Direct field ionisation

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ArcPIC simulations

Field, time = 0.004 ns

Courtesy of Andreas Kyritsakis, Kyrre Ness Sjobaek, Helga Timko
Impact ionisation cross section

ArcPIC is based on impact ionisation mechanism

\[ e^- + Cu \rightarrow 2e^- + Cu^+ \]

Direct field ionisation

- Direct ionisation of atoms under electric fields of magnitude comparable to atomic electric field
  - Laser WakeField Acceleration: huge electric fields from fs lasers ionise gases
  - CLIC: ionisation of residual gas in the vacuum pipes by the field of the (extremely dense) particle bunches

- Field ionisation is a tunneling phenomenon


- Is this relevant for vacuum arcs?
Modelling field ionisation

The probability for direct field ionisation in the ADK model is:

\[ p = 1.52 \times 10^{15} \frac{4^n \xi}{n \Gamma(2n)} \left( \frac{20.5 \frac{\xi^{3/2}}{E}}{E} \right)^{2n-1} \exp \left( -6.83 \frac{\xi^{3/2}}{E} \right) \]

with: \( n = 3.69z\xi^{-1/2} \)

and:

- \( p \) [s^{-1}]: probability of ionisation
- \( \xi \) [eV]: potential of ionisation of a given atom
- \( E \) [GV/m]: electric field
- \( z \): charge number after ionisation

Limit of validity up to \( E_{\text{crit}} = 1.5\xi^{3/2} \) (barrier suppression).

Direct field ionisation probability for Cu

- Calculated for Cu, ionisation state $z = +1$, first ionisation potential $\xi = 7.726$ eV
- Valid for field $E < 32$ GV/m
- (numbers have meaning of course at ps-fs time scales)

<table>
<thead>
<tr>
<th>Field [GV/m]</th>
<th>Probability per unit time</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>1.1x10$^7$</td>
</tr>
<tr>
<td>6</td>
<td>1.1x10$^9$</td>
</tr>
<tr>
<td>7</td>
<td>2.8x10$^{10}$</td>
</tr>
<tr>
<td>8</td>
<td>3.1x10$^{11}$</td>
</tr>
<tr>
<td>9</td>
<td>1.9x10$^{12}$</td>
</tr>
<tr>
<td>10</td>
<td>8.4x10$^{12}$</td>
</tr>
</tbody>
</table>
Cross section vs. probability

- **Cu atom** intercepting a stream of electrons of velocity \( v_e = \frac{d}{t} \), having a current of density \( J_e = n_e v_e \)
- Probability for one Cu atom of being ionised in unit time, thus increasing charge count of 1 Cu\(^+\) and 1 e\(^-\):

\[
P = \sigma_e n_e v_e = \sigma J_e
\]

- Where \( \sigma \) is the electron impact ionisation cross section
- \( J_e = 0.5 \text{ A/\(\mu\text{m}^2\)} \) as in 1D PIC simulations
Ionisation probability per unit time, $J_e = 0.5 \text{ A/µm}^2$

Note: the values are directly proportional to $J_e$.
Impact ionisation vs field ionisation: probabilities

- Purple: direct field ionisation
- Red: impact ionization

Ionisation probability per second vs Electron energy [eV] for different field strengths (5 GV/m to 9 GV/m).

The graph shows a sharp increase in ionisation probability at lower electron energies, followed by a plateau as the electron energy increases. The probability is expressed in units of ionisation events per second.
Conclusion

- Direct field ionisation may be relevant in:
  - Ionisation in the plasma sheath (competition with other mechanisms, i.e. impact ionisation)
  - Ionisation in vicinity of field emitter tip (influence on the breakdown triggering process).

- In ArcPIC simulations, we need 0.015 electrons/neutral copper atom in order to trigger runaway. Including field ionisation in the simulations may lead to relaxing this number.
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Field ionisation

- Simple understanding (hydrogen atom example), it happens if:

\[ E_{ext} > \frac{\text{Ry} (/e)}{a_0} = \frac{13.6 \text{ V}}{0.53 \text{ Å}} = 25.7 \text{ GV/m} \]

- Breakdown experiments show \( E_{loc,Cu} = 10.8 \text{ GV/m} \)
- 1D plasma simulations (which make use of neutral injection and electron impact ionisation) show that plasma sheath develops with \( E \approx 6 \text{ GV/m} \)

- Is field ionisation relevant for us?