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Direct field ionisation

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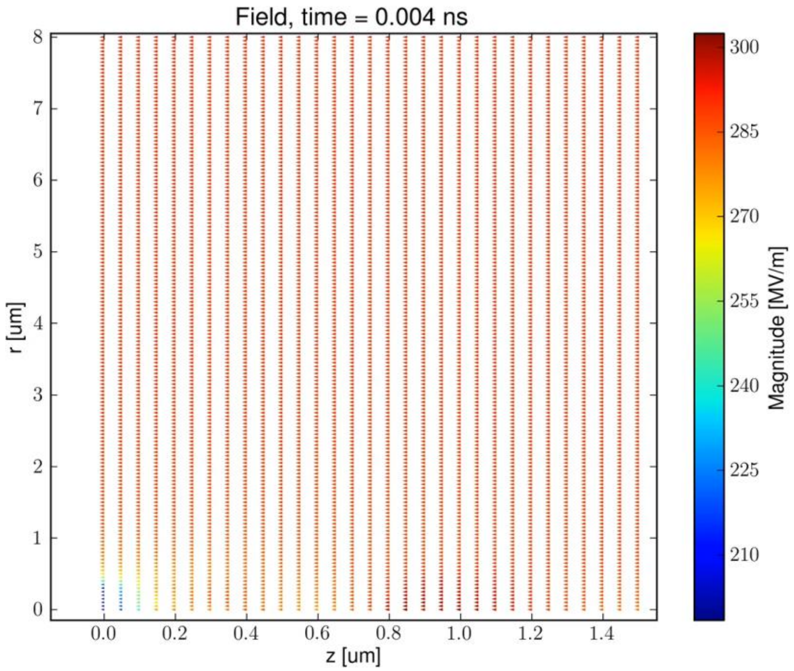
ArcPIC simulations

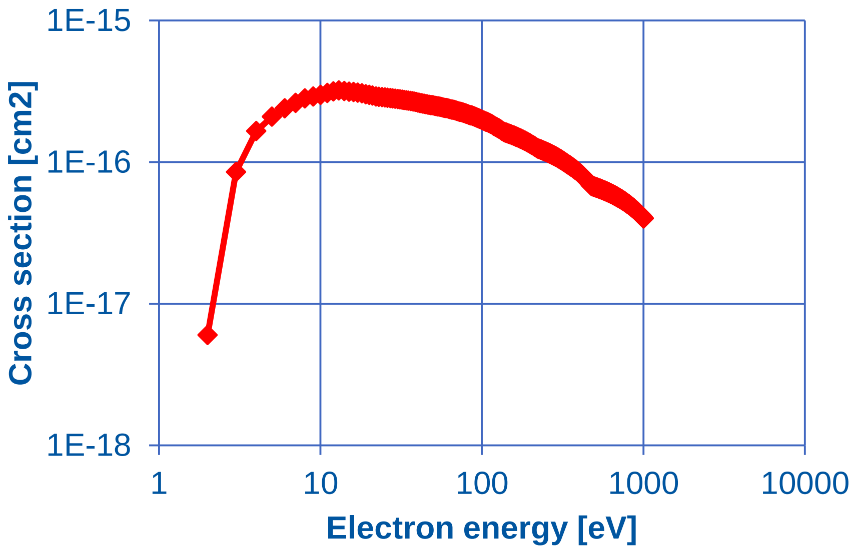


Courtesy of Andreas Kyritsakis, Kyrre Ness Sjobaek, Helga Timko

Impact ionisation cross section

ArcPIC is based on impact ionisation mechanism

$$e^- + Cu \rightarrow 2e^- + Cu^+$$



Courtesy of H. Timko. Values from: M. A. Bolorizadeh et al., J. Phys. B: At. Mol. Opt. Phys. 27 (1994) 175.

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

Review: D. Bauer and P. Mulser, Phys. Rev. A 59, (1999) 569.

- Is this relevant for vacuum arcs?

Modelling field ionisation

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

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

with: $n = 3.69 z \xi^{-1/2}$
and:

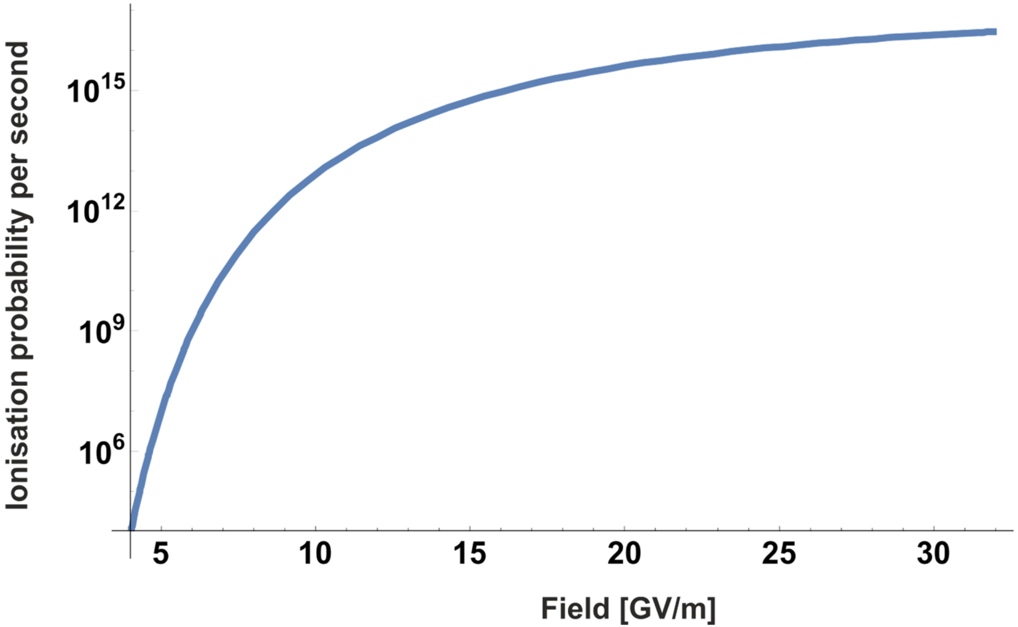
- p [s^{-1}]: probability of ionisation
- ξ [eV]: potential of ionisation of a given atom
- E [GV/m]: electric field
- z : charge number after ionisation

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

ADK model: M.V.Ammosov, N.B.Delone, and V.P.Krainov, Sov. Phys. JETP 64, (1986) 1191.
Solution by: D.L.Bruhwiler et al., Physics of Plasmas 10 (2003) 2022.

Direct field ionisation probability for Cu

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

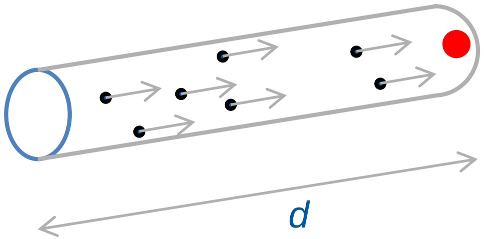


Field [GV/m]	Probability per unit time
5	1.1×10^{7}
6	1.1×10^{9}
7	2.8×10^{10}
8	3.1×10^{11}
9	1.9×10^{12}
10	8.4×10^{12}

Cross section vs. probability

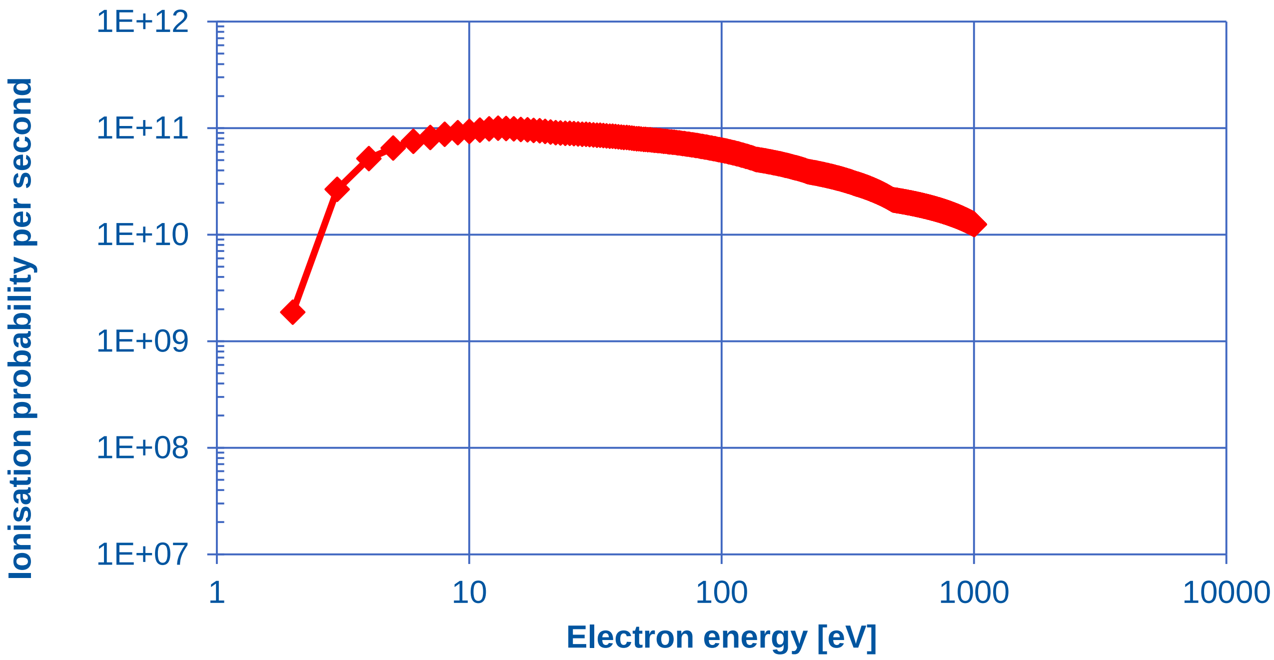
- Cu atom intercepting a stream of electrons of velocity $v_e = d/t$, having a current of density $J_e = n_e v_e$
- Probability for one Cu atom of being ionised in unit time, thus increasing charge count of 1 Cu^+ and 1 e^-

$$P = \sigma_e n_e v_e = \sigma J_e$$



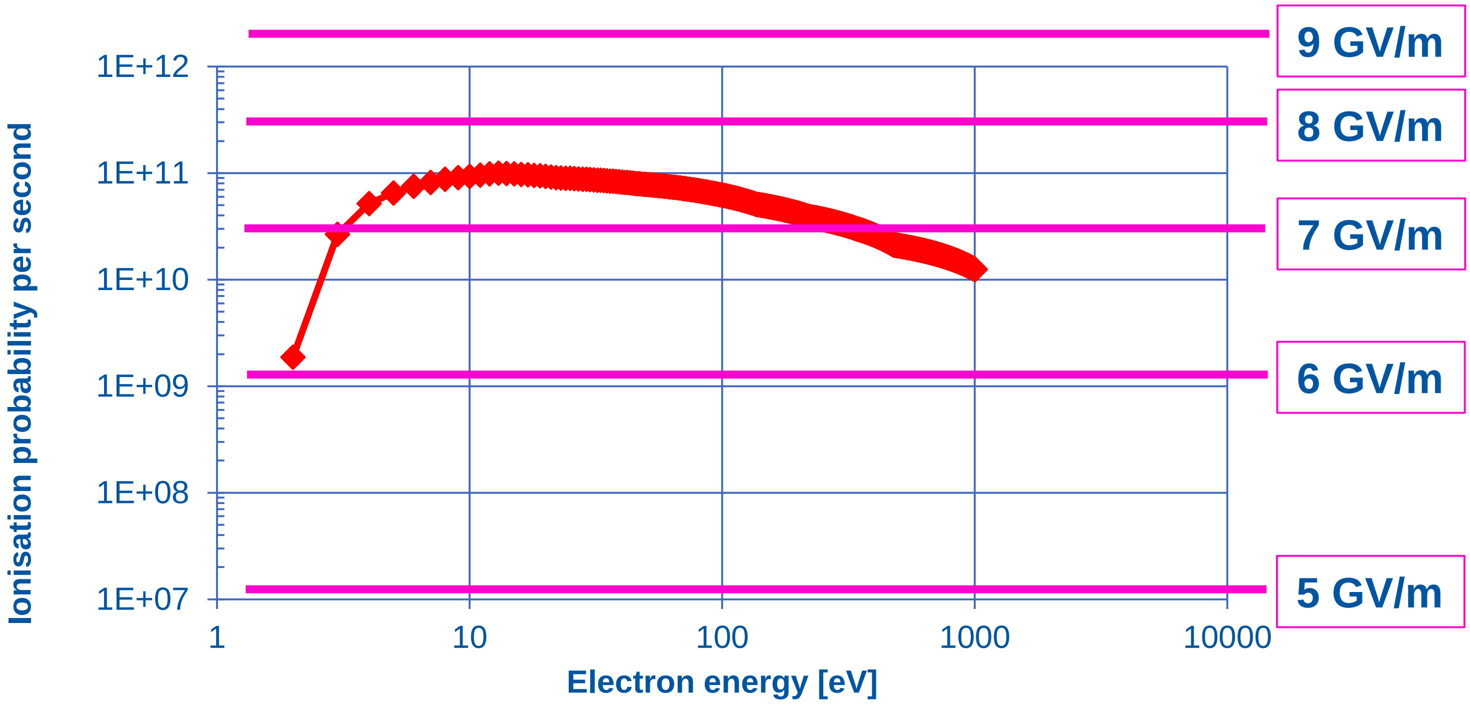
- Where σ is the electron impact ionisation cross section
- J_e =0.5 A/μm^2 as in 1D PIC simulations

Ionisation probability per unit time, $J_e = 0.5$ 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

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:

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

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

- Is field ionisation relevant for us?