Numerical Simulation of the Initial Phase of Unipolar Arcing in Fusion-Relevant Conditions

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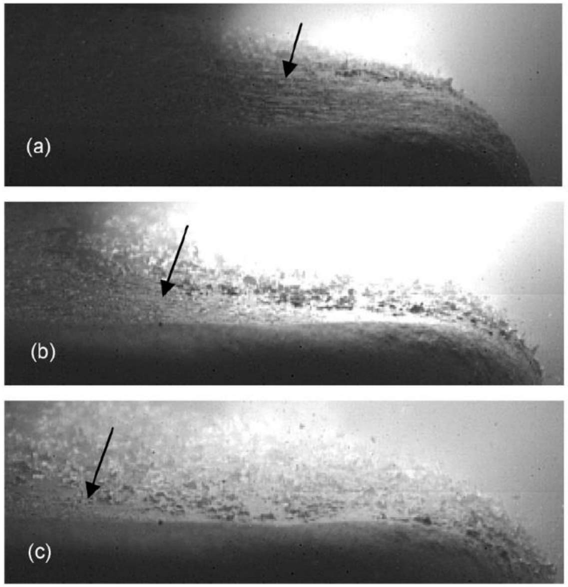
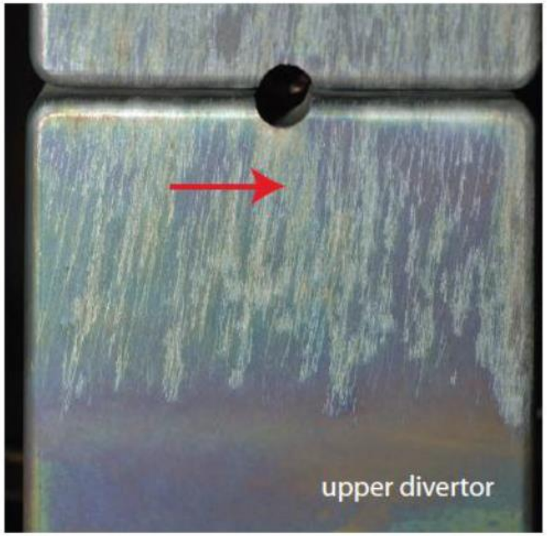
Introduction

The understanding of the plasma-electrode interaction in arc discharges: an important topic concerning arc discharge devices and their application.

- **Erosion of cathode material in vacuum arcs** in high-power circuit breakers: **damage to the contacts reduces their efficiency and lifetime**.



Cathode melting in a vacuum arc.
From Hartmann 2011.



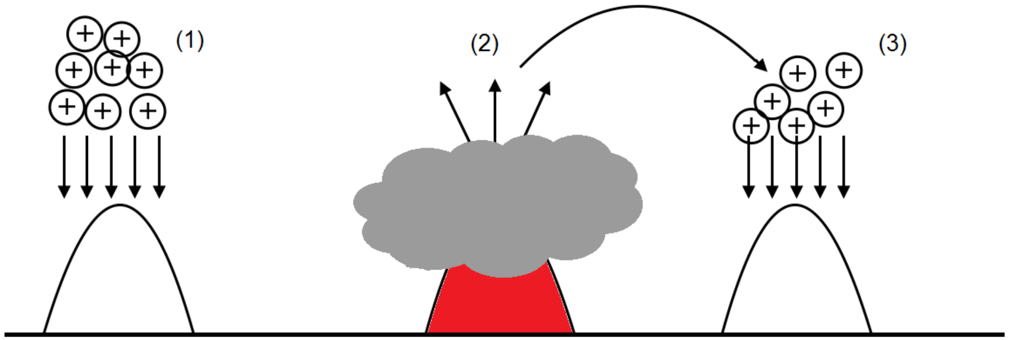
Arc trails on tokamak PFC.
From Rohde 2010.

- **Unipolar arcing on plasma-facing components in fusion devices** is a possible source of impurities in the core plasma.

This work is concerned with the plasma-electrode interaction and erosion in vacuum arcs and unipolar arcs in fusion-relevant conditions.

Vacuum arcs

- **Current transfer** occurs in bright, narrow regions: **cathode spots**.
- Life cycle of individual spot: **ecton mechanism**.

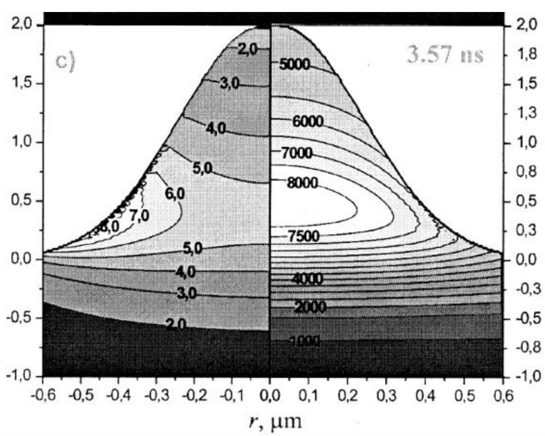


- **Metal vapor left over** from a previous explosion is **ionized and heats an existing microprotrusion** on the cathode surface (1);
- The energy flux density to the cathode surface is sufficient to cause a **rapid overheating of the microprotrusion**, which **explodes**; a dense metal vapor cloud expands in all directions (2);
- This **metal vapor** is, in turn, **ionized** and starts **heating a neighboring microprotrusion** (3);
- The process continues in a similar manner.

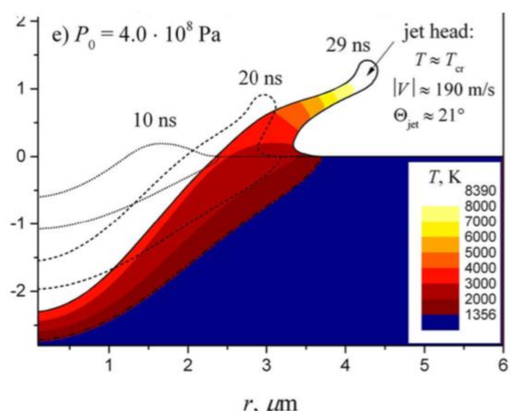
Vacuum arcs

- Modeling approaches available in the literature:
  - **Thermal development of the spot,** neglecting hydrodynamic processes: usually resulting in a microexplosion (**thermal runaway**) within a few nanoseconds;
  - **Hydrodynamic phenomena of the spot development,** neglecting current transfer and plasma production in the spot: **jet formation**, and **detachment of several droplets**.

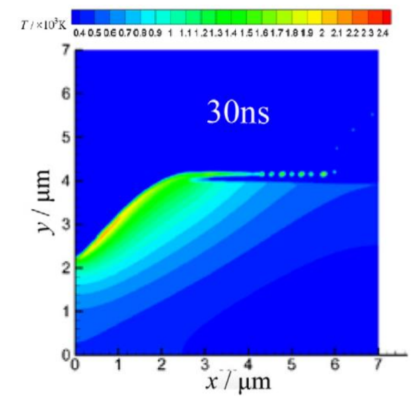
Aim: Develop a model with account of all relevant mechanisms!



Thermal runaway inside protrusion. From Uimanov 2003.



Jet formation. From Mesyats 2015.

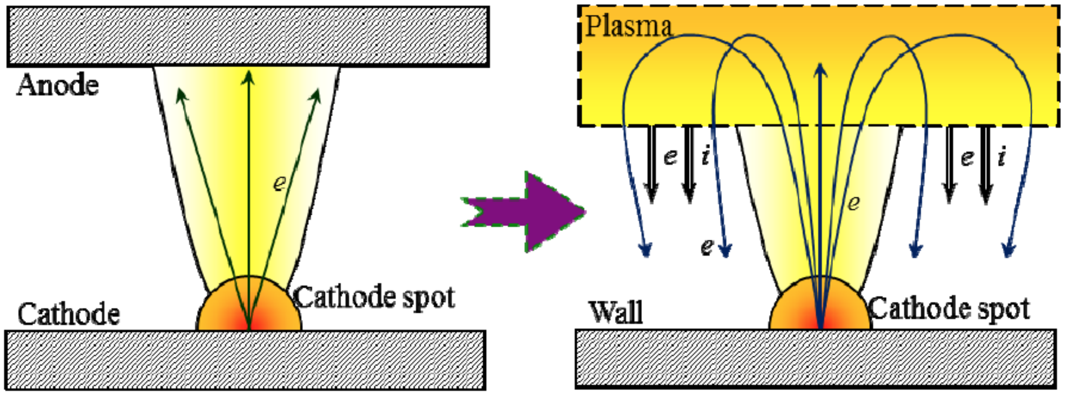


Jet formation and detachment of droplets. From Zhang 2017.

Unipolar arcs

- **Arcing in fusion devices:** issue of minor importance until recently.
- **Triggered by plasma instabilities**: deliver high energy and particle losses to plasma-facing components.
- Plasma-facing components are electrically isolated:
  - Arc triggering: the **current circulates between the plasma and the wall** and the **net current transferred to the wall is zero.**

Unipolar arcing



Schematic of vacuum and unipolar arc. From Barengolts *et al*. 2012.

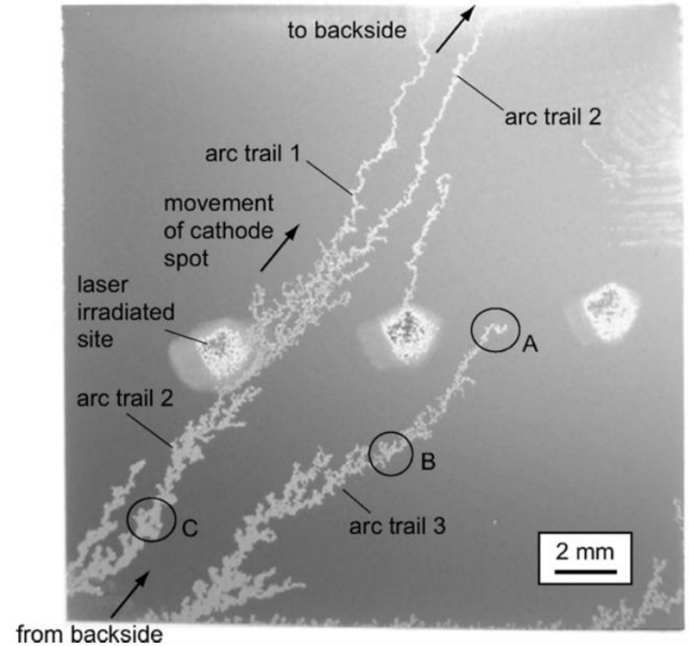
Mechanism of unipolar arc ignition: ecton mechanism (?).

Unipolar arcs

- Experimental observation of unipolar arcing:
  - **Tungsten plate exposed to helium plasma and irradiated by a laser beam**.
  - Arcing seemed to occur in **two phases**.
    1) During laser pulse irradiation (0.6 ms);
    2) After laser pulse is switched off (3 ms).

Initial phase is similar **to formation of cathode spots in vacuum arcs:**

- **Action of intense external energy flux** → significant **vaporization and electron emission** → **ionization** of the emitted vapor.
- **Current transfer initiated** → **ignition of spot** and its subsequent evolution.



Arcing trails on tungsten plate. From Kajita *et al*. 2009.

Laser pulse interaction with the surface = initial phase of unipolar arcing

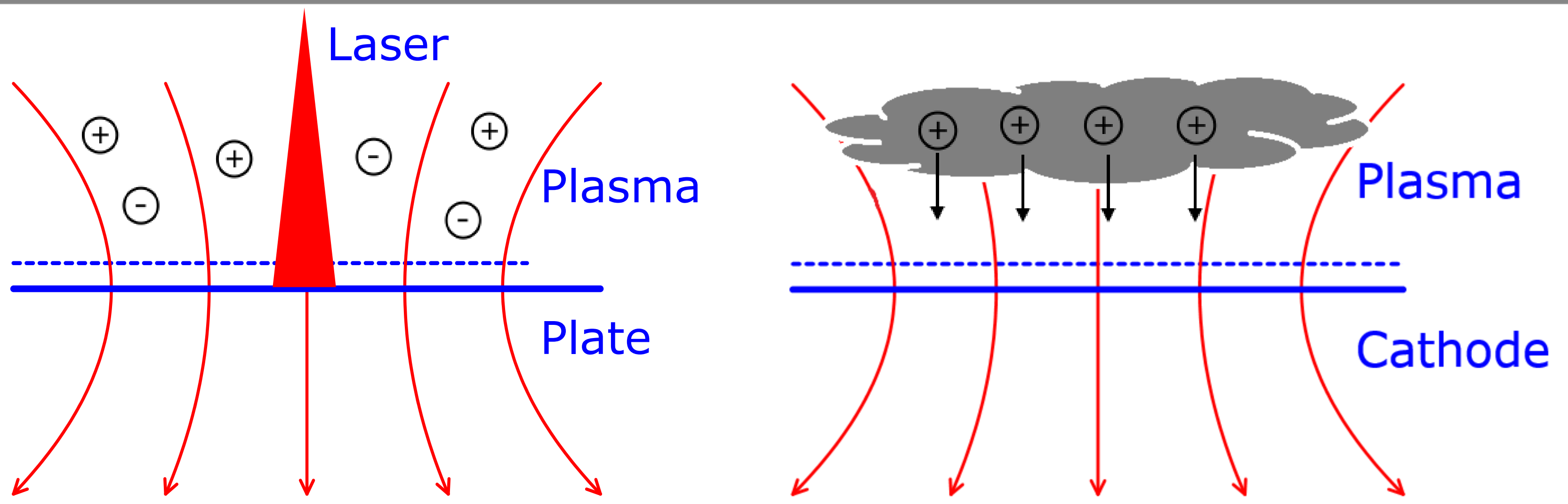
Impact site = arc spot

Cathode spot: physical mechanisms

Mechanisms dominating the physics of cathode spots are complex and diverse:

- An **external plasma left over from a previous spot** or an **external energy source**;
- **Electron emission** and **vaporization of the electrode material in the spot**, its subsequent **ionization**, and **interaction of the produced plasma with the electrode surface**;
- **Joule heat** generation;
- **Melting** of the electrode;
- **Surface tension** effects;
- **Motion of molten metal** due to **Lorentz force** and under the **action of the pressure exerted by the plasma** over the electrode surface;
- **Deformation of the molten surface**;
- Possible molten metal **jet formation** and **droplet ejection**;
- …

Model of plasma-electrode interaction



The electrode body:

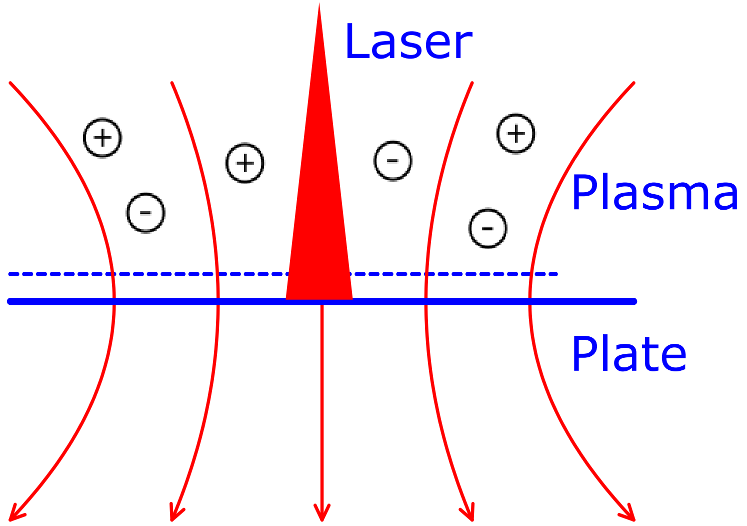
$$\rho c_p \frac{\partial T}{\partial t} + \rho c_p \mathbf{u} \cdot \nabla T = \nabla \cdot (\kappa \nabla T) + \sigma (\nabla \varphi)^2$$

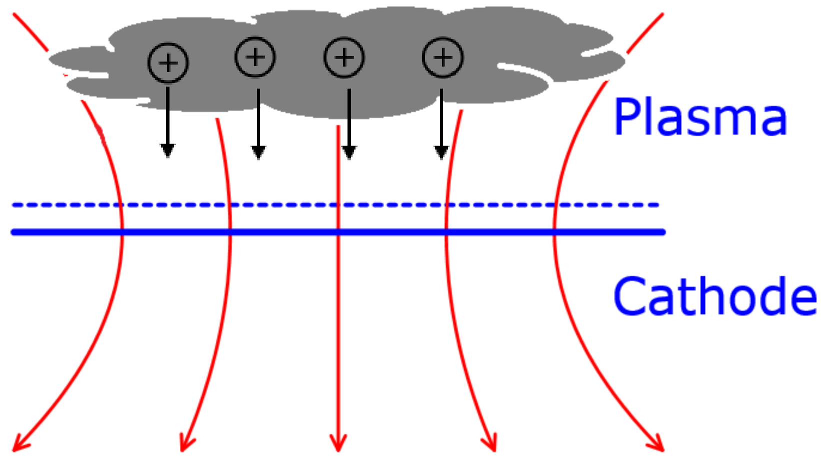
$$\nabla \cdot \mathbf{j} = 0$$

$$\nabla \cdot \mathbf{u} = 0$$

$$\rho \frac{\partial \mathbf{u}}{\partial t} + \rho (\mathbf{u} \cdot \nabla) \mathbf{u} = \nabla \cdot [-p\mathbf{I} + \mu (\nabla \mathbf{u} + (\nabla \mathbf{u})^T)] + \mathbf{j} \times \mathbf{B}$$

Model of plasma-electrode interaction





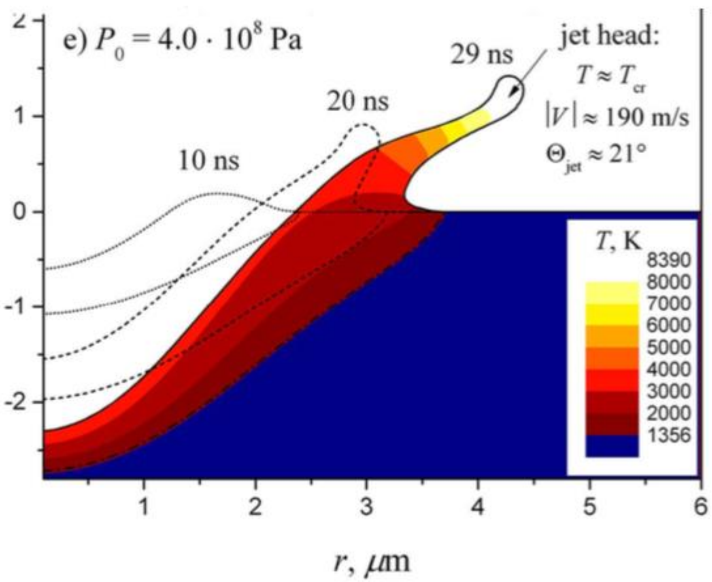
The electrode surface:

Plasma is taken into account through **boundary conditions** on the surface of the electrode (**energy flux density** q, **electric current density** j, **pressure** p_{pl}).

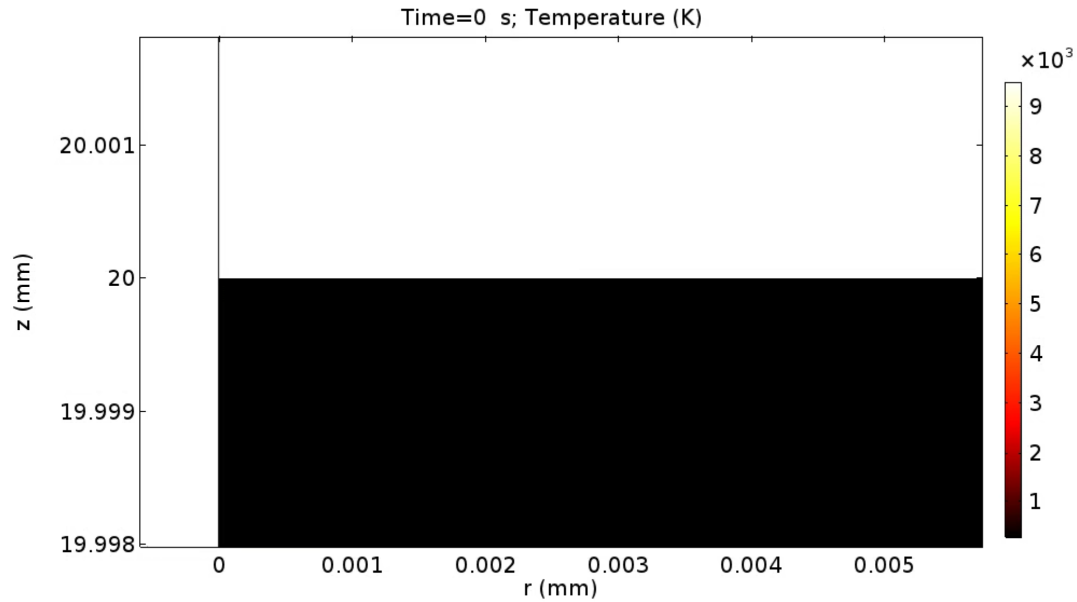
1) **Plasma produced by ionization of metal vapor emitted in the spot** (vaporized atoms, ions, emitted electrons, plasma electrons);
2) **Background plasma;**
3) **External energy flux** or **leftover plasma cloud;**
4) **Radiation;**
5) **Surface tension effects.**

Validation of the model

- A simplified hydrodynamic model: **account of current transfer was discarded**, and **contributions of the plasma produced by ionization of metal vapor in the spot were neglected**.



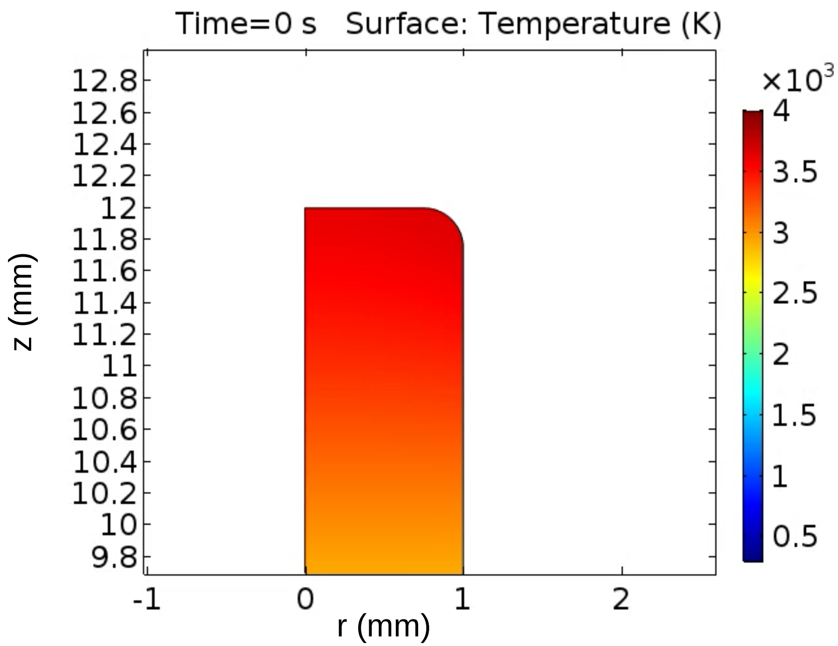
Crater and jet formation. From Mesyats 2015.



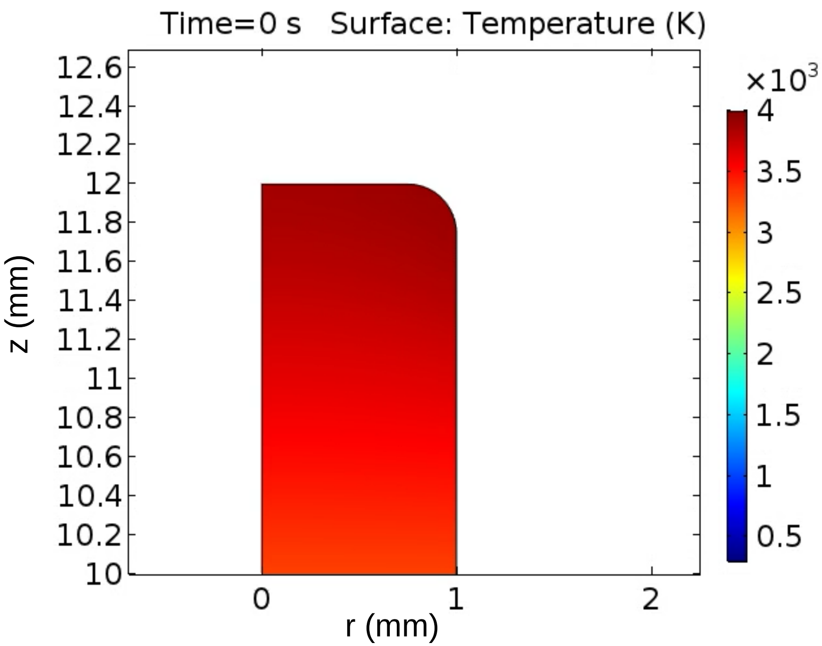
Result of simulation with the simplified test model. The bar in kelvin.

Thermionic cathodes of high-pressure arcs

- Simulations performed in conditions of experiment: **tungsten cathode in atmospheric pressure argon**.
- **Diffuse mode** was simulated; ***I* = 60 A** and ***I* = 140 A**.
- **Good agreement with experimental results**.



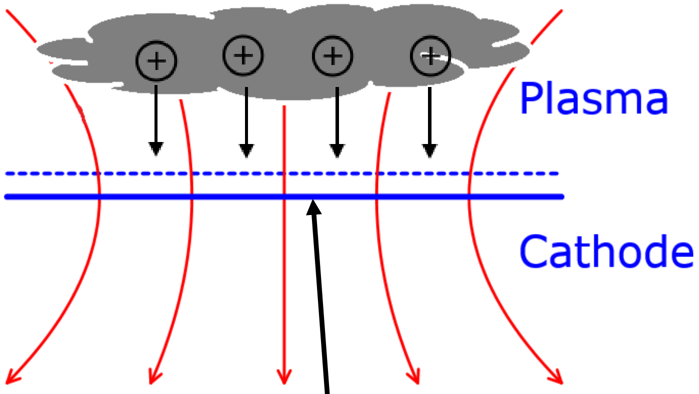
Tungsten cathode, **60 A**.



Tungsten cathode, **140 A**.

From Cunha *et al*. 2019.

Spots on Cu cathodes in vacuum arcs: the model



The cathode body:

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

$$\nabla \cdot \mathbf{j} = 0$$

$$\nabla \cdot \mathbf{u} = 0$$

$$\rho \frac{\partial \mathbf{u}}{\partial t} + \rho (\mathbf{u} \cdot \nabla) \mathbf{u} = \nabla \cdot [-p\mathbf{I} + \mu (\nabla \mathbf{u} + (\nabla \mathbf{u})^T)] + \mathbf{j} \times \mathbf{B}$$

The cathode surface:

1) **Plasma produced by ionization of metal vapor emitted in the spot** (vaporized atoms, ions, emitted electrons, plasma electrons),
   - evaluated using the model of near-cathode plasma layers in vacuum arcs (Almeida *et al*. 2013).

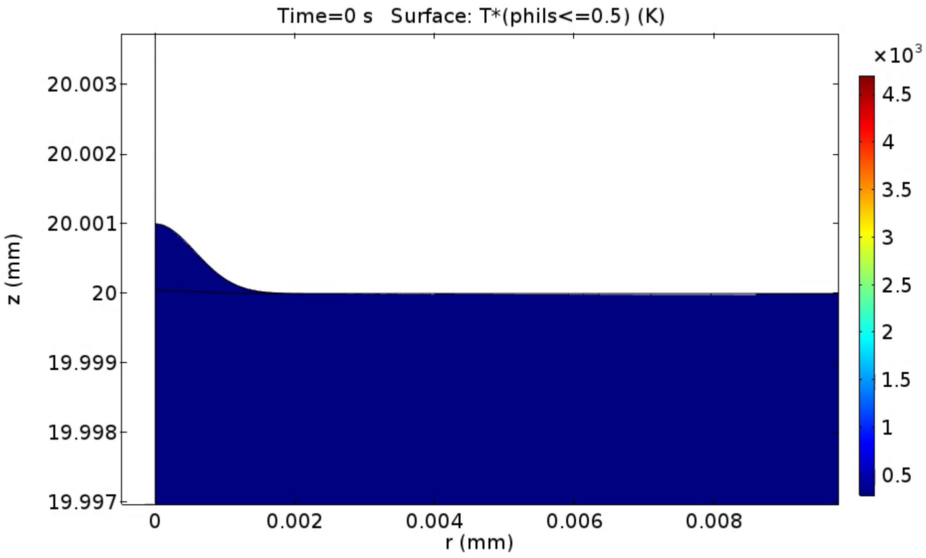
2) **Leftover plasma cloud** (ions),
   - specify the lifetime (25 ns) and spatial distribution (5 µm) of the plasma cloud.

$$q = q_1 + q_2$$

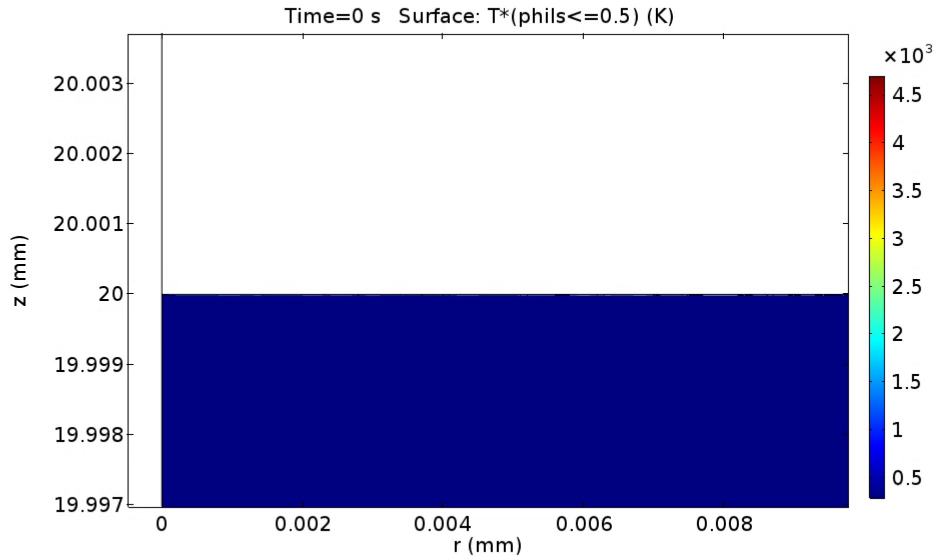
$$j = j_1 + j_2$$

$$\mathbf{F} = -(p_1 + p_2)\mathbf{n} + \mathbf{F}_{st}$$

Spots on Cu cathodes in vacuum arcs: results



Cathode with the microprotrusion.

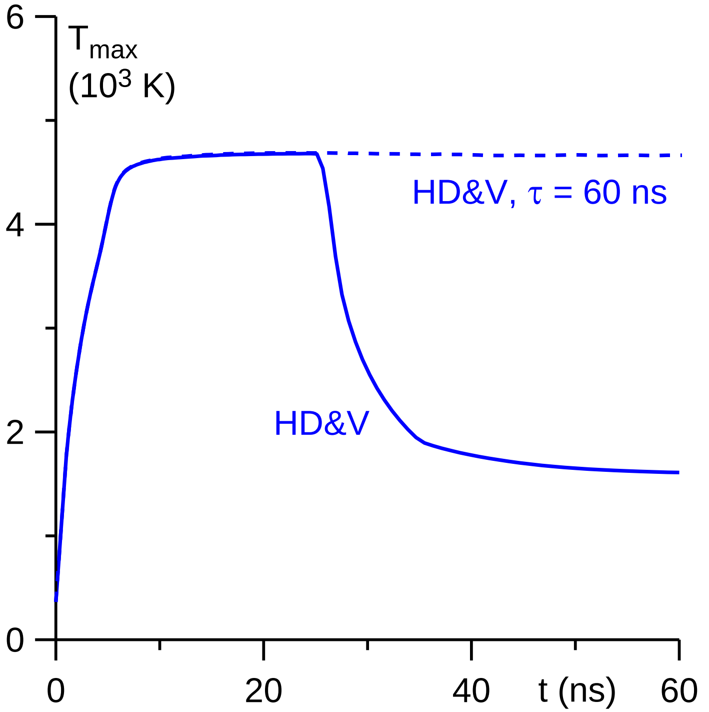


Planar cathode.

- Melting of the protrusion/surface, crater formation and detachment of a droplet. **No explosion (thermal runaway)!**
- After the extinction of the left over plasma, the **spot is quenched by heat removal into the cathode bulk due to thermal conduction**, and the **high melt velocity leads to the formation of a liquid-metal jet under the effect of fluid inertia**.

From Kaufmann *et al*. 2017.

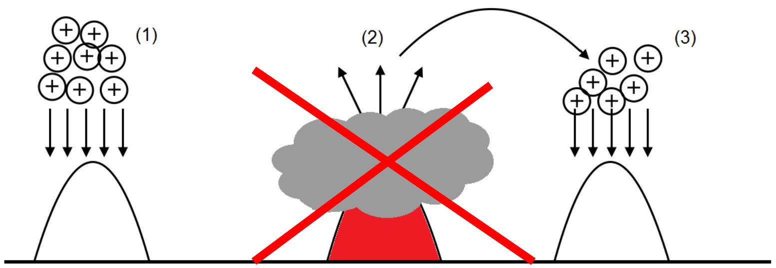
Spots on Cu cathodes in vacuum arcs: results

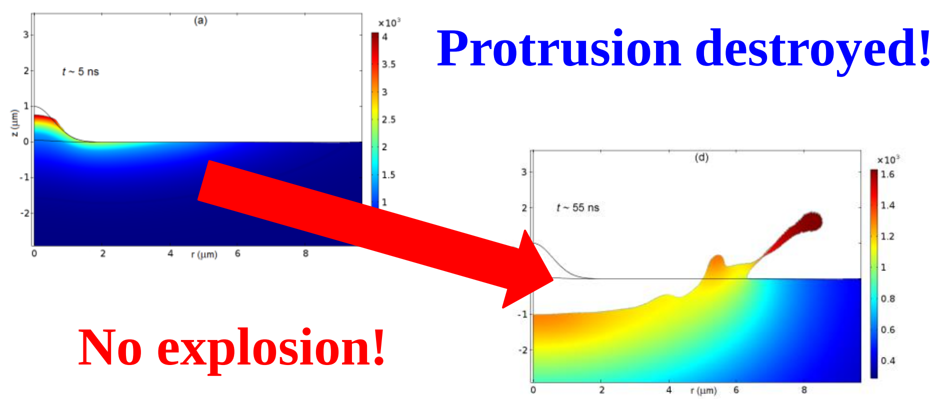


Temporal evolution of the maximum cathode temperature. Cathode with the microprotrusion. HD&V: full model.

- **There is a plateau in the temporal evolution of the spot temperature!**

- **The mechanism of explosive electron emission (ectons):**
  - Electron field emission from surface non-uniformities,
  - Critical temperature => explosion of the non-uniformity.

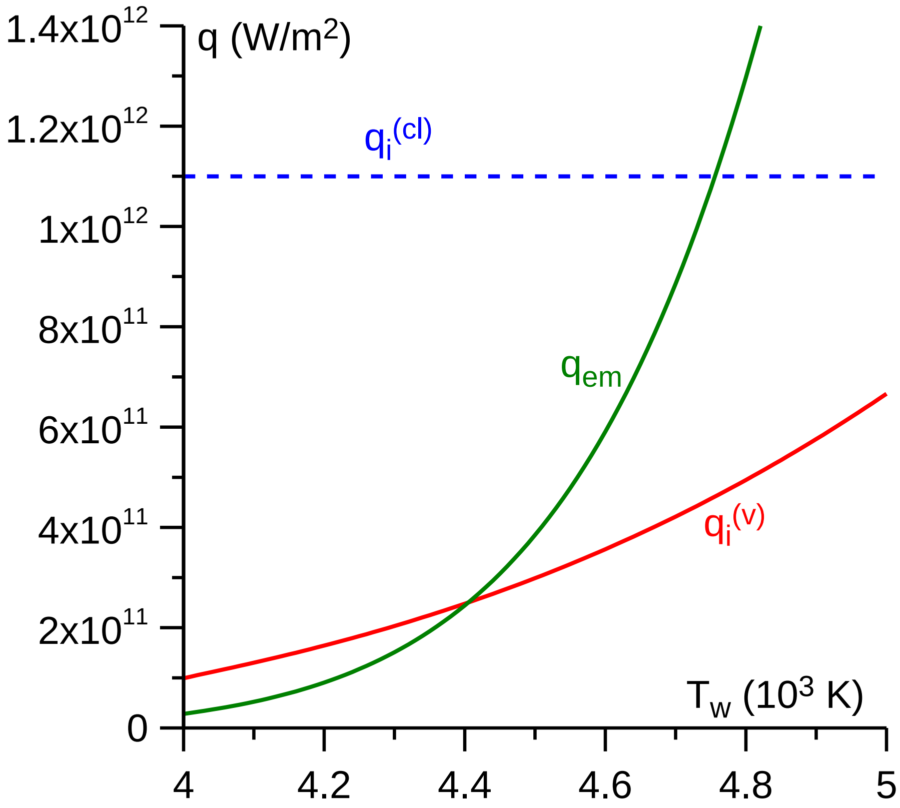




Protrusion destroyed!

No explosion!

Spots on Cu cathodes in vacuum arcs: results



Dependence on temperature of the electron emission energy density (q_{em}) and ion energy density ($q_i^{(v)}$) from the plasma produced by the spot. $q_i^{(cl)}$: ion energy density from the leftover plasma.

- **The spot temperature is limited!**

- Contributions to q_1 increase with increasing temperature.
- Electron emission cooling q_{em} grows faster than ion heating $q_i^{(v)}$.

$$q_{em} >> q_i^{(v)} + q_i^{(cl)}$$

for $T_w > 4700–4800\text{K}$

=> **upper limit of the cathode temperature**!

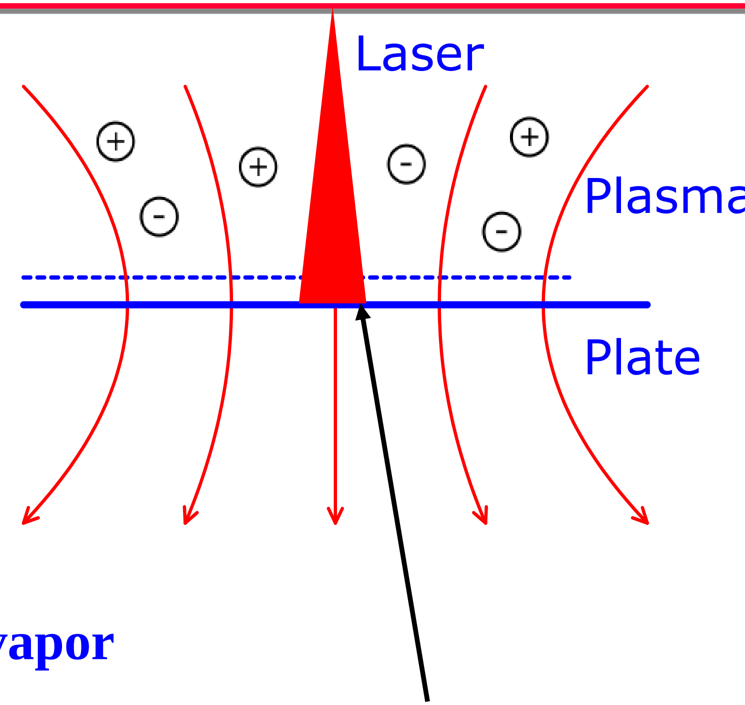
Unipolar arcs: the model

The electrode body:

$$\rho c_p \frac{\partial T}{\partial t} + \rho c_p \mathbf{u} \cdot \nabla T = \nabla \cdot (\kappa \nabla T)$$

$$\nabla \cdot \mathbf{u} = 0$$

$$\rho \frac{\partial \mathbf{u}}{\partial t} + \rho(\mathbf{u} \cdot \nabla)\mathbf{u} = \nabla \cdot [-p\mathbf{I} + \mu(\nabla \mathbf{u} + (\nabla \mathbf{u})^T)]$$



$$q = q_1 + q_2 + q_3 - q_4$$

$$j = j_1 + j_2$$

$$\mathbf{F} = -p_1 \mathbf{n} + \mathbf{F}_{st}$$

The electrode surface:

1) **Plasma produced by ionization of metal vapor emitted in the spot,**
   - Vaporized atoms, ions, emitted electrons, plasma electrons.
2) **Background plasma**,
   - ions and fast electrons of the background plasma.
3) **External energy flux** (laser beam),
4) **Radiation** into the plasma.

Unipolar arcs: the model

Net current transferred to the plate is zero:

$$I_1 = \int j_1\, dA = j_2 A_{plate} \quad \rightarrow \quad \mathrm{U} = \mathrm{U}(t)$$

	Potential of plate **below** plasma potential (U > 0)	Potential of plate **above** plasma potential (U < 0)
Plasma produced in the spot	**vaporized atoms**	**vaporized atoms**
	ions (ionization of all emitted atoms)	------------
	emitted electrons (Richardson-Schottky)	**emitted electrons** (Richardson, reflection by potential barrier)
	plasma electrons (repelled by potential barrier)	------------
Background plasma	**plasma ions**	**plasma ions** (repelled by potential barrier)
	plasma electrons (repelled by potential barrier)	**plasma** electrons

Unipolar arcs: simulation conditions

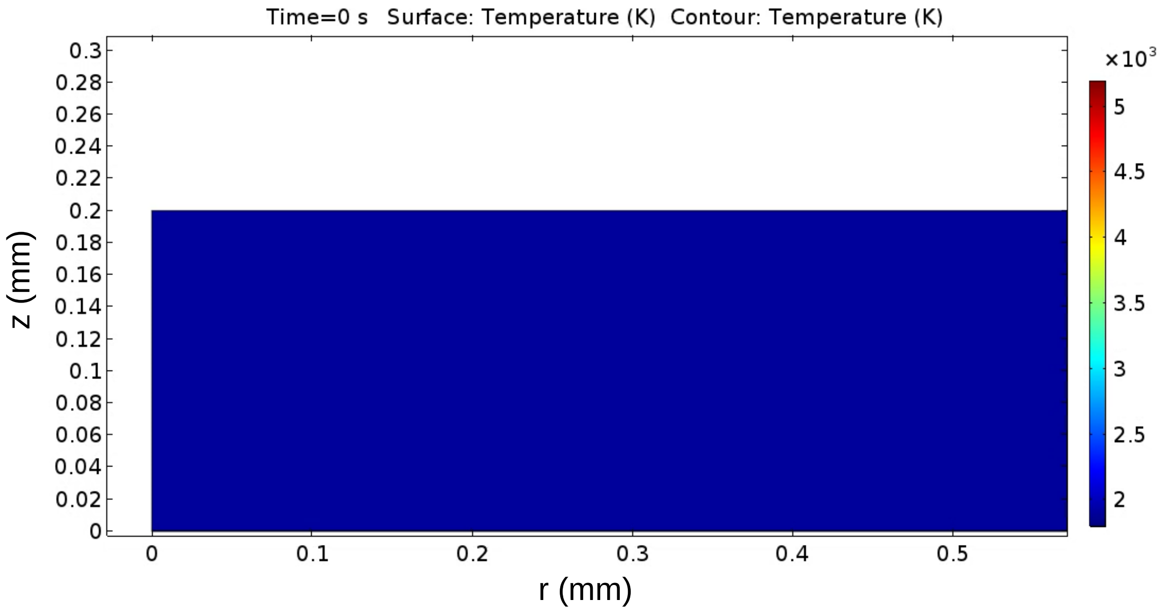
- Circular **tungsten metal plate** immersed in a **helium background plasma**, subjected on one side to a **laser beam** (experiment Kajita *et al*. 2009).
- Laser beam: $\Delta t = 0.6$ ms, **peak power 10^{10} W/m^2** at 5 ms.
- **Initial potential difference U between the plasma and the plate is 40 V** (floating potential).
- Initial plate temperature: 1900 K.

Table 1. Sets of simulation conditions considered for the modeling of this work.

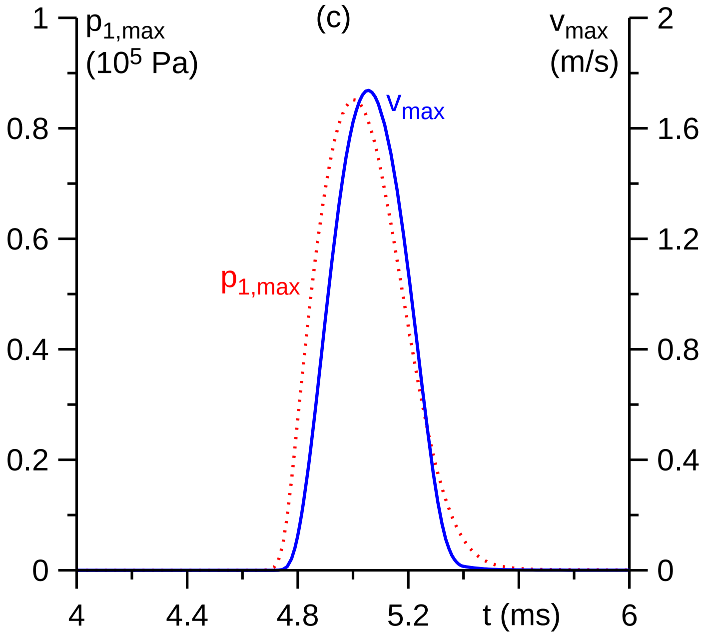
Simulation case	Plate radius R (mm)	Parameter a (mm)
1	100	0.4
2	10	0.1
3	10	0.4

Unipolar arcs: results

Simulation case 1: R = 100 mm; a = 0.4 mm



Evolution of plate temperature and surface deformation. R = 100 mm; a = 0.4 mm.

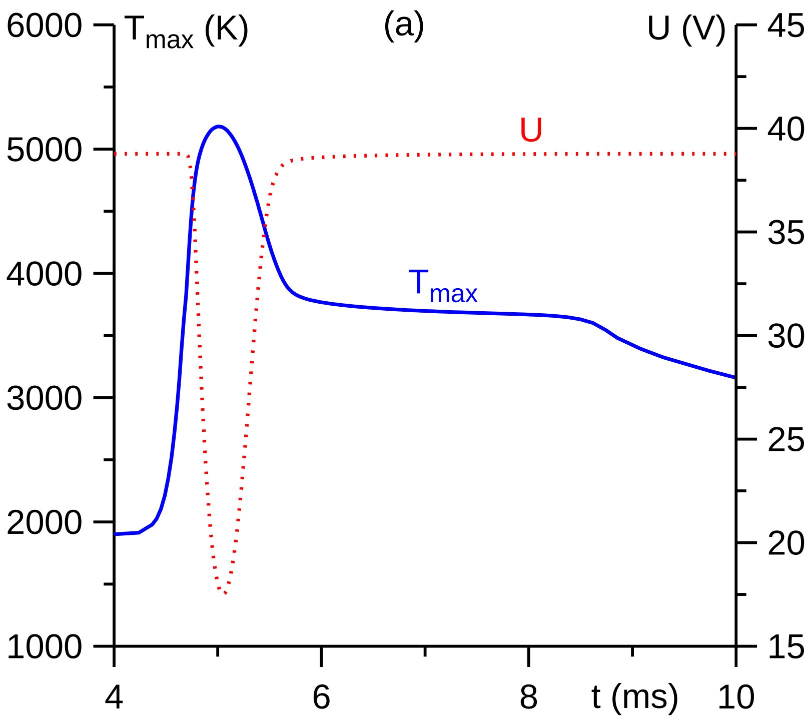


Evolution of maximum melt velocity and plasma pressure. R = 100 mm; a = 0.4 mm.

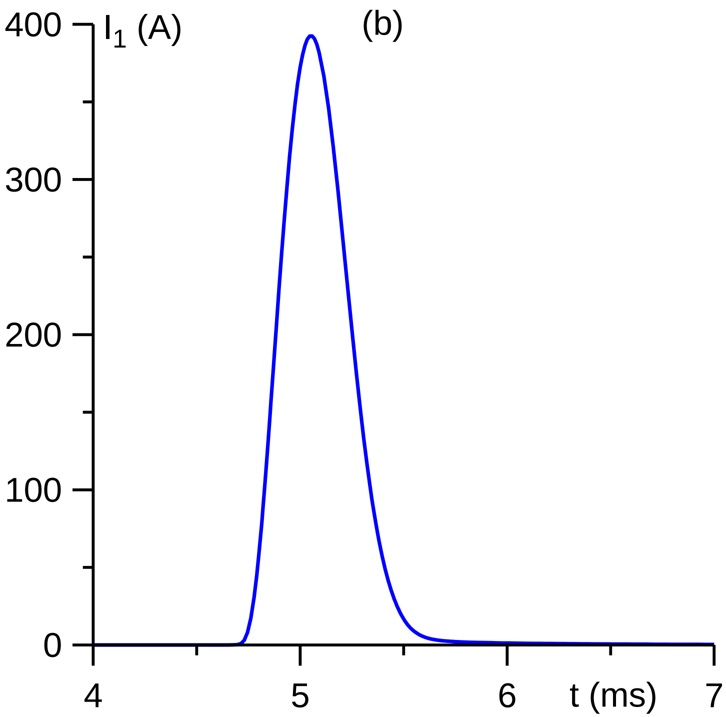
- **Formation of a crater**, but no jet formation or droplet detachment:
  - **Maximum melt velocity ~ 1.8 m/s** (insufficient to drive formation of jets);
  - **Crater:** 50 μm depth, 300 μm radius.

Unipolar arcs: results

Simulation case 1: R = 100 mm; a = 0.4 mm



Temporal evolution of maximum plate temperature and of potential difference between plasma and plate. R = 100 mm; a = 0.4 mm.



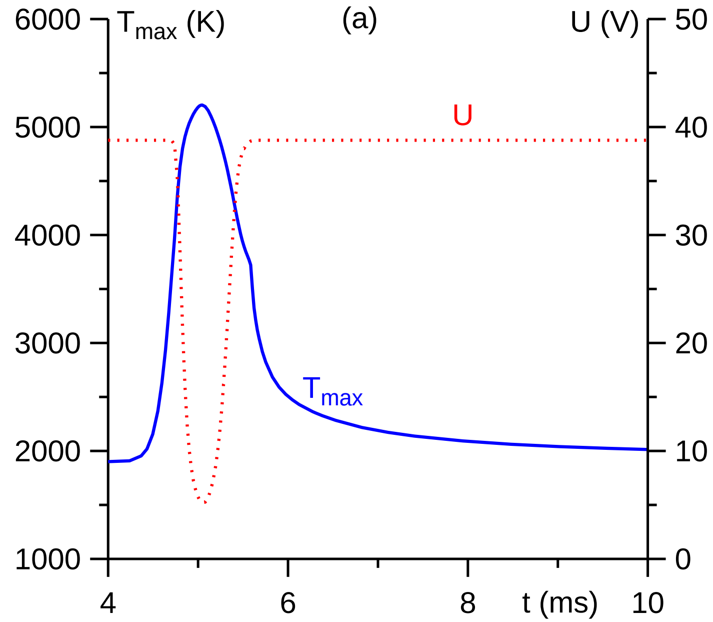
Temporal evolution of the current transferred in the spot. R = 100 mm; a = 0.4 mm.

- Rapid increase of temperature (**5200 K**) => spot ignition => current transfer in the spot (**400 A**).
- **Reduction of the potential difference U:** 40 V → 18 V.

Unipolar arcs: results

Simulation case 2: R = 10 mm; a = 0.1 mm

- **Qualitatively similar to case 1**.
- **Spot and crater are smaller.**
- Variation of *U* more pronounced, but evolution of *T* virtually the same up to 5 ms:
  - **Variation of *U* plays only small role in energy balance in the spot.**
- No inversion of potential difference U: the **potential of the plate is below the plasma potential at every moment.**



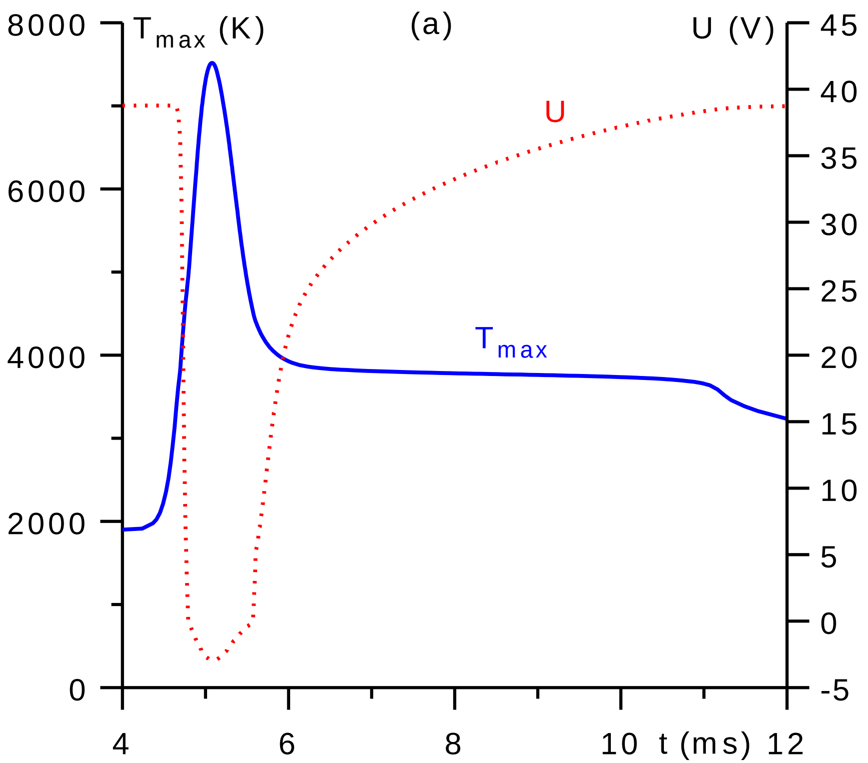
Temporal evolution of T_{max} and *U*.
R = 10 mm; a = 0.1 mm.

Simulation case	R (mm)	a (mm)	T_{max} (K)	U (V)	I (A)	Γ_v (μg)	Crater (μm)
1	100	0.4	5200	18	400	1.4	50 $\times$300
2	10	0.1	5200	5	17	0.066	10 $\times$70

Summary of relevant results; potential of the plate remains below the plasma potential.

Unipolar arcs: inversion of potential

Simulation case 3: R = 10 mm; a = 0.4 mm



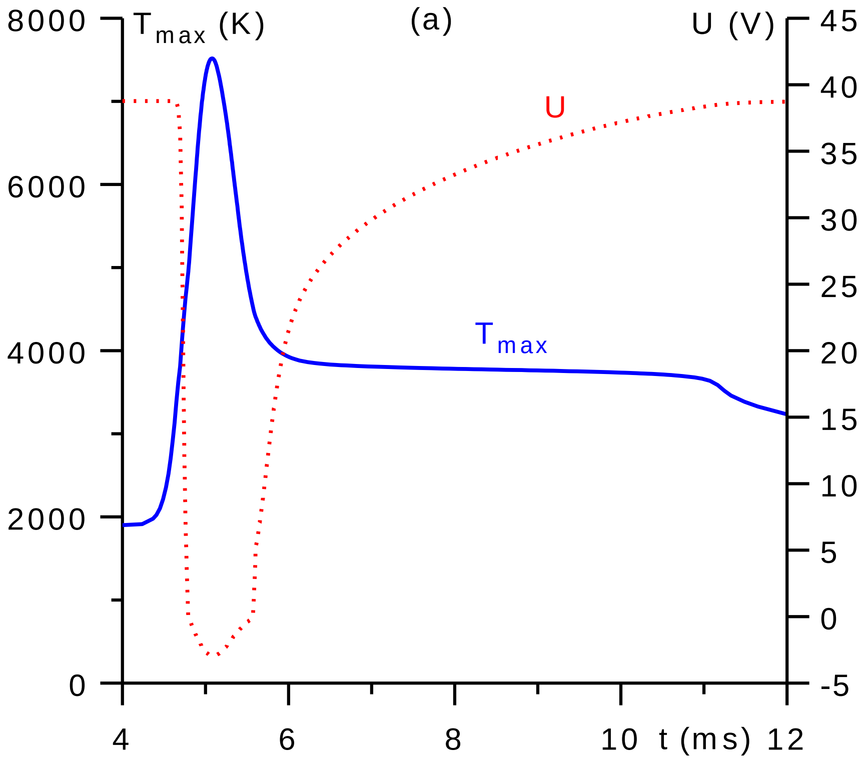
Temporal evolution of maximum plate temperature and of potential difference between plasma and plate. R = 10 mm; a = 0.4 mm.

- Case **most similar** to the conditions of the **experiment** (Kajita et al. 2009).
- Evolution of temperature field and molten surface deformation: **qualitatively similar to previous cases**.

- Notable differences:
  - ***U* turns negative**;
  - **T_{max} ~ 7500 K.**

Unipolar arcs: inversion of potential

Simulation case 3: R = 10 mm; a = 0.4 mm



Temporal evolution of maximum plate temperature and of potential difference between plasma and plate. R = 10 mm; a = 0.4 mm.

U turns negative

- Parameter governing arc spot is large + *R* is small:
  - **large spot current;**
  - much **lower current available from the helium plasma**.

- **Net current** transferred to the plate must be **zero.**

Need: Limitation of current transfer in the spot.

=> **Potential difference** between the plasma and the plate **turns negative.**

Unipolar arcs: inversion of potential

Simulation case 3: R = 10 mm; a = 0.4 mm

Tmax ~ 7500 K

- **Reduction of electron emission cooling** from the plate when plate potential surpasses plasma potential,
  - **electrons** are **reflected** back to the surface **by the potential barrier.**
- Consequently:
  - **Higher temperature**;
  - **Higher** value of **erosion**.

Simulation case	R (mm)	a (mm)	T_{max} (K)	U (V)	I (A)	Γ_v (μg)	Crater (μm)
1	100	0.4	5200	18	400	1.4	50 $\times$300
2	10	0.1	5200	5	17	0.066	10 $\times$70
3	10	0.4	7500	- 3	50	37	50 $\times$300

Summary of relevant results; all three simulation cases.

Comparison with results for vacum arcs

Unipolar arcs

- **Heat flux density q_1** due to the contributions of the plasma produced in the spot **is negative in the whole range**.
- Melt velocity ~ 2 m/s: **insufficient to drive formation of jets or droplet ejection**.
- **Plateau in temperature evolution:**
  - Initial fast decrease reduces electron emission cooling;
  - Further cooling due to heat conduction into the bulk, however much less intense mechanism.

Vacuum Arcs

- **Heat flux density q_1** due to the contributions of the plasma produced in the spot **is positive up to 4300 K, then turns negative**.
- p_1**: can be greater by up to 4 orders of magnitude =>** jet formation and droplet detachment.
- **Plateau in temperature evolution:** balance between ion bombardment heating and electron emission cooling.

Conclusions

- The detailed model developed for the modeling of the plasma-cathode interaction in vacuum arcs was used in order to investigate **spots on copper cathodes of high-current vacuum arcs** and **unipolar arcs burning in tungsten vapor** in fusion-relevant conditions.
- **Vacuum arcs**: crater and jet formation and droplet detachment; the cathode temperature is limited, i.e., no microexplosions.
- **Unipolar arcs**: formation of a crater, but no jet formation or droplet detachment.
  - **Large** (R = 100mm) **plate**: peak temperature of **5200 K**; **plate potential remains below the plasma potential**.
  - **Small** (R = 10mm) **plate**: peak temperature of **7500 K**; **the potential of the plate surpasses the plasma potential**; the erosion (mainly due to the vaporization of the metal atoms in the spot) reaches 37 μg.
- The **model may be used**, with appropriate modifications, for the **investigation of the plasma-electrode interaction in discharges of other types**.

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