Progress on modelling of sheath boundary conditions in highly collisional conditions

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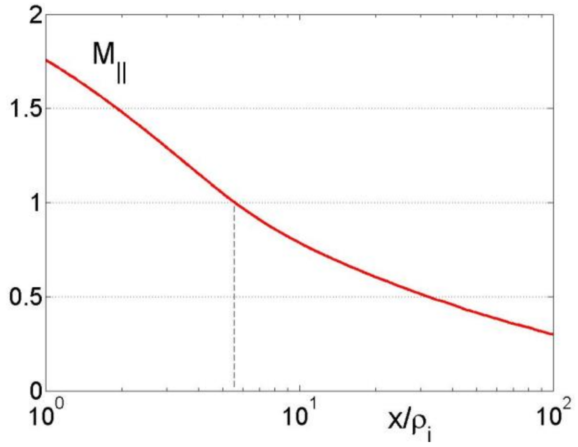
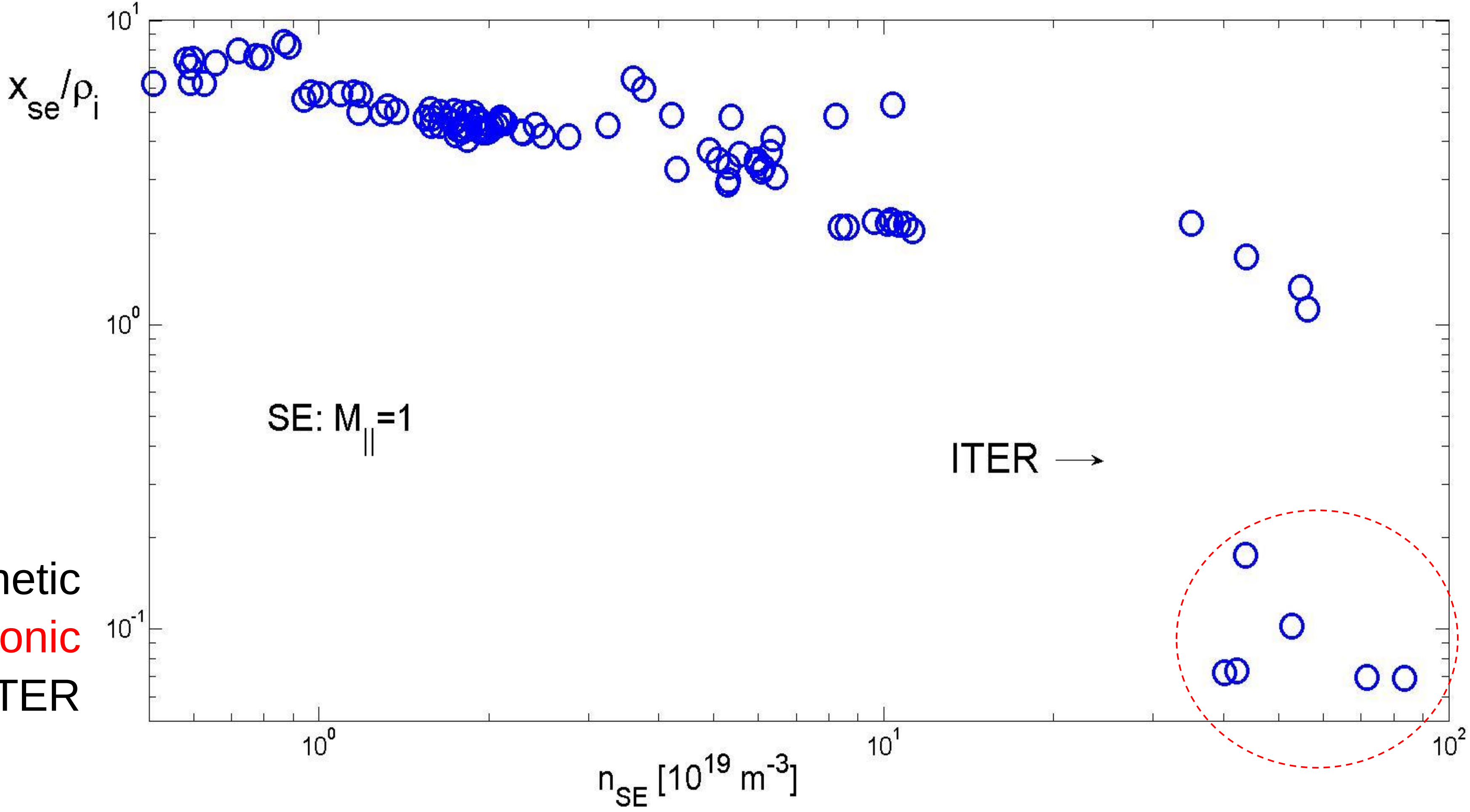
Motivation



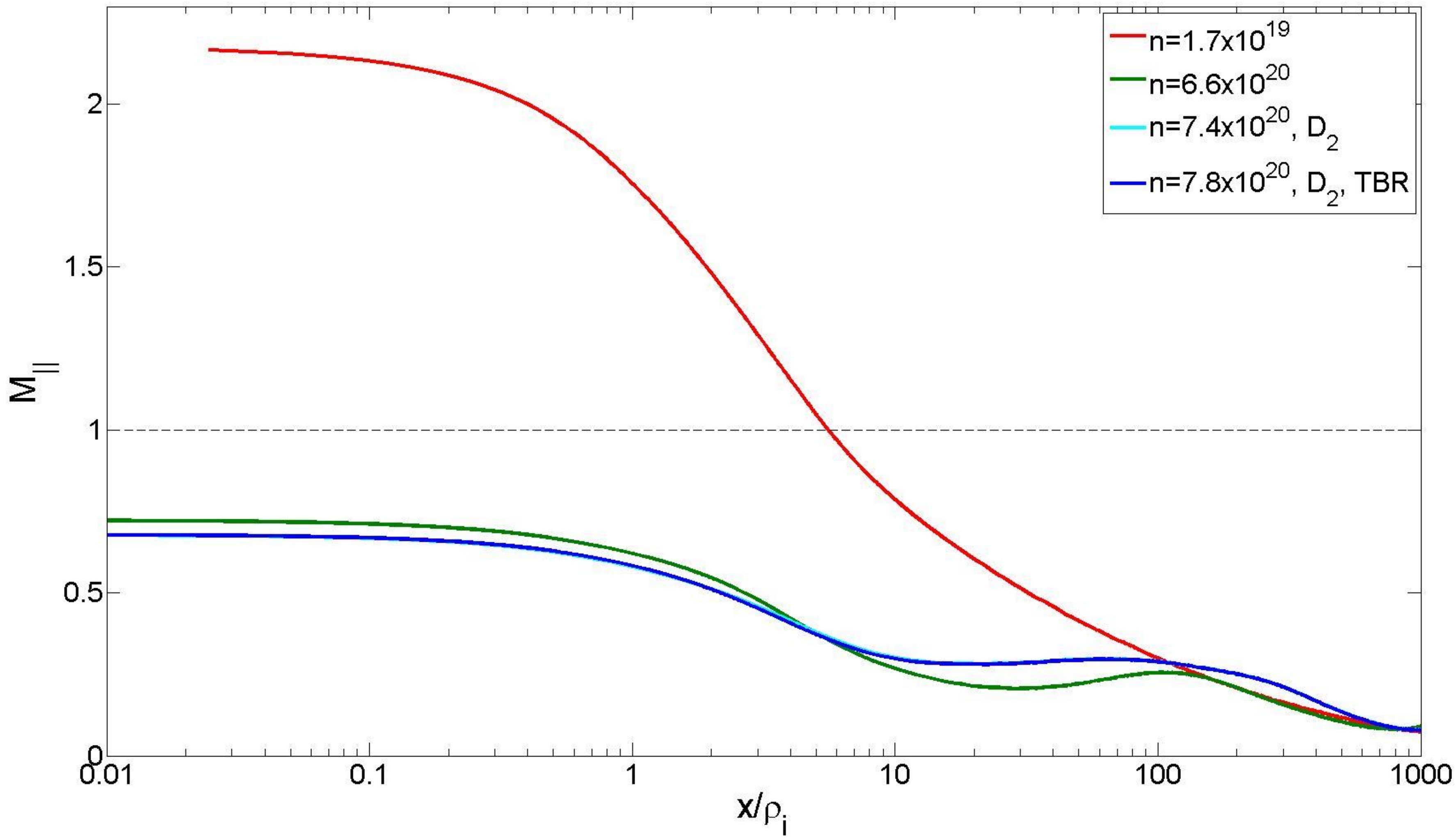
R= 0 – 1, Z_{eff} = 1 – 1.5, θ= 1.5° - 6°

[Tskhakaya PPCF 2017, PSI 2018]



Large set of SOL kinetic modelling indicated subsonic plasma flows for ITER relevant conditions

Profiles of the Mach number



Ion flux in a high density (n_e > 5x10^{20} m^{-3}), cold (T_e< 2 eV) sheath is

sub-sonic

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Sheath scaling

$$\Lambda = 29.9 - 0.5 \ln\left(n / T_e^3\right)$$

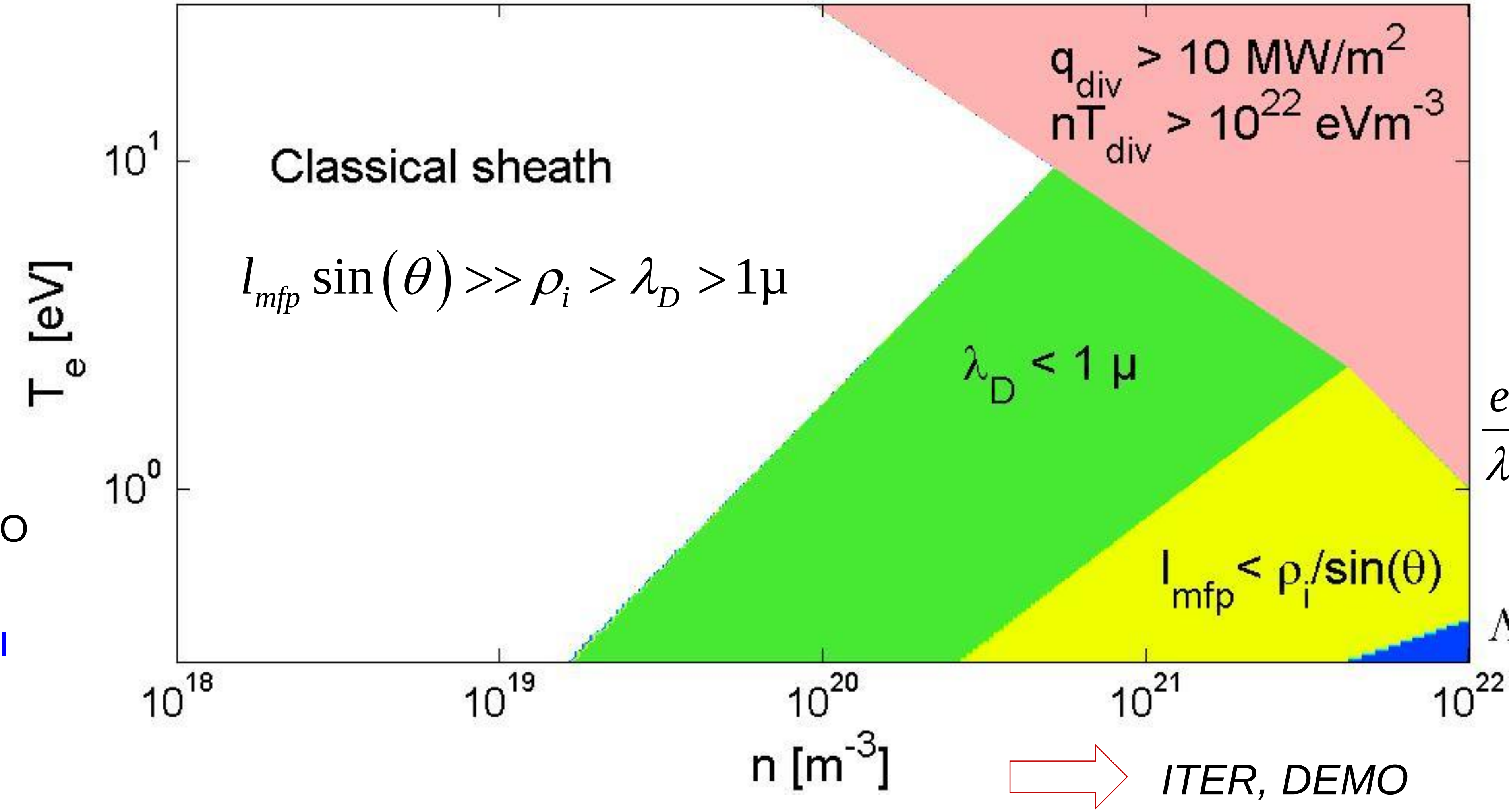
$$q_{div} = \gamma c_s n T_e$$

$$\lambda_D = 7.4 \times 10^3 \sqrt{\frac{T_e}{n_e}}$$

$$\rho_i = \sqrt{T_i m_i} / Z_i B$$

$$l_{mfp} = 2.0 \times 10^{17} \frac{T_i^2}{n \Lambda_{ii}}$$

$$B = 5\,[T], \quad \theta = 3^\circ$$



$$l_{mfp} \sin(\theta) >> \rho_i > \lambda_D > 1\mu$$

$$\frac{e^2}{\lambda_D} \sim T_e$$

↑

$\Lambda < 3$

ITER and DEMO divertor sheath

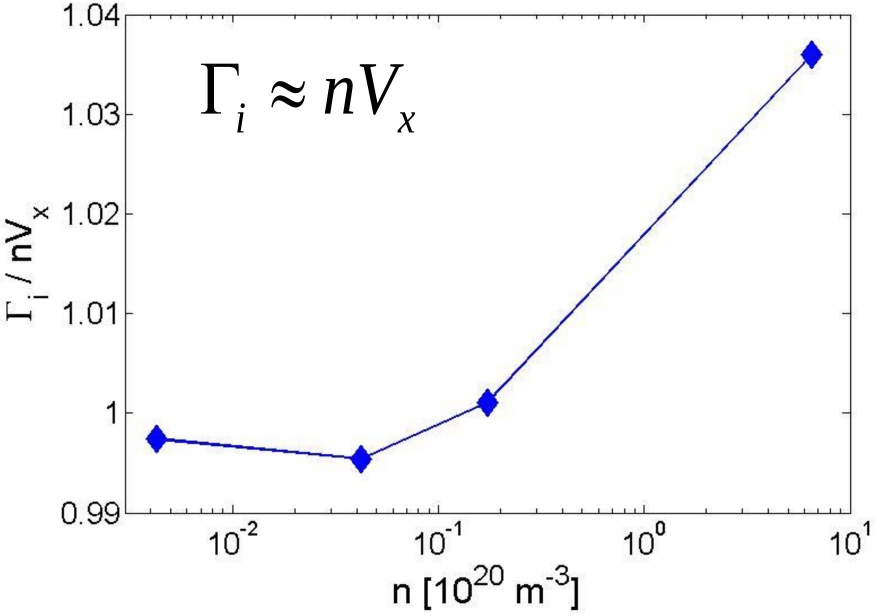
- **Coulomb collisional**
- **Inelastic collisional**
- **Rough** PFC surface

⇨ *ITER, DEMO*

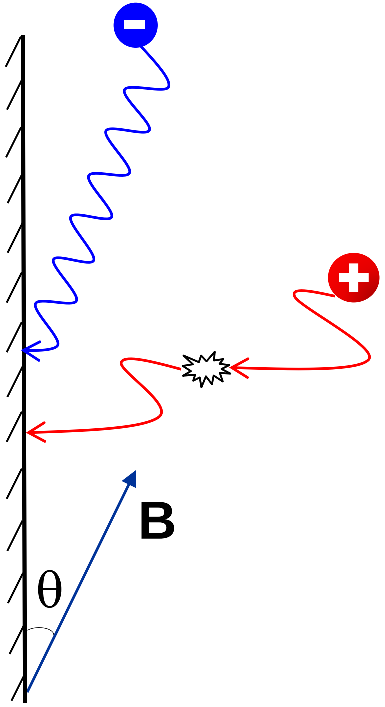
Understanding the mechanism of subsonic flow (i)

Is sheath transport diffusive?

$$\Gamma_i = nV_x + \Gamma_{diff} \ ?$$

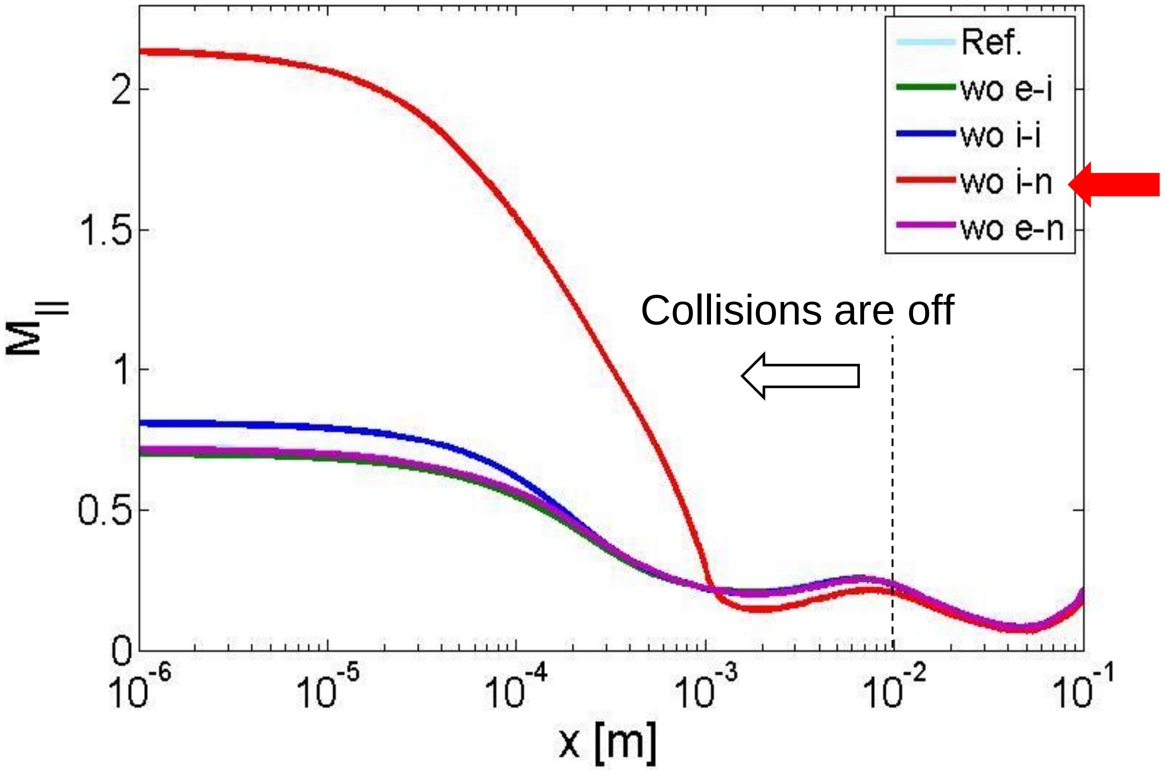


Normalized particle flux to the wall



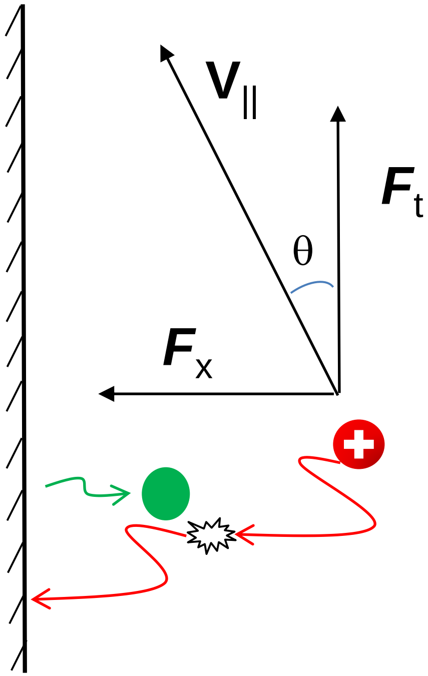
Numerical experiments

Mach number profiles



Ion-neutral friction is responsible
for subsonic plasma flow

Understanding the mechanism of subsonic flow (ii)



Adjusts to “keep” given current

Ion friction
with neutrals

Ion - electron friction

$$F_x \approx eE_x - m\upsilon_{mt} V_\parallel \sin(\theta) - m\upsilon_{ei} V_\parallel \sin(\theta)$$

$$F_t \approx -m\upsilon_{mt} V_\parallel \cos(\theta) - m\upsilon_{ei} V_\parallel \cos(\theta)$$

$$V_x \approx c_s \sin(\theta)$$

$$V_t < c_s \cos(\theta)$$

$$V_\parallel = V_x \sin(\theta) + V_t \cos(\theta) < c_s \longrightarrow$$ **Sub-sonic flow**

De-magnetization of plasma

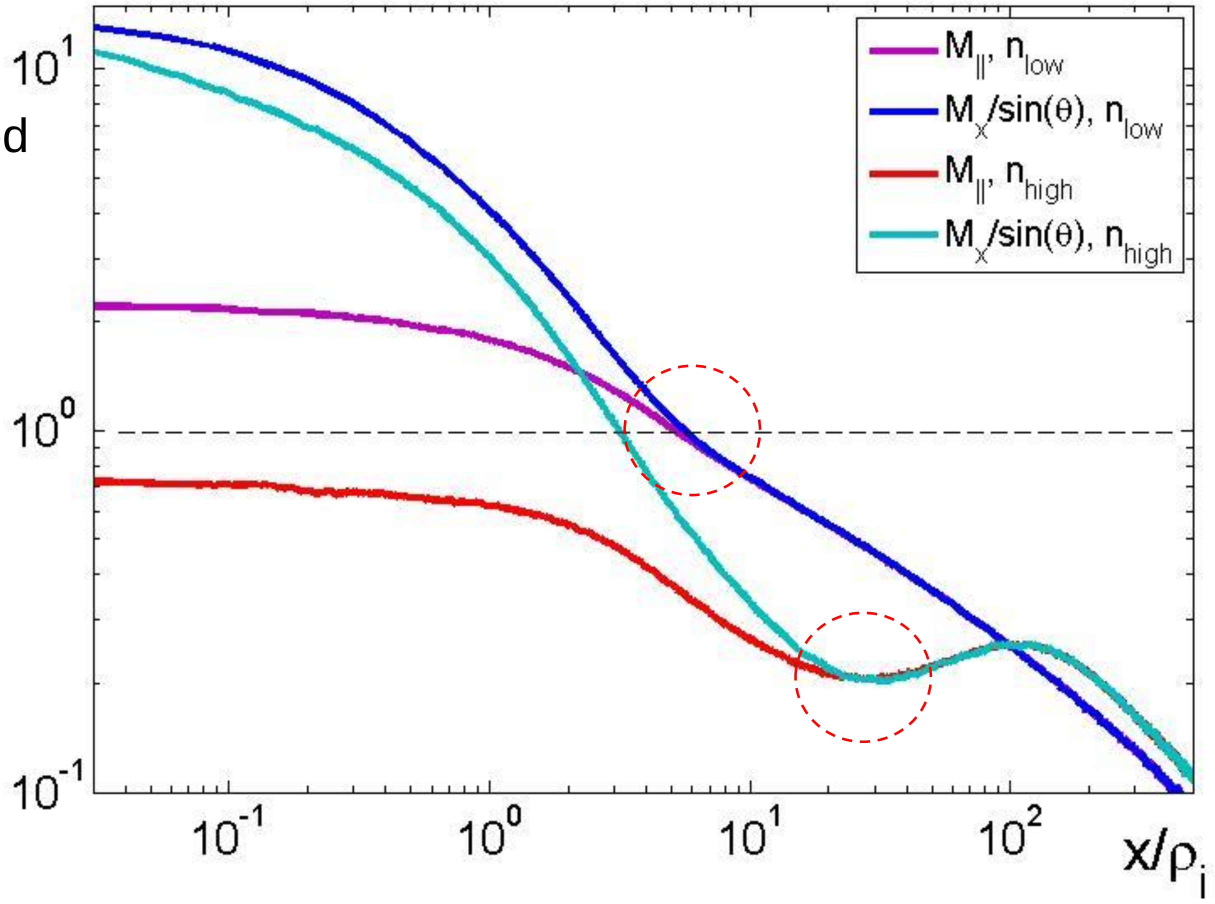
Classical sheath

- $M_{\parallel} = 1$
- plasma is magnetized

$$\vec{V} = \vec{b} V_{\parallel} + \vec{V}_{drifts}$$

Magnetization condition (1D)

$$M_{\parallel} = \frac{M_x}{\sin(\theta)}$$



Plasma is de-magnetized at the distance ~20 ρ_i

Proposal

We define the magnetic sheath entrance (SE) a **point nearest to the wall surface with magnetized ions**

Can be used

- as BC of fluid and gyro-kinetic codes
- for estimates of particle and heat fluxes to the divertors

Analytic model

Particle and momentum conservation equations

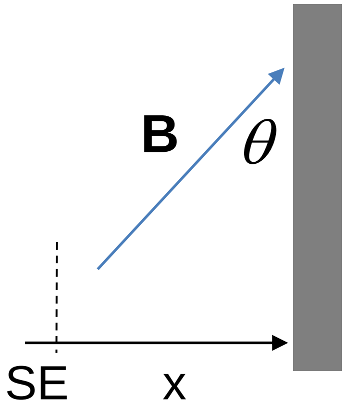
$$\vec{\nabla} n\vec{V} = 0, \qquad \cancel{\upsilon_i n}, \qquad \cancel{|\nabla \ln T|} << |\nabla \ln n|, \qquad |\cancel{\vec{\nabla}\vec{\pi}}| \sim \tau_{col},$$

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

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

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

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

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

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

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

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

$$\boxed{M_\parallel < 1}$$

For constant

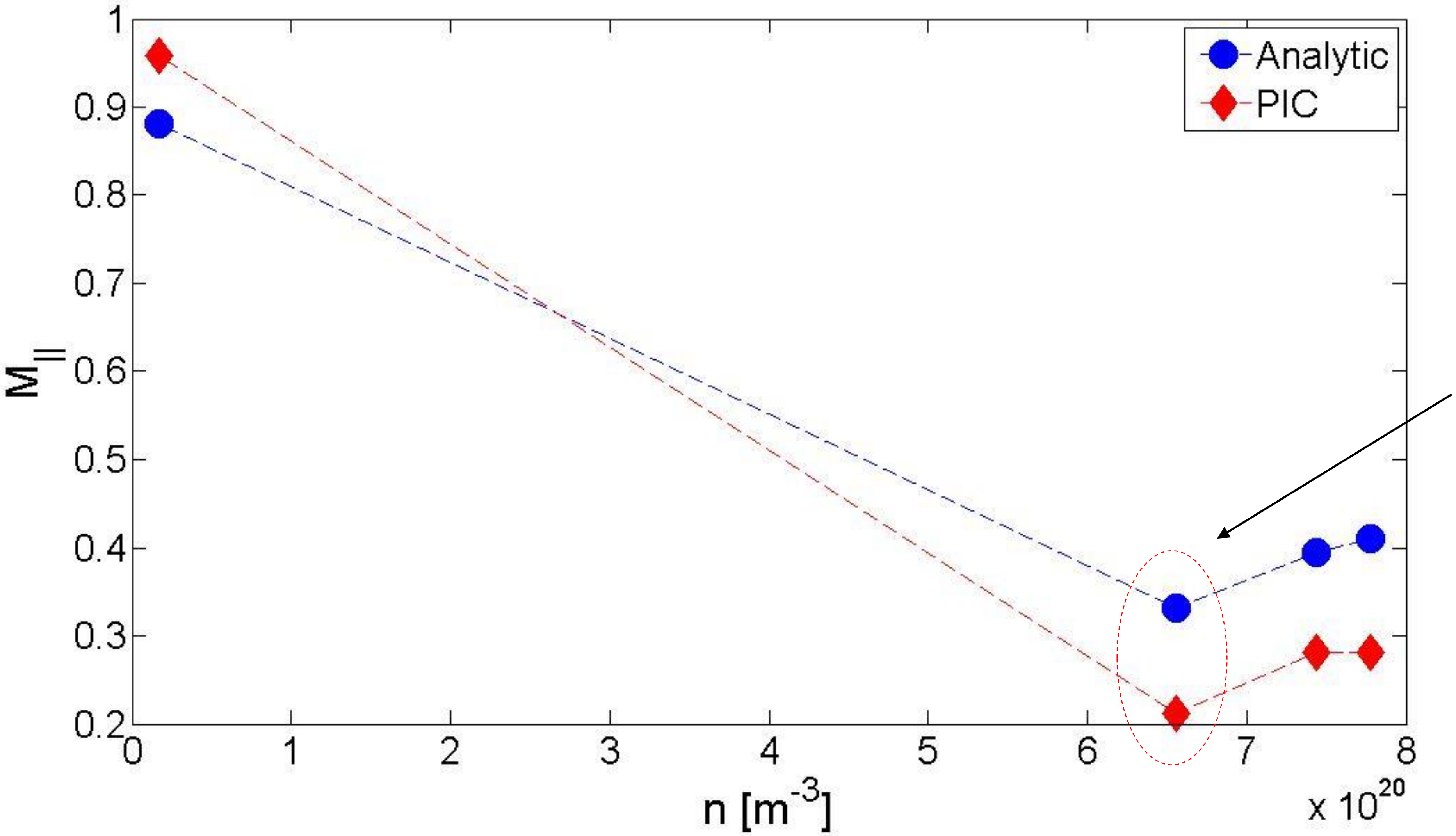
$$\upsilon_{mt},\ \upsilon_{ei},\ \alpha$$

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

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

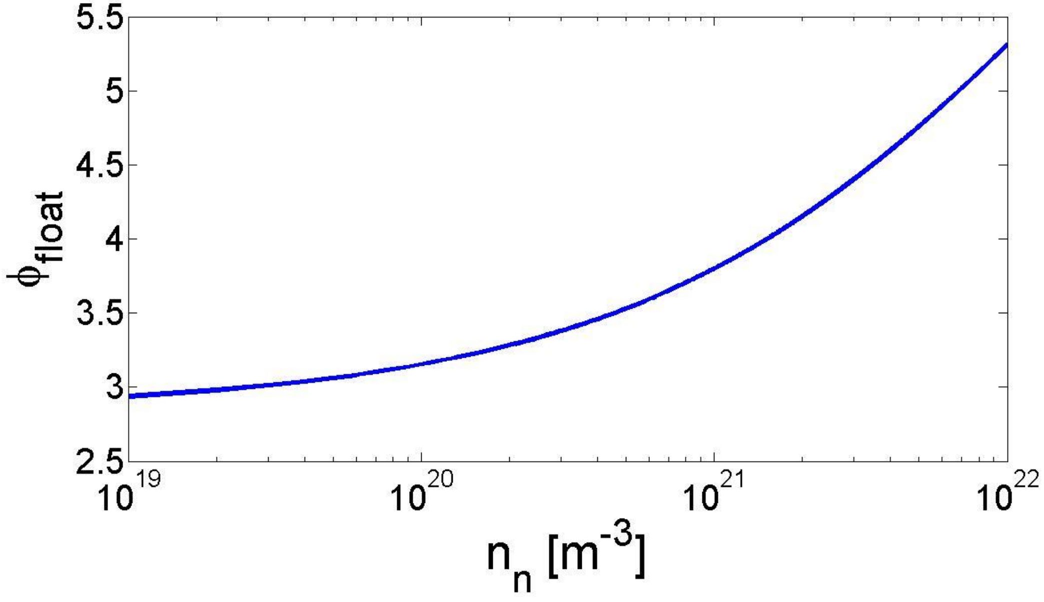
$$M_x\left(x_0\right) = \sin\left(\theta\right),\ x_0 \approx x_{wall}$$

Analytic model / comparison with PIC results



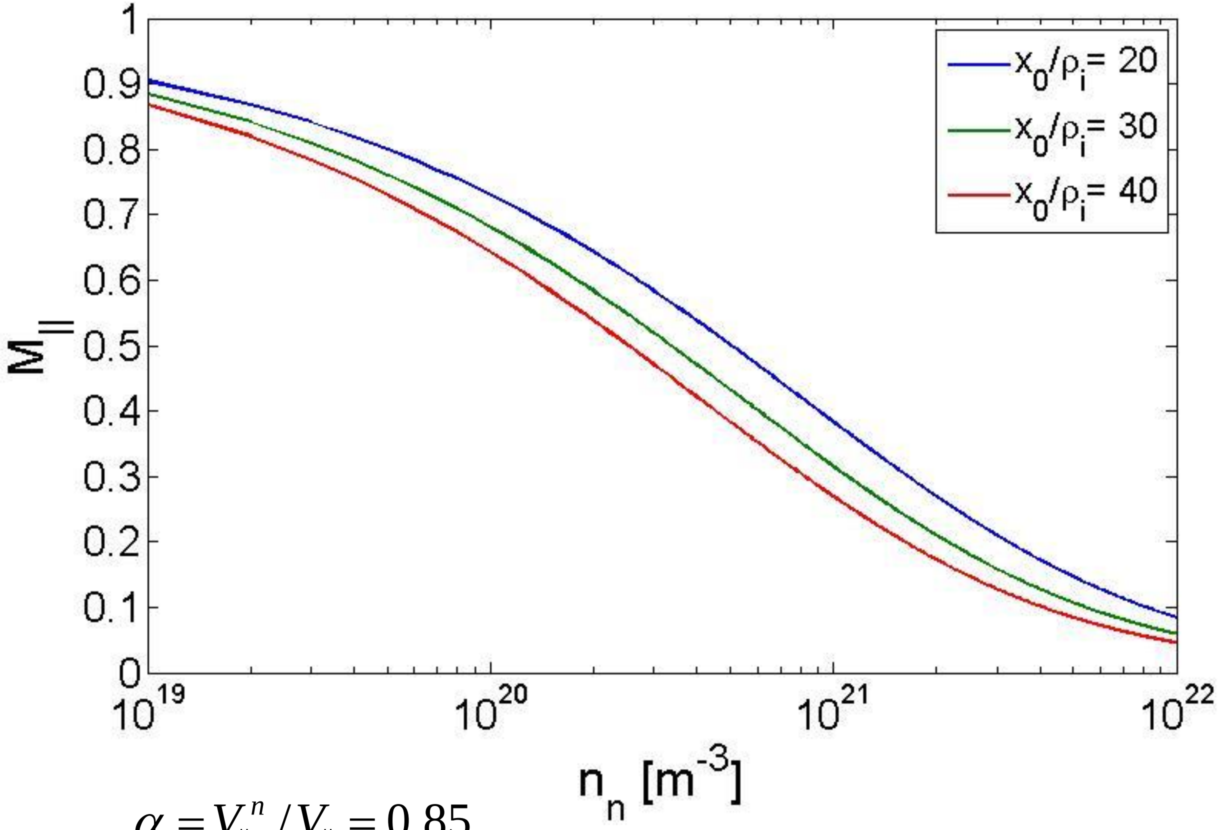
Set of runs with different plasma current

Extrapolation of results



Potential drop across the floating sheath

Weak dependence of $M_{||}$ on x_0



$$\alpha = V_{||}^{n} / V_{||} = 0.85$$

ITER modelling (SOLPS-ITER)

[D. Moulton ISFN 9.2021]

Neglect current for the moment since this formula overstates the importance of current in PIC simulations

Ion-atom momentum transfer collision frequency (see later)

$$\alpha = V_{\parallel}^{D} / V_{\parallel}^{D+}$$

$$\rho_i = \frac{\sqrt{T_i m_{D+}}}{eB}$$

$$\chi = (\upsilon_{mt}(1-\underline{\alpha}) + \upsilon_{ei} I') \frac{\overline{x_0}}{2 c_s \sin(\theta)}$$

Use $x_0 = 20\rho_i$ ($M_{\parallel}$ is insensitive to reasonable choices)

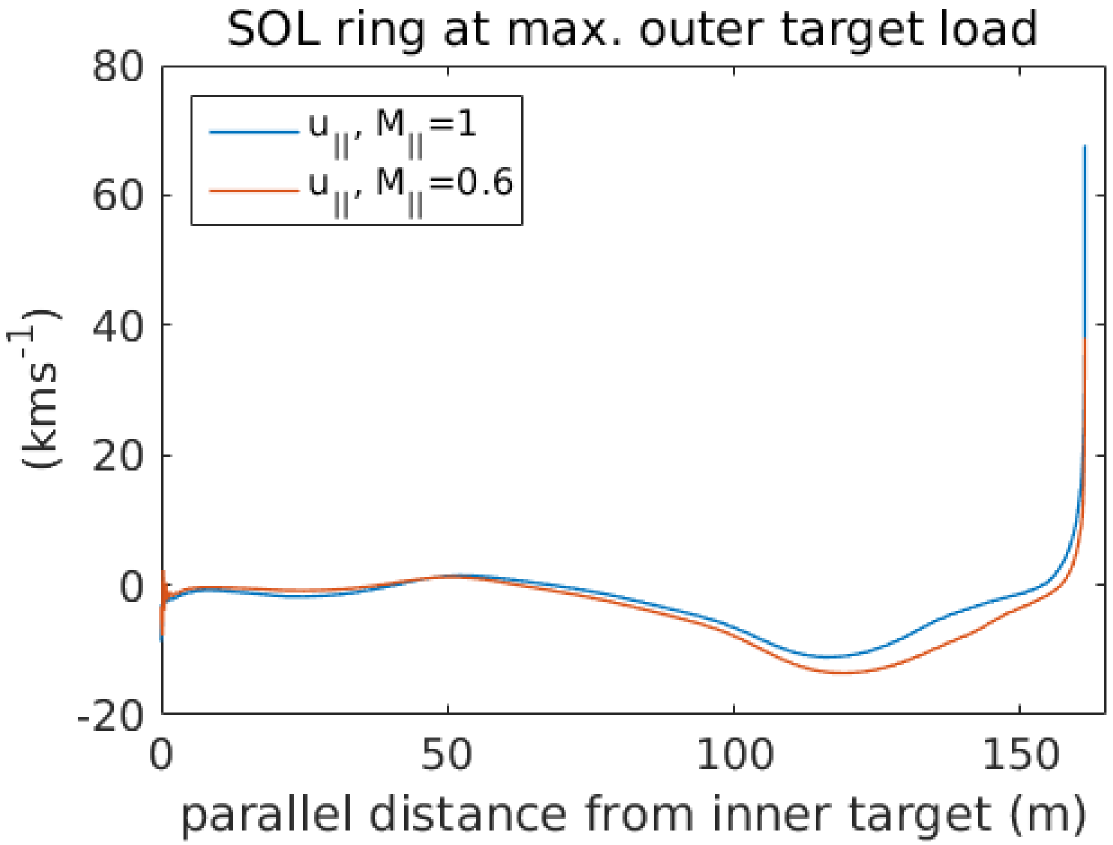
$$\sin(\theta) = B_{\theta} / B_{tot}$$

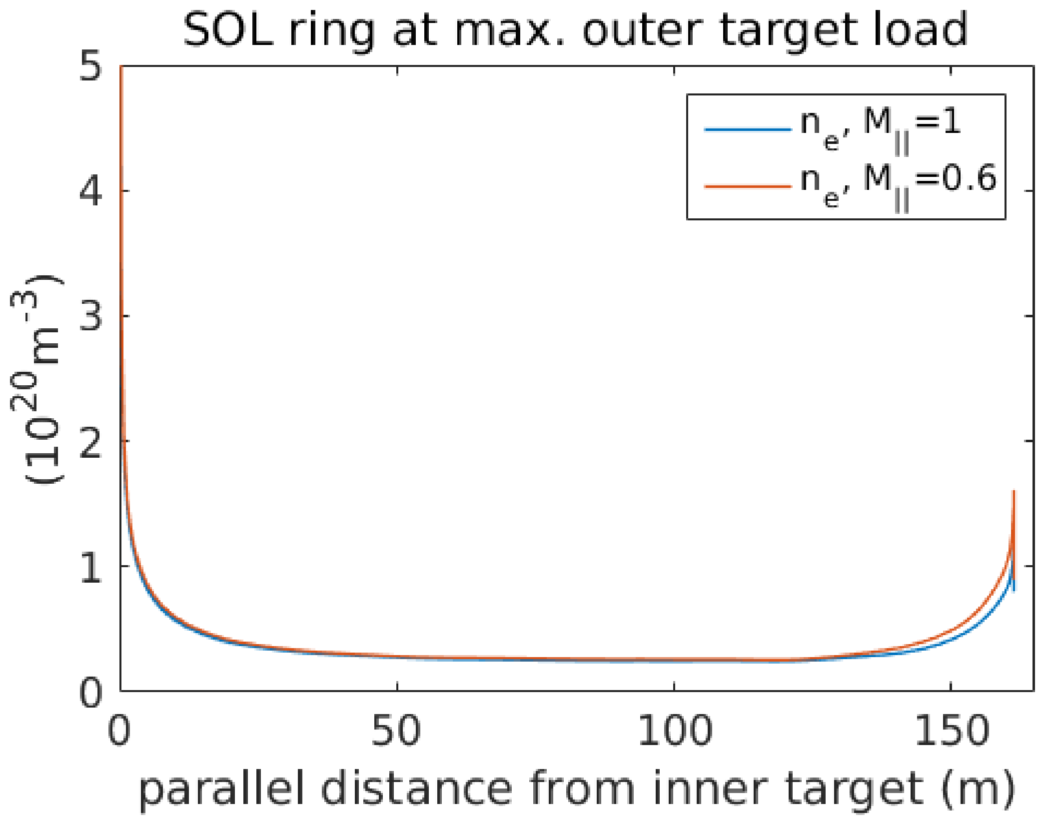
$$\boxed{M_{\parallel} = 1 + \chi - \sqrt{\chi^2 + 2\chi}}$$

$$c_s = \sqrt{\frac{T_e + T_i}{m_{D+}}}$$

ITER modelling: results

[D. Moulton ISFN 9.2021]





The change in n_e doesn't alter the dissipation because there is none in this killer flux tube

Question: what about at higher densities?

conclusions

- Divertor plasma sheath will be **collisional** in next fusion devices. Plasma flow in this sheath is **sub-sonic** and characterised by a significantly lower plasma **particle and heat fluxes** to the wall (for a fixed divertor density)

- The Mach number at the SE depends on plasma collisionality (charge exchange and Coulomb); contrary to this the sheath potential drop depends on collisionality weakly

- A new definition of the magnetic presheath entrance (SE) is proposed:

  a nearest point to the wall surface, where plasma is still magnetised.

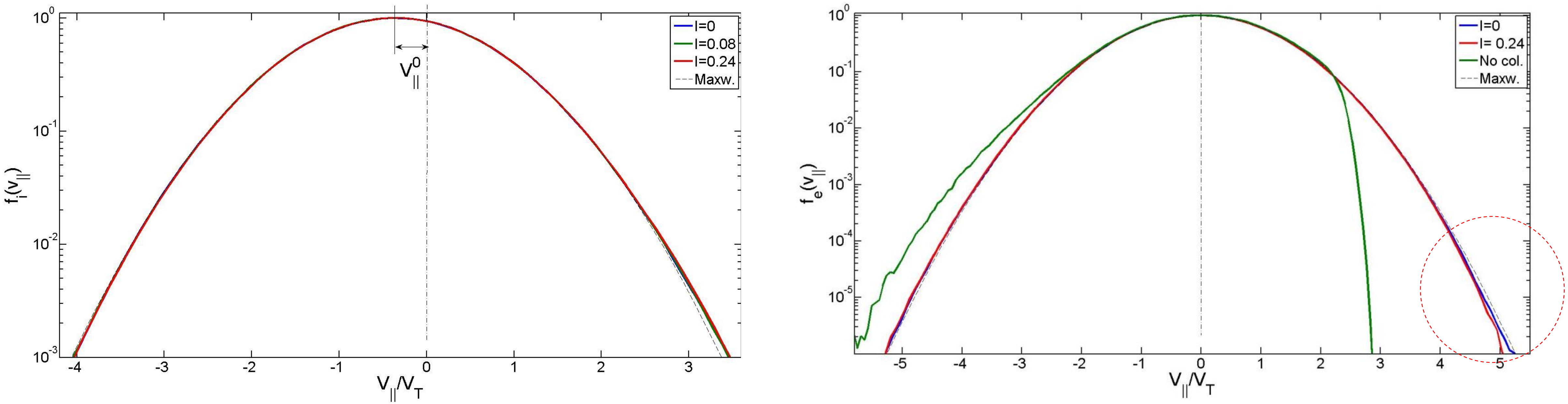
  $$M_{\|} = 1 + \chi - \sqrt{\chi^2 + 2\chi}$$

  For collisionles limit it reduces to the Bohm–Chodura condition – $M_{\|} = 1$

- First ITER simulations (D. Moulton) with updated boundary condition show no significant change of the plasma divertor fluxes for the moderate collisionality case; although plasma density in the vicinity of the target significantly enhances (by the factor ~2)

On electron-ion friction force at the SE

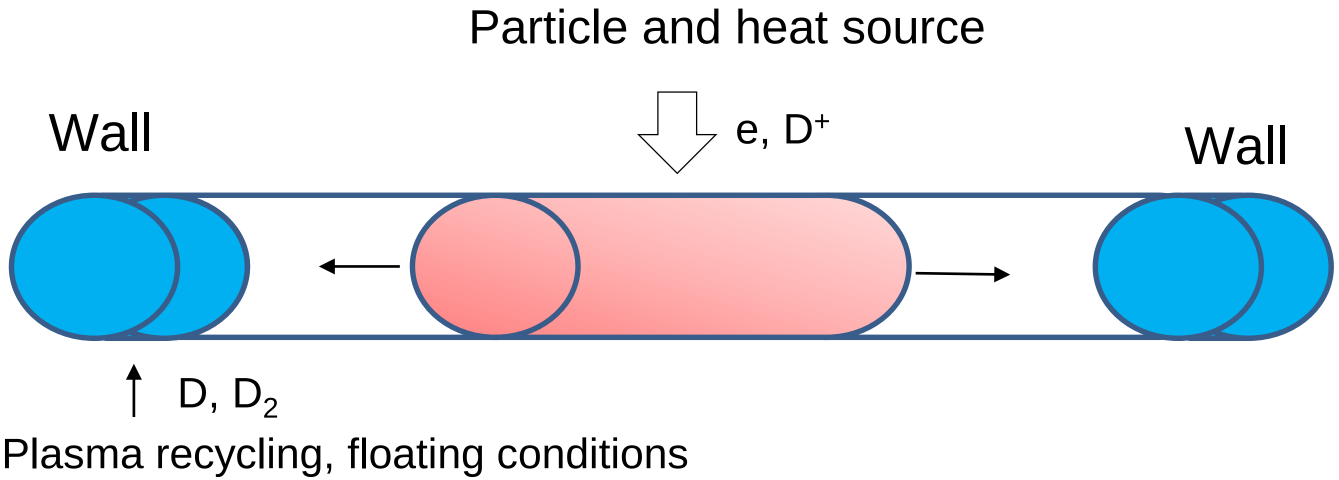
Electron and ion (D^+) VDFs at the high collisional sheath edge for different current regimes ($I = J/J_{sat}$) from the PIC model



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

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

Backup: Simulation model (BIT1)



Particle and heat source

e, D^+

Wall

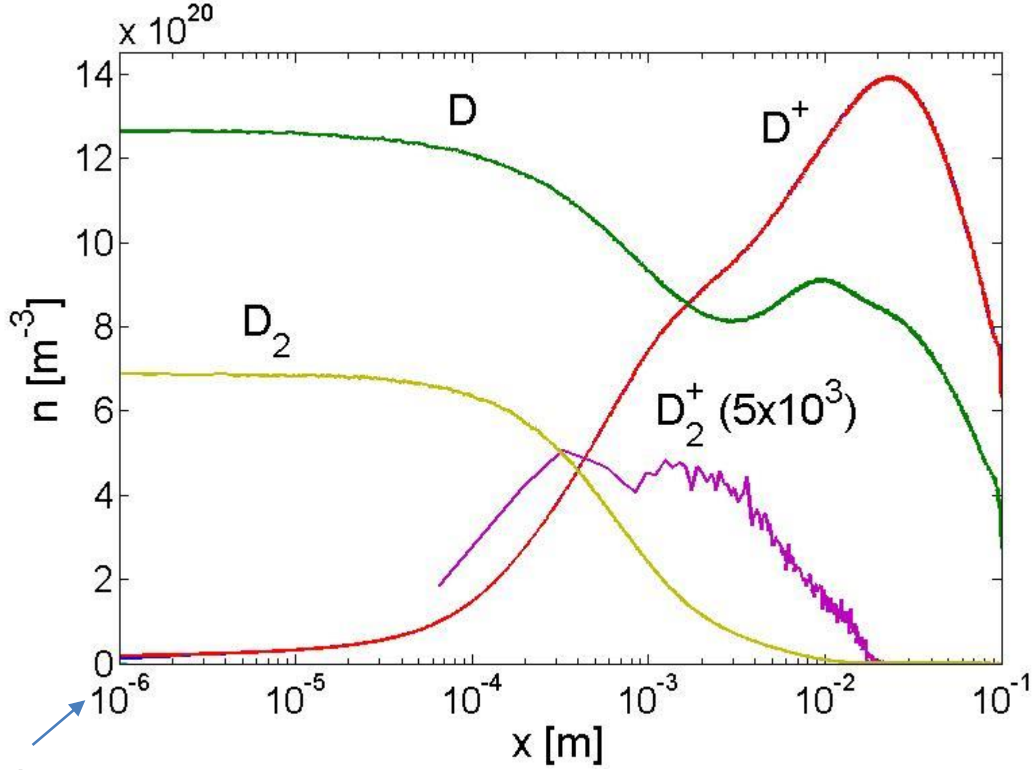
Wall

D, D_2

Plasma recycling, floating conditions

SE density [x10^{20}]	Plasma recycling	Molecules	Three-body recombination	Current in ion sat.
Low 4×10^{-3}	X	X	X	0
Moderate 0.04	X	X	X	0
High 0.17	√	X	X	0
Very high 6.6	√	X	X	0 – 0.24
Very high 7.4	√	√	X	0
Very high 7.8	√	√	√	0

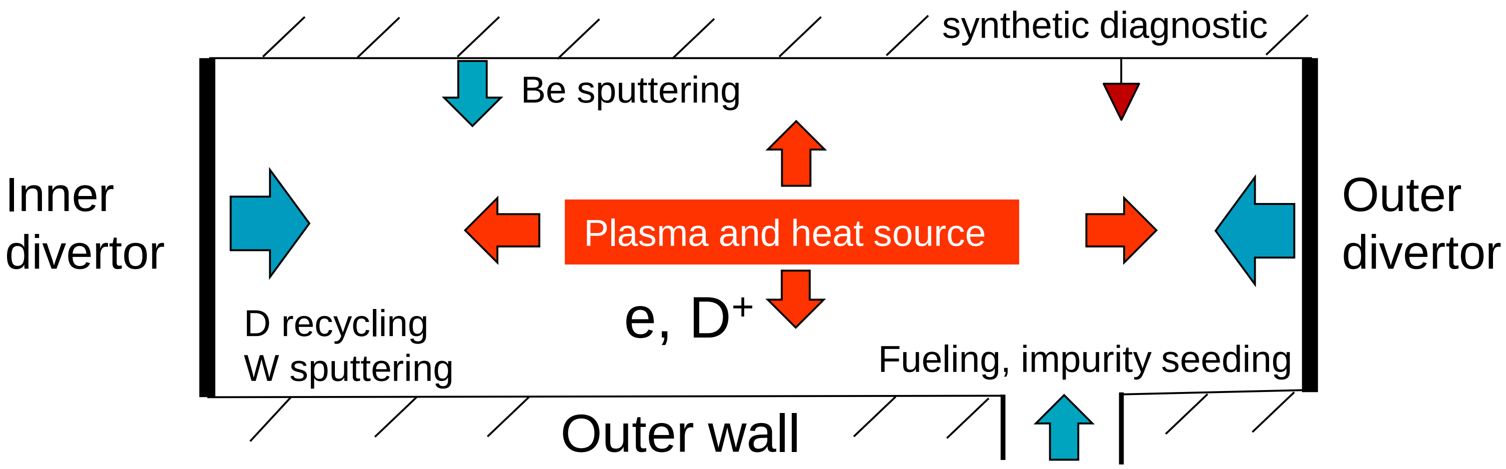
Each simulation takes up to 3×10^6 core hours, 10^9 particles



Divertor plate

Plasma density profiles

Backup: BIT1



- Massively parallel (scaling >$4x10^3$)
- Nonlinear interaction between plasma, neutral and impurity particles, linear PSI (all together ~1000 processes)

Atomic and molecular processes used in presented PIC simulations

$e + M \rightarrow e + M$	Elastic		
$e + M \rightarrow e + M^*$	Excitation (electronic, vibrational, rotational)		
$e + M \rightarrow 2e + M^+$	Ionization		
$e + M \rightarrow e + A + B$	Dissociation	$A + M \rightarrow A + M$	Elastic
$e + M \rightarrow 2e + A^+ + B$	Dissociative ionization	$A + M \rightarrow A + M^*$	Excitation
$e + M^+ \rightarrow A + B$	Dissociative recombination	$A^+ + M \rightarrow A + M^+$	Charge exchange
$e + M^+ \rightarrow M + vh$	Recombination	$A + M^+ \rightarrow A^+ + M$	Charge exchange
$2e + M^+ \rightarrow e + M$	Three-body recombination	$A + M \rightarrow A + B + G$	Dissociation

M – molecule, or atom
A – atom