Modelling vacuum arcs with 2D Arc-PIC code

Miika Haataja

University of Helsinki

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Overview

1. Introduction
   - What?
   - Why?
   - How?

2. My work
   - Field emission
   - Space charge
   - Distribution of neutrals

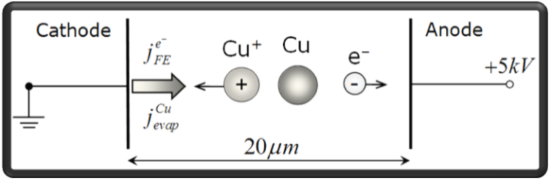
What?

Vacuum arc

A continuous self-maintaining electric discharge between two electrodes in a vacuum.

Arc formation

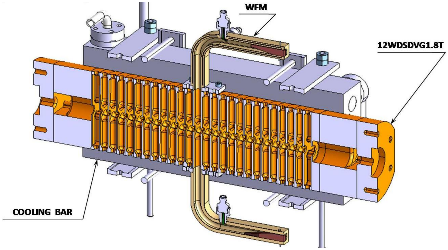
1. Field emission of electrons + evaporation of neutrals = ionization
2. Sudden avalanche of ionization
3. Formation of plasma and plasma sheath
4. Self-maintaining "burning" of plasma (while energy is available)
5. Neutrals fill entire gap



Why?

The Compact Linear Collider (CLIC)

- Reducing size reduces cost
- Compactness requires high accelerating gradients (100 MV/m)
- Efficiency relies on low breakdown probability
- Lowering the breakdown rate also lowers operating costs



http://irfu.cea.fr

CLIC accelerating structure (length 300 mm)

How?

2D Arc-PIC code (orig. by Helga Timkó)

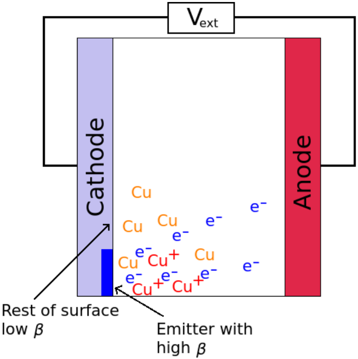
- 2d3v electrostatic PIC code with cylindrical symmetry
- Particles: e^-, Cu and Cu^+
- Monte Carlo collision routines
- Ionization through impacts: $e^- + Cu \rightarrow 2e^- + Cu^+$

Emission models

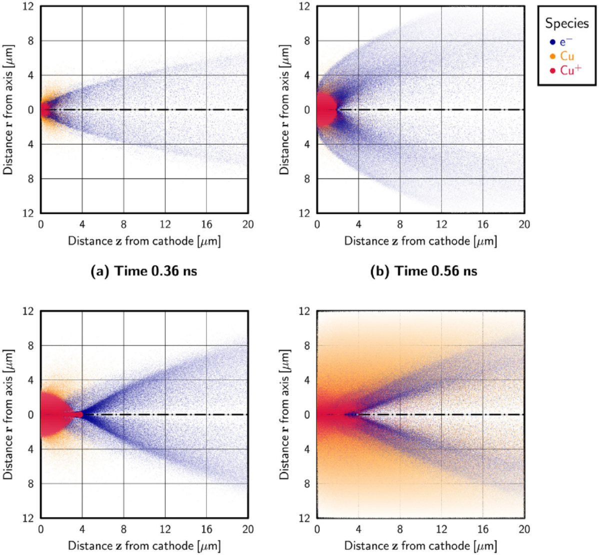
- Fowler-Nordheim field emission (field enhancement factor β)
- Cu evaporation as a fraction of e^- emission
- Sputtering (experimental, Yamamura & Tawara)
- Heat spike sputtering (MD, Timkó et.al)
- Secondary electron yield (constant)

External RC circuit

- Capacitor's potential drained by arc current



Typical simulation



(a) Time 0.36 ns

(b) Time 0.56 ns

(c) Time 0.60 ns

(d) Time 3.23 ns

Field emission

Fowler-Nordheim field emission (Wang & Loew approximation)

$$J_{FN} = 4.7133 \cdot 10^9 E_{loc}^2 \cdot exp(-\frac{62.338}{E_{loc}})$$

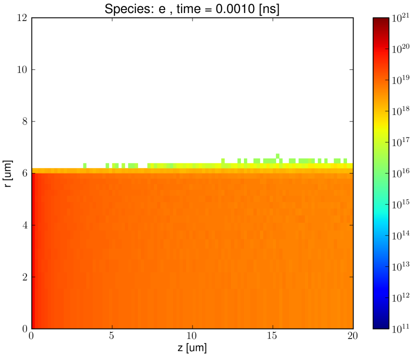
$$[J_{FN}] = \mathrm{A/cm^2} \quad [E_{loc}] = \mathrm{GV/m}$$

Code-to-code comparisons

- Can increase confidence in results
- Help in finding problems in code
- Do not prove if solution is correct

Simple field emission test

- Only electrons
- All interactions switched off
- Emitter radius 6 μm



Space charge

- Particle interactions switched back on
- How does space charge limit the current density?

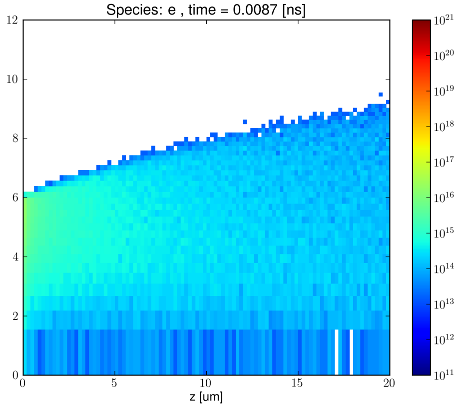
Child-Langmuir Law

$$J_{CL} = \frac{4\epsilon_0}{9}\sqrt{2e/m_e}\frac{V^{3/2}}{d^2}$$

V = voltage over gap

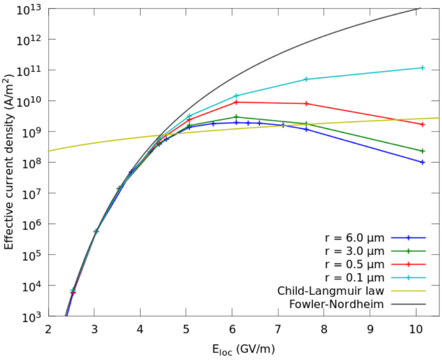
d = gap distance 20 μm

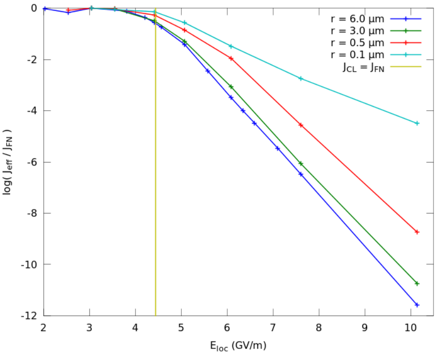
Gives the maximum space charge limited current density (with certain assumptions).



Space charge

- Space charge begins to have effect when Fowler-Nordheim emission reaches Child-Langmuir Law





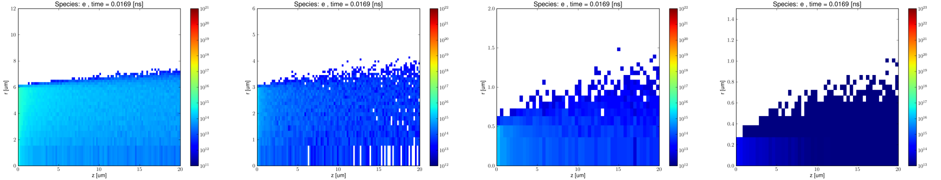
Space charge

Assumptions:

1. Only electrons ✓
2. Current limited by space charge ✓
3. Planar, parallel electrodes of infinite dimension ✗
4. Zero velocity at cathode surface ∼✓
5. Electrons travel ballistically (no scattering) ✗

Dispersion greater with smaller emitters. Collisions not significant.

6.0 μm | 3.0 μm | 0.5 μm | 0.1 μm



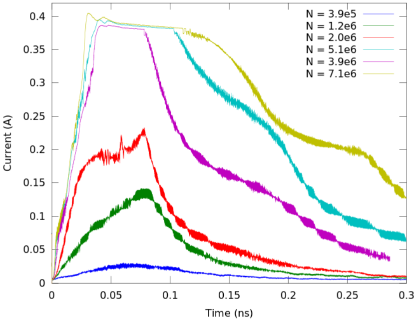
$\sim 30\%$ | $\sim 30\%$ | $\sim 150\%$ | $\sim 1000\%$

Distribution of neutrals

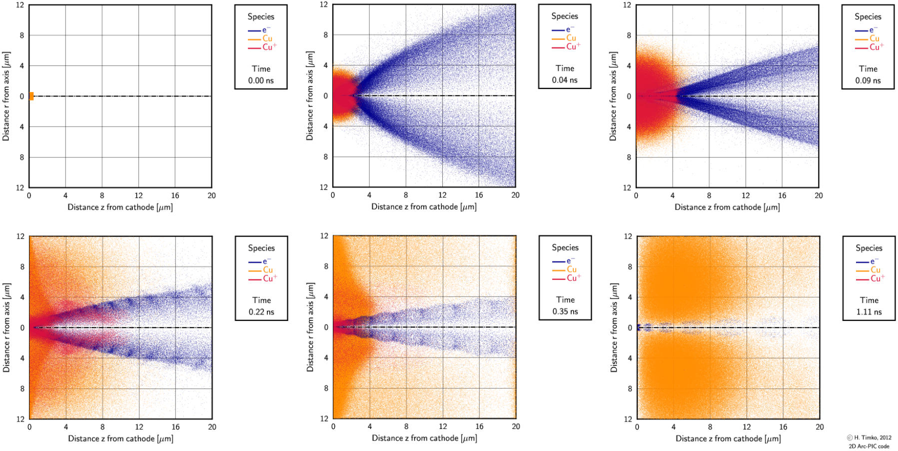
- Initial distribution of neutrals in the gap
- No evaporation of neutrals

Results

- Only the distribution right in front of the emitter has significance
- Breakdown current reached only briefly (even with high densities)

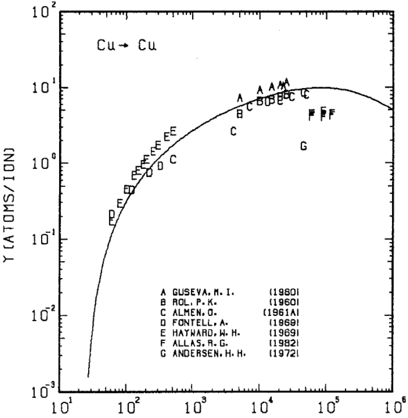


Distribution of neutrals



Distribution of neutrals

- Current model of sputtering alone not sufficient for self-sustaining arc
- With our energies classical sputtering yield < 1
- New heat spike model added, but not in time for these runs



Yamamura & Tawara. Atom Data Nucl. Data 62 (1996) 149