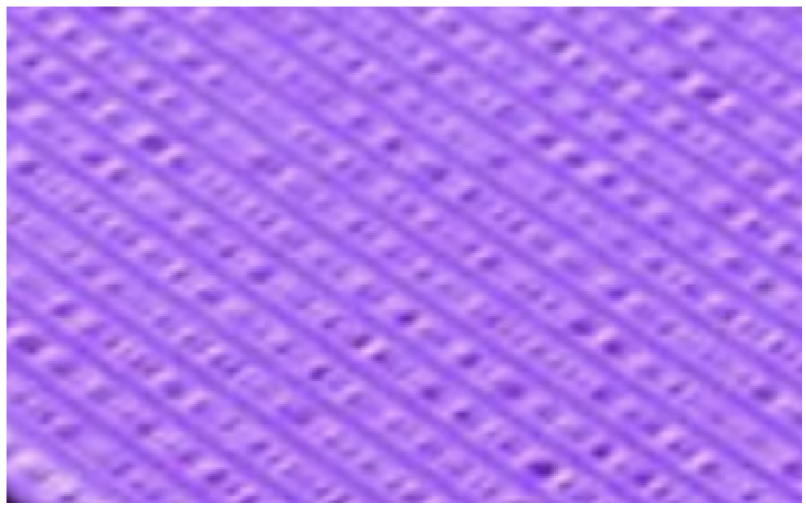
Plasma Physics 2

6. Dielectric barrier discharge



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Lecture series contents

1. Townsend breakdown theory, Paschen‘s law
2. Glow discharge
3. Electric arc at low and high pressures
4. Magnetized low-pressure plasmas and their role in material deposition methods.
5. Brief introduction to high-frequency discharges
6. Streamer breakdown theory, corona discharge, spark discharge
7. **Barrier discharges**
8. Leader discharge mechanism, ionization and discharges in planetary atmospherres
9. Discharges in liquids, complex and quantum plasmas
10. Thermonuclear fusion, Lawson criterion, magnetic confinement systems, plasma heating and intertial confinement fusion.

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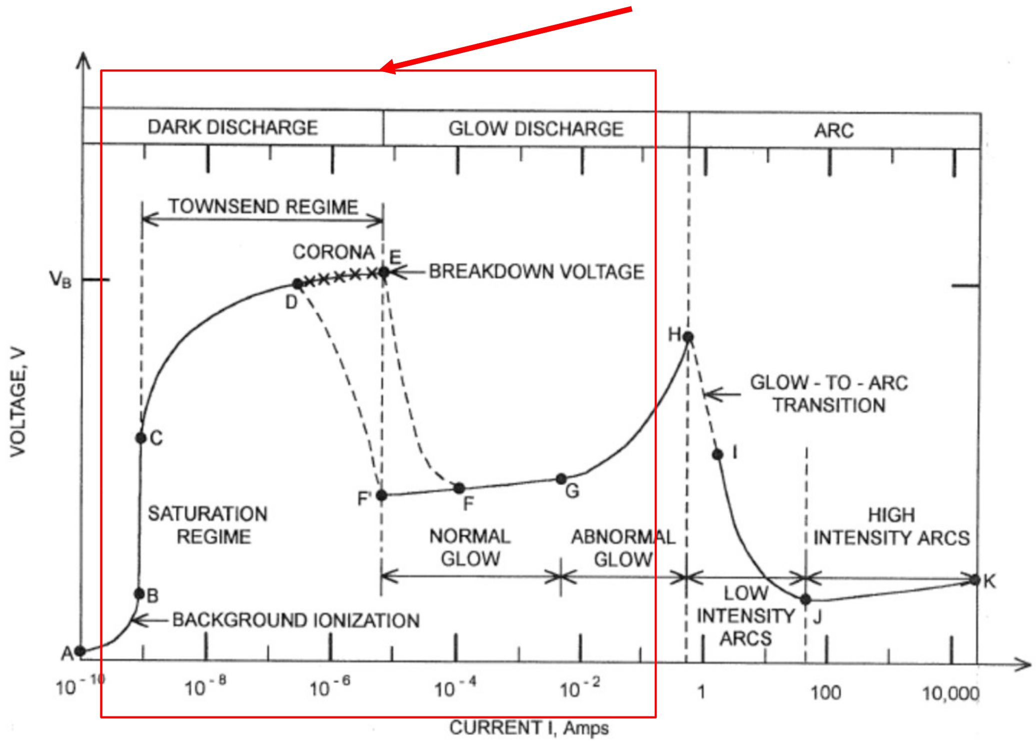
Where are we in the IV chart?

- We have seen last time that the deformation of the E field in various real-life scenarios leads to a formation of non-uniform discharge structures (streamers, arcs, coronas).
- Today, we are expanding further on those by analyzing DBDs which operate in Townsend/Glow part of the IV characteristic

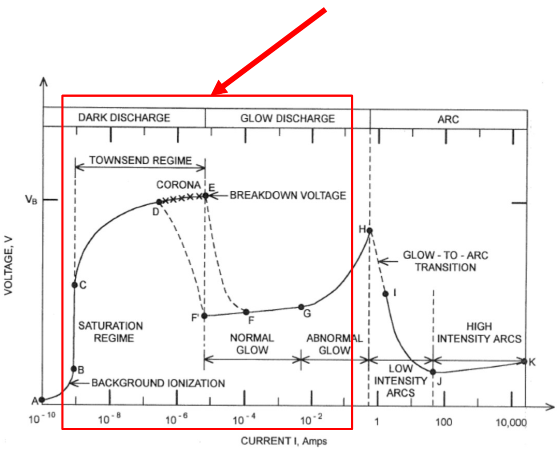


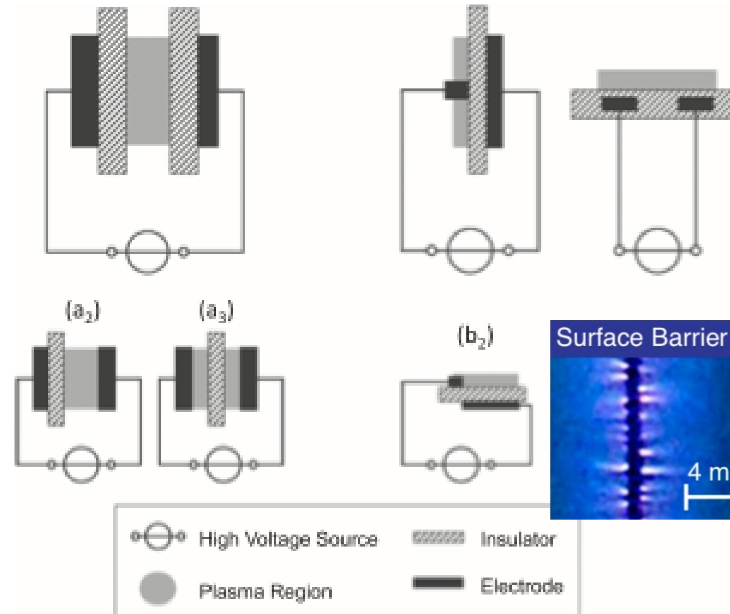
volt-ampérová charakteristika elektrických DC výbojů
(vznik jednoho mikro-výboje bariérového výboje můžeme
pro daný čas uvažovat jako DC)

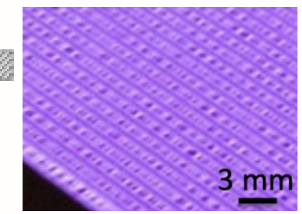
Barrier discharge fundamentals

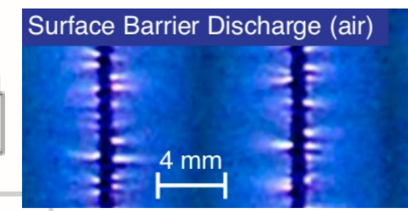
- A barrier discharge is characterized by the fact that there is a dielectric between the electrodes, preventing the formation of a conductive channel – an electrical short cannot occur

- Some fundamental configs (Brandenburg 2017):

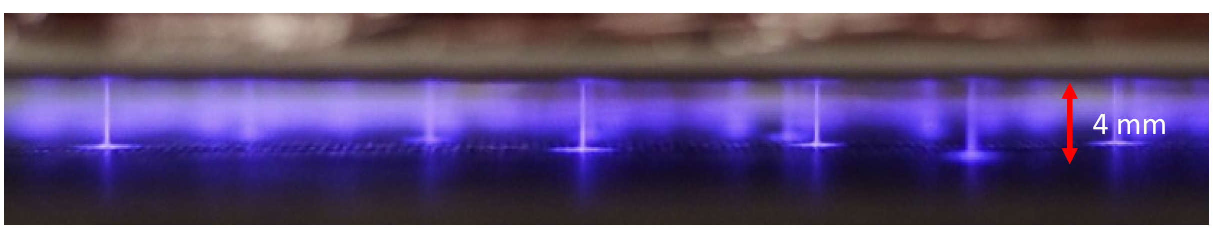






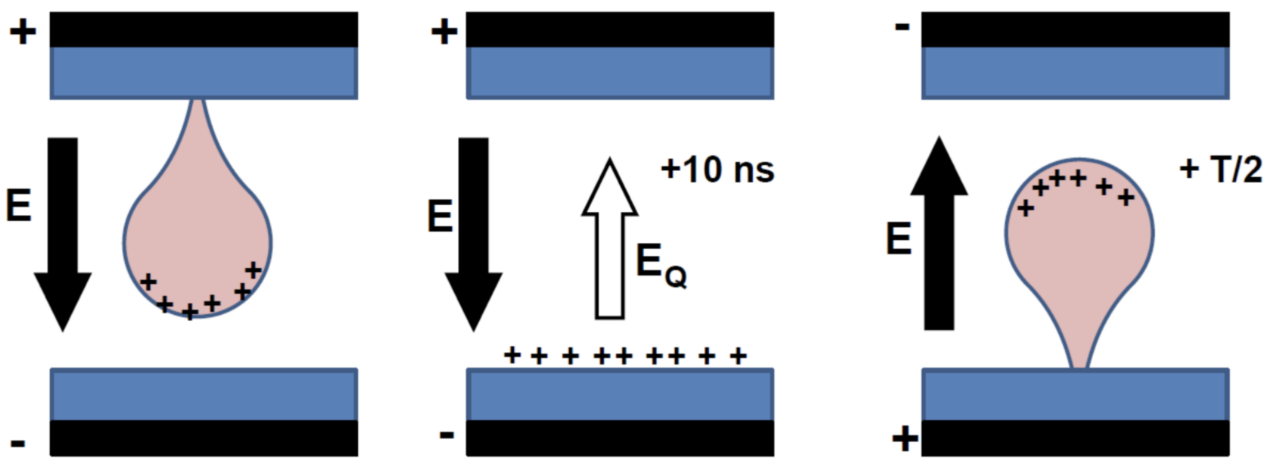


- Often filamentary, here is a glow discharge at the atm. pressure:



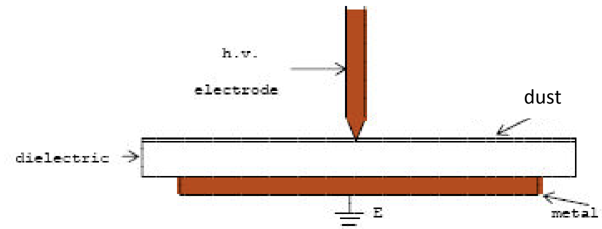
General barrier discharge mechanism

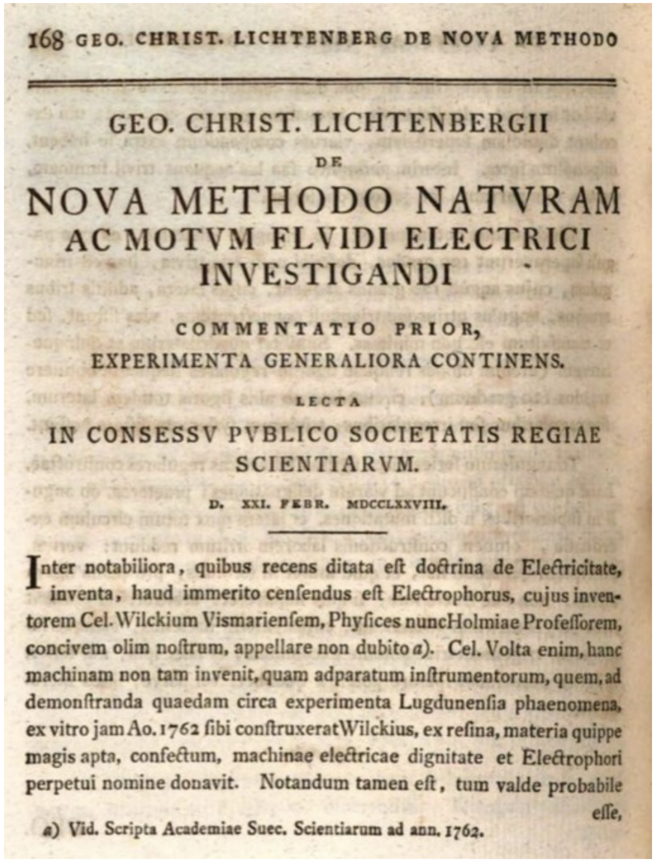
- (Dielectric) barrier discharge occurs between electrodes, at least one of which is covered by a dielectric.
- An important driver for DBD formation is charge accumulation on the dielectric.
- When described by an equivalent circuit, it behaves like a capacitor.
- Due to the dielectric, it **always has to be driven by an AC field**



Dielectric barrier discharge – ancient history

- Ancient history - G.C.Lichtenberg (1777):





168 GEO. CHRIST. LICHTENBERG DE NOVA METHODO

GEO. CHRIST. LICHTENBERGII
DE
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LECTA
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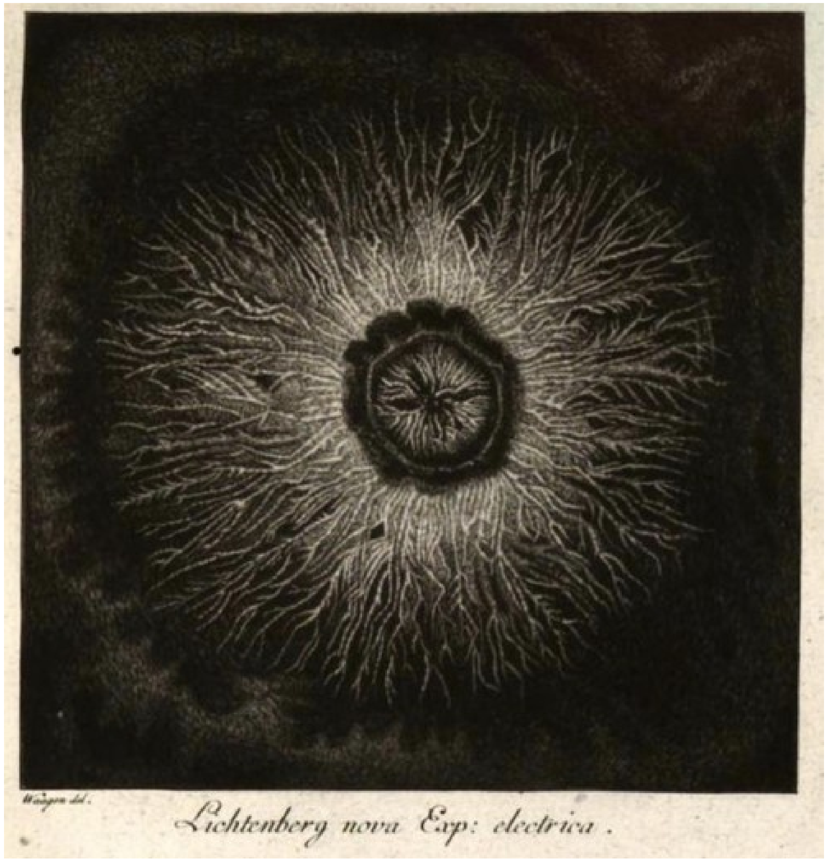
D. XXI. FEBR. MDCCLXXVIII.

Inter notabiliora, quibus recens ditata eſt doctrina de Electricitate, inventa, haud immerito cenſendus eſt Electrophorus, cujus inventorem Cel. Wilckium Vismarienſem, Phyſices nunc Holmiae Profeſſorem, concivem olim noſtrum, appellare non dubito a). Cel. Volta enim, hanc machinam non tam invenit, quam adparatum inſtrumentorum, quem, ad demonſtranda quaedam circa experimenta Lugdunenſia phaenomena, ex vitro jam Ao. 1762 ſibi conſtruxerat Wilckius, ex reſina, materia quippe magis apta, confectum, machinae electricae dignitate et Electrophori perpetui nomine donavit. Notandum tamen eſt, tum valde probabile eſſe,

a) Vid. Scripta Academiae Suec. Scientiarum ad ann. 1762.



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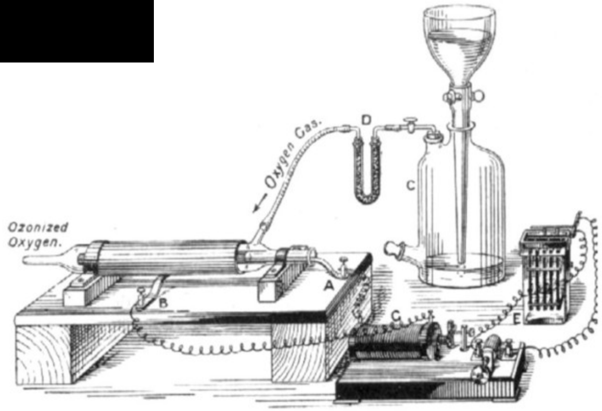
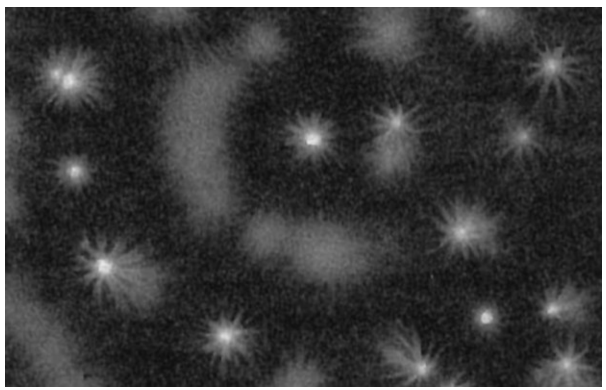
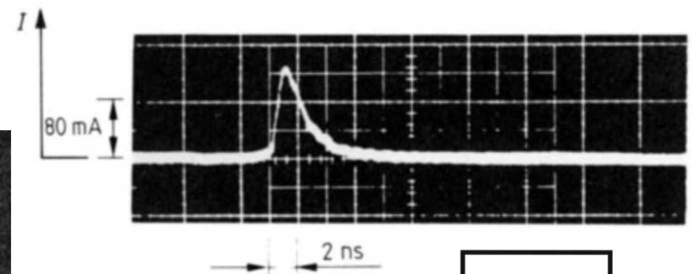
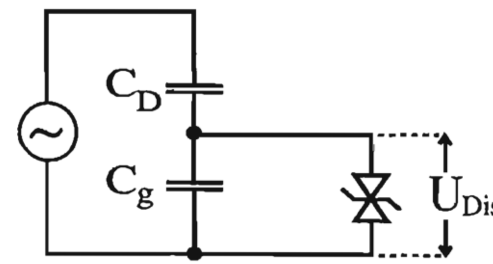
Brief history of the dielectric barrier discharge

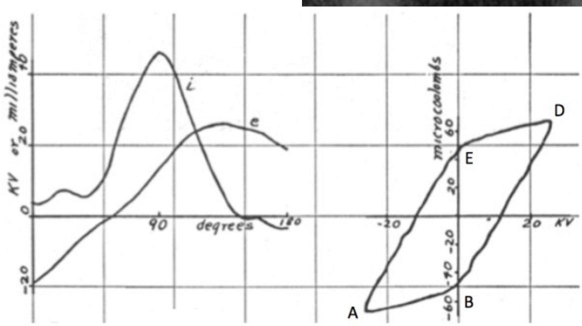
- Ozone generation, Lichtenberg figures, streak measurements.

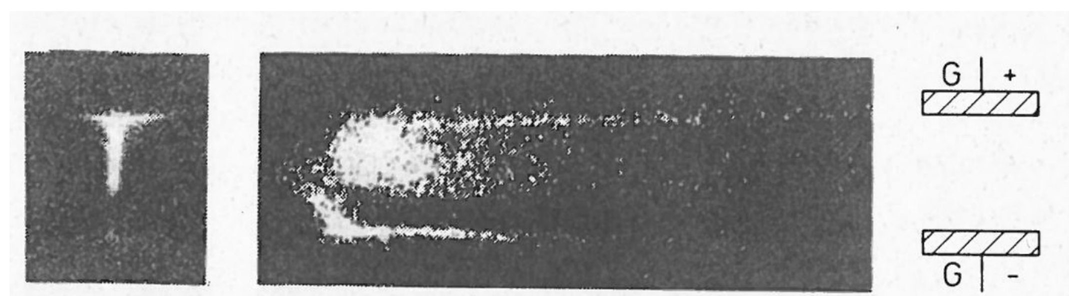










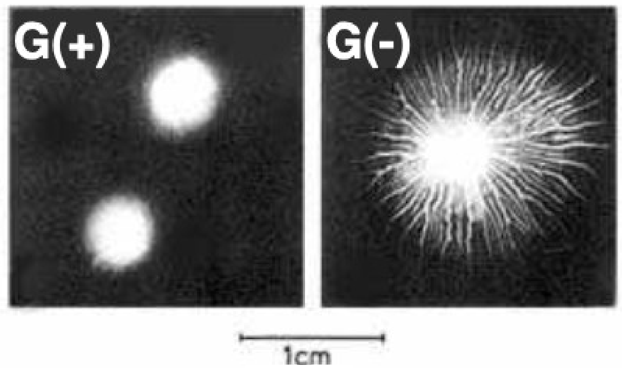


W. Siemens 1857 and Buss 1932, Klemenc 1937, Manley 1943, Samoilovich 1966, Gibalov 1981, Eliasson, Kogelschatz 1983, Heuser 1985, Okazaki 1993, Zhu, Hidaka 1996, Guikema 2000, Kozlov 2001, Wagner 2010

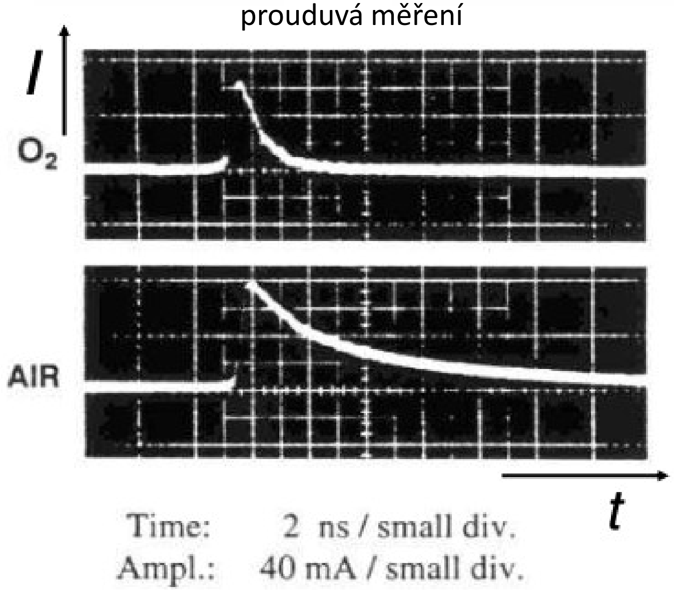
Initial observations of DBD discharges

- Optical and electrical studies historically performed in Aachen (Pietsch, Heuser, Gibalov) and in ABB (Hirth, Kogelschatz, Eliasson):

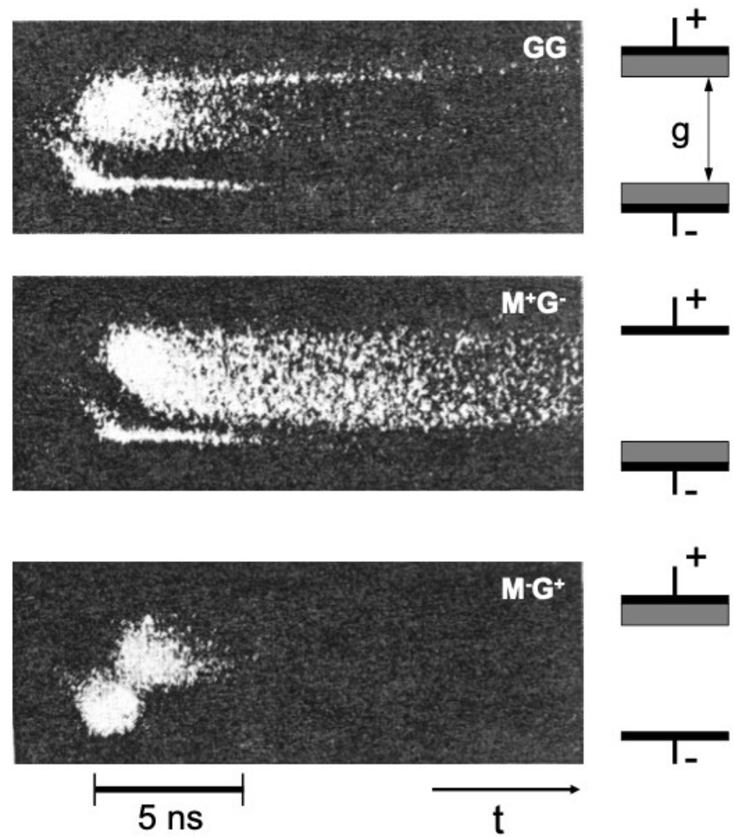
Lichtenberg figures



prouduvá měření



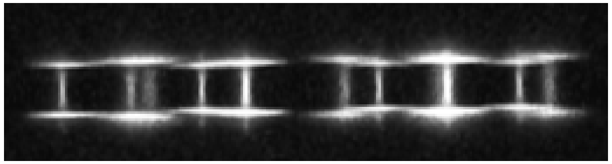
Streak camera – pulsed barrier discharge

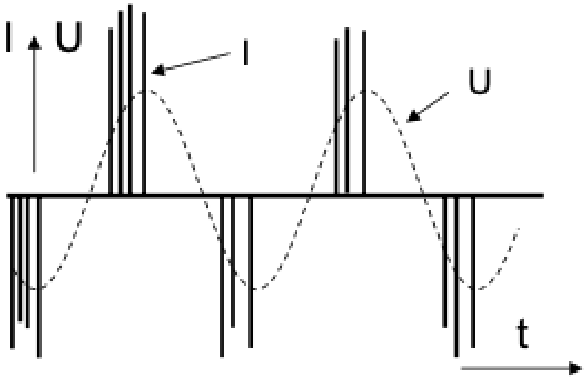


General forms of the DBD discharge

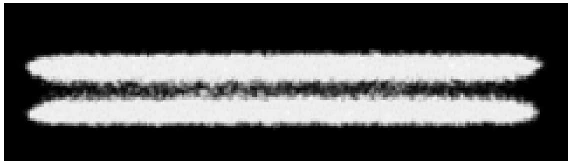
- Basic modes of the DBD are filamentary and (Brandenburg 2004):

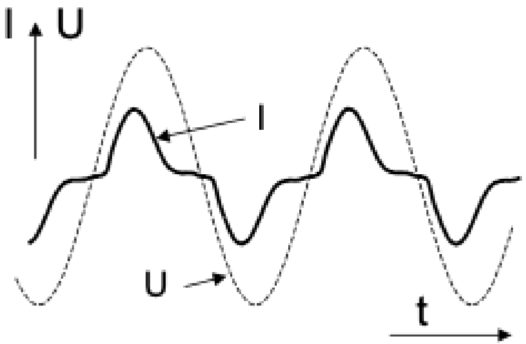
filamentary





diffuse

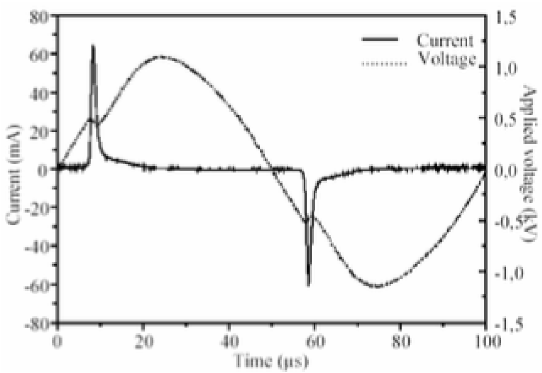


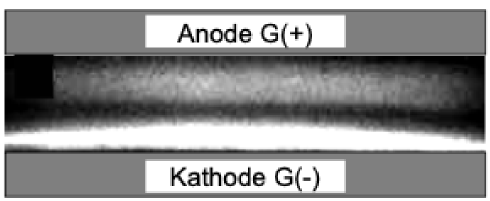


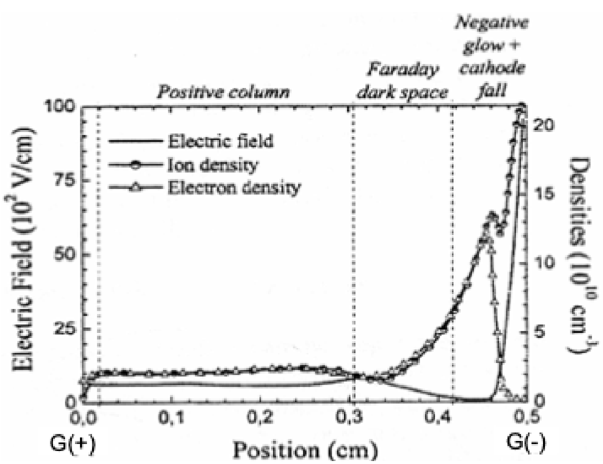
- In the filamentary mode, the fialment diameter is sub-millimeter. Individual filaments také nanoseconds and the electric field is hundreds of Td owing to the streamer mechanism.
- In the diffuse mode, the discharge size is given by electrode width but the mode is not universaly stable.
- **Penning ionization – one of phenomena contributing to the stability of the discharge**
- Diffuseness is important for various applications of the discharge. Note that even the filaments can be distributed uniformly and the discharge is pseudo-diffuse.

Diffusion barrier discharges (Massines)

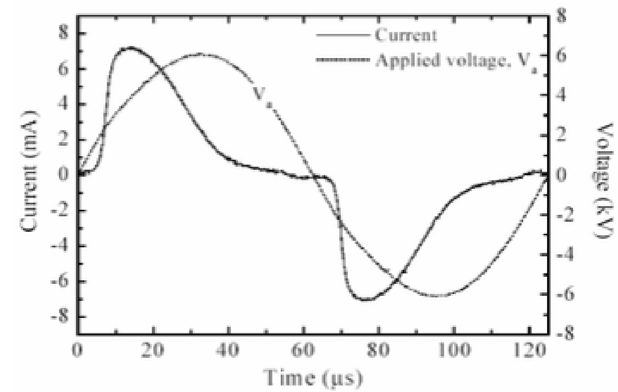
Diffusion barrier discharge in He

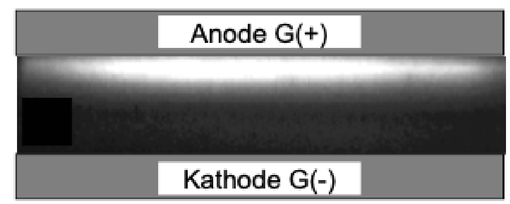


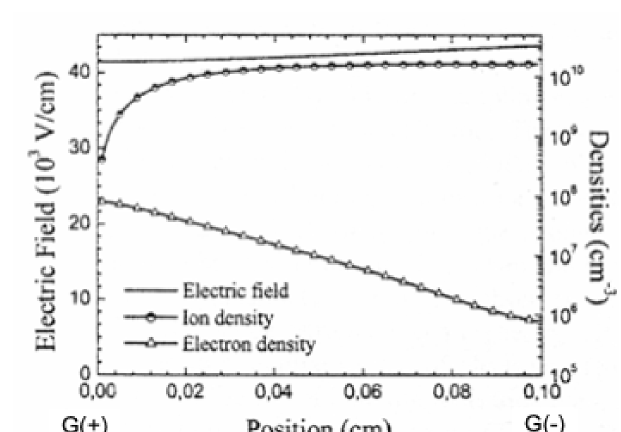




Diffusion barrier discharge in N2



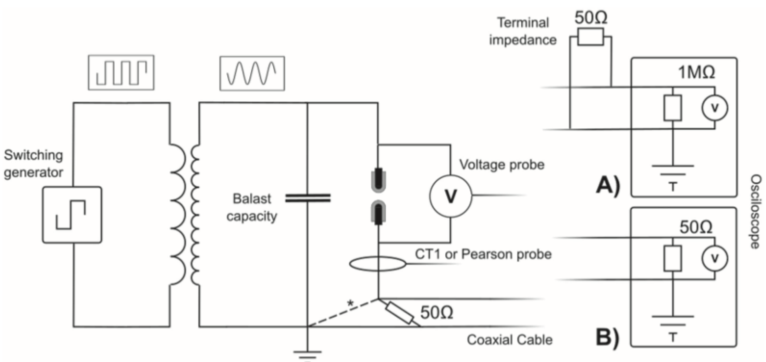


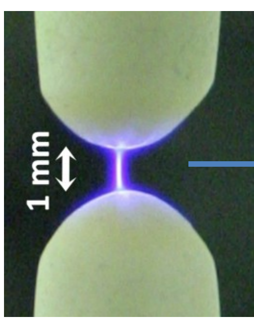


CURRENT IN DBD DISCHARGES

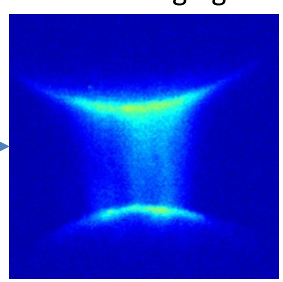
Measuring electrical current in a DBD discharge

- You can either measure current using induction-based probes or by measuring voltage on a parallel resistor.
- Equivalent circuit for a single-filamentary discharge in air.

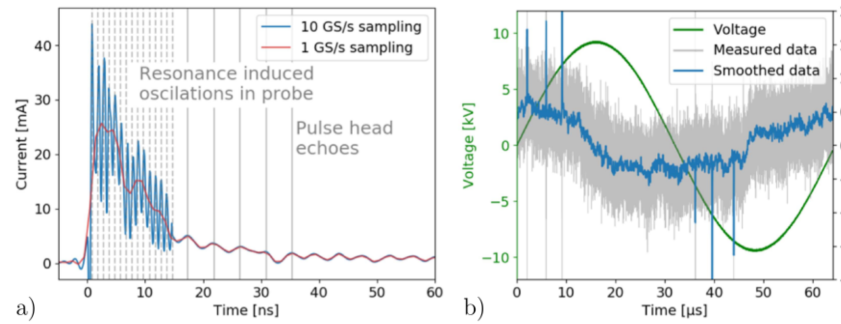




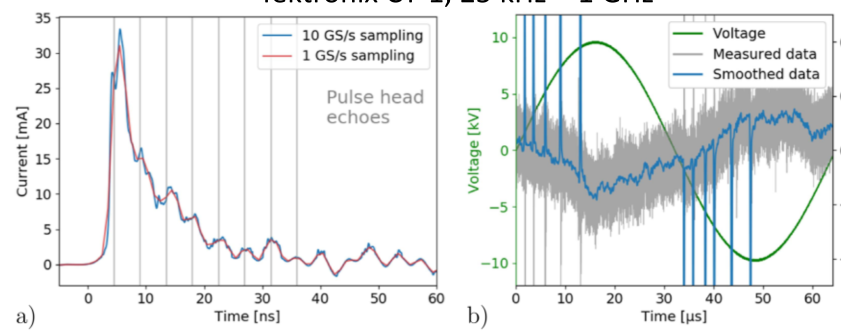
ICCD imaging:



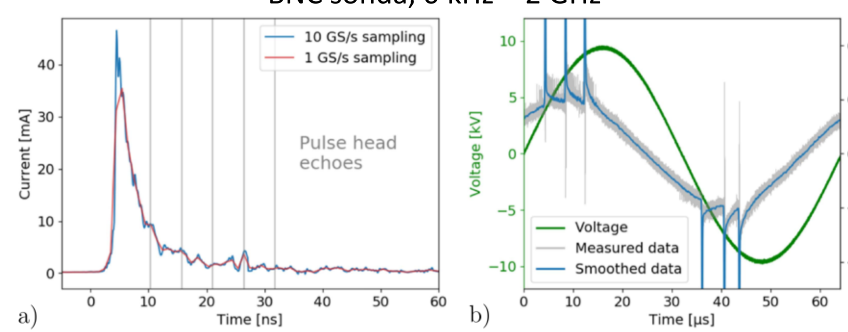
Pearson 2877, 300 Hz – 200 MHz



Tektronix CT-1, 25 kHz – 1 GHz



BNC sonda, 0 kHz – 2 GHz



Synek et al. 2018 PSST

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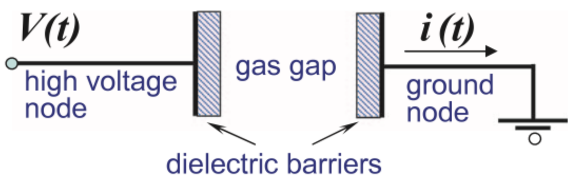
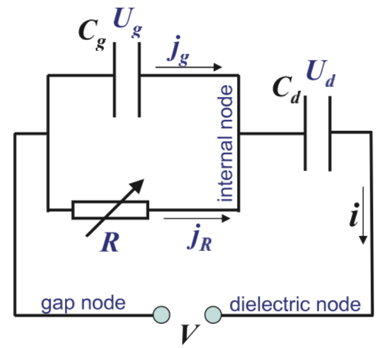
Electrical characterization of a DBD discharge

- To measure the actual current is challenging, because the Maxwell translation current makes a major contribution.





- the gap voltage determines the effective electric field between the dielectrics $E_{eff} = U_{gap}/g$
- j_R is the pure discharge current
- q is the charge transferred by a discharge

- The following factor is not negligible:

$$\left[1 + \frac{C_g}{C_d}\right]$$

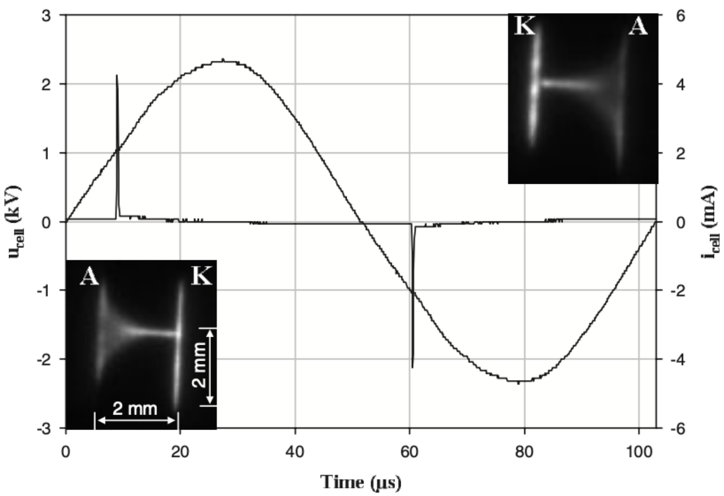


Figure 2. Supply voltage, cell current, and 5-μs time-integrated photographs of the discharge, in the visible range for $P_{Ar} = 400$ Torr, $f = 10$ kHz, $g = 2$ mm, $U_{max} = 2.36$ kV.

$$C_{cell} = \frac{C_d C_g}{C_d + C_g}$$

$$U_d(t) = \frac{Q(t)}{C_d},$$

$$U_g(t) = V(t) - U_d(t),$$

$$j_g(t) = C_g \frac{dU_g(t)}{dt},$$

$$j_R = i(t) - j_g(t),$$

$$U_g(t) = V(t) - \frac{Q(t)}{C_d}$$

$$j_R(t) = \left[1 + \frac{C_g}{C_d}\right] i(t) - C_g \frac{dV(t)}{dt}$$

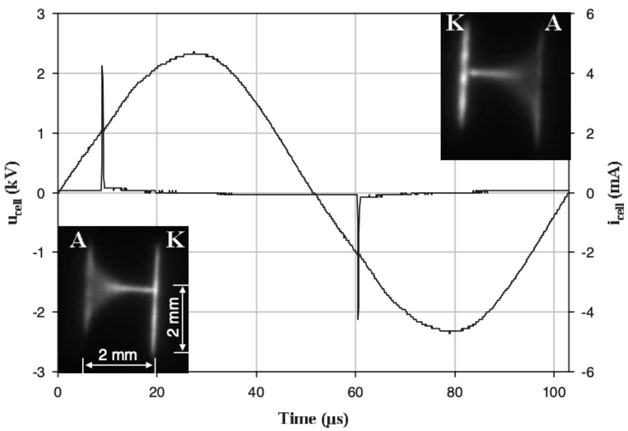
$$j_R(t) = \frac{1}{1 - \frac{C_{cell}}{C_d}} \left[i(t) - C_{cell} \frac{dV(t)}{dt} \right]$$

$$q(t) = \frac{1}{1 - \frac{C_{cell}}{C_d}} [Q(t) - C_{cell} V(t)] + q_0$$

Merbahi 2004, Pipa 2012

Analyzing electrical measurements

- Single-filamentary volume barrier discharge in atmospheric pressure argon.



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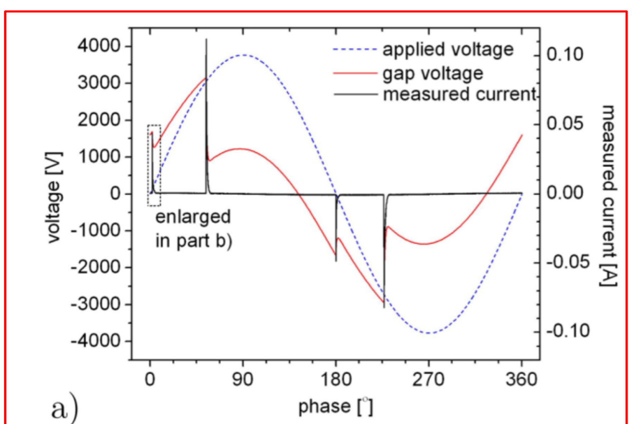

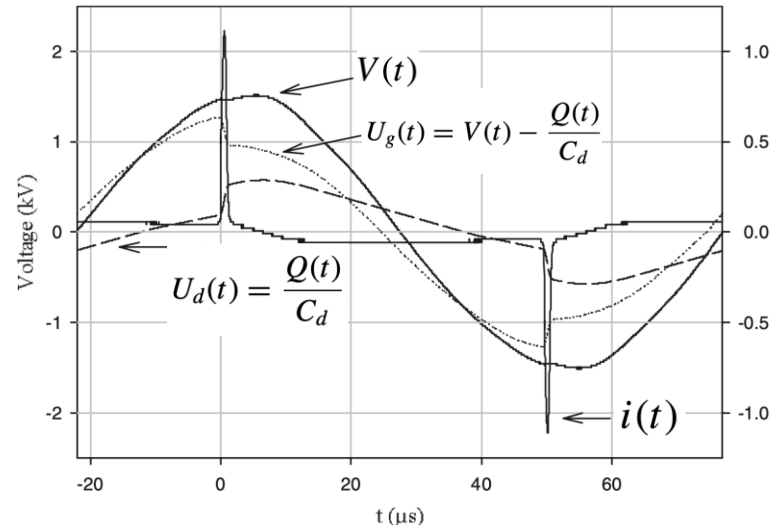

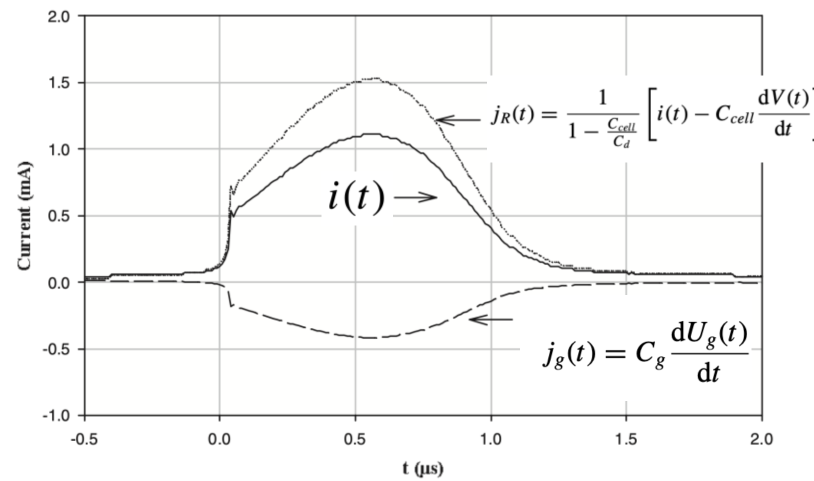

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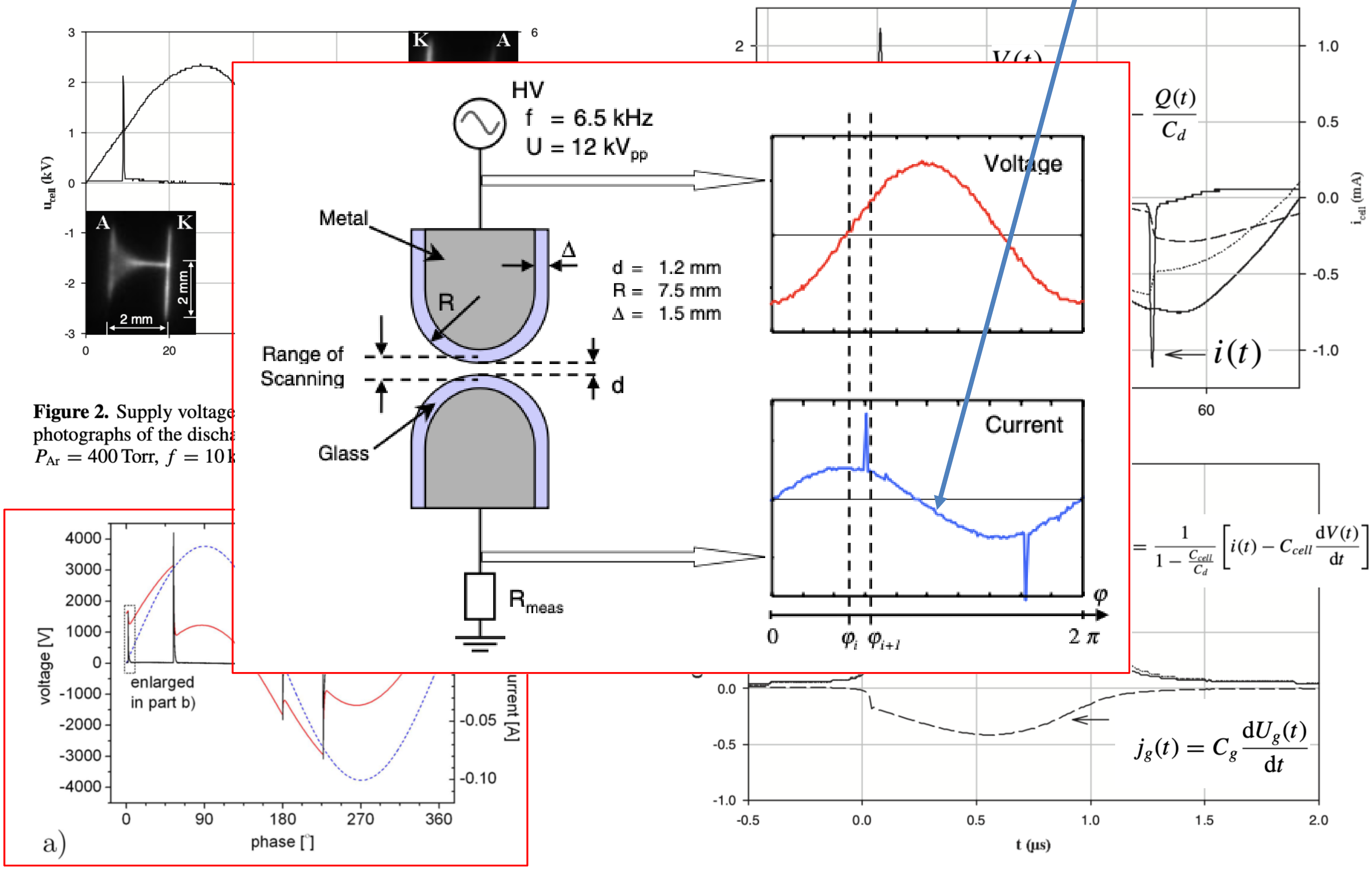
Analyzing electrical measurements

You cannot simply subtract the sine component to get the correct current

- Single-filamentary volume barrier discharge in atmospheric pressure argon.



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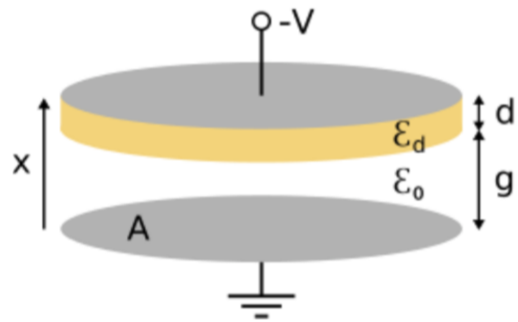
An alternative method for obtaining j_R

- Let's start with the equation for the total current



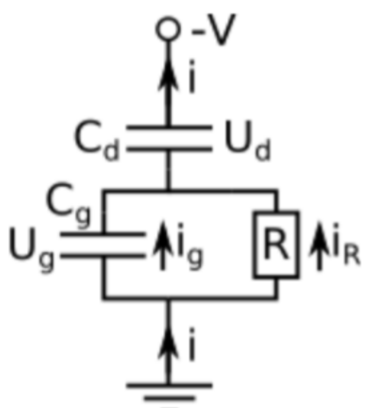


plate capacitor capacitance

$$C = \varepsilon \frac{A}{d}$$

$$\varepsilon = \varepsilon_0 \varepsilon_r$$

From Kirchhoff's laws

$$j_R(t) = \frac{1}{1 - \frac{C_{cell}}{C_d}} \left[i(t) - C_{cell} \frac{\mathrm{d}V(t)}{\mathrm{d}t} \right]$$

Conduction current

Translational current

$$i_t(t) = i_c(x,t) + \varepsilon(x)\varepsilon_0 \frac{\partial E(x,t)}{\partial t}$$

$$i_c(x,t) = q[\Gamma_p(x,t) - \Gamma_e(x,t)]$$

$$= i(t)/A$$

Measured current density

$$\frac{i_t(t)}{\varepsilon_0} \int_0^{d+g} \frac{\mathrm{d}x}{\varepsilon(x)} = \int_0^{d+g} \frac{i_c(x,t)}{\varepsilon(x)\varepsilon_0} \mathrm{d}x + \frac{\partial}{\partial t} \int_0^{d+g} E(x,t) \mathrm{d}x$$

$$j_t(t) \left(\frac{1}{C_d} + \frac{1}{C_g} \right) = \frac{1}{A\varepsilon_0} \int_0^{d+g} \frac{j_c(x,t)}{\varepsilon(x)} \mathrm{d}x + \frac{\mathrm{d}V(t)}{\mathrm{d}t}$$

$$\varepsilon(x \leq g) = 1$$

$$j_t(t) \left(\frac{1}{C_d} + \frac{1}{C_g} \right) = \frac{1}{C_g} j_c(t) + \frac{\mathrm{d}V(t)}{\mathrm{d}t}$$

$$j_R(t) = j_c(t) = \frac{1}{1 - \frac{C_{cell}}{C_d}} \left[i(t) - C_{cell} \frac{\mathrm{d}V(t)}{\mathrm{d}t} \right]$$

An alternative method for obtaining j_R

- If we take into account the deposited surface charge, then (Bonaventura 2020):

$$i_t(t) = i_c(x,t) + \varepsilon(x)\frac{\partial E_g(t)}{\partial t} = \varepsilon(x)\varepsilon_0\frac{\partial E_d(t)}{\partial t} = i(t)/A$$

surface charge deposition

$$\frac{\partial \sigma}{\partial t} = i_c$$

step condition on the boundary of a dielectric (Tirpák)

$$E_g = \varepsilon_r E_d - \sigma/\varepsilon_0$$

after a few modifications:

$$\begin{aligned}\frac{j_t(t)}{A} &= \int_0^g j_c(x,t)\mathrm{d}x + \left(\frac{\partial \sigma}{\partial t}\right)\left(\frac{dg(\varepsilon_r - 1)}{\varepsilon_r g + d}\right) - \frac{g+d}{\varepsilon_r g + d}\varepsilon_r\varepsilon_0\frac{\partial V}{\partial t} \\ &= \frac{\partial \sigma}{\partial t}\left[\frac{\varepsilon_r g(g+d)}{\varepsilon_r g + d}\right] + \frac{g+d}{\varepsilon_r g + d}\varepsilon_r\varepsilon_0\frac{\partial V}{\partial t}\end{aligned}$$

$$j_R(t) = j_c(t) = \frac{1}{1 - \frac{C_{cell}}{C_d}}\left[i(t) - C_{cell}\frac{\mathrm{d}V(t)}{\mathrm{d}t}\right]$$

the calculated current j_R obtained from Kirchhoff laws is identical to conduction current j_C

QV diagrams of the DBD discharge

- Manley 1943 showed that the energy dissipated in a DBD can be obtained from Lissajouse figures, graphically.
- Today, these plots are called more accurately – QV plots/diagrams

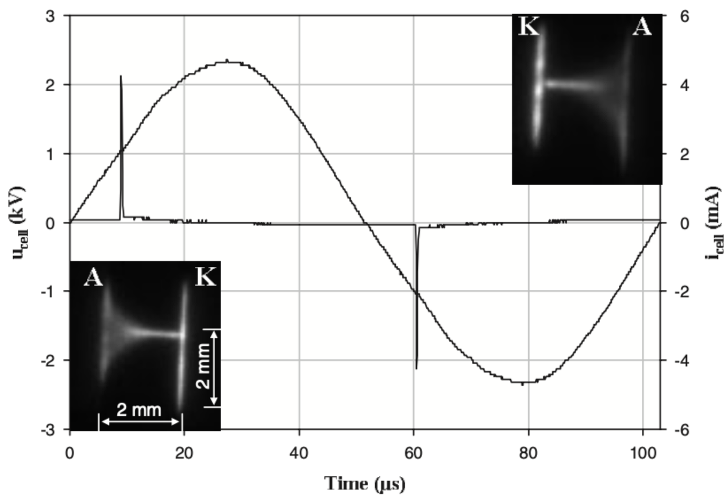
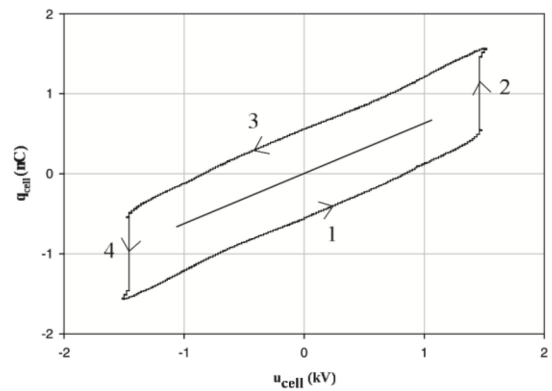
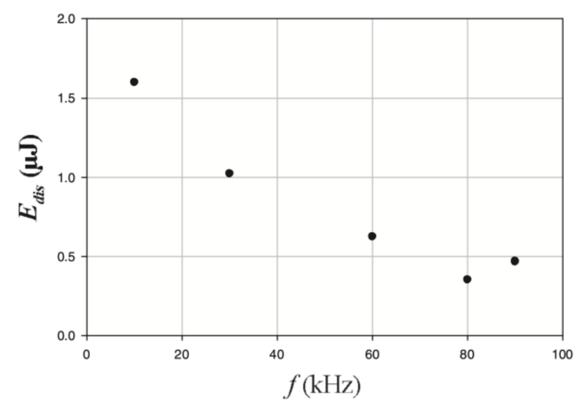


Figure 2. Supply voltage, cell current, and 5-μs time-integrated photographs of the discharge, in the visible range for $P_{\mathrm{Ar}} = 400$ Torr, $f = 1g$ Hz, $d = 2$ mm, $U_{\mathrm{max}} = 2.36$ kV.





Merbahi et al. 2004 JPDAP

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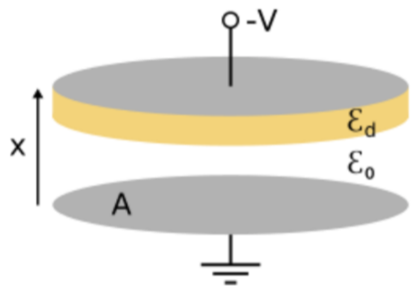
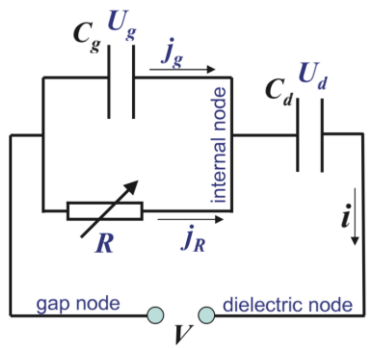
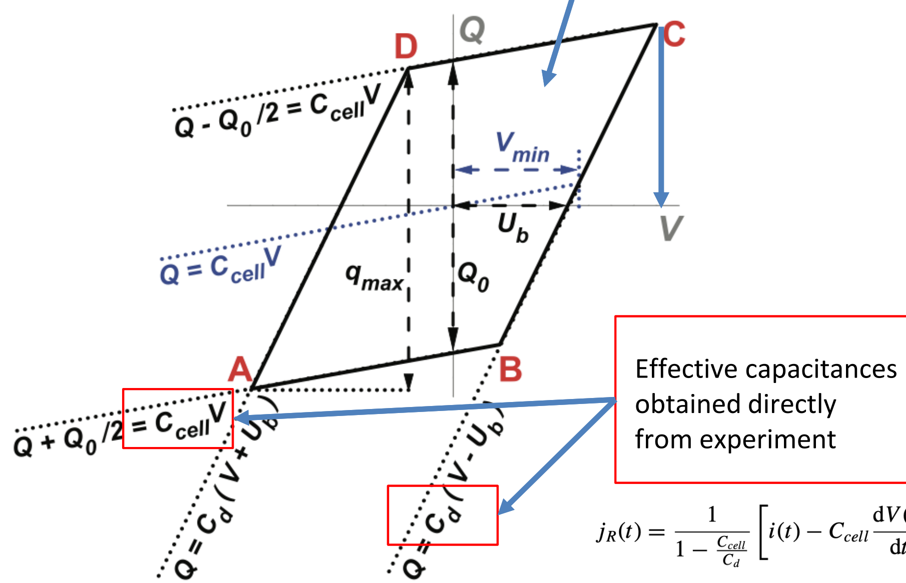
QV diagrams of the DBD discharge

- So how do the equivalent circuit and QV plots play together?

$$E(t) = \int_0^t P(\tau)\mathrm{d}\tau$$







$$j_R(t) = \frac{1}{1 - \frac{C_{cell}}{C_d}}\left[i(t) - C_{cell}\frac{\mathrm{d}V(t)}{\mathrm{d}t}\right]$$

- Power dissipated in the discharge can be obtained from current and voltage: $P(t) = j_R(t)U_g(t)$

- And for total dissipated energy, it has to hold that: $\int_0^T i(\tau)V(\tau)\mathrm{d}\tau = \int_0^T j_R(\tau)U_g(\tau)\mathrm{d}\tau$

VOLUME DIAGNOSTICS OF DBD PLASMAS

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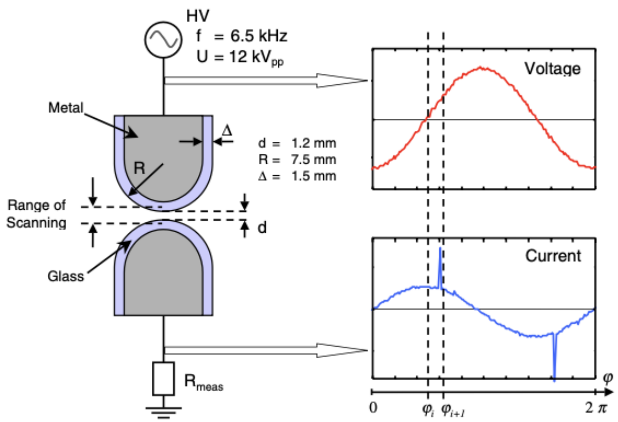
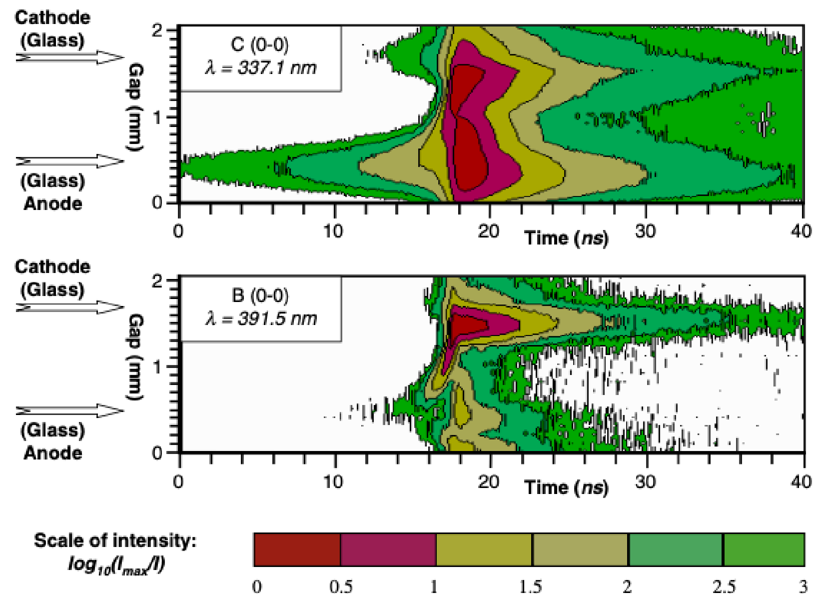
Applying cross-correlation spectroscopy to understand DBDs (Kozlov 2001)

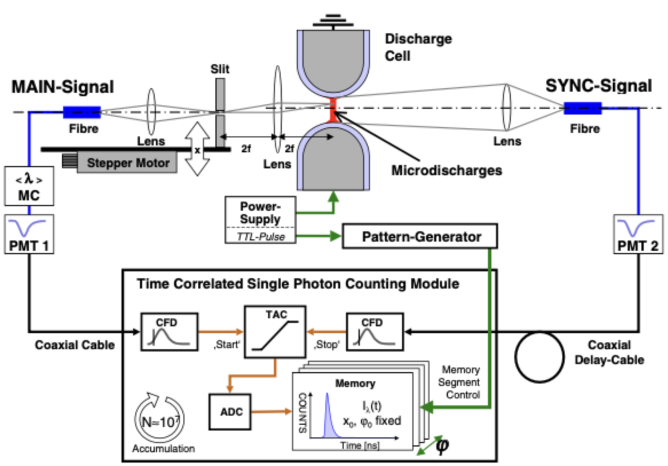
Symmetrical atm. pressure discharge



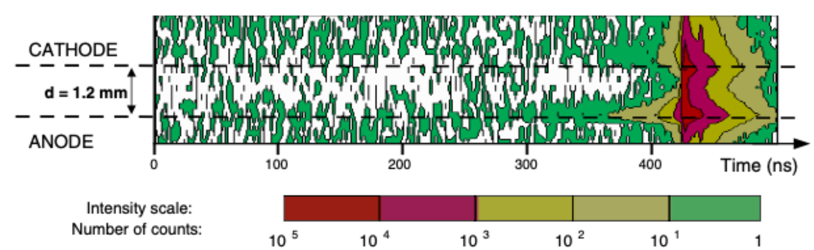
Light emission during the discharge



Time-correlated photon counting technique



Light emission in the Townsend phase



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Measuring the electric field in DBDs

- Spectroscopic method based on nitrogen emission bends, developed by Kozlov in 2001

SPS

$$e + N_2(X\,^1\Sigma_g^+)_{v=0} \rightarrow N_2(C\,^3\Pi_u)_{v'=0} + e \quad (\Delta E = 11.0\,\mathrm{eV}),$$

$$N_2(C\,^3\Pi_u)_{v'=0} \rightarrow N_2(B\,^3\Pi_g)_{v''=0} + h\nu \quad (\lambda_C = 337.1\,\mathrm{nm}),$$

$$N_2(C\,^3\Pi_u)_{v'=0} + N_2/O_2 \xrightarrow{K^C_{N_2}/K^C_{O_2}} \text{Products},$$

$$\frac{dn_C(r,t)}{dt} = k_C\left(\frac{E}{n}\right) n_{N_2} n_e(r,t) - \frac{n_C(r,t)}{\tau^C_{\mathrm{eff}}}$$

$$\frac{1}{\tau^C_{\mathrm{eff}}} = K^C_{N_2} n_{N_2} + K^C_{O_2} n_{O_2} + \frac{1}{\tau^C_0} = K^C_{N_2} n_{N_2} + K^C_{O_2} n_{O_2} + \sum_{v''=0}^{\infty} \frac{1}{\tau^C_{0v''}}$$

FNS

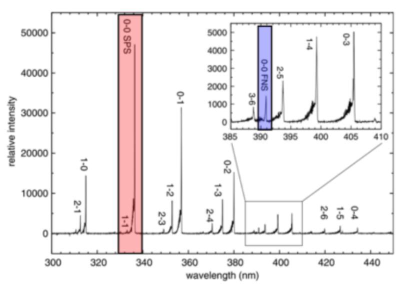
$$e + N_2(X\,^1\Sigma_g^+)_{v=0} \rightarrow N_2^+(B\,^2\Sigma_u^+)_{v'=0} + 2e \quad (\Delta E = 18.7\,\mathrm{eV}).$$

$$N_2^+(B\,^2\Sigma_u^+)_{v'=0} \rightarrow N_2^+(X\,^2\Sigma_g^+)_{v''=0} + h\nu \quad (\lambda_B = 391.5\,\mathrm{nm}).$$

$$N_2^+(B\,^2\Sigma_u^+)_{v'=0} + N_2/O_2 \xrightarrow{K^B_{N_2}/K^B_{O_2}} \text{Products}.$$

$$\frac{dn_B(r,t)}{dt} = k_B\left(\frac{E}{n}\right) n_{N_2} n_e(r,t) - \frac{n_B(r,t)}{\tau^B_{\mathrm{eff}}}$$

$$\frac{1}{\tau^B_{\mathrm{eff}}} = K^B_{N_2} n_{N_2} + K^B_{O_2} n_{O_2} + \frac{1}{\tau^B_0} = K^B_{N_2} n_{N_2} + K^B_{O_2} n_{O_2} + \sum_{v''=0}^{\infty} \frac{1}{\tau^B_{0v''}}$$

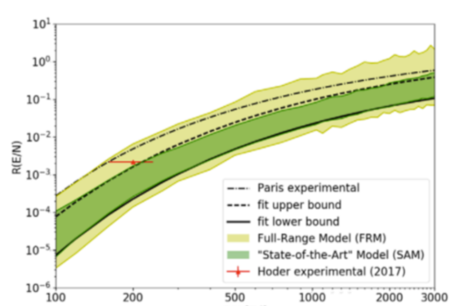


FNS 18.7eV: $N_2^+(B^2\Sigma_u^+)_{v'=0} \rightarrow N_2^+(X^2\Sigma_g^+)_{v''=0} + h\nu$, $\lambda = 391.5$ nm

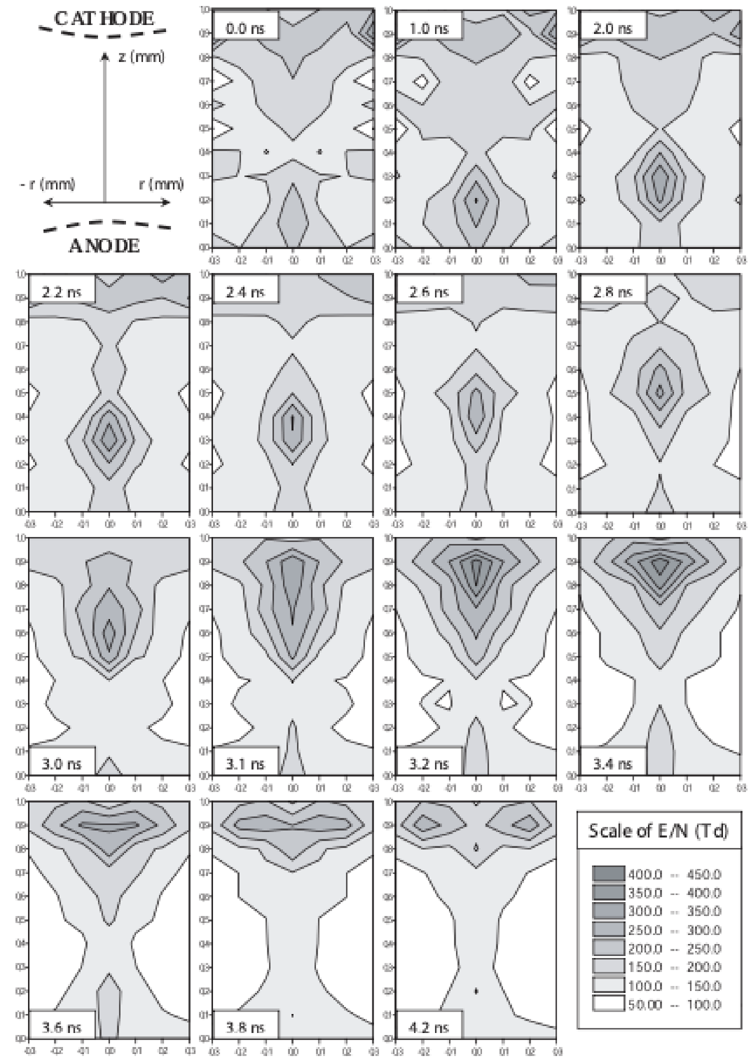
SPS 11eV: $N_2(C^3\Pi_u)_{v'=0} \rightarrow N_2(B^3\Pi_g)_{v''=0} + h\nu$, $\lambda = 337.1$ nm

measured | rate coefficients

$$\left(\frac{dI_{FNS}/dt + I_{FNS}/\tau^{FNS}_{\mathrm{eff}}}{dI_{SPS}/dt + I_{SPS}/\tau^{SPS}_{\mathrm{eff}}}\right)\frac{\tau^{FNS}_{\mathrm{eff}}}{\tau^{SPS}_{\mathrm{eff}}} = R_{FNS/SPS}(E/N)$$



Paris et al. 2005 JPD
Obrusnik et a. 2018 PSST
Bilek et al. 2018 PSST



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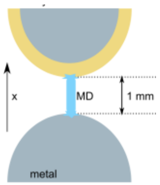
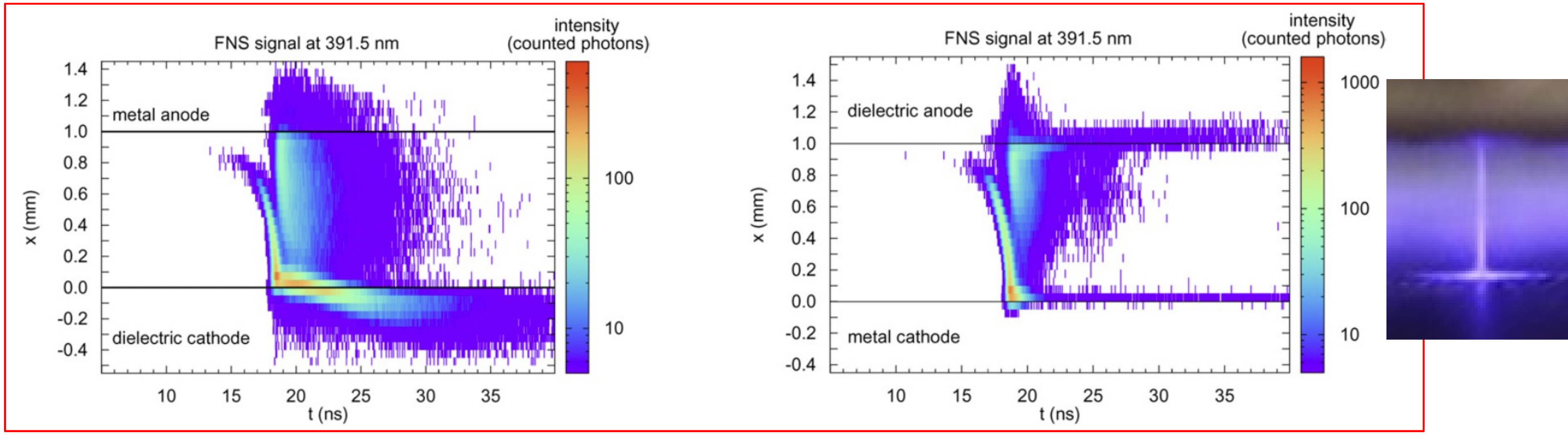
Spatio-temporal evolution of DBDs

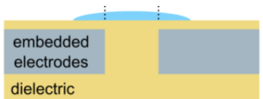
- Applicable to different types of DBDs

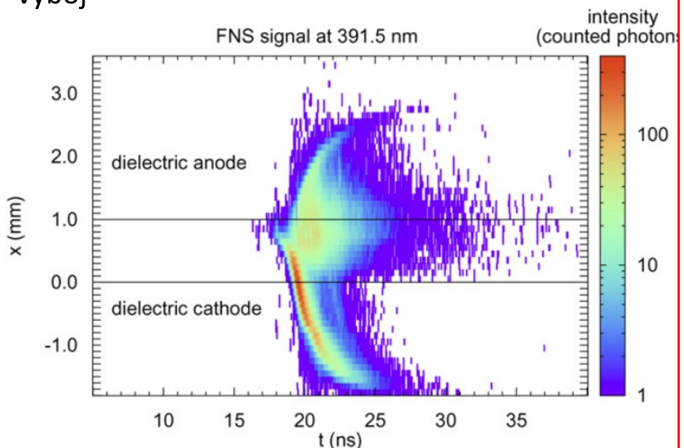


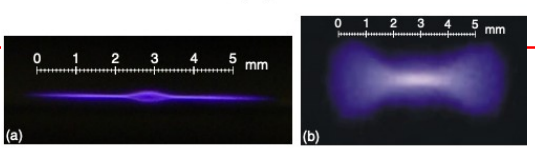
objemový bariérový výboj



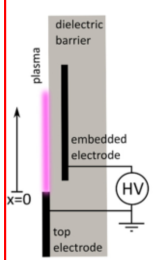
koplanární bariérový výboj

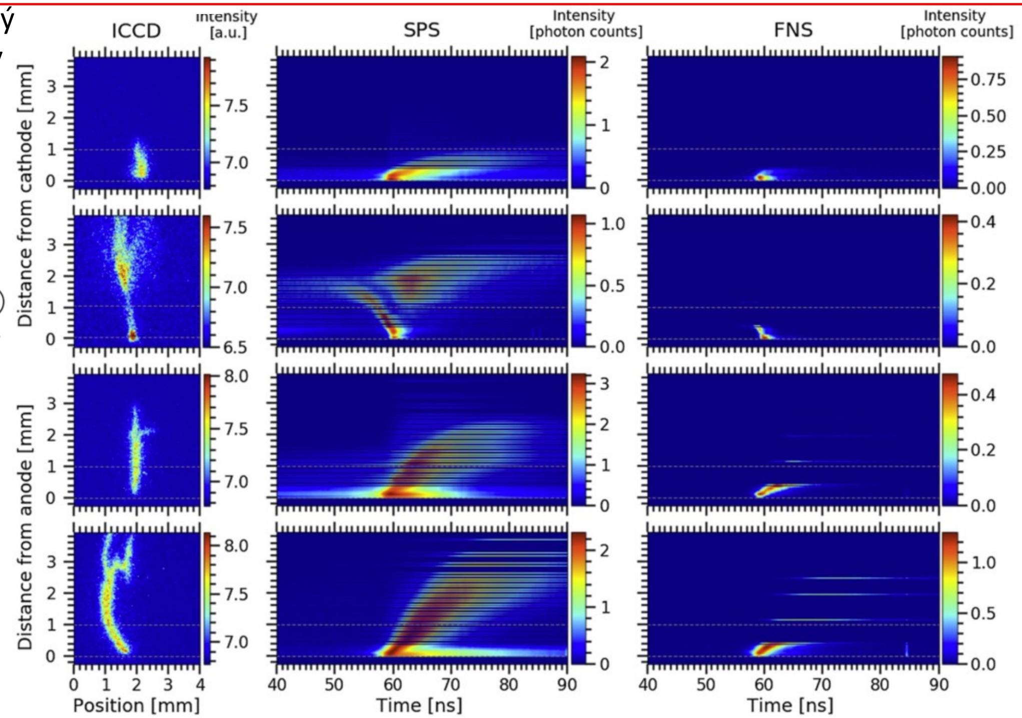






povrchový bariérový výboj





Spatially resolved simulations of DBD discharges

- Simulating a co-planar DBD discharge, Jánský 2022

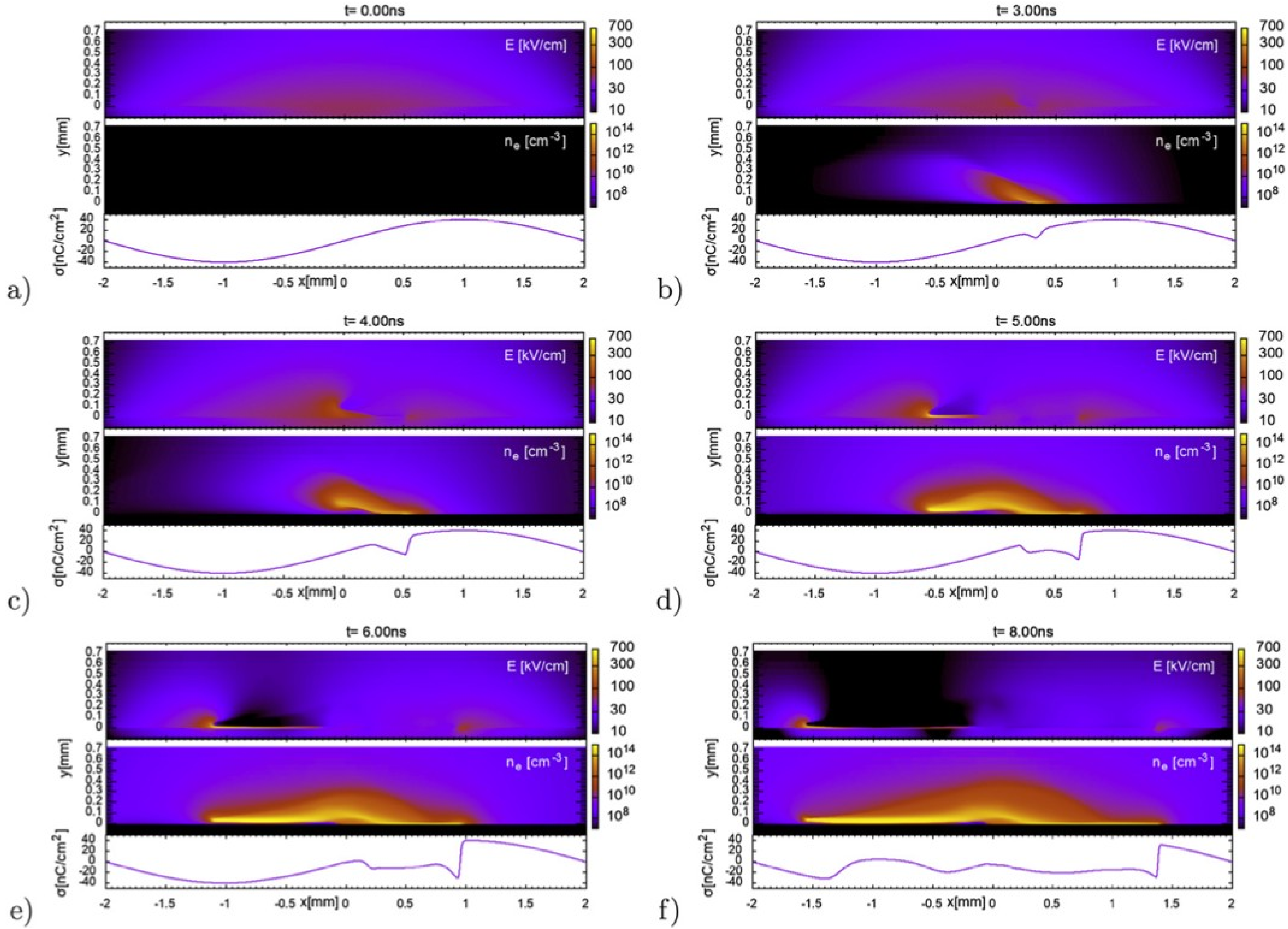


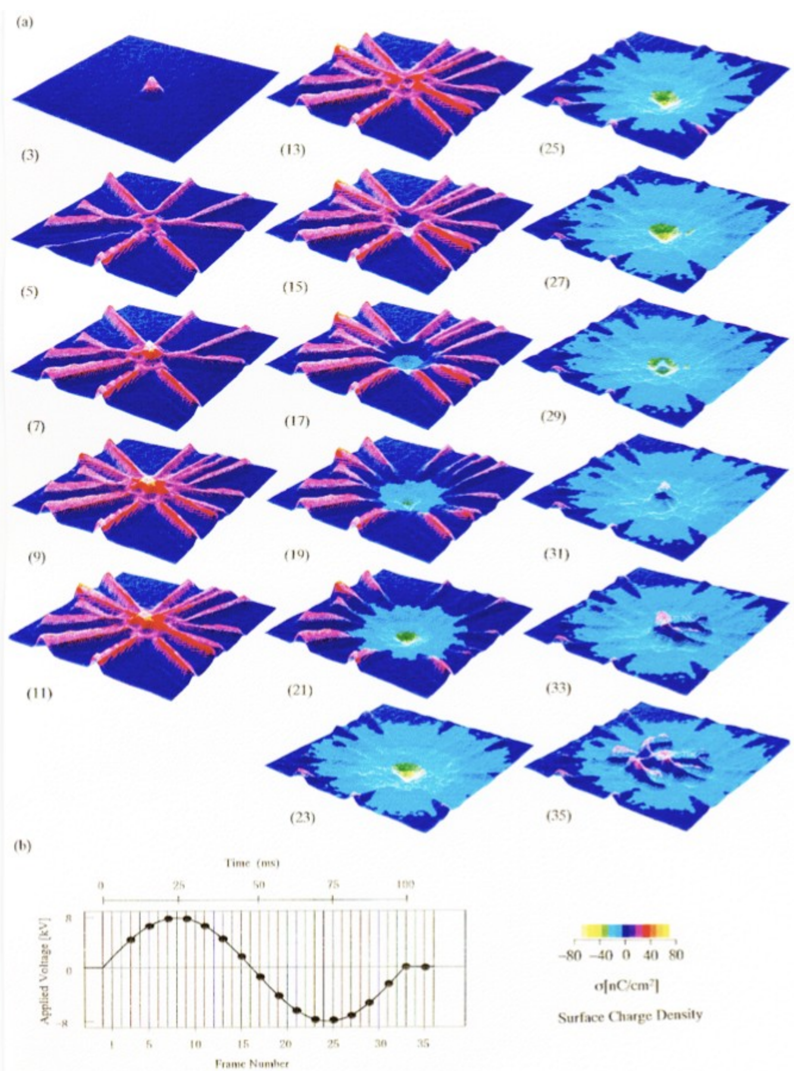
Figure 6. Two-dimensional side-view development of the discharge electric field strength (logarithmic scale), electron (logarithmic scale) and surface charge densities for coplanar discharge in atmospheric pressure air. Case for photoemission of 5×10^{-5}.

SURFACE CHARGE IN DBD DISCHARGES

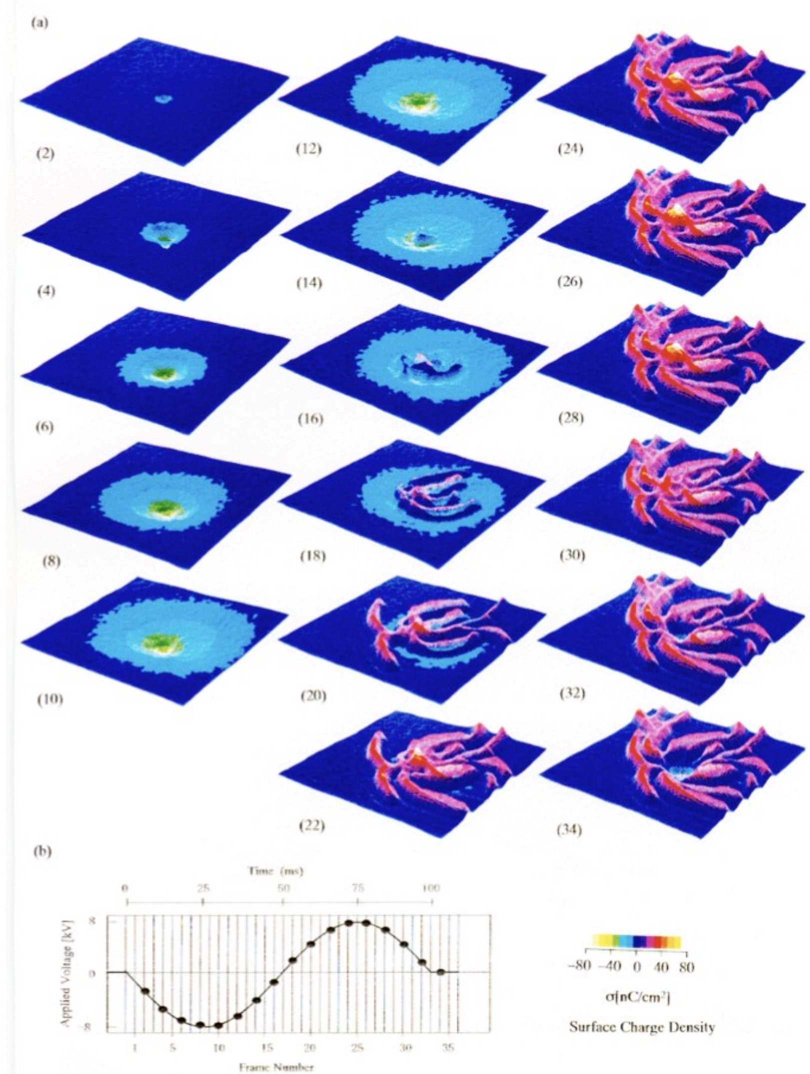
Surface charge in DBDs

- Pockels effect has been used to measure surface charge (Zhu 1996), for a point-to-plane config

Positive tip transitioning to negative polarity

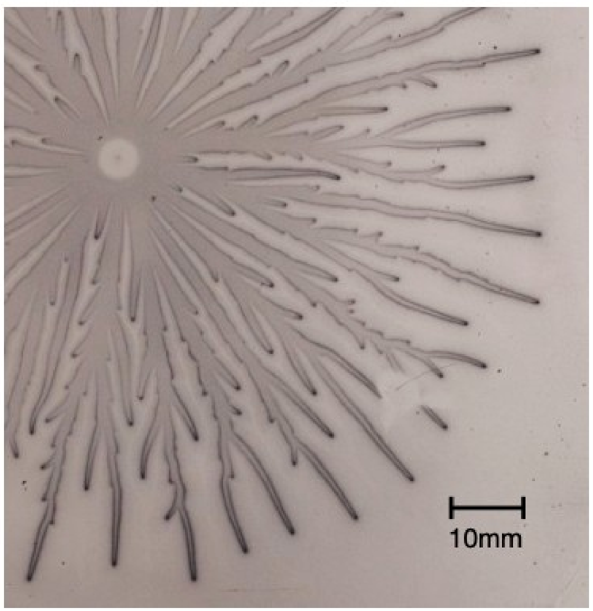


Negative tip transitioning to positive polarity



Surface charge in DBDs

- There is a „surface streamer“ forming in point-to-plane DBDs (Kumada 2009)
- The electric field exceeded an equivalent of 30kV/cm at higher pressure (experiments done at low pressure)



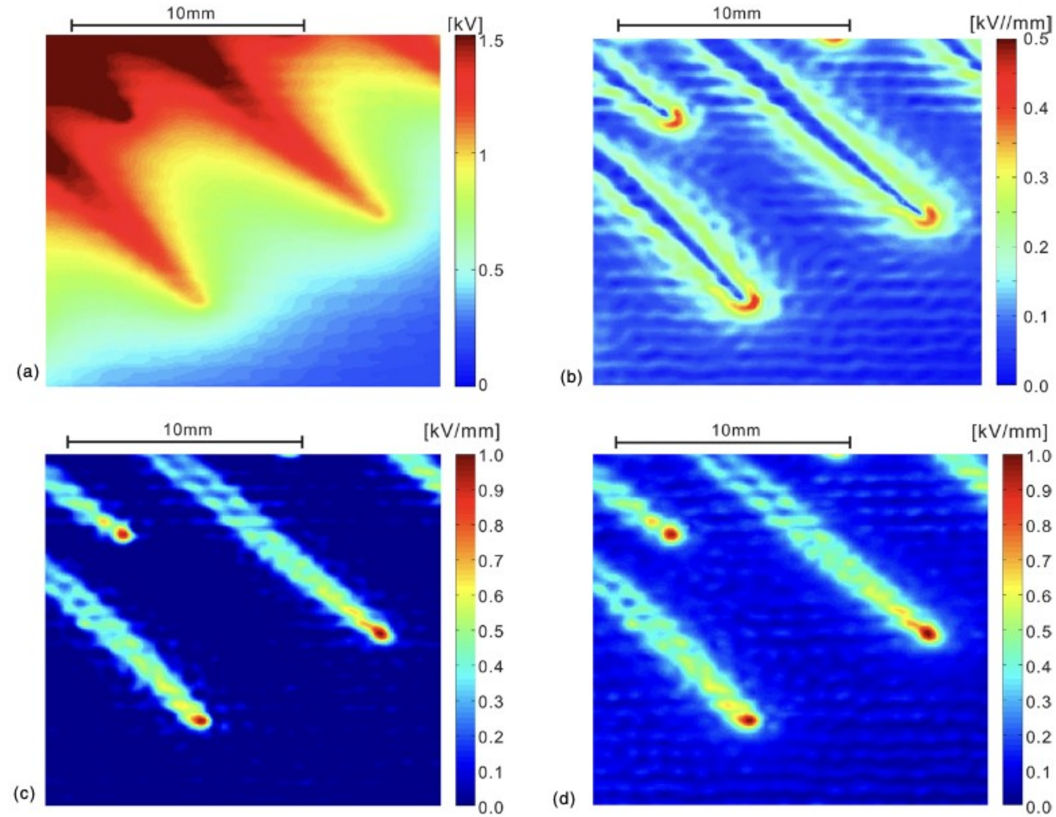


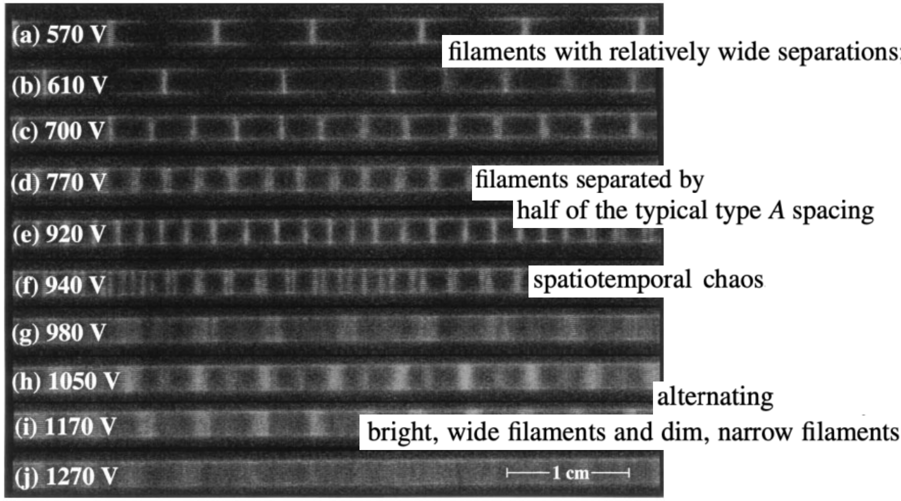
Figure 14. Computed results. Distribution of (*a*) potential V; (*b*) horizontal component of electric field, $\sqrt{E_x^2 + E_y^2}$; (*c*) perpendicular component of electric field, E_z; (*d*) intensity of electric field, $|\boldsymbol{E}|$.

SELF ORGANIZATION OF FILAMENTARY DBD DISCHARGES

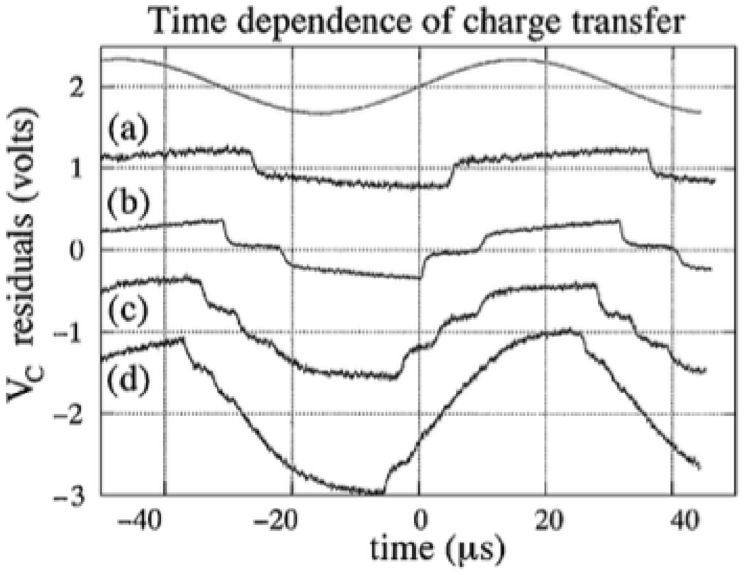
Self organization of filamentary DBDs (Guikema 2000)

Localized filaments – they „prefer“ to ignite in discrete places, rather than randomly.

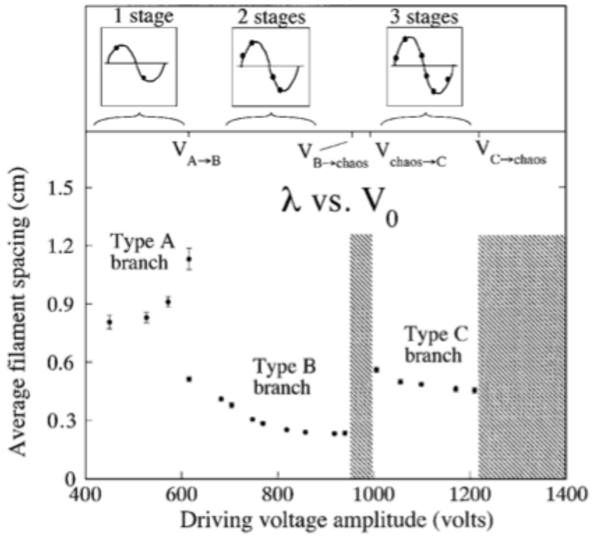
The decisive mechanism is the surface charge accumulation and the „dose“ of charge deposited by individual discharges.



přenos náboje skrze jednotlivé výboje



střední vzdálenost filamentů



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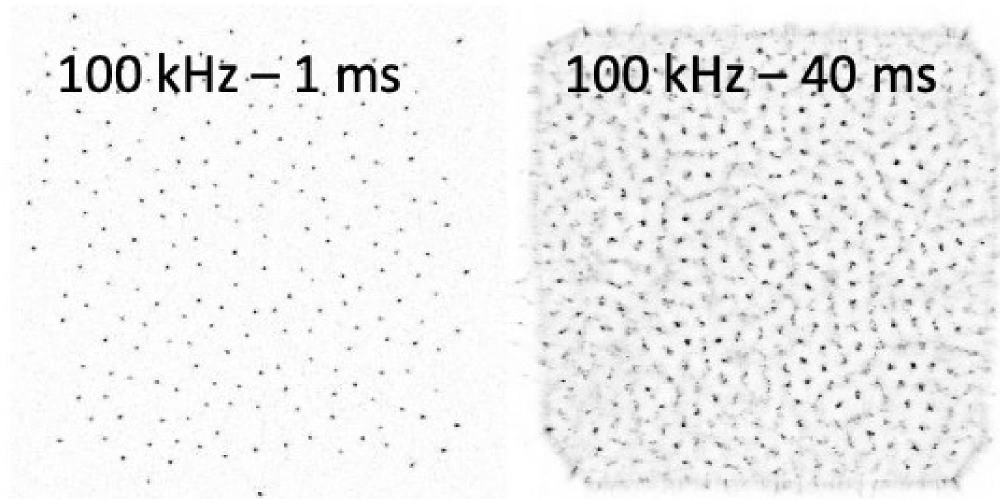
Self organization of filamentary DBDs

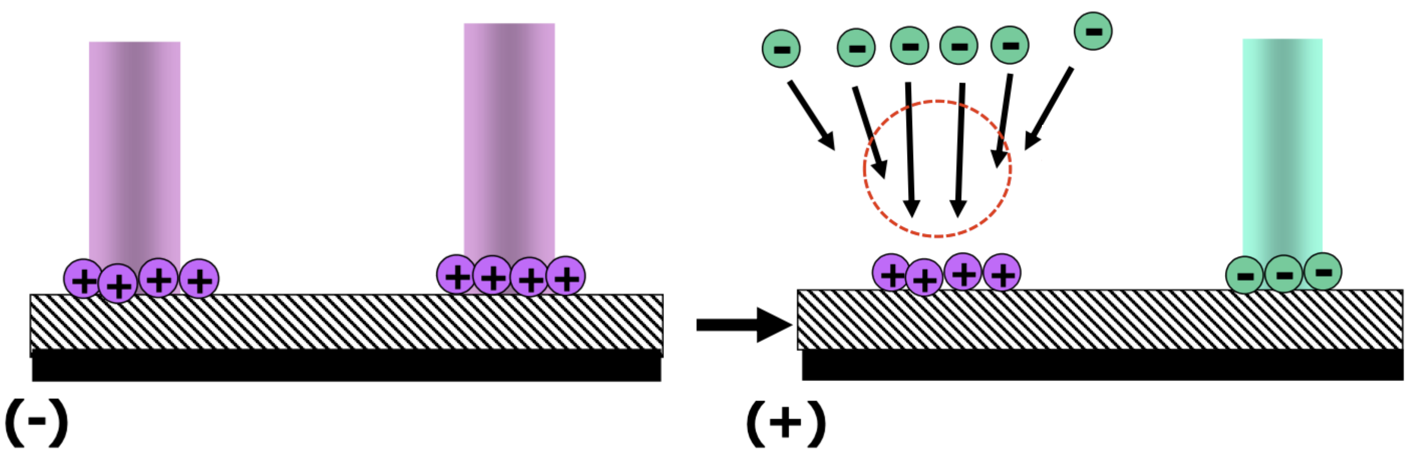
Microscopic view of the charge accuulation effect



Akishev Yu, Aponin G, Balakirev A *et al*. Acta Technica (2011) 56: T3-T14

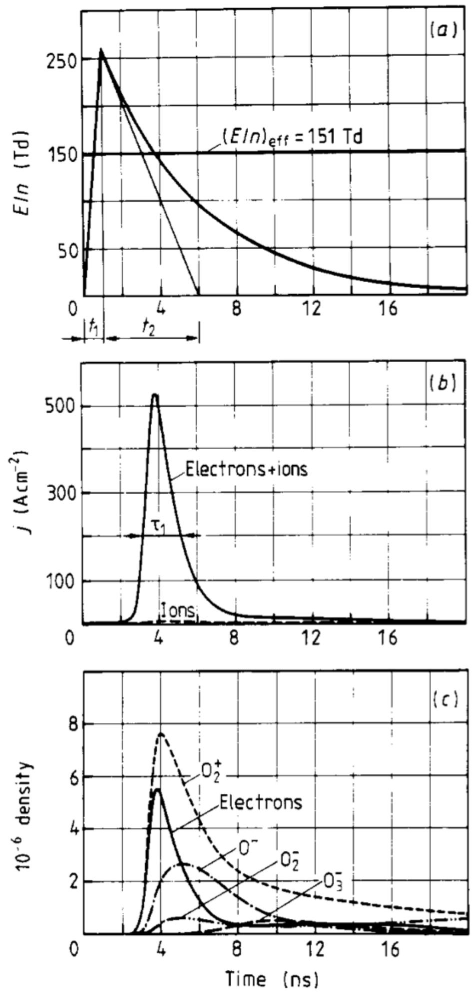
neúplné pokrytí nábojem

reprodukce polohy skrze lokální elektrické pole



DBD APPLICATIONS

Ozone generation (Eliasson 1987)



- Possibly oldest application of DBD discharges
- Motivated formulation of the first physical and chemical models.
- 1D model described the formation of a transient glow discharge at high pressure.
- Actuall EEDF was calculated and from it, rate coefficients and transport properties were deduced.

The mechanism for ozone formation and potential ozone loss was identified as follows:

$$e + O_2 \rightarrow 2O + e$$

$$O + O_2 + M \rightarrow O_3 + M$$

$$O + O_3 \rightarrow 2O_2$$

[redacted]

Ozone production – oxygen dissociation

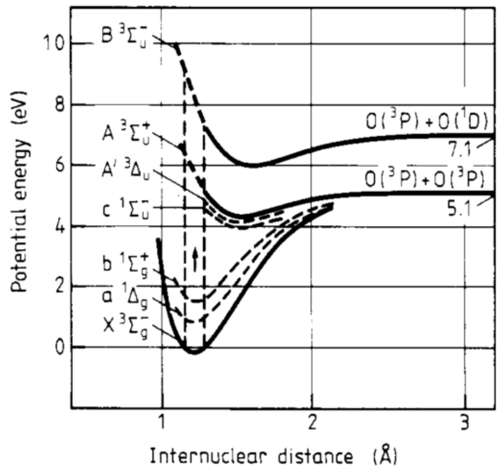


Figure 6. Simplified potential energy diagram of O_2. The arrow indicates the Franck–Condon region for excitation from the ground state.

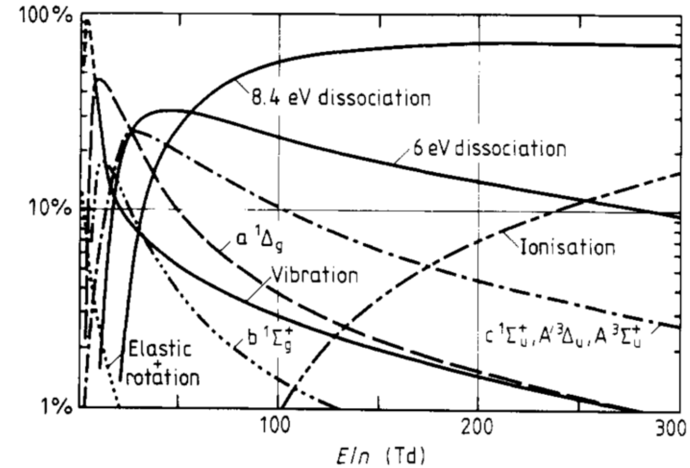


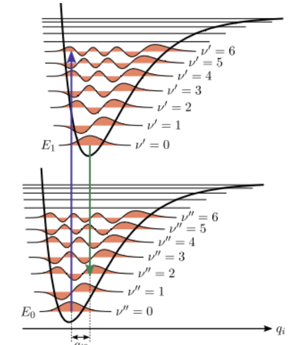
Figure 7. Distribution of electron energy losses as a function of the reduced electric field; energy branching in oxygen.

$$e + O_2 \rightarrow e + O_2\,(A\ ^3\Sigma_u^+)$$
$$\rightarrow e + O\,(^3P) + O\,(^3P)$$

$$e + O_2 \rightarrow e + O_2\,(B\ ^3\Sigma_u^+)$$
$$\rightarrow e + O\,(^3P) + O\,(^1D)$$

$$O\,(^1D) + O_3 \rightarrow 2O_2$$

Classically, the Franck–Condon principle is the approximation that an electronic transition is most likely to occur without changes in the positions of the nuclei in the molecular entity and its environment. The resulting state is called a Franck–Condon state, and the transition involved, a vertical transition. The quantum mechanical formulation of this principle is that the intensity of a vibronic transition is proportional to the square of the overlap integral between the vibrational wavefunctions of the two states that are involved in the transition.



Ozone production – effect of admixtures

In industrial production, gases that form metastable excited species are often added, further enhancing the dissociation rate of oxygen by plasma.

$$e + N_2 \xrightarrow{k_{17}(E/n)} N_2^* + e$$

$$N_2^* + O_2 \longrightarrow N_2 + O + O$$

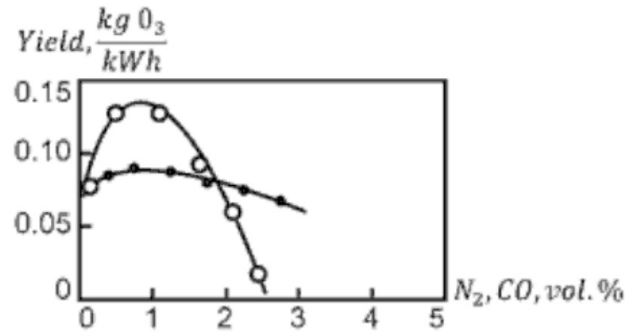
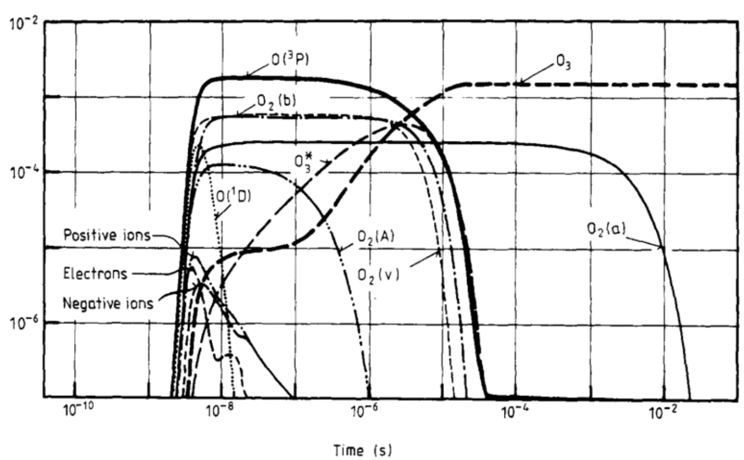
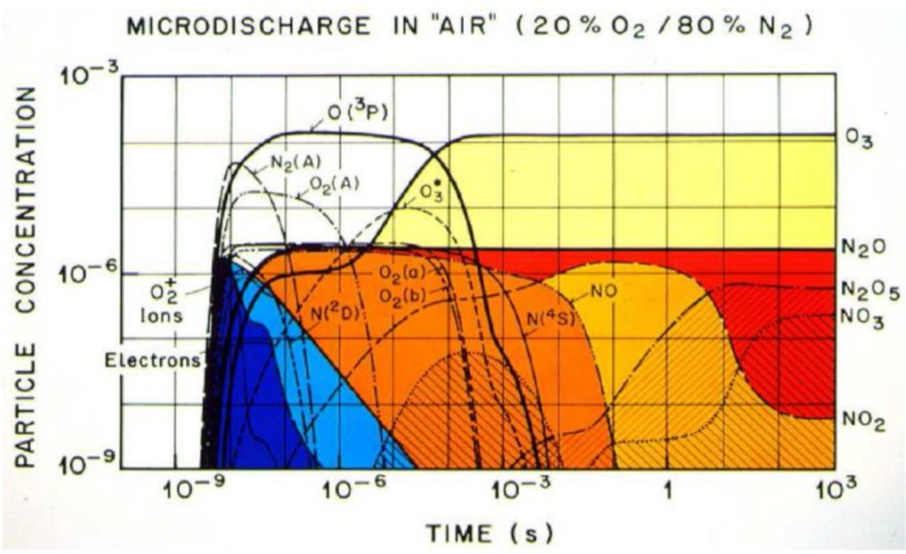


Figure 6–32. Influence of admixtures of N_2 and CO on ozone yield in a DBD in room-temperature oxygen: black circles correspond to molecular nitrogen, white circles correspond to carbon monoxide.

Microdischarge in pure oxygen





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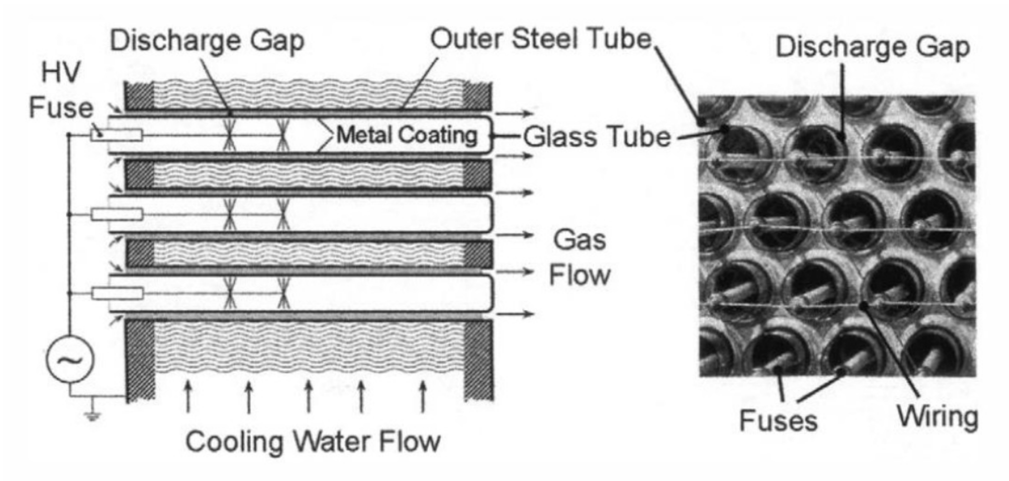
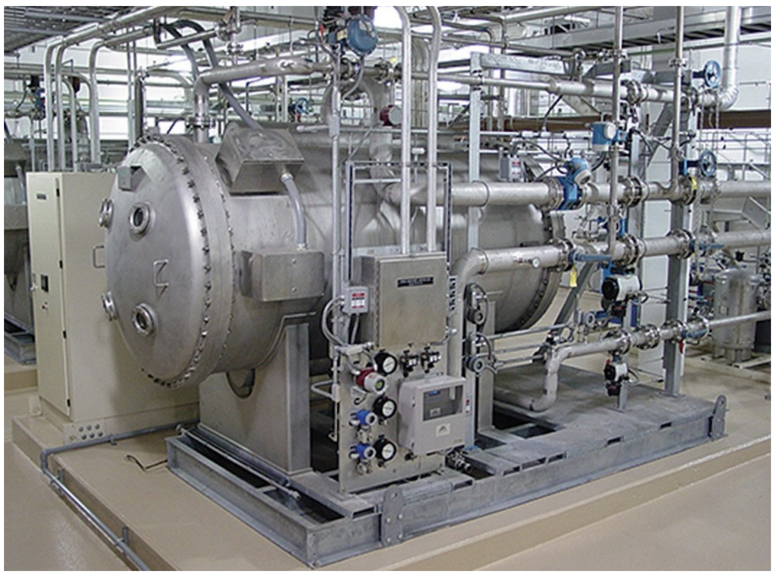
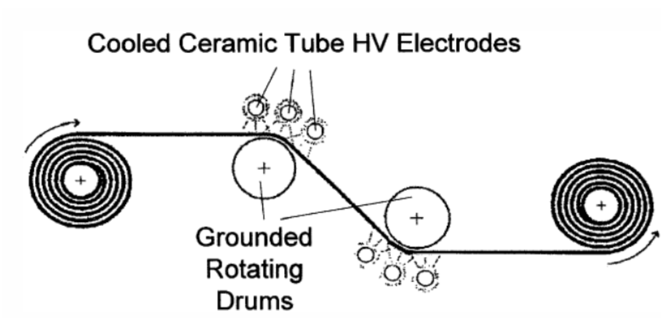
Ozone production – an industrial setup



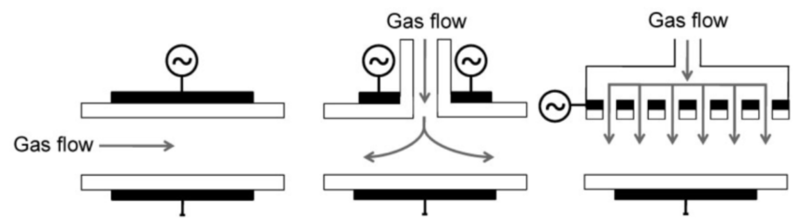


Surface processing

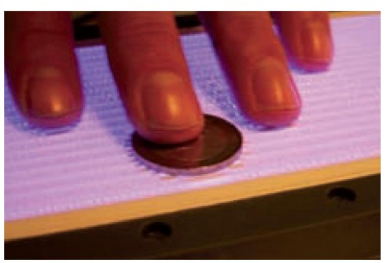


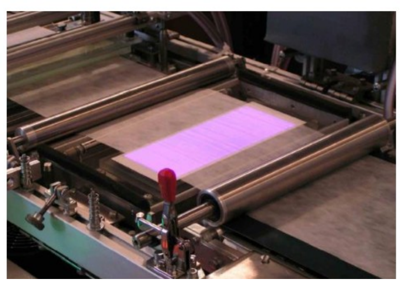
SOFTAL GmbH

pro reaktivní plyny a depozice (Massines 2012)

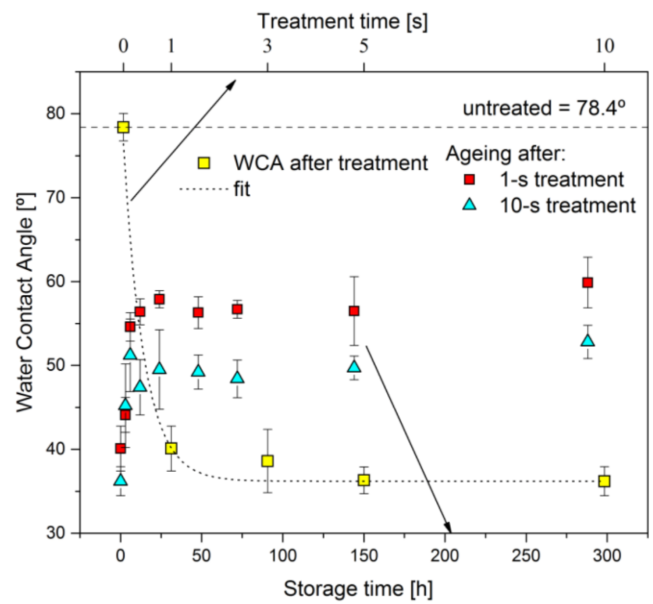


DCSBD – in-line opracování, no-pinholing, i tepelně citlivé povrchy/vzorky





změna kontaktního úhlu, PET povrch, DCSBD (Homola 2017)

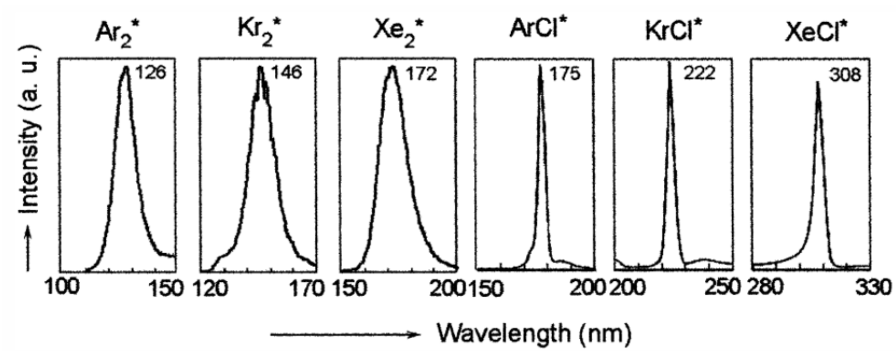


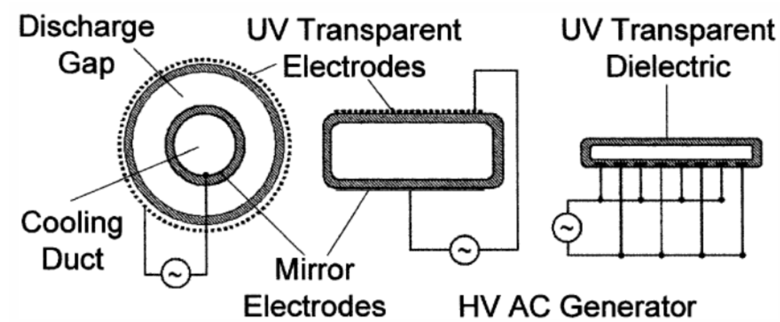
Excimer light sources

$R^* + R \rightarrow R_2^*$ R^* - excited atom

$R_2^* \rightarrow 2R + h\nu$ R_2^* - excited dimer (AB* = exciplex)

Ar_2^*	Kr_2^*	F_2^*	Xe_2^*	ArCl*	ArF*	KrCl*	KrF*	XeI*	Cl_2^*	XeBr*	Br_2^*	XeCl*	I_2^*	XeF*
126	**146**	157	**172**	175	193	**222**	248	253	259	282	289	**308**	342	354





Very intense UV light sources

- surface and water cleaning by UV
- UV curing and photopolymerization
- excimer lasers for semiconductor applications

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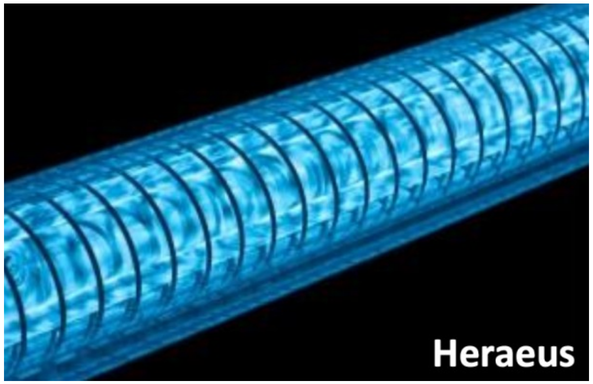
Excimer light sources



Quark technology

Very intense UV light sources

- surface and water cleaning by UV
- UV curing and photopolymerization
- excimer lasers for semiconductor applications

Takeaways

- What is a DBD and what are its various arrangements
- Where is the voltage drop in DBDs, what are the methods for accurately measuring plasma power and voltage?
- What are some methods of DBD diagnostics.
- DBD applications