The role of the sheath in magnetized plasma fluid turbulence

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Turbulence in open field lines is an outstanding issue

in basic plasma devices...

in fusion devices...
Properties of open field line plasma turbulence

- $L_{\text{fluc}} \sim L_{\text{eq}}$
- $n_{\text{fluc}} \sim n_{\text{eq}}$
- Collisional magnetized plasma
- Low frequency modes $\omega \ll \omega_{ci}$
- Plasma losses at the sheaths
Magnetized plasma turbulence via drift-fluid models

▶ Starting from the Braginskii equations,
Magnetized plasma turbulence via drift-fluid models

- Starting from the Braginskii equations,
  - Quasi-neutrality $n_e \approx n_i$ is assumed
  - A drift ordering is usually adopted, $d/dt \ll \omega_{ci}$, leading to the ion drift approximation:
    $$v_{\perp i} = v_{ExB} + \frac{b}{\omega_{ci}} \times \frac{d^0}{dt} v_{ExB}$$
Magnetized plasma turbulence via drift-fluid models

Continuity:
\[
\frac{dn}{dt} = \frac{2}{eB} \left[ \hat{\mathcal{C}}(p_e) - en\hat{\mathcal{C}}(\phi) \right] - \nabla_{||}(nV_{||e}) + S_n
\]

\nabla \cdot j = 0:
\[
\frac{d\omega}{dt} = \frac{2B}{nm_i} \hat{\mathcal{C}}(p_e) - V_{||i} \nabla_{||} \omega + \frac{m_i \Omega_{ci}^2}{e^2 n} \nabla_{||} j_{||}
\]

Ohm’s:
\[
m_e \frac{dV_{||e}}{dt} = - m_e V_{||e} \nabla_{||} V_{||e} - \frac{T_e}{n} \nabla_{||} n + e \nabla_{||} \phi - 1.71 \nabla_{||} T_e + e \nu j_{||}
\]

Momentum:
\[
m_i \frac{dV_{||i}}{dt} = - m_i V_{||i} \nabla_{||} V_{||i} - \frac{1}{n} \nabla_{||} p_e
\]

Heat:
\[
\frac{dT_e}{dt} = \frac{4}{3} \frac{1}{eB} \left[ \frac{7}{2} T_e \hat{\mathcal{C}}(T_e) + \frac{T_e^2}{n} \hat{\mathcal{C}}(n) - e T_e \hat{\mathcal{C}}(\phi) \right] + \frac{2}{3} \frac{T_e}{en} 0.71 \nabla_{||} j_{||} - \frac{2}{3} T_e \nabla_{||} V_{||e} - V_{||e} \nabla_{||} T_e + S_T
\]
Magnetized plasma turbulence via drift-fluid models

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\]
\[
+ \frac{2}{3} \frac{T_e}{en} 0.71 \nabla_{||}j_{||} - \frac{2}{3} T_e \nabla_{||}V_{||e} - V_{||e} \nabla_{||}T_e + S_T
\]

Need BC for \( n, v_{||e}, v_{||i}, T_e, \omega = \nabla_{\perp}^2 \phi \) and \( \phi \).

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Questions we need to answer

- How to describe the plasma-wall transition region?
- What BC for the fluid fields at the end of the field lines?
- How does this affect the main plasma dynamics?
Outline

- Motivation
- Study of the plasma-wall transition region
- Scrape-off layer simulations with the GBS code
- Sheath effects on:
  - Electrostatic potential in open field lines
  - Intrinsic toroidal rotation in the Scrape-off-layer
  - Scrape-off-layer width in limited plasmas
- Conclusions
What can we learn from kinetic simulations?
What can we learn from kinetic simulations?

\[ \phi \]

\[ \frac{n_i - n_e}{n_{se}} \]

\[ V_- \]

\[ \rho_s \]

COLLISIONAL PRE-SHEATH
MAGNETIC PRE-SHEATH
DEBYE SHEATH

DRIFT VELOCITY

DRIFT-REDUCED MODEL VALID
DRIFT APPROXIMATION BREAKS

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The role of the sheath in magnetized plasma fluid turbulence
Derivation of the magnetic presheath entrance condition

\[ \nabla \cdot B = 0, \quad T_i \ll T_e \]

\[ \frac{\partial s}{\partial x} T_e = 0, \quad T_i \ll T_e \]
Derivation of the magnetic presheath entrance condition

- Gradients dominant along $s$
Derivation of the magnetic presheath entrance condition

- Gradients dominant along $s$
- Gradients along $x$ with $\epsilon = \rho_s/L_x \ll 1$
Derivation of the magnetic presheath entrance condition

- Gradients dominant along $s$
- Gradients along $x$ with $\epsilon = \rho_s/L_x \ll 1$
- Isothermal electrons $\partial_s T_e = 0$, $T_i \ll T_e$
Derivation of the magnetic presheath entrance condition

- Steady-state fluid equations valid in the collisional presheath:
Derivation of the magnetic presheath entrance condition

- Steady-state fluid equations valid in the collisional presheath:
  
  *Ion continuity*
  
  *Ion parallel momentum*
  
  *Electron parallel momentum*
Derivation of the magnetic presheath entrance condition

- Steady-state fluid equations valid in the collisional presheath:

Ion continuity

\[ \nu_{si} \partial_s n + n \sin \alpha \partial_s \nu_i - \partial_x n \cos \alpha \partial_s \phi = S_{pi} \]

Ion parallel momentum

\[ n \nu_{si} \partial_s \nu_i + n (\sin \alpha - \partial_x \nu_i \cos \alpha) \partial_s \phi = S_{\parallel mi} \]

Electron parallel momentum

\[ \mu \sin \alpha T_e \partial_s n - \mu \sin \alpha n \partial_s \phi = S_{\parallel me} \]
Derivation of the magnetic presheath entrance condition

- Steady-state fluid equations valid in the collisional presheath:

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- Can write this system as a matrix system \( \mathbf{M} \mathbf{X} = \mathbf{S} \), where
Derivation of the magnetic presheath entrance condition

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  \[
  \vec{X} = \begin{pmatrix}
  \partial_s n \\
  \partial_s v_{||i} \\
  \partial_s \phi
  \end{pmatrix},
  \quad
  \vec{S} = \begin{pmatrix}
  S_{pi} \\
  S_{||mi} \\
  S_{||me}
  \end{pmatrix}.
  \]
Derivation of the magnetic presheath entrance condition

- Steady-state fluid equations valid in the collisional presheath:

  - Ion continuity
    \[ v_{si} \partial_s n + n \sin \alpha \partial_s v_{||i} - \partial_x n \cos \alpha \partial_s \phi = S_{pi} \]

  - Ion parallel momentum
    \[ n v_{si} \partial_s v_{||i} + n(\sin \alpha - \partial_x v_{||i} \cos \alpha) \partial_s \phi = S_{||mi} \]

  - Electron parallel momentum
    \[ \mu \sin \alpha T_e \partial_s n - \mu \sin \alpha n \partial_s \phi = S_{||me} \]

- Can write this system as a matrix system \( \mathbf{M} \bar{\mathbf{X}} = \bar{\mathbf{S}} \), where

  \[ \bar{\mathbf{X}} = \begin{pmatrix} \partial_s n \\ \partial_s v_{||i} \\ \partial_s \phi \end{pmatrix}, \quad \bar{\mathbf{S}} = \begin{pmatrix} S_{pi} \\ S_{||mi} \\ S_{||me} \end{pmatrix}, \]

  \[ \mathbf{M} = \begin{pmatrix} v_{si} & n \sin \alpha & -\partial_x n \cos \alpha \\ 0 & n v_{si} & n(\sin \alpha - \partial_x v_{||i} \cos \alpha) \\ \mu \sin \alpha T_e & 0 & -\mu n \sin \alpha \end{pmatrix} \]
Derivation of the magnetic presheath entrance condition

- In the collisional presheath, $\mathbf{M} \vec{X} = \vec{S}$, gradients are small and due to the presence of the sources.
Derivation of the magnetic presheath entrance condition

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- At the magnetic presheath entrance, gradients become large, $\partial_s \sim 1$, and can be sustained without sources: $\mathbf{M}\vec{X} \sim 0$
Derivation of the magnetic presheath entrance condition

▶ In the collisional presheath, $M\vec{X} = \vec{S}$, gradients are small and due to the presence of the sources

▶ At the magnetic presheath entrance, gradients become large, $\partial_s \sim 1$, and can be sustained without sources: $M\vec{X} \sim 0$

▶ Thus $\text{det}(M) = 0$ at the magnetic presheath entrance:
Derivation of the magnetic presheath entrance condition

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- At the magnetic presheath entrance, gradients become large, $\partial_s \sim 1$, and can be sustained without sources: $\mathbf{M}\mathbf{X} \sim 0$.

- Thus $\text{det} (\mathbf{M}) = 0$ at the magnetic presheath entrance:

$$v_{si} = c_s \sin \alpha \left( \frac{\rho_s}{2 \tan \alpha} \frac{\partial_x n}{n} \pm \sqrt{1 + \left( \frac{\rho_s}{2 \tan \alpha} \frac{\partial_x n}{n} \right)^2 - \frac{\rho_s}{2 \tan \alpha} \frac{\partial_x T_e}{T_e}} \right)$$

$$\sim c_s \sin \alpha \left( 1 + \epsilon/\alpha \right) \quad \epsilon = \rho_s/L_x$$
Derivation of the magnetic presheath entrance condition

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\[
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\]

\[
\sim c_s \sin \alpha \left( 1 + \frac{\epsilon}{\alpha} \right) \quad \epsilon = \frac{\rho_s}{L_x}
\]

- $\lim_{\alpha \to \pi/2} \nu_{si} = c_s$ (Bohm).
Derivation of the magnetic presheath entrance condition

- In the collisional presheath, $\mathbf{M}\vec{X} = \vec{S}$, gradients are small and due to the presence of the sources.

- At the magnetic presheath entrance, gradients become large, $\partial_s \sim 1$, and can be sustained without sources: $\mathbf{M}\vec{X} \approx 0$.

- Thus $\text{det}(\mathbf{M}) = 0$ at the magnetic presheath entrance:
  
  $$v_{si} = c_s \sin \alpha \left( \frac{\rho_s}{\tan \alpha} \frac{\partial_x n}{n} \pm \sqrt{1 + \left( \frac{\rho_s}{2 \tan \alpha} \frac{\partial_x n}{n} \right)^2 - \frac{\rho_s}{2 \tan \alpha} \frac{\partial_x T_e}{T_e}} \right)$$

  $$\sim c_s \sin \alpha \left( 1 + \frac{\epsilon}{\alpha} \right), \quad \epsilon = \frac{\rho_s}{L_x}$$

- $\lim_{\alpha \to \pi/2} v_{si} = c_s$ (Bohm), $\lim_{\epsilon \to 0} v_{si} = c_s \sin \alpha$ (Bohm-Chodura).
Summary of the BC

\[ v_{\parallel i} = c_s \left[ 1 + \theta_n - \frac{1}{2} \theta T_e - \frac{2\phi}{T_e} \theta \phi \right] \]

\[ v_{\parallel e} = c_s \left[ \exp(\Lambda - \eta) - \frac{2\phi}{T_e} \theta \phi + 2(\theta_n + \theta T_e) \right] \]

\[ \frac{\partial \phi}{\partial s} = -c_s \left[ 1 + \theta_n + \frac{1}{2} \theta T_e \right] \frac{\partial v_{\parallel i}}{\partial s} \]

\[ \frac{\partial n}{\partial s} = -\frac{n}{c_s} \left[ 1 + \theta_n + \frac{1}{2} \theta T_e \right] \frac{\partial v_{\parallel i}}{\partial s} \]

\[ \frac{\partial T_e}{\partial s} \simeq 0 \]

\[ \omega = -\cos^2 \alpha \left[ (1 + \theta T_e) \left( \frac{\partial v_{\parallel i}}{\partial s} \right)^2 + c_s (1 + \theta_n + \theta T_e/2) \frac{\partial^2 v_{\parallel i}}{\partial s^2} \right] \]

where \( \theta_A = \frac{\rho_s}{2 \tan \alpha} \frac{\partial x A}{A} \), and \( \eta = e(\phi_{mpe} - \phi_{wall})/T_e \). [Loizu et al PoP 2012]
The GBS code, a tool to simulate open field line turbulence

- Developed by steps of increasing complexity
- Drift-reduced Braginskii equations
- Global, 3D, Flux-driven, Full-$n$
Examples of 3D simulations

\[ n \]
\[ T_e \]
\[ \phi \]
\[ v_{||i} \]
\[ v_{||e} \]
\[ \omega \]
Which mechanism sets the value of $\phi$?
Which mechanism sets the value of $\phi$?

- Electric fields
  - determine mean plasma flows
  - regulate turbulence
Which mechanism sets the value of $\phi$?

- Electric fields
  - determine mean plasma flows
  - regulate turbulence

- Typical relation used: $\phi \sim 3T_e \implies E_r \sim -3\partial_r T_e$
Which mechanism sets the value of $\phi$?

- Electric fields
  - determine mean plasma flows
  - regulate turbulence

- Typical relation used: $\phi \sim 3T_e \implies E_r \sim -3\partial_r T_e$

- Generalized Ohm’s law:

$$m_e n \frac{dV_{||}}{dt} = en\nabla_{||} \phi - \nabla_{||} p_e - 0.71n\nabla_{||} T_e + en\nu j_{||}$$

$\Lambda = \log(\sqrt{m_i/(2\pi m_e)}) \approx 3$ for hydrogen.
Which mechanism sets the value of $\phi$?

- Electric fields
  - determine mean plasma flows
  - regulate turbulence
- Typical relation used: $\phi \sim 3T_e \implies E_r \sim -3\partial_r T_e$
- Generalized Ohm’s law:
  \[
  m_e n \frac{dV_e}{dt} = en\nabla||\phi - \nabla||p_e - 0.71n\nabla||T_e + en\nu j||
  \]
  - Time-average, integrate along the field line
  - No average current to the walls $j_{wall} = 0 \implies \phi^\pm \sim \Lambda T_e^\pm$
  - $\Lambda = \log \left( \sqrt{m_i/(2\pi m_e)} \right) \approx 3$ for hydrogen
Analytical relation $\phi = \phi(n, T_e)$

\[
e^{-\phi(z)} = \frac{1}{2} \Lambda(T_e^+ + T_e^-) + 1.71 \left[ \bar{T}_e(z) - \frac{1}{2}(T_e^+ + T_e^-) \right] + \delta_0 \left[ \bar{n}(z) - \frac{1}{2}(n^+ + n^-) \right]
\]
Analytical relation $\phi = \phi(n, T_e)$

$$e\bar{\phi}(z) = \frac{1}{2}\Lambda(T_e^+ + T_e^-) + 1.71 \left[ \bar{T}_e(z) - \frac{1}{2}(T_e^+ + T_e^-) \right] + \delta_0 \left[ \bar{n}(z) - \frac{1}{2}(n^+ + n^-) \right]$$

- **Limit of** $T_e(z) \equiv T_0$ and $n(z) \equiv n_0$

  $$e\bar{\phi} = \Lambda T_0 \quad \text{(}\phi \text{ set by the sheath)}$$
Analytical relation $\phi = \phi(n, T_e)$

$$e\bar{\phi}(z) = \frac{1}{2}\Lambda(T_e^+ + T_e^-) + 1.71\left[\bar{T}_e(z) - \frac{1}{2}(T_e^+ + T_e^-)\right] + \delta_0\left[\bar{n}(z) - \frac{1}{2}(n^+ + n^-)\right]$$

- **Limit of $T_e(z) \equiv T_0$ and $n(z) \equiv n_0$**
  $$e\bar{\phi} = \Lambda T_0 \quad (\phi \text{ set by the sheath})$$

- **Limit of $T_e^\pm = n^\pm = 0$ and $T_e/n \sim \text{const}$**
  $$e\bar{\phi}(z) = 2.71 \bar{T}_e(z) \quad (\phi \text{ set by adiabaticity})$$
Analytical relation $\phi = \phi(n, T_e)$

$$e\phi(z) = \frac{1}{2} \Lambda(T^+ + T^-) + 1.71 \left[ \bar{T}_e(z) - \frac{1}{2}(T^+ + T^-) \right] + \delta_0 \left[ \bar{n}(z) - \frac{1}{2}(n^+ + n^-) \right]$$

- Limit of $T_e(z) \equiv T_0$ and $n(z) \equiv n_0$
  $$e\phi = \Lambda T_0 \quad (\phi \text{ set by the sheath})$$

- Limit of $T_e^{\pm} = n^{\pm} = 0$ and $T_e/n \sim const$
  $$e\phi(z) = 2.71 \bar{T}_e(z) \quad (\phi \text{ set by adiabaticity})$$

▶ Conclusion: It depends on the operational regime!
SOL simulations agree with the analytical prediction

\[
\Lambda = 3
\]

\[
\bar{\Phi}_{sim}
\]

\[
\bar{\Phi}_{th}
\]

\[
\Lambda T_0
\]
SOL simulations agree with the analytical prediction

\[ \Lambda = 3 \]  
\[ \Lambda = 6 \]

\[ \bar{\phi}_{sim} \]  
\[ \bar{\phi}_{th} \]  
\[ \Lambda T_0 \]
What is the origin of intrinsic toroidal rotation in the SOL?

- There is a finite volume-averaged toroidal rotation ($\sim 0.3c_s$)
A theory of SOL intrinsic rotation

- Conservation of parallel momentum:

\[ \partial_t v_i + v_i \nabla ||v_i|| + (v_i E \times B) \cdot ||v_i|| + \frac{1}{m_i} \nabla ||p|| = 0 \]

Time-average

Estimate turbulent momentum flux

\[ \Gamma_x \sim \langle \tilde{v}_i \partial_t \tilde{\phi} \partial_y \rangle \sim -D_I \partial_x \bar{v}_i \partial_x^2 \]
A theory of SOL intrinsic rotation

- Conservation of parallel momentum:

\[
\frac{\partial v_{||i}}{\partial t} + v_{||i} \nabla_{||} v_{||i} + (v_{E \times B} \cdot \nabla) v_{||i} + \frac{1}{m_i n} \nabla_{||} p = 0
\]
A theory of SOL intrinsic rotation

- Conservation of parallel momentum:

\[
\frac{\partial v_{||i}}{\partial t} + v_{||i} \nabla_{||} v_{||i} + (v_E \times B \cdot \nabla) v_{||i} + \frac{1}{m_i n} \nabla_{||} p = 0
\]

- Time-average

- Estimate turbulent momentum flux

\[
\Gamma_x \sim \langle \tilde{v}_{||i} \frac{\partial \tilde{\phi}}{\partial y} \rangle_t \sim -D_I \frac{\partial \tilde{v}_{||i}}{\partial x^2}
\]
2D equation for the toroidal rotation

\[-D_I \frac{\partial^2 \tilde{v}_{||i}}{\partial x^2} + v_I \frac{\partial \tilde{v}_{||i}}{\partial x} + \frac{1}{B_\varphi} \frac{\partial \phi}{\partial x} \frac{\partial \tilde{v}_{||i}}{\partial y} + \alpha \tilde{v}_{||i} \frac{\partial \tilde{v}_{||i}}{\partial y} + \frac{\alpha}{m_i \tilde{n}} \frac{\partial \tilde{p}}{\partial y} = 0\]

**Sheath** is crucial to determine

- Radial electric field
- Boundary conditions

**Outcome** : analytical solution \( \tilde{v}_{||i}(x, y) \)
GBS simulations agree with the theory

Simulation
GBS simulations agree with the theory
Analytical solution explains observed trends

\[ M(x, 0) = M_s e^{-x/l} + (M_{sh} - M_a) \left( 1 - e^{-x/l} \right) \]
Analytical solution explains observed trends

\[ M(x, 0) = M_s e^{-x/l} + (M_{sh} - M_a) \left(1 - e^{-x/l}\right) \]
Analytical solution explains observed trends

\[ M(x,0) = M_s e^{-x/l} + \left( M_{\text{sh}} - M_a \right) \left( 1 - e^{-x/l} \right) \]

- \( M_{\text{sh}} = \Lambda \rho_s / (2 \alpha L_T) \sim 0.5 \)
- Co-current rotation
- Rice scaling \( V_\varphi \sim T_e / I_p \)
Analytical solution explains observed trends

\[ M(x, 0) = M_s \frac{e^{-x/l}}{\text{separatrix}} + \left( M_{\text{sh}} - M_a \right) \left( 1 - e^{-x/l} \right) \]

- \( M_{\text{sh}} = \Lambda \rho_s / (2 \alpha L_T) \sim 0.5 \)
- Co-current rotation
- Rice scaling \( V_\varphi \sim T_e / I_p \)
- \( M_a \sim (n^+ - n^-) / n_0 \)
- Co/Counter-current rotation
- Reverses with \( B \) and topology
The SOL width depends on the limiter position

\[ \langle p_e \rangle_t \]

\[ \langle p_e \rangle_t \]

\[ \langle p_e \rangle_t \]

\[ \langle p_e \rangle_t \]
Summary of the results presented

- Provided **BC for all fluid fields**, thus supplying the sheath physics to drift-fluid codes
- Implemented BC in the turbulence code **GBS**
- Investigated **sheath effects** on plasma turbulence and flows:
  - **Electrostatic potential** in open field lines results from the combined effect of the sheath physics and the electron adiabaticity
  - **Scrape-off layer intrinsic toroidal rotation** driven by the sheath and transported due to the turbulence
  - **Scrape-off layer width** strongly depends on the limiter position
The role of the sheath in magnetized plasma fluid turbulence
Extra slides: Why global? why full-n?

- **Global vs Local?**
  - Flux-tube only valid if $k_x L_{eq} \gg 1$ but $k_x L_{eq} \sim \sqrt{k_y L_{eq}} \gtrsim 1$

- **Full-n vs Delta-n?**
  - In the SOL $\delta n/n \sim 1$ so cannot separate $\bar{n}$ and $\tilde{n}$

- **Flux-driven vs Gradient-driven?**
  - Need to evolve the equilibrium profile (e.g. mode saturation)
Extra slides : Effect of the source details?

- Details of the radial shape of the source not important
- Poloidal shape of the source may be important (asymmetries, recycling) - to be studied
- Effect of source strength being explored : what do we expect?
  - If $\gamma_{\text{lin}} > V_{E\times B}'$ : no difference i.e. $L_p \sim \rho_s$
  - If source strong to make $\gamma_{\text{lin}} \sim V_{E\times B}'$ : turbulence suppression?

[Ricci et al PRL 2007]
Extra slides: How about kinetic effects?

- SOL is fairly collisional:
  - $\lambda_{ei} \ll L_{||}$
  - $\nu^* > 1$
  - $\nu_{ei} > \gamma L$

- Kinetic effects may be considered as a higher order correction
  - e.g. Landau damping in Ohm’s law
Extra slides: Importance of neutrals?

- For the magnetic presheath BC: inertia $\gg$ i-n collisions?
  - Yes, as long as: $\omega_{ci} \sin \alpha \gg \nu_{in}$

- For the SOL equilibrium: ionization? recombination?
  - High recycling can affect the $V_{||i}$ profile - to be studied
  - Intrinsic rotation theory may breakdown in detached regime

- For the SOL fluctuations: effect on the turbulence? blobs?
  - Nature of turbulence unchanged, but can add some damping
  - Cross-field currents due to i-n collisions can affect blobs
Extra slides: Is the sheath resistive? Ryutov’s model?

- Misconception about the concept of "sheath resistivity":
  - The sheath is essentially collisionless, $\lambda_D \ll \rho_s \ll \lambda_{ie}$
  - How to define an effective resistivity if $j_{||} \neq j_{||}(E_{||})$?

- Ryutov model for sheath resistivity:
  - Linearized Ohm's law written as $\nabla_{||} \tilde{\phi} = \nu \tilde{j}_{||} \sim \nu \tilde{\phi}$
Extra slides: Parallel vs Toroidal rotation?

\[ V_\varphi = V_\parallel \cos \alpha + V_d \sin \alpha \]

\[ V_d = \frac{E_x \times B}{B^2} - \frac{(\nabla p_i)_x \times B}{enB^2} \]

\[ V_d/c_s \sim \rho_s/L_\phi \ll 1 \]
Extra slides: Ion temperature effects?

- For the magnetic presheath:
  - FLR effects on wall absorption can affect BC - to be studied

- For the SOL equilibrium:
  - Finite $T_i$ introduces Pfirsch-Schluter flows

- For the SOL fluctuations: effect on turbulence?
  - RBM physics similar with ion temperature
  - ITG physics appears, but not critical for SOL
Extra slides: Electromagnetic effects?

- GBS has EM effects - ideal ballooning modes present
- GBS could be used to get a "wall BC" for MHD codes
- Magnetic presheath BC are electrostatic - to be extended

[Ricci et al PPCF 2012, Halpern et al PoP 2013]