Please connecting to the Rain Classroom

Department of Electrical Engineering
Tsinghua University

High Voltage Engineering

Spring 2025, Lecture 2

Xidong LIANG

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- The large-scale transmission of electrical energy is the foundation for the widespread application of electrification
- **HV power transmission** is the most important technology to achieve large-scale transmission of electrical energy

- The long-distance bulk power transmission require HV
- The instantaneous balance between electricity production and consumption requires a big power grid (based on HV)
- Various HV power equipment are the material base of HV power grid
- The biggest application scenario of HV technology is the HV power grid

What are the special problems under HV and high electric stress?

Special problems under high voltage and high electrical stress

- ✓ Mastering scientific principles
- ✓ Understand technical measures
- ✓ Understanding Engineering Specifications

Chapter 1 Analysis of Gas Discharge Process

1.1 Charged particle and gas discharge

1.2 Townsend's theory and Paschen's law of self-sustained discharge in a uniform electric field under low gas pressure

1.3 Streamer of self-sustained discharge in a uniform electric field under high gas pressure

1.4 Development process of gas breakdown in non-uniform electric field under high air pressure

- Research on HV starts from phenomena observation, analyze results, speculate reasons, verify conclusions, and determine the causality of experimental conditions and phenomena/results

What is the relation between gas discharge and HV?

What is low-pressure here for?

Any special phenomena and processes?

Special principles?

Special means?

……

Ask more question to yourself

Core concepts of this chapter:

collision ionization, self-sustained discharge, Townsend discharge, Paschen's law, electron avalanche, streamer, leader, corona discharge, polarity effect, long gap discharge

Chapter 1 Analysis of Gas Discharge Process

1.1 Charged particle and gas discharge

- The holding of HV depends on the effectiveness of insulation.
- Air is the most widely used and the cheapest insulation material, so bare conductor is used for HV OHL (over head transmission line)
- Gas discharge is a unique phenomenon of gas under high electric stress

- Understanding of HV starts from the appearance of discharge phenomena

How many types of gas discharge have you ever seen?

1.1 Charged particle and gas discharge

- The phenomenon of a certain amount of charged particles flowing in gases under electric stress is called as ***Gas Discharge***.
- **Gas** that is in a normal state and isolated from various external ionization factors is completely ***non-conductive***, but there will always be various radiations from space in the air, and there will always be a small number of ***charged particles***.

- Generally, there are about 500-1000 electron-ion pairs/cm^3 in air. However, due to the extremely small number of the charged particle and its poor conductivity, air is still a high-performance insulator.

1.1 Charged particle and gas discharge

When a sufficiently high voltage applied to the gas gap, the current flowing through the gap increases sharply, and the gas gap loses its insulation ability.

This change from insulating state to conducting state is called electrical breakdown.

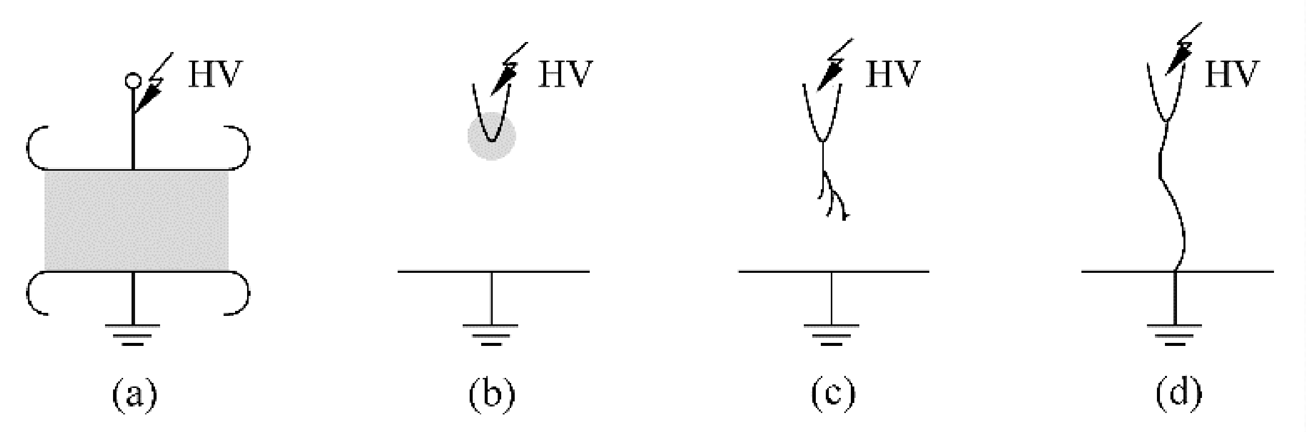
Is current flowing through the gap (whatever the current value) always means breakdown?

1.1 Charged particle and gas discharge

1.1.1 Main forms of gas discharge

Starting from physical phenomena, explore principles and laws, and speculate on the next...

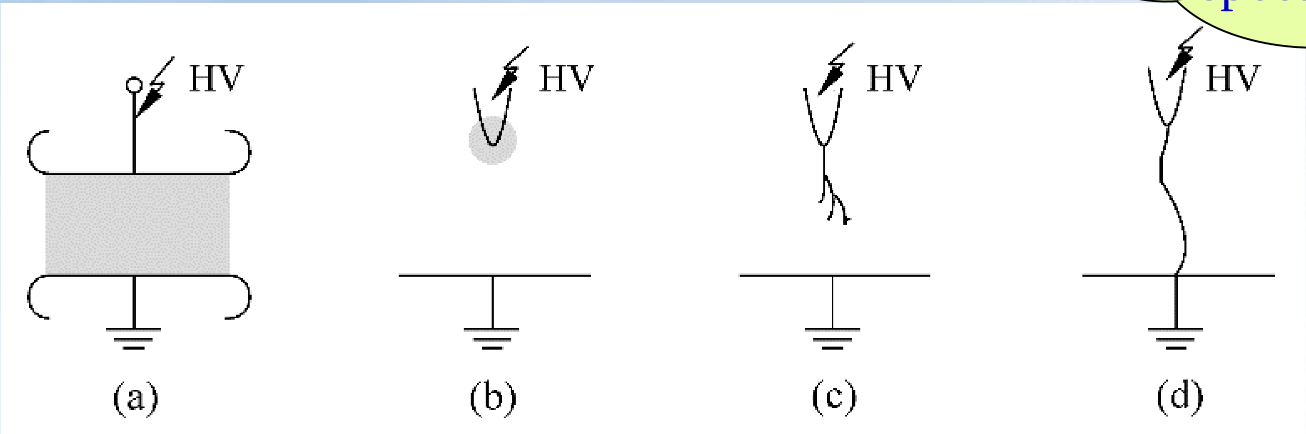
Because of the differences in gas pressure, electric field distribution, and power supply on the gas gap between electrodes, gas discharge before and after air gap breakdown usually present different features.



1.1 Charged particle and gas discharge

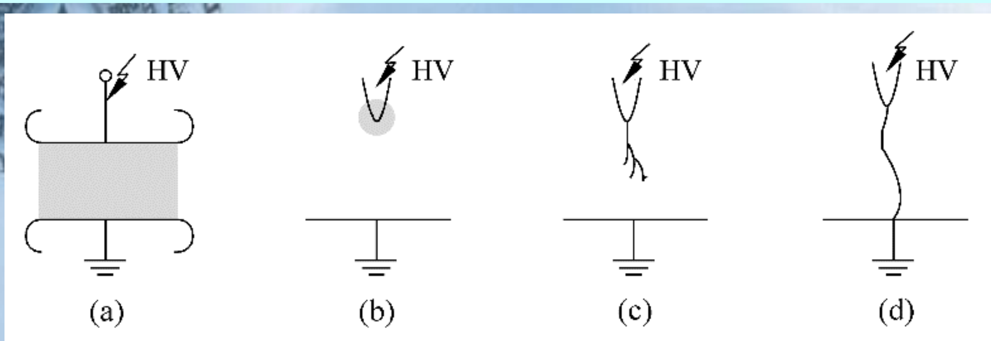
1.1.1 Main forms of gas discharge

Starting from physical phenomena, explore principles and laws, and speculate on the next...

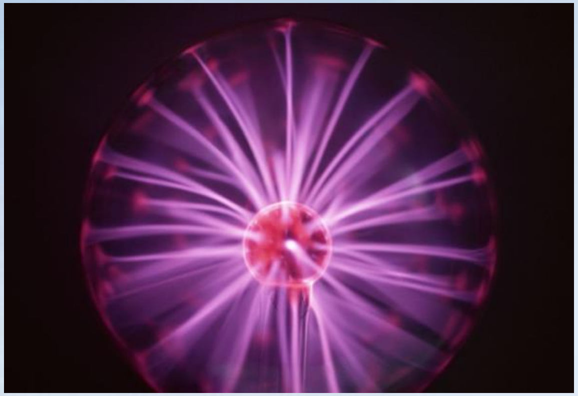


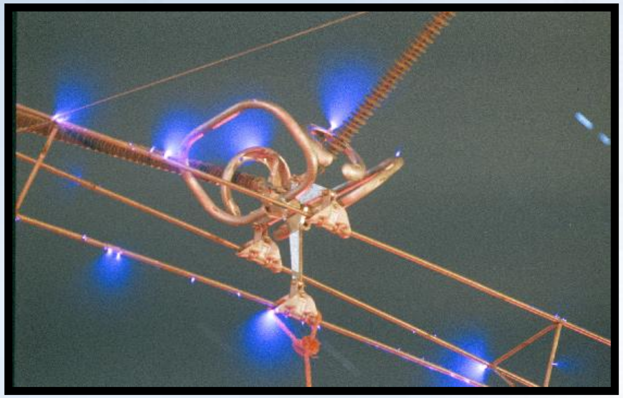
	Low gas pressure (<<1 atmosphere)	High gas pressure (≥1 atmospheric pressure)
Uniform electric field	glow discharge	sparkover discharge, arc discharge
Extremely non-uniform electric field	glow discharge	corona discharge, brush discharge, sparkover discharge, arc discharge

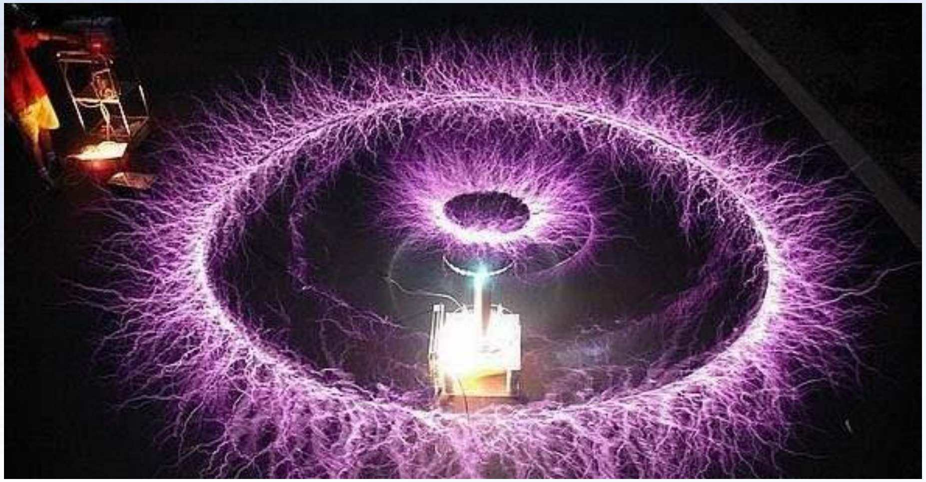
1.1 Charged particle and gas discharge

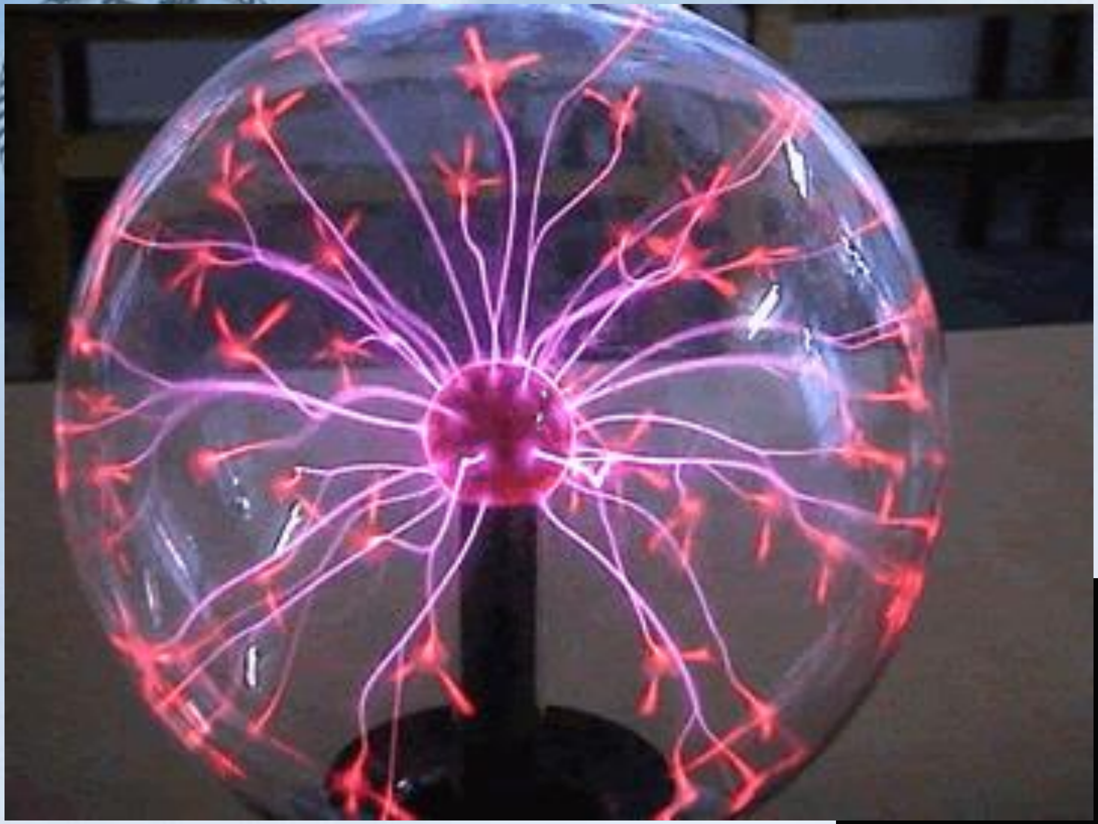


Discharge appearance and phenomenon

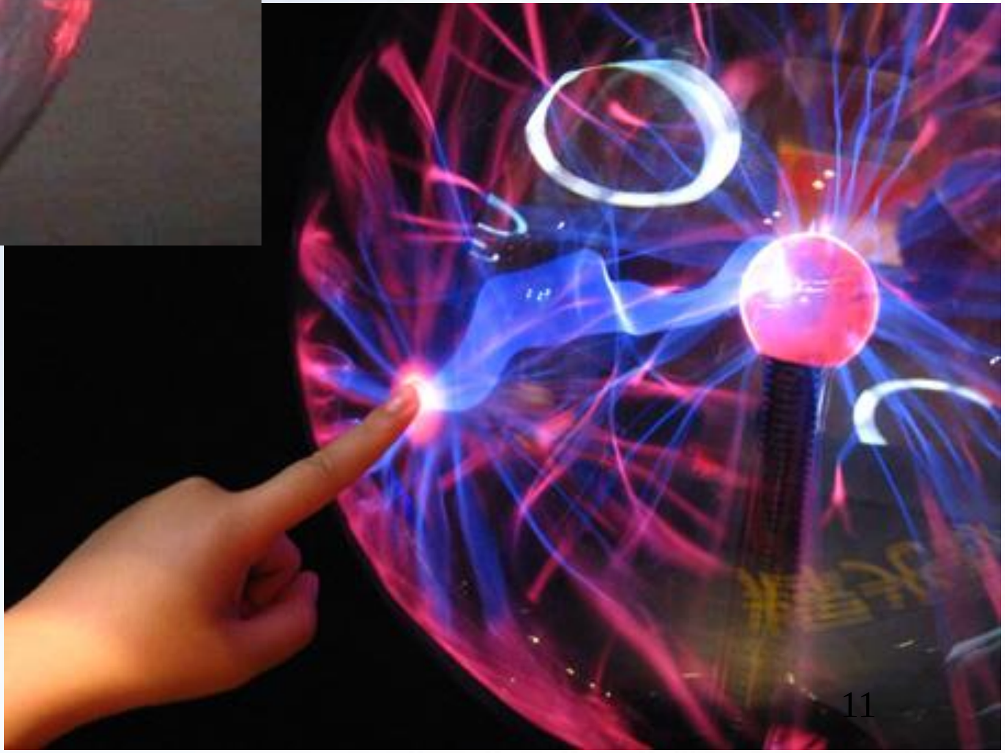


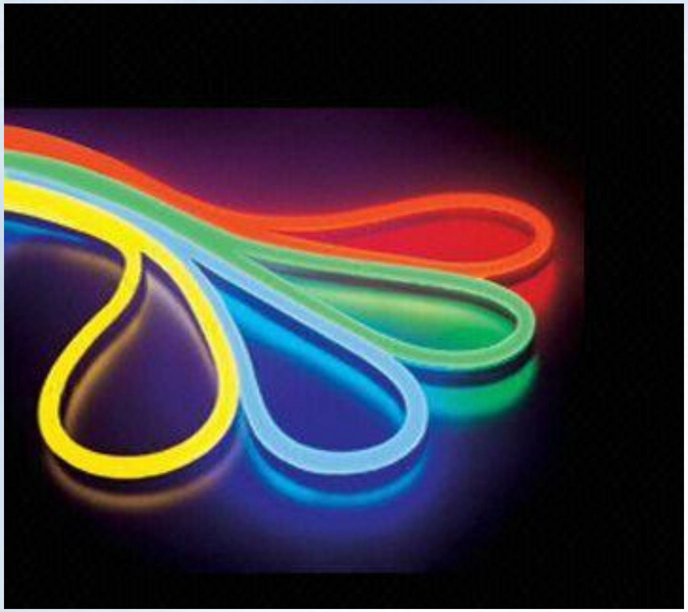




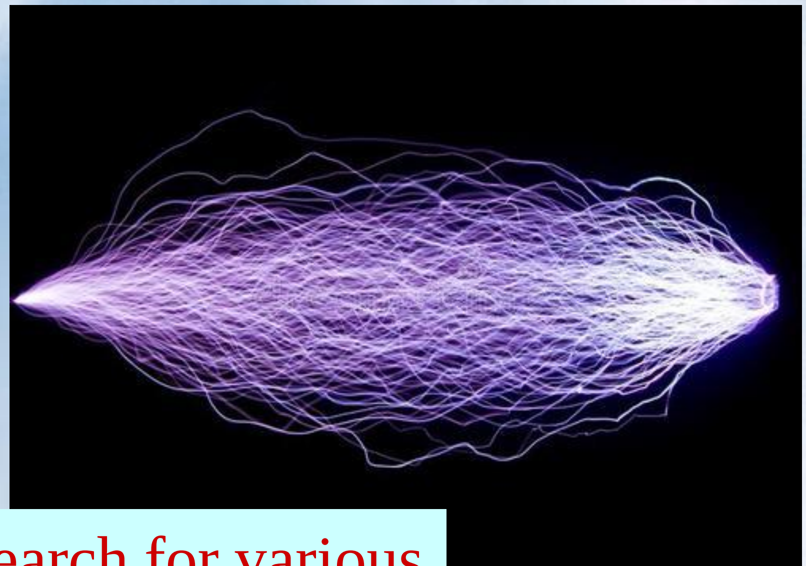


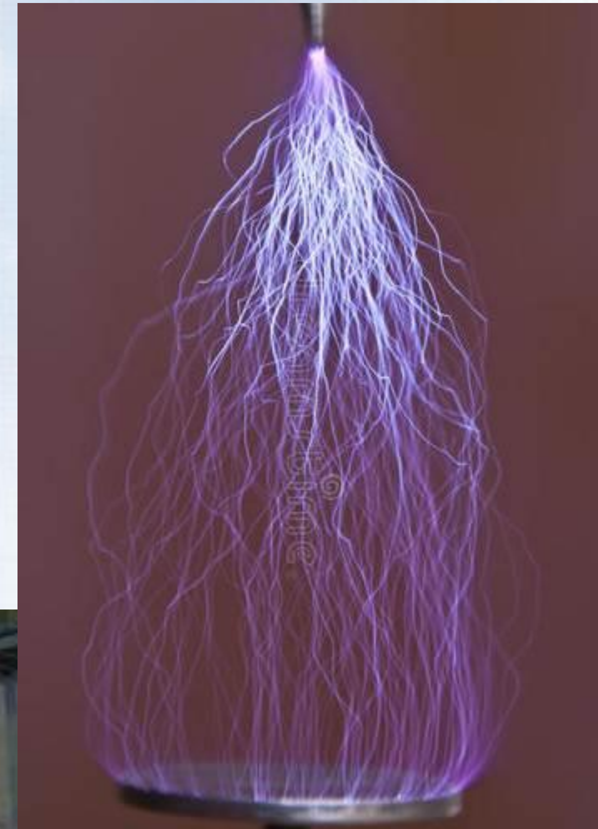
Low pressure glow discharge ball





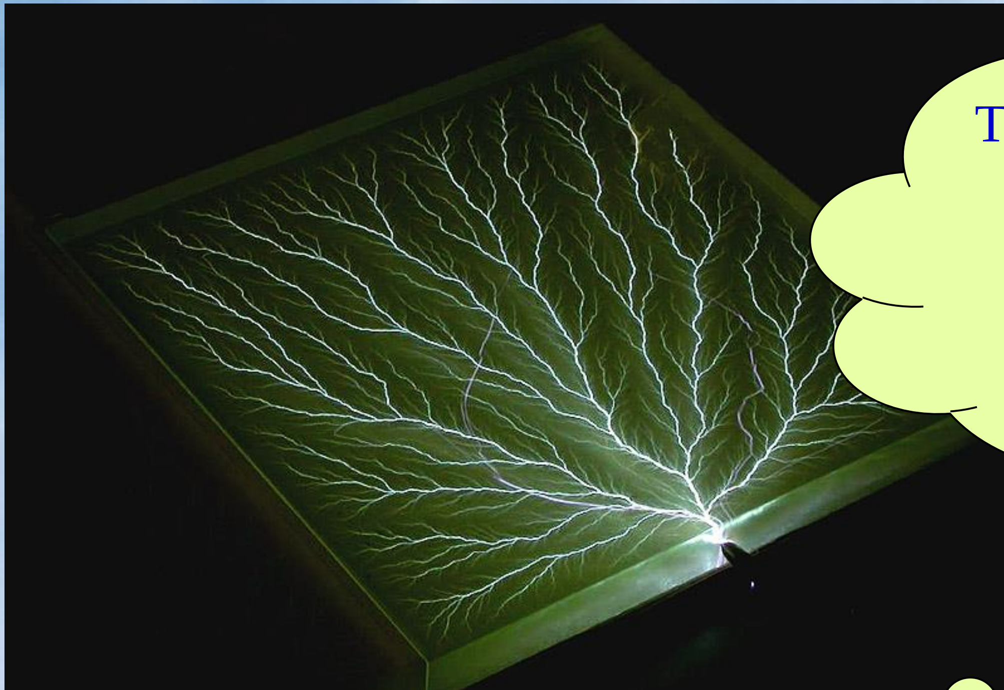
Glow discharge
in neon lights



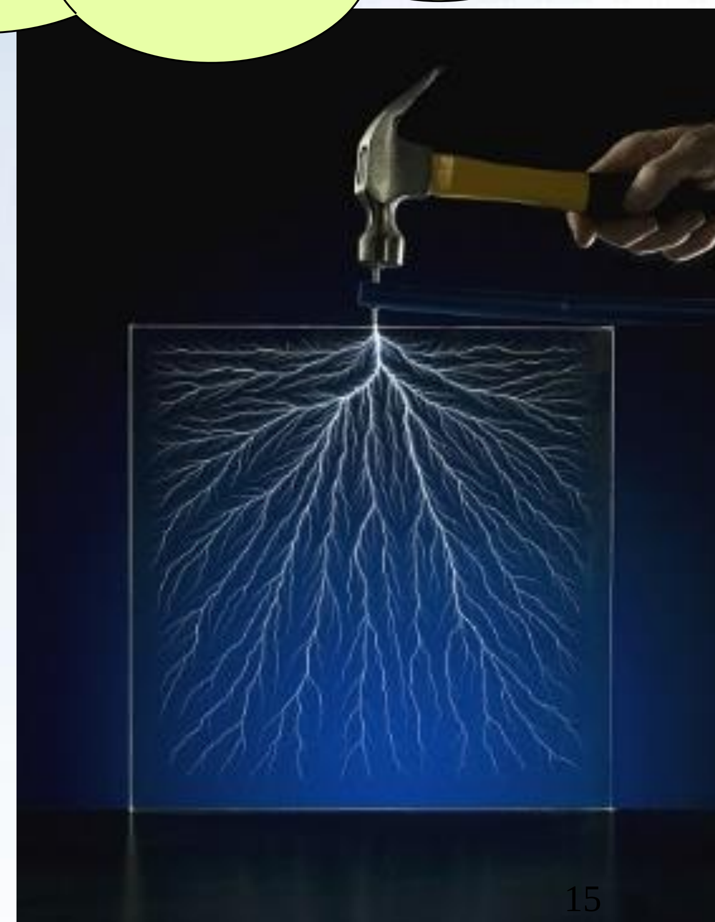


It is easy to search for various discharge phenomena

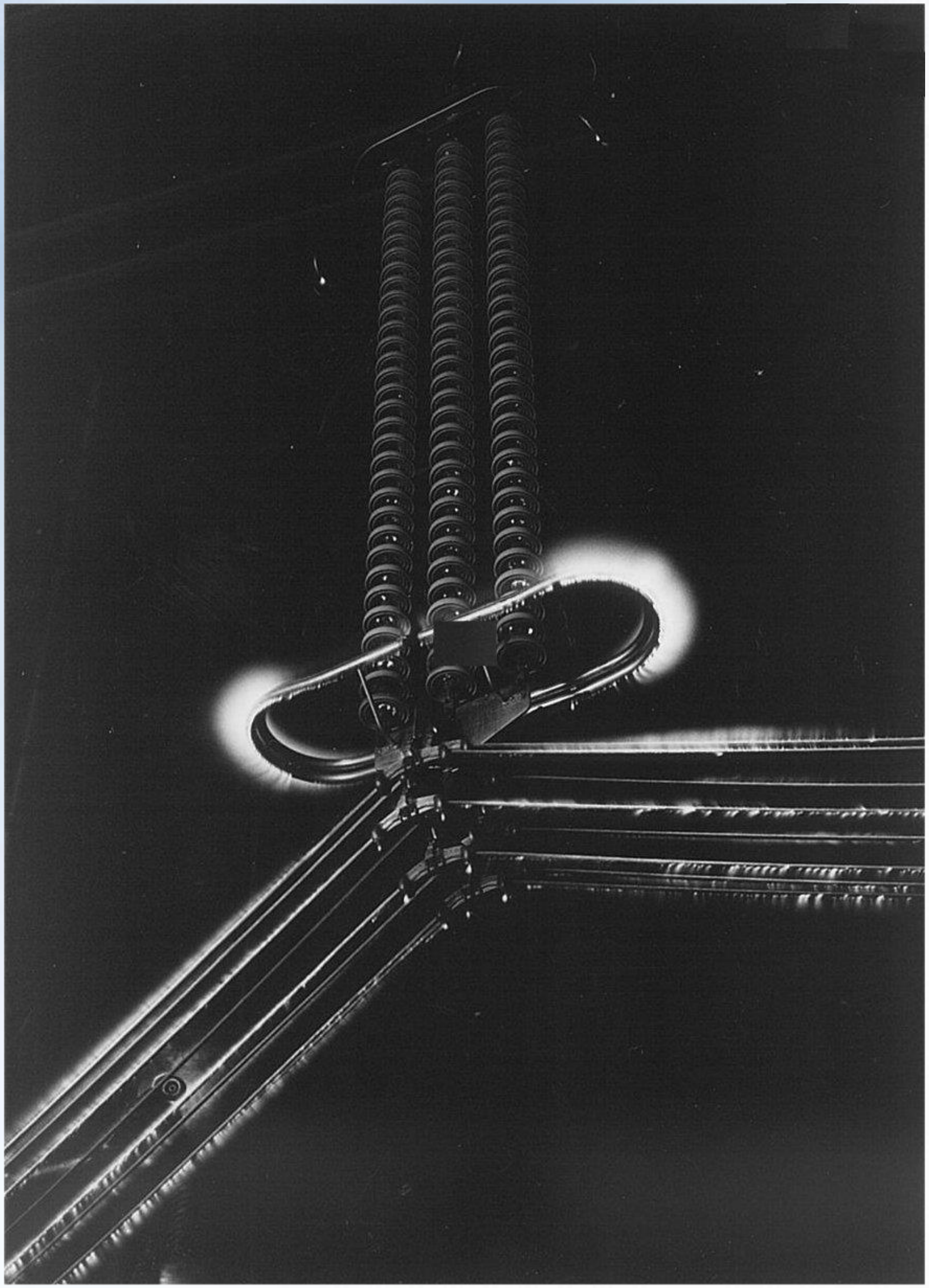
There are also a large number of carefully taken lightning discharge photos that you can search for and take a look at

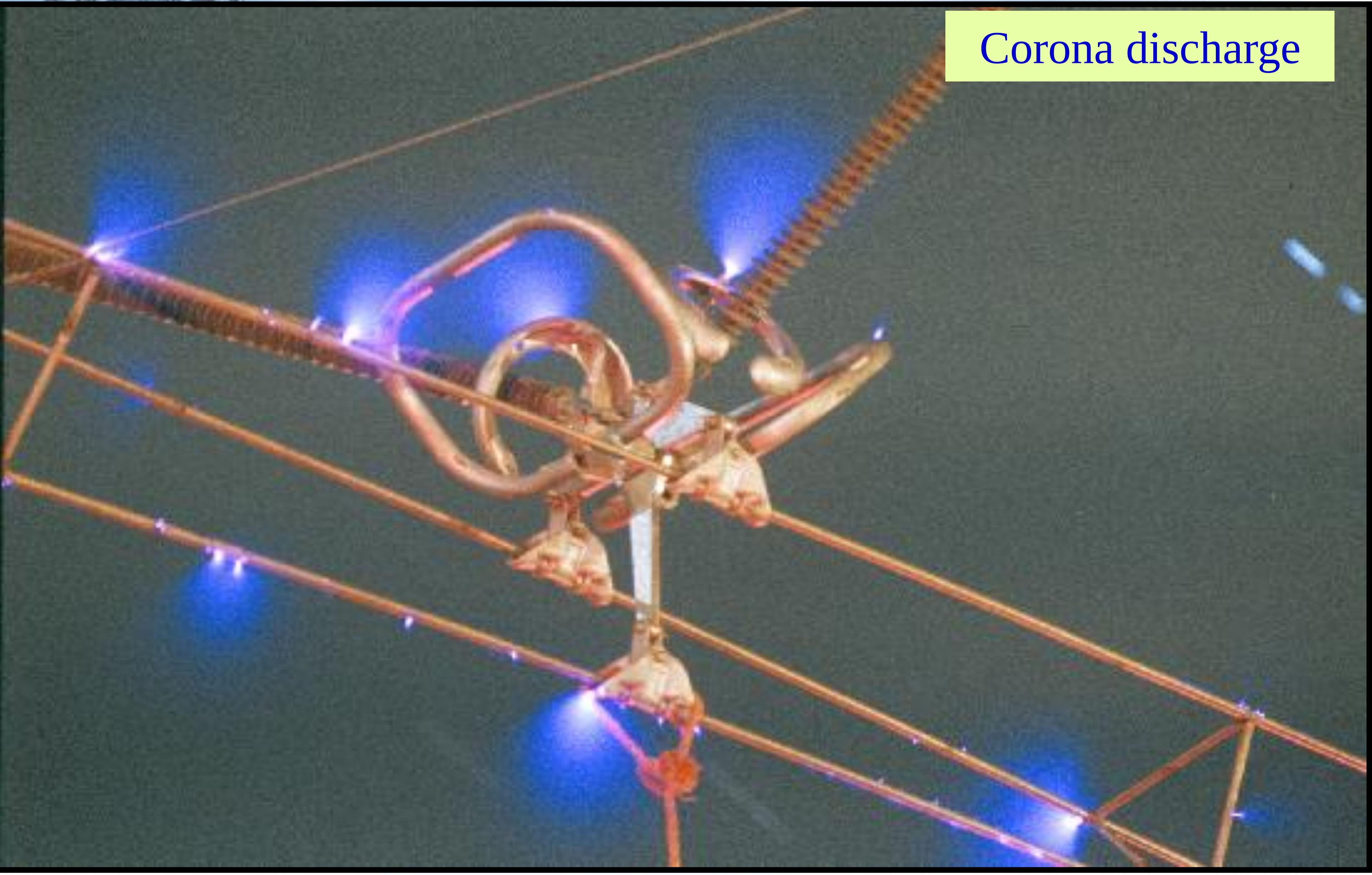


There are also a large number of artificially prepared exquisite pictures on high-voltage discharge, why not search for them



Corona discharge under high field strength around electrode edge/corner




Corona discharge

To observe discharge, high-voltage test halls generally do not have windows

Flashover of insulator gap (right)

and brush discharge before flashover (left)

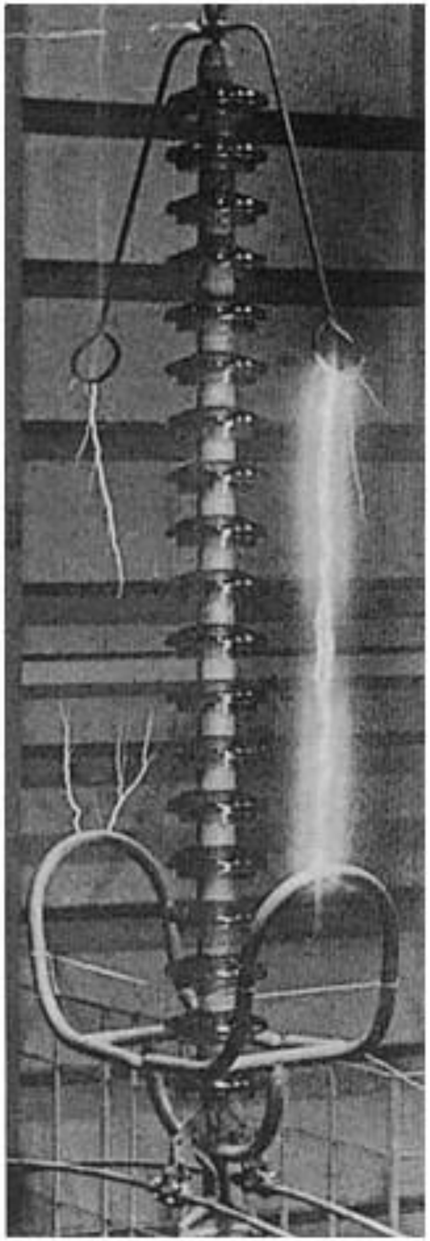
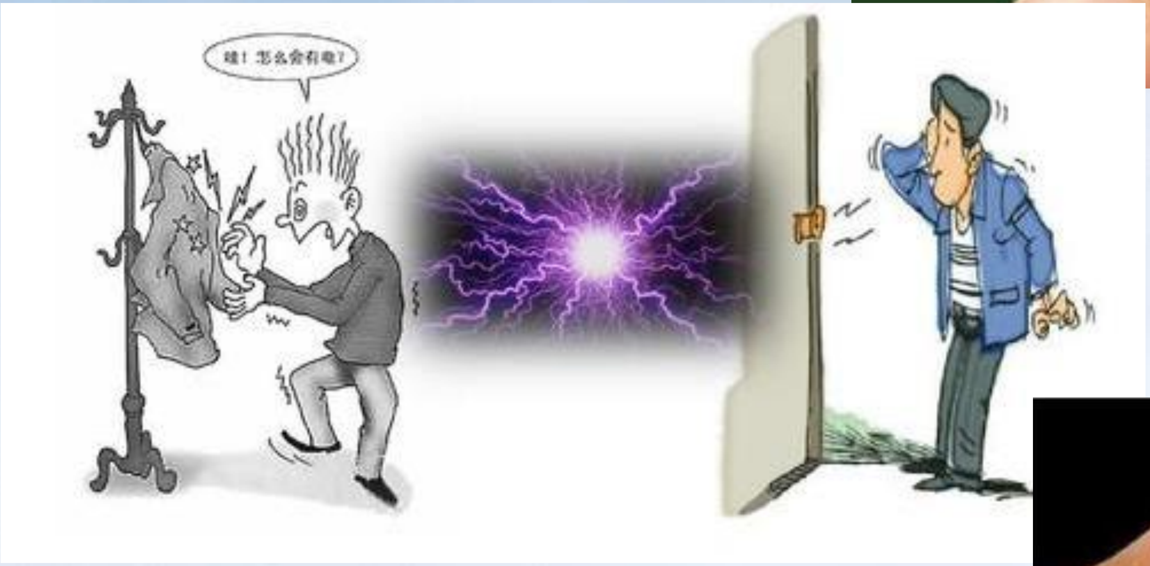


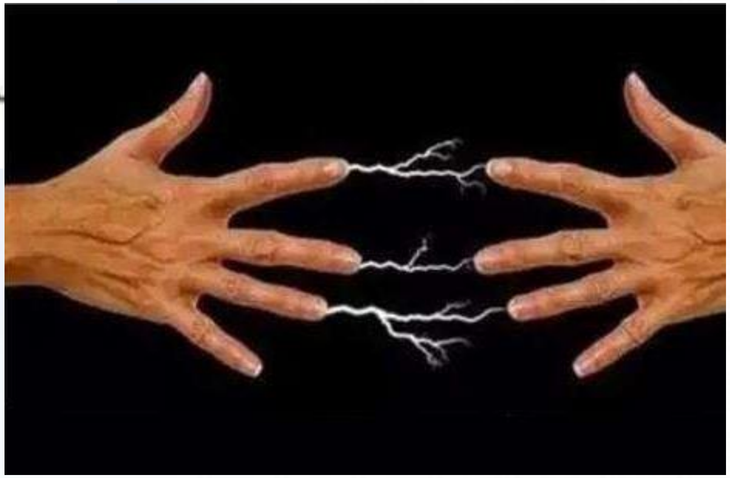
Figure 2.26 Line gap flashover

Air gap breakdown

Insulator surface pollution flashover (arc discharge)

There are various electrostatic discharges in daily life





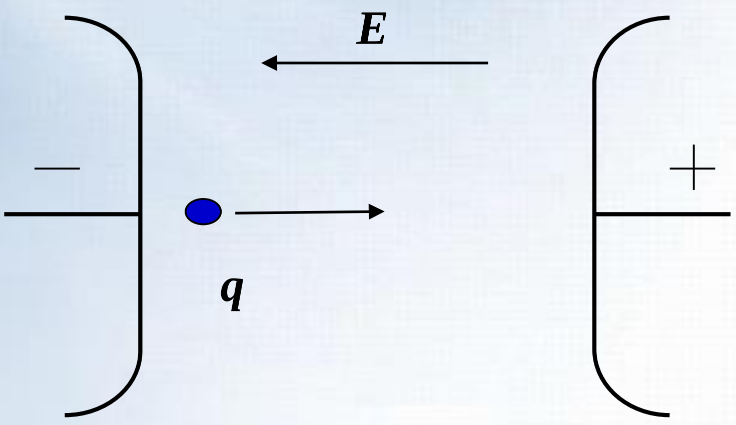
1.1.2 Generation of charged particle

Charge conservation! It cannot be created or destructed

1. Generation of charged particle in electrode gap space:

(1) Electron impact neutral ionization:

unique under high field strength



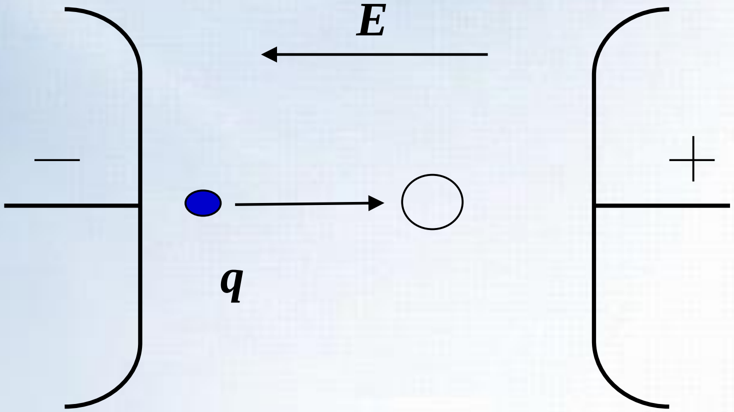
Due to the effect of electric field E, a charged particle with a mass of m and a charge of q is accelerated, and after moving along/against the direction of the electric field for a distance of x, it **obtains a certain amount of energy qEx** with a certain velocity v, converting the ***electric potential energy*** into ***kinetic energy of the charged particles.***

1.1.2 Generation of charged particle

Charge conservation! It cannot be created or destructed

1. Generation of charged particle in electrode gap space:

(1) Electron impact neutral ionization: unique under high field strength



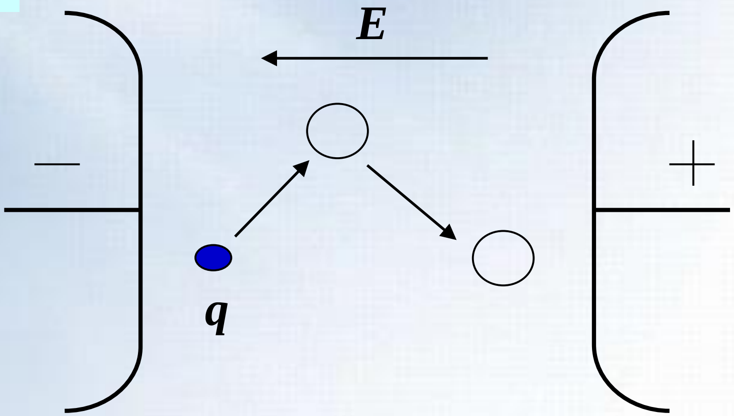
When the kinetic energy of a charged particles (energy obtained from an electric field) reaches or exceeds the ionization threshold energy W_i of a gas molecule, if it collides with the gas molecule, it is possible to ionize the molecule into electrons and positive ion. The condition for collision ionization is expressed by the formula as $\frac{1}{2}mv^2 \geq W_i$

When charged particles obtain enough energy from the electric field, they will collide and ionize with neutral gas molecules

1.1.2 Generation of charged particle

1. Generation of charged particle in electrode gap space:

(1) Electron impact neutral ionization: unique under high field strength



The probability of ionization caused by each collision is very small. Most of the collision are elastic collision.

Free path: The distance at which a particle freely passes between every two collisions.

Mean free path λ: The average free path of numerous charged particles

$\lambda = KT / [\pi(r_1 + r)^2 p]$

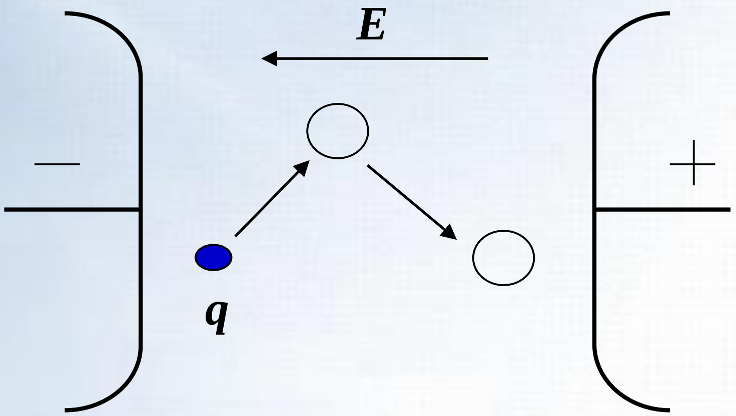
Mean free path λ

If the mean free path λ is large, the accumulated kinetic energy is also high, which can more easily lead to gas ionization.

1.1.2 Generation of charged particle

1. Generation of charged particle in electrode gap:

(1) Electron impact neutral ionization: unique under high field strength



In a gas ionization, ionization is mainly caused by ***electrons*** (rather than negative ions). At room temperature and under normal air pressure, the mean free path of electrons in the air is on the order of 10^{-5} cm

$$\lambda = KT / [\pi(r_1 + r)^2 p]$$

1.1.2 Generation of charged particle

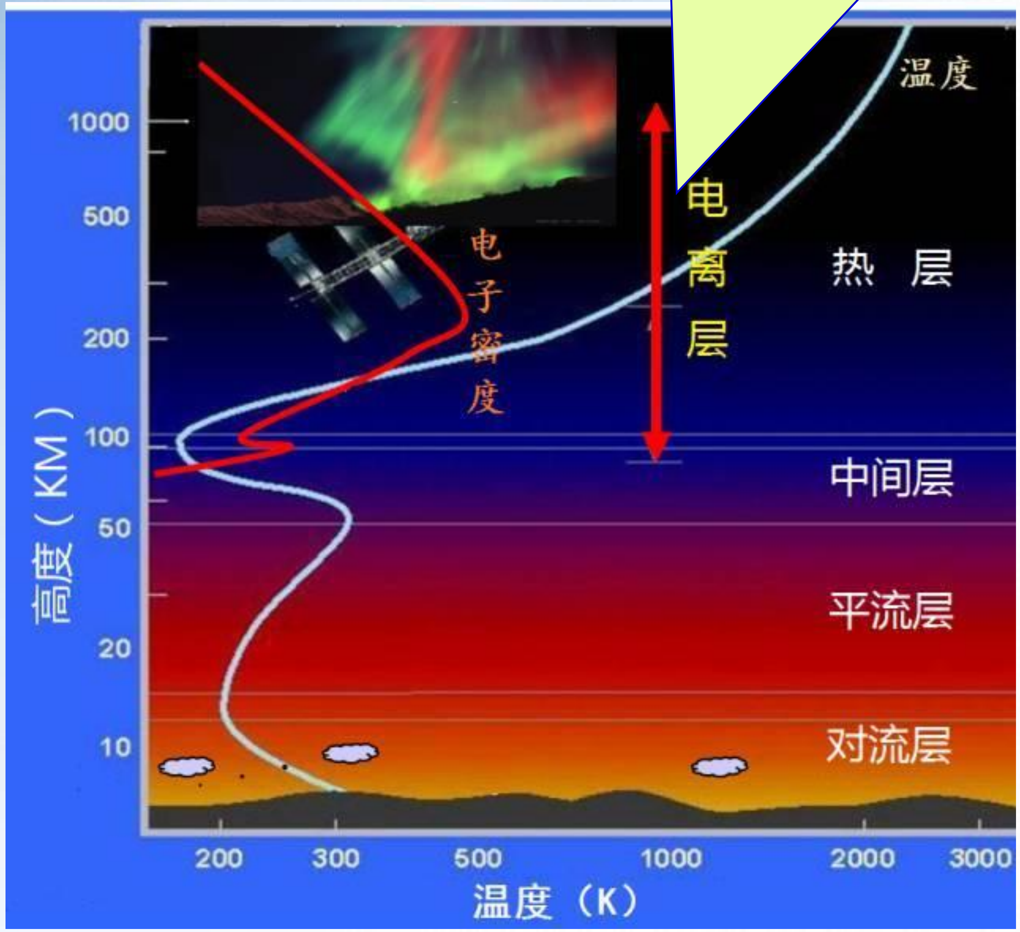
Atmosphere: troposphere, stratosphere, neutral layer, ionosphere...

1. Generation of charged particle in electrode gap:

(2) Photo-ionization

When gas molecules are exposed to light radiation, if the photon energy W is greater than the ionization threshold energy W_i of the gas molecule, it may cause the photo-ionization:

$$W = h f = hc / \lambda \geq W_i$$



Thus, the critical wavelength that causes photoionization can be obtained $\lambda_0 = hc / W_i$

1.1.2 Generation of charged particle

1. Generation of charged particle in electrode gap:

(2) Photo-ionization

The ionosphere of the Earth is the upper atmosphere ionized by high-energy solar radiation and cosmic rays.

R. Marskar, Plasma Sources Sci. Technol. 33 025024 (2024)

1.1.2 Generation of charged particle

1. Generation of charged particle in electrode gap:

(2) Photo-ionization

The critical wavelength that causes photoionization can be obtained $\lambda_0 = hc / W_i$

Table 1-2 Ionization potentials and photoionization critical wavelengths of several gases

Gas or metal vapor	O_2	H_2O	CO_2	H_2	N_2	Air	He
Ionization potential (V) or ionization energy (eV)	12.2	12.7	13.7	15.4	15.5	16.3	24.6
Photoionization critical wavelength (nm)	102	97.7	90.6	80.6	80.1	76.2	50.4

Ordinary sunlight reaching the ground ($\lambda \geq 290$nm) is far from sufficient to cause photoionization of gas molecules

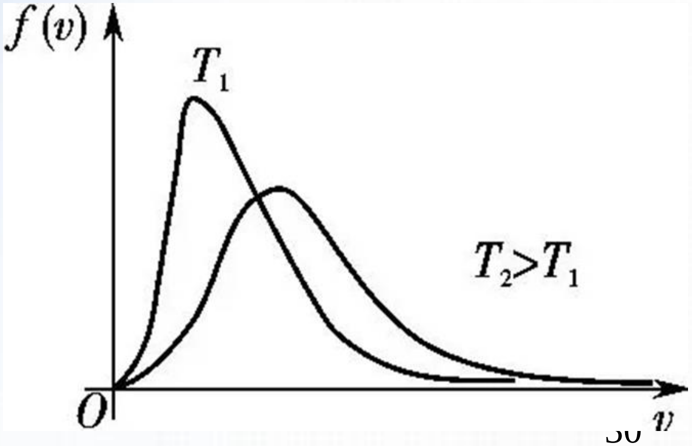
1.1.2 Generation of charged particle

1. Generation of charged particle in electrode gap:

(3) Thermal ionization

Ionization caused by the thermal state of a gas is called ***thermal ionization***. The essence of thermal ionization is still the collision ionization and photoionization of rapidly moving gas molecules, but its energy does not come from the electric field, but from the thermal energy of the gas molecules themselves.

- Gas temperature is the indicator of the intensity of thermal motion of gas molecules.

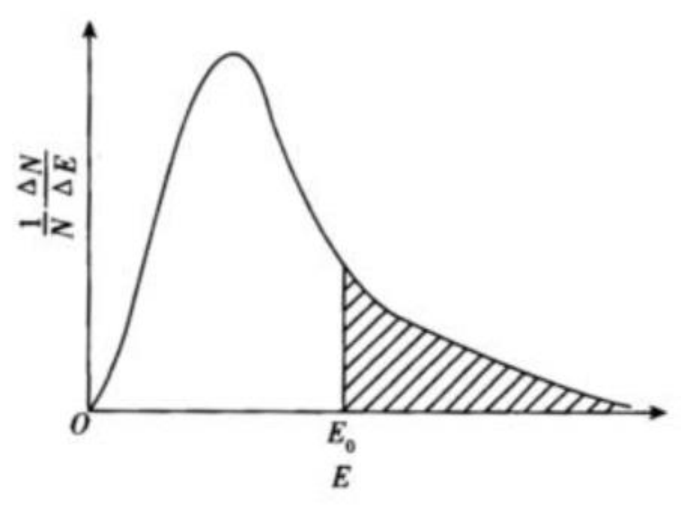


1. Generation of charged particle in electrode gap:

(3) Thermal ionization

- At room temperature, the average kinetic energy of gas molecules $W_m \approx 3.88\times10^{-2}$ eV is much smaller than the ionization energy of air W_i =16.3 eV, which is far from enough to cause air ionization.

- When an arc discharge occurs, the gas temperature can reach several thousand degrees centigrade or above. At this time, high-energy molecules with fast thermal motion in the gas can cause ionization through collision or radiation.

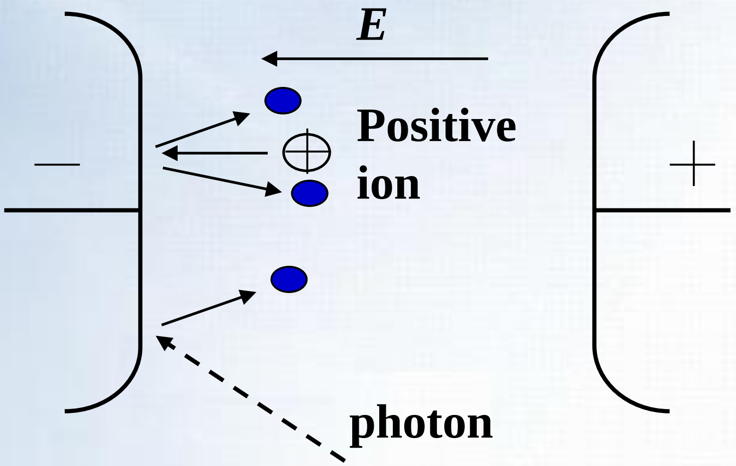


1.1.2 Generation of charged particle

2. Generation of charged particle from **electrode surface**:

(1) Positive ion induced cathode emission

- Positive ions driven by the electric force move towards the cathode until they collide with the cathode.
- If the kinetic energy of a positive ion is large enough to collide with two electrons, one electron recombines with the positive ion, and the other electron becomes a free electron (so-called secondary electron).



(2) Photoelectric effect (photon irradiation on cathode)

1.1.2 Generation of charged particle

Think about the current booming photovoltaic power generation

2. Generation of charged particle from electrode surface:

(2) Photoelectric effect (photon irradiation on cathode)

Injecting more energy into the cathode than the work function will cause the cathode to emit electrons (or equivalently, ionizing the cathode surface)

Table 1-3 Work function of Several Metals and Metal Oxides

Metal	Ce	Zn	Al	Cr	Fe	Ni	Cu	Ag	W	Au	Pt	CuO
Work function (eV)	1.88	3.30	4.08	4.37	4.48	5.24	4.70	4.73	4.54	4.82	6.30	5.34

1.1.2 Generation of charged particle

Table 1-3 Work function of Several Metals and Metal Oxides

Metal	Ce	Zn	Al	Cr	Fe	Ni	Cu	Ag	W	Au	Pt	CuO
Work function (eV)	1.88	3.30	4.08	4.37	4.48	5.24	4.70	4.73	4.54	4.82	6.30	5.34

Compared to gas, the cathode surface is more prone to be ionized (emission)

Table 1-2 Ionization potentials and photoionization critical wavelengths of several gases

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Photoionization critical wavelength (nm)	102	97.7	90.6	80.6	80.1	76.2	50.4

(2) Photoelectric effect (photon irradiation on cathode)

In 1922, Albert Einstein won the Nobel Prize in Physics in 1921 for his explanation of the photoelectric effect

- In 1887, Hertz conducted research on the speed, wavelength, reflection, and other aspects of electromagnetic waves, and concluded that ***light is electromagnetic waves***, providing the strongest evidence for the theory of light waves. However, when Hertz conducted experiments with different metal electrodes and light sources, it was found that **high-frequency ultraviolet light can enhance electric sparks**. Confusion!

- In 1902, Lerner discovered that each cathode metal in a photoelectric tube corresponds to a specific frequency, and *no photoelectric effect occurs when the incident light is less than that frequency*. But according to classical electromagnetic theory, the energy of light waves (electromagnetic waves) is determined by their **amplitude** and is independent of their **frequency**!
- Leonard proposed the "trigger theory", which believed that the energy emitted by photoelectrons came from the internal ultraviolet radiation of specific atoms and only had an excitation effect. He was awarded the Nobel Prize in Physics in 1905.

(2) Photoelectric effect (photon irradiation on cathode)

- In 1905, Albert Einstein proposed the concept of "***light quantum***", which states that "the energy of light emitted from a point light source is not continuously distributed in larger and larger spatial volumes during propagation, but is composed of a limited number of energy mass points concentrated at certain points in space. These energy mass points can move, but cannot be separated, and can only be absorbed or produced as a whole." Light is viewed as a quantum of light, seemingly returning to the theory of mass points, Causing widespread opposition.

- In 1916, Millikan's precise experiment confirmed that ***the slope of the function curve between the initial kinetic energy of photoelectrons and the frequency of light was exactly equal to the constant h used by Planck to explain blackbody radiation***. Einstein's photon hypothesis successfully explains the photoelectric effect and Compton effect (scattering experiment)!

1.1.2 Generation of charged particle

1. Generation of charged particle in **electrode gap**:

(1) Electron impact neutral ionization (high field strength)

(2) Photoionization (light generated by discharge or other reasons)

(3) Thermal ionization

2. Generation of charged particle from **electrode surface**:

(1) Ion induced cathode emission (unique to high field strength)

(2) Photoelectric effect (photon irradiation on the cathode, light generated by discharge or other reasons)

(3) Cathode thermionic emission

(4) Cathode field emission (under sufficiently high electric field stress at cathode surface)

Obtaining energy from an electric field, light, and heat source. In short, an external energy input generates charged particles!

Disappear of charged particles from gas gap:

Inflow into electrodes under electric field force, drift and diffusion of charged particles, and recombination of charged particles

- The process in which particles with different charges meet and undergo charge transfer, neutralization, and reduction to neutral particle is called ***recombination***.
- ***Light radiation*** occurs during the recombination process of charged particle.
- The higher the concentration of charged particle, the stronger the recombination. Therefore, ***a strong ionization zone is usually also a strong recombination zone***.

- Sometimes when *electrons collide with gas molecules*, not only do not ionize ***new electrons***, but instead the colliding electrons are adsorbed by the molecules to form ***negative ions***.
- After electrons are captured by molecules and form negative ions, the ionization ability is greatly reduced. ***The formation of negative ions plays a role in hindering a discharge***.

Chapter 1 Analysis of Gas Discharge Process

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1.3 Streamer of self-sustained discharge in a uniform electric field under high gas pressure

1.4 Development process of gas breakdown in non-uniform electric field under high air pressure

Core concepts of this chapter:

collision ionization, self-sustained discharge, Townsend discharge, Paschen's law, electron avalanche, streamer, leader, corona discharge, polarity effect, long gap discharge

1.2 Townsend's theory and Paschen's law of self-sustained discharge in a uniform electric field under low gas pressure

1.2.1 Townsend's theory

Self-sustained discharge and its criterion,

electron avalanche, collision ionization coefficient α, γ and its process

1.2.2 Paschen's law and uniform electric field breakdown voltage

Paschen's Law and the breakdown voltage of a uniform electric field

1.2.3 Applicable range of Townsend's theory

● At the beginning of the 20th century, British physicist **J. S. Townsend** proposed a gas discharge theory based on collision ionization through extensive experiments

● Before Townsend's theory was proposed, German physicist **F. Paschen** summarized the Paschen's law of gas gap breakdown voltage from a large number of experiments

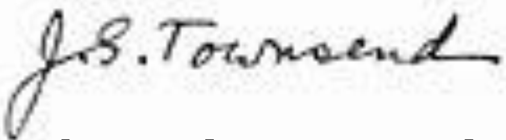
1.2 Townsend's theory and Paschen's law of self-sustained discharge in a uniform electric field under low gas pressure

1.2.1 Townsend's theory

Background: cathode ray, Rontgen X ray,
J.J.Thomson discover electron
J.S.townsend study electrical conductivity of gases

At the Cavendish laboratory, he studied under J. J. Thomson. He developed the "*Townsend's collision theory*". Townsend supplied important work to the electrical conductivity of gases ("Townsend discharge" circa 1897).

Works:
The Theory of Ionisation of Gases by Collision (1910)
Motion of Electrons in Gases (1925)
Electricity and Radio Transmission (1943)
Electromagnetic Waves (1951)

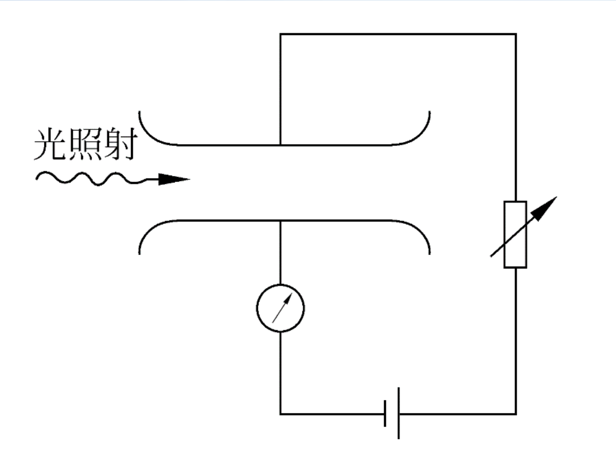


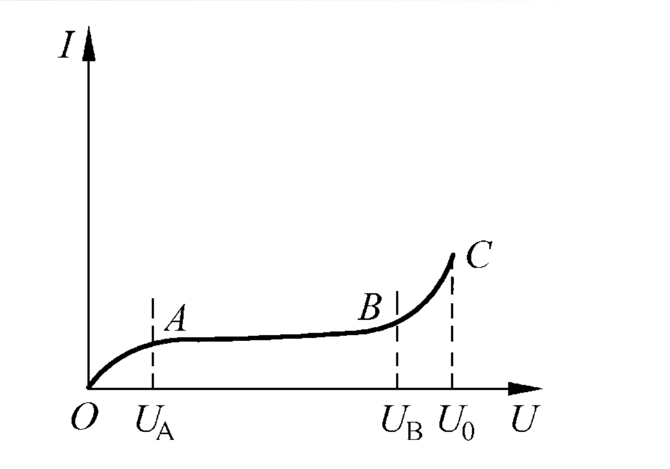
John Sealy Townsend
(1868.6.7–1957.2.16)

1.2.1 Townsend's theory

New phenomenon Townsend faced:

- The current from O to B is easy to understand. But the current increase significantly from B to C. Why? There should be some new ionization factor.
- When applied voltage is less than U_0, and the external ionization factor is removed, the current disappears (*why*?)

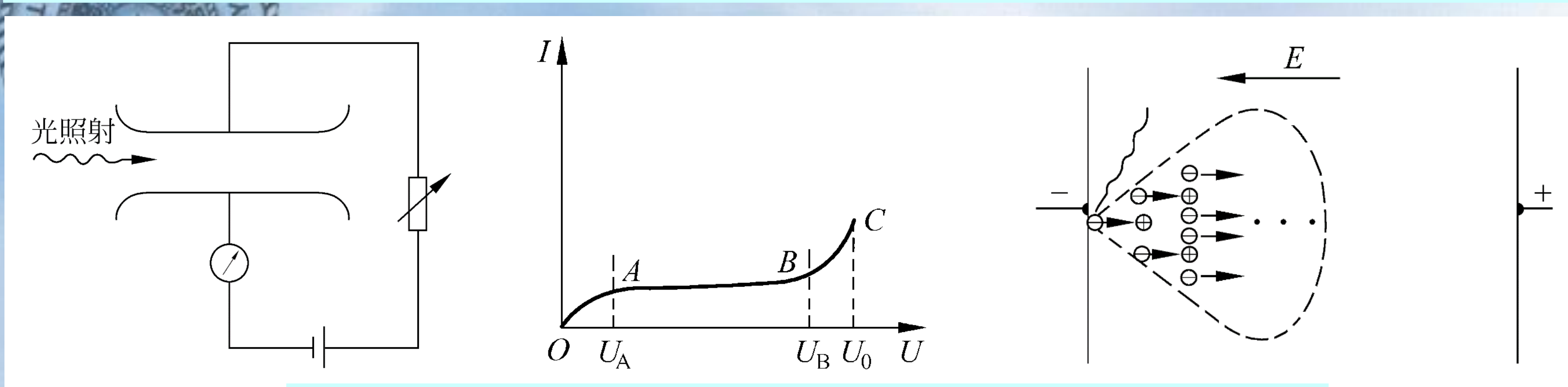




Introducing "self-sustained discharge": When the applied voltage reaches U_0, the discharge can keep continue and the current can be maintained whatever the external ionization factor is on or removed (*Why*?).

U_0 is called the self-sustained discharge voltage

1.2.1 Townsend's theory



Schematic diagram of electron avalanche formation

Introducing “electron avalanche”: The electron avalanche caused by collision ionization allows the initial electrons to multiple significantly in the electric field. Therefore the current increase significantly from B to C.

Introduce "electron collision ionization coefficient α": the average number of collision ionization occurred when an electron travels of 1cm along the field. If each collision ionization only produces one new electron, α represents the number of new produced electrons per unit length path in the direction of electric field from one electron.

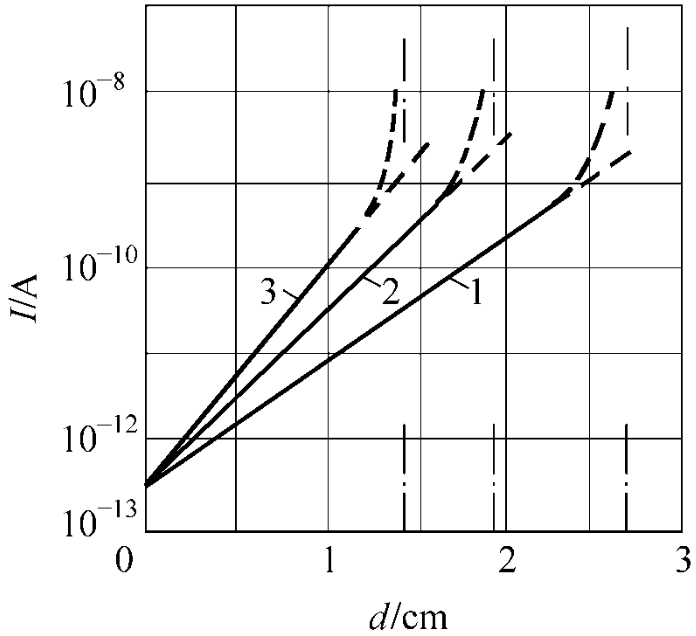
According to the definition of coefficient α, $\mathrm{d}n = n\alpha\,\mathrm{d}x$ or $\mathrm{d}n/n = \alpha\,\mathrm{d}x$, the integral can be obtained as $n = n_0\,\mathrm{e}^{\alpha x}$, then the current in the external circuit is $I = I_0\,\mathrm{e}^{\alpha d}$

1.2.1 Townsend's theory

From the electron collision ionization coefficient, it can be inferred that the external circuit current for collision ionization is

$$I = I_0 e^{\alpha d}$$

It could be checked through experiment !

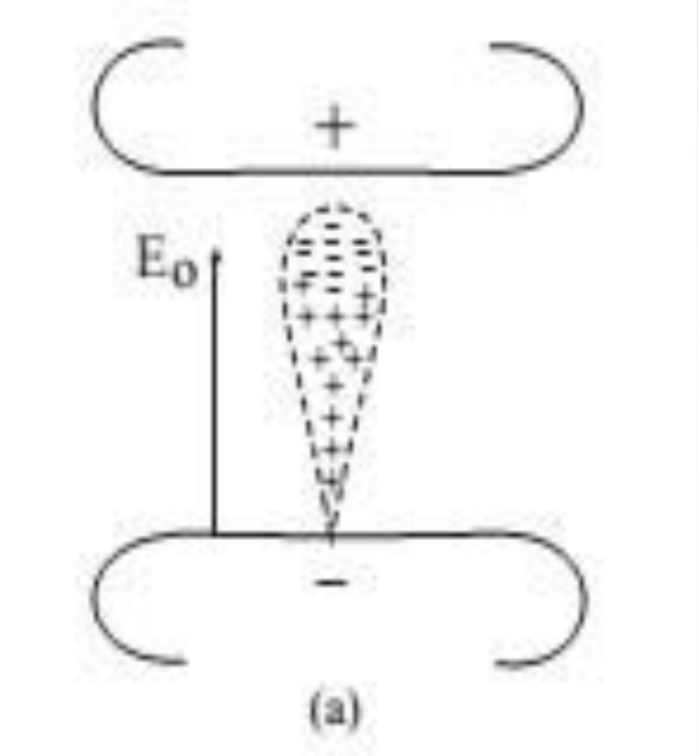


The experimental results are shown in the logarithm figure (straight line segment), which supports the hypothesis of collision ionization.

The slope of the straight line in the figure represent the collision ionization coefficient α

$$\alpha = \frac{1}{d_2 - d_1} \ln \frac{I_2}{I_1}$$

The coefficient α can be easily obtained from the current in the straight line segment of the graph



Actual
electron avalanche
captured

Schematic diagram of
electric charge distribution in
electron avalanche

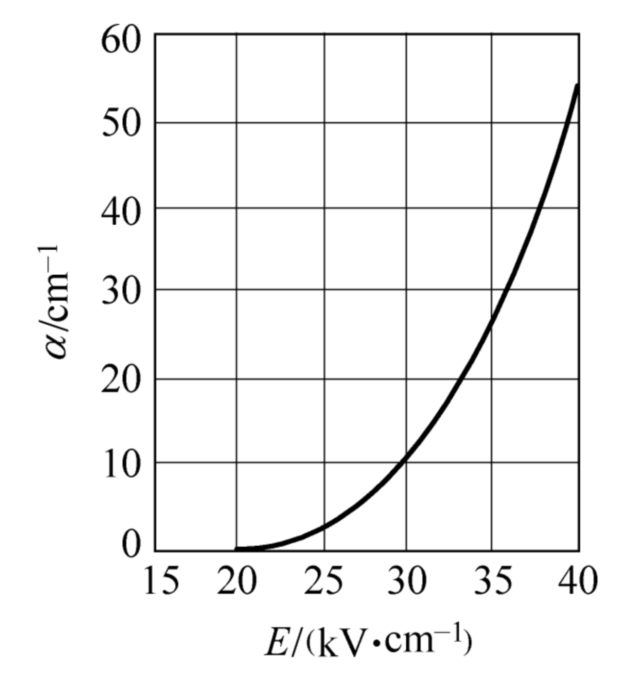
1.2.1 Townsend's theory

After making appropriate assumptions about collision ionization, the relationship between coefficient α and the strength of the applied electric field strength E can also be calculated as

$$\alpha/\delta = A \exp(-B\delta/E)$$

or $\alpha/\delta = f(E/\delta)$

The field strength has a significant impact on the strength of collision ionization



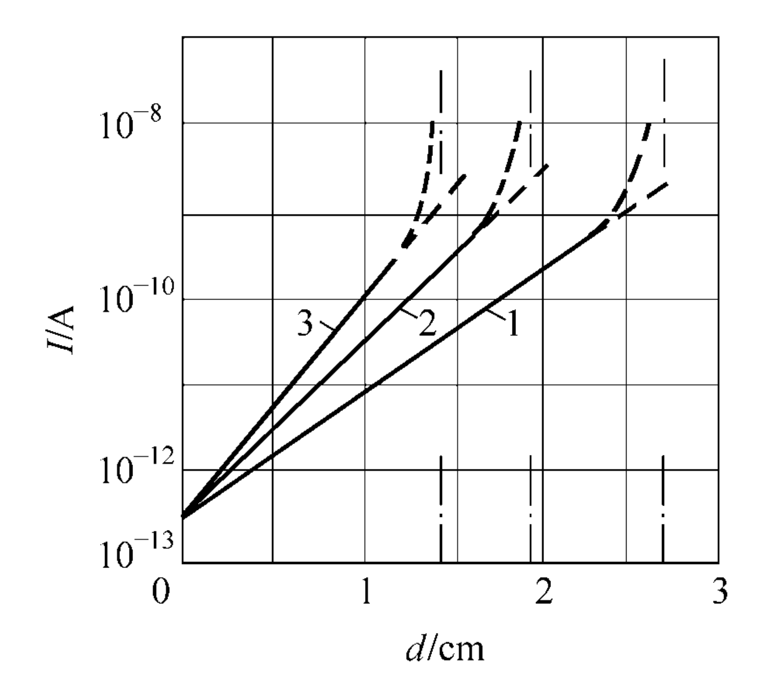
The relationship between electron ionization coefficient α and field strength E in the air

1.2.1 Townsend's theory

Introducing self-sustained discharge, electron avalanche and collision ionization coefficient α, there is still some phenomenon difficult to explain. The current at the part of dashed line

The α process only discussed collision ionization in electrode space.

Townsend introduced the ionization coefficient γ on the cathode surface, where γ is the number of free electrons released from the cathode per collision of positive ions (including the recombination produced photos irradiate to cathode). For copper, $\gamma \approx 0.025$



External circuit current from $I = I_0 e^{\alpha d}$ to $I = I_0 e^{\alpha d}/(1-\gamma e^{\alpha d})$

1.2.1 Townsend's theory

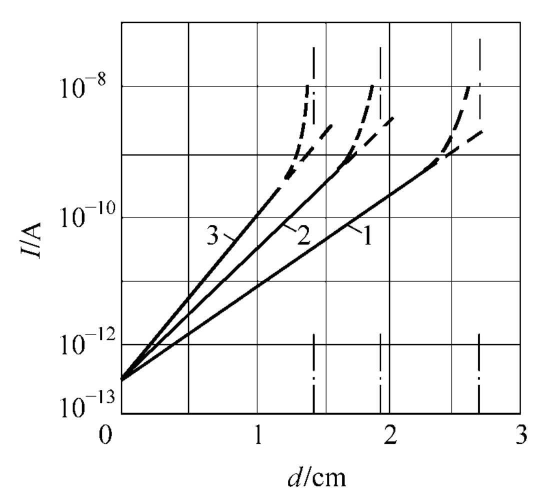
	Cathode surface	Space of gas gap	Anode surface
1st cycle	one electron escapes	Forming $(e^{\alpha d}-1)$ positive ions	$e^{\alpha d}$ electrons entering
2nd cycle	$\gamma(e^{\alpha d}-1)$ electrons	$\gamma(e^{\alpha d}-1)^2$ positive ions	$\gamma(e^{\alpha d}-1)e^{\alpha d}$ electrons
3rd cycle	$\gamma^2(e^{\alpha d}-1)^2$electrons	$\gamma^2(e^{\alpha d}-1)^3$ positive ions	$\gamma^2(e^{\alpha d}-1)^2e^{\alpha d}$ electrons

It can be inferred that the external circuit current

$$I = I_0\, e^{\alpha d}/(1-\gamma(e^{\alpha d}-1))$$

Simplified as $I = I_0\, e^{\alpha d}/(1-\gamma e^{\alpha d})$

Considering the γ process, the current is greater than only considering the α process



Self-sustained discharge criterion $\gamma e^{\alpha d} = 1$

1.2.1 Townsend's theory

The breakdown voltage U_b can also be derived from the self-sustained discharge criterion of Townsend's theory $U_b = \dfrac{B\delta d}{\ln\left(\dfrac{A\delta d}{\ln\gamma^{-1}}\right)}$

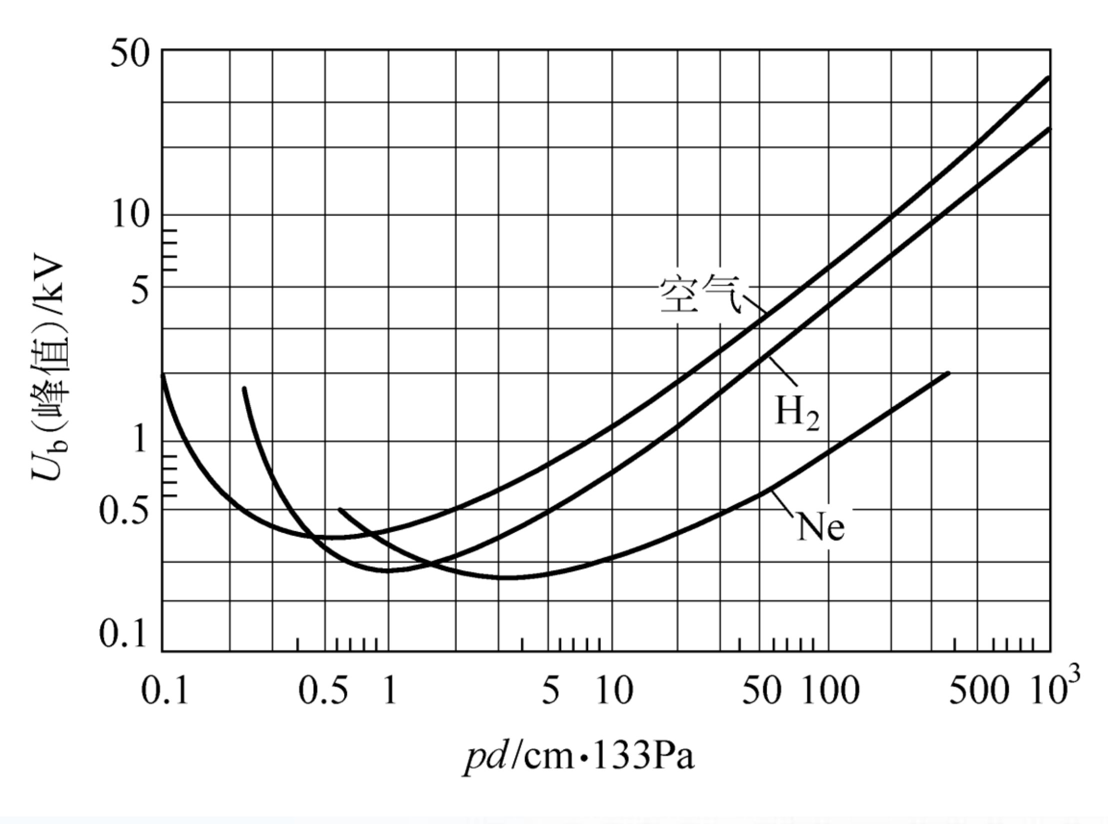
This is also a U-shaped curve. There is a minimum value of U_b

How to understand the left and right part of the curve?

The curve of

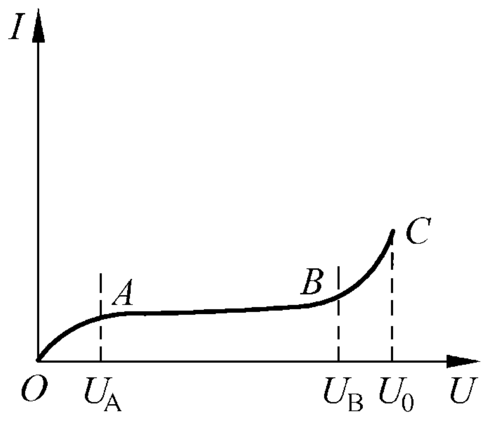
$U_b = f(pd)$

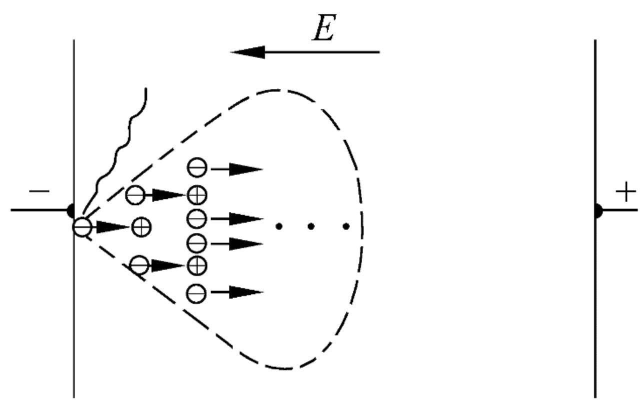
obtained from experiments in varies gas gaps in uniform electric field

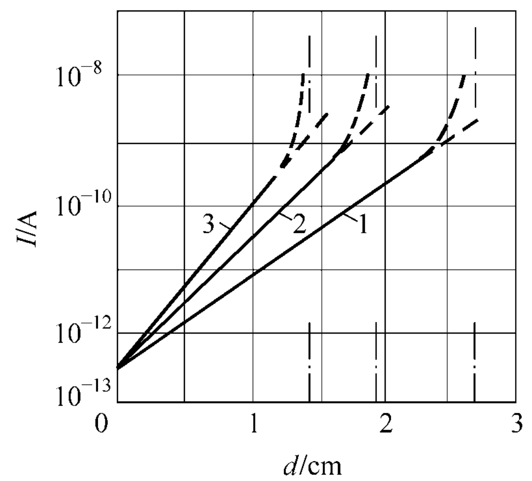


1.2.1 Townsend's theory

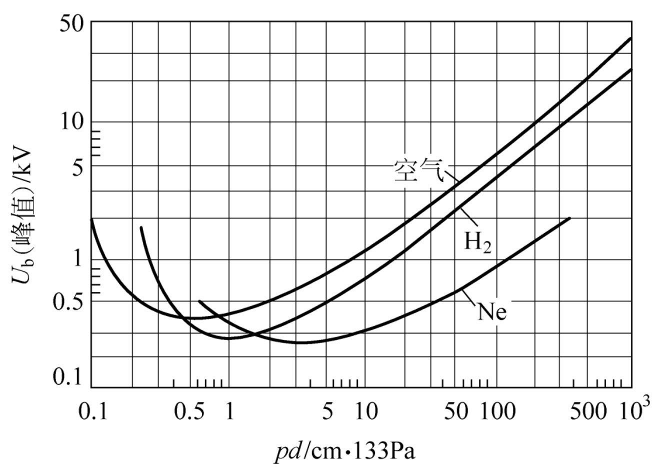
Self-sustained discharge and its criterion, electron avalanche, collision ionization coefficient α, γ and its process





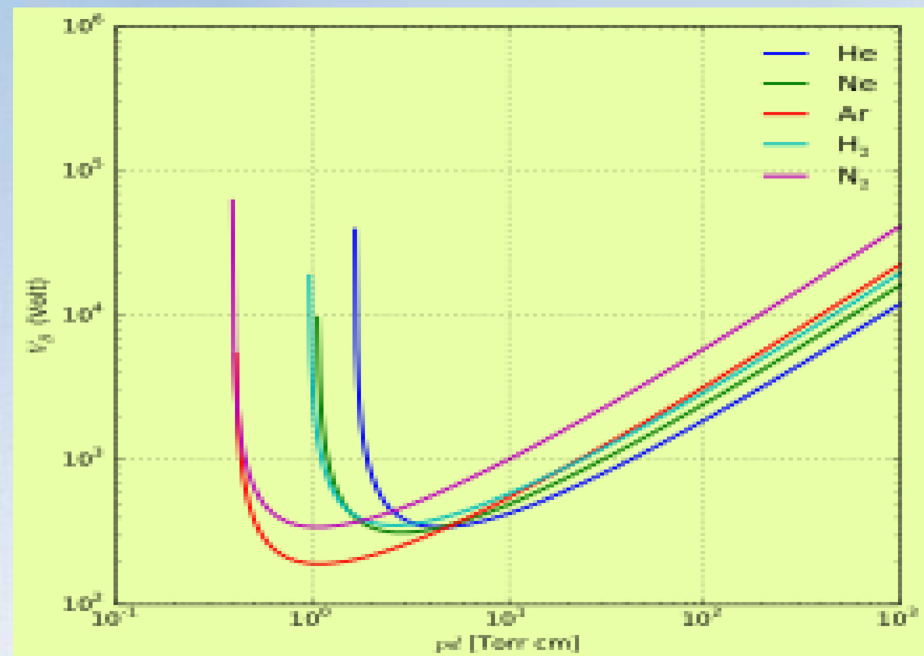


- Facing a new phenomenon: current increase in B-C, photo radiation and current
- Introduce new concept: self-sustained discharge, electron avalanche, collision ionization
- Provide quantitative and checkable conclusions: coefficient α, γ , $I = I_0 \, e^{\alpha d}$ and $I = I_0 \, e^{\alpha d}/(1-\gamma e^{\alpha d})$ Self-sustained discharge criterionγ e α d = 1 and breakdown voltage U_b
- Finally proven by experiment



1.2.2 Paschen's law and uniform electric field breakdown voltage

Friedrich Paschen was known for his work on electrical discharges. He established the now widely used Paschen curve. *Paschen's Law is named after Friedrich Paschen who discovered it empirically in 1889*.



Friedrich Paschen
(1865–1947)

During the war he had the Chinese scientist He Zehui to stay at his house and she became like a daughter to him.

Paschen curve of air

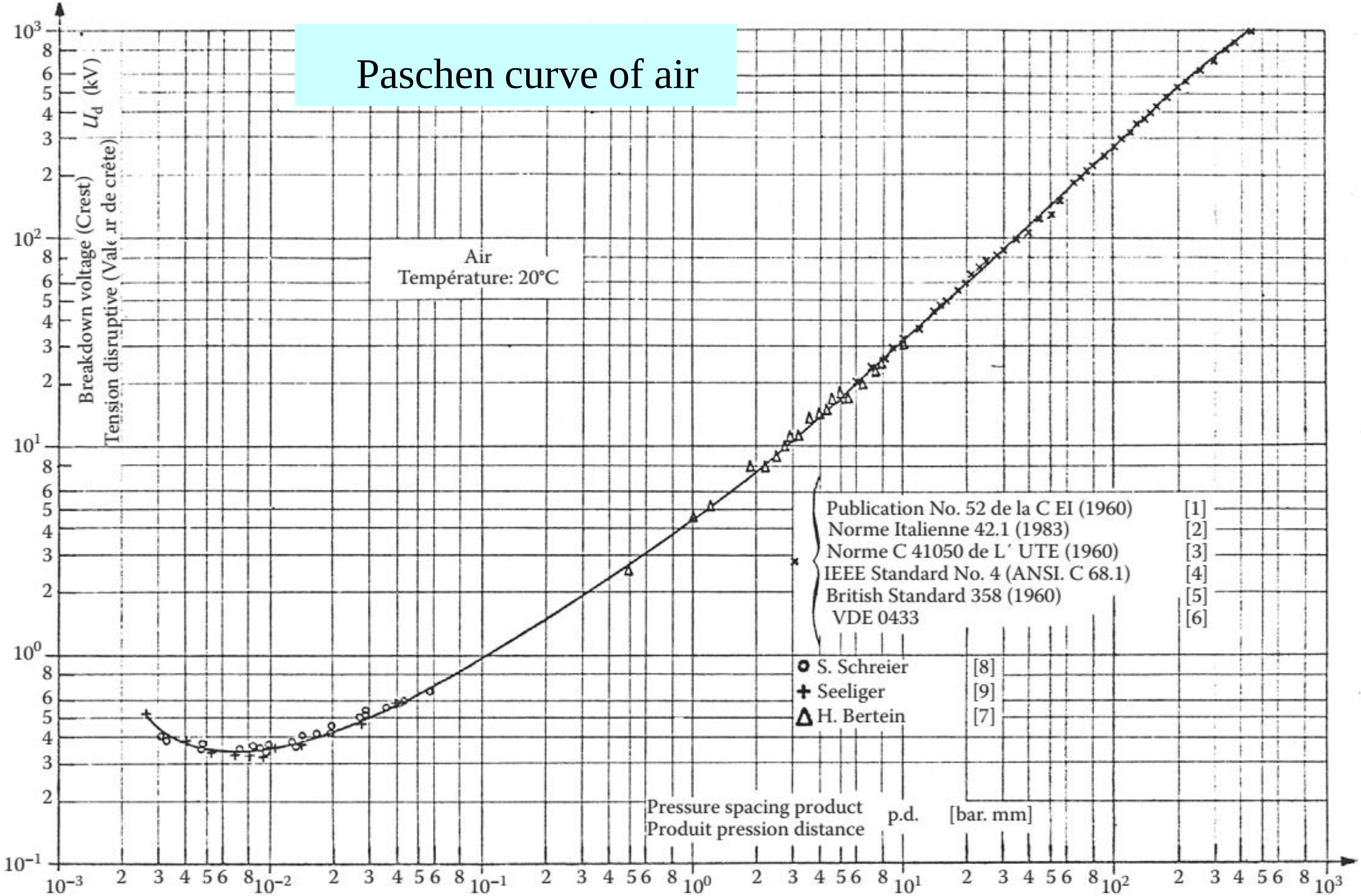


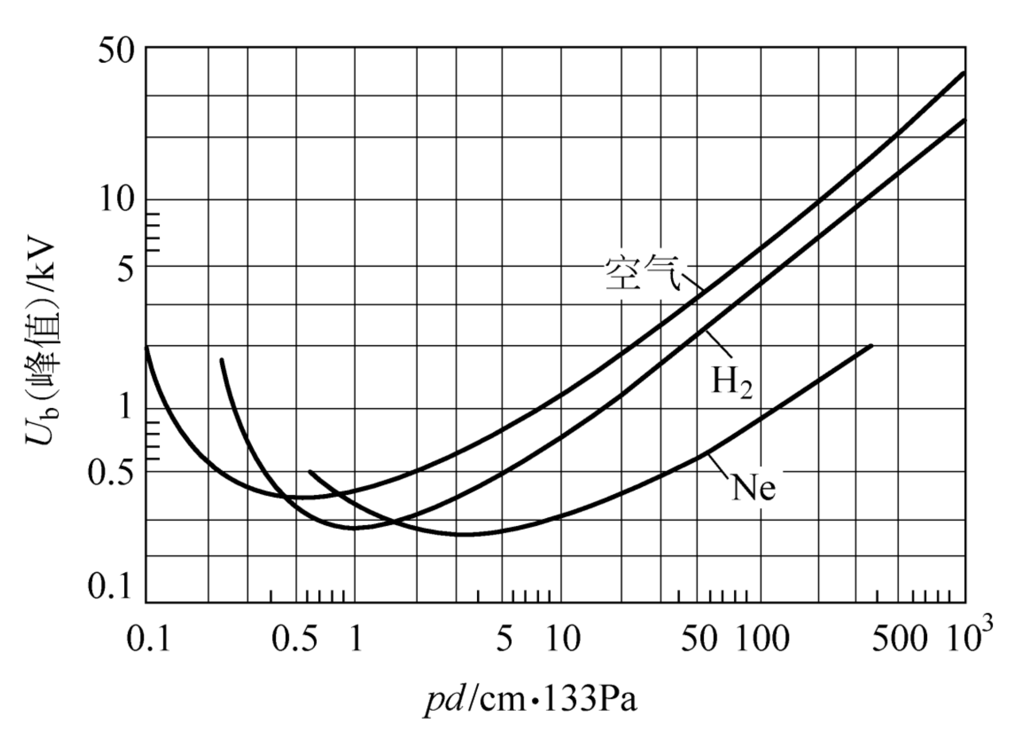
FIGURE 4.29 Paschen's curves in air. (From Dakin, T.W. et al., *Electra*, 32, 61, 1974.)

1.2 Townsend's theory and Paschen's law of self-sustained discharge in a uniform electric field under low gas pressure

1.2.1 Townsend's theory

1.2.2 Paschen's law and uniform electric field breakdown voltage

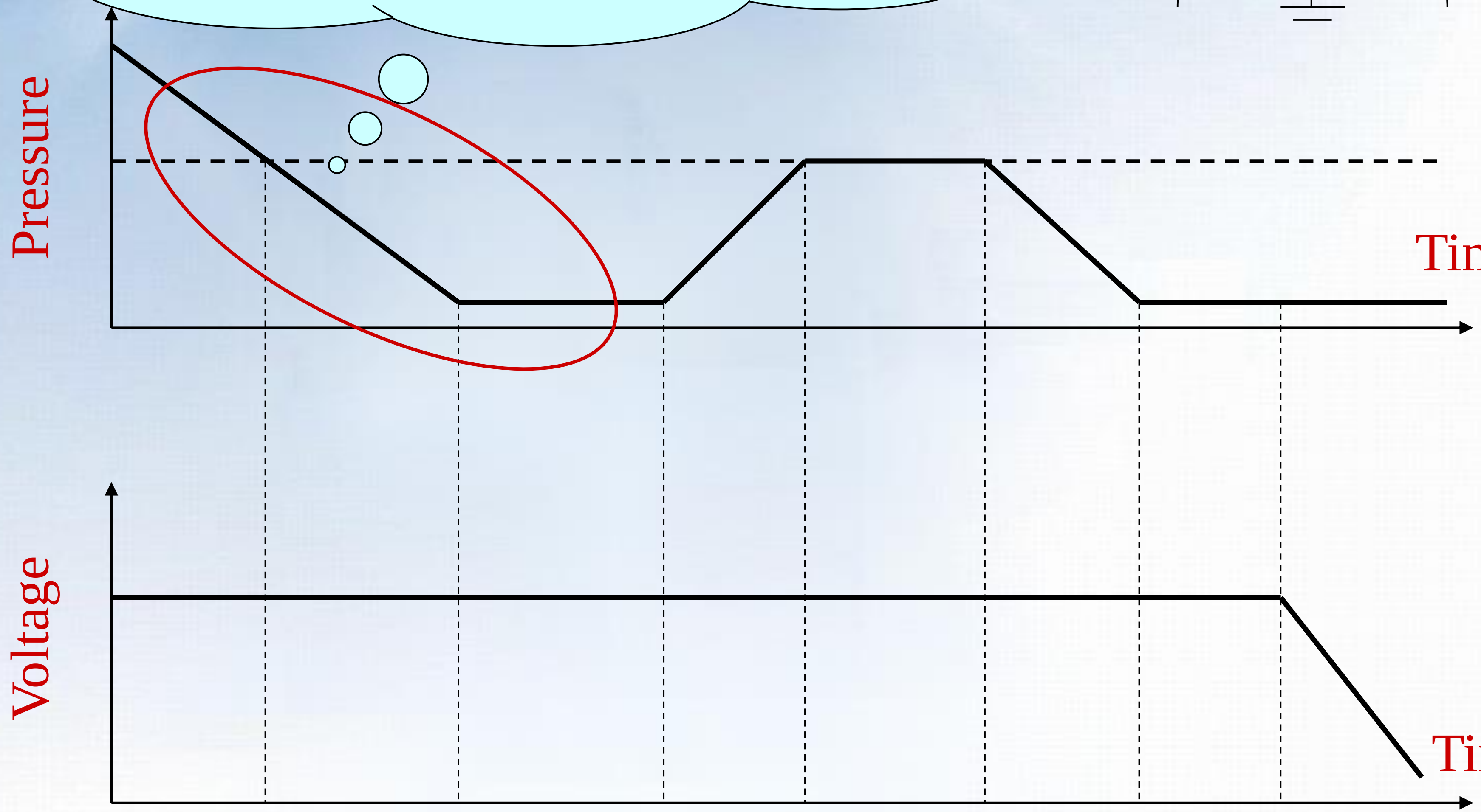
1.2.3 Applicable range of Townsend's theory

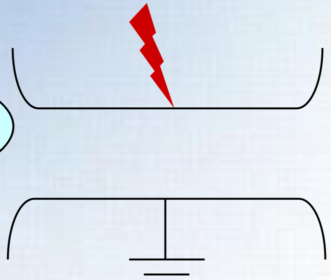


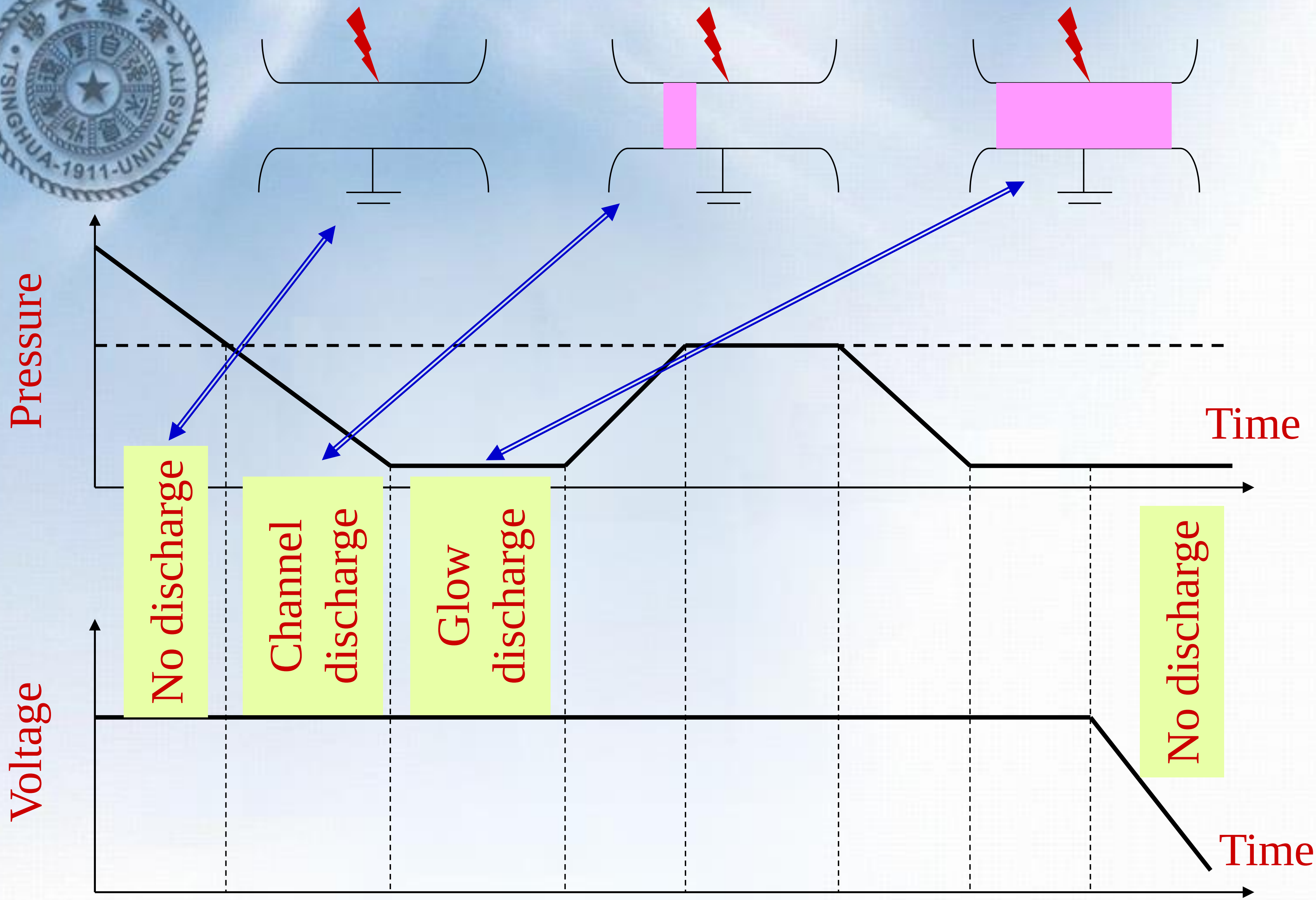
Townsend's theory is based on the experiment results at low gas pressure and small *pd* value. If the *pd* is too small or very large, discharge phenomenon and mechanism will change significantly.

Townsend's theory is no longer applicable when *pd* >200(cm•133Pa)

What would happen to the experimental phenomenon of keeping the voltage constant and only reducing the air pressure for the gap between the plates?






Pressure
Time
No discharge
Channel discharge
Glow discharge
Voltage
No discharge
Time

1.2 Townsend's theory and Paschen's law of self-sustained discharge in a uniform electric field under low gas pressure

Self-sustained discharge criterion $\gamma\,(e^{\alpha d}-1) = 1$ or $\gamma\, e^{\alpha d} = 1$

1.3 Streamer theory of self-sustained discharge in a uniform electric field under high gas pressure

1.3.1 Distortion of electric field caused by space charge

1.3.2 Formation of streamers

The formation of positive and negative streamers

1.3.3 Self-sustained discharge criterion in a uniform electric field

Self-sustained discharge criterion $\gamma\, e^{\alpha d} = 1$

1.3.4 Explanation of discharge phenomenon by streamer theory

1.3 ***Streamer theory*** of self-sustained discharge in a uniform electric field under ***high gas pressure***

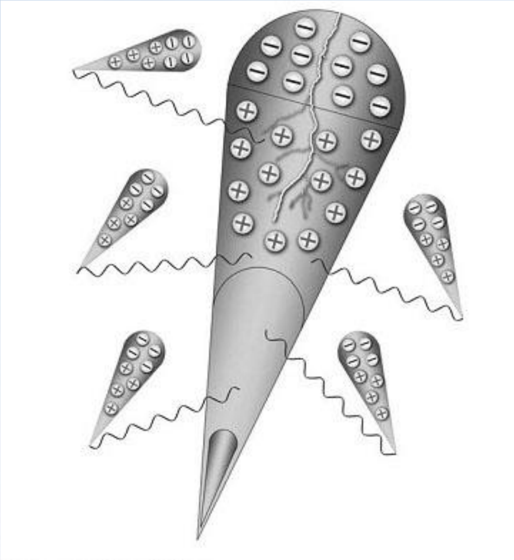
1.3.1 Distortion of electric field caused by space charge

At high pressure, the air density is much higher than under low pressure, and the ***mean free path of electrons is greatly reduced***, resulting in a significant increase in the electric field strength required for collision ionization.

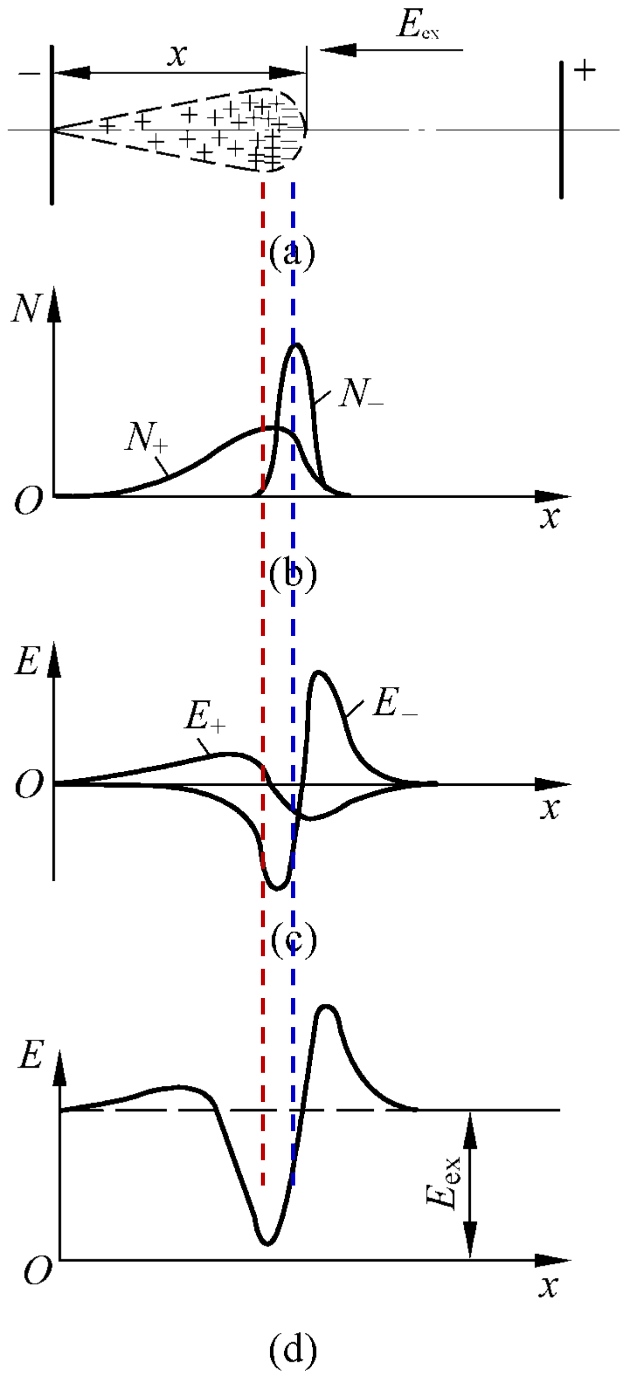
Once the field strength reaches the threshold for collision ionization, the number of space charges generated by collision ionization per unit space is much larger than at low pressure, to the extent that ***these newly generated space charges significantly distort the original external electric field***.

1.3.1 Distortion of electric field caused by space charge

The degree of electric field distortion depends on the number of electrons in the electron avalanche

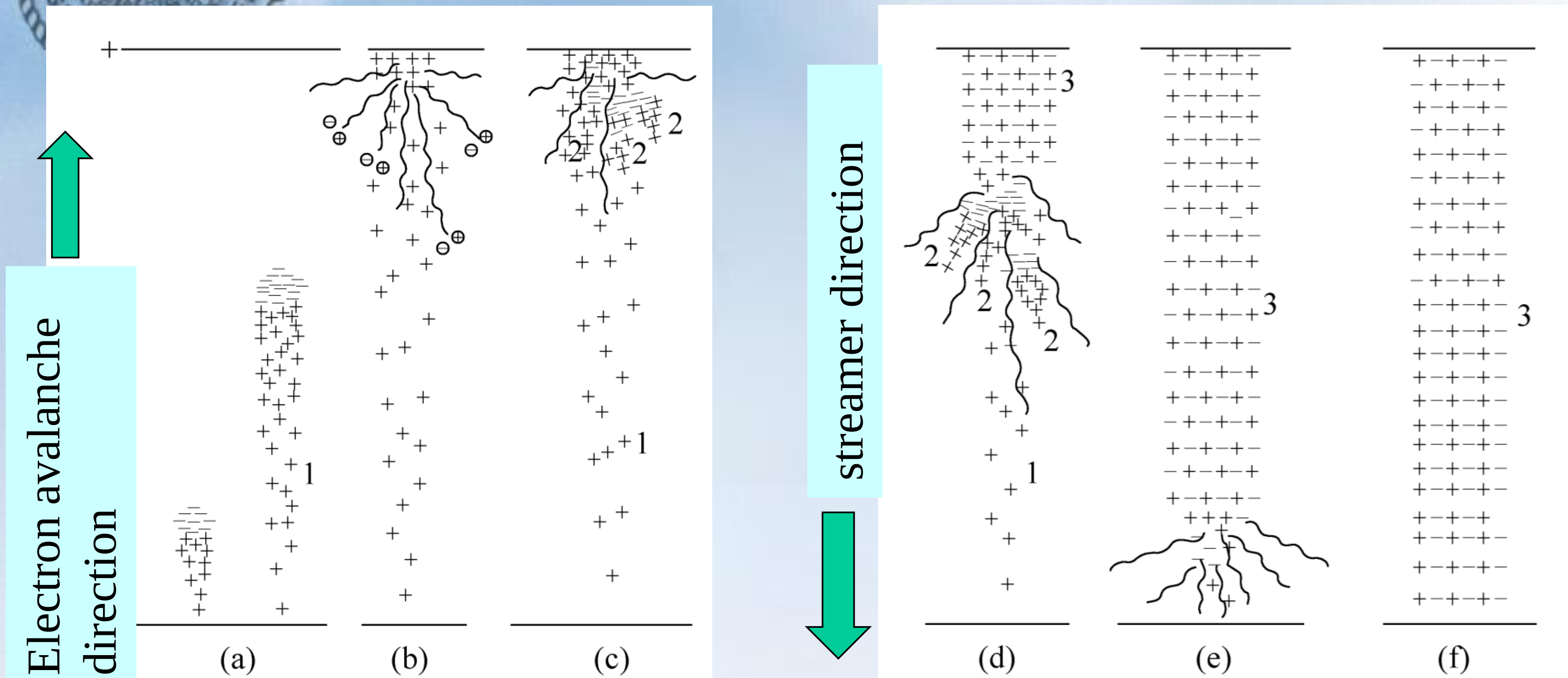


Initial electron avalanche and secondary electron avalanche induced by spatial photoionization



1.3.2 Formation of streamers

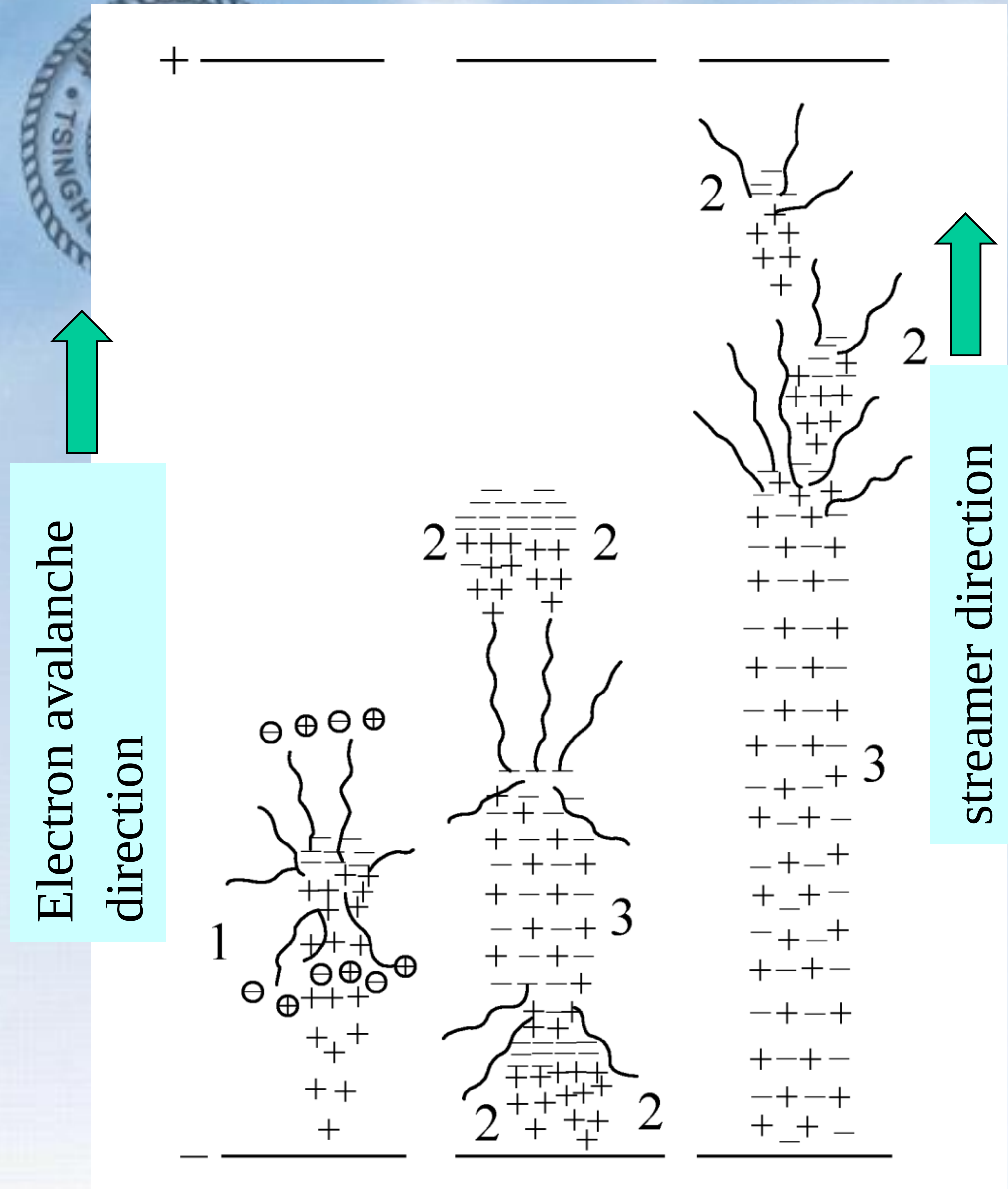
The self-sustained discharge criterion of the streamer: the number of electrons in the electron avalanche head reaches a certain number, and the distortion of the electric field is high enough



The formation and development of ***positive streamer***

1- Initial electron avalanche (main electron avalanche);
2- Secondary electron avalanche; 3- Streamer

The development speed of positive streamer is about (1-2)×10^8 cm/s, and the electron avalanche is about 1.25×10^7 cm/s



In another word, the self-sustained discharge criterion of streamer: the total number of electrons in the electron avalanche ($e^{\alpha d}$) reaches a certain number, so the distortion of the electric field is high enough to trigger the nearby photoionization and produce secondary avalanche

The formation and development of ***negative streamer***

1- Initial electron avalanche (main electron avalanche)
2- Secondary electron avalanche
3- Streamer

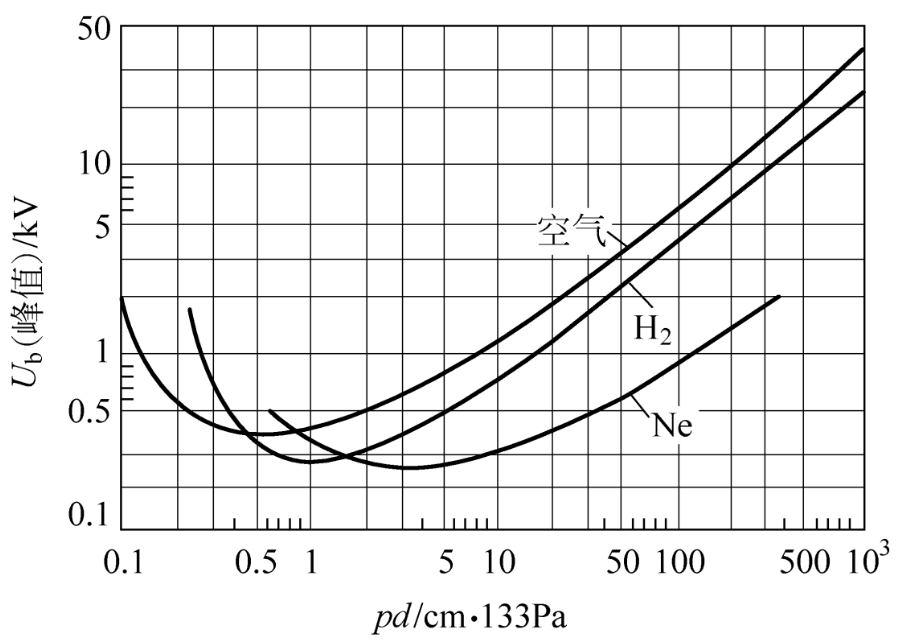
The development speed of negative streamers is about $(0.7\text{-}0.8)\times10^{8}$ cm/s, which is much faster than electron avalanche.

1.3.4 Explanation of discharge phenomenon by streamer theory

- The self-sustained discharge criterion of the streamer could be written as: $e^{\alpha d} = 1/\gamma$, or $\gamma e^{\alpha d} = 1$ (looks the same as the criterion at low pressure)

The physical meaning of γ here is different from the previous γ, and there is also a significant difference in numerical values (here, $1/\gamma \approx 10^8$, previous $\gamma \approx 0.025$)

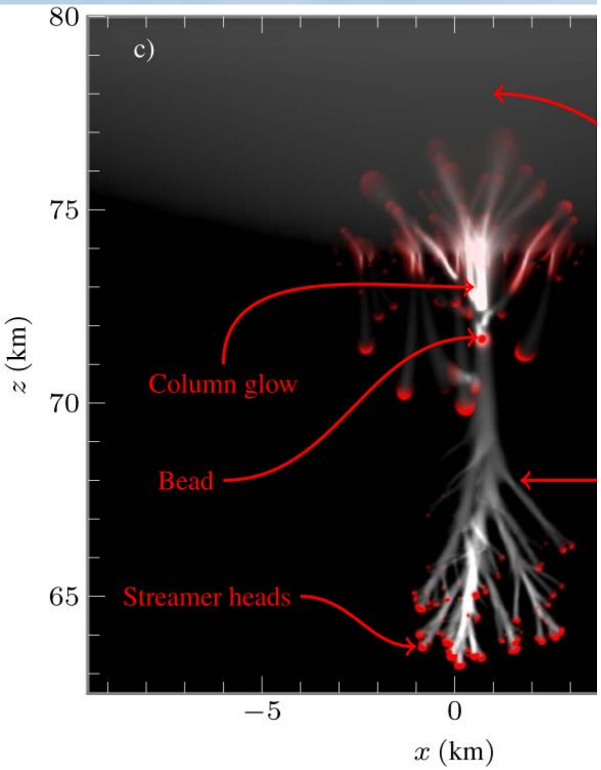
Within a wide range of *pd*, the gap breakdown voltage follows a *U*-shaped curve

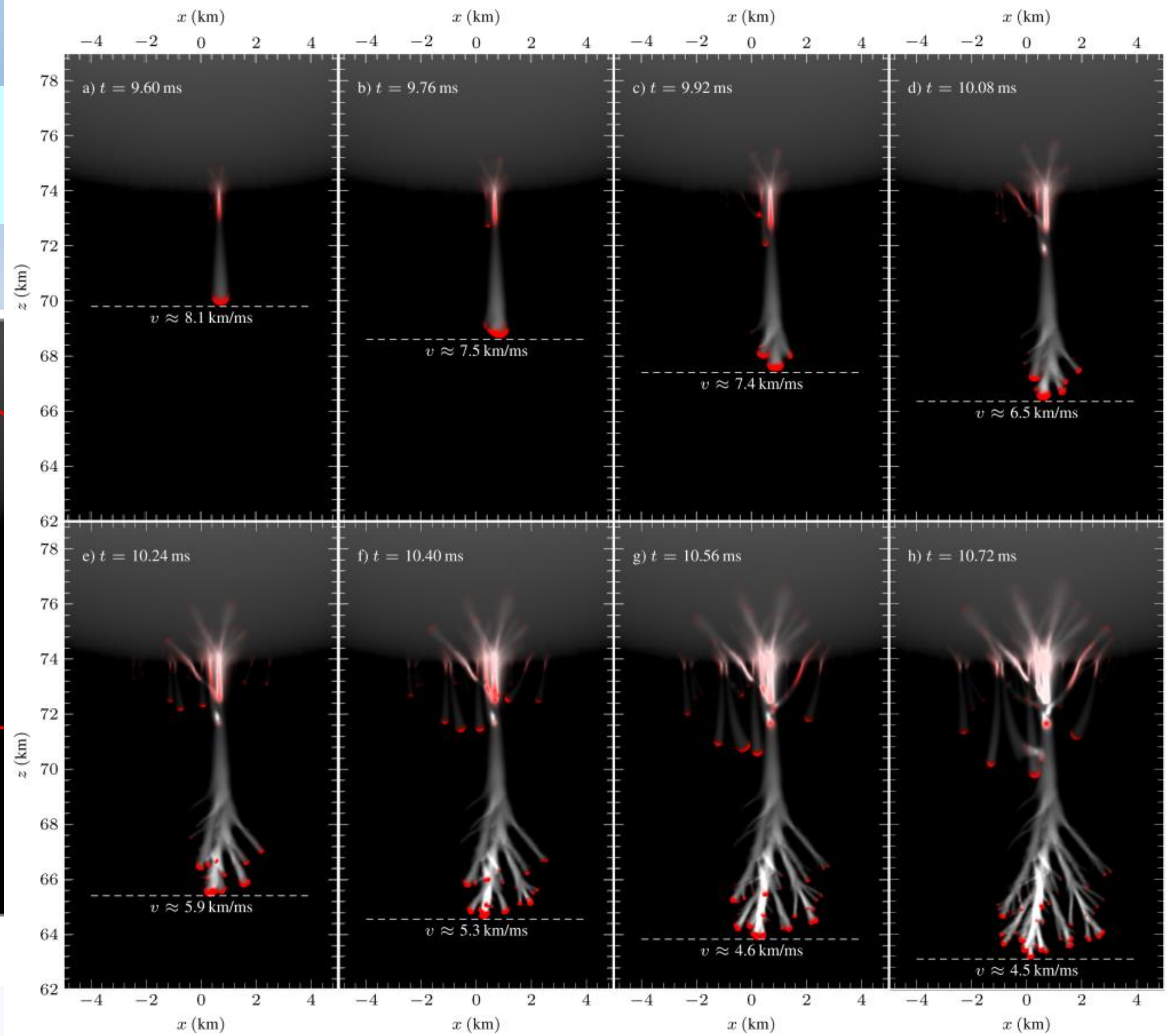


$U_b = f(pd)$ curve obtained from experiments in uniform electric field varies gas gap conditions

Digital simulation is another research tool recent years

Digital simulation of sprite emissions





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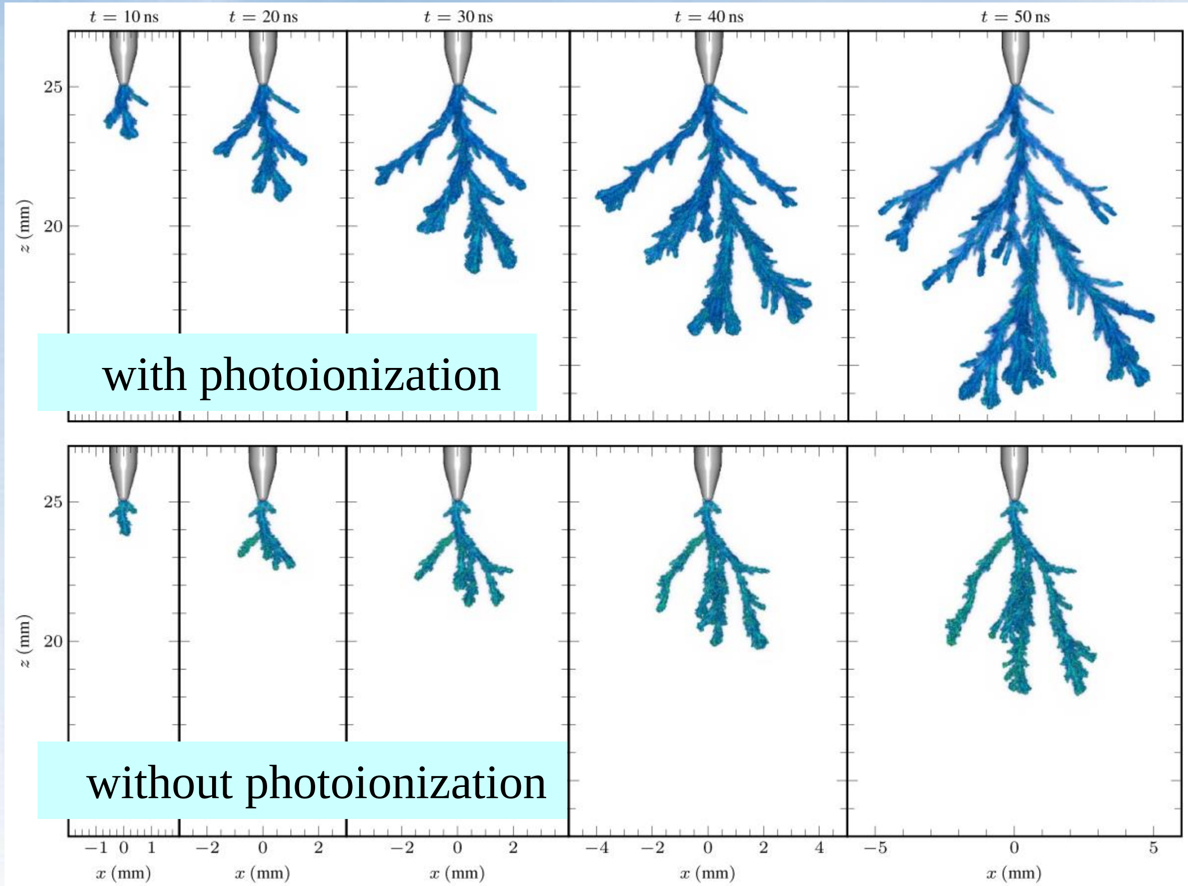
Digital simulation is another research tool recent years

Photoionization plays an important role in the development of the streamer

Digital simulation in CO_2



Positive streamer

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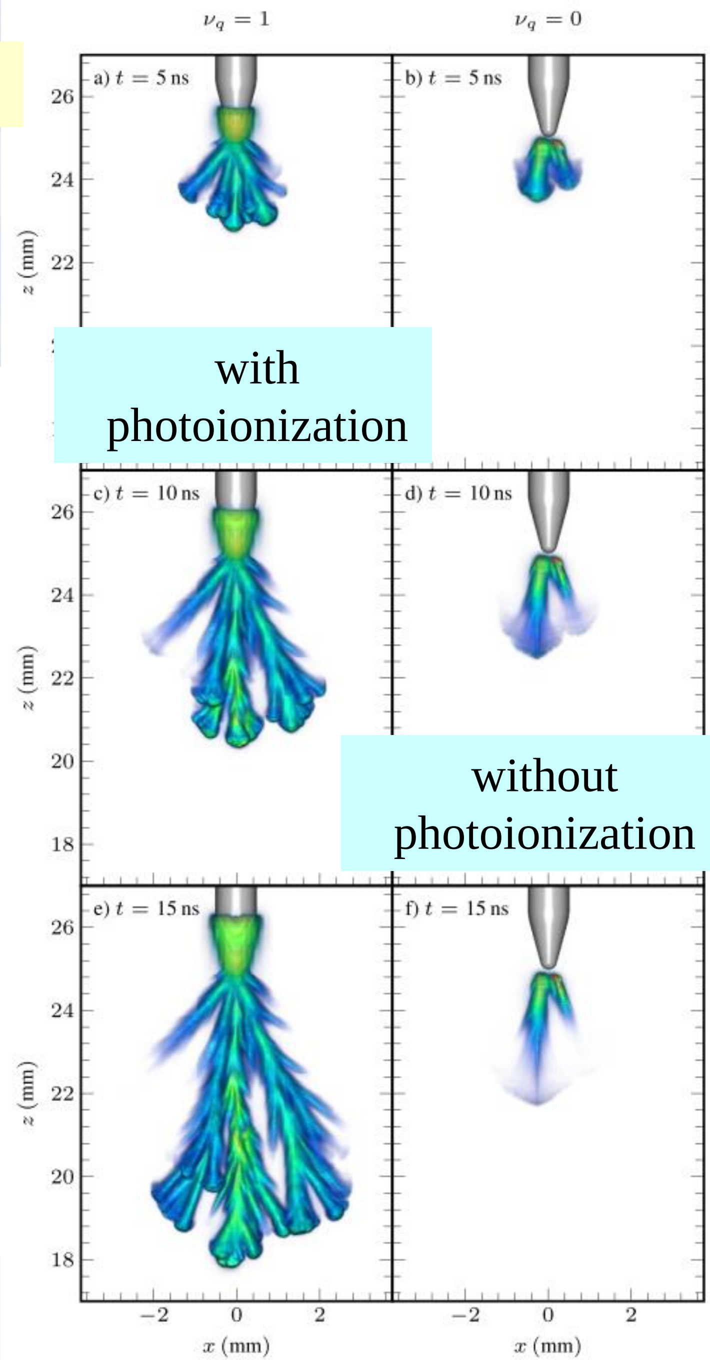
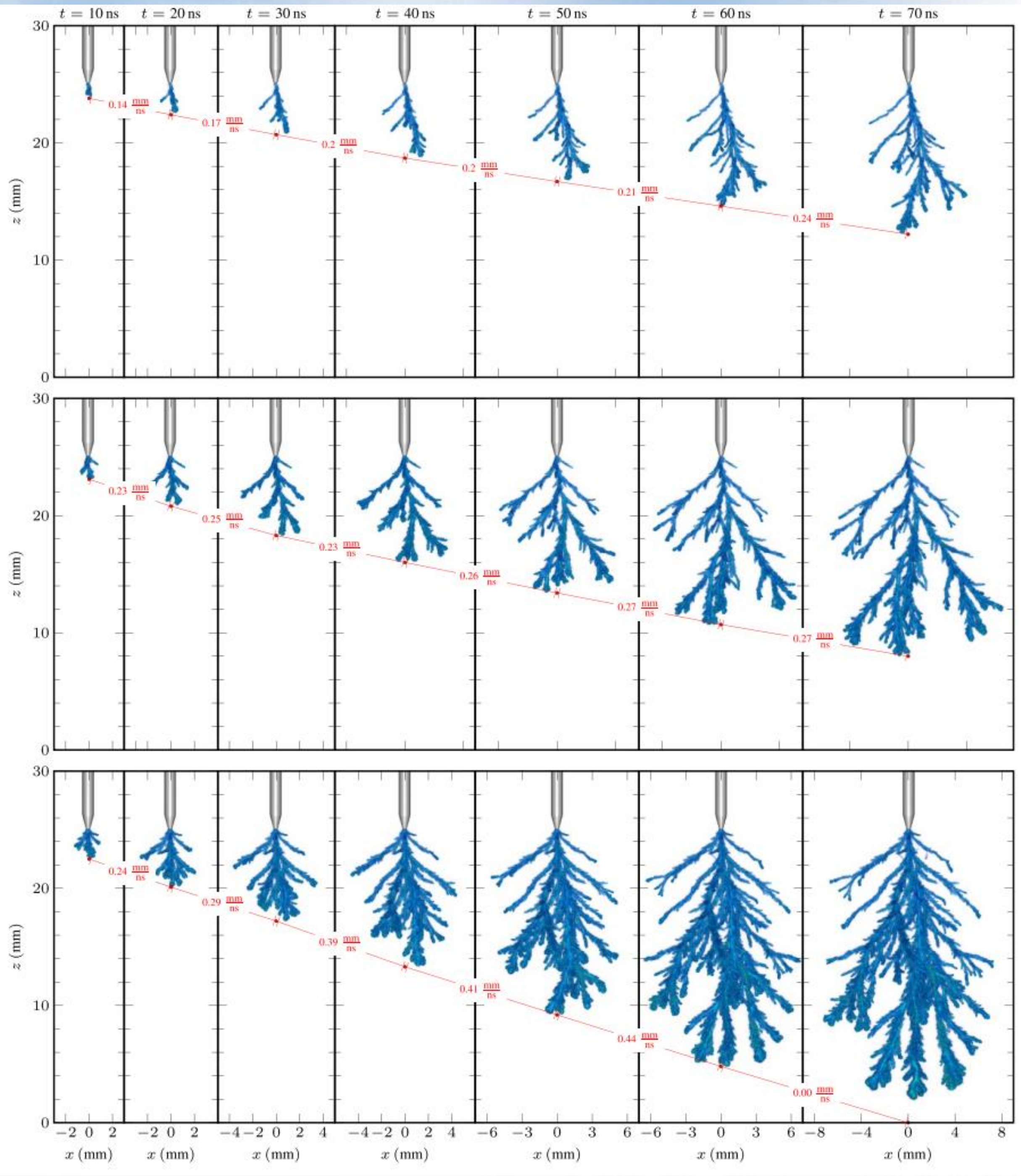


Negative streamer

Digital simulation is another r

Influence of applied voltage on flow injection development

Digital simulation in CO_2



Positive streamer

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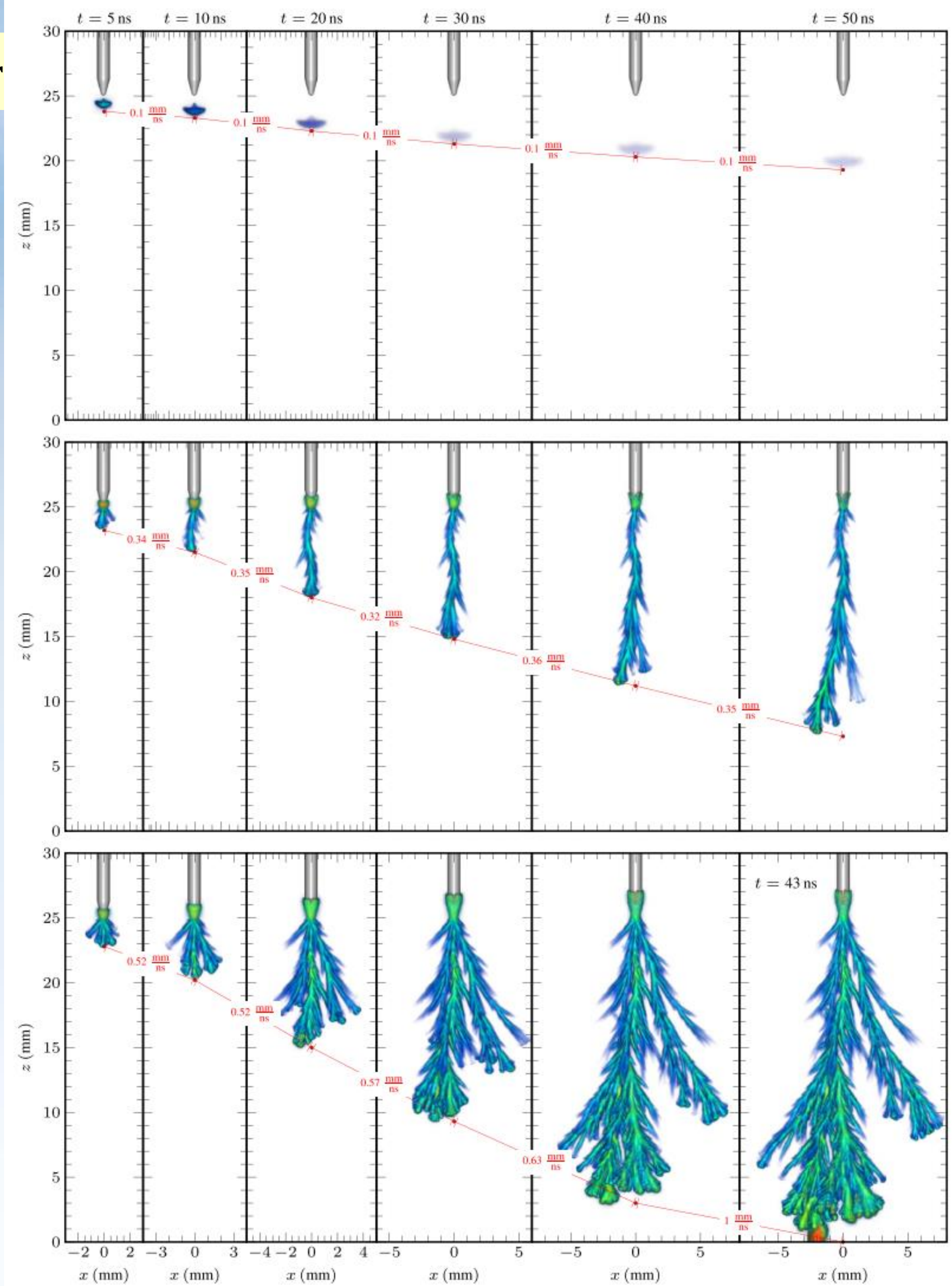
Digital simulation is another resear

Influence of applied voltage on flow injection development

Digital simulation in CO_2



Negative streamer

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