ExB Circulation at the Tokamak Divertor X–Point

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DIII–D
NATIONAL FUSION FACILITY

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ExB CIRCULATION
AT THE TOKAMAK DIVERTOR X–POINT

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

- Potential ($\Phi$) and electron pressure ($p_e$) hills found near X–point in L–mode.
  - Experiment and 2D transport (UEDGE).
- Electric field drives $\text{ExB}_T$ 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 $\nabla B$ drifts enrich physics at the tokamak edge.
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} \text{ m}^{-3} line-average density
Single–null diverted
Detached at inner divertor
Almost detached at outer divertor

Both \( B_T \) directions:
Ion \( \nabla B \) drift toward and away from X–point
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 $>> p_e$

4 mm at outer equator
\( p_e \) IS LARGER NEAR X–POINT THAN UPSTREAM ON SAME SURFACE

- 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 \( \nabla B_T \) 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).
\( n_e \) IS LARGER NEAR X–POINT THAN UPSTREAM ON SAME SURFACE

- 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 \( \nabla B_T \) drift directions, \( \downarrow \) and \( \uparrow \).
**$T_e$** is approximately constant on a surface.

- **$T_e$** 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 BT direction ($\uparrow$).

### Electron Temperature (eV)

<table>
<thead>
<tr>
<th>R (m)</th>
<th>Z (m)</th>
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<tr>
<td>1.30</td>
<td>-1.10</td>
</tr>
<tr>
<td>1.40</td>
<td>-1.20</td>
</tr>
<tr>
<td>1.50</td>
<td>-1.30</td>
</tr>
<tr>
<td>1.60</td>
<td>-1.40</td>
</tr>
<tr>
<td>1.70</td>
<td>-1.50</td>
</tr>
</tbody>
</table>

Legend:
- Ion
- $\nabla B$
- Drift

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**DIII-D**

National Fusion Facility
San Diego
THOMSON SCATTERING SHOWS $p_e$, $n_e$ and $T_e$ LARGER NEAR X–POINT THAN UPSTREAM ON THE SAME MAGNETIC SURFACE

- 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 $T_e$.

Ion $\nabla B$ Drift

**Radius $\leq$ X-Point**

- Pressure (Pa)
- Density ($10^{19}$ m$^{-3}$)
- Temperature (eV)

**Radius $\geq$ Xpoint**

- Pressure (Pa)
- Density ($10^{19}$ m$^{-3}$)
- Temperature (eV)

X–region is shown with red dots, upstream is shown with black squares, and closed surfaces are shown with closed circles.

Shot 96358
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).

Moyer (GP1.129), Boedo (GP1.137)
ELECTRIC POTENTIAL IS HIGHER NEAR X–POINT THAN UPSTREAM

Probe Results

Vertically Through X-Point

Radially, SOL Near X Height

Mapped as Midplane $\Delta R$ from Separatrix

+ 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 $\to$ H.
  - Fixed X–point
  - Ion B drift $\downarrow$ 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.
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: $p_e + p_i = p$ constant.
- Parallel Ohm’s law (electron momentum equation) governs electric potential $\Phi$ along magnetic lines, whether open or closed:

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

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

- 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.
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**

- $n = 0.6 \, \text{e}^{19} \, \text{m}^{-3}$
- $T_e = 45 \, \text{eV}$
- $p_e = 43 \, \text{Pa}$
- $T_i = 125 \, \text{eV}$
- $p_i = 120 \, \text{Pa}$
- $p = 163 \, \text{Pa}$

**X–Point, Just Inside Separatrix**

- $n = 1.5 \, \text{e}^{19} \, \text{m}^{-3}$
- $T_e = 45 \, \text{eV}$
- $p_e = 108 \, \text{Pa}$
- $T_i = 23 \, \text{eV}$
- $p_i = 55 \, \text{Pa}$
- $p = 163 \, \text{Pa}$

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

$+$ Zaniol (Post Deadline)
ExB CONVECTION ACROSS SEPARATRIX IS IMPORTANT TO KNOW. HERE IS HOW WE CALCULATE IT.

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

$$N = \int_a^b n \frac{\vec{E} \times \vec{B}}{B^2} \cdot \hat{e}_n \ 2\pi R \ ds$$

$$= \int_a^b 2\pi R \ n \ \frac{B_\phi}{B^2} \ (-\vec{E} \cdot ds)$$

$$\approx \int_a^b 2\pi R \ n \ \frac{1}{B_\phi} \ d\Phi$$

$$= \frac{2\pi}{R_0 B_0} \left\langle R^2 n \right\rangle (\Phi_b - \Phi_a)$$

- Depends on average density along $ab$ and potential difference.

- Similarly for convected energy $(5/2 \ p)$ and toroidal angular momentum $(m \ n \ \Omega \ R^2)$. 
**ExB Mixing**

<table>
<thead>
<tr>
<th>Category</th>
<th>ExB Mixing</th>
<th>Total Transport Across Separatrix</th>
</tr>
</thead>
<tbody>
<tr>
<td>Particles</td>
<td>$3 \times 10^{21} \text{ s}^{-1}$</td>
<td>$5 \times 10^{21} \text{ s}^{-1}$</td>
</tr>
<tr>
<td>Energy</td>
<td>0.14 MW</td>
<td>0.7 MW</td>
</tr>
<tr>
<td>Toroidal Angular Momentum</td>
<td>0.14 N·m</td>
<td>0.165 N·m (NB injected)</td>
</tr>
<tr>
<td>Exchange Rate</td>
<td>3000 s$^{-1}$</td>
<td>300 s$^{-1}$ (charge exchange*)</td>
</tr>
</tbody>
</table>

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

+ Owen (GP1.130), Colchin (MO1.012)
HIGH POTENTIAL IN DIVERTOR YIELDS LARGE POLOIDAL ExB FLOW, ESPECIALLY IN PRIVATE REGION

- Ion $\nabla B$ drift $\downarrow$ toward X
- ELMy H–mode
- 1.4 MA, 3.5 MW NBI
- Potential is insensitive to $B_T$ sign.
- Private ExB flow convects $\approx 1 \cdot 10^{22}$ ions/s from one target to the other.
  
  $cf.$ total target ion current $\approx 3 \cdot 10^{22}$ 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)
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 $\nabla B$ in divertor.
  - UEDGE private ion ExB flow $\approx 0.7 \cdot 10^{22}$ ion /s is close to DIII–D $\approx 1.0 \cdot 10^{22}$ 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.

![Potential](image1.png)

![Electron Pressure](image2.png)
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.

UEDGE MODELING RESULTS EXPAND EXPERIMENTAL RESULTS

- Low power tokamak boundary layer inside the separatrix is far from poloidally uniform.

- $\mathbf{E} \times \mathbf{B}$ dominates below X–point.

- $\nabla \mathbf{B}$ 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.
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$\Rightarrow$H transition.

Need X–region power to break cold $T_i$ attractor.

- Ion conduction power $\sim 0.1$ MW into X;
- Ion circulation power $\sim 0.1$ MW out of X.

Need a $B_T$–sign–dependent power to explain dependence of L$\Rightarrow$H transition threshold.

- Vertical ion $\nabla B$ drift power into X– region is enough* $\sim 0.1$ MW into X.

X–point circulation and mixing have correct sign and magnitude to play a role.

CONCLUSION
SUMMARY AND CONCLUSIONS

- Potential ($\Phi$) 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 $\nabla$B drifts enrich physics at the tokamak edge.