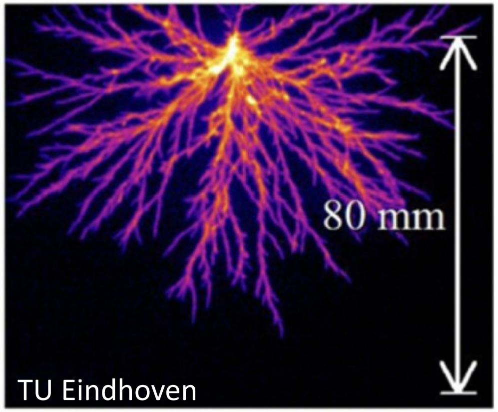
Plasma Physics 2

5. 5. Streamer breakdown mechanism

Korona discharge

Spark discharge



[redacted]

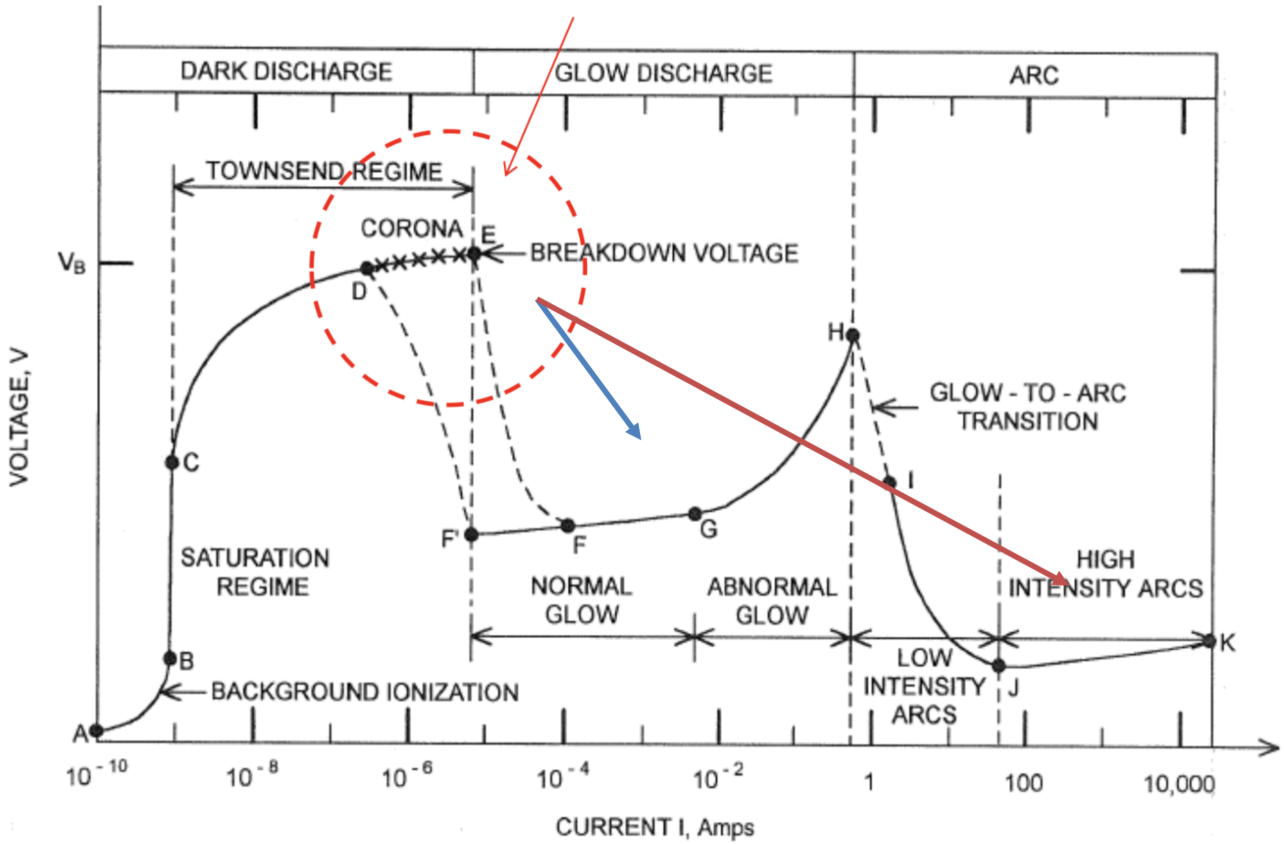
Lecture series contents

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.

[redacted]

Where are we on the IV chart

- At some conditions, the transition from Townsend to glow si not as „smooth“ and gradual as we explained.
- At high fields, low currents and typically higher pressures, a filamentary structure typically called a „Streamer“ starts to form



https://en.wikipedia.org/wiki/Streamer_discharge Explore video of streamer formation

[redacted]

Streamer physics is a living topic

- Even though the interest peaked around the mid 2010s, it is still of interest
- There are no „definitive answers“, so whatever we are teaching here is an attempt to capture **the best current theory for streamer formation** that will likely be improved in future.

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Topical Review

Universal nature and specific features of streamers in various dielectric media

Natalia Yu Babaeva and George V Naidis

Joint Institute for High Temperatures, Russian Academy of Sciences, Moscow 125412, Russia

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Plasma Sources Sci. Technol. **29** (2020) 013001 (31pp) https://doi.org/10.1088/1361-6595/ab5051

Topical Review

Streamer breakdown: cathode spot formation, Trichel pulses and cathode-sheath instabilities

Mirko Černák, Tomáš Hoder and Zdeněk Bonaventura

Department of Physical Electronics, Masaryk University, Kotlářská 2, 61137 Brno, Czech Republic

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Plasma Sources Sci. Technol. **29** (2020) 103001 (49pp) https://doi.org/10.1088/1361-6595/abaa05

Topical Review

The physics of streamer discharge phenomena

Sander Nijdam[1,*], Jannis Teunissen[2,3] and Ute Ebert[1,2]

[1] Eindhoven University of Technology, Department of Applied Physics, P.O. Box 513, 5600 MB Eindhoven, The Netherlands
[2] Centrum Wiskunde & Informatica (CWI), Amsterdam, The Netherlands
[3] KU Leuven, Centre for Mathematical Plasma-Astrophysics, Leuven, Belgium

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Topical Review

Physics of plasma jets and interaction with surfaces: review on modelling and experiments

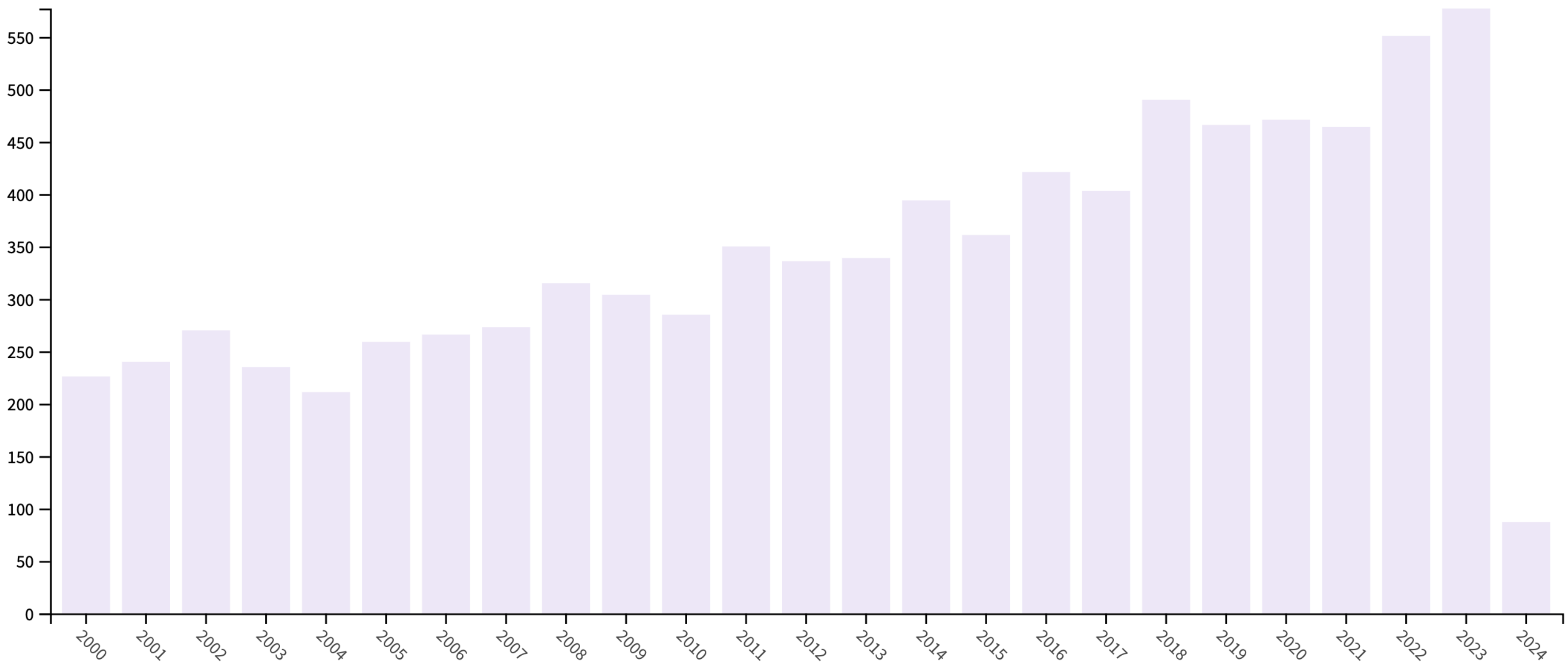
Pedro Viegas[1,2,*], Elmar Slikboer[1,3], Zdenek Bonaventura[2], Olivier Guaitella[1], Ana Sobota[4] and Anne Bourdon[1]

[1] Laboratoire de Physique des Plasmas (LPP), CNRS, Sorbonne Université, Université Paris Saclay, École Polytechnique, Institut Polytechnique de Paris, 91128 Palaiseau, France
[2] Department of Physical Electronics, Faculty of Science, Masaryk University, 61137 Brno, Czech Republic
[3] Centre for Plasma Microbiology, Department of Electrical Engineering and Electronics, The University of Liverpool, Brownlow Hill, Liverpool, L69 3GJ, United Kingdom
[4] Department of Applied Physics, EPG, Eindhoven University of Technology, 5600 MB Eindhoven, The Netherlands

[redacted]

Streamer physics is a living topic

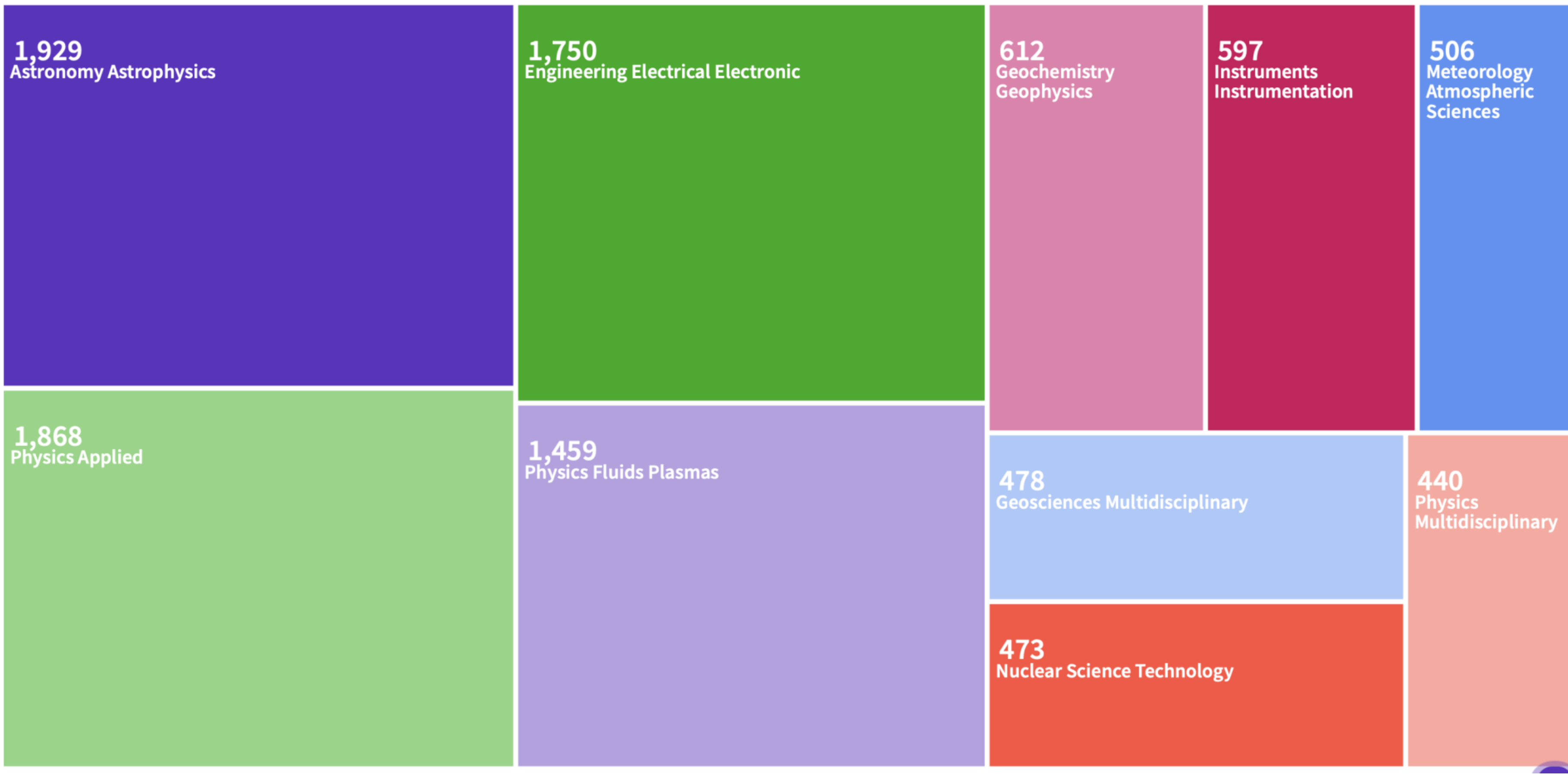
- Even though the interest peaked around the mid 2010s, it is still of interest
- There are no „definitive answers“, so whatever we are teaching here is an attempt to capture **the best current theory for streamer formation** that will likely be improved in future.



[redacted]

Streamer physics is a living topic

- Even though the interest peaked around the mid 2010s, it is still of interest
- There are no „definitive answers“, so whatever we are teaching here is an attempt to capture **the best current theory for streamer formation** that will likely be improved in future.
- Streamers are important in **geophysics, biophysics, and in planetary plasma research**, as well as on-ground uses

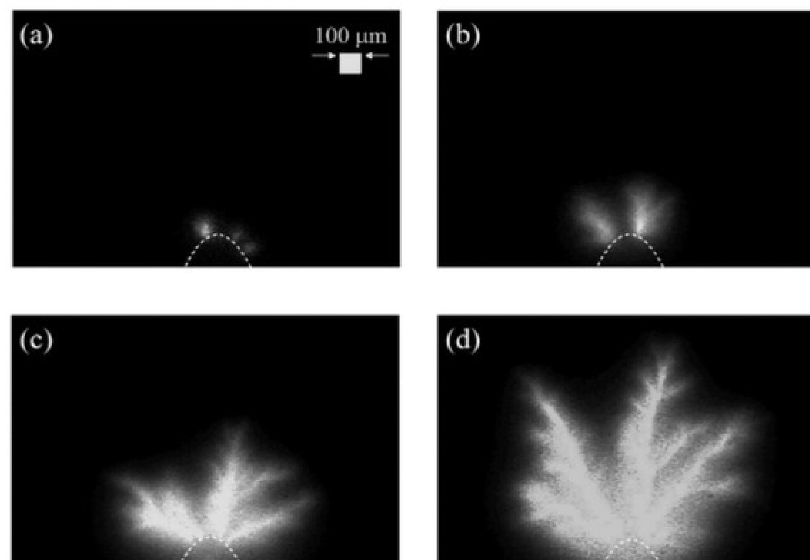


Examples of streamers

- There are no „definitive answers“, so whatever we are teaching here is an attempt to capture **the best current theory for streamer formation** that will likely be improved in future.

gigantic jet over Oklahoma in May 2018.
Chris Holmes

Upper atmospheric lightning



Nanosecond discharge in liquid water
(M.Šimek, CAS, Praha)

Terminology associated with streamers

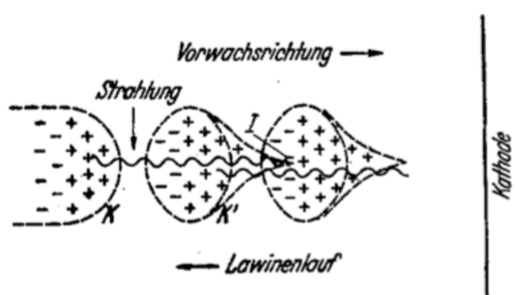
Engineering / historical understanding of
streamer = filamentary discharge

Die Entwicklung der Elektronenlawine in den Funkenkanal.

(Nach Beobachtungen in der Nebelkammer.)

Von **H. Raether** in Jena.

Mit 8 Abbildungen. (Eingegangen am 28. Februar 1939.)



Physics description of a "streamer head"

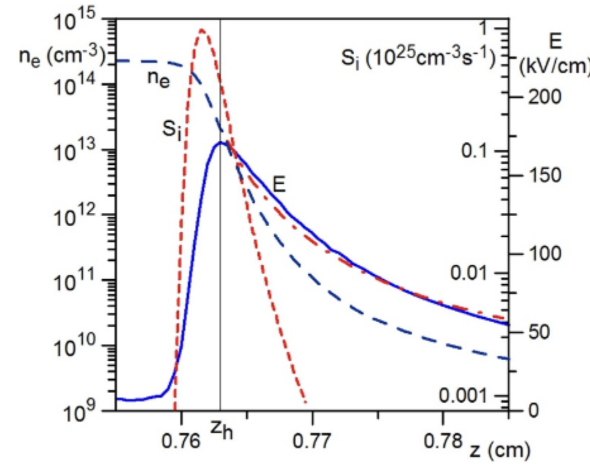
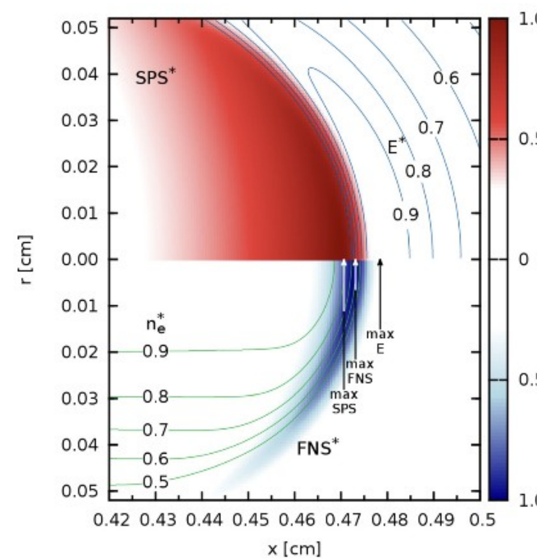
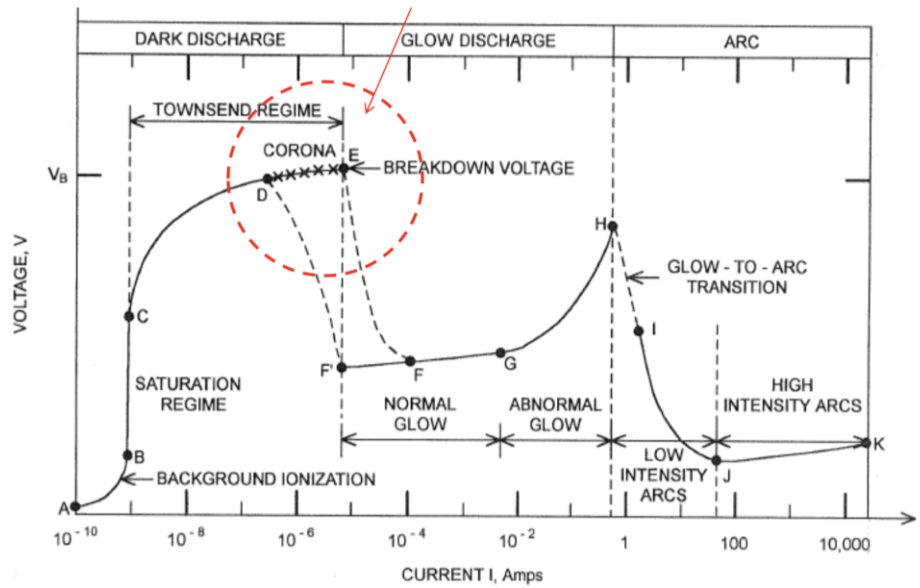


Figure 2. Axial distributions of electric field E, number density of electrons n_e and ionization rate S_i in the streamer head. The dot-dashed line shows approximation (11) for the electric field.



Streamer formation and its similarities with Townsend > Arc transition

- In the previous description of glow discharge ignition, we have always assumed that the electron avalanche creates charge carriers and these move around between the electrodes, forming a diffuse discharge
- But it can occur that **electron avalanche itself forms sufficient space charge and turns into a plasma**?



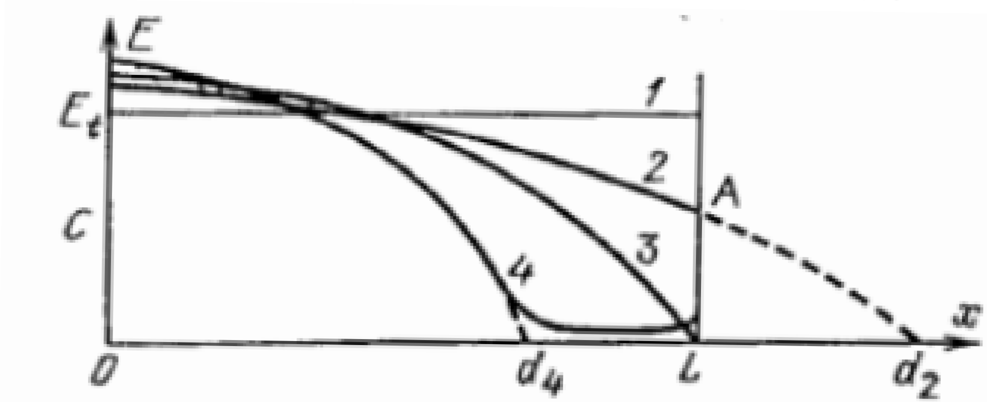
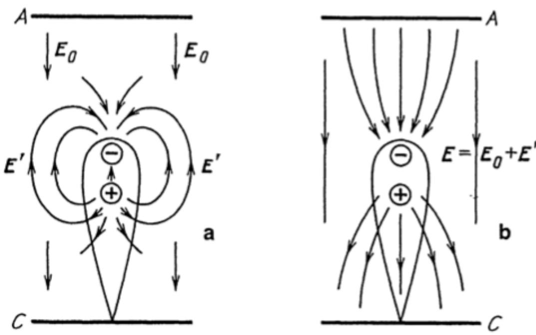


Fig. 8.7. Field evolution due to space charge: *(1)* undisturbed fields as $j \to 0$; *(2)* weak current, $j < j_L$; *(3)* $j = j_L$; *(4)* $j > j_L$, transition to glow discharge

[redacted]

Electron avalanche and its transition to quasineutral plasma

- If the avalanche has enough space and the external field E_0 is large enough, the space charge field E‘ becomes non-negligible



$$E' = eN_e/R^2$$

- Electrons accumulate in the “head” of the streamer and the electric field drives further ionization and causes expansion.

- The expansion rate of the approx. spherical ”streamer head” is driven by the electric field of the electrons themselves.

$$\frac{dR}{dt} = \mu_e E' = e\mu_e R^{-2} \exp(\alpha x)\,, \quad x = \mu_e E_0 t$$

- The field E‘ is proportional to R but the electron density is independent of E‘:

$$R = \left(\frac{3e}{\alpha E_0}\right)^{1/3} \exp\left(\frac{\alpha x}{3}\right) = \frac{3}{\alpha}\frac{E'}{E_0}\,, \quad n_e = \frac{\alpha E_0}{4\pi e}$$

- If the space-charge field becomes non-negligible compared to the external field, **typically E‘ > 0.03 E_0, the effects of space charge become dominant and the avalanche transforms into a “negative streamer”** – a filamentary type of plasma (quasineutral, collective)

Electron avalanche and its transition to quasineutral plasma

We can have a look at the (minimum) streamer physics through equations
https://arxiv.org/pdf/physics/0508109.pdf

- Electrons are created in ionization collisions and lost through attachment
- Positive are created through collisions and depend only on **local** electron density => streamers are so fast, that **positive ions do not have time to be transported**.
- Same for negative ions, which are formed by attachment

$$\partial_t \, n_e \; = \nabla_{\mathbf{R}} \cdot \left(D_e \nabla_{\mathbf{R}} n_e + \mu_e \, \mathbf{E} \, n_e\right) + \left(\mu_e \, |\mathbf{E}| \, \alpha_i(|\mathbf{E}|) - \nu_a\right) n_e,$$

$$\partial_t \, n_+ = \mu_e \, |\mathbf{E}| \, \alpha_i(|\mathbf{E}|) \, n_e,$$

$$\partial_t \, n_- = \nu_a \, n_e,$$

$$\nabla^2_{\mathbf{R}} \Phi = \frac{\mathrm{e}}{\epsilon_0} \left(n_e + n_- - n_+\right) \quad , \quad \mathbf{E} = -\nabla_{\mathbf{R}} \Phi,$$

[redacted]

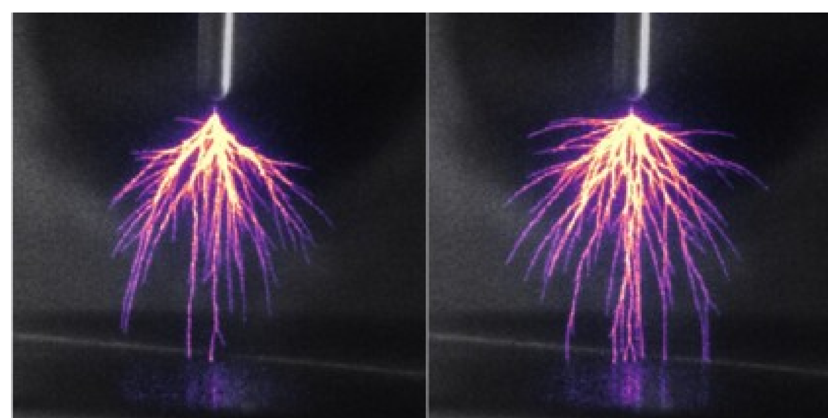
Raether-Meek criterion

- The Raether-Meek criterion states the condition for streamer breakdown.
- If the space charge field is E‘ > 0.03 E_0, the streamer forms.
- Through numerical modeling, this can be translated to „Townsend terminology“ arriving at

$$\mathrm{e}^{\alpha(|\mathbf{E}|)d} \approx 10^8 \text{ to } 10^9$$

$$\alpha(|\mathbf{E}|)\, d \approx 18 \text{ to } 21$$

- **This can be understood as a criterion describing at what conditions will an avalanche transition to a streamer, as opposed to a situation when an avalanche serves as a “seed” of charge carriers for igniting glow discharge plasma**



[redacted]

Positive vs negative streamers

- Experience shows that there are two types of streamers – those propagating from a cathode and those propagating from an anode.
- In positive streamers, the dominant ionization mechanism is photoionization.
- In negative streamers, the dominant ionization mechanism is direct electron-impact ionization.
- In both cases, the **ionization occurs mostly in the streamer head, because the electric field is strong there**.

Cathode streamer = positive streamer

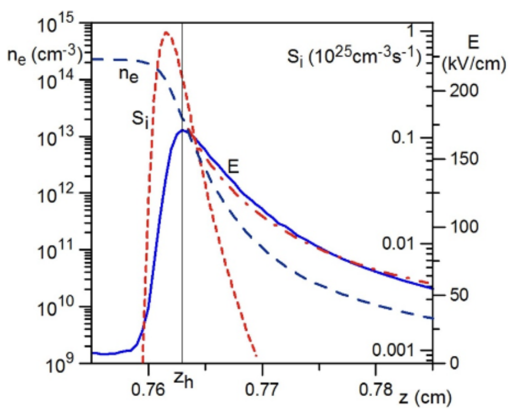
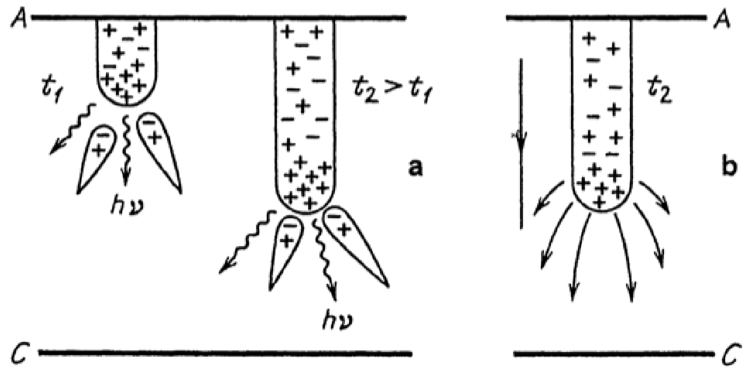
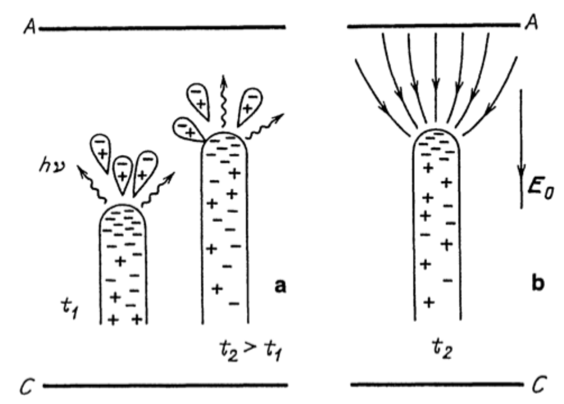


Figure 2. Axial distributions of electric field E, number density of electrons n_e and ionization rate S_i in the streamer head. The dot-dashed line shows approximation (11) for the electric field.



Anode streamer = negative streamer



Statistical nature of breakdown in gases

- Same as with Townsend breakdown, the **streamer breakdown is also a statistical/random phenomenon**!
- After Wijsman (1943) and his work on statistical breakdown through Townsend mechanism, other theories have emerged which could also capture the transition from a Townsend mechanism to a streamer mechanism , e.g.Hodges (1985):

Breakdown probability for Townsend breakdown:
[Wijsman]

$$\mu = \gamma\left(e^{\alpha d} - 1\right) \qquad P = \begin{cases} 0 & pre \quad \mu \leq 1 \\ 1 - \dfrac{1}{\mu} & pre \quad \mu > 1 \end{cases}$$

Breakdown probability for streamer breakdown:

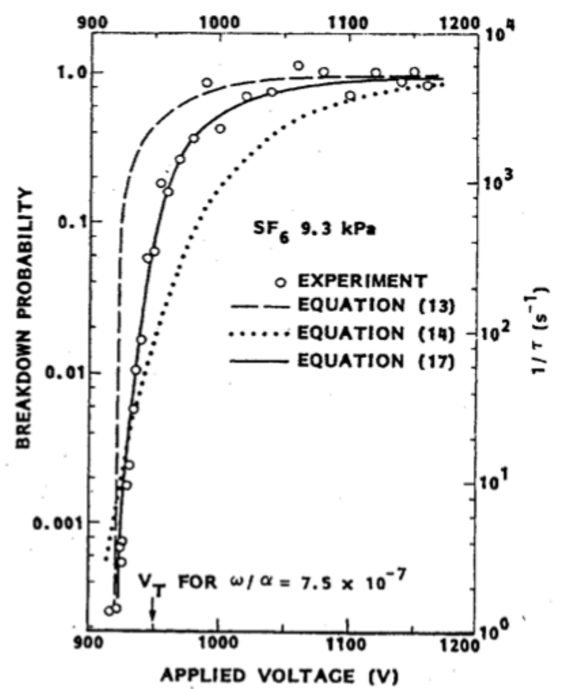


FIG. 10. Experimental average spark delay times and calculated initiation probabilities for SF_6 at 9.3 kPa (70 Torr). Parameters: $d = 0.45$ mm, $\omega/\alpha = 1.2\times10^{-6}$ [Eq. (13)], $\omega/\alpha = 7.5\times10^{-7}$ [Eq. (17)], $n_c = 5\times10^{6}$ [Eq. (14)], $n_c = 5\times10^{7}$ [Eq. (17)].

$$P^* = \begin{cases} 0 \quad \text{for } \mu^* \leq 1 \\ (1-\eta/\alpha)(1-1/\mu^*) \quad \text{for } \mu^* > 1\ . \end{cases} \tag{13}$$

Including attachment in Wijsman theory

$$P^* = \int_{n_c}^{\infty} v^*(n^*)dn^* = (1-\eta/\alpha)\exp(-n_c/\bar{n}^*)\ . \tag{14}$$

Purely streamer breakdown with avalanches transitioning into streamers

$$P^* = \begin{cases} (1-\eta/\alpha)\displaystyle\int_{n_c}^{\infty} V(n_p^*)dn_p^* \quad \text{for } \mu^* \leq 1 \\ (1-\eta/\alpha)\left[1-1/\mu^* + \displaystyle\int_{n_c}^{\infty} V(n_p^*)dn_p^*\right] \quad \text{for } \mu^* > 1\ . \end{cases} \tag{17}$$

Unified ignition probability, considering both Townsend breakdown and Streamer breakdown

Statistical nature of breakdown in gases

- With increasing pressure, the ignition probaibility curve is shifting towards higher E and its shape is changing too
- Qualitatively, this is similar to Townsend breakdown but the physics behind is a bit more complex ☺

4 kPa

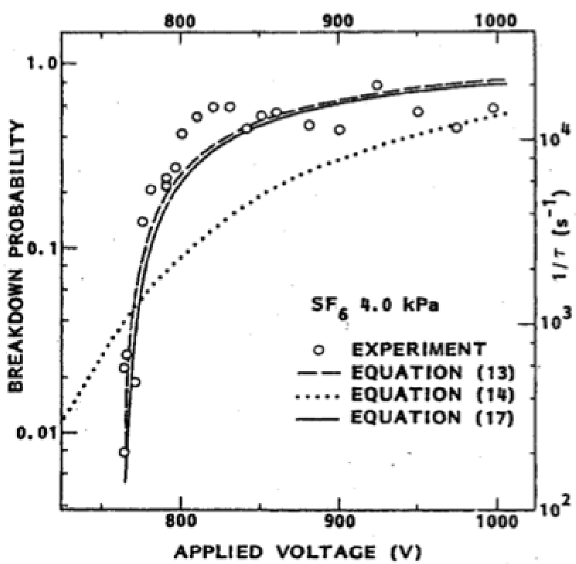


FIG. 9. Experimental average spark delay times and calculated initiation probabilities for SF_6 at 4.0 kPa (30 Torr). Parameters: $d=0.45$ mm, $\omega/\alpha=3.2\times10^{-5}$ [Eq. (13)], $\omega/\alpha=2.9\times10^{-5}$ [Eq. (17)], $n_e=1\times10^5$ [Eq. (14)], $n_e=5\times10^7$ [Eq. (17)].

9.3 kPa

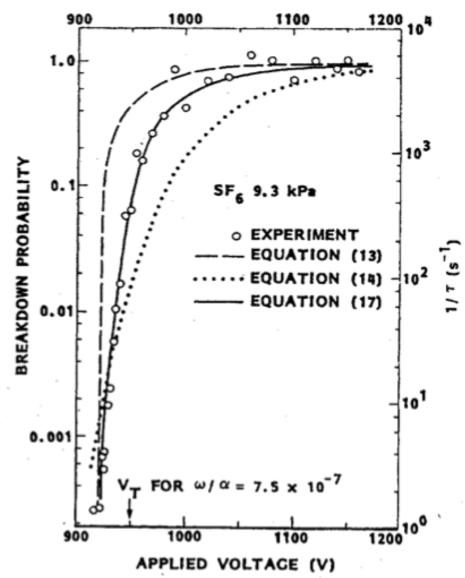


FIG. 10. Experimental average spark delay times and calculated initiation probabilities for SF_6 at 9.3 kPa (70 Torr). Parameters: $d=0.45$ mm, $\omega/\alpha=1.2\times10^{-6}$ [Eq. (13)], $\omega/\alpha=7.5\times10^{-7}$ [Eq. (17)], $n_e=5\times10^6$ [Eq. (14)], $n_e=5\times10^7$ [Eq. (17)].

26.7 kPa

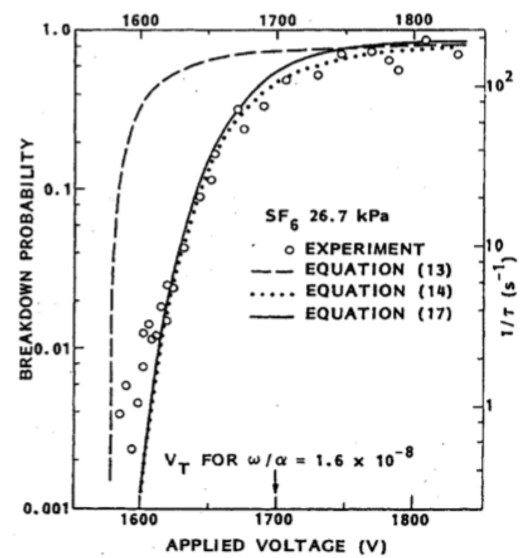
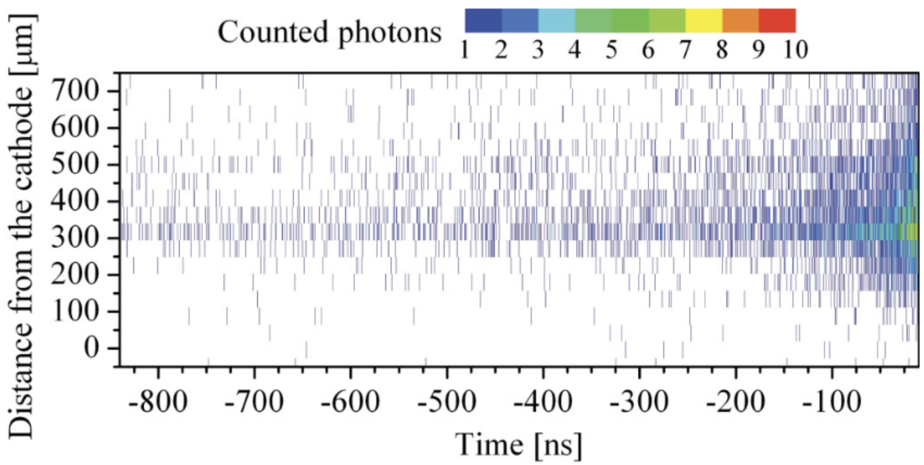


FIG. 11. Experimental average spark delay times and calculated initiation probabilities for SF_6 at 26.7 kPa (200 Torr). Parameters: $d=0.45$ mm, $\omega/\alpha=4.1\times10^{-7}$ [Eq. (13)], $\omega/\alpha=1.6\times10^{-8}$ [Eq. (17)], $n_e=3.3\times10^7$ [Eq. (14)], $n_e=5\times10^7$ [Eq. (17)].

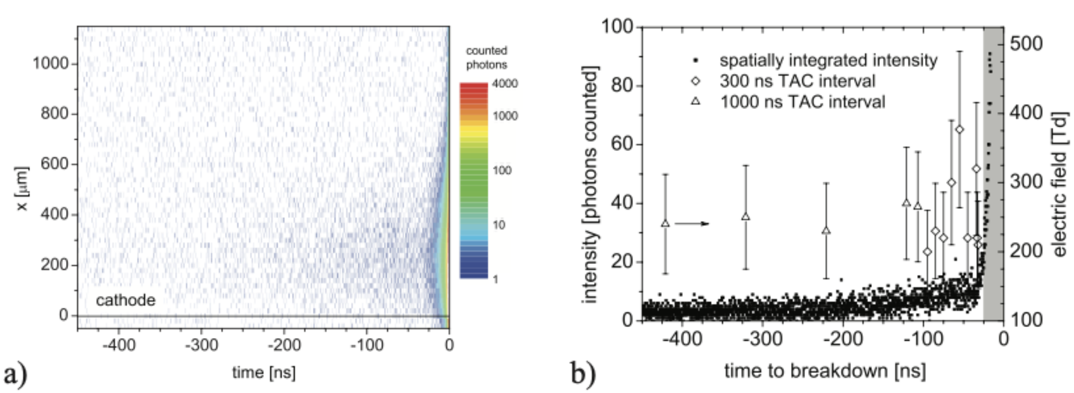
[redacted]

The Brno trace in streamer research ☺

- Not-so-historically (1980s-2000s), streamers were researched y prof Mirko Cernak.
- An important technique for quantifying streamers is TCSPC = time-correlated single-photon counting pioneered a.o. by Tomas Hoder



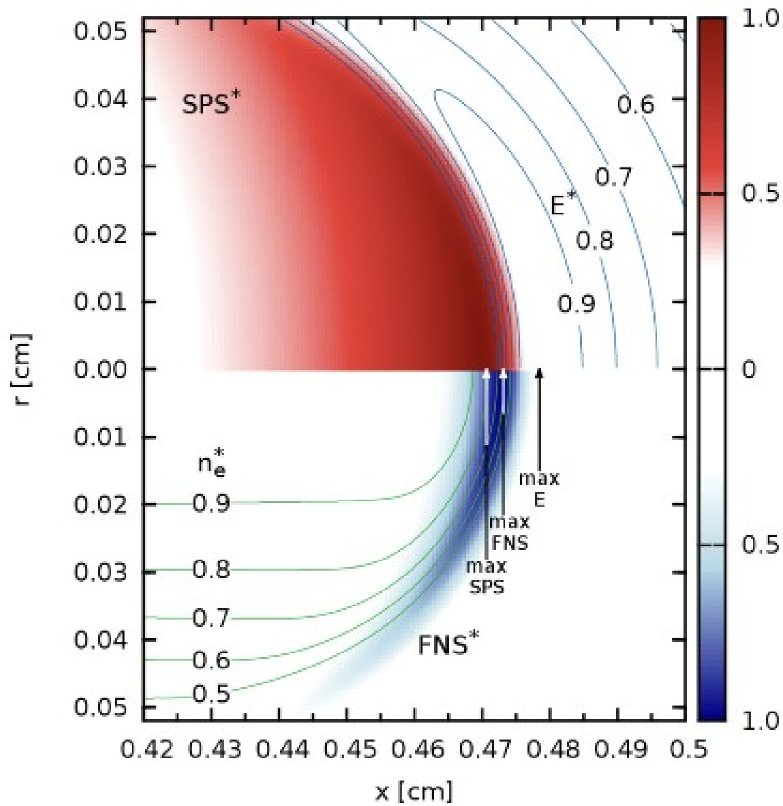
- By time-correlating the origin of individual photons, light was emitted with the exponential spatial resolution up to 1 microsecond before the streamer, which suggested the Townsend mechanism



The Brno trace in streamer research ☺

- Explaining the fundamentals through simulations – Zdeněk Bonaventura and team.

Bonaventura, Bourdon:



Ebert, Teunissen:

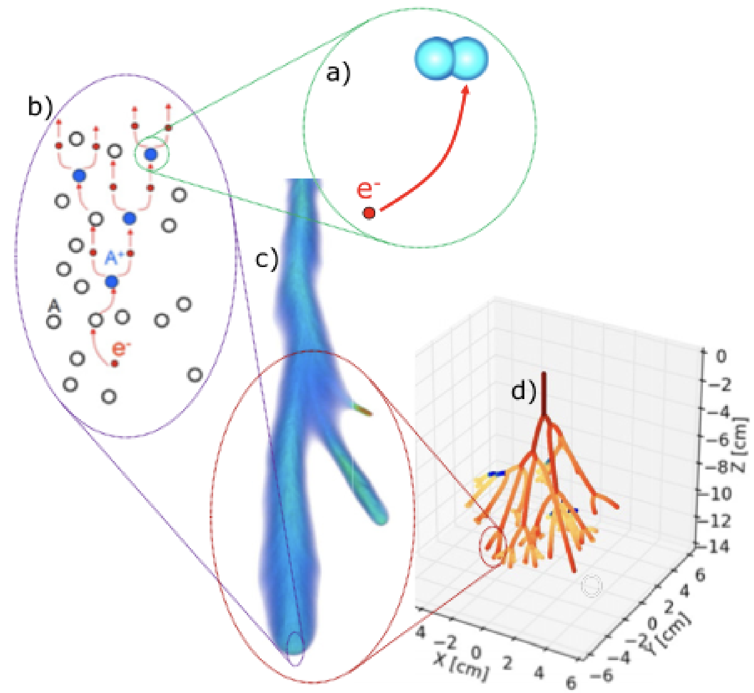


Figure 4. The multiple spatial scales in streamer discharges: (a) collision of an electron with an atom or molecule, (b) multiple electrons accelerate in a local electric field, collide with neutral gas molecules and form an ionization avalanche, (c) a branching streamer discharge with field enhancement at the tips, (d) a discharge tree with multiple streamer branches. Panel (d) is reproduced from a figure in [29].

But what happens next with the streamers?

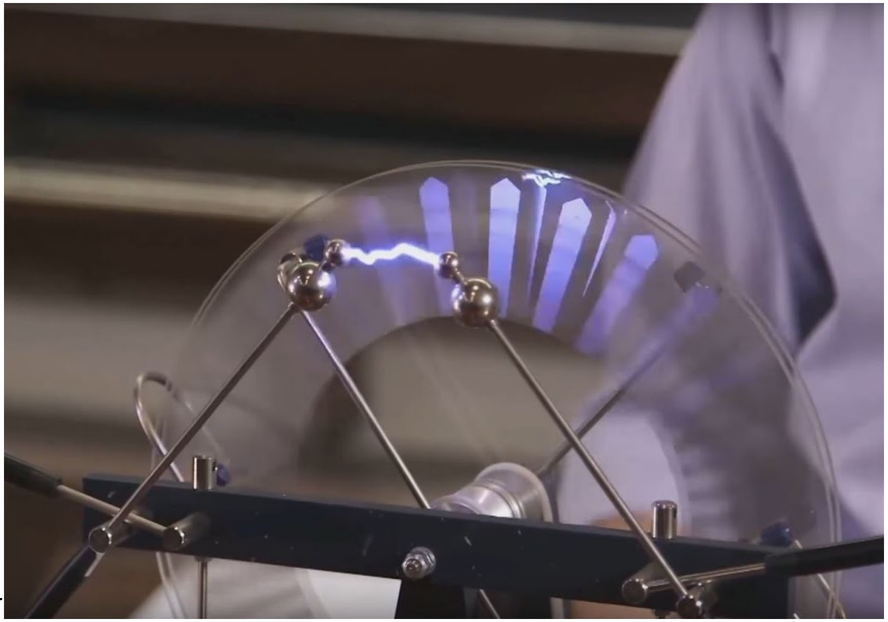
Q: What do you think could happen when we have such a propagating plasma structure?

A1: Streamer reaches a counter-electrode

- Conductive channel is formed
- Electric field drops significantly
- We see an **arc plasma forming** if the power supply can support it.
- We see a **spark plasma** forming if the power supply cannot support an arc

A2: Streamer does not reach a counter-electrode

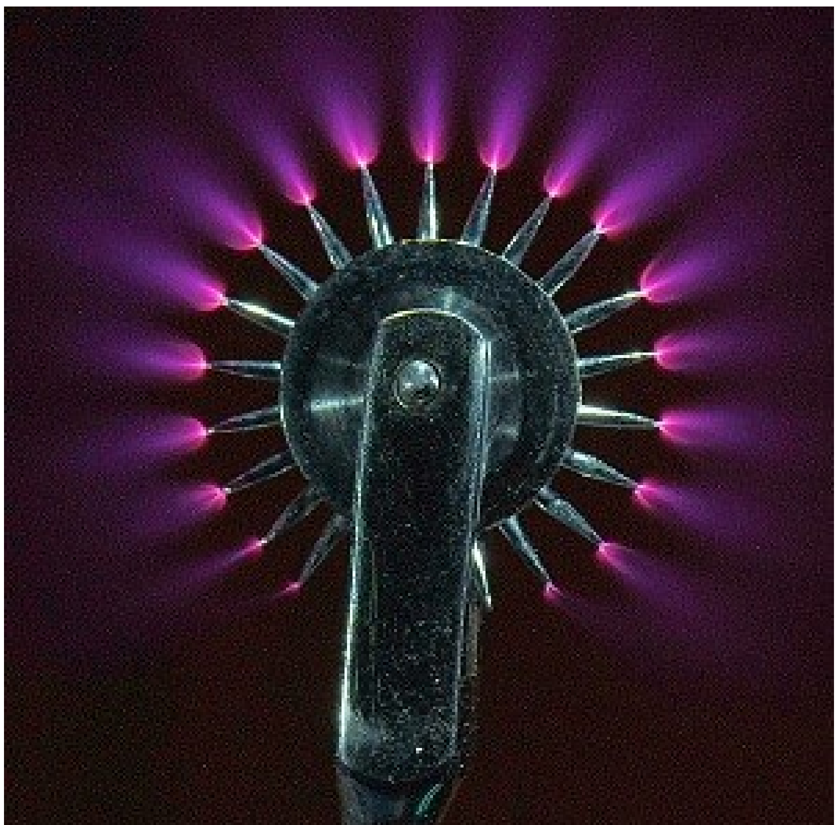
- The counter electrode is large and far
- Ionization stops to increase and ultimately starts to decrease in space because the plasma is expanding to a large volume.
- Streamers can exist as semi-stable structures in time, called **corona discharge**



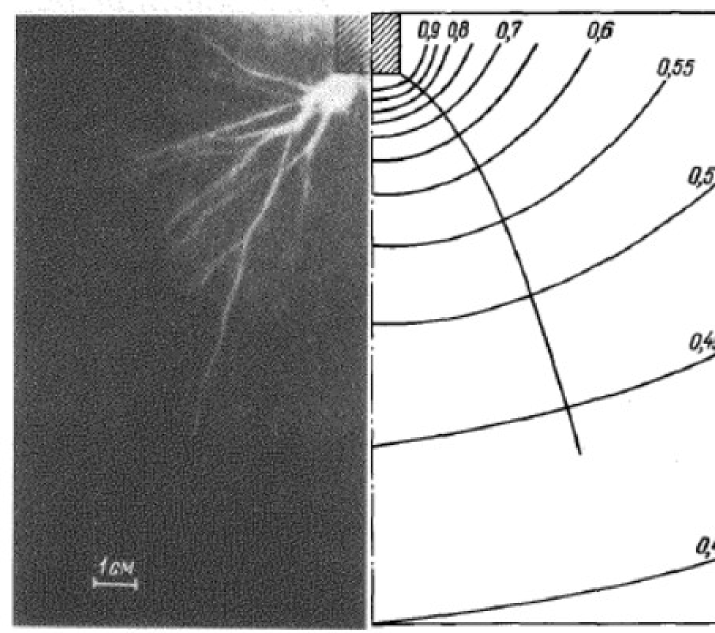
CORONA DISCHARGE

Corona discharge

- If the field is highly non-uniform, e.g. close to sharp tips surrounded by ground, a corona discharge can appear
- There is no counter-electrode to reach but streamers still form and consume some energy
- Sometimes referred to as **partial discharge**



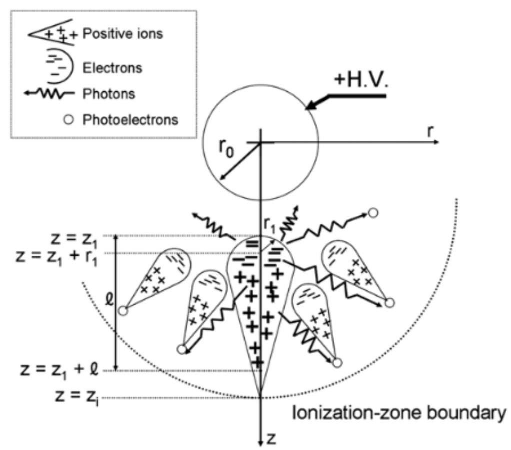
positive corona at 125 kV
in atmosphere



Corona discharge

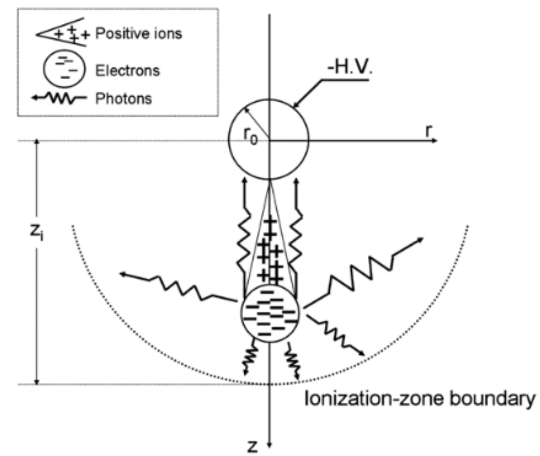
- Corona can form in the proximity of both a positive and negative tip

Positive corona – tip is extended by a positive streamer



Photoionization important
Appears as diffuse glow around a wire.
Stable in all gases.

Negative corona – negative streamers propagate towards the tip



Secondary emission and volume ionization important
Has a glow discharge structure.
Appears as a series of luminous spots.
Stable only in electronegative gases.

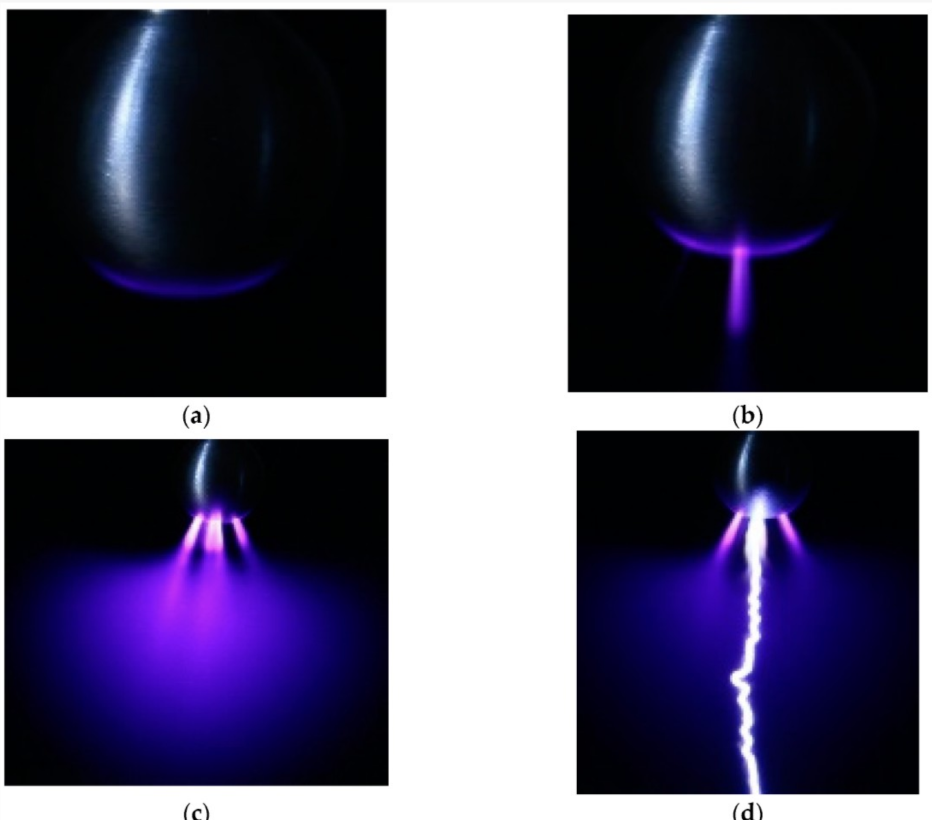
[redacted]

Corona discharge

- Corona can form in the proximity of both a positive and negative tip

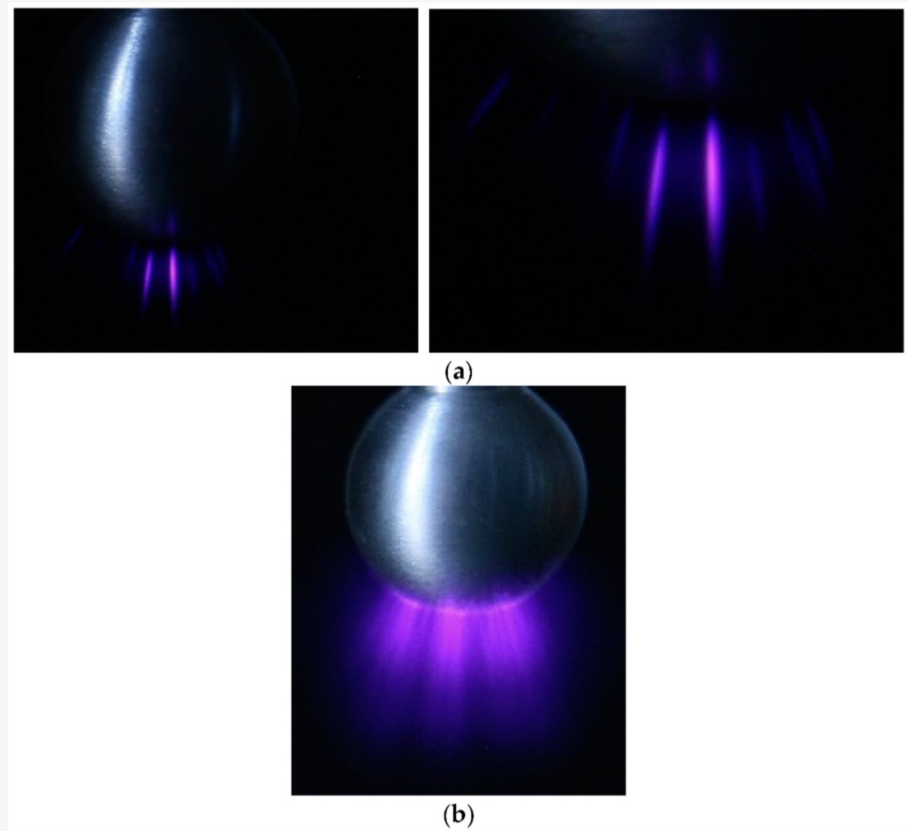
Positive corona – tip is extended by a positive streamer

Figure 3. Positive polarity dc corona (sphere diameter of 20 mm, h = 15 cm). (**a**) Initial corona glow at +55.5 kV; (**b**) Corona glow and streamer initiation at +56.0 kV; (**c**) Advanced positive corona combining glow and streamers at +62 kV; (**d**) Spark breakdown at approximately +80 kV.



Negative corona – negative streamers propagate towards the tip

Figure 4. Negative polarity dc corona (sphere diameter of 20 mm, h = 15 cm). (**a**) Corona close to the extinction conditions (−54.5 kV) with few moving streamers; (**b**) Advanced negative corona at −75 kV showing an amalgam of moving surface streamers.



Negative corona structure

- **The negative corona has a structure similar to a glow discharge with highly asymmetrical electrodes**

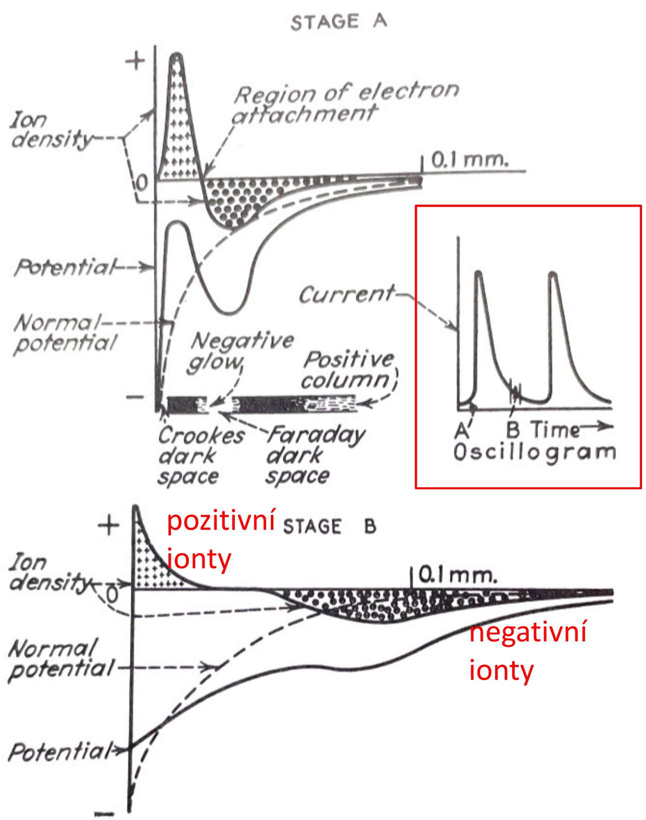
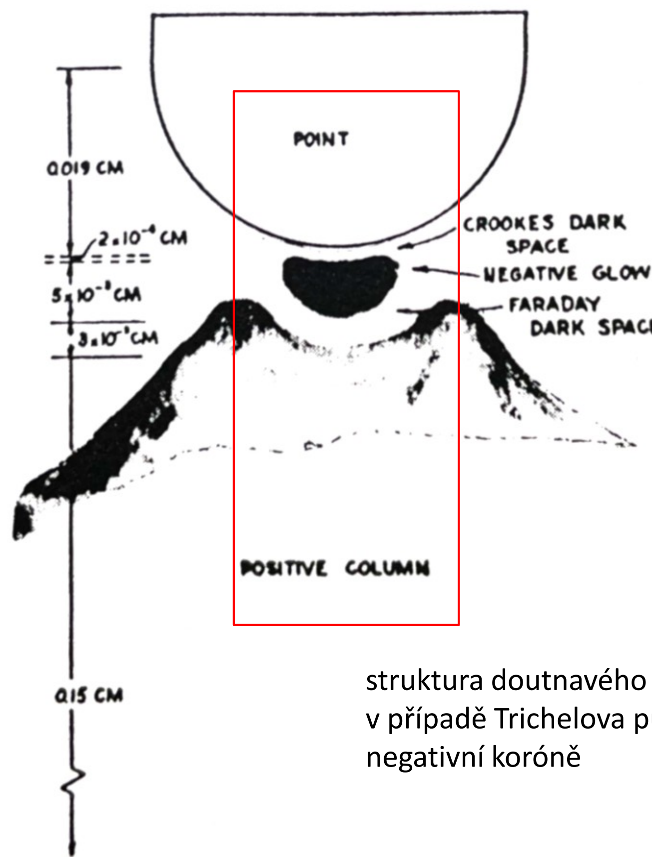


FIG. 8.28.—Space-charge distribution in negative-point corona. (*A*) Just after ionization starts. (*B*) During the last clearing of the positive-ion space charges.



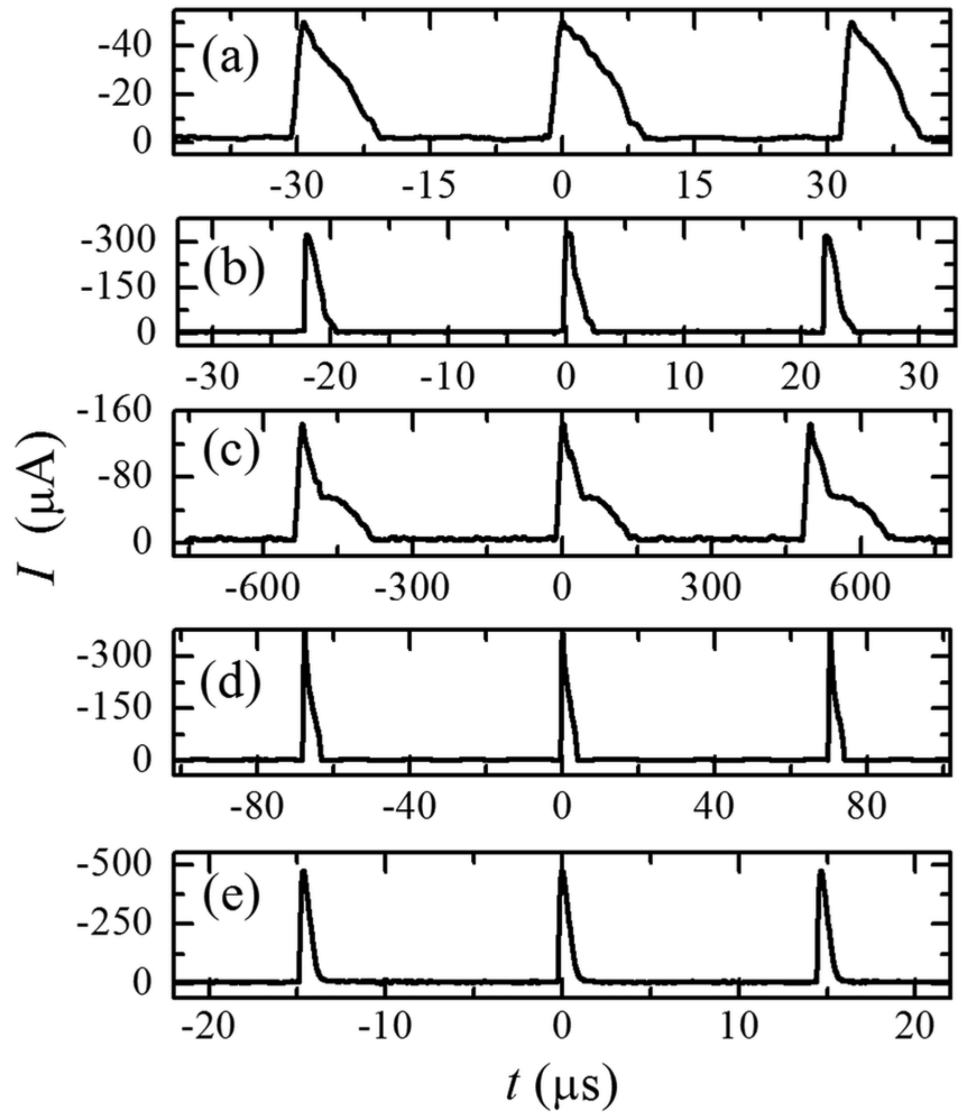
struktura doutnavého výboje v případě Trichelova pulzu v negativní koróně

[redacted]

Trichel pulses in negative corona

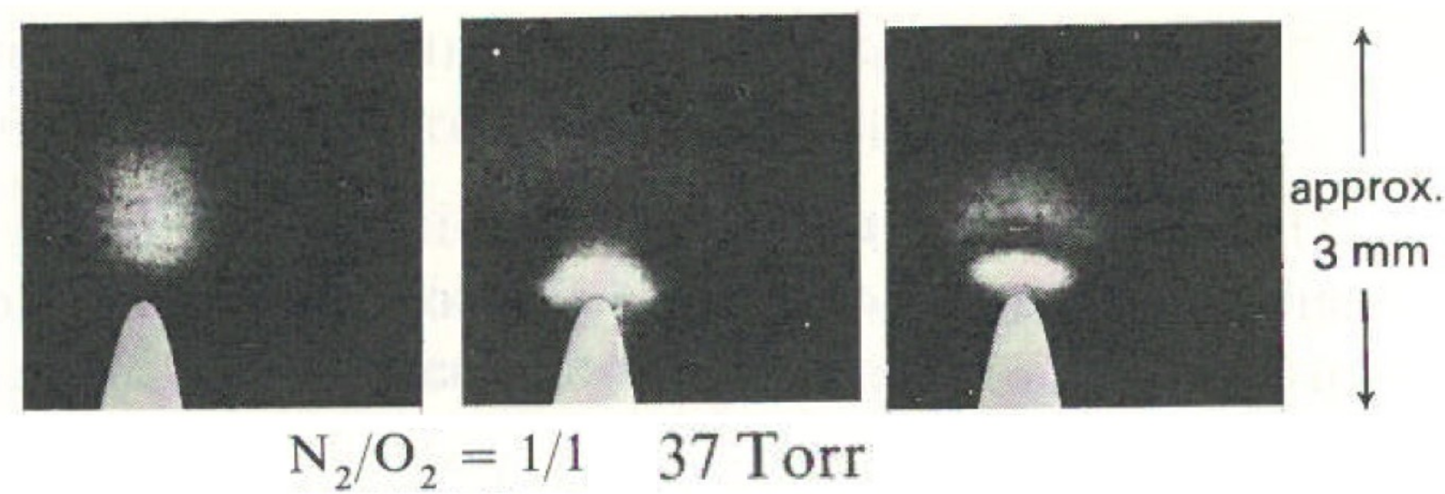
- Trichel pulses are kHz – MHz oscillations inherent to negative corona discharges.
- The fundamental physics is driven by the nature of the plasma:

1. A negative streamer starts to form
2. Ionization grows exponentially
3. Formed charge carriers start to shield the external E field.
4. At some point, the external field is shielded perfectly by the discharges => no more corona
5. Plasma takes some characteristic time to "dissipate" – that time scale is typically microseconds, determined by the plasma ambipolar diffusion time scale.
6. As the plasma dissipates, external field starts to dominate again
7. A negative streamer starts to form …



Trichel pulses in negative corona

Time recording of a Trichel pulse (Sigmond 1973):



We see electron multiplication, space charge formation and ultimately a glow discharge structure – but what is the dynamics behind it?

[redacted]

Trichel pulses in negative corona – current measurement

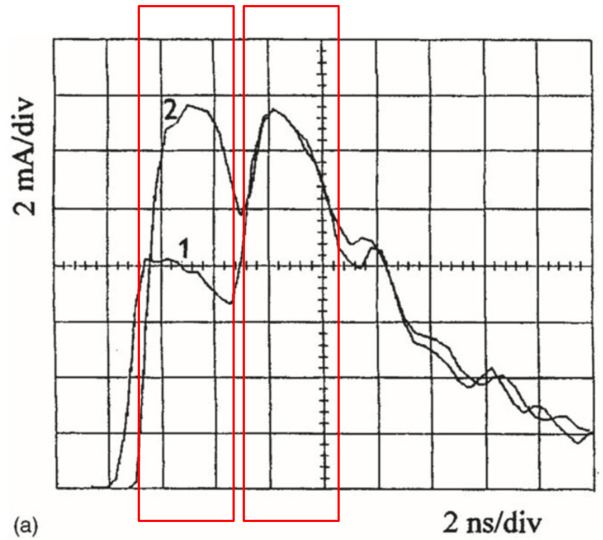


Figure 16. First Trichel pulses measured in dry air at 40 kPa, $r = 0.625$ mm, $S = 10$ mm and a gap voltage of 5.28 kV using the brass (1) and the CuI-coated cathode (2). From Černák *et al* [220].

Photoemission coefficient

$$\gamma_{p\text{-CuI}} > \gamma_{p\text{-brass}}$$

Has no effect on the maximum but it affects the rise time!

First current peak sensitive to material, second current peak is not!

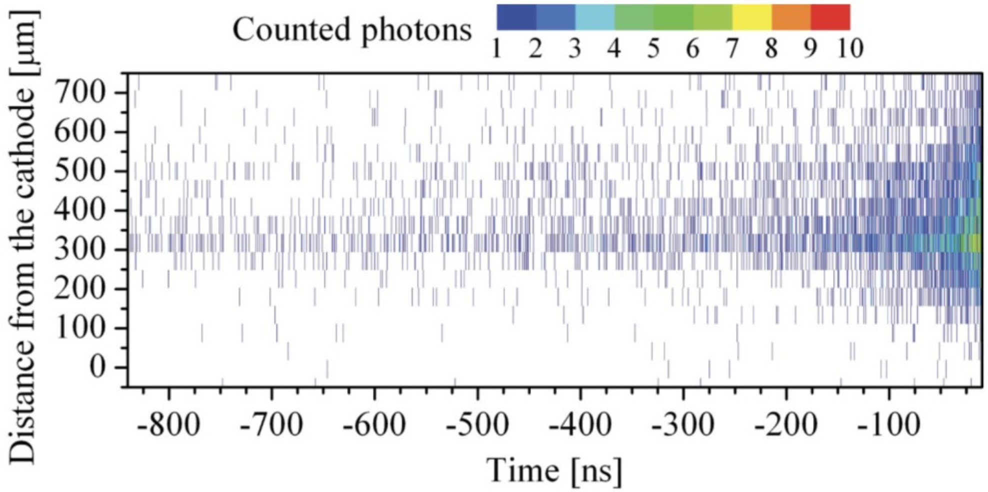
- streamer initiation and generation of energetic photons. First peak is probably the impact of the streamer onto the cathode – probably the first Trichel pulse

- for repeated Trichel pulses, it is likely that transient glow discharge starts to form, as qualitatively outlined a few slides back.

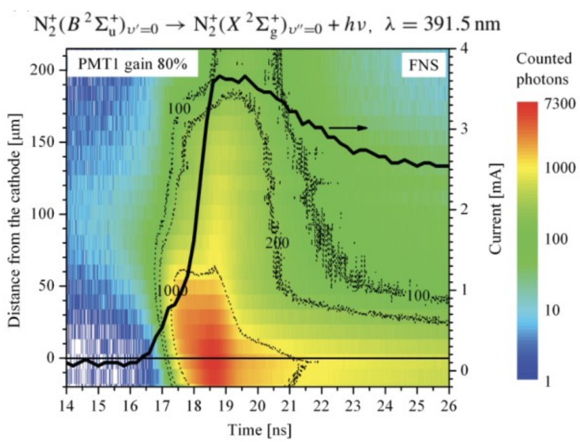
[redacted]

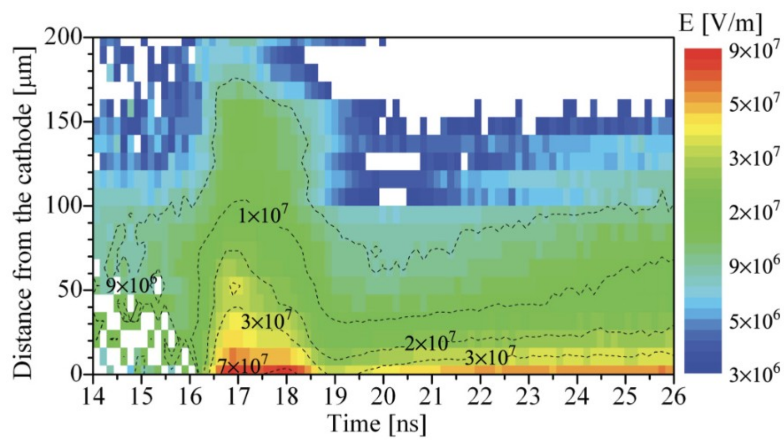
Trichel pulses in negative corona – emission measurement

Nitrogen emission in time and space before the Trichel pulse:



Nitrogen emission, current and E field in time and space during the Trichel pulse:

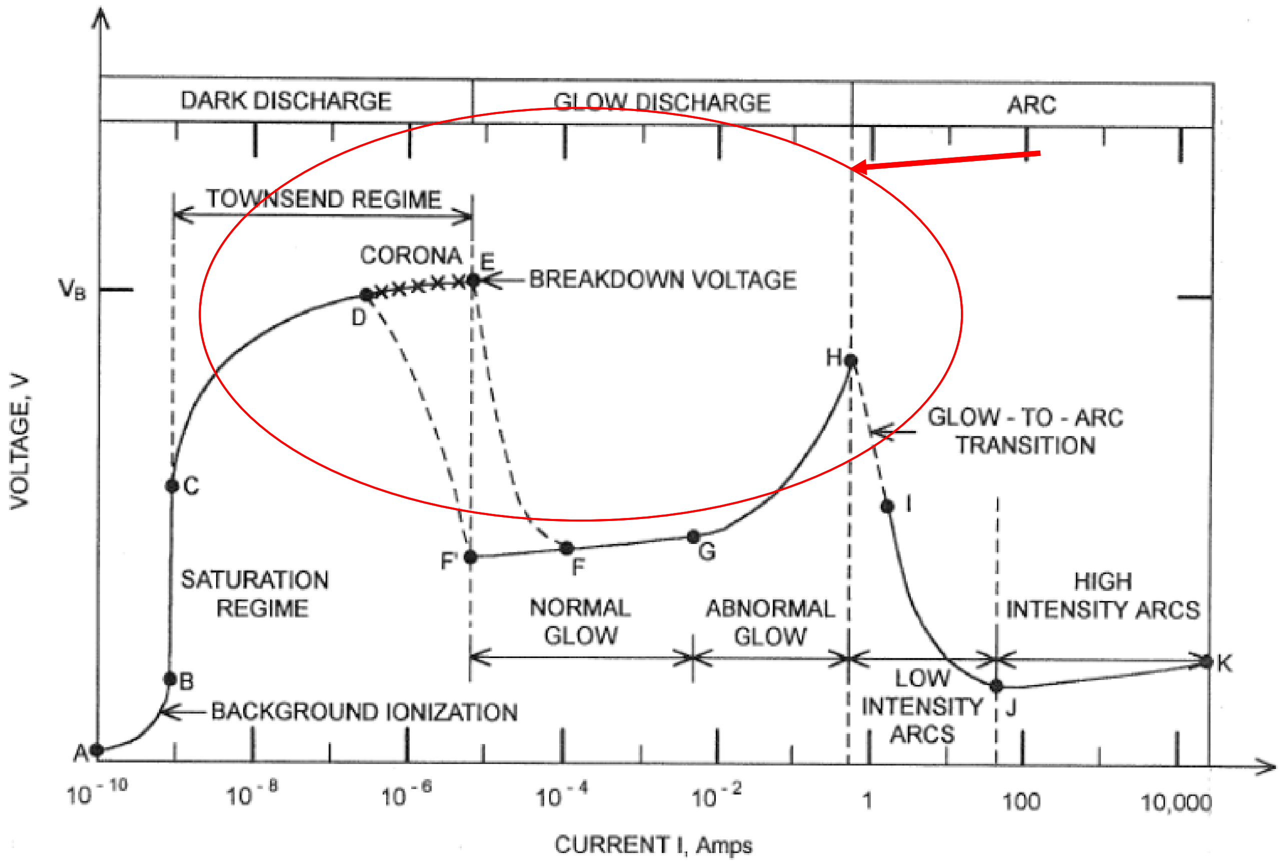




SPARK DISCHARGE

Spark discharge

- If a sufficient amount of current is available and the streamer reaches a counter-electrode, what we call a **spark discharge** starts to form.
- This can be understood as an. **early stage of an arc discharge** but arc itself will operate only if the power supply can provide ample current.



Spark discharge (Janda, Machala 2010)

- If the voltage is pulsed at the right frequency and duty cycle, the spark can be transient.
- Interesting special case of this plasma source, used at UK Bratislava.

Figure 3. Photograph of TS in positive needle–plane gap of 4 mm, $f = 2\,\mathrm{kHz}$, $R = 6.6\,\mathrm{M\Omega}$ and exposure 0.05 s.

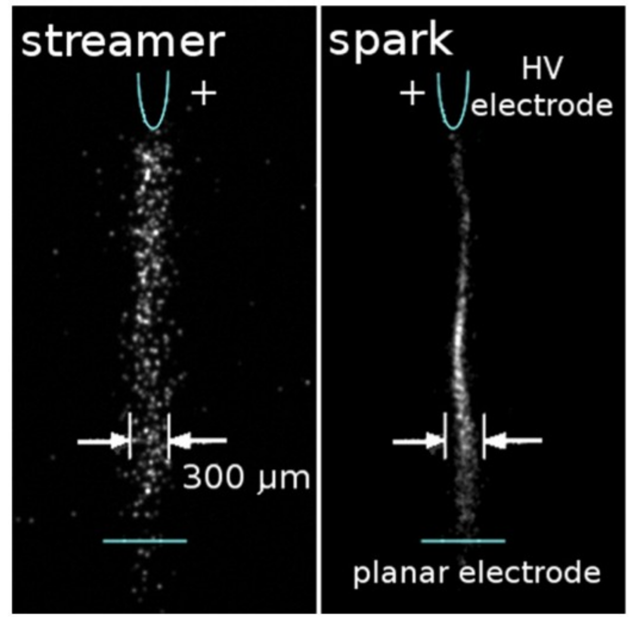
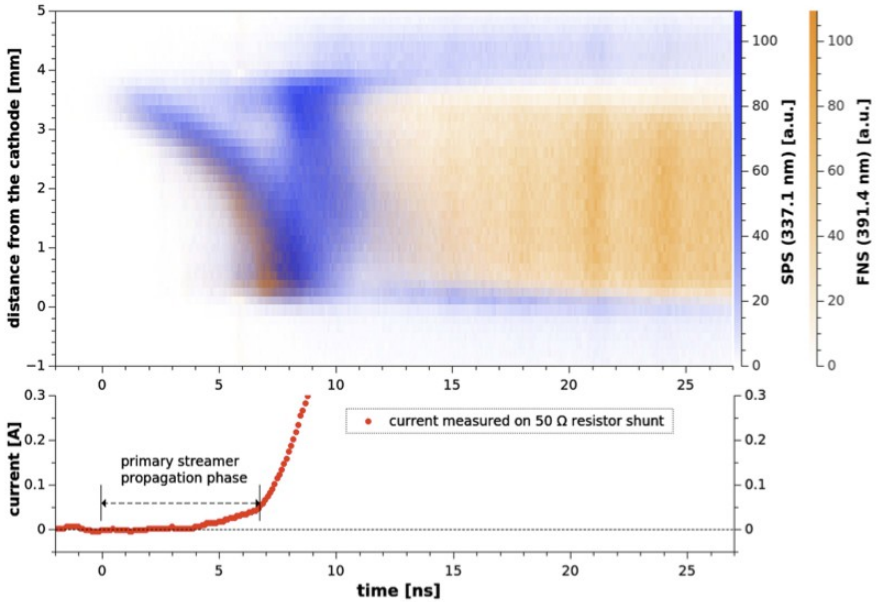
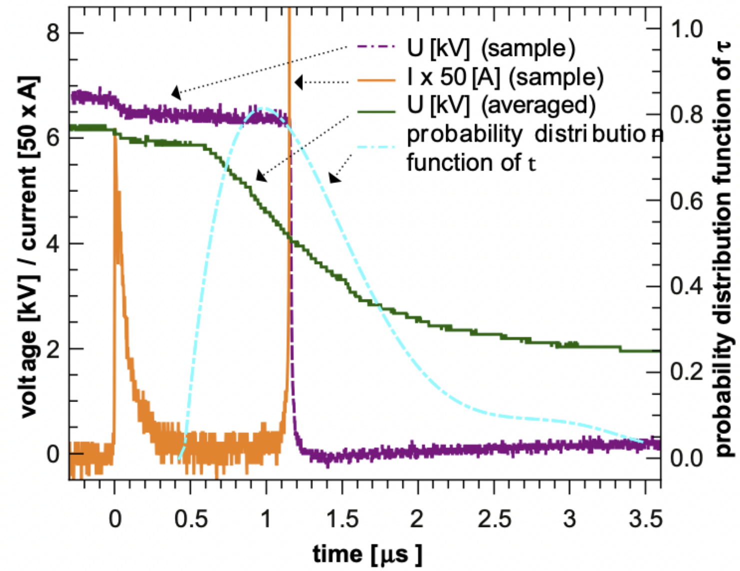


Figure 14. Images of the streamer and spark of a single TS pulse taken by iCCD camera, exposure 25 ns, acquisition started ~25 ns after the beginning of the streamer and spark, respectively, $r = 0.9\,\mathrm{k\Omega}$, $f \approx 2\,\mathrm{kHz}$, $R = 6.6\,\mathrm{M\Omega}$, $C = 32 \pm 4\,\mathrm{pF}$ and $d = 4\,\mathrm{mm}$.

Spark discharge formation (Janda, Machala 2016)

- The IV measurements of a pulsed spark discharge shed more lithght onto how it is formed.





- We see around 1.2 us, that if the discharge would not be stopped, the current would run away exponentially and an arc discharge would be formed.

- We also see the voltage decreasing, as the plasma is becoming ore conductive.

Spark discharge formation (Janda, Machala 2016)

- Measurements of electron density in spark plasma suggest that the plasma densities reach **full ionization**
- If the supply of power is not interrupted by the power supply at microsecond scales, the plasma will thermalize and an arc discharge will form.

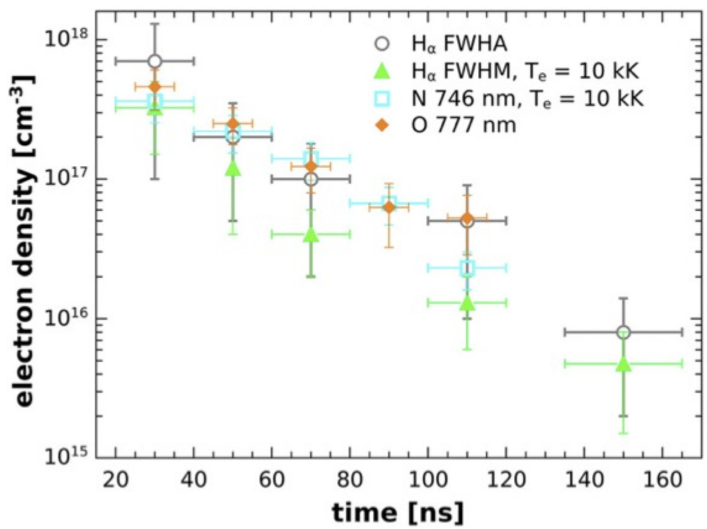


Figure 6. Comparison of electron density evolution after the beginning of the spark phase of the TS, calculated from the Stark broadening of H_α line, N line at 746 nm and O triplet near 777 nm, $f \sim$ 1–2 kHz.

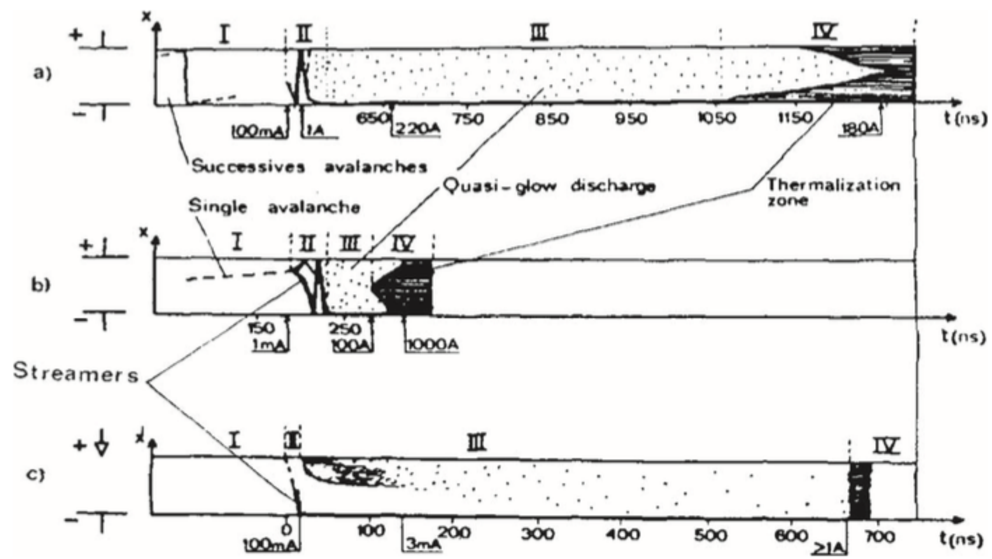
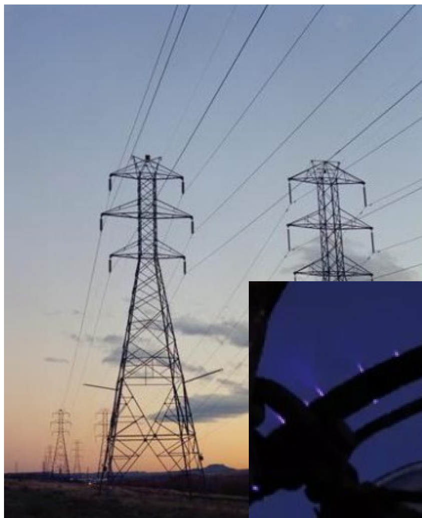


Figure 1. Comparison between typical streak photographs of the spark formation in different cases according to Marode [96]. (a) Uniform field gap: nitrogen, pulsed gap with small overvoltage (7.55%), generation mechanism, p = 300 Torr, d = 2 cm (after Doran in [97]), (b) uniform field gap: nitrogen, pulsed gap with high overvoltage (35%), streamer mechanism, p = 300 Torr, d = 2 cm, (after Koppitz [98] and Chalmers and Duffy [99], (c) non-uniform field gap: air, DC potential, p = 760 Torr, d = 1 cm, point radius 100 μm (after Marode [28]). The picture is taken from [96].

APPLICATION OVERVIEW

Corona discharge applications

- Corona discharge is often unwanted, appearing on high voltage components where it induces loss power.
- One major application are **electrostatic precipitators**. In these devices, corona discharge softly charges microparticles of combustion products so that they can be captured and not contaminate the environment.



Peek's Formula:

$$P_L = 241 \text{ X } 10^{-5} \left(\frac{f+25}{\delta}\right)\left(\frac{\mathrm{r}}{\mathrm{d}}\right)^{\frac{1}{2}}(V_o - V_c)^2 \ \text{kW/Km/ phase}$$

Loss power on HV lines

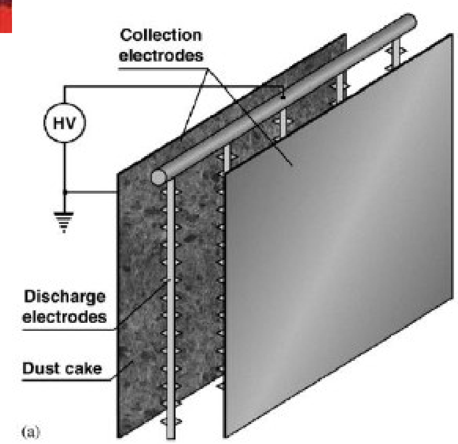
Deutch-Anderson efficiency:

$$E = 1 - e^{-(wA/q)}$$

flow rate

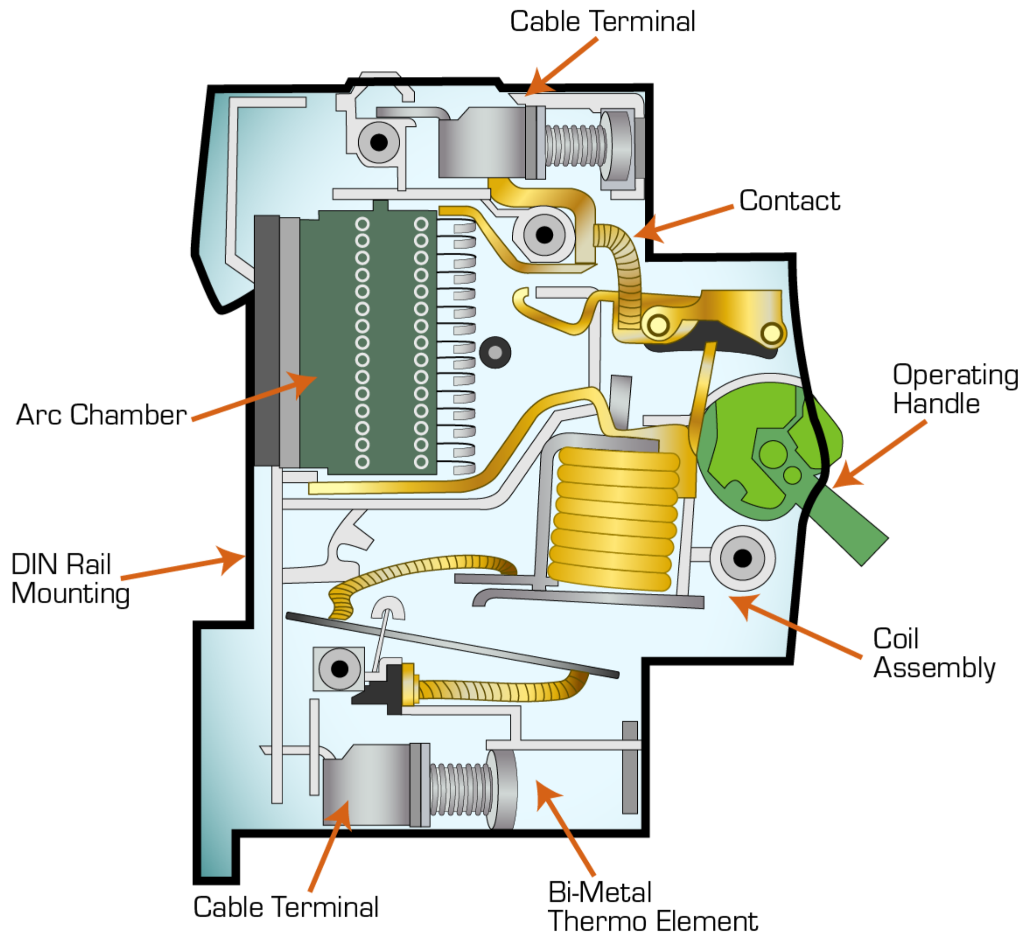
Drift of a charged microparticle

$$w = \frac{q_{\mathrm{p}} E_{\mathrm{p}}}{6(\pi)\mu r}$$



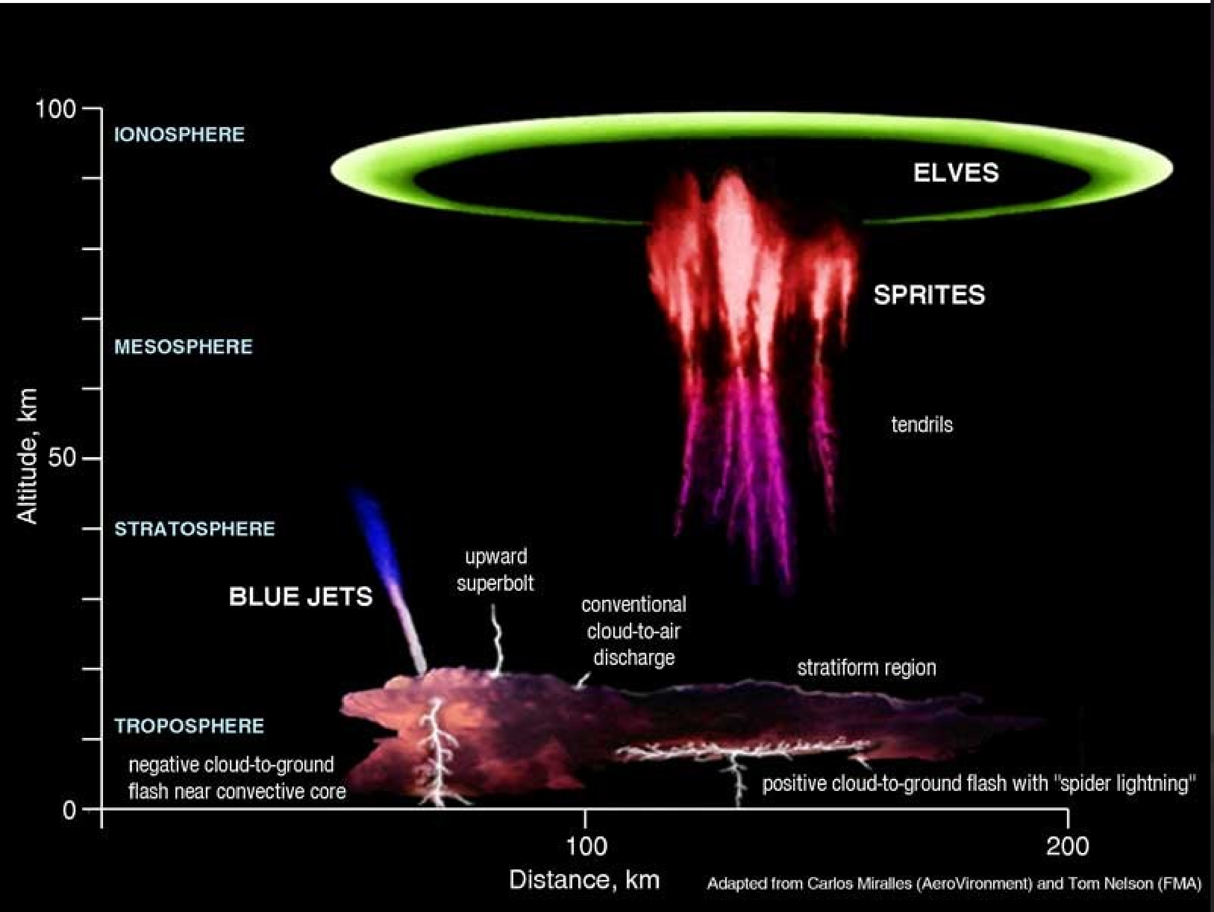
Spark discharge applications

- Historically spark plugs… we all know where that is going ☺
- Understanding of sparks, Trichel pulses, etc.. is still super important in circuit breakers because it affects how fast you are able to switch current on/off in the grid.



Streamer „applications“

- Understanding streamers is absolutely crucial in geophysics, biophysics and planetary plasmas.
- Thanks to the, we can understand upper atmospheric lighting
- They also help to elucidate how life started to form – plasma was one of the “activation channels” converting inorganic molecules to organic ones.



Takeaways

- What is a streamer, positive and negative
- What are the main physics phenomena
- What happens when a streamer reaches a counter-electrode
- The few applications of streamers and their importance for fundamental science.