Particle-in-cell simulation of vacuum arc ignition and development

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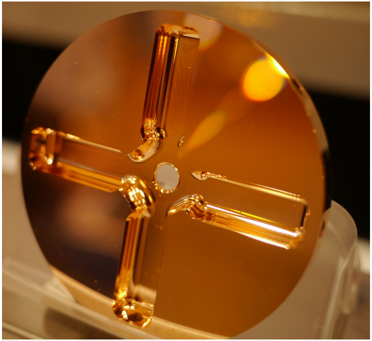
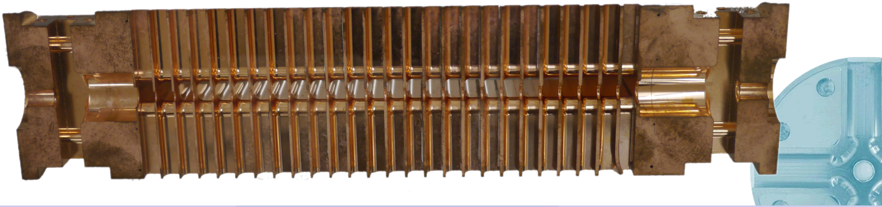
Outline

Motivation

- Want to build high-gradient ($E_{\mathrm{acc}} \geq 100\mathrm{MV/m}$) particle accelerators
- Highest gradient achieved in normal-conducting structures
- Gradient limited by arcs
- Understand arc ignition!

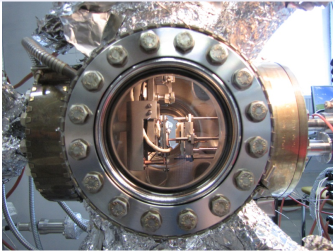
→ Design structures more resistant to arcing

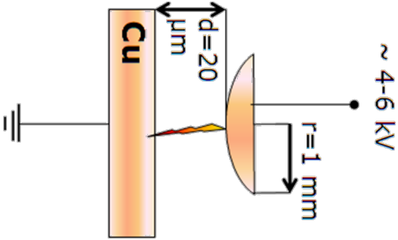


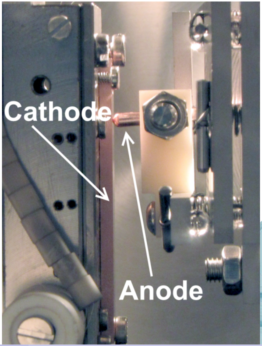


Experimental comparison: DC spark experiment

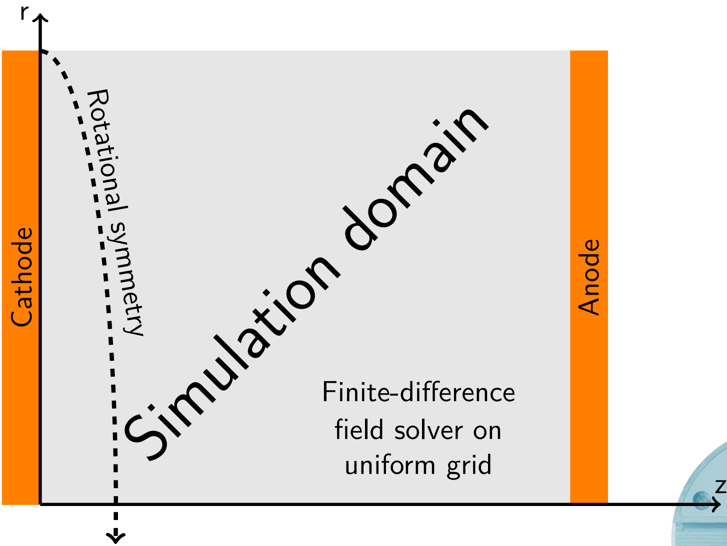
- High-voltage DC pulses on spark gap in ultra high vacuum
- Understand basic behavior of vacuum arc breakdowns
- Measure gap voltage & current through the breakdown







Physics model



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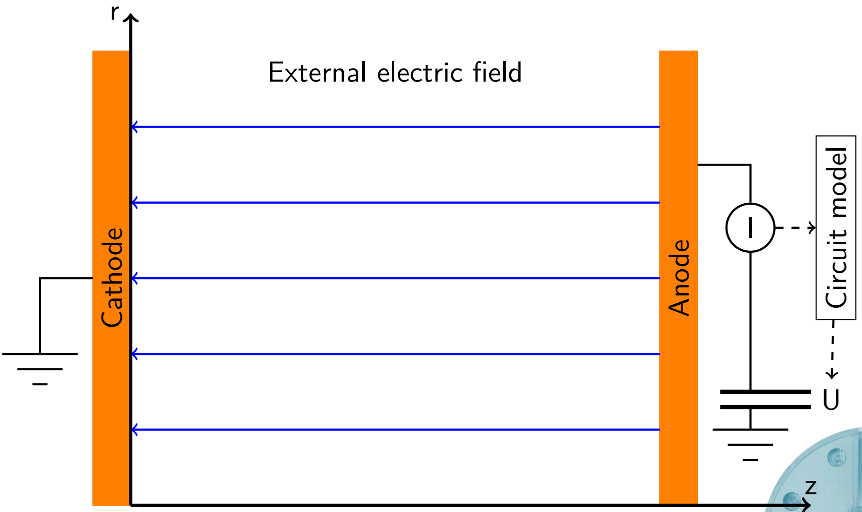

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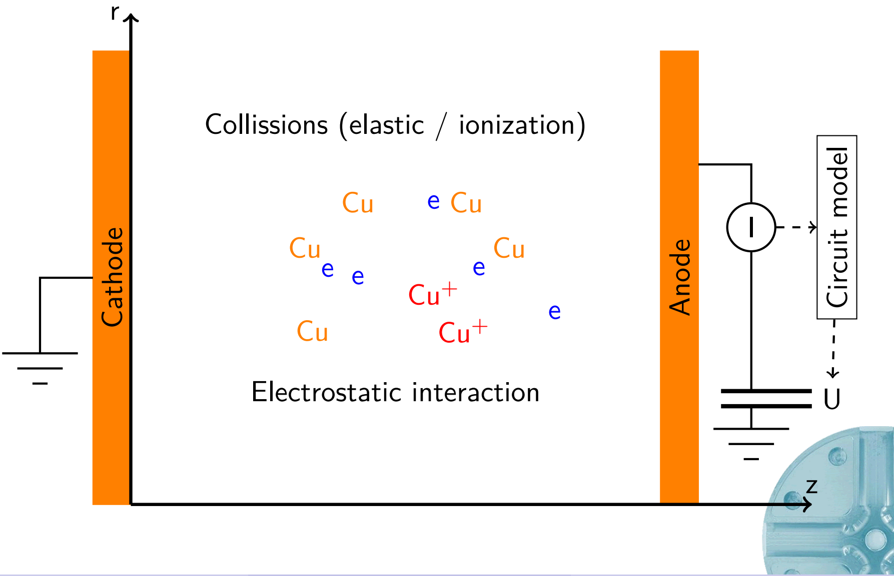

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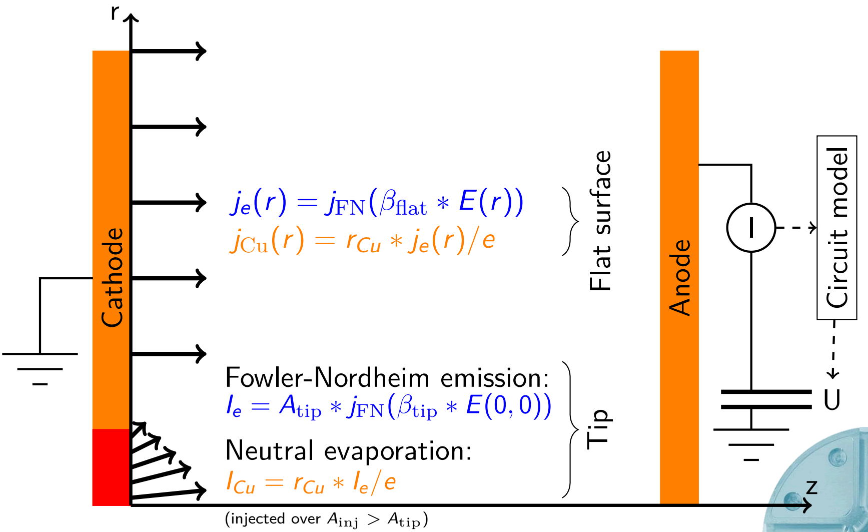

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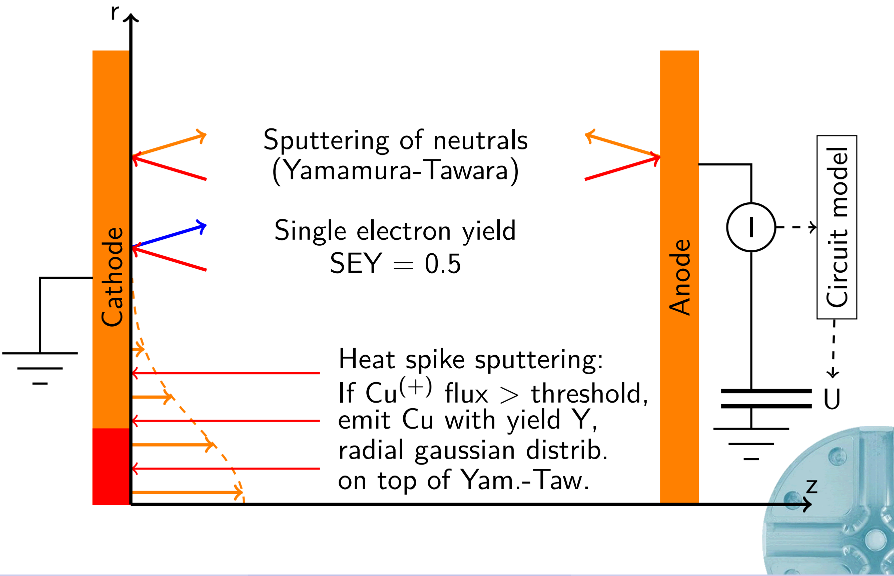
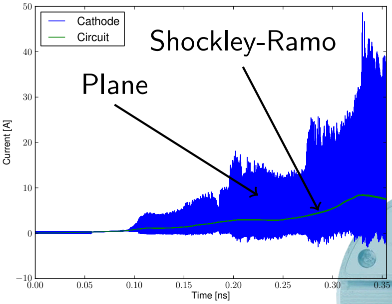


Current calculation: Shockley-Ramo theorem

- Calculation of instantanious currents on electrodes
  - Particles/time through plane incorrect & noisy
  - Noise is a problem for circuit models
- Use the Shockley-Ramo theorem to calculate currents
  - Charges in the gap induce charges on electrodes
  - Induced charge dependent on position
  - Moving charges ⇒ current
- Assumes electrostatic fields



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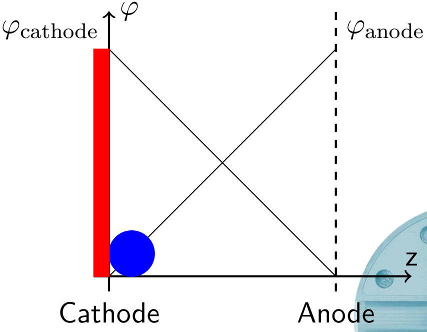
Get φ for an electrode by solving $\nabla^2\varphi = 0$ with $\varphi = 1$ on electrode of interest, $\varphi = 0$ for all other electrodes.

$$Q_{\text{ind}} = -q\varphi(\vec{r})$$



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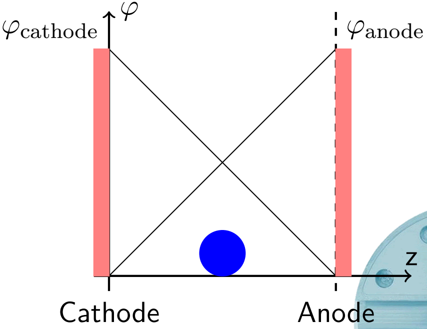

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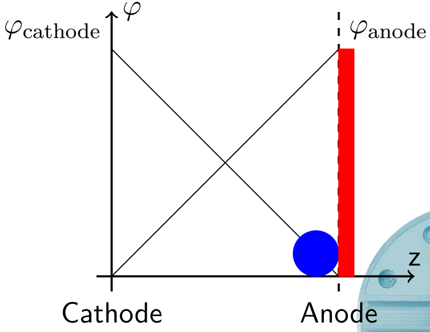

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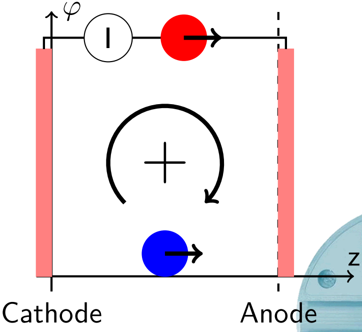

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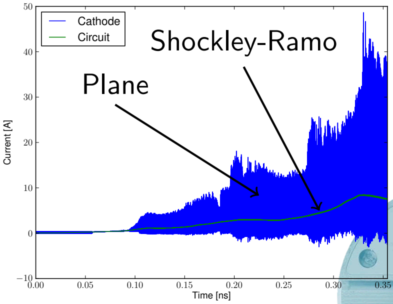
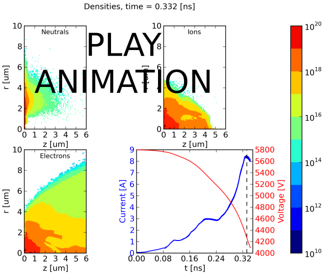


Arc evolution

Main stages of vacuum arc ignition are visible:

1. Field emission and gas creation
2. Ionization
3. Bombardment and growth

- Current growing together with transverse size
- Capacitor discharged
- Ions accelerated against field



Fast discharge:

- U = 5800 V, C = 0.5 pF
- $\beta_{\mathrm{tip}} = 35$, $\beta_{\mathrm{flat}} = 2$
- Heatspike Y = 1, threshold = 10^{25} ions/cm^2/s
- Sim. domain 6x24 μm
- $\Delta t = 0.9$ fs, $\Delta z = 50$ nm

Emission process

- Parameters for emission:
  - Field emission:
    $\beta_{\mathrm{tip}} = 35$
    $\beta_{\mathrm{flat}} = 1 \,/\, 2$
  - Evaporation ratio
    $r_{\mathrm{Cu}} = 0.015$
  - Heatspike
    Yield $= 0 \,/\, 1 \,/\, 2$
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- Initial fields:
  967 and 290 MV/m
- Effects:
  - Time-to-breakdown
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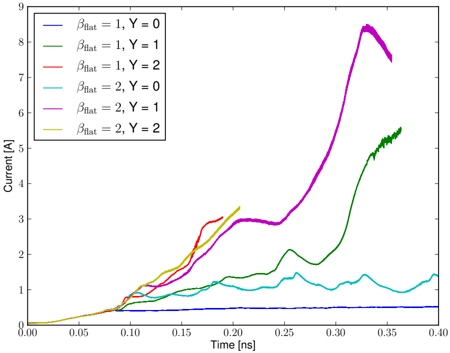

- Increasing Y or $\beta_{\text{flat}} \Rightarrow$ Faster growth
  - No growth without heatspike

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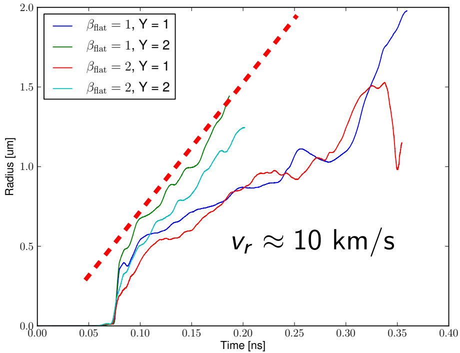

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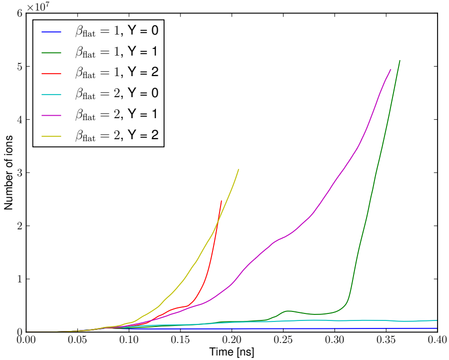

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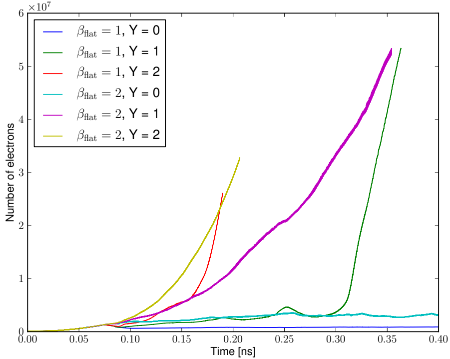

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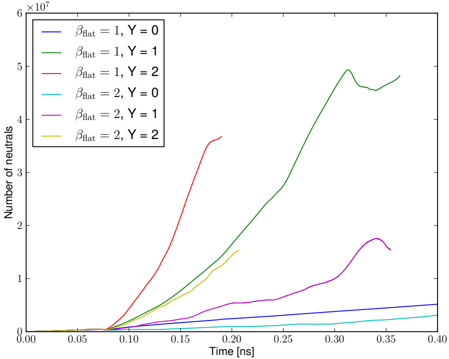

- Increasing Y or $\beta_{\text{flat}} \Rightarrow$ Faster growth
  - No growth without heatspike
- $N_{\text{ion}} \approx N_{\text{elec}}$
- Less ionization with $\beta_{\text{flat}} = 1$

Emission process

Initial voltage = 1740 V:

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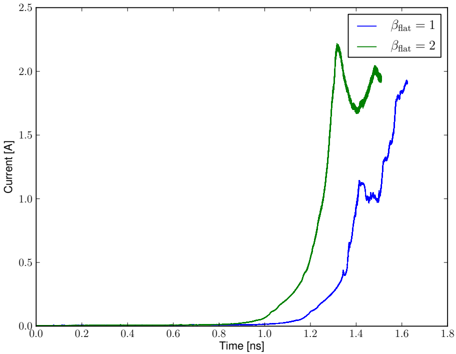

- Lower voltage ⇒ $t_{\text{breakdown}}$ increased
- Higer β_{flat} ⇒ faster rise, fewer neutrals
- Difference in $t_{\text{breakdown}}$ is random
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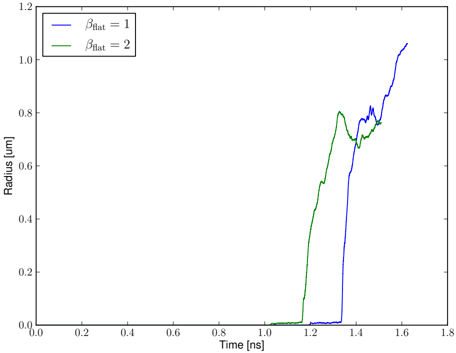

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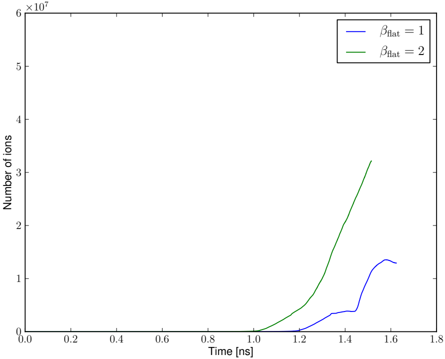

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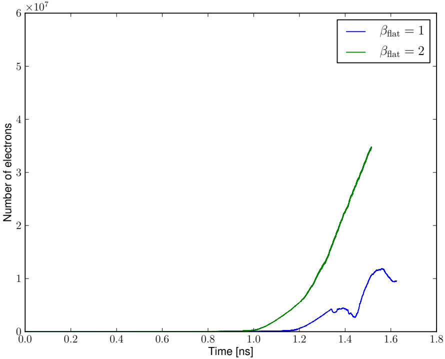

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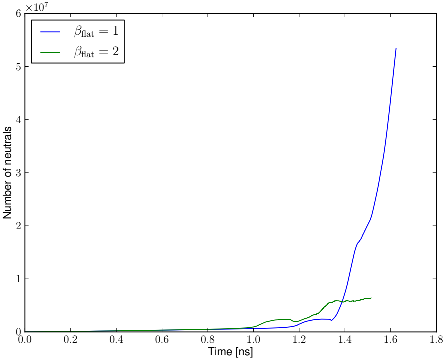

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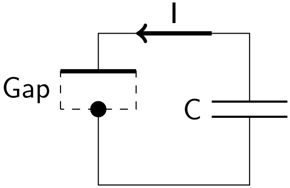
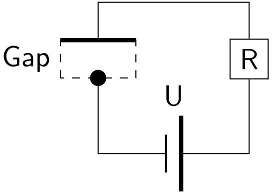
External circuit

- Circuit types tested:
  - Capacitive – prev. slide
  - Resistive
- Varied parameters:
  - Resistance
  - Initial voltage
- All simulations ran with:
  - $\beta_{\text{tip}} = 35$, $\beta_{\text{flat}} = 2$
  - Heatspike Y = 1, threshold $= 10^{25}/\text{cm}^2/\text{s}$



$$V_{\text{gap}} = V_{t=0} - \frac{1}{C}\int_0^t I \, \mathrm{d}t$$



$$V_{\text{gap}} = U - RI$$

External circuit   Resistive, U=5800 V:

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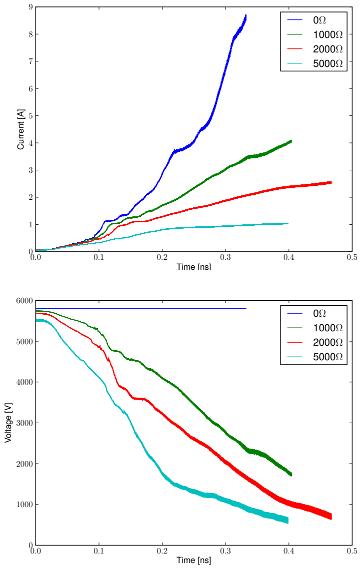

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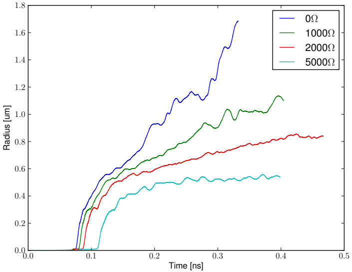

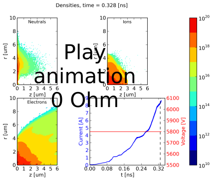

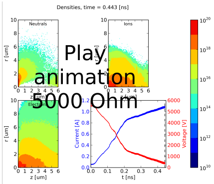

External circuit

Resistive, U=1740 V:

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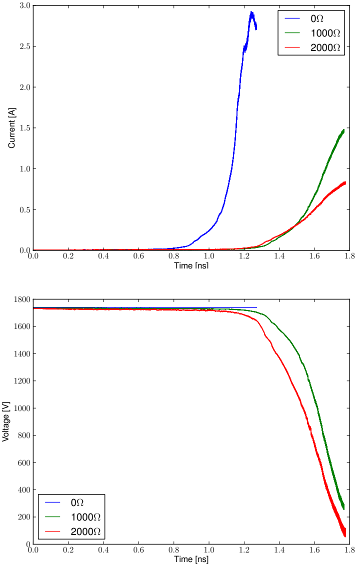
  - Capacitive – prev. slide
  - Resistive
- Varied parameters:
  - Resistance
  - Initial voltage
- All simulations ran with:
  - $\beta_{\text{tip}} = 35$, $\beta_{\text{flat}} = 2$
  - Heatspike Y = 1, threshold = $10^{25}/\text{cm}^2/\text{s}$

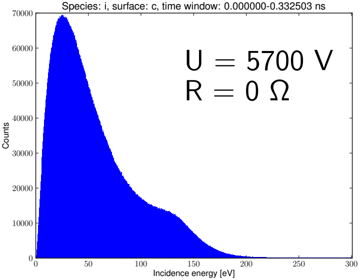
Results

- Smaller U ⇒ longer $t_{\text{breakdown}}$
- Larger R ⇒ slower growth
- Small V_{gap} ⇒ plasma bridge



Ion bombardment of cathode

- Energy distribution
  mostly determined by sheath
  - Most probable value ≈ 30 eV
- Average yield from
  Yamamura-Tawara sputtering ≈ 0.1
  - Not enough to sustain arc
  - Heat-spike sputtering needed
- Bombardment flux density
  $\approx 10^{24} - 10^{25}/\mathrm{cm}^2/\mathrm{s}$
- Slow "pulsing" in the bombardment
  - Associated with high gap voltage



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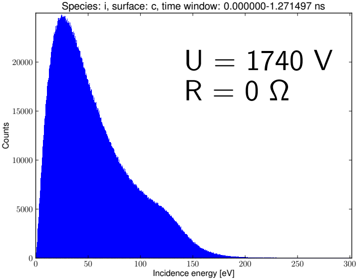

Ion bombardment of cathode

- Energy distribution mostly determined by sheath
  - Most probable value ≈ 30 eV
- Average yield from Yamamura-Tawara sputtering ≈ 0.1
  - Not enough to sustain arc
  - Heat-spike sputtering needed
- Bombardment flux density $\approx 10^{24} - 10^{25} / \mathrm{cm}^2/\mathrm{s}$
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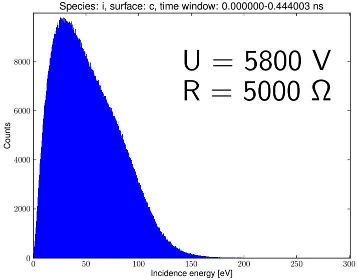

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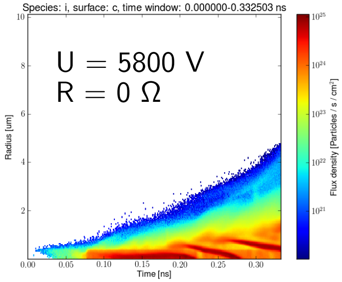

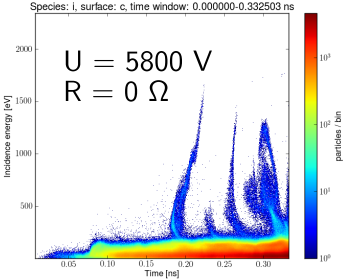

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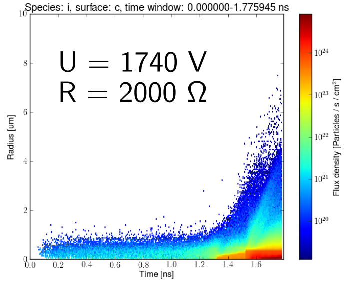
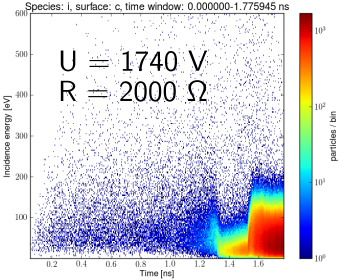
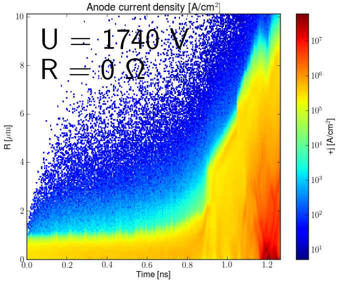
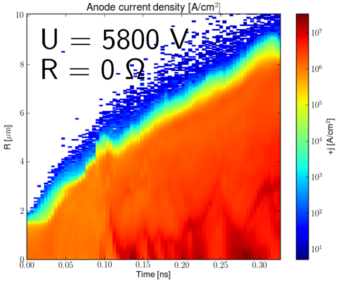




Surface current density

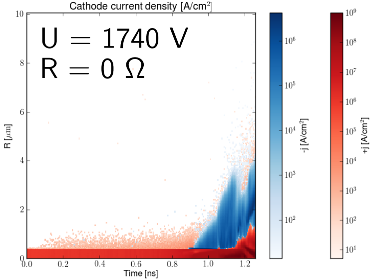
- Anode dominated by electron plume
  - Current densities reach $\approx 10^7\,\mathrm{A/cm^2}$

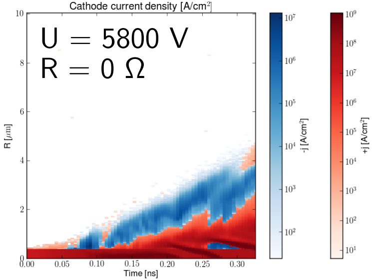




Surface current density

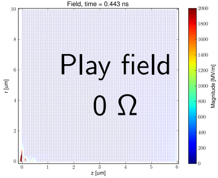
- Anode dominated by electron plume
  - Current densities reach $\approx 10^7 \mathrm{A}/\mathrm{cm}^2$
- Cathode sees both electron emission, ion bombardment, and returning electrons
  - "Pulsing" can reverse current under sheath

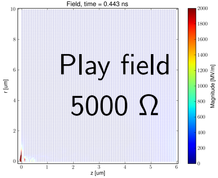


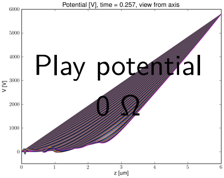


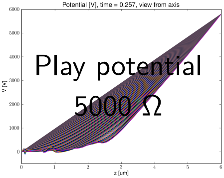
Field distribution

- Sheath field $\approx 10 GV/m$
- Field expelled
  from quasineutral plasma
  - Some oscillations still visible,
    fewer at smaller V_{gap}
- If V_{gap} remains high,
  high gradient between
  top of plasma and anode







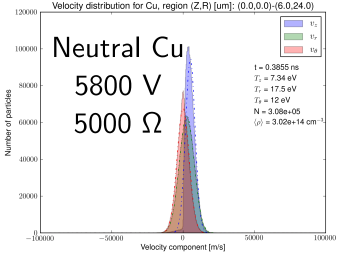


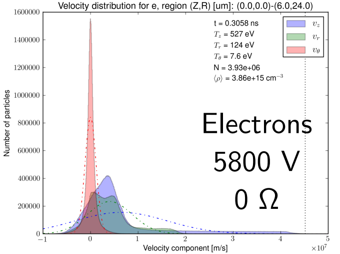
All using resistive circuit,
U = 5800 V

Temperature

- If Maxwellian, velocity components are Gaussian
  - $v = \mathcal{N}(\mu, \sigma)$
  - $T_{[\mathrm{K}]} = \frac{(\sigma_{[\mathrm{m/s}]})^2 * m_{[\mathrm{kg}]}}{k_{[\mathrm{J/K}]}}$

  or $T_{[\mathrm{eV}]} = \frac{(\sigma_{[\mathrm{m/s}]})^2 * m_{[\mathrm{kg}]}}{e_{[\mathrm{J/eV}]}}$
- To be expected if plasma dominated by collissions
  - Not always the case
  - Especially at high gradients
  - Especially not for electrons
- Typical temperatures 5–20 eV (10^5–10^6 K)
  - Higher at larger voltages
  - Where defined





Summary

- ArcPic2D: 2D3V PIC+MCC code
- Heat spike sputtering needed for plasma growth
- Higher voltage ⇒
  - Shorter $t_{\mathrm{breakdown}}$
  - Faster growth
  - Less anode splashing
  - More turbulent plasma
  - High gradient between plasma and anode
- Large circuit resistance ⇒ slower current growth
- Ion impact energy on cathode ≈ 30 eV
  - Defined by sheath
  - Independent of circuit and emission parameters
- Plasma densities ≈ 10^{20} ions/cm^3
- "Temperatures" ≈ 5-20 eV (ions & neutrals)
- Expansion rate ≈ 10 km/s

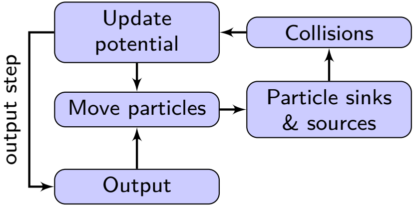
Thanks to: Lotta, Helga, Nick, Anders, Walter, Sergio

BACKUP SLIDES

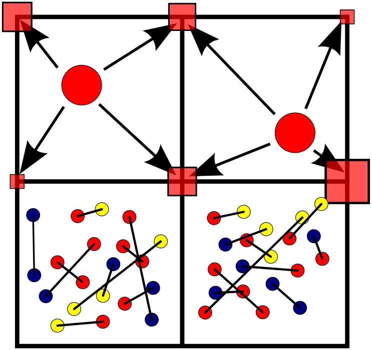
Particle in cell (PIC) + Monte Carlo Collisions (MCC)

- Volume divided into grid
  - Field solver
  - Proximity for collisions
- Macro-particles moves in continuous phase-space

Main loop:



Distribute charges to grid points



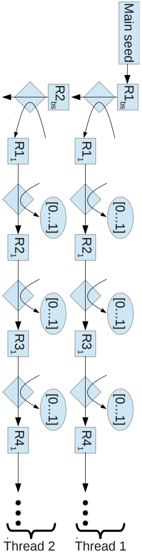
Collide random pairs of particles in each cell

Monte-Carlo collisions

- Particles inside same cell
  are considered “close enough” to collide
- For each collision type, create random particle pairs
- Implemented collisions:
  - Coulomb scattering (e^-,e^-), (Cu^+,Cu^+), (Cu^+, e^-)
  - Elastic collisions (e^-,Cu), (Cu, Cu)
  - Charge exchange/momentum transfer (Cu^+,Cu)
  - Impact ionization $e^- + Cu \rightarrow 2\ e^- + Cu^+$

ArcPic2D parallelism

- OpenMP multithreading
  - Shared memory
  - Requiring few code changes
- Multi-stream RNG
- Parallel neutral-neutral collisions
- Load balancing
- Test case:
  - 1.8 M neutral particles
  - 5x5 µm cylinder
  - T=300 eV, $\rho = 10^{17}/\mathrm{cm}^3$
- Quite good scaling
  - Almost linear
  - Slower than ideal due to serial sections



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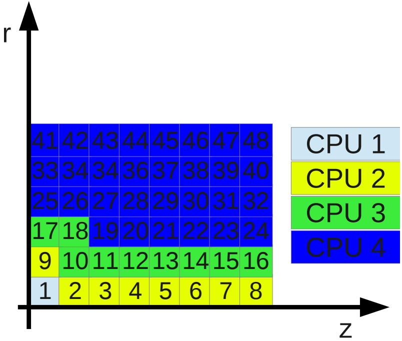

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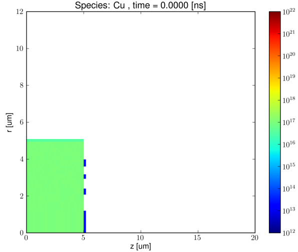

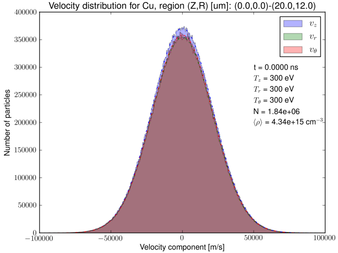

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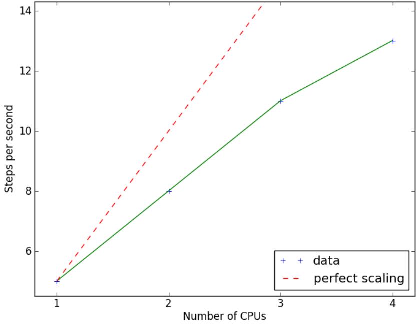
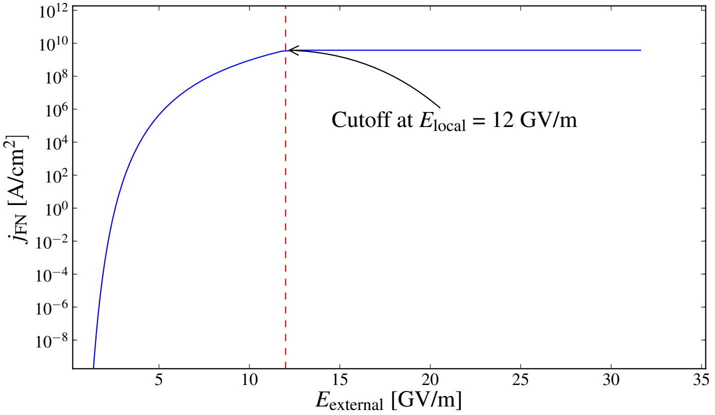


Fowler-Nordheim emission



Yamamura-Tawara sputtering