Plasma-physics aspects of high-intensity discharge lamps

Mikhail Benilov

Departamento de Física, FCEE, Universidade da Madeira, Portugal

Instituto de Plasmas e Fusão Nuclear, IST, Universidade de Lisboa, Portugal

Summer school on plasma physics PlasmaSurf 2016

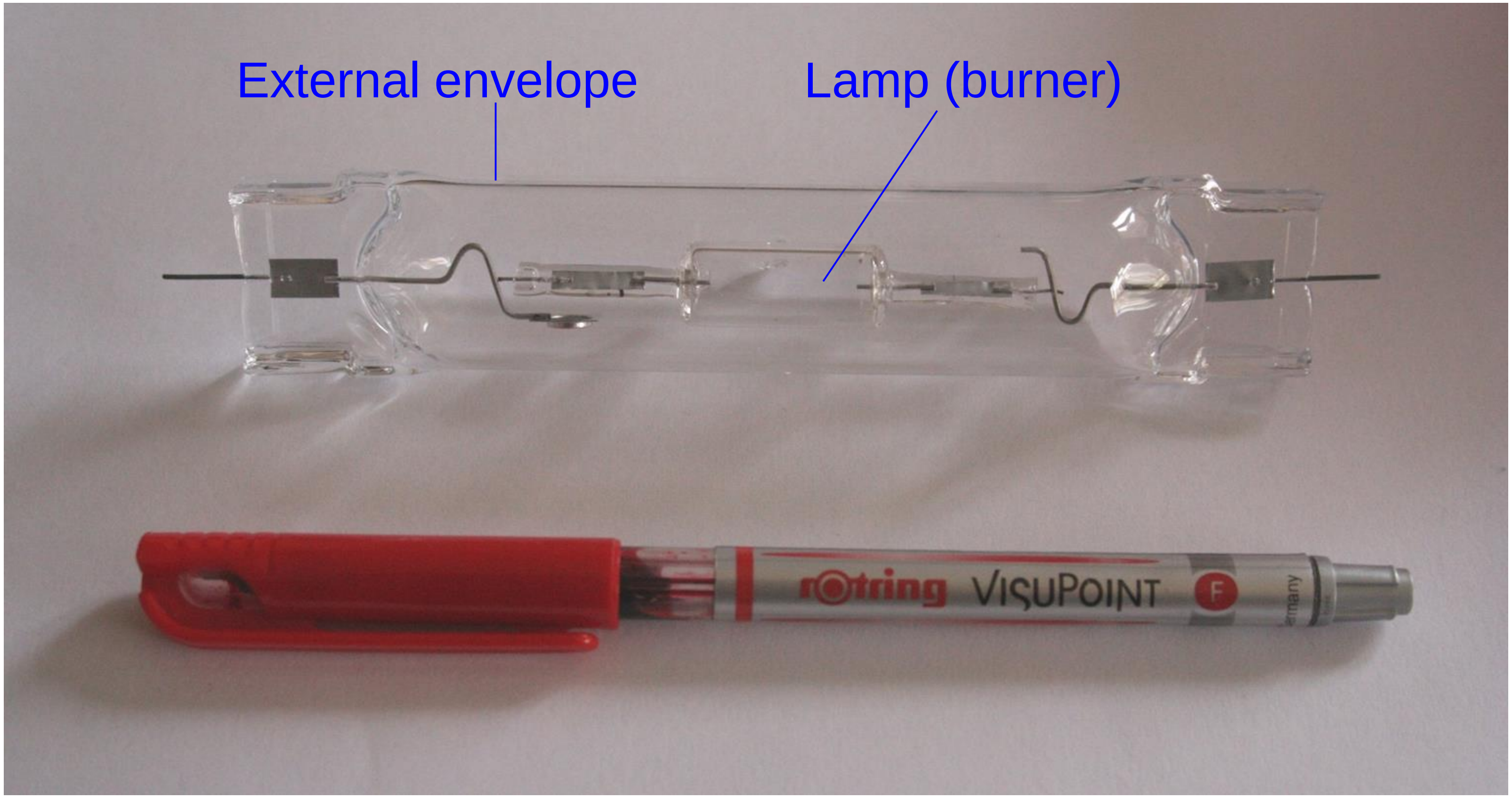
Oeiras, July 15, 2016

Contents of the talk

- Gas discharge lamps
- Plasmas in gas discharge lamps
- Usage of gas discharge lamps
- Fundamental and/or applied research for lighting
- Instability in xenon lamps
- Theory of current spots on cathodes of high-pressure arcs
  - The idea
  - Connection to self-organization in bi-stable nonlinear dissipative systems and a complete theory
  - Applications: MH lamps for street illumination, UHP lamps, arc welding, high power circuit breakers

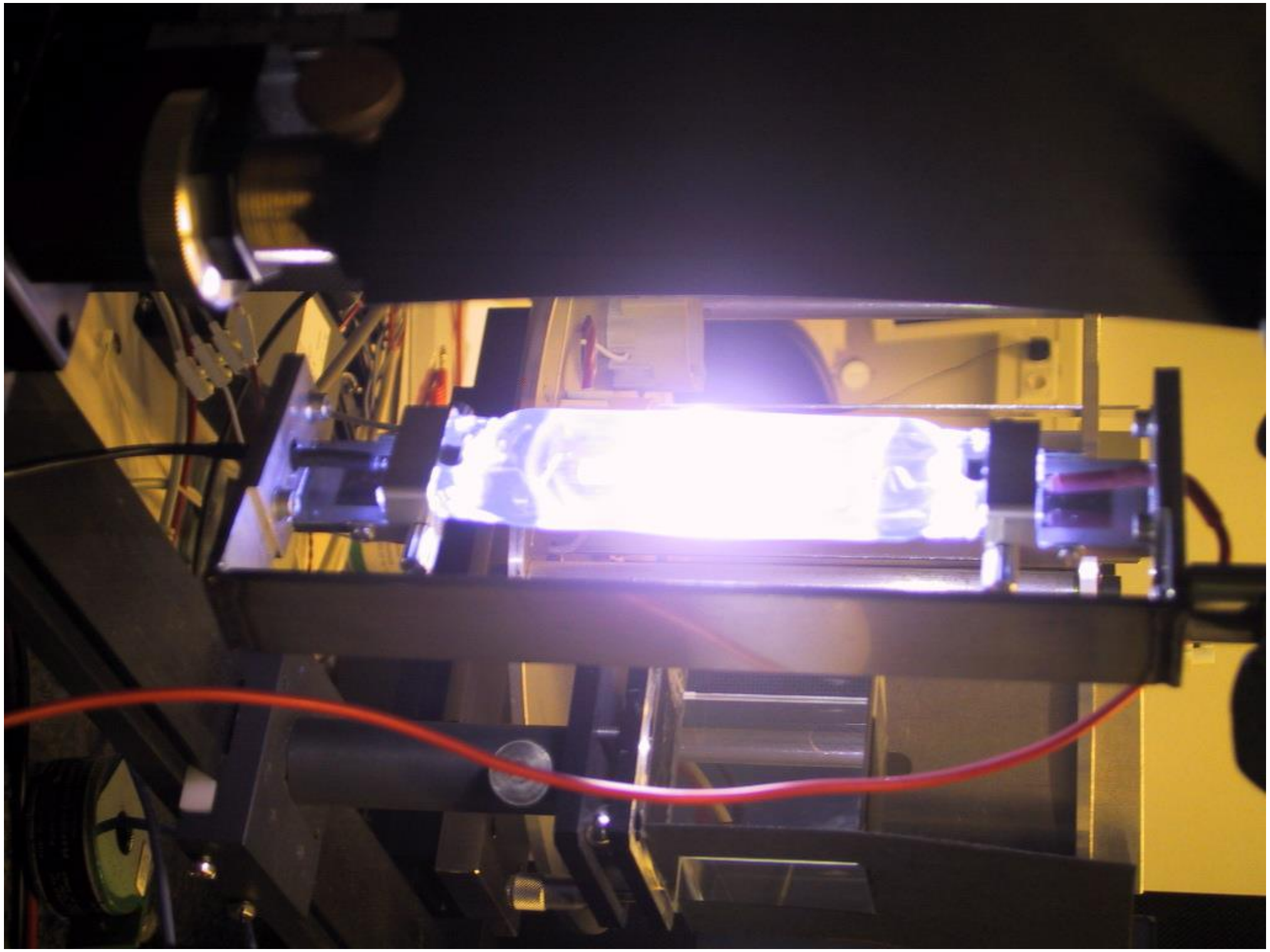
Gas discharge lamps

Example: a high-pressure gas discharge lamp



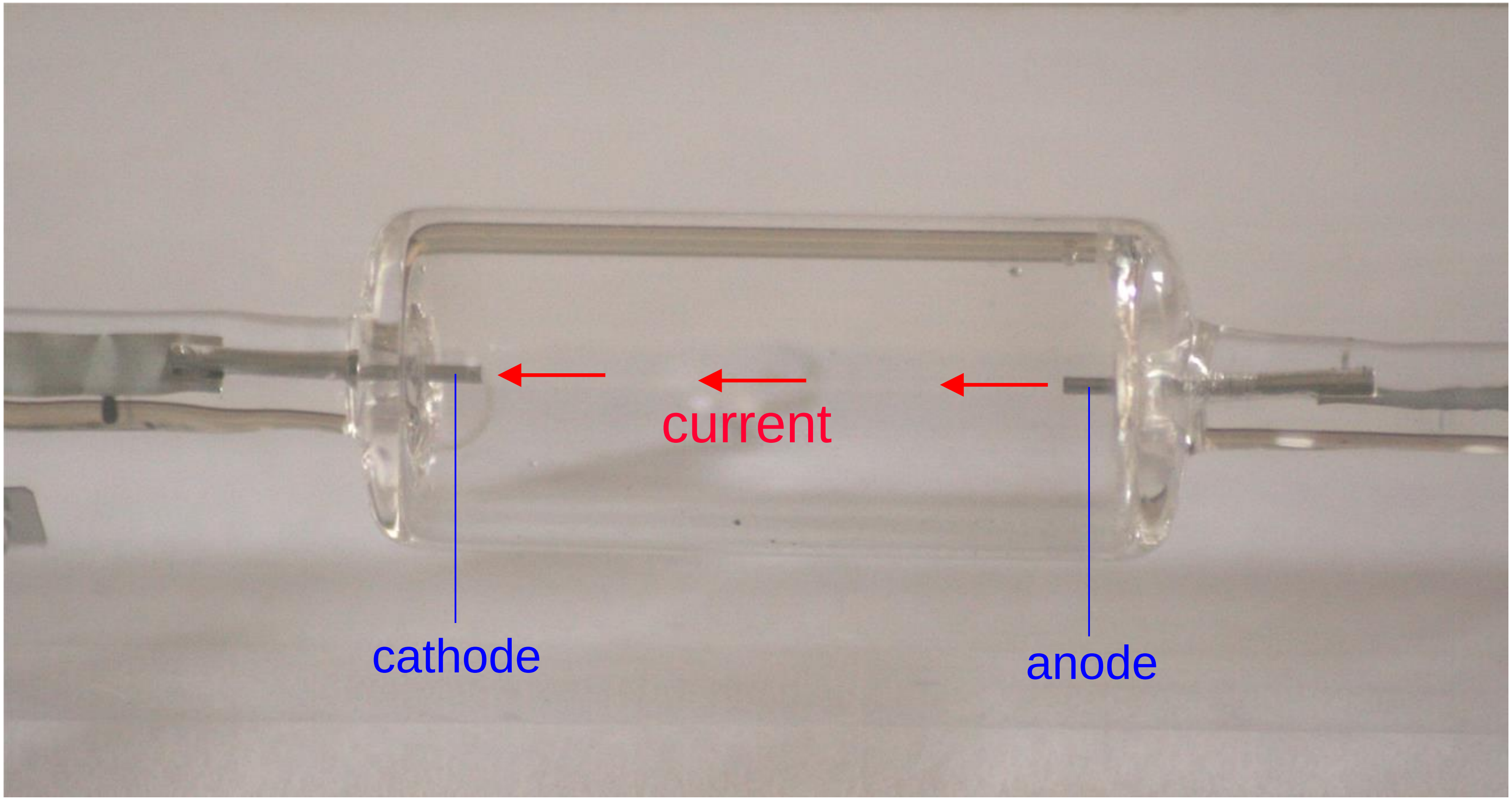
Standard lamp COST-529 supplied by Philips

Gas discharge lamps



Standard lamp COST-529 supplied by Philips

Gas discharge lamps



Burner of the standard lamp COST-529 supplied by Philips

Gas discharge lamps

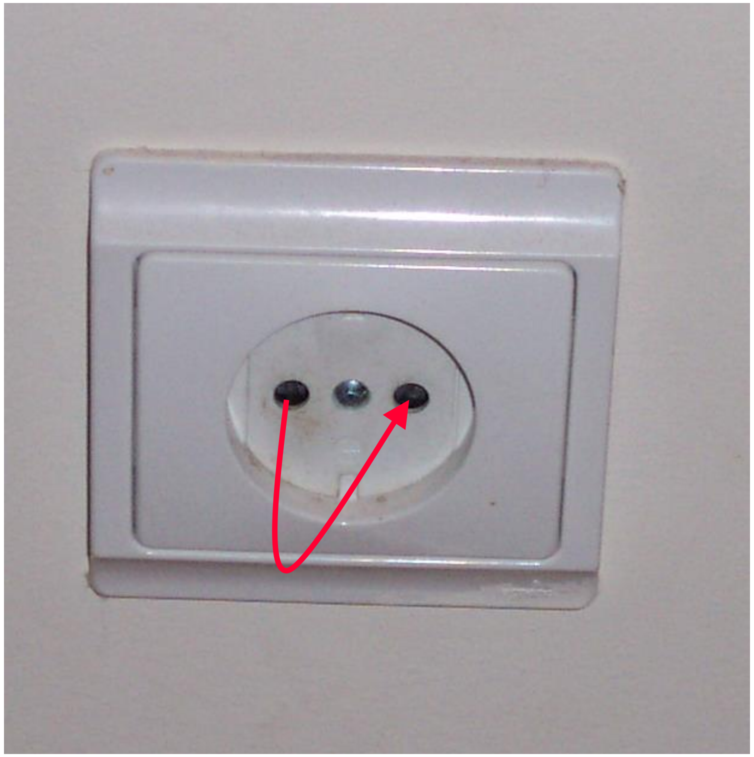
- **An incandescent lamp**: a **solid** conductor carries electric current, is heated by the current and emits light.

- **A gas discharge lamp**: a **gaseous** conductor carries electric current, is heated by the current and emits light.

Univ. Madeira
ipfn INSTITUTO DE PLASMAS E FUSÃO NUCLEAR
FCT Fundação para a Ciência e a Tecnologia

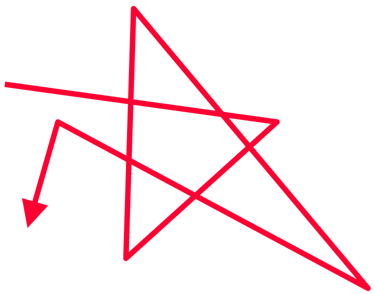
Plasmas in gas discharge lamps

Can a gas conduct electricity?



Plasmas in gas discharge lamps

- The molecules in gases perform a chaotic movement.
- Under normal conditions, each molecule undergoes around 10^{10} collisions per second.



- If the kinetic energy of the relative motion of the particles is higher than the ionization energy, it may happen that a particle becomes ionized after collision:

$$A + A \rightarrow A^{+} + e + A$$

- The probability of ionization is higher in collisions between a neutral particle and an electron:

$$A + e \rightarrow A^{+} + e + e$$

- If the amount of ions and electrons in a gas is not too small, the gas is able to conduct electricity: a plasma.

Plasmas in gas discharge lamps

One way to create a plasma is to heat a gas by means of an electric field applied to the gas. Heat is produced due to the Joule effect:

$$P = jE \qquad j = j_i + j_e \Rightarrow P = j_i E + j_e E$$

$$m_e \ll m_i \Rightarrow j_e \gg j_i \Rightarrow P \approx j_e E$$

Power is supplied by the electric field mainly to the electrons, which transfer a part of this energy to the heavy particles, i.e., atoms and ions. The transfer occurs through collisions.

- If the pressure is high, collisions between electrons and heavy particles are frequent. The energy transfer is effective $\Rightarrow T_e \approx T_{heavy\ particles}$. The plasma is called **thermal**.
- If the pressure is low, $T_e > T_{heavy\ particles}$. The plasma is called **non-equilibrium**.

Ionization can also be produced by an external radiation (cosmic rays, high-intensity X-rays, radiation from a nuclear reactor). Such plasmas are also non-equilibrium.

Plasmas in gas discharge lamps

Example: ionization degree of Ar thermal plasma at 1 atm

T	500	5000	10000	20000	30000
ω	0.78×10^{-79}	0.39×10^{-06}	0.87×10^{-02}	0.89	1
x_+	1	1	1	0.99	0.21
x_{++}	0	0.43×10^{-18}	0.92×10^{-8}	0.86×10^{-2}	0.77
x_{+++}	0	0.11×10^{-49}	0.21×10^{-22}	0.37×10^{-07}	1.8×10^{-2}

$$x_+ = \frac{n_+}{n_i}, \qquad x_{++} = \frac{n_{++}}{n_i}, \qquad x_{+++} = \frac{n_{+++}}{n_i}$$

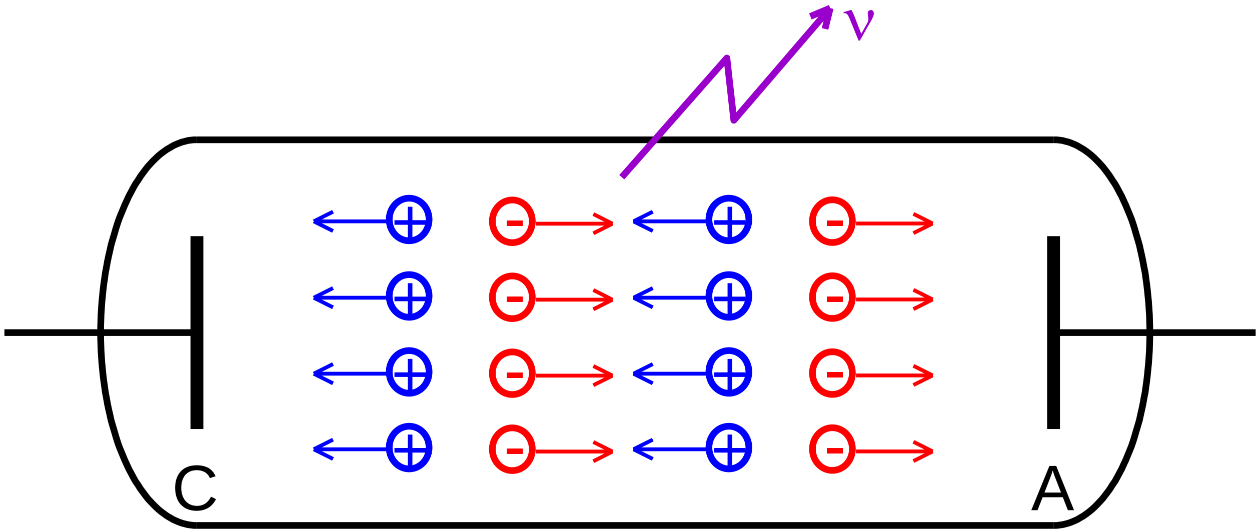
$$\omega = \frac{n_i}{n_i + n_a}$$

General classification of plasmas

- Plasmas
  - Plasmas in nature
    - Space plasmas
    - Plasmas of lightning
  - Artificial plasmas
    - Low-temperature plasmas
      - Thermal plasmas
      - Non-equilibirium plasmas
    - Fusion plasmas

Of course, the term "**low-temperature plasma**" should not be understood literally. For example, a thermal plasma produced by an arc torch has a temperature of about 20,000 K, but belongs to the class of low-temperature plasmas. **This temperature is low only in comparison to the temperature of nuclear fusion plasmas.**

Plasmas in gas discharge lamps



High-pressure lamps

Thermal plasma

Arc discharge

p = 5...200 bar

T = 5,000-7,000 K

Fluorescent lamps

Non-equilibrium plasma

Glow discharge

p = 0.3% bar

T_e = 1 eV, T_h = 300–700 K

Usage of gas discharge lamps

World lamp market

Annual lamp sales in EU (2004): 1.8 billion.

Number of lamps operating in EU (2004): 3.3 billion.

Number of lamps operating in the world: > 7.5 billion.

Fraction of the electrical power used for public lighting

- 9-12% in developed countries except the US for which about 21% (Las Vegas!)
- It is much higher in developing countries (for example, 31% in Tunisia and still more in Tanzania)
- 20% is the global average.

Usage of gas discharge lamps

High-pressure lamps (high-intensity discharge, or HID, lamps; high-intensity lamps; arc lamps; …)

- Contain a combination of gases: a buffer gas, usually Hg (plus a trace of an inert gas) or Xe, plus elements chosen to generate a good color-quality light.

    Example: Metal halide lamps use a mixture of molecular and atomic species composed of Hg and (some of) the following elements: Hg, Na, Tl, Dy, Sc, Cs, I, and Ar. The most important neutral species are typically Hg, Na, Tl, Cs, Dy, Sc, I, NaI, TlI, CsI, DyI, DyI_2, DyI_3, ScI, ScI_2, ScI_3.

- Are used for:

    - public places illumination, including streets;
    - projection applications;
    - car headlights;
    - …

Fluorescent lamps

- Are mainly used for indoor lighting.
- Cannot operate at high powers (these lamps operate with the glow discharge which transits into the arc discharge at high currents).

Usage of gas discharge lamps

Lamp types and their typical characteristics

Source: Annex 45, Int. Energy Agency, 2010.
GLS = general lighting service = standard incandescent light-bulb.

The limit value of the lamp efficiency is 390 lm/W => still a long way to go ...

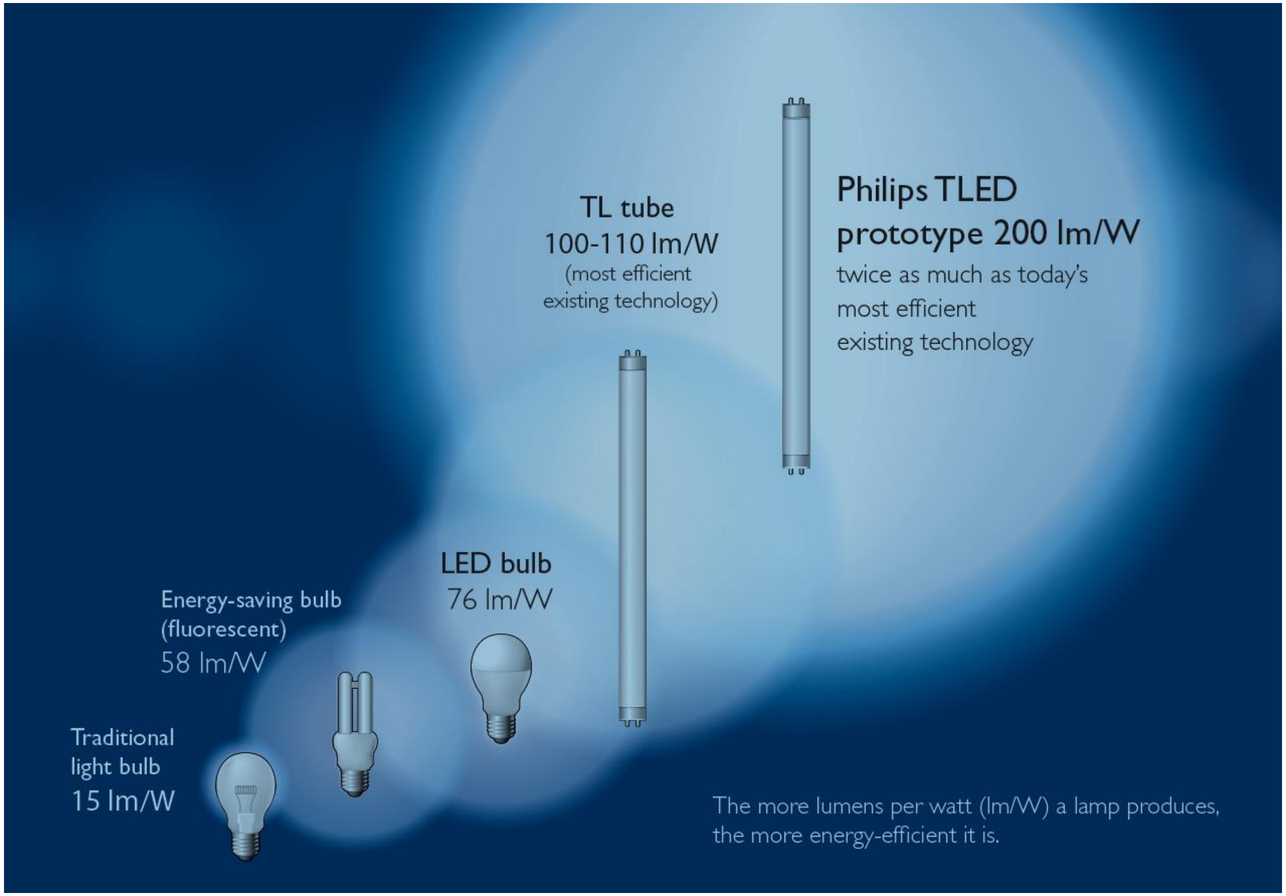
Lamp type	Characteristics							
	Luminous efficacy (lm/W)	Lamp life h	Dimming control	Re-strike time	CRI	Cost of installation	Cost of operation	Applications
GLS	5-15	1000	excellent	prompt	very good	low	very high	general lighting
Tungsten halogen	12-35	2000-4000	excellent	prompt	very good	low	high	general lighting
Mercury vapour	40-60	12000	not possible	2-5 min	poor to good	moderate	moderate	outdoor lighting
CFL	40-65	6000-12000	with special lamps	prompt	good	low	low	general lighting
Fluorescent lamp	50-100	10000-16000	good	prompt	good	low	low	general lighting
Induction lamp	60-80	60000-100000	not possible	prompt	good	high	low	places where access for maintenance is difficult
Metal halide	50-100	6000-12000	possible but not practical	5-10 min	good	high	low	shopping malls, commercial buildings
High pressure sodium (standard)	80-100	12000-16000	possible but not practical	2-5 min	fair	high	low	Outdoor, streets lighting, warehouse
High pressure sodium (colour improved)	40-60	6000-10000	possible but not practical	2-6 min	good	high	low	outdoor, commercial interior lighting
LEDs	20-120	20000-100000	excellent	prompt	good	high	low	all in near future

Usage of gas discharge lamps

Competition: LEDs

- Several companies have managed to exceed the limit of **200 lm/W** (Philips Lumileds, Osram, Cree ...)

- **But the unit power is low, the price is high, and the brightness is low** (yet?) => the use is not universal ...

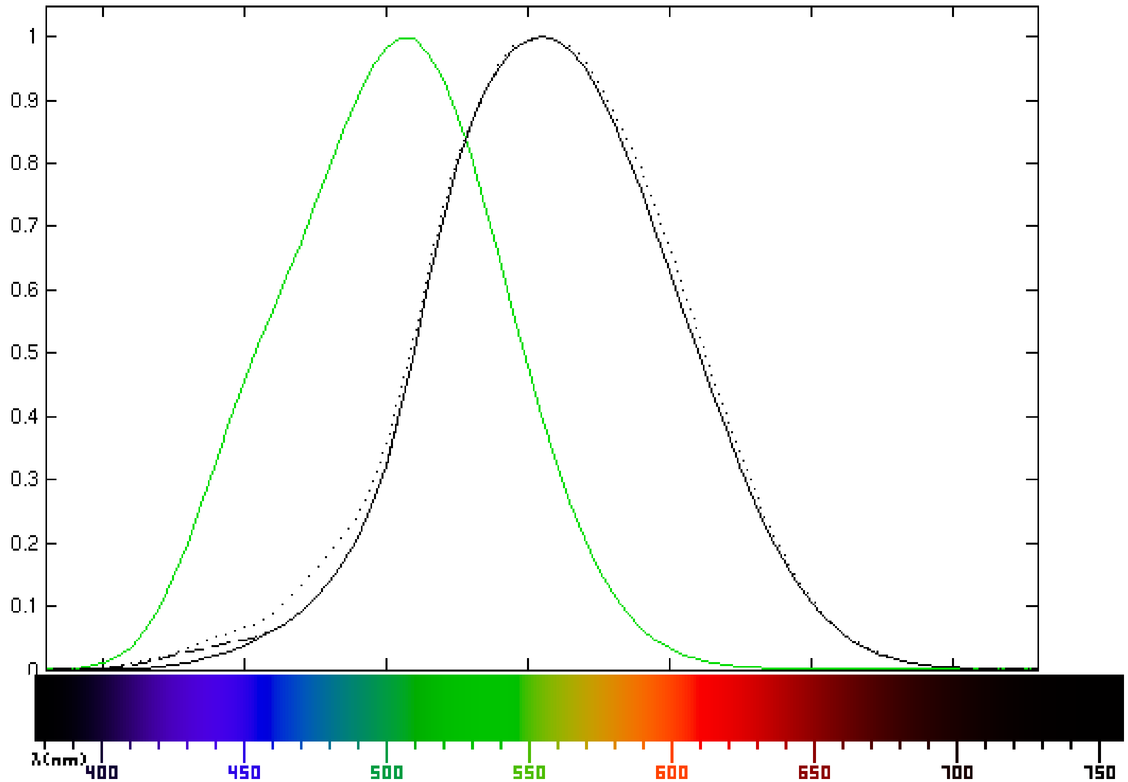


Btw: why do some people complain that LEDs give less light?

- A reasonable-quality 40 W incandescent lamp provides 40 W x 12 Lm/W = 480 Lm > 400 Lm!
- A reasonable-quality 65 W incandescent lamp provides 65 W x 12 Lm/W = 780 Lm > 670 Lm!

Btw: how relevant is the number of lumens?

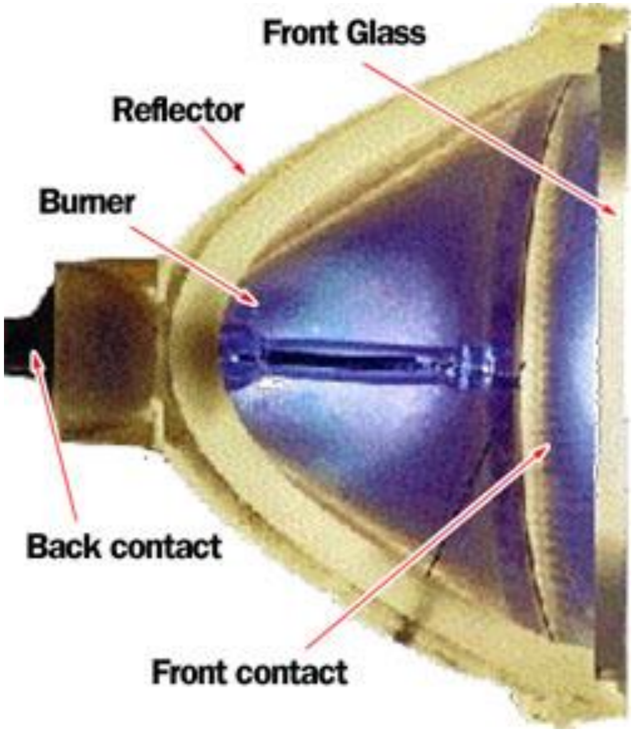
- Lumens: a quantity of (visible) light = radiation flux integrated over the spectrum of present wavelengths weighted with the standard luminosity function (**photopic!**)



Black: **photopic luminosity** function including CIE 1931 (solid), Judd-Vos modified (dashed), and Sharpe, Stockman, Jagla & Jägle 2005 (dotted). Green: **scotopic luminosity** function, CIE 1951.

Usage of gas discharge lamps

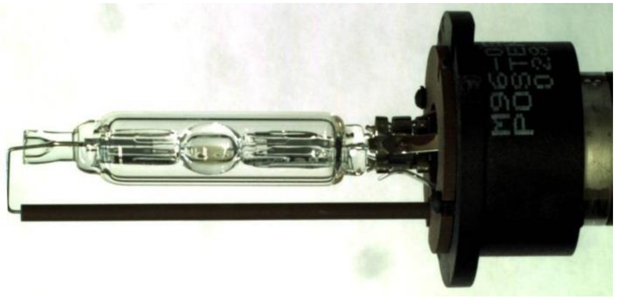
UHP (Ultra High Performance/Pressure) Lamps

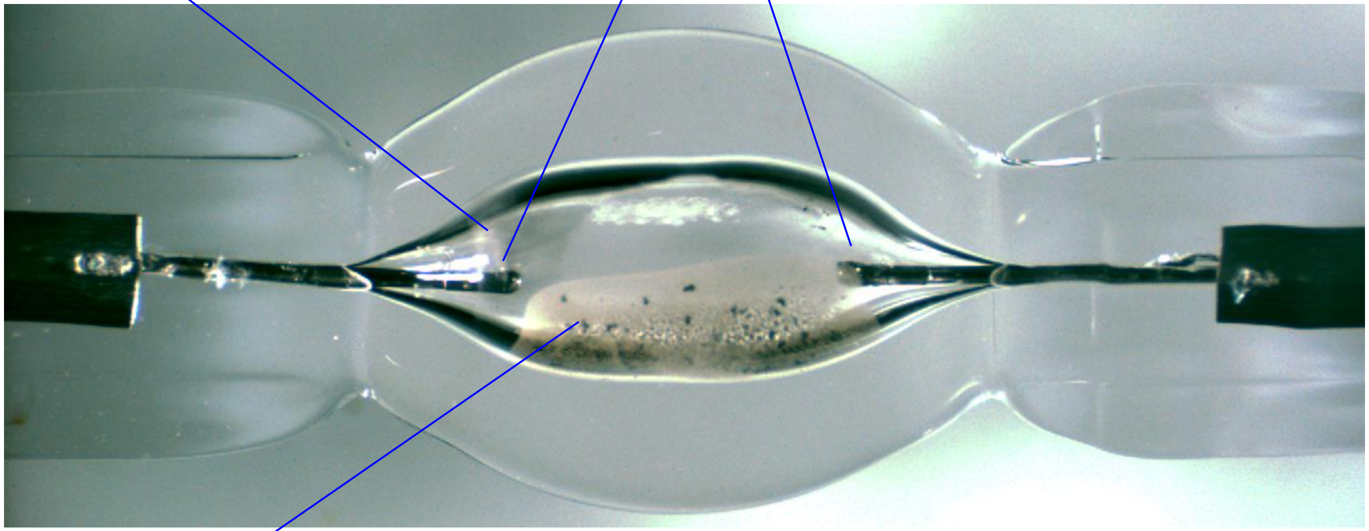


- Pure mercury vapor, 200 bar, the arc gap typically 0.7 to 1.3 mm.
- Compactness, outstanding arc luminance (**brighter than the sun!**), a well suited spectrum, long life, …
- The UHP lamp is the ideal light source for projection applications.

Usage of gas discharge lamps

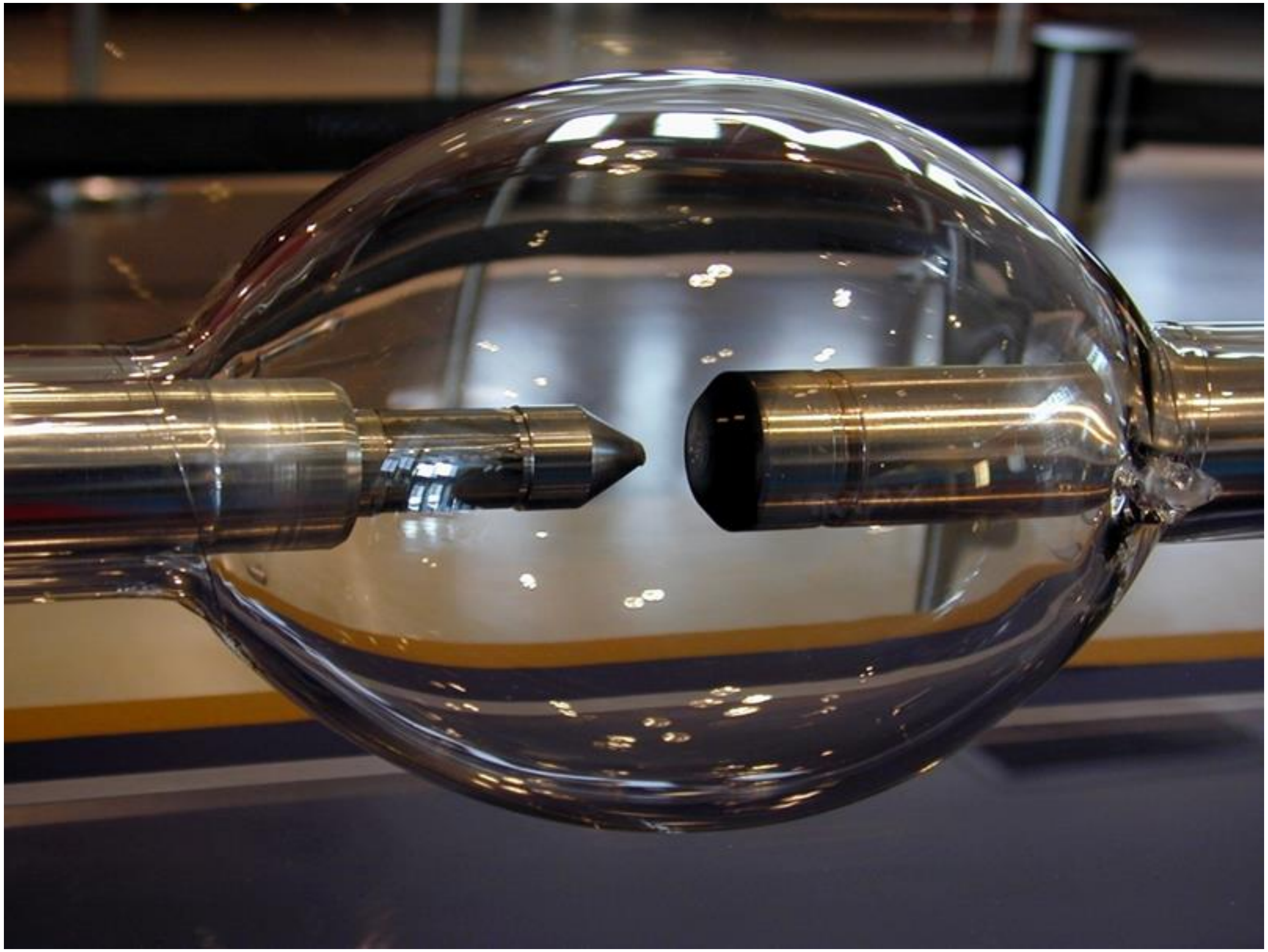
Car Headlights





XenEco automotive lamps of Philips (35W).

Usage of gas discharge lamps



15 kW xenon short-arc lamp used in IMAX projectors.

Fundamental and/or applied research for industrial needs

- The word “plasma” was introduced for designation of an ionized gas in the famous 1928 paper of Irving Langmuir.

- From 1909 to 1957, Langmuir conducted fundamental research while working at GE.

Vol. 14, 1928 PHYSICS: I. LANGMUIR 627

cisely the plane grating formula. It will be noted that, with the exception of two, all of the points fall to the right of the regions of "anomalous dispersion," and that none of them falls in this region. It is due to this circumstance presumably that the displacements of the electron diffraction beams from their x-ray analogues display no marked abnormalities. It will be noted also that although the values of μ calculated from the diffraction beams are rather scattered they are not inconsistent with the dispersion curve constructed from the more precise data of the reflection beams.

[1] Davisson and Germer, *Proc. Nat. Acad. Sci.*, **14**, 317 (1928).
[2] Davisson and Germer, *Nature*, **119**, 558 (1927); *Phys. Rev.*, **30**, 705 (1927).
[3] Eckart, *Proc. Nat. Acad. Sci.*, **13**, 460 (1927).
[4] Bethe, *Naturwiss.*, **15**, 787 (1927).
[5] Bethe, *Ibid.*, **16**, 333 (1928).
[6] Andrewes, Davies and Horton, *Proc. Roy. Soc.*, **117**, 660 (1928).

OSCILLATIONS IN IONIZED GASES

By Irving Langmuir

Research Laboratory, General Electric Co., Schenectady, N. Y.

Communicated June 21, 1928

In strongly ionized gases at low pressures, for example in the mercury arc, the free electrons have a Maxwellian velocity distribution correspond-

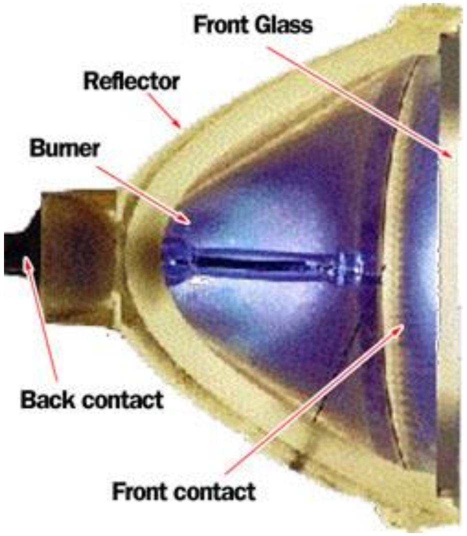
Paper by Irving Langmuir in Proc. Nat. Acad. Sci.

Fundamental and/or applied research for industrial needs

- It is amazing how little sometimes need engineers to know about underlying physics in order to develop an excellent product!

Ultra High Performance/Pressure Lamps

- What is the dominating mechanism of production of light?
- Motivation of the inventor: dimers Hg_2 will be formed at very high pressures, and these **dimers will effectively radiate**.
- It was found later that for mercury pressures of 200 bar or above **more light is emitted in the continuum radiation** than in spectral lines!



Fundamental and/or applied research for industrial needs

- *In principle, given all our diagnostic possibilities, we thought that we could pin down the essential parameters just by varying all kinds of parameters and observing if that removed the problem or not. However, the lamp is so complicated that it has too many status variables – the approach did not work out, so far.*

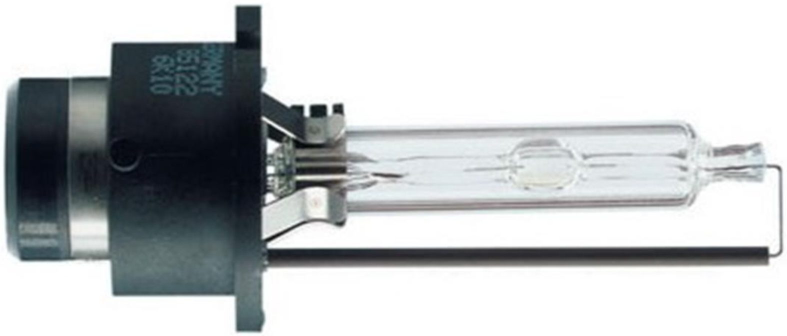
From a letter from an industrial physicist

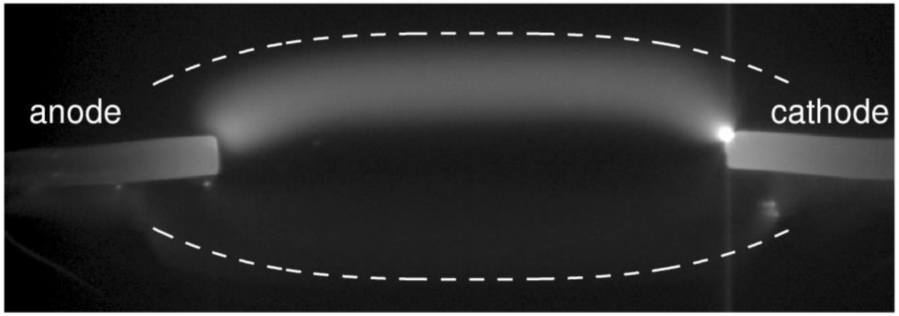
- Physicists from academia can help the industry by:

  - identifying underlying physical mechanisms;
  - developing detailed computational models capable of describing complex phenomena on the basis of first principles without invoking empirical and/or fit parameters

=> **application-oriented fundamental research**.

Instability in high-pressure xenon arcs

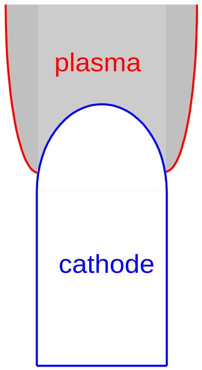




Xe-based metal halide automotive lamp (35W, Philips).

- High-pressure xenon arcs can develop **voltage oscillations** accompanied by electromagnetic interference (EMI).
- The initial conclusion was that the perturbations develop in the plasma column and are due to **instability of the energy balance of the electron gas in the plasma column**, which originates in the variations of heating of the electron gas by the electric field occurring faster than the variations of cooling by collisions with heavy particles.
- **Subsequent investigations have pinned down the instability to the near-anode region rather than to the plasma column**.

Current 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); the **spot mode**.

Cathode of Bochum model lamp. Arc discharge in argon. W, R = 0.75 mm, p = 4.5 bar, I = 2.5 A.

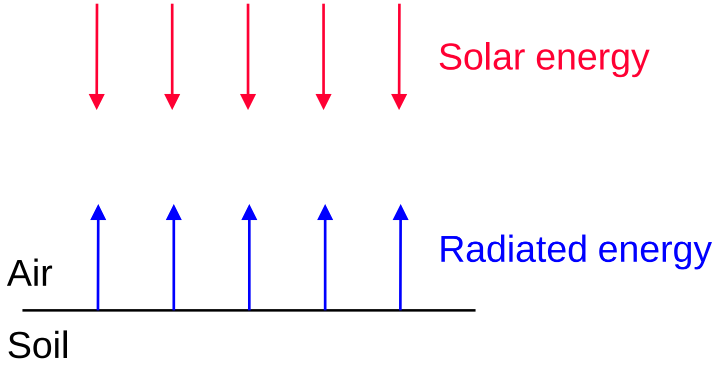
Current spots on cathodes of high-pressure arcs

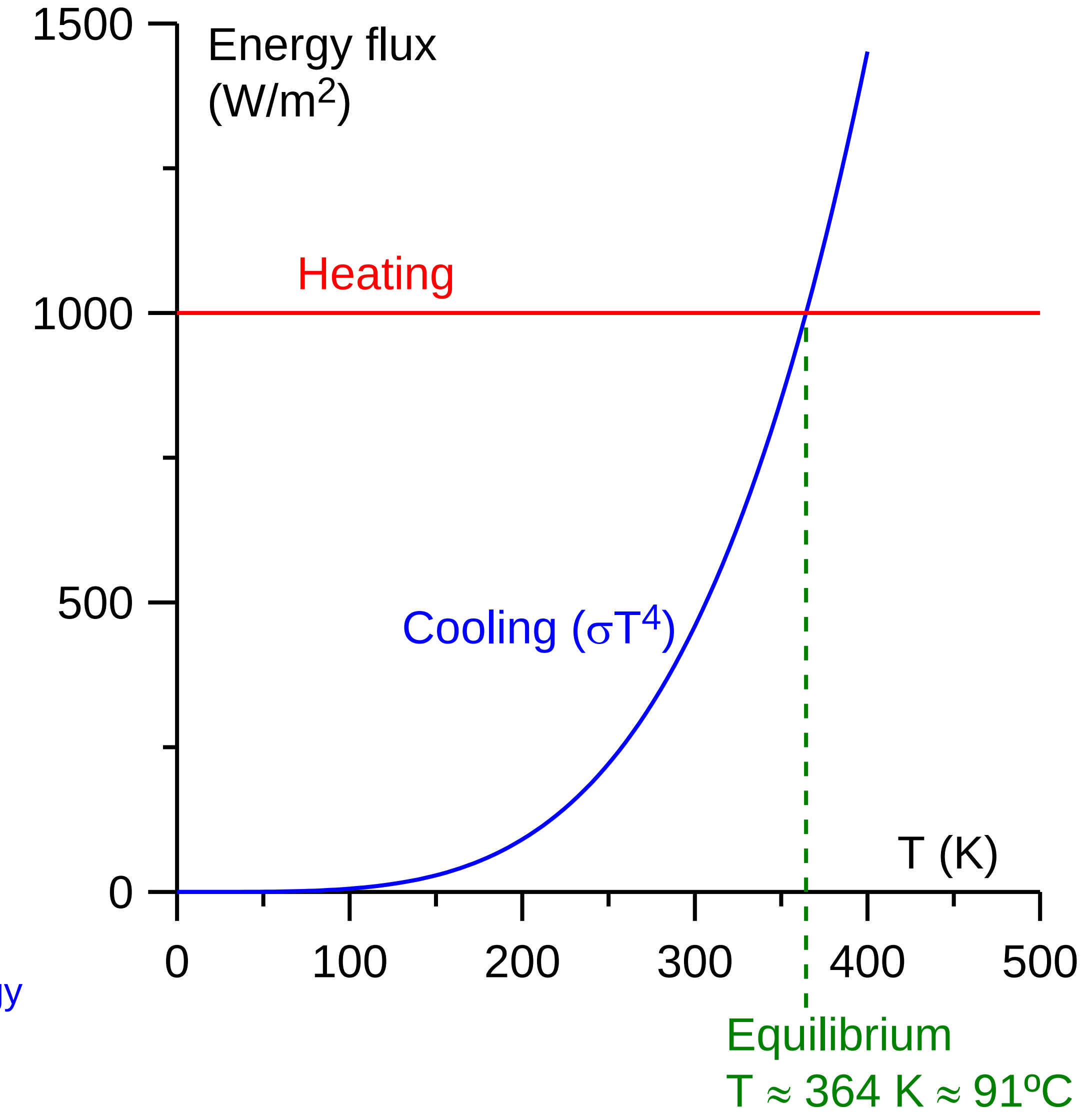
- The existence of multiple modes of current transfer to cathodes of high pressure discharges is very interesting from the point of view of fundamental science and important for technology.
- Several hundred of papers have been published on this subject since 1951.
- A self-consistent and universally accepted theory began to appear only in the late 1990s.
- This theory treats multiple modes of current transfer to arc cathodes as a self-organizing phenomenon.
- The theory is based on a very simple idea which is perfectly accessible to 1st-year physics students.

Thermal balance of soil on a hot day

What is the temperature of the soil (sand, asphalt) when the sun is at its zenith?

Hint: assume that the only soil cooling mechanism is radiation.
Resnick and Halliday, Physics II





Is thermal balance of soil stable?

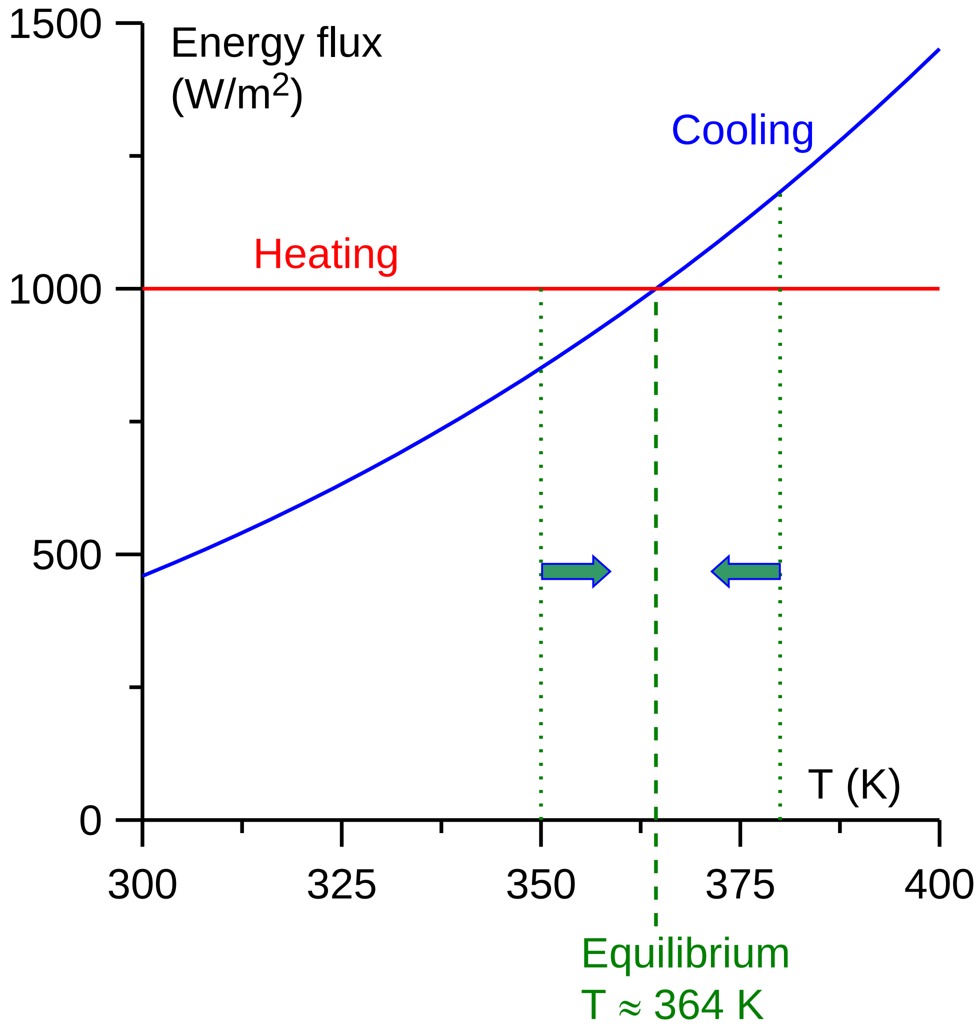
***T* < 364 K:**

Heating > Cooling => T ↑

***T* > 364 K:**

Heating < Cooling => T ↓

Conclusion: thermal balance of soil is stable.

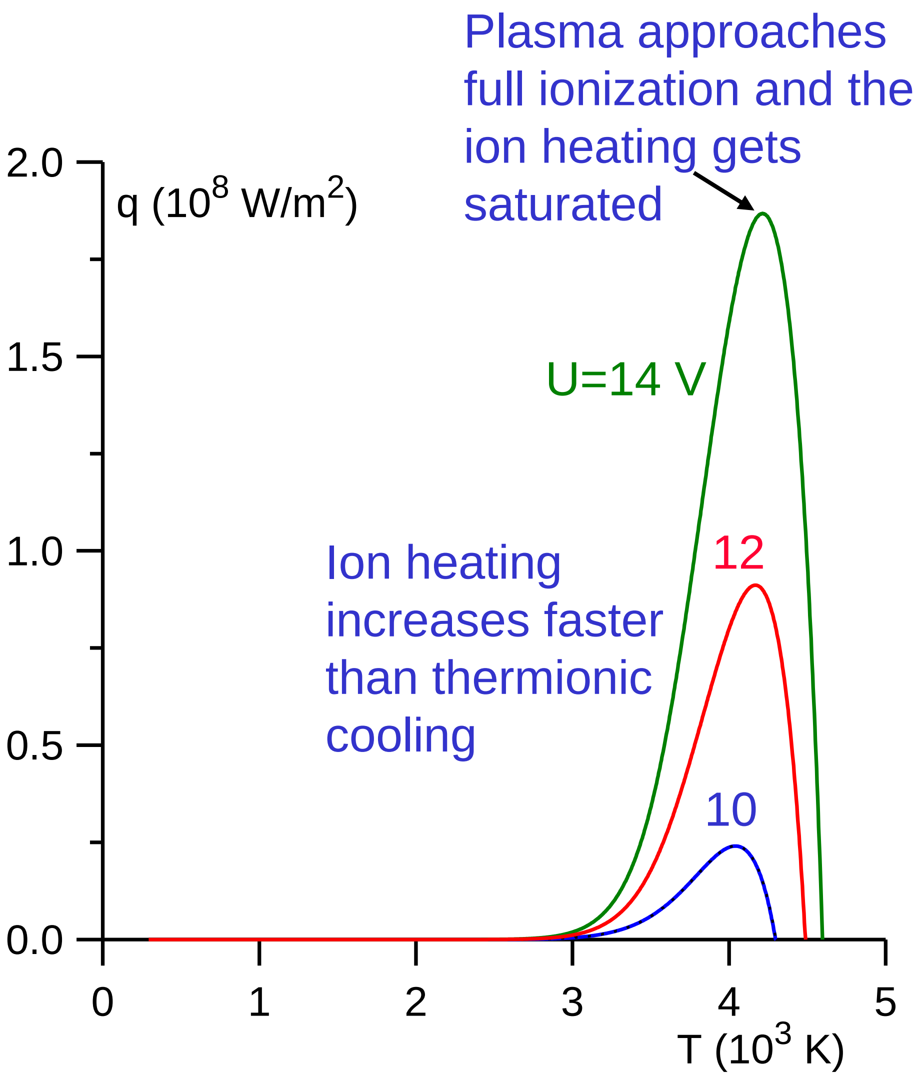


Energy flux from the plasma to the cathode

- Main mechanisms: **heating of the cathode surface by incident ions** and **cooling due to thermionic emission**.

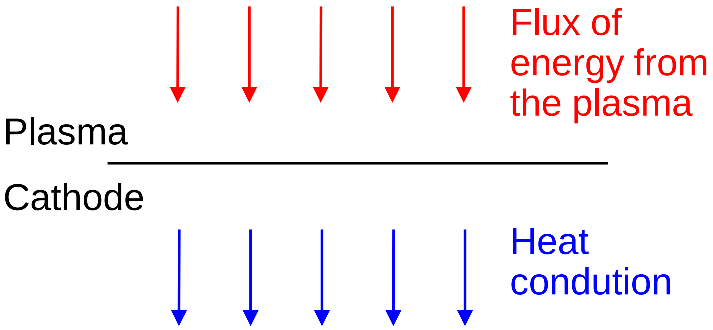
- The dependence of *q* on *T* is non-monotonic.

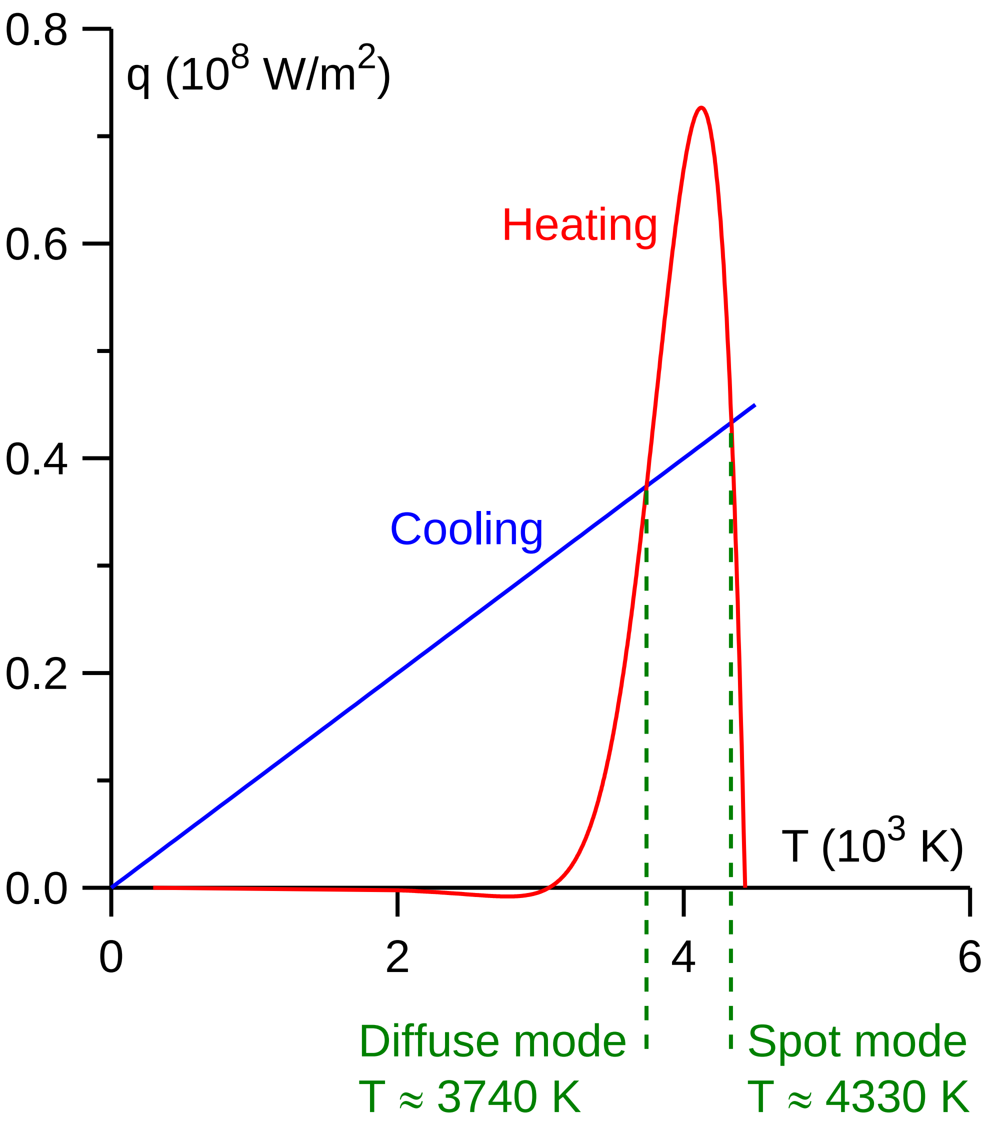
- In the conventional heat exchange, *q(T)* is falling!



W, Ar, 1 bar. From M. S. Benilov and M. D. Cunha 2002.

Thermal balance of a cathode





Ar plasma, p = 1atm, W cathode,
h = 10 mm, U = 12 V.

Is thermal balance of cathode stable?

Spot mode

***T* < 4330 K:**

Heating > Cooling => T ↑

***T* > 4330 K:**

Heating < Cooling => T ↓

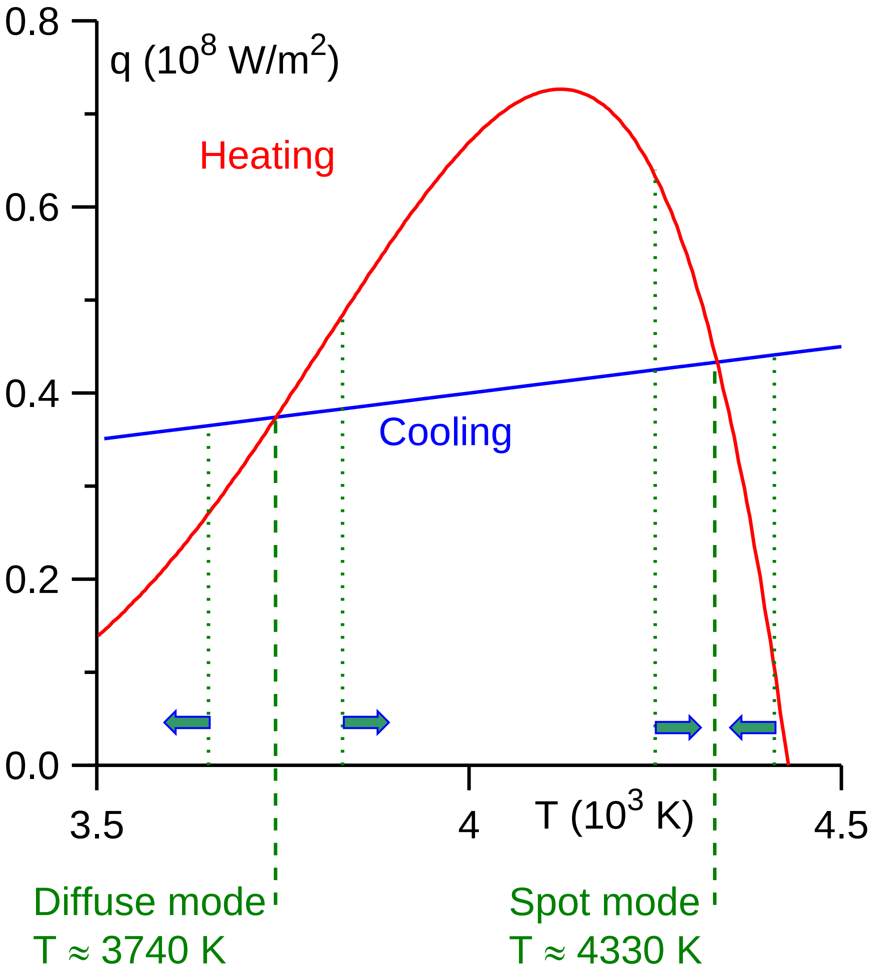
Diffuse mode

***T* < 3740 K:**

Heating < Cooling => T ↓

***T* > 3740 K:**

Heating > Cooling => T ↑



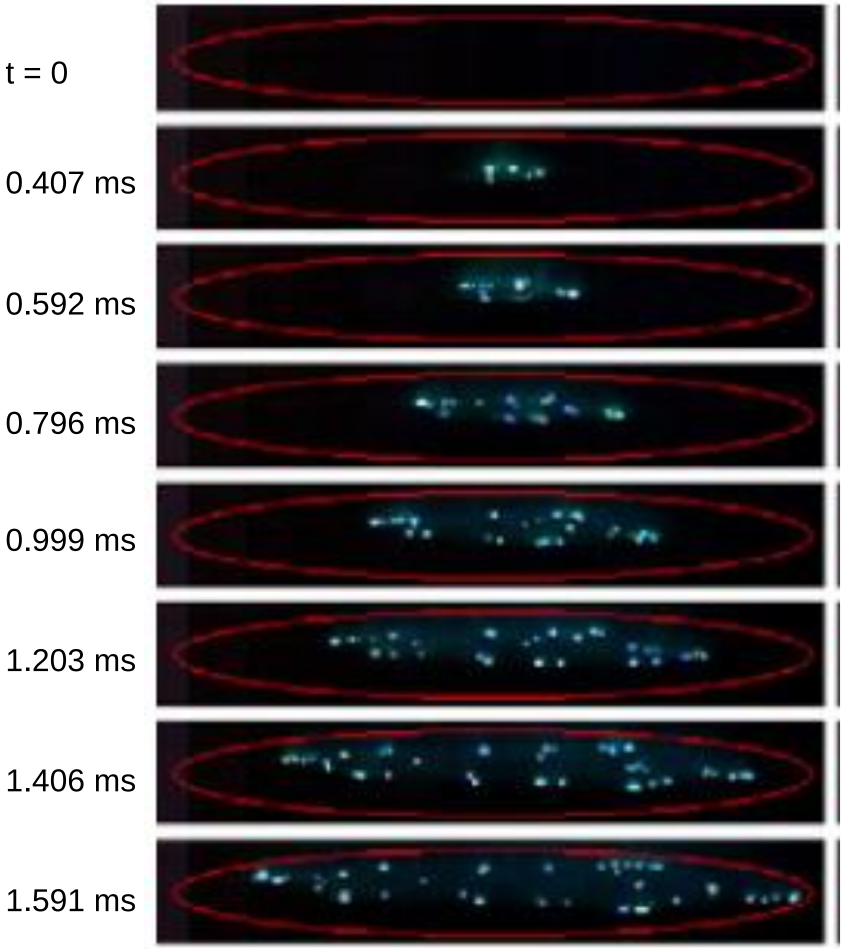
Conclusion: the diffuse mode is unstable, the spot mode is stable.

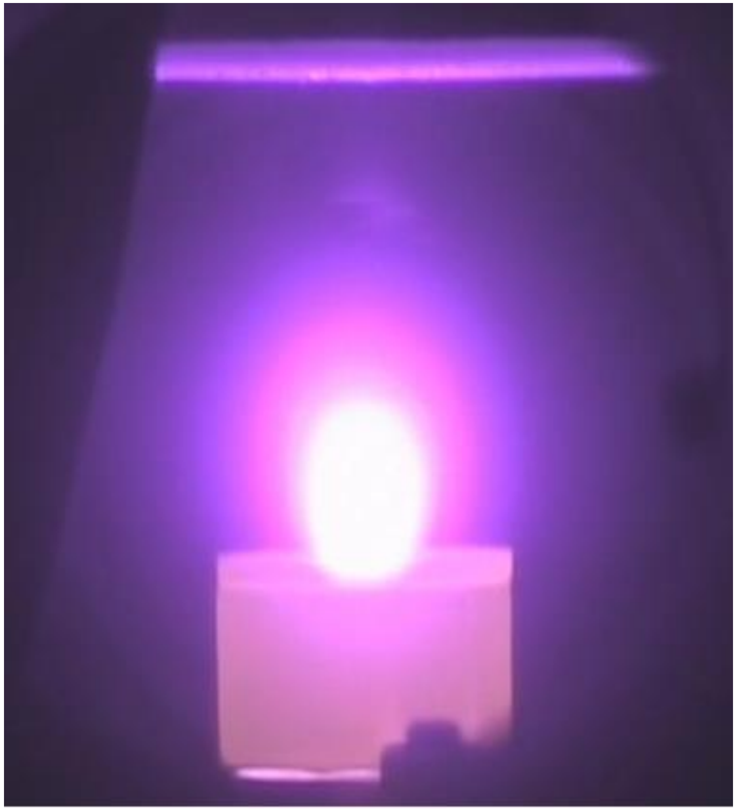
The theory

- Spotless modes and modes with spots have been observed on cathodes of other discharges.

- Therefore, there is not much sense in developing a separate theory for high-pressure arcs – one should aim at a general theory of spots on cathodes of DC gas discharges.

Different modes on cathodes of vacuum arcs

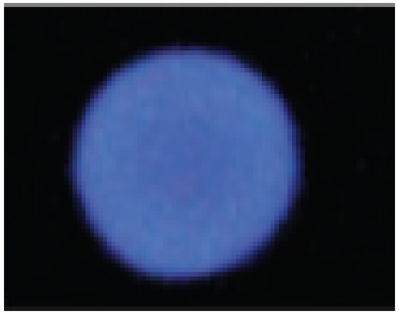




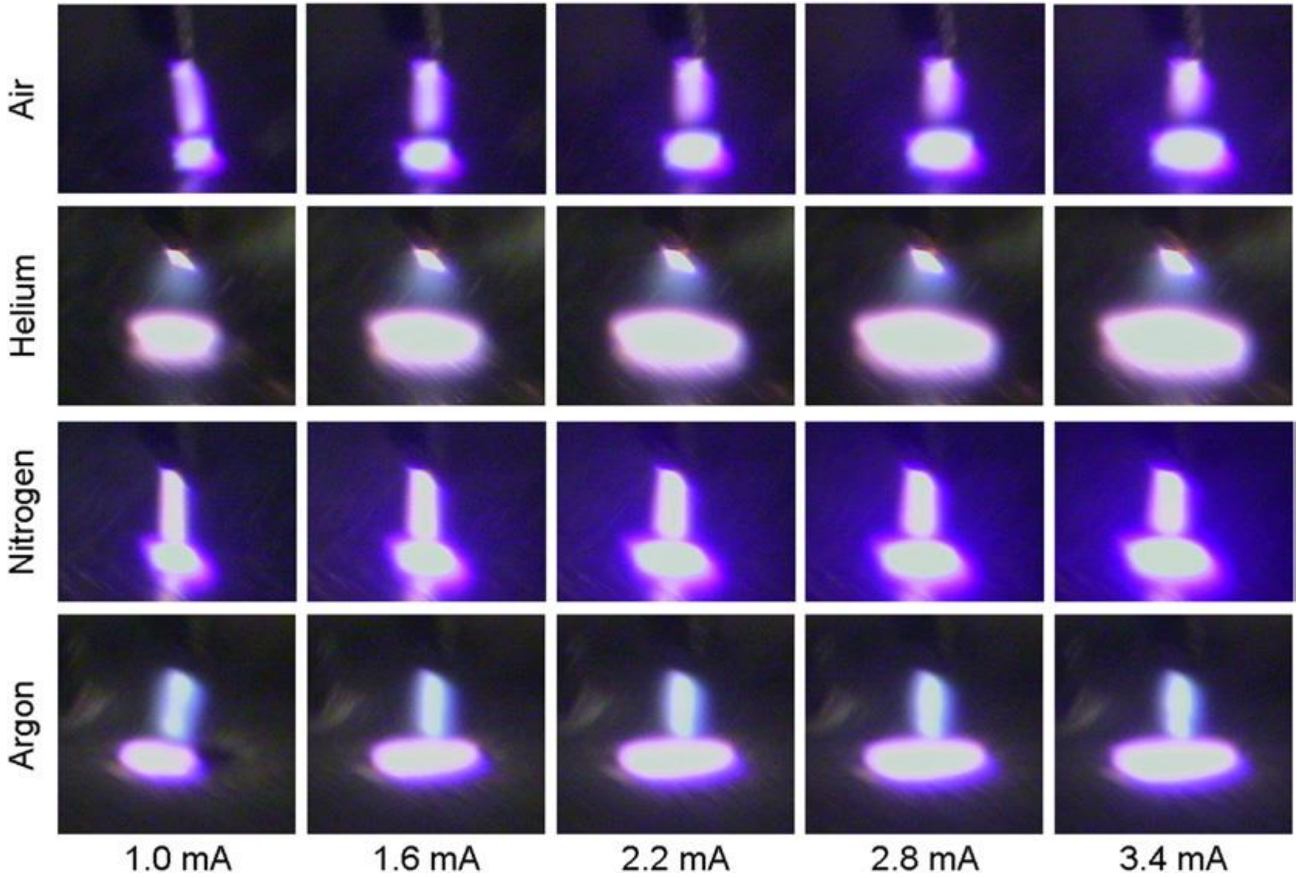
Cathode **spots** on Cu contact of vacuum arc in the initial expansion stage. Current peak 7 kA. From Song *et al* 2013.

Vacuum arc discharge with **spotless** cathodic attachment. I = 20 A. Pb (Cr, Gd) cathode. From Amirov *et al* 2015.

Spots on cathodes of DC glow discharges

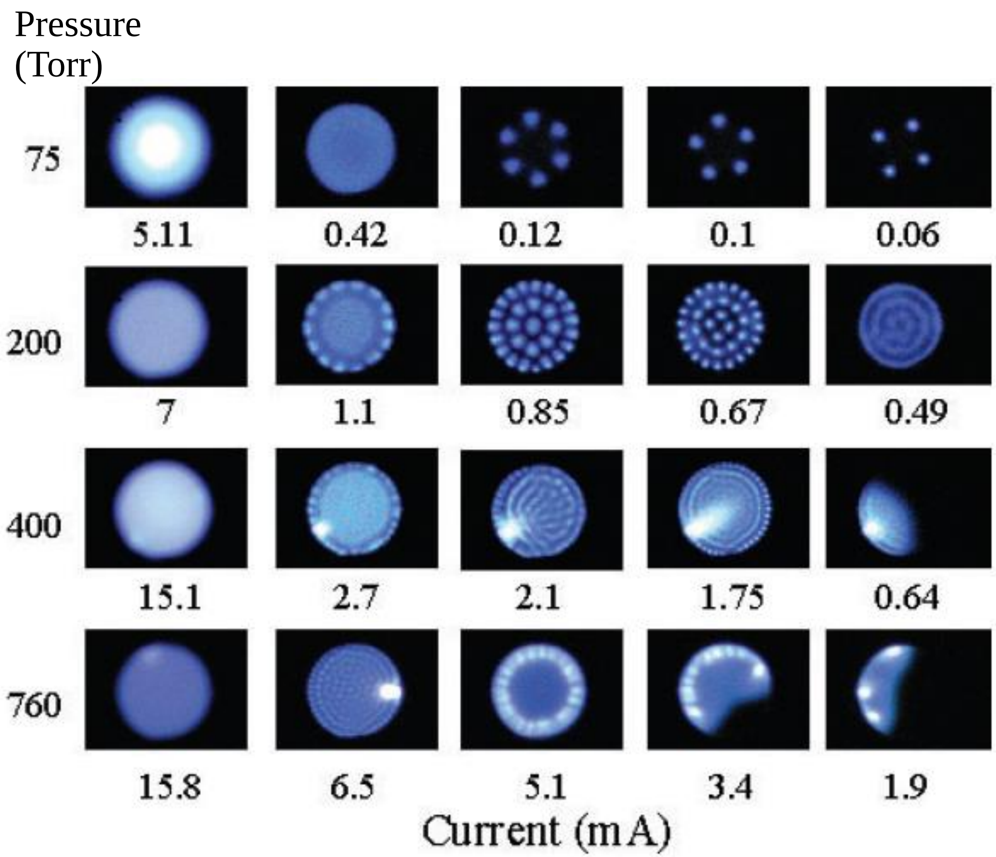


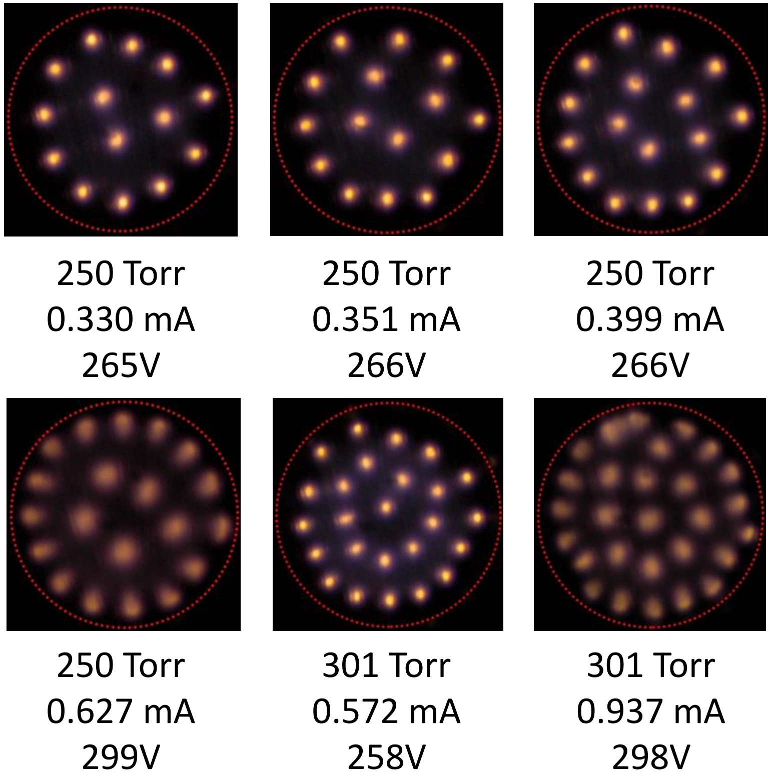
Abnormal **(spotless)** glow discharge. Xe, 75 torr, 0.42 mA. *R* = 0.375 mm, *h* = 0.25 mm. From K. H. Schoenbach *et al* 2004.



Mode with **one spot** (the normal discharge). Different gases, *p* = 1 bar, *h* = 0.4 mm. From D. Staack *et al* 2008.

Spots on cathodes of DC glow discharges





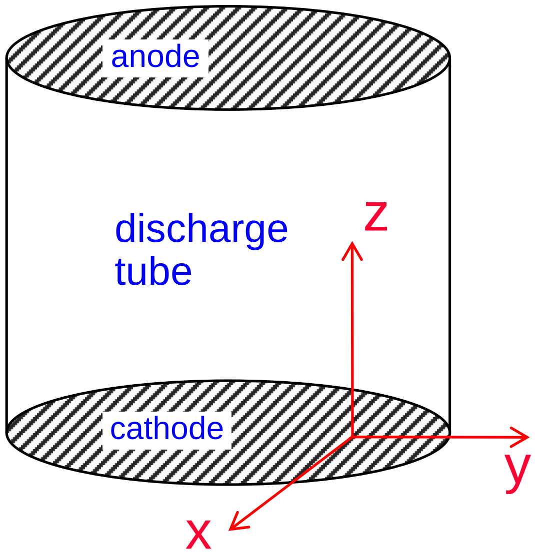
Xe, R = 0.375 mm, h = 0.25 mm. From K. H. Schoenbach, M. Moselhy, and W. Shi 2004.

Kr, R = 0.375 mm, h = 0.25 mm. From W. Zhu, P. Niraula, P. G. C. Almeida, M. S. Benilov, and D. F. N. Santos 2014.

Modes with **multiple spots** on cathodes of DC glow discharges.

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.

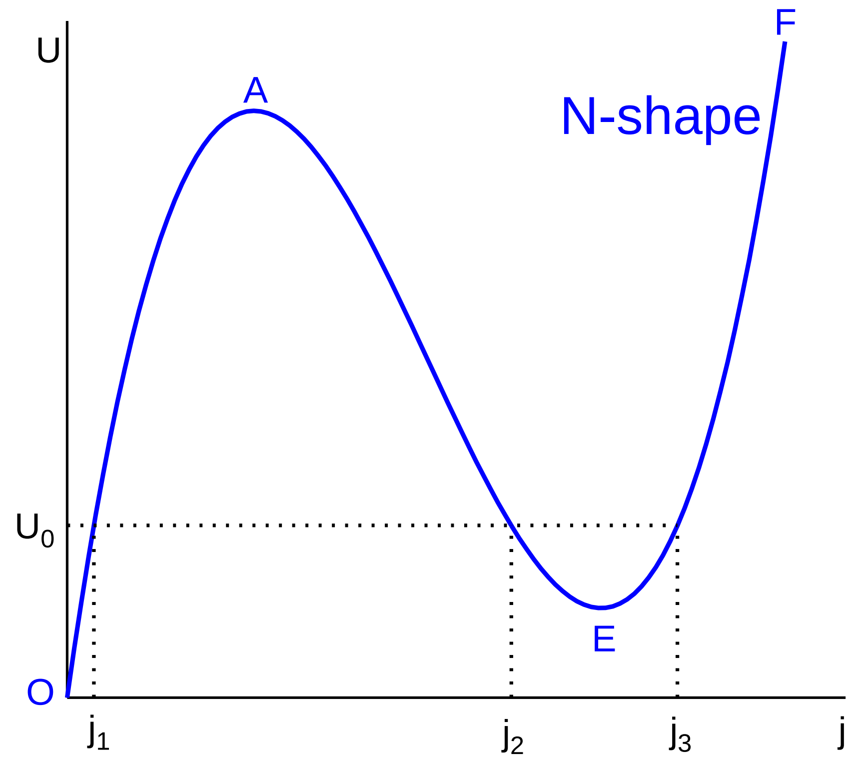
- A boundary-value problem describing current transfer to the cathode is invariant with respect to x and y **=> 1D solution, *f=f(z)***: the spotless mode [the abnormal mode on the glow cathode; the diffuse mode on an arc cathode].
- **Multidimensional solutions, *f=f(x,y,z)*:** modes with spots.
- What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

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

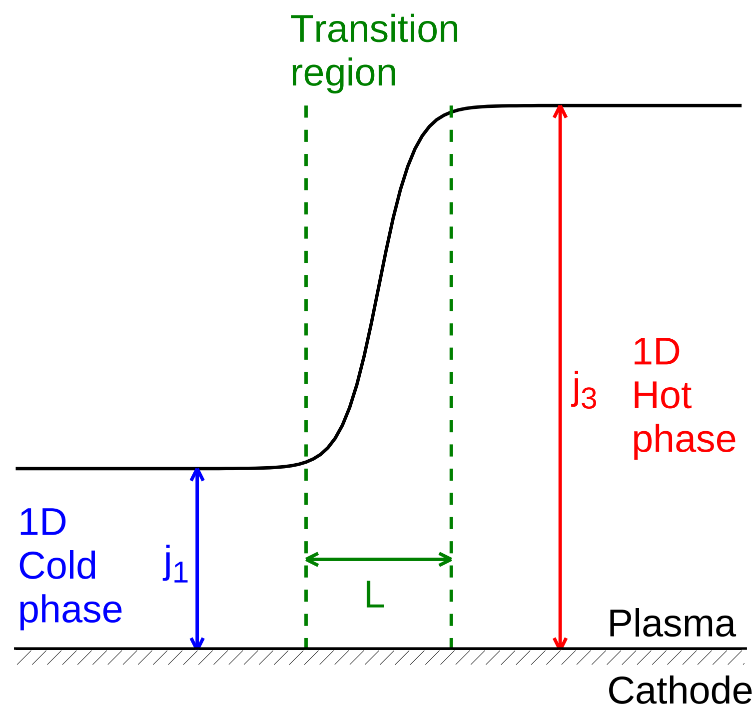
The plan

- 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

General predictions of the self-organization theory



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

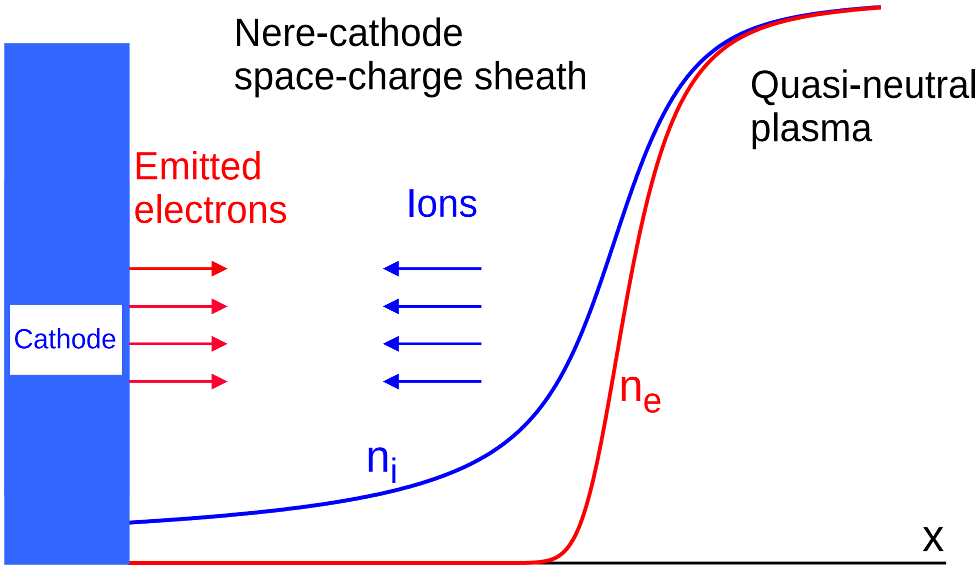


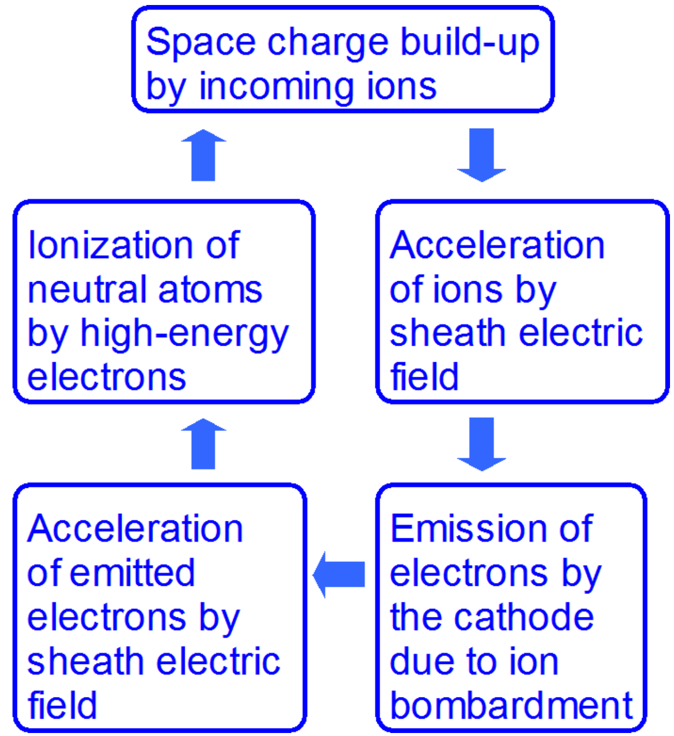
***$U = U_0$*:** **Three 1D solutions**

$j = j_1$: 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





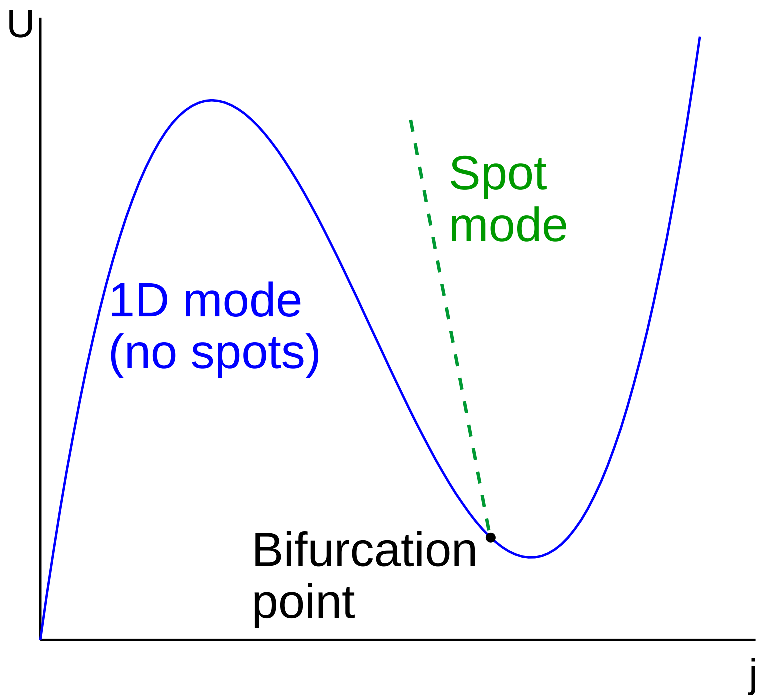
Glow discharge (cold cathode)
Ion bombardment => secondary electron emission (γ-process) $j_{em}/j_i = 1...10\%$

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

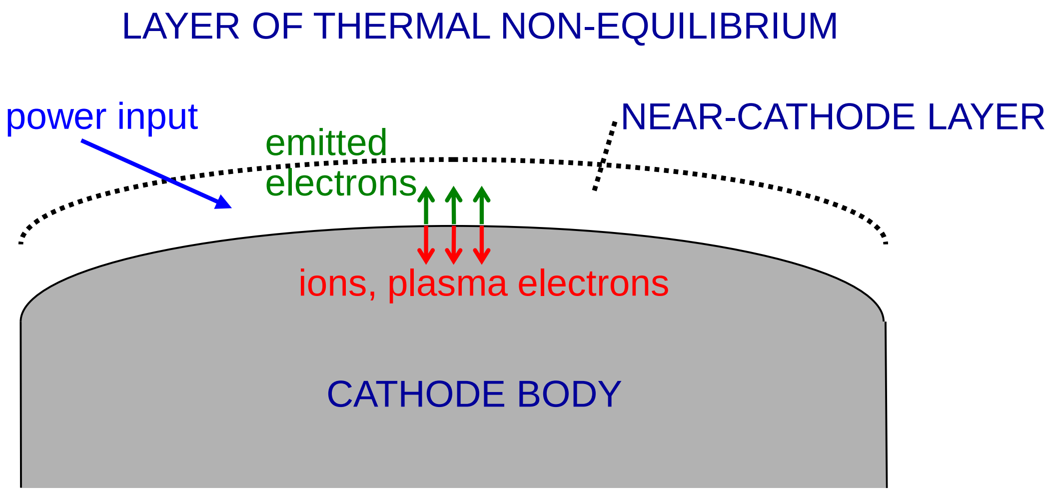
1. To formulate a model of plasma-cathode interaction for the particular discharge. While being multidimensional in nature, this model must admit 1D solutions;

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



- A very significant **power is deposited into the near-cathode space-charge sheath.**
- => The plasma-cathode interaction is governed by a thin layer comprising the sheath and the ionization layer.
- A complete solution can be found in two steps:
  - **Solution on the plasma side**: the 1D problem describing the near-cathode 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 and current continuity equations are solved with the boundary conditions $\kappa \frac{\partial T}{\partial n} = q(T_w, U)$, $\sigma \frac{\partial \varphi}{\partial n} = j(T_w, U)$.

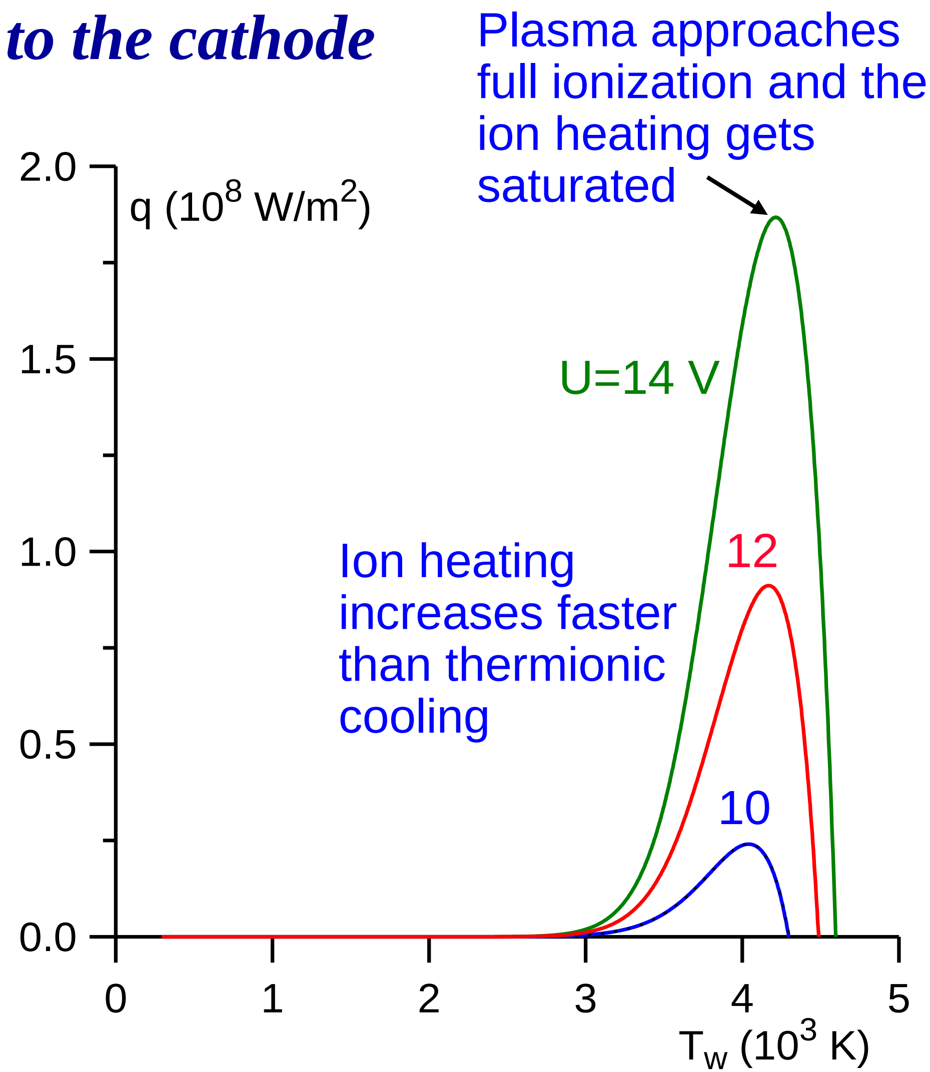
Historical comments

Functions $q(T_w, U)$ for ambient-gas and vacuum arcs

Arc cathodes, step 1: the model

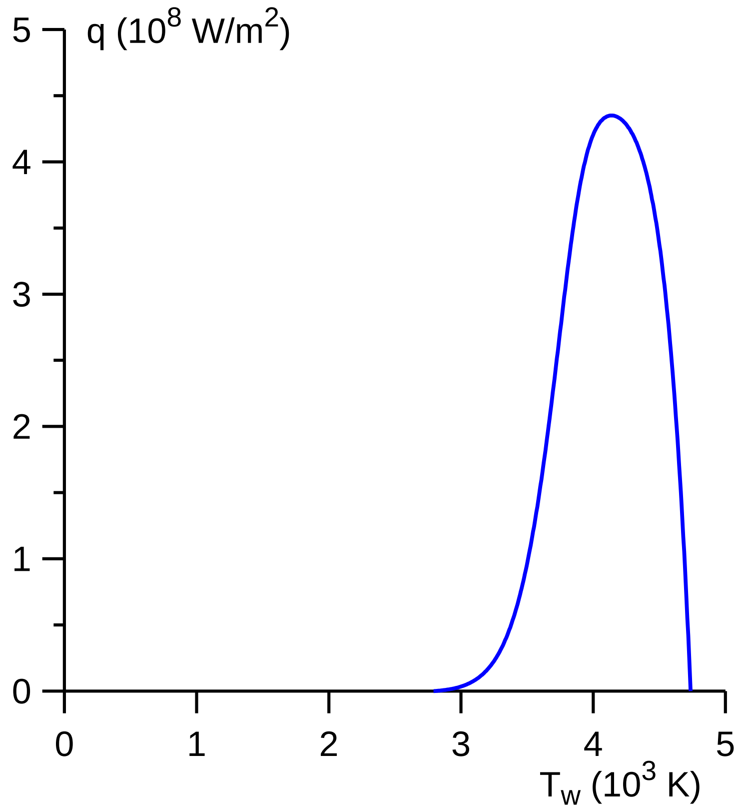
Energy flux from the plasma to the cathode

- Main mechanisms: heating of the cathode surface by incident ions and cooling due to thermionic emission.
- The dependence of q on T_w is non-monotonic.
- In the conventional heat exchange, $q(T_w)$ is falling!
- **The rising section of the dependence $q(T_w)$ is a source of thermal instability.**

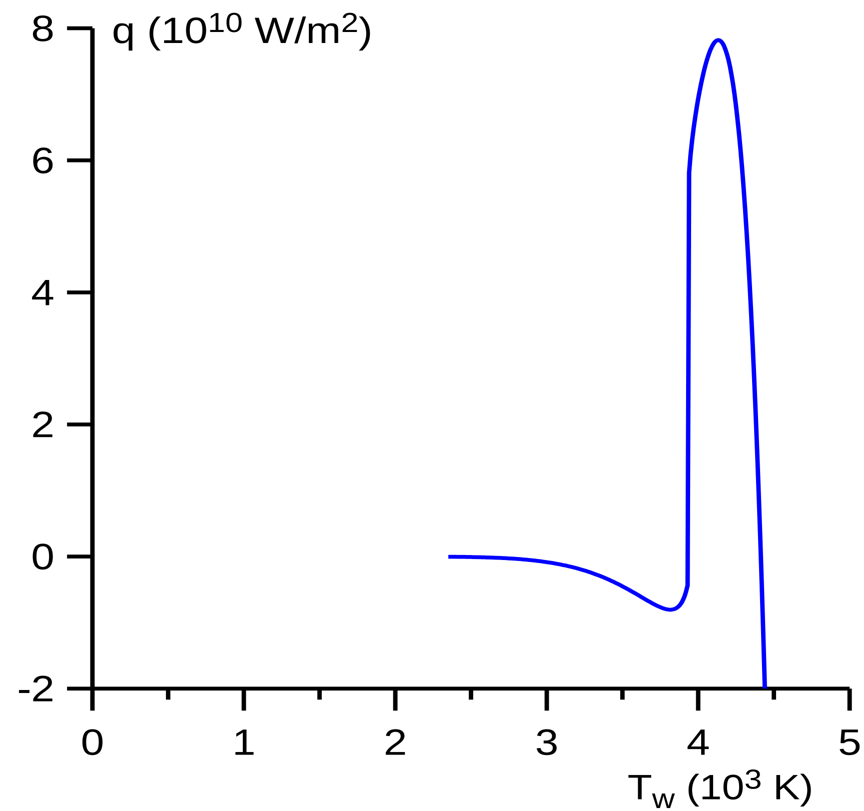


W, Ar, 1 bar. From M. S. Benilov and M. D. Cunha 2002.

Arc cathodes, step 1: the model



Ambient-gas arc. Ar, 1 bar, W cathode, *U* = 20V.
Computed by the tool http://www.arc_cathode.uma.pt



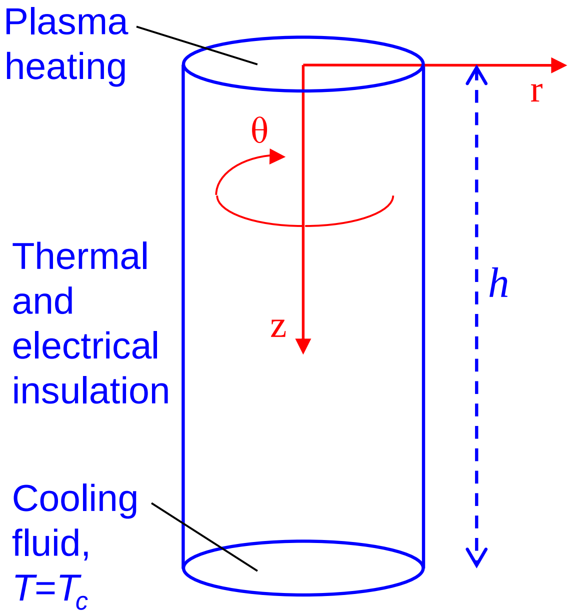
Vacuum arc. Cu cathode, *U* = 20V.
From N. A. Almeida *et al* 2013.

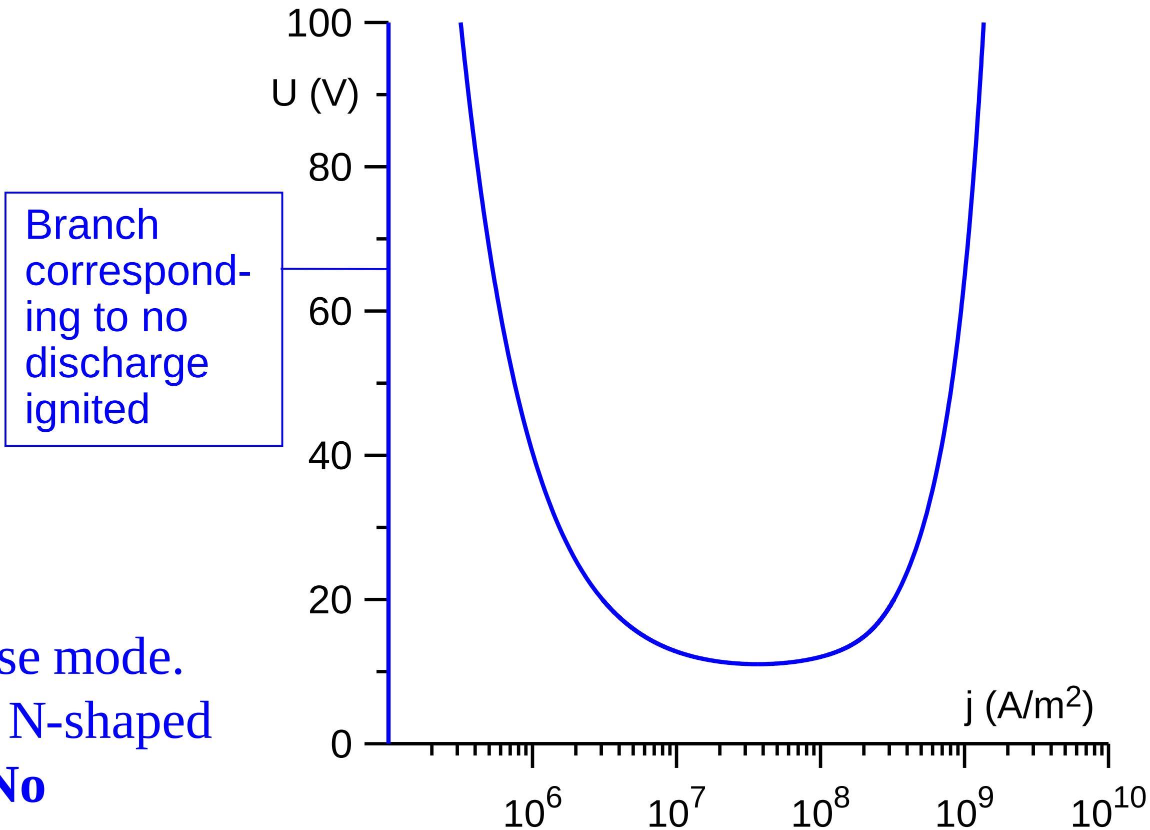
- The energy flux from the vacuum arc plasma is higher by two orders of magnitude and is localized in a more narrow range of T_w.
- **=> The computed parameters of spots are very different!**

Univ. Madeira ipfn INSTITUTO DE PLASMAS E FUSÃO NUCLEAR FCT Fundação para a Ciência e a Tecnologia

Arc cathodes, step 2: the 1D solution

Cylindrical cathode with an insulated lateral surface

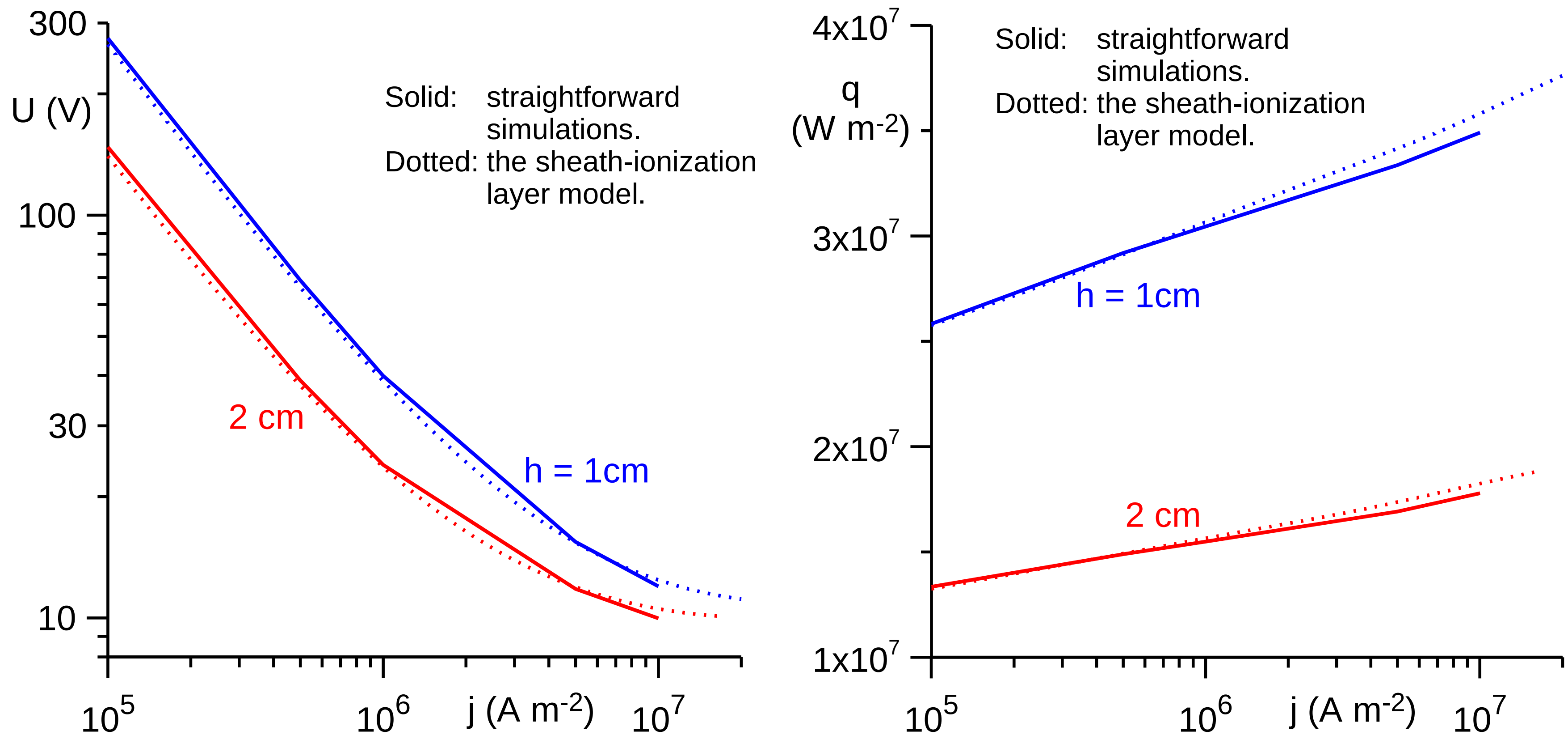




CDVC of the diffuse mode on a cylindrical cathode with an insulated lateral surface. W, h = 10 mm, Ar, 1 bar. From M. S. Benilov 1998.

- 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.

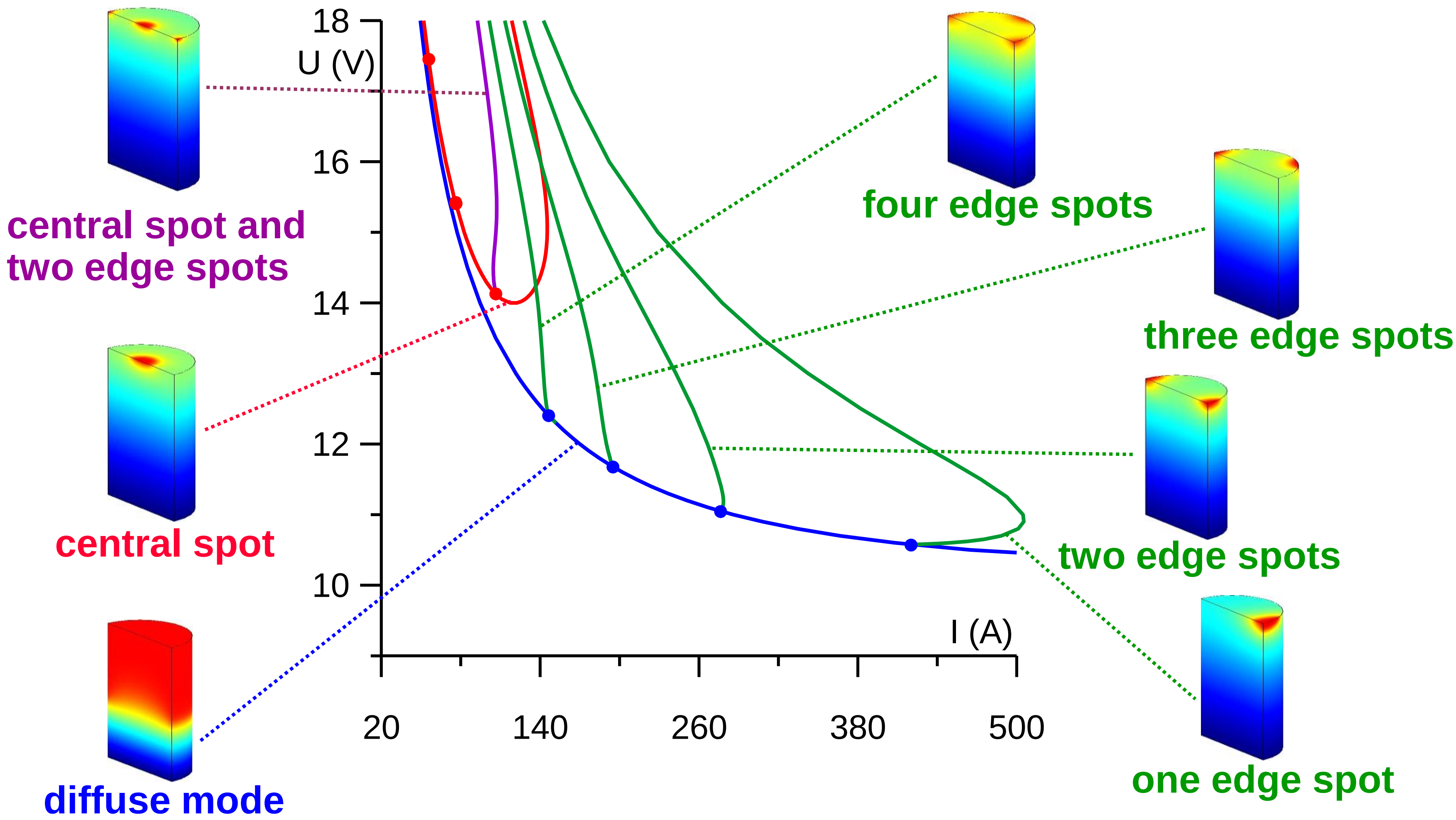
Arc cathodes, step 2: the 1D solution



Integral characteristics of the diffuse mode on a cylindrical cathode with an insulated lateral surface. W cathode, Ar plasma, 1 bar. Solid: the code N. A. Almeida *et al* 2008. Dotted: the tool http://www.arc_cathode.uma.pt. From M. S. Benilov *et al* 2016.

- Predicted integral characteristics of plasma-cathode interaction are not strongly affected by details of the model if **the basic physics is right**.

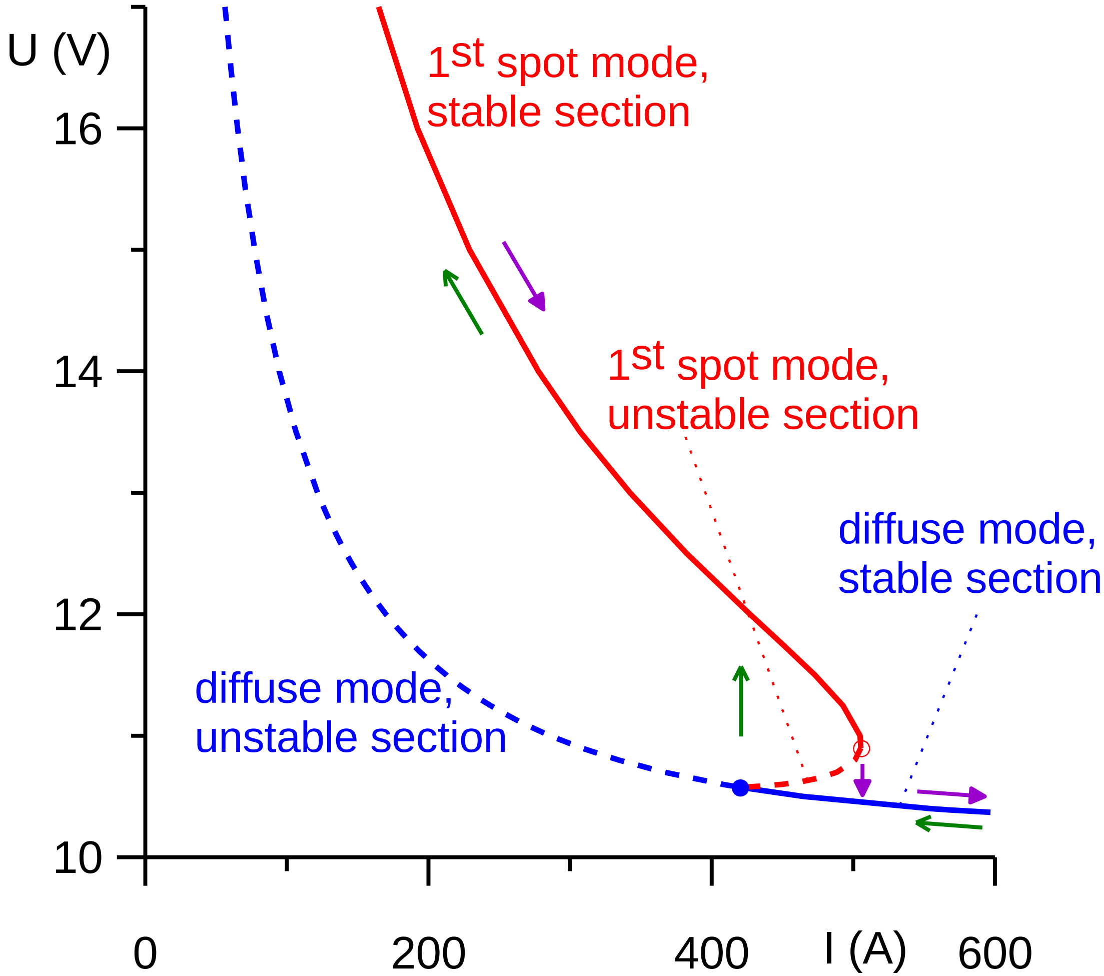
Arc cathodes, step 3: pattern of modes on a rod cathode



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.

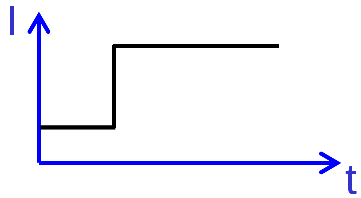


Stability of different modes on a rod cathode. W, *R* = 2 mm, *h* = 10 mm, Ar, 1 bar. From M. S. Benilov 2007 and M. S. Benilov and M. J. Faria 2007.

Comparison with the experiment

- **Detailed experimental data on plasma-cathode interaction in high-pressure arc discharges 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**.

Example: transient spots



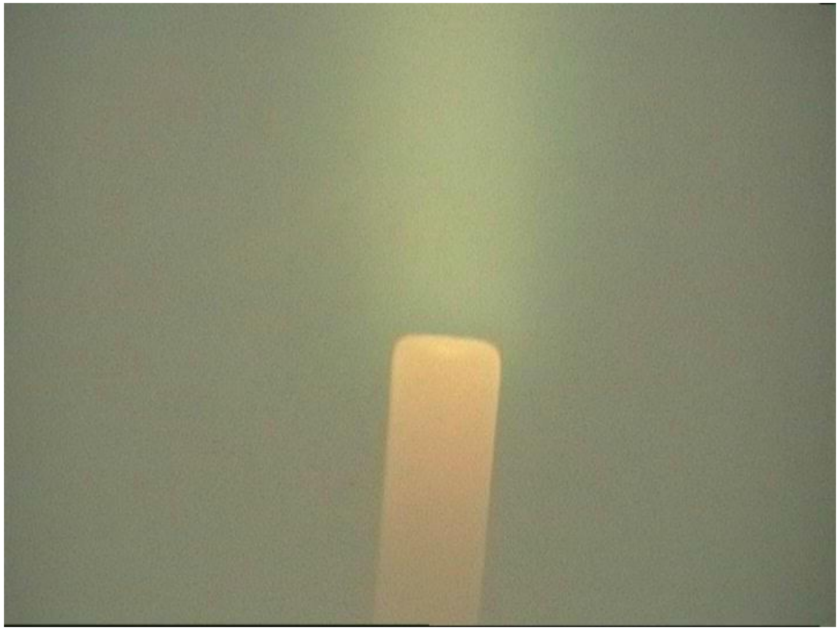
R. Bötticher, W. Graser, and A. Kloss 2004

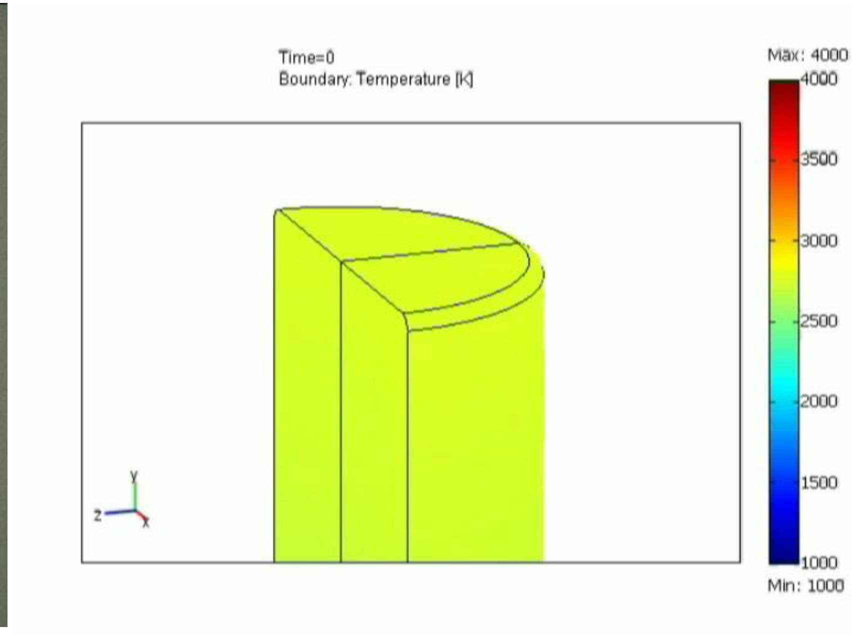
R. Bötticher and M. Kettlitz 2006

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.

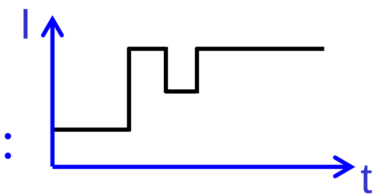
Comparison with the experiment: transient spots





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:

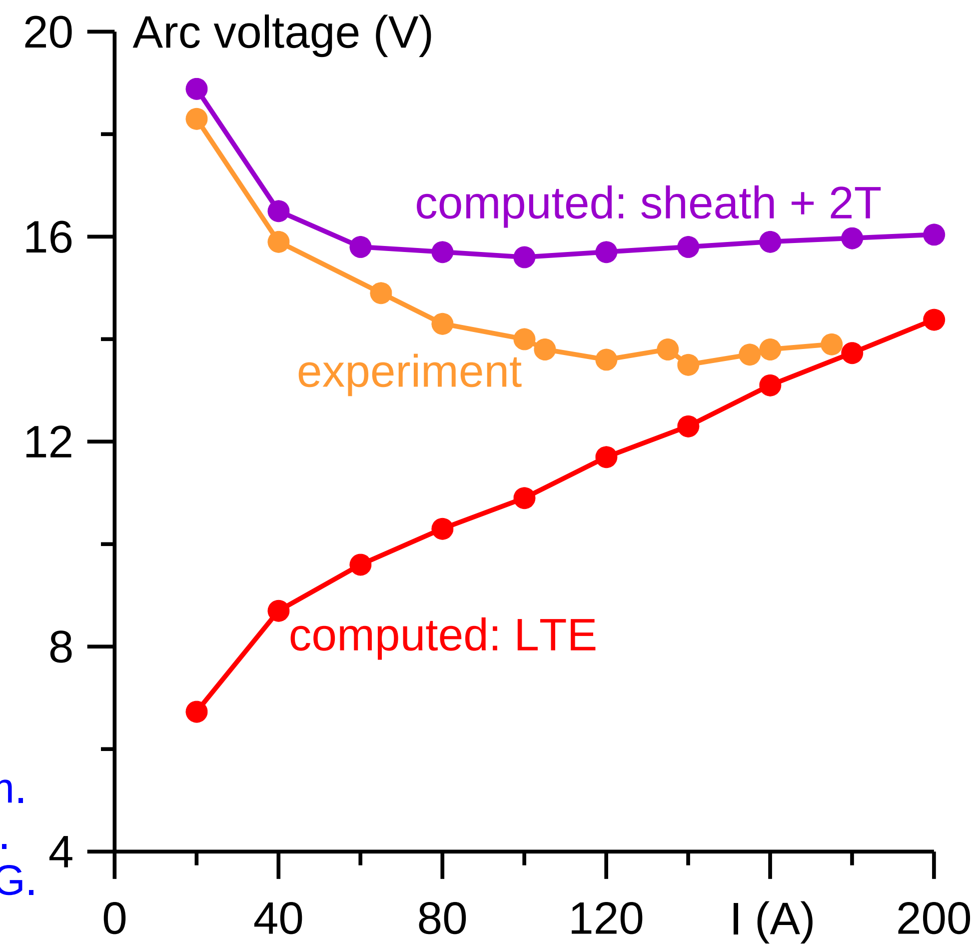


From P. G. C. Almeida *et al* 2013.

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.

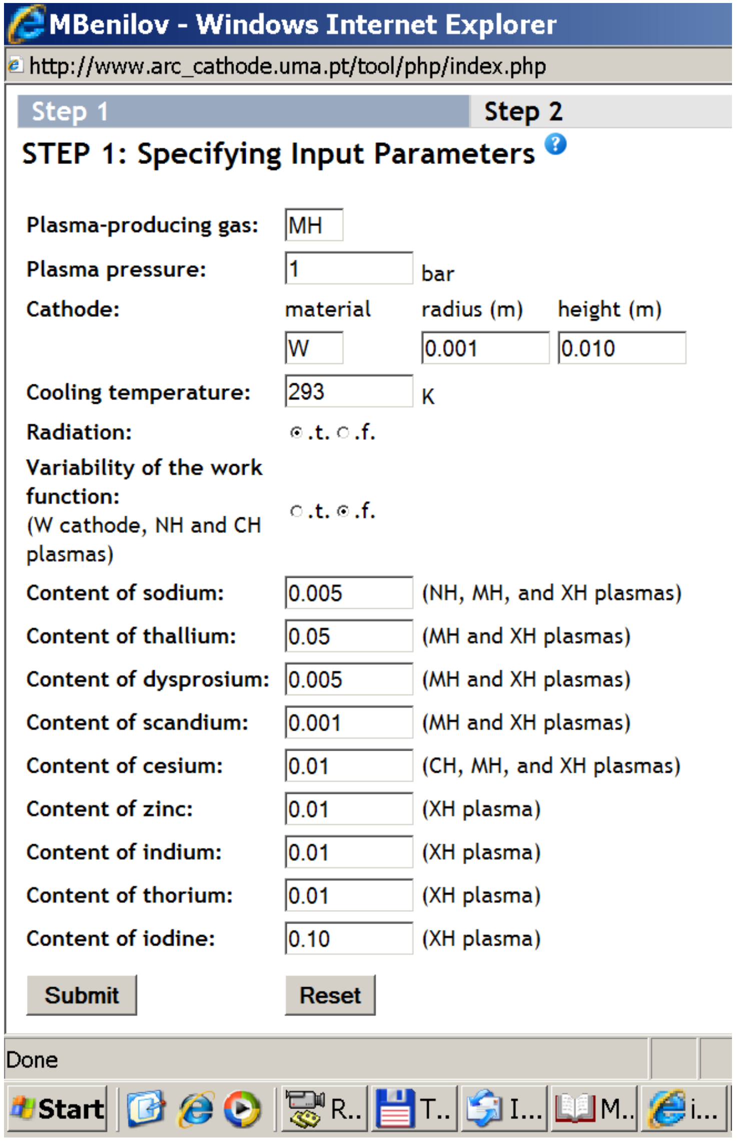


Voltage over a 1 cm long free-burning arc in 1 bar Ar. Cathode with a hemispherical tip, *R* = 1mm, h = 12 mm. Experiment: N. K. Mitrofanov and S. M. Shkolnik 2007. From M. S. Benilov, L. G. Benilova, H.-P. Li, and G.-Q. Wu 2012.

Further examples of comparison with the experiment

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;
- **Self-organization vs. geometrical current concentrations** View ;
- **Diffuse mode on cathodes of vacuum arcs**;
- **Stability of cathode spots** and evolution of unstable spots View ;
- Theory and modelling of **cathode spots of vacuum arcs** with application to contacts of high-power circuit breakers 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*:

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

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

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

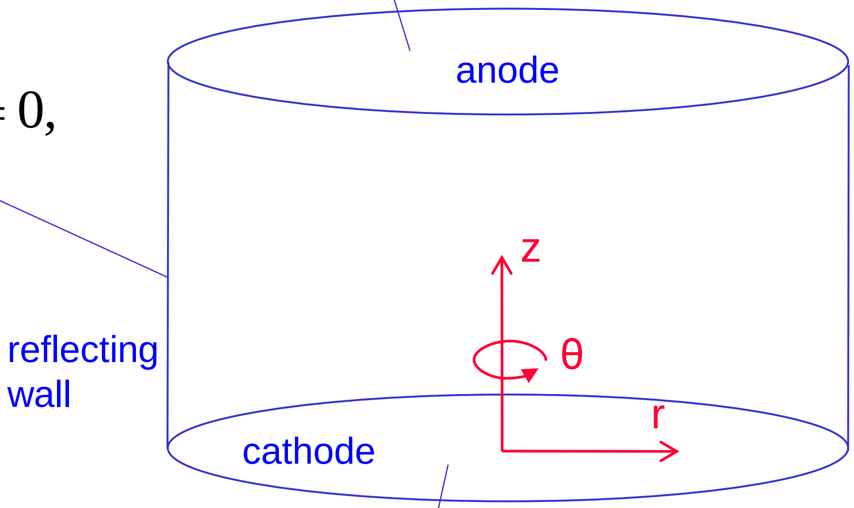
Glow cathodes, step 1: the model

Geometry and boundary conditions: discharge between parallel electrodes

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

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

$$j_r = 0$$



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

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

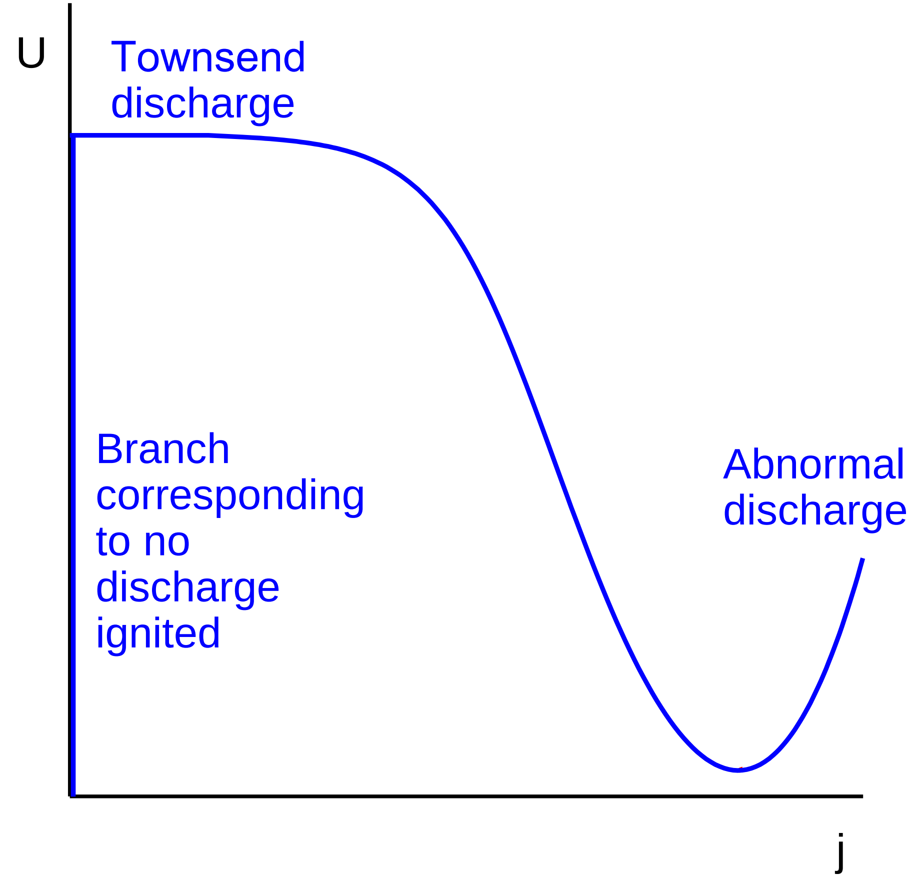
Historical comments

Glow cathodes, step 2: 1D solution

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

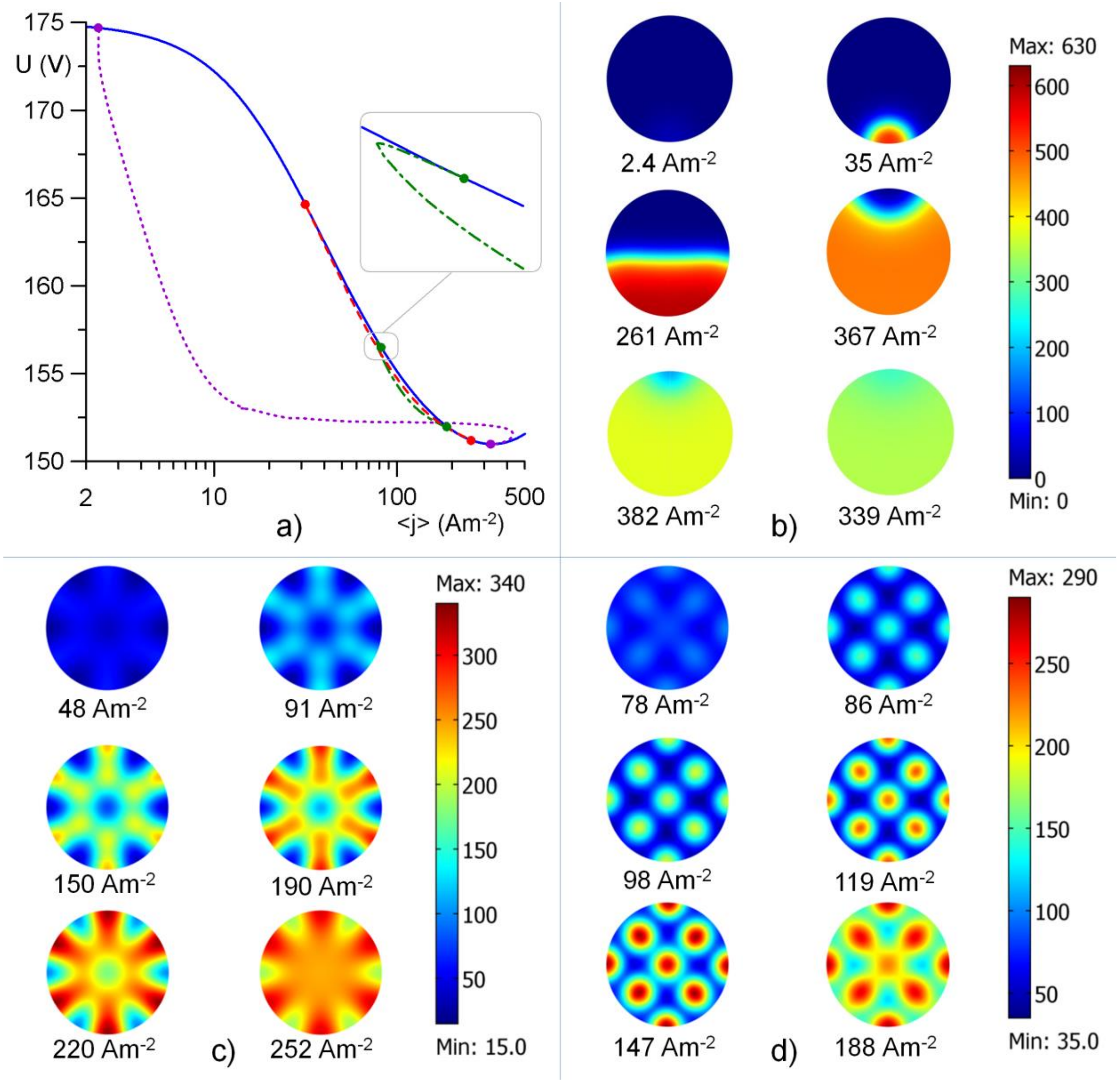
- The growing section: **the ionization coefficient approaches saturation**.

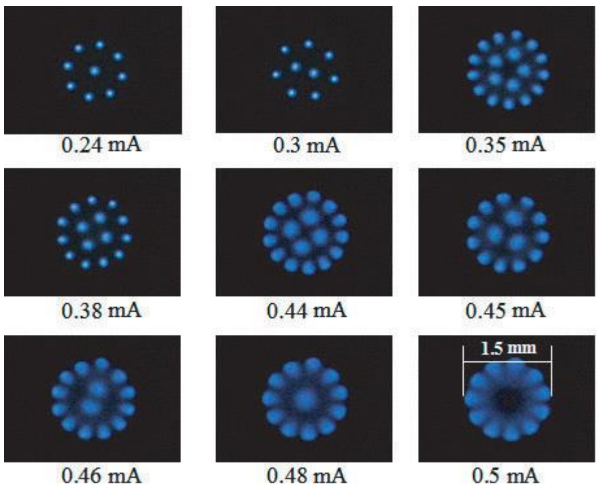
- The CVC of the near-cathode layer on the whole is N-shaped **=> No additional mechanisms are required to describe spot modes.**



CDVC described by the 1D solution.

Glow cathodes, step 3: solutions describing pattens



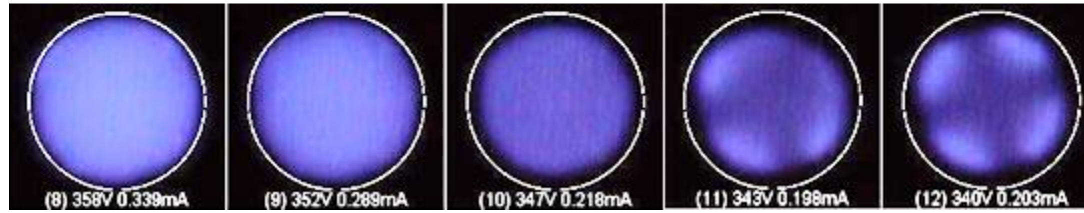


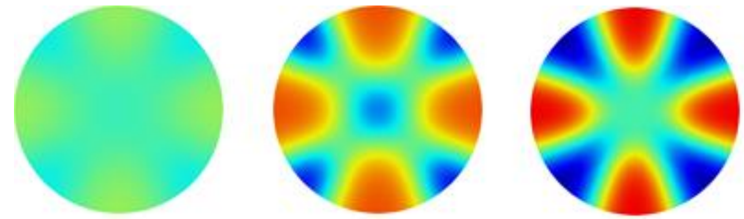
Glow discharge in Xe. From K. H. Schoenbach, M. Moselhy, and W. Shi 2004.

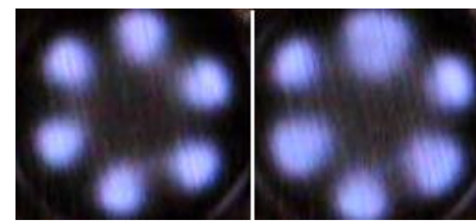
Xe, *p* = 30 Torr, *R* = 0.5mm, *h* = 0.5mm, diffusion losses neglected. a): Solid: the 1D mode. Dashed, dashed-dotted, dotted: the 1st, 8th, and 12th 3D modes. b): 1st 3D mode. c): 8th 3D mode. d): 12th 3D mode. From P. G. C. Almeida, M. S. Benilov, and M. J. Faria 2010, 2011.

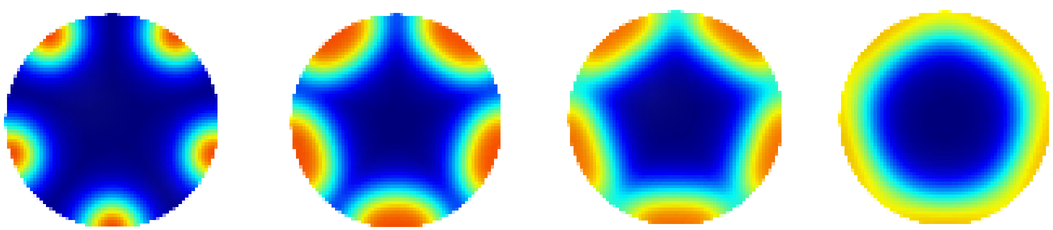
Comparison with the experiment

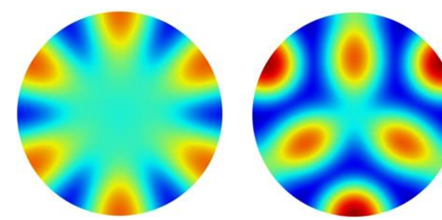
- There are quite a few observations of patterns in glow microdicharges, mostly by Schoenbach and coworkers.
- The agreement between the modelling and the experiment is good, although the comparison has been merely qualitative up to now.









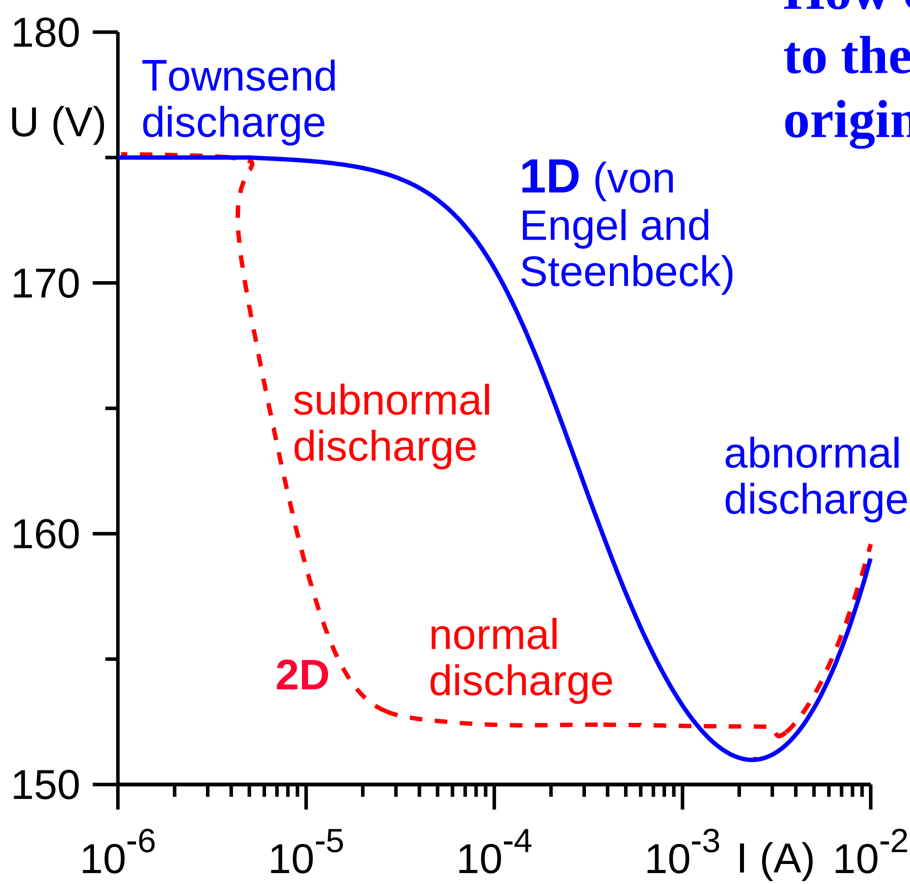


Bifurcations of steady states of glow discharge. Experiment: W. Zhu and P. Niraula 2014. Modelling: P. G. C. Almeida, M. S. Benilov, and D. F. N. Santos 2013, 2014.

There is more to say about glow cathodes …

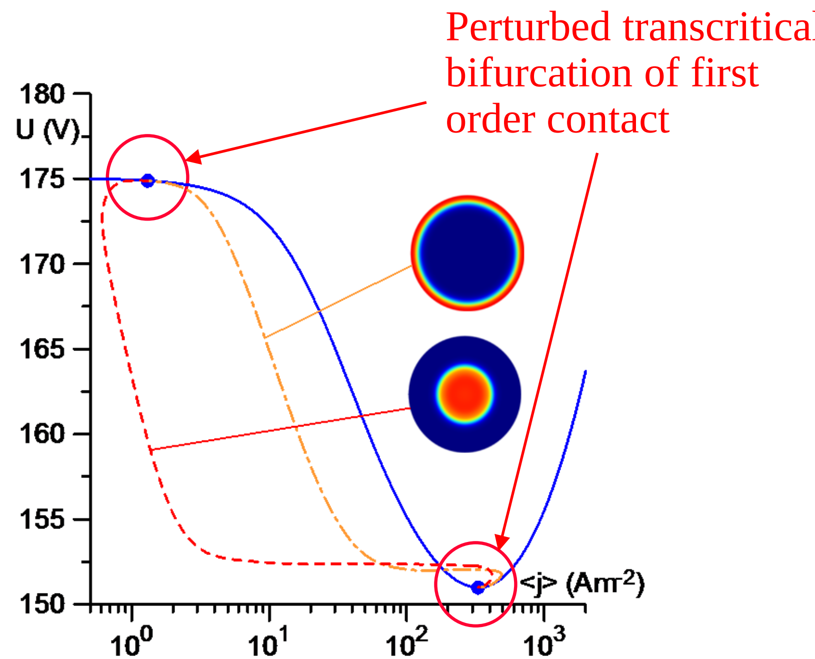
- **Modelling has guided the experiment** to observing spot patterns in gases other than Xe (Kr, Xe with 0.5% air impurity);
- **The normal current density exceeds the value corresponding to the minimum of the CDVC** by a factor of about two;
- Simulation of patterns in Xe and Ar with a **detailed account 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**;
- Patterns in discharges of complex configurations;
- Results on **stability** of axially symmetric states View ;
- **Simple situations, complex behavior**;
- …

Simple situations, complex behaviour



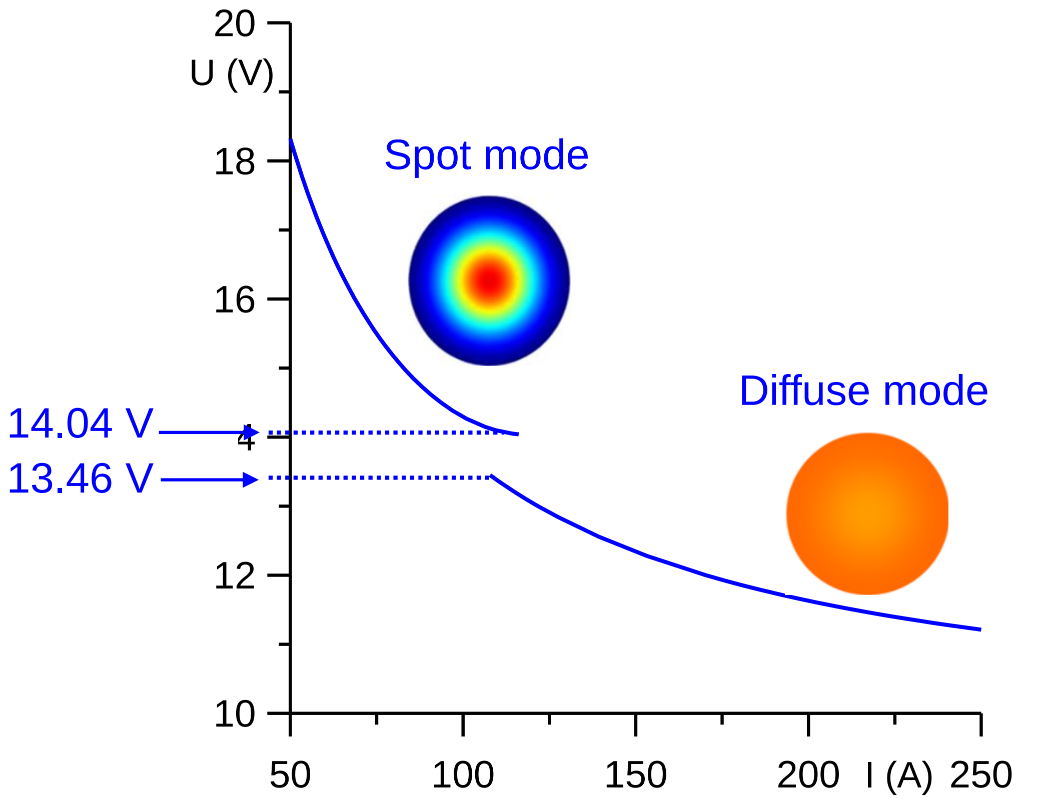
Xe, p = 30 Torr, R = 1.5 mm, h = 0.5 mm.
From P. G. C. Almeida, M. S. Benilov, M. D. Cunha, and M. J. Faria 2009.

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



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

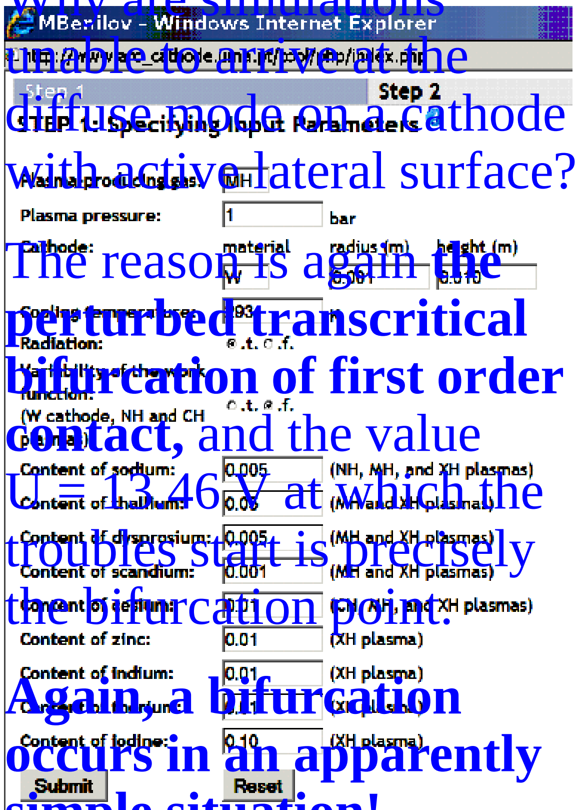
Simple situations, complex behaviour



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.

Further examples

- 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, a bifurcation occurs in an apparently simple situation!**



Univ. Madeira ipfn INSTITUTO DE PLASMAS E FUSÃO NUCLEAR FCT Fundação para a Ciência e a Tecnologia

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.

Fundamental and applied results

- This is a fundamental research in physics of gas discharges => papers in physics journals, MSc and PhD theses, public-funding fundamental-research projects.

- The theory has high-tech applications => applied projects funded by industry and the EU:
  - Metal halide lamps for street illumination (NumeLiTe project of EU);
  - UHP lamps (General Electric Co, USA);
  - Arc welding (ABB, Sweden and Switzerland);
  - Automotive lamps (Philips, Germany);
  - Plasma-chemical reactors (PMFP project of EU, Daimler, Airbus);
  - High power circuit breakers (ABB, Sweden and Switzerland; Siemens, Germany).

Metal halide lamps (NumeLiTe project of EU)

Objective of the project: to reduce electricity consumption and improve the quality of light. The lamps are filled by Hg with added NaI, TLI, CsI, DYI. A particular task was to develop the theory in order to know how to prevent the cathode spots.

CMH lamp 150W TT 4000K E40 developed within the NumeLiTe project of EU (GE Lighting).

Univ. Madeira
ipfn INSTITUTO DE PLASMAS E FUSÃO NUCLEAR
FCT Fundação para a Ciência e a Tecnologia

MH lamps for street illumination

Rue de la Berchère

Avenue Joffre

Demonstrator of metal halide lamps installed in the city of Albi (France) in the framework of NumeLiTe project of EU.

MH lamps for street illumination

Operation on the 100% power (150W).

Operation on the 50% power (70W).

Demonstrator of metal halide lamps installed in the city of Albi (France) in the framework of NumeLiTe project of EU. Avenue Gambetta.

MH lamps for street illumination

- NumeLiTe proposal target for energy gain was in the order of 30%.
- The achieved energy gains combining all system characteristics is higher than 50%!
- The achieved performance of the system is due to high degree of fundamental understanding of each system component and also of the interactions between components.

MH lamps for street illumination

Metal halide lamps installed in the city of Funchal (Madeira, Portugal)
as a follow-up of NumeLiTe project of EU. Rua de Queimada de Baixo.

MH lamps for street illumination

Metal halide lamps installed in the city of Funchal (Madeira, Portugal) as a follow-up of NumeLiTe project of EU. Praça de Autonomia.

Current transfer to cathodes of UHP lamps and welding arcs

UHP lamps

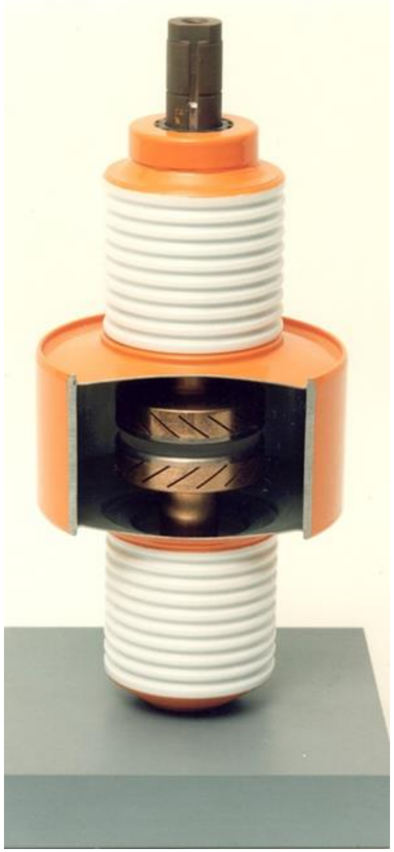
Objective of research: to develop a theory in order to increase the operating time of the electrodes.

Arc welding machines

Objective of research: to develop a theory in order to optimize the process by varying the control parameters (wire supply speed, the robot arm motion, inclination of the wire ...)

Current transfer to cathodes of high-power circuit breakers

- Research objective: to develop a theory in order of increasing lifetime of contacts.
- High-pressure circuit breakers (**ABB**).



- Vacuum circuit breakers (**Siemens**).