Modelling of caesium dynamics in the negative ion sources at BATMAN and ELISE

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Dominant production of negative ions:

**Surface process**

Mostly conversion of H/D atoms

**Efficiency increases by decreasing**

the **work function** of the surface

**Caesium (bulk work function = 2.1 eV)**

evaporated in the source
Size scaling

Prototype source
(59×30 cm²)
BATMAN test facility

Size scaling: half ITER source size test facility ELISE
(100×90 cm²)

Source for ITER NBI (190×90 cm²)
Cs dynamics

- Only neutral Cs

- Ballistic transport \( (p \approx 10^{-4} \text{ Pa}) \)

- Dynamics determined by:
  - Oven outflow profile
  - Source geometry
  - Wall sticking probability (temperature and impurities)
Cs dynamics

**VACUUM PHASE**

- Only neutral Cs
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**PLASMA PHASE**

- Both Cs neutrals and ions
- Collisions \((p \approx 0.3 \text{ Pa})\):
  - Hydrogen gas
  - Plasma particles
- Cs redistribution by plasma
Cs dynamics

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Beam pulse
Cs dynamics

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- The ITER source has to operate for **one hour**: stability of the work function is a fundamental issues to achieve high performances.
- **Sufficient flux of Cs towards the grid** is needed during the pulse to counteract the degradation of the work function.
CsFlow3D code

Probabilistic particle transport algorithm

**INPUT**
- Oven nozzle
  - outflow profile, position, direction
- Surface sticking probability
- Sputtering and plasma erosion

**Determination of transport probabilities**
- Evap. from the oven \( O_i \)
- Transp. between the walls \( P_{ij} \)

**OUTPUT**
- Cs flux onto surfaces
- Cs coverage
- Neutral Cs density along particular lines of sight
Prototype source

Maximum Power: 100 kW
Total HV: 22 kV
Plasma pulse time: $\approx 7$ s
Beam pulse time: $\approx 4.5$ s
Prototype source

**Driver**

\[ n_{\text{plasma}} \approx 10^{18} \text{ m}^{-3} \]
\[ T_{e} \approx 10 \text{ eV} \]

**Plasma grid**

\[ n_{\text{plasma}} \approx 10^{17} \text{ m}^{-3} \]
\[ T_{e} \approx 1 \text{ eV} \]

<table>
<thead>
<tr>
<th>Maximum Power</th>
<th>100 kW</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total HV</td>
<td>22 kV</td>
</tr>
<tr>
<td>Plasma pulse time</td>
<td>\approx 7 s</td>
</tr>
<tr>
<td>Beam pulse time</td>
<td>\approx 4.5 s</td>
</tr>
</tbody>
</table>
✓ **Neutral Cs density experimentally measured** by Tunable Diode Laser Absorption Spectroscopy (TDLAS)

✓ **2 horizontal lines-of-sight** (LOS) available: TOP and BOTTOM, 2 cm from the plasma grid plane.

✓ **The code calculates the avg. Cs density along the LOS**: comparison between simulated and experimental time traces.
Simulation of **one vacuum phase** \((t = 240 \text{ s})\) followed by **one plasma pulse** \((t = 8 \text{ s})\). Starting with a clean source (no Cs present at the beginning).
Results – prototype source

• Simulation of **one vacuum phase** \((t = 240 \text{ s})\) followed by **one plasma pulse** \((t = 8 \text{ s})\). Starting with a clean source (no Cs present at the beginning).

![Graph showing Cs flux over time in vacuum and plasma phases.](image-url)
Results – prototype source

- Simulation of **one vacuum phase** \( (t = 240 \text{ s}) \) followed by **one plasma pulse** \( (t = 8 \text{ s}) \). Starting with a clean source (no Cs present at the beginning).

\[
\text{Cs flux} \left[ 10^{12} \text{ cm}^{-2} \text{ s}^{-1} \right]
\]

\[
\begin{align*}
\text{time [s]} & \quad -2 \quad 0 \quad 2 \quad 4 \quad 6 \quad 8 \quad 10 \\
\text{vacuum} & \quad \text{plasma phase} & \quad \text{vacuum}
\end{align*}
\]

\[
\begin{align*}
\text{Cs coverage on the side wall} & \quad \text{Avg. Cs Flux}
\end{align*}
\]

\[
\begin{align*}
\text{Cs coverage [10^{14} \text{ cm}^{-2}]} & \quad 0 \quad 2 \quad 4 \quad 6 \quad 8 \quad 10 \quad 12 \quad 14 \quad 16 \quad 18 \\
\text{PG} & \quad y [\text{mm}] & \quad z [\text{mm}]
\end{align*}
\]

\[
\begin{align*}
\text{Driver} & \quad 0 \quad -100 \quad -50 \quad 0 \quad 50 \quad 100 \\
\text{t = 0 s} & \quad \text{t = 8 s}
\end{align*}
\]

\[1 \text{ monolayer} = 4.5 \cdot 10^{14} \text{ cm}^{-2} \text{ (onto Molybdenum)}\]
• **Simulations of 20 pulses** in order to reach good conditioning.
• Calculation of neutral Cs density for the top and bottom lines of sight
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• Calculation of neutral Cs density for the top and bottom lines of sight
• Introduction of a plasma asymmetry in the model
Results – prototype source

- Introduction of a plasma asymmetry in the model ($\Delta = 10$ cm)
- Asymmetry in the plasma parameter $\rightarrow$ Asymmetry in Cs redistribution

![Image of experimental setup with Cs-ABS labels](image1)

**20th pulse – experimental and simulated time traces**

- Neutral Cs density $\left[10^{14} \text{ m}^{-3}\right]$ vs. time [s]

- PLASMA ON

- Graph shows time traces for:
  - bottom exp.
  - bottom sim.
  - top exp.
  - top sim.

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• Comparisons of two oven positions (with plasma asymmetry included)
<table>
<thead>
<tr>
<th>Feature</th>
<th>Specification</th>
</tr>
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<tbody>
<tr>
<td>Maximum Power</td>
<td>360 kW</td>
</tr>
<tr>
<td>Total HV</td>
<td>60 kV</td>
</tr>
<tr>
<td>Plasma pulse time</td>
<td>up to 3600 s</td>
</tr>
<tr>
<td>Beam pulse time</td>
<td>10 s every ≈ 150 s</td>
</tr>
</tbody>
</table>

- 4 drivers (1/2 ITER size)
- Long pulses
- Cs evaporation towards the back-plate
- Back-streaming ions relevant
- Plasma drift neglected
Cs emission detection in front of the plasma grid

- Plasma grid
- Bias plate
- Port openings
- Drivers

Horizontal section

Cs evap.
Back-plate

1.0 m
ELISE – experimental observation

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
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<tr>
<td>RF power</td>
<td>30 kW / driver</td>
</tr>
<tr>
<td>Extraction voltage</td>
<td>8 kV</td>
</tr>
<tr>
<td>Acceleration voltage</td>
<td>25 kV</td>
</tr>
<tr>
<td>Plasma phase time</td>
<td>20 s</td>
</tr>
<tr>
<td>Beam on time</td>
<td>10 s</td>
</tr>
<tr>
<td>Pressure</td>
<td>0.3 Pa</td>
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- Cs emission decreases during the pulse
- Jump due to back-streaming ions (≈ 10%)
• Cs emission decreases during the pulse
• Jump due to back-streaming ions (≈ 10%)
• Co-extracted electron increases during the pulse!
RF power | 30 kW / driver
---|---
Extraction voltage | 8 kV
Acceleration voltage | 25 kV
Plasma phase time | 20 s
Beam on time | 10 s
Pressure | 0.3 Pa

- Cs emission decreases during the pulse
- Jump due to back-streaming ions (≈ 10%)
- Co-extracted electron increases during the pulse!
- Statistical correlation between the decrease of Cs and the increase in co-extracted electrons?
- Worse at 0.3 Pa!
• As before, **20 pulses** in order to reproduce conditioning.
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Simulations for 3 **different vacuum phase time**:
- 200 s
- 400 s
- 600 s
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Simulations for 3 **different vacuum phase time**:
- 200 s
- 400 s
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**Neutral Cs density** in the top LOS for the **20th shot** calculated:
- Without extraction (no back-streaming ions)
- With extraction (with back-streaming ions)
ELISE – simulation results

• As before, **20 pulses** in order to reproduce conditioning.

• Simulations for 3 **different vacuum phase time**:
  • 200 s
  • 400 s
  • 600 s

• **Neutral Cs density** in the top LOS for the **20th shot** calculated:
  • Without extraction (no back-streaming ions)
  • With extraction (with back-streaming ions)
Conclusions and outlook

- **Building up of Cs reservoirs** in the walls (1\textsuperscript{st} pulse ≠ 20\textsuperscript{th} pulse)
  - Effect on Cs flux stability onto the PG during the pulse

- **Vacuum phase time** is relevant (ELISE 200 s ≠ 600 s):
  - Increase of vacuum phase $\rightarrow$ increase of Cs density during plasma

- **Plasma drift drives the Cs redistribution in plasma**: only minor contribution of the oven position, which mostly affects the “velocity” of the conditioning.

- **Back-streaming ions** additional source term of Cs, can be an issue during long pulses:
  - Comparisons between long pulses with pulsed extraction (as in ELISE) and with continuous extraction (as for ITER) ?

- **Future investigations of long pulses and benchmarking/comparisons with ELISE experimental data**:
  - Optimization of Cs evaporation and management $\rightarrow$ ITER requirements
  - Reduction of Cs consumption $\rightarrow$ industrial scale power plant DEMO
Measurement of sticking

\[ S = 1 - \frac{\Gamma_{\text{reflected}}}{\Gamma_{\text{incident}}} \]