Arc simulations using *Aleph*

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Breakdown Physics Workshop @ CERN

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Presentation outline

1. What is the "state-of-the-art" in arc modeling?
2. Comparison with CERN simulations
3. Thermal BC at anode
4. Fowler-Nordheim BC at cathode
5. Scale-up
6. Small parameter sweep study

State-of-the-art in arc modeling

Literature survey summary of prior arc modeling efforts:

- Continuum models, no particles
- Ionization events not explicitly modeled
- Simplistic electrodes
- Conservation of energy, momentum, mass

Other particle simulation effort: group at CERN doing 1D particle model of vacuum arc breakdown

Summary of simple 1D arc model

Simulation description:

- 1D PIC simulations
- 20 micron gap, 10kV potential drop
- Cu electrodes
- Assume constant emission of electrons and Cu neutrals from the cathode.
- "Sputtering" model: particles hitting electrodes knock off more Cu neutrals.
- Include elastic collisions and ionization collisions.
- 80 cells, 3.5 fs timesteps, 10^6 particles

Results:

- Cu neutrals build up in the gap
- Ionization occurs, creating plasma in the gap
- Breakdown occurs once the ionization mean free path < gap distance, which happens when the Cu neutral density surpasses 10^{24} m^{-3}
- Space charge starts to affect fields when the electron density surpasses 10^{21} m^{-3}

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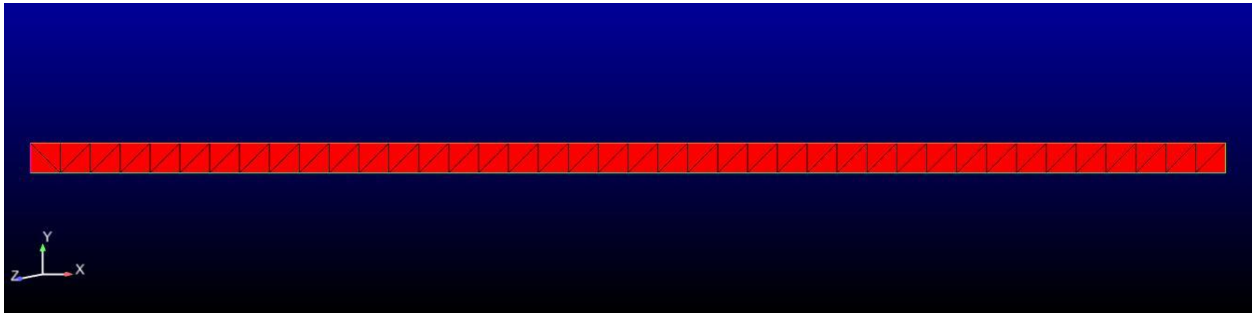
Our "repeat" of CERN model

Key differences vs. CERN model

- **Using *Aleph* instead of their code**
- **2D instead of 1D**
- **Triangular mesh elements**
- **No momentum transfer collisions**
- **Fewer computational particles**
- **Much larger influx of particles**



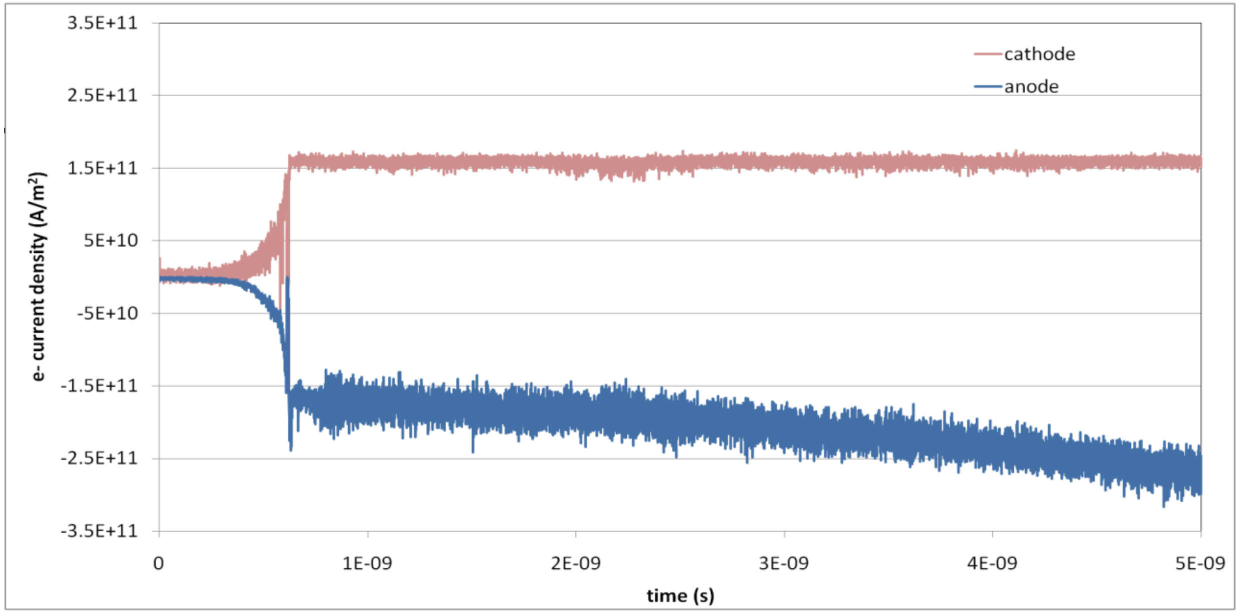
Our "repeat" of CERN model (cont.)

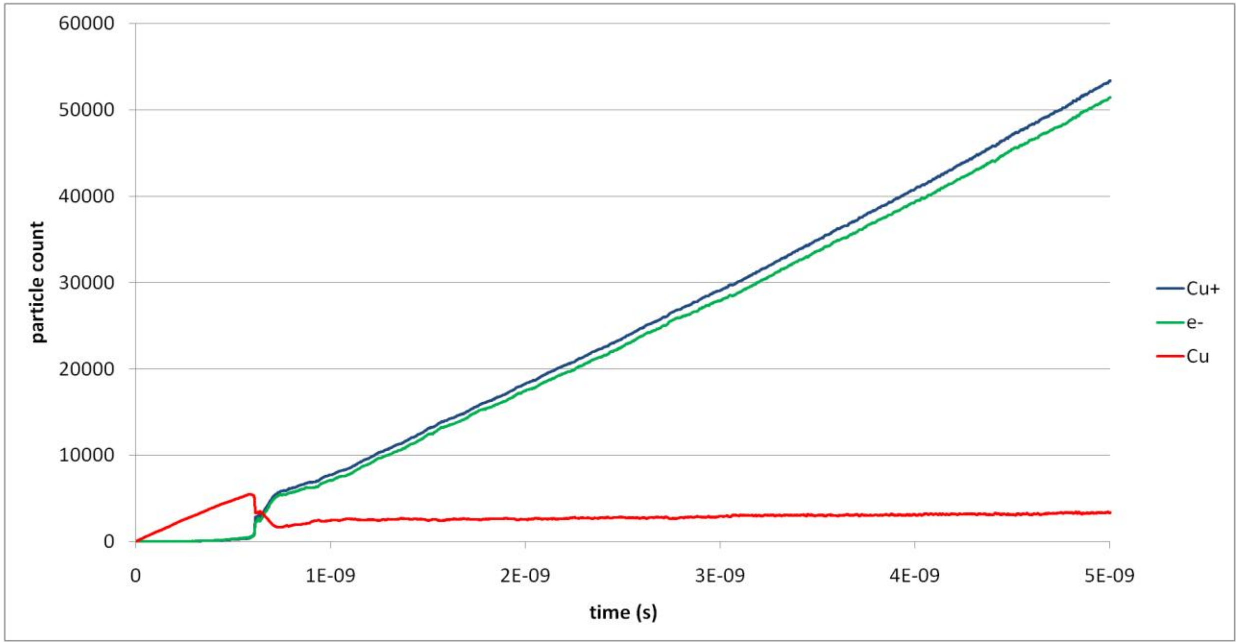
Run #16

Breakdown clearly occurs at around 0.6 ns.

After breakdown, current matches injection current.

After breakdown, plasma density grows monotonically.





Better comparison with CERN results

"Exact" match of all BCs --- using personal communication information from CERN group. Matched voltage BCs, influx rates, sputter rates, etc.

Remaining differences:

- Using *Aleph* instead of their code
- "Quasi-1D" instead of 1D
- Triangular mesh elements
- No momentum transfer collisions
- Fewer computational particles
- Mixed particle weighting

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Better influx value

- Revised values given on April 7, 2010:
  - I_e = 2.376*10^6 A/cm^2,
  - Electron injection flux of F_e = 1.483*10^25 1/s/cm^2.
  - Neutral injection flux is 1/100th of this, F_e = 1.483*10^23 1/s/cm^2.
- Works much better now!

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New simulations with latest info from CERN

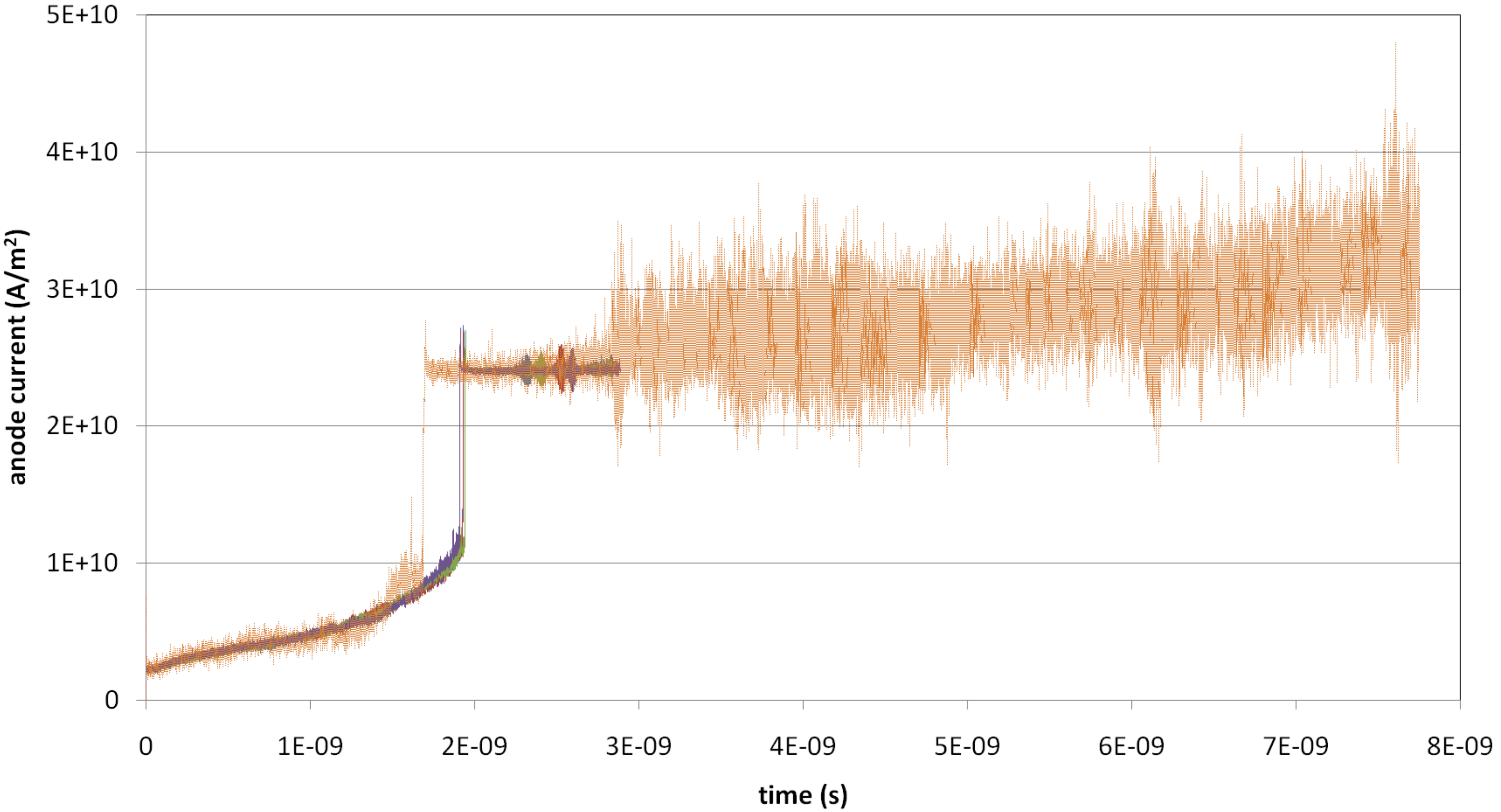
Run #37

- Includes e- + Cu momentum transfer collisions.
- Increased injection rates to match CERN's.
- Particle weighting = 10^8

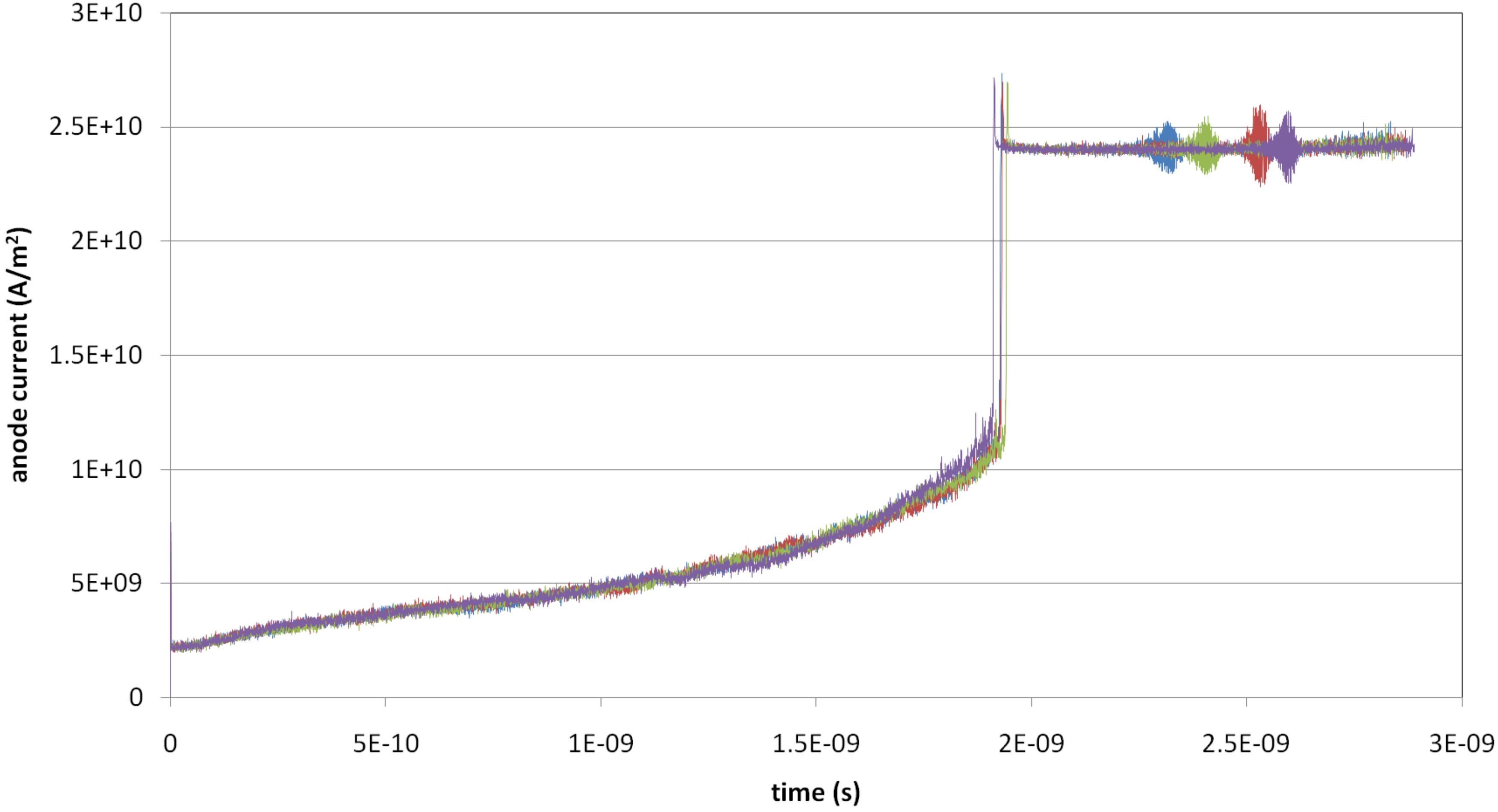
Run #38

- Same as run #37, except:
  - Particle weighting = 10^7
  - Also doing 4 repeats (a, b, c, d) for stats

Anode current: runs 37 and 38 (a, b, c, d)



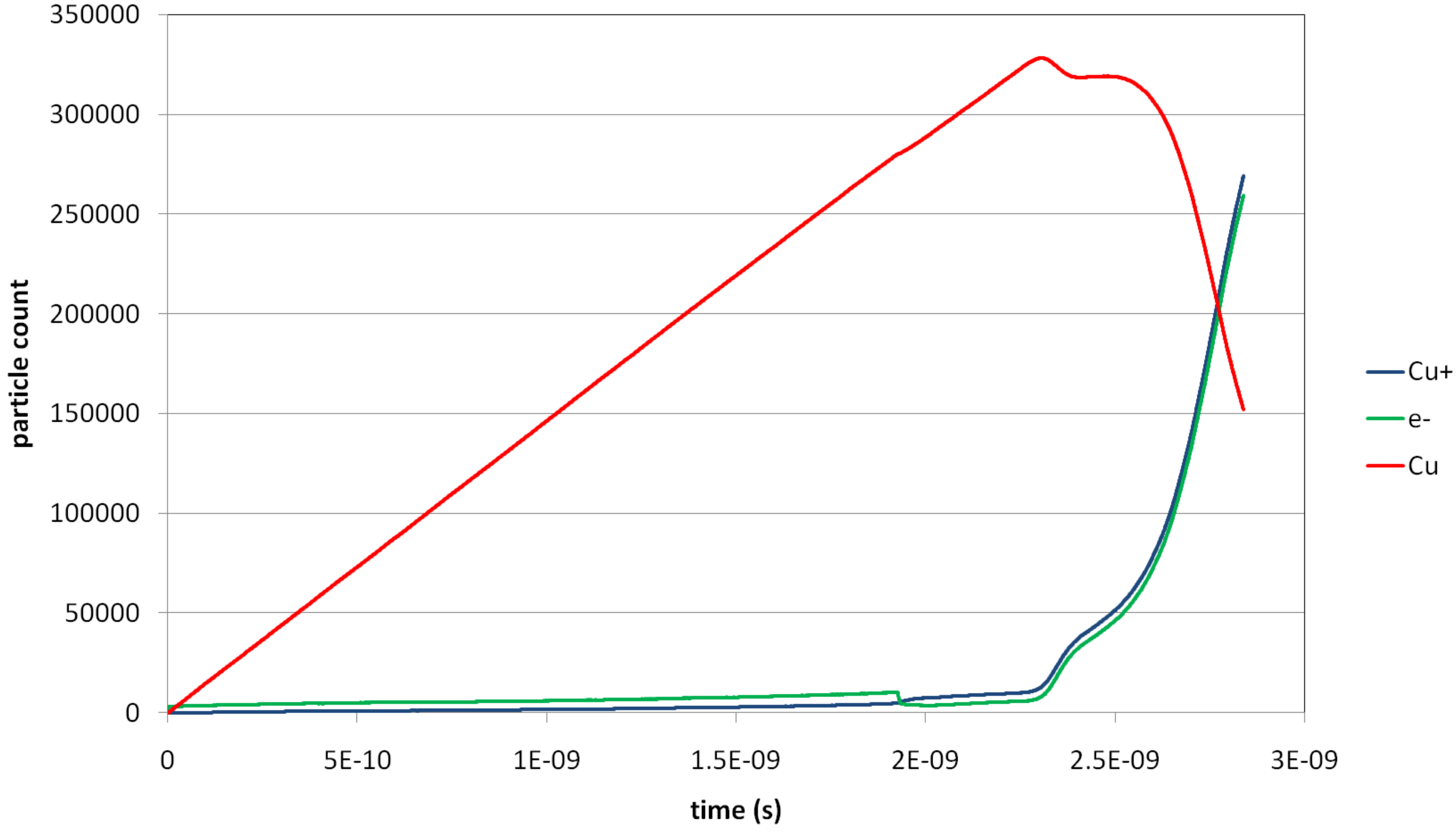
Anode current: runs 38 (a, b, c, d)



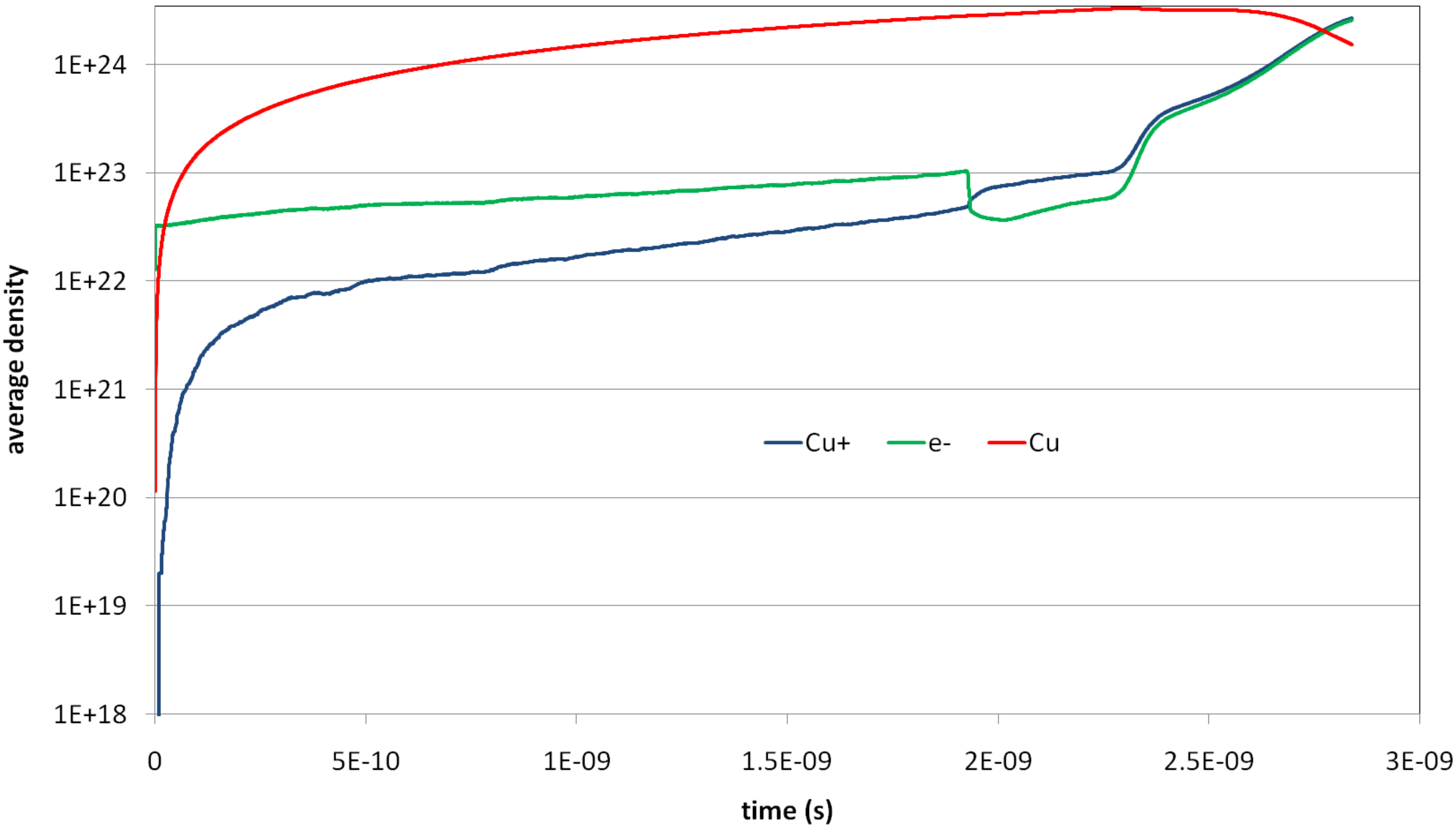
Time-to-breakdown

- **Run #37: 1.697 ns**
- **Run #38: 1.929 ns (+/- 0.0126 ns)**

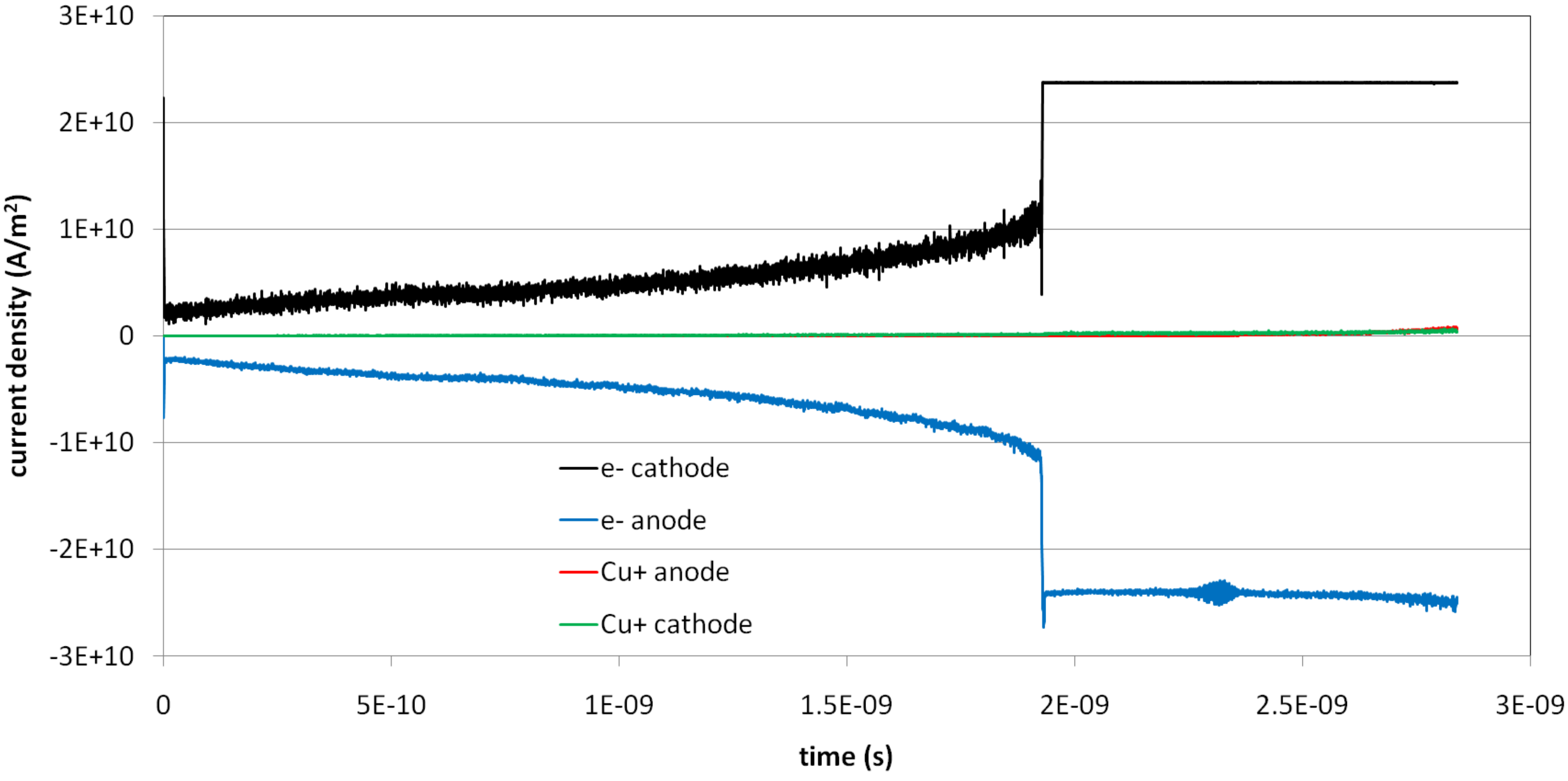
Particle count vs. time (Run 38a)



Average density vs. time (Run 38a)



Current densities (Run 38a)



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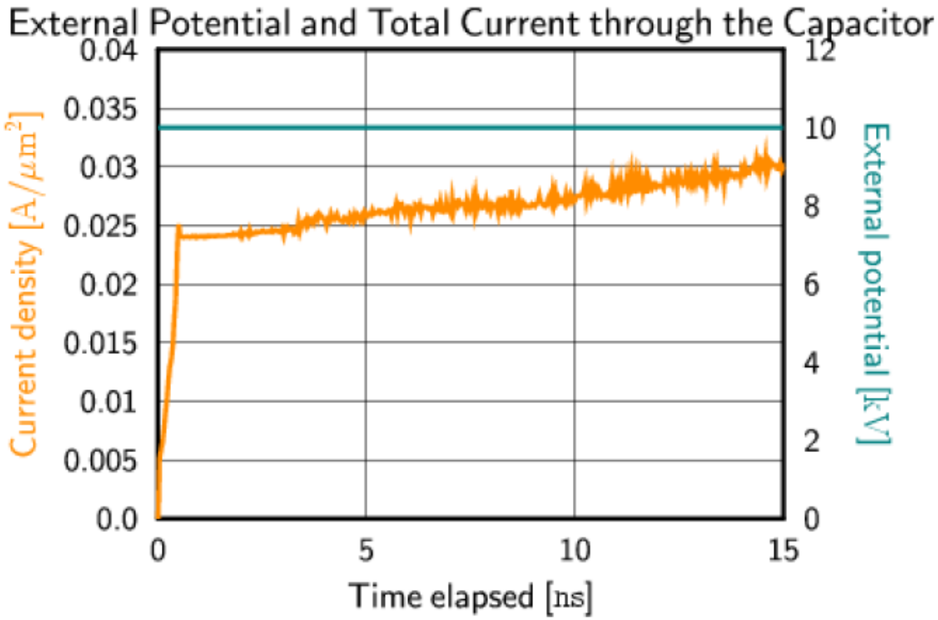
Density vs x and t (Run 37)

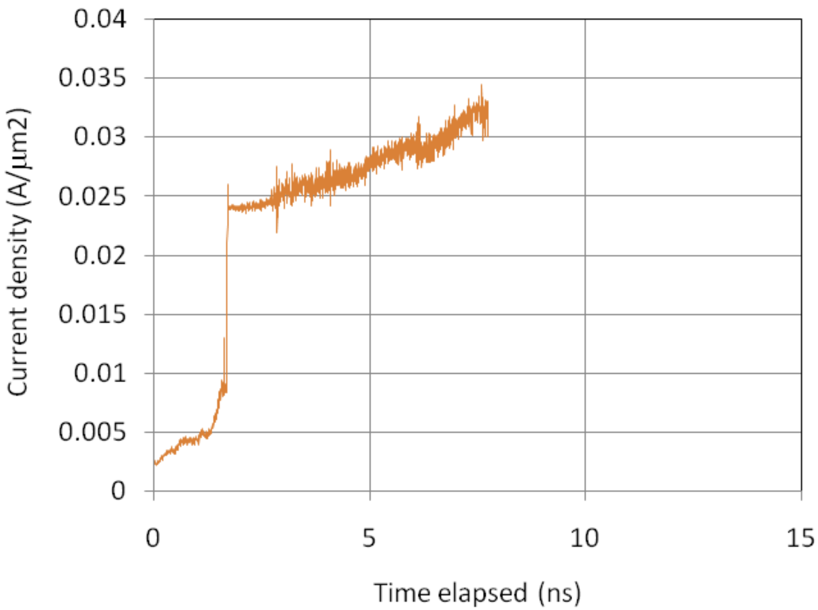
Potential vs x and t (Run 37)

Latest results comparison

From Helga



Our results (run 37)



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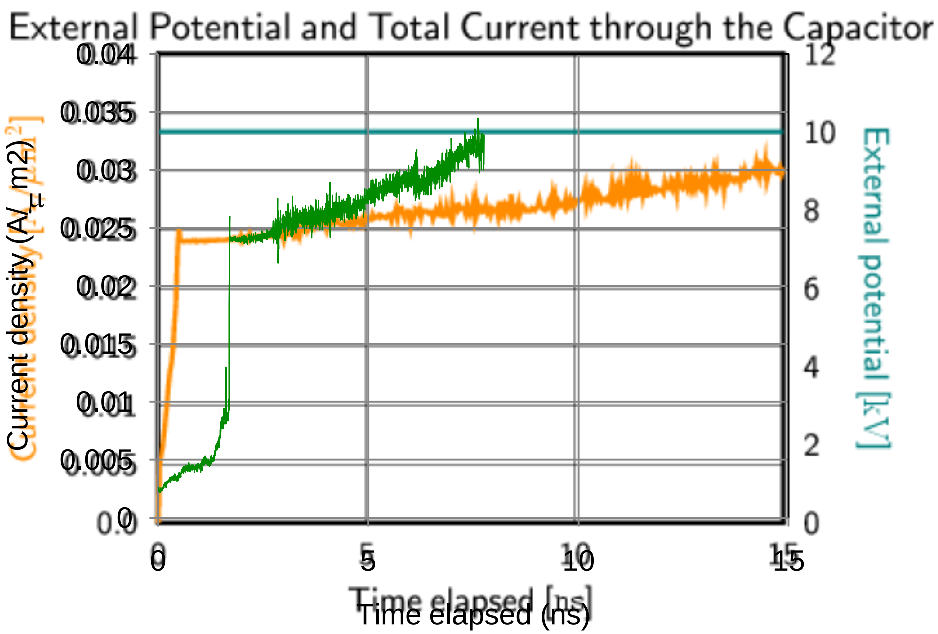
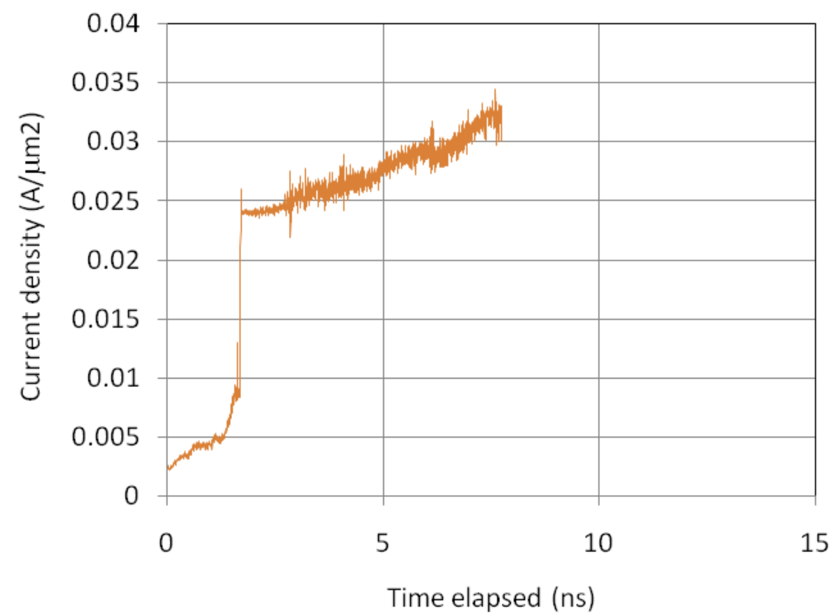
Latest results comparison

From Helga



Our results (run 37)



Thermal BC at the anode

Run #20: no sputtering at the anode --- use thermal emission model instead.

Result: anode quickly overheated (>10,000 K) to the point of making the thermal model numerically unstable.

Conclusion: power into the anode (2×10^{13} W/m^2) unrealistically high. Try again with lower power.

Thermal BC at the anode (cont.)

Run #21: used 100x smaller e- injection rate.

Result: anode quickly overheated (>8,000 K) to the point of making the thermal model numerically unstable.

Conclusion: power into the anode (1.5×10^{13} W/m^2) *still* unrealistically high. Try again with lower power. 100x smaller e- injection rate doesn't guarantee 100x smaller power to the anode!

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Fowler-Nordheim BC at the cathode

- **Need to make code change to Aleph: add fudge factor.**
- **If we can arbitrarily set this parameter, we can get whatever electron emission from the cathode that we want.**
- **Some experimental data available for Cu --- parameter depends on surface finishing process.**
- **With this model in place, and the thermal model at the anode, we should be able to simulate breakdown without any particle fountains.**

Electron emission: From the Fowler–Nordheim relation to the Child–Langmuir law

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(Received 9 September 1993; accepted 14 February 1994)

$$J = AE_s^2 e^{-B/E_s} = J_0 \left(\frac{E_s}{E_0} \right)^2 e^{-1/(E_s/E_0)}$$

Electron emission theory and its application: Fowler–Nordheim equation and beyond

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$$J(F) = \frac{q\sqrt{\mu/\phi}}{4\pi^2\hbar(\mu+\phi)} F^2 \exp\left(-\frac{4}{3\hbar F}\sqrt{2m\phi^3} \right)$$

Fabrication of ultra-clean copper surface to minimize field emission dark currents

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Further studies of electron emission areas on electropolished copper surfaces in vacuum

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(Received 3 September 1974)

A lead transfer technique described in an earlier publication has been applied to the problem of locating electron emission areas on broad-area electrodes in vacuum. The objective of this work is to identify and analyze microscopic emission areas on electropolished copper and to determine their Fowler–Nordheim characteristics. The results suggest that insulating inclusions play an important part in the emission from such surfaces and indeed have emission characteristics which are similar to those expected for metallic emitters.

Scale-up to “macroscopic” gap

- Used 100x the gap size → 2 mm
- Didn’t see breakdown, even after 14.3 million timesteps, 0.35 ps each = 5 μs.
- But Cu neutral density in the gap climbed to over 10^{26} m^{3} !
- Why no breakdown?
  - Influx rate too high?
  - Timestep too large?
  - Cells too large?
  - Particle weighting too high?

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Small parameter study

Base case:

- **Quick breakdown (0.6 ns)**
- **300,000 timesteps = 1 ns simulation**
- **1.7 hours to completion on a single 2.8 GHz proc.**

Test cases:

1. **10x as many computational particles**
2. **Mixed particle weightings**
3. **Momentum transfer**

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Small parameter study (cont.)

Run #	Case	Time to breakdown (ns)	CPU time (hrs.)
27	Base case	0.61 +/- 0.007	1.7
28	10x particles	0.83 +/- 0.010	19
29	Mixed weightings	0.84 +/- 0.032	8.5
30	Momentum transfers	0.63 +/- 0.018	3.0

Conclusions:

1. Small error bars --- good repeatability of simulations.
2. We haven’t been using enough computational particles.
3. Possible that the 0.5 μm cell size isn’t small enough.
4. Mixed particle weightings seems OK.
5. Collisions not all that important.
6. Likewise, higher ionization states probably not all that important since their cross sections are tiny.

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Remaining challenges

- Comparison with CERN results imperfect. A better match would be nice.
- We'd like to simulate vacuum breakdown in a macroscopic gap.
- Need more realistic electrode models.
- Like to be able to use dynamic particle reweighting to cut computational costs.
- Like to move to 3D.