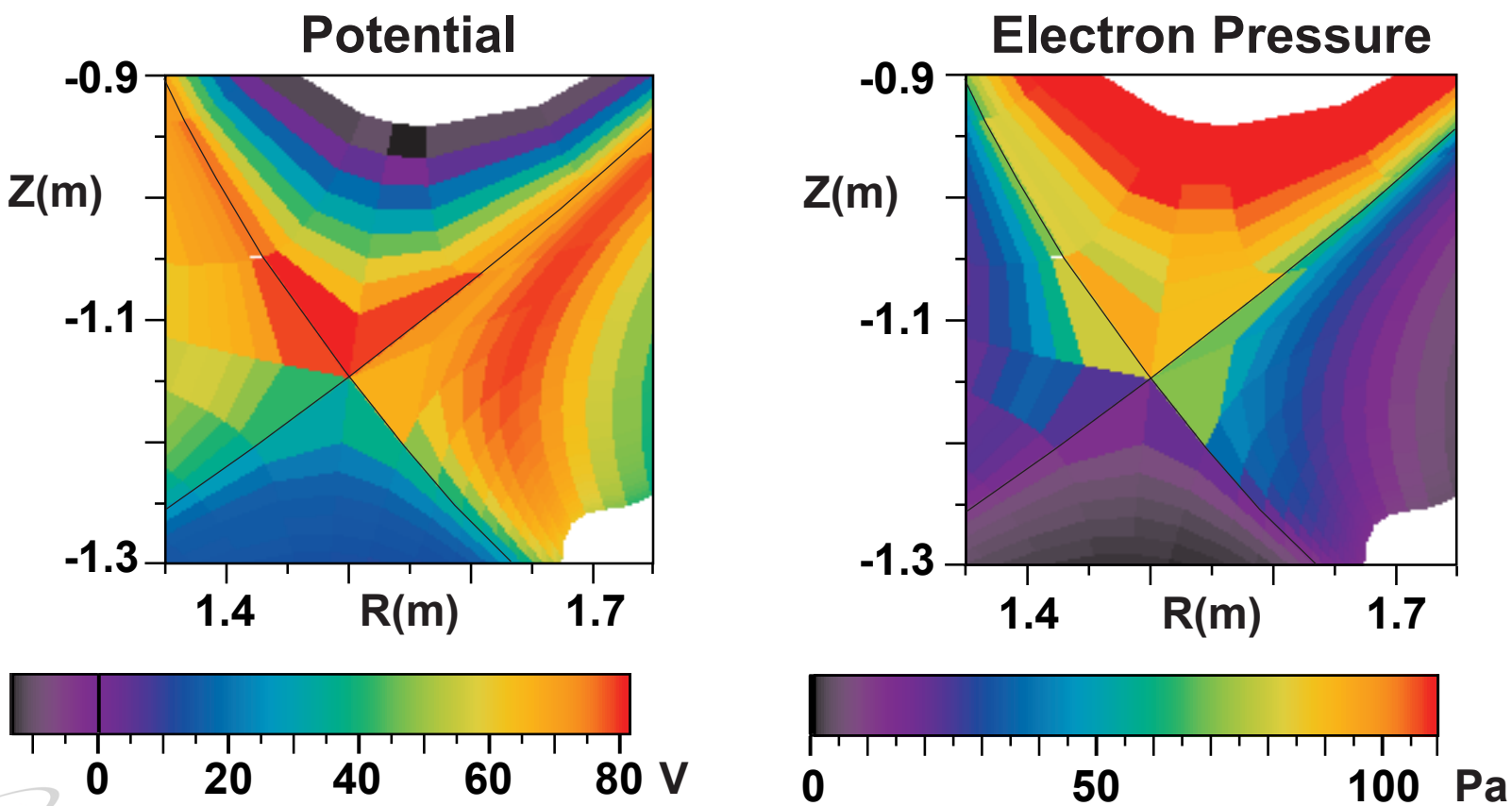




Plots from Rognlien, Porter, Ryutov, 13th PSI (1998)

PRELIMINARY 2D NUMERICAL TRANSPORT MODELING by UEDGE with DRIFTS YIELDS POTENTIAL and p_e HILLS IN X–REGION

- Model has impurity, gas and self–consistent drifts.
- Confirms that drifts can produce potential and pressure hills.
- A different divertor geometry and warmer divertor plasma contribute to differences from experiment.



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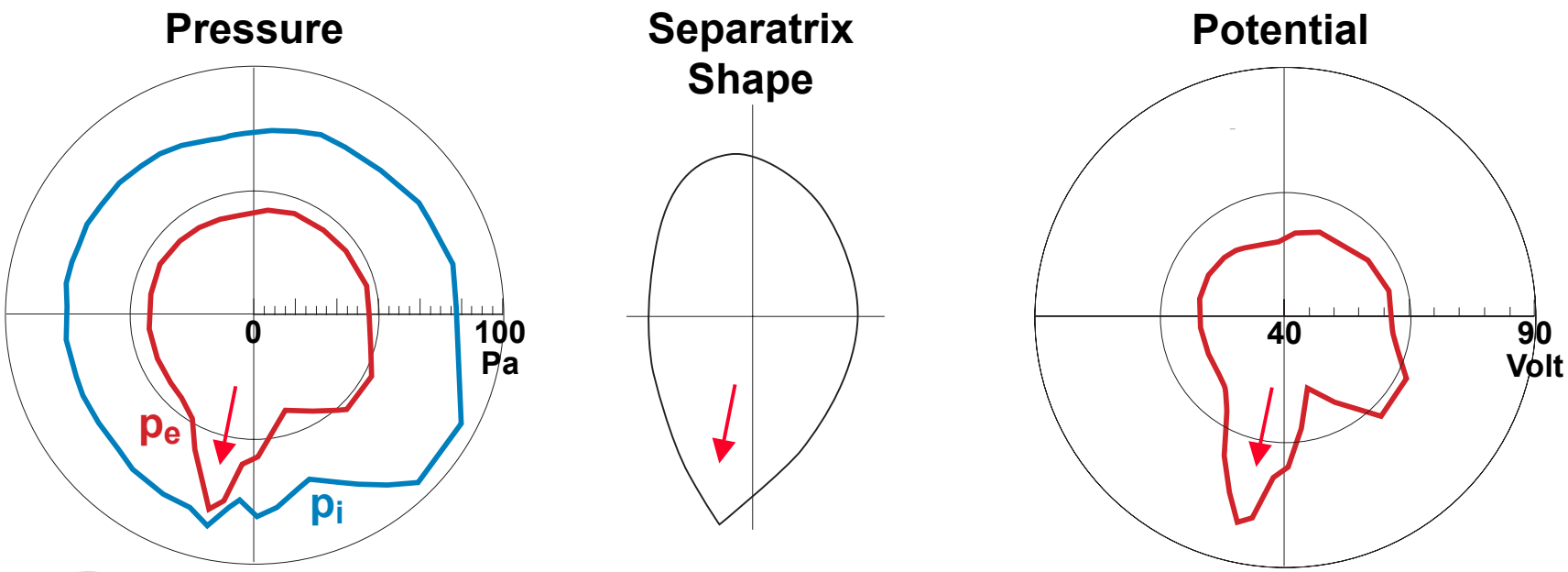
PRESSURE AND POTENTIAL ARE POLOIDALLY NONUNIFORM INSIDE SEPARATRIX IN UEDGE SOLUTION with DRIFTS

- Boundary layer* (~2% of poloidal flux) is poloidally nonuniform.
- Potential hill is smaller than in experiment.
  - Hills in UEDGE seem to be made by parallel viscosity impeding Pfirsch-Schlüter parallel return flow of B ion drift. (Preliminary!)
- An additional pressure and potential hill appears below outer equator.
  - Triggered by magnetic "bump" of nearby poloidal field coil.



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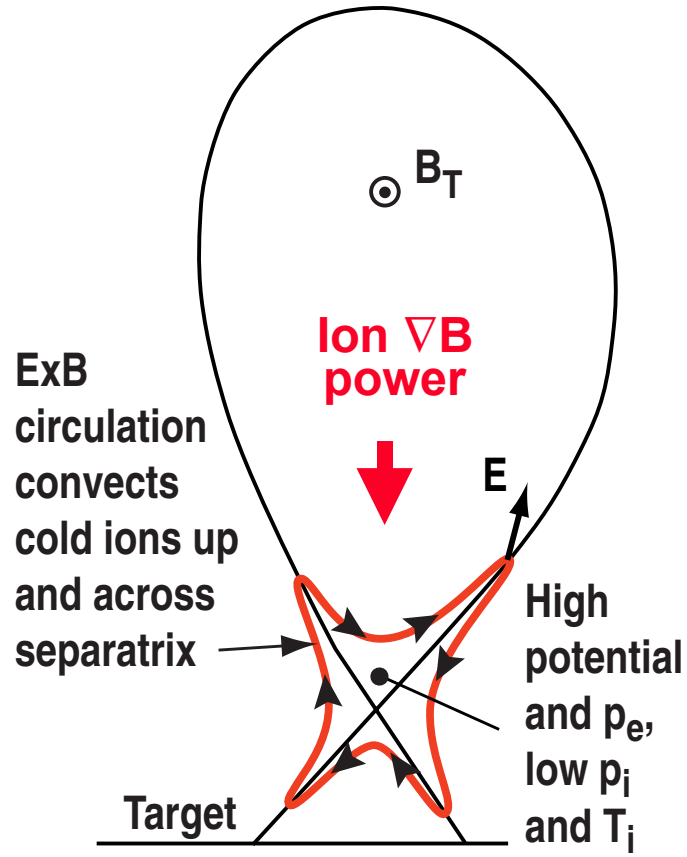
*F.L.Hinton and Y.-B. Kim, NF **34** (1994) 899.

UEDGE MODELING RESULTS EXPAND EXPERIMENTAL RESULTS

- Low power tokamak boundary layer inside the separatrix is far from poloidally uniform.
- ExB dominates below X–point.
- ∇B drift is main driver above X–point.
- Parallel viscosity impedes Pfirsch–Schlüter return flow.
- Edge plasma is sensitive to perturbations.
- "Potential cells" might be a common feature of low confinement edges.
  - "Bumpy" fields might cause L– to H–mode transition power threshold to vary in a non-scalable way among tokamaks.

SPECULATION ON X–POINT CIRCULATION AND H–MODE

- In H–mode we observe $p_e \approx$ constant between X–region and upstream.
  - Implies no ExB mixing in H–mode.
- Hypothesis: Mixing incompatible with H–mode; suppression is necessary for L→H transition.
- Need X–region power to break cold T_i attractor.
  - Ion conduction power ~ 0.1 MW into X;
    Ion circulation power ~ 0.1 MW out of X.
- Need a B_T –sign–dependent power to explain dependence of L→H transition threshold.
  - Vertical ion ∇B drift power into X– region is enough* ~ 0.1 MW into X.
- X–point circulation and mixing have correct sign and magnitude to play a role.



*Hinton, NF **25** (1985) 1457.

CONCLUSION

SUMMARY AND CONCLUSIONS

- Potential (Φ) and electron pressure (p_e) hills exist near X–point in L–mode plasmas.
- Potential gradient drives ExB plasma circulation around the X–point.
- It mixes particles, energy and toroidal momentum, etc. across the separatrix.
- The pressure hill appears to be absent from H–mode.
- Simple model explains potential hill formation at low power.
- UEDGE 2D modeling also exhibits X–point potential and p_e hills.
- Poloidal nonuniformity might be common in low confinement edges and absent in high confinement.
- ExB and ∇B drifts enrich physics at the tokamak edge.

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