The role of the sheath in magnetized plasma fluid turbulence

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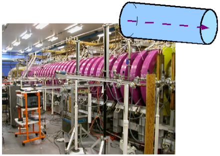
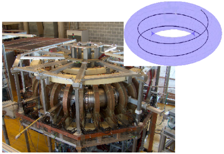
Turbulence in open field lines is an outstanding issue

in basic plasma devices...



LAPD, USA



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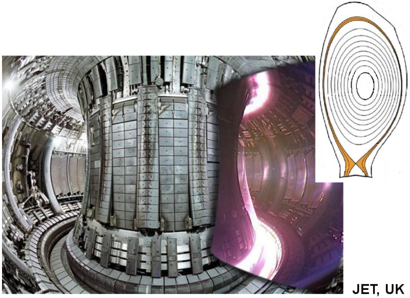
in fusion devices...



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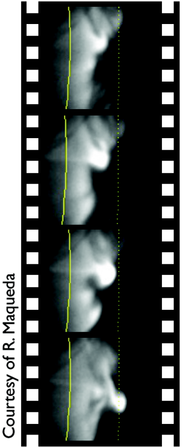
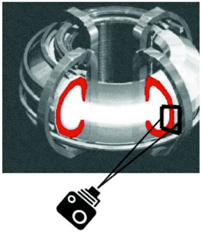
Properties of open field line plasma turbulence





- $L_{fluc} \sim L_{eq}$
- $n_{fluc} \sim n_{eq}$
- 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 $n_e \simeq n_i$ is assumed
  - A drift ordering is usually adopted, $d/dt \ll \omega_{ci}$, leading to the ion drift approximation :

$$\mathbf{v}_{\perp i} = \mathbf{v}_{ExB} + \frac{\mathbf{b}}{\omega_{ci}} \times \frac{d^0}{dt}\mathbf{v}_{ExB}$$

Magnetized plasma turbulence via drift-fluid models

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

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

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 :
$$\frac{dT_e}{dt} = \frac{4}{3}\frac{1}{eB}\left[\frac{7}{2}T_e\hat{C}(T_e) + \frac{T_e^2}{n}\hat{C}(n) - eT_e\hat{C}(\phi)\right] + \frac{2}{3}\frac{T_e}{en}0.71\nabla_{||}j_{||} - \frac{2}{3}T_e\nabla_{||}V_{||e} - V_{||e}\nabla_{||}T_e + S_T$$

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

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?

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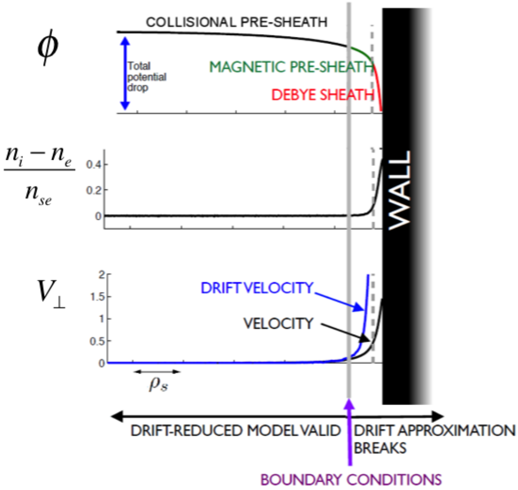
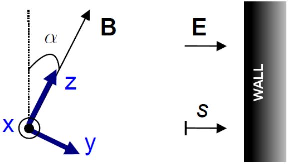


Derivation of the magnetic presheath entrance condition



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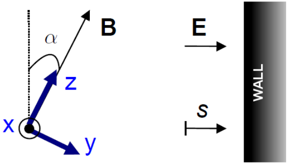

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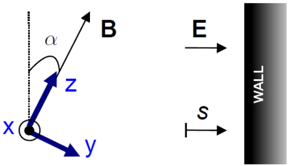

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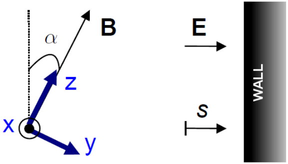

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- Isothermal electrons $\partial_s T_e = 0$, $T_i \ll T_e$

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Ion parallel momentum	$nv_{si}\partial_s v_{\|\|i} + n(\sin\alpha - \partial_x v_{\|\|i}\cos\alpha)\partial_s\phi = S_{\|\|mi}$
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$$\mathbf{M} = \begin{pmatrix} v_{si} & n\sin\alpha & -\partial_x n\cos\alpha \\ 0 & nv_{si} & n(\sin\alpha - \partial_x v_{||i}\cos\alpha) \\ \mu\sin\alpha T_e & 0 & -\mu n\sin\alpha \end{pmatrix}$$

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

Summary of the BC

$$v_{||i} = c_s \left[1 + \theta_n - \frac{1}{2}\theta_{T_e} - \frac{2\phi}{T_e}\theta_\phi \right]$$

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

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

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

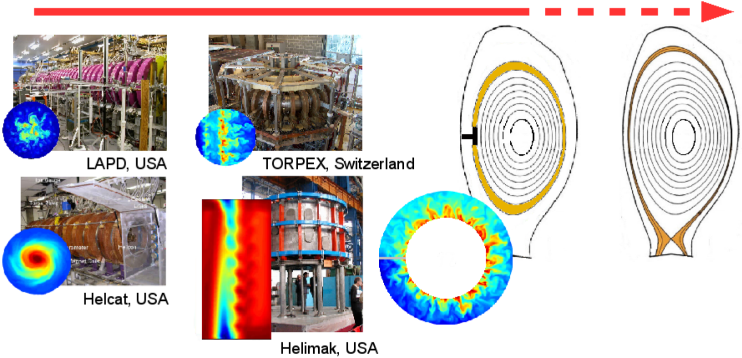
$$\frac{\partial T_e}{\partial s} \simeq 0$$

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

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

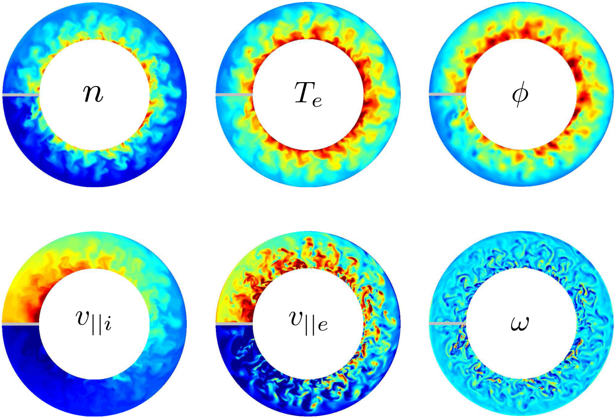
- Developed by steps of increasing complexity

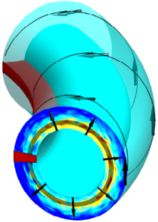


- Drift-reduced Braginskii equations
- Global, 3D, Flux-driven, Full-n

[Ricci et al PPCF 2012]

Examples of 3D simulations





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  - Time-average, integrate along the field line
  - No average current to the walls $j_{wall} = 0 \implies \phi^{\pm} \simeq \Lambda T_e^{\pm}$
  - $\Lambda = \log\left(\sqrt{m_i/(2\pi m_e)}\right) \approx 3$ for hydrogen

Analytical relation $\phi = \phi(n, T_e)$

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

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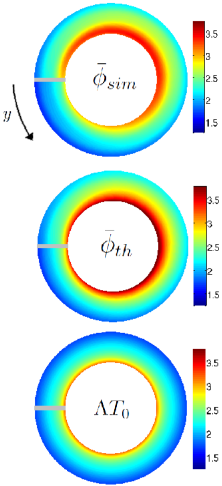
- **Conclusion : It depends on the operational regime !**

SOL simulations agree with the analytical prediction

$\Lambda = 3$



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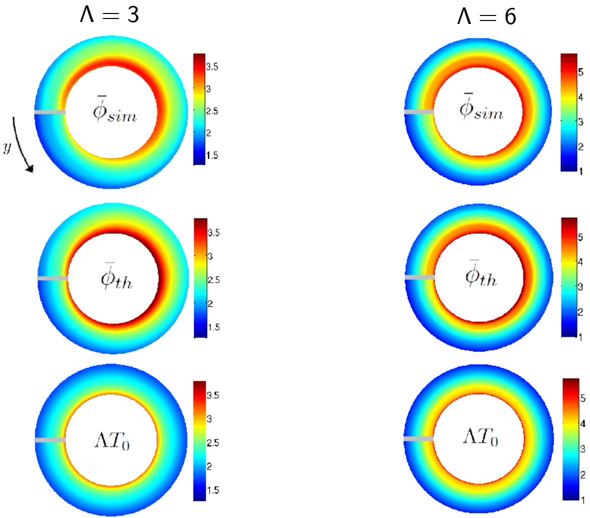
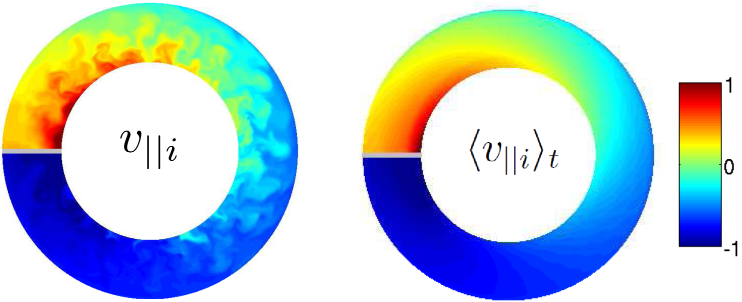


What is the origin of intrinsic toroidal rotation in the SOL ?



Snapshot Time-average

- There is a finite volume-averaged toroidal rotation ($\sim 0.3c_s$)

A theory of SOL intrinsic rotation

- Conservation of parallel momentum :

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$$\frac{\partial v_{||i}}{\partial t} + v_{||i}\nabla_{||}v_{||i} + (\mathbf{v}_{E\times B}\cdot\nabla)v_{||i} + \frac{1}{m_i n}\nabla_{||}p = 0$$

A theory of SOL intrinsic rotation

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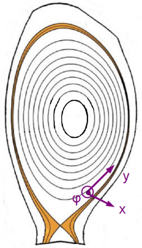
$$\frac{\partial v_{||i}}{\partial t} + v_{||i}\nabla_{||}v_{||i} + (\mathbf{v}_{E\times B}\cdot\nabla)v_{||i} + \frac{1}{m_i n}\nabla_{||}p = 0$$

  - Time-average
  - Estimate turbulent momentum flux

$$\Gamma_x \sim \langle \tilde{v}_{||i}\frac{\partial\tilde{\phi}}{\partial y}\rangle_t \sim -D_I\frac{\partial \bar{v}_{||i}}{\partial x^2}$$



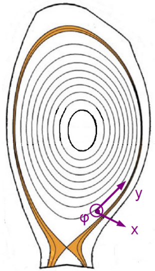
2D equation for the toroidal rotation

$$\underbrace{-D_l \frac{\partial^2 \bar{v}_{||i}}{\partial x^2} + v_l \frac{\partial \bar{v}_{||i}}{\partial x}}_{radial} + \underbrace{\frac{1}{B_\varphi} \frac{\partial \bar{\phi}}{\partial x} \frac{\partial \bar{v}_{||i}}{\partial y}}_{poloidal} + \underbrace{\alpha \bar{v}_{||i} \frac{\partial \bar{v}_{||i}}{\partial y}}_{parallel} + \underbrace{\frac{\alpha}{m_i \bar{n}} \frac{\partial \bar{p}}{\partial y}}_{generation} = 0$$

Sheath is crucial to determine

- Radial electric field
- Boundary conditions

Outcome : analytical solution $\bar{v}_{||i}(x, y)$



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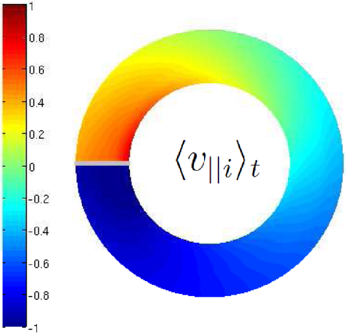

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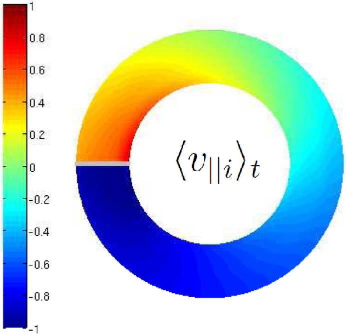
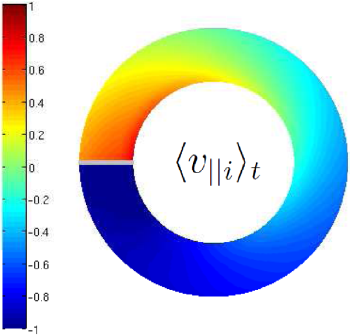


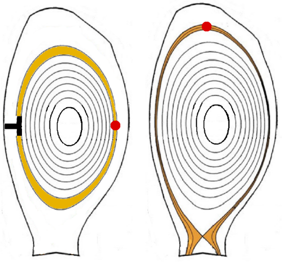
Simulation



Theory

Analytical solution explains observed trends

$$M(x,0) = \underbrace{M_s}_{separatrix} e^{-x/l} + \left(\underbrace{M_{sh}}_{sheath} - \underbrace{M_a}_{asymmetry} \right) \left(1 - e^{-x/l}\right)$$



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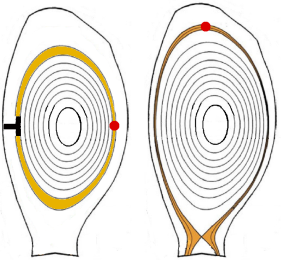

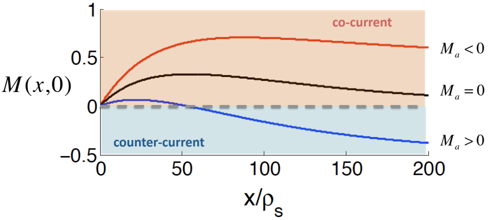

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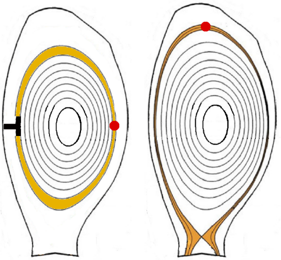
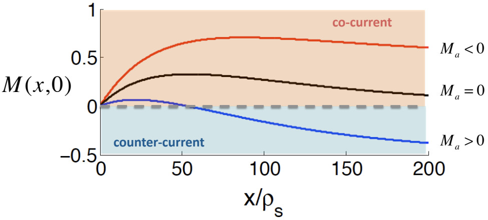
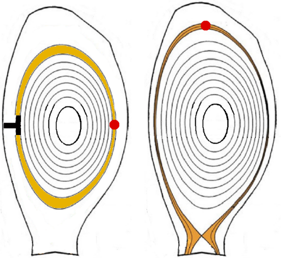


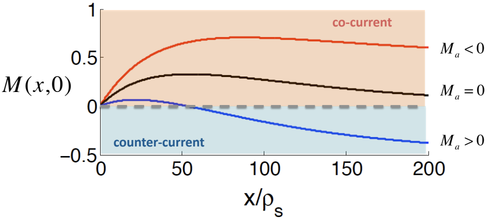


- $M_{sh} = \Lambda\rho_s/(2\alpha L_T) \sim 0.5$
- Co-current rotation
- Rice scaling $V_\varphi \sim T_e/I_p$

Analytical solution explains observed trends

$$M(x,0) = \underbrace{M_s}_{separatrix} e^{-x/l} + (\underbrace{M_{sh}}_{sheath} - \underbrace{M_a}_{asymmetry}) \left(1 - e^{-x/l}\right)$$

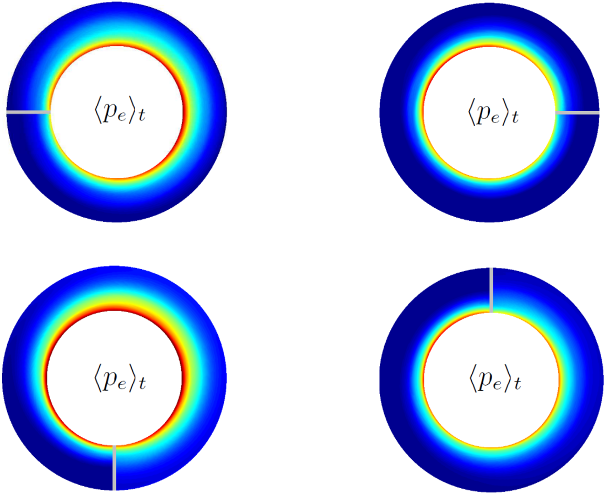




- $M_{sh} = \Lambda\rho_s/(2\alpha L_T) \sim 0.5$
- Co-current rotation
- Rice scaling $V_\varphi \sim T_e/I_p$

- $M_a \sim (n^+ - n^-)/n_0$
- Co/Counter-current rotation
- Reverses with **B** and topology

The SOL width depends on the limiter position



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

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 $\gamma_{lin} > V'_{ExB}$: no difference i.e. $L_p \sim \rho_s$
  - If source strong to make $\gamma_{lin} \sim V'_{ExB}$: 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 ?

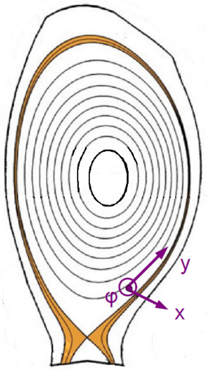
- For the magnetic presheath BC : inertia $\gg$ i-n collisions ?
  - Yes, as long as : $\omega_{ci} \sin\alpha \gg \nu_{in}$
- For the SOL equilibrium : ionization ? recombination ?
  - High recycling can affect the $V_{||i}$ profile - to be studied
  - Intrinsic rotation theory may breakdown in detached 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 ?

- $V_\varphi = V_{||} \cos\alpha + V_d \sin\alpha$
- $V_d = \frac{\mathbf{E}_x \times \mathbf{B}}{B^2} - \frac{(\nabla p_i)_x \times \mathbf{B}}{enB^2}$
- $V_d / c_s \sim \rho_s / L_\phi \ll 1$



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]