Introduction to ArcPIC

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Madeira CERN plasma simulation meeting
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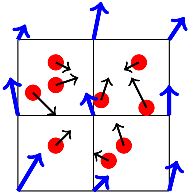
https://indico.cern.ch/event/878402/

Sources and References

- *From Field Emission to Vacuum Arc Ignition: A New Tool for Simulating Copper Vacuum Arcs* (2015)
  https://onlinelibrary.wiley.com/doi/abs/10.1002/ctpp.201400069
- *Avoiding vacuum arcs in high gradient normal conducting RF structures* (2016)
  https://www.duo.uio.no/handle/10852/52944
- *2D ArcPIC Code Description: Description of Methods and User / Developer Manual (second edition)* (2014)
  https://cds.cern.ch/record/1951304
- The ArcPIC code
  https://github.com/arcpic/arcpic

The PIC-MCC method

- Track *super-particles* in continious phase-space to approximate particle density
- Compute electromagnetic fields on a mesh
- No apriori assumptions on shape of distribution needed
- Straight-forward method, easy to expand
  - Collissions: Pair up particles within same mesh cell and collide
  - Particle boundaries: Remove or inject from edges



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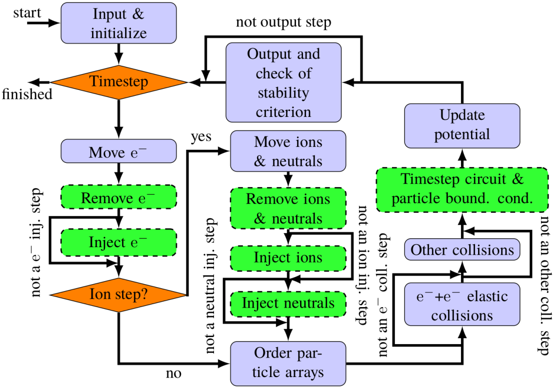
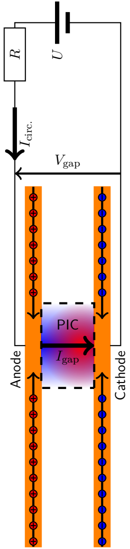
ArcPic main timestep loop:



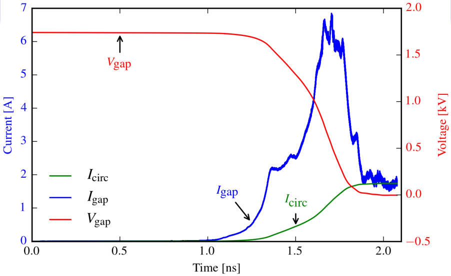
Why do ArcPIC simulations?

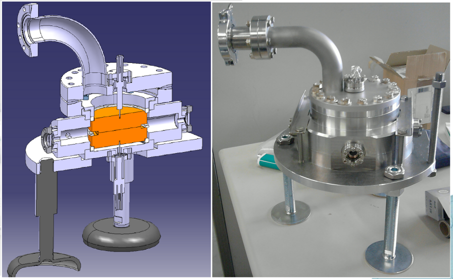
- Increase understanding of vacuum arc initial stages
  - Effects of different processes
  - Interplay between processes
- PIC simulation of the plasma, incl.
  - Collissions
  - Surface processes
  - External circuit
- Follow the development of the plasma “from field emission to vacuum arc ignition” (and beyond)
- DC spark type geometry and field
  - Expect physics to be mostly the same as RF
  - Easier and “cleaner” experiments



Simulated system

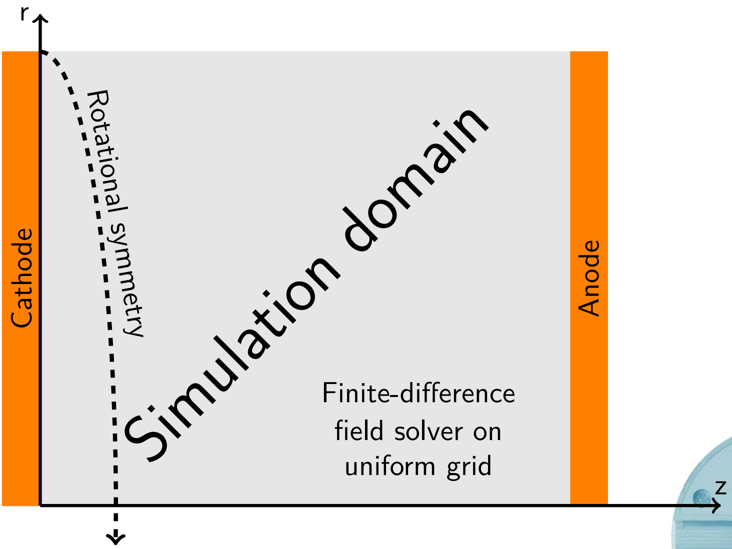
- Geometry is similar to the fixed gap system
- Simulation output:
  - IV curves,
  - Particle densities
  - Electric potential
  - Surface conditions
- Modelled with 3 species:
  - Electrons
  - Copper atoms
  - Singly ionized copper





From "*Experimental study of DC vacuum breakdown and application to high-gradient accelerating structures for CLIC*", PhD thesis, Nicholas Shipman (2014)

Physics model



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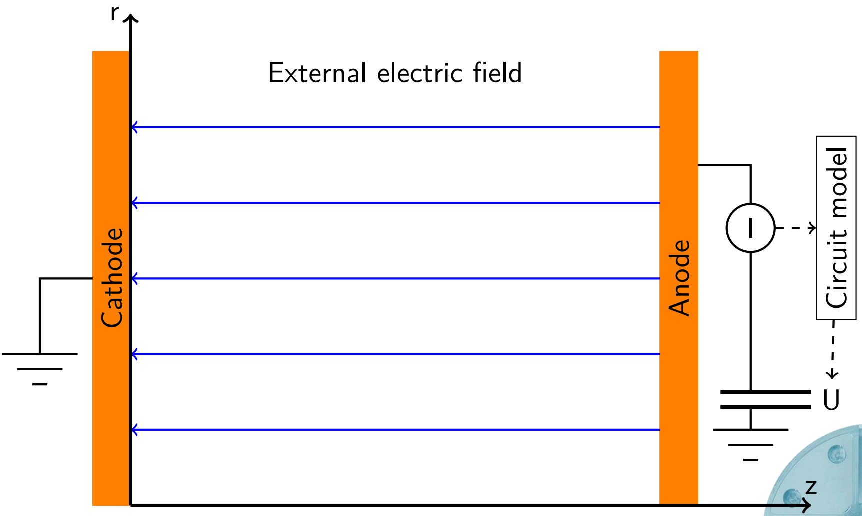

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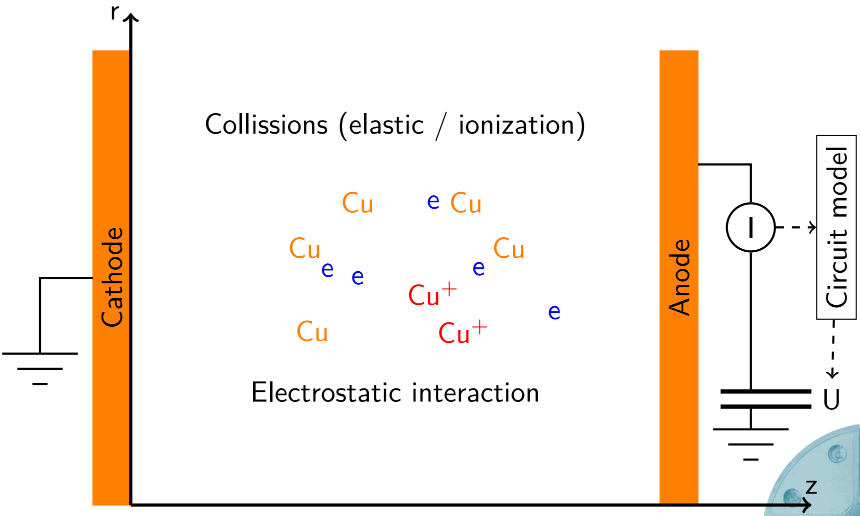

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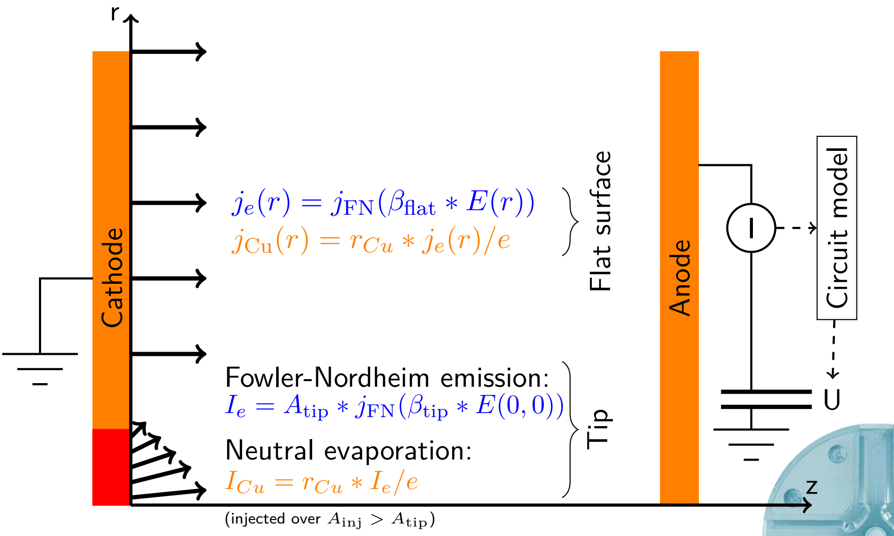

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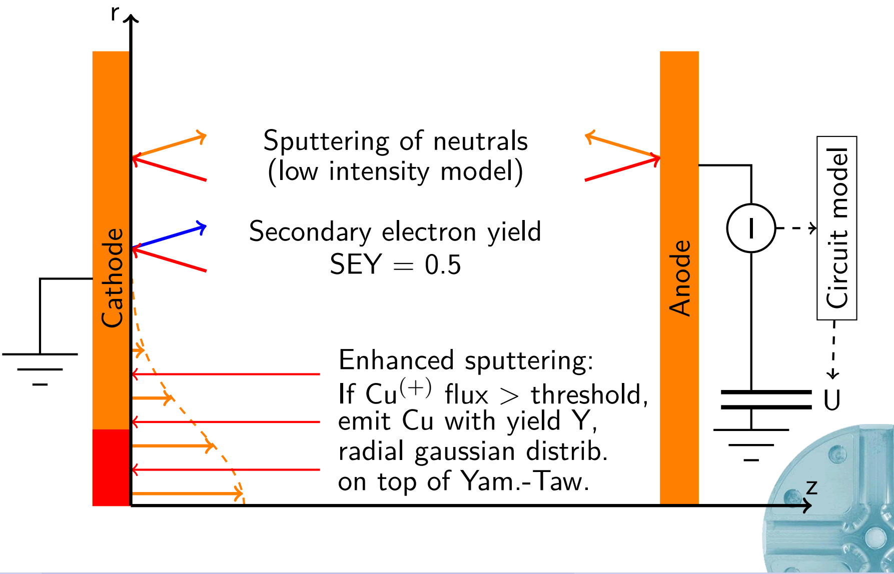
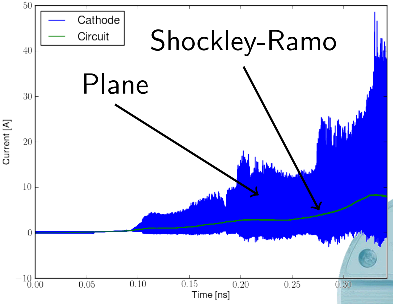


Current calculation: Shockley-Ramo theorem

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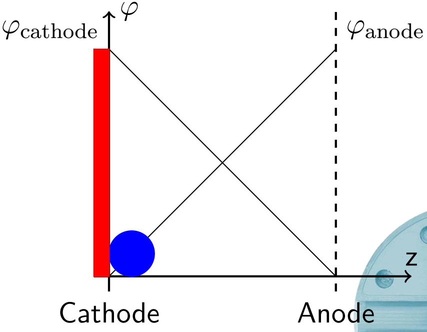
Get φ for an electrode by solving $\nabla^2\varphi = 0$ with $\varphi = 1$ on electrode of interest, $\varphi = 0$ for all other electrodes.

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



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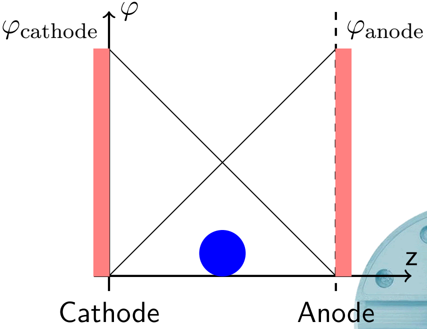

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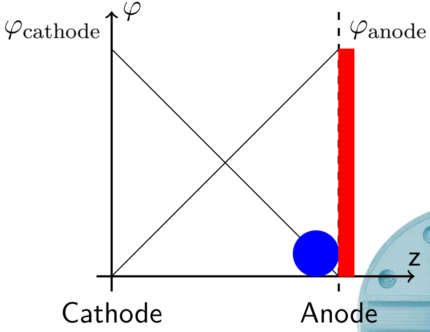

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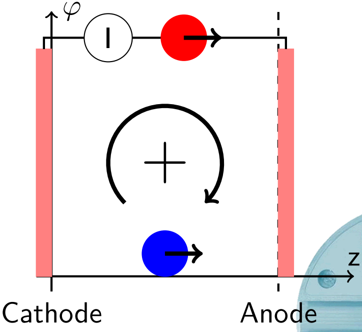

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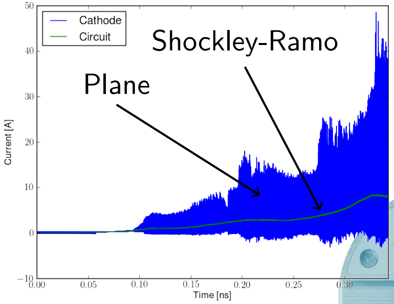
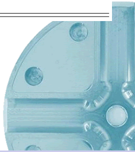


Some key results from "From Field Emission to Vacuum Arc Ignition: . . . "

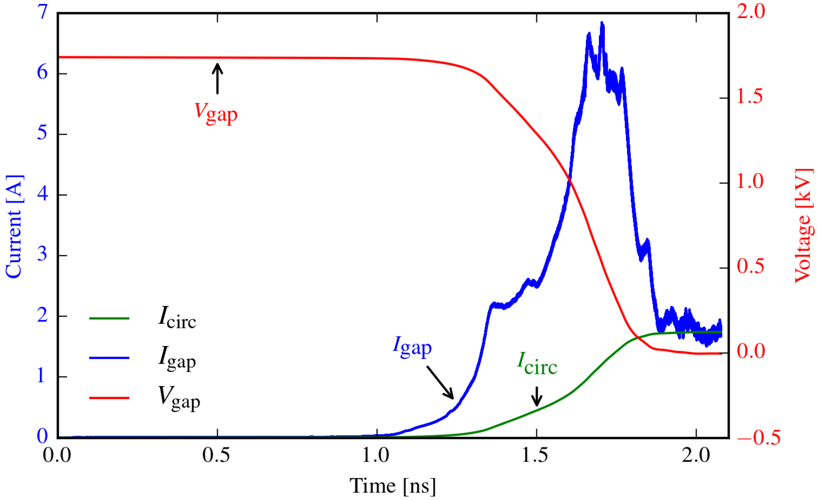
- Followed arc development in detail for a reference case
- Also varied surface- and circuit parameters:
  - $Y_{\text{enhanced}} = 0, 2$
  - $j_{\text{enhanced}} = 10^{26}, 10^{24} \frac{\text{ions}}{\text{cm}^2}$
  - $r_{\text{Cu/e}} = 0.01$
  - $\beta_{\text{flat}} = 1$
  - R, C, U_{gap}

Parameters for reference simulation:

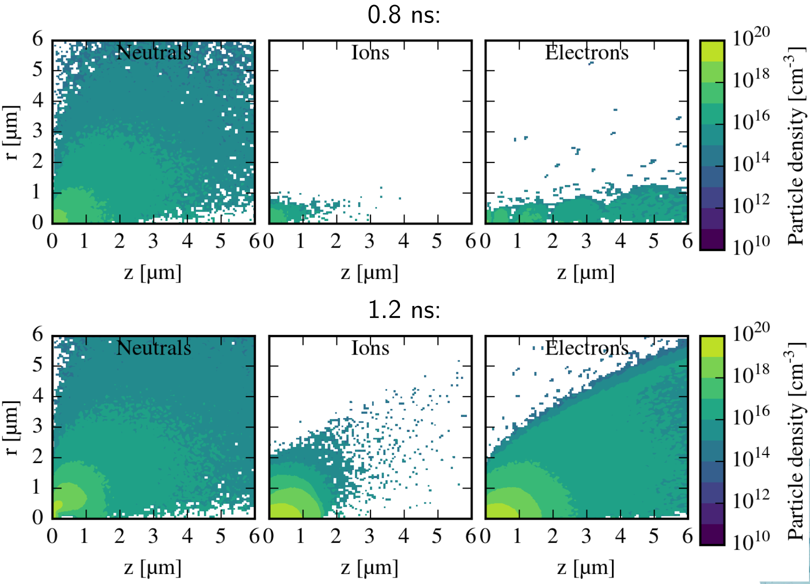
	Parameter	Value	Unit	Comment
General	Δt	0.886	fs	Time step
	Δz	50	nm	Grid spacing
	N_{sp}	10.68		Particle/super-particle weighting ratio
	Z	6 (120 cells)	µm	Domain size
	R	24 (480 cells)	µm	
Surface	β_{tip}	35		Field enhancement factor for "tip"
	β_{flat}	2		Field enhancement factor outside "tip"
	R_{tip}	56.4	nm	Radius used for calculating "tip" current
	R_{emit}	400	nm	Radius used for injection of "tip" current
	Y_{SEY}	0.5		Secondary electron yield
	$r_{\text{Cu/e}}$	0.015		Cu/e$^-$ injection ratio
	j_{enhanced}	10^{25}	cm^{-2}s^{-1}	Enhanced (high-flux) sputtering threshold
	Y_{enhanced}	1		Enhanced (high-flux) sputtering yield
Circuit	U	1740	V	Supply and initial gap voltage
	E_z	290	MV/m	$E_z(t=0) = U/Z$
	R	1000	Ω	Series resistance
	C	1.0	pF	Gap capacitance



Current- and voltage profile

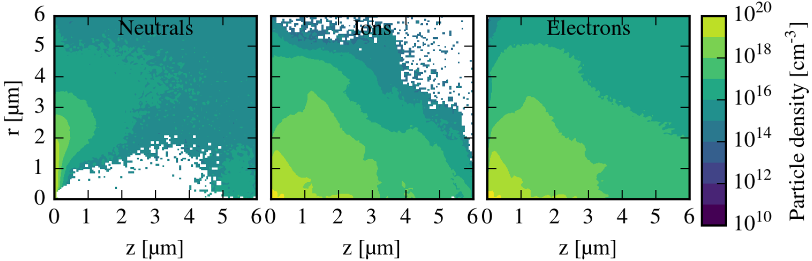


PIC simulations: Density development

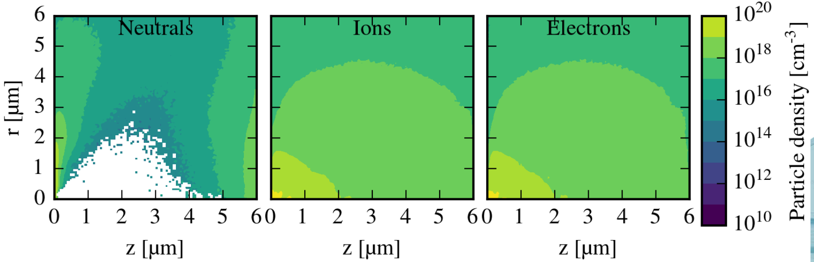


PIC simulations: Density development

1.5 ns:



2.0 ns:



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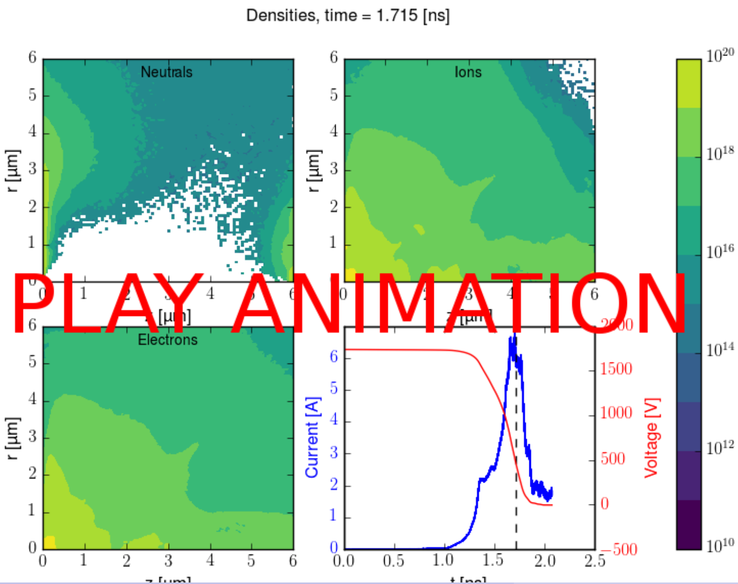
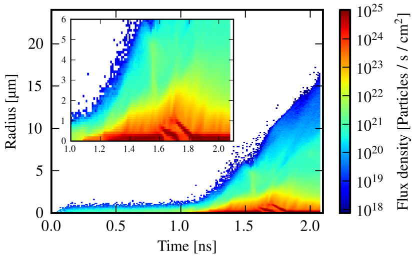
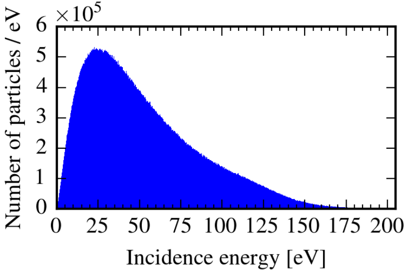


PIC simulations: Surface conditions





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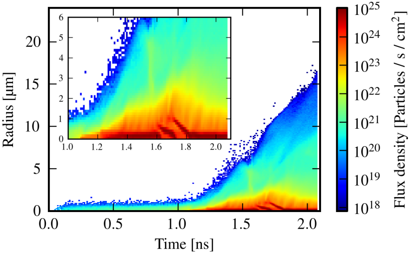
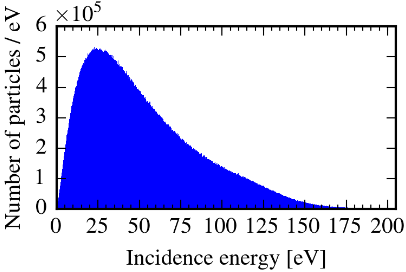
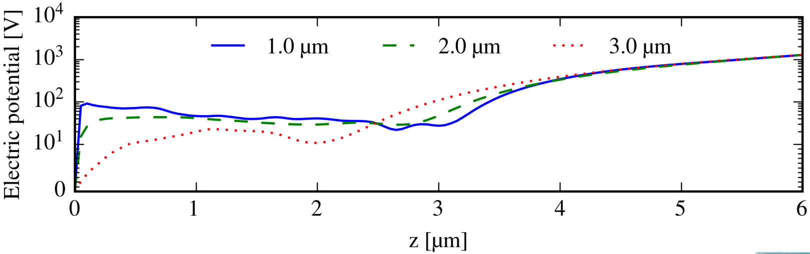
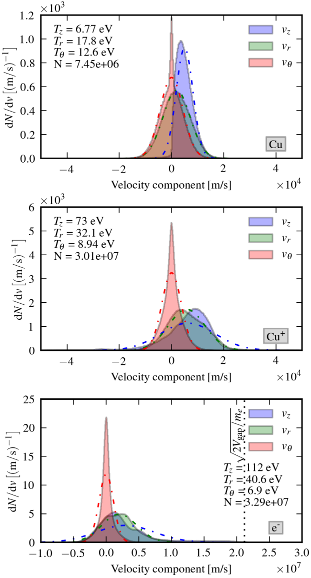




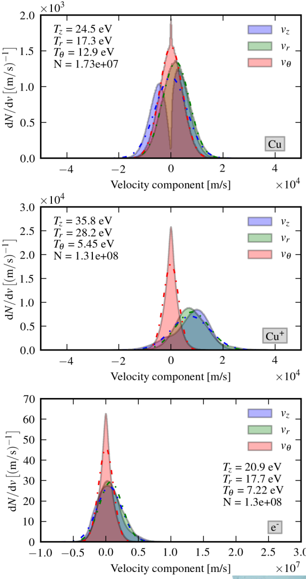


Velocity distributions

1.5 ns:



2.0 ns:

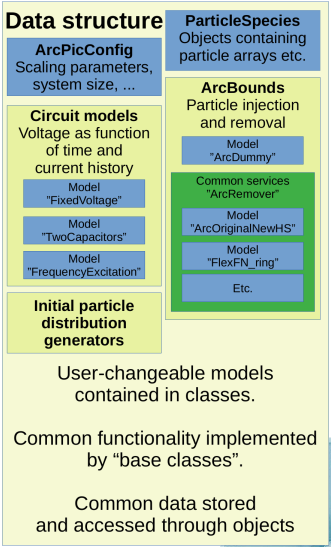


Some key conclusions from "From Field Emission to Vacuum Arc Ignition: ..."

- Able to follow development from field emission throuh ignition to spreading in a single model
- Development of computational laboratory for arc ignition
- Quantified how much evaporation is needed to start ($r_{\mathsf{Cu/e}} > 0.015\ \mathrm{Cu/e^-}$)
    - Does not describe mechanism of evaporation
- Pointed out some issues with sputtering
    - With burning voltage O(50 V) and average charge state 1, average single-particle sputtering yield $\ll 1$
    - Enhanced sputtering or evaporation needed for spreading (volume defined phase)
- Showed some dependence on energy supply
    - Large $R \Rightarrow$ arc starts, but dies down when local energy store is exhausted

Recent improvements to ArcPIC

- Ongoing project: Code modernization and structure improvements
- ArcPIC is a modular C++ code; surface physics, circuit models contained in classes
- Scaling parameters and particle arrays now contained in generalized classes
- System size is now automatically scaled on demand
- HDF5 output supported (speed and storage size improvements)
- CMake used for configuring external libraries
- Preparation to make it easier to add species, processes, and more



EXTRA

Yamamura-Tawara sputtering