INSTITUTE OF PLASMA PHYSICS
OF THE CZECH ACADEMY OF SCIENCES

Atomic data needs for studying of W sputtering in a high-density divertor plasmas

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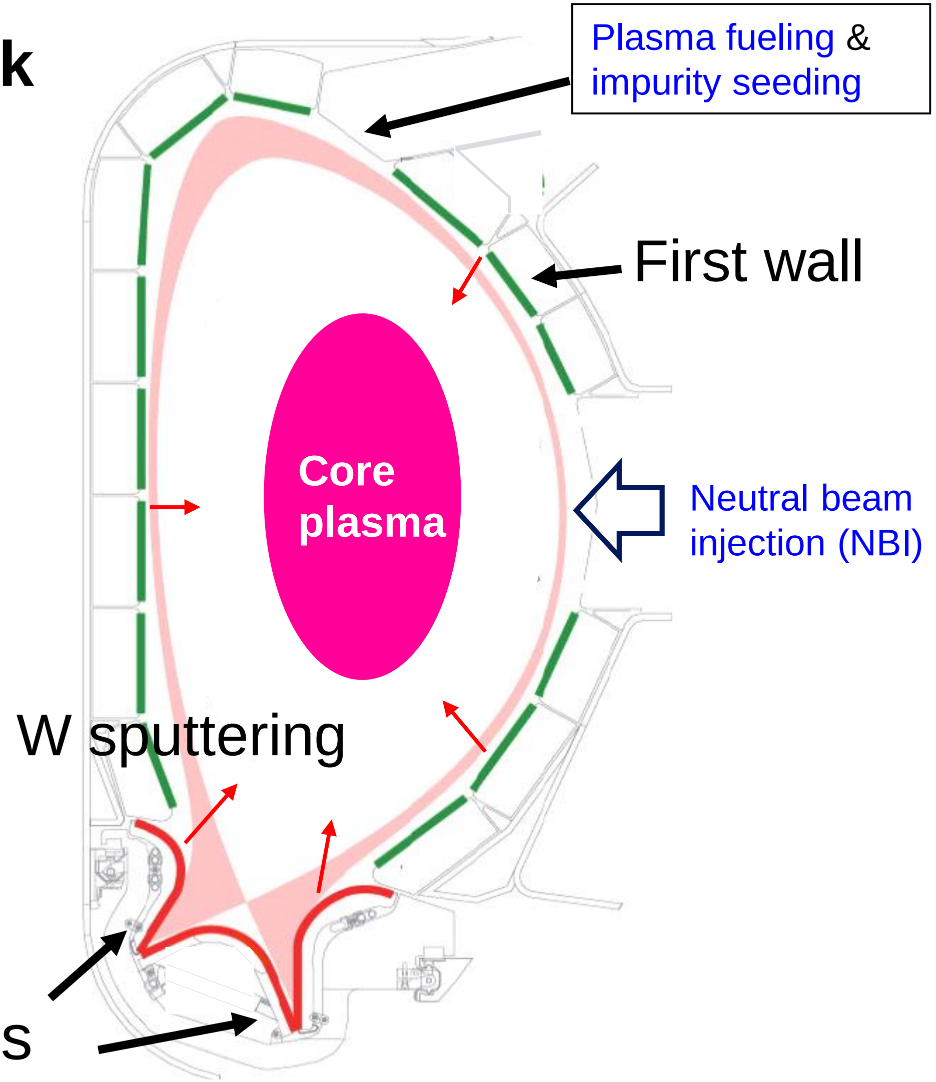
MINISTRY OF EDUCATION,
YOUTH AND SPORTS

Outline

- Introduction
- Analytic desription of the W prompt re-deposition
- PIC simulation results
- Identification of atomic data needs
- Conclusions

Statement of the problem

Tokamak cross-section



W ions penetrate into the core plasma leading to its significant cooling.

Critical W concentration $C_{W\,cr.} \sim 3\times10^{-5}$ [1]

W outflux

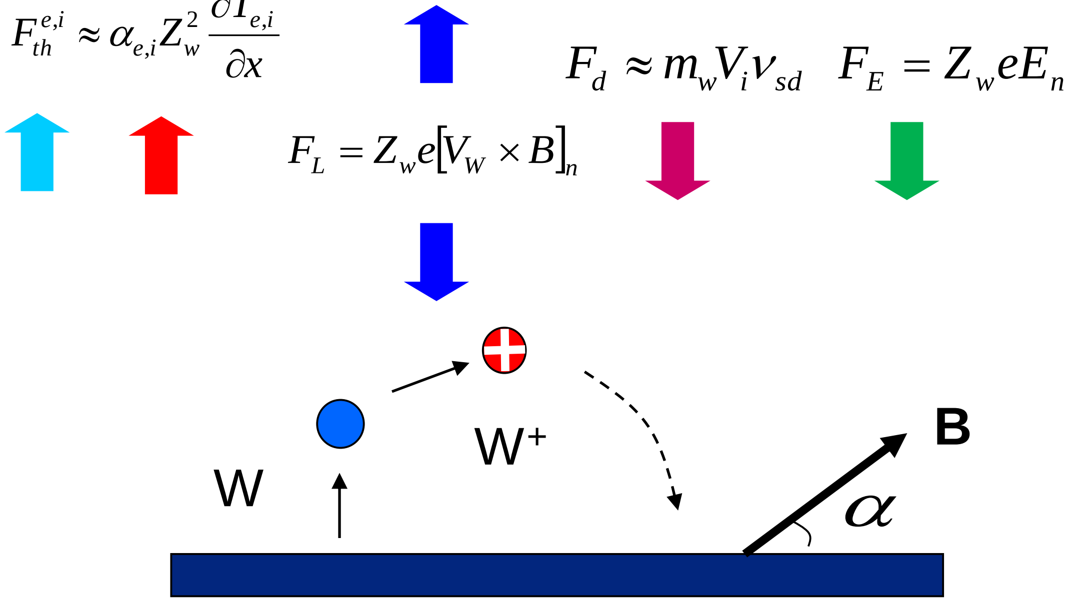
$$F_W = \left(1 - f_{prompt}\right)\left(R_p F_p + R_n F_n + \sum_i R_i F_i\right)$$

Prompt re-deposition coefficient (at the divertors) [2]

$$f_{prompt} > 0.9$$

[1] T. Pütterich, et al., Nucl. Fusion, 50 (2010)
[2] D. Tskhakaya, et al., J. Nuc. Mat., 463 (2015)

W prompt re-deposition (classical models)



$$F_{th}^{e,i} \approx \alpha_{e,i} Z_w^2 \frac{\partial T_{e,i}}{\partial x}$$

$$F_L = Z_w e \left[V_W \times B \right]_n$$

$$F_d \approx m_w V_i \nu_{sd} \qquad F_E = Z_w e E_n$$

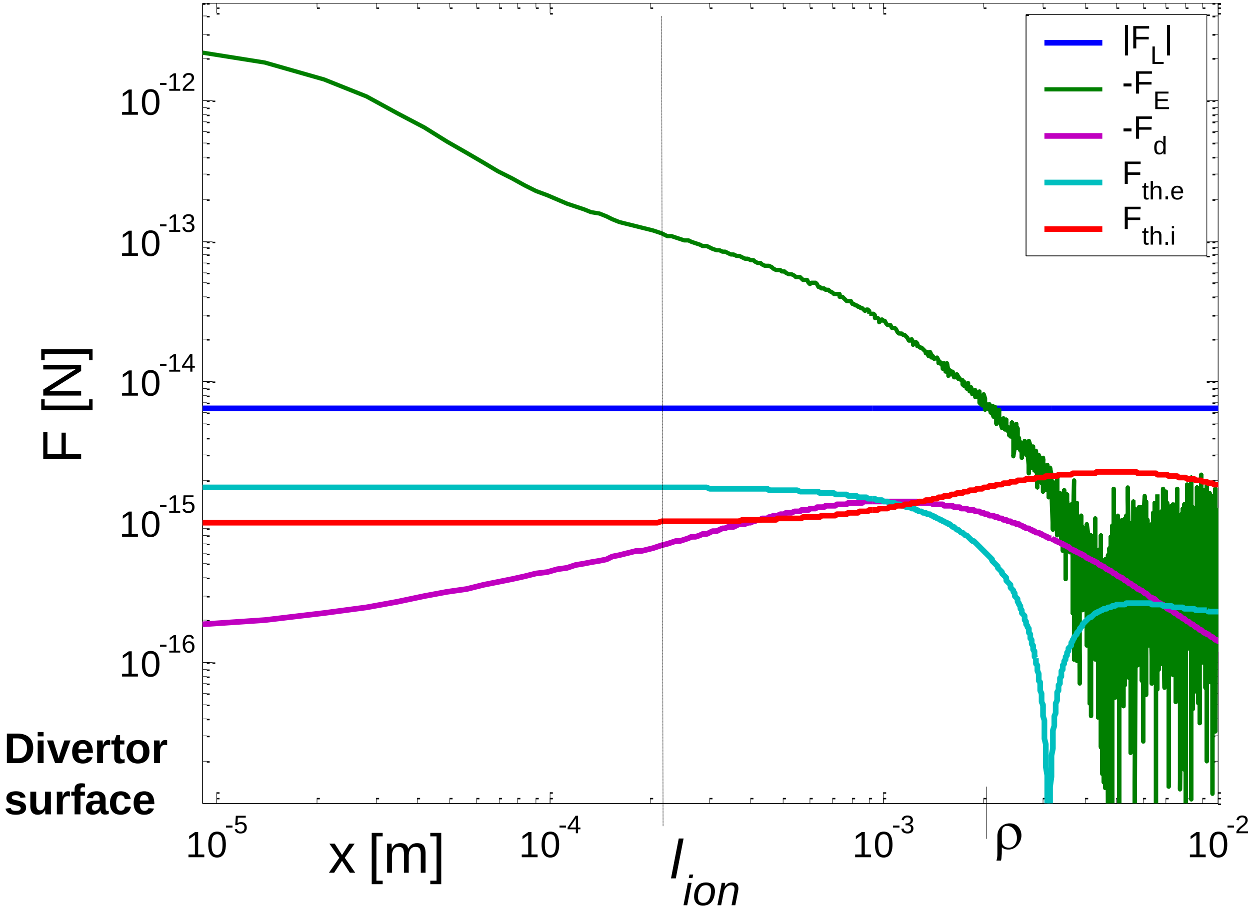
$$f_{prompt}(n_e, T_e) = \left(1 + \left(l_{ion} / \underline{\rho_W} \right)^2 \right)^{-1}$$

$$f_{prompt}(n_e, T_e) = \left(1 + 0.01 \frac{l_{ion}}{\underline{\rho_i}} \frac{T_i}{T_e} \right)^{-1}$$

l_{ion} - W ionization *mfp*

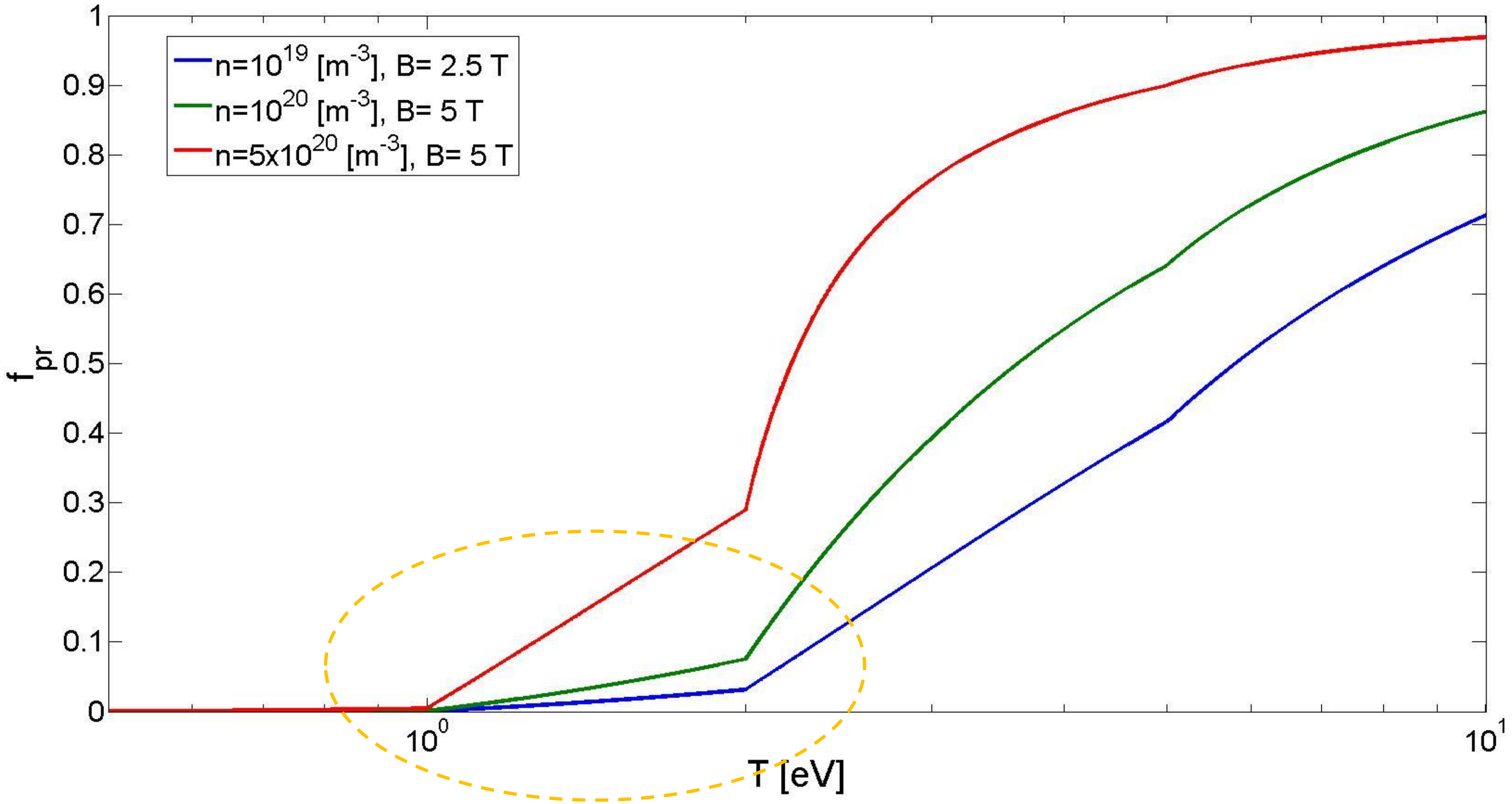
ρ – gyro-radius

[D. Tskhakaya, JNM, 2015]



Forces acting on W+ ion in the magnetized plasma sheath

W prompt re-deposition in a cold high density plasma



$$f_{prompt}(n_e, T_e) = \frac{1}{1 + 0.01\frac{l_{ion}}{\rho_i}\frac{T_i}{T_e}}$$

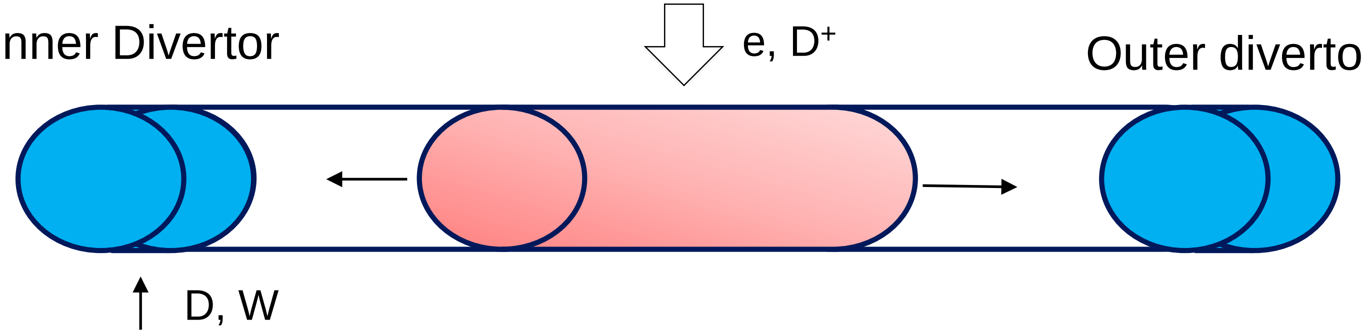
PIC simulation

⬇

$$f_{prompt}(T_e \leq 2eV) \approx 0$$

W prompt re-deposition reduces with the electron temperature

PIC simulation of W sputtering



Particle and heat source

e, D^+

Inner Divertor

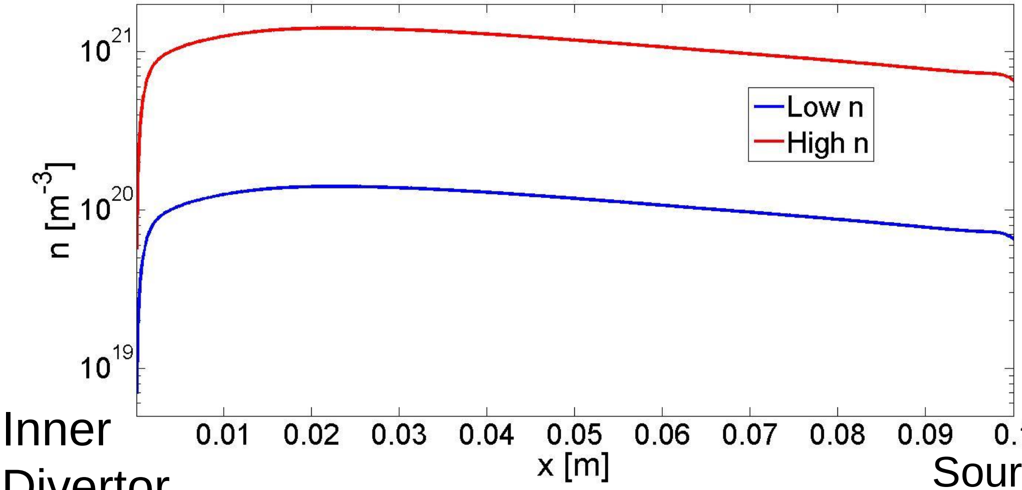
Outer divertor

D, W

Plasma recycling, **W injection 10^{21} m^2/s**

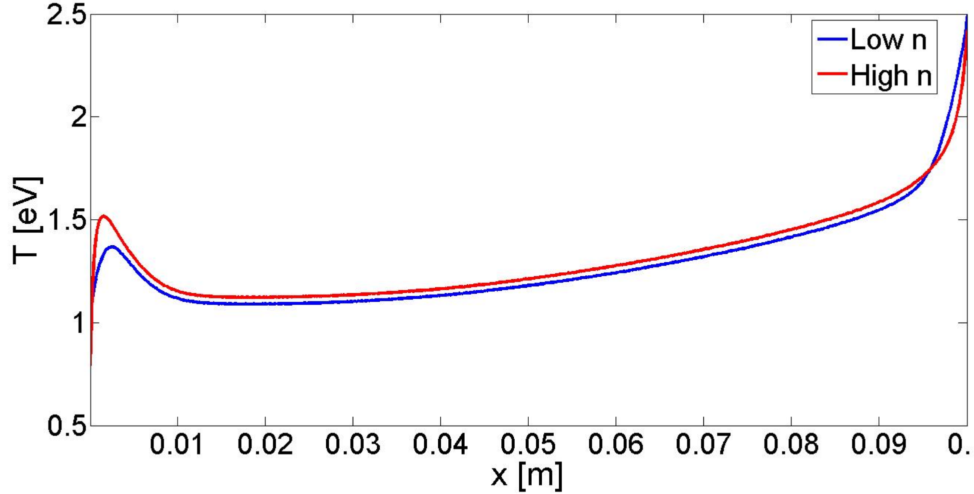
Each simulation takes up to 2 M core hours

Simulated plasma	**W re-deposited fraction**	**CX collisions**
High density	0.0	no
Low density	0.0	no
High density	0.1%	$\sigma_{CX}=10^{-19}$ m^2
High density	30%	$\sigma_{CX}=5x10^{-19}$ m^2



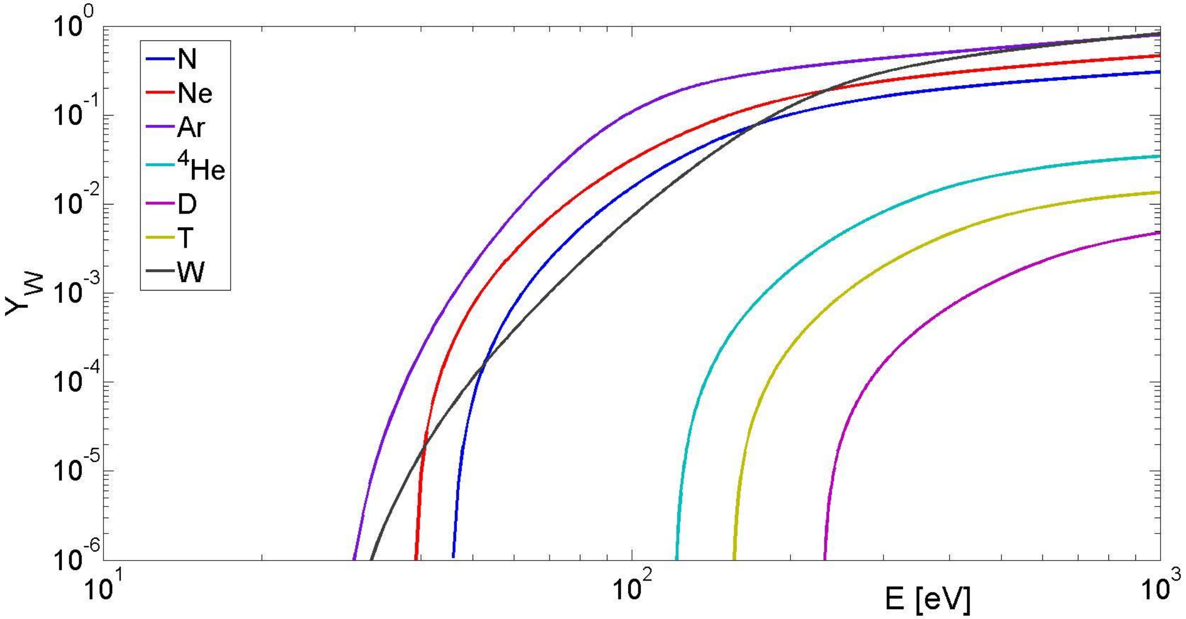
Inner Divertor

Source region



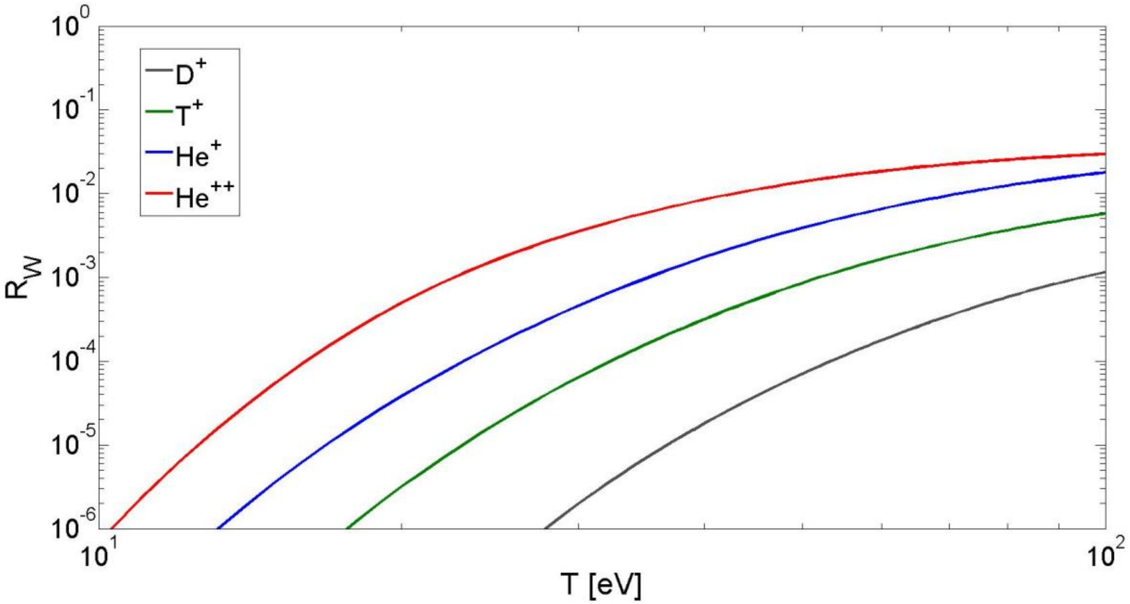
W sputtering yields and rate coefficients

W. Eckstein, Vacuum, 82 (2008)



W sputtering yields vs ion energy

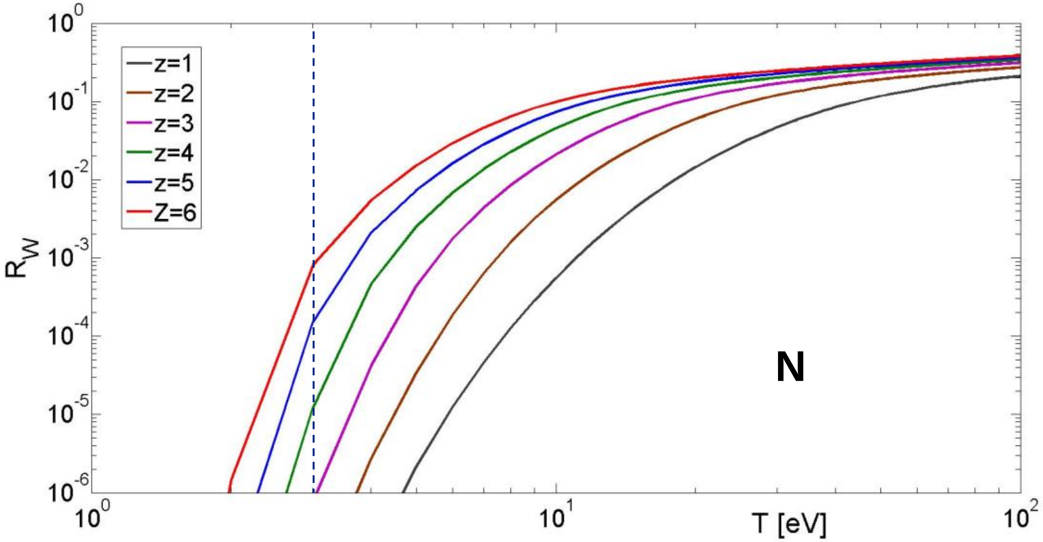
$$R_W(T) = \int_0^\infty \gamma_W\left(Z_i \varphi T + E_\perp + E_\parallel\right) f_i\left(E_\parallel, E_\perp\right) dE_\perp dE_\parallel$$

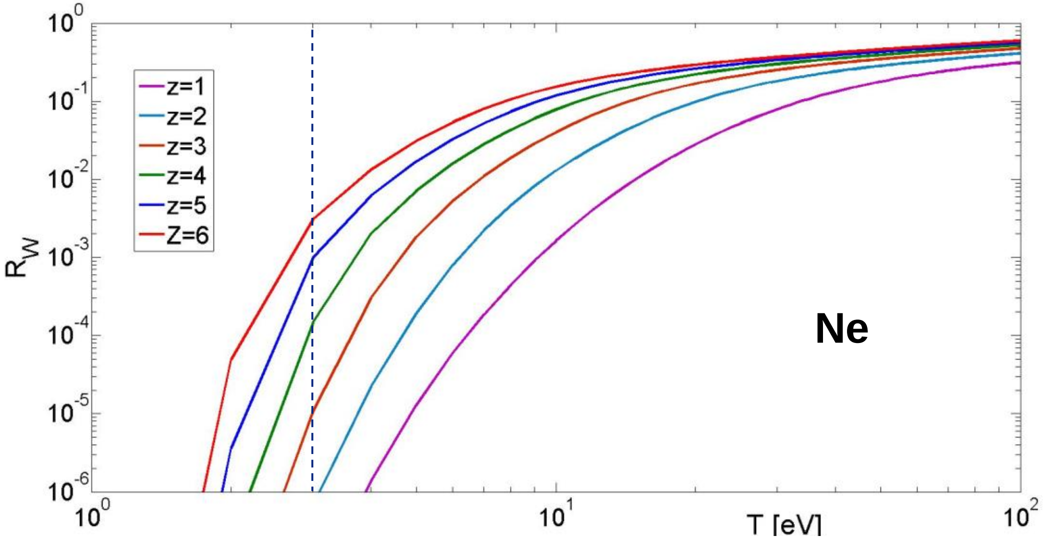


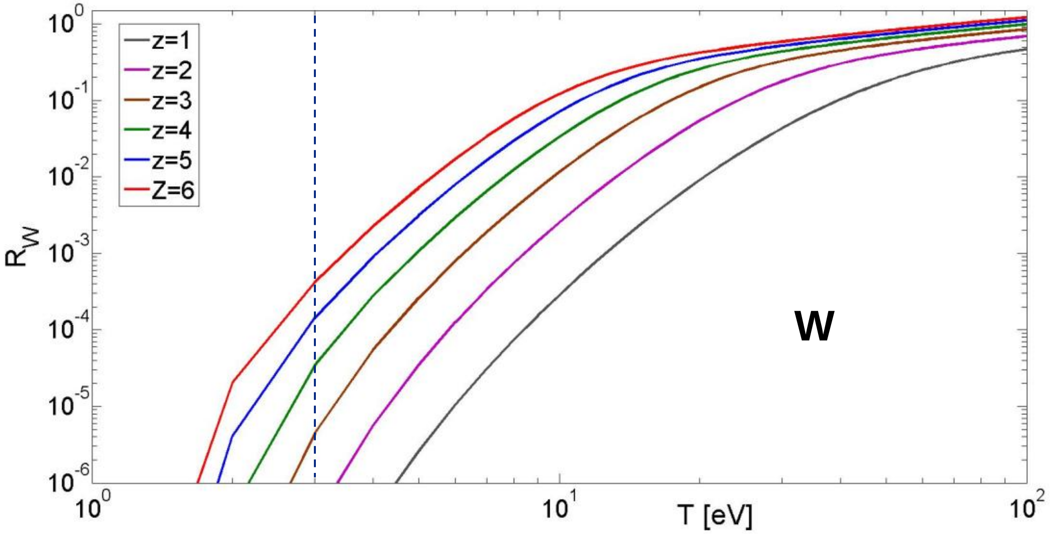
W sputtering rate coefficients vs plasma temperature

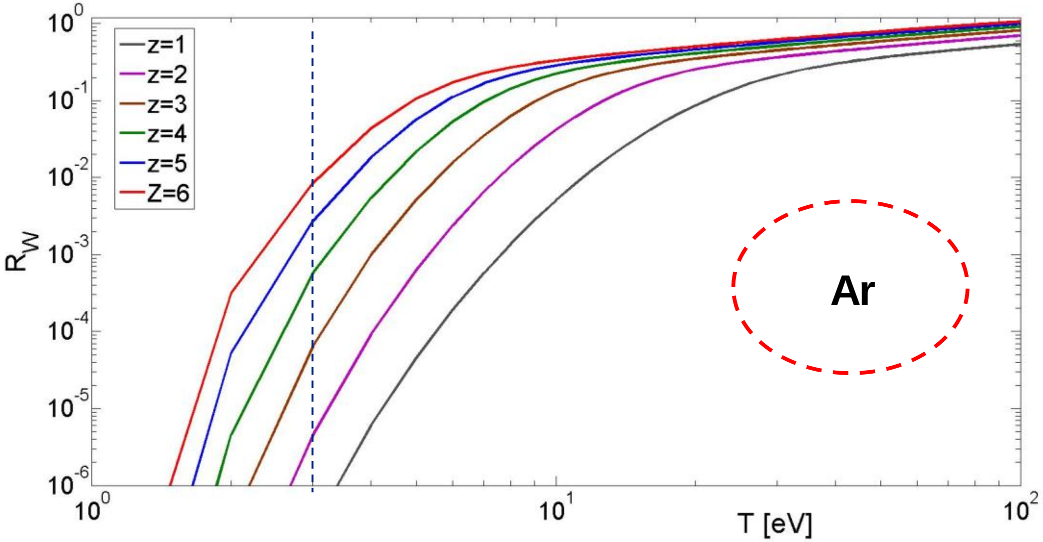
Negligibly small W-sputtering rates due to the main and He ions

W sputtering rates for impurity ions









Effective W sputtering rate coefficients

D/T

JET

$$R_W^{net} = \left(1 - f_{prompt}\right)\left(c_d R_D + \sum_i R_i c_i\right)$$

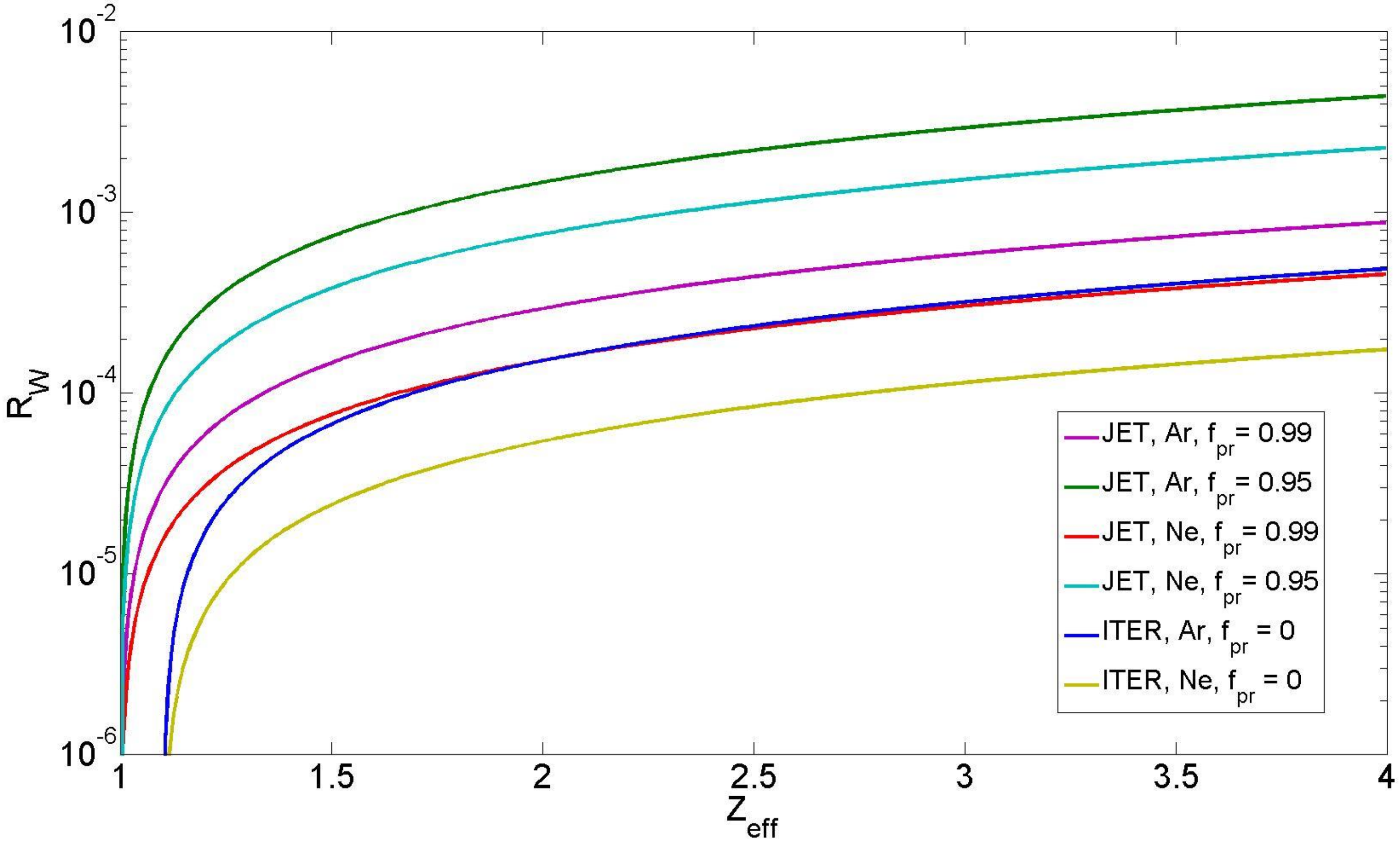
$$f_{prompt} = 0.99, \; or \; 0.95$$

ITER

$$R_W^{net} = c_d\left(R_D + R_T\right) + 0.05\left(R_{He^+} + R_{He^{++}}\right) + \sum_i R_i c_i$$

[3]

$$Z_{eff} = \sum_k Z_k^k c_k \qquad F_W^{net} = R_W^{net} F_{plasma}$$

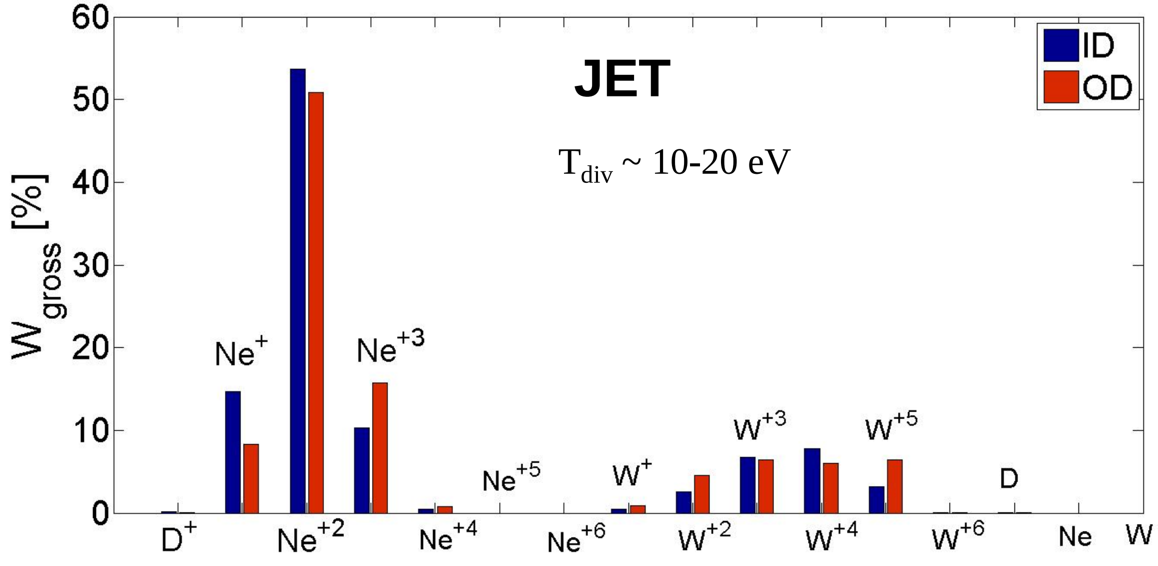


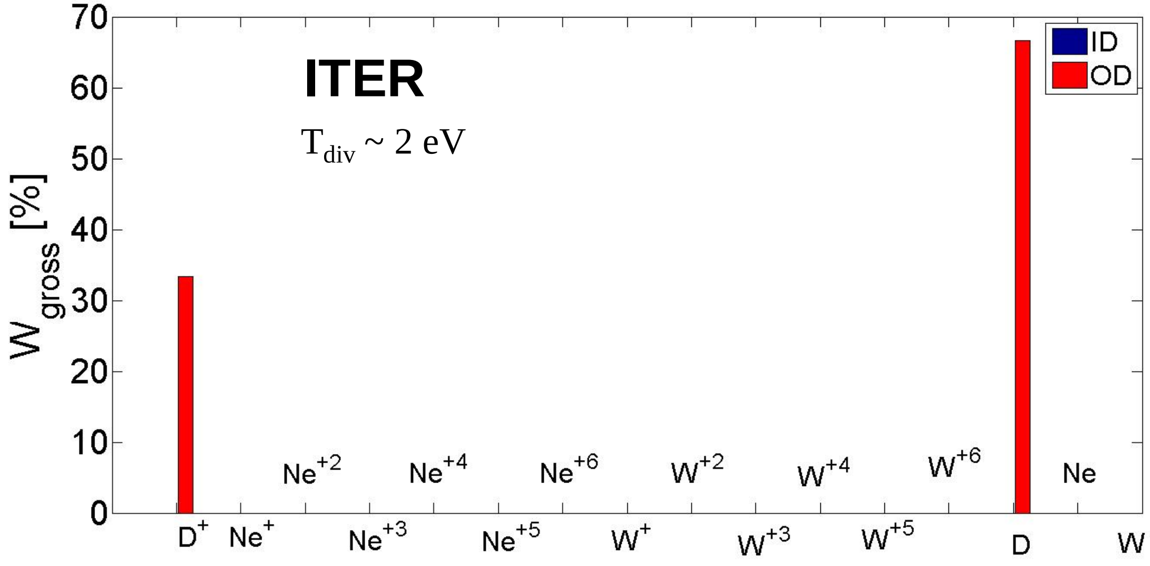
In ITER (DEMO?) divertor W sputtering via Ar (and more heavier) impurities can be non-negligible

$$F_{plasma}^{ITER} >> F_{plasma}^{JET}$$

[3] A. Wisitsorasak, et al., J. of Fus. Energy, 41 (2022)

W sputtering from PIC simulations of the SOL





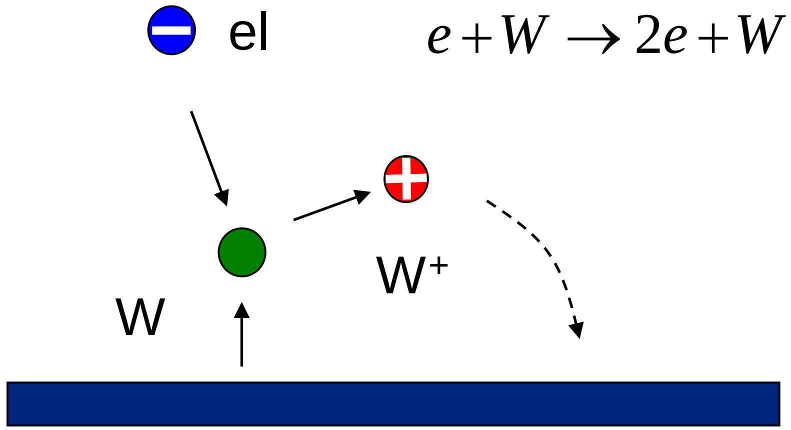
He, Ar?

	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%)

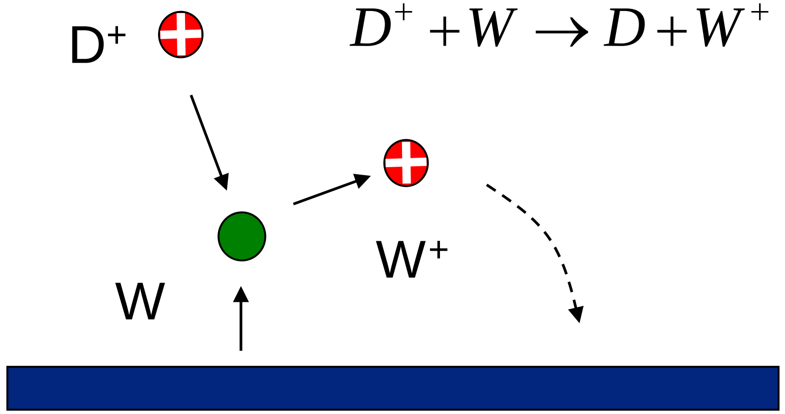
	Gross [10^{21} $m^{-2}s^{-1}$]	Nett [10^{21} $m^{-2}s^{-1}$]
ID	0	0
OD	0.015	0.015

Other channels of prompt re-deposition

$$e + W \rightarrow 2e + W^{+}$$



$$D^{+} + W \rightarrow D + W^{+}$$



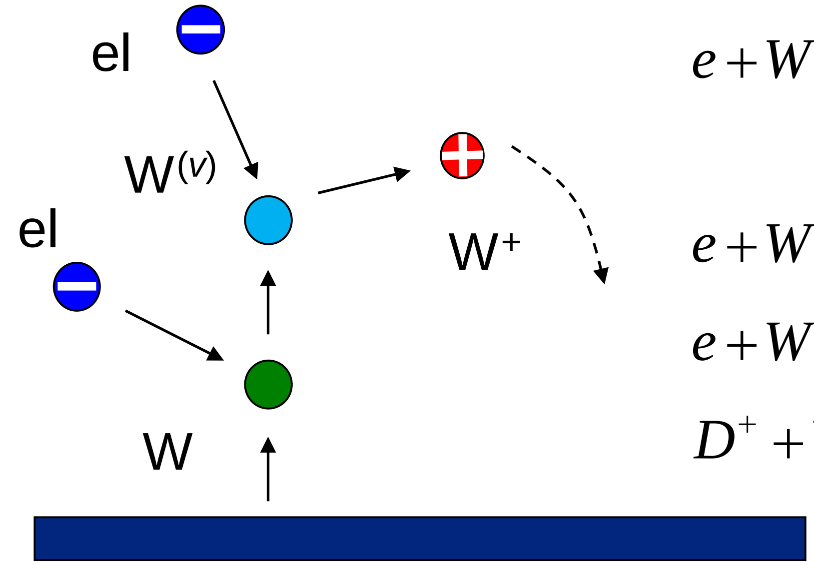
$$e + W \rightarrow 2e + W^{(n)}$$

$$\dots$$

$$e + W^{(n')} \rightarrow 2e + W^{(\nu)}$$

$$e + W^{(\nu)} \rightarrow 2e + W^{+}$$

$$D^{+} + W^{(\nu)} \rightarrow D + W^{+}$$



Simulated plasma	**W re-deposited fraction**	**CX collisions**
High density	0.1%	$\sigma_{CX}=10^{-19}$ m^2
High density	30%	$\sigma_{CX}=5\text{x}10^{-19}$ m^2

Needs for atomic data

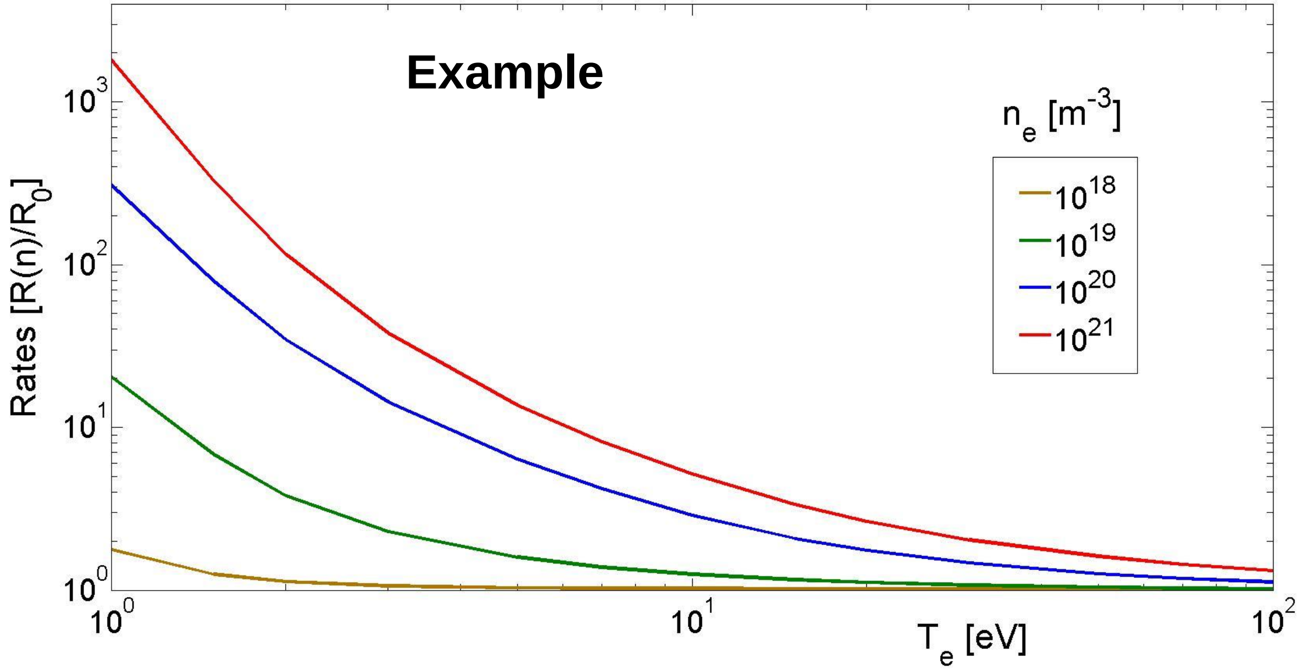
Charge-exchange CS or rates

$$D^{+} + W^{(v)} \rightarrow D + W^{+}$$

$$T^{+} + W^{(v)} \rightarrow T + W^{+}$$

Effective ionization rates

$$e + W \rightarrow e + W^{(v)} \ldots \rightarrow 2e + W^{+}$$



Normalized rates of e + Ne ionization collisions for different plasma density

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

Conclusions

- Our study indicates that with decreasing plasma temperature the **prompt re-deposition** (f_{prompt}) **decreases faster than the gross sputtering rate,** (R_{gr}); as a result, the net sputtering rate, $R_{net} = (1- f_{\mathrm{prompt}})R_{\mathrm{gr}}$, can be still significant. This might have **significant consciences** for future generation fusion devices like ITER and DEMO.

- The above given results were obtained under the **coronal approximation** and neglecting the main ion + W charge exchange collisions. The **first tests** with charge exchange channel show rapid increase of the prompt re-deposition and consequently, decrease of the net W sputtering, with (artificially) increasing the corresponding cross-section

- In order to study this process a new atomic data is needed: effective H^+, W **charge exchange** and e + W **multy step ionization** rate coefficients (or cross-sections)

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