INSTITUTE OF PLASMA PHYSICS
OF THE CZECH ACADEMY OF SCIENCES

Latest results from sheath kinetic modelling

D. Tskhakaya and TSVV3 team

Institute of Plasma Physics of the CAS, Prague, Czech Republic

MINISTRY OF EDUCATION, YOUTH AND SPORTS

Outline

- High density sheath

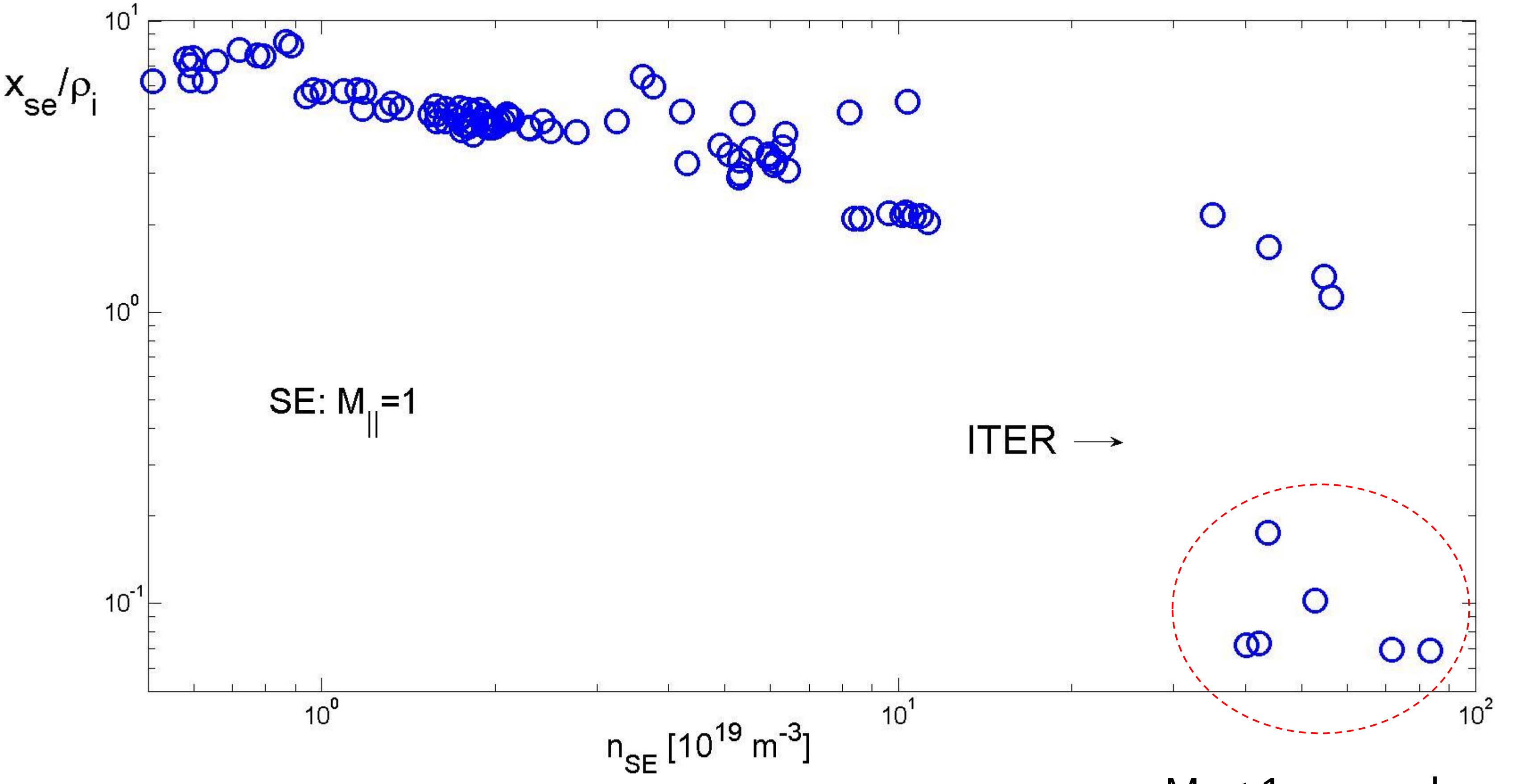
  one ion species (reminder)

  with impurity: $Ar^{+i<5}$

  with D+T

- Sheath with the magnetic field parallel to the wall surface
- W sputtering study

Position of the magnetized sheath edge



$M_{||} < 1$ everywhere

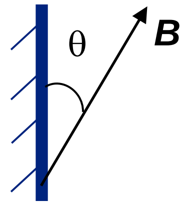
Simulation parameters

R= 0 – 1

Z_{eff} = 1 – 1.5

θ= 1.5°, 3°, 4°, 6°

~100 simulation runs



D. Tskhakaya | PSI | Princeton | 21.06.18 3 /30

Analytic model

Particle and momentum conservation equations

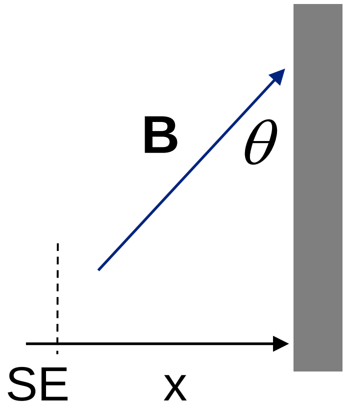
$$\vec{\nabla} n \vec{V} = 0, \qquad \upsilon_i n, \qquad |\nabla \ln T| << |\nabla \ln n|, \qquad |\vec{\nabla} \vec{\vec{\pi}}| \sim \tau_{col},$$

$$m_i \vec{V}\vec{\nabla}\vec{V} = e\vec{E} + e\vec{V} \times \vec{B} - T\vec{\nabla} n / n - m_i \upsilon_i \vec{V} - m_i \upsilon_{mt} \left(\vec{V} - \vec{V}^n\right) - m_i \upsilon_{ei} \vec{J} / en$$

$$eE_x = -T_e \partial_x n / n$$

1D sheath edge (SE)

$$\partial_x \delta\vec{V}, \ \delta\vec{V} \to 0, \quad \delta\vec{V} = \vec{V} - \vec{b} V_{\parallel}$$



Boundary condition at the sheath edge

$$\left(\frac{1}{M_{\parallel}^2} - 1\right) \partial_{\varsigma} M_x = \upsilon'_{mt}(1-\alpha) + \upsilon'_{ei}$$

$$\upsilon_{mt}, \upsilon_{ei} \to 0, \qquad M_{\parallel}^2 \to 1$$

$$\upsilon'_{mt} = \frac{\upsilon_{mt}}{\Omega}, \quad \upsilon'_{ei} = \frac{\upsilon_{ei}}{\Omega}, \quad \xi = \frac{x}{\rho_i}, \quad \rho_i = \frac{c_s}{\Omega}, \quad \alpha = V_{\parallel}^n / V_{\parallel}$$

- BC depend on the **sheath collisionality** as well as on the **current**

$$\partial_{\varsigma} M_x > 0, \qquad V_{\parallel} > V_{\parallel}^n$$

$$M_{\parallel} < 1$$

For constant

$$\upsilon_{mt}, \ \upsilon_{ei}, \ \alpha$$

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

$$\chi = \frac{\left(\upsilon_{mt}(1-\alpha) + \upsilon_{ei}\right) x_0}{2 c_s \sin(\theta)}$$

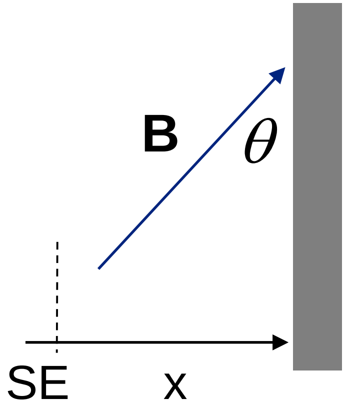
$$M_x(x_0) = \sin(\theta), \quad x_0 \approx x_{wall}$$

Final 1D BC

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

$$\alpha = V_{\parallel}^{n} / V_{\parallel}$$

$$\chi = \frac{\left(\upsilon_{mt}(1-\alpha) + \upsilon_{ei}\right) x_0}{2 c_s \sin(\theta)}$$

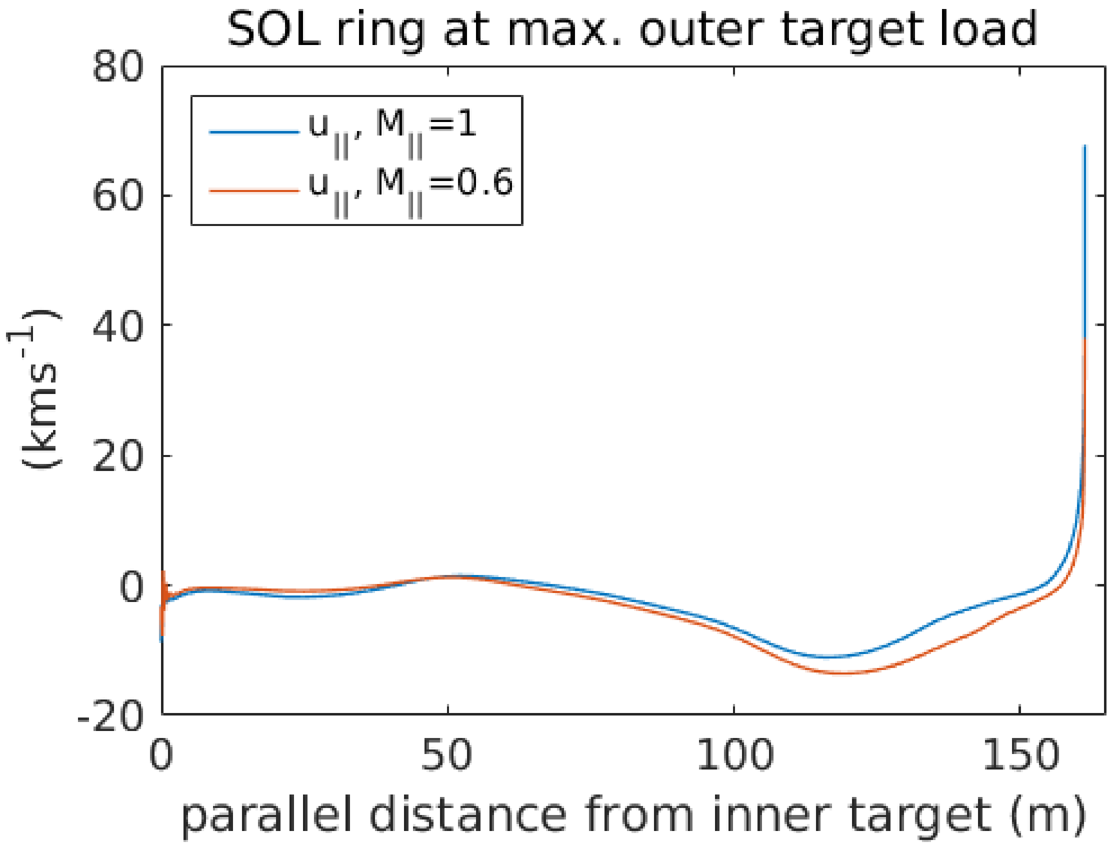


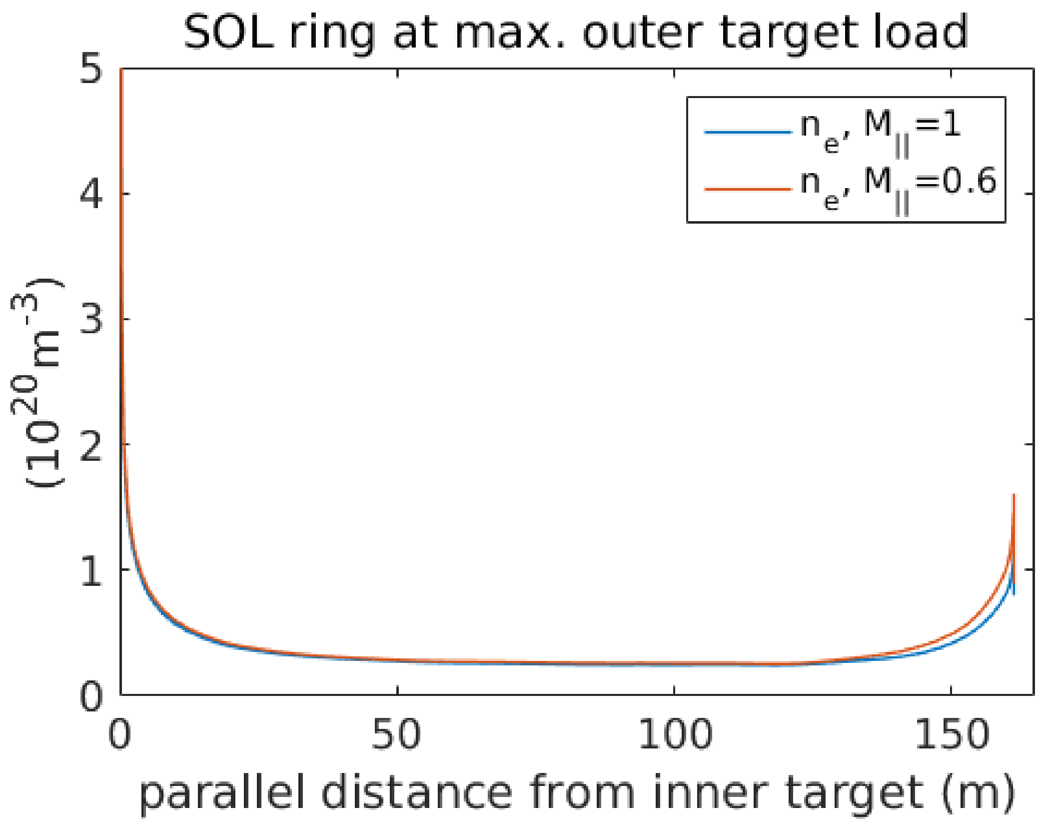
$$M_{\perp}(x_0) = \sin(\theta), \quad x_0 \approx x_{wall} \sim 20\rho_i$$

P. Macha (IPP CAS) and GBS team is implementing and will test this BC into the GBS (2024)

Implementation of collisional sheath in SOLPS-ITER

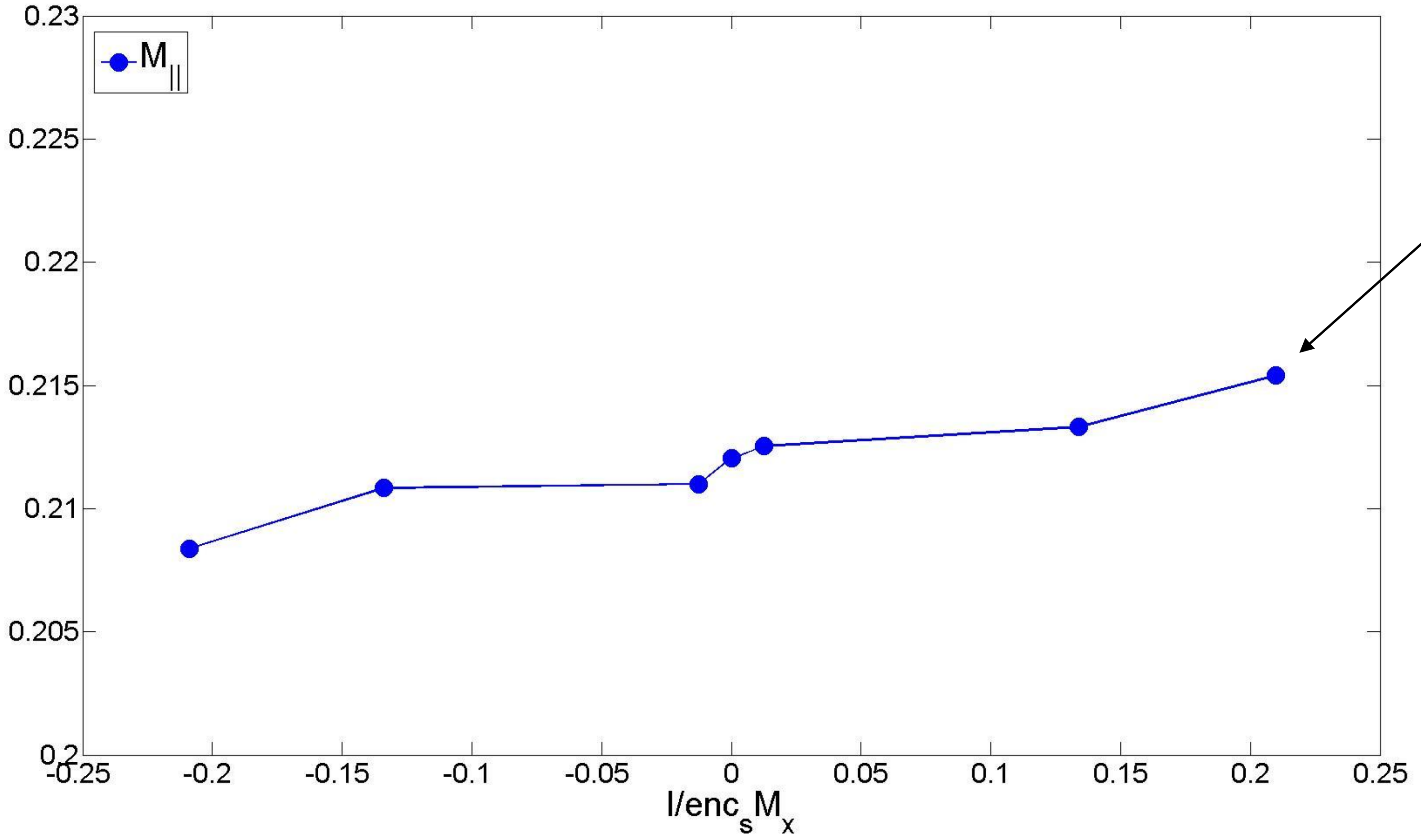
[D. Moulton, ISFN DivSOL, 2021]





SOLPS-ITER simulation show no changes in particle flux, but increasing of density in the divertor plasma.

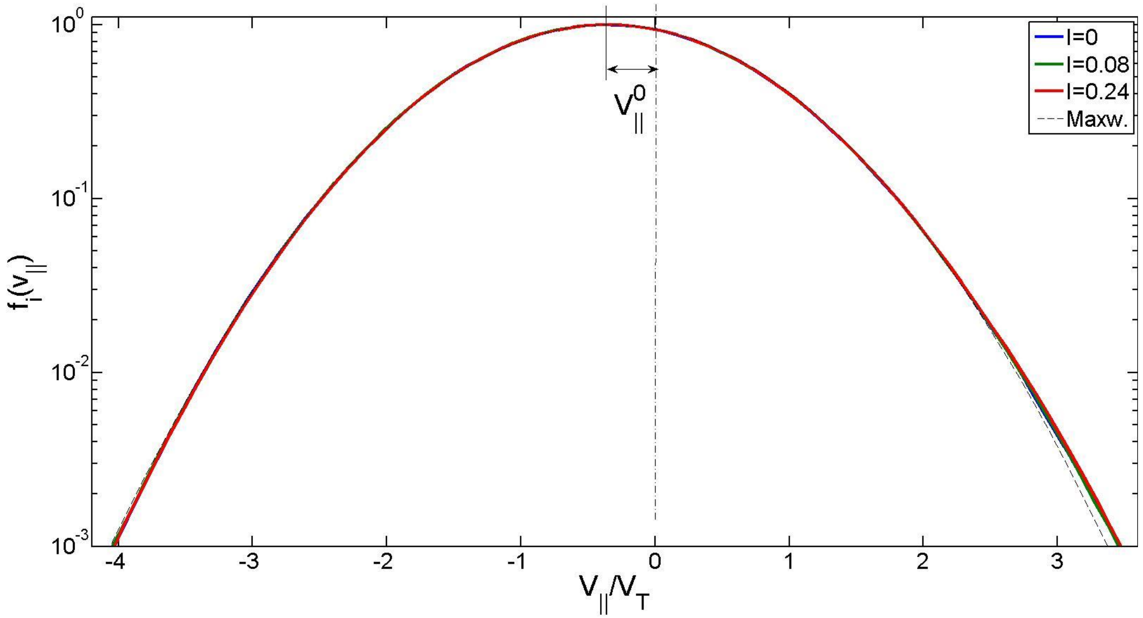
Simulation results

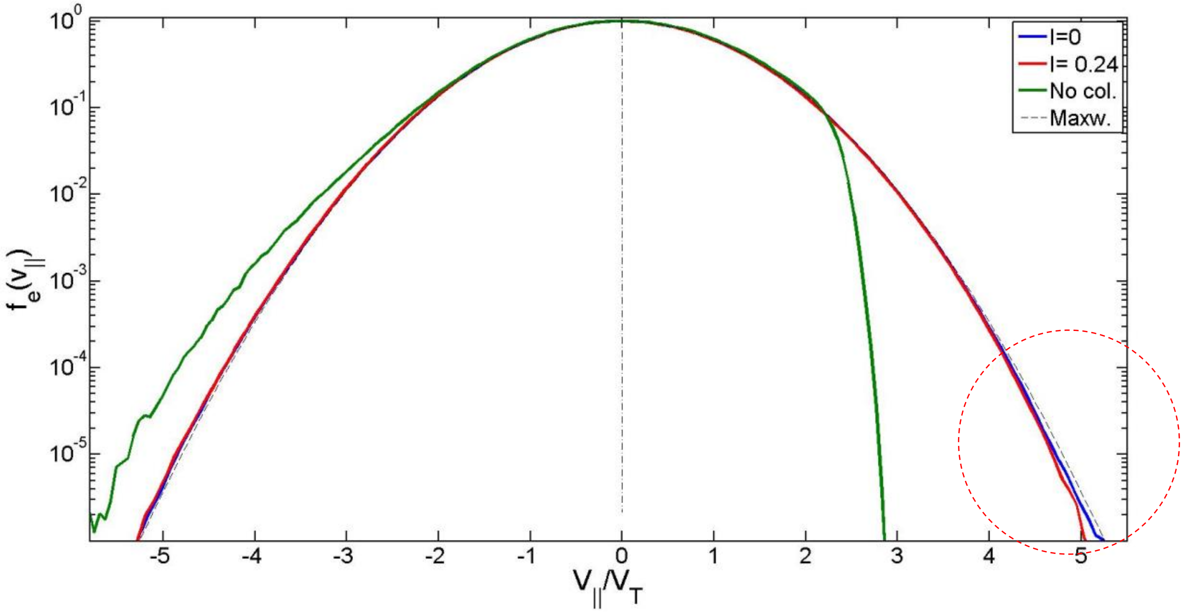


50 V biasing >> $T_{e,div}$ ~ 1 eV

On electron-ion friction force at the SE

Electron and ion (D^+) VDFs at the high collisional sheath edge for different current regimes ($I = J/J_{sat}$) from the PIC model

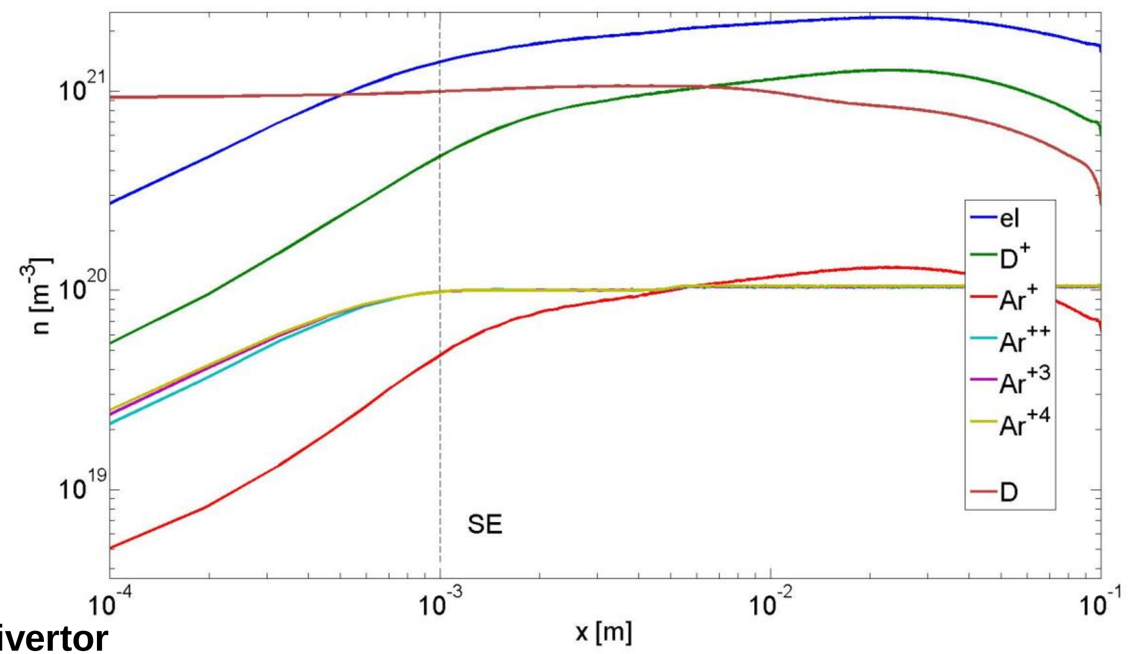




$$R_{||}^{ei} = -m\upsilon_{ei}\left(V_{||}^{i} - V_{||}^{e}\right) \Rightarrow -m\upsilon_{ei}V_{||}^{i}$$

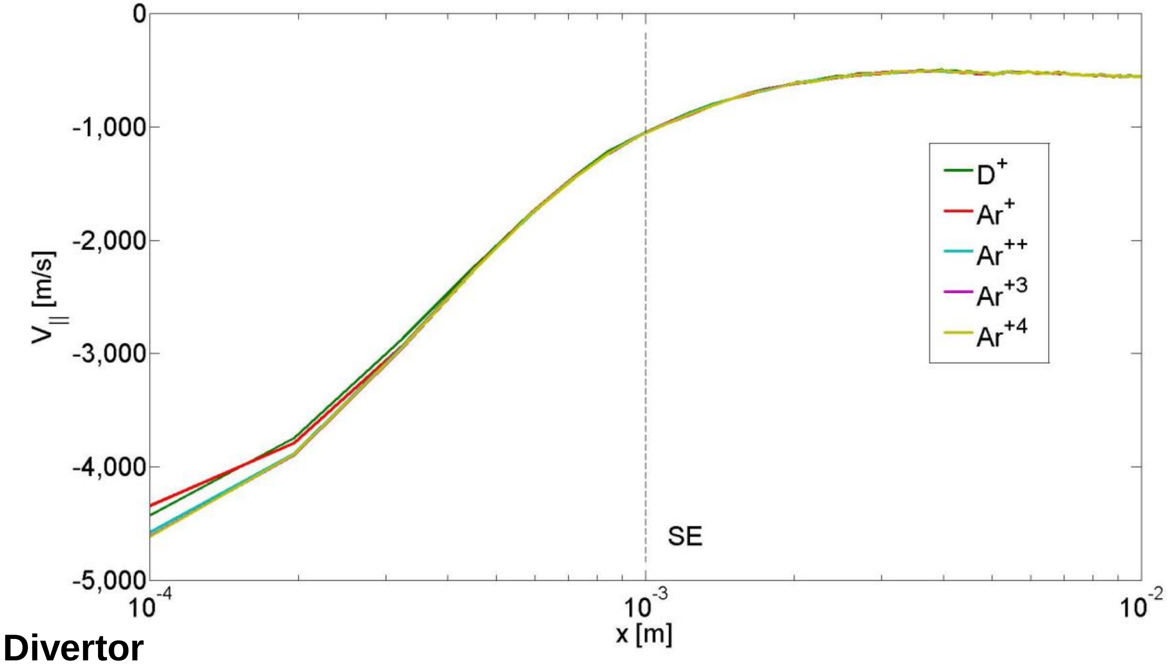
Electron-ion friction at the sheath edge is **independent** of the current regime

High density sheath with impurity



Divertor surface

Density profiles in the sheath

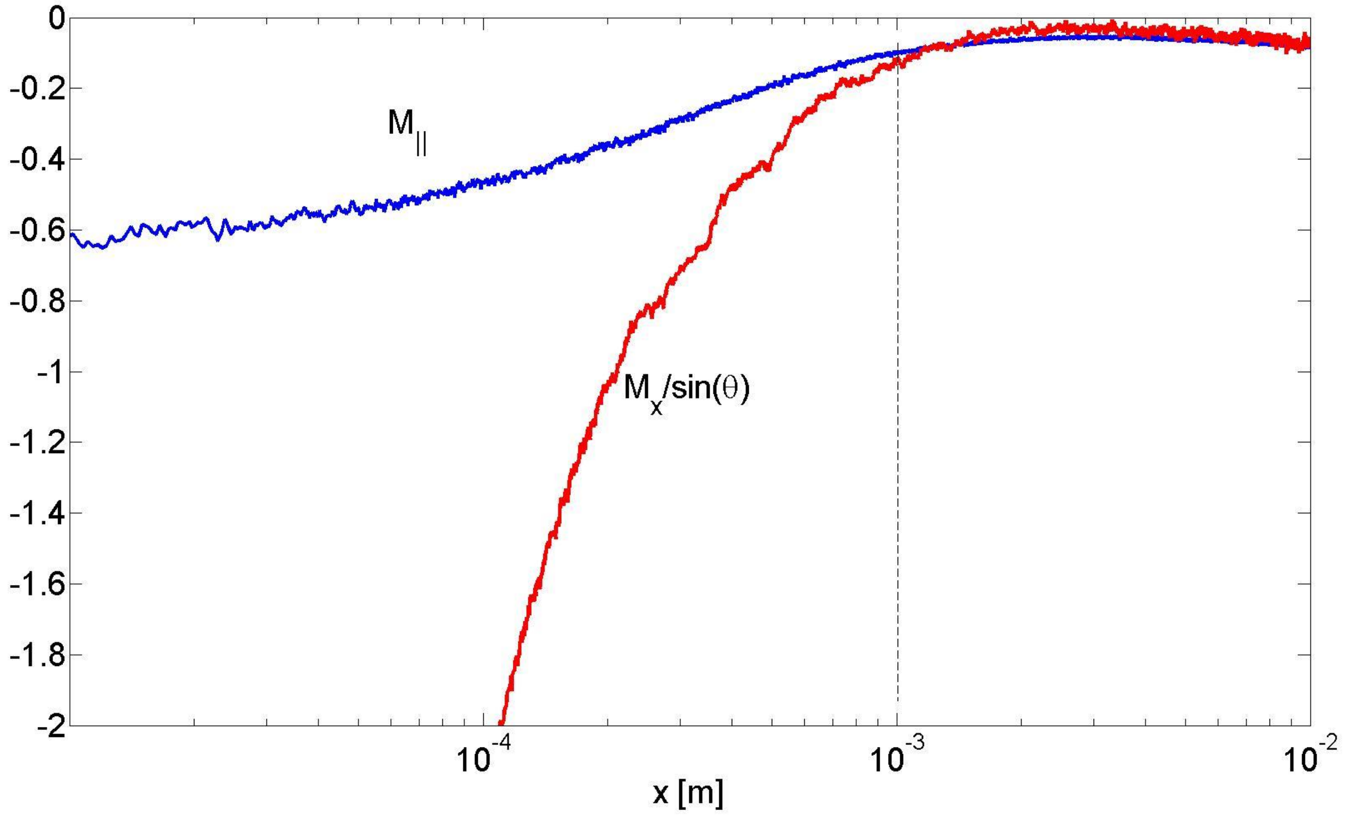


Divertor surface

$V_{||}$ profiles in the sheath

Strong coupling between the main and impurity ions

High density sheath with impurity: BCs



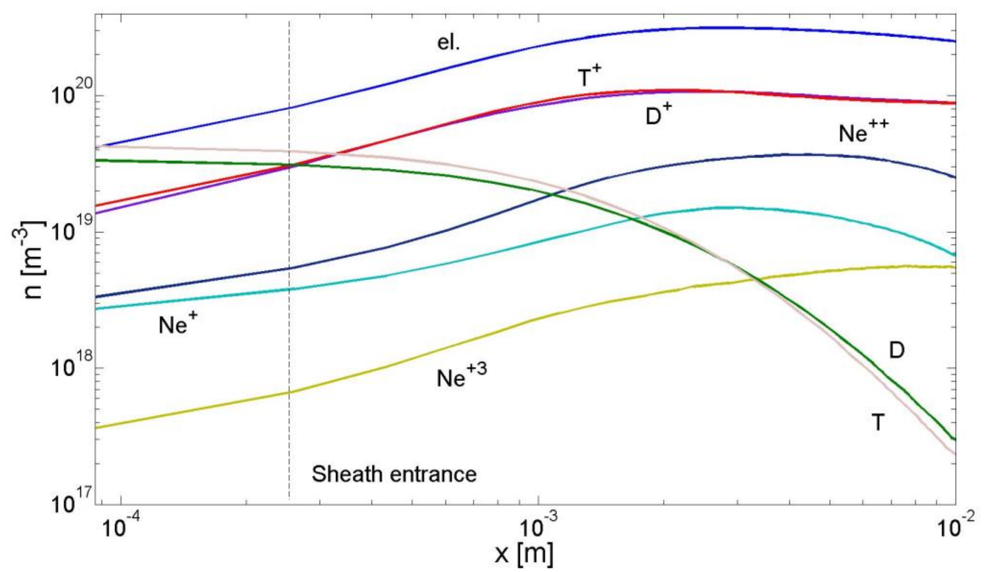
D^+ $V_{||}$ and $V_{poloidal}$ profiles in the sheath

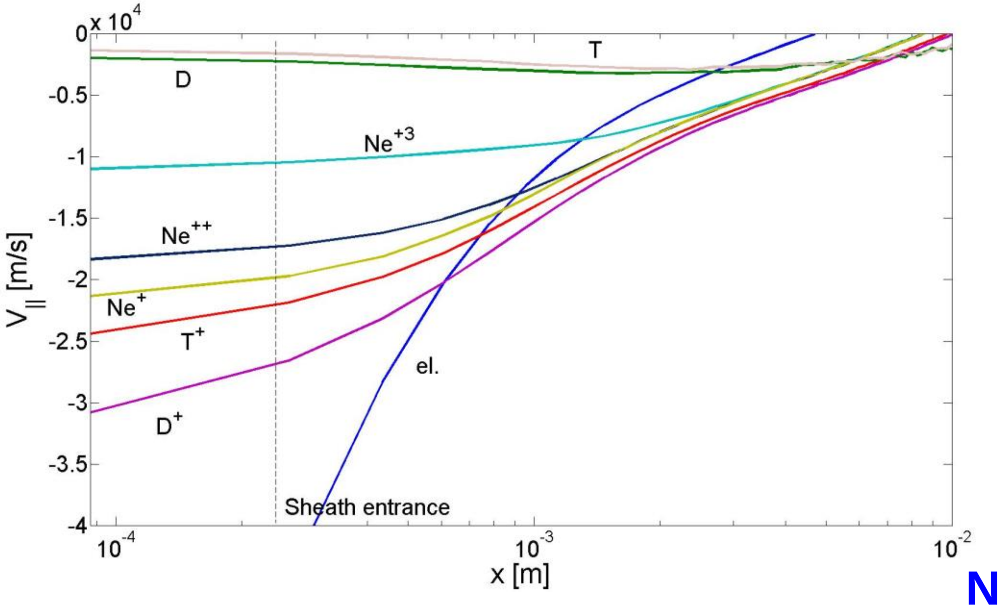
1D magnetized plasma: $M_{||} = M_{poloidal} \sin(\theta)$

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

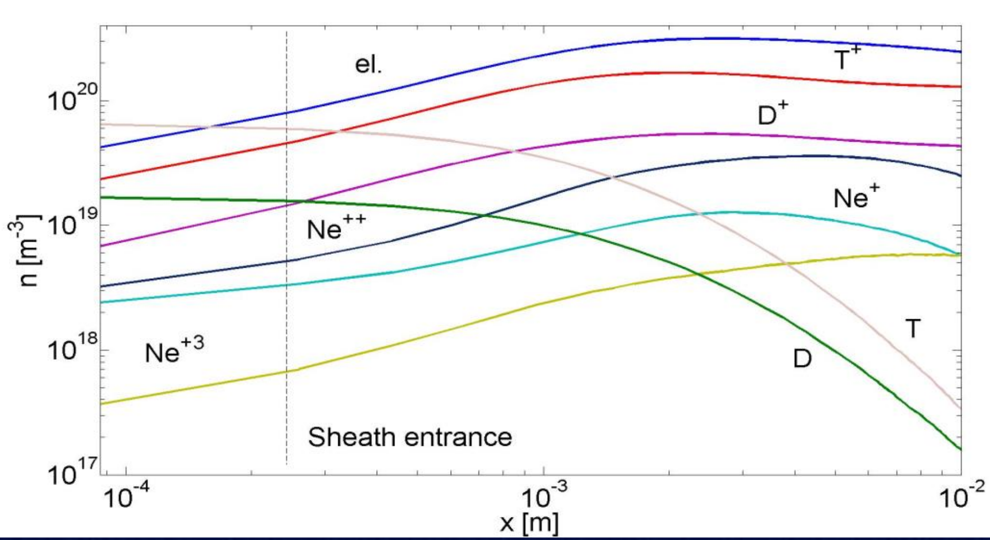
$$M_{||}^{main} = 1 + \chi - \sqrt{\chi^2 + 2\chi}$$

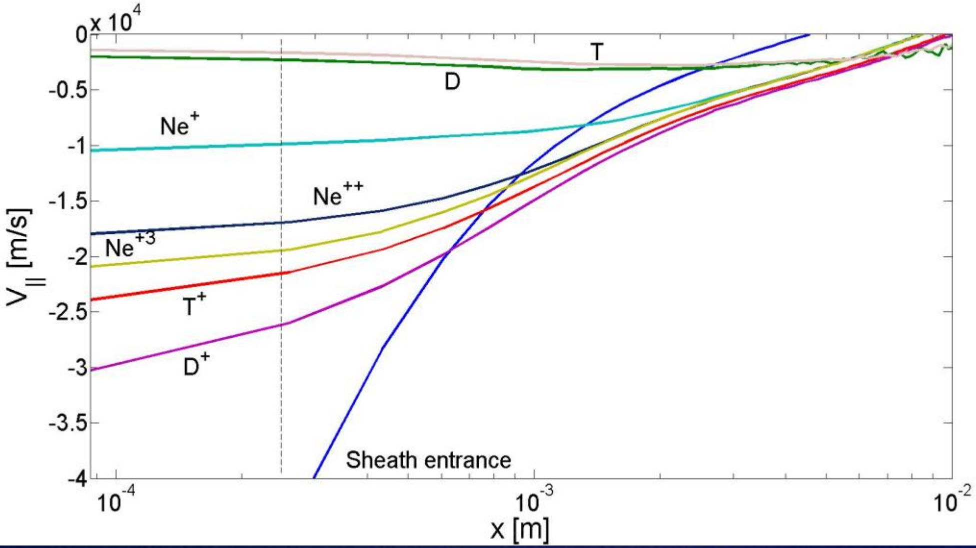
Multiple main ions: JET



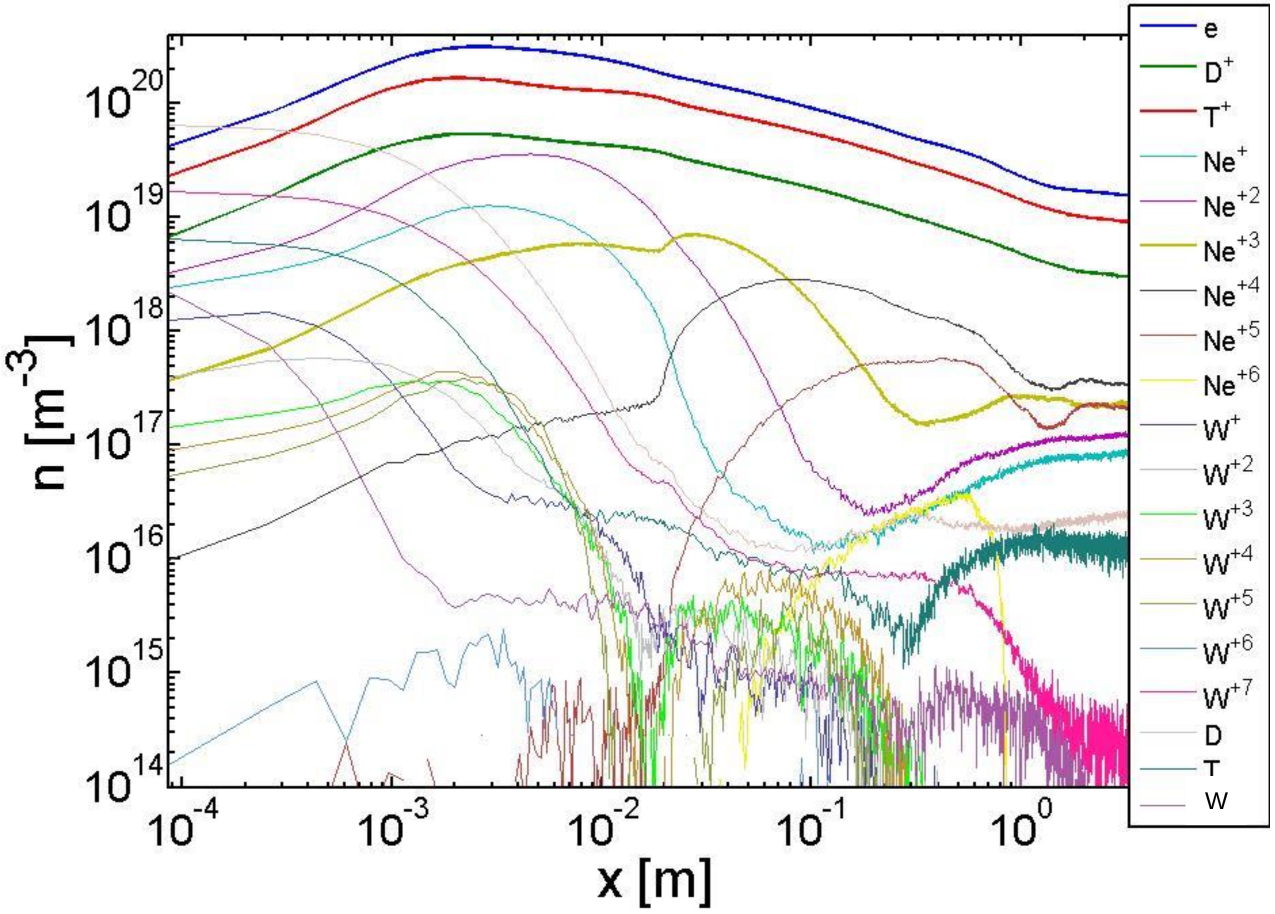


NO D T coupling!





Multiple main ions: high density case



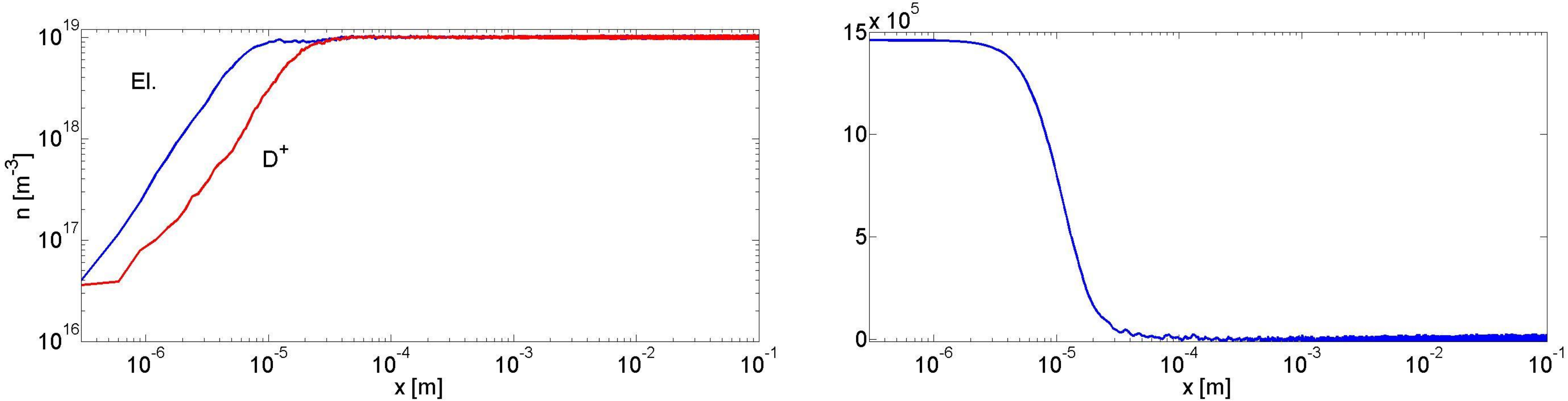
Density profiles from kinetic modelling of the JET SOL

A guess for a high density case

$$M_{\parallel} = c_D M_{\parallel}^D + c_T M_{\parallel}^T + \ldots$$

$$M_{\parallel}^i = 1 + \chi_i - \sqrt{\chi_i^2 + 2\chi_i}$$

Sheath with a parallel magnetic field



Density and electric field profiles in the sheath

The sheath is **positively charged**
wall repels positive ions?

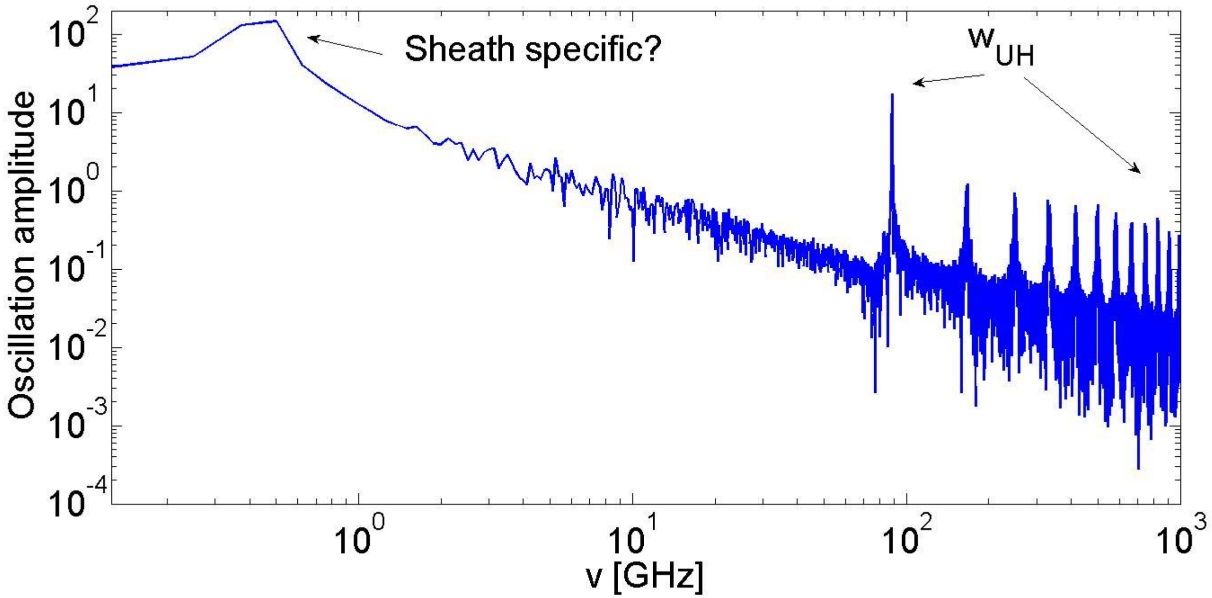
Different cases are running with and without neutrals, with different plasma radial profiles

Sheath with a parallel magnetic field: analysis

Radial transport in a partially ionized plasma

$$V_r = \frac{\mu}{1+\left(\omega_c / \nu_{mt}\right)^2} E_r - \frac{D}{1+\left(\omega_c / \nu_{mt}\right)^2} \frac{\partial_r n}{n}$$

$$\mu = \frac{e}{m\nu_{mt}}, \quad D = V_T^2 \frac{1}{\nu_{mt}}$$



Potential oscillation spectrum

Open questions

- Is such a sheath stable at all (2D study is required)?
- What is the actual critical angle α_{crit}, when negative sheath turns into the positive one? Previous study (e.g. [*Tskhakaya JNM 2003*]) indicates that $\alpha_{crit} < (m_e/M_i)^{1/2} \sim 0.5^\circ$