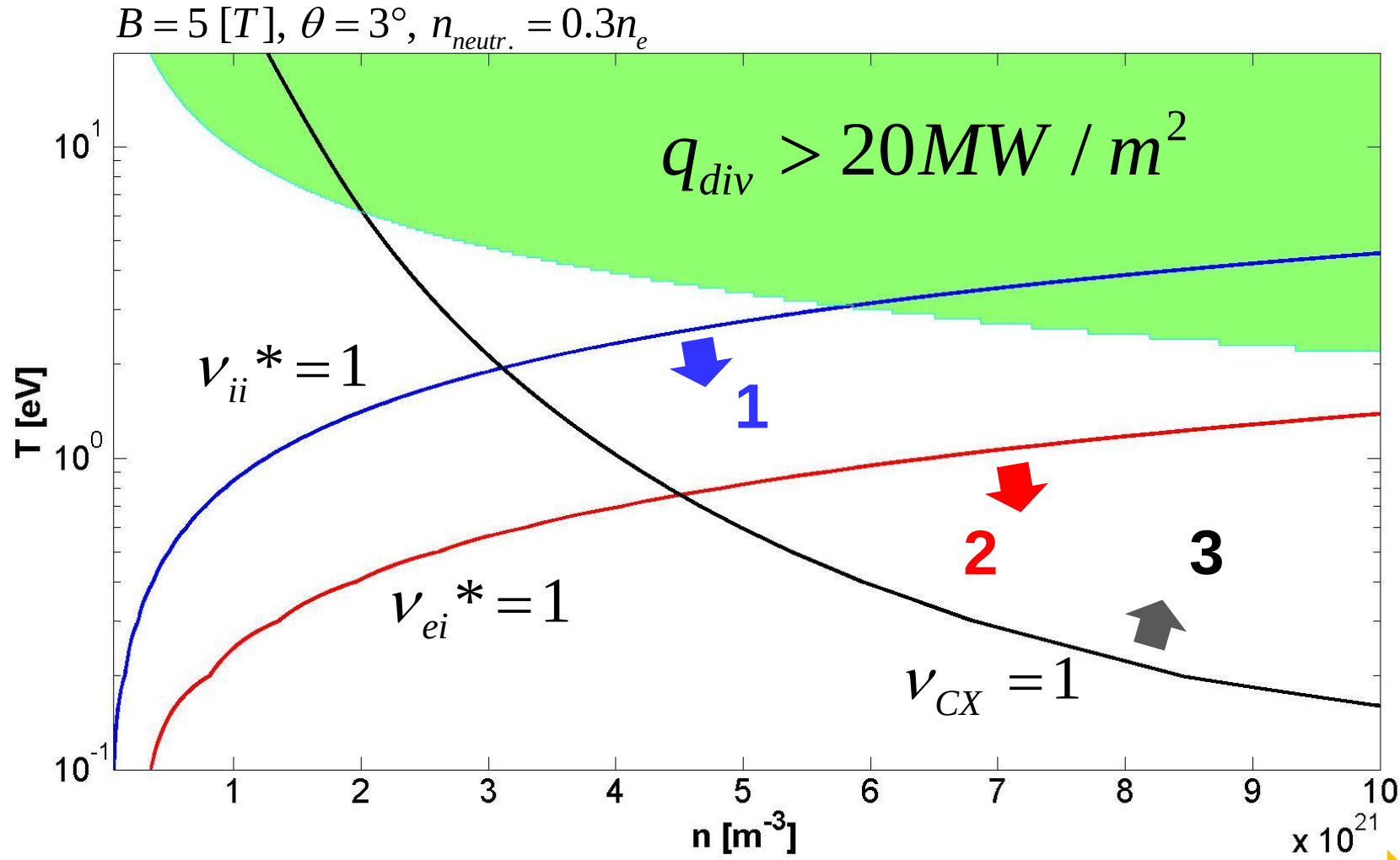


Status of collisional sheath modelling with He and recent developments of BIT1 code

D. Tskhakaya

Institute of Plasma Physics of the Czech Academy of Sciences, Prague, Czech Republic

- Summary of the collisional sheath model (from PSI 2026)
- Collisional sheath with mid-z impurity
- Recent results with He
- Status of the updated BIT1
- Conclusions



$$\nu_{ii}^* = \frac{V_{ii}}{\Omega_i} \quad \nu_{cx}^* = \frac{V_{cx}}{\Omega_i \sin \theta}$$

$$\nu_{ei}^* = \frac{V_{ei}}{\Omega_i \sin \theta}$$

1	Ion de-magnetization
2	Electron-ion collisional sheath
3	CX collisional sheath

ITER, BEST, DTT, SPARC, STEP, COMPASS-U, ...

[D. Tskhakaya, PSI, 2026]

Particle and momentum conservation equations

$$\left(\left(1 + v_{ei}^{*2} \right) / M_{\parallel}^2 - 1 \right) \partial_x M_{\parallel} = v_{CX}^* A + v_{ei}^* B$$

Generalized boundary condition

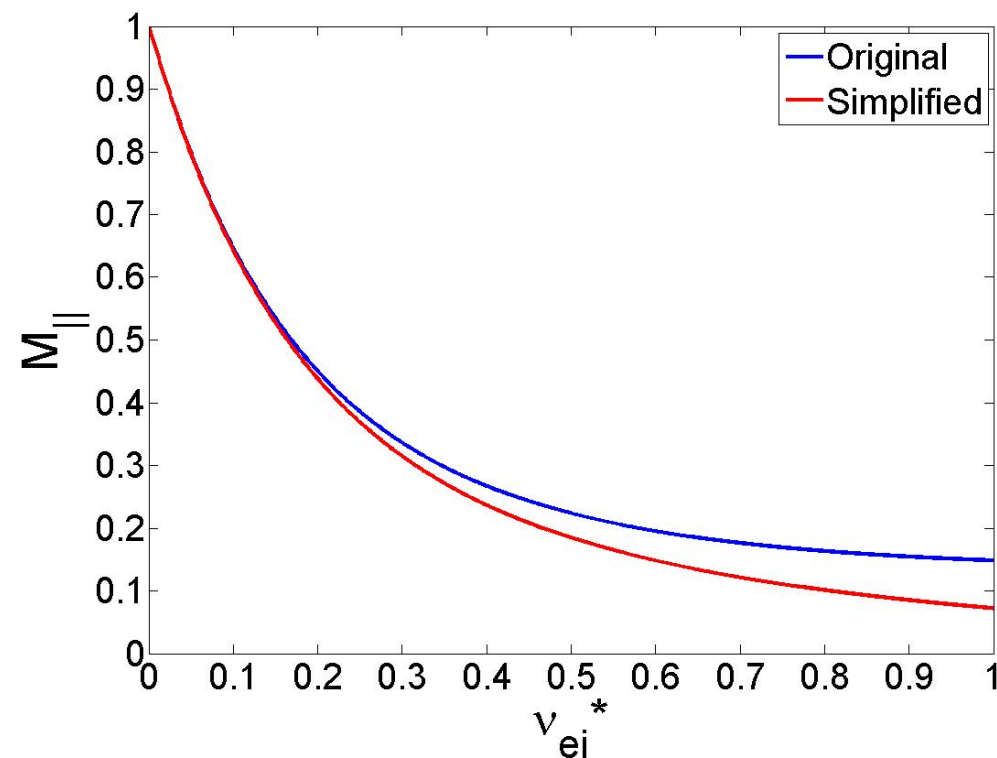
$$M_{\parallel} = 1 + v_{ei}^{*2} / 2 + \chi - \sqrt{\chi^2 + \left(2 + v_{ei}^{*2} \right) \chi + v_{ei}^{*4} / 4}$$

If we neglect nonlinear terms

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

$$\chi = \frac{1}{2} \left(\delta \sin(\vartheta) v_{CX}^* + v_{ei}^* \right) x_{SE}$$

$\delta \sim 1$



- ✓ Mach number **decreases rapidly** with increasing collisionality
- ✓ The **simplified expression** of the Mach number **well-reproduces** the original one

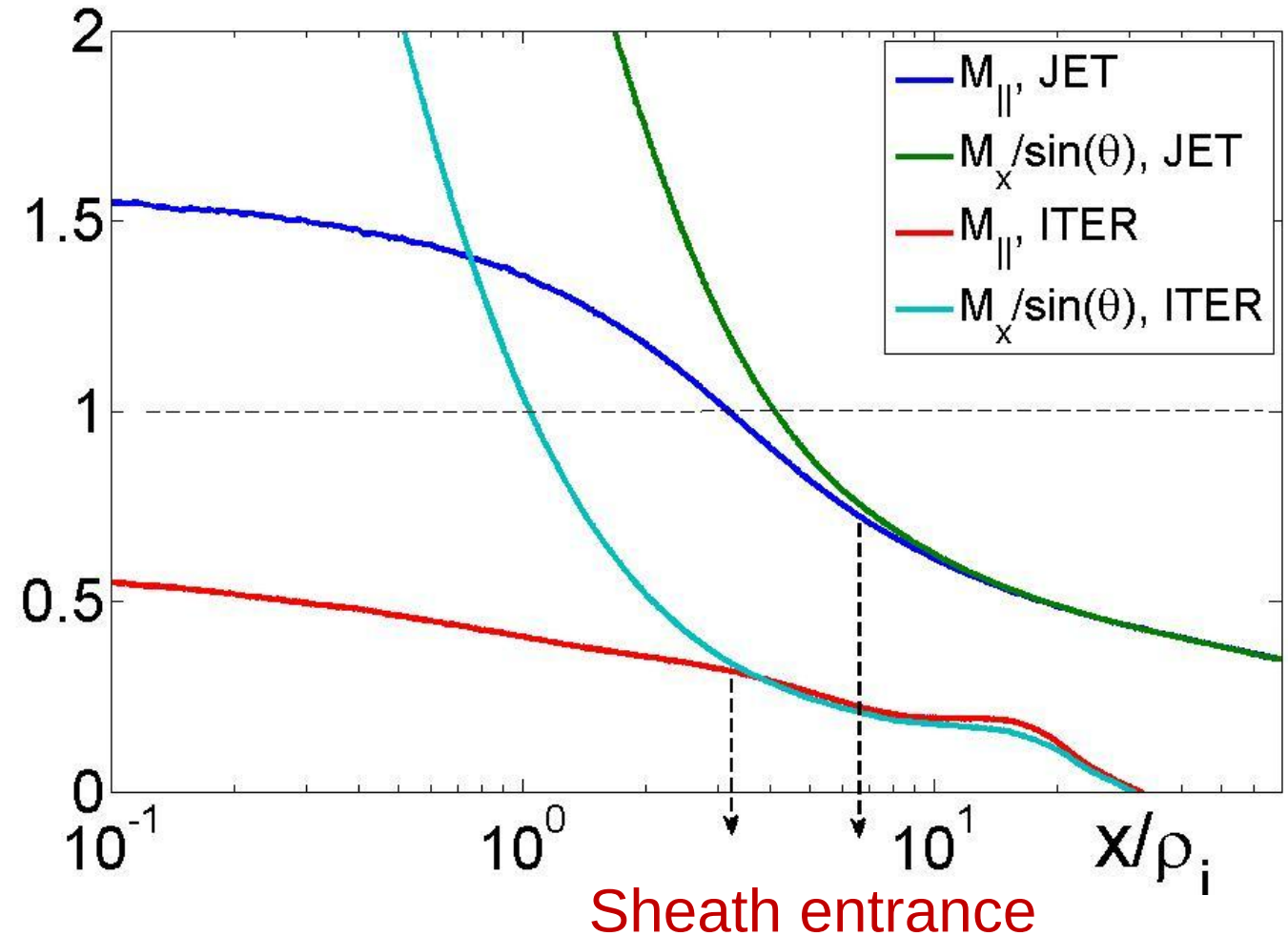
Classical sheath

- $M_{\parallel} = 1$
- Plasma (1D) is magnetized when

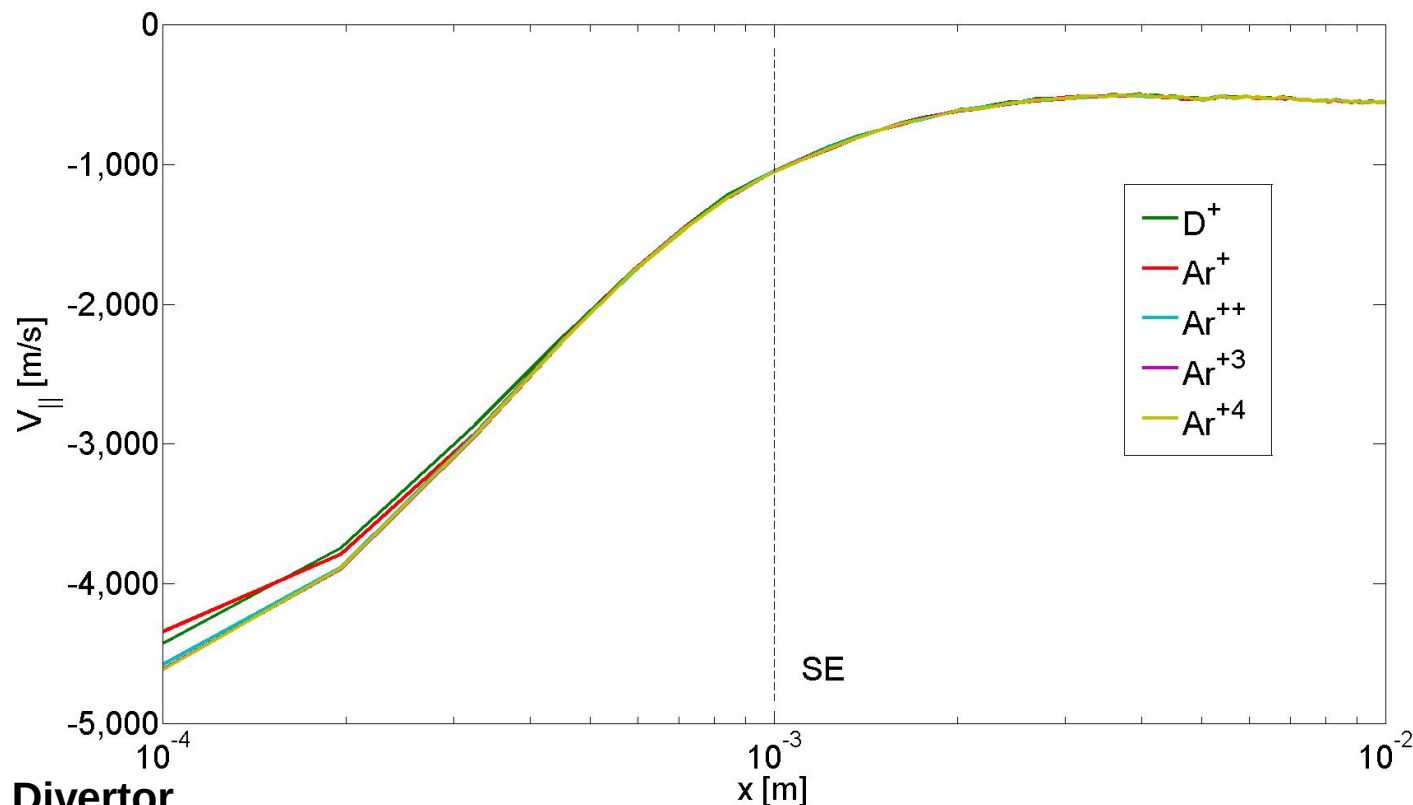
$$M_{\parallel} = \frac{M_x}{\sin(\theta)}$$

Collisional sheath (proposal)

We define the magnetic sheath entrance (SE) as **a point nearest to the wall surface, where ions are still magnetized**



What about the impurity in the CS?



Divertor
surface

$V_{||}$ profiles in the CS

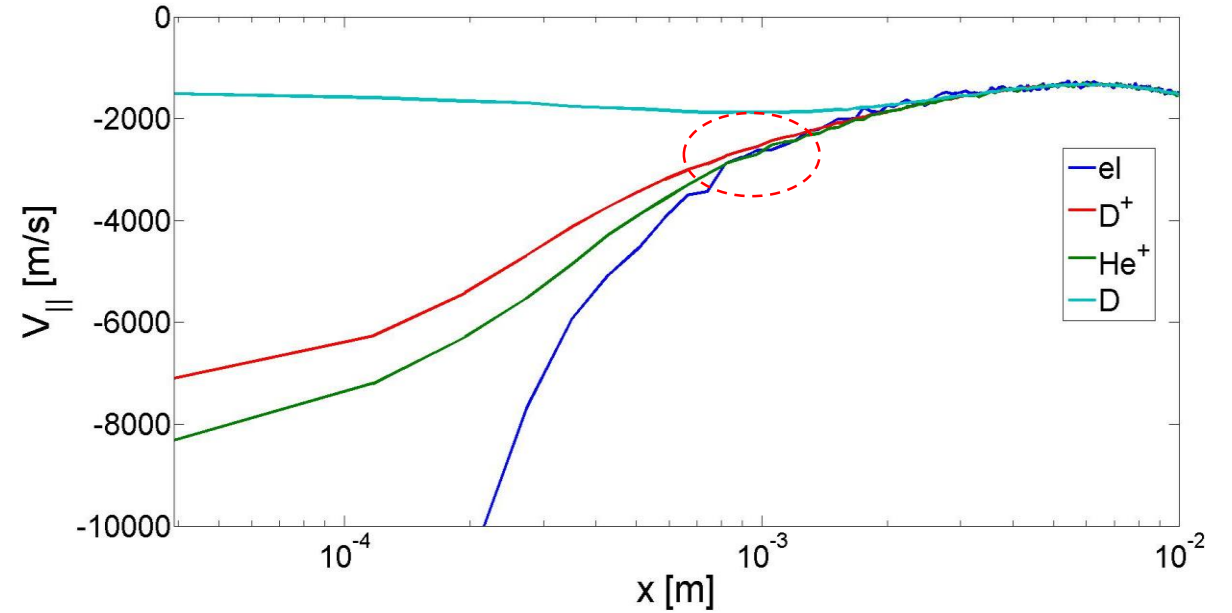
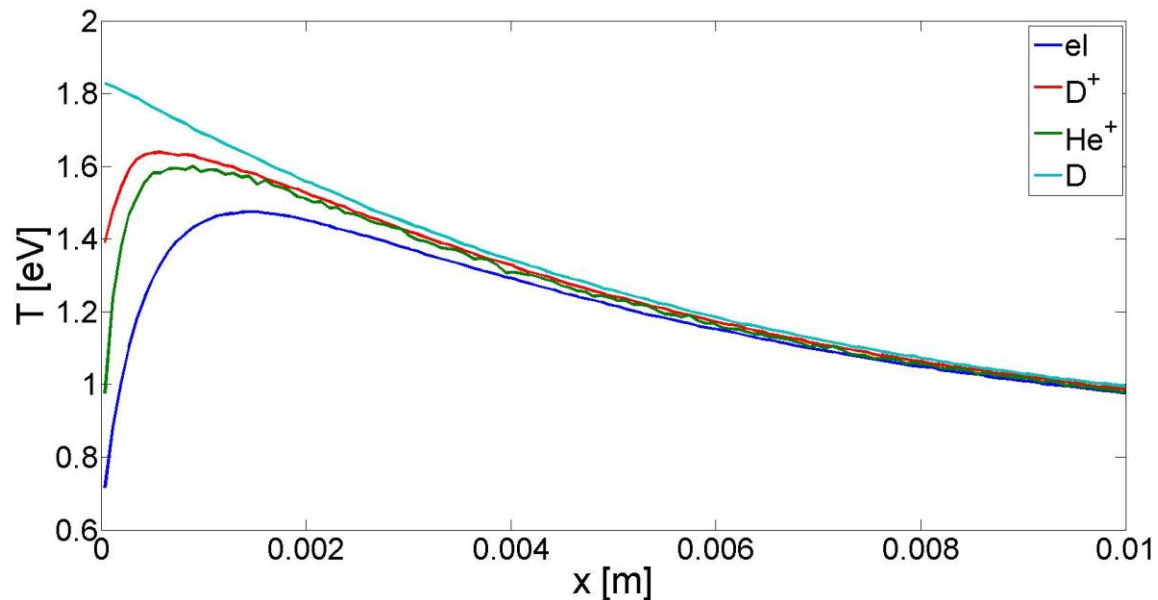
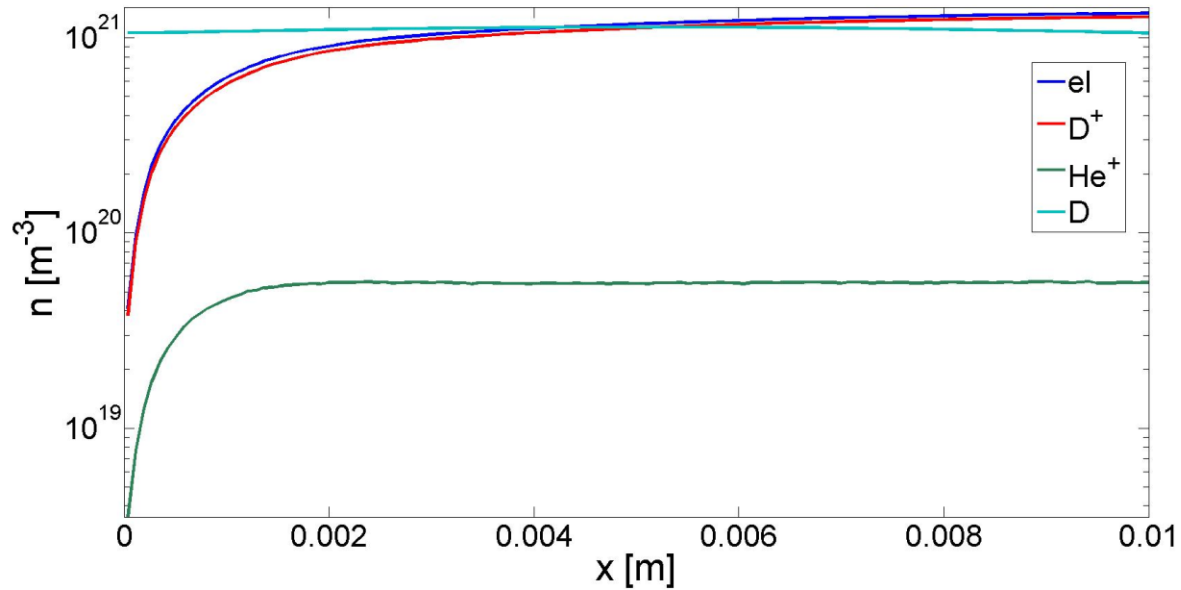
Strong coupling between the main and impurity ions

$$M_{||}^{imp} = M_{||} \sqrt{\frac{m_{imp}}{m_i}} \quad (T_{imp} \sim T_i)$$

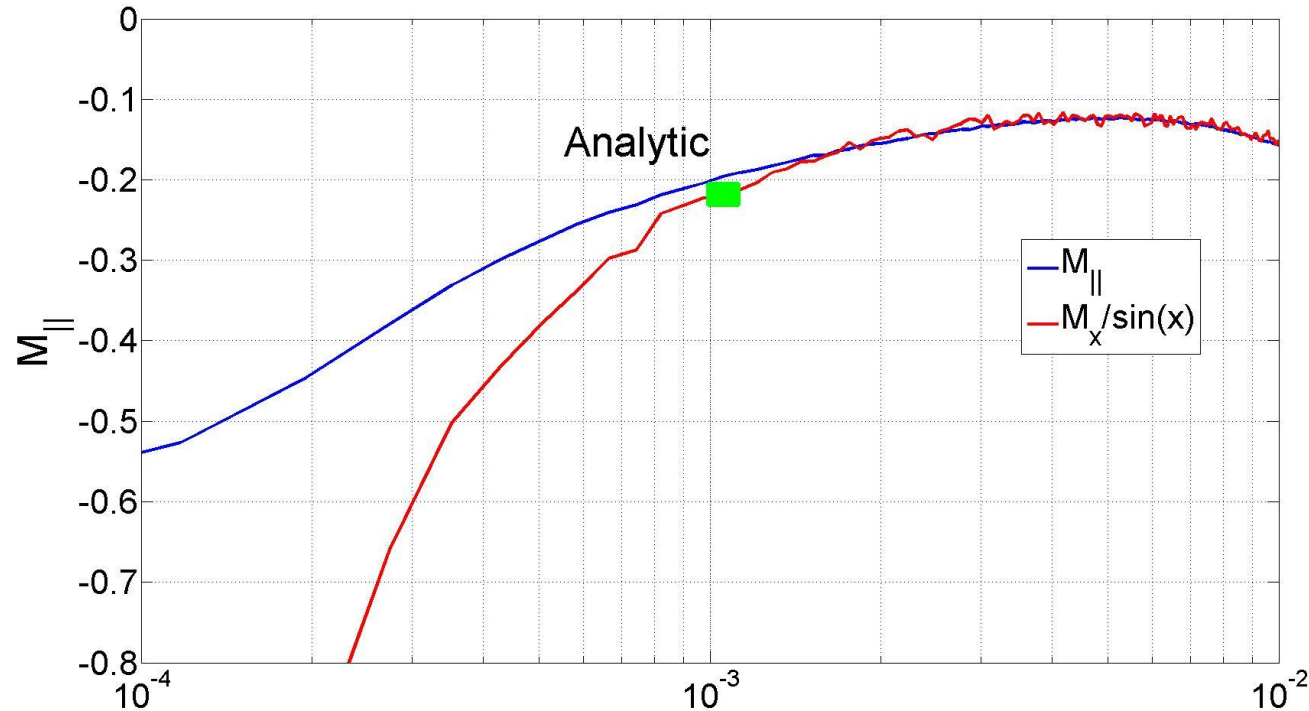
$$M_{||} = 1 + \chi - \sqrt{\chi^2 + 2\chi}$$

[D. Tskhakaya, TSVV-3 TSVV, 2024]

CS with low-z impurity



- ✓ Strong coupling of the main and He⁺ ions
- ✓ He concentration ~10%
- ✓ $T_i = T_{He}$
- ✓ The simulation is still running



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

	Without He	With He
Pot/T _e	3.39	3.37
M	0.21	0.20

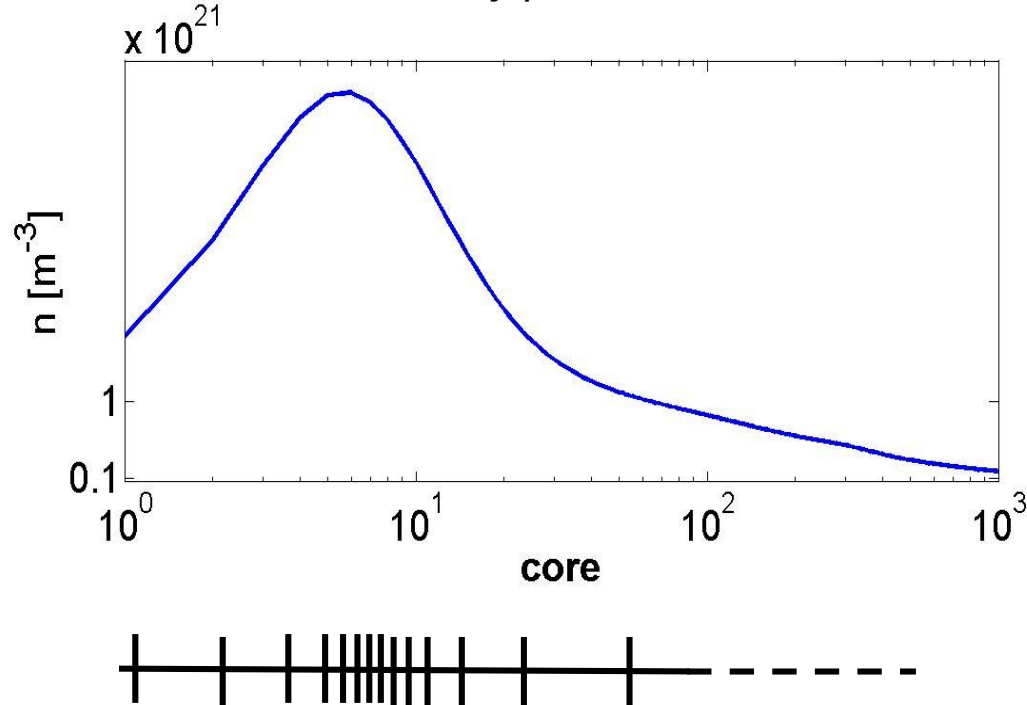
No significant influence of He on CS parameters ($c_{He} \sim 10\%$)

What about DT mixture?

✓ Simulation technique with impurity has been optimized.

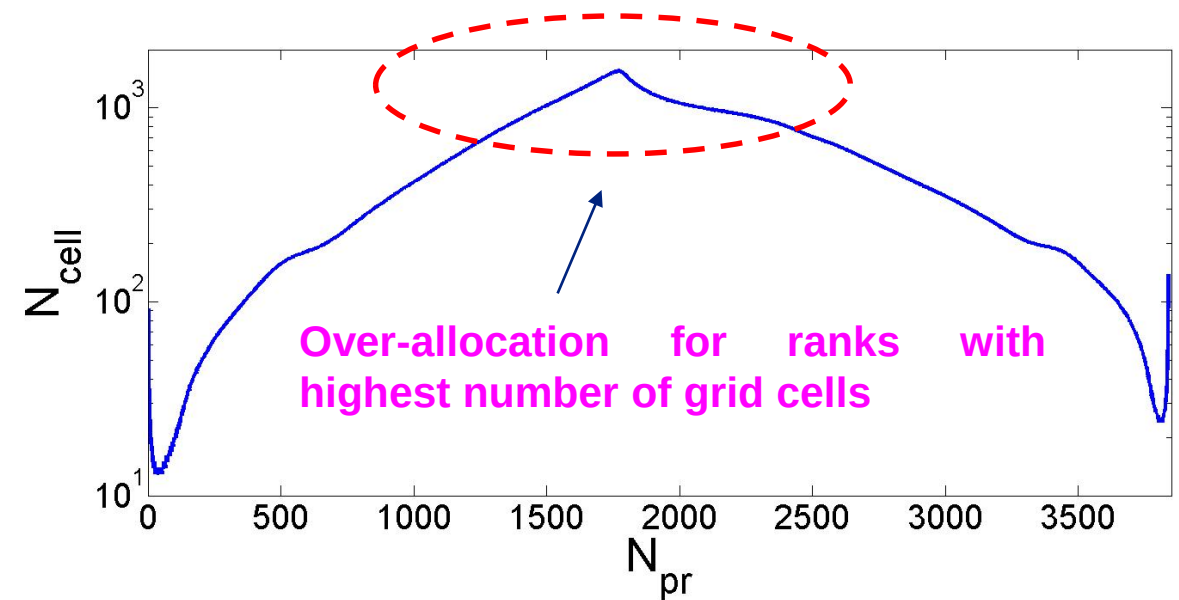
Status of the updated BIT1

Plasma density profile in COMPASS-U tokamak



Core boundaries have to be **calculated exactly** (!), otherwise small „mistakes“ accumulate and **last processors** (for $N_{pr} \gg 10^3$) **will not be uniformly loaded**

First tests on quasi uniform system were **not successful**: **degradation of the speed** ~20%

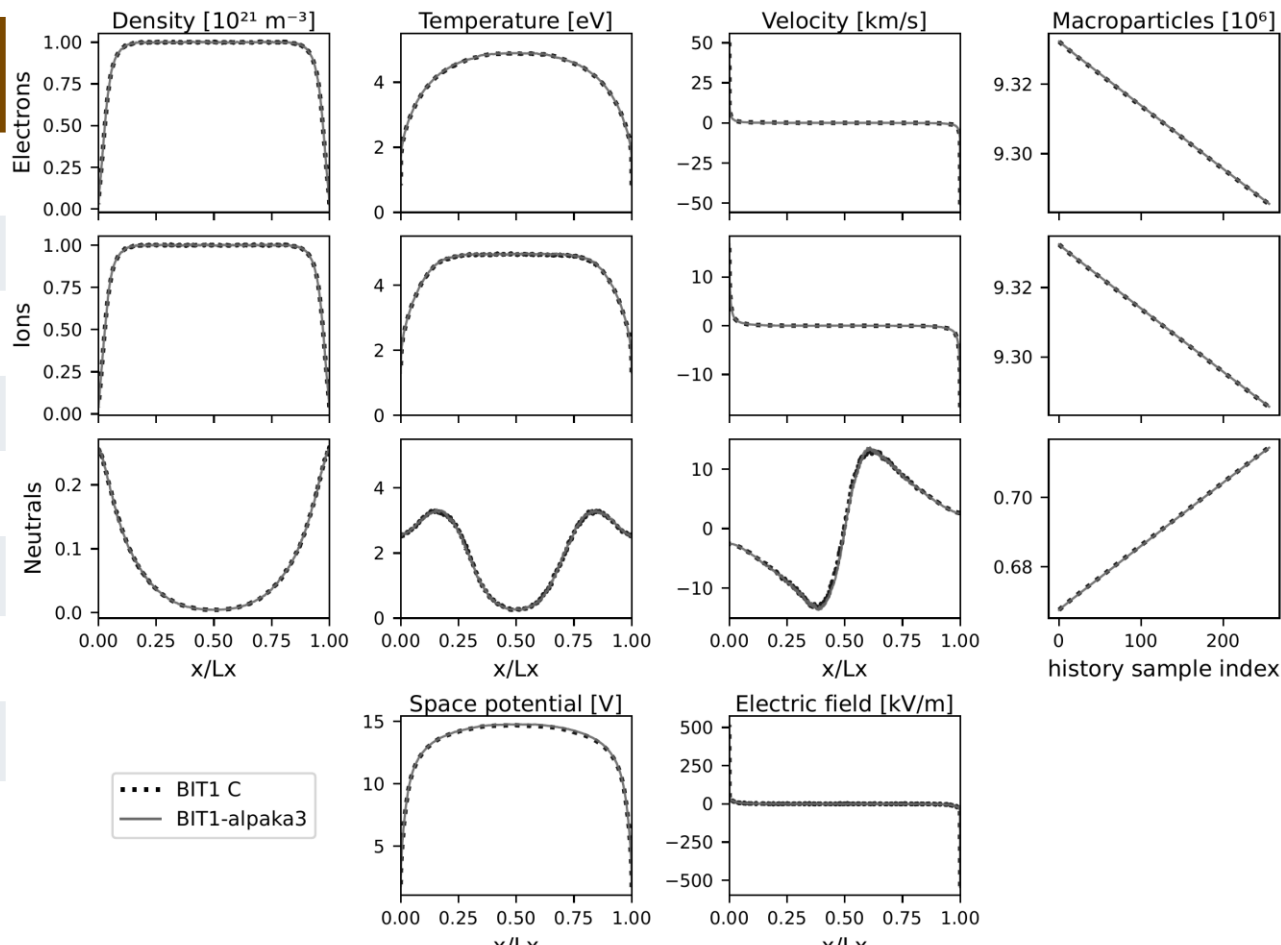


Next model used **nonuniform memory allocation**:

$$\text{memory} \sim 1 / N_{cell}$$

Speedup > 10!

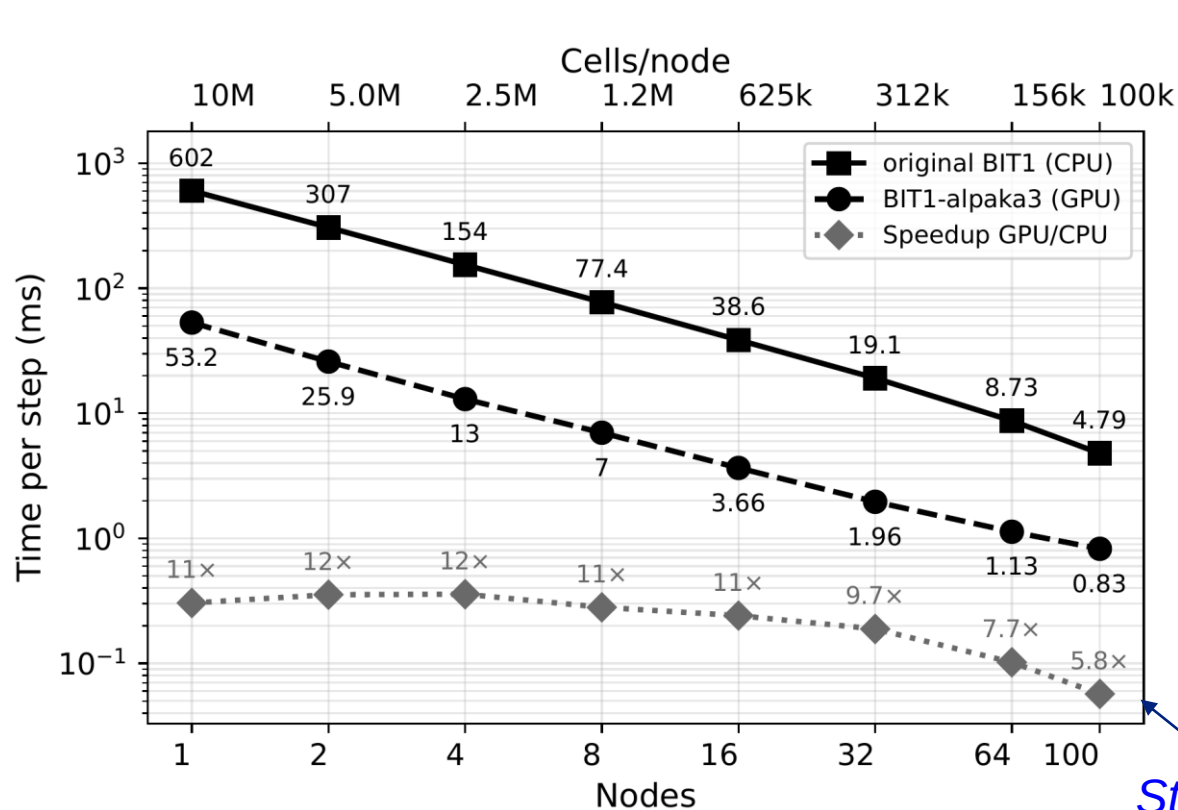
Bit-exact	Statistically equivalent:	difference
Checkpoint dump/restore format	Boris / electrostatic / free movers	P
Collision-type → reaction decoder	Density smoother (1-2-1)	P
Cross-section table read + interpolation	Poisson field solve	P
Cell-index and guard classification	MCC null-collision driver †	R, A
Velocity CDF table + quasi-random index	Coulomb collisions (Takizuka–Abe-Tskhakaya)	R, A
Initial load (positions, parallel velocity)	Surface emission decision	R
Analytic surface yields (sputter/SEE/recycle)	Charge deposition (CIC ρ)	P
Configuration parsing + sanity checks	Moment profiles (n, V, T, Q)	P
	Velocity / energy distributions	R



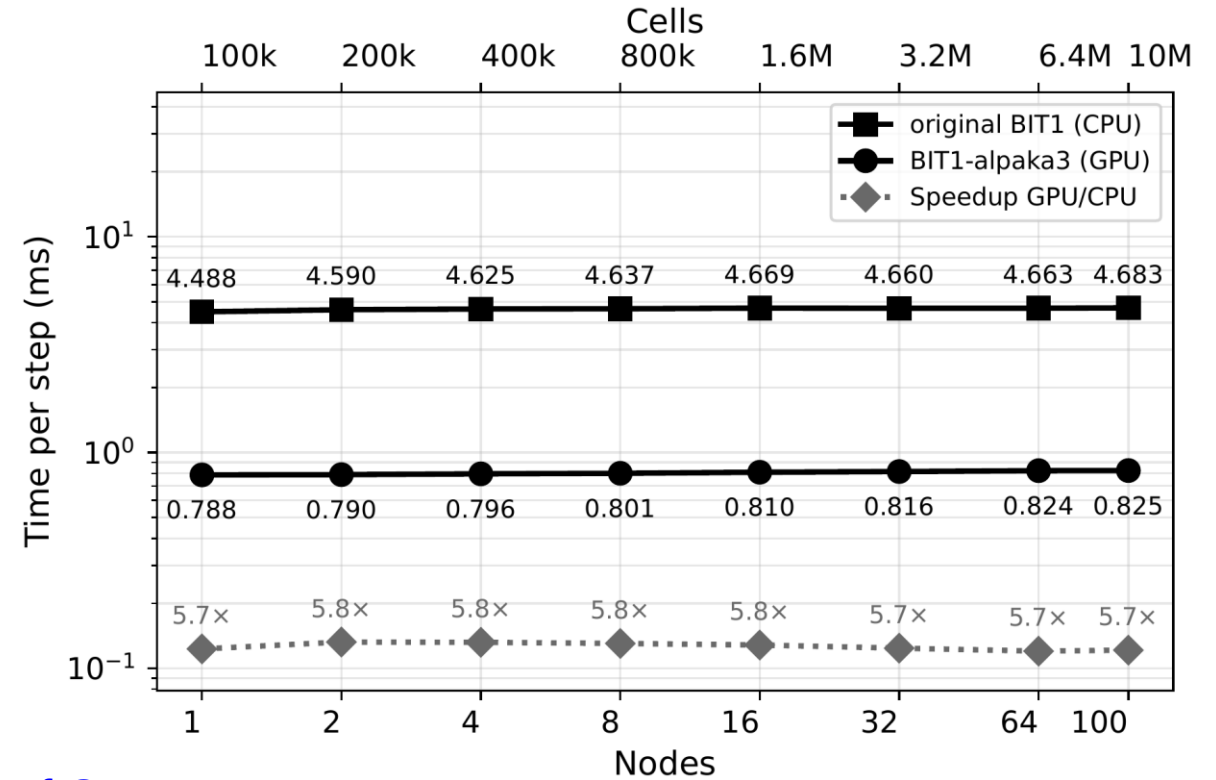
Representative fidelity classification. Causes: R = RNG stream, A = atomic / intra-cell ordering, P = precision / operation order.

Plasma profiles from the CPU (solid line) and the GPU (dashed line) BIT1 simulations.

MareNostrum5 ACC (4×H100/node) vs. GPP (112 cores/node)



Start of CPU hyper-scaling



One 4×H100 node replaces roughly six to twelve 112-core CPU node

- **Plasma flow** in the CS is **subsonic**. The **parallel Mach** number SE is **independent of the current regime**
- **Sheath potential drop** is **below** the classical value ($\sim 3T_e$); for **ITER** ~ 2.3
- Plasma and ion **divertor heat loads** are **significantly lower** than the classical ones; for **ITER** by the **factor 2**
- **High-z impurity (W)**: no (or partial) coupling with main ions; negligible prompt redeposition [PSI 2025]
- **Middle-z trace impurity (Ar)**: good coupling with the main ions [TSVV, 2024]
- **Low-z impurity (He)**: good coupling with the main ions [2026]

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

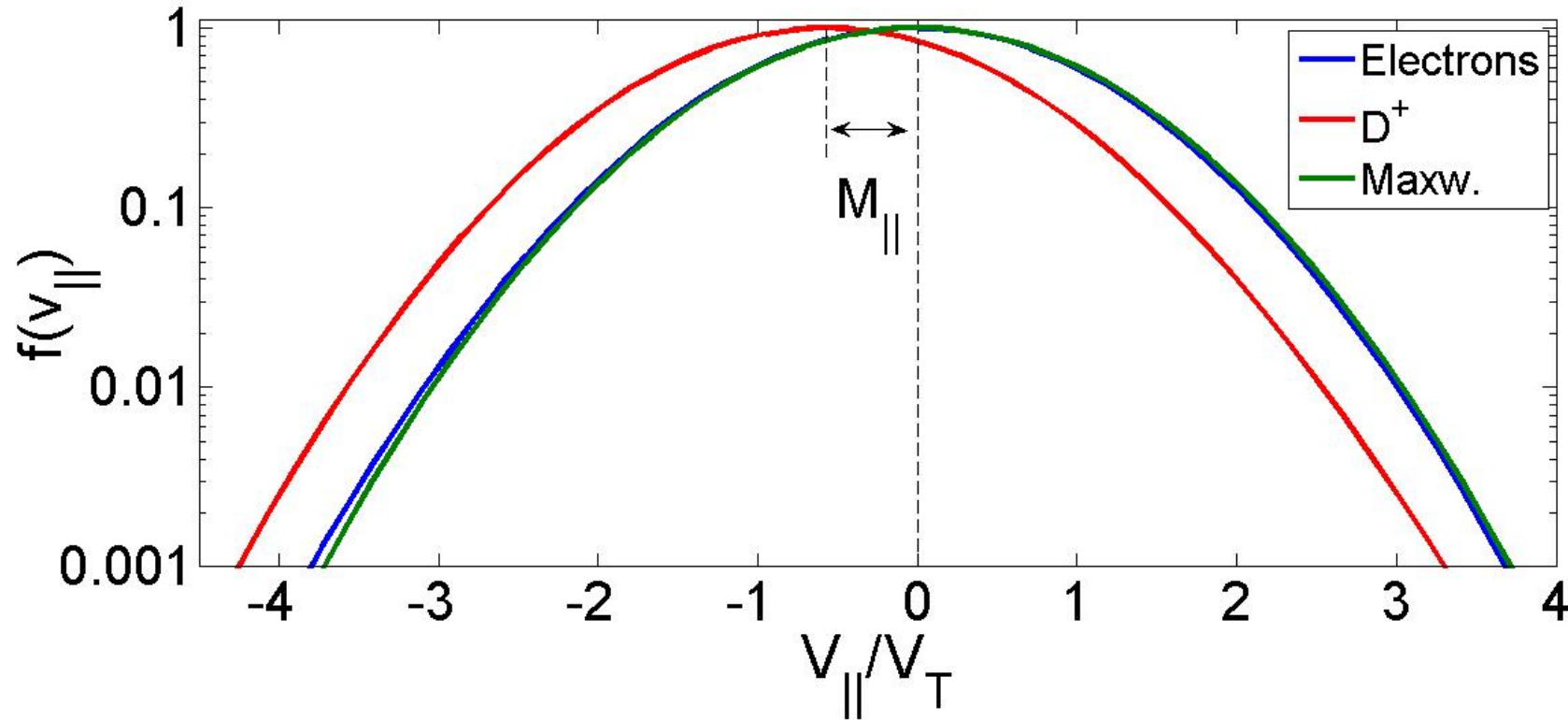
$$M_{\parallel}^{imp} = M_{\parallel} \sqrt{\frac{m_{imp} (T_e + T_i)}{m_i (T_e + T_{imp})}}$$

Plans for 2027:

Study **DT mixture**,

Try to derive **sheath Pot. Drop** and **SHTF analytically**

Explanation of results: independence from the current



*Electron and ion (D^+) normalized DFs at the sheath edge
(PIC simulation of ITER SOL)*

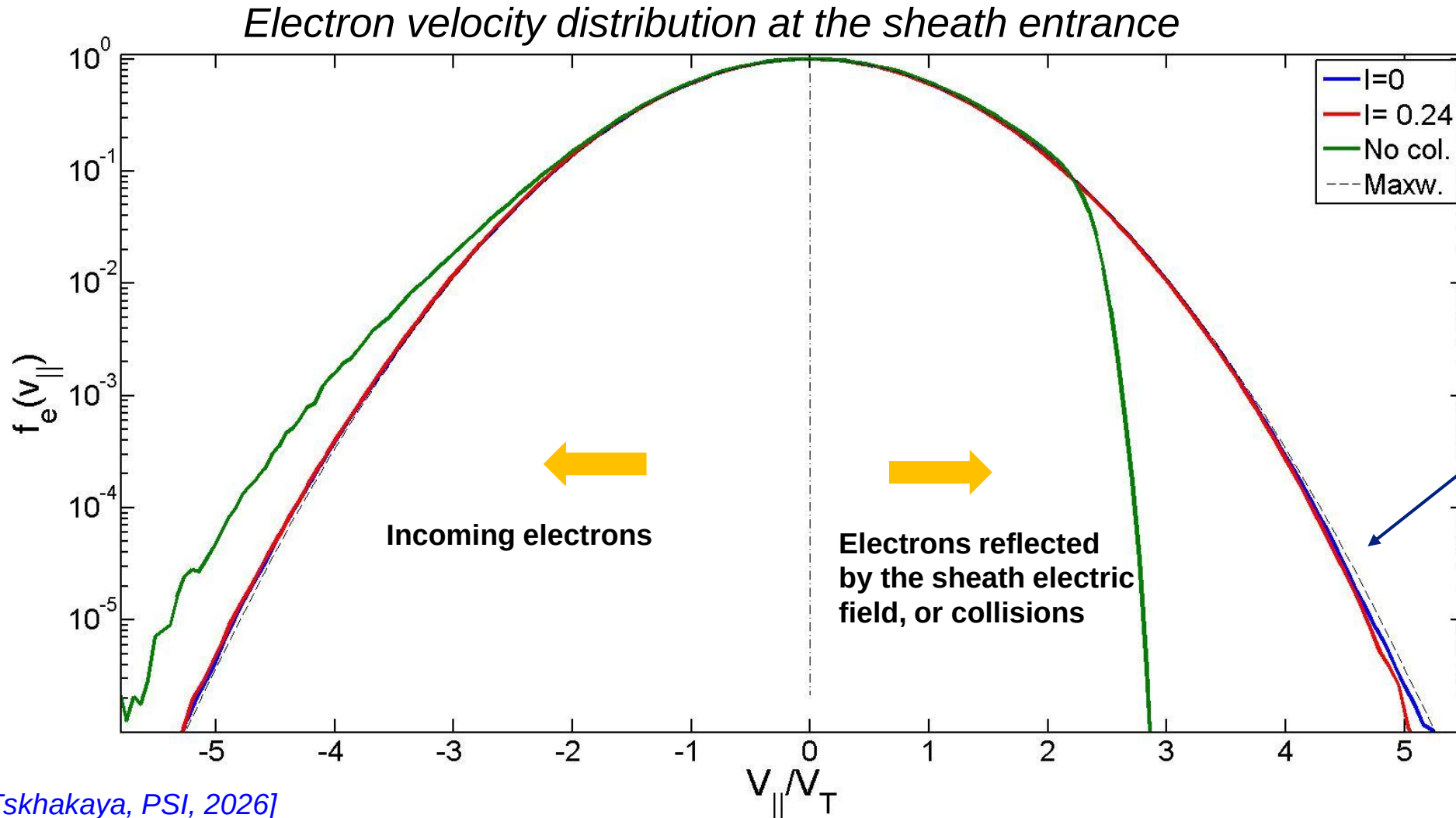
There is a “constant” **shift** between the electron and the ion VDFs at the sheath edge

$$R_{\parallel}^{ei} = -m\nu_{ei} (V_{\parallel}^i - V_{\parallel}^e)$$

$$R_{\parallel}^{ei} \approx -m\nu_{ei} V_{\parallel}^i = m\nu_{ei} I_{\parallel, \text{sat}} / e$$

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

[D. Tskhakaya, PET 9, 2003]



$$F_e \sim F_i$$

Collisions fill up the electron and reduce their flux



Electron reflection by a strong sheath field is no longer required

[D. Tskhakaya, PSI, 2026]

Explanation of results: low energy of absorbed ions

$$E_i = \langle q_{i,wall} \rangle / F_i T_i \approx 2.5 + \Delta\psi_{sheath} + M_{\parallel}^2 - \delta E_{sheath} \quad \leftarrow \text{Losses inside the collisional sheath}$$

$$\Delta\psi_{sheath} < \Delta\psi_0 \approx 2.8$$

Three reasons for energy reduction

- ✓ $M_{\parallel} < 1$
- ✓ Reduced acceleration in the sheath
- ✓ Collision losses inside the sheath and the pre-sheath

[D. Tskhakaya, PSI, 2026]

