PLASMA INTIATION
IN VACUUM ARCS – Part 1: Modelling

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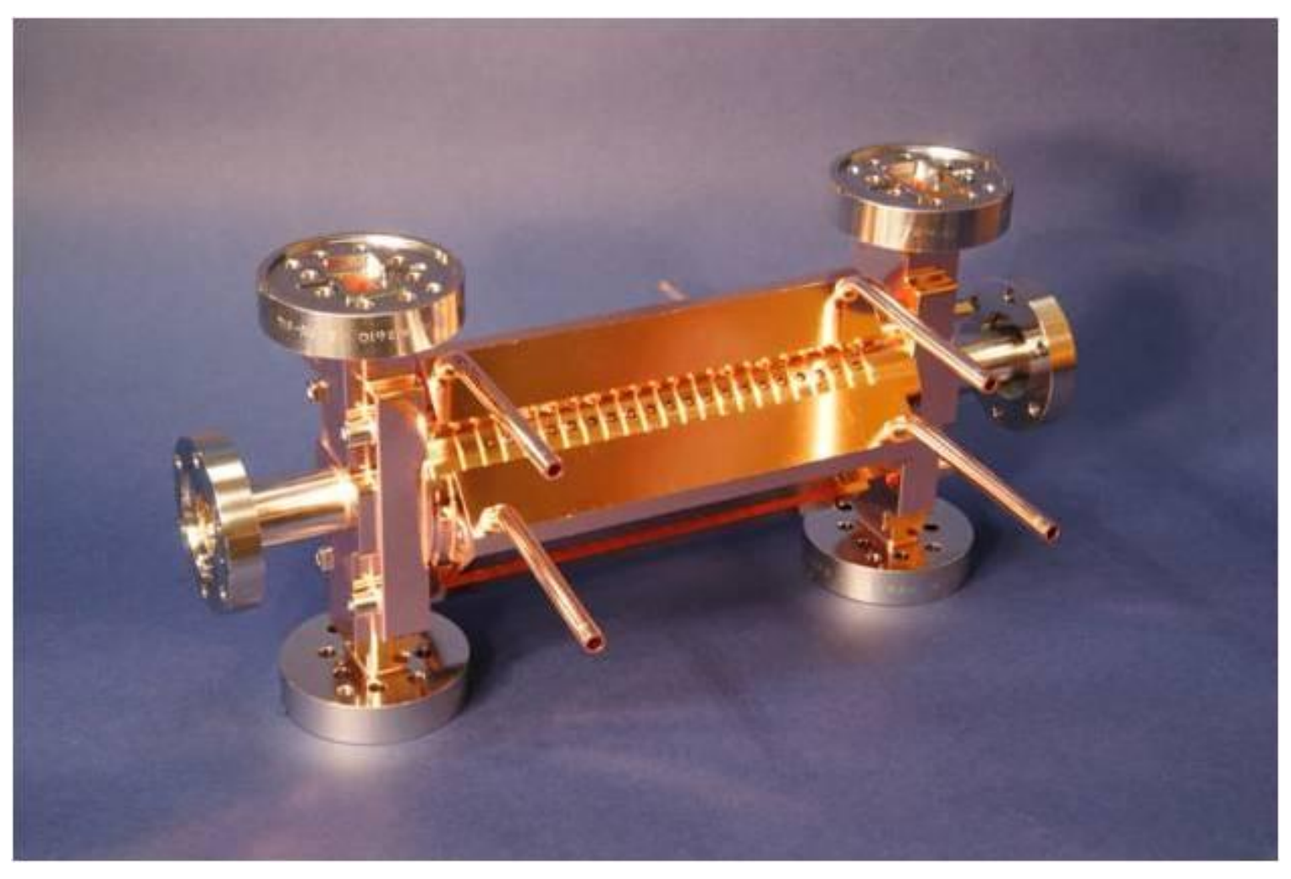
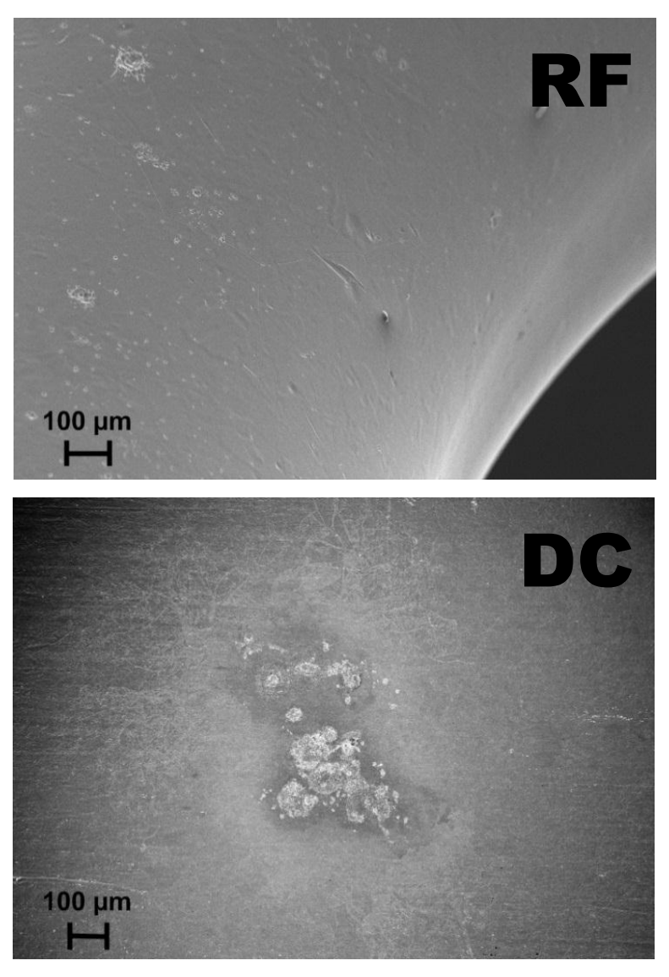
WHY MODEL THE PLASMA?

Measuring vacuum arcs *in situ* in high-gradient RF accelerating cavities or in dedicated DC devices is a challenging task. Modelling the plasma formation in arcs can help to **(i)** link microscopic surface phenomena to macroscopic damage, and to **(ii)** interpret experimental results.



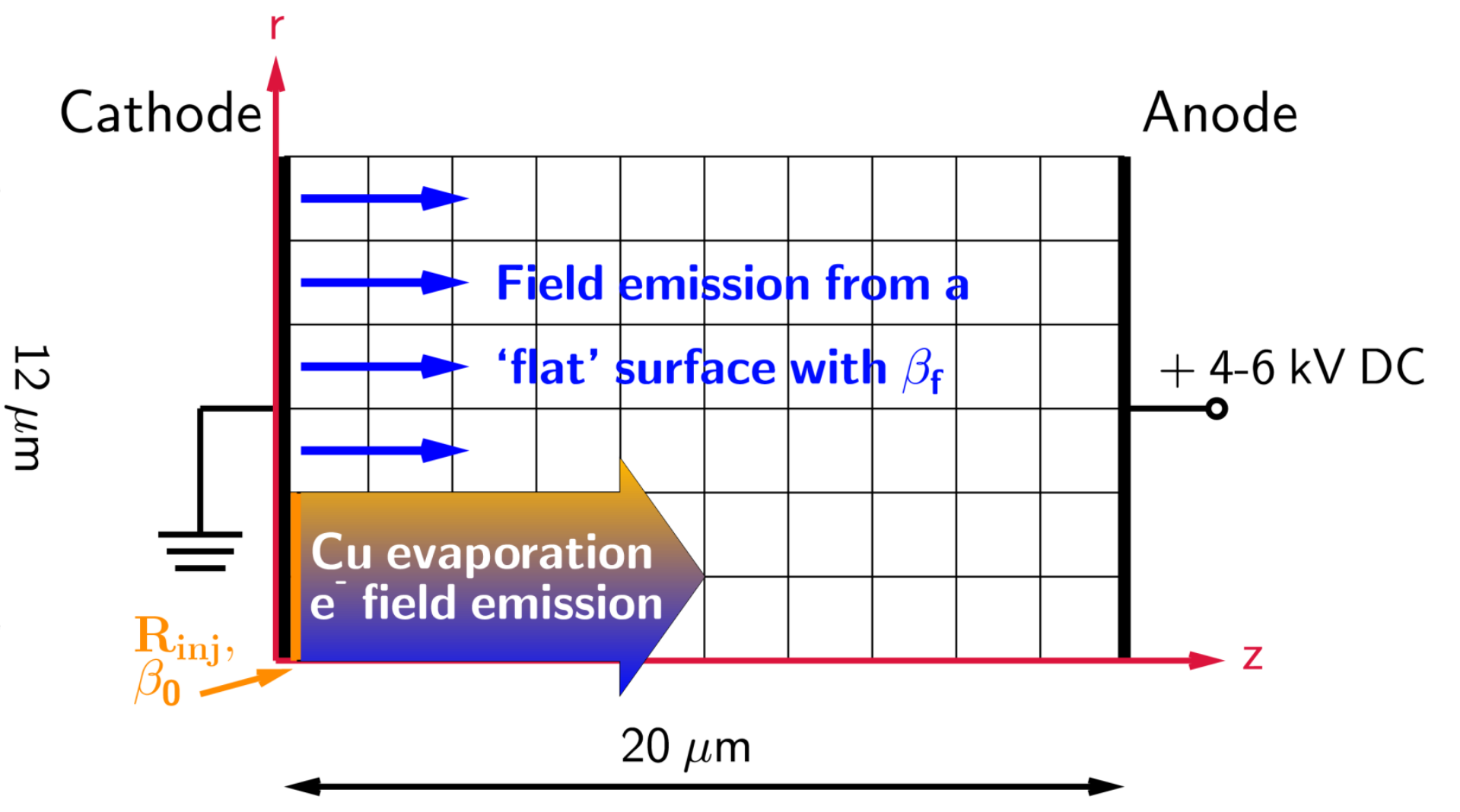
Vacuum arcs limit the operational gradient of CLIC accelerating cavities (left).



Breakdown-caused surface damage on a cavity iris (top right) and a copper sample (bottom right).

THE TOOL

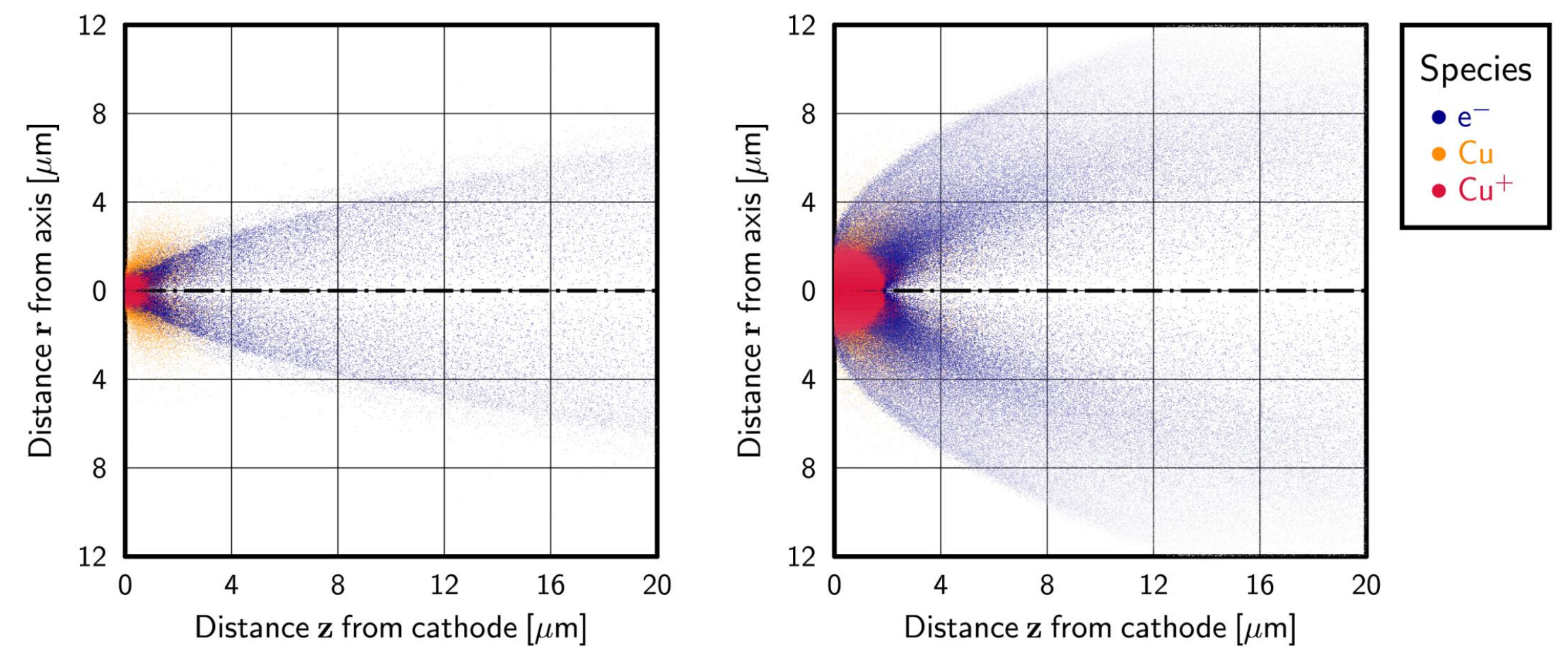
The 2D ARC-PIC code was developed at CERN/HIP to study vacuum arcs. The special feature of the code is the incorporated vacuum arc physics model. The model assumes a field emitter which is source of emission electrons and evaporated neutrals. Plasma-wall interactions are taken into account with a thorough sputtering model.



Schematic of the cylindrical simulation system: the vacuum arc is initiated by a field emitter in the centre of the cathode, when high DC electric fields (200 – 300 MV/m) are present.

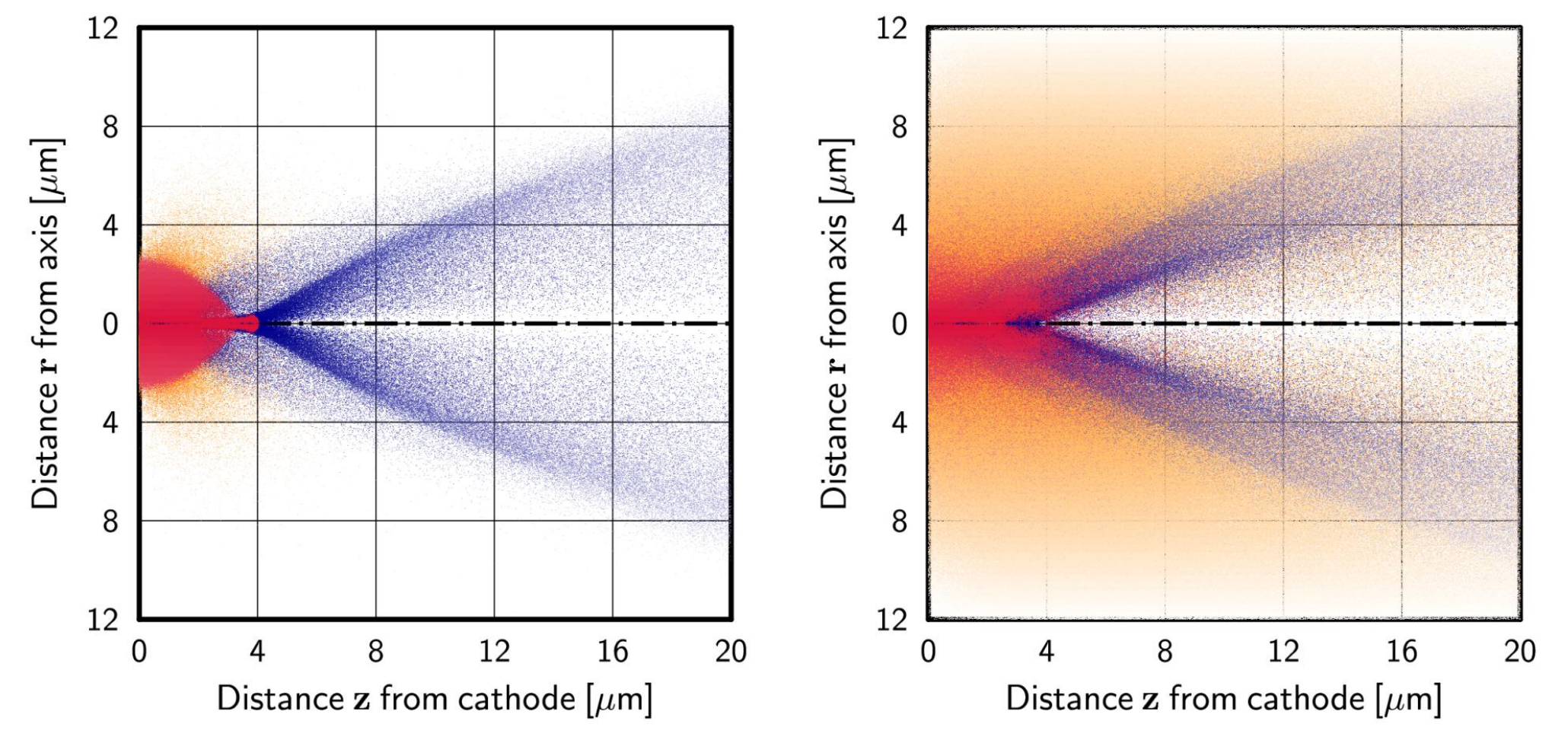
A PLASMA FORMS

From field emission to a developed arc, the discharge goes through two transitions [1,2]. Firstly, a rapid transition from field emission to local arc plasma as a consequence of an ionisation avalanche and plasma sheath formation. Secondly, a gradual transition from a local arc to a volume defined discharge, as neutrals fill the discharge gap.



(a) Time 0.36 ns

(b) Time 0.56 ns



(c) Time 0.60 ns

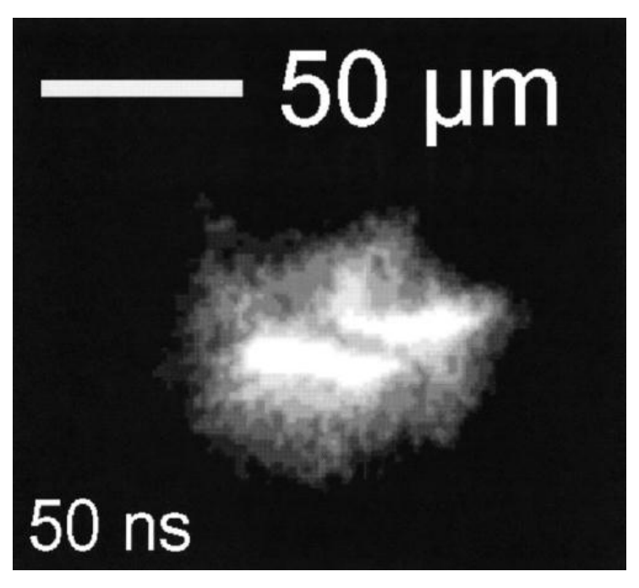
(d) Time 3.23 ns

Stages of the vacuum arc: (a) weak and (b) strong field emission, (c) local arc plasma, (d) volume-defined discharge. From (a) to (c), the arc spot area expands with 20 μm²/ns.

The plasma is now self-maintaining:
(i) Sheath → field enhancement → electrons
(ii) Ion bombardment → sputtering → neutrals

THE ARC SPOT

The cathode spot, which supplies the plasma is known to first expand and then wander during the burning of the arc. The expansion of the spot can be explained with the expansion of the plasma sheath that enhances the external electric field and thus starts to involve a larger and larger area into the field emission process. This could explain how field emission areas of $10^{-20} – 10^{-16}$ m² can turn into a vacuum arc that damages a region of $10^{-12} – 10^{-8}$ m².



With high speed cameras, the expansion and the 'movement' of the cathode spot can be observed.

B. Jüttner (1999)

Hence, in a real 3D system, a spot will also seem to 'wander', since the plasma will always centre itself around the strongest field emitter.

ARC FORMATION

Simulations identified two criteria that have to be fulfilled in order for the plasma to form:

(i) A strong enough initial field emission translating to a local electric field of $E_{loc} \gtrsim 10$ GV/m above the emitter;

(ii) A strong enough source of neutral evaporation that can create a local density of $n_{Cu} \gtrsim 10^{18}$ 1/cm³ above the emitter.

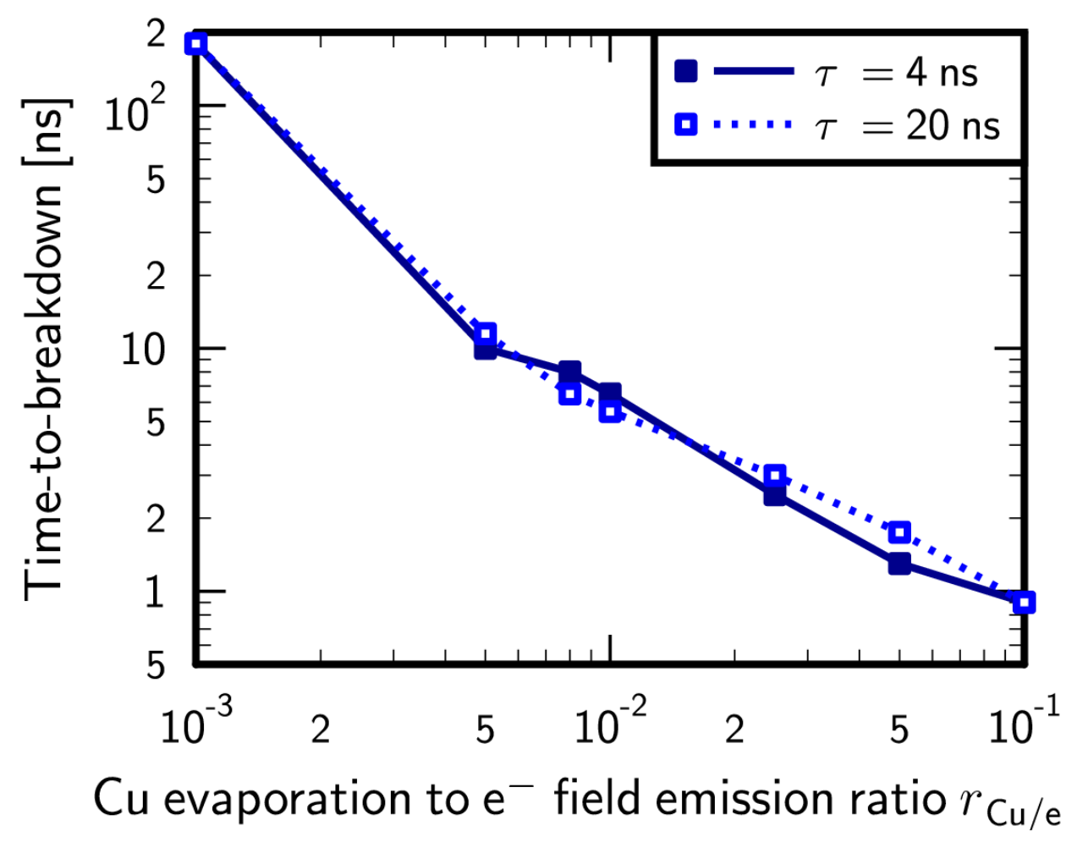
TIME-TO-BREAKDOWN

In our model, several parameters related to the ionisation can influence the time after which a breakdown, i.e. the first transition, occurs:

(i) The strength of the neutral evaporation from the emitter, determined by the *'Cu evaporation to e⁻ field emission ratio'* $r_{Cu/e}$ in our model;

(ii) The numerical implementation of ionisation collisions affecting the cross-section σ;

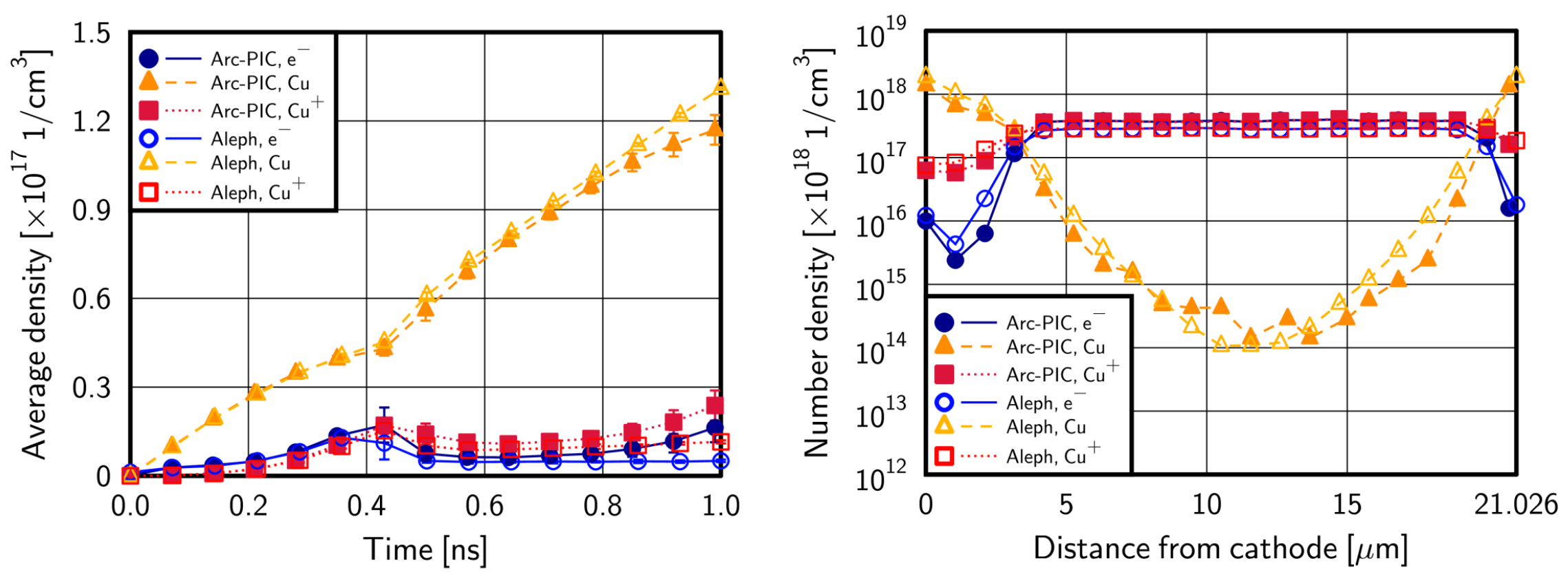
(iii) Grid size and E-field interpolation affecting the relative velocity of colliding particles.



The Cu evaporation to e⁻ field emission ratio chosen in the simulation largely affects the time-to-breakdown.

CONFIDENCE IN THE RESULTS

When experimental data is unavailable, code-to-code comparisons can be performed to increase confidence in our results. Starting from our previous 1D model [3], we engaged in a fruitful comparison [4] with Sandia National Laboratories.



The good agreement between Aleph and 1D ARC-PIC consolidates our results.

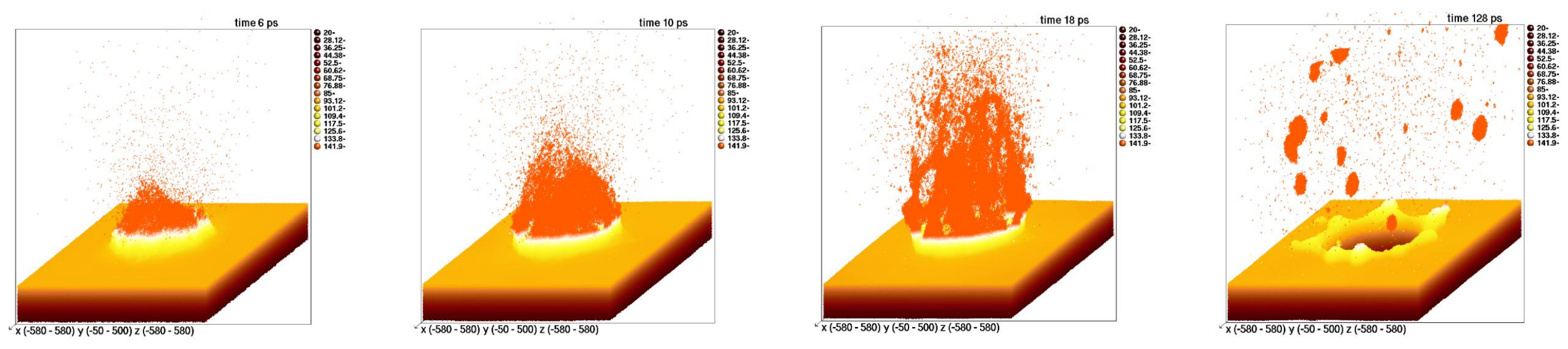
References:

[1] H. Timko et al., *Modelling of cathode plasma initiation in copper vacuum arc discharges via particle-in-cell simulations*, **Contrib. Plasma Phys., submitted for publication (2012)**

[2] H. Timko, *Modelling vacuum arcs: from plasma initiation to surface interactions*, **PhD Thesis**, https://helda.helsinki.fi/handle/10138/28262 **(2011)**

[3] H. Timko et al., *A one-dimensional particle-in-cell model of plasma build-up in vacuum arcs*, **Contrib. Plasma Phys., 51, 5-21 (2011)**

[4] H. Timko et al., *Why perform code-to-code comparisons: a vacuum arc discharge simulation case study*, **Contrib. Plasma Phys., in print (2012)**



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