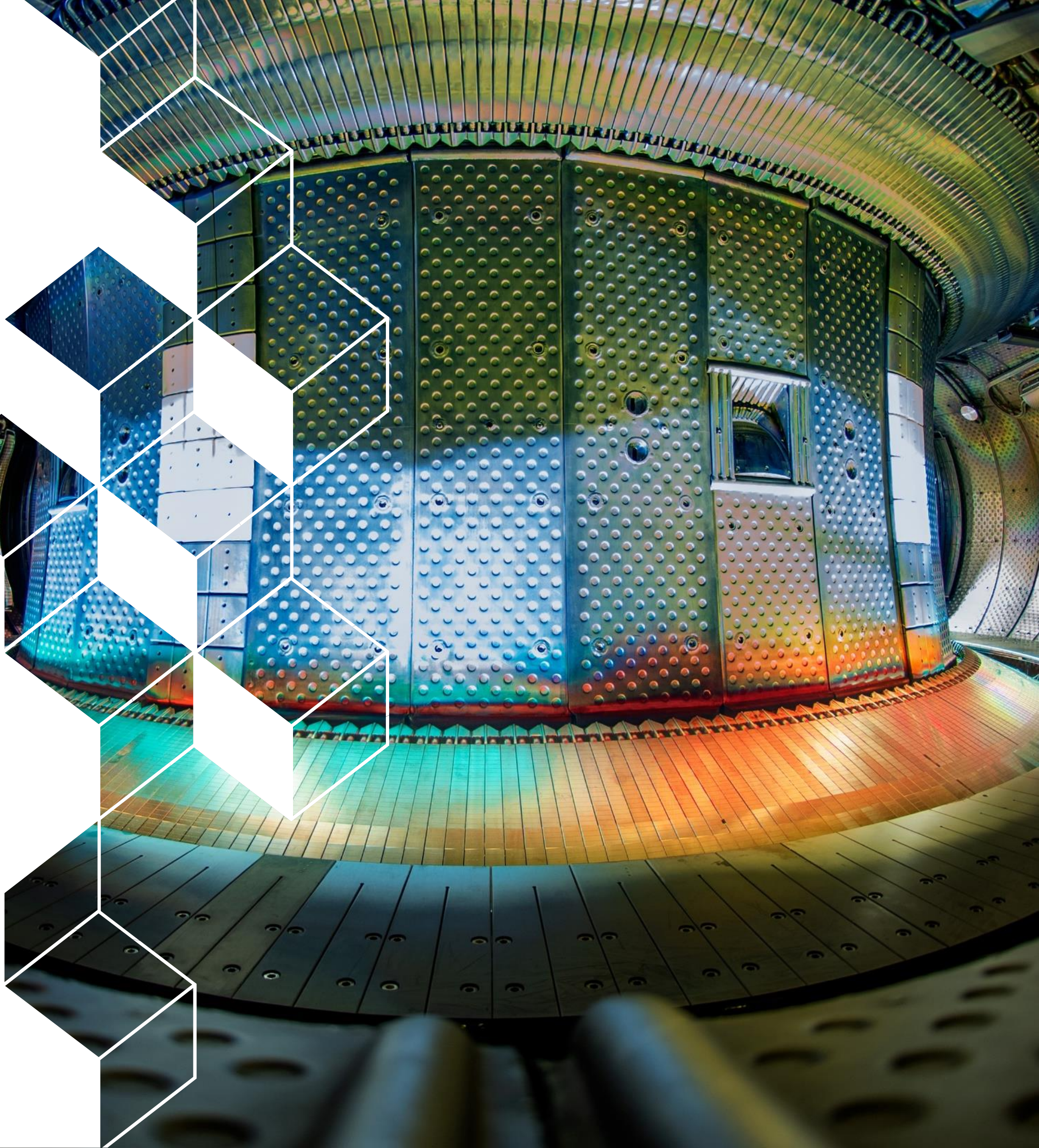
Gaine et modélisation fluide du plasma de bord en fusion magnétique: besoins, questions ouvertes…

P. Tamain pour l ’équipe SOLEDGE3X*

* H. Bufferand, G. Ciraolo, J. Denis, R. Düll, Y. Marandet, B. McGibbon, V. Quadri, N. Rivals, E. Serre, S. Suresh-Kumar, N. Varadarajan, H. Yang

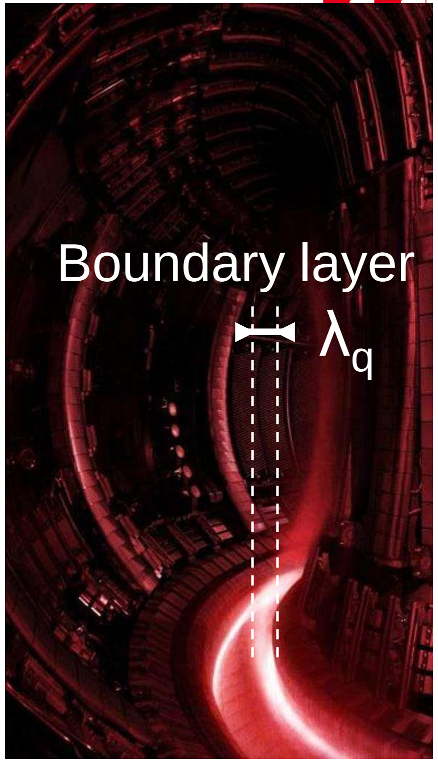


The heat exhaust issue in a nutshell

- In magnetic fusion devices (e.g. tokamaks), a large amount of power is convected by the plasma to the wall of the machine
- Anisotropy of magnetized plasma => **power deposited on very thin layer on the wall**
- E.g., in ITER: unacceptable heat loads!

$$= \overset{50\ MW}{P_{heat}} + \overset{100\ MW}{0.2\,P_{fus}} - \overset{50\ MW}{P_{rad}} \approx 100MW$$

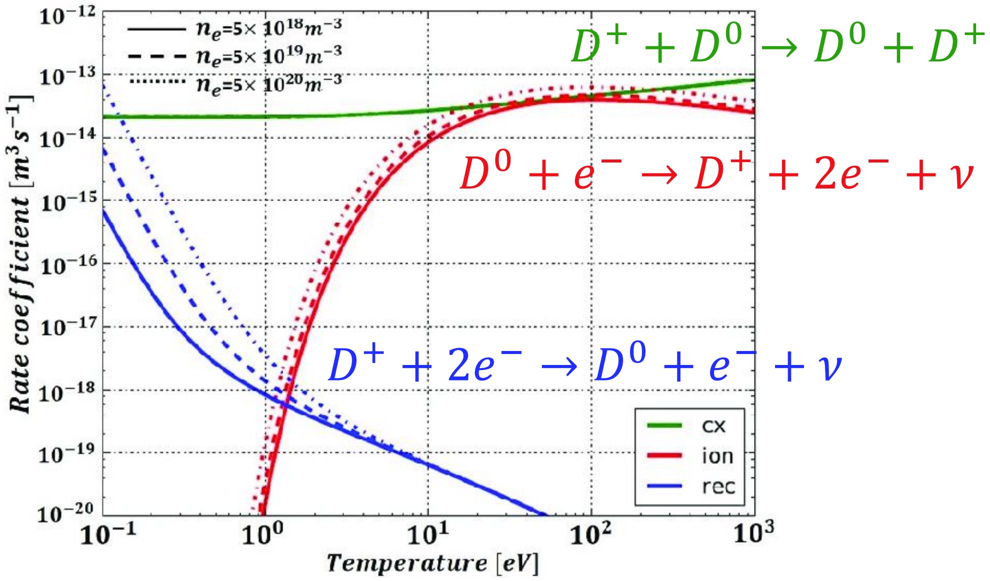
$$P_{wall} = \frac{P_{plasma}}{4\pi \underset{6\ m}{R}\, \underset{\sim 10}{f_{geo}}\, \underset{\sim 1\ mm}{\lambda_q}} \boldsymbol{\sim 130\ MW.m^{-2}} \gg \boldsymbol{P_{max}}$$




Molten tungsten tile Alcator C-mod [B. Lipschultz et al 2012 Nucl. Fusion 52 123002]

Plasma neutral interactions in the divertor

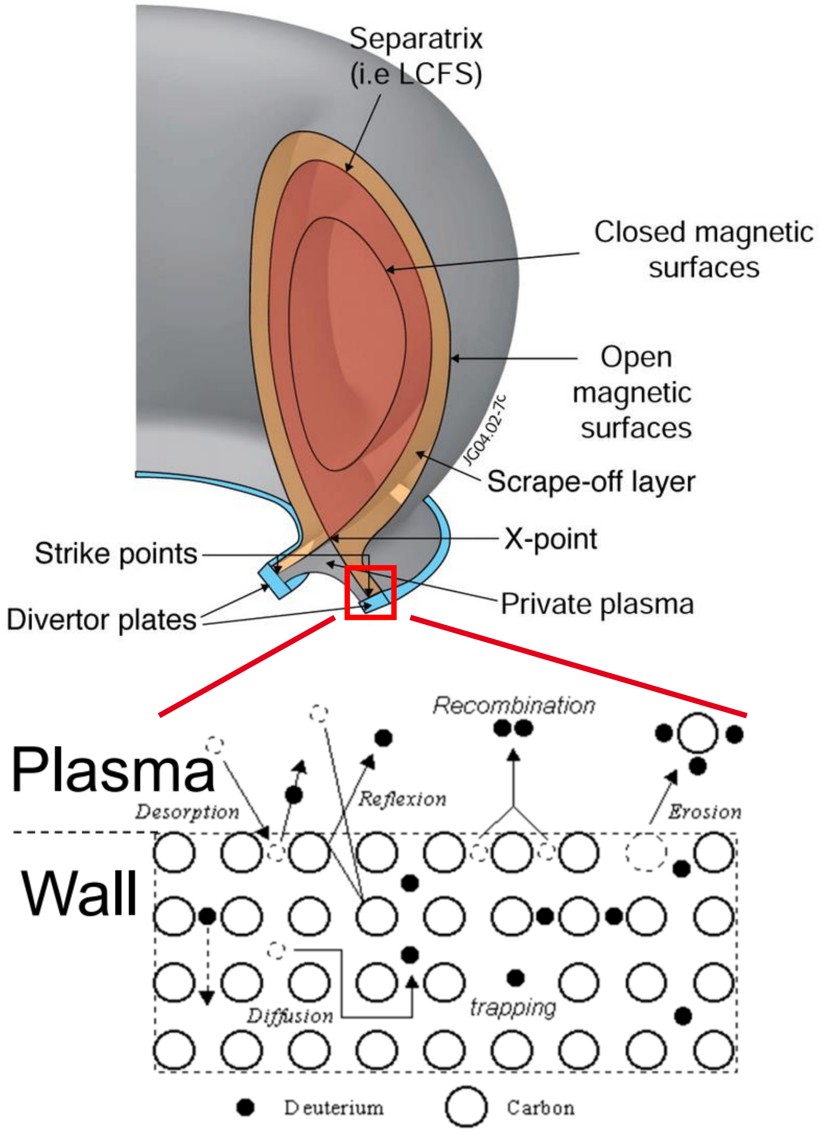
- **Divertor recycling**: ions impact wall re-enter the plasma after recombining at the wall
  - on metallic surfaces, $\mathbf{R}_n \approx \mathbf{100\%}$
  - re-enter as atoms or molecules
- Zoo of **plasma-neutrals interactions**
  - Transfer of **plasma momentum and energy to non-confined particles**



$$D^+ + D^0 \rightarrow D^0 + D^+$$

$$D^0 + e^- \rightarrow D^+ + 2e^- + \nu$$

$$D^+ + 2e^- \rightarrow D^0 + e^- + \nu$$

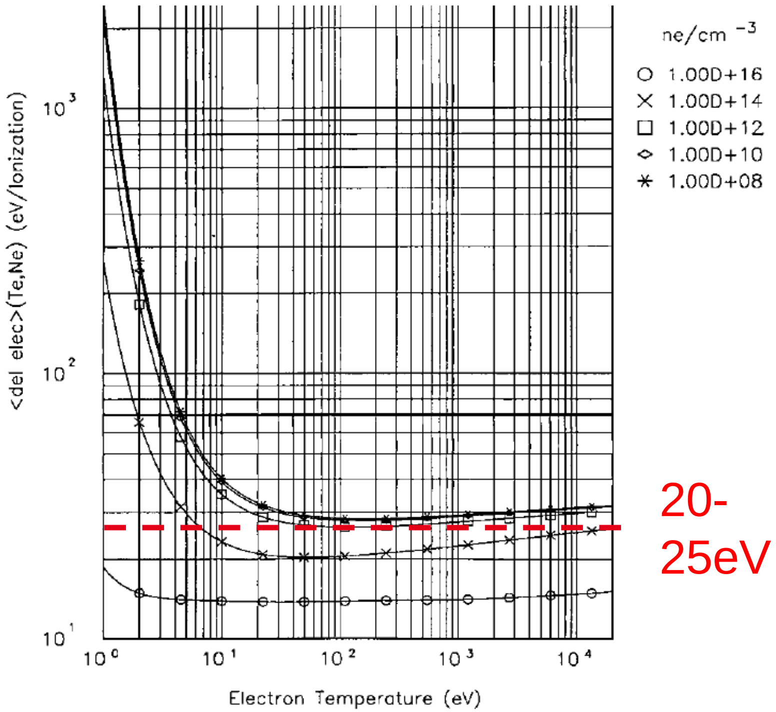


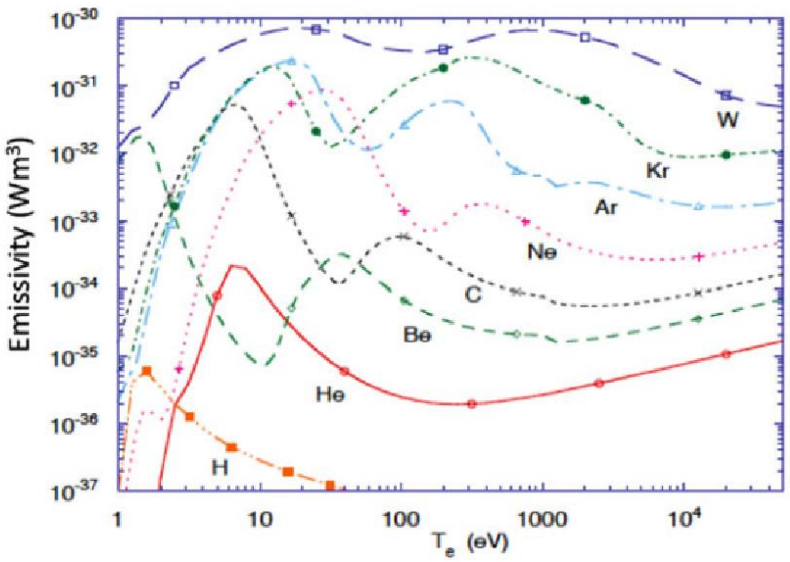
Detachment as a heat exhaust strategy

- 2-point model: $$\Gamma_t = \frac{n_u^2}{q_\parallel}\left(\frac{7}{2}\frac{q_\parallel L}{\kappa_{0e}}\right)^{4/7}\frac{\gamma e^2}{2m_i}$$

  [Stangeby, The Plasma Boundary of Magnetic Fusion Devices]

  - At least 20eV lost per recycling particle => **drop of temperature and heat flux**
  - Can be amplified by **seeding mid-heavy impurities** (e.g., N or Ne)

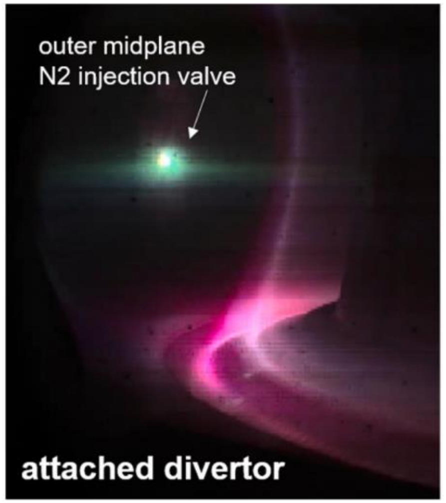




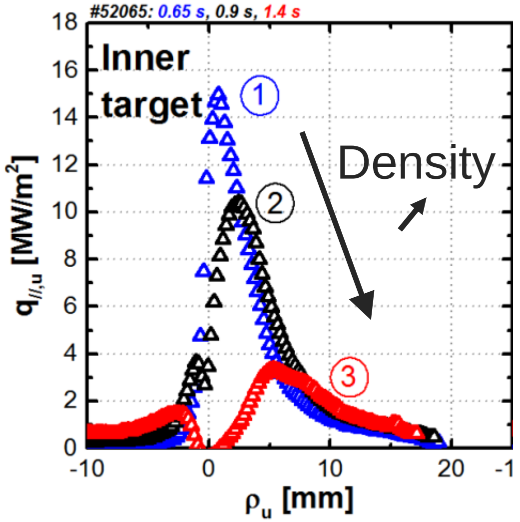
- High enough density ⇒ plasma momentum and energy entirely transferred to photons and neutrals
  - Below 1eV: recombination before the wall => **detachment**

Detachment in practise

- In experiments:

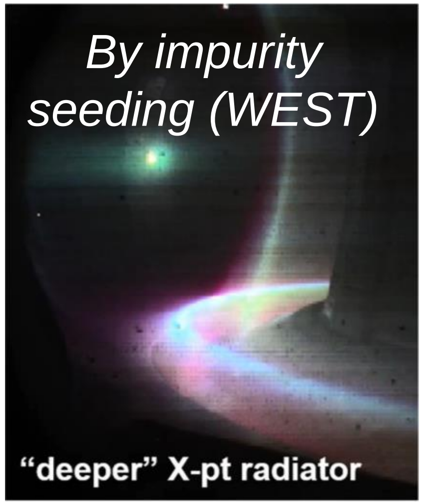


By density increase (TCV)



[Maurizio, EPS plasma 2017]

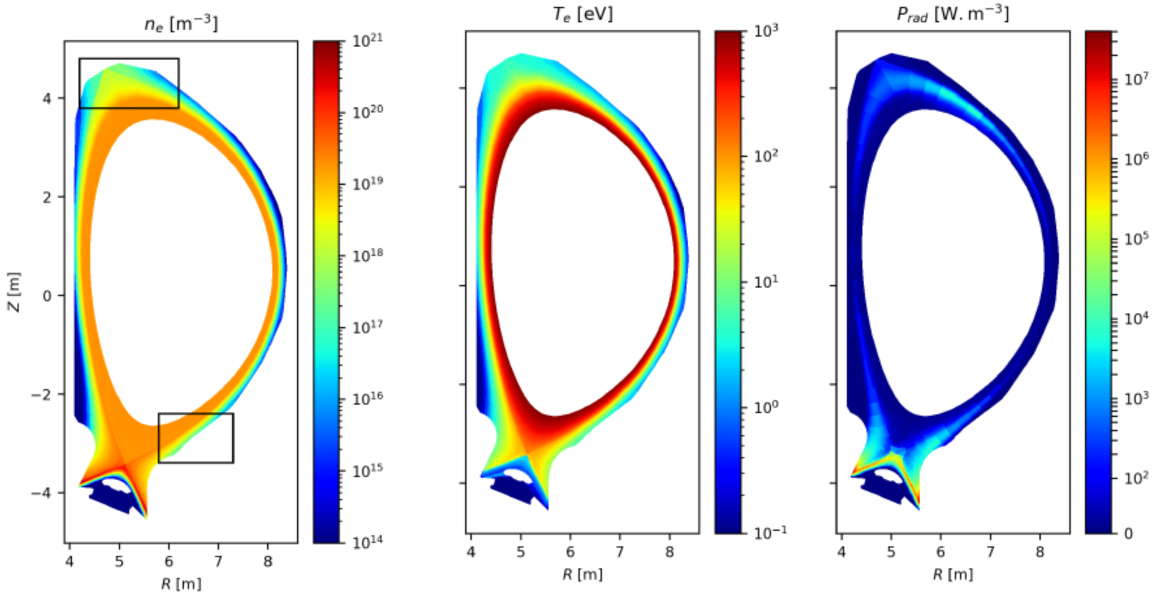
$$n \sim 10^{19} - 10^{20} m^{-3}$$
$$T_e \sim T_i \sim 0.1 \; - 10 eV$$
$$B \sim 1 - 8T$$

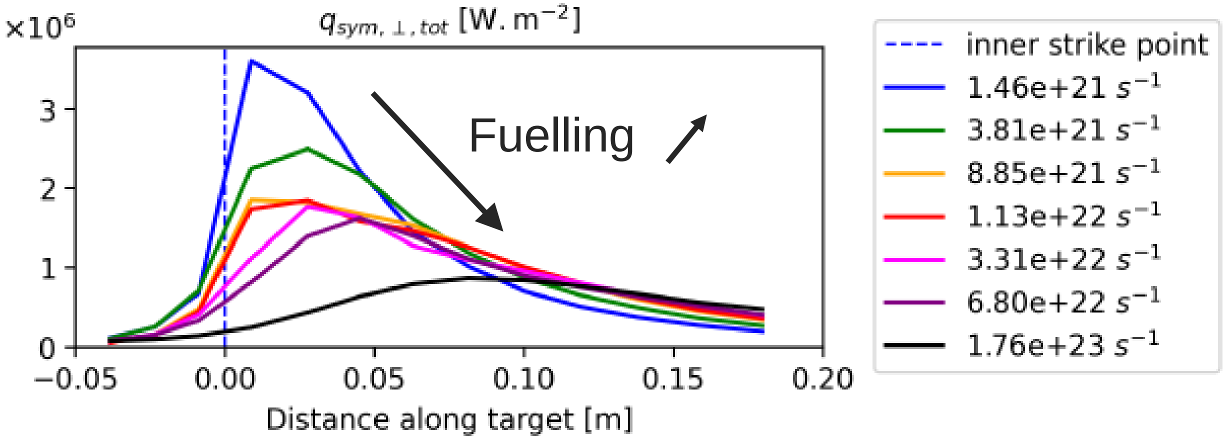


By impurity seeding (WEST)

[Rivals, NME 2024]

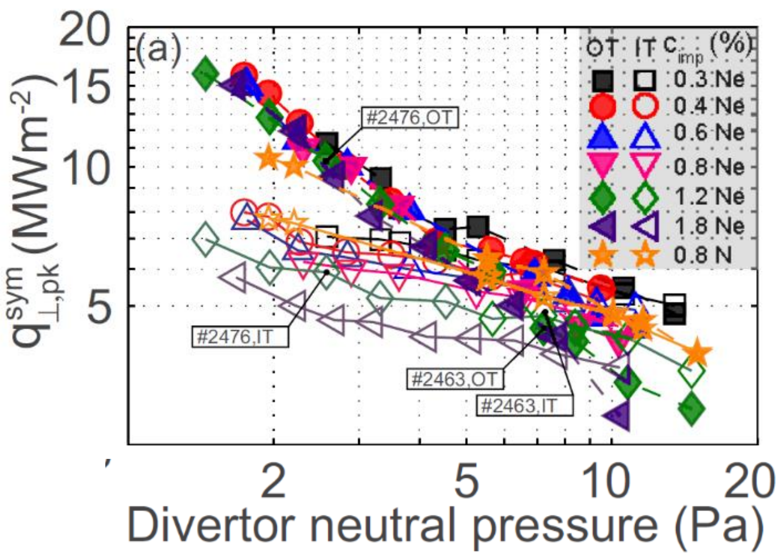
- In numerical modelling (SOLEDGE3X applied to ITER):





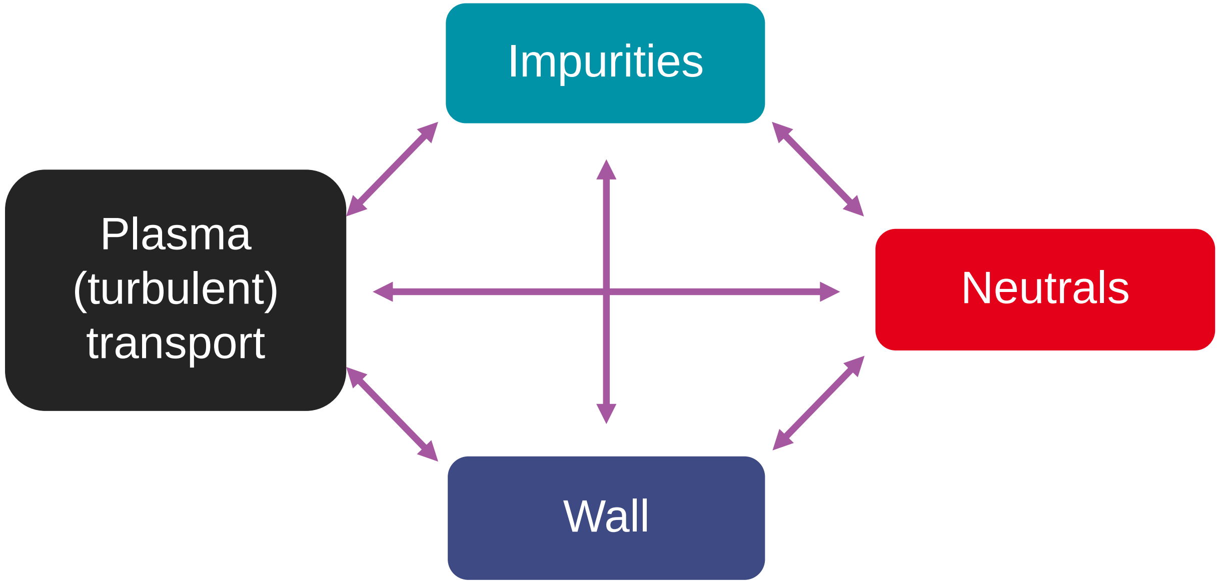
Fluid edge plasma codes as the work-horse

- Key question: can one reach **detachment** without impacting negatively discharge **performance and stability**?
  - **Design** of divertor and sub-systems
  - Determine **operational space**: fuelling, upstream density, impurity seeding…



[Pitts et al, NME 2019]

- Extremely non-linear & multi-physics system



Impurities

Fluid! Plasma (turbulent) transport

Neutrals **Kinetic!**

Wall

SOLEDGE3X: a versatile fluid code for the edge plasma

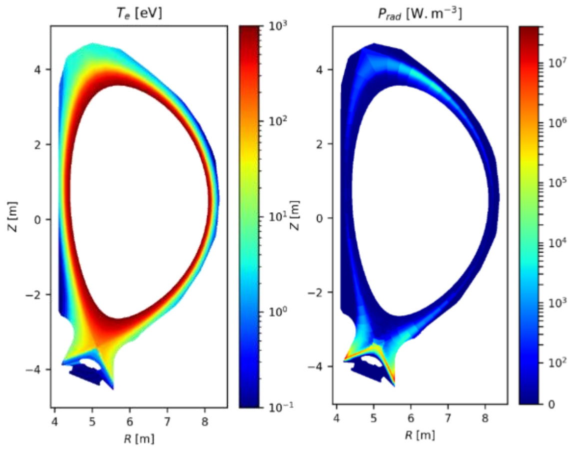
- **SOLEDGE3X**: **multi-fluid** modelling tool for the edge plasma resulting from merge of SOLEDGE2D (2D transport code like SOLPS) and TOKAM3X (3D turbulence code)

- Key features:
  - **Neutrals** either fluid (embedded) or kinetic (EIRENE)
  - **Arbitrary plasma composition** based on Zhdanov closure
  - Complete plasma **geometrical flexibility** (arbitrary number of X-points)
  - Simulations **up-to-the first wall** with full wall geometry
  - Usable in **2D or 3D**
  - Usable as **mean-field or self-consistent turbulence** code

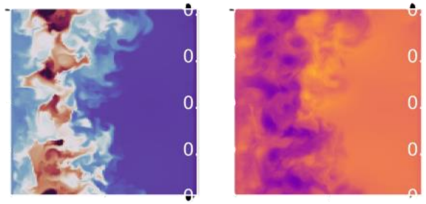
	Mean-field	Turbulence
2D	✓	✓
3D	✓	✓

- More information and references on www.soledge3x.com

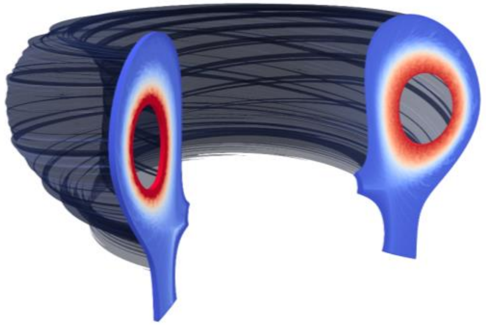
2D mean-field



2D turbulence



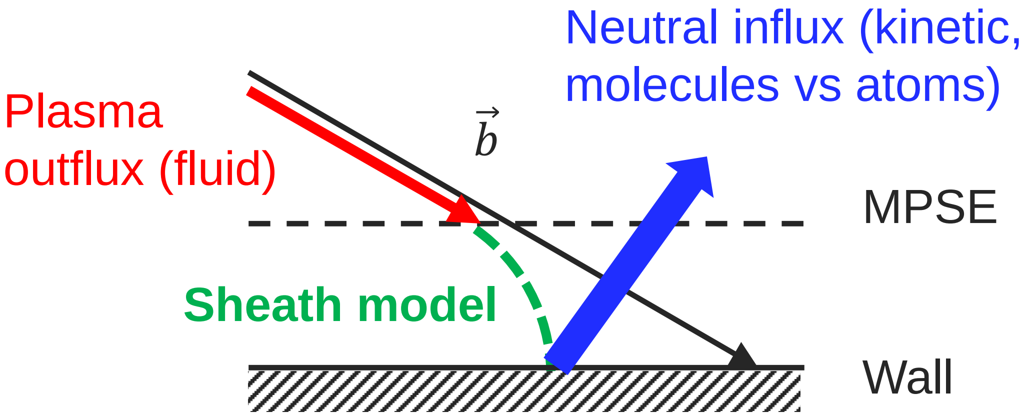
3D turbulence



And the sheath in all this?

- Sheath physics enters the modelling at 2 places:
  - **Boundary condition for the plasma fluid code**
    - Typically at magnetic pre-sheath entrance
    - Position assumed to be the same as the wall in spite of extremely short mean-free path for molecules
  - **Boundary conditions for kinetic neutrals**
    - Emitted from the wall
    - Implicit sheath model to determine link with local plasma properties (flux, density, temperature, composition…)

Plasma fluid:
- fluxes (particle, momentum, energy)?
- Electrostatic and magnetic potential?



Kinetic neutrals:
- Energy and angular distribution function?
- Chemical nature?

Sheath boundary conditions in SOLEDGE3X

- Edge plasma fluid codes all rely on some flavor of Bohm boundary conditions

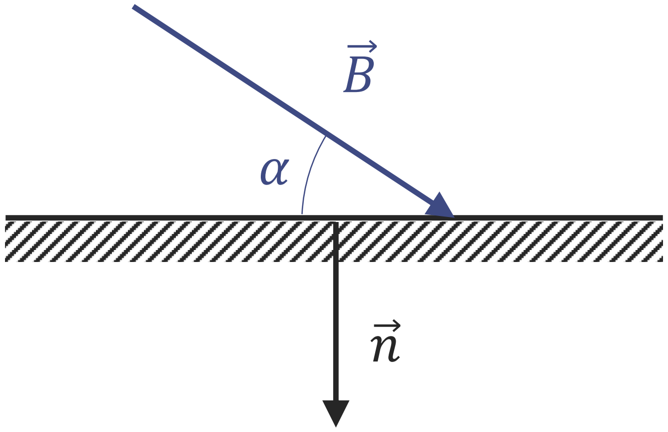
- In SOLEDGE3X, **Bohm-Chodura** for oblique incidence with drifts and single ion species

$$\boxed{\begin{aligned} & u_{\parallel i}\vec{b}\cdot\vec{n} \geq c_s\vec{b}\cdot\vec{n} - \vec{u}_{\perp i}\cdot\vec{n} \\[2em] & \vec{j}\cdot\vec{n} = \vec{\Gamma}_{\mathrm{n_i}}\cdot\vec{n}\left(1 - e^{\Lambda - \frac{e\Phi}{T_e}}\right) \\[2em] & \vec{\Gamma}_{\mathrm{E}_{e/i}}\cdot\vec{n} = \gamma_{e/i}T_{e/i}\vec{\Gamma}_{\mathrm{n}_{e/i}}\cdot\vec{n} \end{aligned}}$$

$$c_s = \sqrt{\frac{Z_iT_e + T_i}{m_i}}$$

$$\Lambda = -0.5\,ln\left(2\pi\frac{m_e}{m_i}\left(1 + \frac{T_i}{T_e}\right)\right)$$

Typically $\gamma_i = 2.5$ and $\gamma_e \approx 4$



Alternate fluid boundary conditions exist but similar

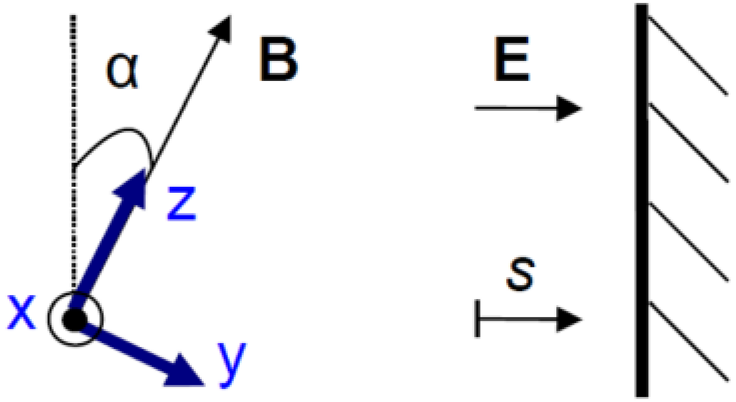
- Loizu et al. proposed **alternate sheath boundary conditions** for fluid codes *[Loizu, PoP 2012]*

$$\boxed{u_{\parallel i} = c_s\left(1 + \underbrace{\theta_n - \frac{1}{2}\theta_{T_e}}_{\uparrow \atop \partial_x(nc_s)/n} - \frac{2\Phi}{T_e}\underset{\uparrow \atop u_{\perp i}}{\theta_\Phi}\right)} \qquad \theta_X \equiv \frac{c_s}{2\tan\alpha}\frac{\partial_x \mathrm{X}}{\mathrm{X}}$$

$$\partial_s\Phi = -c_s\left(1 + \theta_n + \theta_{T_e}/2\right)\partial_s u_{\parallel i}$$

$$\partial_s \mathrm{n} = -\,n/c_s\left(1 + \theta_n + \theta_{T_e}/2\right)\partial_s u_{\parallel i}$$

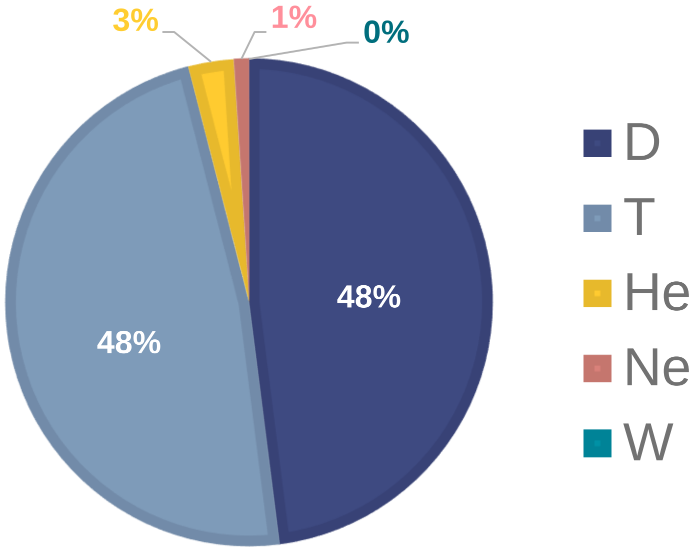
$\partial_s \mathrm{T_e} = 0$ (“for consistency”!)



- Overall **similar to Bohm-Chodurah** with additional correction terms
  - Boundary condition on T_e raises **questions concerning heat fluxes**

So what is the issue?

- Issue: **relevant reactor plasma conditions** are not compatible with collison-less sheath for simple plasma at large incidence angle
  - Sheath **heat transmission factors** and fluid plasma description
  - Large **range of collisionalities** from collision-less to diffusive sheath
  - Complex **plasma mix** with possibly several dominant ion species
    - E.g., ITER high power seeded plasma: D + T + He + Ne + W
  - **Small incidence angles** are ubiquitous



	Low ν_{col}	High ν_{col}
Single ion	Bohm	
Trace imp.		
Arbitrary		

Sheath heat transmission factors

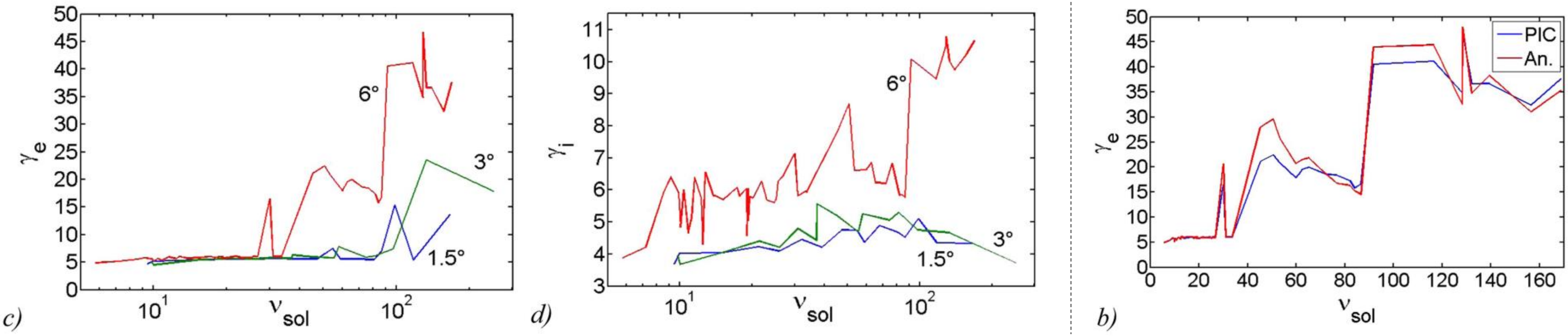
- Sheath heath transmission factors = kinetic correction to fluid model

$$\vec{\Gamma}_{\mathrm{E}_{e/i}} \cdot \vec{n} = \gamma_{e/i} T_{e/i} \vec{\Gamma}_{\mathrm{n}_{e/i}} \cdot \vec{n}$$

Typically $\boldsymbol{\gamma_i = 2.5}$ and $\boldsymbol{\gamma_e \approx 4}$

- Small fraction of hot electrons enough to **deviate strongly from classical values**
  - Very dependent on plasma conditions
  - Can be problematic even at high collisionality (example here)

$$\gamma_e \approx \frac{2 + \psi + (2\tau + \psi)F}{(1 + F)(1 + \boxed{s_{\mathrm{omp}}}\tau)}$$



[Tskhakaya, PPCF 2017]

Friction with neutrals pushes away from Bohm (1)

- BIT1 (1D/3V kinetic SOL) simulations at high density
  - $M_\parallel < 1$ everywhere due to **friction with neutrals**

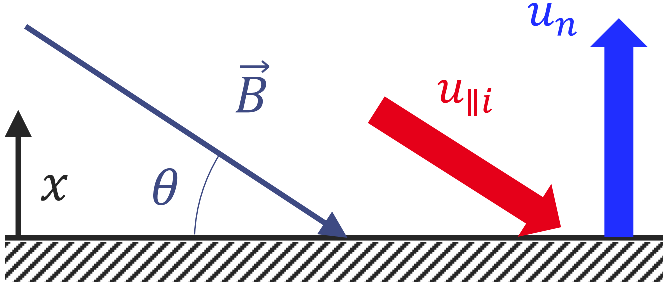
- If SE = last point where plasma still magnetized

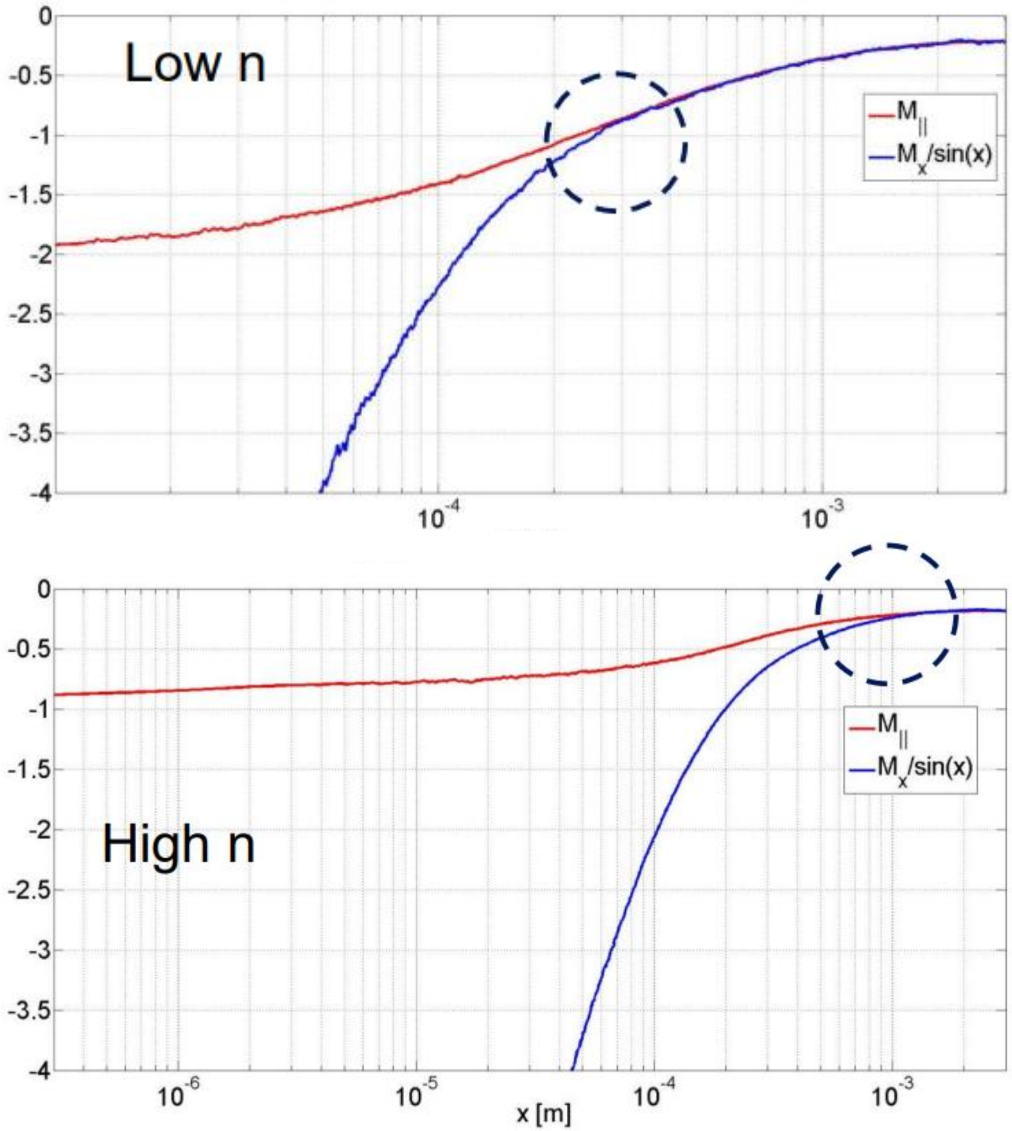
$$M_\parallel = M_x / \sin\theta$$

  - Correction to Bohm: $\boxed{M_\parallel = 1 + \chi - \sqrt{\chi^2 + 2\chi}}$

$$\chi = \frac{(\nu_{mt}(1-\alpha) + \nu_{ei})x_0}{2 c_s \sin\theta} \qquad \alpha = \frac{u_{\parallel n}}{u_{\parallel i}}$$

$$M_\perp(x_0) = \sin\theta \sim 20\rho_i$$

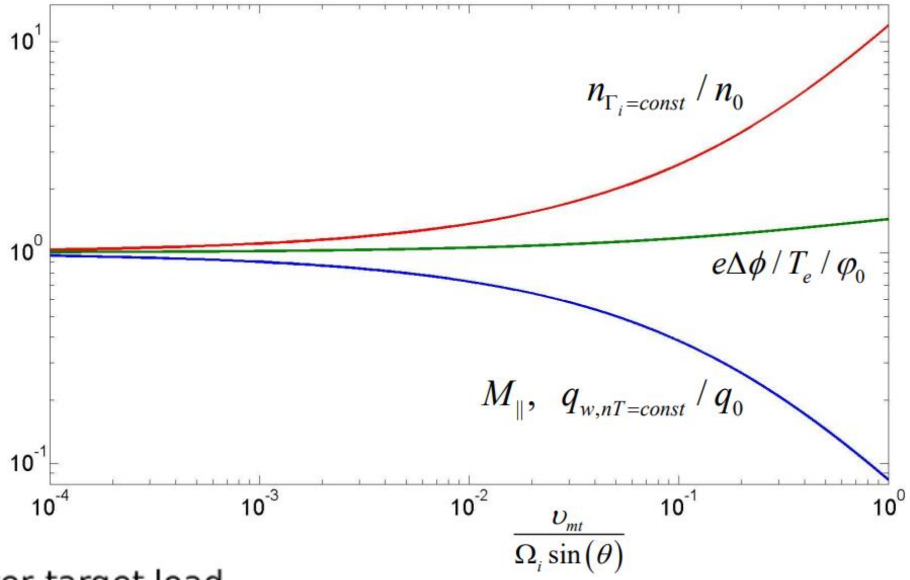




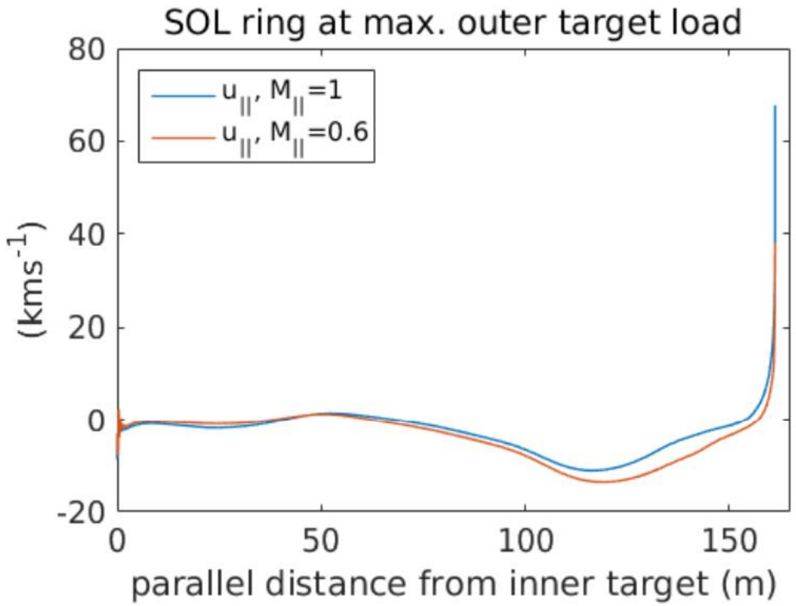
[Tskhakaya, TSVV3 internal meeting]

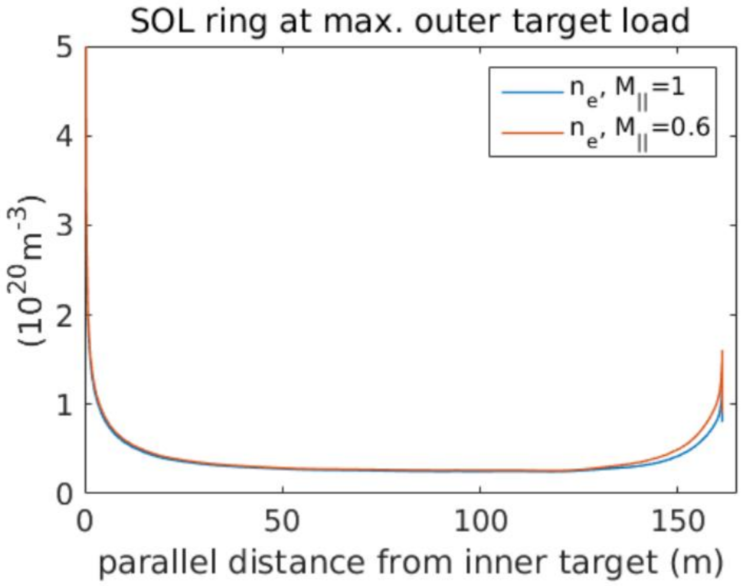
Friction with neutrals pushes away from Bohm (2)

- Consequences:
  - Potential drop: $\frac{e\Delta\Phi}{T_e} = \Lambda T_e - 0.5 \ln M_\parallel$
  - Wall density increases
  - Heat flux to the wall decreases in spite of γ_e ↗



- Application to ITER low power case:



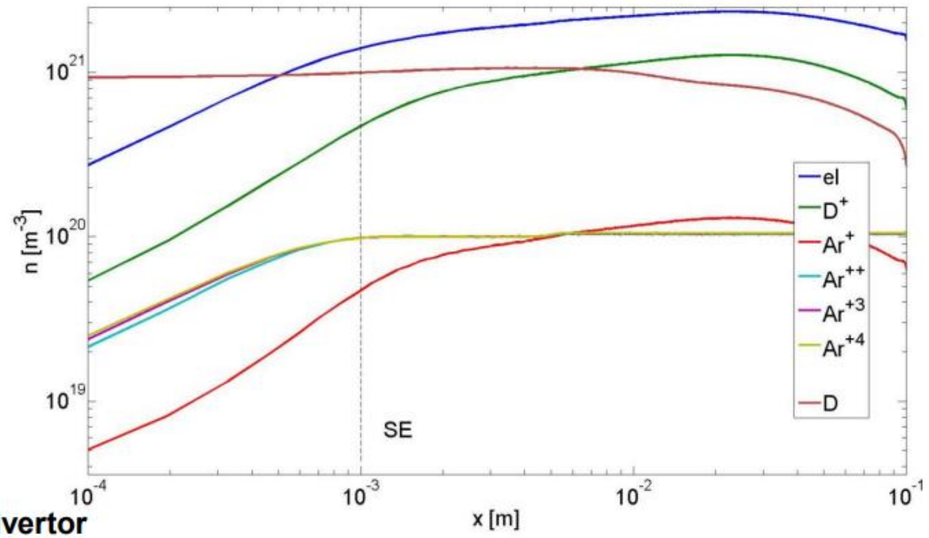


	Low ν_{col}	High ν_{col}
Single ion	Bohm	Tskhakaya
Trace imp.		
Arbitrary		

[Tskhakaya, TSVV3 internal meeting]

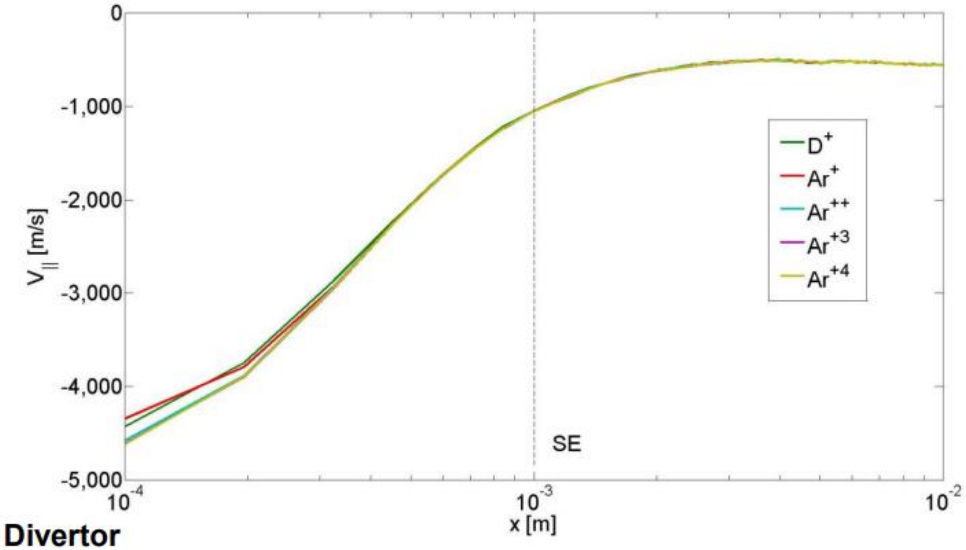
Single dominant species at high collisionality

- Multi-species BIT1 (1D/3V kinetic SOL) simulations at high density with 1 dominant species (D)



Divertor surface

Density profiles in the sheath



Divertor surface

$V_\parallel$ profiles in the sheath

- **Strong coupling** between main and impurity ions

$$\boxed{M_{\parallel i} = M_\parallel^{main}\sqrt{\frac{m_i}{m_{main}}}}$$

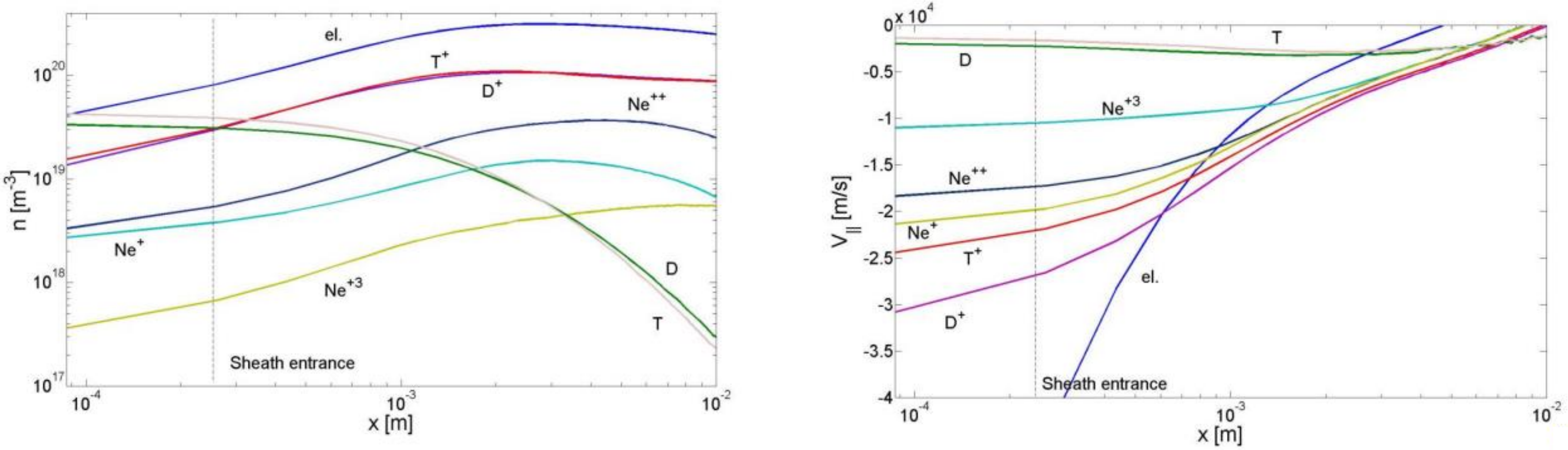
$$M_\parallel^{main} = 1 + \chi - \sqrt{\chi^2 + 2\chi}$$

[Tskhakaya, TSVV3 internal meeting]

	Low ν_{col}	**High ν_{col}**
Single ion	Bohm	Tskhakaya 1
Trace imp.	?	Tskhakaya 2
Arbitrary		

Arbitrary mix: no clear solution at low-medium ν_{col}

- Initial kinetic simulations with multi-dominant species => **no D-T coupling!**



[Tskhakaya, TSVV3 internal meeting]

	Low ν_{col}	**High ν_{col}**
Single ion	Bohm	Tskhakaya 1
Trace imp.	?	Tskhakaya 2
Arbitrary	?	

Arbitrary mix: a guess for high ν_{col} (1)

- Haven't heard (⚠ not expert!) of sheath BC for fluid models with arbitrary ion mix
  - Here attempt at guessing a back-of-the-envelop behavior

- Reasonable assumption: **high $\boldsymbol{\nu_{col}}$ => $\boldsymbol{\forall i, j \;\; u_{\parallel i} = u_{\parallel j} = u_{\parallel}}$**

$$\forall i \quad \partial_t n_i + \partial_z(n_i u_{\parallel i}) = S_{n_i}$$

$$\forall i \quad m_i \partial_t(n_i u_{\parallel i}) + m_i \partial_z\left(n_i u_{\parallel i}^2\right)$$

$$= -\partial_z(n_i T_i) + Z_i e n_i E_\parallel + R_{\parallel i} + S_{p_i}$$

$$n_e = \Sigma_i Z_i n_i$$

$$0 = -\partial_z(n_e T_e) - e n_e E_\parallel + R_{\parallel e} + S_{p_e}$$

$$\Sigma_i R_{\parallel i} + R_{\parallel e} = 0$$

Multi ion species plasma

$$\Leftrightarrow$$

$$\partial_t N + \partial_z(N u_\parallel) = S_N$$

$$M \partial_t(N u) + M \partial_z\left(N u_\parallel^2\right)$$

$$= -\partial_z(NT) + ZeNE_\parallel + R_\parallel + S_p$$

$$n_e = ZN$$

$$0 = -\partial_z(n_e T_e) - e n_e E_\parallel + R_{\parallel e} + S_{p_e}$$

$$R_\parallel + R_{\parallel e} = 0$$

Equivalent single ion species plasma

⚠ Z, M and T are now spatially varying ⚠

$$\boldsymbol{N = \Sigma_i n_i} \qquad \boldsymbol{MN = \Sigma_i m_i n_i}$$

$$\boldsymbol{ZN = \Sigma_i Z_i n_i} \qquad \boldsymbol{NT = \Sigma_i n_i T_i}$$

Arbitrary mix: a guess for high ν_{col} (2)

- Single-ion-species plasma equivalent to arbitrary ion mix:

$$N = \Sigma_i n_i \qquad MN = \Sigma_i m_i n_i$$

$$ZN = \Sigma_i Z_i n_i \qquad NT = \Sigma_i n_i T_i$$

- Then apply standard Bohm / Bohm-Chodurah / Tskhakaya:

$$\Delta\Phi \equiv \Lambda \mathrm{T_e} = -0.5 T_e \ln\left(2\pi \frac{m_e}{M}\left(Z + \frac{T}{T_e}\right)\right)$$

$$\mathrm{u}_\parallel \geq \sqrt{\frac{ZT_e + T}{M}}$$

$$\gamma_i = 2.5$$

$$\gamma_e = 2 + \frac{e\Phi}{T_e}$$

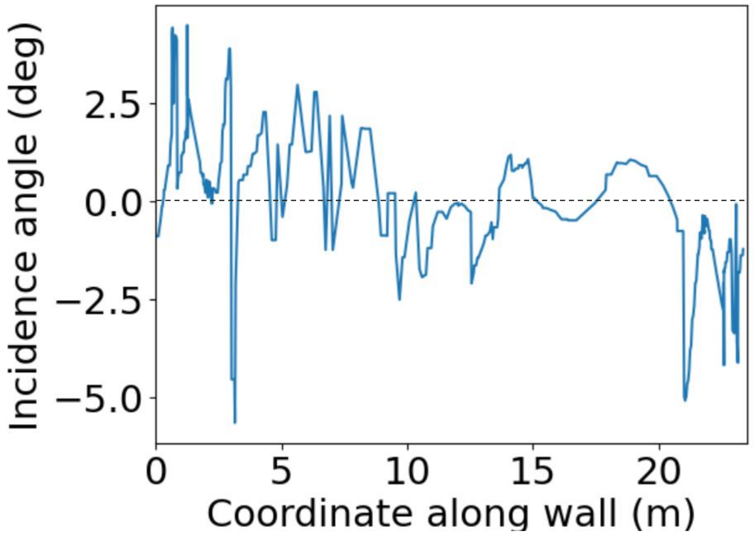
	Low ν_{col}	**High ν_{col}**
Single ion	Bohm	Tskhakaya 1
Trace imp.	?	Tskhakaya 2
Arbitrary	?	Mean spec.?

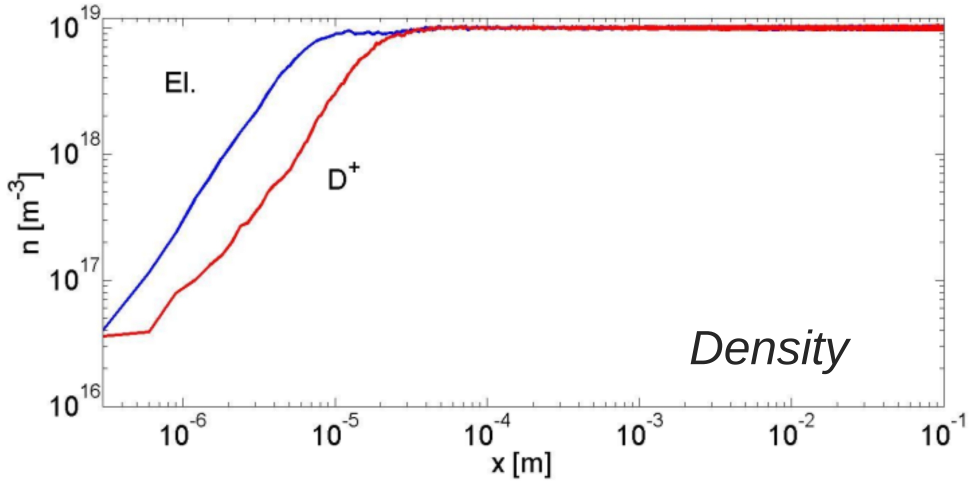
The problem of grazing angles

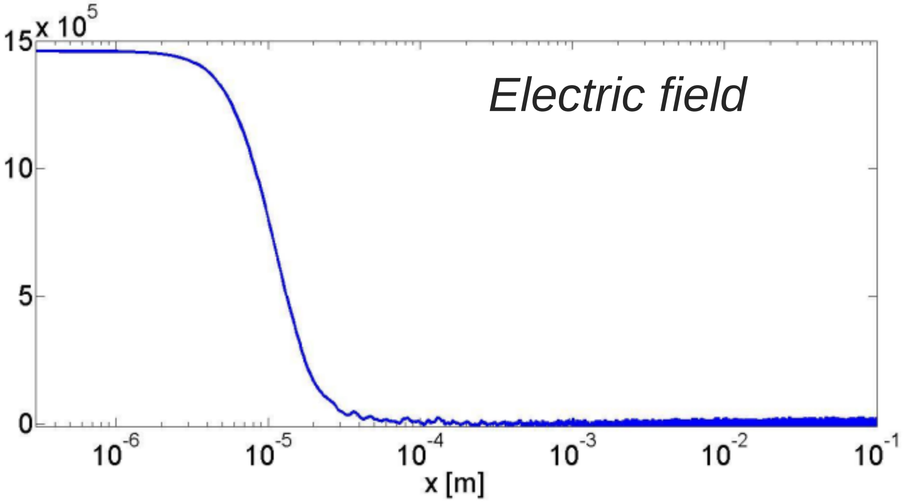
- Parallel incidence BIT1 simulations without drifts show expected **reverse sheath** *[Tskhakaya, TSVV3 internal meeting]*
  - Transition seems to occur at very low incidence => does it matter?
- And in the presence of drifts? **Bohm-Chodurah diverges**… ☹
  - Not clear down to which angle this is valid

$$u_{\parallel i}\vec{b}\cdot\vec{n} \geq c_s\vec{b}\cdot\vec{n} - \vec{u}_{\perp i}\cdot\vec{n} \quad \Rightarrow \quad u_{\parallel i} = c_s - \boxed{\frac{\vec{u}_{\perp i}\cdot\vec{n}}{\vec{b}\cdot\vec{n}}} \quad \propto \tan^{-1}\alpha \ \ !$$

Incidence angle along ITER wall







Which drift velocity?

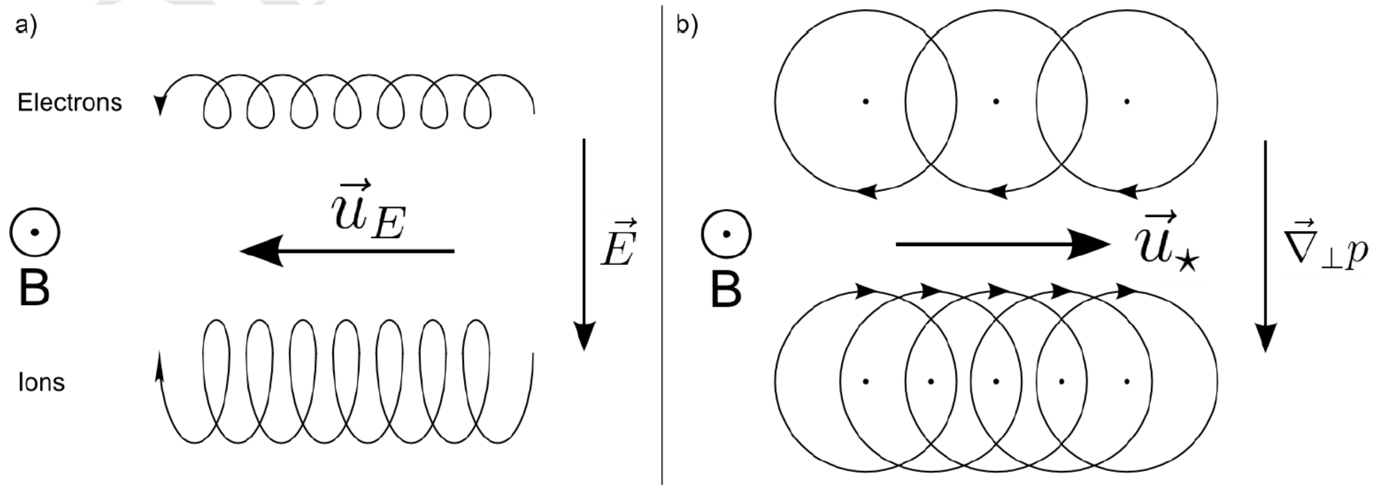
- Bohm-Chodura and Loizu boundary conditions depend on drift-velocities
  - Both derived for cold ions, considering only ExB drift
  - At low incidence, drift term is not just a minor correction

$$u_{\parallel i} = c_s - \boxed{\frac{\vec{u}_{\perp i} \cdot \vec{n}}{\vec{b} \cdot \vec{n}}}$$

dominant if $\tan \alpha < \frac{|\vec{u}_{\perp i}|}{c_s}$

- But fluid-drift theory involves 2 first order drifts: ExB and diamagnetic
  - Should one retain the diamagnetic drift even though it does not transport gyrocenters? What about additional drifts due to friction with neutrals?

$$\vec{u}_E \equiv \frac{\vec{E} \times \vec{B}}{B^2}$$

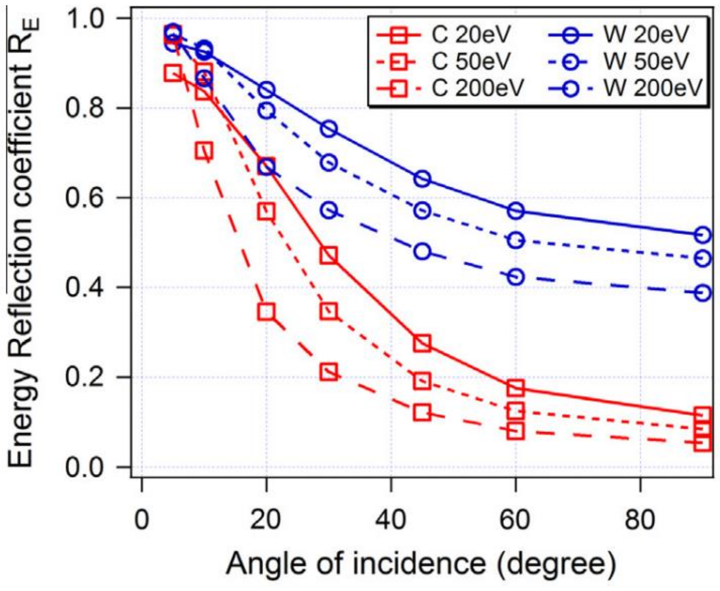


$$\vec{u}_* \equiv \frac{\vec{B} \times \vec{\nabla} p}{nqB^2}$$

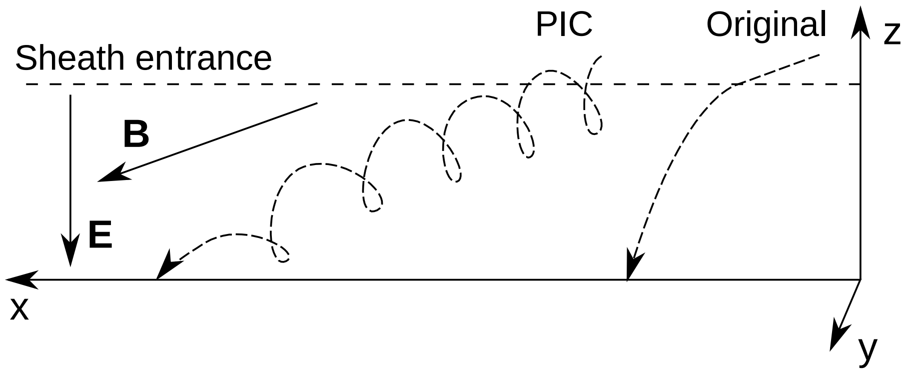
EADF at the wall matters (1)

- Energy recycling coefficient sensitive to angle of incidence
  - probability of fast specular reflection vs thermalization
  - **Energy and Angular Distribution Function** (EADF) at the solid surface matters

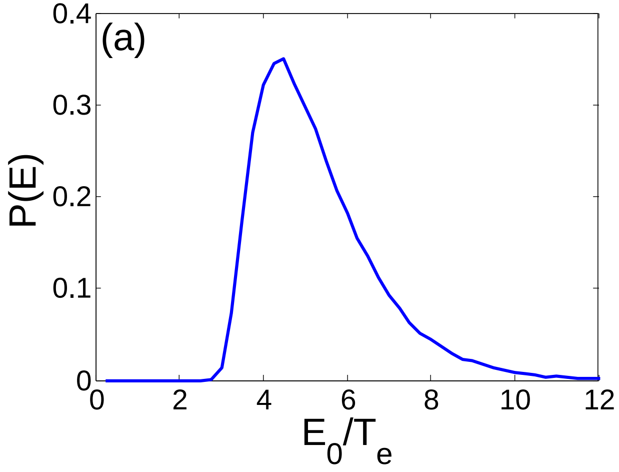
[Bufferand, J. Nucl. Mater. 2015]

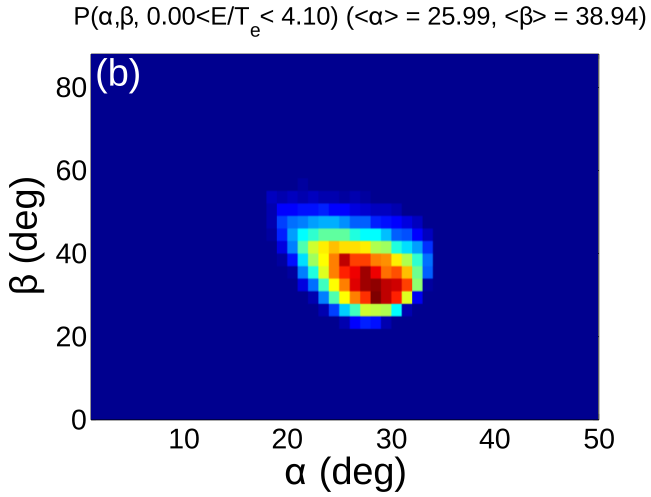


- Standard sheath model (shifted Maxwellian) over-simplified and does not account for gyro-motion
  - Use **PIC code database** instead



[Marandet, Plasma Surface 2018]

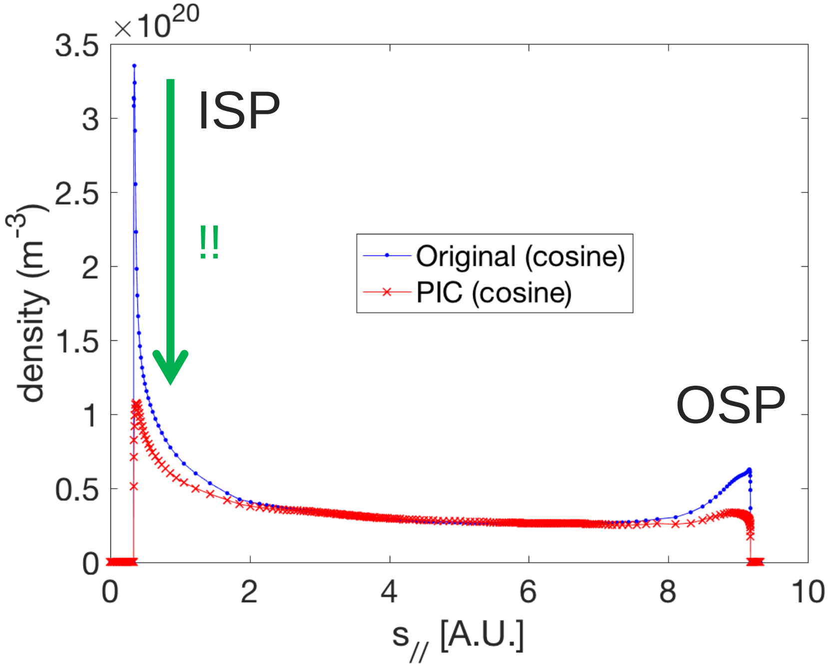


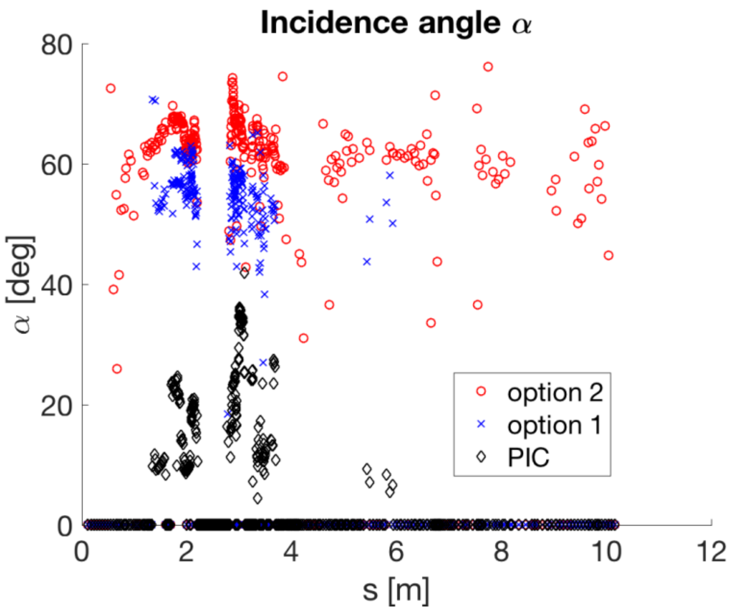


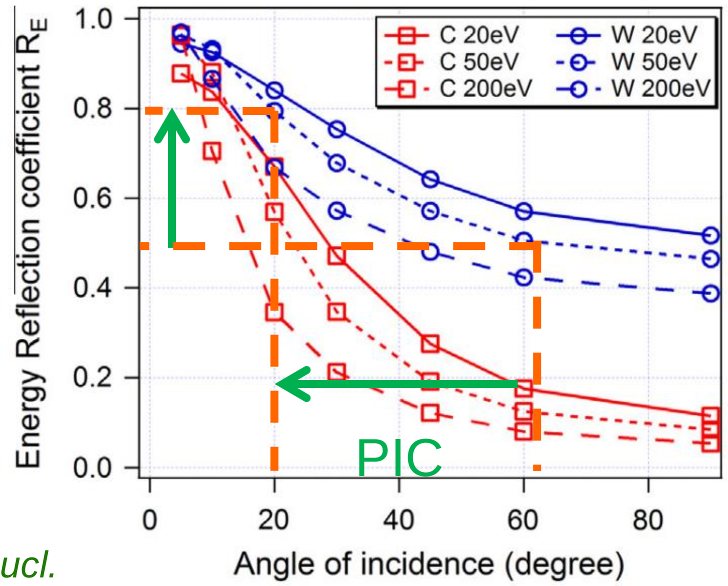
EADF at the wall matters (2)

- PIC database results in very different incidence angle
  - Mainly due to gyro-motion

- Changing the sheath model **can significantly change plasma solution** *[Marandet, PSI conf. 2018]*







[Bufferand, J. Nucl. Mater. 2015]

- Results currently being revisited and extended at LAPLACE laboratory within ANR PLATUN

Conclusion

- **Sheath is not explicitly modelled in edge plasma codes** because of lengths and time scales
  - Appear as boundary conditions or 0D implicit models

- The choice of the **sheath model heavily influences results** as it determines all fluxes to the wall

- Here browsed many issues related to **limits of available sheath models**:
  - Consistency between **fluid (pre-sheath) and kinetic (sheath)** models
  - Sheath for **arbitrary plasma mix**
  - Large **range of collisionalities**, especially large collisionality
  - Low **incidence angles** making perpendicular motion important (gyro-motion and/or drifts)
  - others exist, e.g. inclusion of secondary electron

- Current state of the art: pieces of solutions for each sub-issue, but **no model covering all the needs**