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

D. Tskhakaya

Institute of Plasma Physics of the CAS, Prague, Czech Republic
➢ Introduction
➢ Analytic description of the W prompt re-deposition
➢ PIC simulation results
➢ Identification of atomic data needs
➢ Conclusions
Statement of the problem

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

Critical W concentration $C_{w, cr.} \approx 3 \times 10^{-5}$ \cite{1}

W outflux

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

Prompt re-deposition coefficient (at the divertors) \cite{2}

$$f_{prompt} > 0.9$$

\cite{1} T. Pütterich, et al., Nucl. Fusion, 50 (2010)
**W prompt re-deposition (classical models)**

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

\[ F_d \approx m_w V_i v_{sd} \quad F_E = Z_w e E_n \]

\[ F_L = Z_w e [V_w \times B]_n \]

\[ f_{prompt} (n_e, T_e) = \left(1 + \frac{l_{ion}}{\rho_w} \right)^{-1} \]

\[ f_{prompt} (n_e, T_e) = \left(1 + 0.01 \frac{l_{ion}}{\rho \, T_i} \left( \frac{T_i}{T_e} \right) \right)^{-1} \]

\( l_{ion} \) - W ionization mfp

\( \rho \) – gyro-radius

**Forces acting on W+ ion in the magnetized plasma sheath**

[D. Tskhakaya, JNM, 2015]
W prompt re-deposition in a cold high density plasma

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

PIC simulation

\[
f_{\text{prompt}}(T_e \leq 2 \text{eV}) \approx 0
\]

W prompt re-deposition reduces with the electron temperature
**PIC simulation of W sputtering**

Particle and heat source

Inner Divertor ★ Outer divertor

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

Each simulation takes up to 2 M core hours

<table>
<thead>
<tr>
<th>Simulated plasma</th>
<th>W re-deposited fraction</th>
<th>CX collisions</th>
</tr>
</thead>
<tbody>
<tr>
<td>High density</td>
<td>0.0</td>
<td>no</td>
</tr>
<tr>
<td><strong>Low density</strong></td>
<td>0.0</td>
<td>no</td>
</tr>
<tr>
<td>High density</td>
<td>0.1%</td>
<td>$\sigma_{\text{CX}}=10^{-19}$ m$^2$</td>
</tr>
<tr>
<td>High density</td>
<td>30%</td>
<td>$\sigma_{\text{CX}}=5\times10^{-19}$ m$^2$</td>
</tr>
</tbody>
</table>
W sputtering yields and rate coefficients

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

\[ R_w(T) = \int_0^\infty \gamma_w \left( Z_i \varphi T + E_\perp + E_\parallel \right) f_i(E_\parallel, E_\perp) \, dE_\perp \, dE_\parallel \]
W sputtering rates for impurity ions

Graphs showing sputtering rates for different elements:
- Ne (Nitrogen)
- W (Tungsten)
- Ar (Argon)
Effective W sputtering rate coefficients

\[ R_{W}^{net} = \left( 1 - f_{\text{prompt}} \right) \left( c_d R_D + \sum_i R_i c_i \right) \]

\[ f_{\text{prompt}} = 0.99, \text{ or } 0.95 \]

**JET**

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

\[ Z_{eff} = \sum_k Z_k^c c_k \]
\[ F_{W}^{net} = R_{W}^{net} F_{\text{plasma}} \]

**ITER**

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


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

\[ F_{\text{ITER}}^{\text{plasma}} >> F_{\text{JET}}^{\text{plasma}} \]
W sputtering from PIC simulations of the SOL

**JET**

\[ T_{\text{div}} \sim 10-20 \text{ eV} \]

<table>
<thead>
<tr>
<th>Species</th>
<th>Gross [ \times 10^{21} \text{m}^{-2}\text{s}^{-1} ]</th>
<th>Nett [ \times 10^{21} \text{m}^{-2}\text{s}^{-1} ]</th>
</tr>
</thead>
<tbody>
<tr>
<td>ID</td>
<td>6.21</td>
<td>1.00 (~16%)</td>
</tr>
<tr>
<td>OD</td>
<td>17.03</td>
<td>0.64 (~4%)</td>
</tr>
</tbody>
</table>

**ITER**

\[ T_{\text{div}} \sim 2 \text{ eV} \]

<table>
<thead>
<tr>
<th>Species</th>
<th>Gross [ \times 10^{21} \text{m}^{-2}\text{s}^{-1} ]</th>
<th>Nett [ \times 10^{21} \text{m}^{-2}\text{s}^{-1} ]</th>
</tr>
</thead>
<tbody>
<tr>
<td>ID</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>OD</td>
<td>0.015</td>
<td>0.015</td>
</tr>
</tbody>
</table>

He, Ar?
Other channels of prompt re-deposition

\[ e + W \rightarrow 2e + W^+ \]

\[ D^+ + W \rightarrow D + W^+ \]

<table>
<thead>
<tr>
<th>Simulated plasma</th>
<th>W re-deposited fraction</th>
<th>CX collisions</th>
</tr>
</thead>
<tbody>
<tr>
<td>High density</td>
<td>0.1%</td>
<td>[\sigma_{\text{CX}}=10^{-19} \text{ m}^2]</td>
</tr>
<tr>
<td>High density</td>
<td>30%</td>
<td>[\sigma_{\text{CX}}=5\times10^{-19} \text{ m}^2]</td>
</tr>
</tbody>
</table>
Needs for atomic data

**Charge-exchange CS or rates**

\[ D^+ + W^{(v)} \rightarrow D + W^+ \]
\[ T^+ + W^{(v)} \rightarrow T + W^+ \]

**Effective ionization rates**

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

**Example**

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

[https://open.adas.ac.uk]
Our study indicates that with decreasing plasma temperature the **prompt re-deposition** ($f_{\text{prompt}}$) decreases faster than the **gross sputtering rate**, ($R_{\text{gr}}$); as a result, the net sputtering rate, $R_{\text{net}} = (1-f_{\text{prompt}})R_{\text{gr}}$, 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).