INSTITUTE OF PLASMA PHYSICS
OF THE CZECH ACADEMY OF SCIENCES

BIT1 – sheath models

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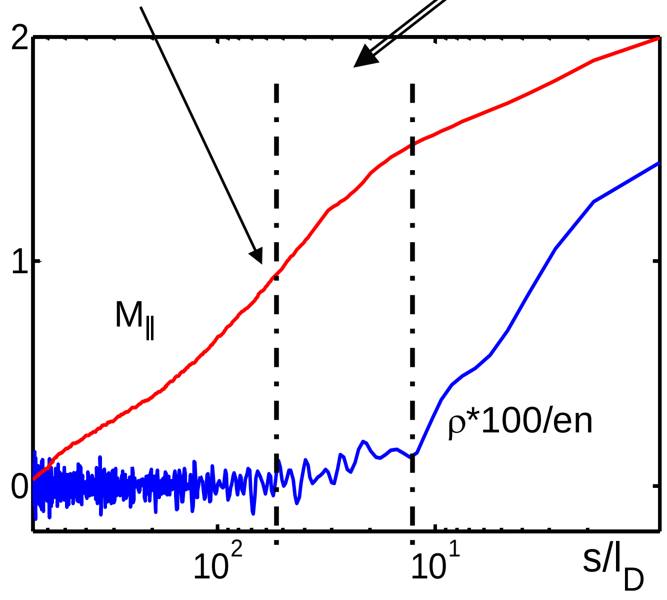
Based on TSVV-4-sheath (22.4.2025) and TSVV-3 presentation (11.6.2025)

MINISTRY OF EDUCATION,
YOUTH AND SPORTS

Plasma sheath and boundary conditione there

Systematic study of the magnetized PWT has been started with Codura's work [PF 1982]



Charge densities and Mach numbers ($M=V/C_s$) are form BIT1 simulation

Boundary conditions (BC)

- What is the sheath entrance?
- For which physics quantities are BC formulated?
- What is the explicit form of the BC?

How sensitive are results to the choice of BC?

- Field-line transport codes – moderate
- Fluid transport codes – extream (at least sometimes :)
- Gyrokinetic codes - ?

[Tskhakaya, ICPP, Nice, 2004, PPCF 2005]

1D fluid boundary conditions (classical)

Multi-positive-ion-component plasma sheath (fluid)

$$\Gamma_i = n_i V_i \ , \quad \Gamma_e = I/e - \sum_{i=1}^{N} Z_i \Gamma_i \ , \quad \Delta\phi = \psi \frac{T_e}{e} \quad \psi = \ln\left[\sqrt{\frac{T_e}{2\pi m_e}} \frac{1}{\sum_{i=1}^{N} s_i Z_i V_i - I/en_e} \right],$$

$$Q_e = (2+\psi)\Gamma_e T_e \ , \quad Q_i = \left(2.5 T_i + m_i V_i^2/2\right)\Gamma_i \ , \quad i = 1,\dots,N$$

.

$$V_i \equiv V_{\parallel,i}$$

Magnetic sheath entrance (general condition)

$$1 = T_e \sum_{i=1}^{N} \frac{s_i Z_i^2}{m_i V_i^2 - T_i}$$

$$V_i = \sqrt{\left(T_i + Z_i \frac{\partial_x \ln n_e}{\partial_x \ln n_i} T_e\right)/m_i}$$

$$\gamma_i \approx 1$$

Inconvenient terms

[Tskhakaya, JNM 2005]

Single-ion plasma sheath

Fluid BC

$$V_i = C_{s,i} = \sqrt{\left(T_i + Z_i T_e\right)/m_i}$$

$$\psi = 2 \div 5$$

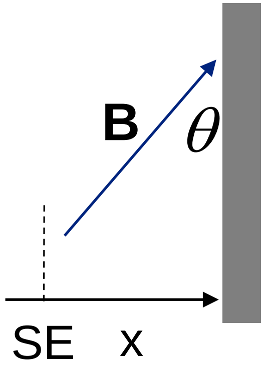
$$Q_e = (2+\psi)\Gamma_e T_e$$

$$Q_i = (3T_i/T_e + Z_i/2)\Gamma_i T_e$$

Kinetic BC

$$\left\langle V_i^{-2} \right\rangle \le C_{s,i}^{-2}$$

Fluid boundary conditions at the divertors / limiters



BC for	1D				2D	
	Single ion	Multi-ion	Collisional	Multi-fraction	Single ion	Multi-ion, -fraction / collisional
ϕ	🟢	🟡	🟡	🟡	🟡	🔴
$V_{i,\parallel}$	🟢	🟡	🟢	🟡	🟢 (light green)	🔴
$\partial T/\partial x$, or $q_{\parallel}$	🟢	🟡	boundary 🔴	🟡	🔴	🔴
Higher moments, vorticity	🔴				🟢	🔴

🟢 BC exist and relatively easy to implement

🟡 BC exist, but hard to implement (contains strong gradients, or code becomes unstable)

🔴 BC does not exist

🟢 (light green) Newly proposed BC

[J. Loizu, PoP, 2012]

$$\tau_{sheath} \approx \frac{\alpha\rho_i}{V_{T_e}} \sim \sqrt{\frac{m_e}{M_i}}\frac{1}{\Omega_i}$$

Multi-fraction ~ time dependent (τ_{sheath} << τ_{other})

Kinetic boundary conditions (ES)?

$$I/e=\sum_{i=1}^{N}Z_i\Gamma_i-\Gamma_e^{+}exp(-\psi)=n_iV_i\ ,\quad \Delta\varphi=\psi\frac{T_e}{e}\ ,\quad \Gamma_e^{+}=f_{Maxw.}$$

$$f_{e,i}^{div}\left(V_{\parallel},\mu\right)=F_{e,i}\left(V_{\parallel},\mu\right),\quad or\quad \left\langle V_{\parallel}^{k}\right\rangle=A\left(n,T,...\right)$$

$$f_{e,i}^{wall}\left(V_{\parallel},\mu\right)\approx 0$$

$$\left\langle V_{\parallel}\right\rangle=C_s$$ Fluid

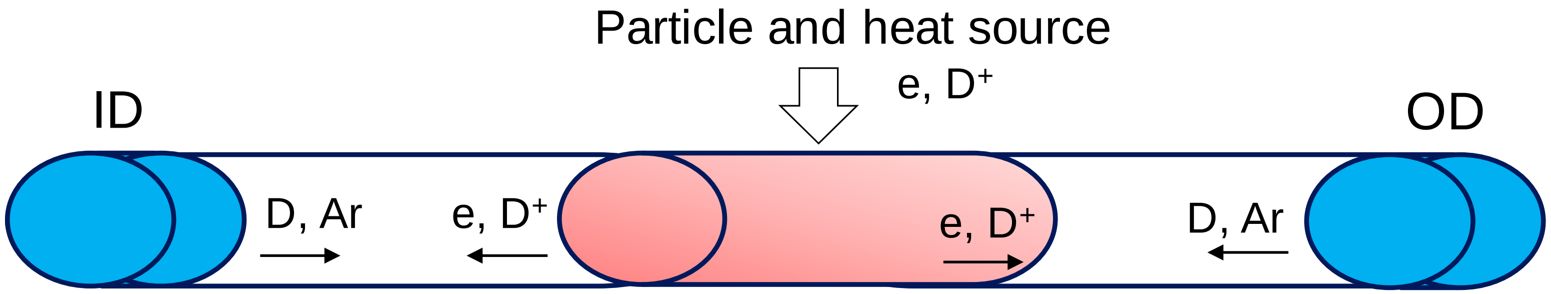
$$\left\langle V_{\parallel}^{-2}\right\rangle\approx C_s^{-2}$$ Kinetic

Reminder

- What is the sheath entrance?
- For which physics quantities are BC formulated?
- What is the explicit form of the BC?

- No model for multi-ion sheath?
- No 2D kinetic sheath model
- No model for the collisional sheath

Descriptiion of the model



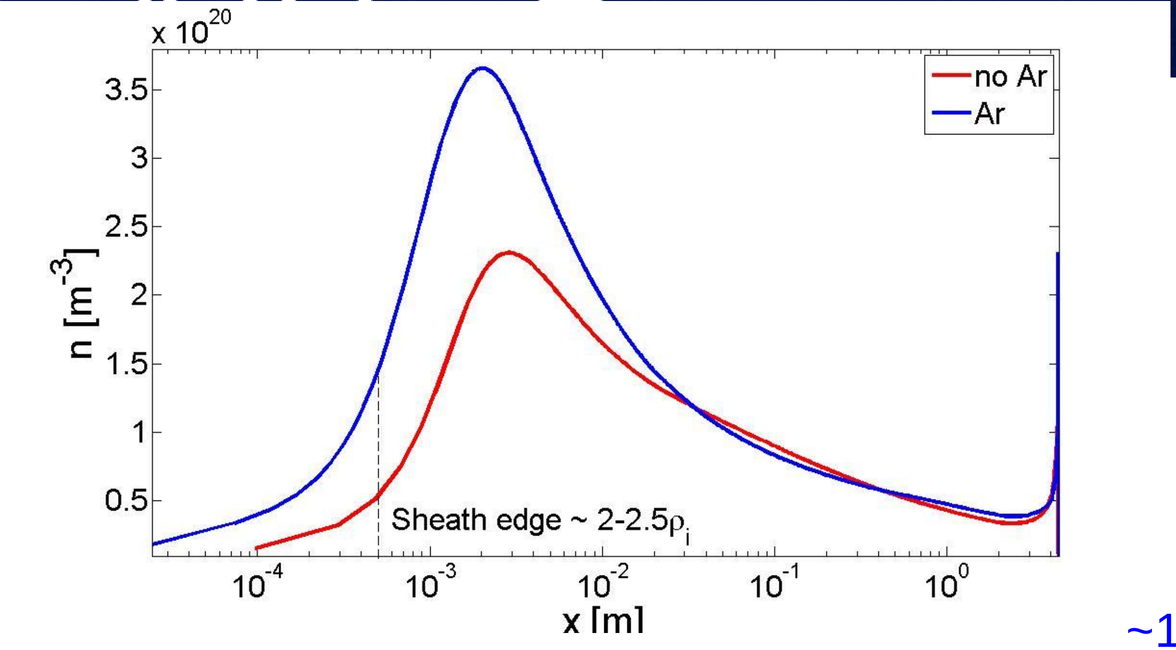
BIT1 – 1D3V electrostatic PIC + MC

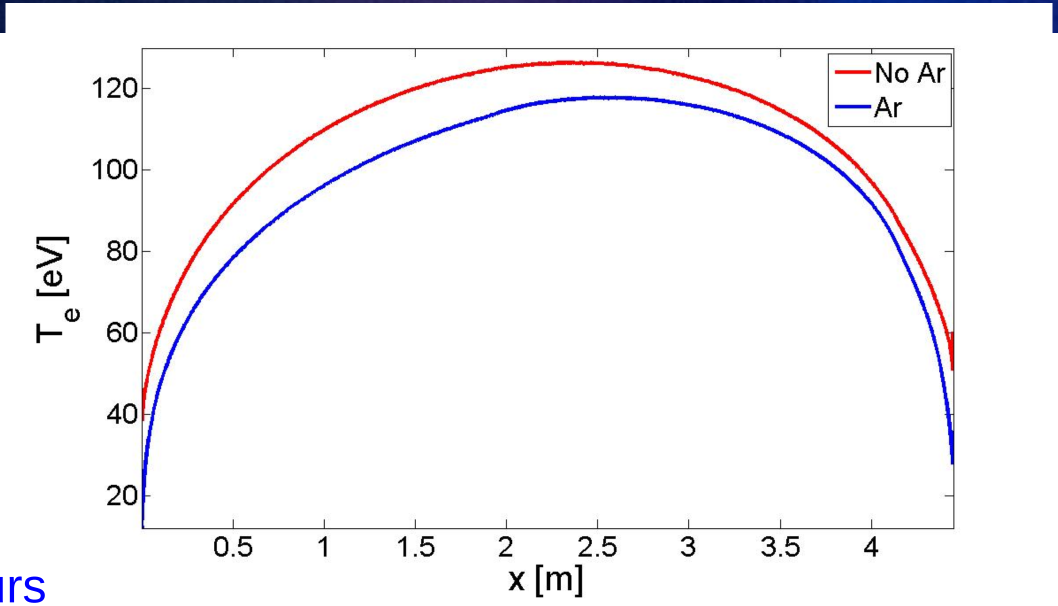
- Simulates **plasma, neutral** and **impurity** particle kinetics
- Number of simulated particle species is limited by the available **computational time** and **atomic/PSI data**
- Resolves plasma sheath, **no BC are applied** there
- **Nonlinear** momentum and energy conserving elastic and inelastic **collision operators**
- Can handle extremely **high density** plasmas (10^{22} m^{-3}): non-coronal interaction model

✓ Validation of the divertor power loads[1]
✓ Plasma sheath parameters[2]
✓ W errosion rates[3]
✓ Divertor temperatures[4]

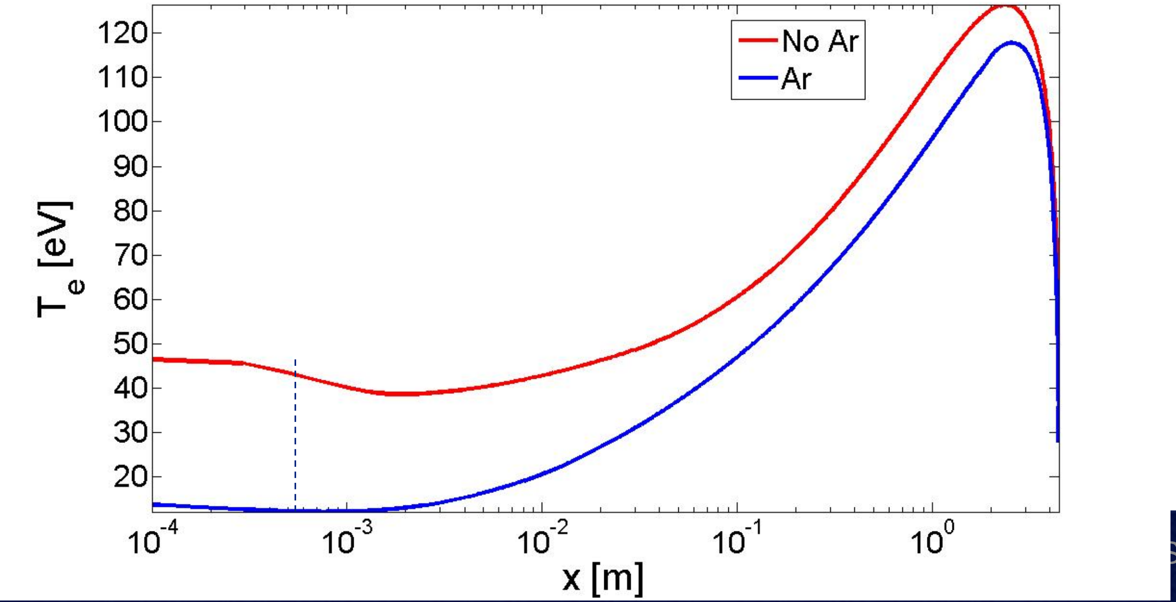
[1] R.A. Pitts, et al., Nucl. Fus., (2007)
[2] D. Tskhakaya, et al., J. Nucl. Mater., (2011)
[3] J A. Huber, et al., Phys. Scr., (2021)
[4] J. Horacek, et al., Nucl. Fus., (2023)

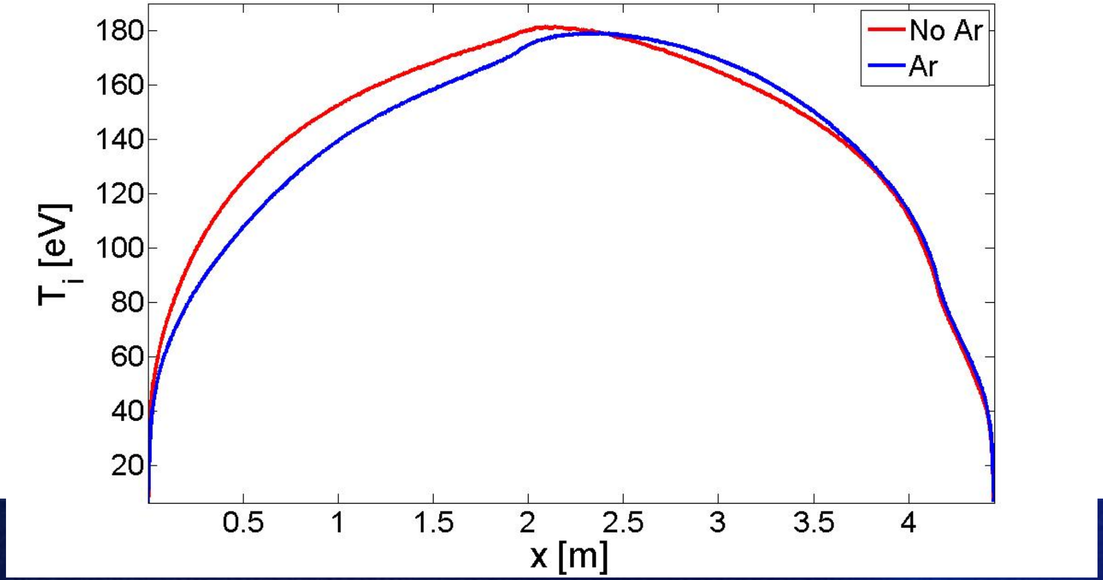
Kinetic simulations of the ASDEX



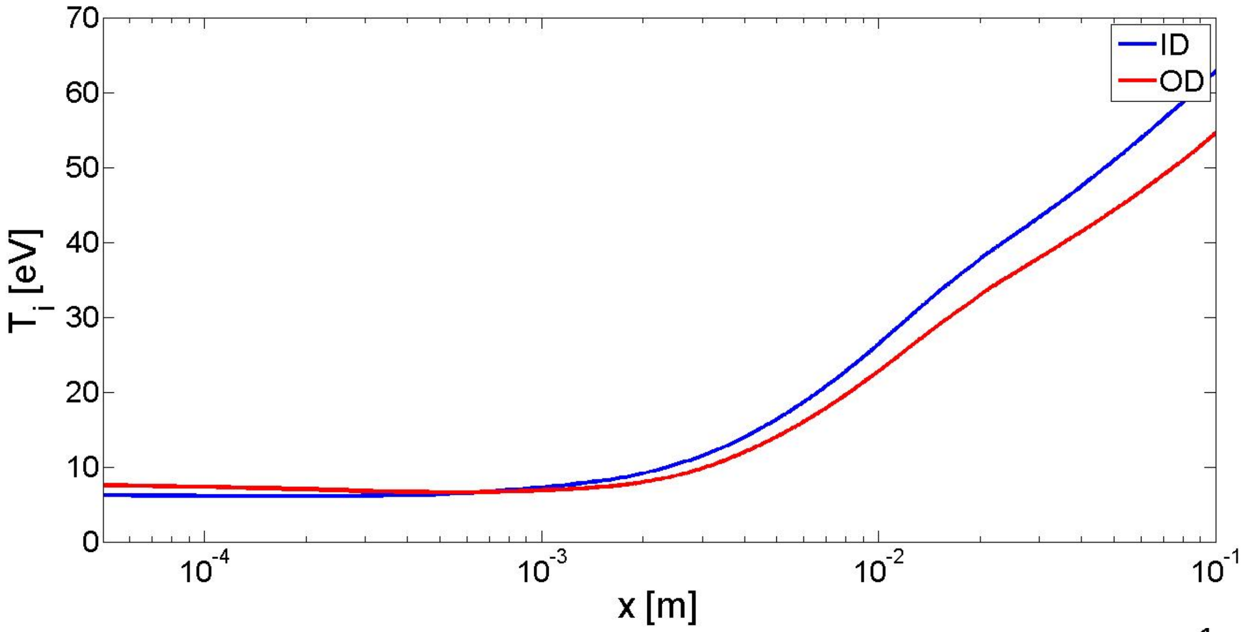


~10M CPU hours

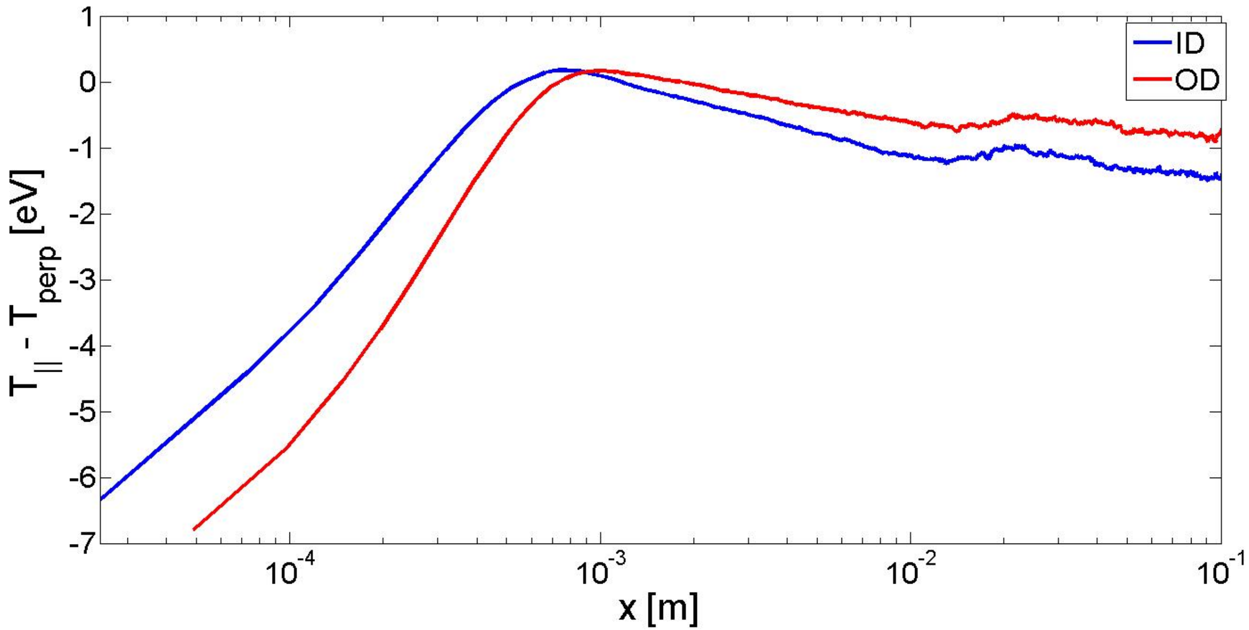




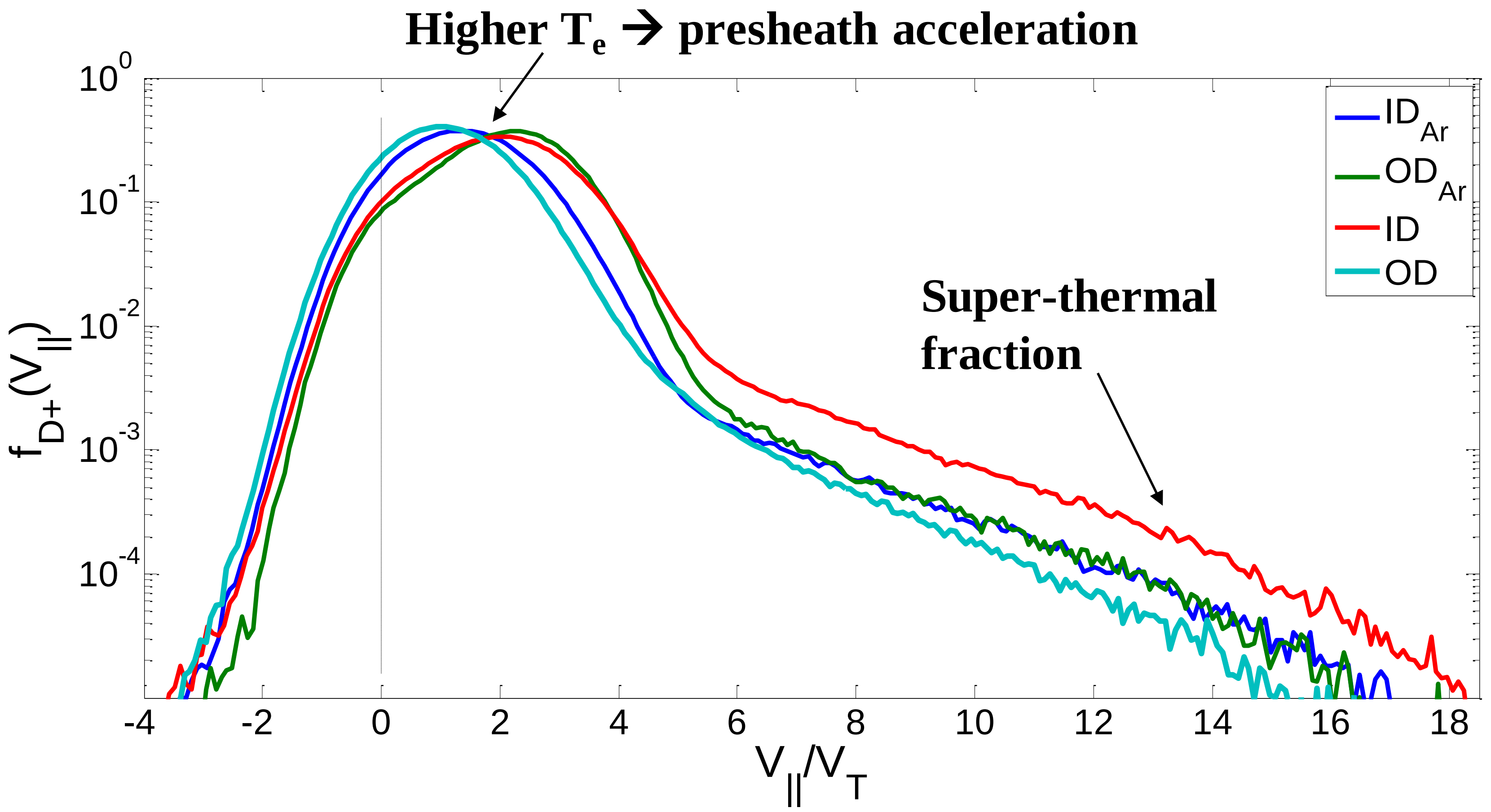
Kinetic simulations of the ASDEX: T_i anisotropy



The case with Ar seeding

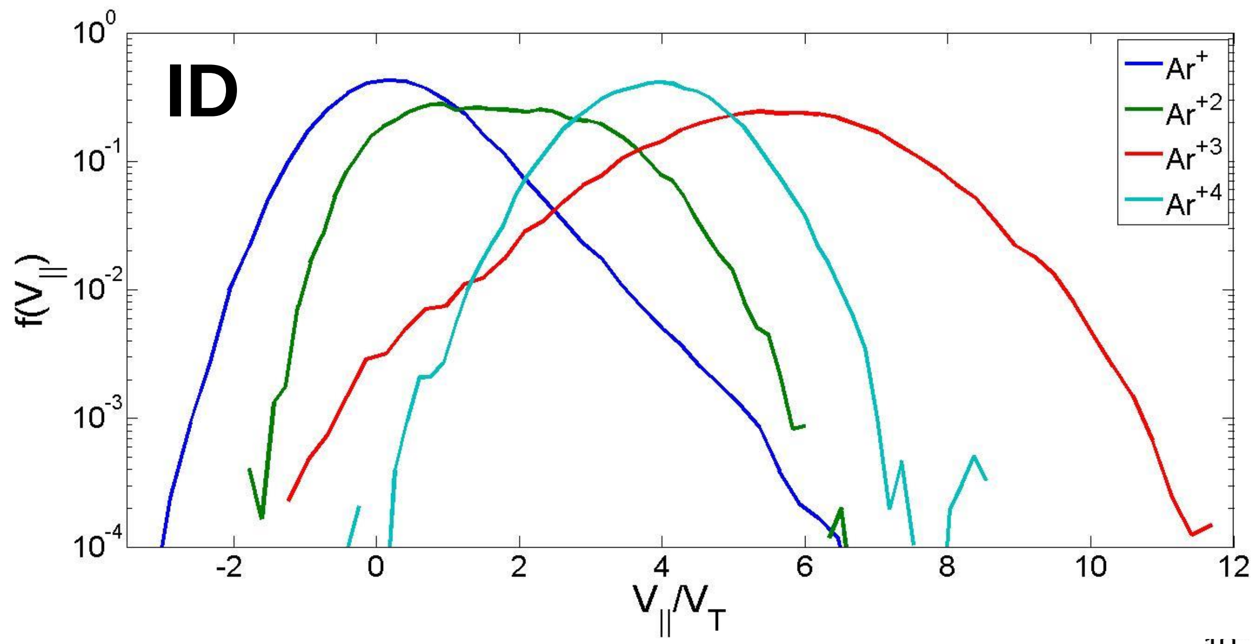


D^+ VDFs at the sheath entrance



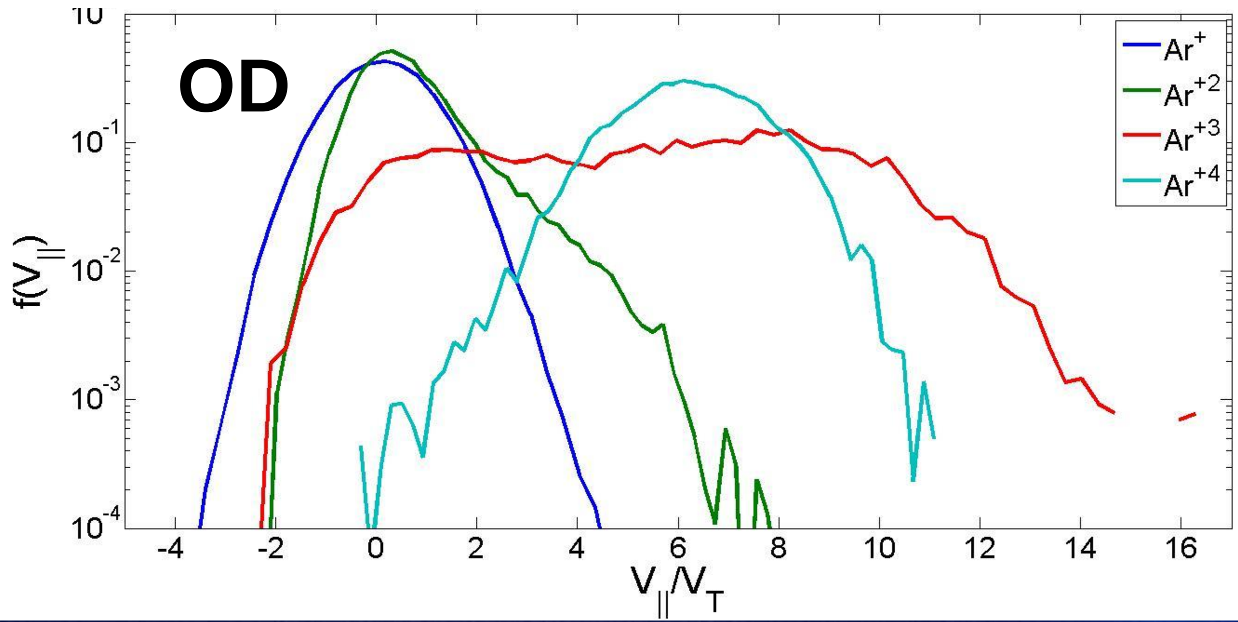
- Quite similar normalized VDFs for broad range of collisionalities
- Ion super-thermal fraction does not contribute to the heat loads (contrary to the electrons)
- $f(V_{||} = 0) > 0$

Ar^{+i} VDFs at the sheath entrance



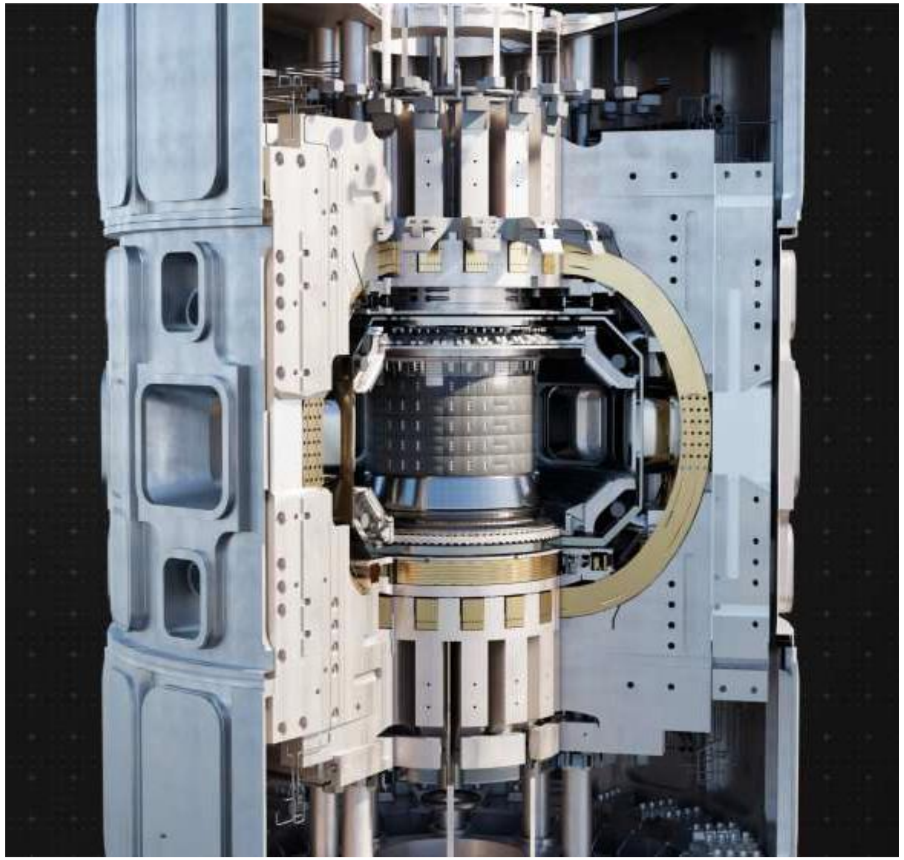
Hard to find some unique BC: **each case is individual**

Low resolution for impurities – longer diagnostic run is required



Boundary conditions for the collisional sheath

COMPASS-U



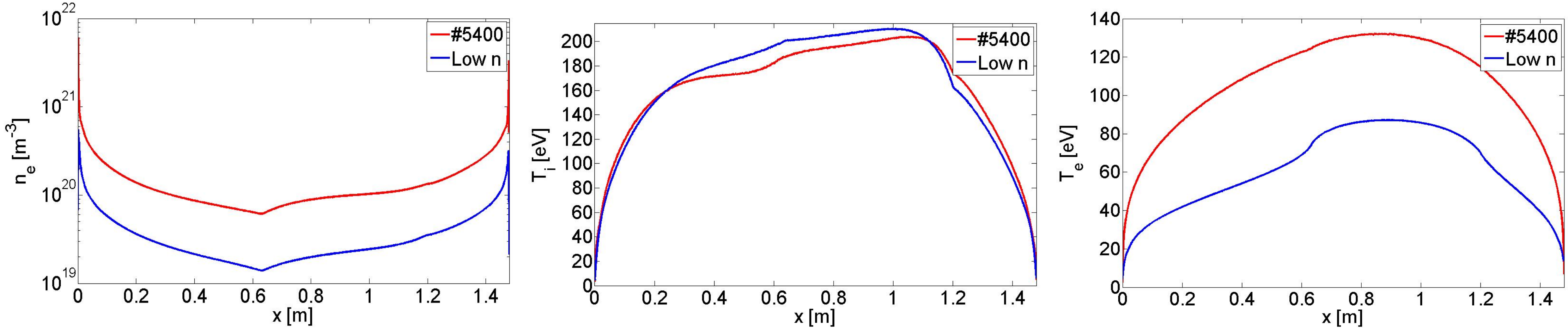
https://www.ipp.cas.cz/Compass_U/

- ✓ R= 0.894 m, a = 0.275 m
- ✓ High magnetic field (BT ≤ 5 T) and high-current (Ip ≤ 2MA)
- ✓ $n_{sep} \sim 10^{20}$ [m^{-3}]
- ✓ High power fluxes in the divertor ($\lambda_q \sim 0.7 - 1$ mm)
- ✓ Metallic first wall and/or liquid metal divertor

	NBI+ECRH [MW]	B [T]	T_{sep} [eV]	n_{sep} [10^{19} m^{-3}]
#5400	4 + 2	5.0	~200	1.0
Low n	?	5.0	~150	0.3

Simulations: no seeded impurity

Kinetic simulations of the COMPASS-U



	Sheath	Pot./T_e	$n_{e,div}$ [10^{21} m^{-3}]	$T_{e,div}$ [eV]	$T_{i,div}$ [eV]	SHTF
#5400	col. / col.	**1.8** / 2.9	6.0 / 3.3	6.5 / 11.3	5.6 / 7.1	5.4 / 7.4
Low n	clas./clas.	3.0 / **3.4**	0.32 / 0.15	4.8 / 13.7	5.1 / 6.6	21.6 / 14.5

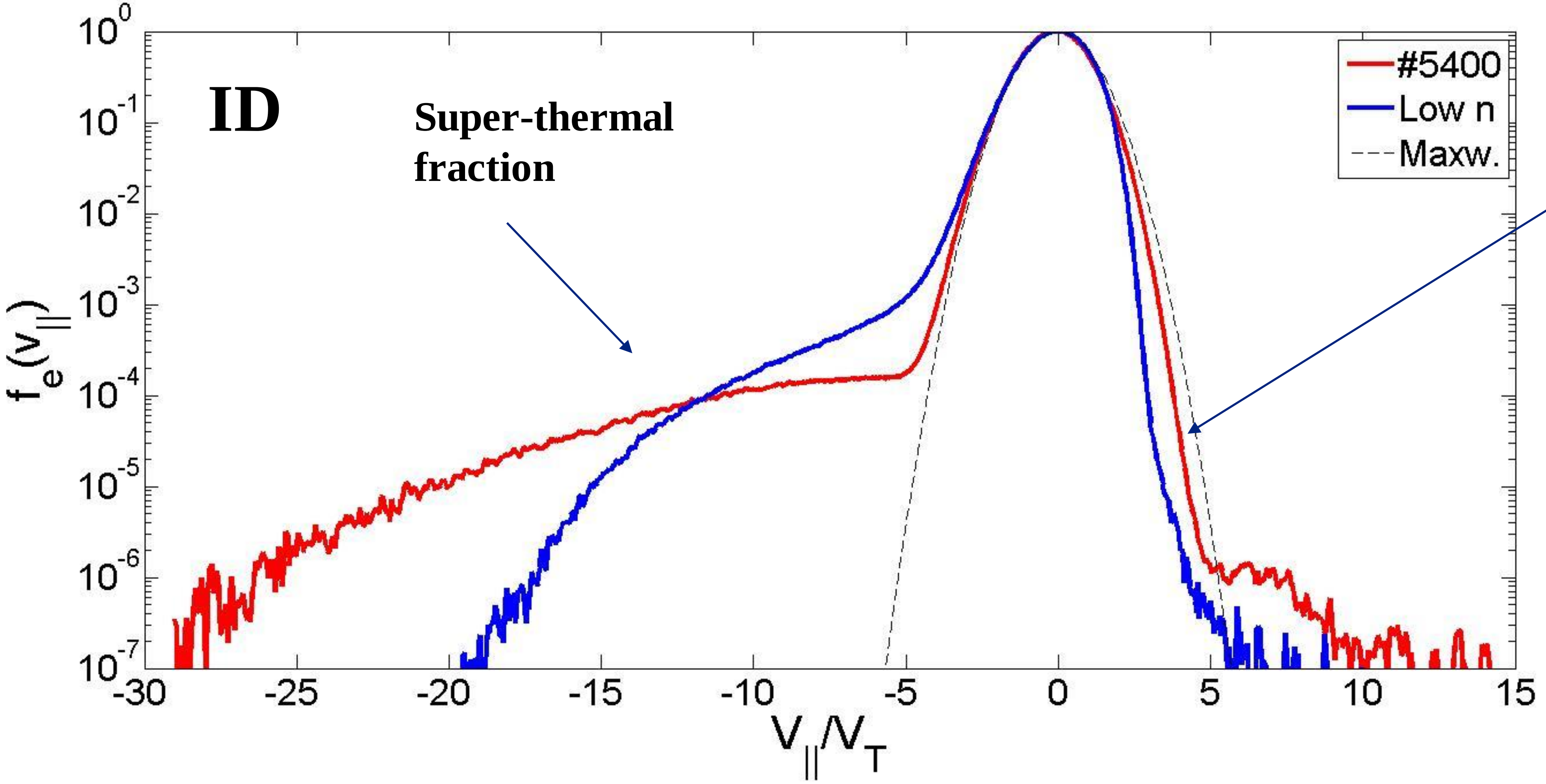
$$\psi \approx 0.5 \ln\left(M_i / 4\pi m_e\right) \sim 3$$

Super-thermal electrons[1]

$$\frac{q_w}{F^i T_e} \approx M_{\parallel}^2 + 4.5 + \psi = 8.5$$

[1] D. Tskhakaya, PPCF 2017

Electron VDF at the divertor plate



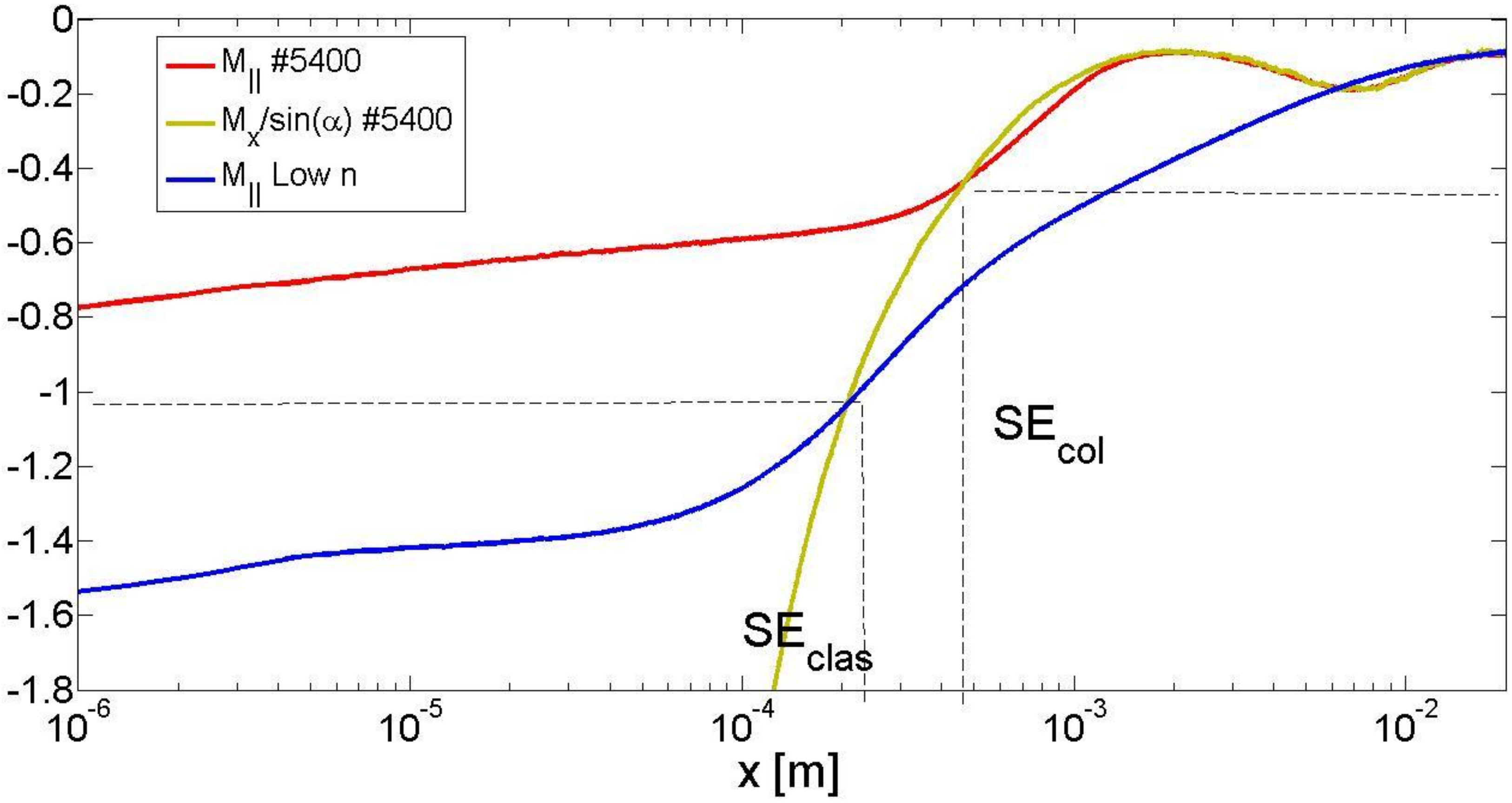
Collision effect

Reduced sheath potential drop

Nonclassical VI characteristics?

[D. Tskhakaya, TSVV-4, 22.4.2025]

Collisional sheath: Mach at COMPASS-U divertors



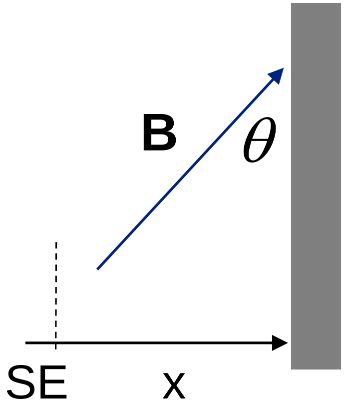
Parallel Mach number profiles at the ID

Sheath edge = last point with

$$M_{\|} \approx \frac{M_{pol}}{\sin(\alpha)}$$

1D boundary conditions for the collisional sheath

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

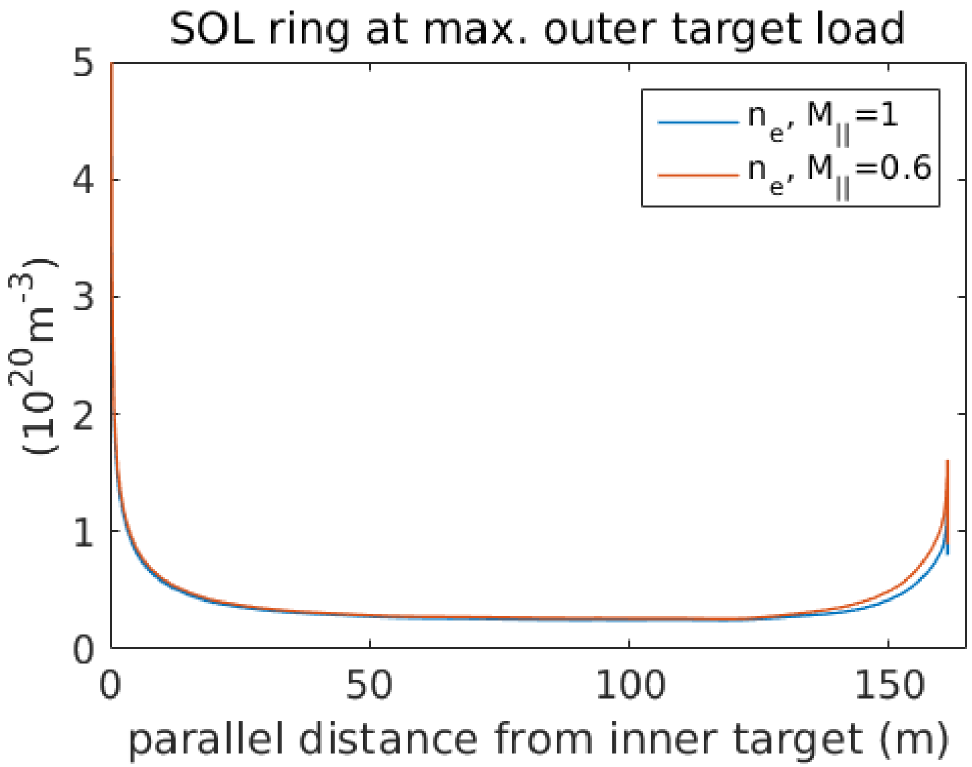


$$\chi = \frac{\left(\upsilon_{mt}(1-\alpha) + \upsilon_{ei}\right) x_0}{2 c_s \sin(\theta)}$$

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

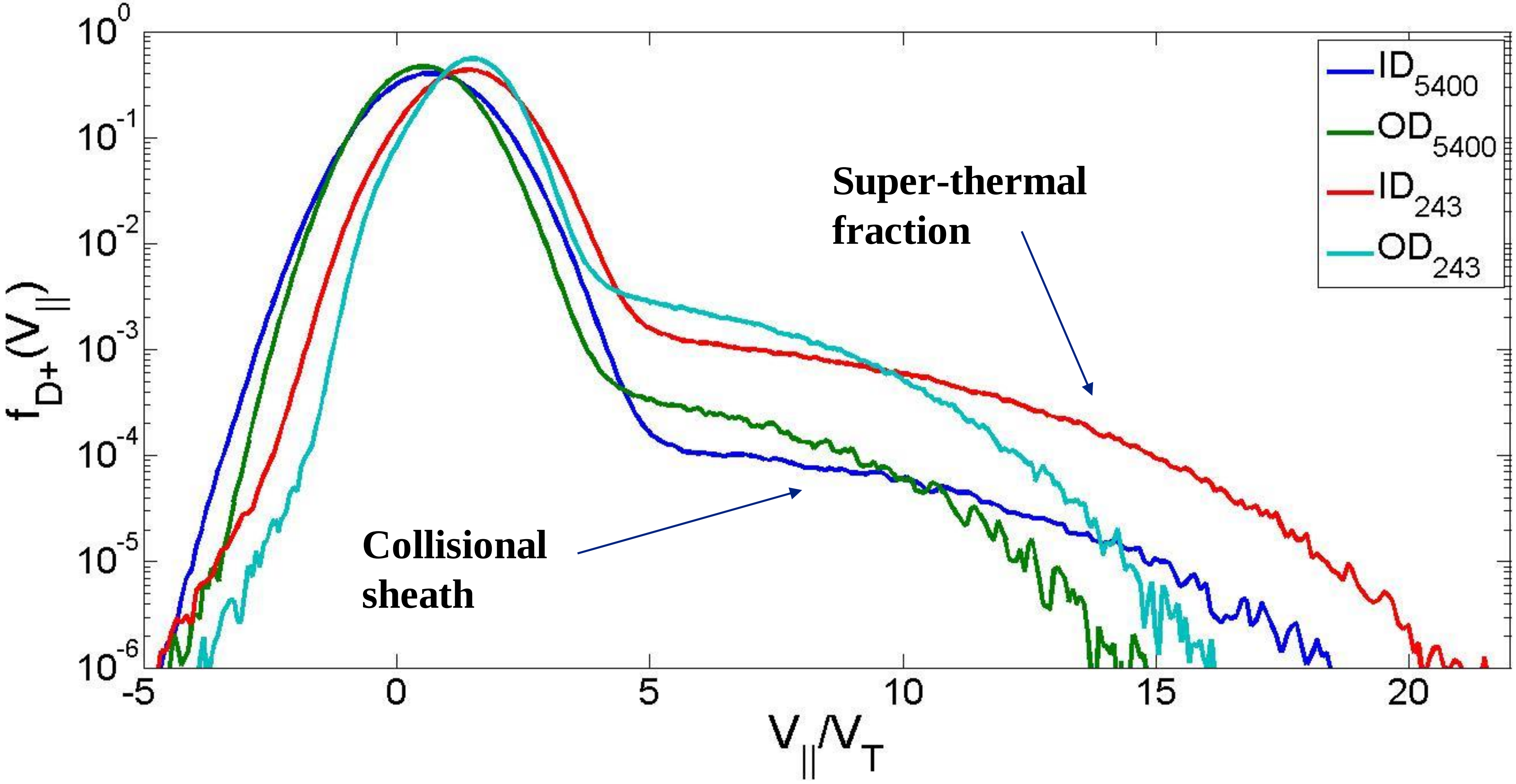
$$M_{\perp}(x_0) = \sin(\theta), \quad x_0 \approx x_{wall} \sim 20\rho_i$$

Implemented in SOLPS-ITER and GBS



[D. Moulton, ISFN DivSOL, 2021]

D^+ VDFs at the sheath entrance



Summary

- Contrary to the fluid BC, we do not have **multi-ion, 2D,** or **collisional sheath** kinetic boundary conditions
- Such BC are probably code-dependent and are different for Eulerian and Lagrangian models*
- *however the BC for the main ions are **well approximated by the shifted Maxwellians**
- In general, $f_i^{SE}\left(V_\parallel = 0\right) > 0$, which makes complicated a direct use of $\left\langle V_\parallel^{-k} \right\rangle > A$, k>0, condition types