Departamento de Física

Understanding and modelling plasma-cathode interaction: Roots of gaseous and vacuum arcs, spots on glow cathodes

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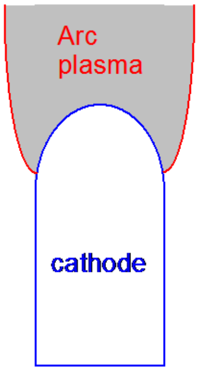
Spots on cathodes of high-pressure arcs



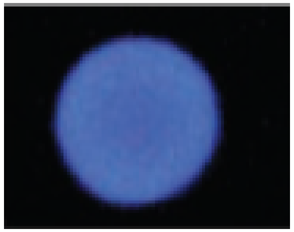
The current is distributed over the front surface of the cathode in a more or less uniform way; the **diffuse mode**.

The current is localized in a region occupying a small fraction of the surface (cathode spot); a **spot mode**.

Side-on observation of a cathode of an arc discharge in the Bochum model lamp. W, R = 0.75 mm, h = 20 mm, Ar, p = 4.5 bar, I = 2.5 A. From S. Lichtenberg *et al* 2002.

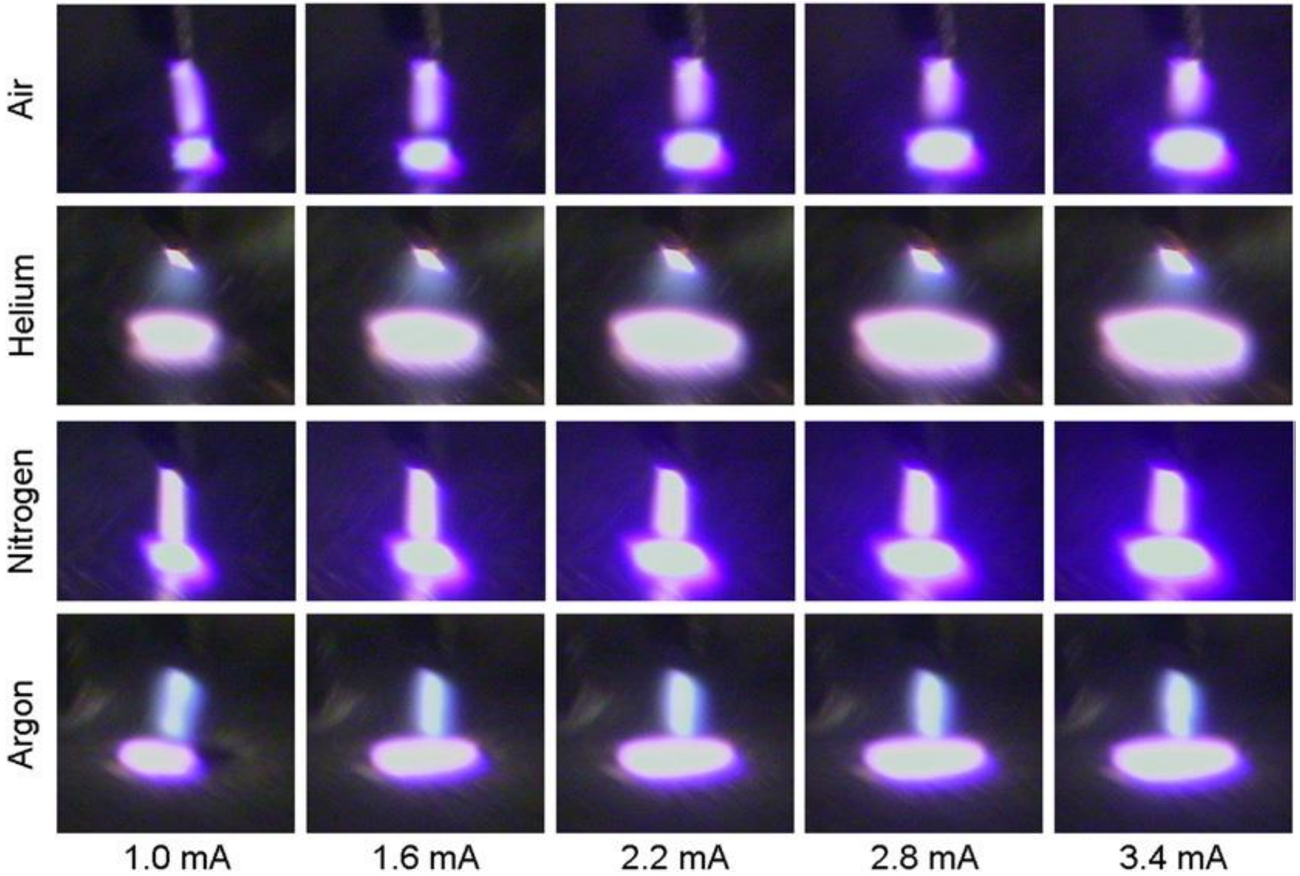
Spots on cathodes of DC glow discharges

- The spotless mode (**abnormal discharge**)



Cathode of glow discharge in Xe. 75 Torr, 0.42 mA. *R* = 0.375 mm, *h* = 0.25 mm. From K. H. Schoenbach *et al* 2004.

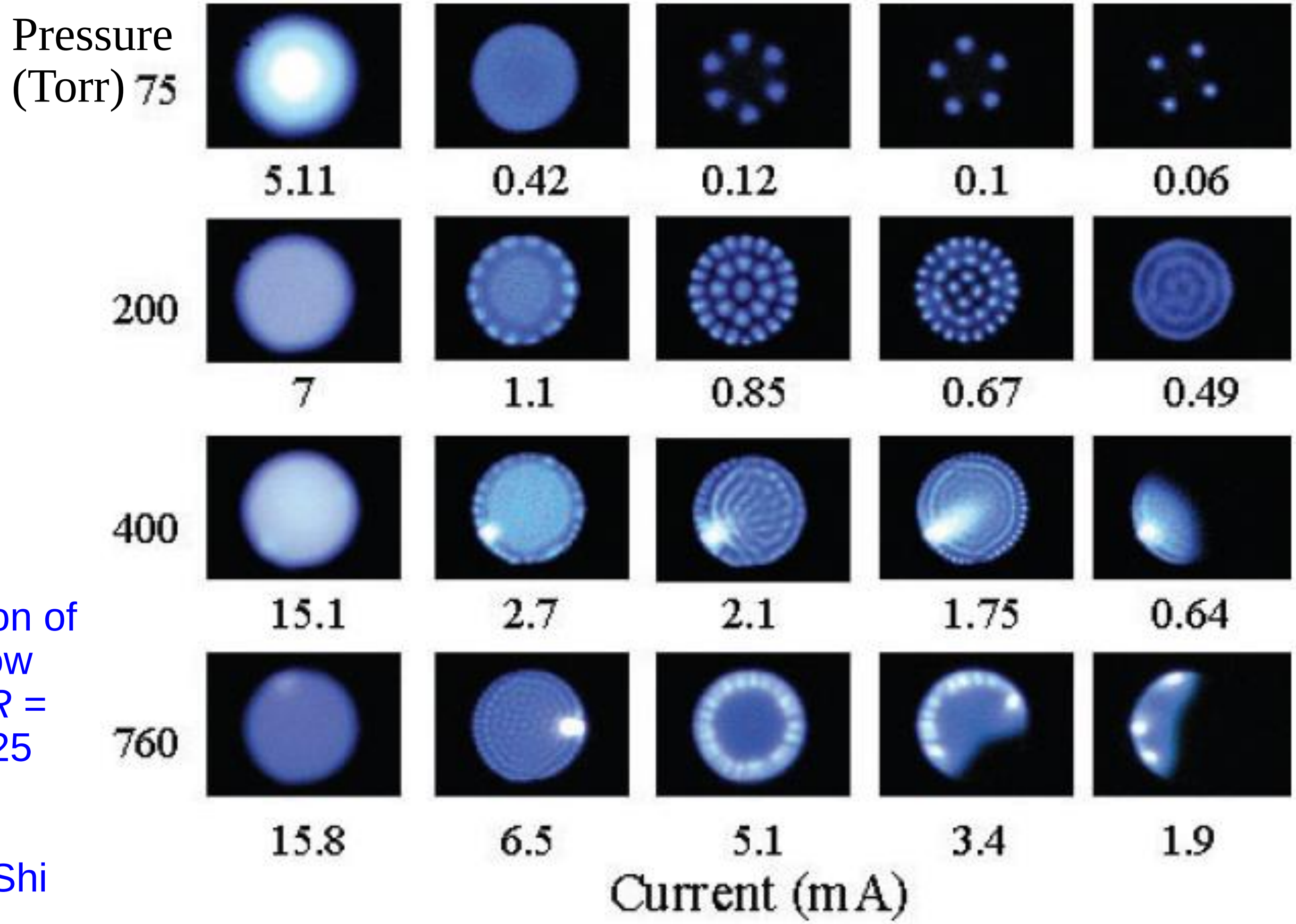
- Mode with one spot (**normal discharge**)



Glow discharges in different gases. p = 1 bar, h = 0.4 mm. From D. Staack *et al* 2008.

Spots on cathodes of DC glow discharges

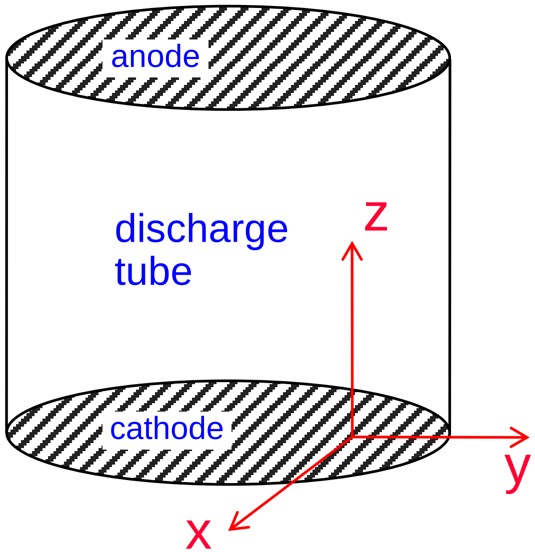
- **Modes with multiple spots**



End-on observation of a cathode of a glow discharge in Xe. R = 0.375 mm, h = 0.25 mm. From K. H. Schoenbach, M. Moselhy, and W. Shi 2004.

Different mechanisms or multiple solutions?

- An adequate theoretical model of current transfer to a DC **cathode must not necessarily involve essentially different physical mechanisms** (such as Schottky-amplified thermionic emission from arc cathodes vs. thermo-field emission).
- Rather, being a **self-organization problem**, it must admit **multiple steady-state solutions** for the same discharge current.



The simplest discharge geometry.

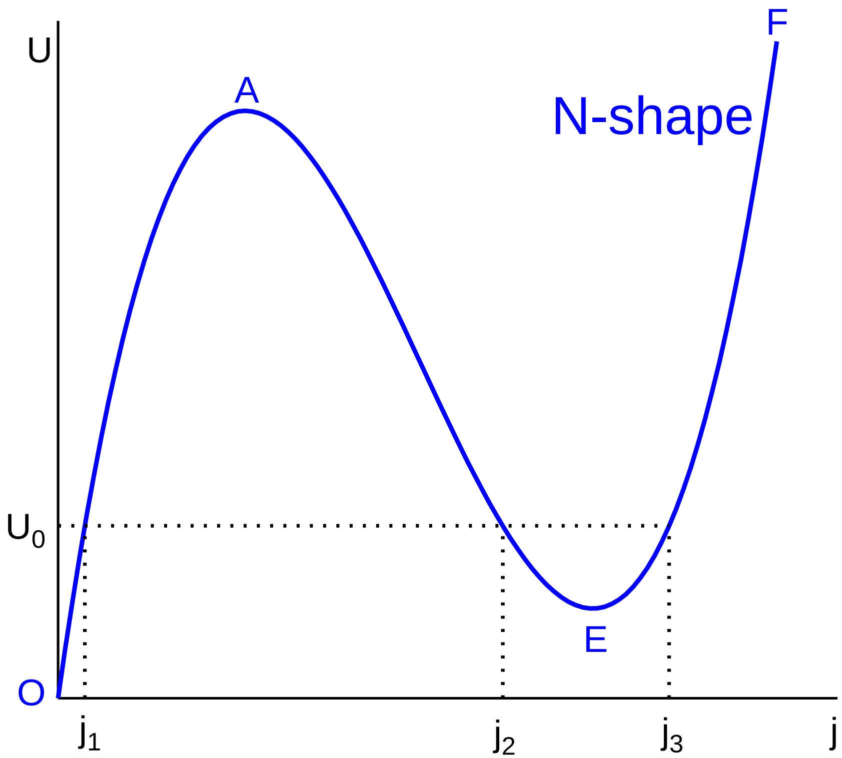
- A boundary-value problem describing current transfer to the cathode is invariant with respect to x and y **=> 1D solution, *f=f(z)***: the spotless mode [the abnormal mode on the glow cathode; the diffuse mode on an arc cathode].
- **Multidimensional solutions, *f=f(x,y,z)*:** modes with spots.
- What these multidimensional solutions are like and where to look for them?

=> The theory of self-organization in bi-stable nonlinear dissipative systems.

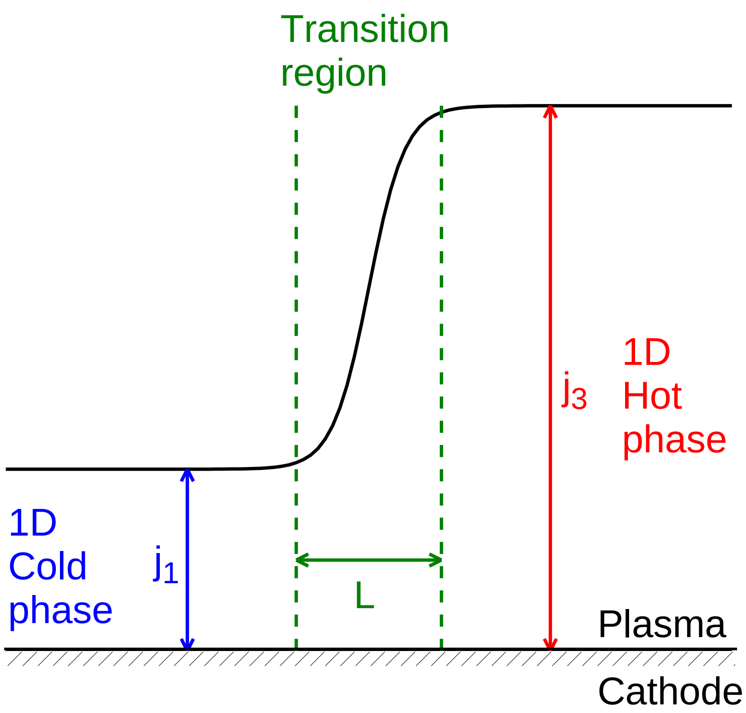
Contents of the talk

- Introduction
- **Modes of current transfer to DC cathodes as predicted by general trends of self-organization in bi-stable nonlinear dissipative systems**
- Current transfer to arc cathodes
- Current transfer to glow cathodes
- Conclusions

General predictions of the self-organization theory



CDVC of the spotless (1D) mode of current transfer.

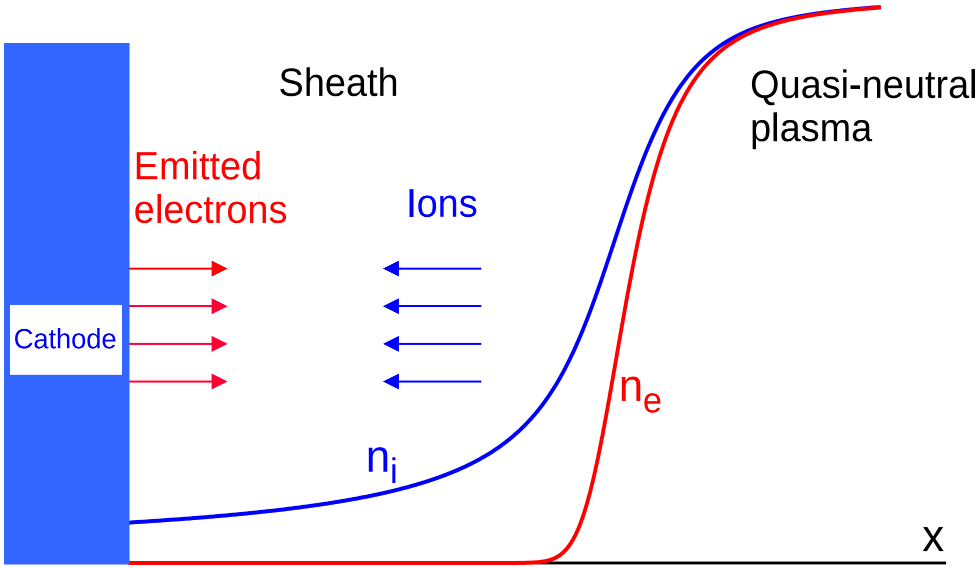


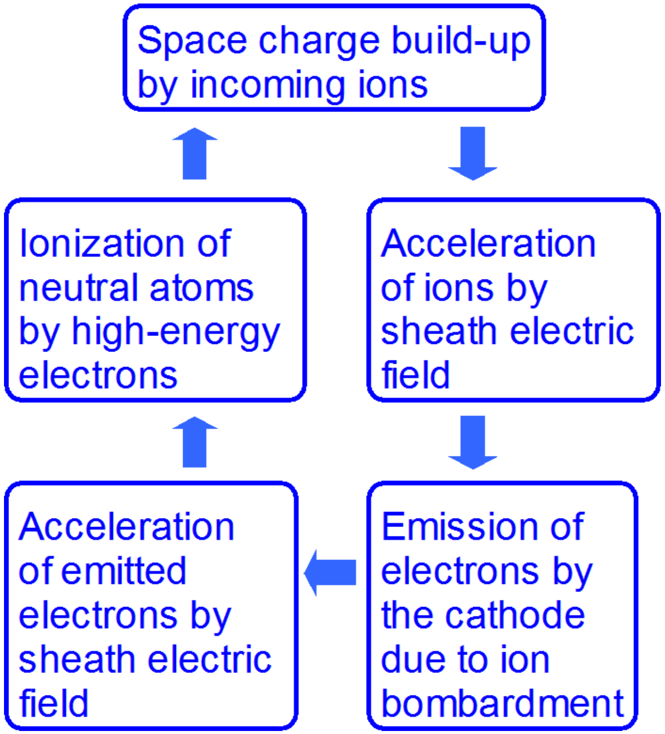
***U= U*$_0$:** **Three 1D solutions**

$j=j_1$: stable (a cold phase),
$j=j_3$: stable (a hot phase),
$j=j_2$: unstable.

Multidimensional solutions: states with co-existence of phases, exist at a certain value of U_0 (Maxwell's construction) provided that cathode transversal dimensions >> L.

The source of positive feedback: the near-cathode sheath





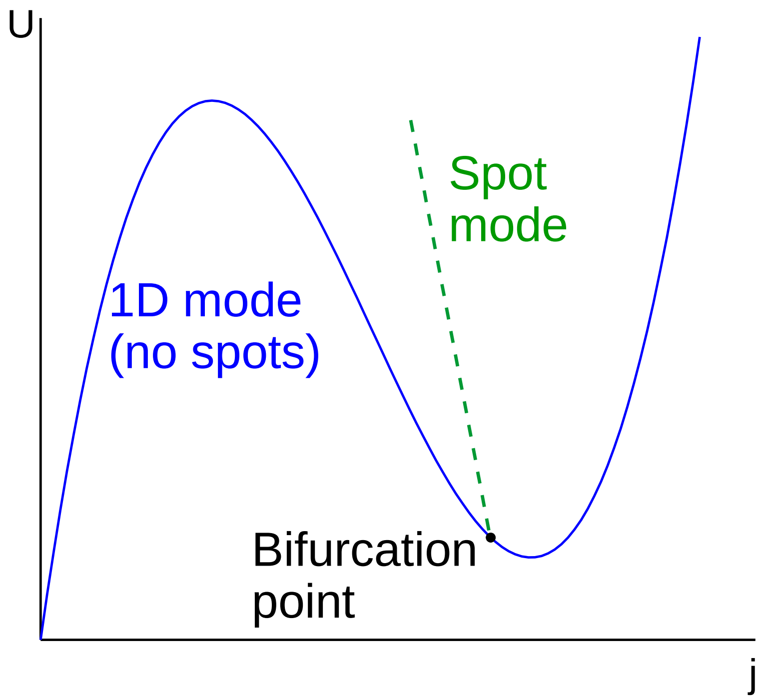
Glow discharge (cold cathode)
Ion bombardment => secondary electron emission (γ-process) $j_{em}/j_i = 1...10\%$

Arc discharge (hot cathode)
Ion bombardment => $T_w = 2{,}000...4{,}000$ K => thermionic/thermofield emission $j_{em}/j_i = 2...5$

A loop = positive feedback!

General predictions of the self-organization theory

- Appearance of spots on DC cathodes is in most cases a **monotonic process** and therefore occurs through a **neutrally stable steady state**.
- Neutral stability means a **bifurcation** of steady-state solutions.
- **Multidimensional solutions branch off from the 1D mode.**
- Presumably, this happens on the falling section of the CDVC of the 1D mode.
- Bifurcation points may be found by means of **linear stability analysis.**



The computation procedure

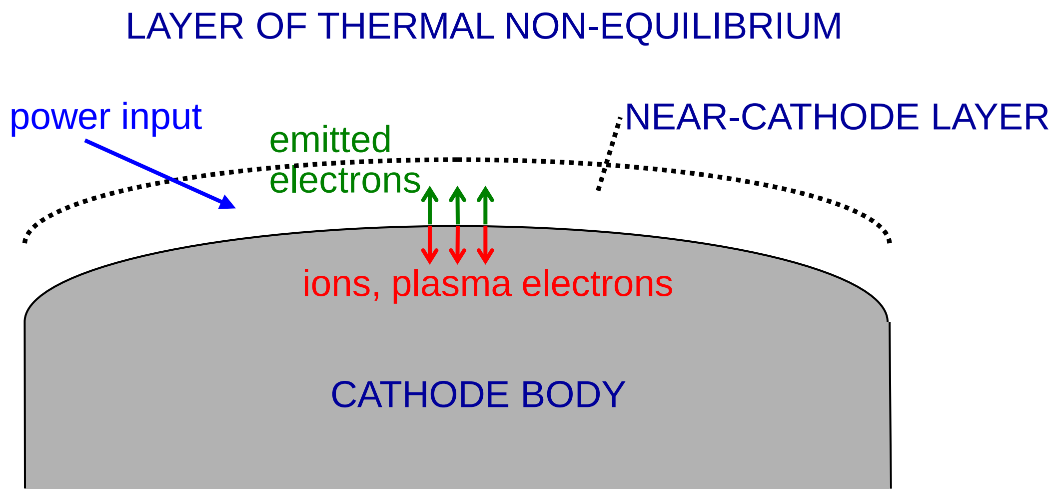
1. To formulate a model of plasma-cathode interaction for the particular discharge. While being multidimensional in nature, this model must admit 1D solutions;

2. To find the 1D solution and the bifurcation points;

3. To find spot modes by means of numerical modelling with the use of results of the bifurcation analysis. To take into account the fact that the spotless mode is not precisely 1D;

4. To investigate stability of different modes.

Arc cathodes, step 1: the model



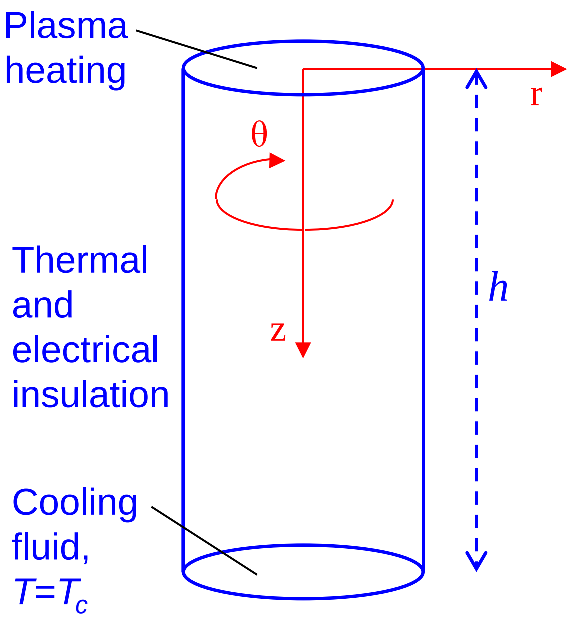
- The plasma-cathode interaction is governed by a thin near-cathode plasma layer comprising the space-charge sheath and the ionization layer.
- Since this layer is thin, it may be calculated locally in 1D.
- A complete solution can be found in two steps:
  - **Solution on the plasma side**: the 1D problem describing the current transfer across the near-cathode plasma layer is solved and all parameters of the layer are determined as functions of T_w and U. In particular, functions $q = q(T_w,U)$ and $j = j(T_w,U)$ are found.
  - **Solution inside the cathode**: the heat conduction equation is solved with the boundary condition $q = q(T_w,U)$.

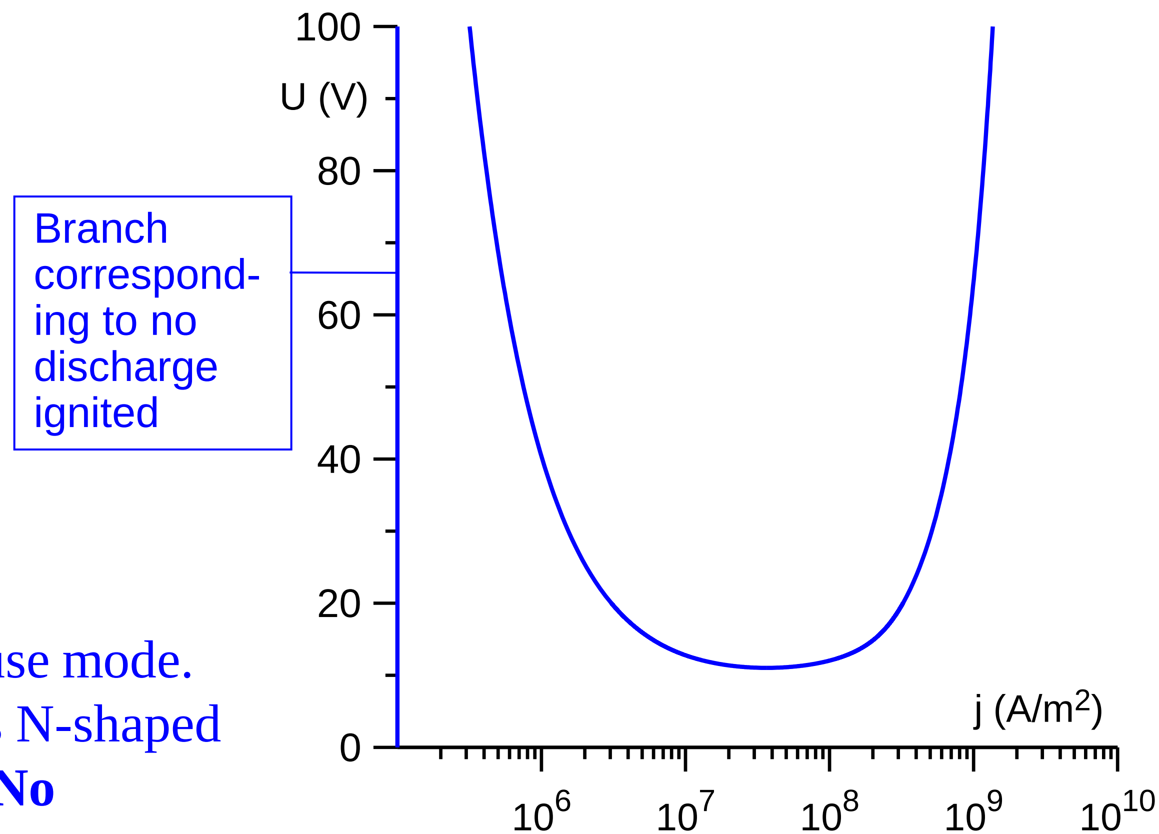
Historical comments

Example of function $q(T_w,U)$

Arc cathodes, step 2: the 1D solution

Cylindrical cathode with an insulated lateral surface

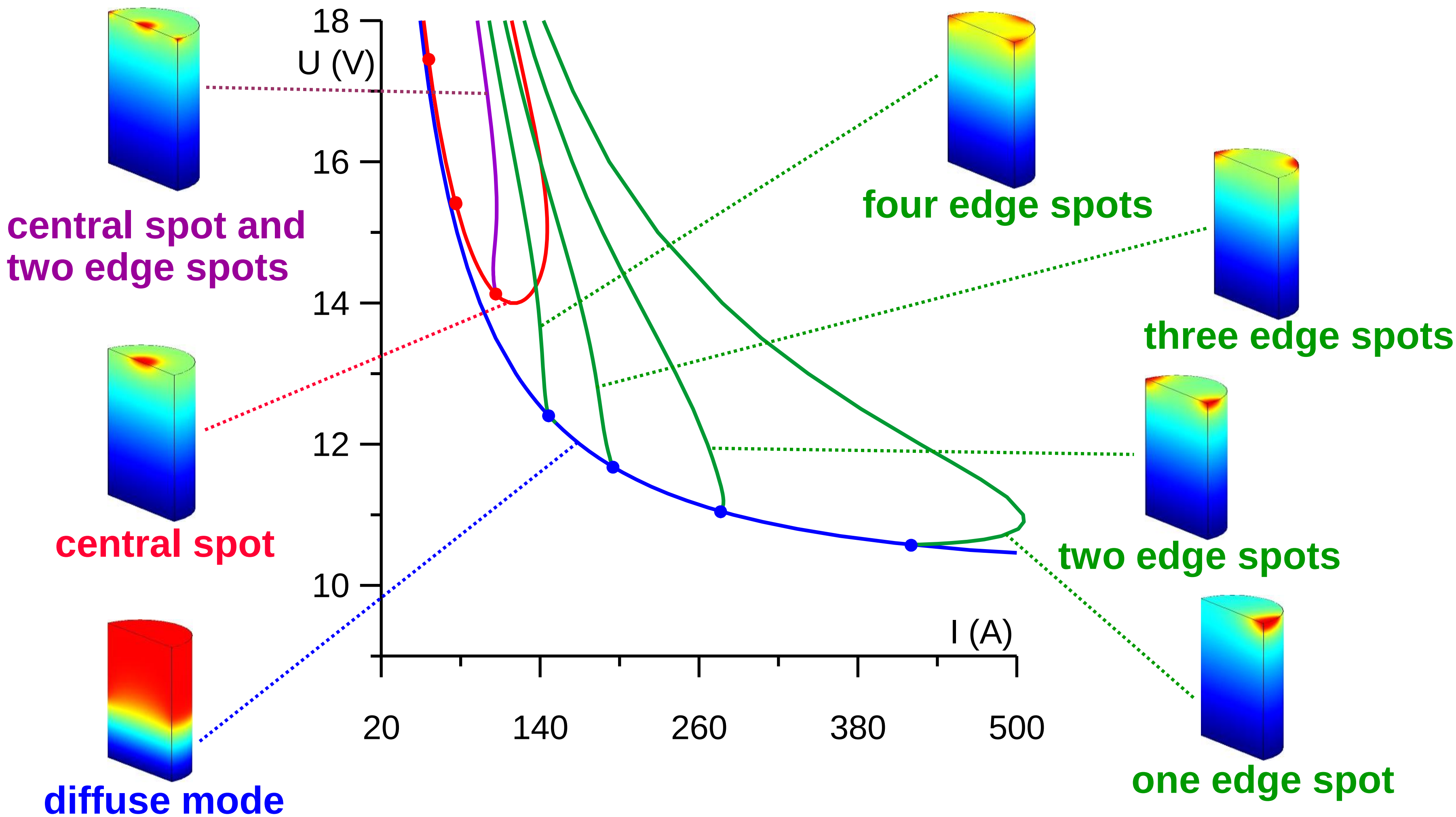




CDVC of the diffuse mode on a cylindrical cathode with an insulated lateral surface. W, h = 10 mm, Ar, 1 bar. From M. S. Benilov 1998.

- 1D solution, $T = T(z)$: diffuse mode. The CDVC on the whole is N-shaped (rather than U-shaped) **=> No additional mechanisms are required to describe spot modes.**
- 2D and 3D solutions: spot modes.

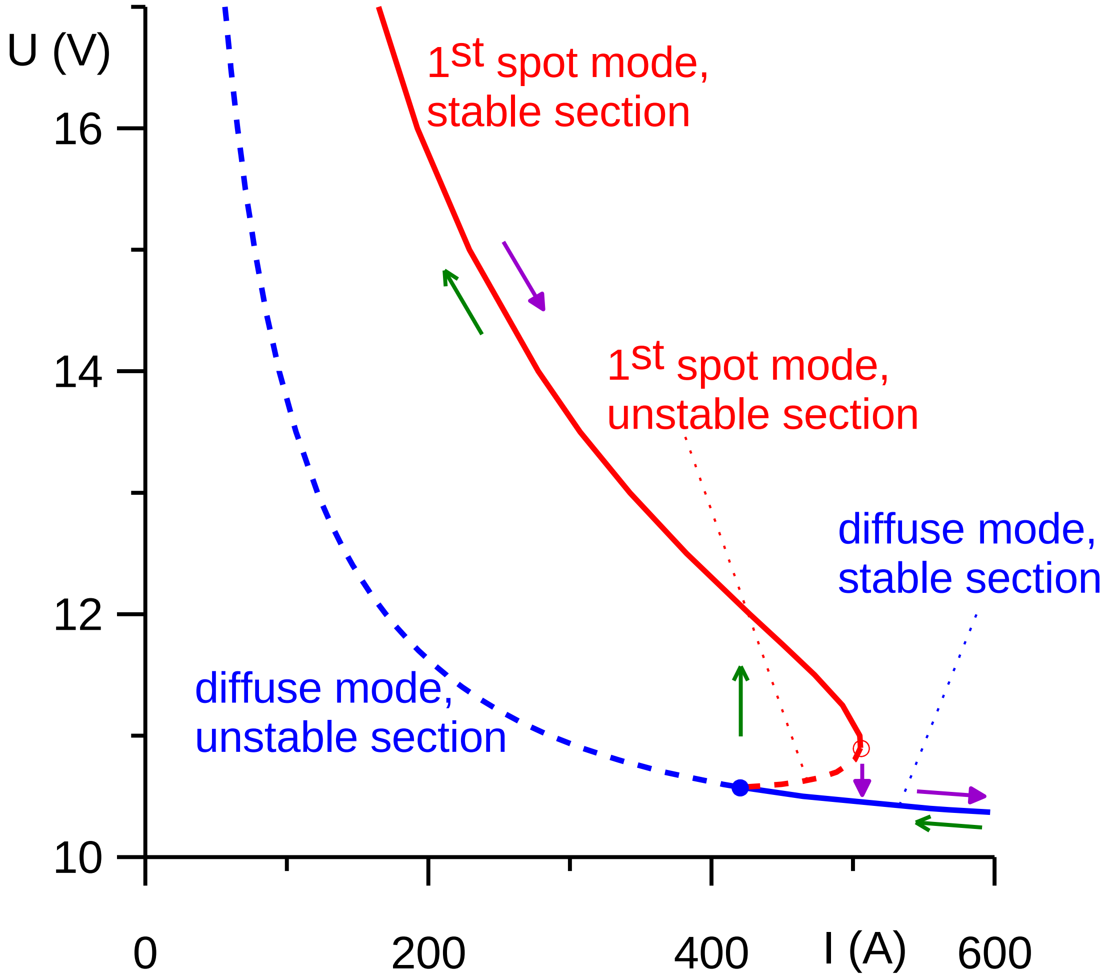
Arc cathodes, step 3: pattern of modes on a rod cathode



Current-voltage characteristics of different modes. W, R = 2 mm, h = 10 mm, Ar, 1 bar.
●, ●: bifurcation points. From M. S. Benilov, M. Carpaij, and M. D. Cunha 2006.

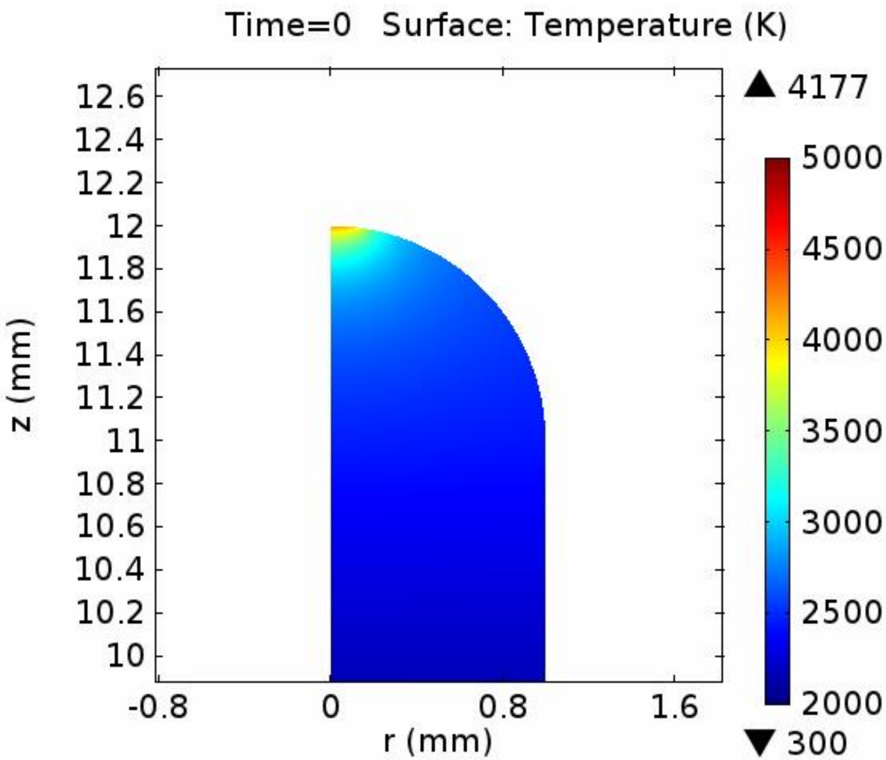
Arc cathodes, step 4: stability of different modes

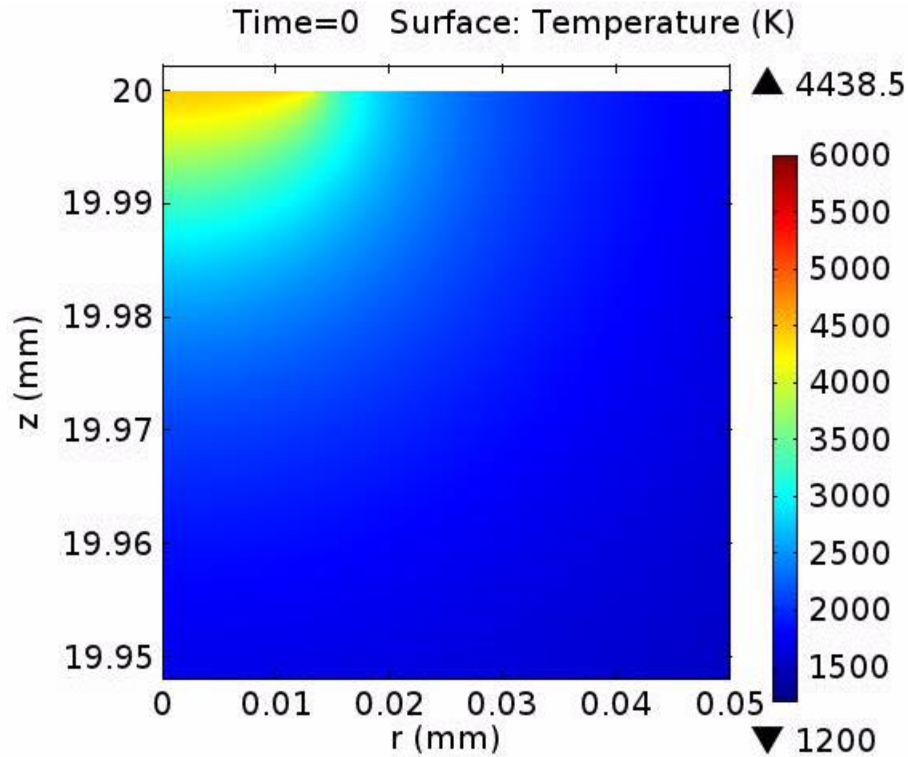
- Modes with a spot at the center or with multiple spots are always unstable.
- The only modes that that can be stable are the diffuse mode and the high-voltage branch of the 1st 3D spot mode.
- The transition between these two modes is non-stationary without oscillations in time and accompanied by hysteresis.



Stability of different modes on a rod cathode. W, *R* = 2 mm, *h* = 10 mm, Ar, 1 bar. From M. S. Benilov 2007 and M. S. Benilov and M. J. Faria 2007.

Arc cathodes, step 4: nonlinear stability of spots





1 bar Ar arc, W cathode, R = 1mm, h = 12 mm. U = 30 V. Initial current: 6 A.

Outcome: massive melting of the cathode surface.

Vacuum arc, planar Cu cathode. U = 20 V. Initial current: 47 A.

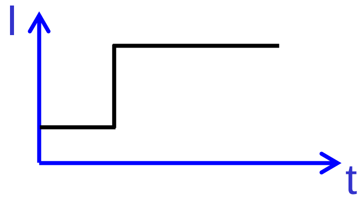
Outcome: thermal explosion of the spot.

Evolution of unstable cathode arc spots. From M. S. Benilov, M. D. Cunha, W. Hartmann, and N. Wenzel 2014.

Comparison with the experiment: transient spots

- **Detailed experimental data on plasma-cathode interaction in low-current arcs have been obtained during the last 15 years**, in particular, by Mentel's group in Bochum.
- **The theory has been convincingly validated by the experiment**. Examples

Transient spots



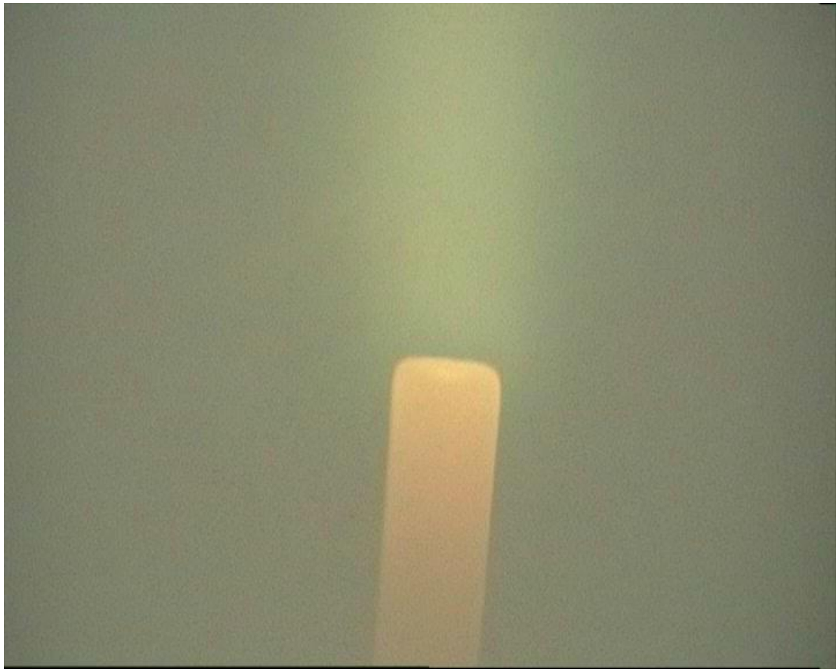
R. Bötticher, W. Graser, and A. Kloss 2004

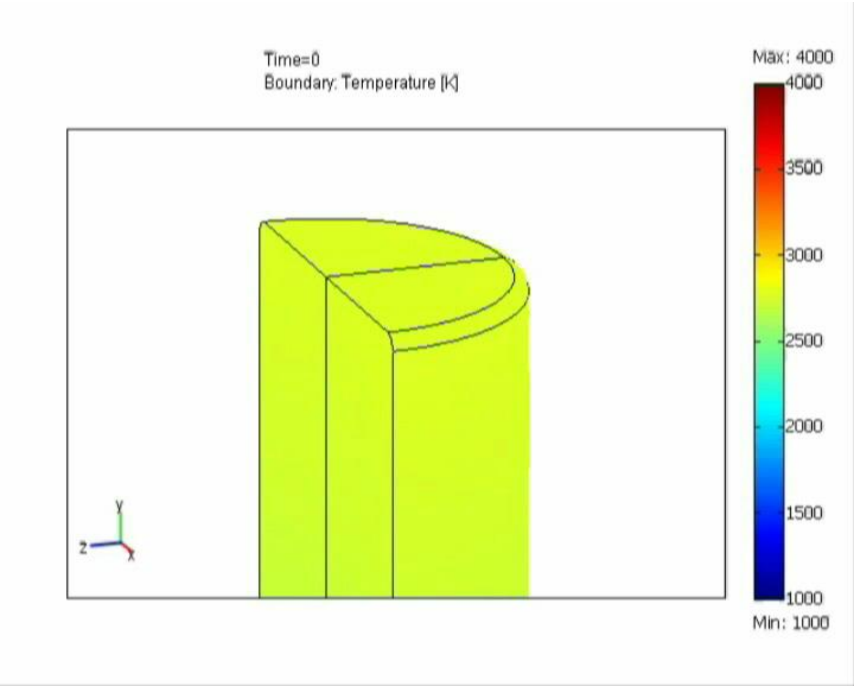
R. Bötticher and M. Kettlitz 2006

P. G. C. Almeida, M. S. Benilov, and M. D. Cunha 2008

- Initial and final steady states are diffuse.
- If the variation of current is below a certain threshold, the diffuse mode is preserved during the transition.
- Otherwise, a transient spot appears.

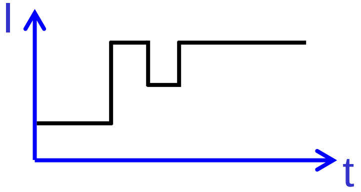
Comparison with the experiment: transient spots





COST-529 standard lamp (Philips), current jumps from 0.3 A to 1.3 A. W, *R* = 0.35 mm, *h* = 11 mm, rounding 25 μm, Hg, 4 bar. P. G. C. Almeida, M. S. Benilov, and M. D. Cunha 2008.

Real-time quenching of formation of spots:

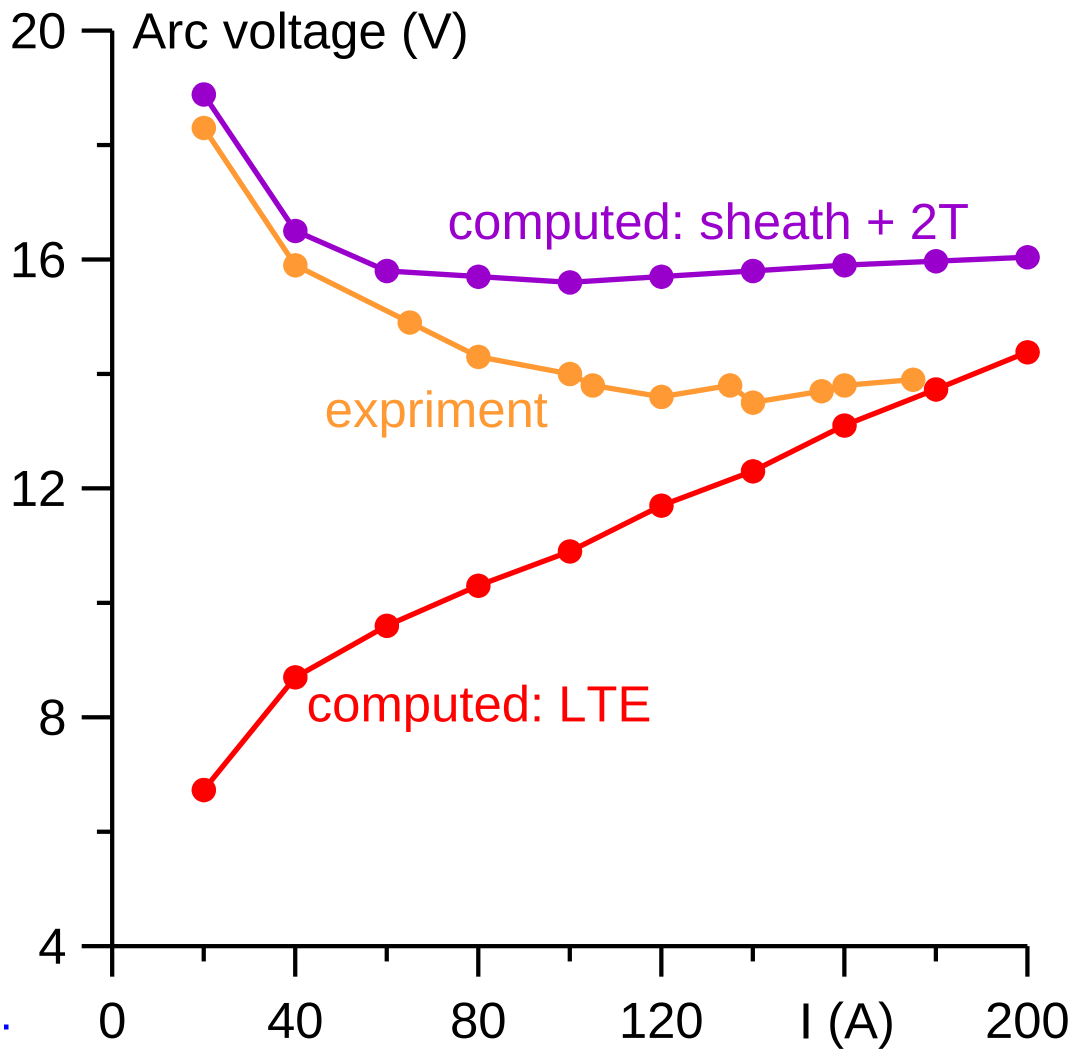


From P. G. C. Almeida *et al* 2013.

Details

Comparison with the experiment: arc voltage

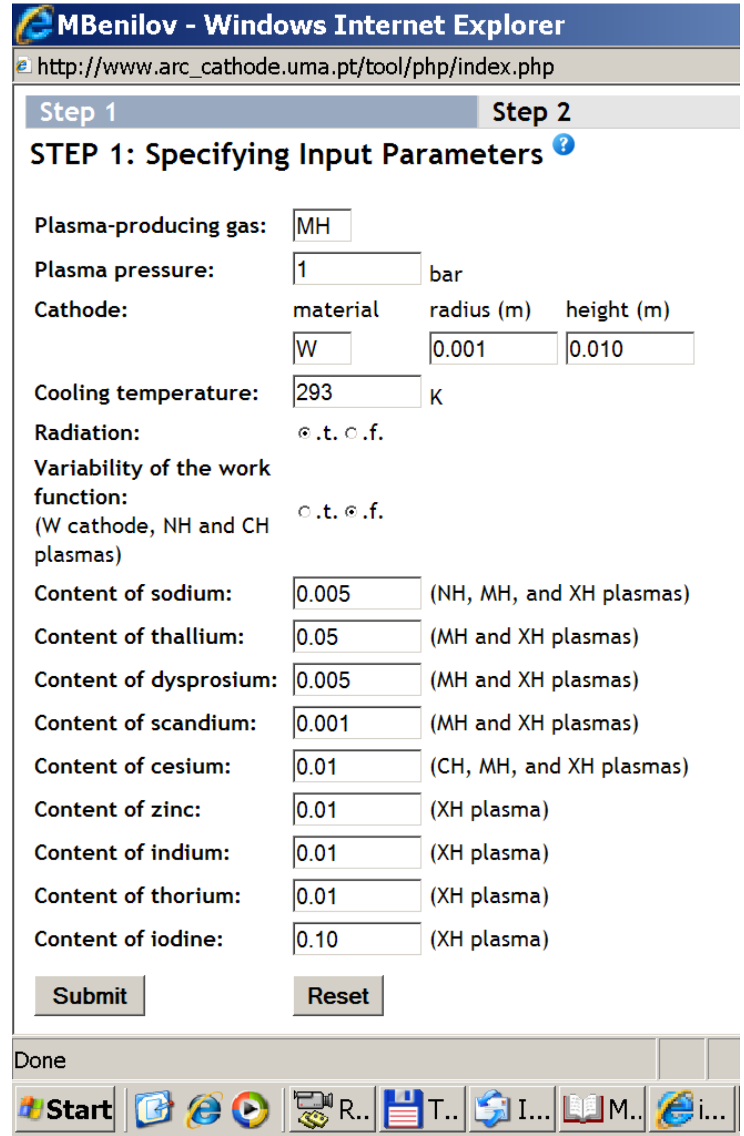
- The arc voltage computed with account of the sheath and deviations between T_e and T_h in the arc column differs from the experiment by no more than 2V in the current range 20-175A.



Voltage over a 1 cm long free-burning arc in 1 bar Ar. Cathode with a hemispherical tip, R = 1mm, h = 12 mm. Experiment: N. K. Mitrofanov and S. M. Shkolnik 2007. From M. S. Benilov, L. G. Benilova, H.-P. Li, and G.-Q. Wu 2012.

A free on-line modelling tool

- A 2D simulation technique has reached a point at which it can be automated.
- A free on-line tool for simulation of diffuse and 2D spot modes on rod cathodes: http://www.arc_cathode.uma.pt
- **There is no need to study theoretical papers in order to be able to use the tool!**



There is a lot more to say about arc cathodes …

- Modelling of **cathodes of a complex shape made of different materials and of multispecies plasmas** with complex chemical kinetics (air, different metal halides plasmas);
- **Variation of the work function** due to deposition of a monoatomic layer of an alkali metal;
- **Theory of solitary spots** (spots on large cathodes): the spot radius is self-consistently determined by means of appropriate Maxwell's construction;
- **Experiments on the diffuse mode on cathodes of vacuum arcs**;
- Theory and modelling of **cathode spots of vacuum arcs** with application to contacts of high-power circuit breakers;
- **Self-organization vs. geometrical current concentrations** View **;**
- …

Glow cathodes, step 1: the model

Differential equations

The simplest self-consistent mathematical model of a DC glow discharge comprises equations of conservation of a single ion species and electrons, transport equations for the ions and the electrons written in the so-called drift-diffusion approximation, and the Poisson equation, with the transport and kinetic coefficients of electrons being functions of the local *E/n*:

$$\nabla \cdot \mathbf{J}_i = n_e \alpha \mu_e E - \beta n_e n_i , \quad \mathbf{J}_i = -D_i \nabla n_i - n_i \mu_i \nabla \varphi,$$

$$\nabla \cdot \mathbf{J}_e = n_e \alpha \mu_e E - \beta n_e n_i , \quad \mathbf{J}_e = -D_e \nabla n_e + n_e \mu_e \nabla \varphi,$$

$$\varepsilon_0 \nabla^2 \varphi = -e\left(n_i - n_e\right).$$

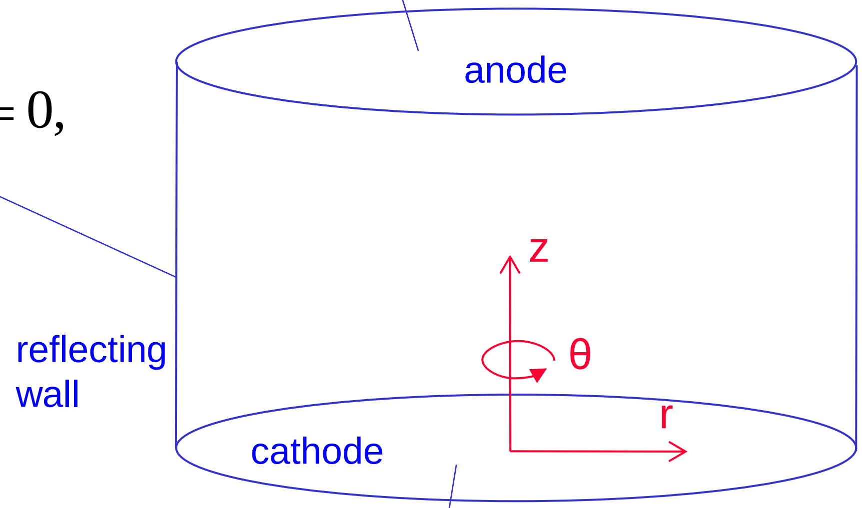
Glow cathodes, step 1: the model

Geometry and boundary conditions: discharge between parallel electrodes

$$n_i = 0,\ \frac{\partial n_e}{\partial z} = 0,\ \varphi = U$$

$$\frac{\partial n_i}{\partial r} = \frac{\partial n_e}{\partial r} = 0,$$

$$j_r = 0$$



$$\frac{\partial n_i}{\partial z} = 0,\ \left(\mathbf{J}_e\right)_z = -\gamma\left(\mathbf{J}_i\right)_z,\ \varphi = 0$$

- $f = f(z)$: a solution given in textbooks (von Engel and Steenbeck)
- $f = f(z,r,\theta)$?

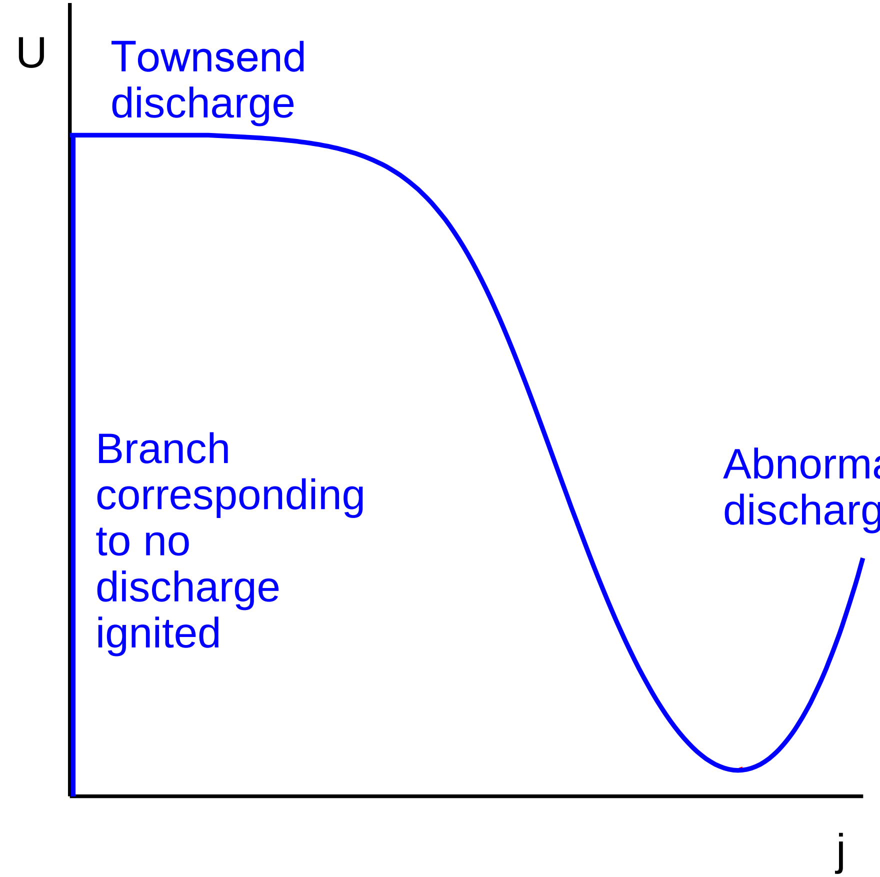
Historical comments

Glow cathodes, step 2: 1D solution

- The falling section: the ionization coefficient rapidly increases => the **positive feedback is strong.**

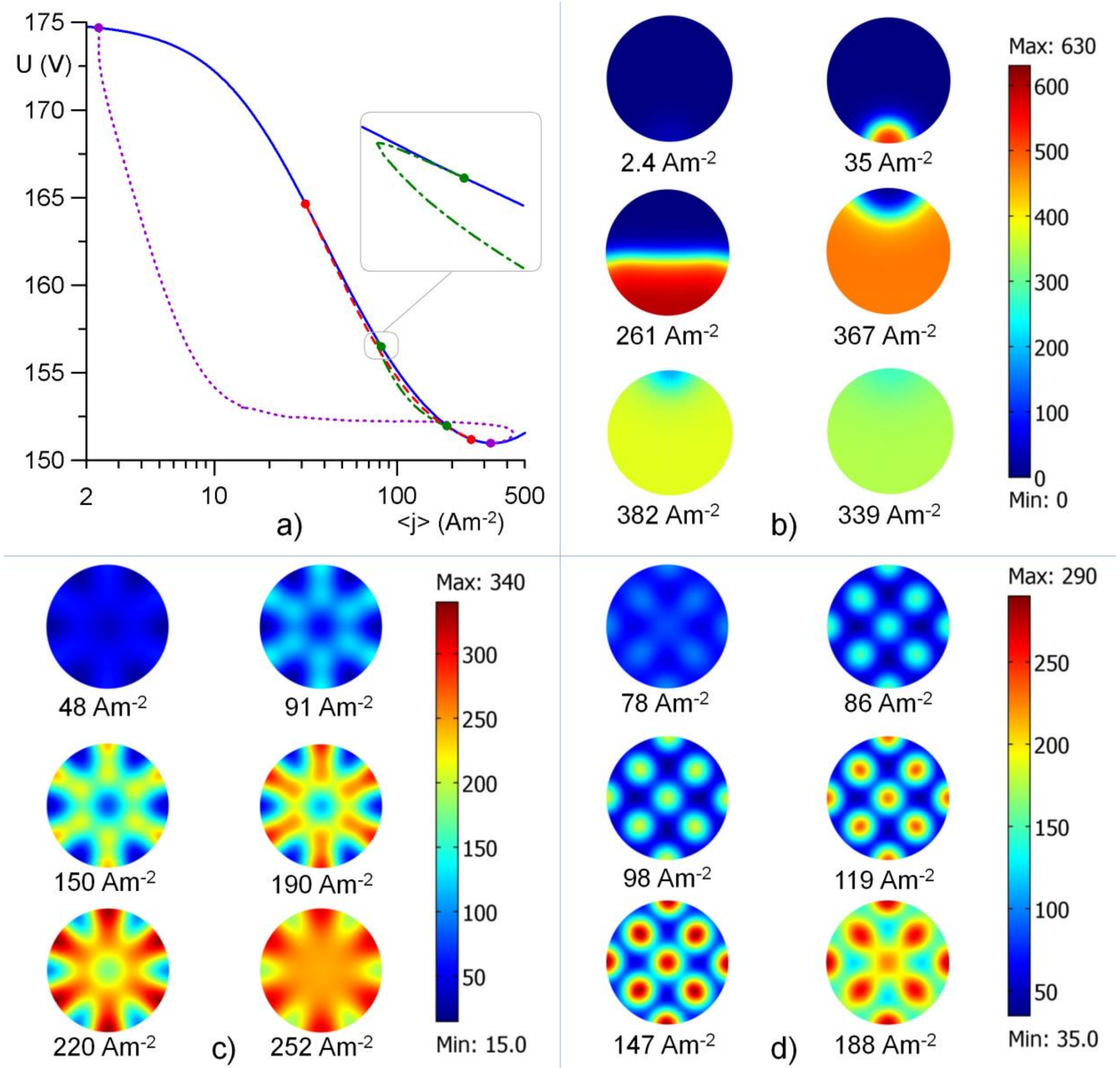
- The growing section: **the ionization coefficient approaches saturation**.

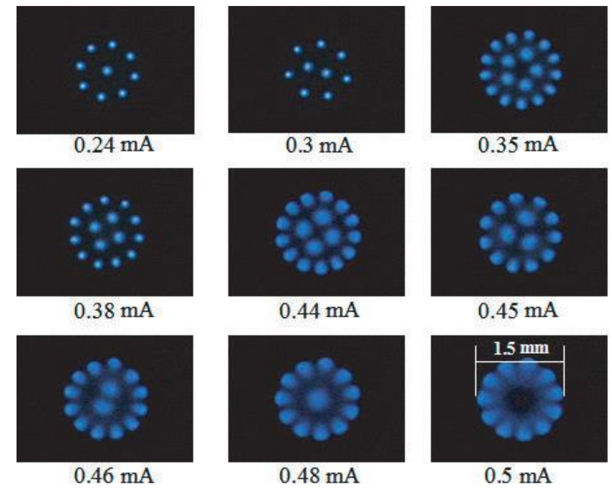
- The CVC of the near-cathode layer on the whole is N-shaped **=> No additional mechanisms are required to describe spot modes.**



CDVC described by the 1D solution.

Glow cathodes, step 3: solutions describing pattens



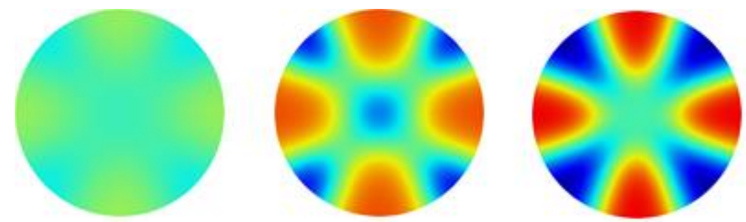


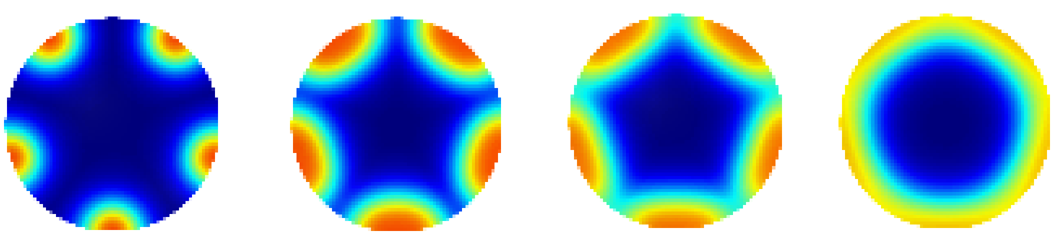
Glow discharge in Xe. From K. H. Schoenbach, M. Moselhy, and W. Shi 2004.

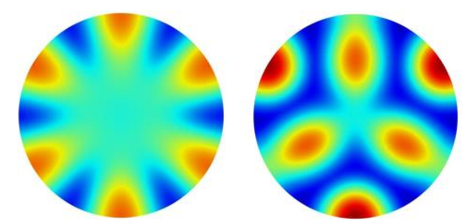
Xe, *p* = 30 Torr, *R* = 0.5mm, *h* = 0.5mm, diffusion losses neglected. a): Solid: the 1D mode. Dashed, dashed-dotted, dotted: the 1st, 8th, and 12th 3D modes. b): 1st 3D mode. c): 8th 3D mode. d): 12th 3D mode. From P. G. C. Almeida, M. S. Benilov, and M. J. Faria 2010, 2011.

Comparison with the experiment

- There are quite a few observations of patterns in glow microdicharges, mostly by Schoenbach and coworkers.
- The agreement between the modelling and the experiment is good, although the comparison has been merely qualitative up to now.





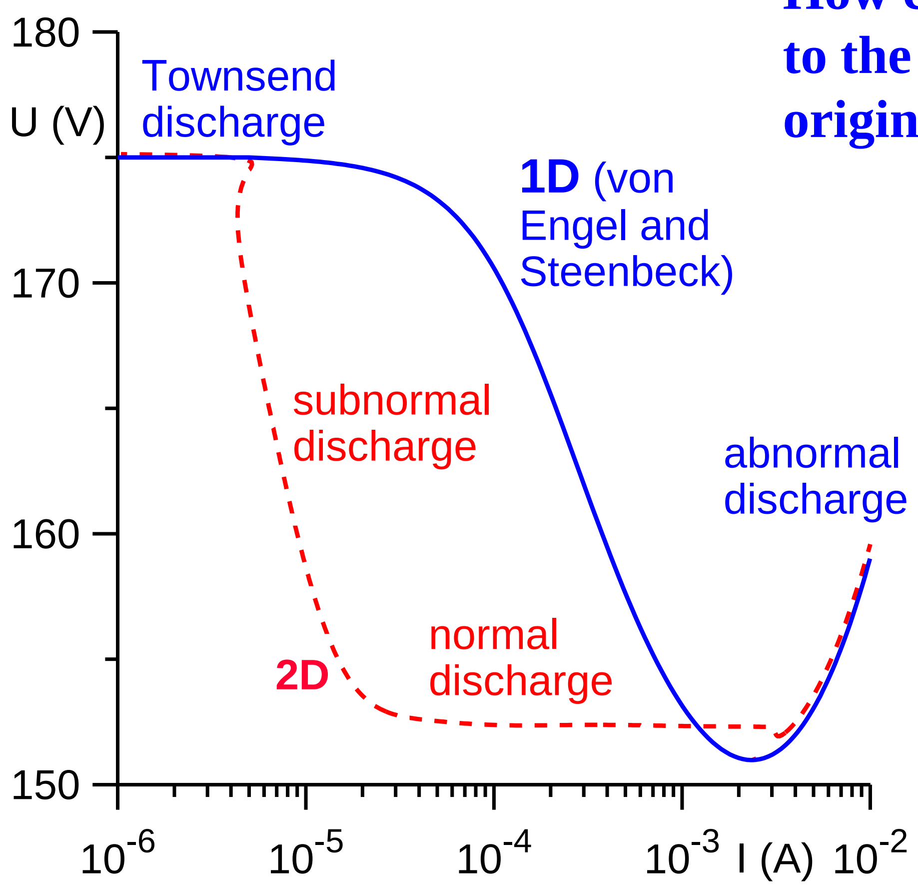


Bifurcations of steady states of glow discharge. Experiment: W. Zhu and P. Niraula 2014. Modelling: P. G. C. Almeida, M. S. Benilov, and D. F. N. Santos 2013, 2014.

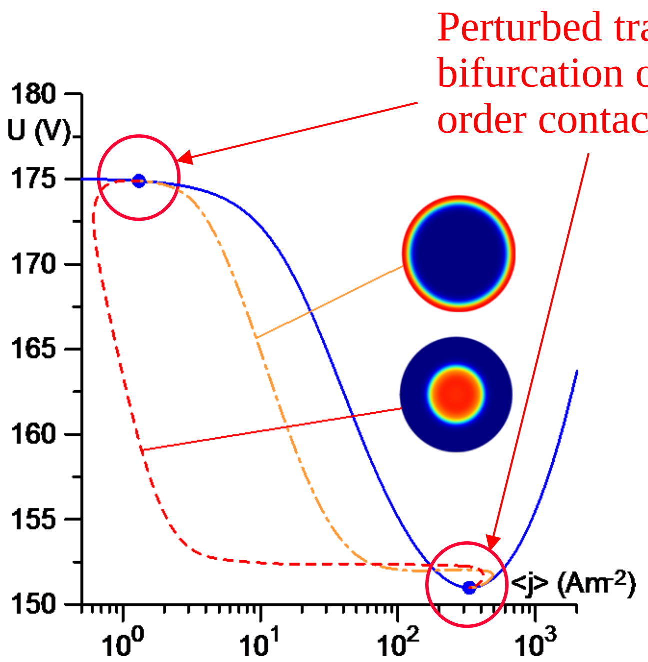
There is more to say about glow cathodes …

- Modelling guided the experiment to observing spot **patterns in gases other than Xe** (Kr, Xe with 0.5% air impurity);
- **The normal current density exceeds the value corresponding to the minimum of the CDVC by a factor of about two**;
- Simulation of patterns in Xe and Ar with a **detailed account of kinetics** (singly charged atomic ions, molecular ions, electrons, excited atoms, and excimers) **and non-locality** through electron energy equation;
- **Bifurcations of different types**, including pitchfork bifurcations caused by different kinds of breaking of symmetries, merging of bifurcation points, **common for glow and arc cathodes**;
- Results on **stability** of axially symmetric states;
- **Simple situations, complex behavior**; …

Simple situations, complex behaviour



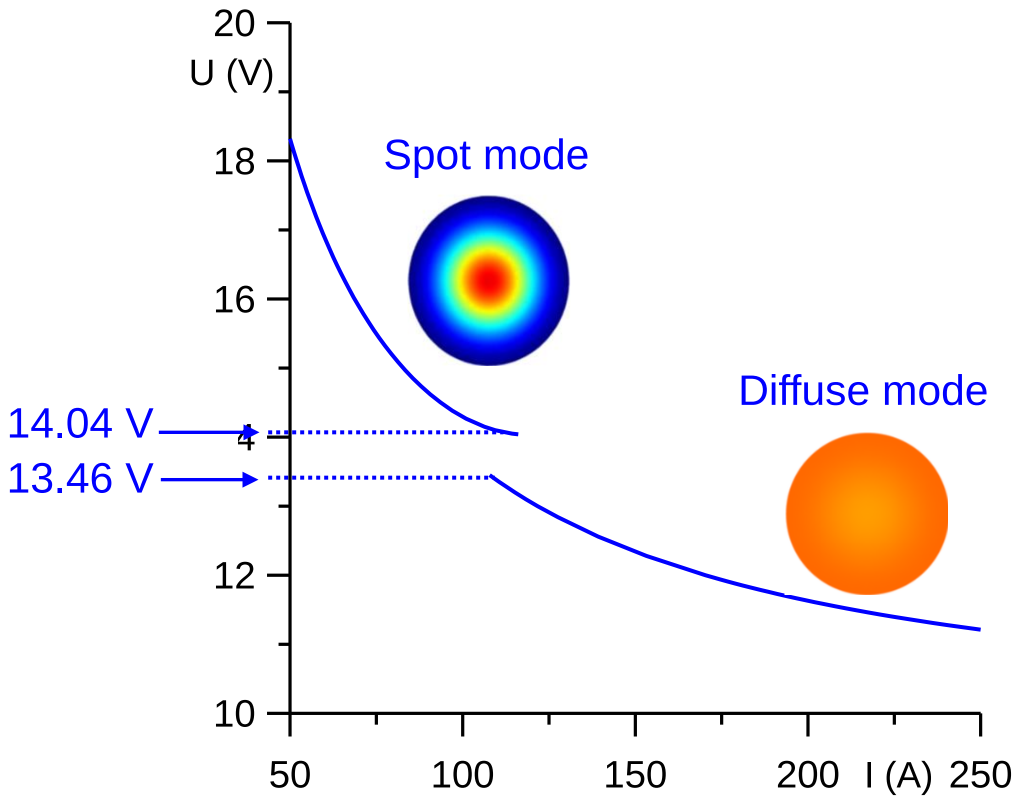
- **How can diffusion of the charged particles to the wall, which is a weak effect (10^{-3}), originate such a large difference?**



Xe, *p* = 30 Torr, *R* = 1.5mm, *h* = 0.5mm. From P. G. C. Almeida, M. S. Benilov, M. D. Cunha, and M. J. Faria 2009.

- **Bifurcations may occur in apparently simple situations where multiple solutions are not of primary concern!**

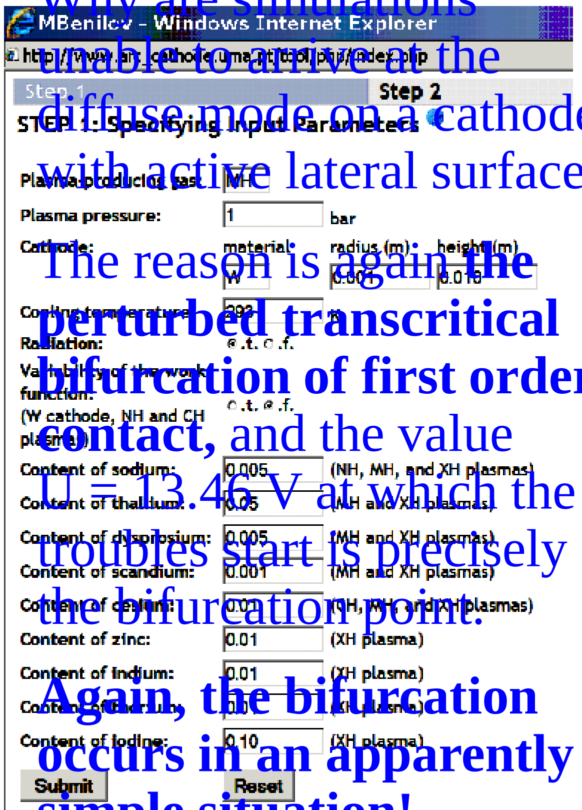
Simple situations, complex behaviour



Ar, p = 1 bar, R = 2 mm, h = 10 mm. Simulation by means of the free on-line modelling tool http://www.arc_cathode.uma.pt with the use of the built-in initial approximation. From P. G. C. Almeida, M. S. Benilov, M. D. Cunha, and M. J. Faria 2009.

More exampes

- Simulations start from the diffuse mode on a cathode with the insulating lateral surface.
- Why are simulations unable to arrive at the diffuse mode on a cathode with active lateral surface?
- The reason is again **the perturbed transcritical bifurcation of first order contact,** and the value U = 13.46 V at which the troubles start is precisely the bifurcation point.
- **Again, the bifurcation occurs in an apparently simple situation!**



Why have not these phenomena been calculated earlier?

- It is important to employ a **steady-state solver rather than non-stationary** one, in order to **decouple questions of numerical and physical stability**. We used
  - **A finite-difference 2D Fortran code** for arc cathodes:
    - ✓ Based on the Newton linearization with a direct (non-iterative) solution of the linearized equations,
    - ✓ Freely available on Internet at http://www.arc_cathode.uma.pt
  - **COMSOL Multiphysics software**:
    - ✓ Powerful steady-state solvers,
    - ✓ An eigenvalue solver,
    - ✓ The possibility of easy and seamless switching between discharge current and discharge voltage as a control parameter.
- In order to calculate **multiple solutions**, one needs to know **what they are like and where to look for them**. The bifurcation theory is a suitable tool.

Summary of results

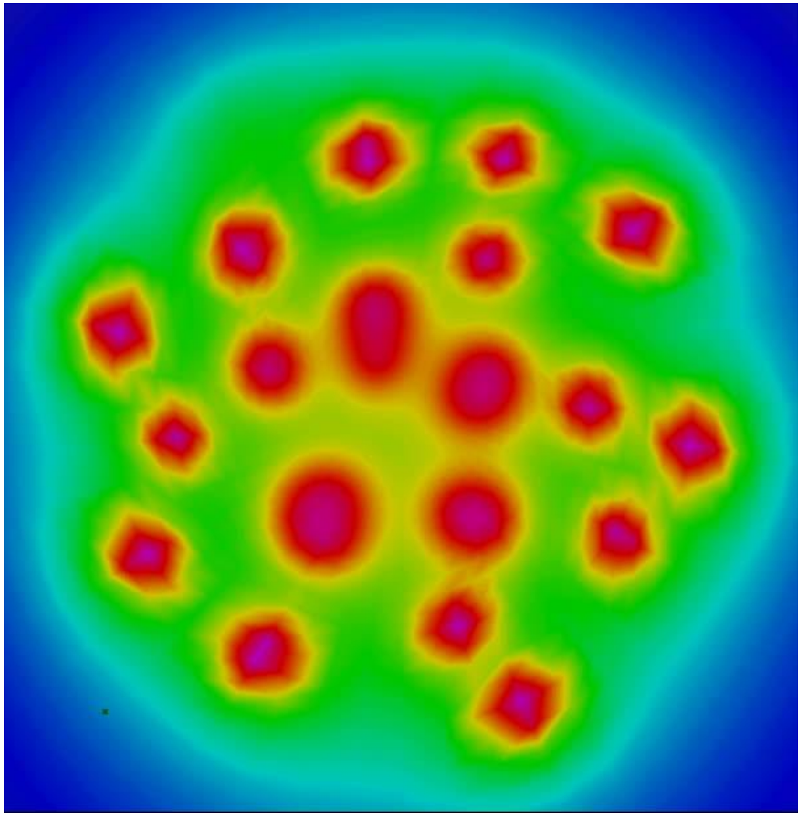
- **A new and important class of solutions exists even in the most basic models of DC gas discharges**.
- **Basic processes in the near-cathode space-charge sheath are sufficient to produce self-organization**.
- In spite of physical mechanisms of discharges on cold (glow) and hot (arc) cathodes being very different, **the multiple modes on cold and hot cathodes fit into the same pattern**: self-organization in bi-stable nonlinear dissipative systems.
- **A theory of diffuse and spot modes of current transfer to arc cathodes** has gone through a detailed experimental validation and **proved relevant for industrial applications.**
- **Multiple solutions computed in the theory of glow discharges agree with the experiment** as well. The comparison has been merely qualitative up to now but the agreement is convincing.
- Discharges may exhibit **complex behavior in apparently simple situations** where multiple solutions are not of primary concern.

A lot has been done during the last 15 years…

The results shown up to now represent just a part of a vast set of experimental, theoretical and modelling data on spots and patterns on electrodes of gas discharges obtained recently by various groups:

- Mentel and coworkers;
- Schoenbach and coworkers;
- Boeuf and coworkers;
- Raizer and Mokrov;
- Purwins and coworkers;
- Heberlein and coworkers;
- …

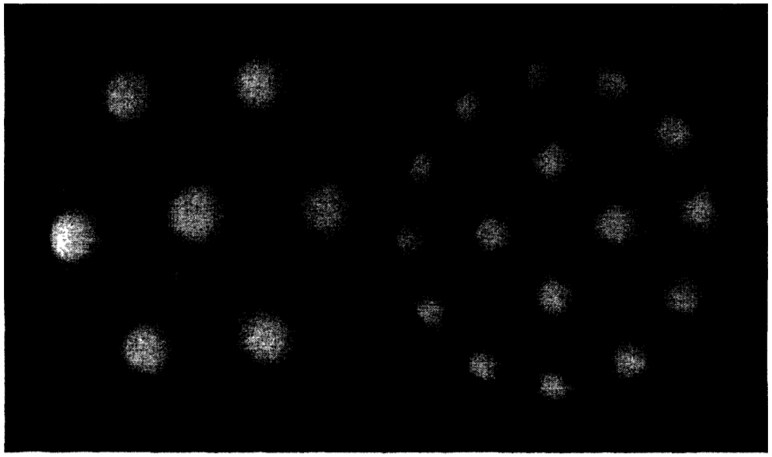
However, **there are still many more questions than answers!**



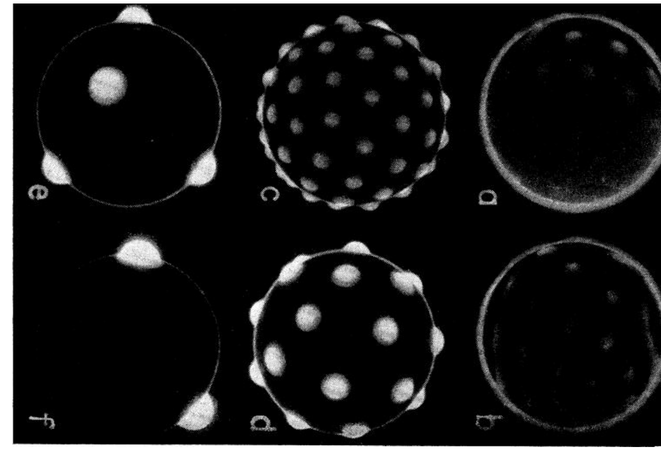
Numerical simulation of anode spots. Free-burning Ar arc, 1 bar, 100 A. From J. P. Trelles 2014.

There are more questions than answers…

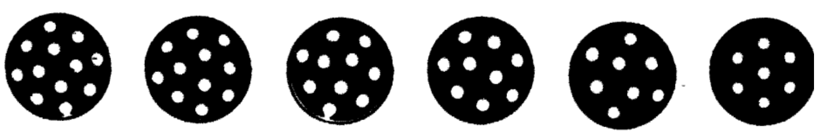
Spot patterns on anodes of dc glow discharges



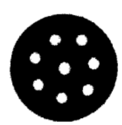
From C. H. Thomas and
O. S. Duffendack 1930.



From S. M. Rubens and
J. E. Henderson 1940.



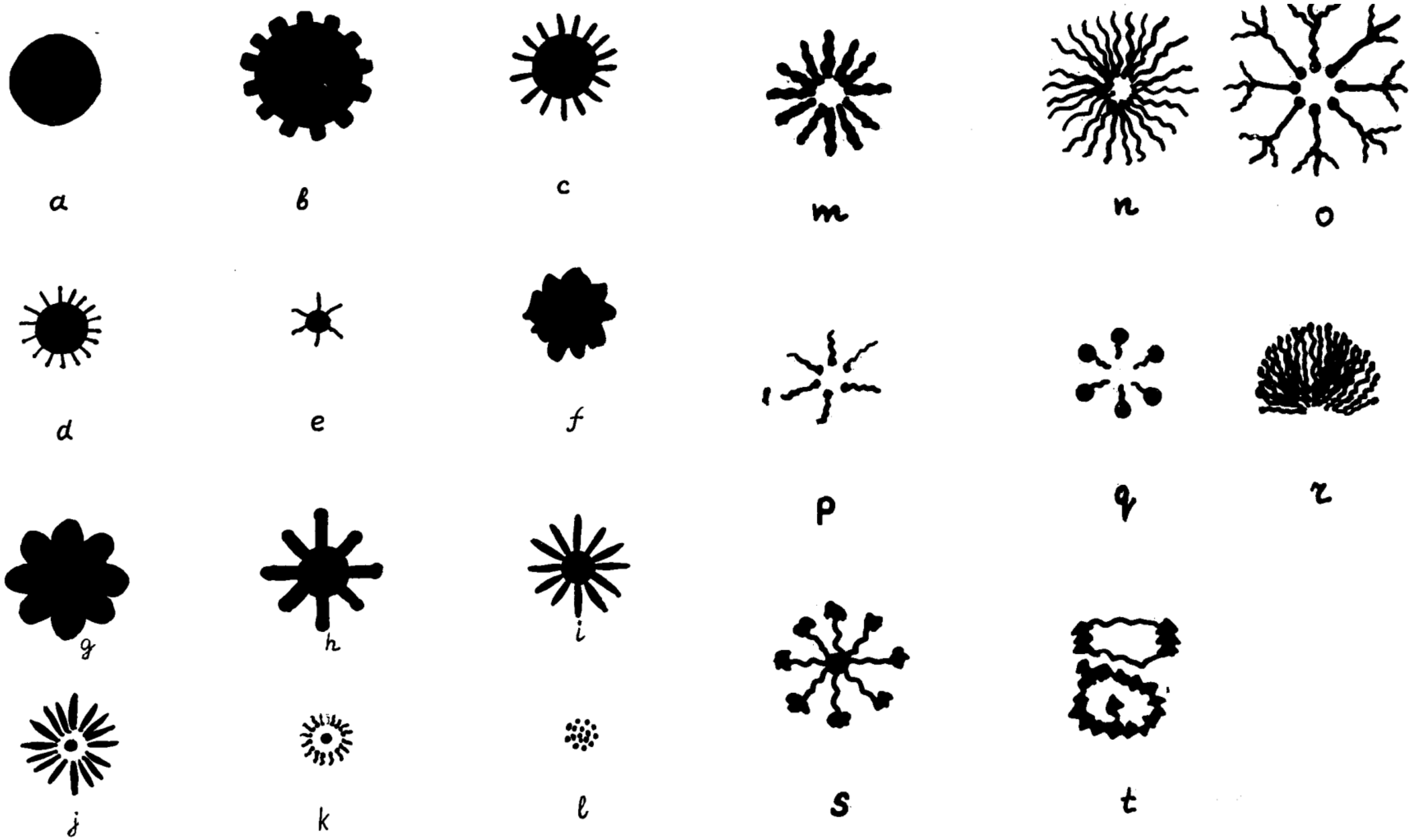
From K. G. Mueller 1988.



From V. I. Arkhipenko
et al 2013.

There are more questions than answers…

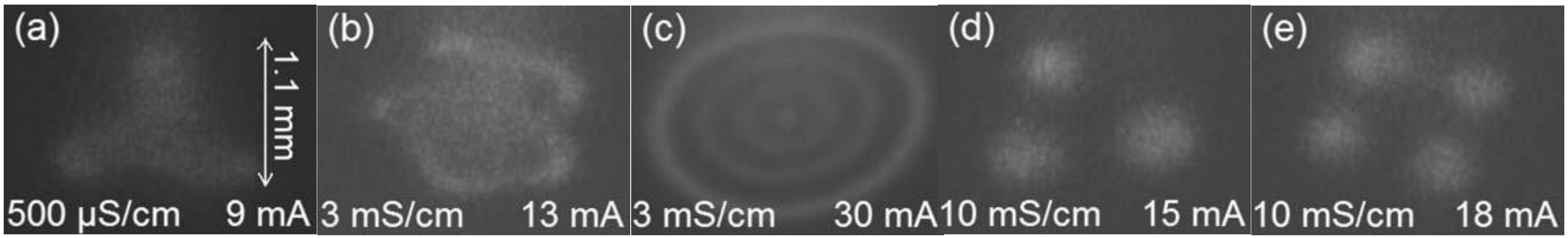
Spot patterns on liquid cathodes of glow discharge

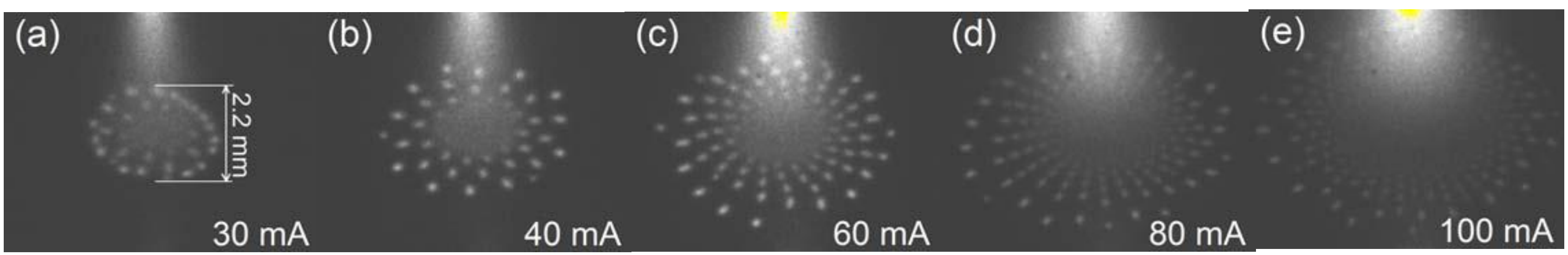


From F. M. Gaysin and E. E. Son 1989 and F. M. Gaysin, E. E. Son, and V. D. Shakirov 1990.

There are more questions than answers…

Spot patterns on liquid anodes of glow discharge

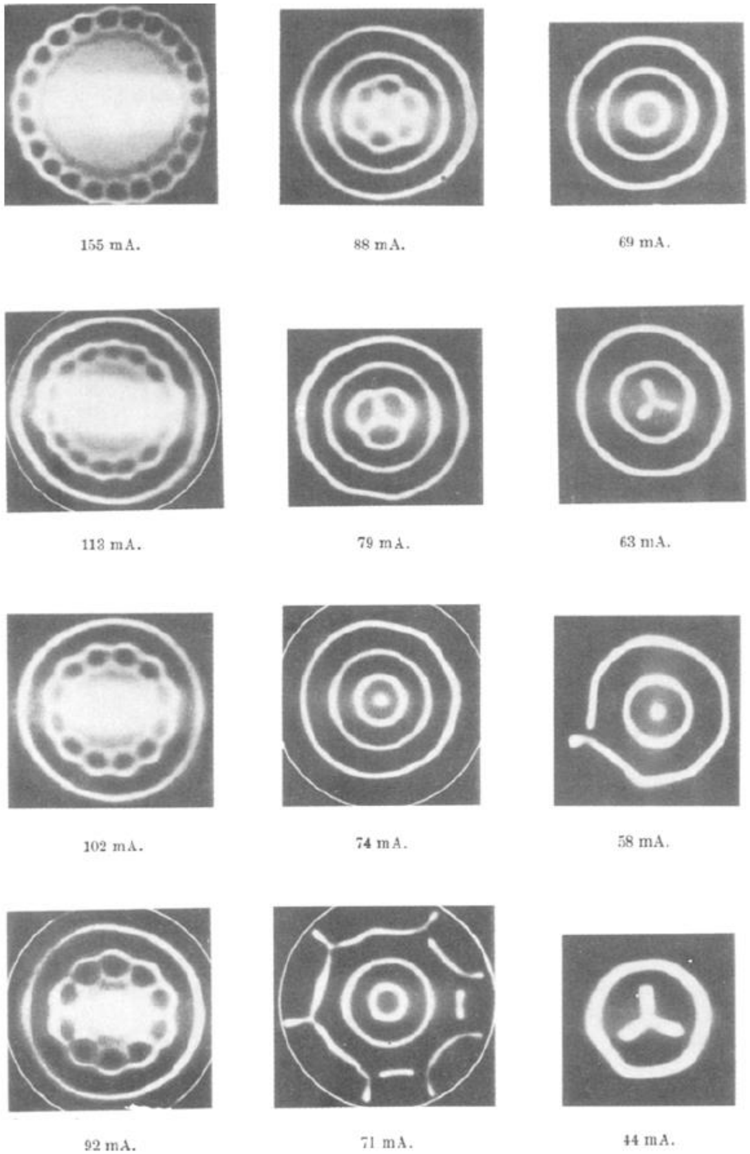




From T. Verreycken, P. Bruggeman, and C. Leys 2009.

There are more questions than answers…

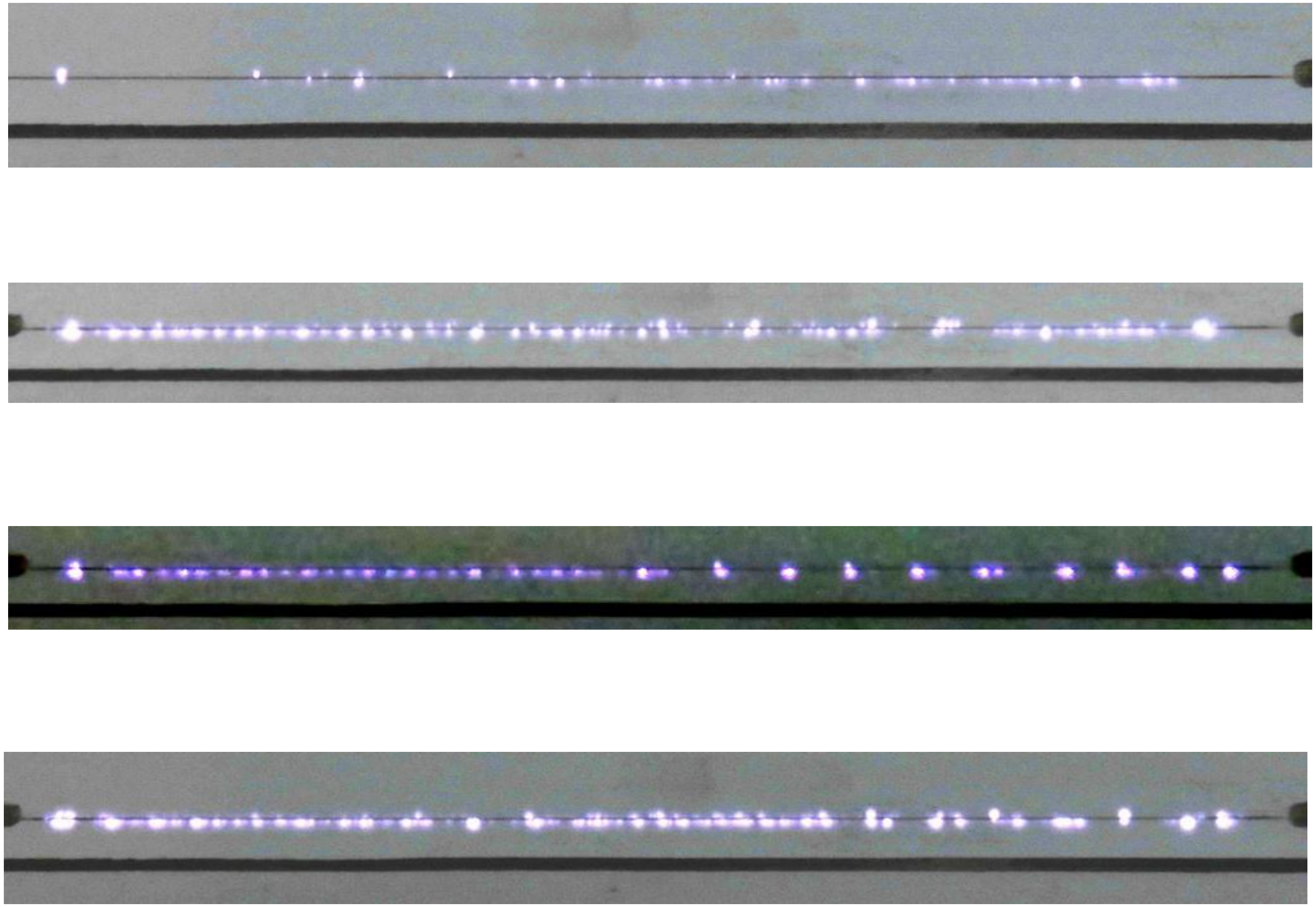
Spot patterns on anode of a low-current low-pressure arc discharge



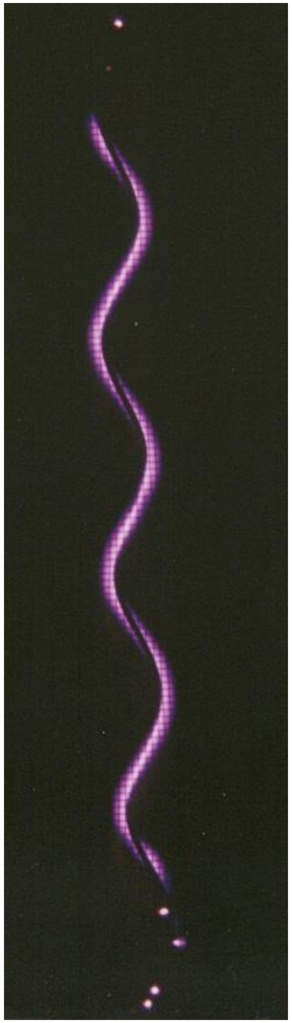
From A. Güntherschulze, W. Bär, and H. Betz 1938.

There are more questions than answers…

Tufts on negative corona electrodes



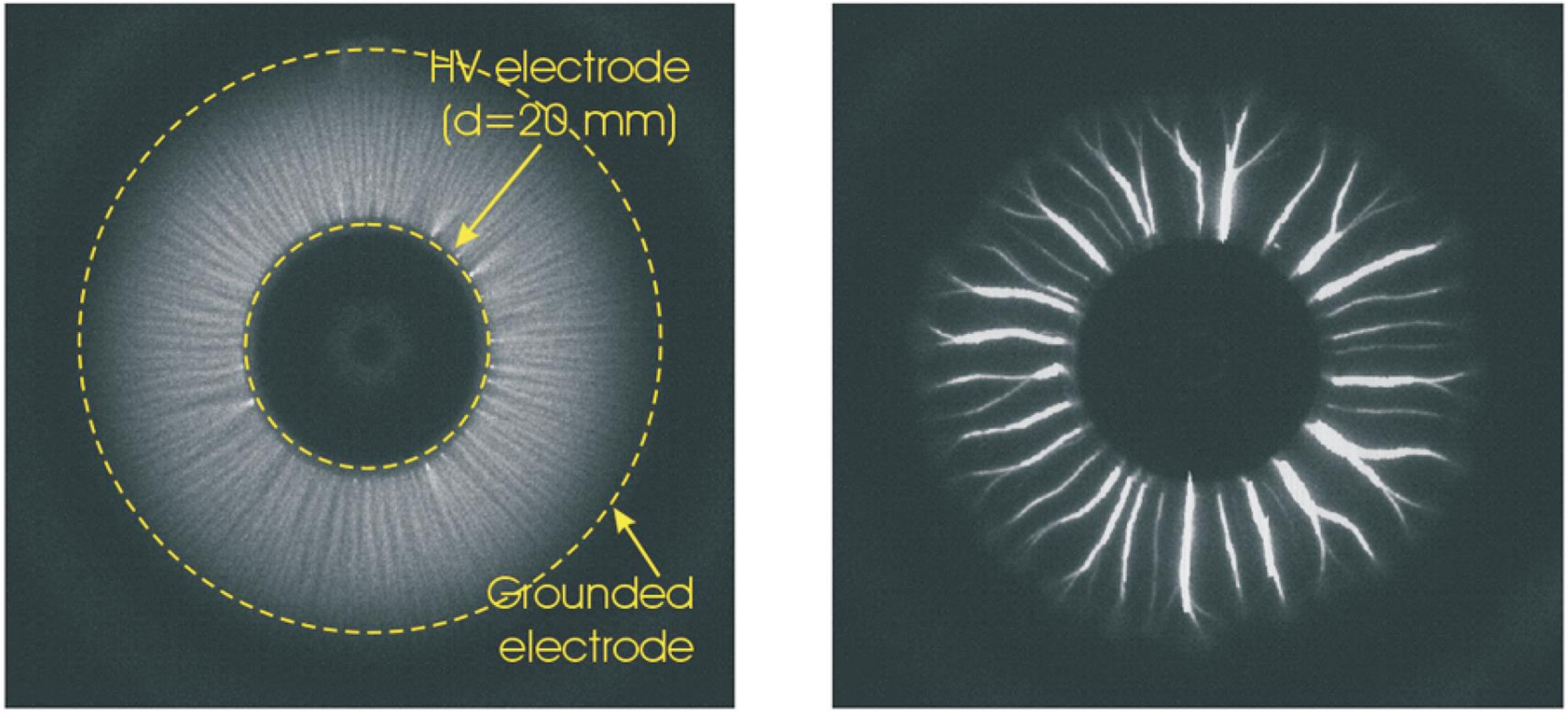
From A. F. Gutsol and W. R. Pyle 2014.



From W. Egli *et al* 1994.

There are more questions than answers…

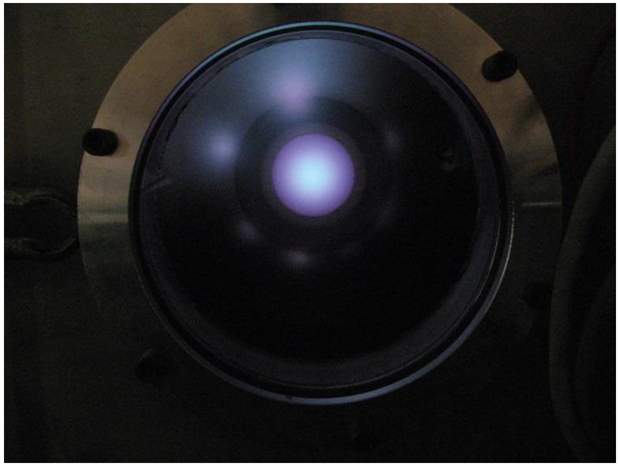
A regular filamentary structure in a negative polarity nanosecond surface DBD

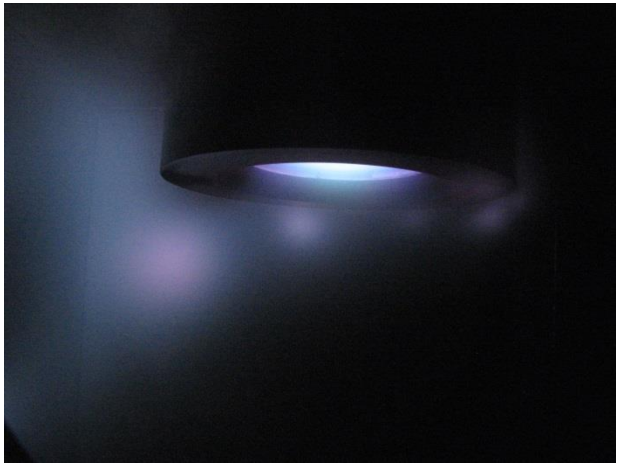


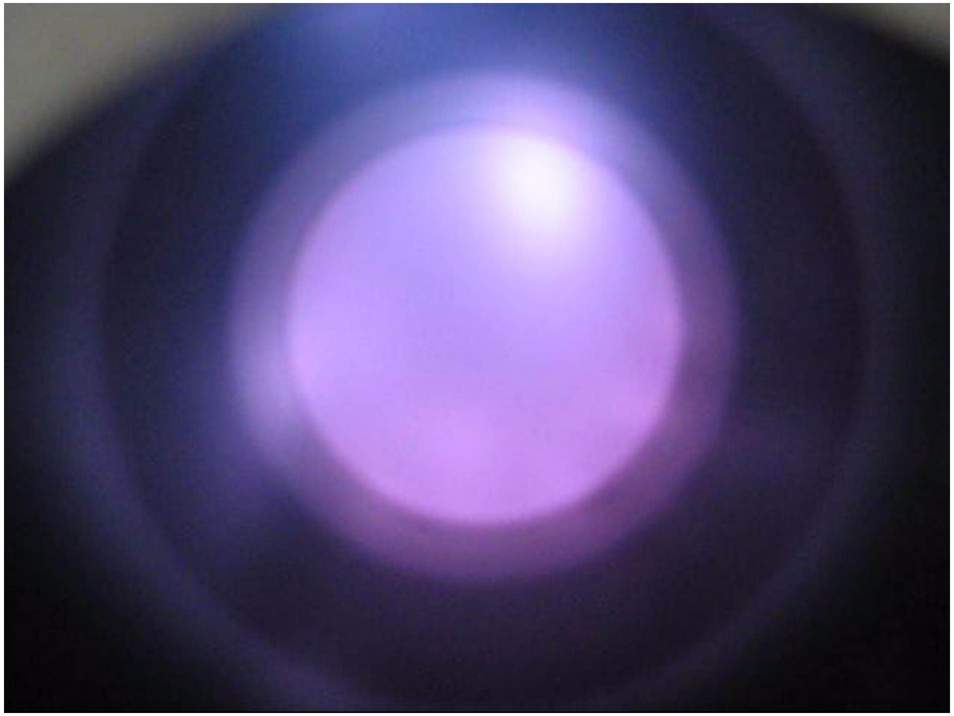
Two phases of a negative polarity nanosecond surface DBD in air. 5 bar, - 52 kV. From S. A. Stepanyan, A. Yu. Starikovskiy, N. A. Popov, and S. M. Starikovskaia 2014.

There are more questions than answers…

Spot patterns in a pulsed rf discharge







From M. Voronov *et al* 2014.

There are more questions than answers…

Further examples:

2012 Impact Factor: 2.515

The research field is highly interesting, important for applications, and largely unexplored!

IOP Publishing — Plasma Sources Science and Technology

Plasma Sources Sci. Technol. **22** (2013) 050401 (1pp) — doi:10.1088/0963-0252/22/5/050401

CALL FOR PAPERS

Cluster issue on ‘Spots and patterns on electrodes of gas discharges’

Guest Editors
Mikhail S Benilov
Universidade da Madeira, Portugal

Ulrich Kogelschatz
Retired from ABB Corporate Research, Switzerland

Concentration of electrical current onto the surface of electrodes of gas discharges in well-defined patterns, or current spots, is often the rule rather than the exception. These patterns occur on otherwise uniform electrode surfaces, a regime where one might expect a uniform distribution of current over the surface. In some cases, multiple spots may appear, forming beautiful regular patterns and surprising the observer. The appearance of current spots on electrodes is a phenomenon of high scientific interest and significant importance for applications. *Plasma Sources Science and Technology* is delighted to announce a forthcoming cluster of papers entitled ‘Spots and patterns on electrodes of gas discharges’, to appear in the summer of 2014.

Papers are invited that report on experimental, first-principles theoretical and/or computational investigations on

- all types of electrical discharges, including, for example, dc glow, RF, arc, corona and DBD,
- all classes of electrodes, including bare metal, semiconductor, liquid, dielectric covered metal,
- all varieties of spots and patterns that are self-organized—that is, patterns that are unrelated to non-uniformities of the electrode surface or applied voltage.

Both regular papers and brief communications reporting new experimental, theoretical or computational results are welcome.

You are invited to submit your paper by 17 January 2014. Submissions received after this date will be considered for the journal, but may not be included in the cluster. All submitted papers will be fully refereed to the journal’s usual high standards and corresponding authors whose papers are published in the cluster will receive a complimentary copy. Upon publication, the cluster will be widely promoted to the gas discharge community, ensuring that your work receives maximum visibility.