IPP INSTITUTE OF PLASMA PHYSICS OF THE CZECH ACADEMY OF SCIENCES

Plasma sheath under reactor relevant conditions

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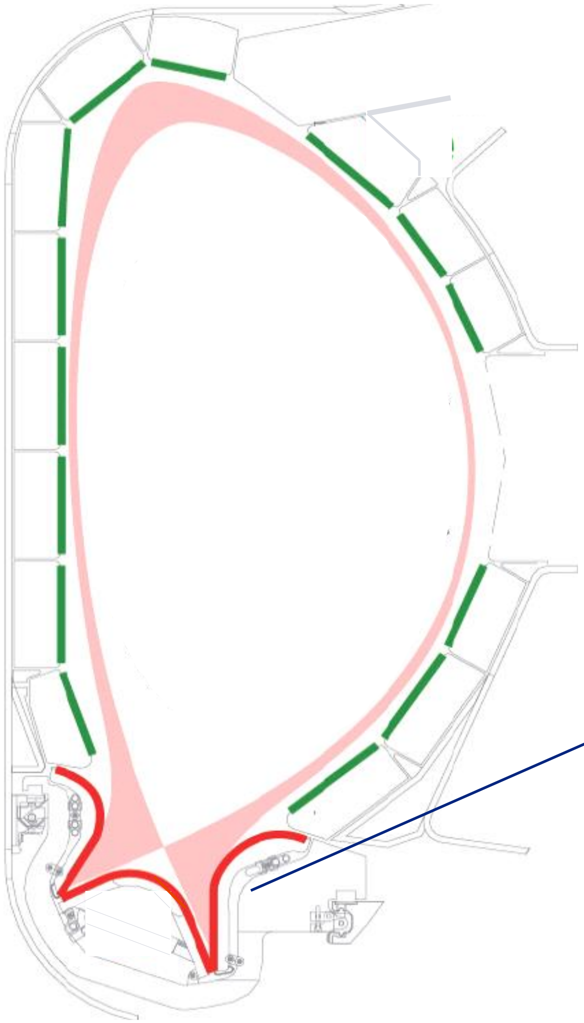
Outline

- Introduction
- High density - collisional sheath
- Implementation of new BC into GBS and the first results
- BC for sputtered high-z ions

Divertor plasma sheath parameters in tokamaks

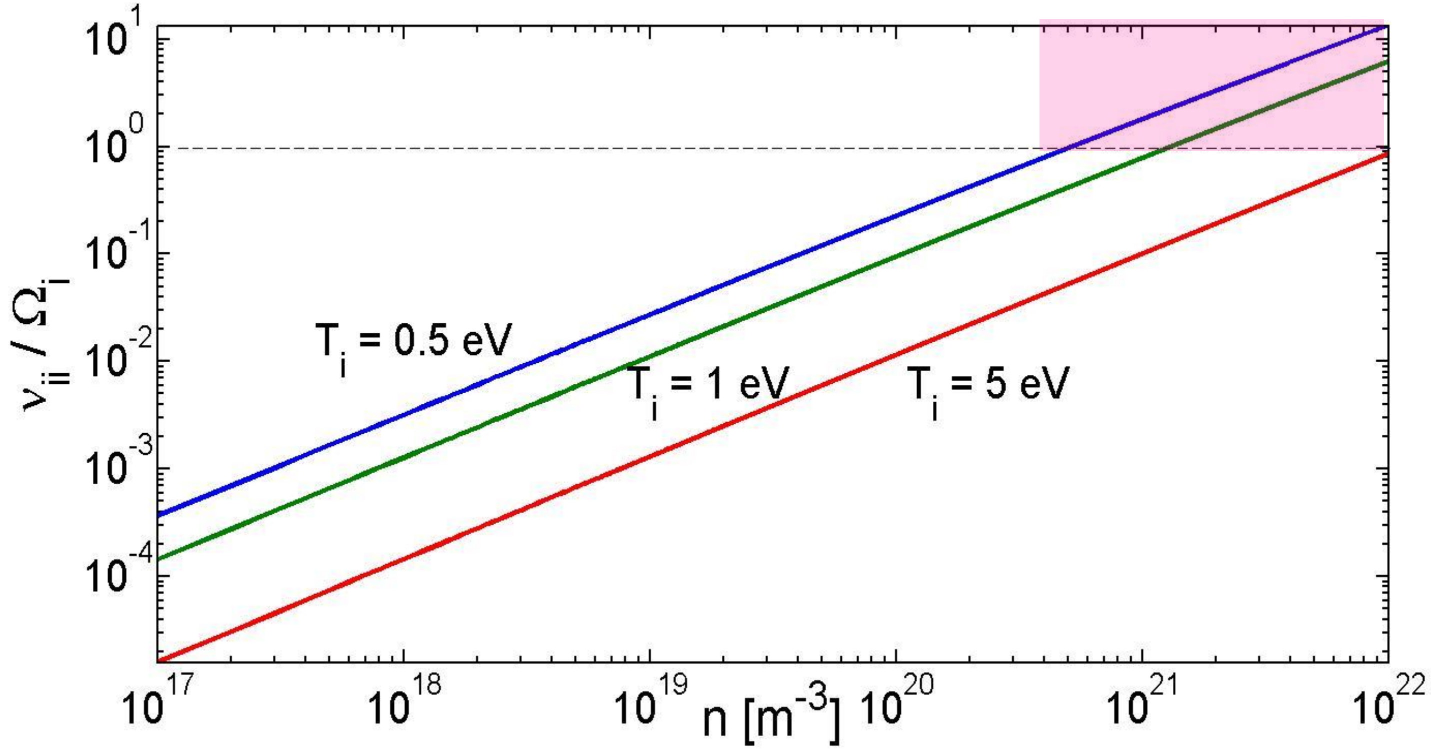


	B_0 [T]	Q= P_{fusion}/P_{inj}	Divertor sheath n_{max} $[10^{20}\ m^{-3}]$	Divertor sheath T_{min} [eV]
COMPASS	2.1	-	0.3	10
ASDEX-U	3.1	-	2	1
JET	3.5	0.67	5	1
ITER	5.2	10	50	0.3
EU DEMO	5.9	25	~100	0.2 (?)

What will change in large devices?

- Divertor plasma sheath becomes collisional
- $\rho_i << \lambda_{T,n}$, probably, drifts at the sheath entrance become negligible

Collisionality of the plasma sheath



From BIT1 simulations

	Sheath collisionality	
	Electrons	Ions (D^+)
Classical	0.0	0.0
JET	2.6	0.6
ITER	14.6	39.6

Divertor **plasma edge** in next generation tokamaks will be **collisional**

Position of the classical magnetized sheath edge

Classical sheath (izotermal case) *[Riemann, Tokar,…]*

$$T_e \sum_{i=1}^{N} \frac{s_i Z_i^2}{m_i V_{\|,i}^2 - T_i} = 1.$$

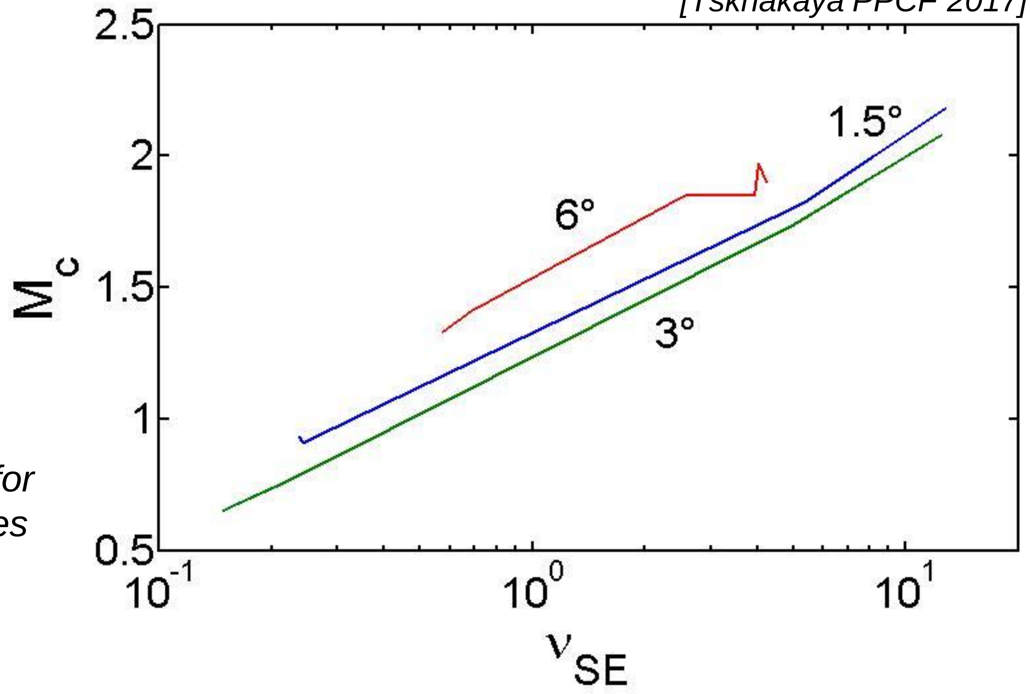
[Tskhakaya JNM 2005]

$$V_{\|,i} = \sqrt{\left(T_i + Z_i \frac{\partial \ln n_e}{\partial \ln n_i} T_e \right) / m_i}$$

Single ion case

$$V_{\|,i} = c_s = \sqrt{(T_i + Z_i T_e) / m_i}$$

[Tskhakaya PPCF 2017]



Mach number of C^+ for different sheath collisionalities

Collisionless limit

Main ions $$2e\varphi / m_D = V_{\|,SE}^2 - V_{\|,0}^2 \approx V_{\|,SE}^2 = c_{s,D}^2$$

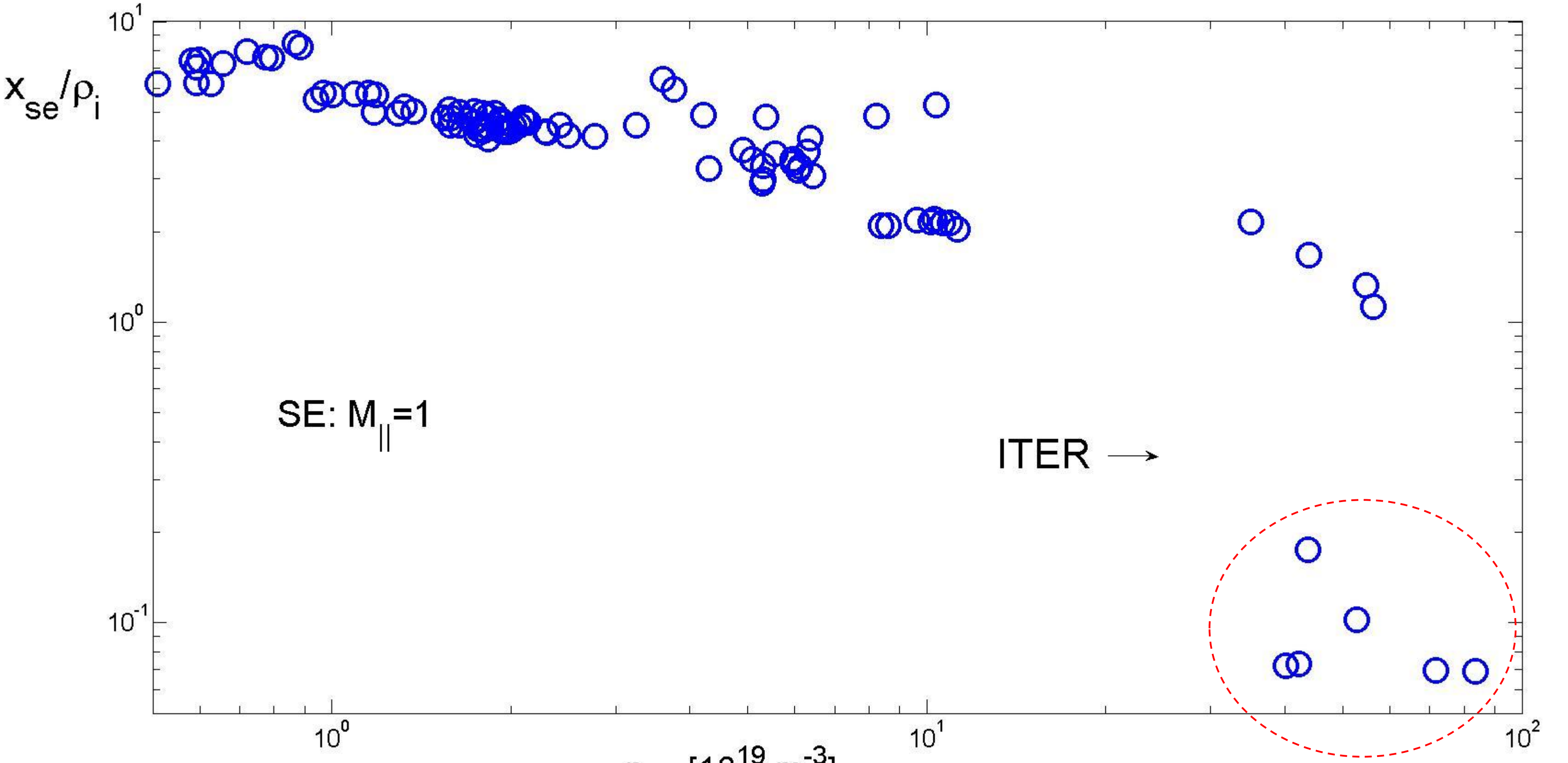
Low concenration impurity ions

$$V_{i,\|} \approx \sqrt{2e\varphi / m_i} = c_{s,D} \sqrt{m_D / m_i} = c_{s,i} \sqrt{\frac{T_D + T_e}{T_i + Z_i T_e}}$$

High collisional limit

$$V_{i,\|} \approx V_{D,\|} = c_{s,i} \sqrt{\frac{m_i}{m_D}}$$

Position of the magnetized sheath edge



$M_{||}$ < 1 everywhere

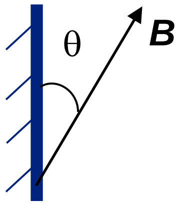
Simulation parameters

R= 0 – 1

Z_{eff} = 1 – 1.5

θ= 1.5°, 3°, 4°, 6°

~100 simulation runs



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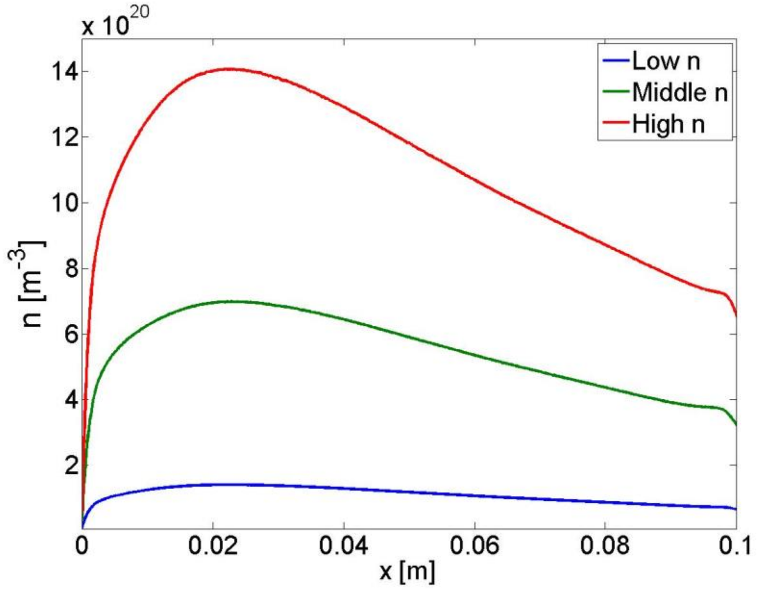
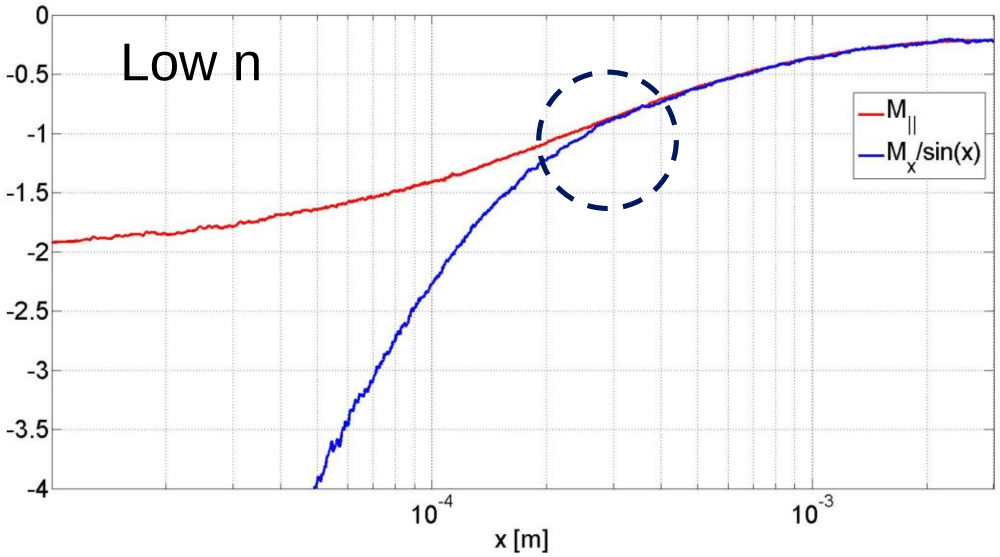
Parallel Mach numbers

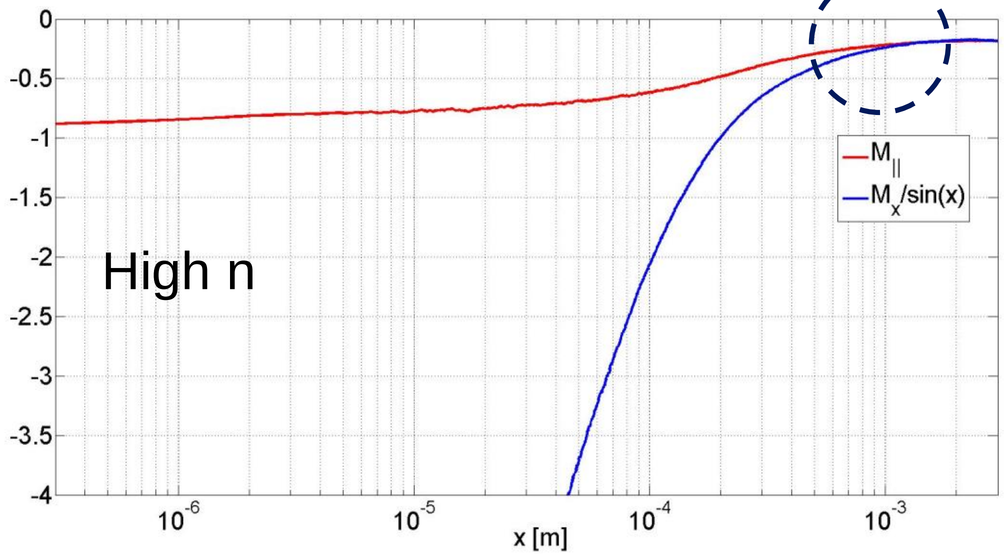


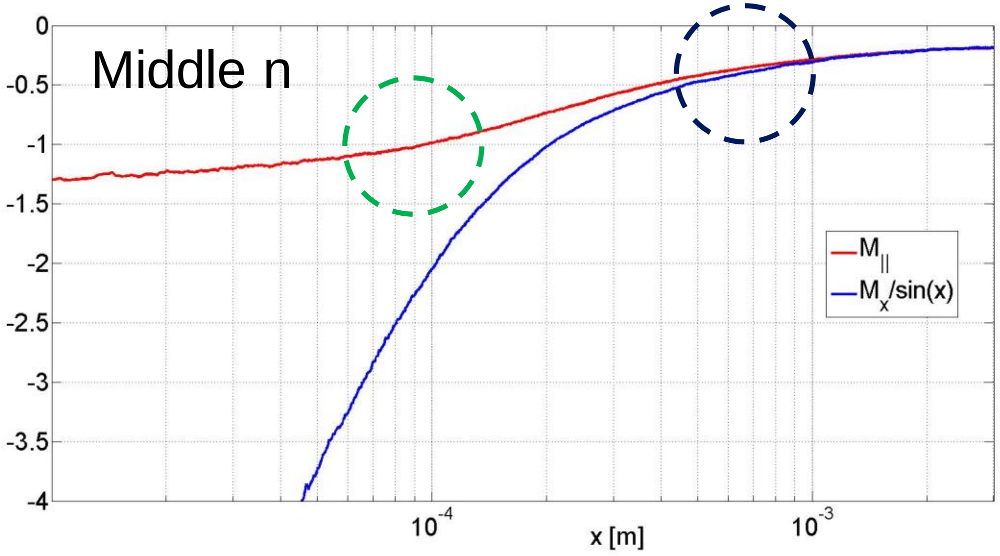
$$M_{\|} = 1$$

or

$$M_{\|} = M_x / \sin(\vartheta)$$





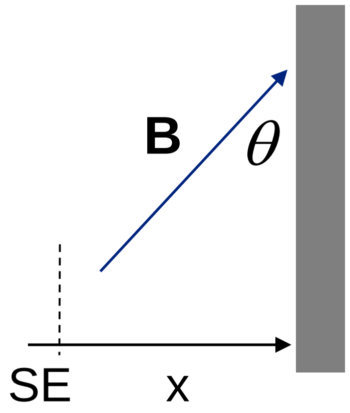


Re-definition of the magnetized sheath entrance

SE: the point nearest to the wall surface were plasma is still magnetised

$$M_{\|} = M_x / \sin(\vartheta)$$

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



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

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

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

Consequences

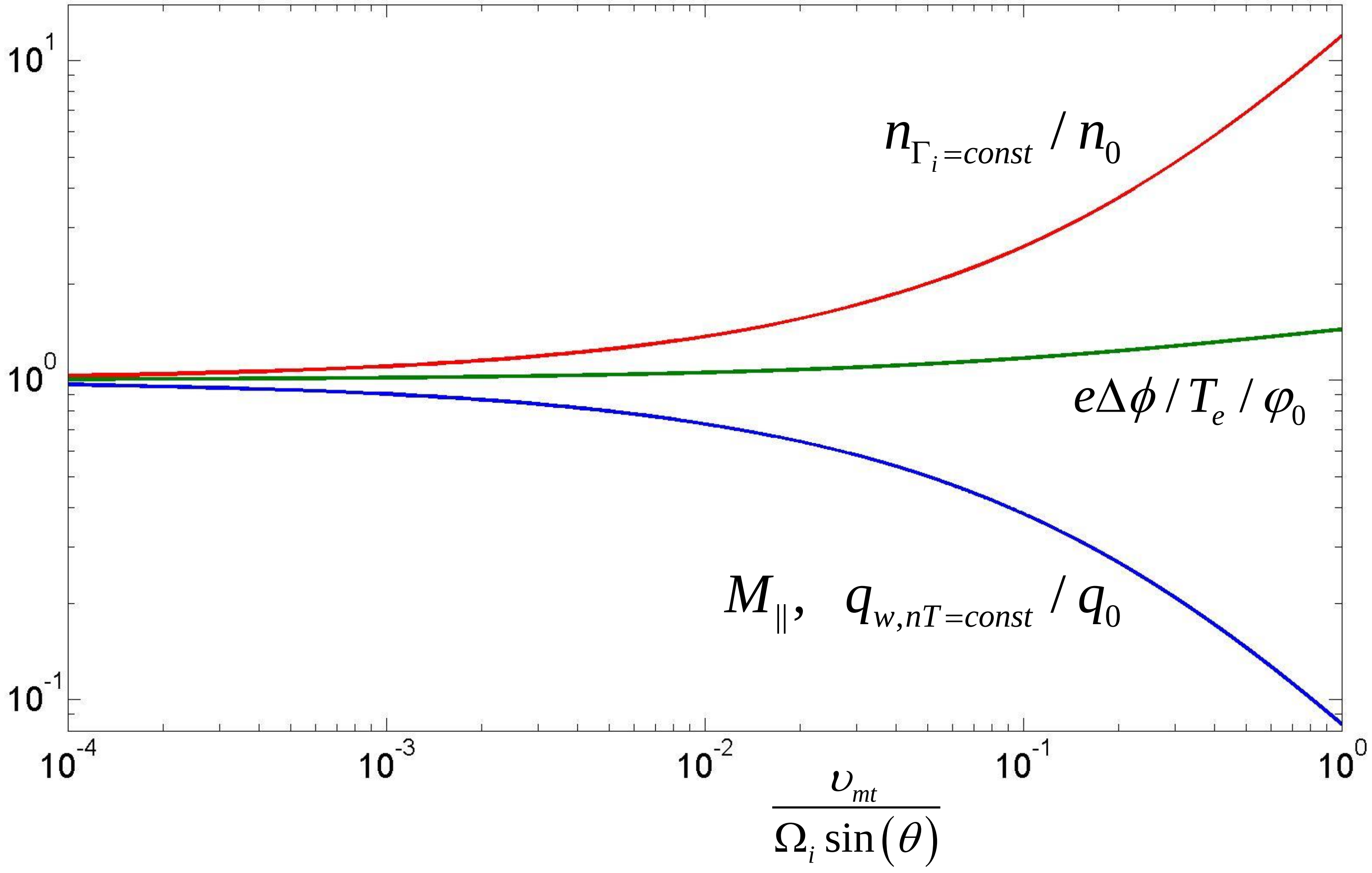
$$\Gamma_i = M_{\|} n c_s$$

$$q_w = \gamma \Gamma_i T_e, \quad \gamma \sim 10$$

$$e\Delta\phi / T_e = \varphi_0 - 0.5 \ln\left(M_{\|}\right)$$

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

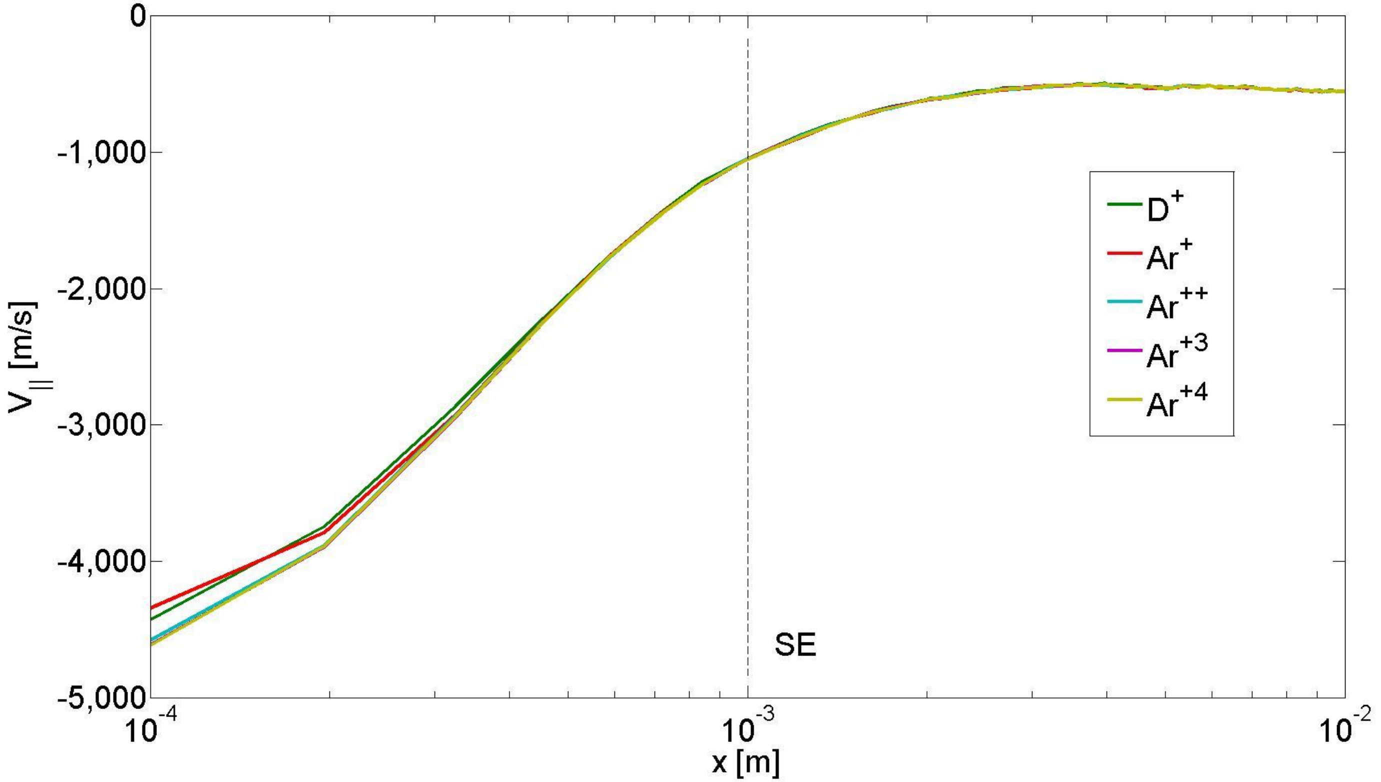
$$\chi = \frac{\upsilon_{mt}\left(1 - V_{\|}^D / V_{\|}\right)}{\Omega_i \sin(\theta)} \frac{x_{wall}}{\rho_i}$$



BC for impurity in a collisional sheath

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

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



$V_{\|}$ *profiles in the sheath*

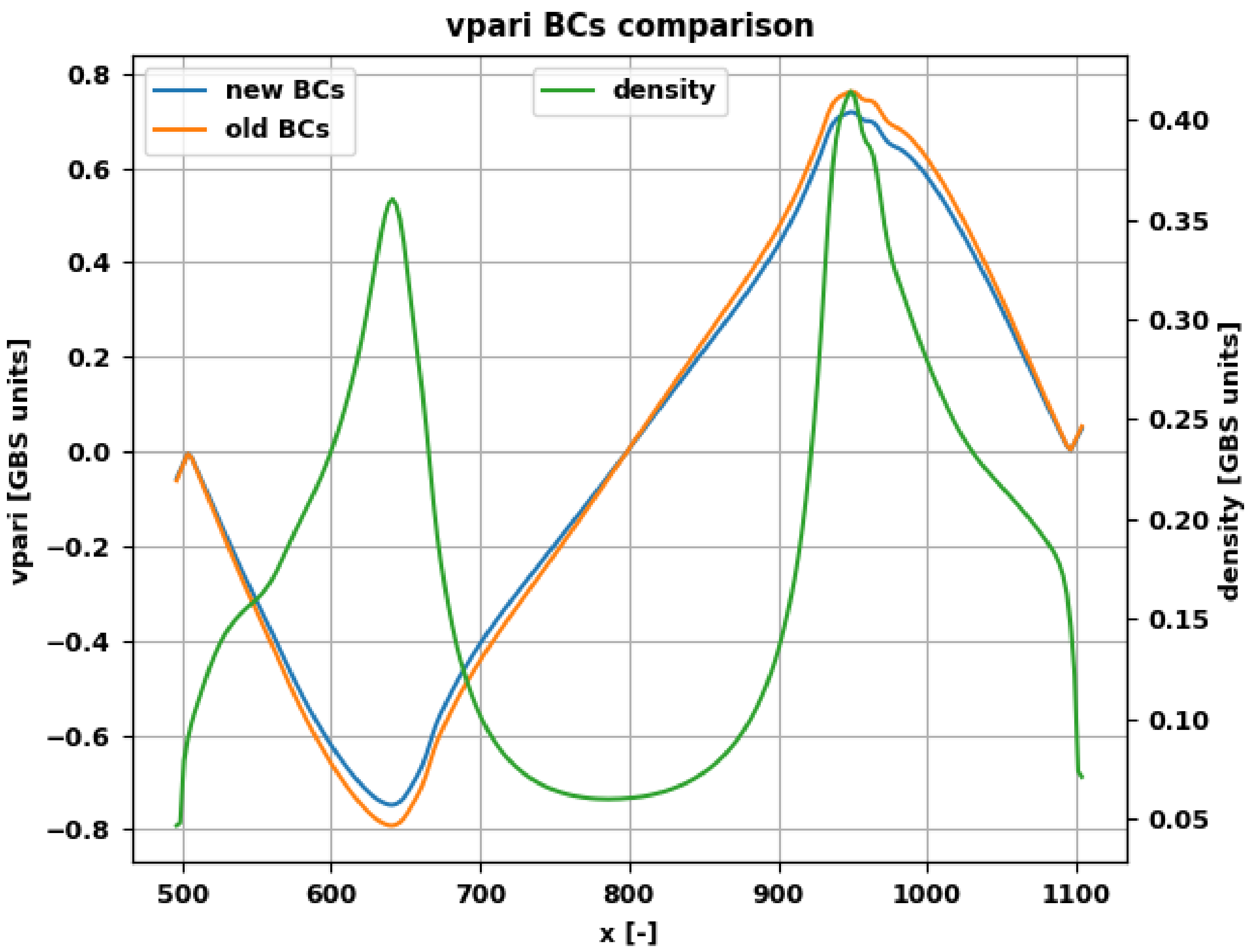
We expect a strong coupling between the main and the impurity ions

Implementation of new BC into the GBS code

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

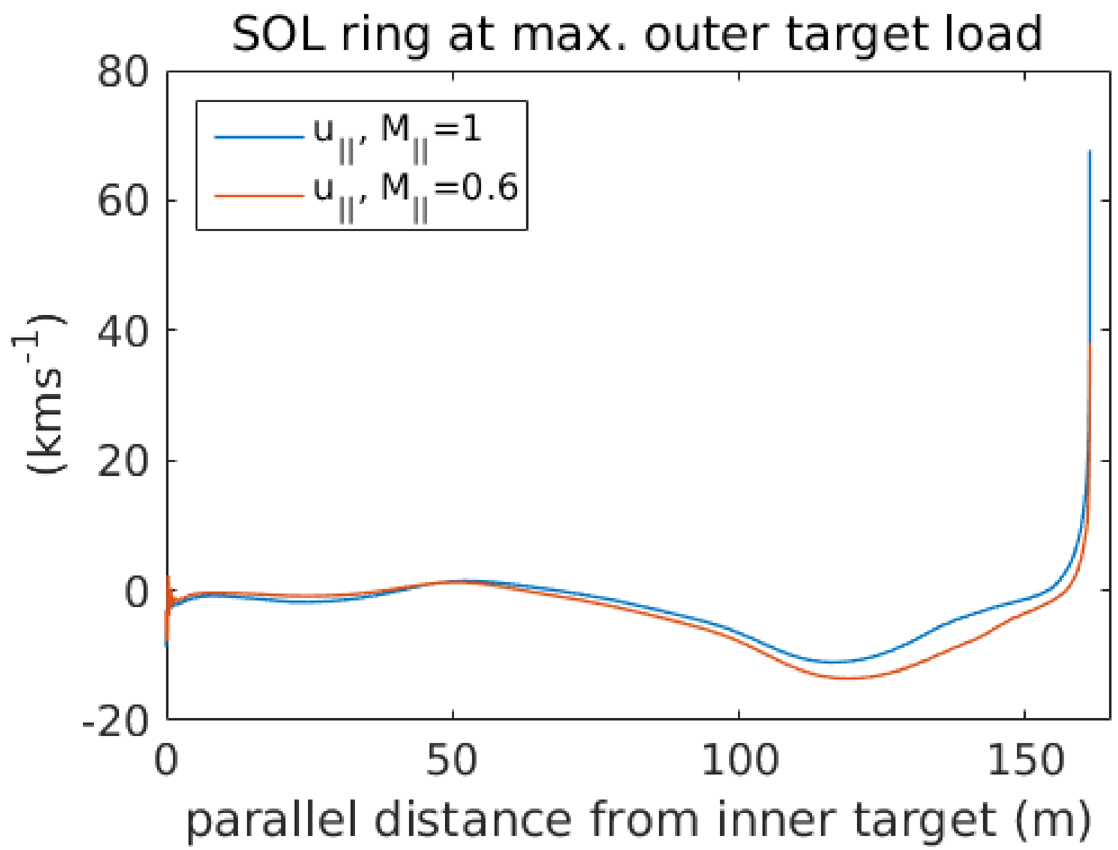
$$\chi = \frac{\left(\upsilon_{mt}(1-\alpha) + \upsilon_{ei}\right) 20\rho}{2c_s \sin(\theta)}$$

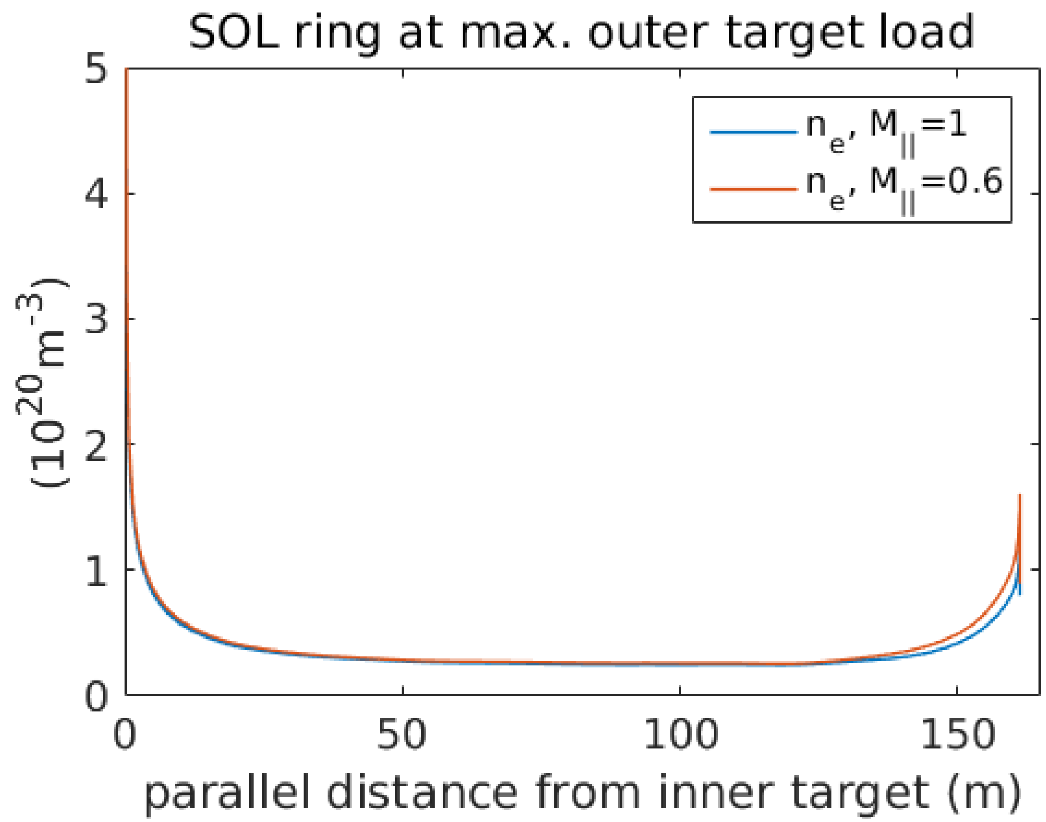
- Results from **divrec** simulation.
- **Values of $V_{\parallel,i}$ are reduced** in regions of high density:
  - Charge exchange - **dominant**
  - Electron-ion collisions - weak effect
- **BCs not affected at the smoothed region** (where magnetic field changes angle)
- The change in BCs did not introduce any numerical issues, **no performance degradation**.



Implementation of collisional sheath in SOLPS-ITER

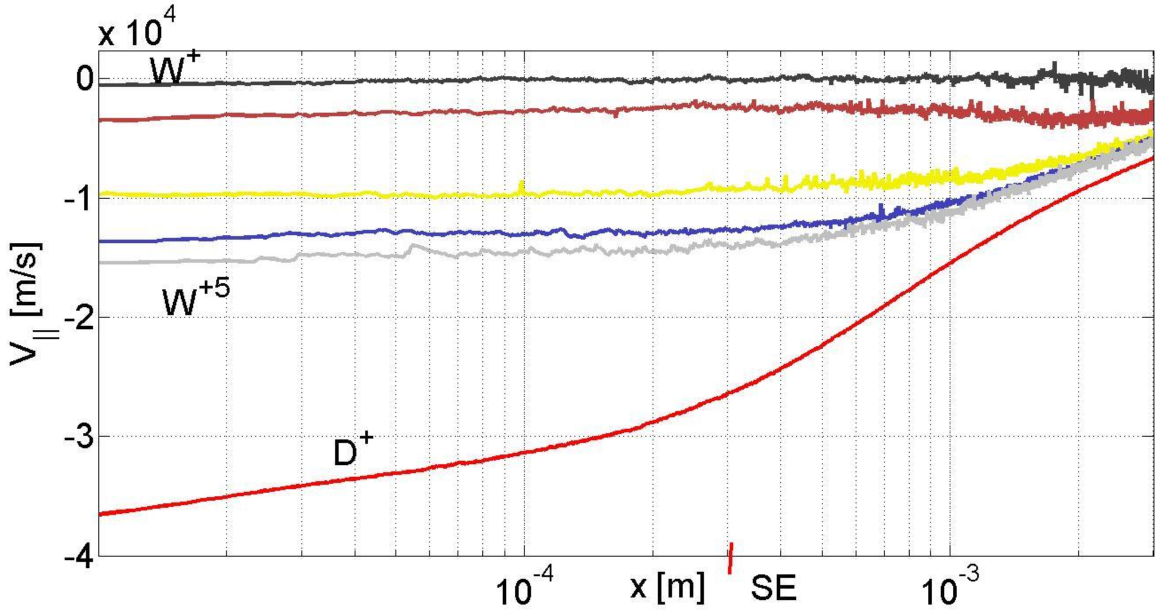
[D. Moulton, ISFN DivSOL, 2021]



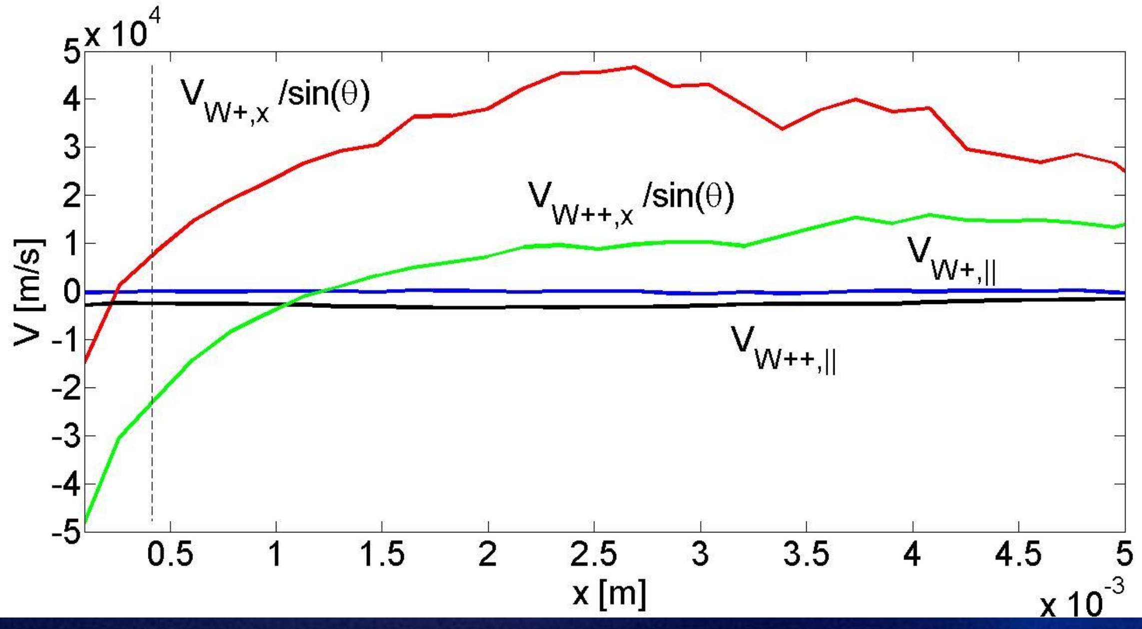


SOLPS-ITER simulation show no changes in particle flux, but increasing of density in the divertor plasma.

Boundary conditions for sputtered heavy ions



JET D/D, BIT1



W ions do not satisfy the Bohm-Chodura condition and are not magnetized even in the pre-sheath

Conclusions

- Divertor plasma sheath in reactor relevant conditions (RRC) will be **collisional** with **subsonic** plasma flow.
- The corresponding static divertor power loads will be **overestimated** by the classical sheath model
- At least the low- and the middle-z impurity particles will be **coupled with the main ions** and enter the plasma sheath with the same parallel velocity.
- A new model of boundary conditions has been successfully implemented into the GBS code.
- Collisional effects seem to start at $n_{sheath} > 10^{20}$ m^{-3} (T ~ 1 eV).