INSTITUTE OF PLASMA PHYSICS
OF THE CZECH ACADEMY OF SCIENCES

On new results from high density plasma sheath modelling

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WP-PWIE SP D report

MINISTRY OF EDUCATION,
YOUTH AND SPORTS

Status of task: kinetic modelling of the plasma sheath and SOL

Completed tasks

- BIT1 updated: DCSM for ionization and recombination (relevant also for TSVVs: 3, 4 and 7)
- SPICE2 updated: radially nonuniform injection
- ITER and DEMO-relevant plasma sheath modelling
- Modelling of AUG, JET and ITER inter-ELM and AUG and JET ELM-ing SOLs

Ongoing tasks

- DEMO-relevant plasma sheath including DCSM recombination
- AUG, JET and ITER ELM-ing SOL with DCSM
- W redeposition rates in collisional sheath
- Multi-dimensional plasma sheath modelling

Main target

To study plasma sheath properties for high density divertor:

boundary conditions, divertor particle and heat loads, W sputtering and thermionic emission rates

Numerical tools used

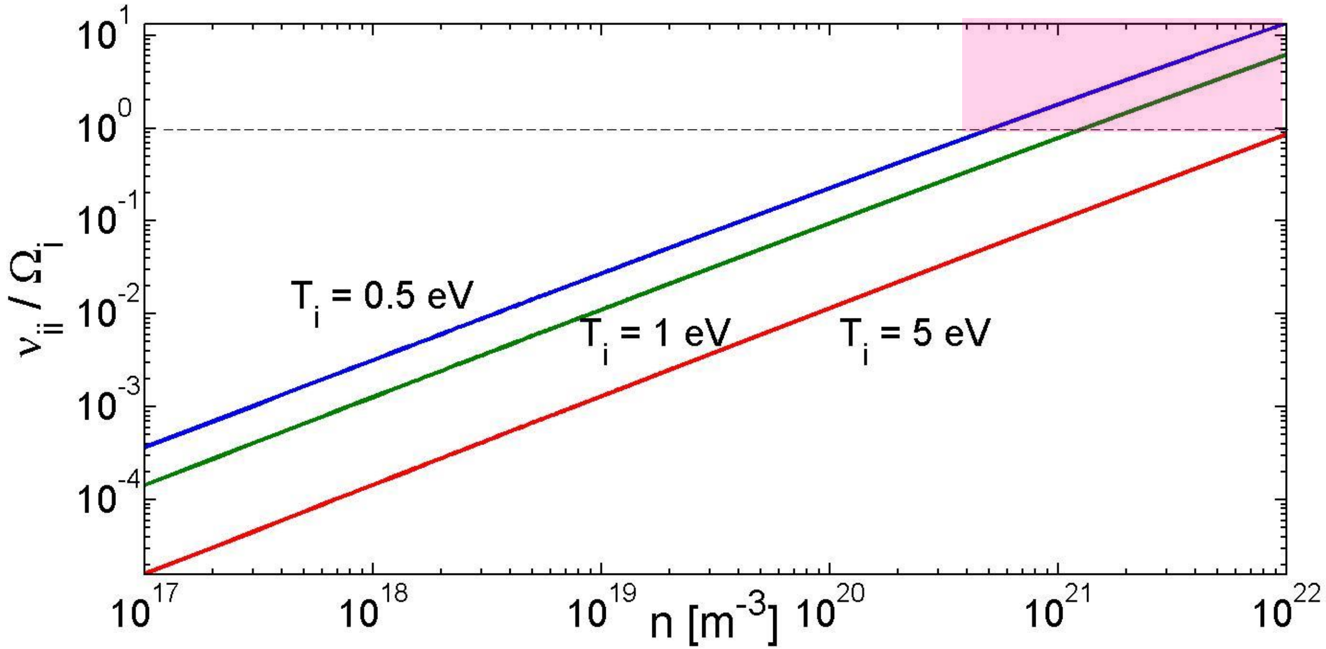
BIT1, SPICE2 and 3 PIC (+MC)

Outline

- Motivation
- Explanation of results from 2021
- Discussion on neutral particle fluxes
- conclusions

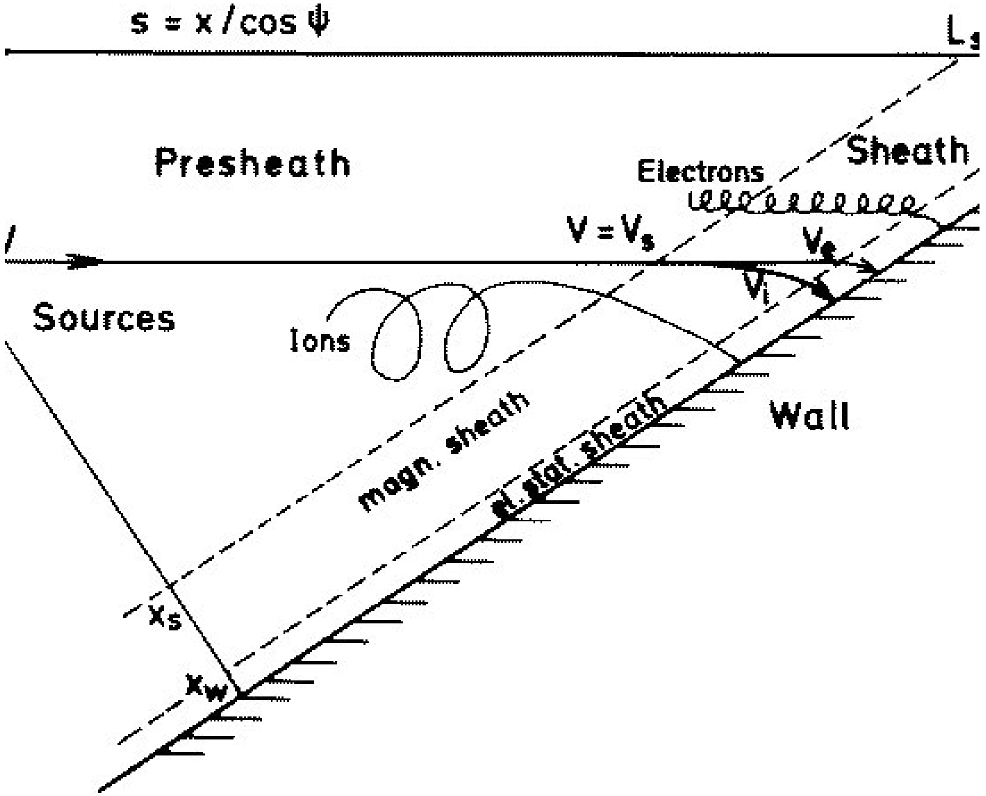
	Divertor sheath	
	n_{max} [10^{20} m^{-3}]	T_{min} [eV]
COMPASS	0.3	10
ASDEX-U	2	1
JET	5	1
ITER	50	0.5
EU DEMO	~100	0.2 (?)

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



Plasma sheath theory

Collisionless magnetised plasma sheath[1]



$$\Gamma_i \sim \underline{M_\parallel} n c_s$$ **- Plasma flux density**

$$c_s = \sqrt{(T_i + Z_i T_e)/m_i}, \quad M_\parallel = V_{\parallel,i}/c_s = 1$$

$$q_w \sim \gamma \Gamma_i T_e$$ **- Heat flux density**

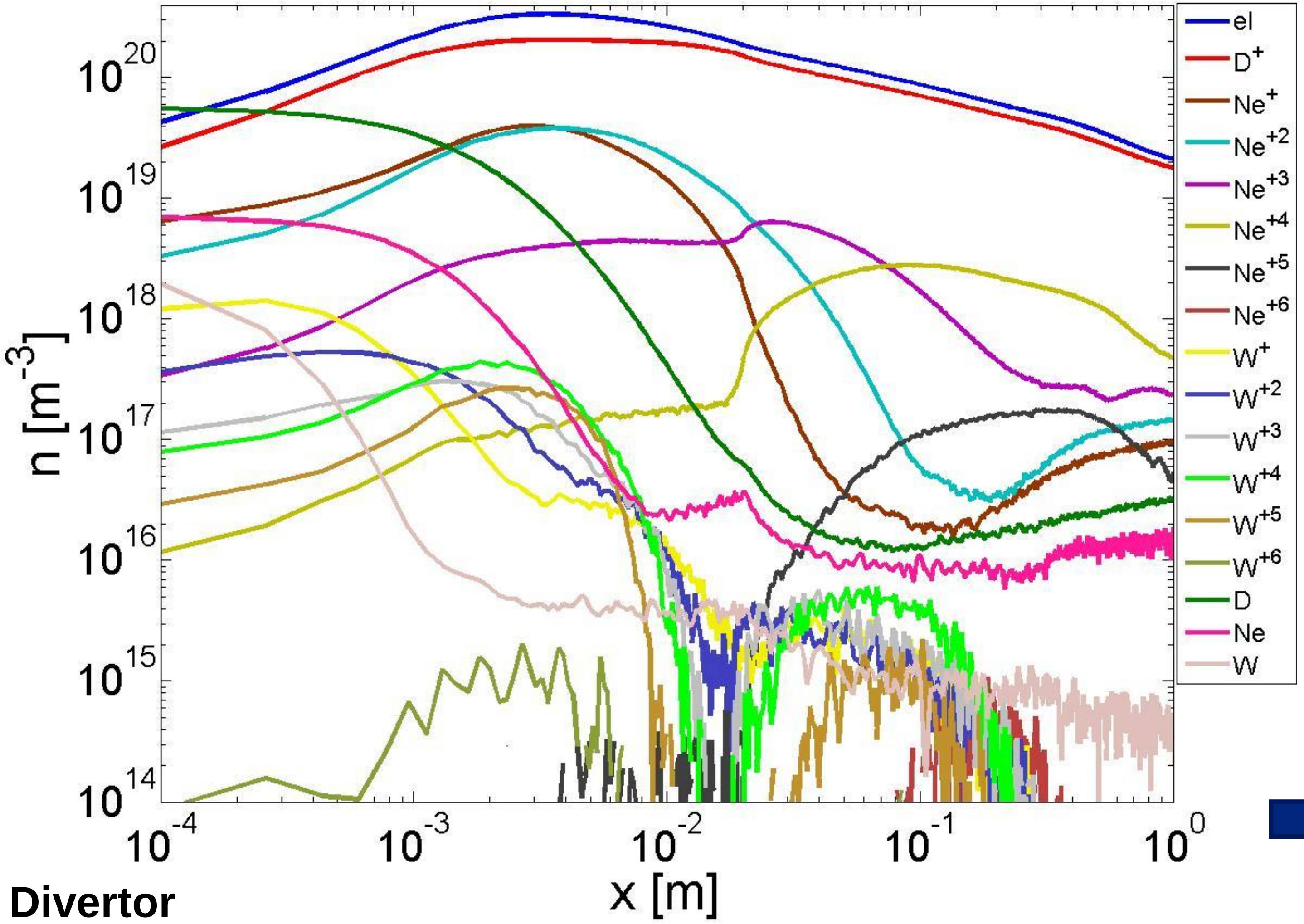
$$\gamma \approx 2 + 6$$

$$\Delta\varphi \sim T_e \ln\left(\underline{M_\parallel} \sqrt{m_e / m_i}\right)$$ **- Potential drop**

- **Plasma profiles in the sheath -** used for prompt redeposition modelling
- **Energy and angular Distribution of absorbed particles** – used for PWI study

[1] *Chodura Phys. PWI Contr. Fus. 1984*

Description of simulation



- Nonlinear model for Plasma, impurity and neutral particles
- Collisions are treated via binary collision model, all **relaxation times** and **forces** are **self-consistently** included
- 14 charged particle species and **105 types** of Coulomb collisions
- DCSM model – kinetic RCM[2]

➡ **Upstream SOL or second wall**

[2] D. Tskhakaya, ICAMDATA 2022

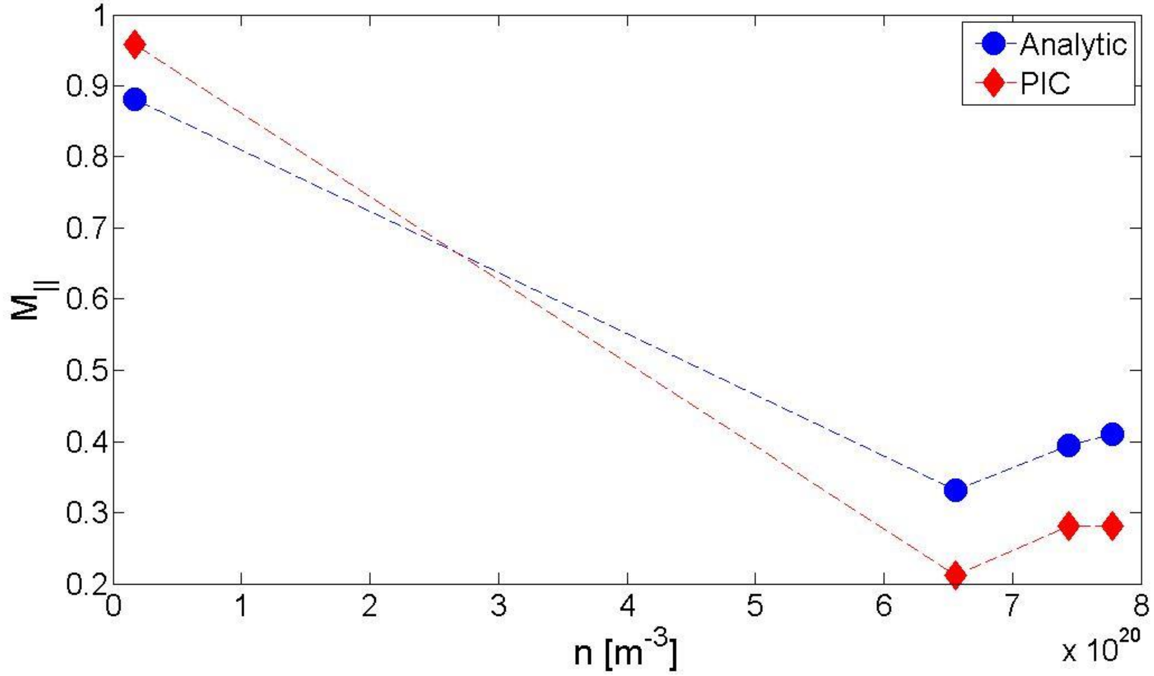
Results from 2021

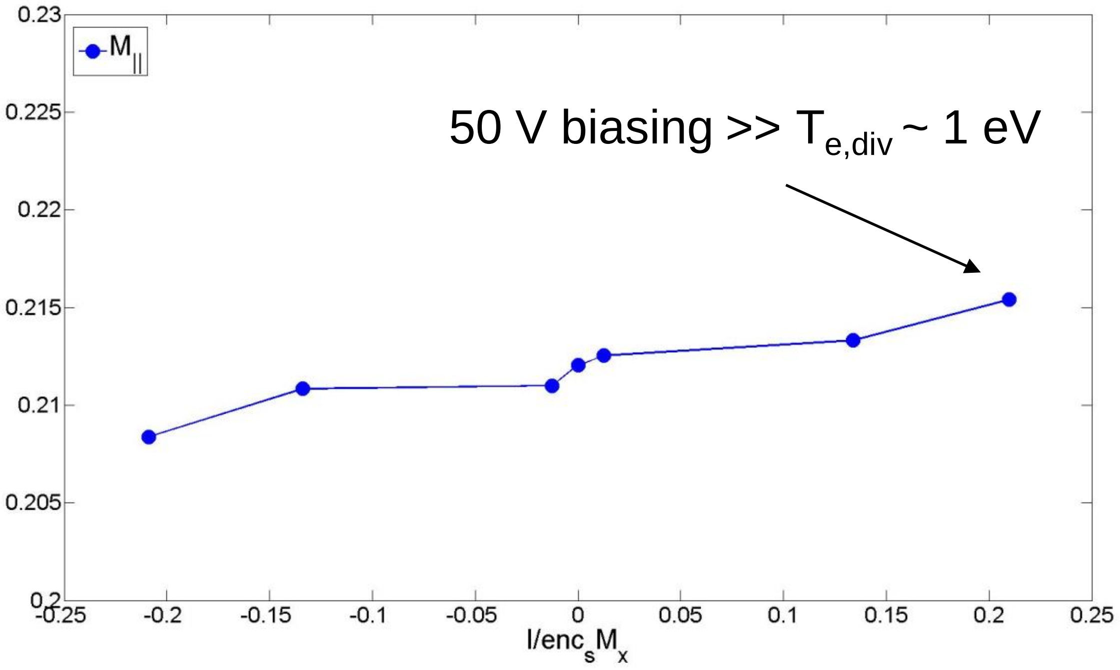
[3] Tskhakaya, 47th EPS 2021

Sheath edge[3]:

$$\boxed{M_{\parallel} = \frac{M_p}{\sin(\theta)} = 1 + \chi - \sqrt{\chi^2 + 2\chi} < 1}$$

$$\chi = \frac{\upsilon_{mt}\left(1 - V_{\parallel}^{n} / V_{\parallel}\right) + \overbrace{\upsilon_{ei} I / I_{isat}}^{?}}{2c_s \sin(\theta)} \quad x_{wall}$$

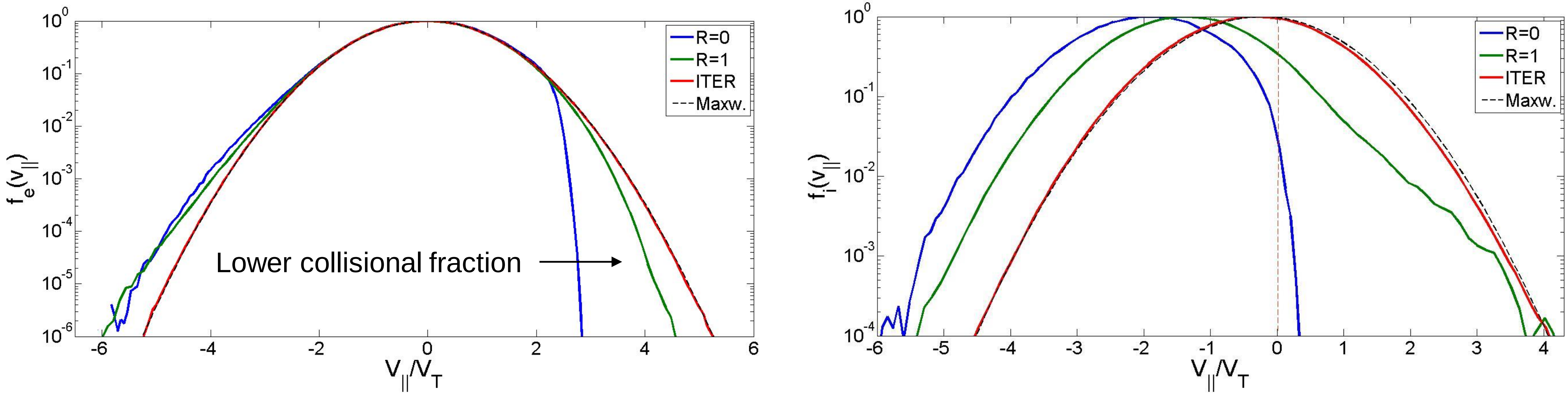




50 V biasing >> $T_{e,div}$ ~ 1 eV

Explanation of current-independence

Electron and ion (D^+) VDFs at the sheath edge (from the PIC model)



Electron *current due to* ***cut-off VDF***, ***ion*** *current due to the* ***shifted VDF***

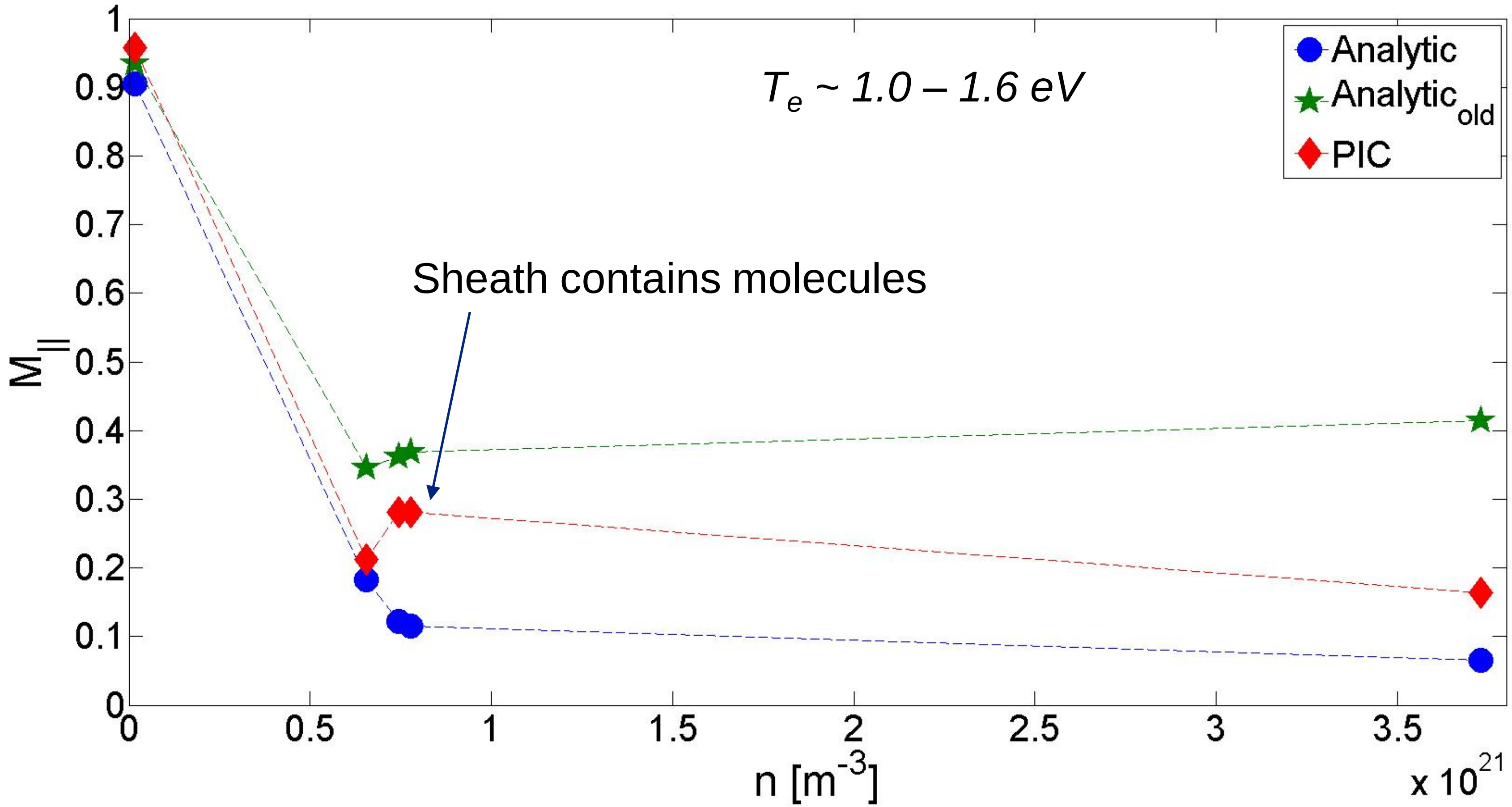
$$R_\parallel^{ei} = -m\upsilon_{ei}\left(V_\parallel^i - \cancel{V_\parallel^e}\right) \Rightarrow -m\upsilon_{ei}V_\parallel^i$$

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

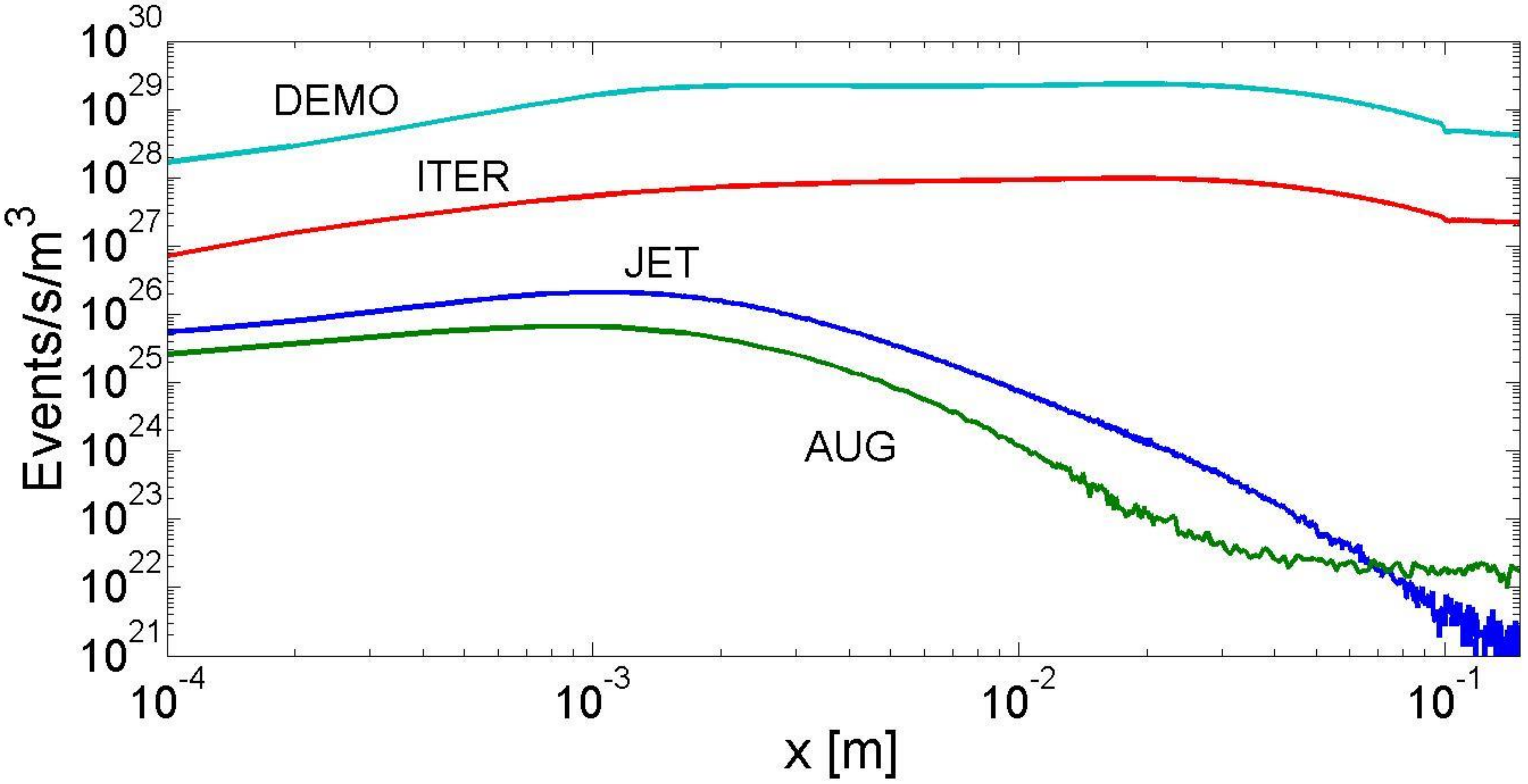
Updated model

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

$$\chi' = \frac{\upsilon_{mt}\left(1 - V_{\parallel}^{n} / V_{\parallel}\right) + \boxed{\upsilon_{ei}}}{2c_{s}\sin(\theta)} x_{wall}$$



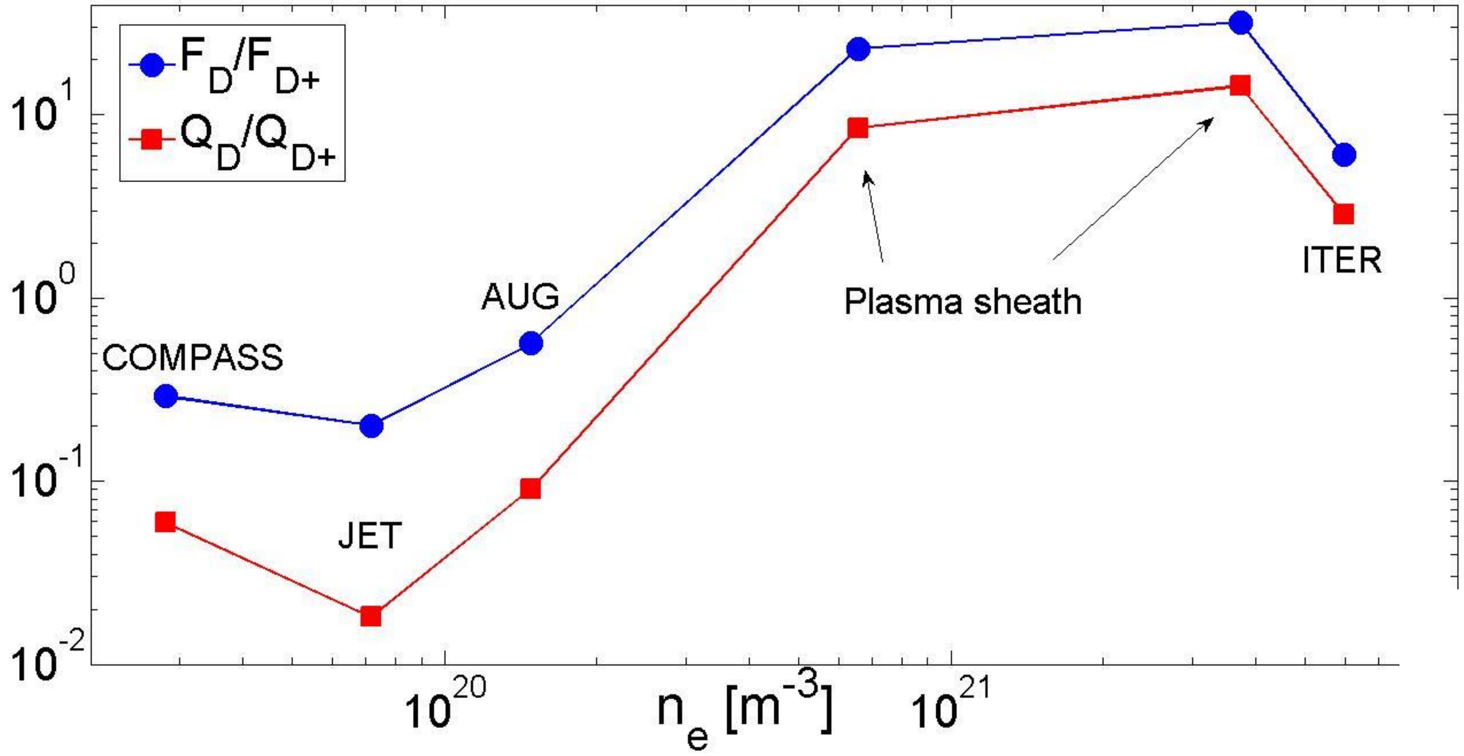
Neutral particle fluxes: sources



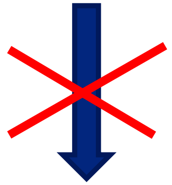
Profiles of D+D$^+$ CX rates at the ID

Increasing neutral flux

Neutral particle fluxes (ii): divertor loads

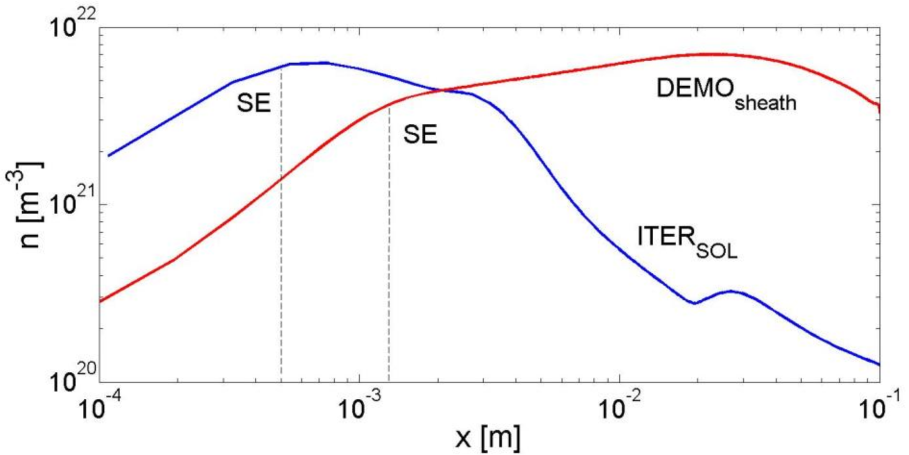


Relative particle and heat divertor loads

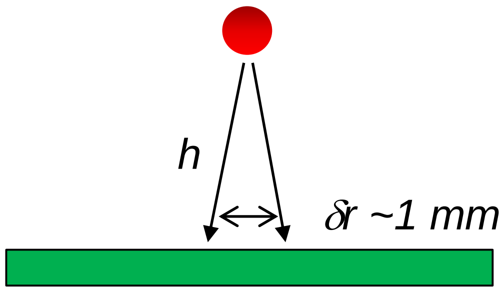


Higher upper density

higher plasma sheath density



Neutral particle fluxes (iii): corrections



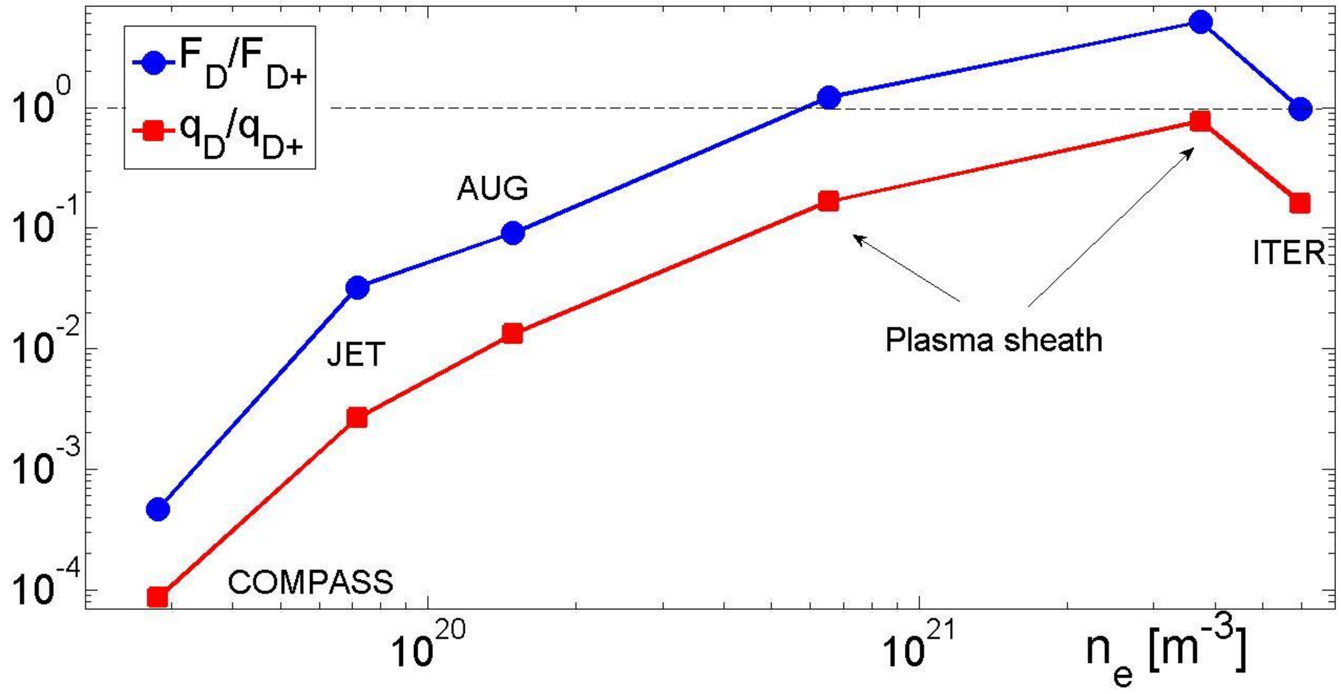
$$F,q\big|_{n,div} \rightarrow \alpha\, F,q\big|_{n,div}$$

$$\alpha \sim \frac{\delta r}{\pi h}$$

Large reduction

$$q_{div}^{plasma} = \left(\underline{8.4+\frac{15.8}{T_e}}\right) T_e F_{div}^{plasma}$$

$$q_{wall}^{neutral} \approx \underline{2}T_e F_{div}^{neutral}$$



$$q_{div}^{plasma} = \gamma T_e F_{div}^{plasma}, \quad F_{div}^{plasma} = M_{\|} n c_s \sin(\theta)$$

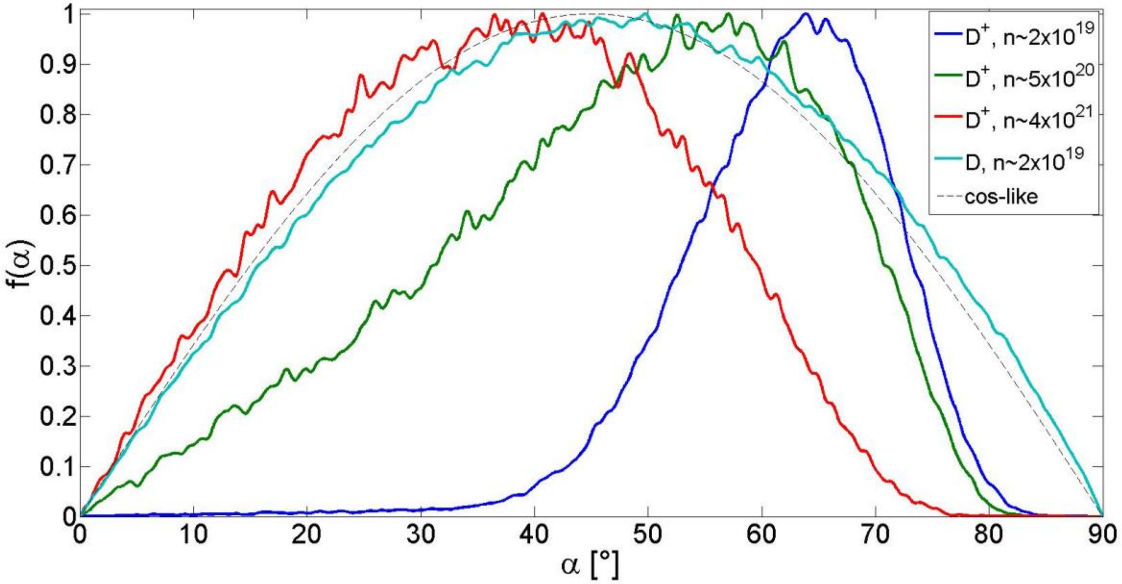
$$\gamma^{[4]} = \gamma_e + \gamma_i + \phi + \frac{\chi_i + \chi_m}{T_e}, \quad \chi_i = 13.6, \quad \chi_m \approx 2.2$$

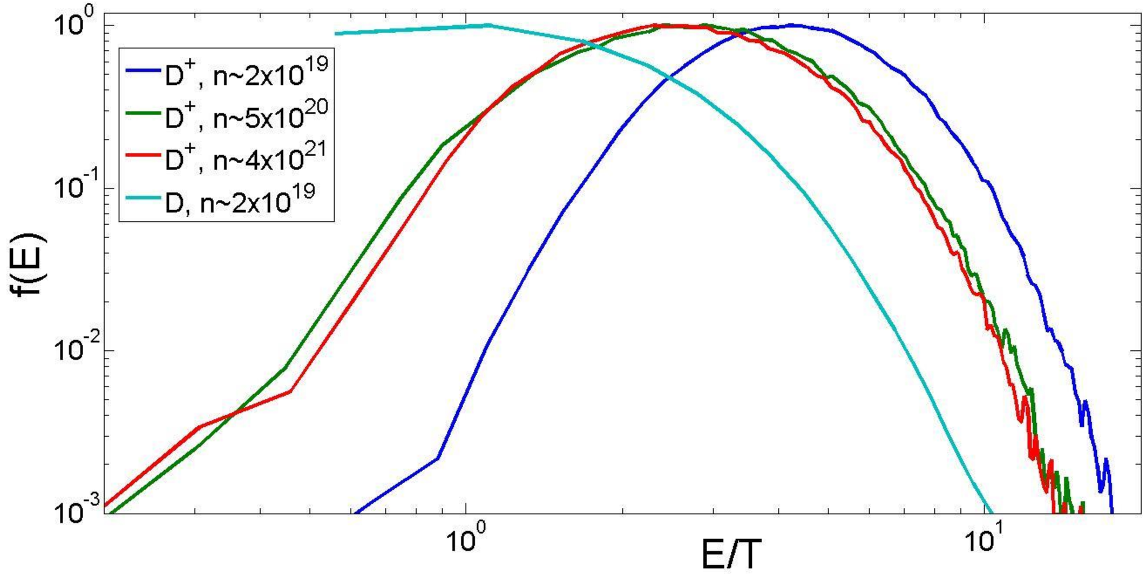
$$\gamma_e = 2, \quad \gamma_i = 2.5 + 0.5\left(1 + T_i / T_e\right) \approx 3.5, \quad \phi \approx 2.9,$$

$$R_E = 0, \quad T_e \sim T_n$$

[4] P. Stangeby, sec. 5 (2000)

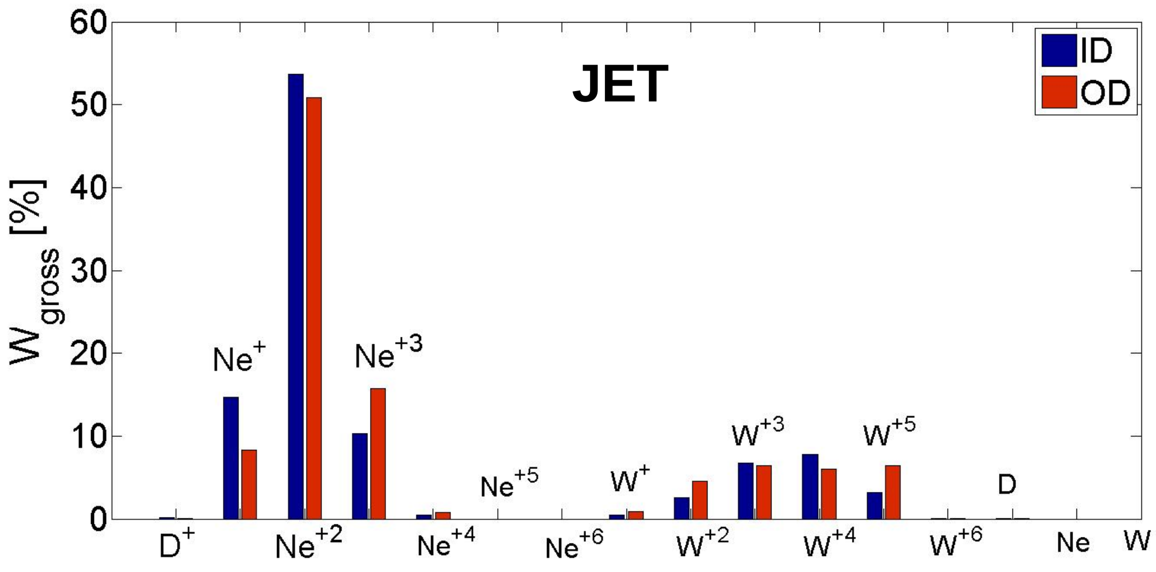
Distribution functions of absorbed ions/neutrals

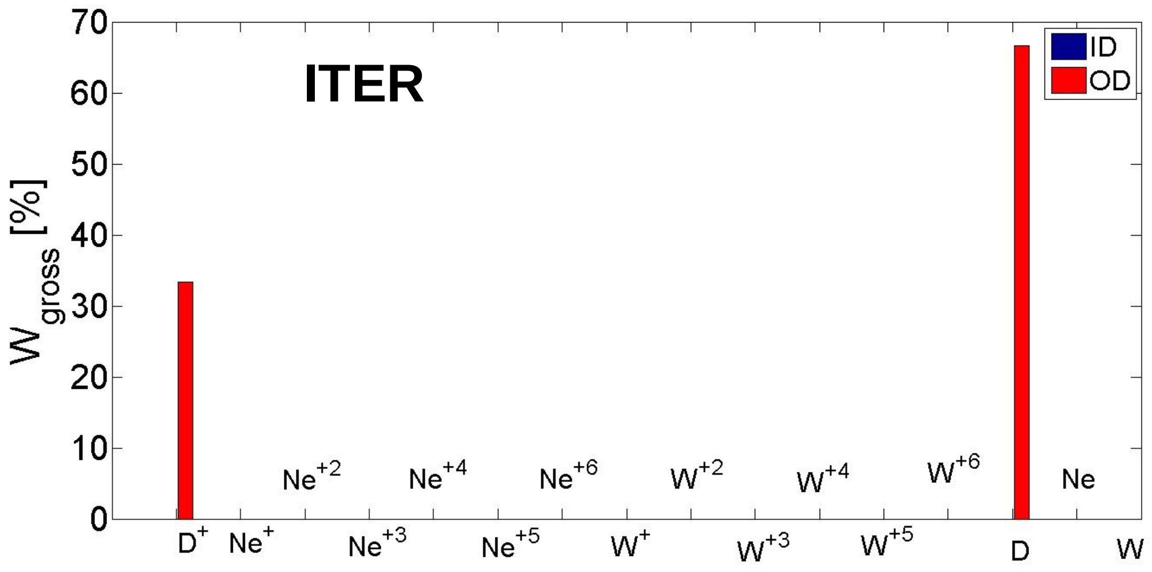




Neutral particle distributions are near to the Maxwellian;
ion distributions “Maxwellize” with increasing density.

W sputtering





	Gross [10^{21} m^{-2}s^{-1}]	Nett [10^{21} m^{-2}s^{-1}]
ID	6.21	1.00 (~16%)
OD	17.03	0.64 (~4%)

	Gross [10^{21} m^{-2}s^{-1}]	Nett [10^{21} m^{-2}s^{-1}]
ID	0	0
OD	0.015	0.015

Conclusions

- New boundary condition for the **ion parallel velocity** was derived
- **Neutral particles** probably will be the **main** particle and heat flux **carriers** to the divertor plasma in future tokamaks → significantly **reduced divertor heat loads**
- Ion-electron **friction term** in the vicinity of the sheath has been revised
- ADF and EDF of particles absorbed at the divertors **"Maxwellize"** with increasing plasma **density**

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

$$q_{div} = \gamma_{plasma} T_e \left(F_{div}^{plasma} + \frac{2}{8.4+15.8/T_e} F_{div}^{neutral} \right)$$

$$<< \gamma_{plasma} T_e \left(F_{div}^{plasma} + F_{div}^{neutral} \right)$$

Ongoing tasks

- DEMO-relevant plasma sheath including DCSM recombination
- AUG, JET and ITER ELM-ing SOL with DCSM
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- Multi-dimensional plasma sheath modelling

Backup: Dressed cross-section method

$$\sigma(E,T,n)=\sigma(E)\frac{R(T,n)}{R_{n=0}(T)}$$

➡

$$\int f_m V\sigma(E,T,n)\,d\vec{V}=R(T,n)$$

$$\sigma(E,T,n\to 0)=\sigma_{n=0}(E)$$

Example from ADAS[6]: e + Ne^{+i} → e + $Ne^{+i,\,(v)}$

Target	states	Number of CS
Ne	89	(N+3)N/2 = 4 096
Ne^{+}	279	39 339
Ne^{+2}	554	154 289
Ne^{+3}	668	224 114
Ne^{+4}	564	159 894
Total	2 154	**~ 5.8x10^{5}**

Impossible to treat this number of transitions directly!

[6] https://open.adas.ac.uk/

Advantage

i. large number of interaction channels are effectively incorporated

ii. cross-sections and rate coefficients are available

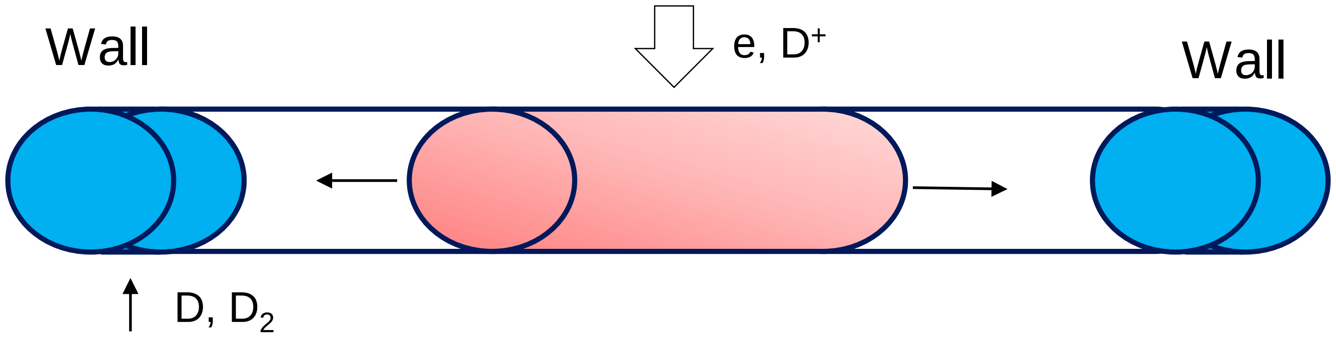
Disadvantage

i. needs calculation of temperature → reduction of the run speed (<10%)

ii. Threshold energies E_{th} are density and temperature independent

iii. EDFs assumed to be near-Maxwellian

Backup: BIT1 modelling of the sheath



Particle and heat source

e, D^+

Wall

Wall

D, D_2

Plasma recycling, floating conditions

Each simulation takes up to 5 M core hours, 10^{10} particles, 10^6 (1D) spatial cells