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PlasMa: teoria e simulação avançada de plasmas relevantes para aplicações energéticas

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Phenomenological Description of Vacuum Breakdown

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Vacuum breakdown: physical picture

- **The central crater(s) represent(s) the epicenter of the breakdown:**
  - Electron emission,
  - Vaporization and ionization of the electrode metal vapor,
  - Formation of the plasma ball.
- **Pressure exerted by the plasma ball:**
  - Formation of the crater,
  - Formation of the crater rim, as molten material in the crater is pushed outwards.

1) **The only possible mechanism of ionization of neutral vapor seems to be ionization by the emitted electrons;**
2) **Formation of crater is a consequence of the interaction of the plasma ball with the metal surface.**

- The physical picture of formation of craters in the course of breakdown is generally similar to what was seen in simulations of **formation of cathode spots in low-voltage vacuum arcs**.

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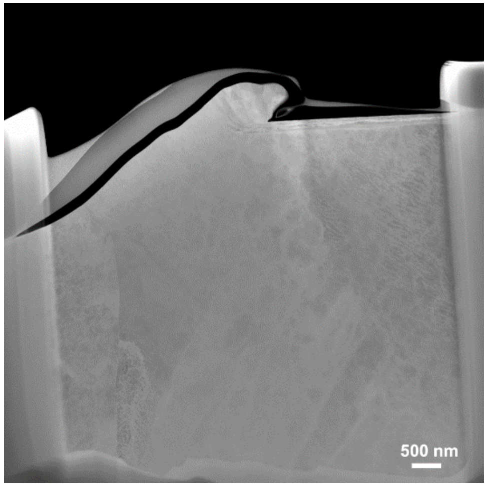
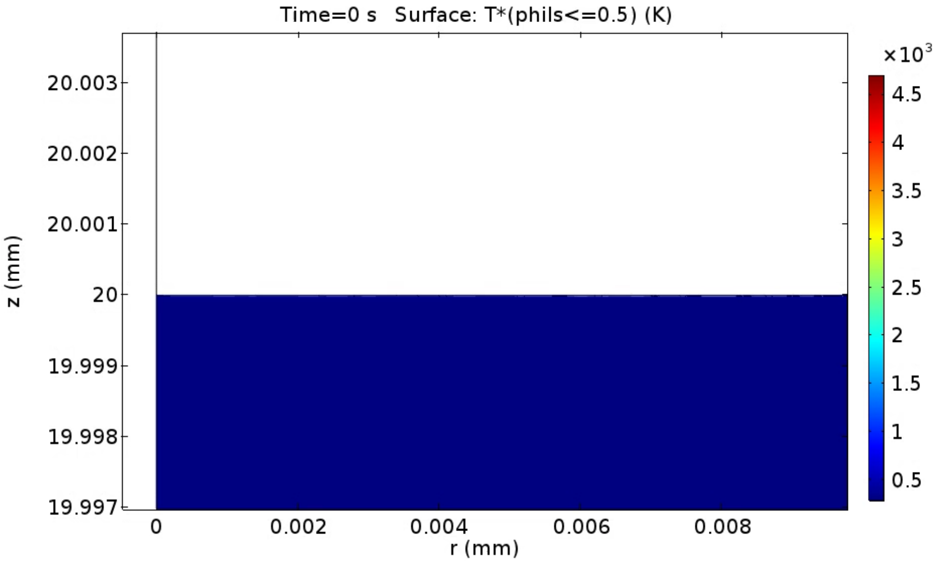
Vacuum breakdown: physical picture

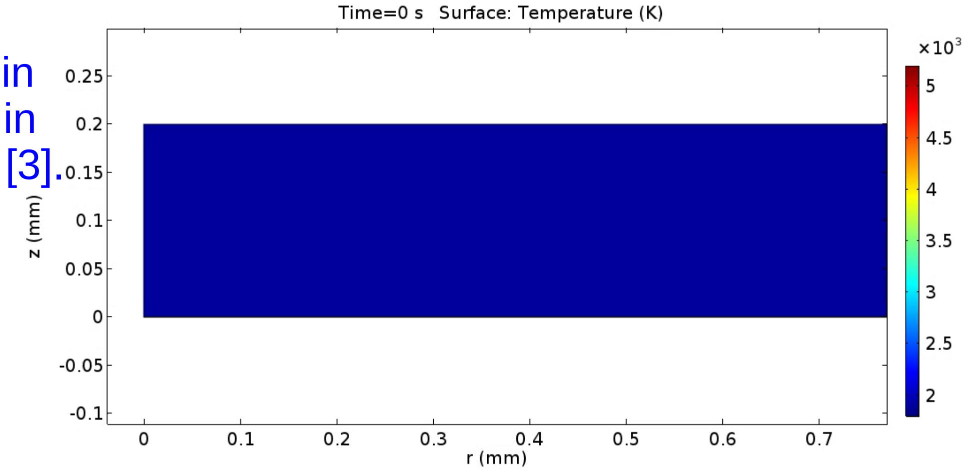


STEM image of FIB cross section of a breakdown crater on a copper cathode tested in the pulsed DC system [1].



Formation of cathode spots under conditions of circuit breakers [2].

Formation of cathode spots in unipolar arc in in fusion devices [3].



[1] Courtesy of Inna Popov, the Hebrew University of Jerusalem. The experiment at CERN.

[2] H. T. C. Kaufmann et al., *J. Appl. Phys*. 2017.

[3] H. T. C. Kaufmann et al., *Plasma Phys. Control. Fusion* 2019.

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Vacuum breakdown: physical picture

However, there is an important difference.

- **External factor provoking the formation of cathode spots in vacuum arcs between separating contacts:** the plasma cloud left over from an (extinct) spot that previously existed in the vicinity of the (new) spot being ignited.
- **External factor provoking the ignition of unipolar arcs:** so-called edge-localized modes, i.e., plasma instabilities which deliver high energy and particle fluxes to the plasma-facing components.

No such external agent which would initiate the breakdown in accelerator conditions.

- The **breakdown voltage is very high** (orders of magnitude higher than in vacuum and unipolar arcs);
- Breakdown in accelerator conditions is initiated by **field electron emission** (irrelevant in vacuum and unipolar arcs);
- The **average gap electric field** in the vacuum breakdown experiments is clearly **insufficient for field emission**;
- <u>The most popular mechanism</u>: **enhancement**, by 10^2 or higher, **of the applied (average) electric field by microprotrusions** present on the cathode surface.

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Vacuum breakdown: previous works

It appears that the **formation of craters has not been simulated in a self-consistent manner up to now**, however the **initial stage of breakdown in high electric field has been simulated in a number of works**.

- **ArcPIC:** PIC simulation of plasma initiation in DC vacuum arc discharges starting from a single field emitter at the cathode [4].
  - Prediction of the current and voltage characteristics, and of properties of the plasma (densities, fluxes and electric potentials).
- **Multi-physics atomistic simulations of the thermal runaway process on emitting nano-tips:** the simulations show that both high current density and sufficiently large tip size are needed to initiate the melting at its apex [5].
  - The field-induced forces gradually deform the tip, elongating and sharpening its apex in a process similar to the Taylor cone formation in liquid metal ion sources.
  - The temperature exceeded 10 000 K and the emission current was about 2 mA, before the tip field induced forces caused detachment of part of the tip.

[4] H. Timko *et al*, Contrib. Plasma Phys. 2015.

[5] A. Kyritsakis *et al*, J. Phys. D: Appl. Phys. 2018.

Vacuum breakdown: previous works

- **Explosion of surface protrusion during breakdown in RF fields:** simulation of the heating and electrical explosion of a microprotrusion under the action of RF electromagnetic fields [6, 7].
  - **Pre-breakdown**: variations in emission characteristics, the role of the main sources of energy release (Nottingham and Joule effects), and the time of heating of the microprotrusion to the critical temperature;
  - **MHD modeling of explosion**: it was assumed that the microprotrusion tip heated by the thermal field emission current had changed to a plasma state before simulation was initiated.
  - The heating times up to the critical temperature (microexplosion) were of the order of a few nanoseconds.
- **Explosion of surface protrusions of various geometries during breakdown in DC field:** very thin protrusions are not critical for the initiation of a microexplosion and subsequent breakdown; rather, the breakdown may be initiated by significantly wider ridge-like structures [8].

[6] S. A. Barengolts, I. V. Uimanov, and D. L. Shmelev, *IEEE Trans. Plasma Sci* 2019.

[7] S. A. Barengolts *et al*., *IEEE Trans. Plasma Sci.* 2019.

[8] H. K. Kaufmann *et al*, *XXIX ISDEIV*, 2020.

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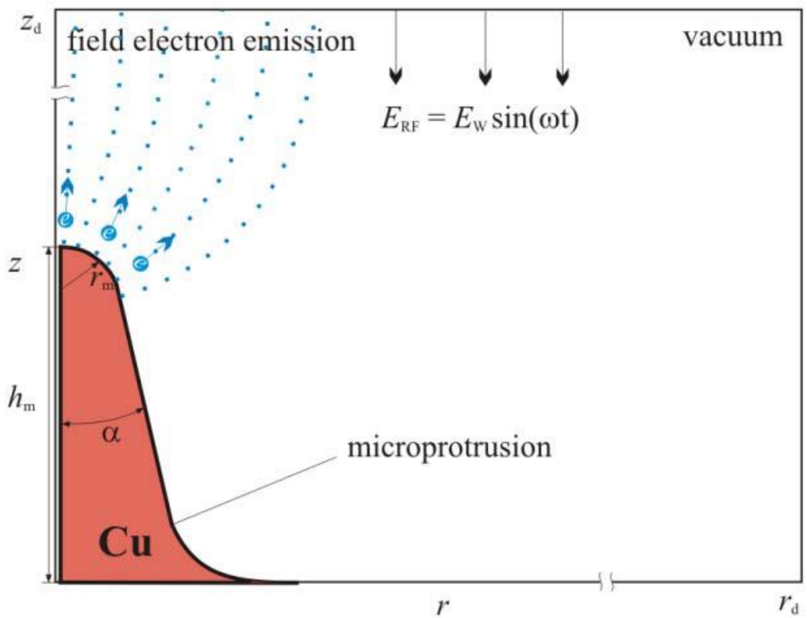
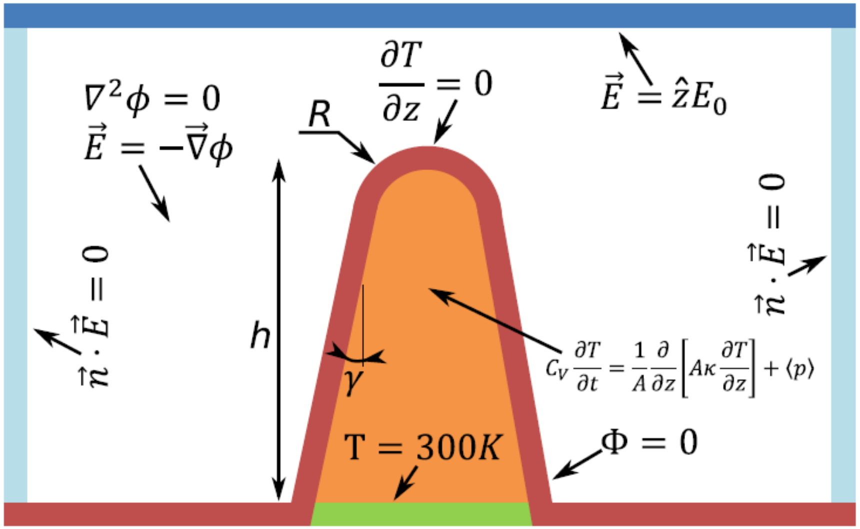
Effect of pre-existing microprotrusions

Example of numerical modeling [6]: conical microprotrusion with a spherical tip, tip radius 10 nm, height 1.3 μm, conical angle 3º.



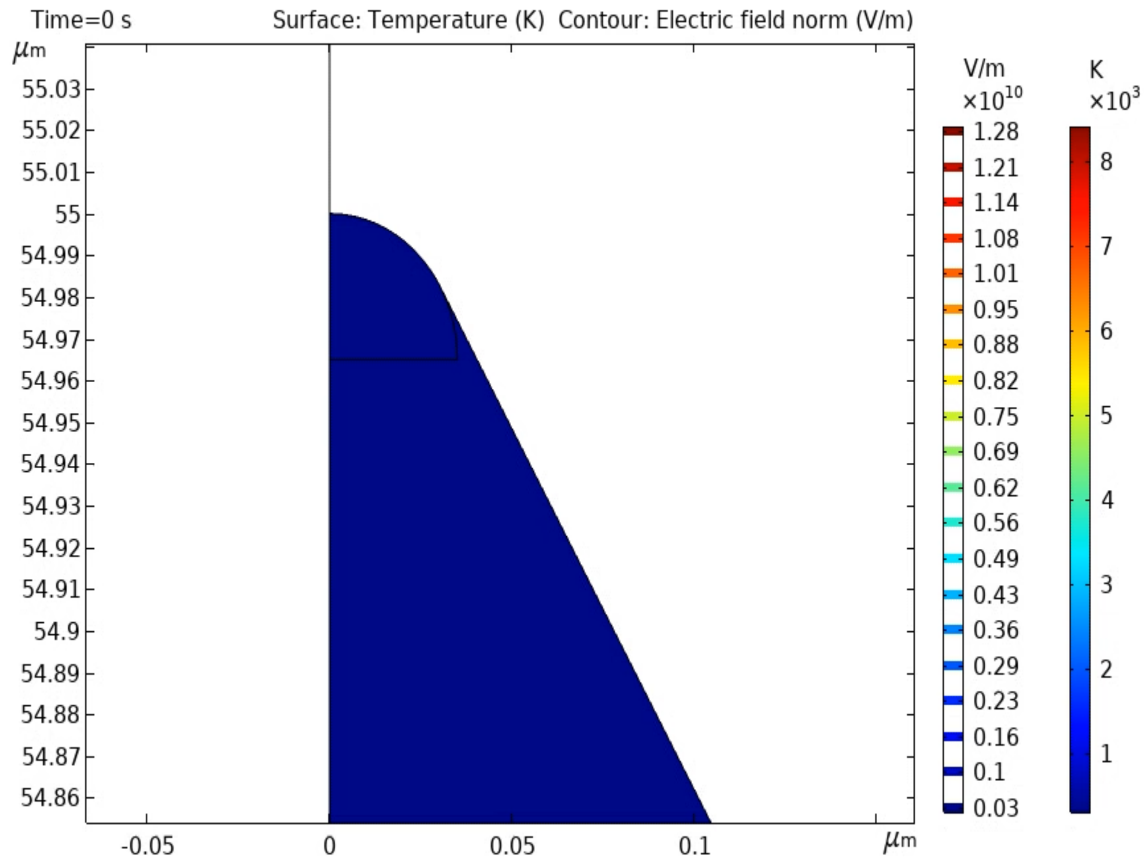


Example of numerical modeling [5]: conical microprotrusion with a spherical tip, tip radius 3 nm, height 93.1 nm, full aperture angle 3º.

Effect of pre-existing microprotrusions

Example of numerical results [8]: conical microprotrusion with a spherical tip, tip radius 35 nm, base radius 2.9 μm, height 5 μm, gap 20 μm.

- T_{max} at t ~ 278 ns is of about 2300 K;
- T_{max} > 8000 K within the next 13 ns and the critical temperature is exceeded => **a microexplosion.**



- This is a **shape-related version of thermal runaway**, an instability that has been extensively studied in the context of low-voltage vacuum arcs e.g., review by Hantzsche [9].

[9] E. Hantzsche., *IEEE Trans. Plasma Sci.* 2003.

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Vacuum breakdown: previous works

- The problem with the hypothesis of pre-existing microprotrusions is that **slender microprotrusions, necessary to explain the field emission current observed in the experiment, are not seen on electrode surfaces.** (Although this point is still not clarified: analysis of deviations from the gas discharge similarity law, observed at high pressures in corona-like configurations, appears to confirm the existence of microprotrusions [10].)
- Other popular mechanisms:
  - Local reduction of the work function, due to lattice defects or adsorbed atoms. (However, this effect seems to be minor; e.g., [11]);
  - `Nonmetallic' electron emission mechanism [12];
  - Enhancement of field emission by waves confined to the metal surface (plasmons) [13];
  - Mobile dislocations near the surface of electrodes [14].

[10] N. Ferreira *et al*., *J. Phys D: Appl. Phys.* 2020.

[11] D. N. Sinelnikov, Ph.D. thesis, National Research Nuclear University "MEPhI", 2014.

[12] R. V. Latham and N. S. Xu, *Vacuum* 1991.

[13] W. Wuensch, in 8th International Workshop on Mechanisms of Vacuum Arcs (Sept.15 - 19, Padova, Italy, 2019).

[14] E. Z. Engelberg *et al*, *Phys. Rev. Accel. Beams* 2020.

Phenomenological approach to description of initial stage of VBD

- Thus, there is still no universally accepted understanding of the mechanism of FE. Modellers must make arbitrary choices => not intellectually gratifying☺
- A **phenomenological description of FE** is used in practice: the Fowler-Nordheim formula is used with the applied electric field E_b being multiplied by the so-called field enhancement factor β, which is of the order of 10^2 or higher.
- There is a **correlation of the applied electric field E_b, measured at vacuum breakdown, with the field enhancement factor β, determined by means of analysis of the measured field emission currents** [15]: βE_b (an "effective" microscopic local breakdown field inside the emission center) is a constant value only dependent on the material and not on β or the gap spacing. $\beta E_b \approx 1.1\times10^{10}$ V/m for copper electrodes.
- It natural to explore the possibility **to describe the initial stage of vacuum breakdown within the framework of the same phenomenological approach,** i.e., in terms of β, **without invoking special mechanisms for the breakdown** apart from the mechanism responsible for the enhancement of FE.

[15] A. Descoeudres *et al*, *Phys. Rev. ST Accel. Beams* 2009.

Phenomenological approach to description of initial stage of VBD

- Such approach is used in ArcPIC (Timko *et al* 2015) for the modelling of development of the plasma in the gap from a single field emitter. **This work: the development of an initial stage of BD inside the cathode**.
- The cathode is planar, the electric field E_b is constant along the surface.
- Axially symmetric: the equations are solved in cylindrical coordinates (r, z).
- $T(r,z,0)$= 300 K at the initial moment.
- The evolution of the temperature distribution is simulated by solving the heat conduction and current continuity differential equations in the half-space:

$$\rho c_p \frac{\partial T}{\partial t} = \nabla \cdot (\kappa \nabla T) + \sigma (\nabla \varphi)^2$$

$$\nabla \cdot \mathbf{j} = 0, \quad \mathbf{j} = -\sigma \nabla \varphi$$

- The thermal and electrical conductivities of the metal are given functions of the local temperature: $\kappa = \kappa(T)$, $\sigma = \sigma(T)$; the dependencies for copper are employed.

Phenomenological approach to description of initial stage of VBD

- **The boundary condition for the current continuity equation**:

$$j(r,t) = j_{em}.$$

j_{em}: the electron emission current density evaluated by means of the Murphy-Good formalism in terms of local values of T and βE_b.

- **The boundary condition for the thermal conduction equation**:

$$-\kappa \frac{\partial T}{\partial z} = \frac{j_{em}}{e}\left(2k_B T + A_{\mathrm{eff}}\right) + q_{\mathrm{rad}}$$

$A_{eff} = A_{eff}\ (\beta E_b, T)$: effective work function.
$A_{eff} > 0$: electron-emission cooling. $A_{eff} < 0$: Nottingham heating.

q_{rad}: radiation cooling of the cathode surface.

- In the framework of this model, **the temperature evolution inside the metal is governed by βE_b, rather than β and/or E_b separately**, in agreement with the experimental findings of Descoeudres *et al* 2009.

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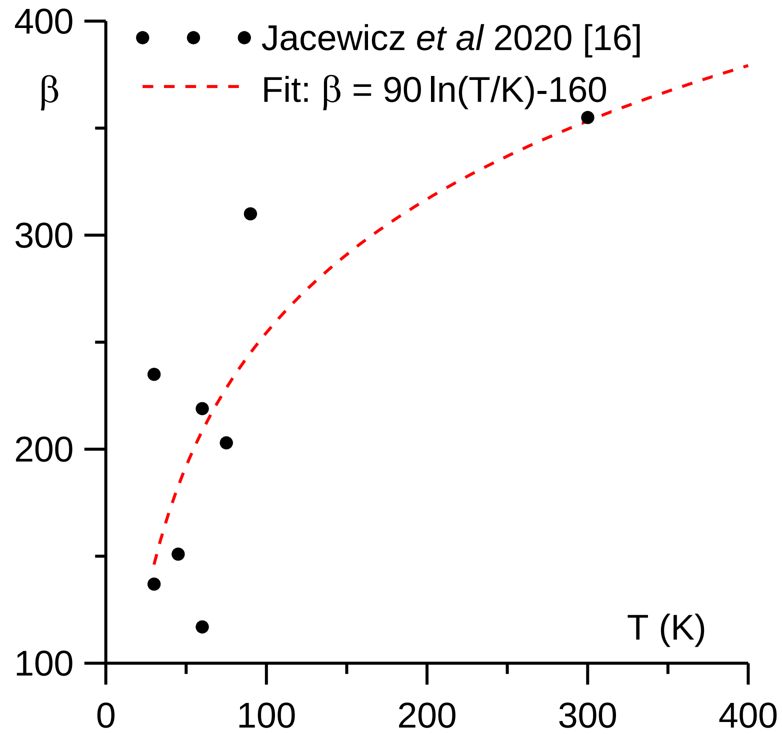
The field enhancement factor

- The field enhancement factor β needs to be specified. The main question: **will the breakdown occur** (thermal runaway instability develop) **for experimental values of E_b and β determined by means of analysis of the measured field emission currents?**

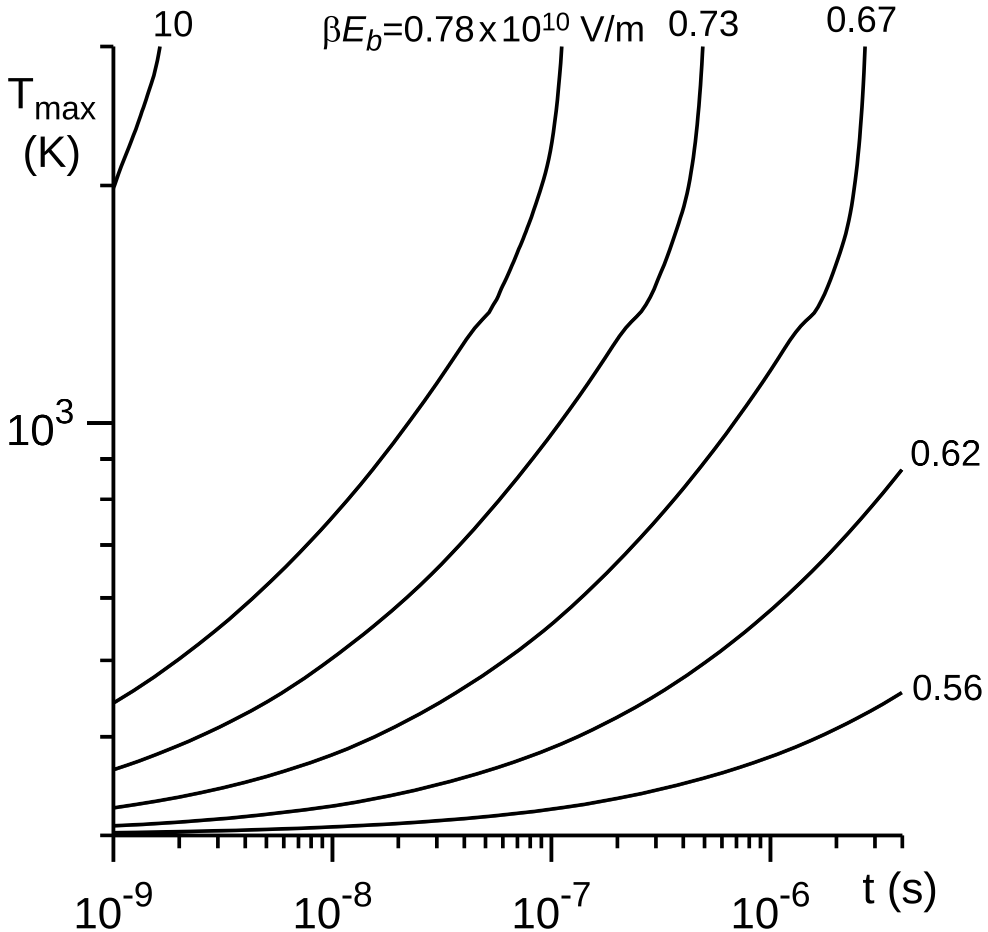
- In this modelling, β was specified in one of three ways:
  - β is a given parameter (the same at each point of the surface and at each instant of time).
  - β is a given function of *r* imitating an emission center.
  - β is a given function of *T*, taken from [16].



[16] M. Jacewicz *et al*., *Phys. Rev. Appl.*, 2020.

β = const

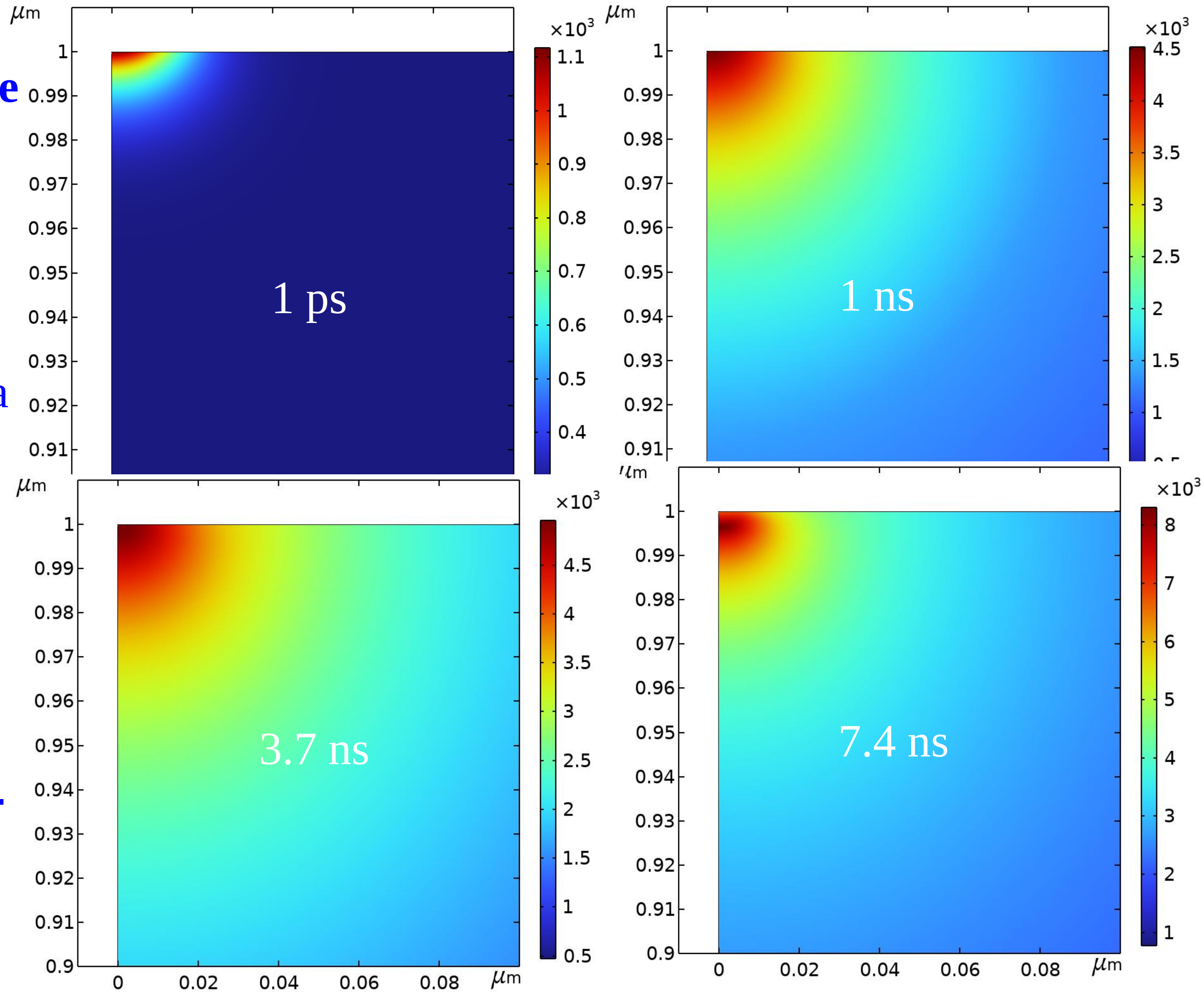
- The heat propagation inside the metal is 1D, $T=T(z,t)$.
- Virtually no heating on the μs time scale for $\beta E_b \leq 0.5\times10^{10}$ V/m.
- T_{max} reaches the critical temperature of Cu (T_{cr}=8390K) within ~1 μs for $\beta E_b = 0.7\times10^{10}$ V/m.
- **T_{max} reaches T_{cr} within 2 ns for $\beta E_b = 10^{10}$ V/m.**
- At high βE_b values, the Joule heating underneath the surface comes into play and overtakes the Nottingham effect => **thermal runaway**.



Phenomenological approach to description of initial stage of VBD

β is variable along the cathode surface and imitates an emission center

- The diameter of the emitting area is typically between 20 to 80nm) (e.g., Descoeudres 2009).
- $\beta = 150 \times \exp[-\frac{(r)^2}{2(40\ \mathrm{nm})2}]$.
- $E_b = 10^8$ V/m.



Conclusions & Outlook

- It appears to be **possible to describe the initial stage of high-voltage vacuum breakdown within the framework of the phenomenological approach to description of FE**, i.e., in terms of field enhancement factor β.
- **No need to invoke any special mechanism for the breakdown** apart from the mechanism responsible for the enhancement of FE.
- Future work: it is of interest to exploit this option in the modelling of advanced stages of vacuum breakdown, on the level comparable to that reached in the modelling of the whole life-cycle of spots in low-voltage vacuum arcs between separating contacts (e.g., in high-power circuit breakers) and unipolar arcs in fusion devices. That would require taking into account
  - transition from the field to thermo-field to thermionic emission,
  - vaporization of the cathode material,
  - production of plasma by ionization of the metal vapor,
  - pressure exerted by the plasma ball over the cathode,
  - melting, motion of the melt, formation of a crater with eventual droplet detachment, …

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