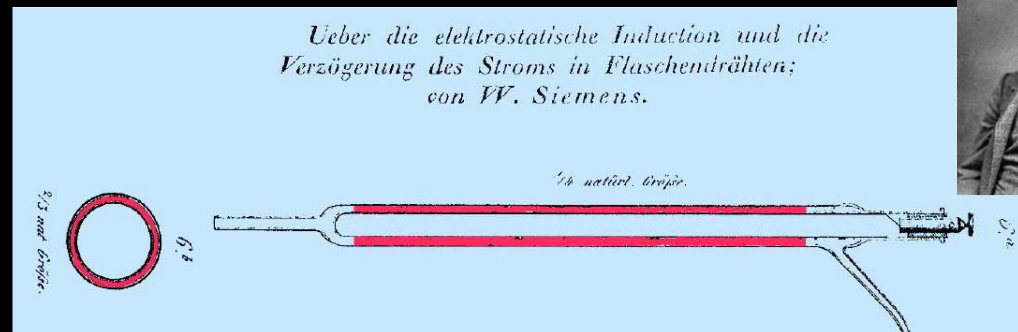
# Dielectric Barrier and Corona Discharges

Olivier Guaitella (LPP, Ecole Polytechnique , Paris)

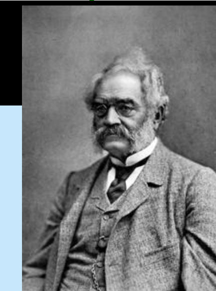
Ana Sobota (EPG, TU/e, Eindhoven)

# Why using Corona and DBDs?

**Technological motivations**




Poggendorff's Annalen der Physik und Chemie **102** **(1857)**, 66 - 122



**Atmospheric plasma sources:**

- Cost reduction
- Works in surrounding air

**Corona and DBD**

**Flexible size**

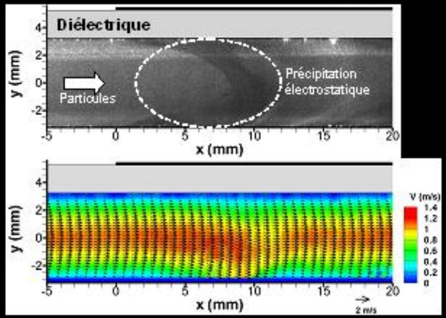
**Chemical efficiency**

**$O_3$ production**

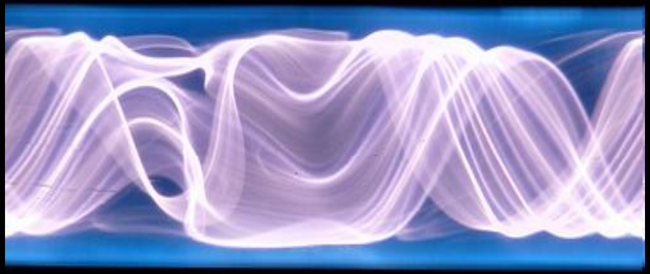
# Main applications of Corona and DBD

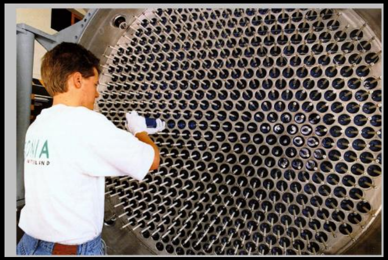
Flow control

Electrostatic precipitation




lighting





$O_3$ production

Ions wind

UV emission

3 body reactions

Corona and DBD

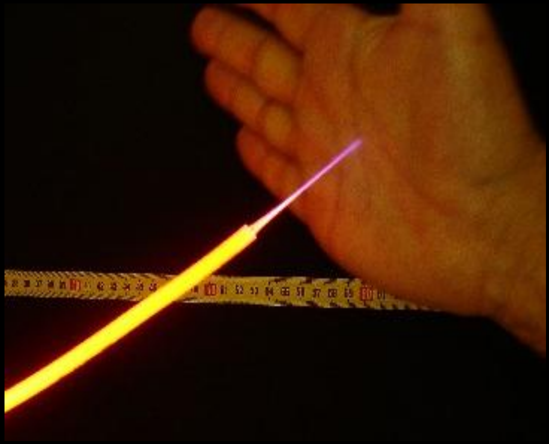
Surface reactivity

Synergy of all

Plasma/catalyst coupling

(air treatment, solar fuels)

Surface functionalization



Biomedical applications

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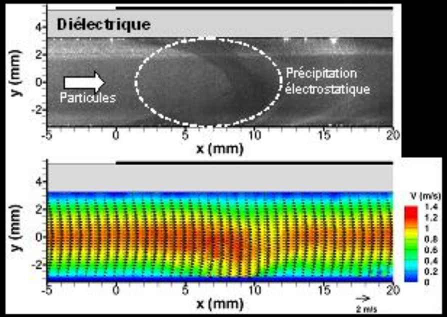


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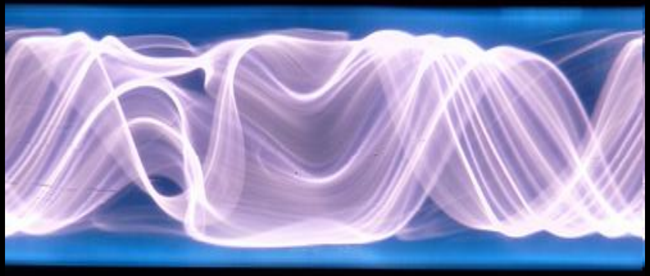

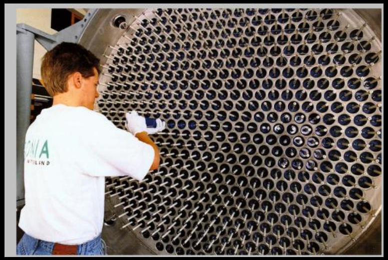

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Very good to prevent gas heating

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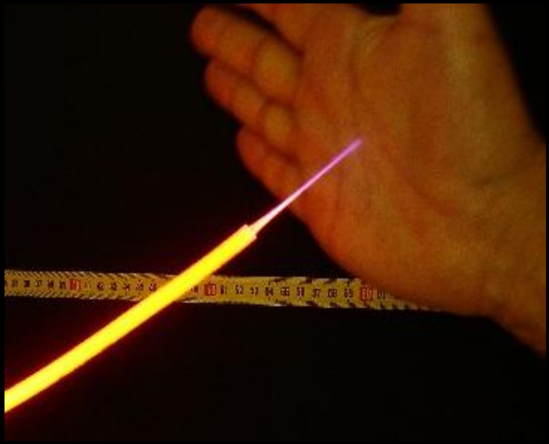
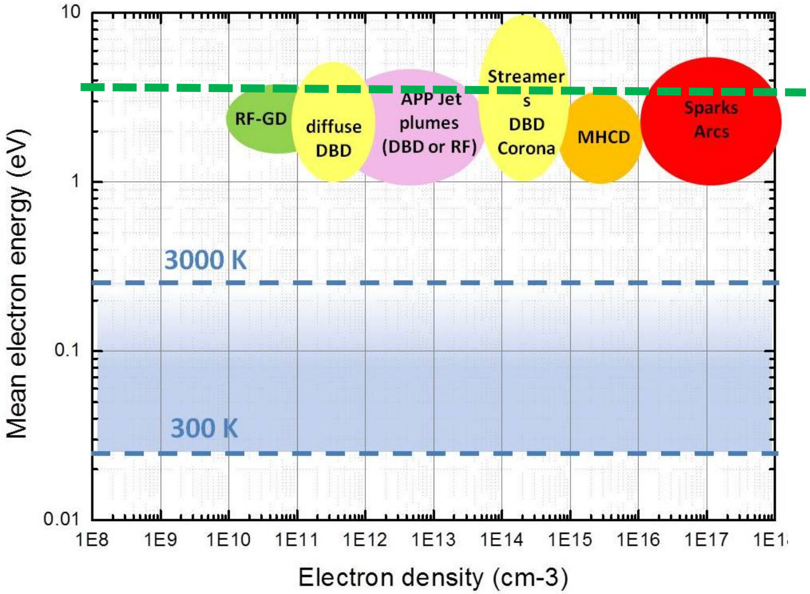


Biomedical applications

# Why Atmospheric Pressure Plasmas heat the gas?




Atmospheric pressure: $n_{gas} \approx 2.5 \times 10^{19}\ cm^{-3}$

**What is different at higher pressure?**

**Collision frequency increases**

$$\lambda = \frac{\langle \upsilon \rangle}{\nu_n} = \frac{1}{n_n \cdot \sigma_n}$$

**e- mean free path ≈ 500 nm**

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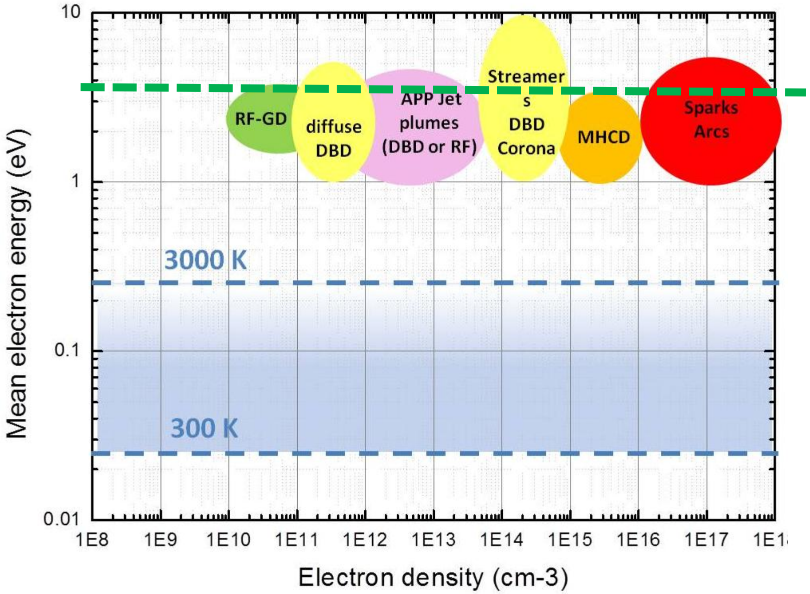


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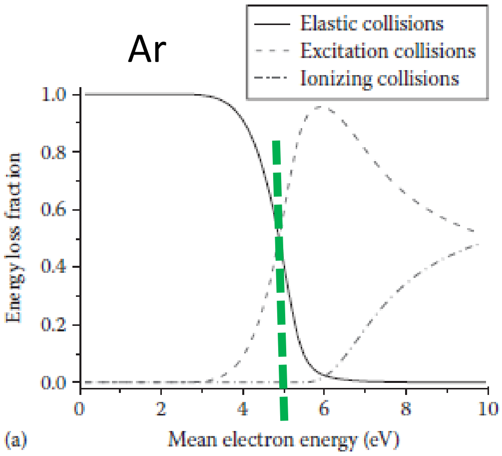
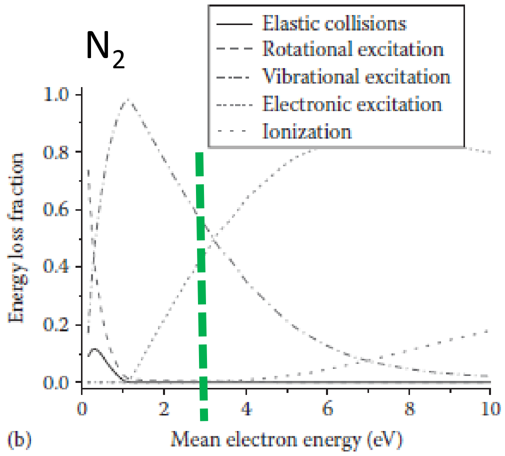
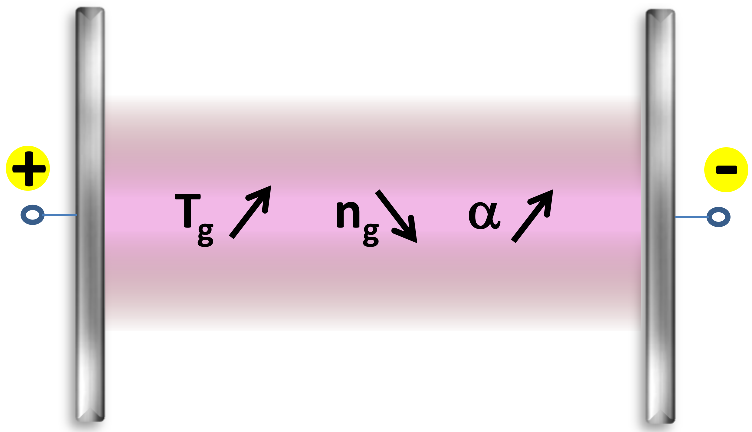
electrons collisions are mostly :

- elastic collisions (atomic gases)
- vibrational excitation (molecular gases



# How to avoid gas heating ?




Very quickly, plasma is easier to sustain where it has started

⇩

Arcing, high current, strong heating

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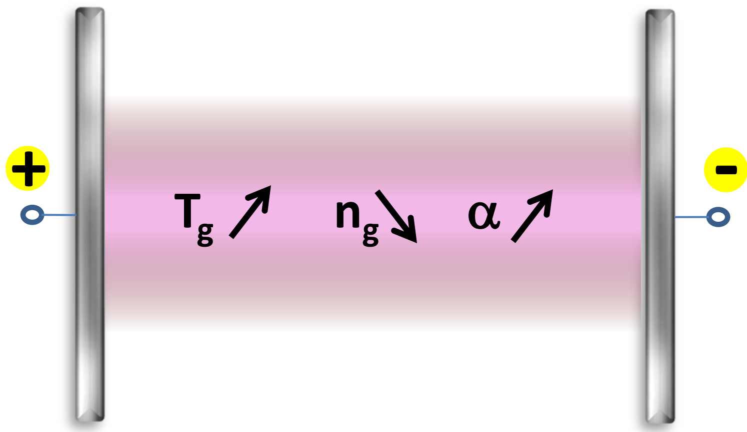


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**How to prevent Arcing ?**

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- Voltage pulse shorter than arc development (<100 ns)

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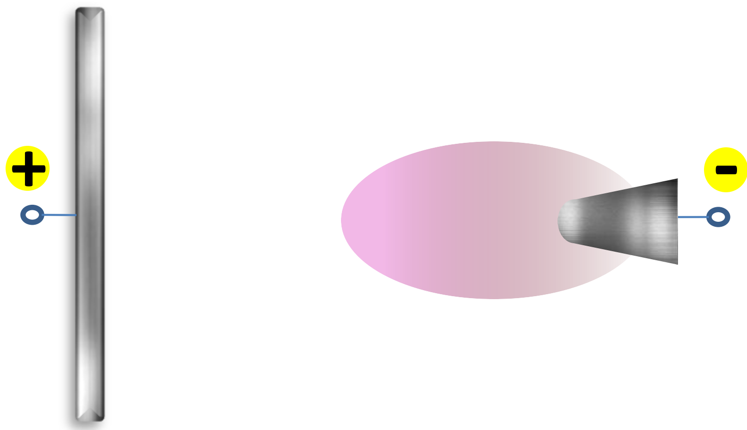


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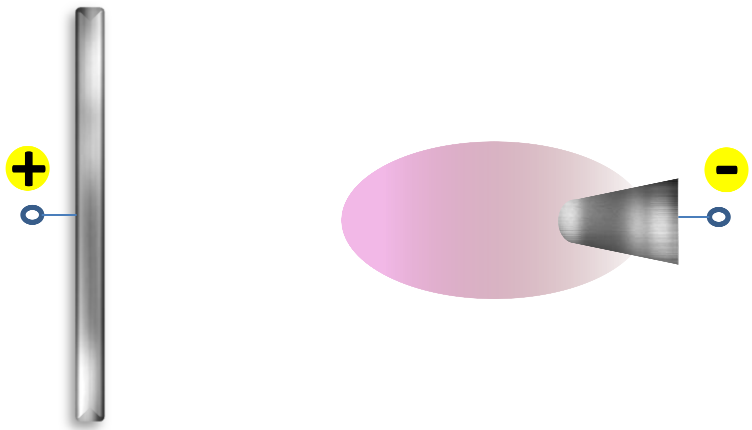

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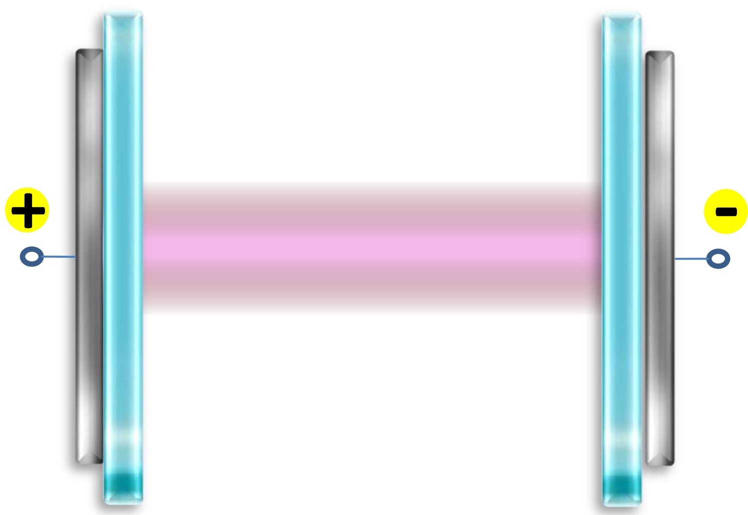
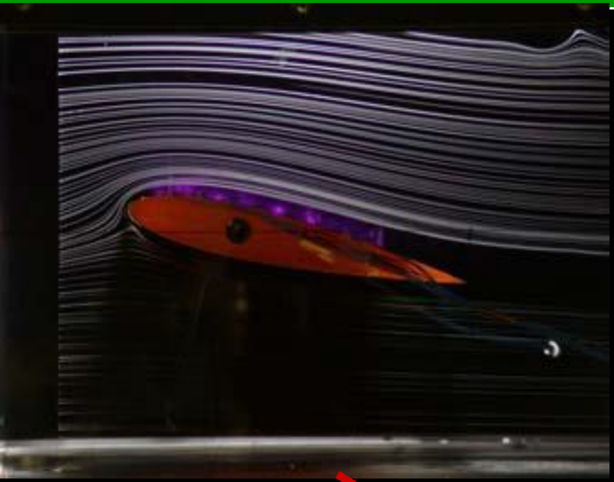
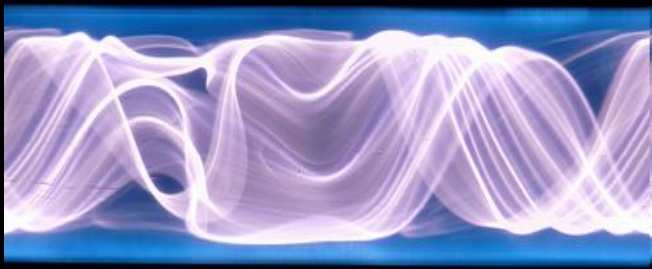
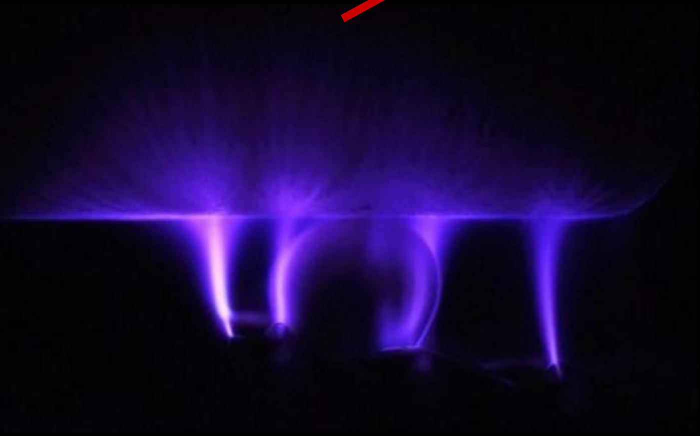


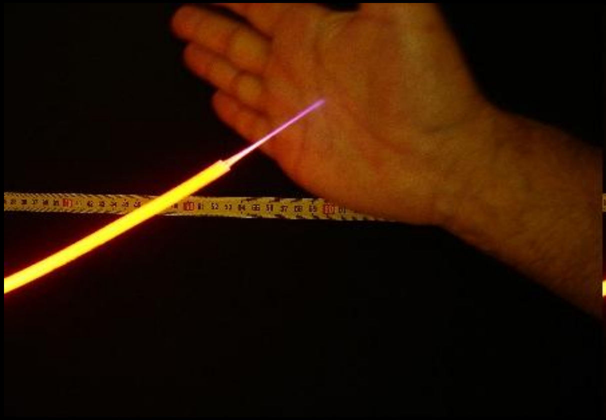
- Limit the current (resistive discharge)
- Voltage pulse shorter than arc development (<100 ns)
- **Strongly non uniform E field (Corona)**
- **Dielectric between the electrode (DBD)**





Most of the time, filamentary discharges





# Semantic confusions…

**"Discharge": any flow of electrical current through ionized gas (extension of initial meaning)**

**"self-sustained" discharge = produces its own current that does not depends on any external source (UV, radioactivity, etc…)**

Coronas and DBDs, are "transient" self-sustained discharges

**"breakdown" ≠ "ignition" ≠ "inception"**

Corona discharges especially can develop at "onset" voltage lower than "breakdown voltage"

**"filament" ≠ "streamer"** **streamer = a breakdown mechanism**

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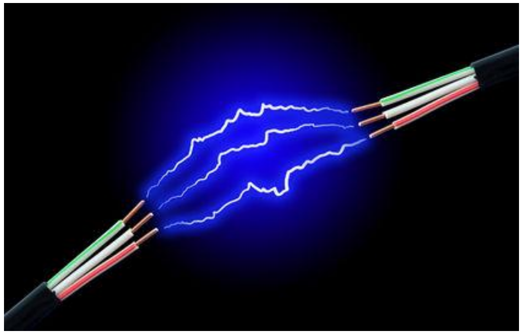
"filament" ≠ "streamer" streamer = a breakdown mechanism



"Corona" and "DBDs" CONFIGURATIONs are reactor geometries

"DBDs" and Corona DISCHARGEs = more than just 2 types of discharges. Often developing with Townsend breakdown or Streamer breakdown mechanism

# Outline

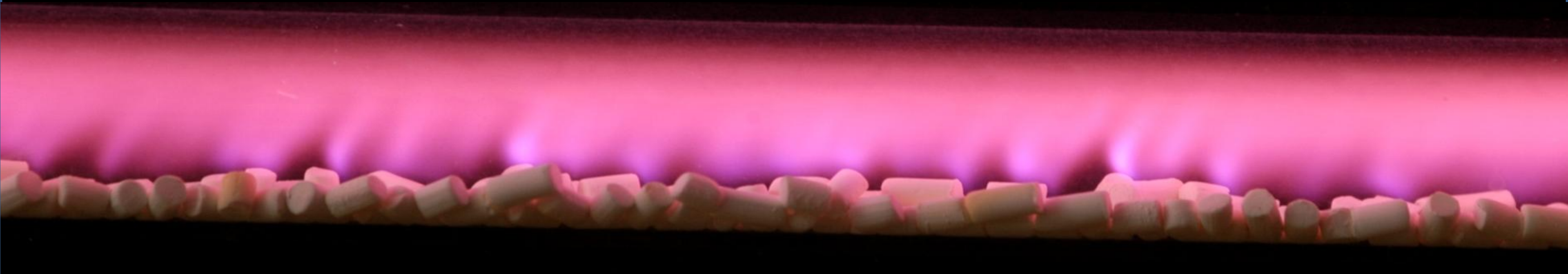
I. **Breakdown mechanisms**
   - a) Townsend mechanism
   - b) Streamer mechanism

II. **Corona discharges**

III. **What is a Dielectric Barrier Discharge?**
   - a) Electrical characteristics
   - b) Development of a single filament
   - c) Role of the dielectric?

IV. **Role of surface vs gas phase dynamics**
   - a) Interaction between filaments
   - b) Diffuse discharges

V. **Confinement and gas motion**



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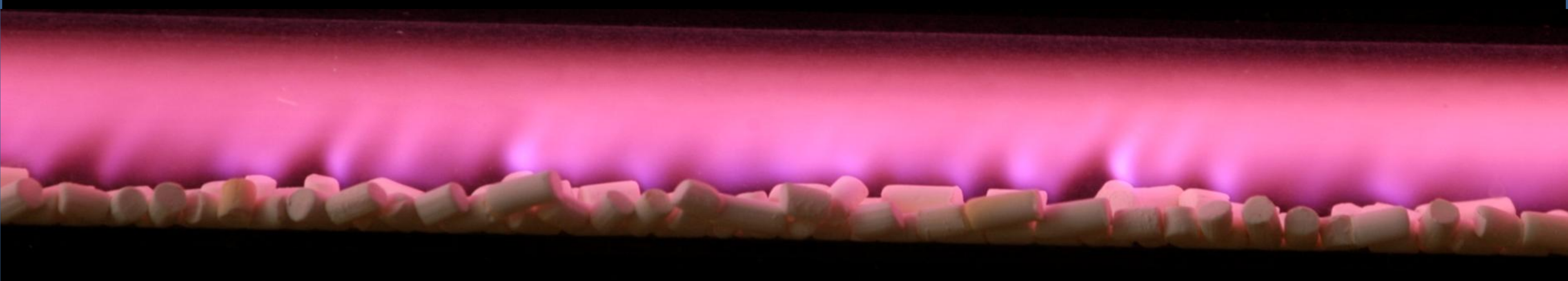
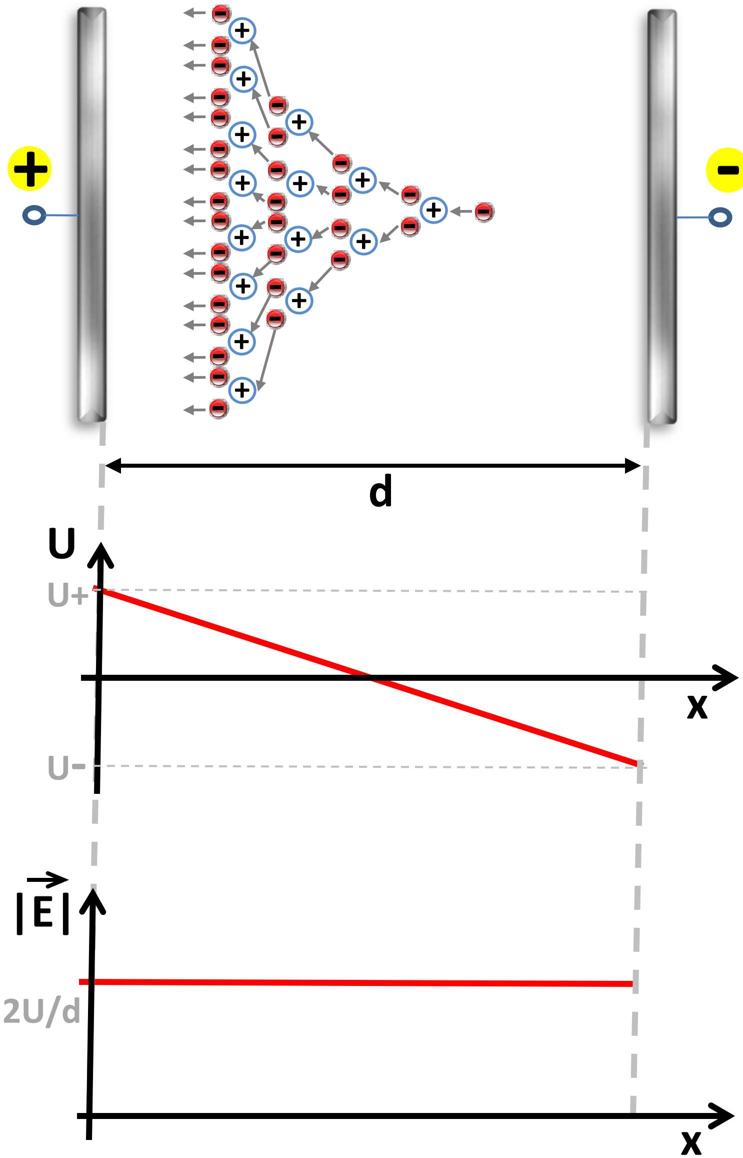


# Townsend breakdown mechanism




Naturally $n_e \approx 10^3 cm^{-3}$ (radioactivity, etc...)

$$dn = \alpha n \cdot dx$$

$$n(x) = n_0 \exp(\alpha x)$$

$$j_-(x) = j_-(0) \exp(\alpha x)$$

α – number of ionization acts from 1 e- drifting in E per unit of length

$$\frac{\alpha}{p} = A \exp\left(-B \frac{p}{E}\right)$$

**α is a steep function of $E/n_g$**

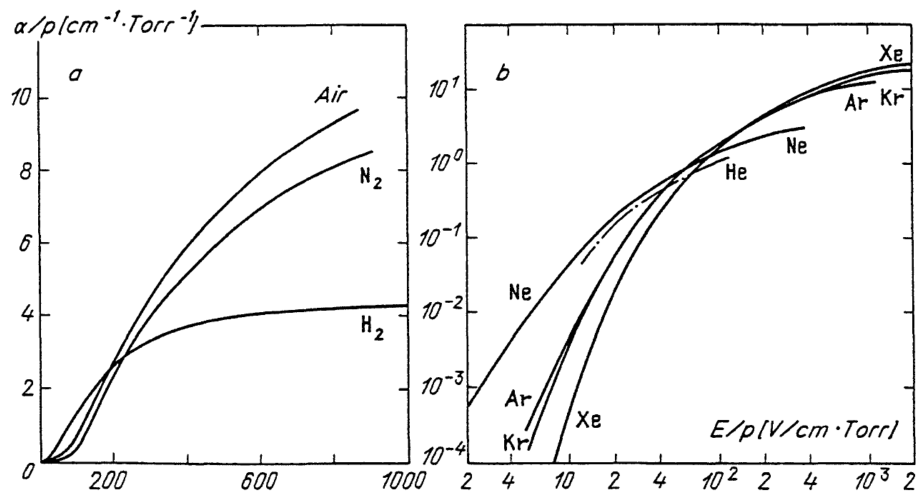
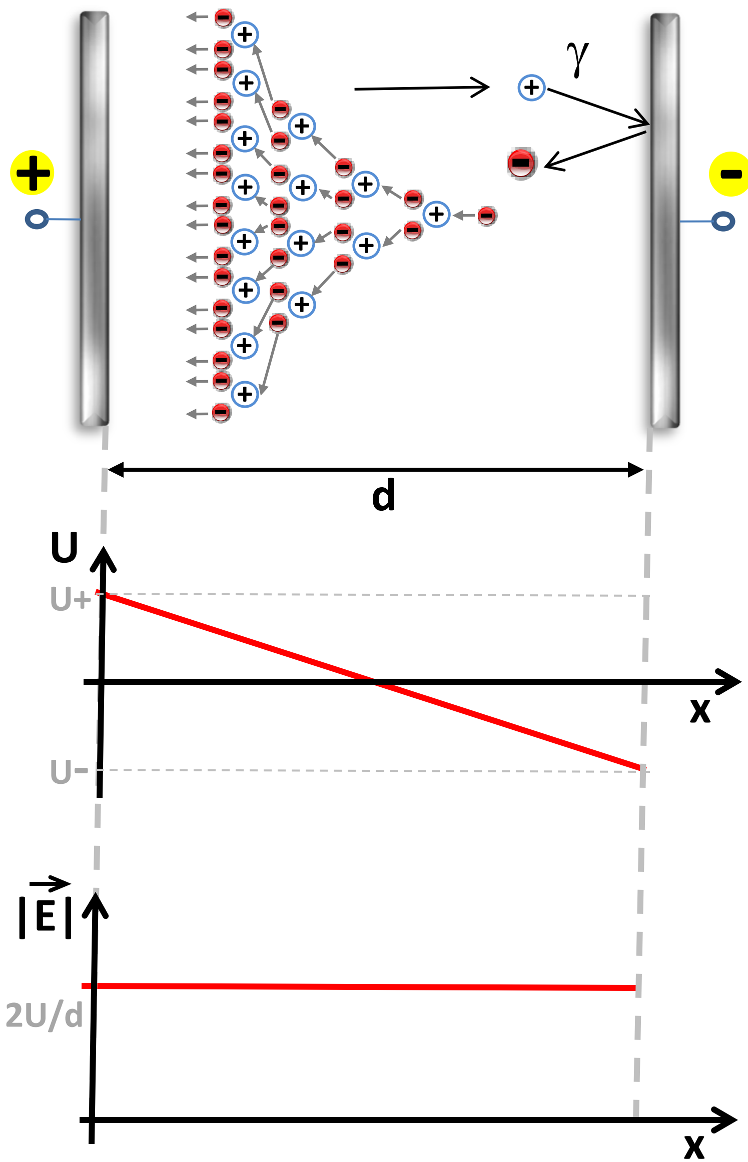



Fig. 4.3. Ionization coefficients for a wide range of $E/p$ values (a) in molecular gases, (b) in inert gases. From [4.3]

Y.P. Raizer, Gas Discharge Physics, Springer Verlag

# Townsend breakdown mechanism

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α – number of ionization acts from 1 e- drifting in E along 1 cm

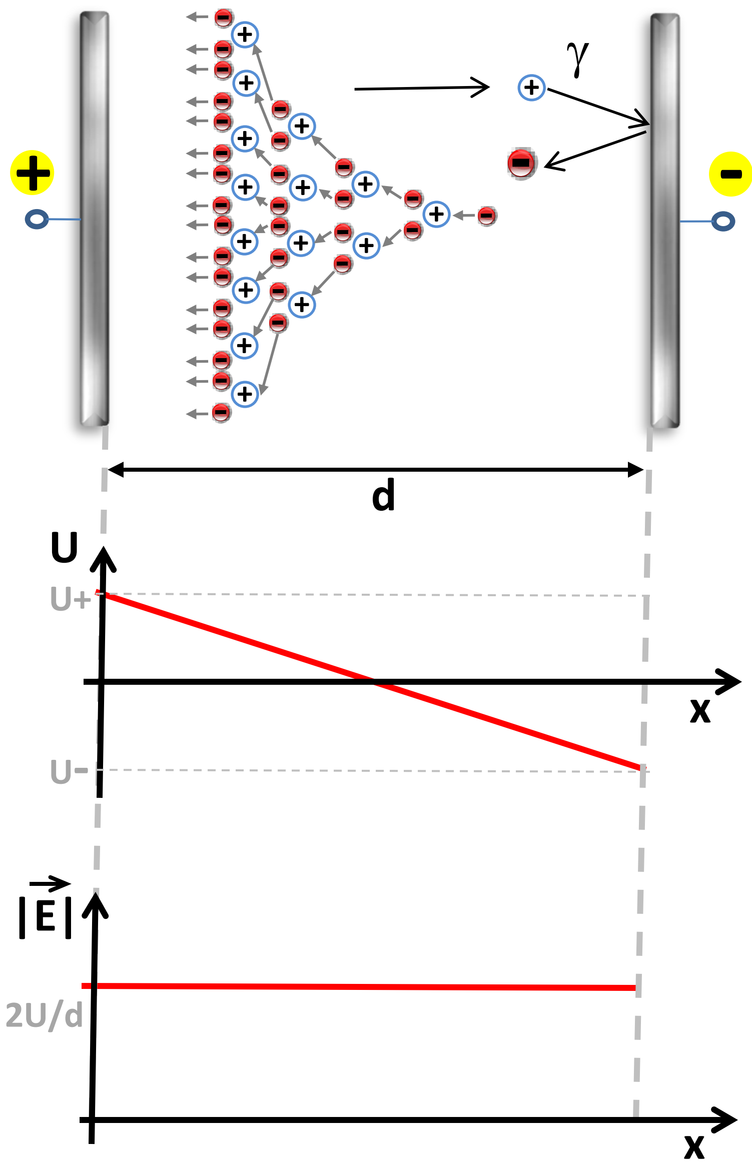
$$\frac{\alpha}{p} = A \exp\left(-B \frac{p}{E}\right)$$

$\gamma$ – number of secondary $e^-$ produced per ion hitting the cathode surface per second

Condition for static breakdown of the gas gap:

$$\gamma(\exp(\alpha d) - 1) = 1$$

# Townsend breakdown mechanism

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in electronegative gases, loss of $e^-$ from attachment have to be taken into account: α –> $\alpha_{eff} = \alpha - \eta$

# Townsend breakdown mechanism

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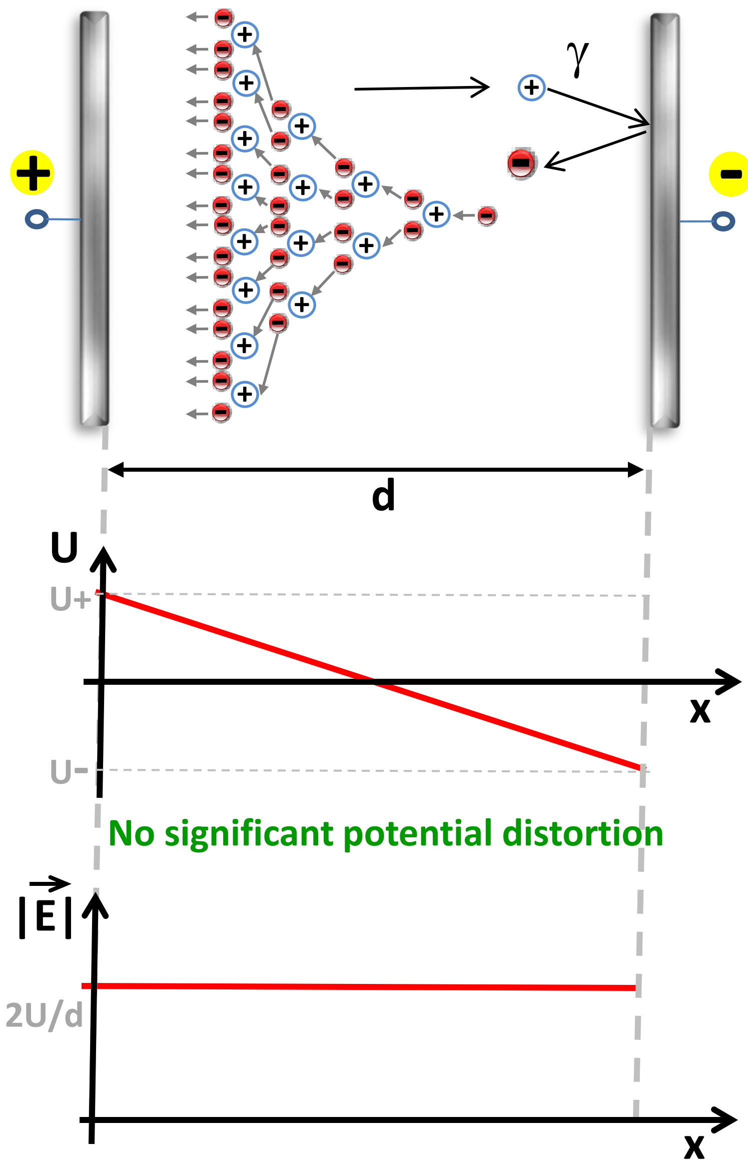
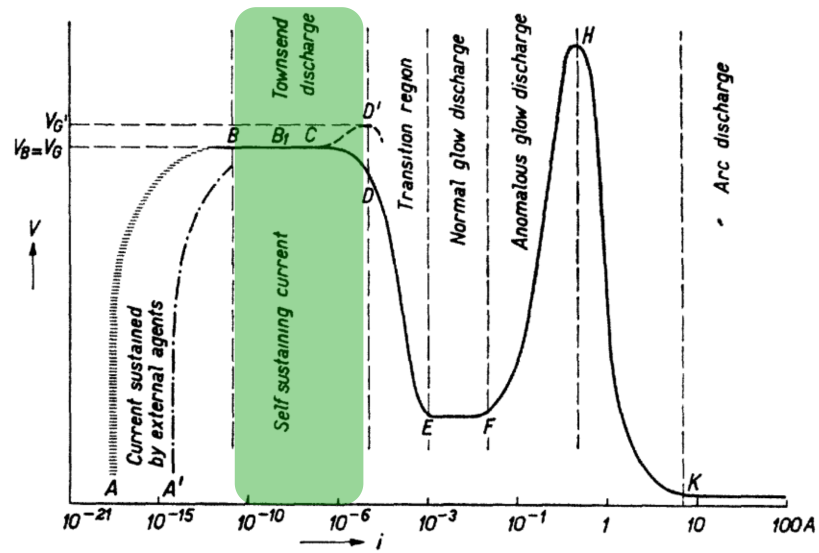
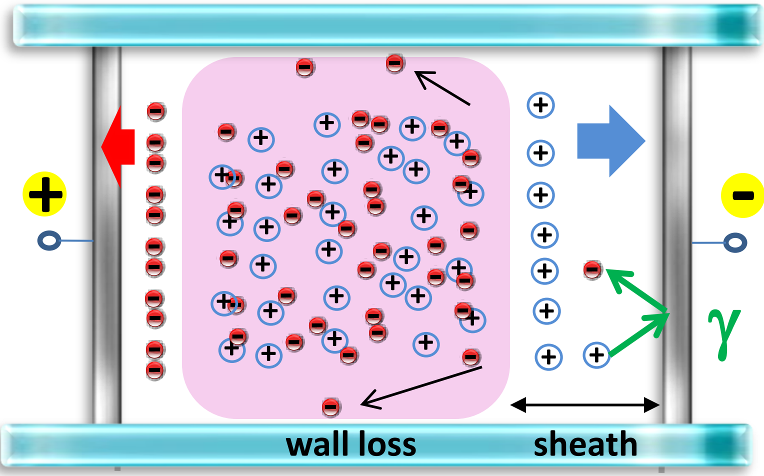
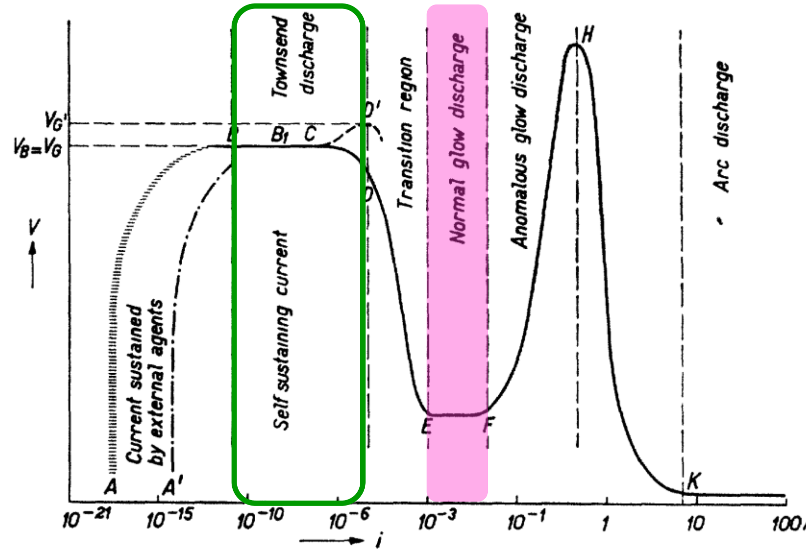
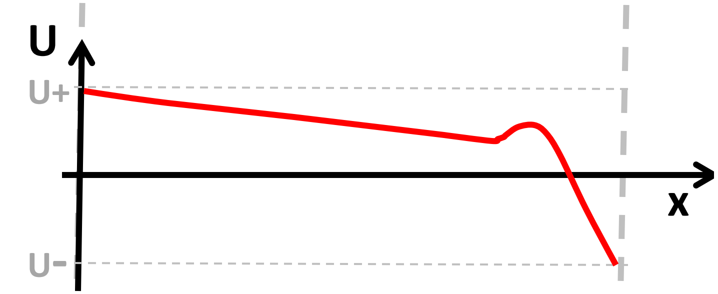


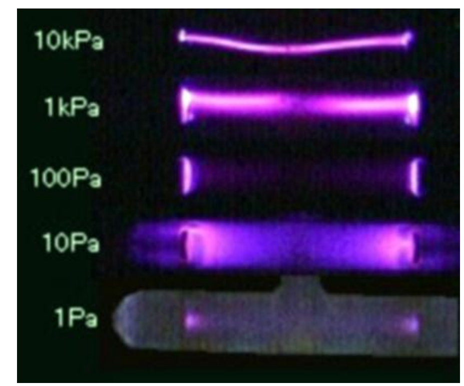
# Avalanche to glow transition



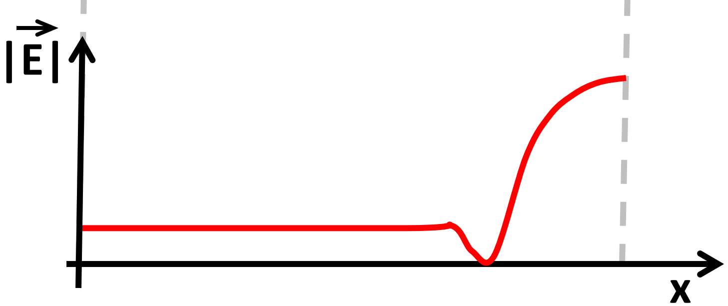



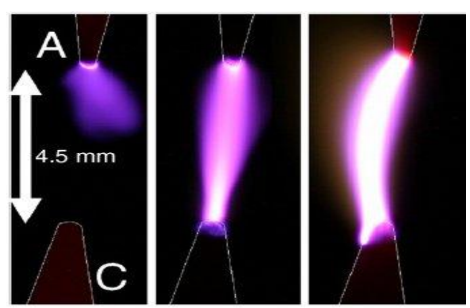








Space charge at the cathode




Difficult to stabilize at atmospheric pressure because of constriction and heating

# About Townsend breakdown…

- ✓ $(\alpha-\eta)$ is a stiff function of E/p

- ✓ Which gas is easier to ignite: He, Ar, Xe?

  $Ei_{(He)}$=24.59 eV

  $Ei_{(Ar)}$=15.76 eV

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$$U_{br(He)} < U_{br(Ar)}$$

Most of the e- collisions are elastic collisions: size of the atom is crucial

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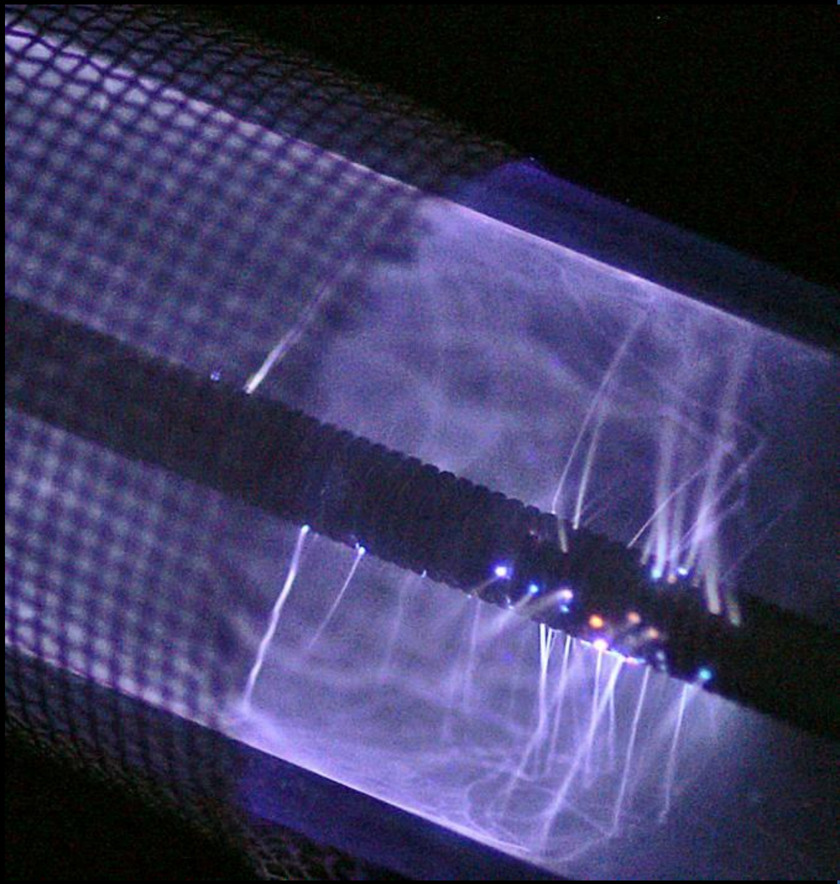
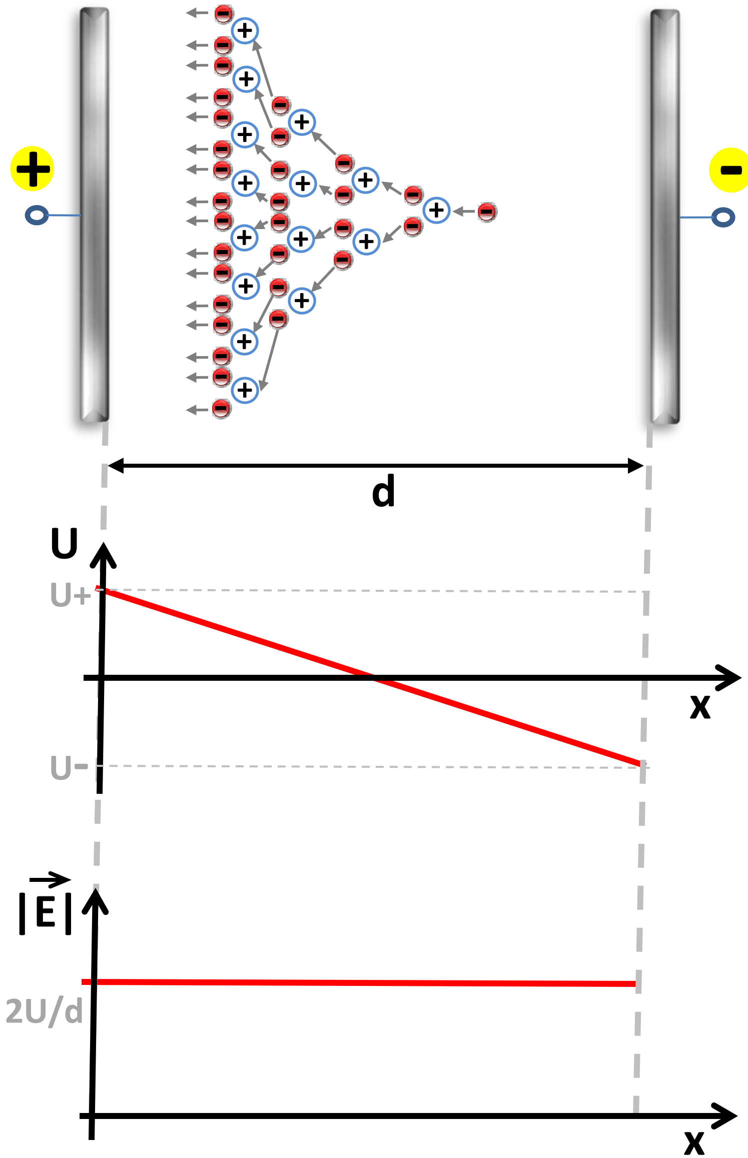


# Streamer growth mechanism

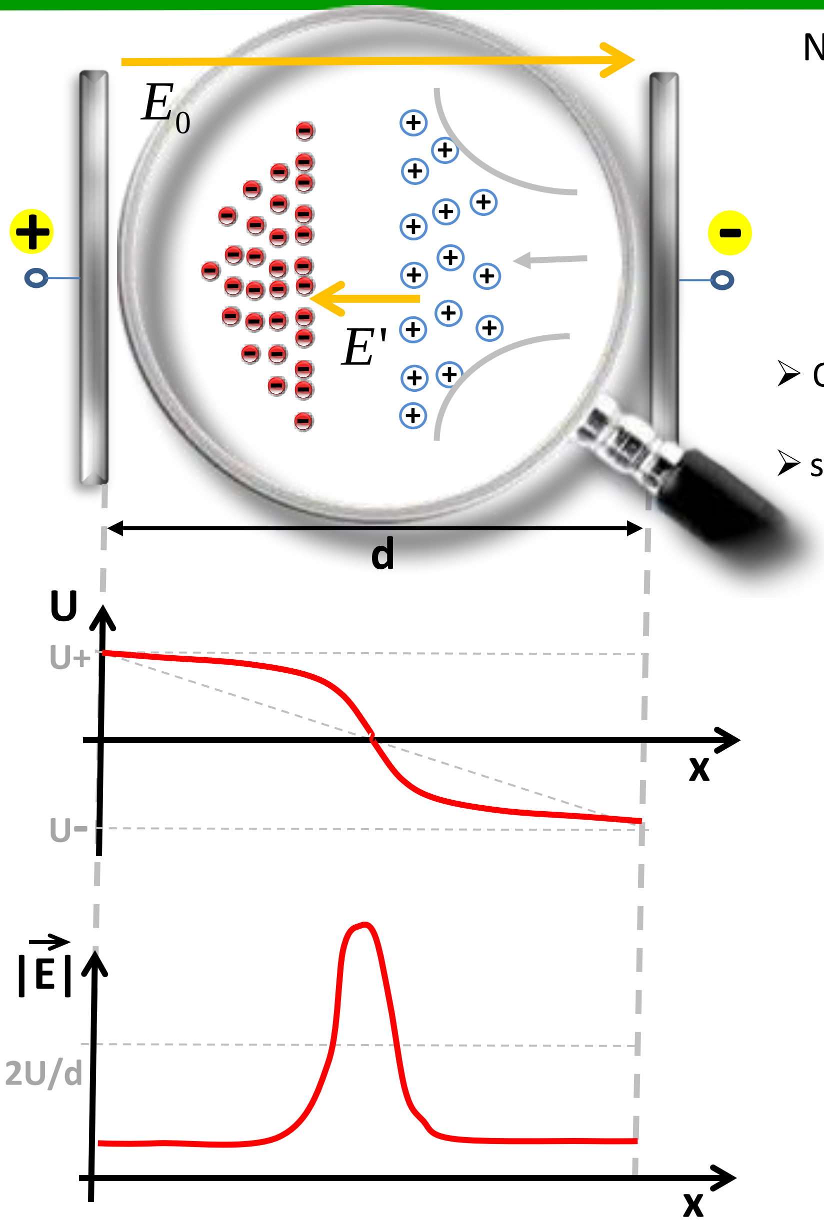



Naturally $n_e \approx 10^3 cm^{-3}$ (radioactivity, etc…)

$$n(x) = n_0 \exp(\alpha_{eff}\, x)$$

**What happens if the amplification is very efficient (large $\alpha$) ?**

# Streamer growth mechanism

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**How much charge for disturbing $E_0$ ?**

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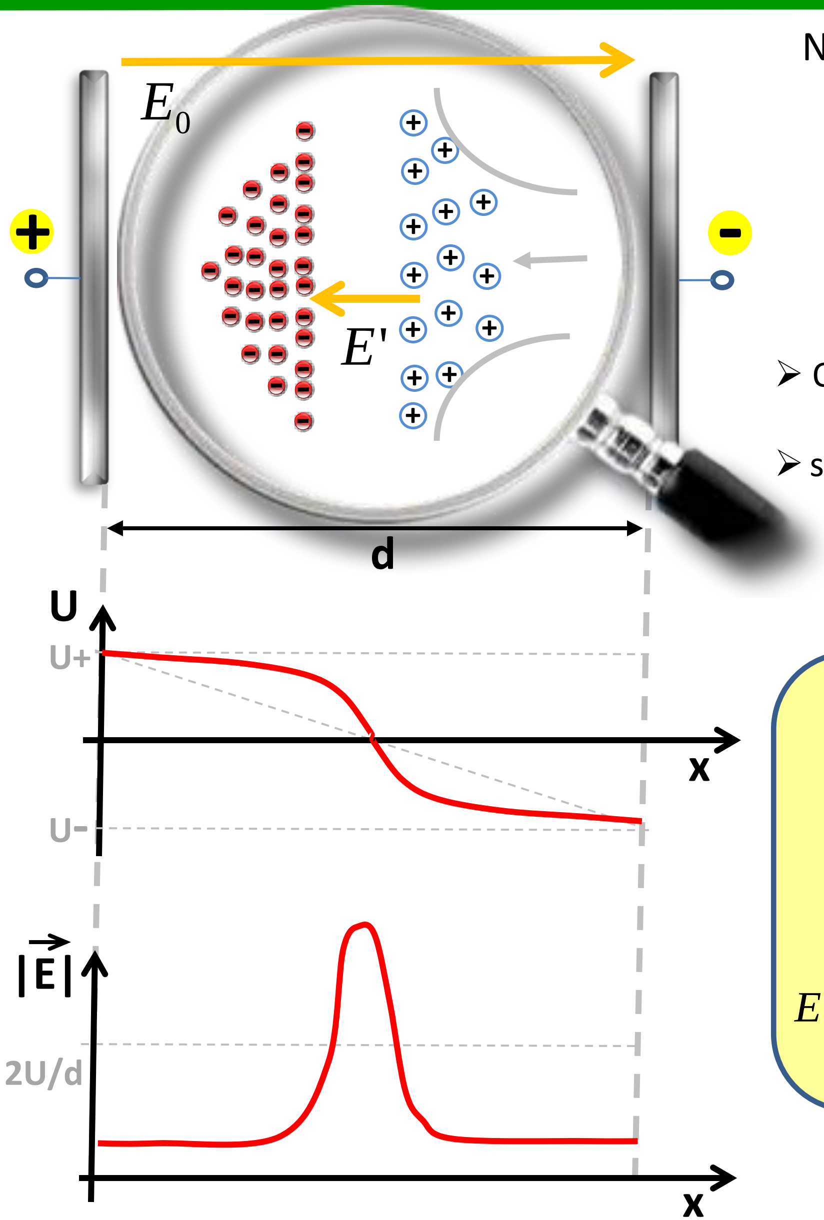


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Breakdown field in air ≈ 30 kV/cm
Mean free path ≈ 0.5µm
ionization length ($\alpha^{-1}$) ≈ 50µm ($\alpha^{-1}$)

In order to have $E_0 \approx E'$ : **Meek criterion**

$$E' \approx \frac{e \cdot N_e}{4\pi\varepsilon_0 R^2} \quad \rightarrow \quad N_e \approx \frac{4\pi\varepsilon_0 (\alpha^{-1})^2 \cdot E_0}{e} \approx 5 \cdot 10^8\ cm^{-3}$$

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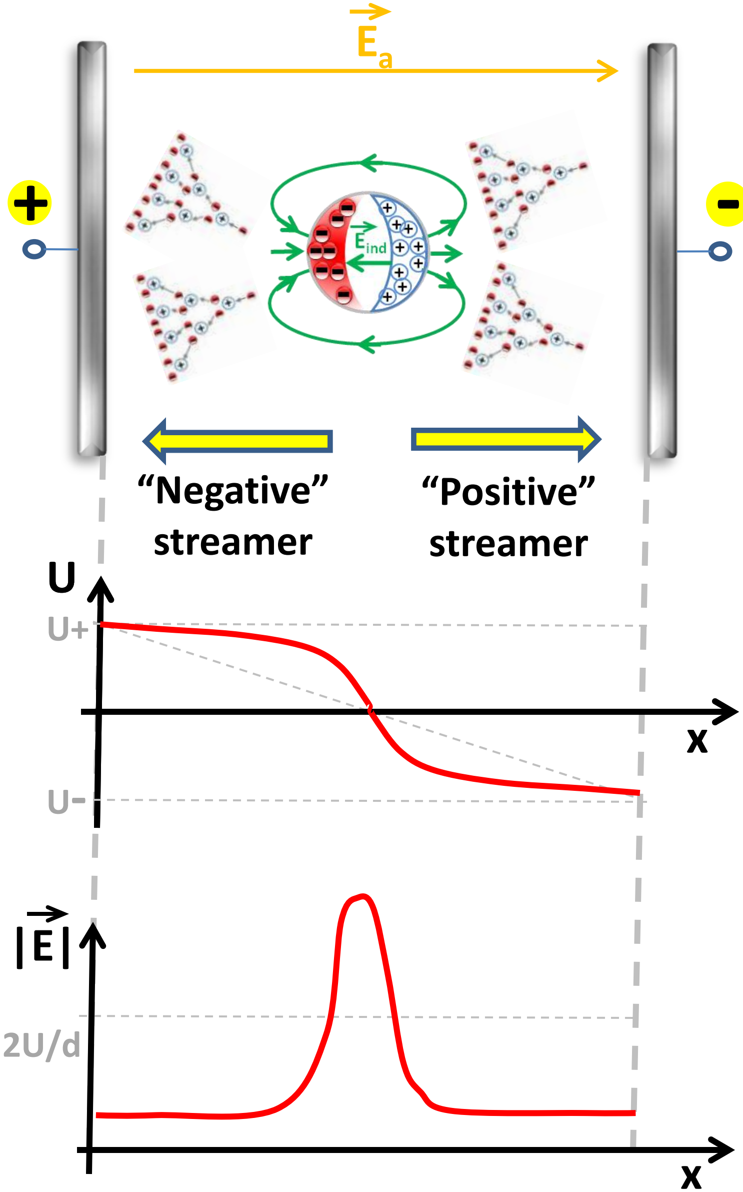


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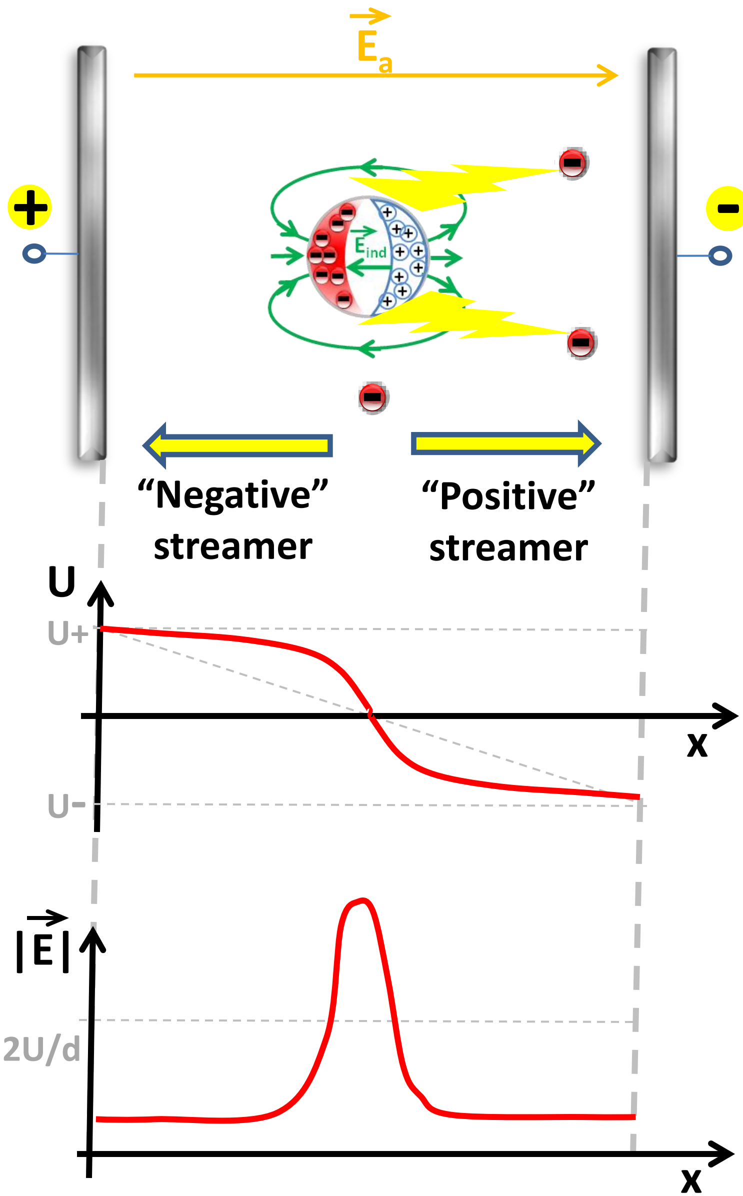
- α increases very fast with E -> secondary avalanches are very efficient

# Streamer growth mechanism

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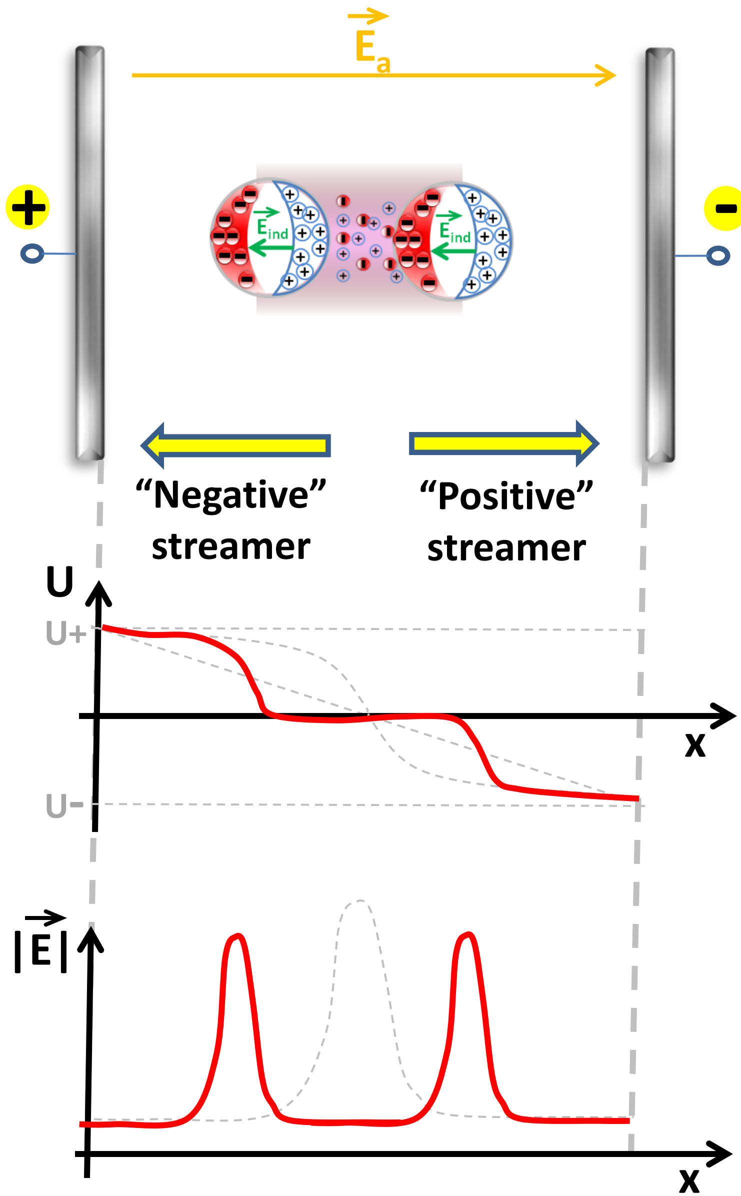
- "positive" streamer: need for electrons in front of streamer head… photoionization?

# Streamer growth mechanism

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- quasi neutral column is growing, space charge is moving further
- streamer growth is much faster than $e^-$ drift velocity

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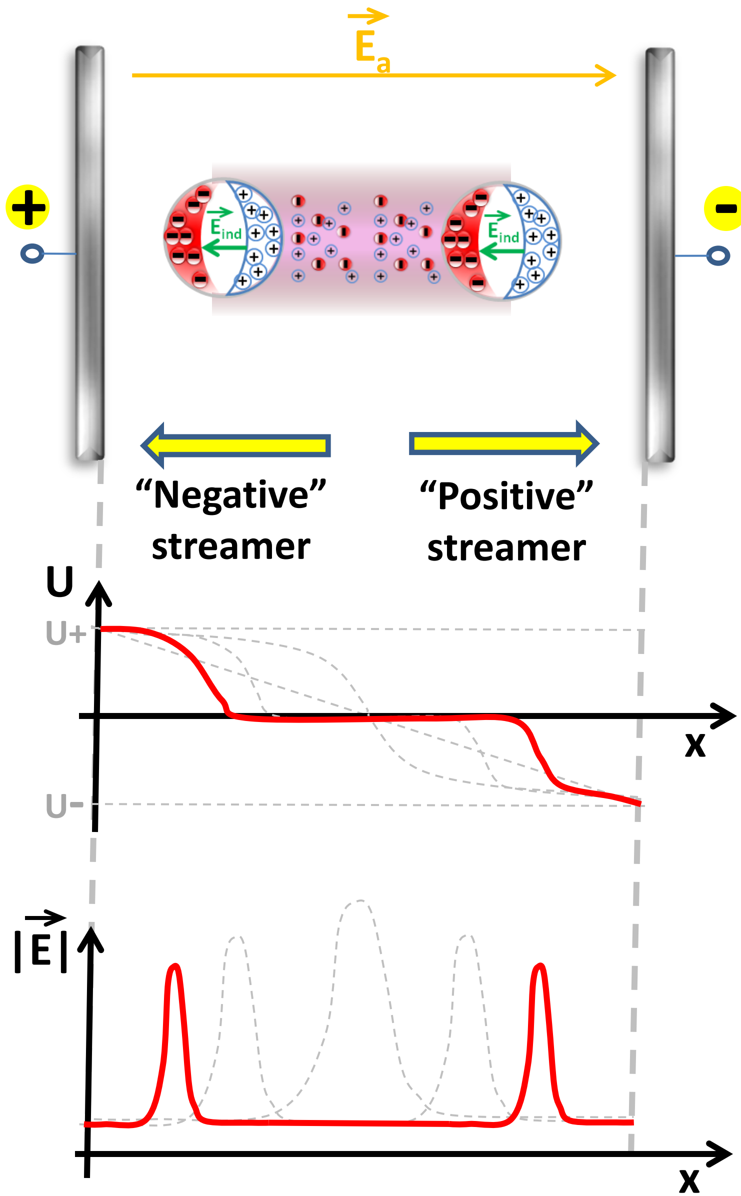


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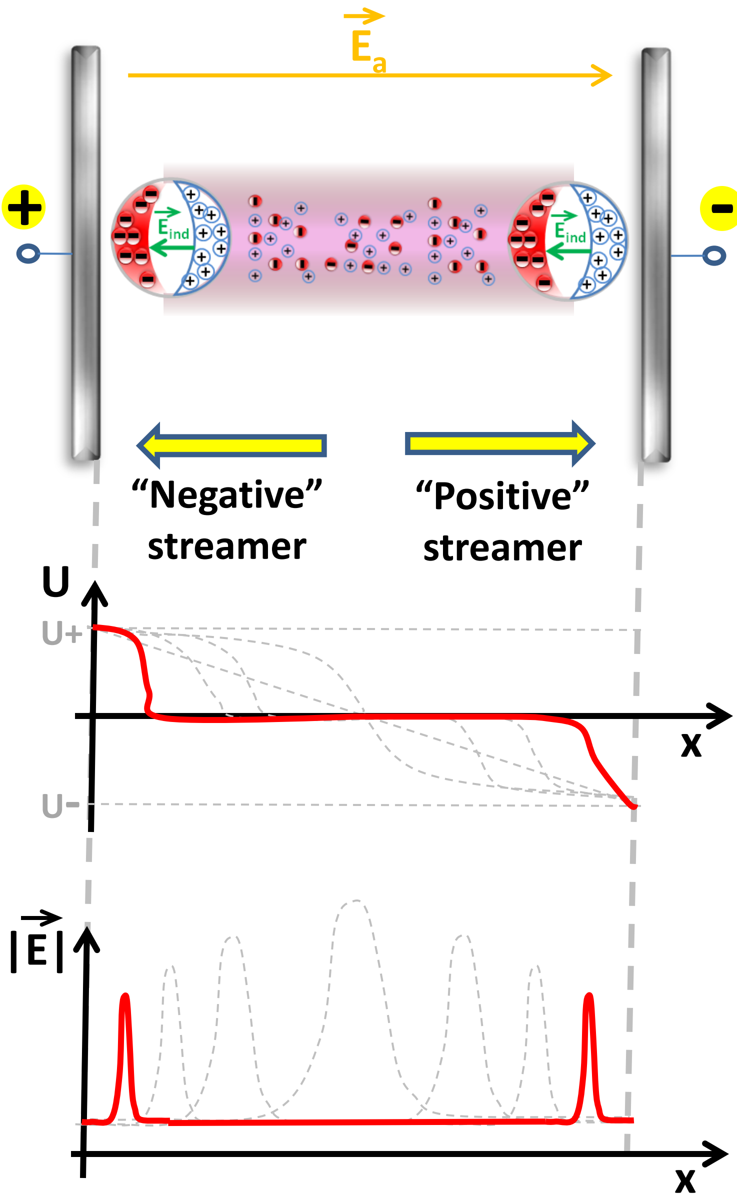
- On short time scale e- drift away from ions (higher mobility)
- space charge → field distortion
- when $1e^- \rightarrow N_e \approx 10^8$ (Meek creeterion) $\left|\vec{E}_{ind}\right| \approx \left|\vec{E}_a\right|$
- $\alpha$ increases very fast with E -> secondary avalanches are very efficient
- for "positive" streamer: need for upfront electrons… photoionization?
- quasi neutral column is growing, space charge is moving further
- streamer growth is much faster than $e^-$ drift velocity

# Streamer growth mechanism




Naturally $n_e \approx 10^3 cm^{-3}$ (radioactivity, etc...)

$$n(x) = n_0 \exp(\alpha_{eff}\, x)$$

**What happens is the amplification is very efficient?**

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- space charge → field distortion
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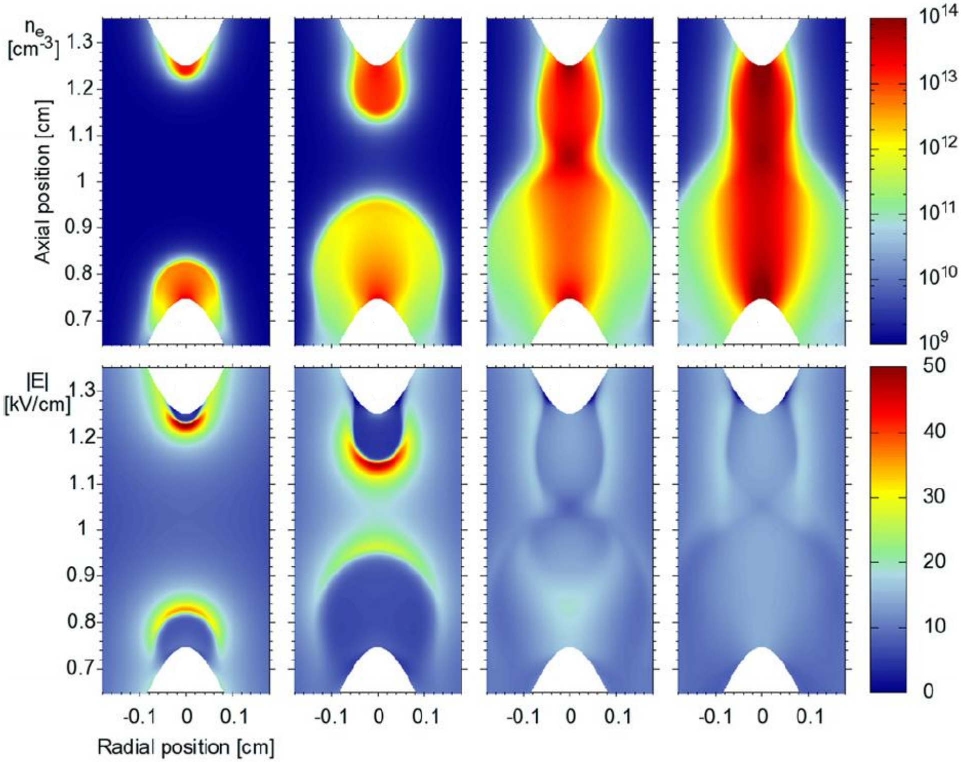
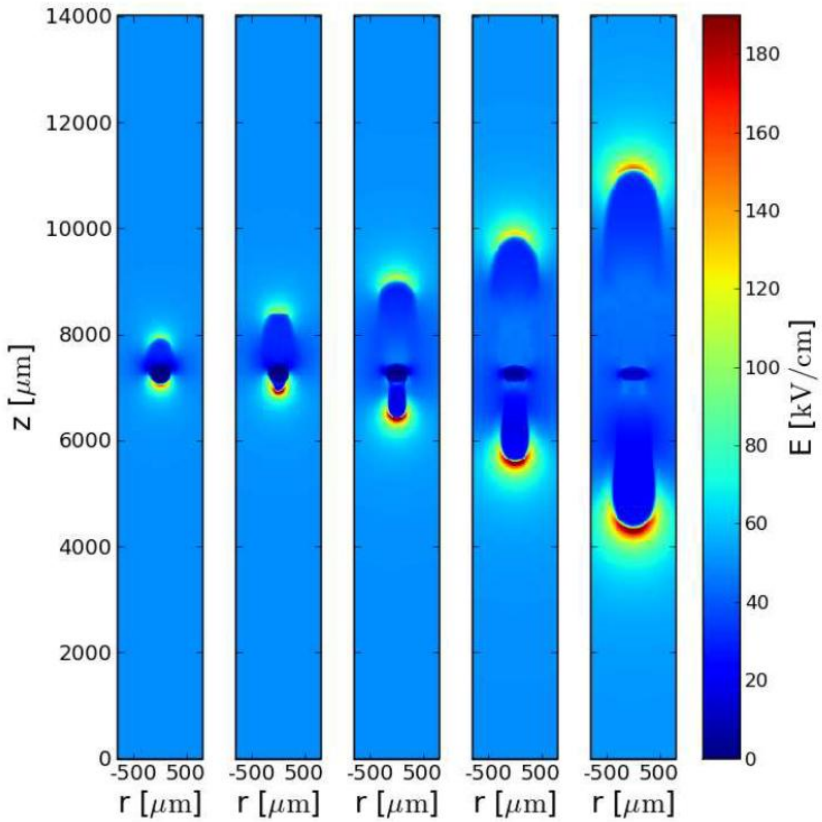
**A streamer is not "propagating", it's "growing"**

# Positive and negative streamer

## where are positive and negative electrodes?



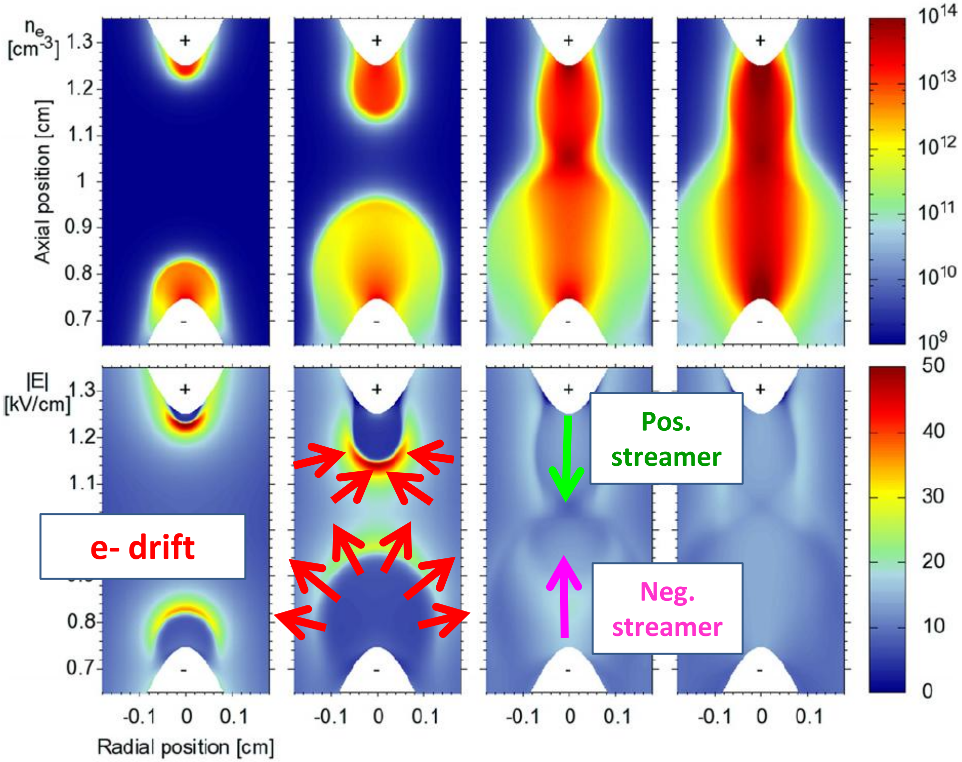

Bourdon et al, *Plasma Sources Sci. Technol.* **19** (2010) 034012



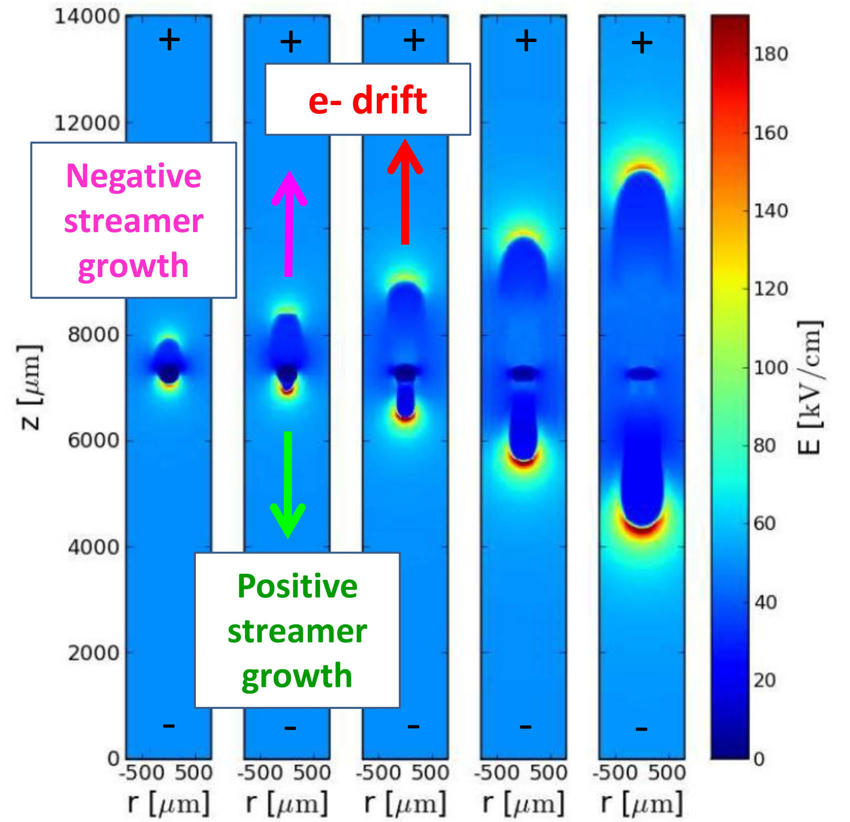

Luque et al, *J. Phys. D: Appl. Phys.* **41**, 234005 (2008)

# Positive and negative streamer

## where are positive and negative electrodes?



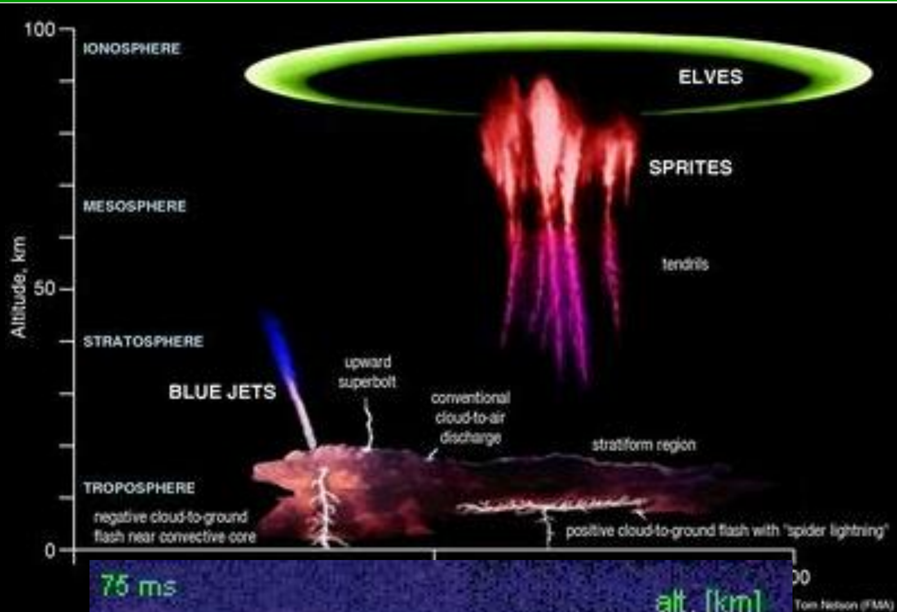

Bourdon et al, *Plasma Sources Sci. Technol.* **19** (2010) 034012

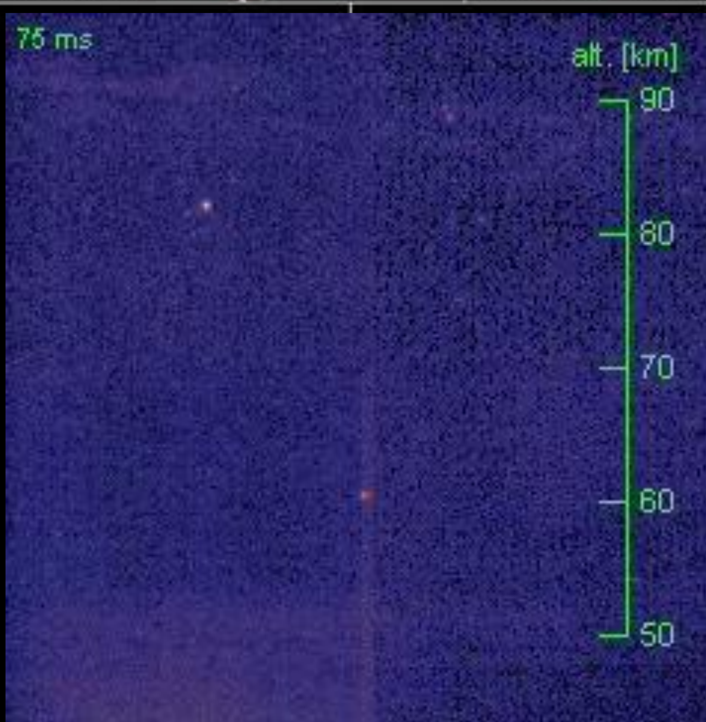



Luque et al, *J. Phys. D: Appl. Phys.* **41**, 234005 (2008)

**Repulsions of electrons → Neg. streamer head wider → lower E/N → higher voltage needed !**

# Streamers in nature : sprites




elves

sprites

# Streamers in nature : sprites

sprites…

Streamer in a lab…

Main difference: contact with electrodes and/or dielectric

# About Streamer breakdown...

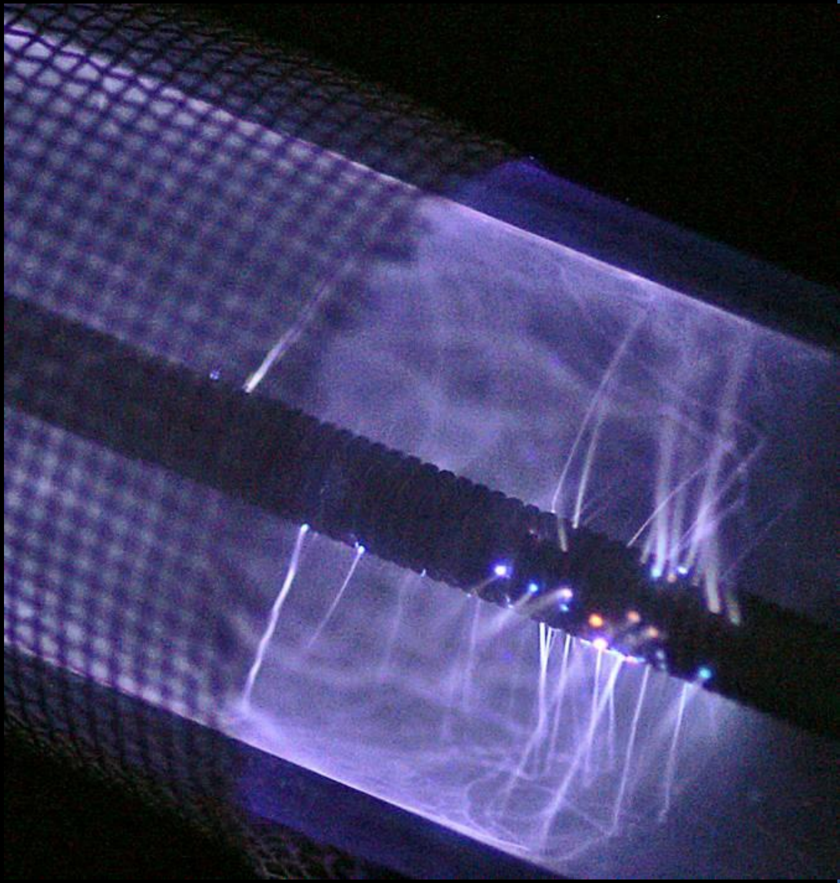
- ✓ Growth duration 1-10 ns
- ✓ radius 100-200 µm
- ✓ Current density 100-1000 $A.cm^{-2}$
- ✓ Electron density $10^{14}$-$10^{15}$ $cm^{-3}$
- ✓ Mean Electron Energy 1-10 eV

- ✓ negative streamer wider and slower than positive ones

- ✓ initial charge density?
- ✓ necessity for photo-ionization?
- ✓ branching mechanism?
- ✓ ...

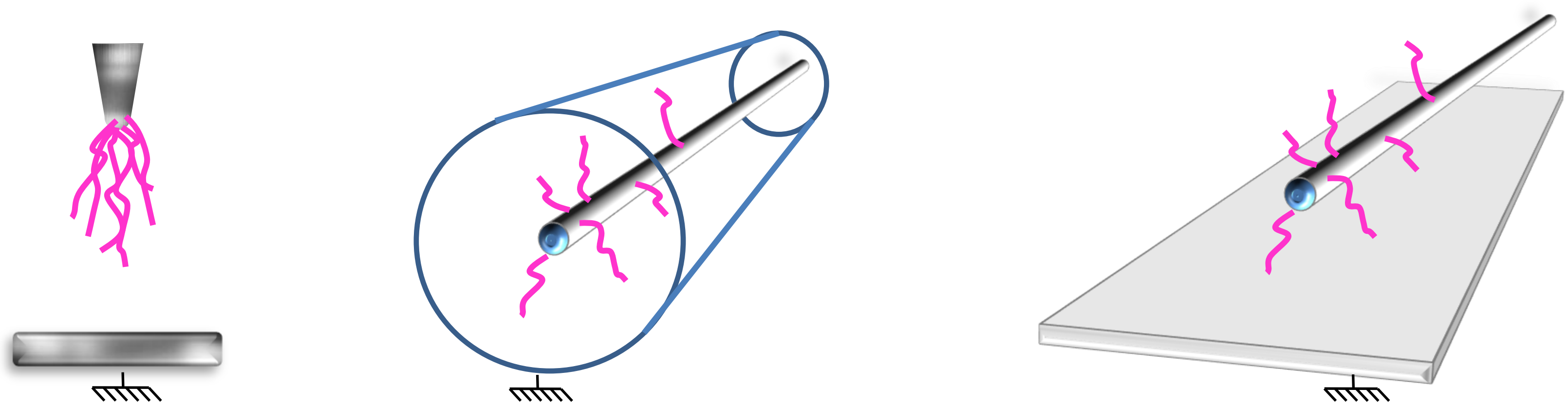
# Outline





# Various geometries for producing Corona discharges

## Strongly Non –uniformed applied electric Field…



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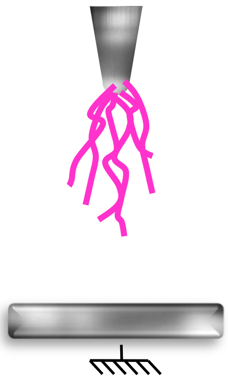

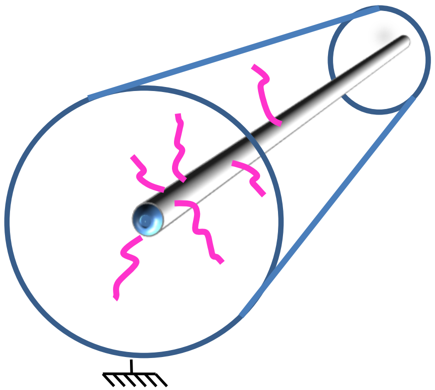

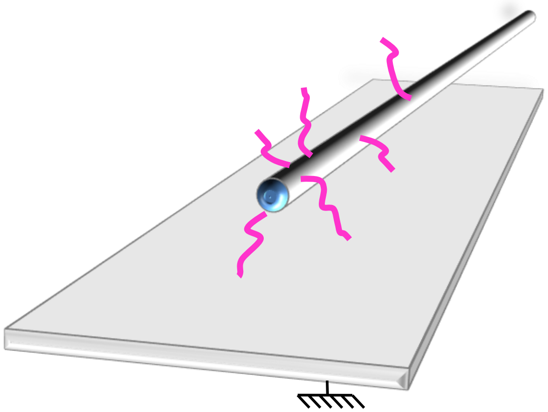

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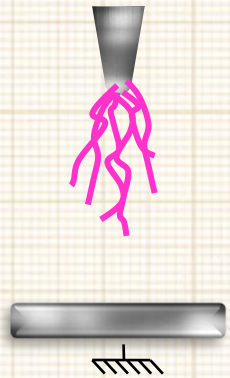
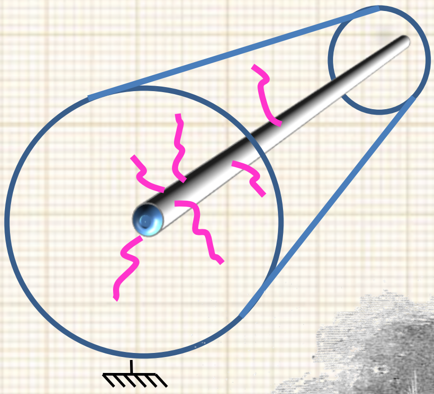
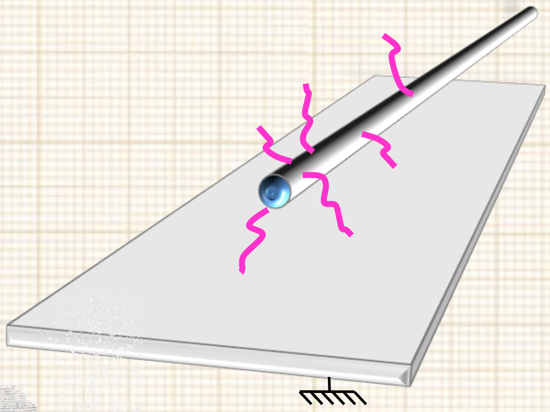
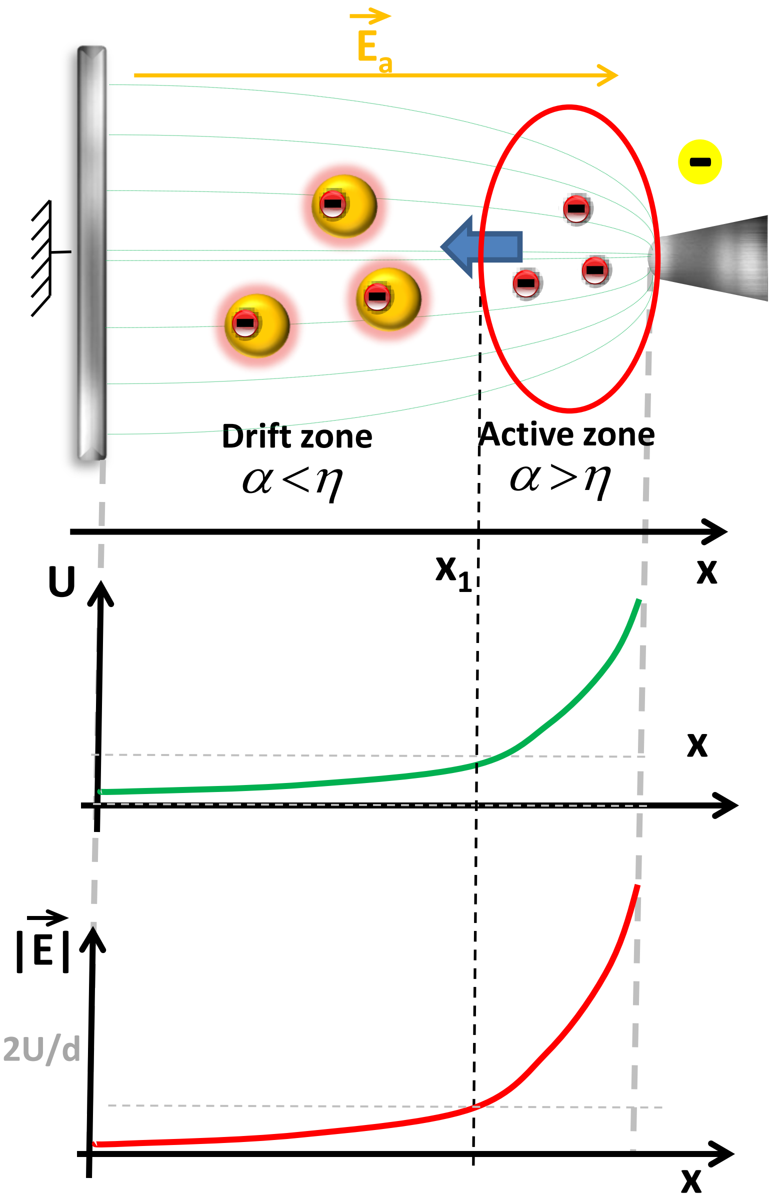






*The Aerial World*, by Dr. G. Hartwig, London, 1886. P. 310

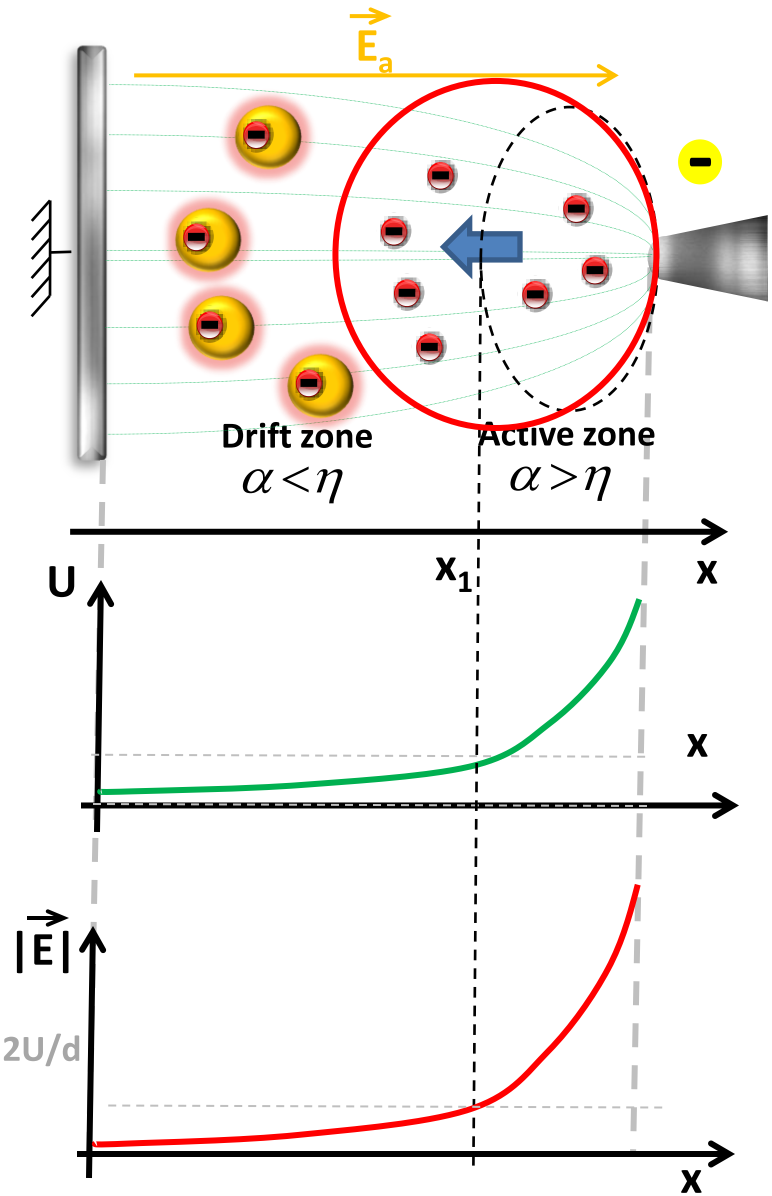
# Corona discharges: principle




$$\int_0^{x_1} \left(\alpha(x)-\eta(x)\right)dx = \ln\left(1+1/\gamma\right)$$

- Ionization occurs only in the active zone
- The current is collected at the ground via ion drift only $I = k \cdot U\left(U-U_0\right)$
- The potential between the electrode is very weakly disturbed by the plasma ignition in the active zone

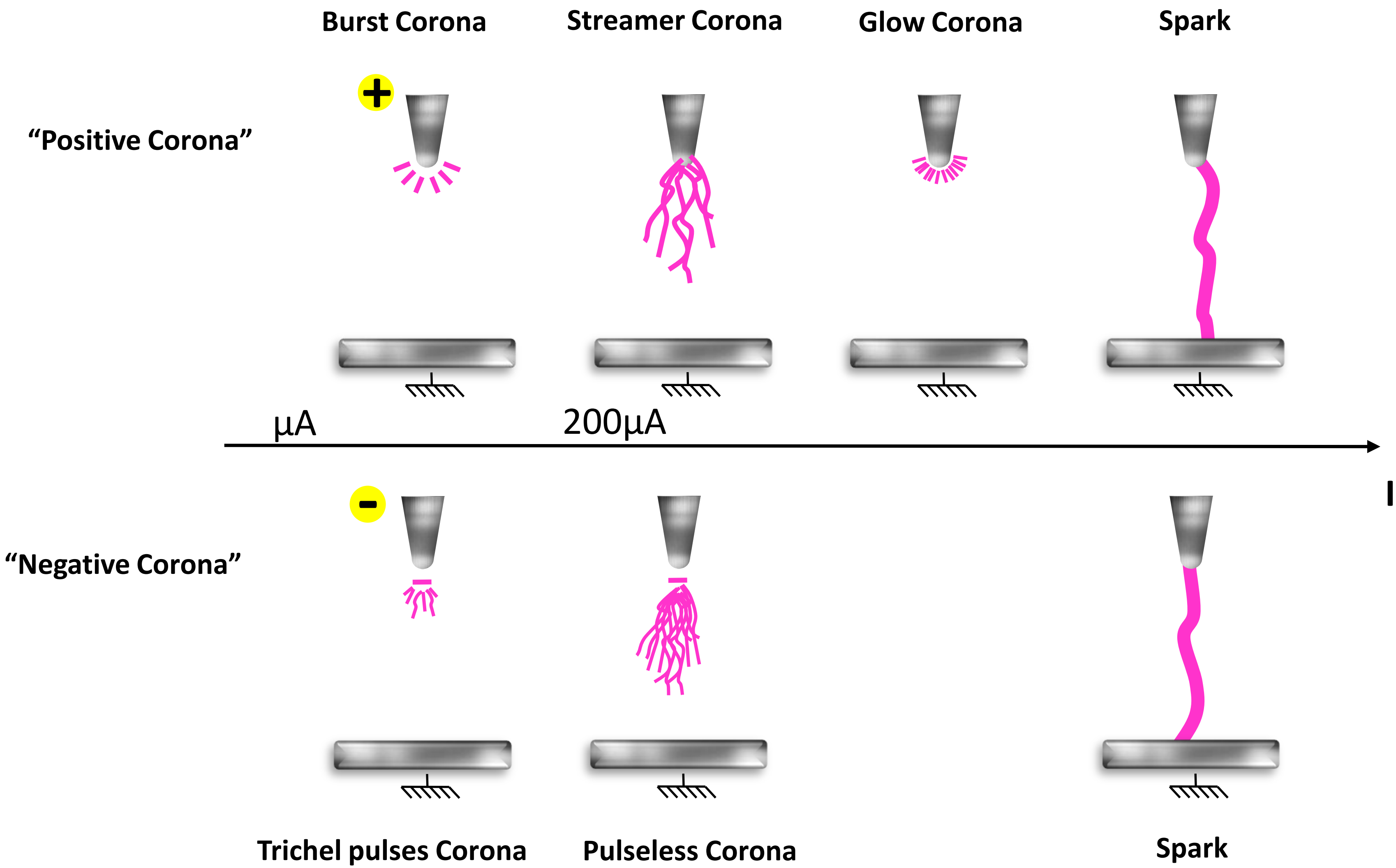
# Corona discharges: principle




$$\int_0^{x_1} (\alpha(x) - \eta(x))dx = \ln(1 + 1/\gamma)$$

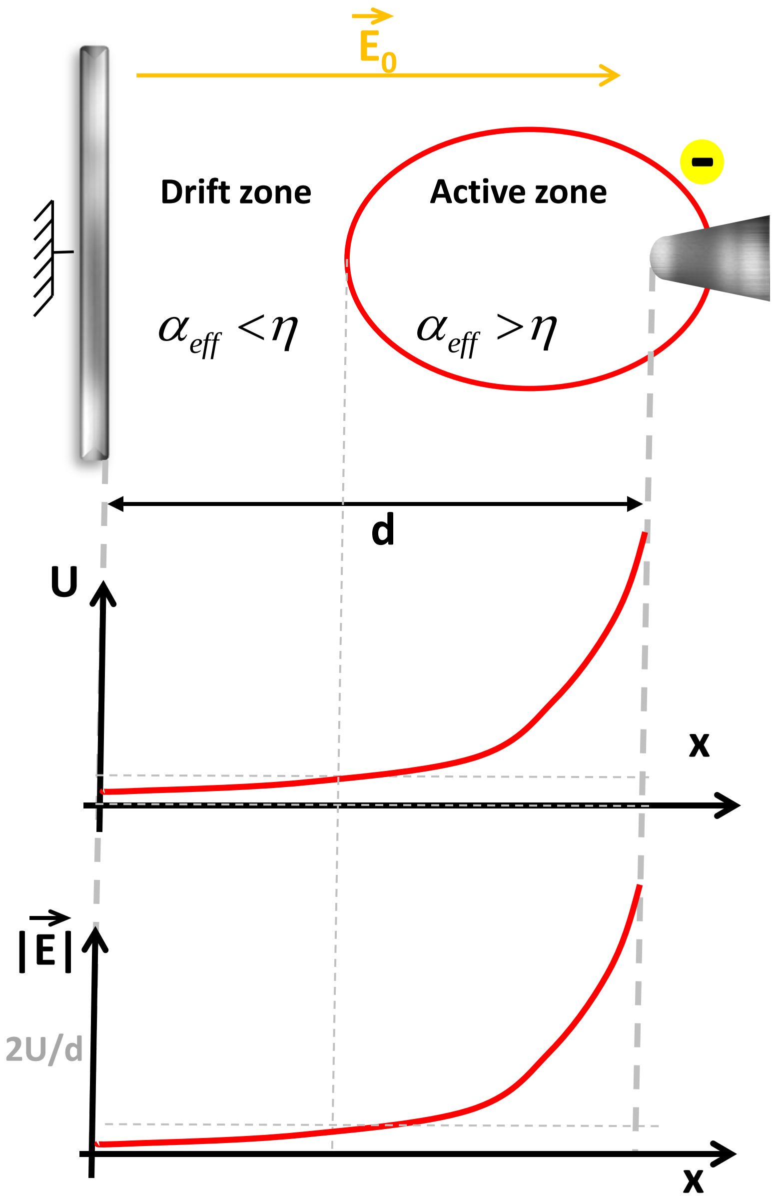
- Ionization occurs only in the active zone
- The current is collected at the ground via ion drift only $I = k \cdot U(U - U_0)$
- The potential between the electrode is very weakly disturbed by the plasma ignition in the active zone
- Active zone increases with U

# Corona discharges



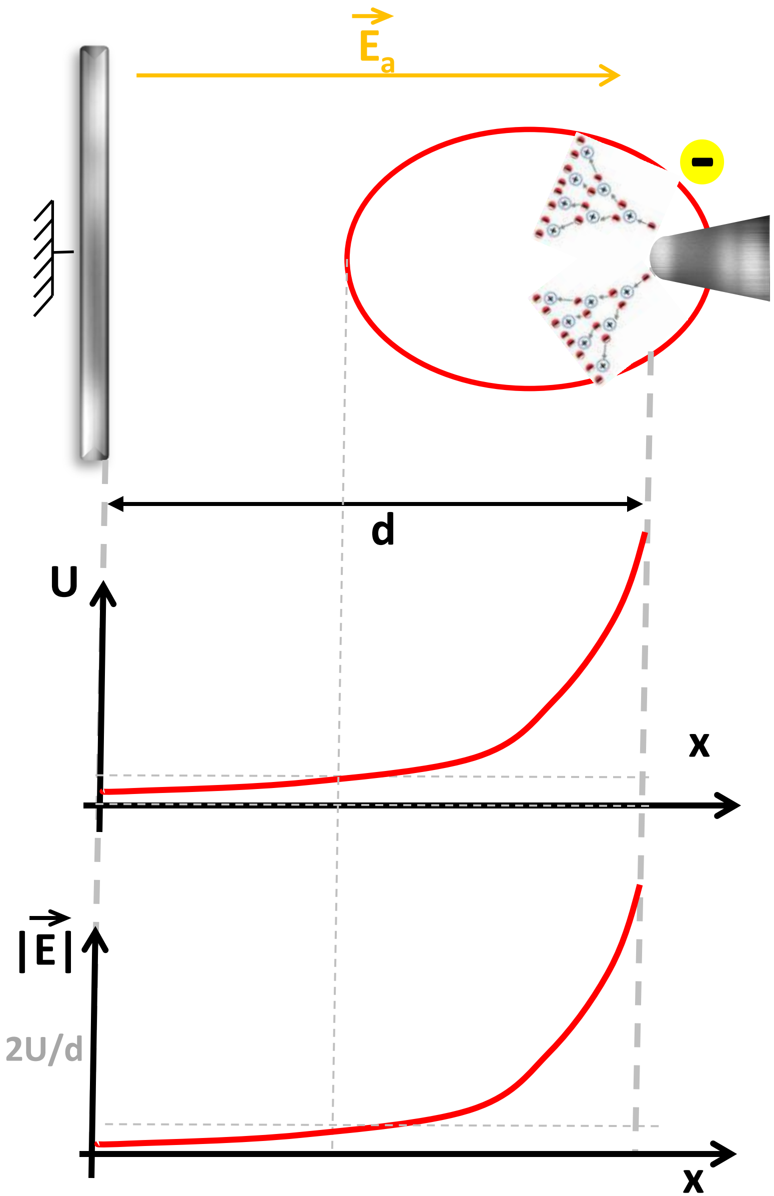

Adapted from Chang et al, *IEEE Trans. Plasma Sci.* **19** (1991) 1102-1166

# Corona discharges: Trichel pulses




- Ionization can occur only in the active zone

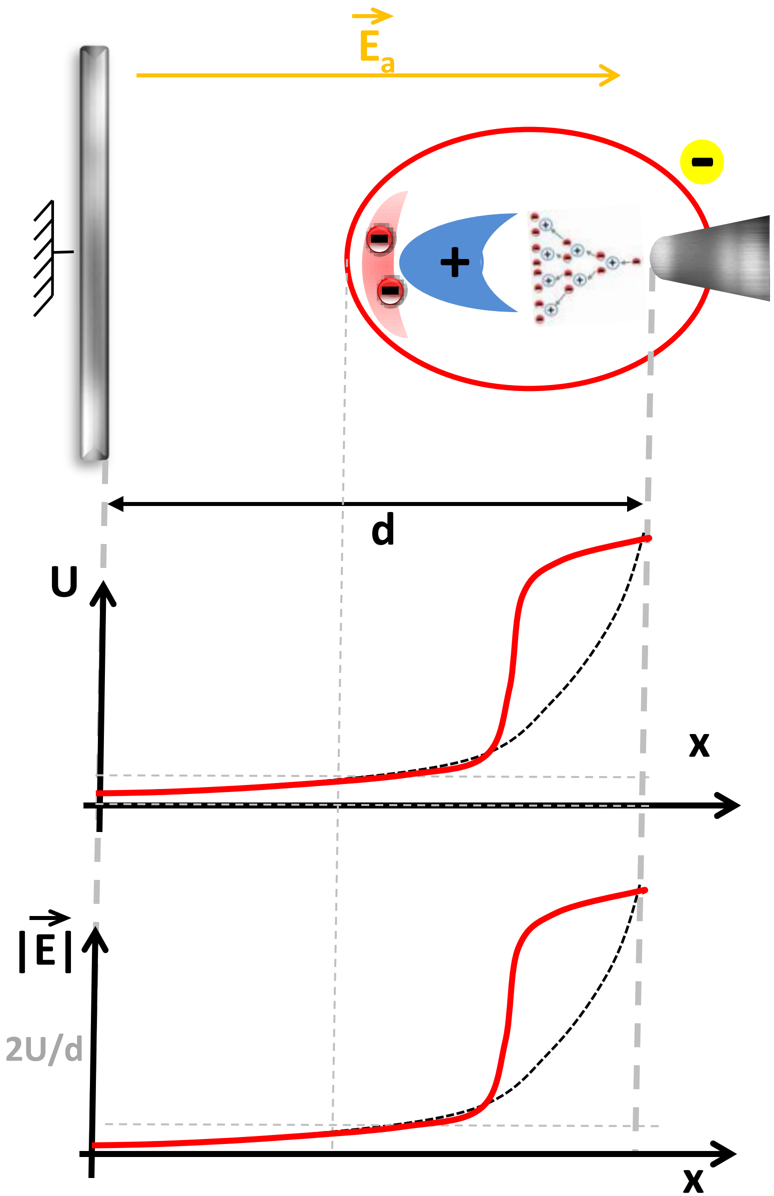
# Corona discharges: Trichel pulses




- Ionization can occur only in the active zone

  1. A space charge starts to build up

# Corona discharges: Trichel pulses




- Ionization can occur only in the active zone

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2. However charge density is too low and $E_a$ is not shielded

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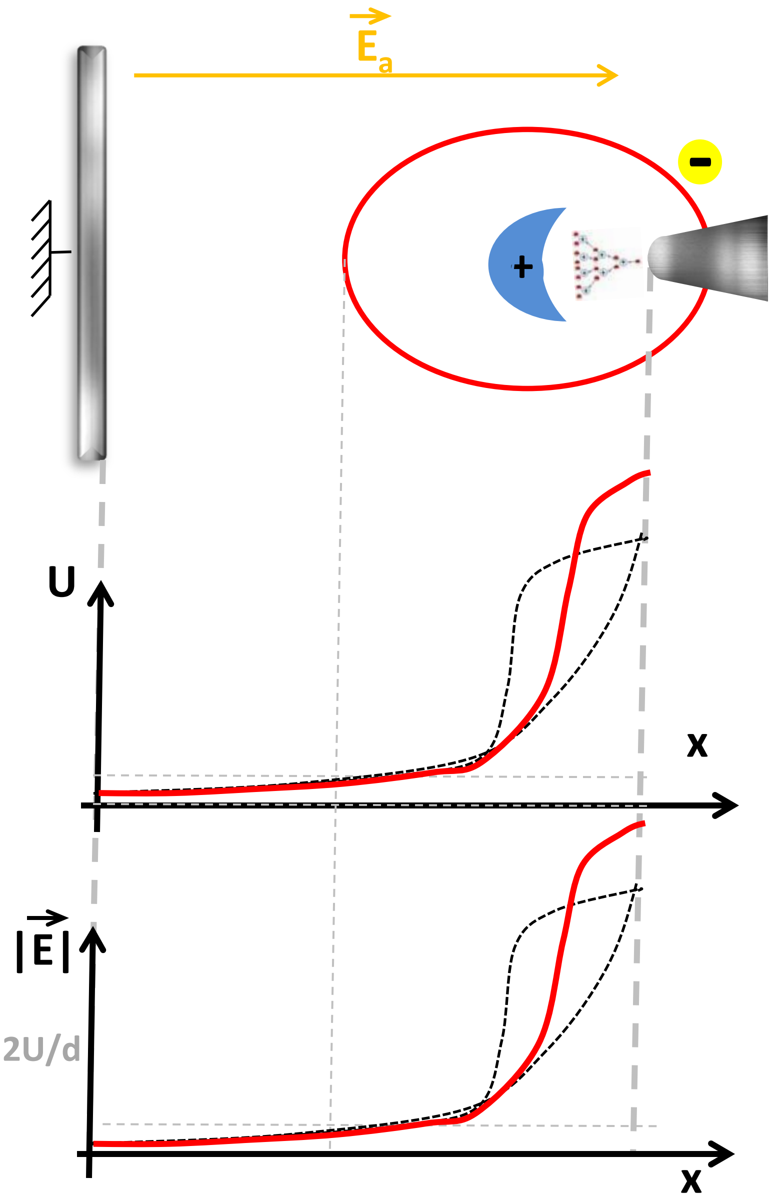


- Ionization can occur only in the active zone

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3. The positive cloud collapses

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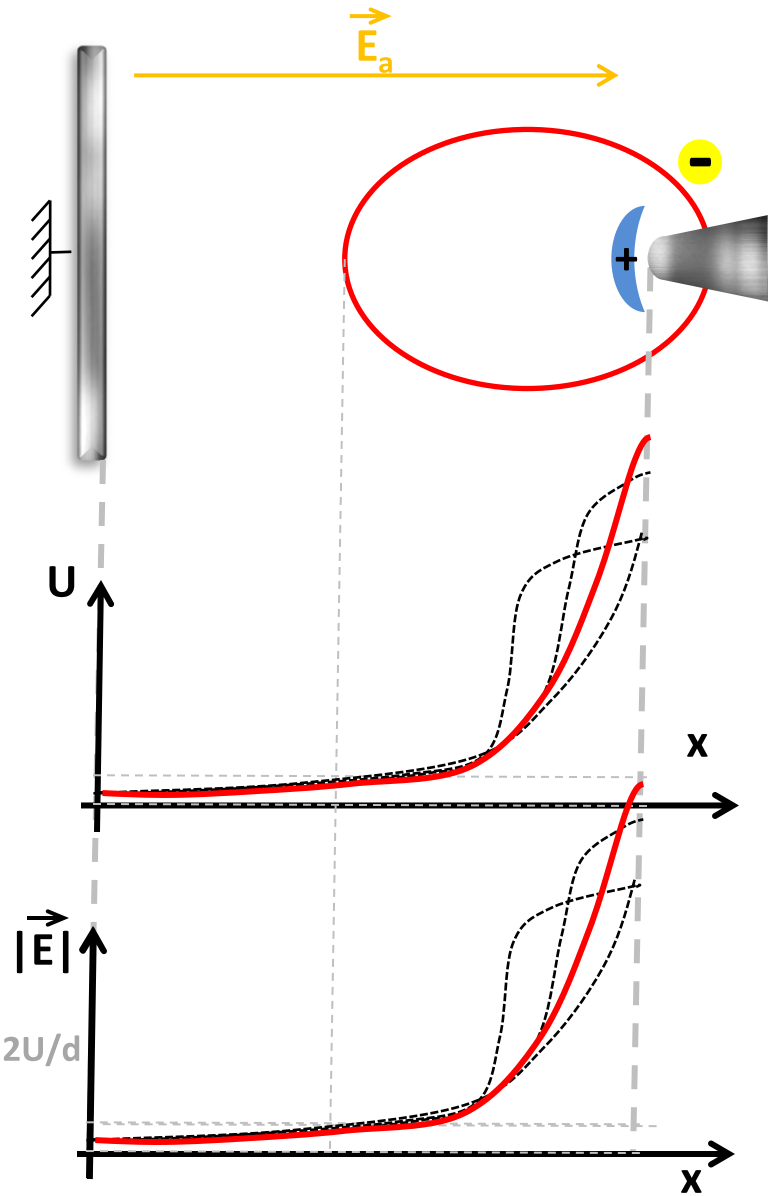
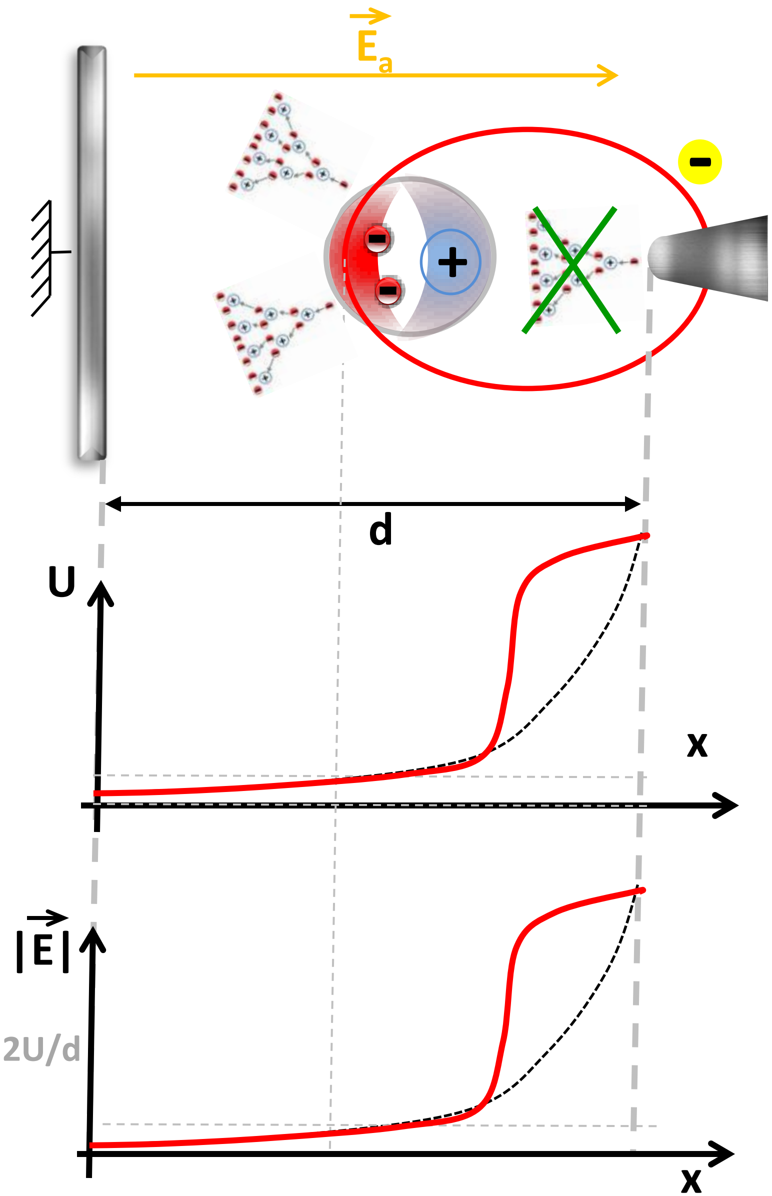



- Ionization can occur only in the active zone
  1. A space charge starts to build up
  2. However charge density is too low and $E_a$ is not shielded
  3. The positive cloud collapses

- the process restarts to produce the next “Trichel pulse”
- frequency is proportional to the current

# Corona discharges: Streamer corona

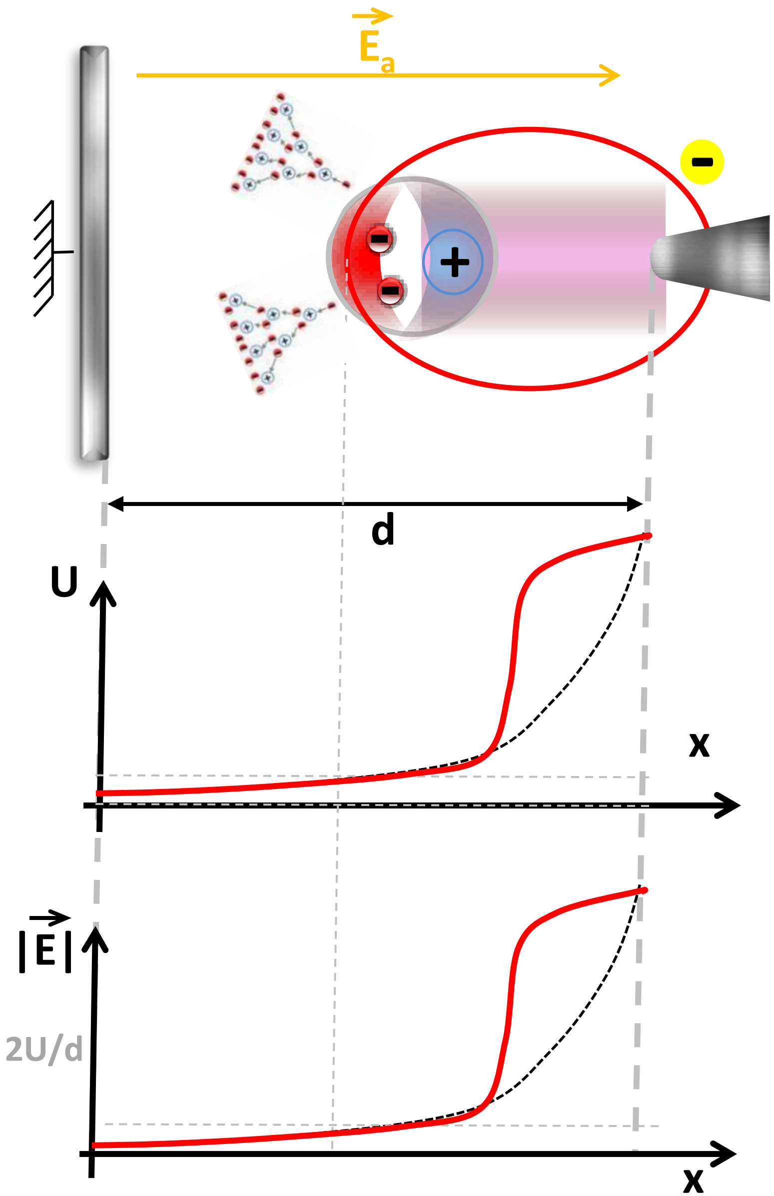



- If the space charge is strong enough (ie charge density high enough)

$E_0$ shielded at the tip, streamer growth starts

Streamer corona

# Corona discharges: Streamer corona




- If the space charge is strong enough (ie charge density high enough)

↓

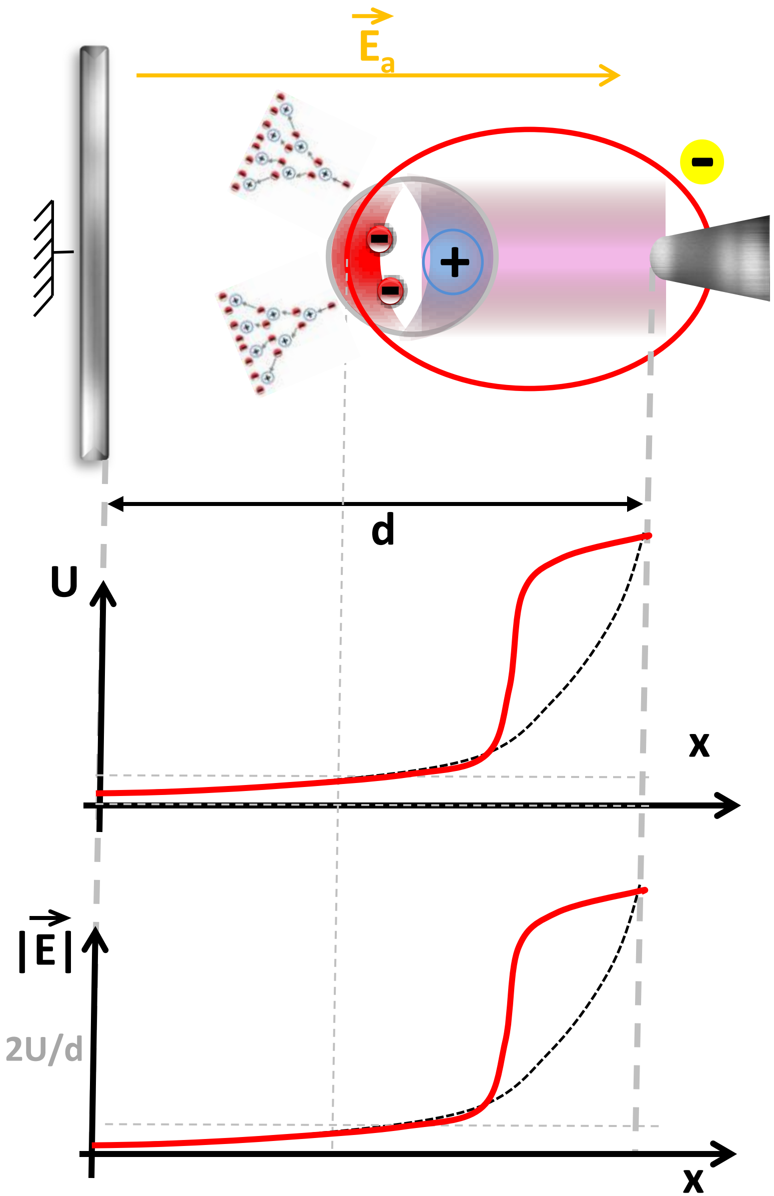
$E_o$ shielded at the tip, streamer growth starts

↓

Streamer corona

**Why does the streamer stop in the drift zone?**

# Corona discharges: Streamer corona

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Streamer corona

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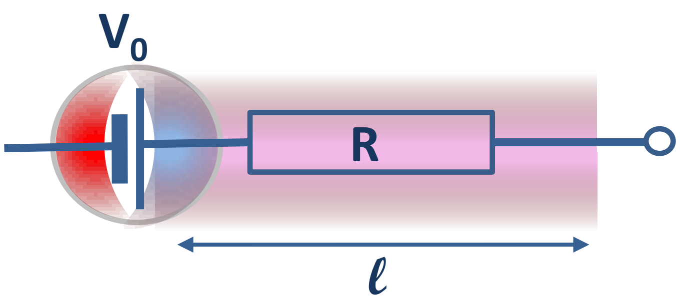



$$R = \frac{\rho \cdot \ell}{S}$$

- Streamer is not an ideal conductor
- Potential in the head decreases with distance

# About Corona discharges…

- ✓ Partial breakdown discharges in non uniform field
- ✓ Different discharges simply by adjusting the current
- ✓ ions drift in the weak field zone
- ✓ streamer stops because of its own resistivity
- ✓ risk of spark at low voltage (leader mechanism)

# Outline

**I. Breakdown mechanisms**

a) Townsend mechanism

b) Streamer mechanism

**II. Corona discharges**

**III. What is a Dielectric Barrier Discharge?**

**a) Electrical characteristics**

b) Development of a single filament

c) Role of the dielectric?

**IV. Role of surface vs gas phase dynamics**

a) Interaction between filaments

b) Diffuse discharges

**V. Confinement and gas motion**

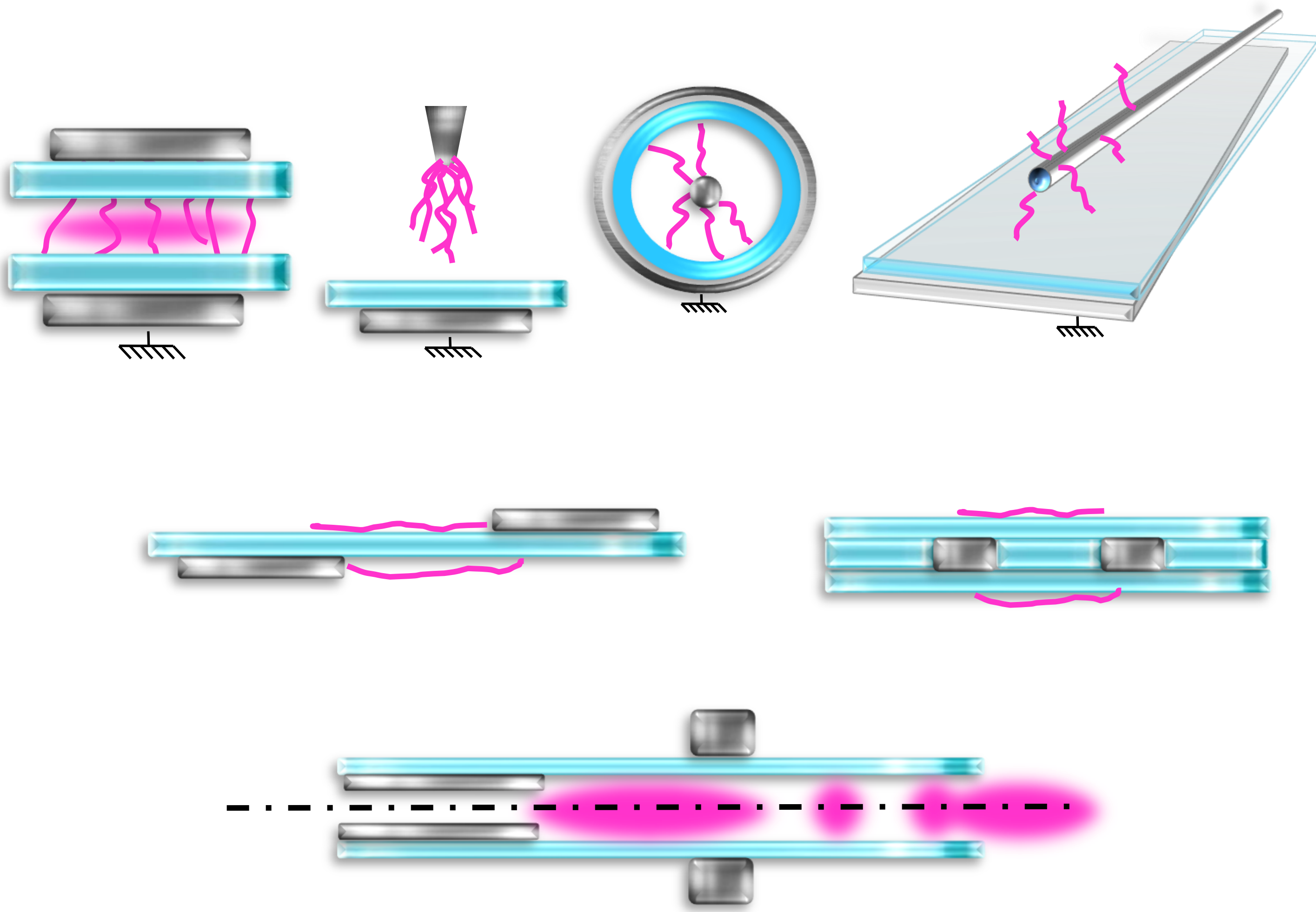
# Many different geometries of DBDs

## Any geometry, but at least 1 dielectric between the electrodes

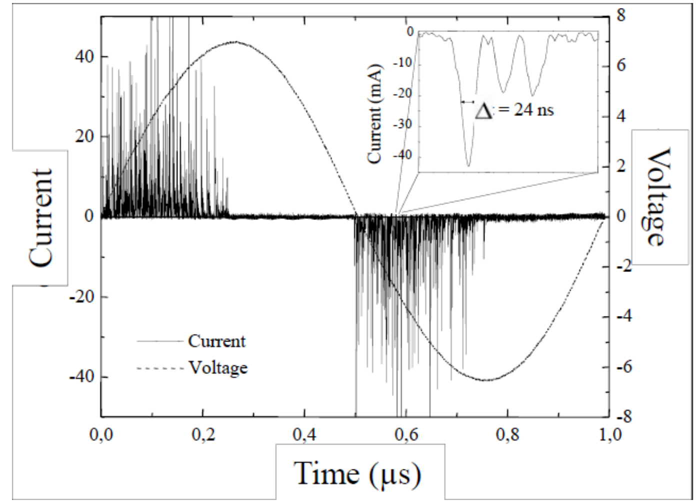
“Volume”
DBD

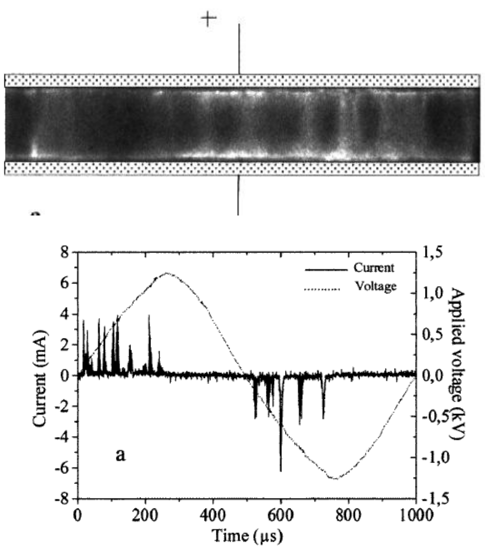
“Surface”
DBD

“jet”
DBD

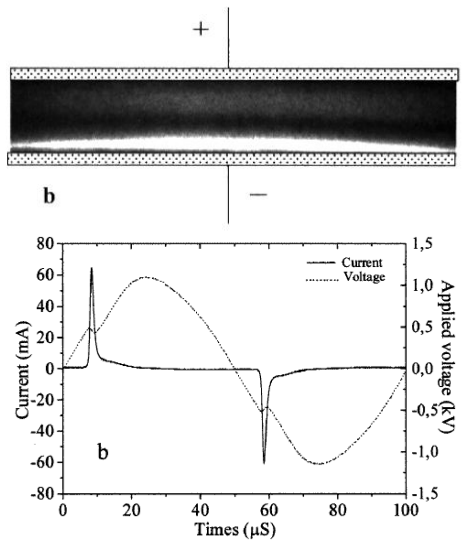


# Dielectric Barrier Discharges: different regimes




(a)




(b)

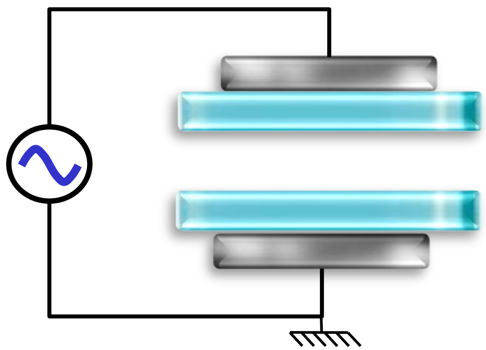
- Most commonly DBD develops into filaments crossing the whole gap
- under peculiar conditions: diffuse Townsend or even glow discharge

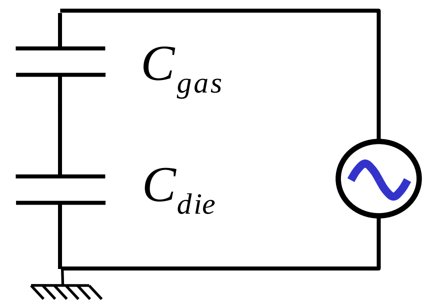
Massines et al, *J. Phys. D: Appl. Phys.* **31** (1998) 3411–3420

# Electrical scheme of DBDs

## DBD geometry is a capacitance

***Plasma "OFF"***






**DBD = capacitive limitation of the current**

**resistive limitation → Joule heating**
**Inductive limitation → current rise time limited**

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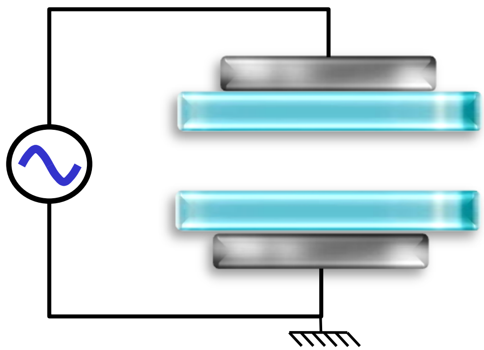

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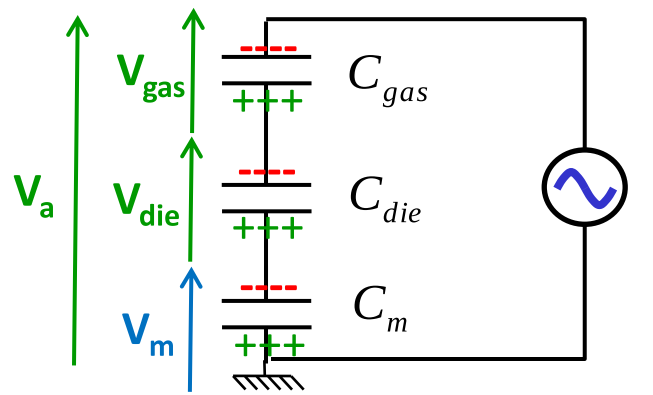
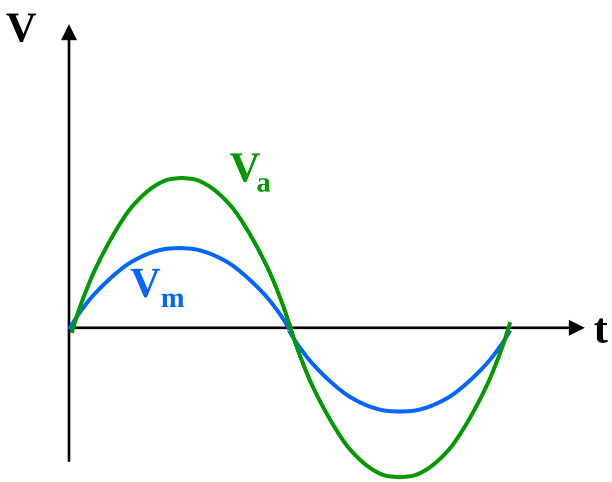
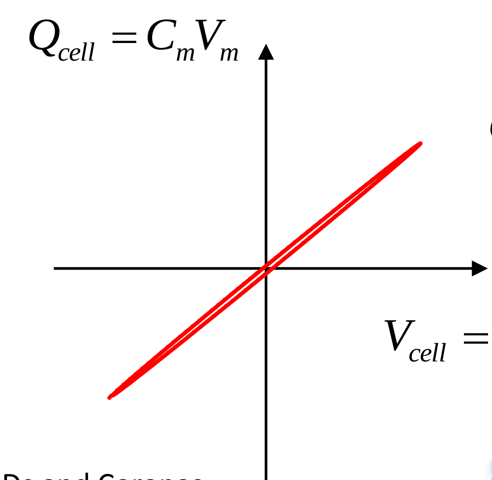



$$C_{gas} < C_{die} << C_m$$

**Measure of power dissipated into the plasma**

Manley, *Trans. Electrochem. Soc.* (1943) 83-96




$$Q = \int I(t)dt = CV$$

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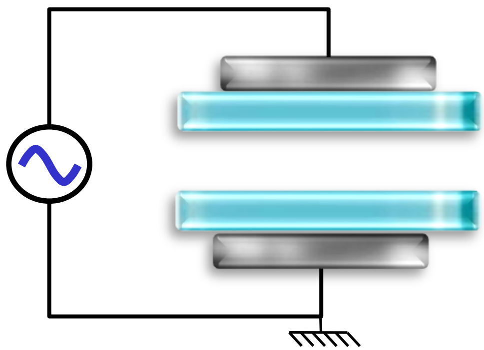

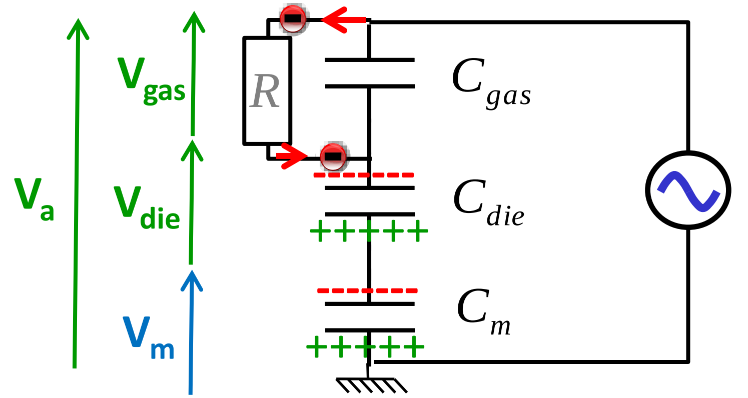


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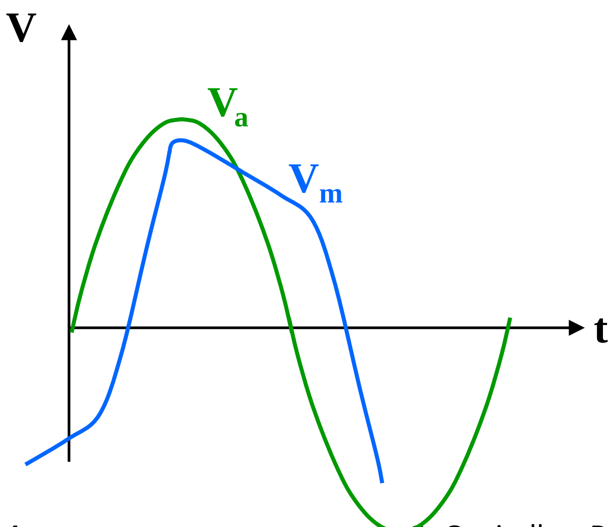


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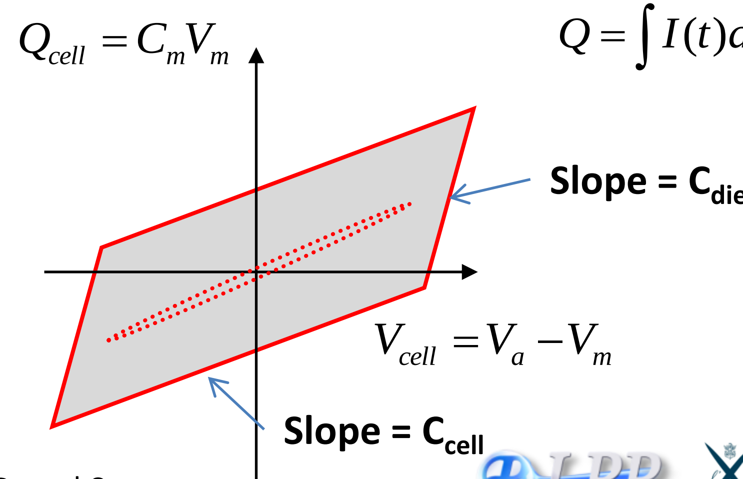

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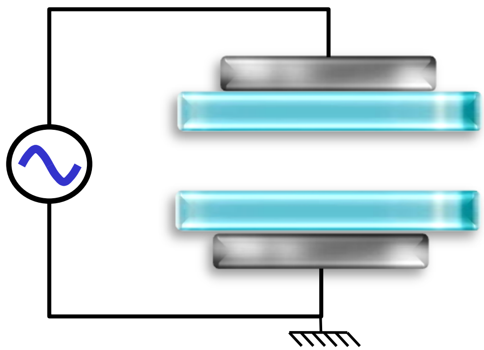

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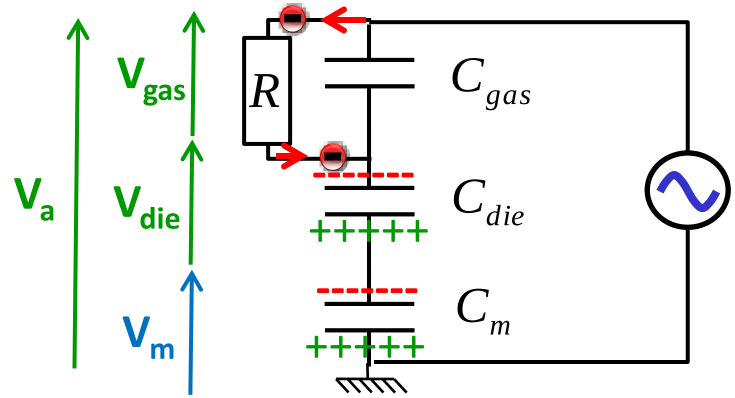
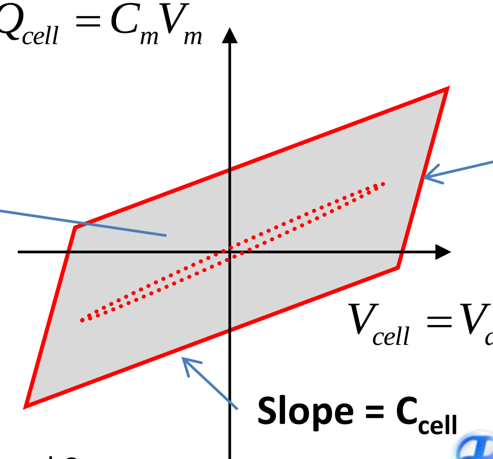



$$C_{gas} < C_{die} << C_m$$

$$Q = \int I(t)dt = CV$$

$$P = 4f \cdot U_b C_{die}\left[U_{peak} - \frac{C_{die}+C_{gas}}{C_{die}} \cdot U_b\right]$$



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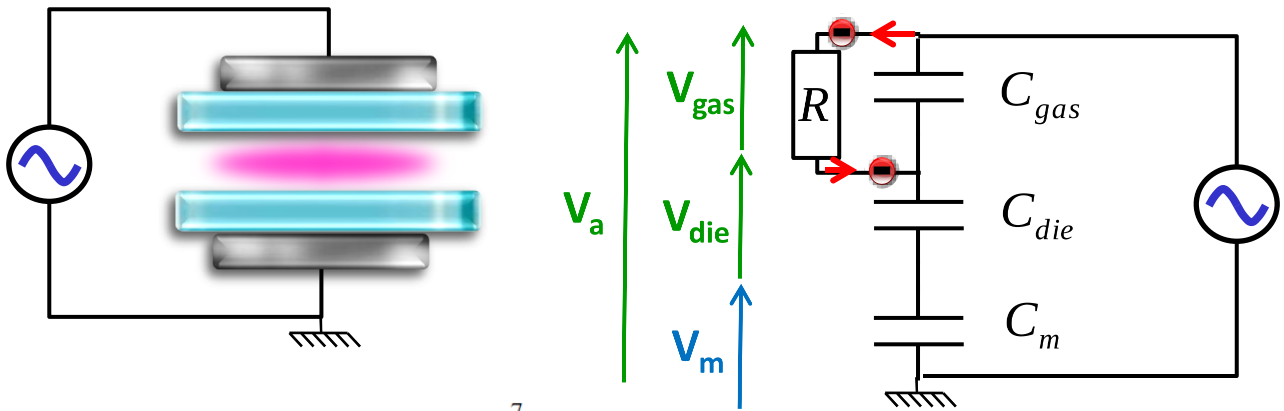


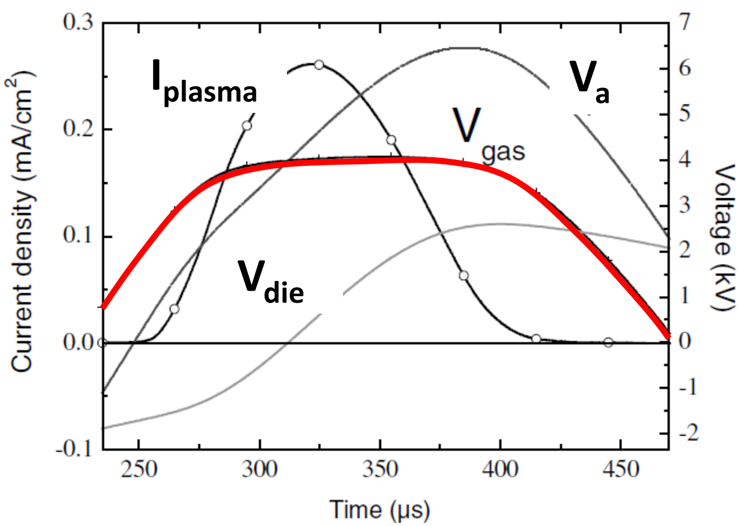


$$I = I_{plasma} + I_{gas}$$

$$V_{gas} = V_a - \frac{1}{C_{die}} \int I(t)dt$$

Voltage across the gas gap remains constant at breakdown voltage

Massines et al, *Plasma Phys. Control. Fusion* **47** (2005) B577–B588

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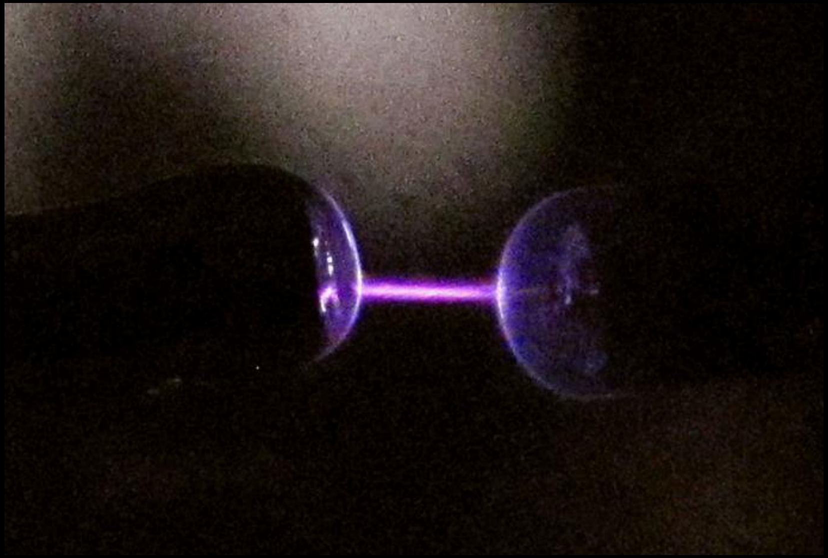
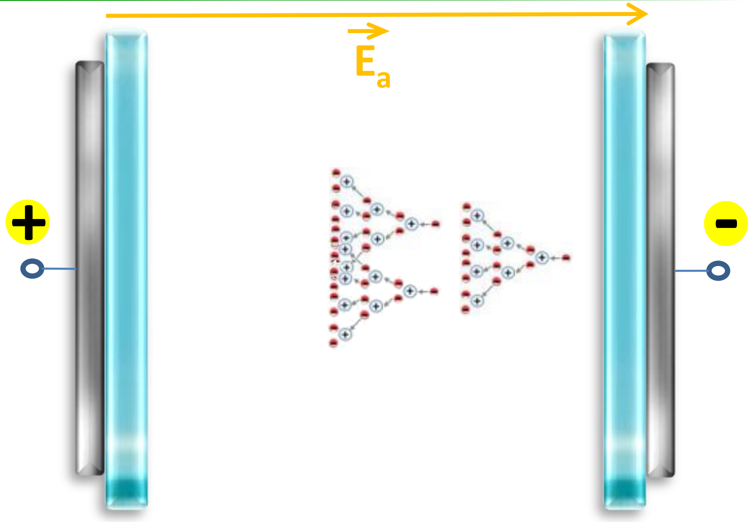
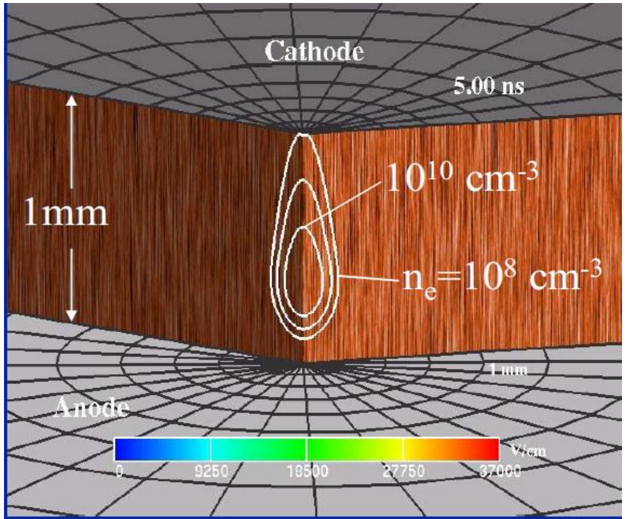


# DBDs: micro-discharge regime (filamentary mode)

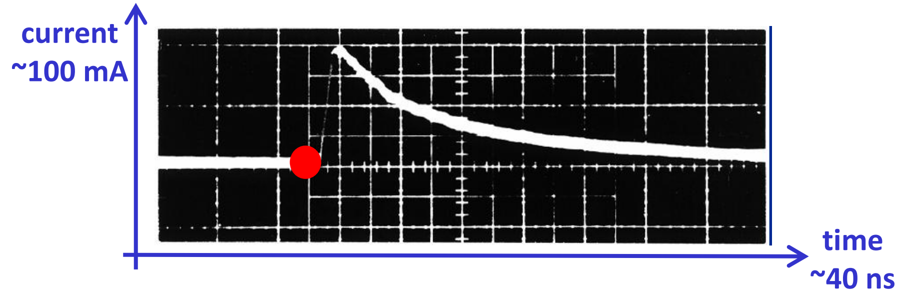



• Avalanches are leaving the cathode

• streamer growth




An electron avalanche propagates towards the anode




Kogelschatz et al, *IEEE Trans. Plasma Sci.* **30** (2002), 4, 1400–1408

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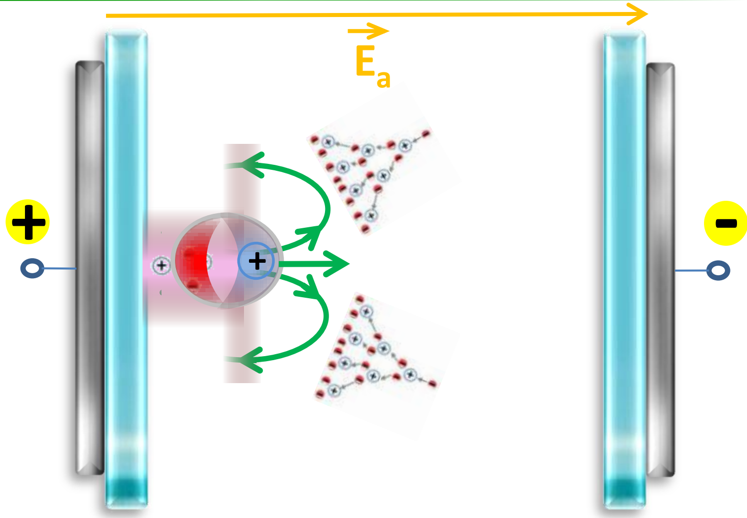
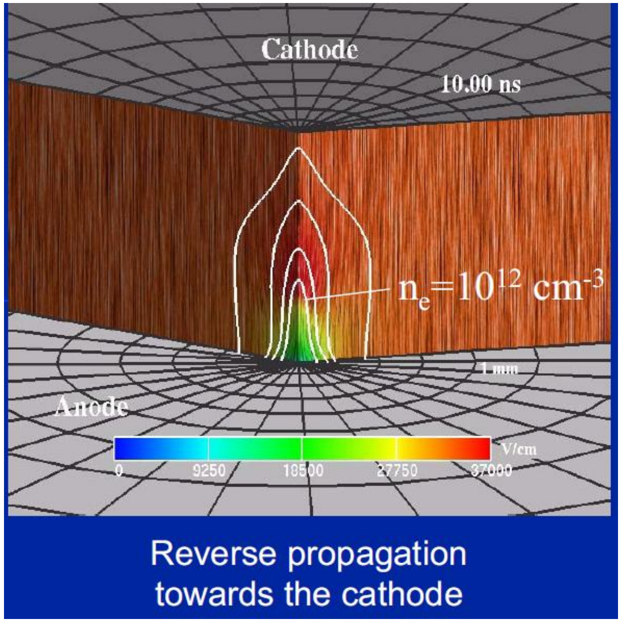
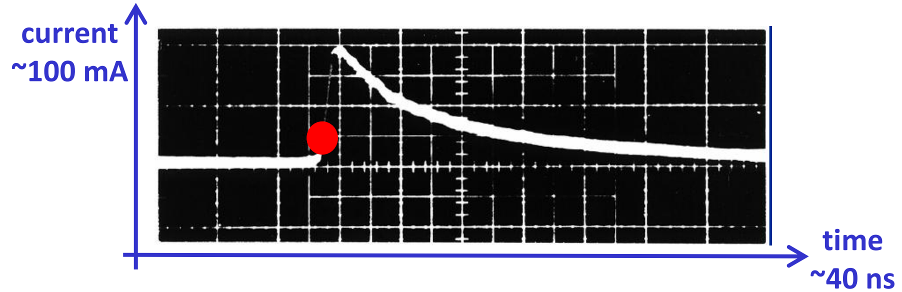



- streamer growth



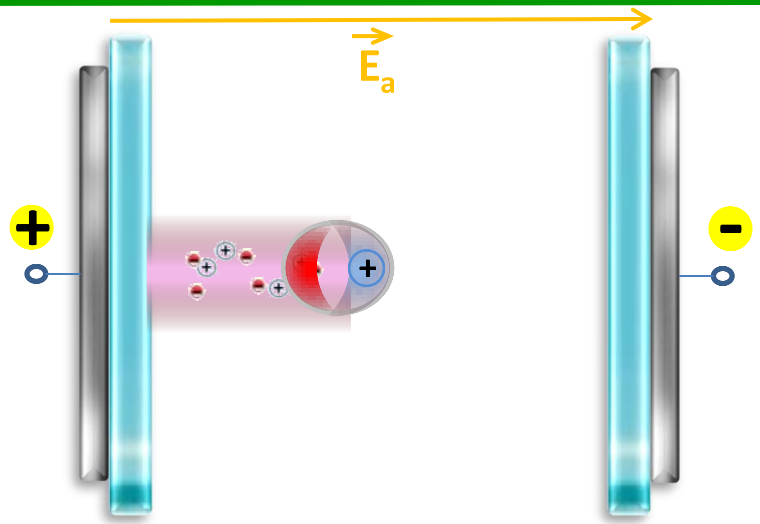

- Avalanches are leaving the cathode

- space charge is formed at the anode



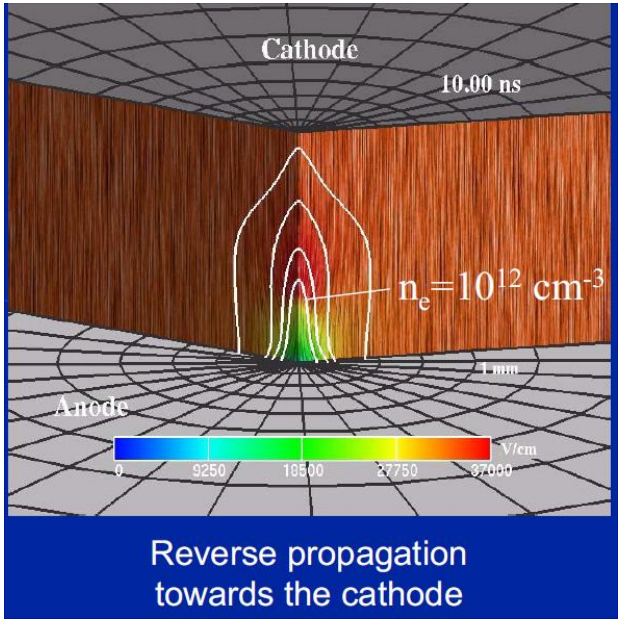

Kogelschatz et al, *IEEE Trans. Plasma Sci.* **30** (2002), 4, 1400–1408

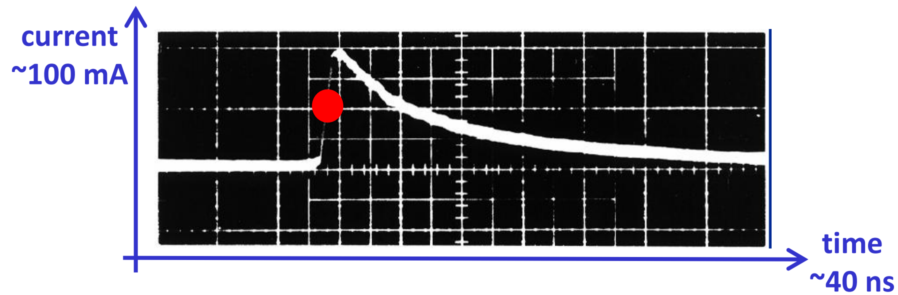
# DBDs: micro-discharge regime (filamentary mode)




- Avalanches are leaving the cathode
- space charge is formed at the anode
- "positive" streamer is growing

- streamer growth




Kogelschatz et al, *IEEE Trans. Plasma Sci.* **30** (2002), 4, 1400–1408

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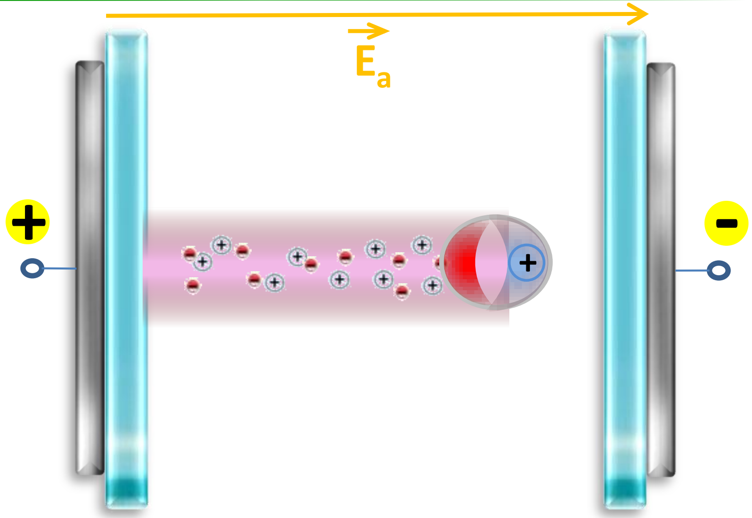


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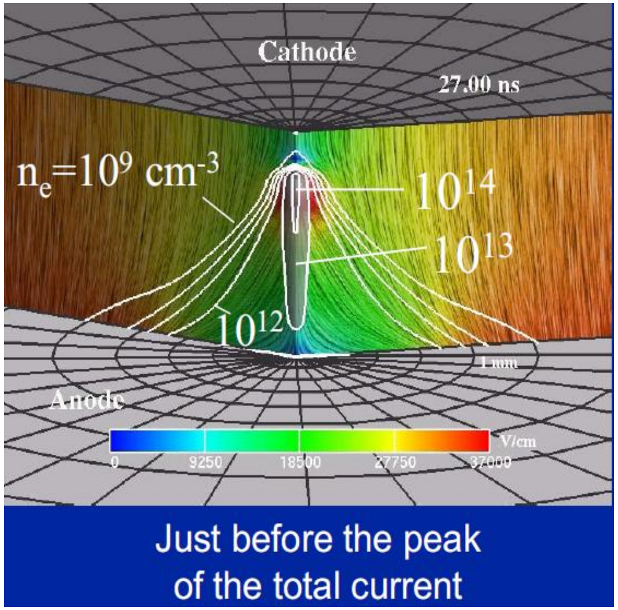
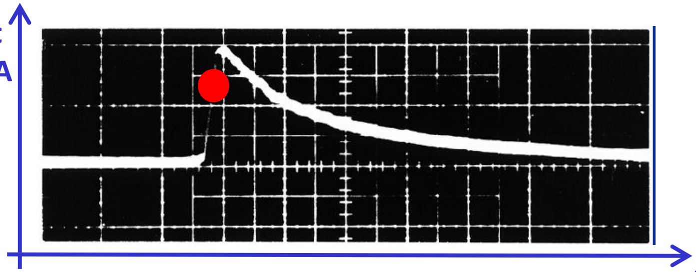
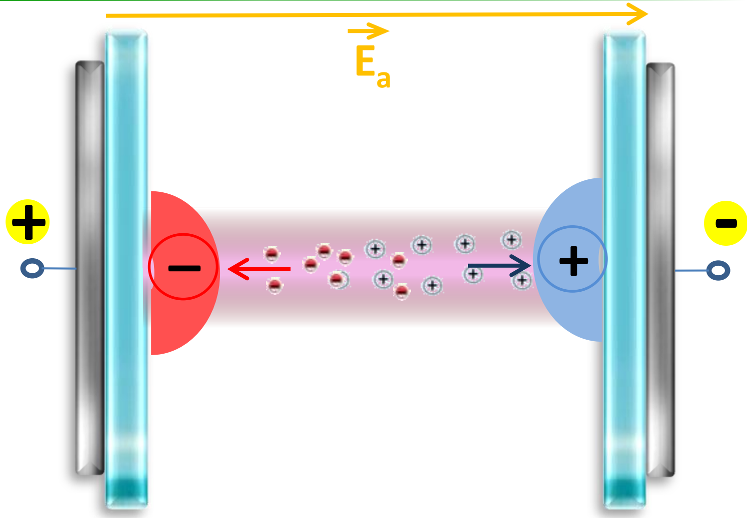


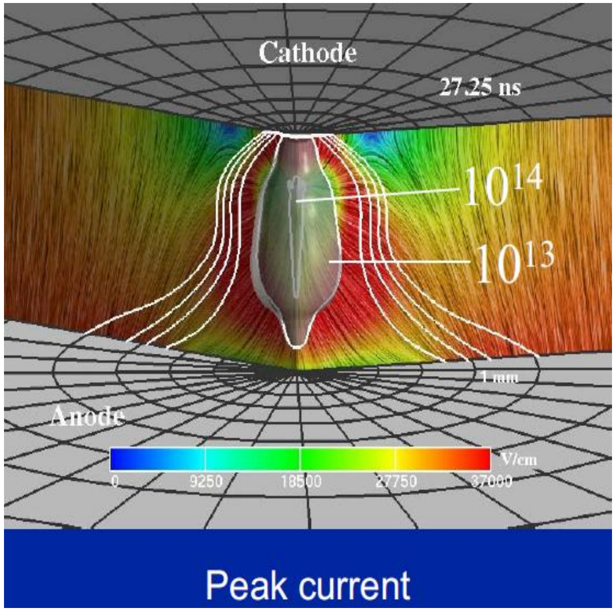




Kogelschatz et al, *IEEE Trans. Plasma Sci.* **30** (2002), 4, 1400–1408

# DBDs: micro-discharge regime (filamentary mode)




• streamer growth

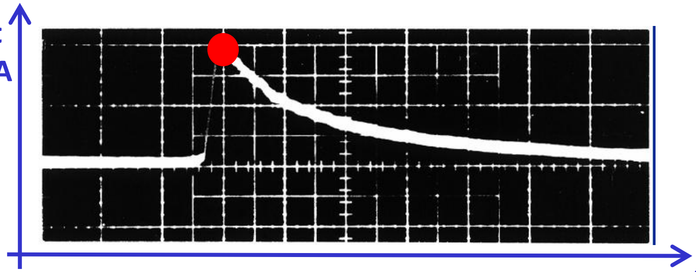



• Avalanches are leaving the cathode

• space charge is formed at the anode

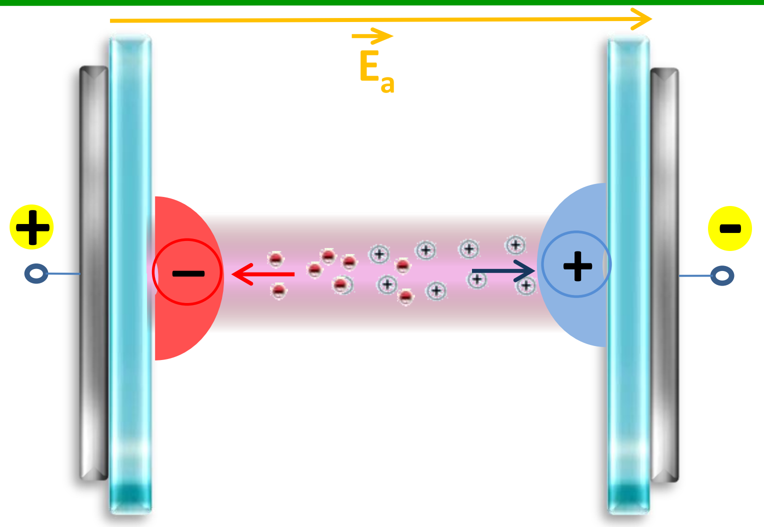
• “positive” streamer is growing

• charge deposition on the dielectric shield the field




Kogelschatz et al, *IEEE Trans. Plasma Sci.* **30** (2002), 4, 1400–1408

# DBDs: micro-discharge regime (filamentary mode)




• Avalanches are leaving the cathode

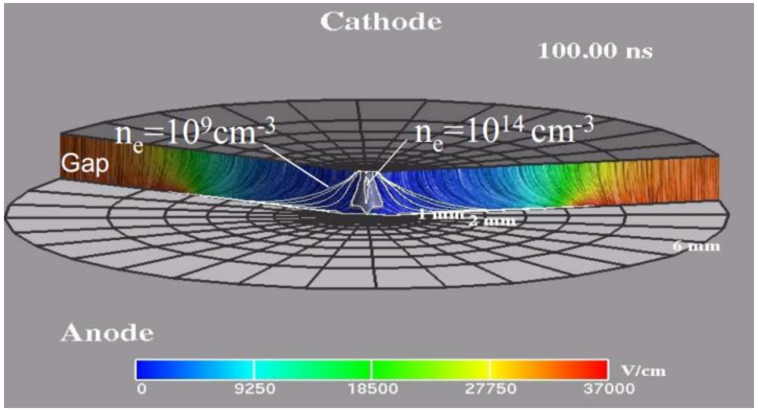
• space charge is formed at the anode

• "positive" streamer is growing

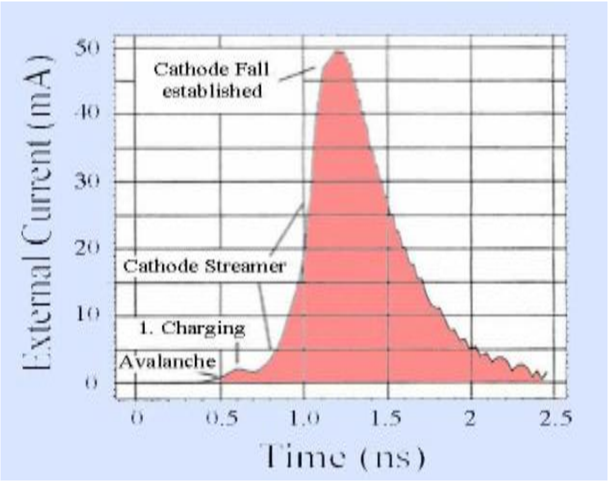
• charge deposition on the dielectric shield the field

• filament vanishes because the field is shielded

• streamer growth
• Applied field is shielded by deposited charges

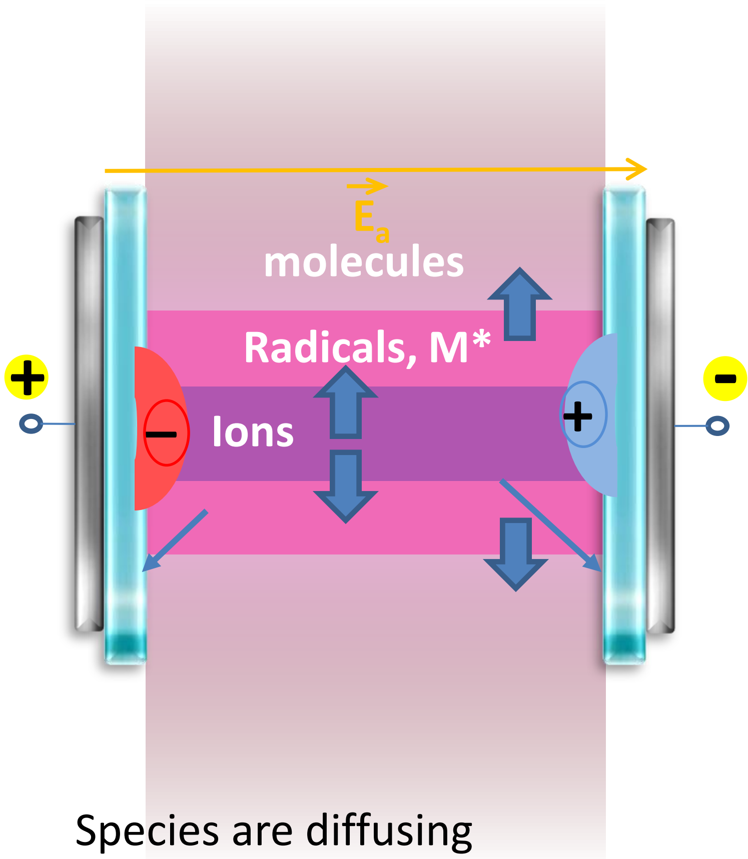



Kogelschatz et al, *IEEE Trans. Plasma Sci.* **30** (2002), 4, 1400–1408

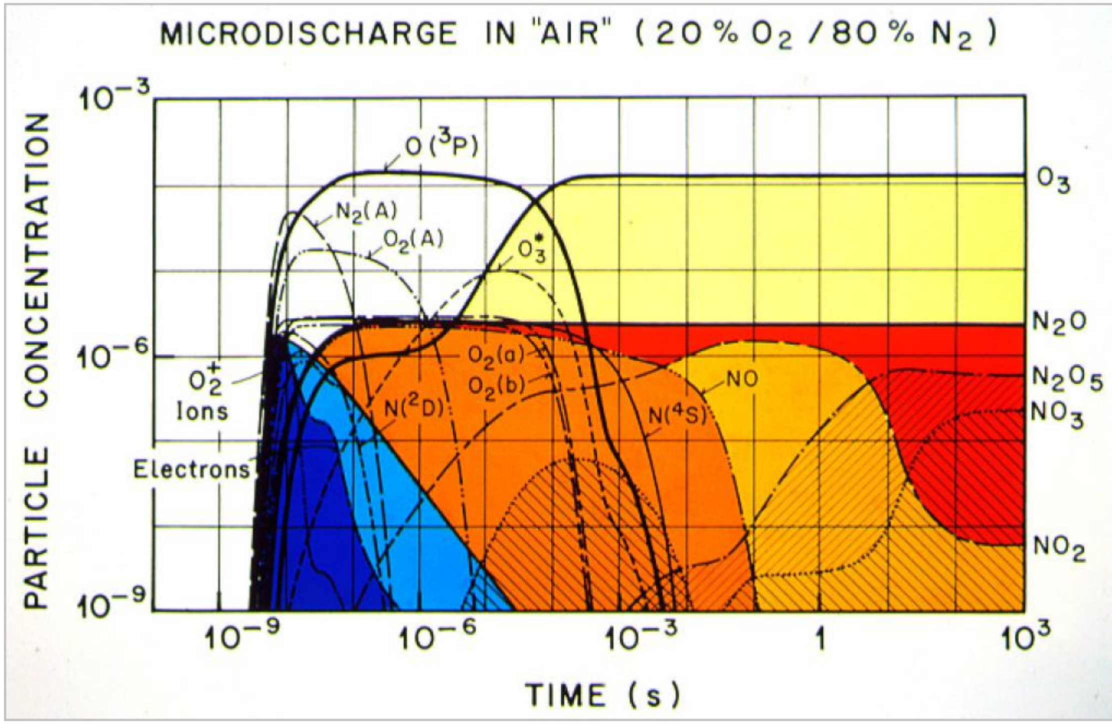



G. Steinle et al. *J. Phys. D: Appl. Phys.* **32** (1999), 1350

# Each filament = micro-chemical reactor



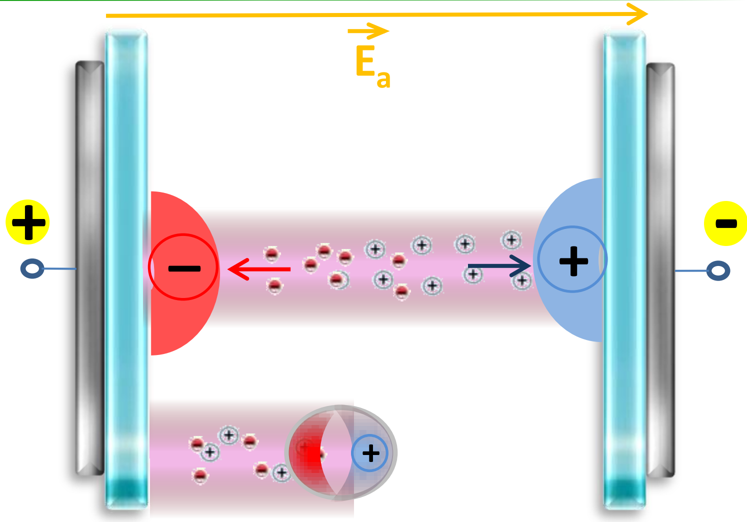

Species are diffusing accordingly to their life time

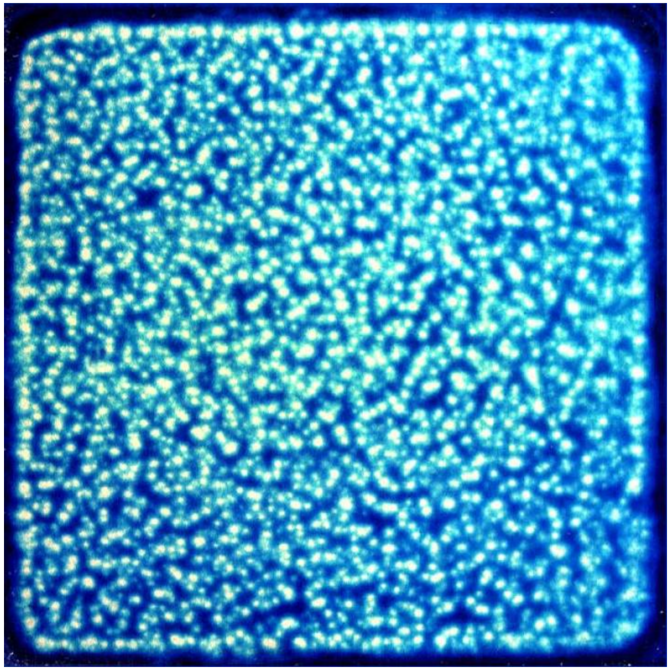



Modeling the chemistry of 1 filament:

- **Need to take into account radial diffusion**
- **Calculation on time scale from 1 ns to 1h !!!**

# DBDs: micro-discharge regime (filamentary mode)



Kogelschatz et al, *IEEE Trans. Plasma Sci.* **30** (2002), 4, 1400–1408

Plate Ozonizer
Size: 6 cm x 6 cm
Exposure Time: 20 ms

**How to ignite another filaments ?**

a) At another place on the dielectric (field not shielded yet)

b) At the same place if the voltage is increased enough

c) at the same place by reversing the polarity

**DBD is never powered by DC voltage**

# About micro-discharges in DBD...

✓Development through positive streamer mechanism (~ 10 ns)

✓ plasma column weakly ionized, similar to a transient high pressure glow discharge

✓ The dielectric is stopping the growth (need for periodic power supply)

- How are charges “adsorbed”?
- Are they only stopping the filament?

**I. Breakdown mechanisms**
- a) Townsend mechanism
- b) Streamer mechanism

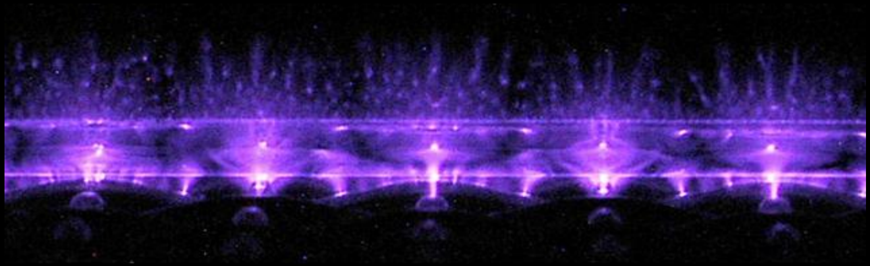
**II. Corona discharges**

**III. What is a Dielectric Barrier Discharge?**
- a) Electrical characteristics
- b) Development of a single filament
- **c) Role of the dielectric ?**

**IV. Role of surface vs gas phase dynamics**
- a) Interaction between filaments
- b) Diffuse discharges

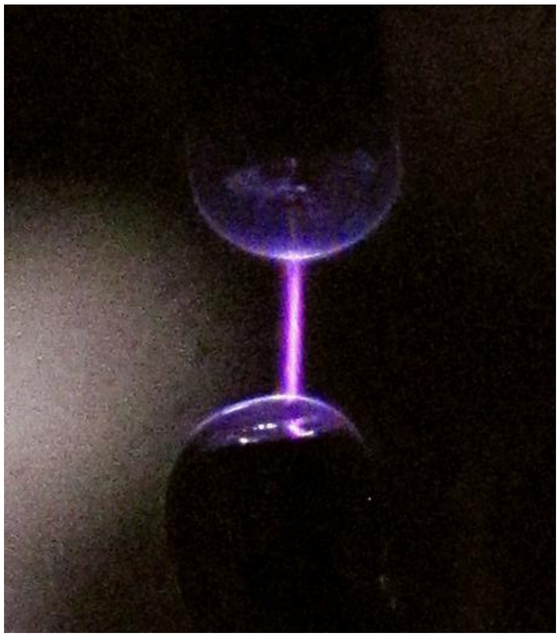
**V. Confinement and gas motion**

$Al_2O_3$



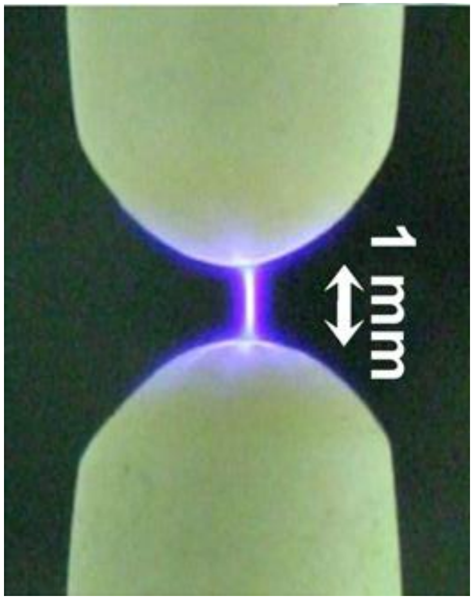
glass

# Role of the dielectric in filament ignition

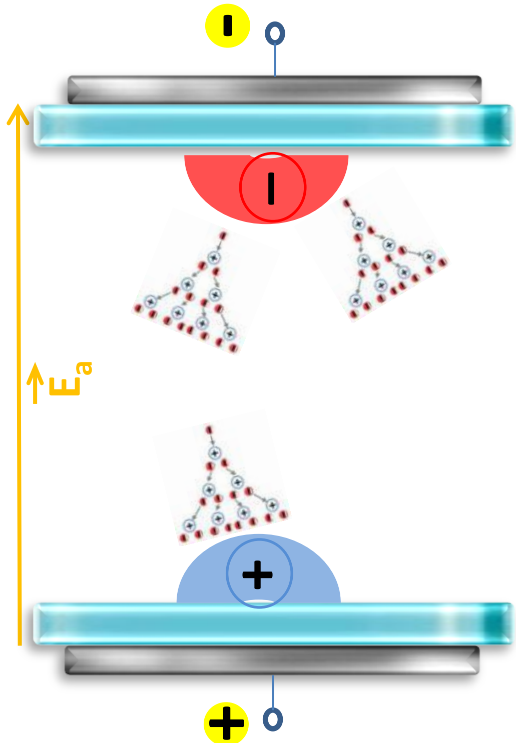


Why a filament in a DBD is never starting in the middle of the gap?

Why is it developing most of the time through a positive streamer?

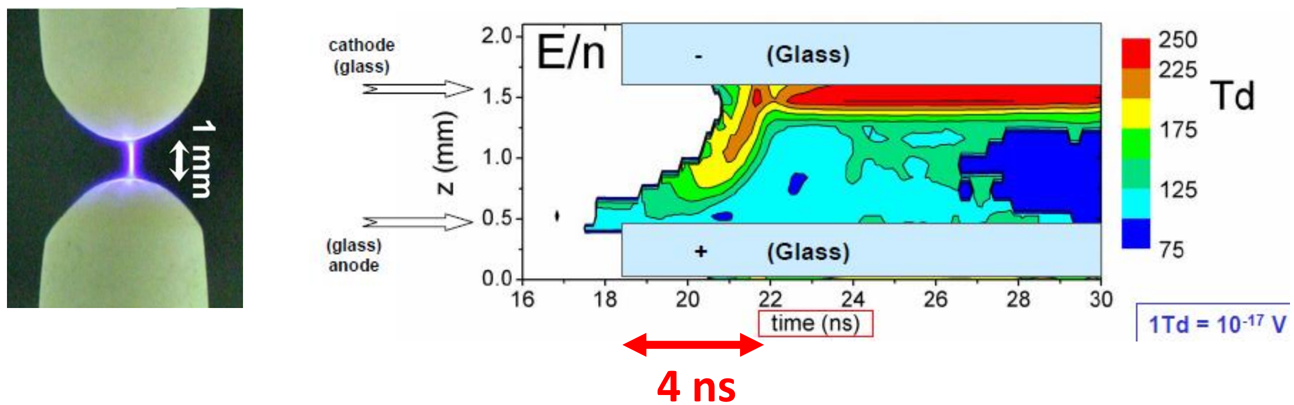


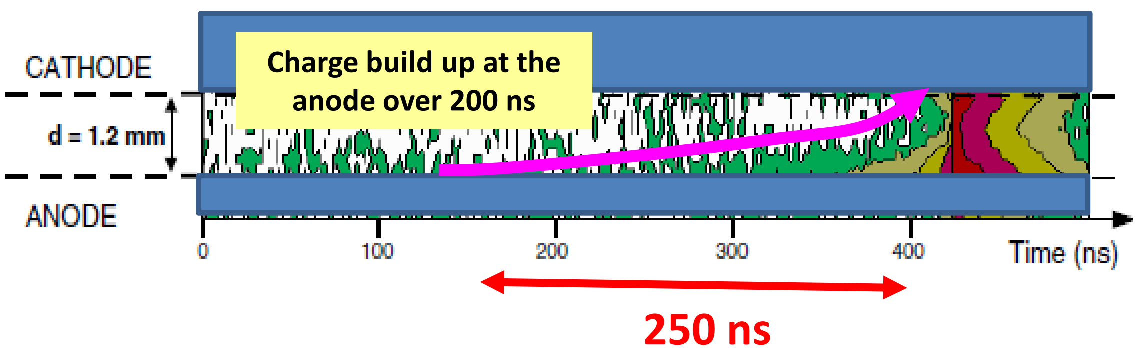
# Role of adsorbed charges in pre-breadown phase?




Microdischarges development measured by Cross-Correlation Spectroscopy

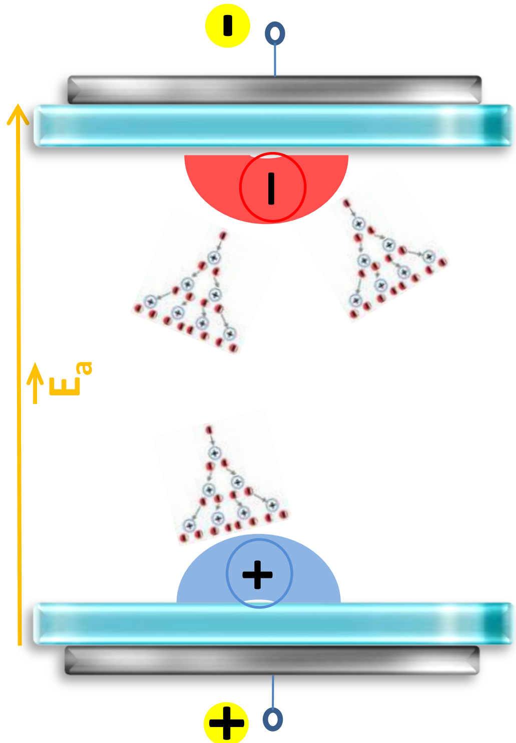
K.V. Kozlov et al. *J. Phys. D: Appl. Phys.*, **34** (2001)




**Charge build-up in front of the anode (>200 ns!) before streamer starts ("pre-breakdown" phase)**

# Role of adsorbed charges in pre-breadown phase?

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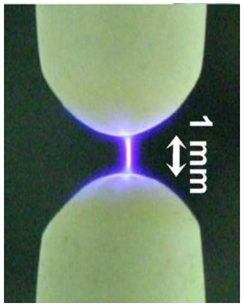
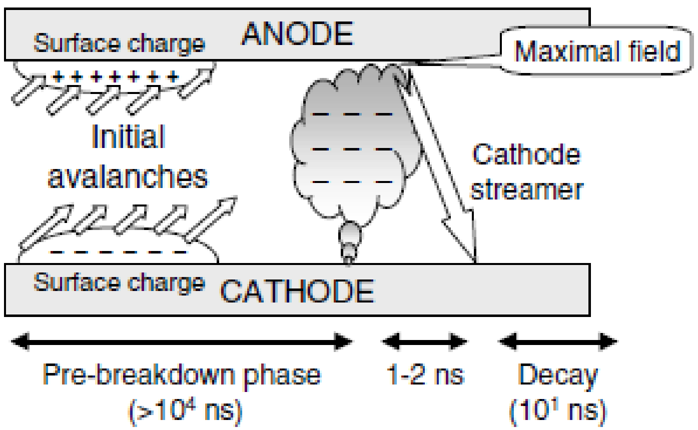
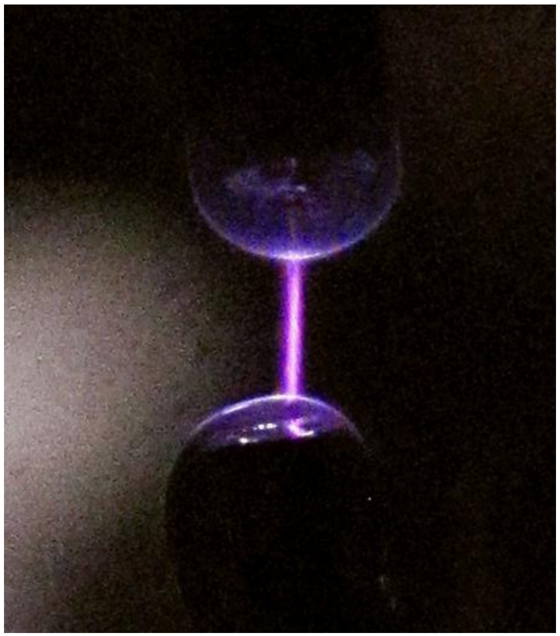


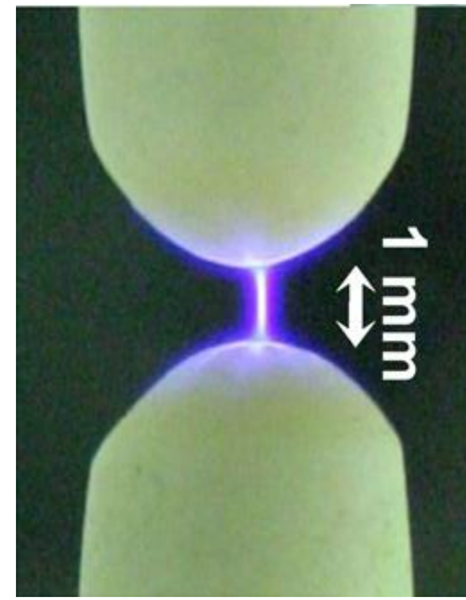




- **Charge build-up in front of the anode (>200 ns!) before streamer starts ("pre-breakdown" phase)**
- **Accumulation of many avalanches**
- **Avalanches become efficient only where the field if enhanced by the adsorbed charge**

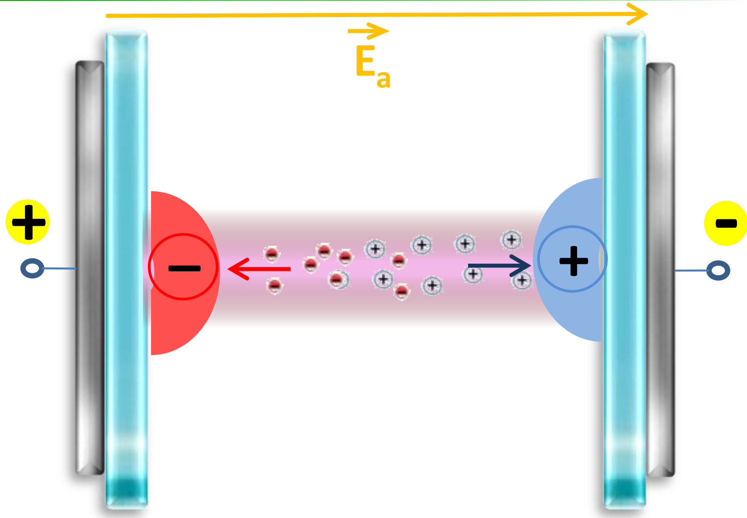
# Role of the dielectric in filament ignition



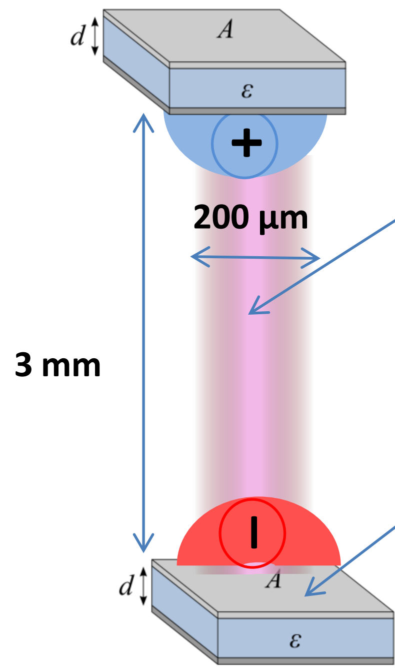
**How the dielectric is stopping the filament?**



# influence of the dielectric in filamentary DBDs




**What happens when the streamer reach the dielectric?**




$$U_{applied} \approx 10^4 V$$

$$n_e = 3 \cdot 10^{13} cm^{-3}$$

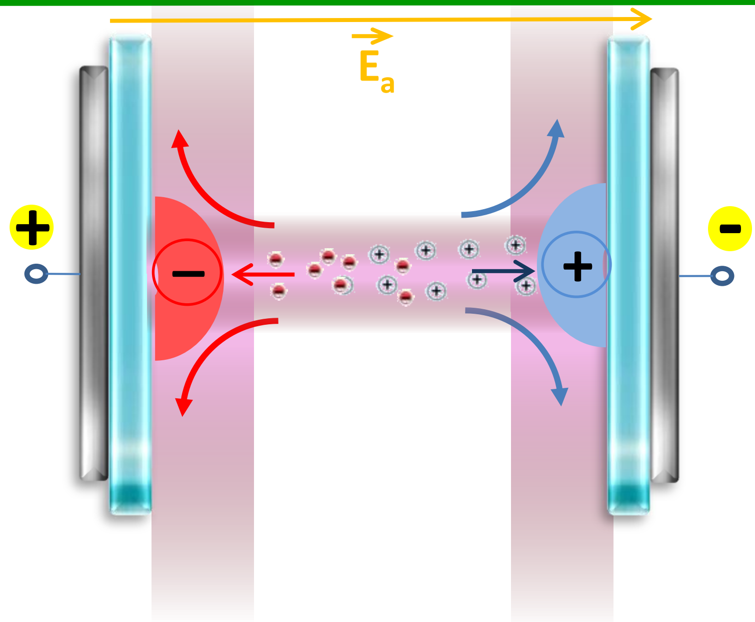
$$Q \approx 0.5 nC$$

$$C_d = \varepsilon_0 \varepsilon_r \frac{A}{d} \approx 10^{-3} pF$$

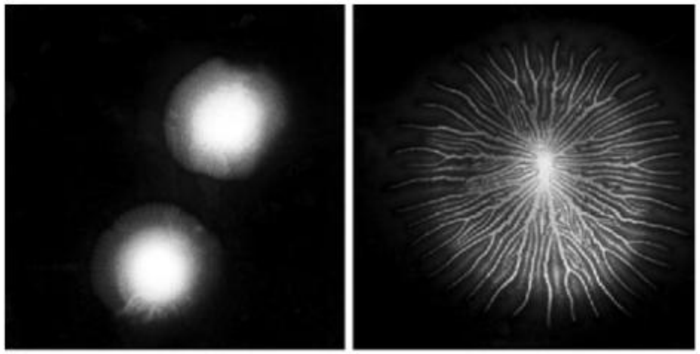
$$U = \frac{Q}{C} \approx 10^6 V!!!$$

**The filament must spread over the dielectric**

# influence of the dielectric in filamentary DBDs




lichtenberg figures: footprint of the filament on the dielectric

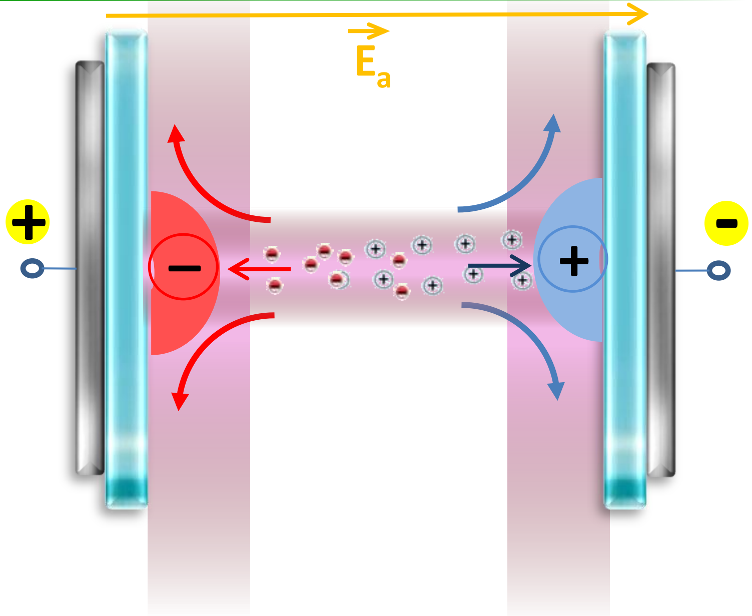


(a) (b)

**which picture is the + electrode?**

Gibalov et al, *Plasma Sources Sci. Technol.* **21** (2012) 024010

# influence of the dielectric in filamentary DBDs

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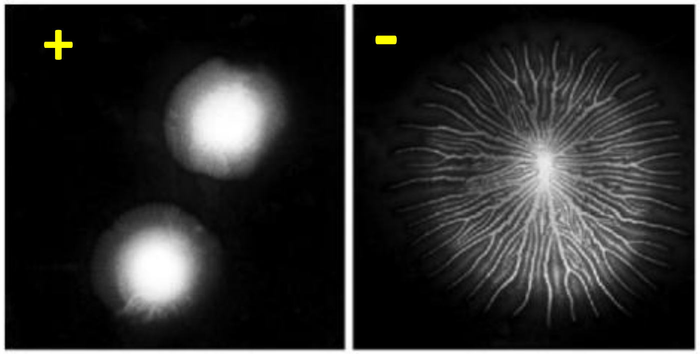


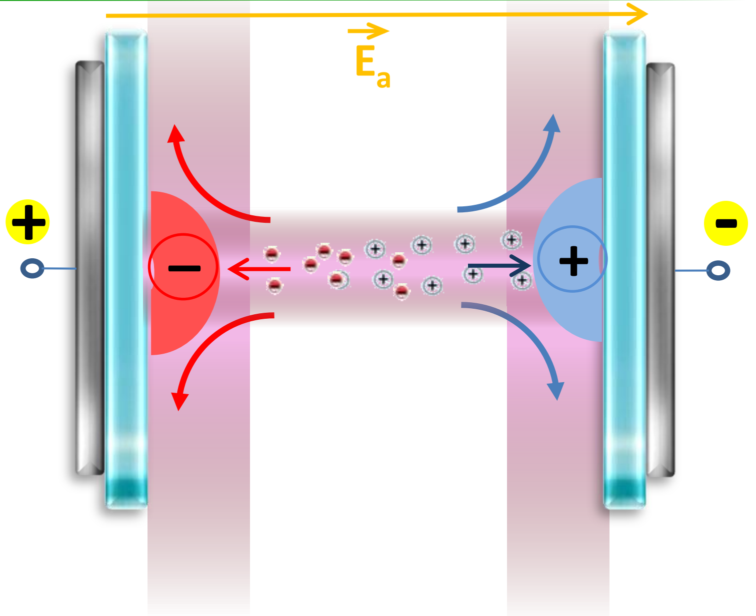

(a) (b)

**which picture is the + electrode?**

Gibalov et al, *Plasma Sources Sci. Technol.* **21** (2012) 024010

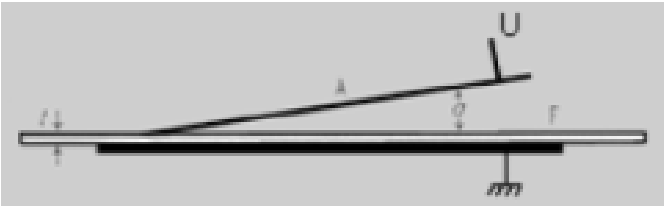
Electrons have a higher mobility

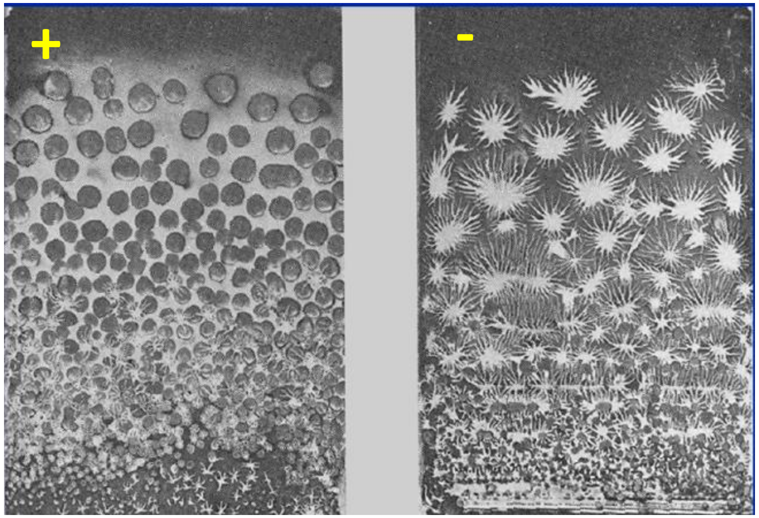
# DBD: streamer spreading over the dielectric




**What happens when the streamer reach the dielectric?**

H. Bertein, *J. Phys. D: Appl. Phys.* **6** (1973), 1910



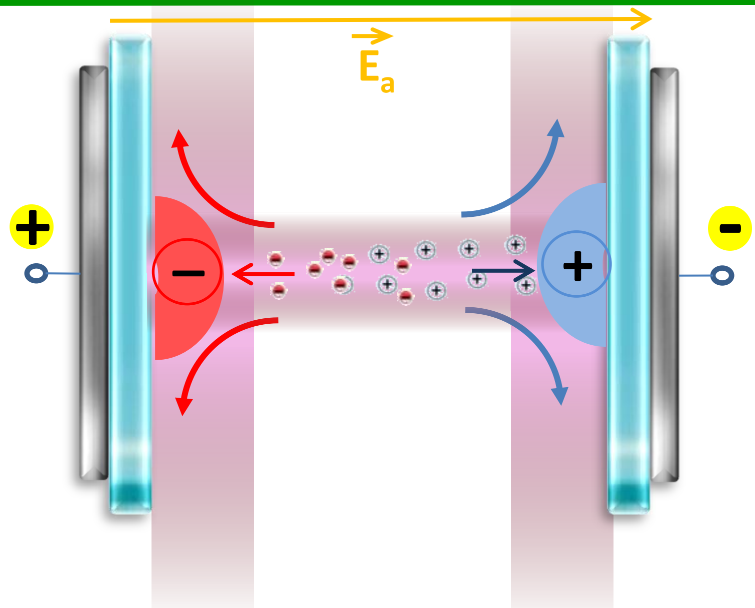




Electrography with red lead
and lycopodium powder

A longer filament carries more charge

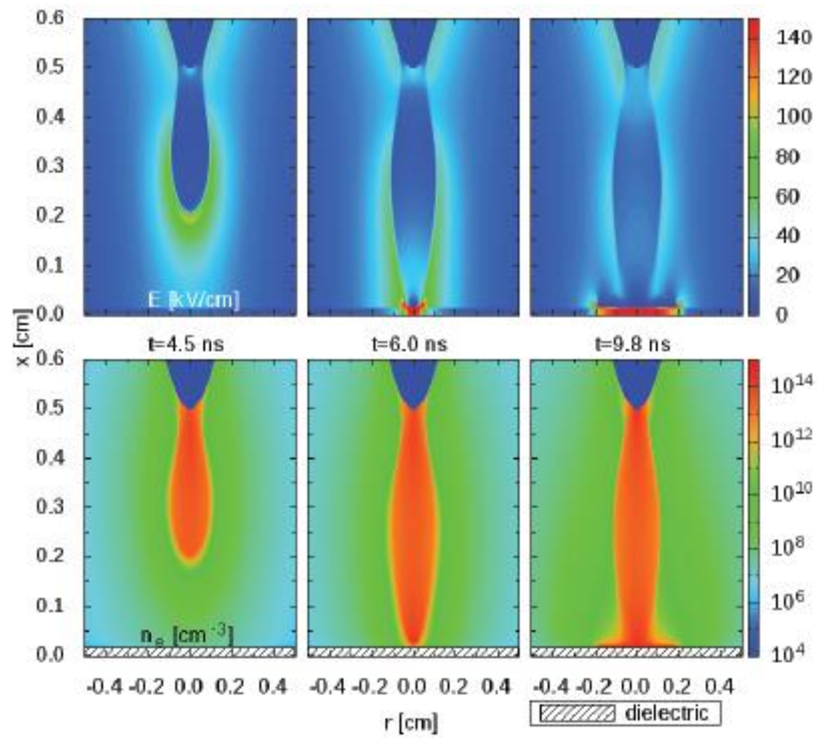
Larger spreading on the dielectric

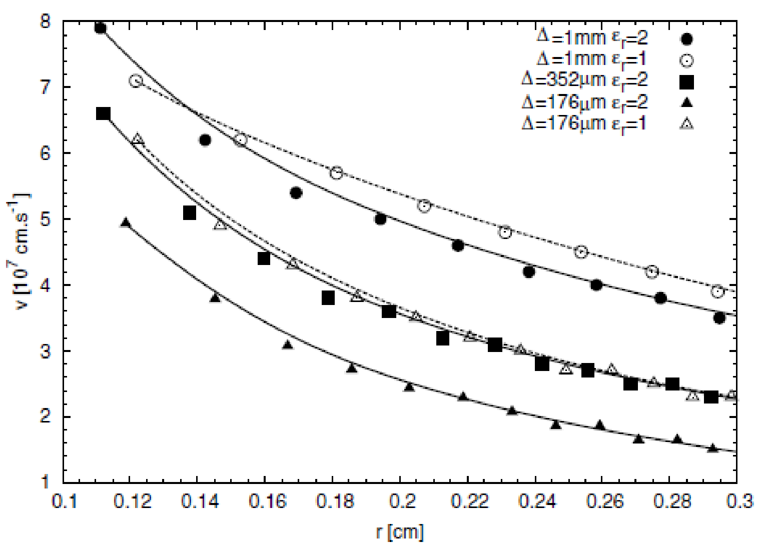
# DBD: streamer spreading over the dielectric




## What happens when the streamer reach the dielectric?

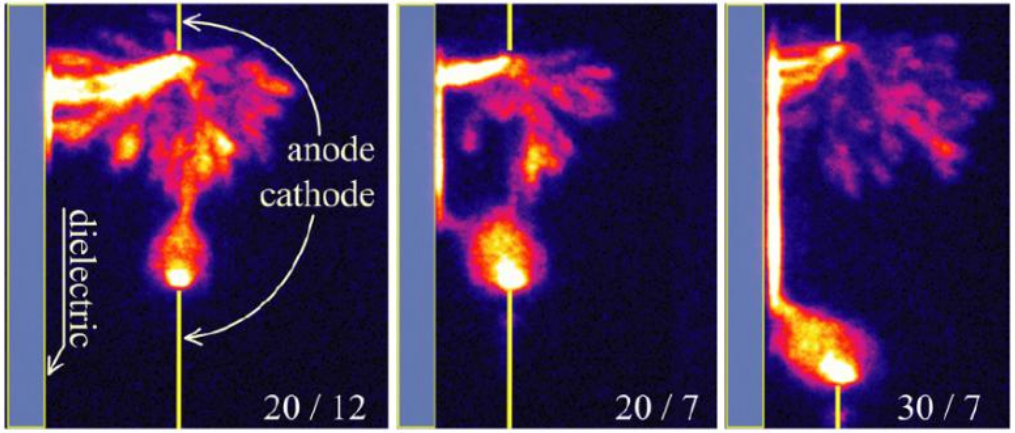
Pechereau et al, *Plasma Sources Sci. Technol.* **21** (2012) 055011

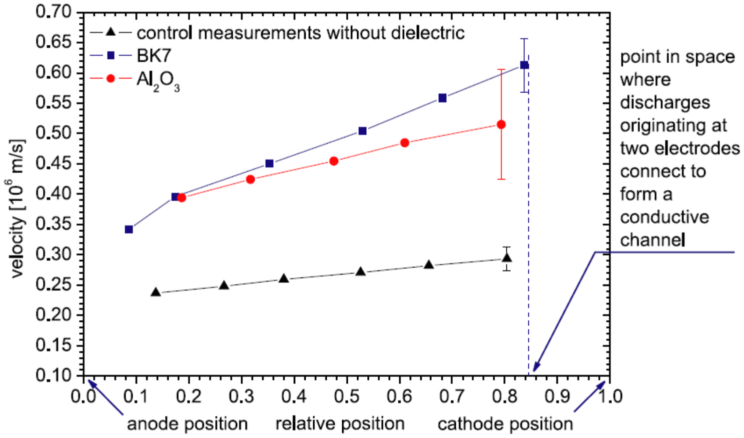



- ➢ The capacitance of the dielectric is driving the filament spreading
- ➢ higher capacitance, slower discharge

# speeding up over surface (lighting, flashover, actuator)



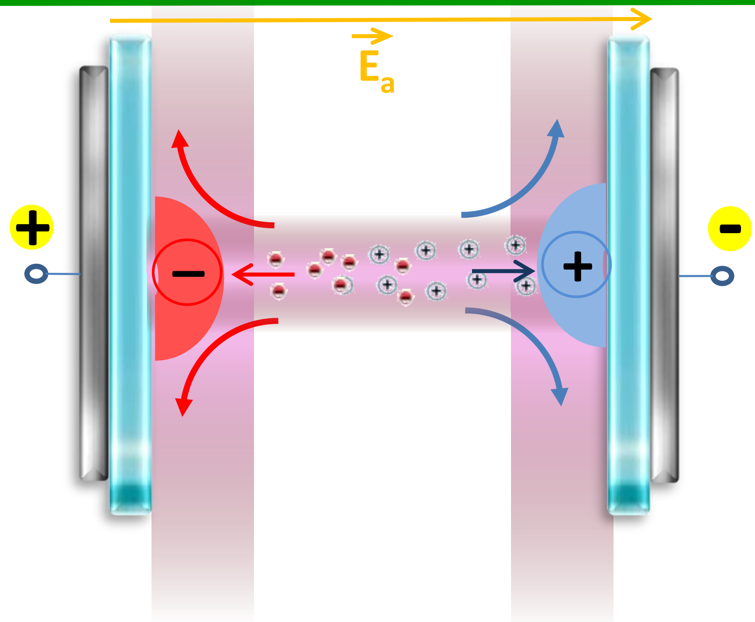




A Sobota et al, J. Phys. D: Appl. Phys. **42** (2009) 015211

Role of permittivity of the dielectric material is different depending on the direction of E field with respect to the surface:

- E perpendicular: Charging of the capacitance make the discharge slowing down
- E parallel: desorption of charges and reinforcement of local field
  Adsorbed negative ions are desorbed and give back electron by detachment

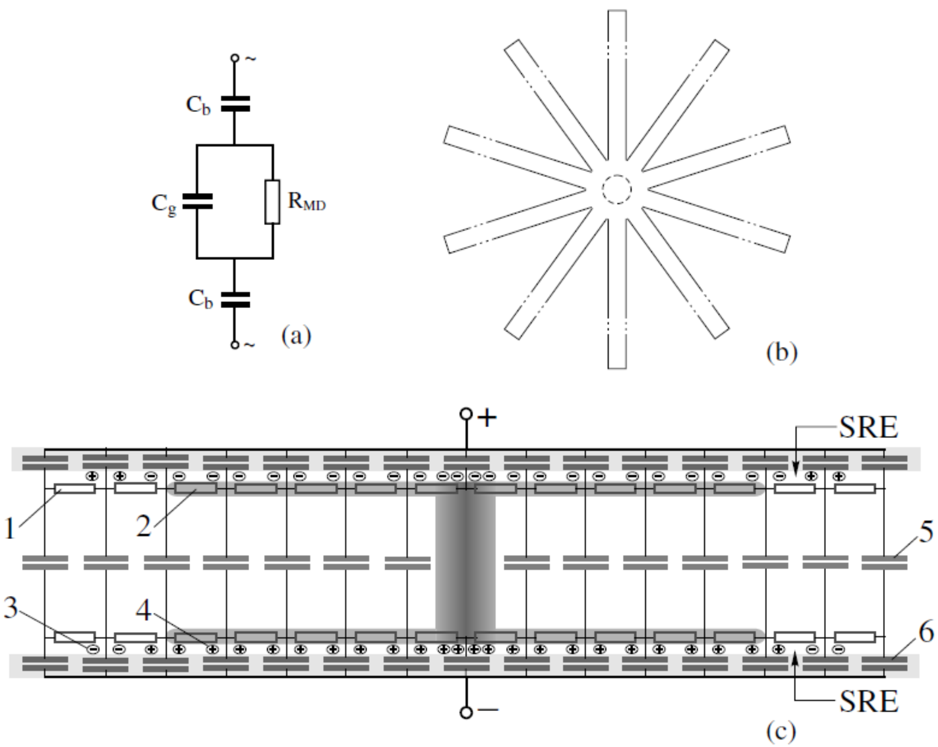
# DBD: streamer spreading over the dielectric




Streamer over a dielectric
= resistor and capacitances in series

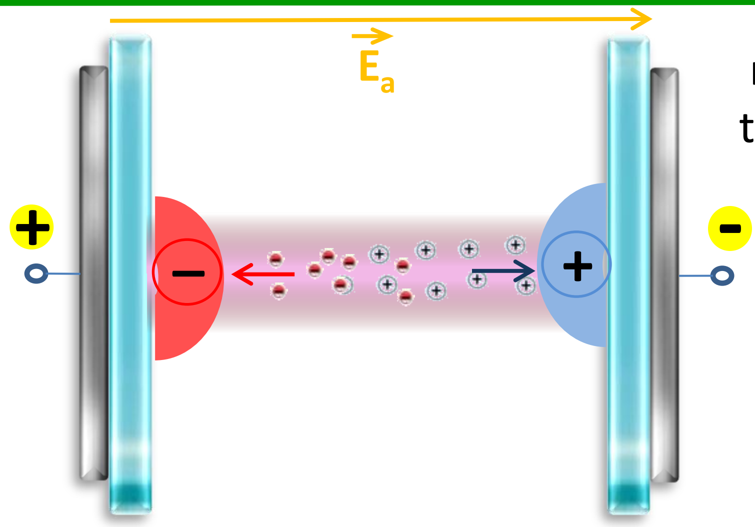
model for describing "n" filaments over the surface

Akishev et al, *Plasma Sources Sci. Technol.* **20** (2011) 024005



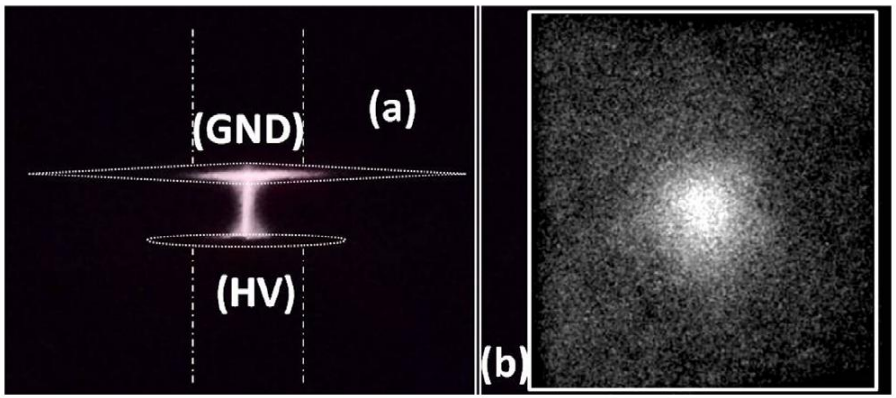

- **About 1/3 of energy dissipated by a streamer, is dissipated over the dielectric surface**
- A "volume" micro-discharge is also a "surface" one…

# How charge is "adsorbed" on the dielectric ?

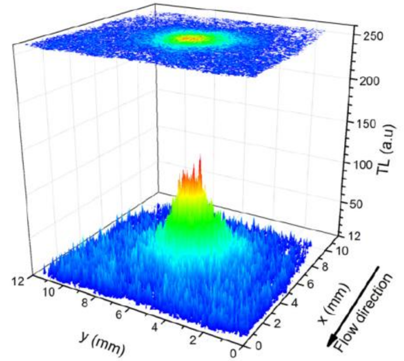



measurement of trapped electron on $Al_2O_3$ by thermoluminescence technic

Ambrico et al, *J. Phys. D: Appl. Phys.* **47** (2014) 305201




- Electrons trapped in lattice default of the material with energy about **1eV**
- negative ions physisorbed? Chemisorbed?
- In any case $\gamma$ is strongly enhanced by charges "adsorbed" on the dielectric



# About micro-discharges in DBD…

✓ Adsorbed charges → Stop the micro-discharges AND Initiate the micro-discharges

✓ “pre-breadown“ phase can be 0.1-1 µs !

✓ adsorbed charges are e- trapped, or negative ions ?

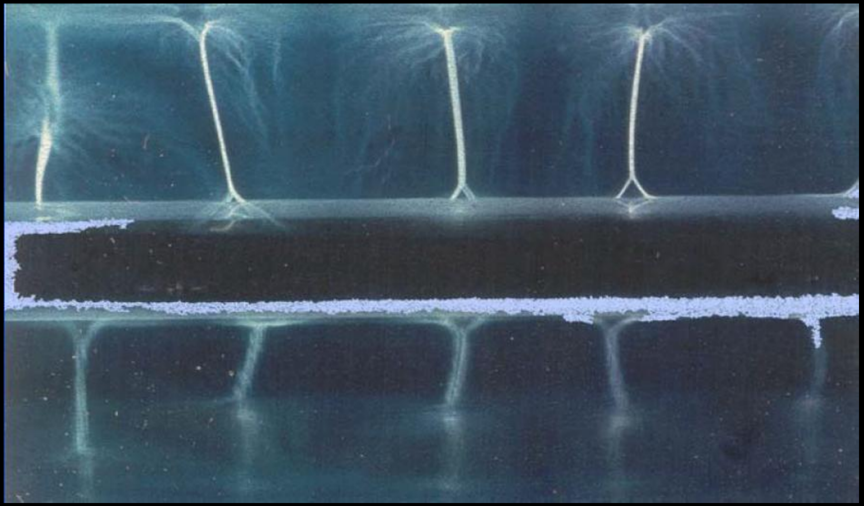
✓ charges adsorbtion energy is weak (~ 1 eV)

# Outline

**I. Breakdown mechanisms**
- a) Townsend mechanism
- b) Streamer mechanism

**II. Corona discharges**

**III. What is a Dielectric Barrier Discharge?**
- a) Electrical characteristics
- b) Development of a single filament
- c) Role of the dielectric ?



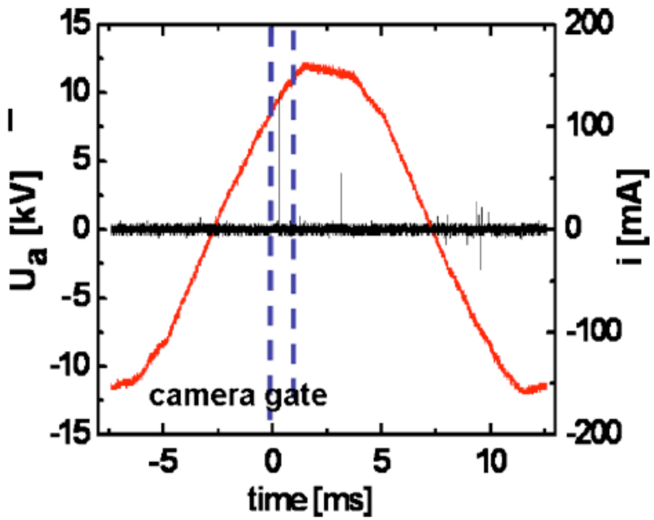
**IV. Role of surface vs gas phase dynamics**
- a) Interaction between filaments
- b) Diffuse discharges

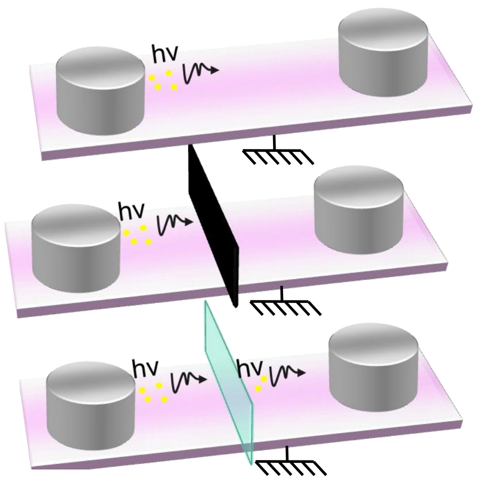
**V. Confinement and gas motion**

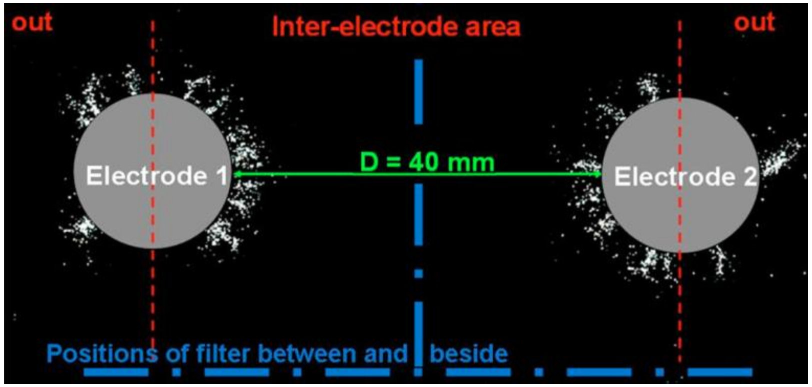
# Self-synchronization: photo-desorption of charge

## self-synchronization of filaments within 20 ns

Guaitella et al, *Appl. Phys. Lett.* **98** (2011) 071502



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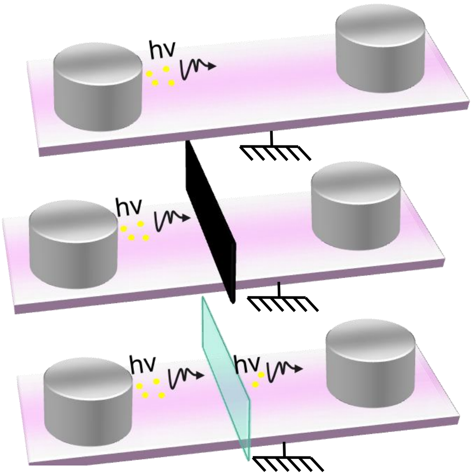
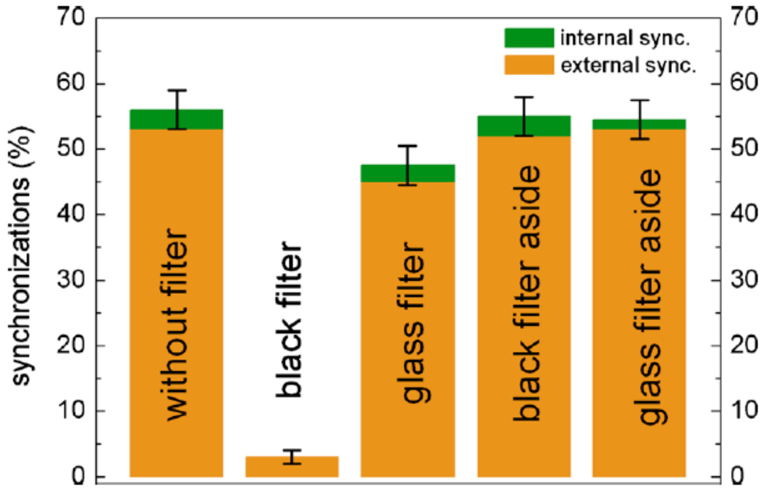
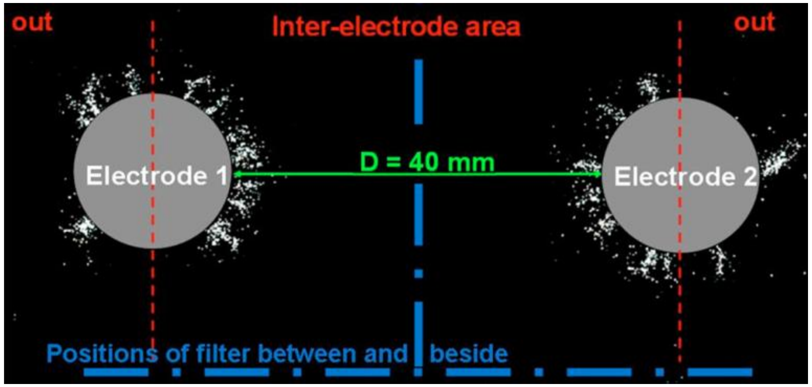
**self-synchronization of filaments within 20 ns**

Guaitella et al, *Appl. Phys. Lett.* **98** (2011) 071502



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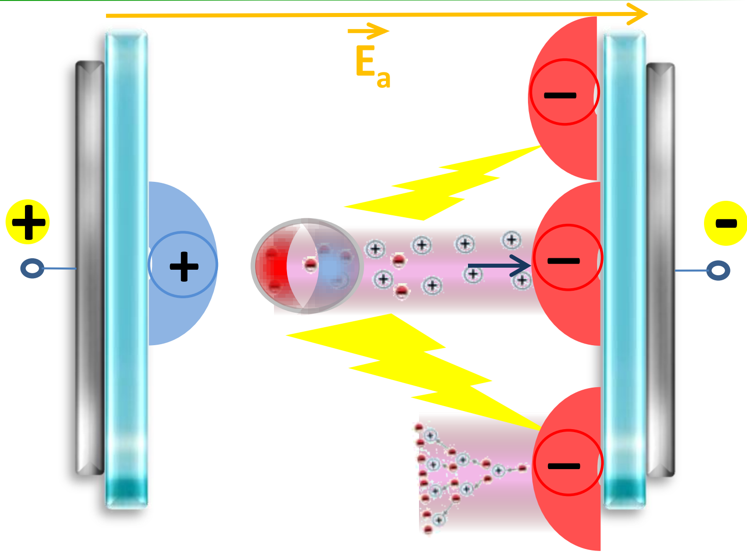


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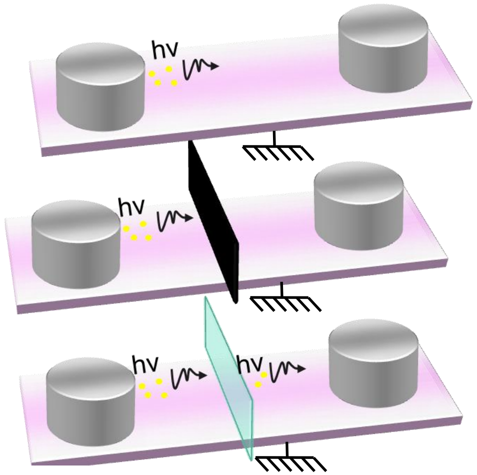
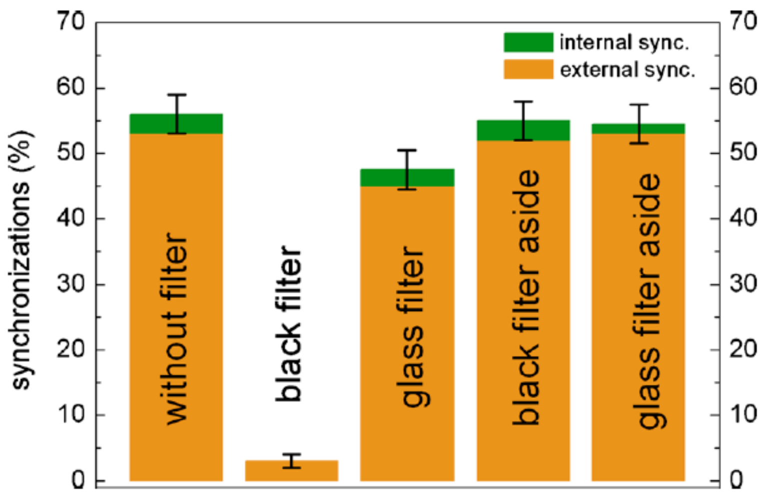
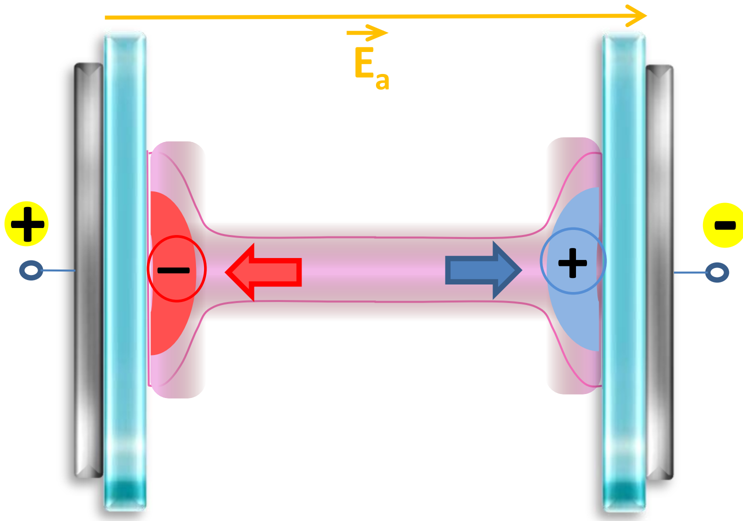


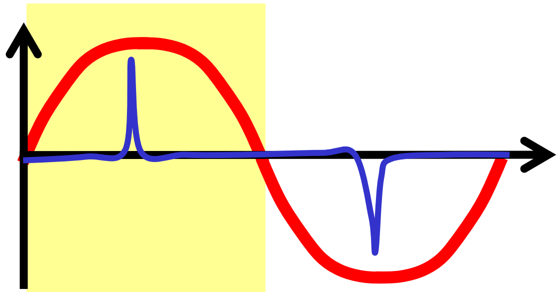




- light emitted by a first filament can trigger its neighbors during their pre-breadown phase

see also desorption of charges under UV exposure (Joshi effect): Falkenstein, *J. Appl. Phys.* **81 (1997)** 11

# Self organization: field shielding

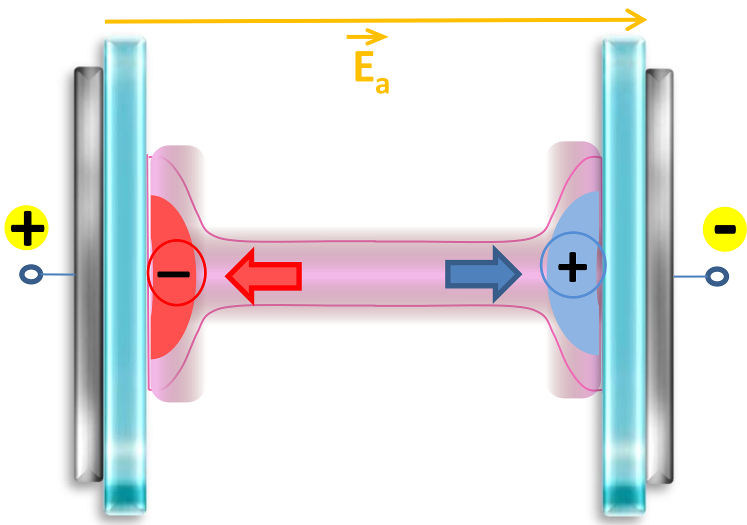


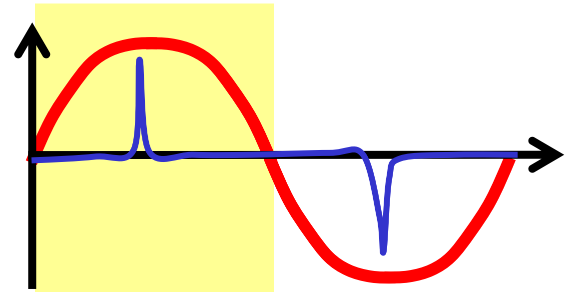



J. Guikema et al., Phys. Rev. Lett. **85 (2000) 3817**

Low voltage

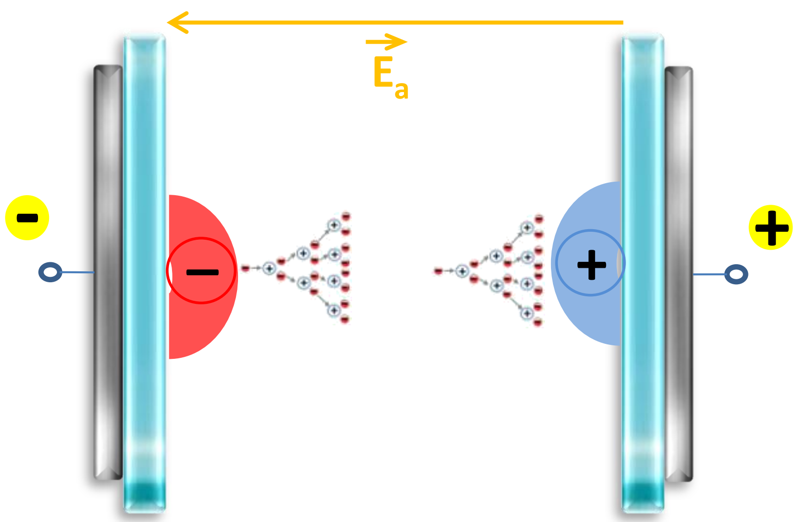
# Self organization: field shielding



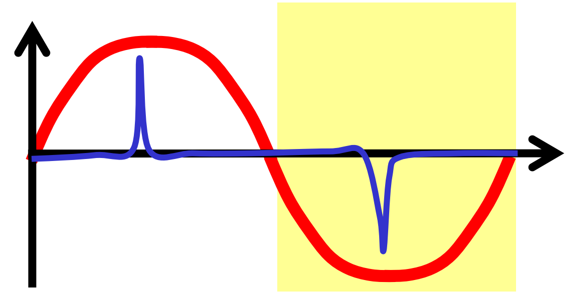



J. Guikema et al., Phys. Rev. Lett. **85 (2000) 3817**

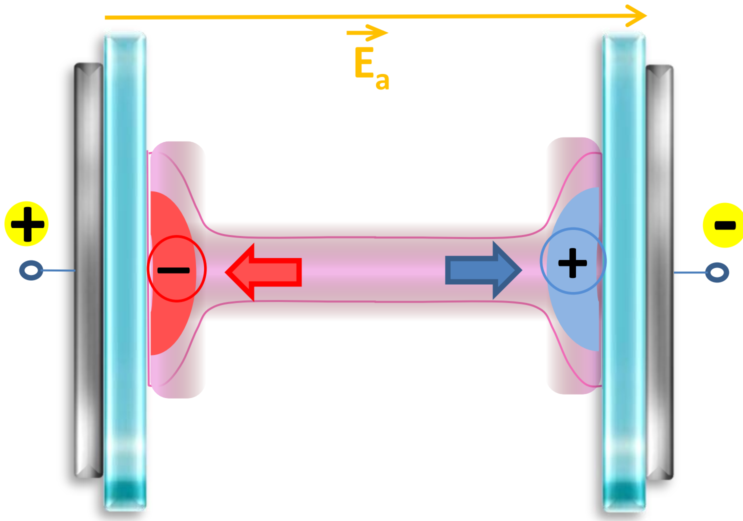
Low voltage

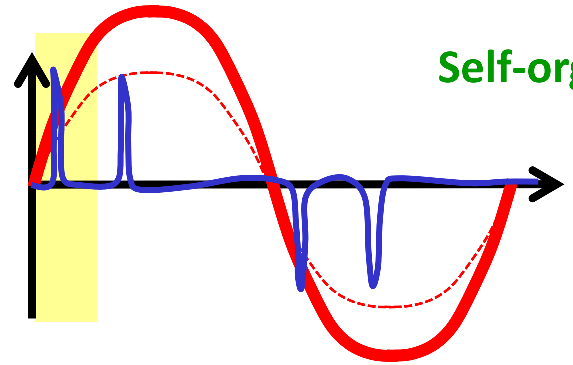




- **Adsorbed charge fix the position of the filaments**
- **Distance between filaments depends on spreading**



# Self organization: field shielding



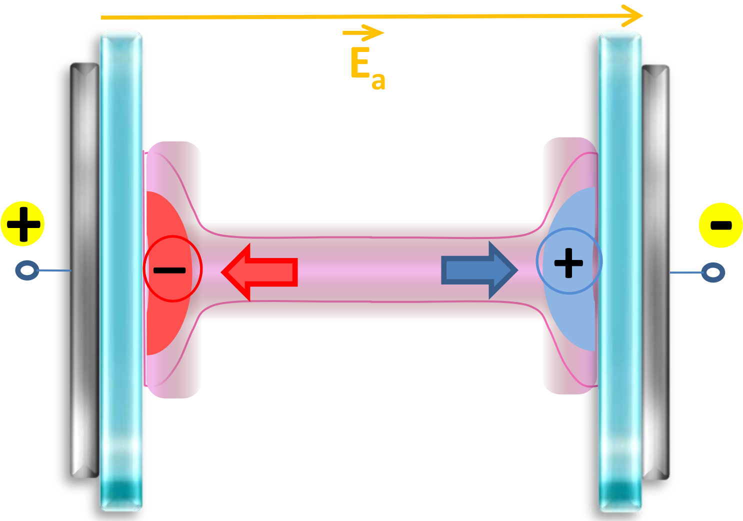



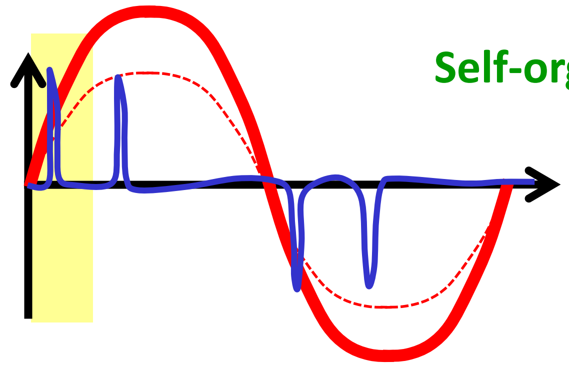
Self-organization in 1D

J. Guikema et al., Phys. Rev. Lett. **85 (2000) 3817**

higher voltage

# Self organization: field shielding



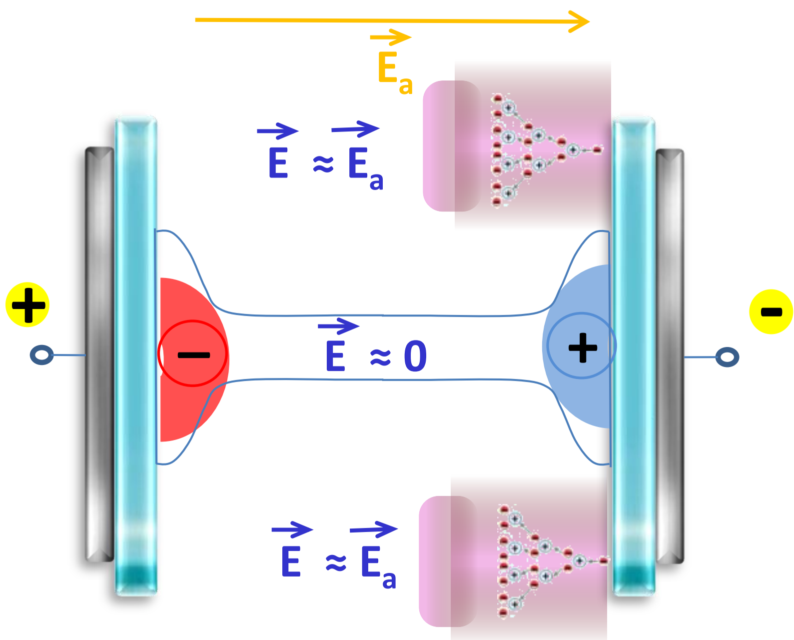



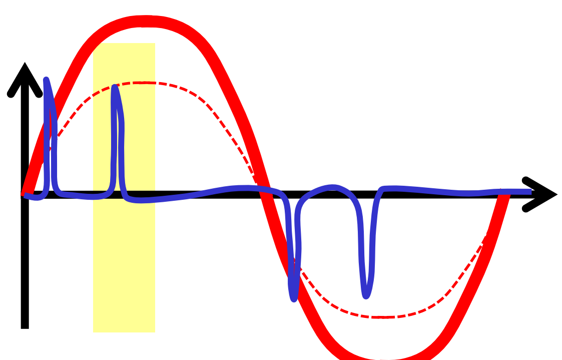
**Self-organization in 1D**

J. Guikema et al., Phys. Rev. Lett. **85 (2000) 3817**

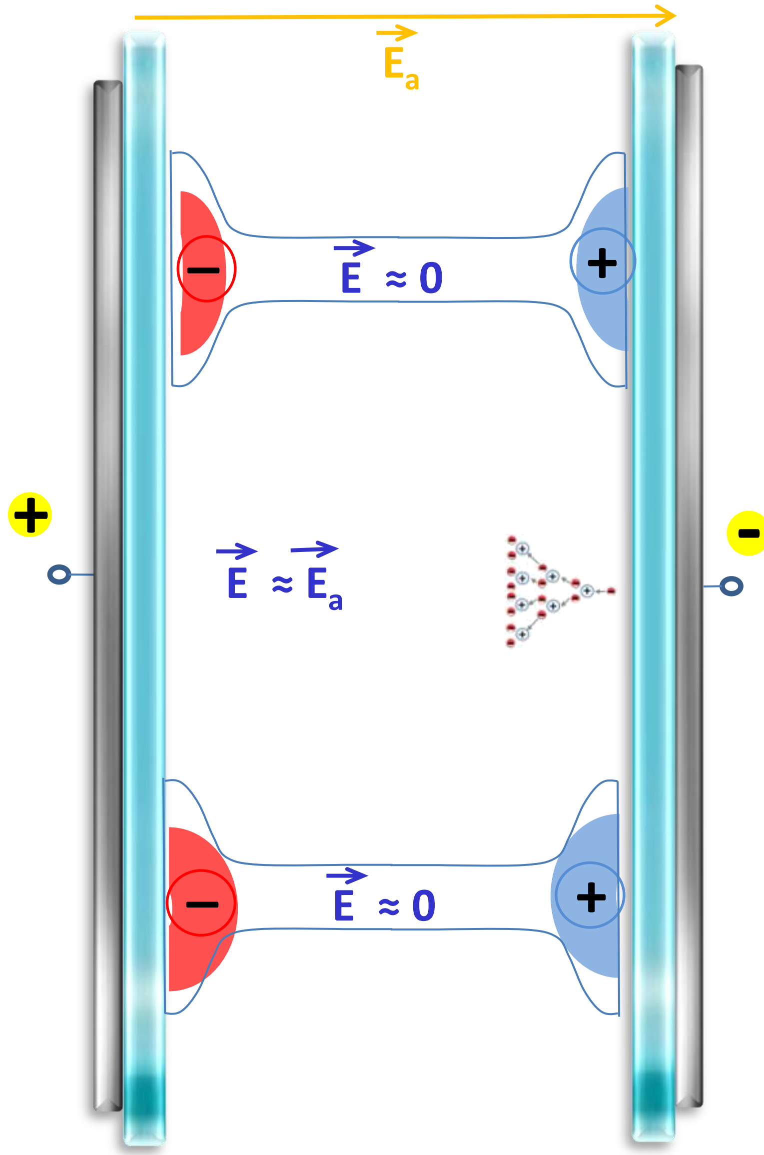
**higher voltage**


**2nd filaments ignite where the field is not shielded**

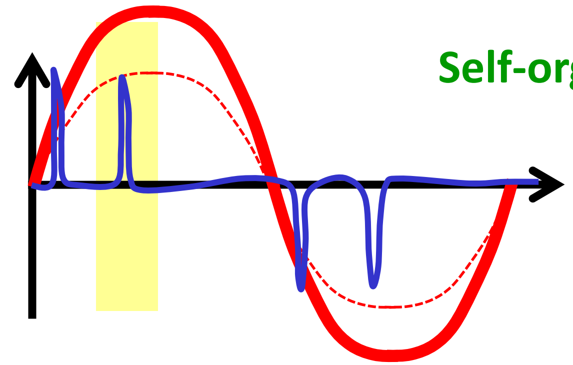


# Self organization: gas phase contribution



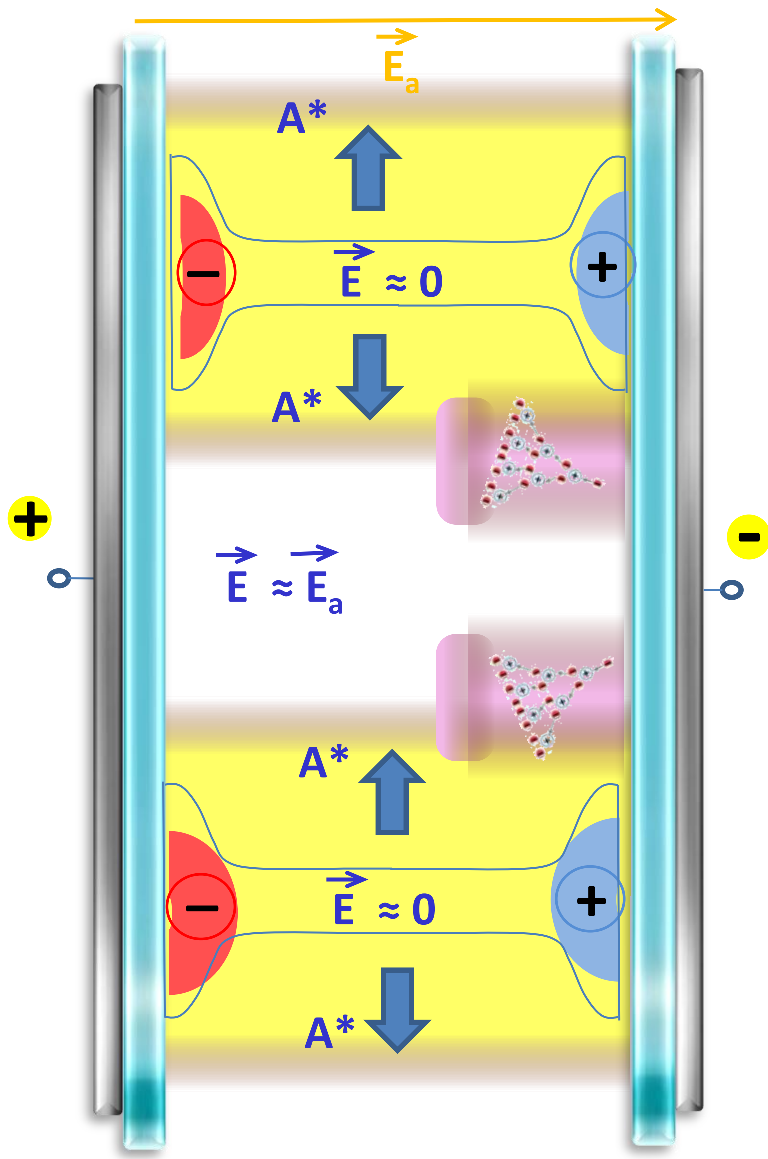

**Self-organization in 1D**

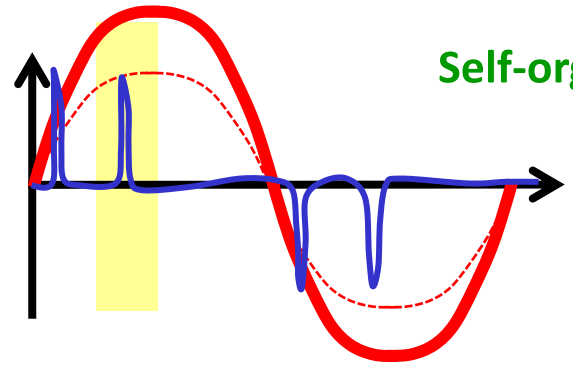


J. Guikema et al., Phys. Rev. Lett. **85 (2000) 3817**

**2nd filament unstable**

# Self organization: gas phase contribution



**Self-organization in 1D**

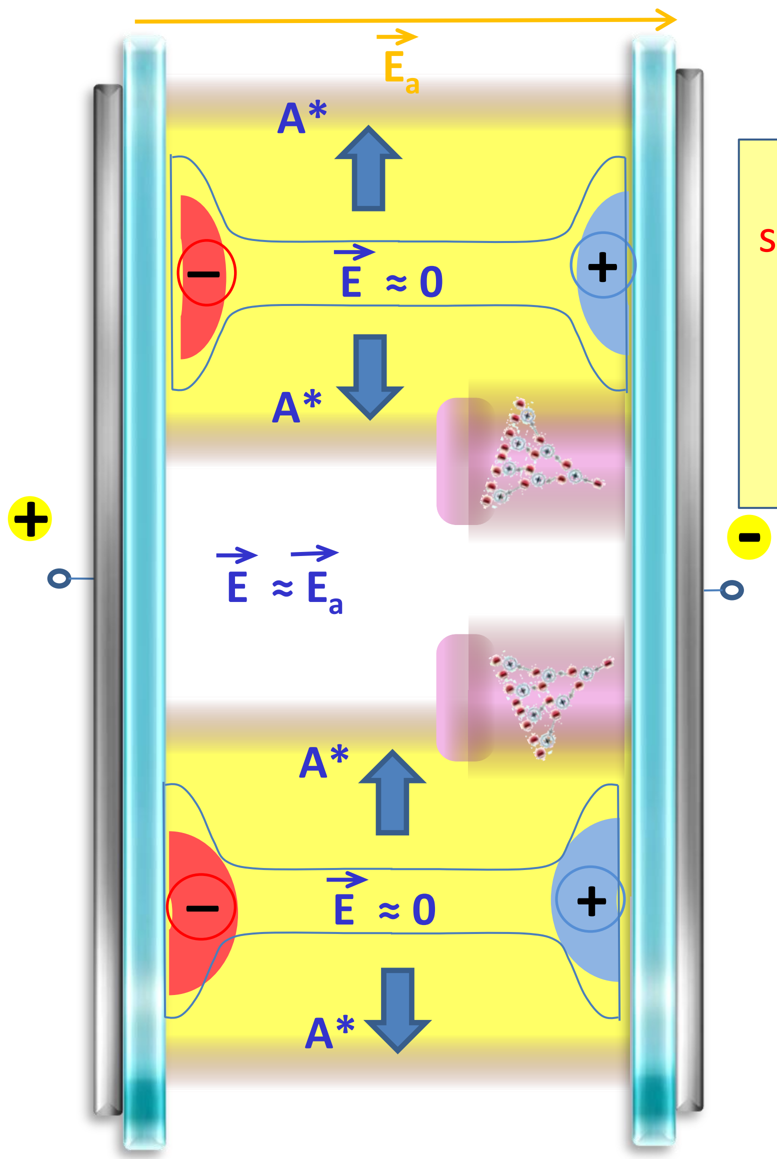
J. Guikema et al., Phys. Rev. Lett. **85 (2000) 3817**

2nd filament unstable


**Instability of 2nd filament: gas phase vs surface**

**Field is higher between the 1st filaments**
**But**
**Gas is "pre-excited" close to 1st filaments**

# Adsorbed charge vs "pre-excited" channel




Behavior of a DBD is driven by this question:

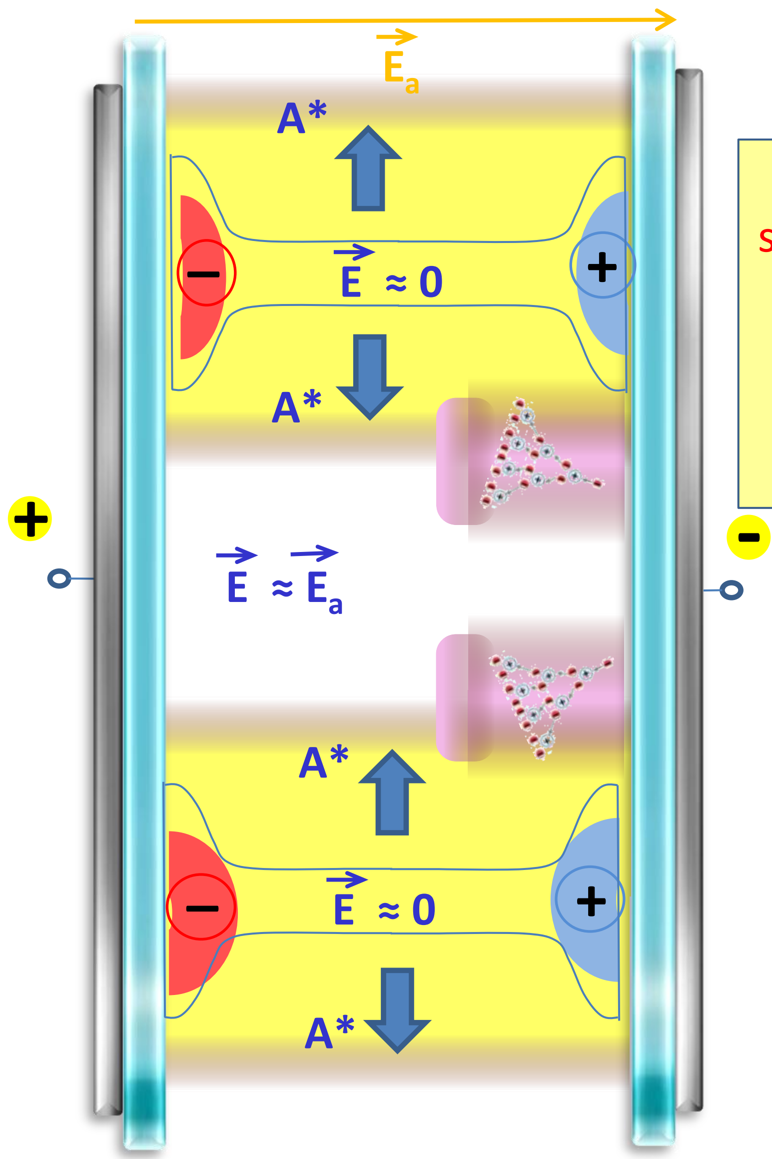
**Where will occurs the most efficient avalanches?**

surface charges distribution → **shield the field during the same half-period** / **Provide first e- when polarity is reversed**

Vs

diffusion of excited species in the gas phase

# Adsorbed charge vs "pre-excited" channel




Behavior of a DBD is driven by this question:

**Where will occurs the most efficient avalanches?**

surface charges distribution → **shield the field during the same half-period** / **Provide first e- when polarity is reversed**

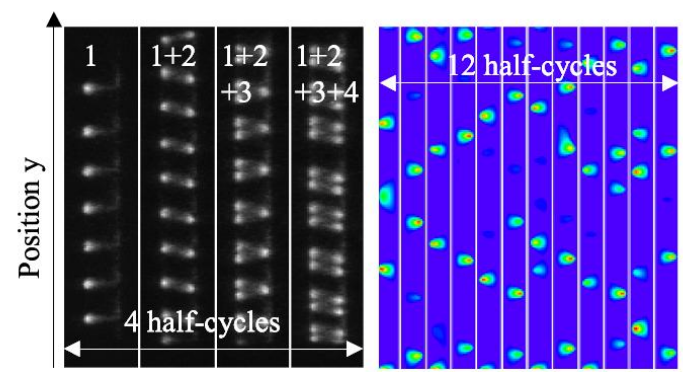
Vs

diffusion of excited species in the gas phase

Equations for describing such system: **activator-inhibitor** equations

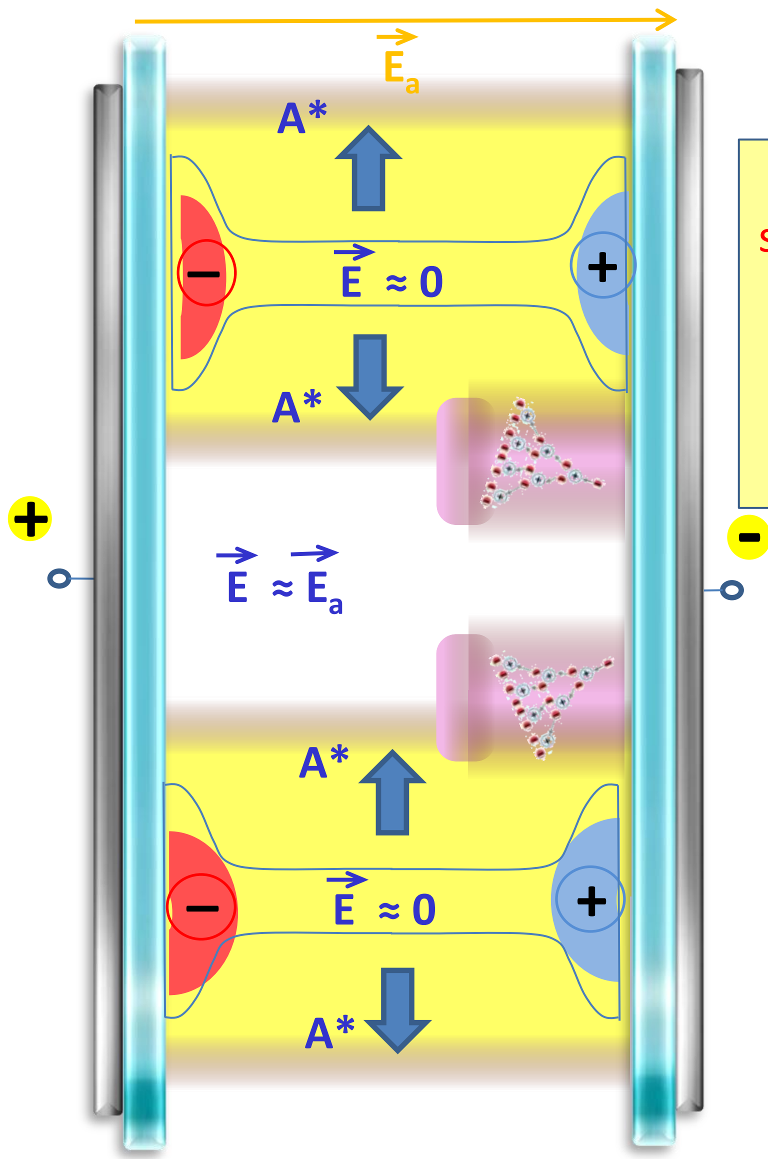
$$\frac{da}{dt} = \frac{pa^2}{h} - \mu a + D_a \frac{d^2 a}{dx^2}$$

$$\frac{dh}{dt} = p' a^2 - \nu h + D_h \frac{d^2 h}{dx^2}$$




Bœuf et al, *Appl. Phys. Lett.* **100** (2012) 244108

# Adsorbed charge vs "pre-excited" channel




Behavior of a DBD is driven by this question:

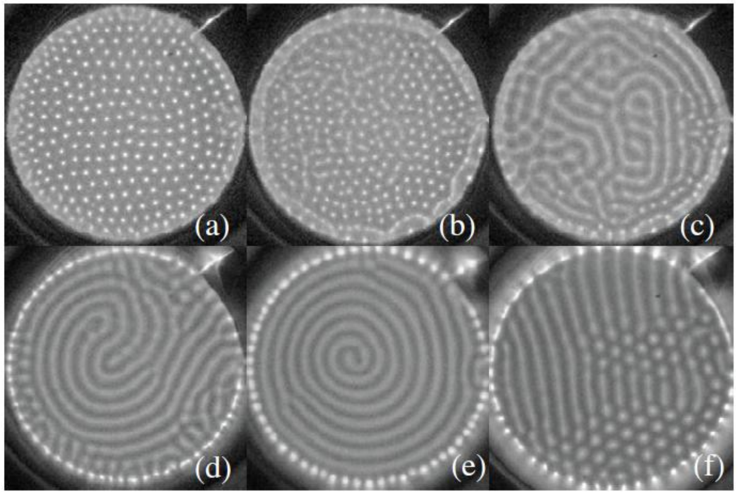
**Where will occurs the most efficient avalanches?**

surface charges distribution → **shield the field during the same half-period** / **Provide first e- when polarity is reversed**

Vs

diffusion of excited species in the gas phase

Dong et al, *New Journal of Physics* **9** (2007) 330



# About filaments interactions

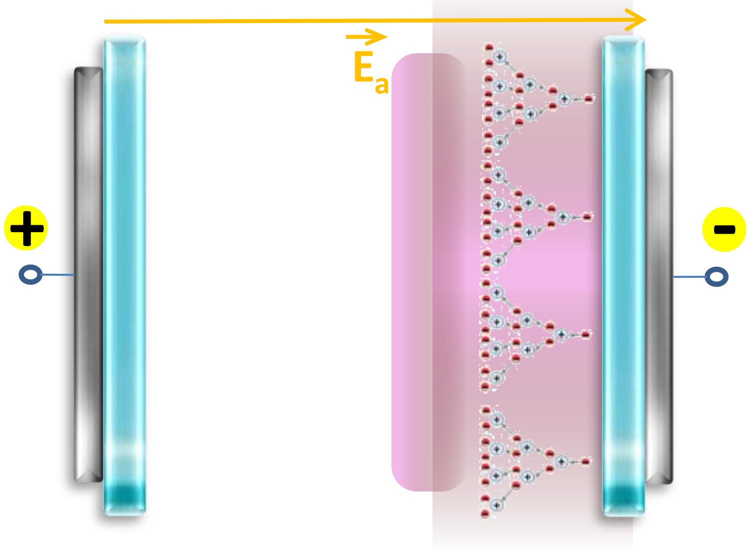
✓ Filaments can be self-synchronized and/or spatially organized

✓ Filaments can interact through:

- field of the streamer itself
- emitted light
- field shielding
- excited species diffusion

**How the surface and gas phase contribution can lead to diffuse discharge?**

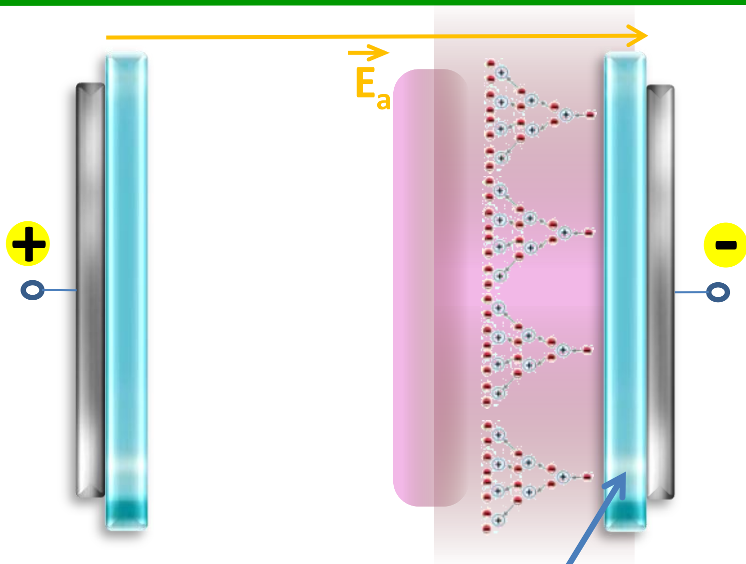
# diffuse discharge: electron emission from the surface

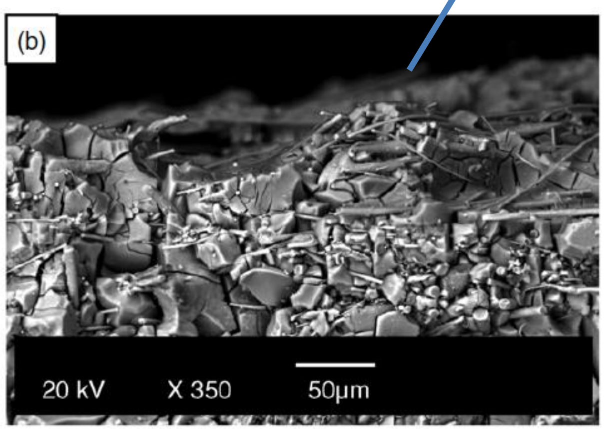



**How to get a diffuse discharge at atmospheric pressure ?**

**1) e- emission from the surface over a large area**

# diffuse discharge: electron emission from the surface




## How to get a diffuse discharge at atmospheric pressure ?

**1) e- emission from the surface over a large area**

a) Increasing $\gamma_{eff}$

Okazaki et al, J. Phys. D Appl. Phys. **26** (1993)

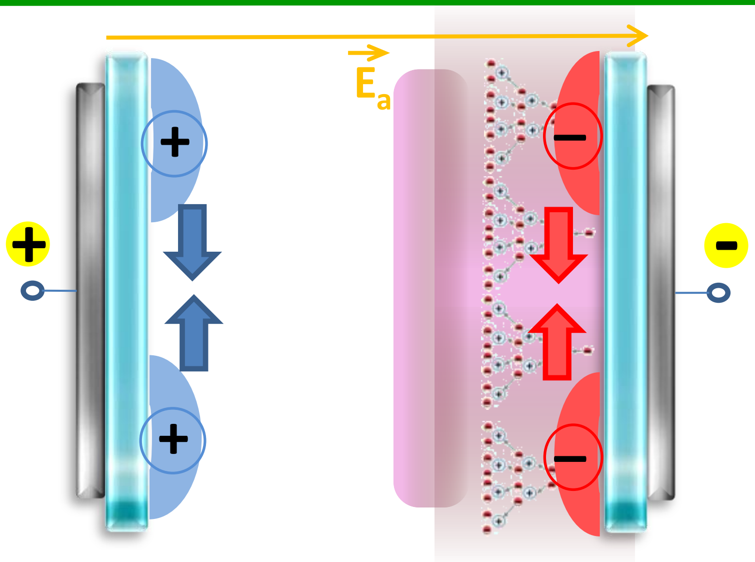
Adsorbed aceton release $e^-$ in Ar discharge

Garamoon et al, Plasma Sources Sci. Technol. **18** (2009) 045006

High $\gamma$ material: $Al_2O_3$, MgO

Warning: it is an effective $\gamma$ that include desorption of electron…

# diffuse discharge: electron emission from the surface



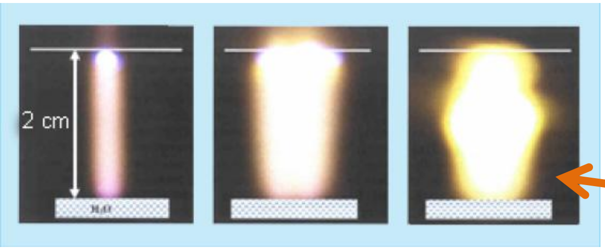

## How to get a diffuse discharge at atmospheric pressure ?

**1) e- emission from the surface over a large area**

a) Increasing $\gamma$
b) lower surface resistivity

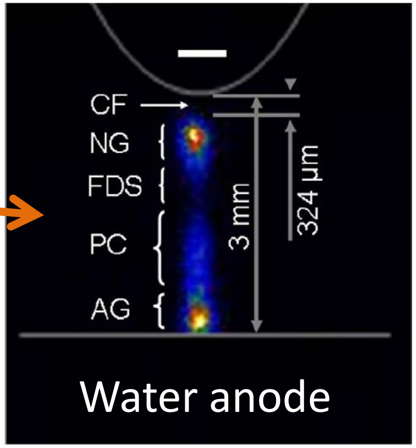
- Use of semi-conductor as "barrier"

- similar idea with discharges above water surface

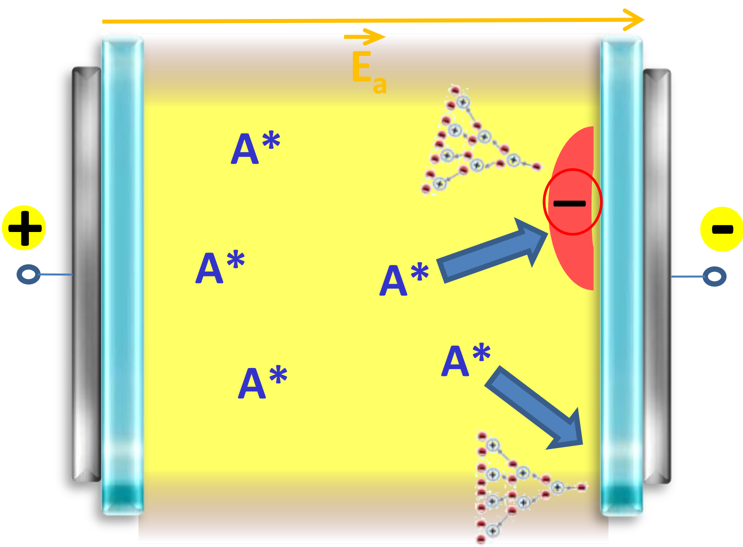



Bruggeman et al, *J. Phys. D: Appl. Phys.* **41** (2008) 215201

M. Laroussi et. al., 2002 Int. Power Modulator Conf



# diffuse discharge: electron emission from the surface



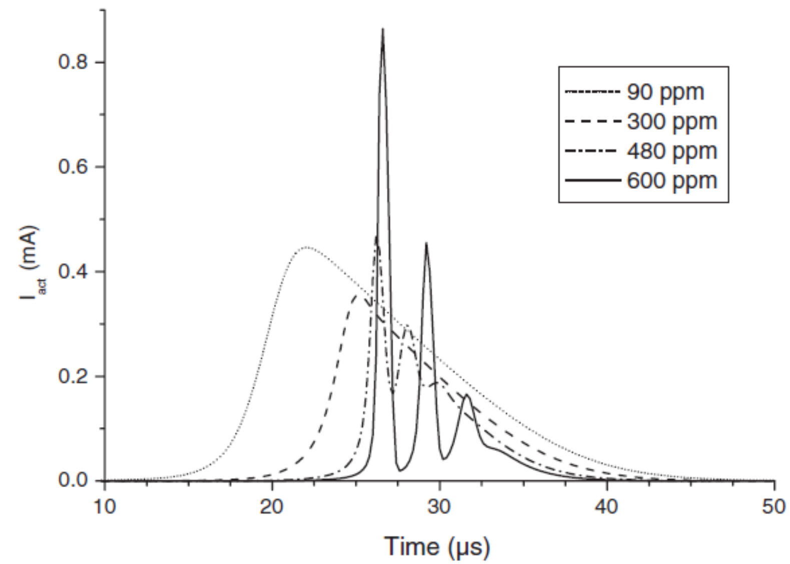

## How to get a diffuse discharge at atmospheric pressure ?

**1) e- emission from the surface over a large area**

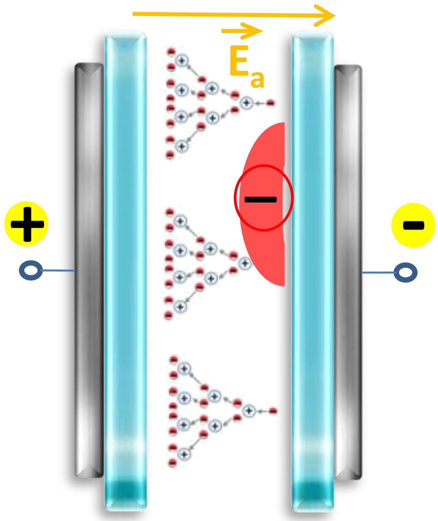
a) Increasing $\gamma$
b) lower surface resistivity
c) High flux of energetic particles to enhance $\gamma_{eff}$ (ions, metastables…)

Brandenburg et al, *J. Phys. D: Appl. Phys.* **38** (2005) 2187–2197

ex: **Diffuse Townsend $N_2$ discharge**:
secondary electron emission from metastable $N_2(A\ ^3\Sigma_u)$ impact
Admixture of $O_2$ quenches $N_2(A\ ^3\Sigma_u)$ (+ attachment)



# diffuse discharge: gas phase conditions

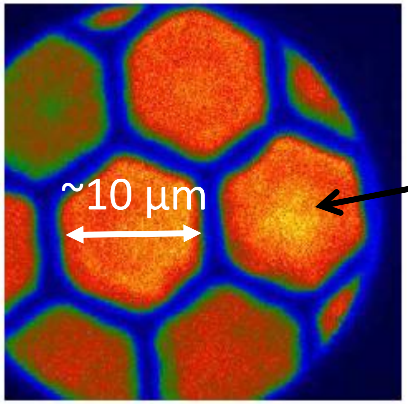



## How to get a diffuse discharge at atmospheric pressure ?

1) e- emission from the surface over a large area

2) gas phase homogenisation

   a) Very short gap

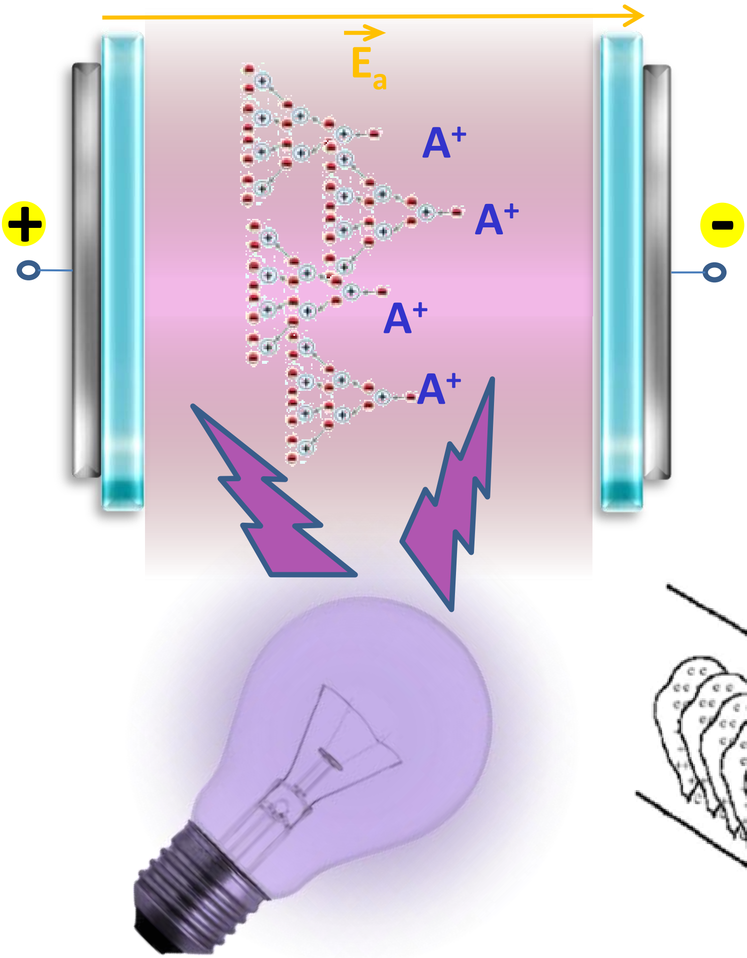



Qiu et al, IEEE Trans. Diel. Elec. Ins. **18** (2011) 1

Townsend discharge in air inside polymer voids

Important topic for plasma/catalyst coupling and insulator damaging

# diffuse discharge: gas phase conditions

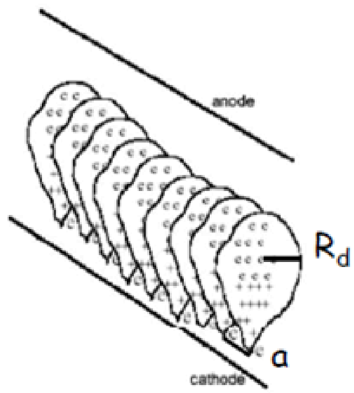



## How to get a diffuse discharge at atmospheric pressure ?

1) **e- emission from the surface over a large area**

2) **gas phase homogenisation**

   a) Very short gap
   b) Pre-ionize the gas



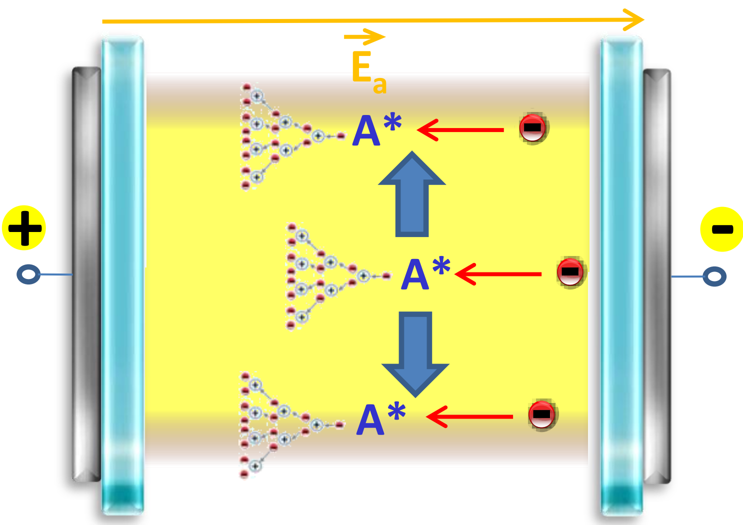

Numerous simultaneous avalanches

Require pre-ionization with $n_{e0} \approx \cdot 10^{6} cm^{-3}$

Palmer et al, J. *Appl. Phys. Lett.* **25** (1974) 3-138

Example: photo-triggered discharge

# diffuse discharge: gas phase conditions




## How to get a diffuse discharge at atmospheric pressure ?

1) **e- emission from the surface over a large area**

2) **gas phase homogenisation**
   a) Very short gap
   b) Pre-ionize the gas
   c) Multi-steps ionization
   d) diffusion of excited species

Ionization of excited species having life time long enough to diffuse "self-pre-excitation" of the gas

$$1) \quad e^- + A \rightarrow A^* + e^-$$

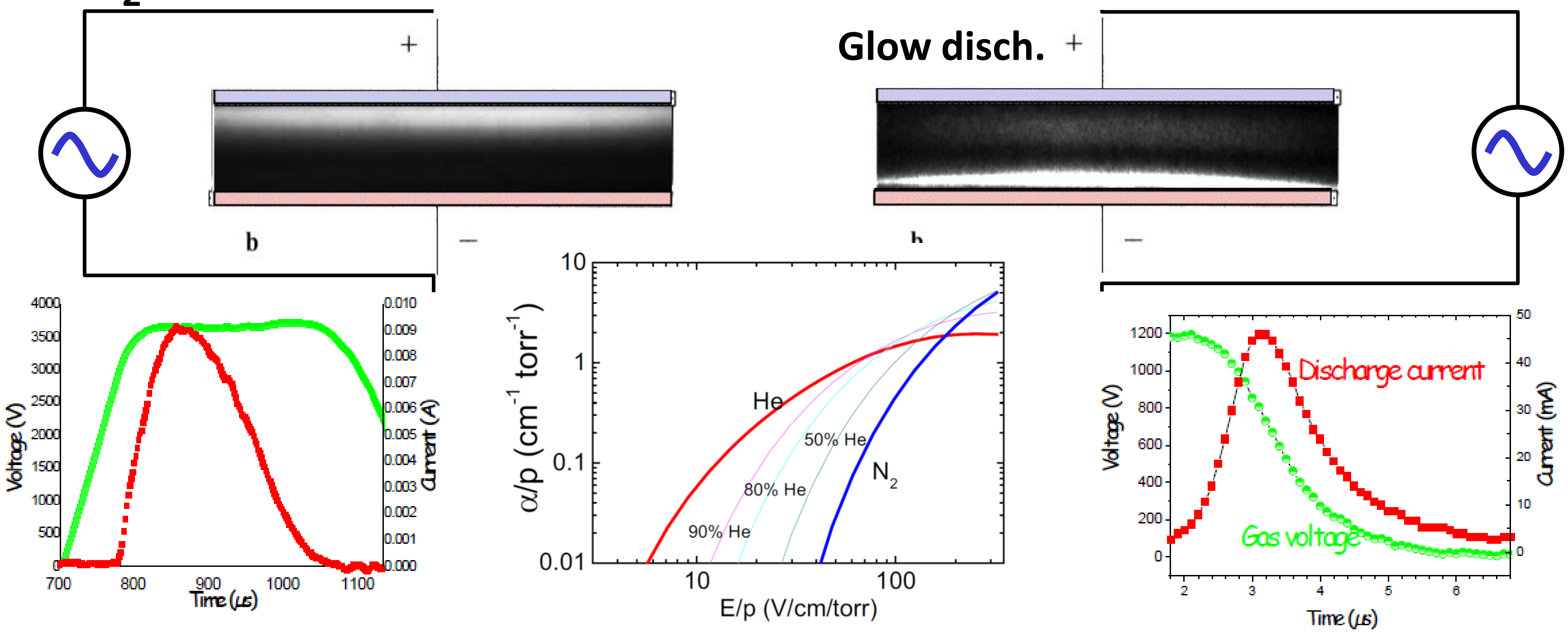
$$2) \quad A^* + B \rightarrow B^+ + e^-$$

Examples:

- penning ionization in Ar/$NH_3$ — Bazinette et al, *Plasma Sources Sci. Technol.* **23** (2014) 035008
- ionization of He metastables — F. Massines et al, *J. Phys. D: Appl. Phys.* **31** (1998) 24; Golubovskii et al, *J. Phys. D: Appl. Phys.* **36** (2003 ) 39

# DBD: homogeneous discharges

**$N_2$** **Townsend , $n_e \approx 10^8$ cm$^{-3}$** **He** **Glow , $n_e \approx 10^{11}$ cm$^{-3}$**




**In Nitrogen:**

- High $\gamma$
- Increased by metastable $N_2(A\ ^3\Sigma_u)$ impact

➢ Surface emission favorable

**In Helium:**

- $\alpha$ slowly varying with E field
- 2 steps ionization (metastables over large volume)
- Penning ionization if impurities

➢ Surface AND gas phase favorable

Massines et al, *Plasma Phys. Control. Fusion* **47** (2005) B577–B588

See also : Golubovskii et al, *J. Phys. D: Appl. Phys.* **36** (2003) 39–49

# About filaments interactions

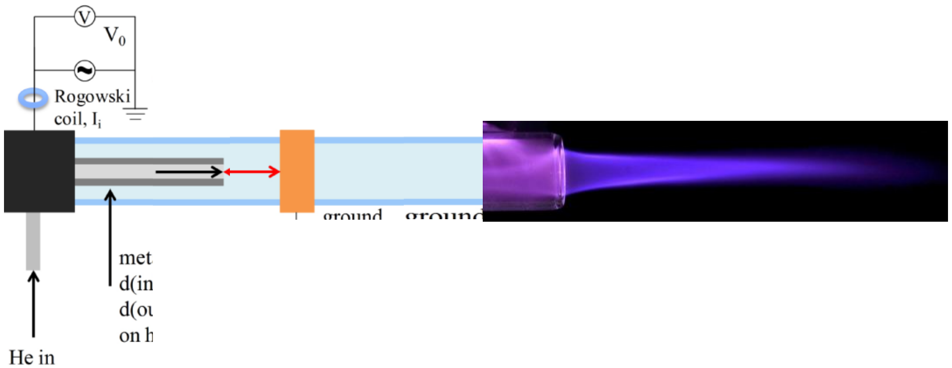
**diffuse DBD discharge can be obtained at atmospheric pressure with:**

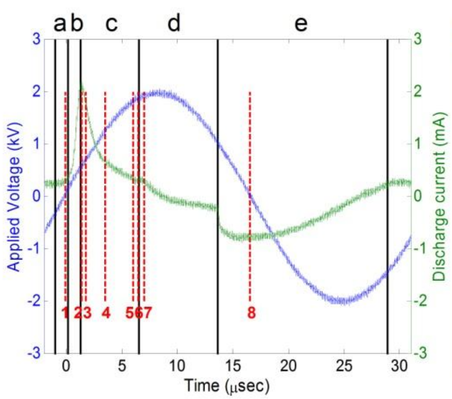
- ✓ **Enhanced electron emission from the surface**
- ✓ **pre-excited species over the whole gas volume**

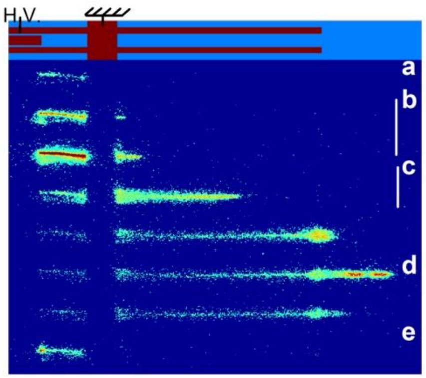
# Outline



# DBD Plasma jet in kHz range



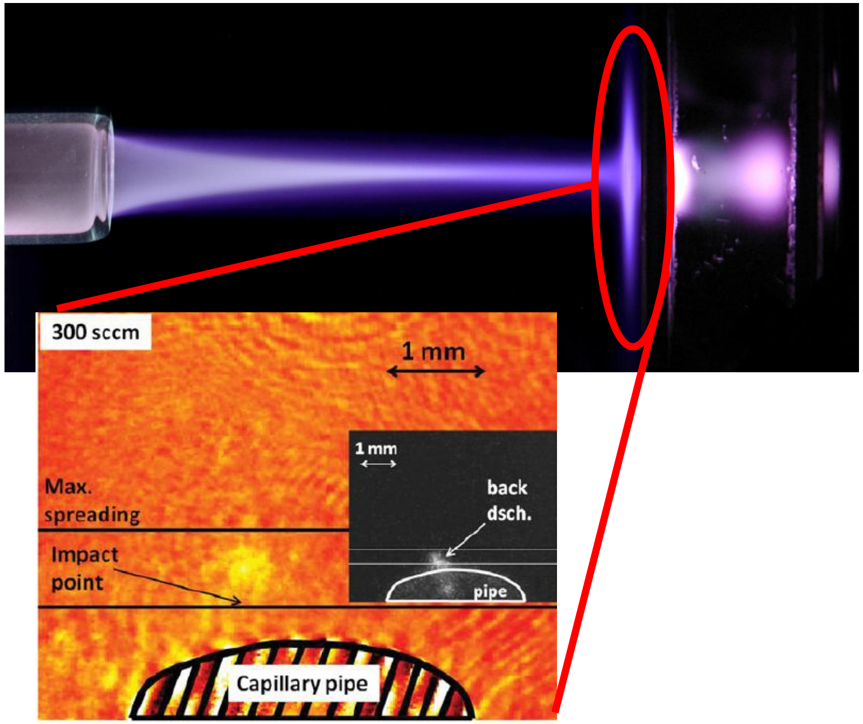




- Capillary discharges in noble gases: “overflowding” of an homogeneous discharge!
- plasma bullet propagation is possible because of confinement of charges
- it is slowed down by the capacitance of the tube
- when it exit in the surrounding atmosphere it is following the flow of He

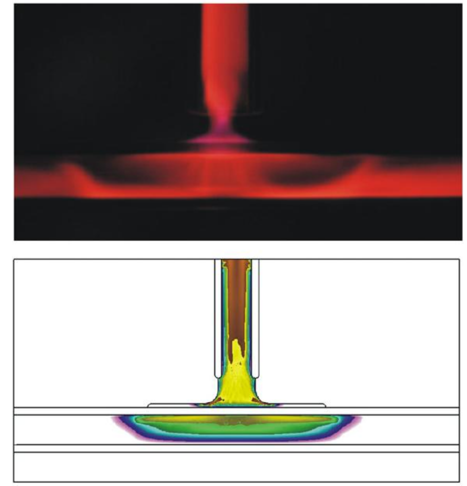
A Sobota, *Plasma Sources Sci. Technol.* **23** (2014) 025016

# Example of "plasma transfer"



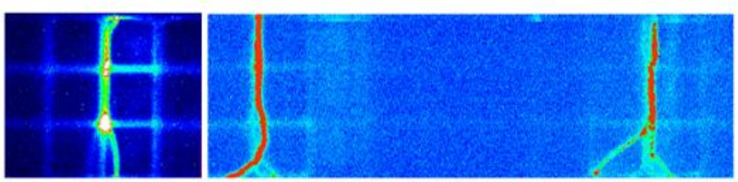

Sobota et al, *J. Phys. D: Appl. Phys.* **46** (2013) 372001

**In rare gases (He, Ne)**

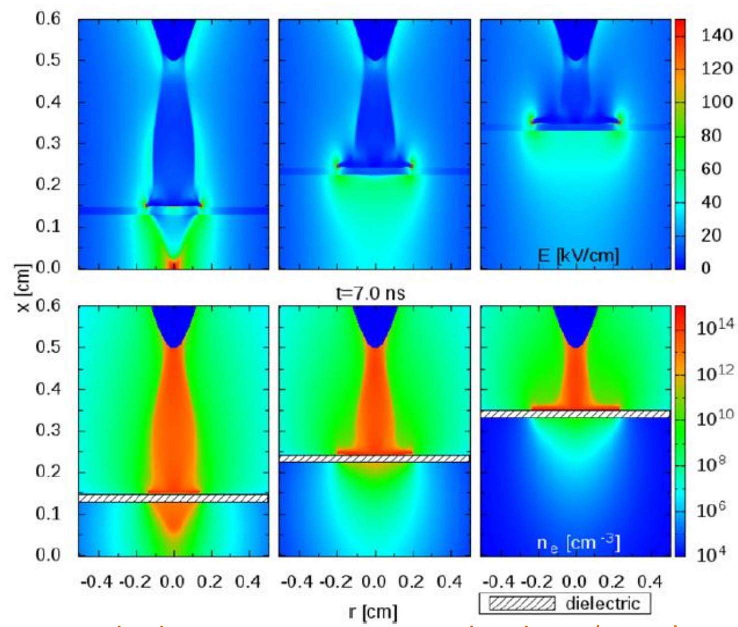


Xiong et al, J. Phys. D: Appl. Phys. 46 (2013) 155203

**In air**



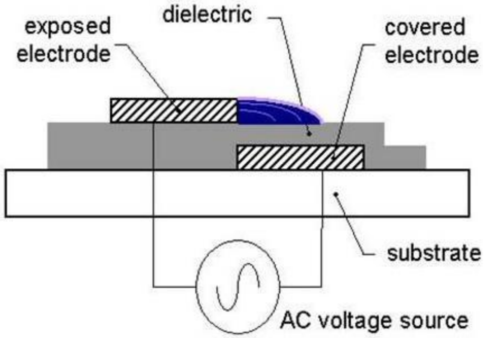
Tardiveau et al, *IEEE transactions on plasma science* **33** (2005) 2, 314-315



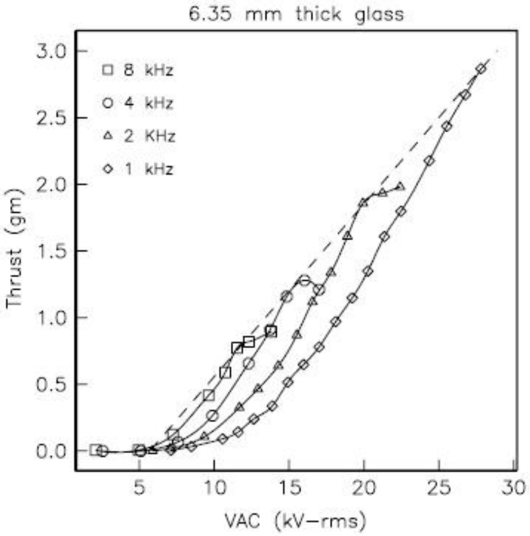

Pechereau et al, Plasma Sources Sci. Technol. **21** (2012) 055011

# Gas motion induced by filaments: ion wind

## Using plasma for limiting turbulences




Corke et al, Exp Fluids **46** (2009) 1–26




# Gas motion induced by filaments: ion wind

The force per unit volume transmitted by positive ions to the neutral molecules = ion momentum loss per unit volume per unit time

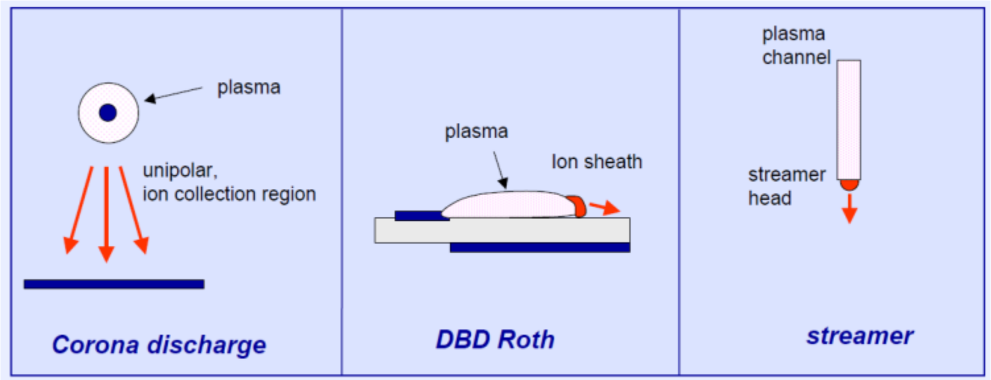
$$f_i = m_i n_i v_{im} v_i = \frac{m_i v_{im}}{e} e n_i v_i = \frac{j_i}{\mu_i}$$

The same for electrons

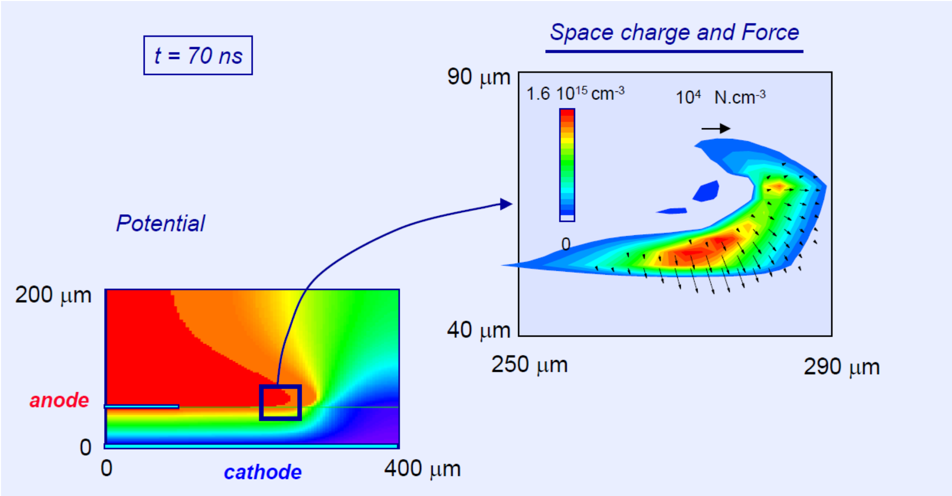
$$f_e = \frac{j_e}{\mu_e}$$

The total force

$$f = \frac{j_i}{\mu_i} - \frac{j_e}{\mu_e} = e(n_i - n_e)E - kT_i \nabla n_i - kT_e \nabla n_e$$




**The force is important only in non neutral zone**




Boeuf et al, *J. Phys. D: Appl. Phys.* **40** (2007) 652–662

# conlusions

RUB

DBDs and Corona develop different discharges

Building up of a localized space charge determine the discharge behavior

Balance between charge adsorption/emission from the surface and remaining excited species in gas phase is essential for DBD

Chemistry very complex but also very efficient

# Books

-**Yu. P. Raizer « Gas Discharge Physics » (Springer)**

- **Nasser E., Fundamental of gazeous ionization and plasma electronics,** Wiley interscience, New-York, 1971

**- J. Reece Roth « Industrial Plasma Engineering » (IOP)- Nato ASI Series**
"Electrical breakdown and discharges in gases:
"Non Thermal Plasma Technologies for Pollution Control" 1993

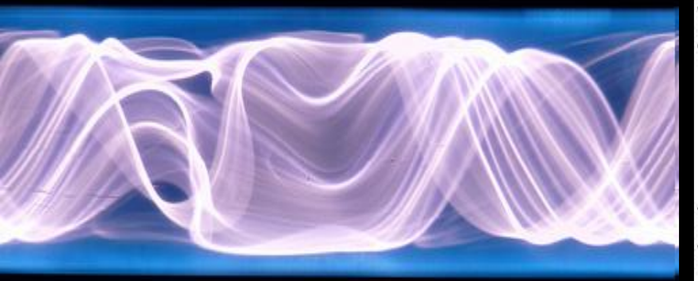
-**Ch. K. Rhodes « Excimer Lasers » (Springer-Verlag)**

- **K.H. Becker, U. Kogelschatz, K.H. Schoenbarch, B. J. Barker** "Non equilibrium air plasmas at atmospheric pressure", IoP,2005

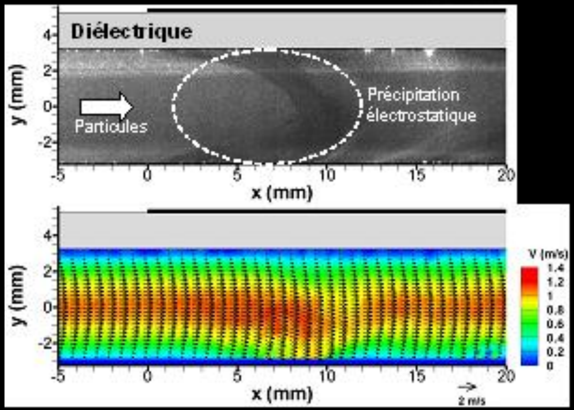
- **A. Fridman** "Plasma chemistry", 2008, Cambridge

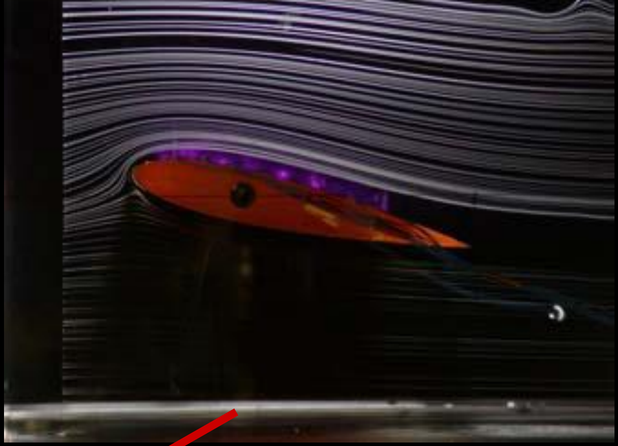
# Filamentary discharges at atmospheric pressure

**Lighting: surface interaction for regular breakdown and salt evaporation**



**Electrostatic precipitation and flow control: ion wind**



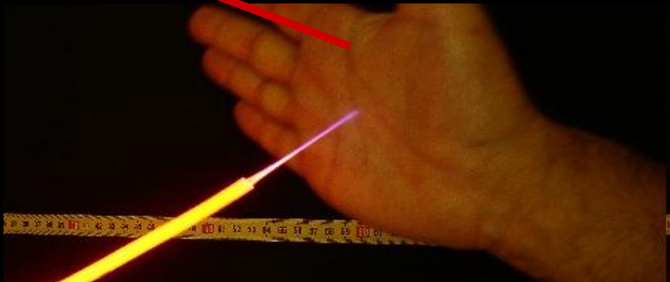



## large variety of reseach topics !!

**Assisted combustion and air treatment:**

**Breadown in voids and high pressure complex chemistry**

**Surface reactivity**



**Biomedical applications:**

**Heating processes, complex chemistry, surface interaction**