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Department of Electrical Engineering
Tsinghua University

High Voltage Engineering

Spring 2025, Lecture 3

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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 air pressure

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

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

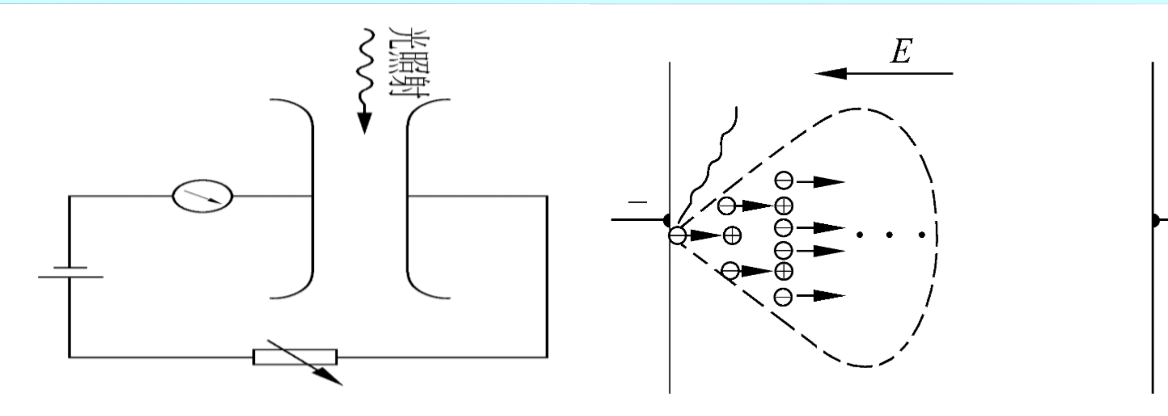
Core concepts of this chapter:

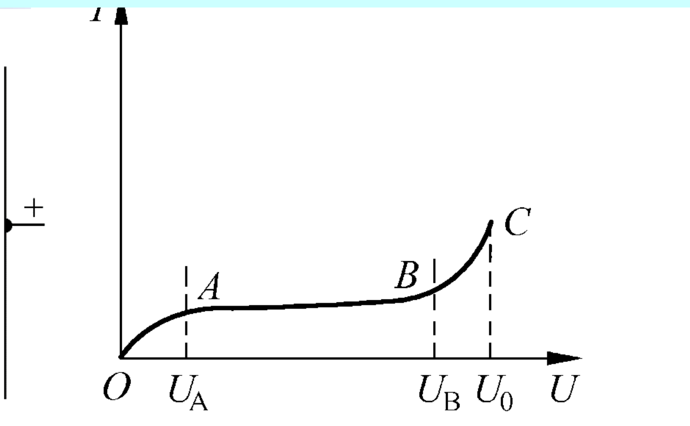
collision ionization, self-sustained discharge, Townsend discharge, Paschen's law, electron avalanche, streamer, leader, corona discharge, polarity effect, long gap discharge

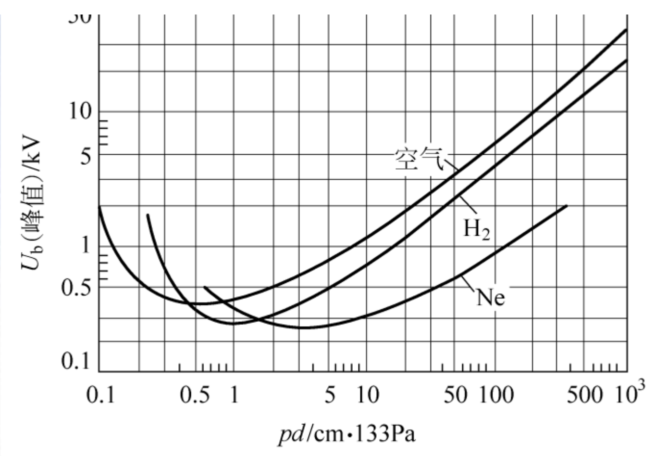
A brief review and discussion of Townsend discharge

Basic knowledge:

- Mean free path of charged particles, Collision ionization
- Electron avalanche and multiplication of charged particle Townsend first and second ionization coefficient α and γ
- Self-sustained discharge
- Self-sustained discharge criterion $\gamma e^{\alpha d} = 1$ and breakdown voltage $U_b = f(pd)$







Why is Townsend's gas discharge theory the basis of all high voltage related disciplines?

What makes Townsend theory the basis of high voltage science?

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1.4.1 Classification of electric field non-uniformity

Uniform field, slightly non-uniform field, extremely non-uniform field, electric field non-uniformity factor $f = E_{max} / E_{av}$

1.4.2 Corona discharge of gas with extremely non-uniform electric field

1.4.3 Polarity effect of non-uniform electric field

1.4.4 Long air gap breakdown process

1.4.5 Self-sustained discharge criterion and polarity effects of slightly non-uniform electric field

1.4.1 Classification of electric field non-uniformity

Electric field non-uniformity factor

$$f = E_{max}/E_{av}$$

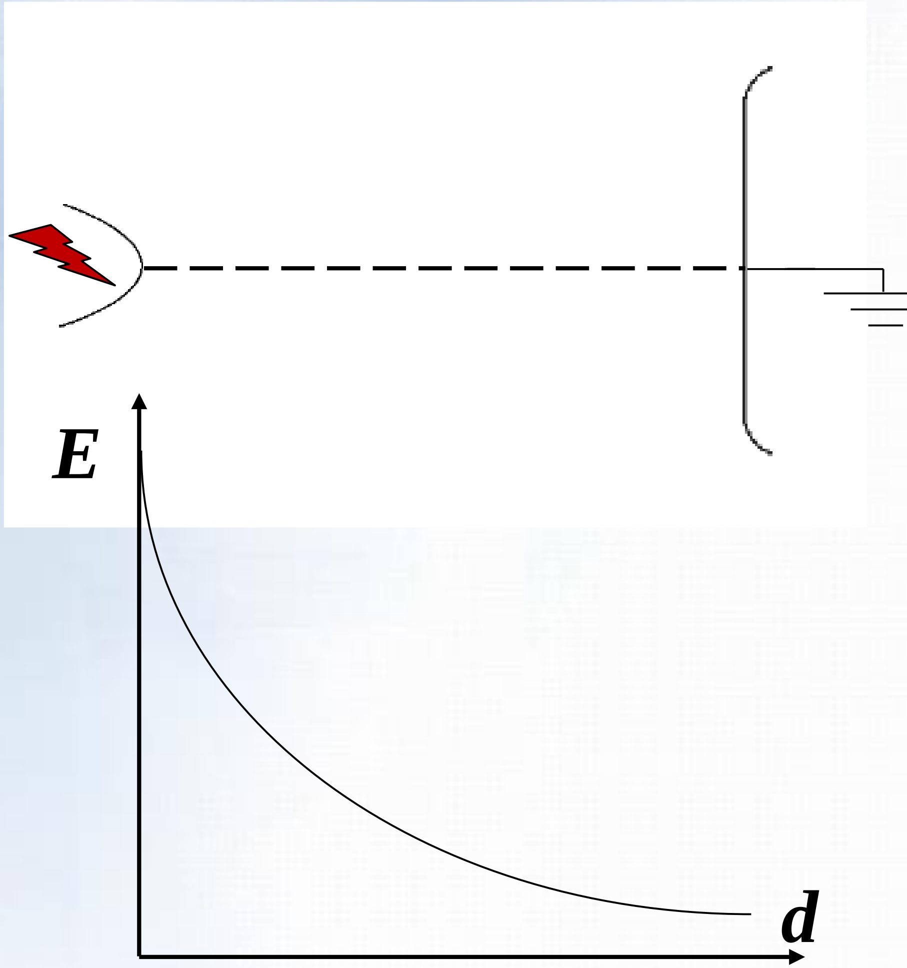
Uniform field $f = 1$

Slightly non-uniform field $f < 2$

Extremely non-uniform field $f > 4$

The key point of distinguishing slightly and extremely non-uniform fields is the difference in discharge characteristics of the two types of electrode system

(Field efficiency factor $\eta = E_{av}/E_{max} = 1/f$)



Electric field distribution along the shortest gap distance (dotted line)

1.4.2 Corona discharge of gas with extremely uneven electric field

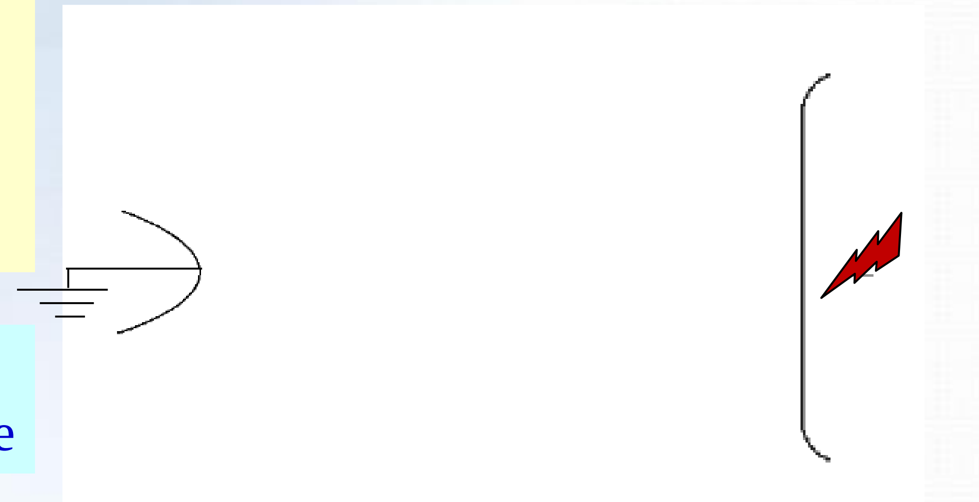
What is an extremely non-uniform electric field?

The field stress of each point in the electrode space vary greatly, *f* >4

What discharge phenomena which may differ from that in uniform fields?

Only local areas meet collision ionization criterion,

Discharge only occurs in local areas with high field stress

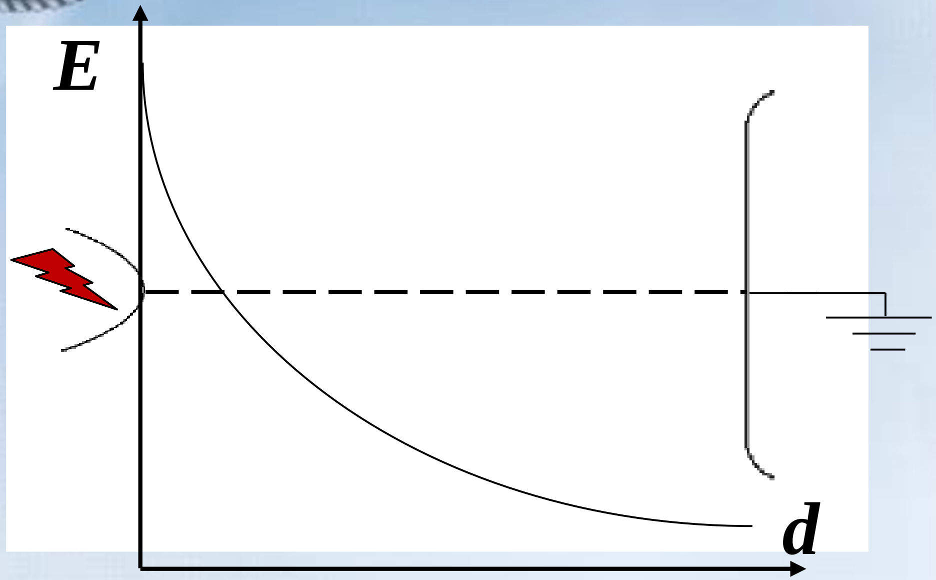


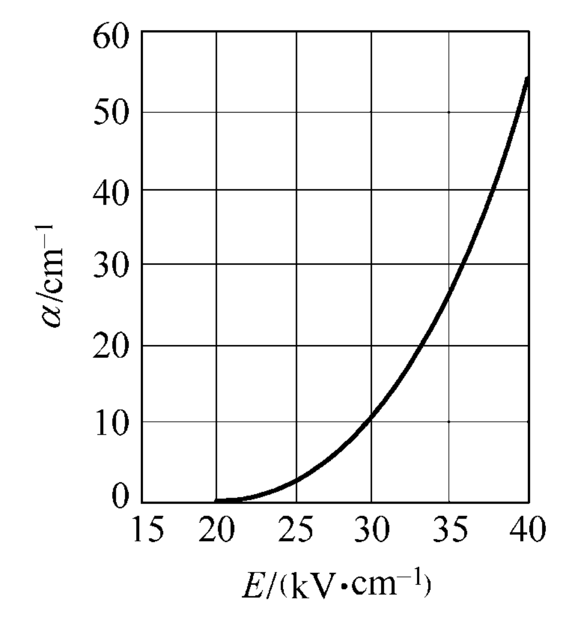
A high field stress electrode may not necessarily be a high potential electrode

The polarity of high field stress electrode influences the discharge significantly

1.4.2 Corona discharge of gas with extremely non-uniform electric field

- ✓ Corona inception field stress
- ✓ Corona inception voltage

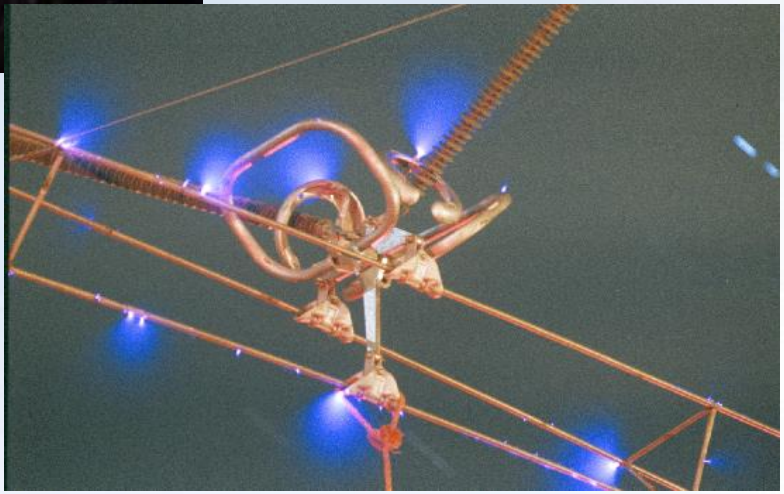


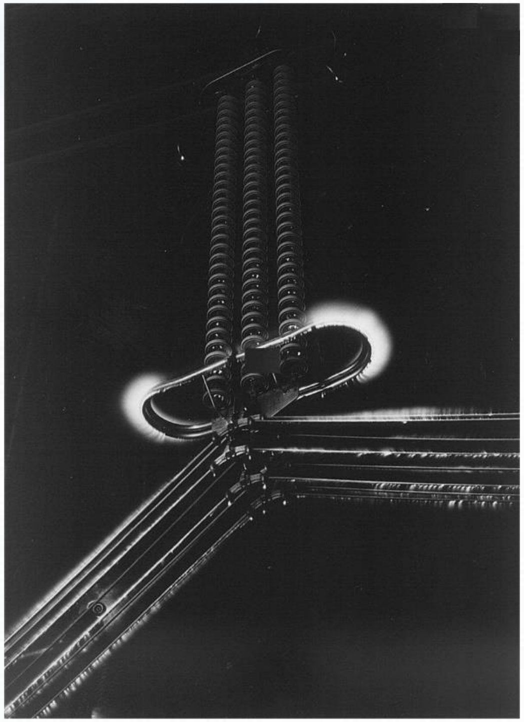


- ➢ The field stress of each point in the electrode space vary greatly
- ➢ Only local areas meet collision ionization criterion, and discharge only occurs in local areas
- ➢ The polarity of high field stress electrode influences the discharge significantly

1.4.2 Corona discharge of gas with extremely non-uniform electric field

- ✓ Corona inception field stress
- ✓ Corona inception voltage





Corona discharge phenomenon at high field stress electrodes

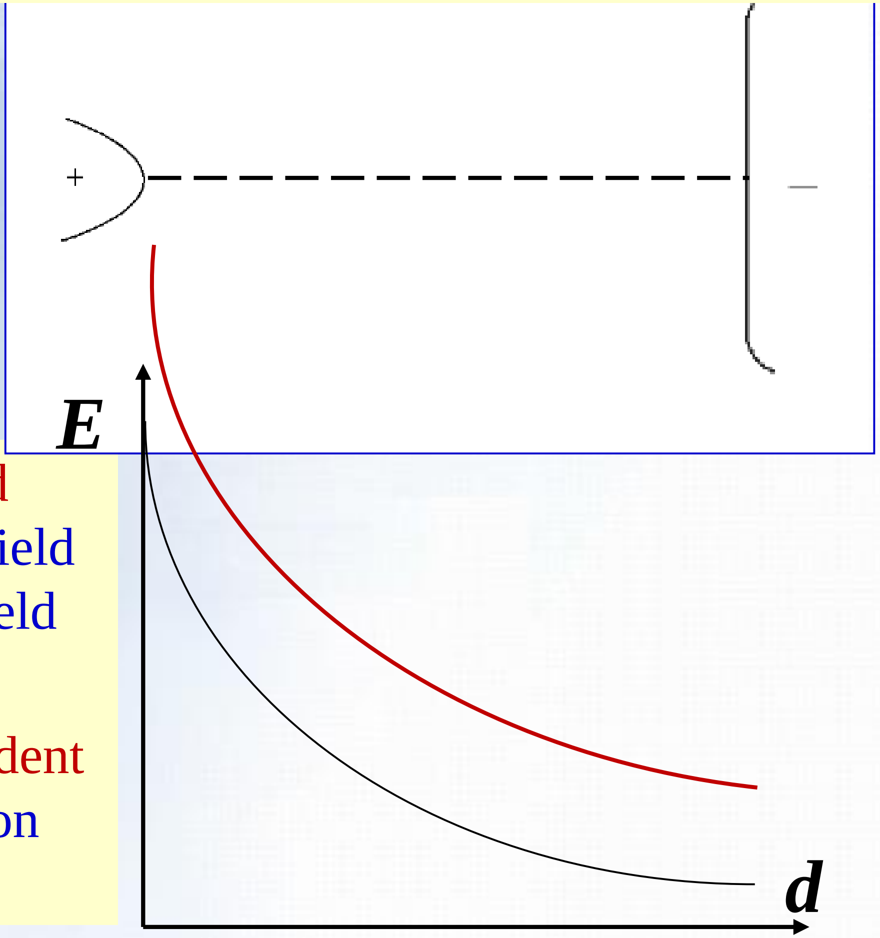
1.4.2 Corona discharge of gas with extremely non-uniform electric field

Electric field non-uniformity factor

$$f = E_{max}/E_{av}$$

Uniform field $f = 1$
Slightly non-uniform field $f < 2$
Extremely non-uniform field $f > 4$

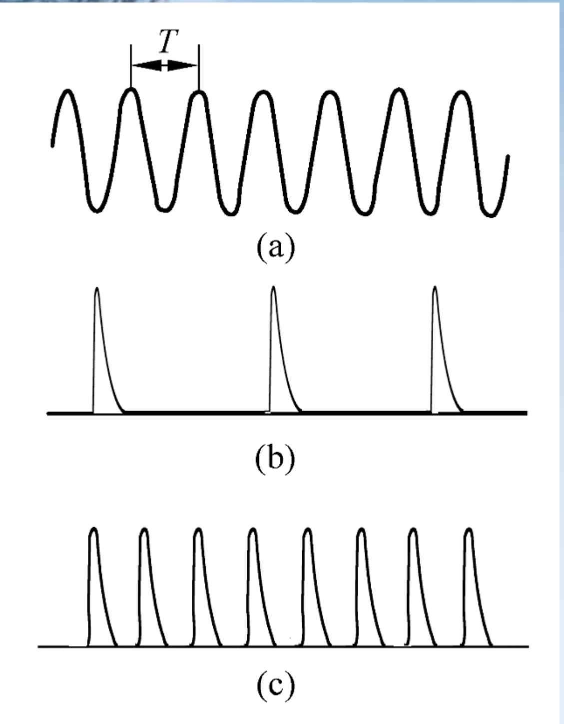
- field distribution can be calculated if there is no space charge



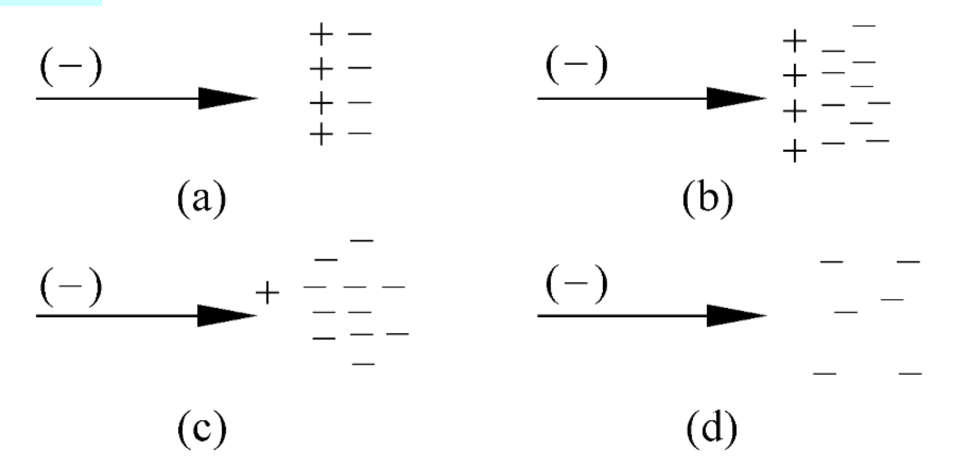
- As the applied voltage increases, the field distribution remains unchanged, but the field stress and potential at each point in the field increase accordingly
- The distribution of field stress is independent of voltage polarity, and also has no relation with potential (high voltage or ground)

- The field stress of each point in the electrode space vary greatly
- Only local areas meet collision ionization criterion, and discharge only occurs in local areas
- The polarity of high field stress electrode influences the discharge significantly

1.4.2 Corona discharge of gas with extremely non-uniform electric field



The waveform of corona current in the point-plan gap under negative polarity (b) and (c)



Explanation of the initial stage of negative polarity corona
(how pulse current is formed)

- Pay attention to the starting position and development direction of electron avalanche
- Pay attention to the direction and speed of motion of electrons, positive ions, and negative ions

1.4.2 Corona discharge of gas with extremely non-uniform electric field

How is the corona inception stress determined?

For two parallel round conductors with a radius of r

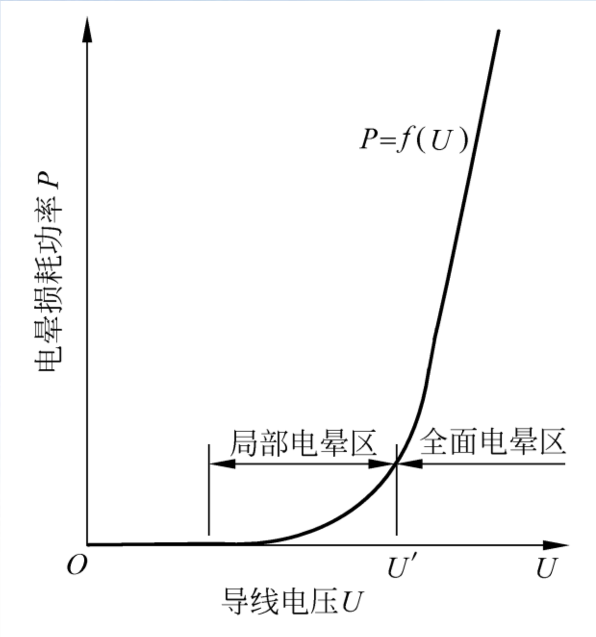
The formula for corona inception stress $\boldsymbol{E}_{\mathbf{c}}$ (peak) and corona inception voltage $\boldsymbol{U}_{\mathbf{c}}$

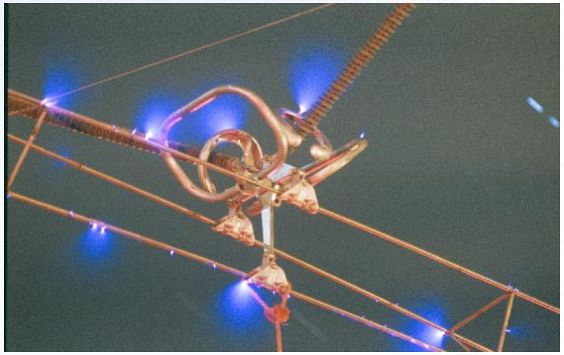
$$E_c = 30.3 m\delta \left(1 + 0.298\sqrt{r\delta}\right) \text{ kVmax/cm}$$

$$U_c = E_c r \ln\left(\frac{d}{r}\right)$$

The formula for other typical electrode configurations can be found in Table 2-1 of the textbook

Corona of transmission lines





Visible corona!

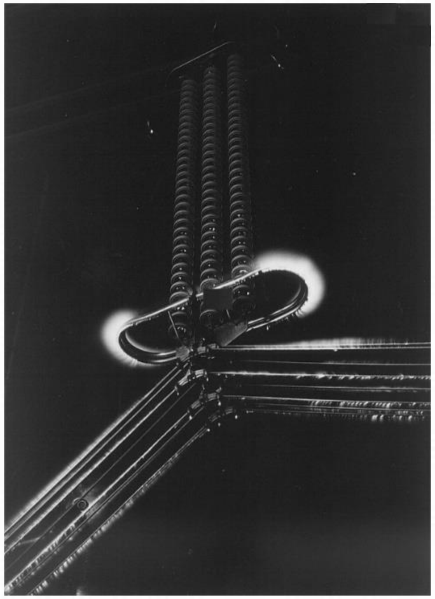
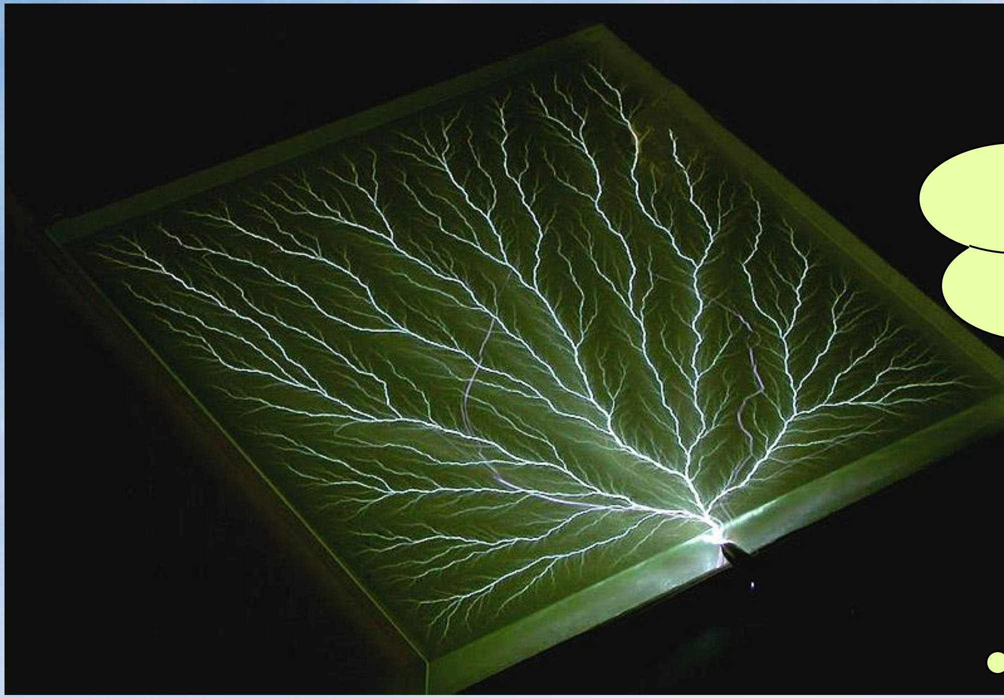


表 2-1 几种典型电极的简化估算公式

电极形状	电极表面最大场强 E_{max}	电场不均匀系数 f	电晕起始场强 E_0	电晕起始电压 U_c
同心球	$E_{max}=\dfrac{RU}{r(R-r)}$ 式（2-1）	$f=R/r$ 式（2-2）	$E_0=24\delta(1+1/\sqrt{r\delta})$ 式（2-3）	$U_c=E_0\dfrac{(R-r)r}{R}$ 式（2-4）
球-平板	$E_{max}=0.9\dfrac{U}{d}(1+\dfrac{d}{r})$ 式（2-5）	$f=0.9(1+\dfrac{d}{r})$ 式（2-6）	$E_0=27.7\delta(1+0.337/\sqrt{r\delta})$ 式（2-7）	$U_c=E_0\dfrac{dr}{0.9(d+r)}$ 式（2-8）
球-球	$E_{max}=0.9\dfrac{U}{d}(1+\dfrac{d}{2r})$ 式（2-9）	$f=0.9(1+\dfrac{d}{2r})$ 式（2-10）	$E_0=27.7\delta(1+0.337/\sqrt{r\delta})$ 式（2-11）	$U_c=E_0\dfrac{d}{0.9(1+d/2r)}$ 式（2-12）
同轴圆柱	$E_{max}=\dfrac{U}{r\ln(R/r)}$ 式（2-13）	$f=\dfrac{R-r}{r\ln(R/r)}$ 式（2-14）	$E_0=31.5\delta(1+0.305/\sqrt{r\delta})$ 式（2-15）	$U_c=E_0 r\ln(\dfrac{R}{r})$ 式（2-16）
圆柱-平板	$E_{max}=\dfrac{0.9U}{r\ln(\dfrac{d+r}{r})}$ 式（2-17）	$f=\dfrac{0.9d}{r\ln(\dfrac{d+r}{r})}$ 式（2-18）	$E_0=30.3\delta(1+0.298/\sqrt{r\delta})$ 式（2-19）	$U_c=E_0\dfrac{r\ln(\dfrac{d+r}{r})}{0.9}$ 式（2-20）
平行圆柱	$E_{max}=\dfrac{0.9U}{2r\ln(\dfrac{d+2r}{2r})}$ 式（2-21）	$f=\dfrac{0.9d}{2r\ln(\dfrac{d+2r}{2r})}$ 式（2-22）	$E_0=30.3\delta(1+0.298/\sqrt{r\delta})$ 式（2-23）	$U_c=E_0\dfrac{2r\ln(\dfrac{d+2r}{2r})}{0.9}$ 式（2-24）

注：表中 E_0、E_{max} 的单位为 kV/cm (峰值)，U_c 的单位为 kV (峰值)，r、R、d 的含义见图 2-2，其单位均为 cm。



Plenty of exquisite pictures with artificially prepared HV discharge, why not search for them?

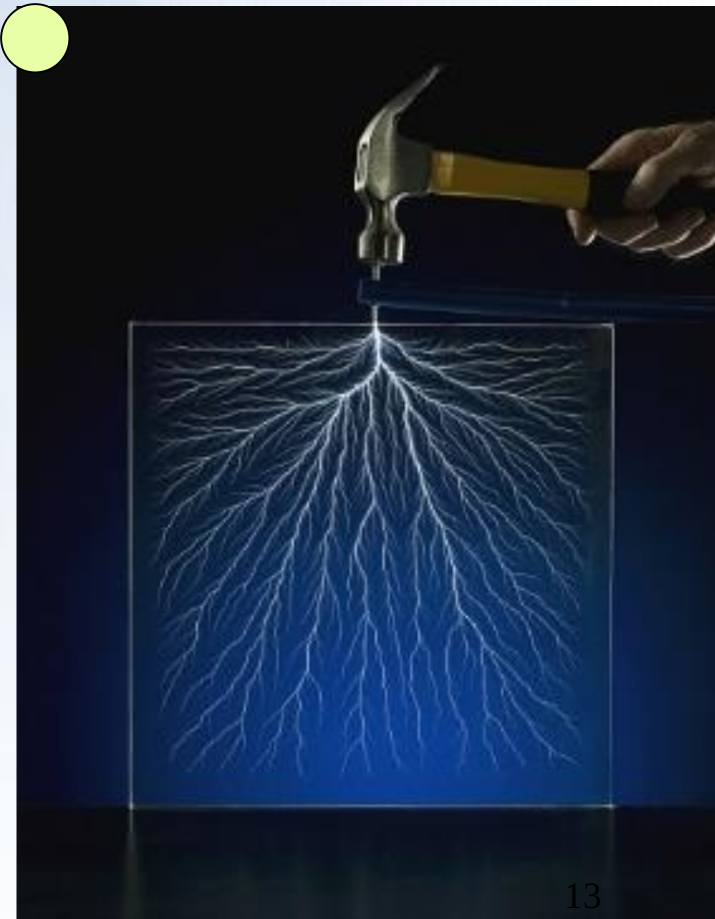


Figure 3.32 Photograph of a positive streamer corona, Lemke [3.38, 3.39].

- For the extremely non-uniform field , if the voltage rise continuously after the inception of corona, then the corona area will expand and streamer discharge will occur
- Different voltage polarity applied to the high stress electrode, resulting in different shapes of streamer discharge

Positive streamer discharge in air gap

with extremely non-uniform electric field

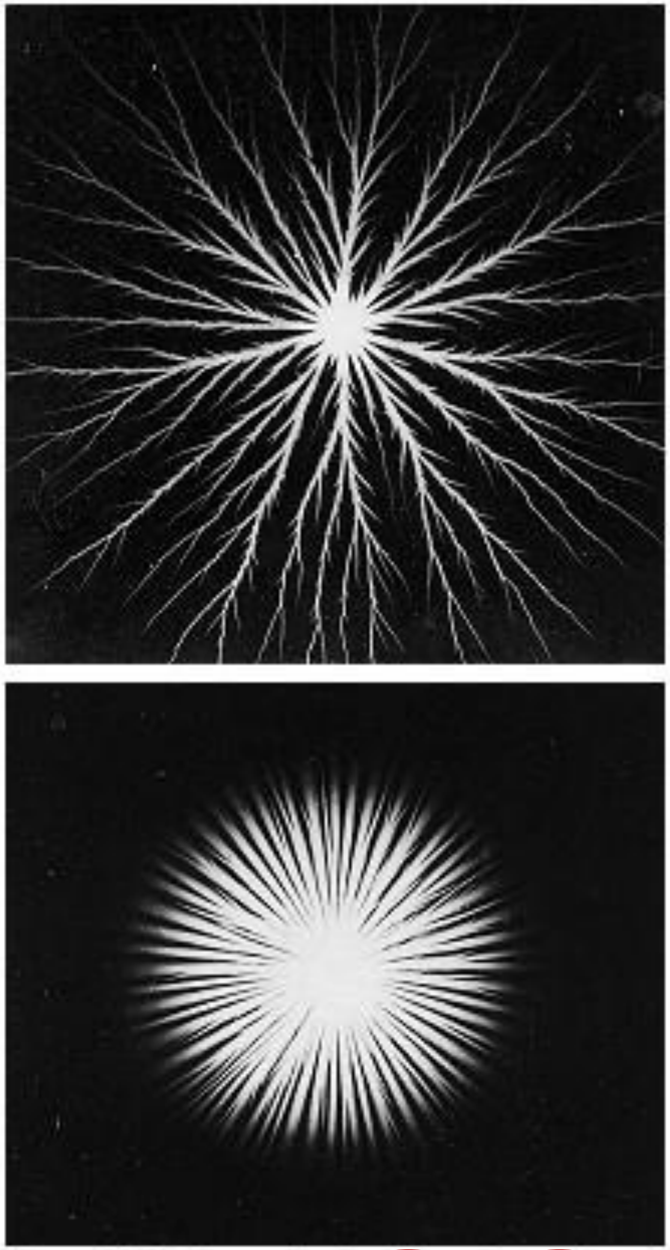


Figure 3.35 Photograph of positive and negative streamer corona, "Lichtenberg Figures" taken by Toepler, TU Dresden.

- For the extremely non-uniform field , if the voltage rise continuously after the inception of corona, then the corona area will expand and streamer discharge will occur
- Different voltage polarity applied to the high stress electrode, resulting in different shapes of streamer discharge

Positive and negative streamers discharge in air gap with extremely non-uniform electric field

1.4.3 Polarity effect of non-uniform electric field

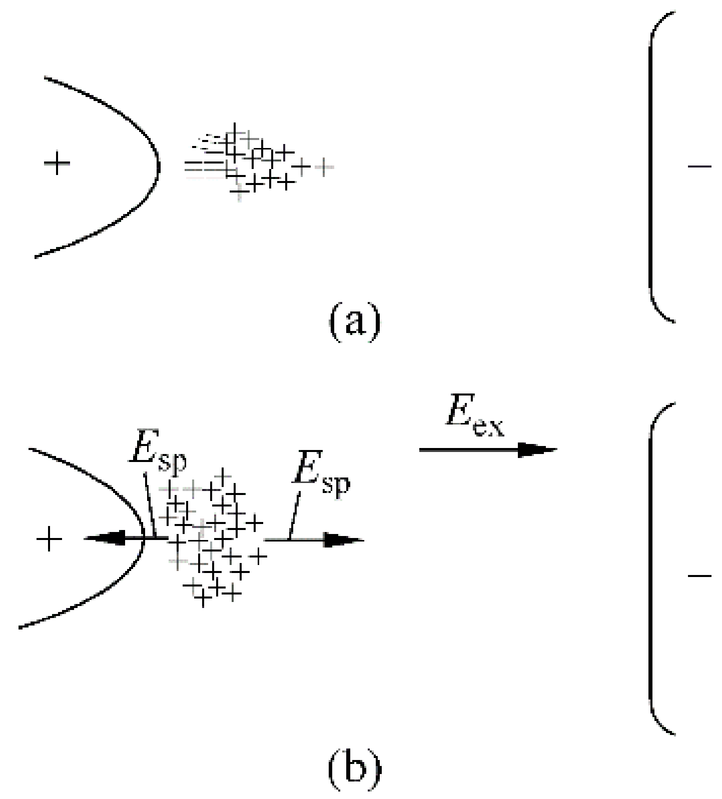
Difference in corona inception voltage

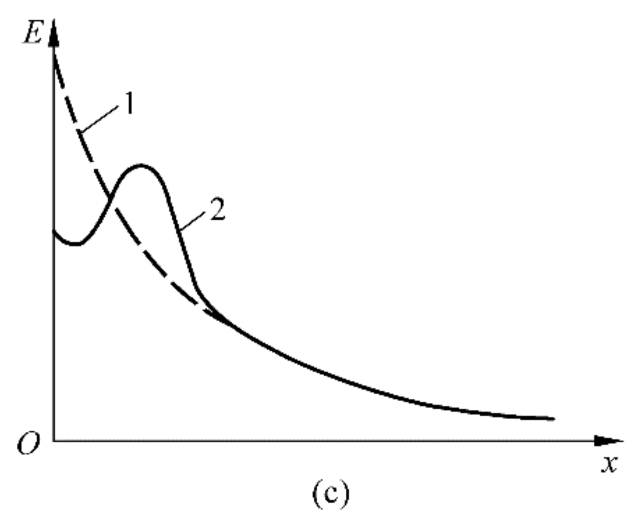
Differences in gap breakdown voltage

- Pay attention to the starting position and development direction of electron avalanches and streamers
- Pay attention to the direction and speed of motion of electrons, positive ions, and negative ions

The appearance of positive corona weakens the field stress in the high stress area

Higher voltage is required to maintain corona discharge





Positive rod-plane gap
Electric field distribution after corona inception

1.4.3 Polarity effect of non-uniform electric field

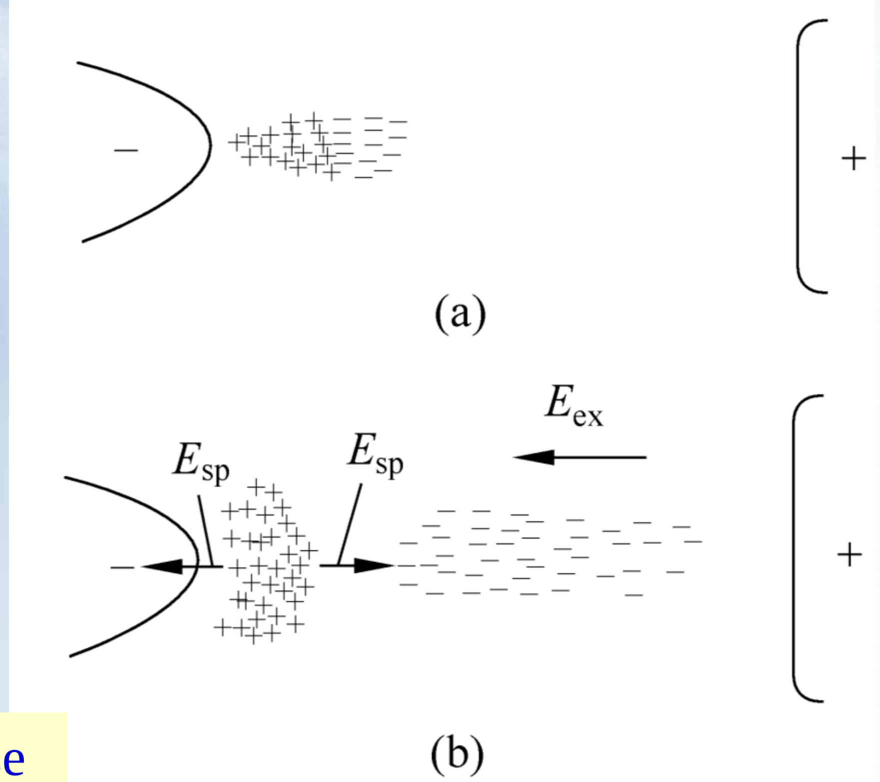
Difference in corona inception voltage

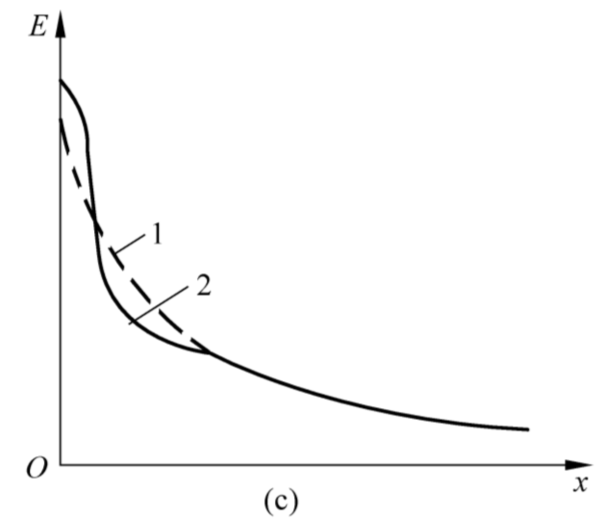
Differences in gap breakdown voltage

- Pay attention to the starting position and development direction of electron avalanches and streamers
- Pay attention to the direction and speed of motion of electrons, positive ions, and negative ions

The initiation of negative corona will increase the field stress in the high stress area and decreases the stress around

Corona can be maintained no higher voltage required, and corona is restricted close to high stress electrode



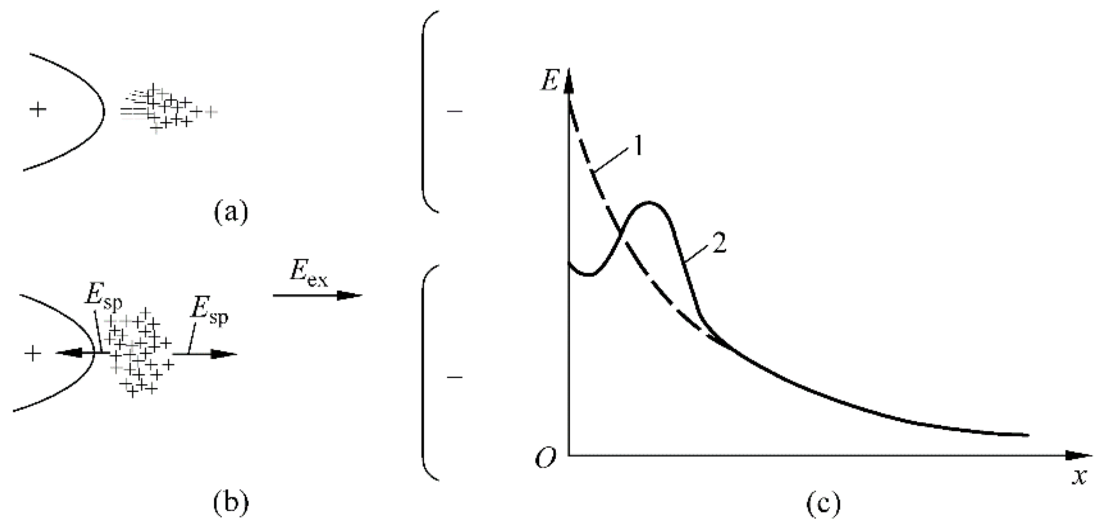


Negative rod-plane gap

Electric field distribution after corona inception

1.4.3 Polarity effect of non-uniform electric field

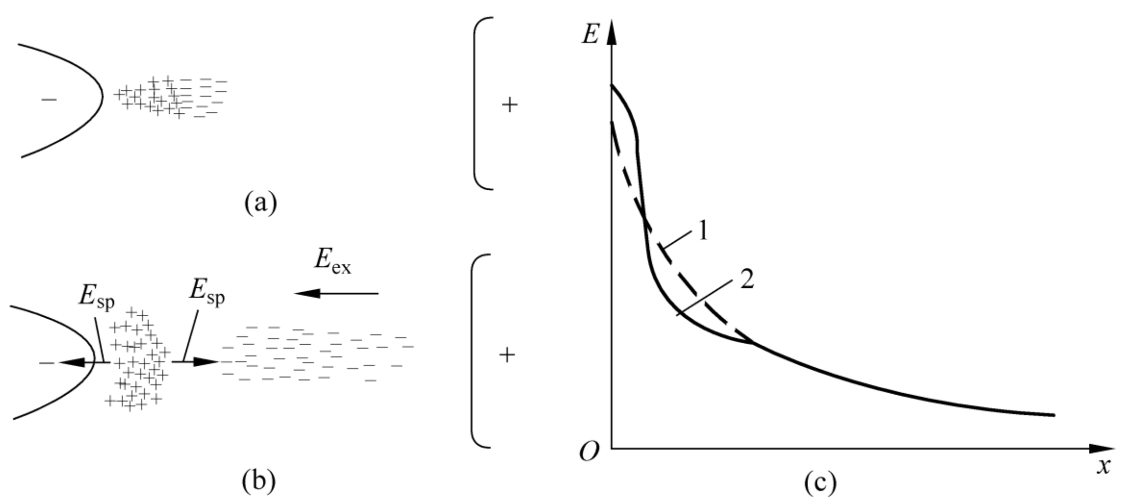
The difference in corona inception voltage, differences in gap breakdown voltage



Positive rod-plane

Higher corona inception voltage required

Positive polarity is less easy to produce corona discharge



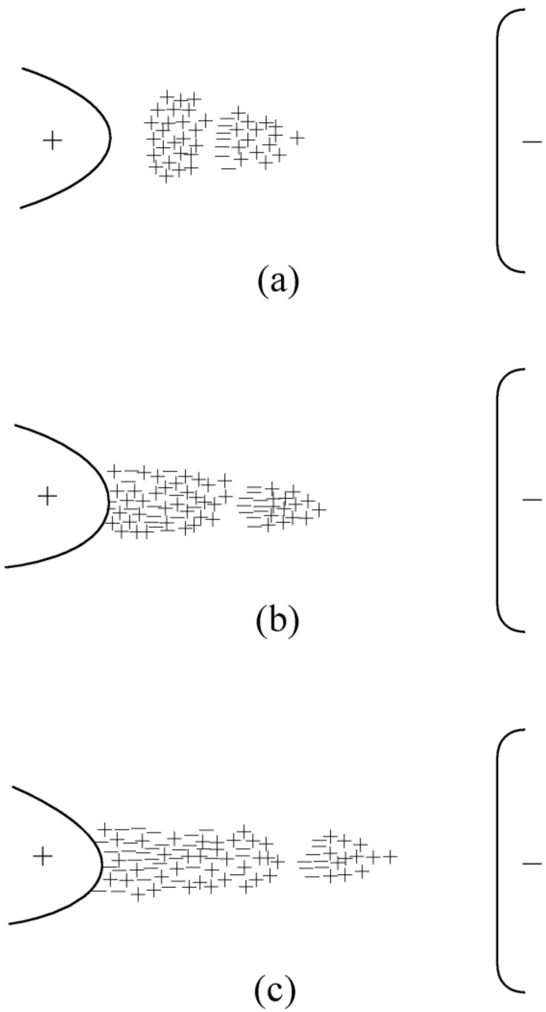
Negative rod-plane

Lower corona inception voltage required

Negative polarity is easy to produce corona discharge

1.4.3 Polarity effect of non-uniform electric field

The difference in corona inception voltage, differences in gap breakdown voltage

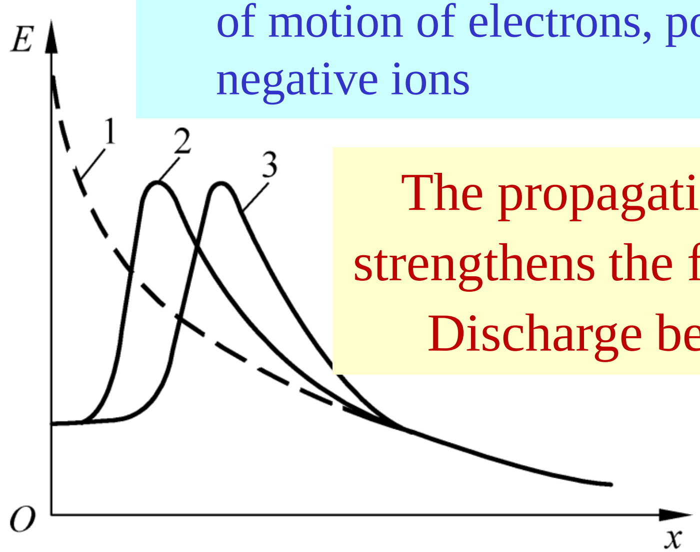


(a)

(b)

(c)

- Pay attention to the starting position and development direction of electron avalanches and streamers
- Pay attention to the direction and speed of motion of electrons, positive ions, and negative ions



(d)

The propagation of streamer strengthens the field stress ahead
Discharge becomes easier

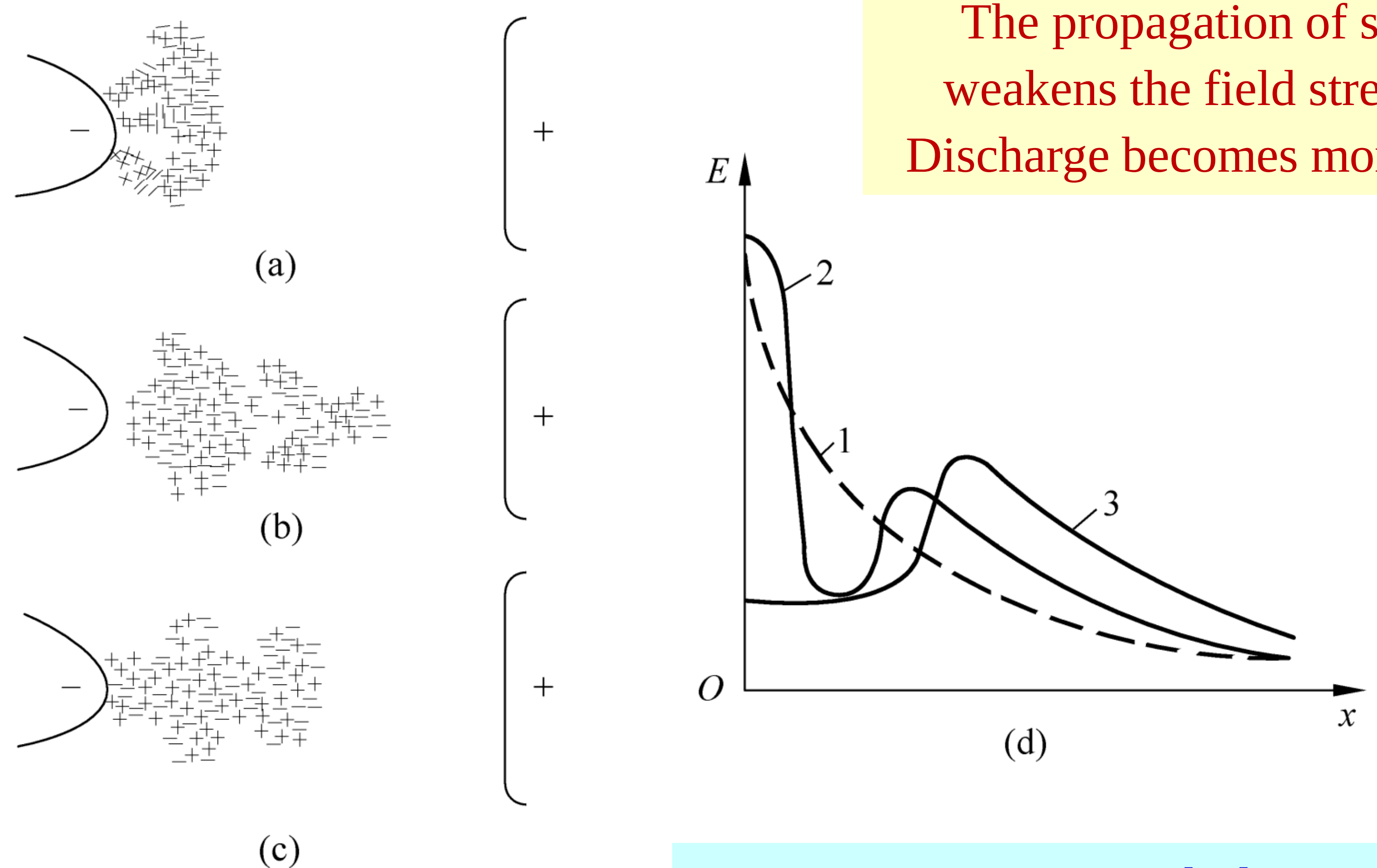
Positive rod-plane gap

Field distribution after streamer propagate

1.4.3 Polarity effect of non-uniform electric field

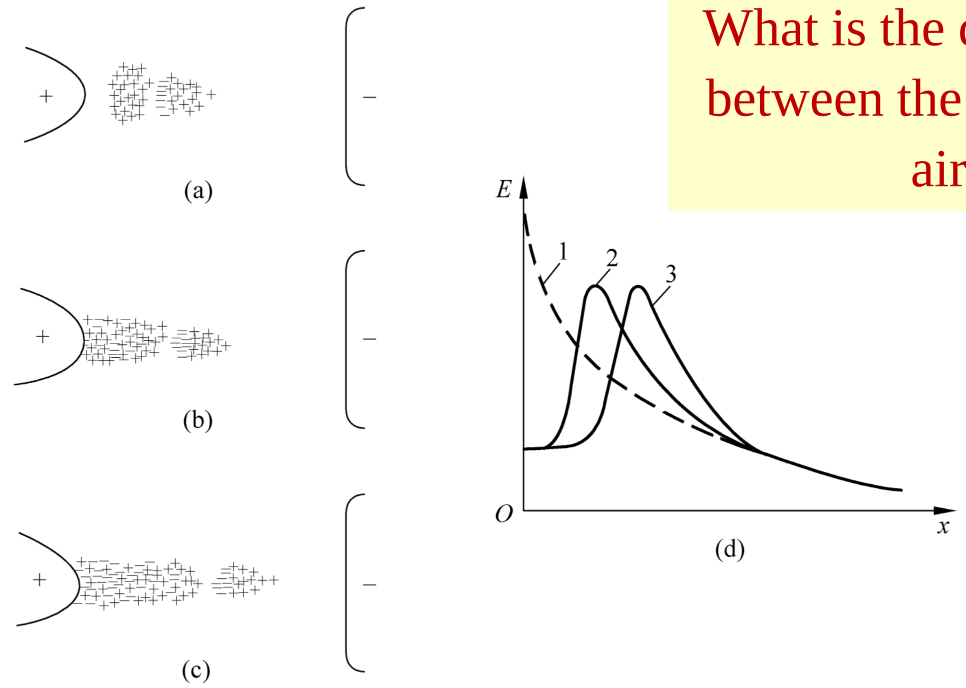
The difference in corona inception voltage, differences in gap breakdown voltage

The propagation of streamer weakens the field stress ahead Discharge becomes more difficult



Negative rod-plane gap

Field distribution after streamer propagate

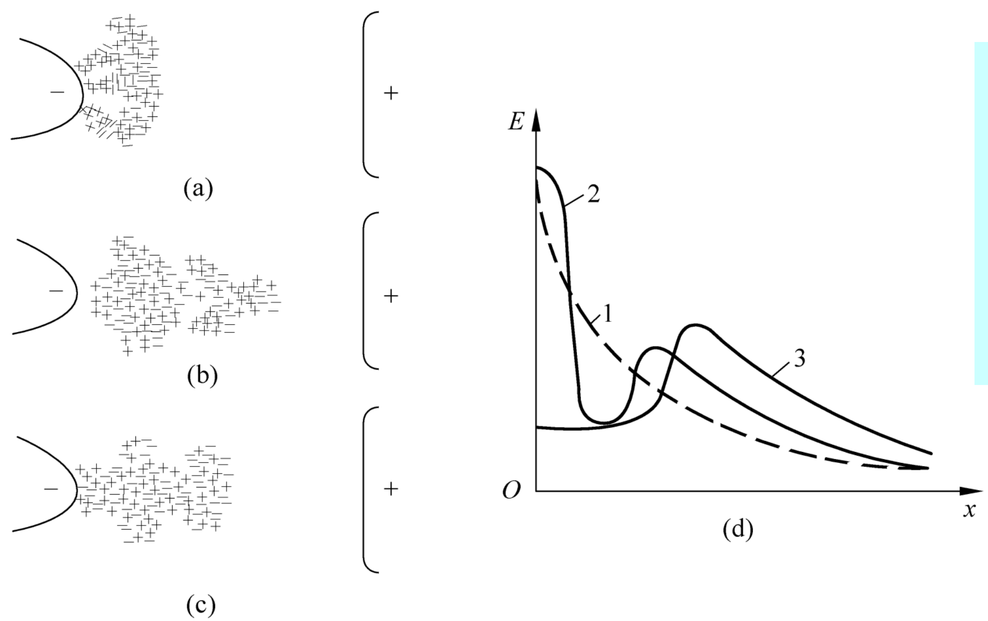


What is the difference in breakdown voltage between the positive and negative rod-plane air gaps? See Chapter 2

Positive rod-plane

Streamer discharge strengthens the field stress ahead, making discharge easier

Lower gap breakdown voltage



Negative rod-plane

Discharge is maintained in a certain area for a long time

Higher gap breakdown voltage

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1.4.5 Self-sustained discharge criterion and polarity effects of slightly non-uniform electric field

1.4.4 Long gap breakdown process

(1) Leader/stepped leader discharge

- The average breakdown strength of long air gap decreases significantly for the occurrence of leader
- The propagation of leader is in steps (stepped leader)
- e.g. positive switching impulse breakdown voltage with a 10m long air gap is only ≈1800kV

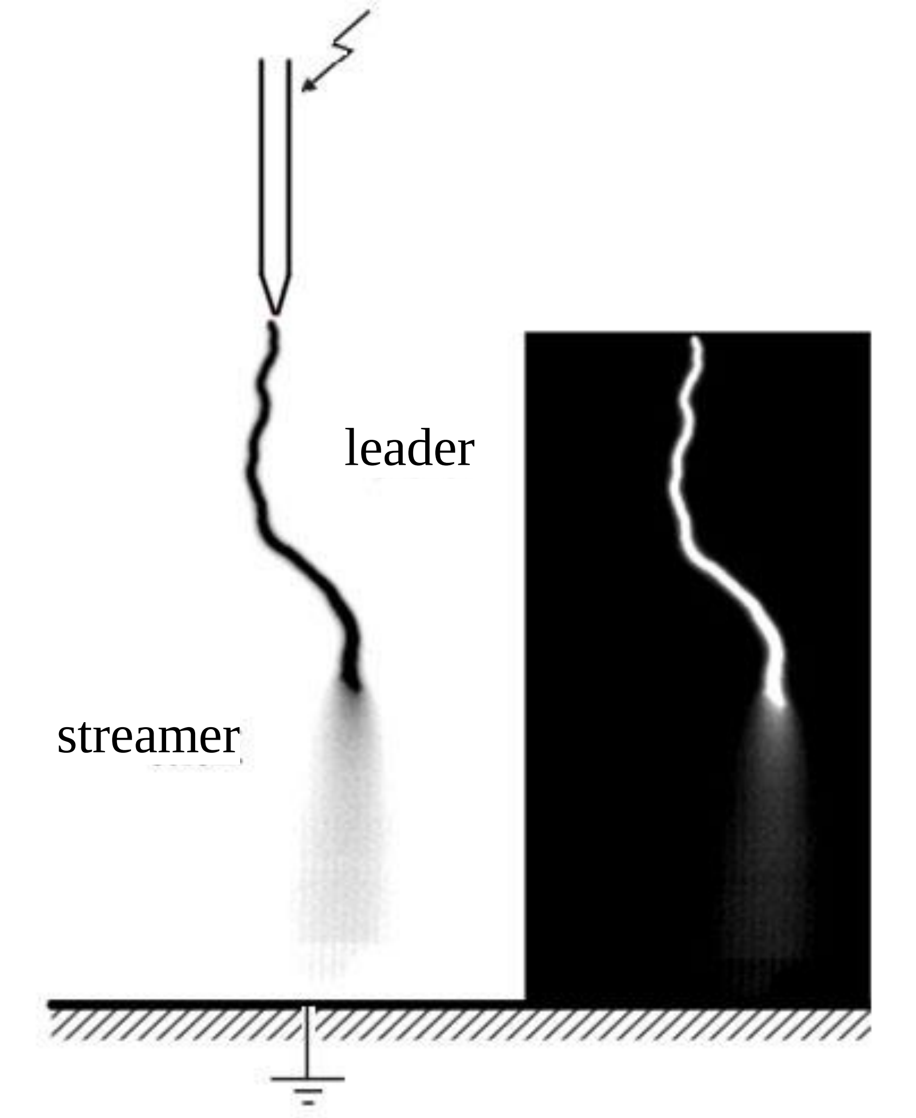
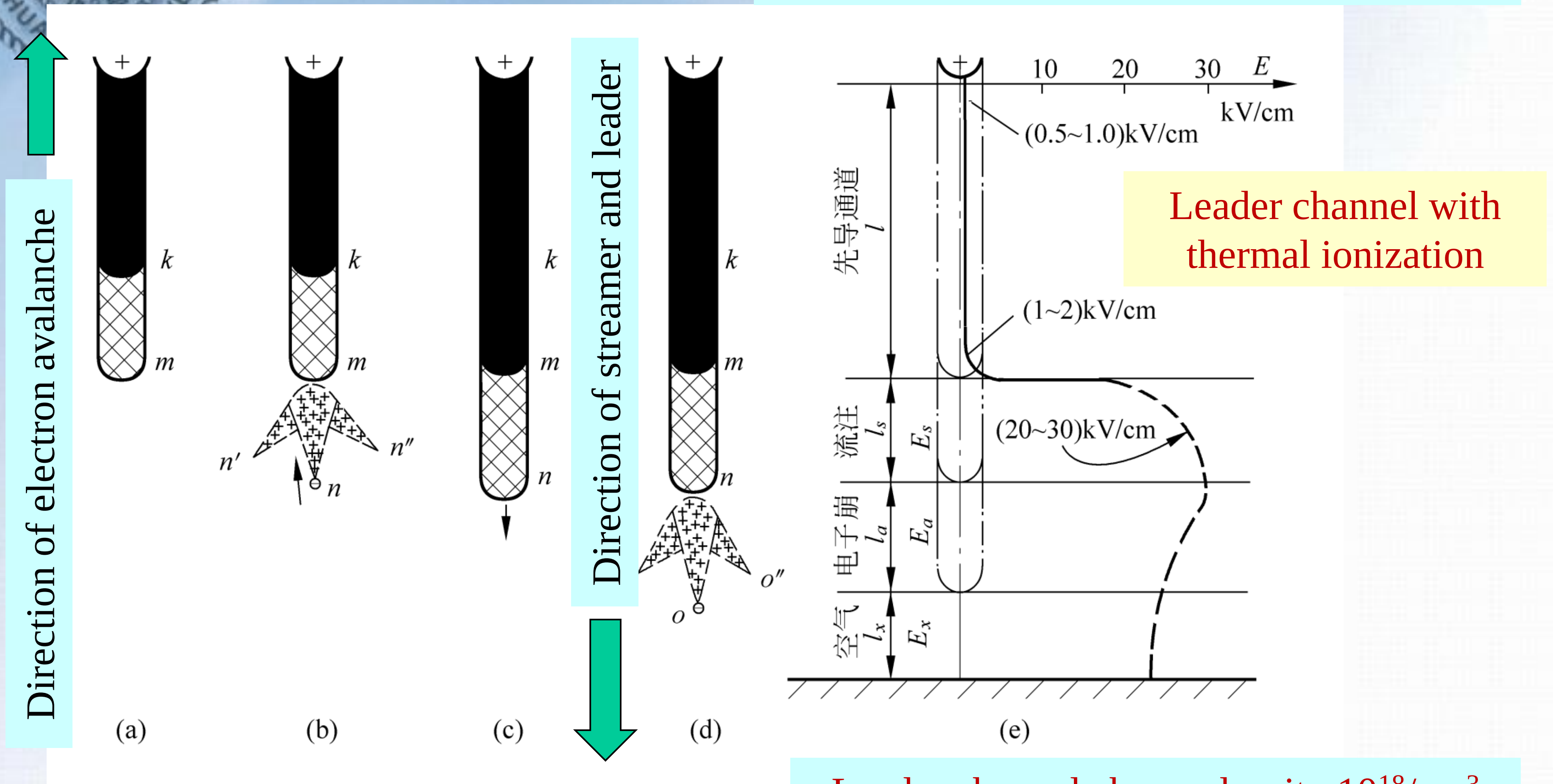


Photo of the leader and front streamer in a rod-plane long air gap

1.4.4 Long gap breakdown process

The average breakdown strength of long air gap decreases significantly for the occurrence of leader/stepped leader

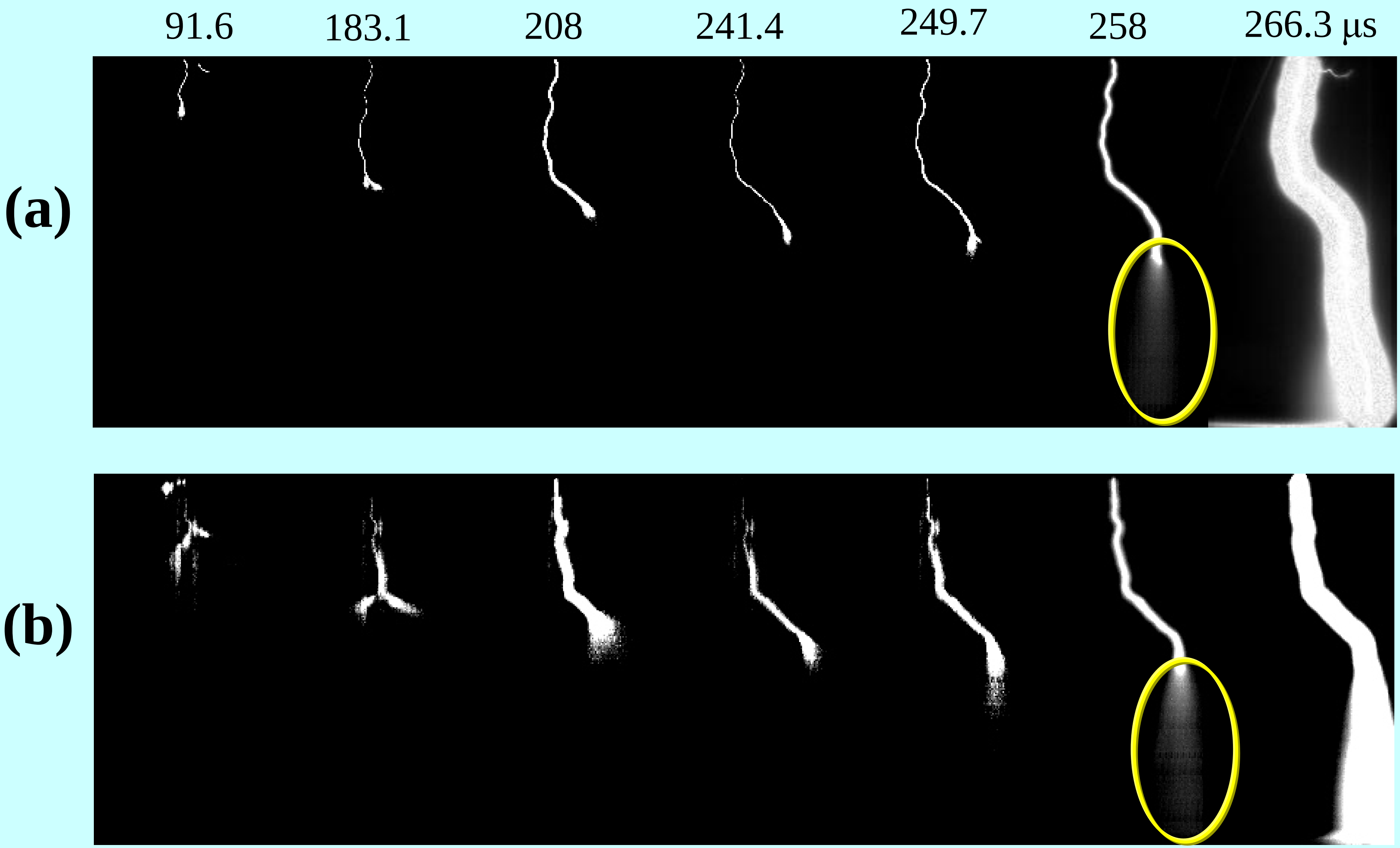


Propagation of the stepped leader in a positive rod plane long gap

Leader channel charge density $10^{18}/cm^3$

The current can reach several hundred A

Stepped leader and streamer in the breakdown process of long air gap



1.4.4 Long gap breakdown process

(2) Main discharge

- When the head of the leader channel develops close to the opposite electrode, the field strength in the remaining gap increases sharply, then the discharge is very strong.
- The strong discharge propagate in the opposite direction along the leader channel to the rod electrode, while neutralizing the excess space charge in the leader channel. This process is called the main discharge (return stroke).
- The main discharge process makes the channel that connecting the two electrodes into a plasma spark channel with high temperature, high conductivity, and low axial field strength (if the power supply is sufficient, it is converted into an arc channel), thereby the long air gap completely lose its insulation and finally breakdown
- The propagation speed in the main discharge stage is very fast, reaching up to 10^9cm/s. It is about 10% of the light.

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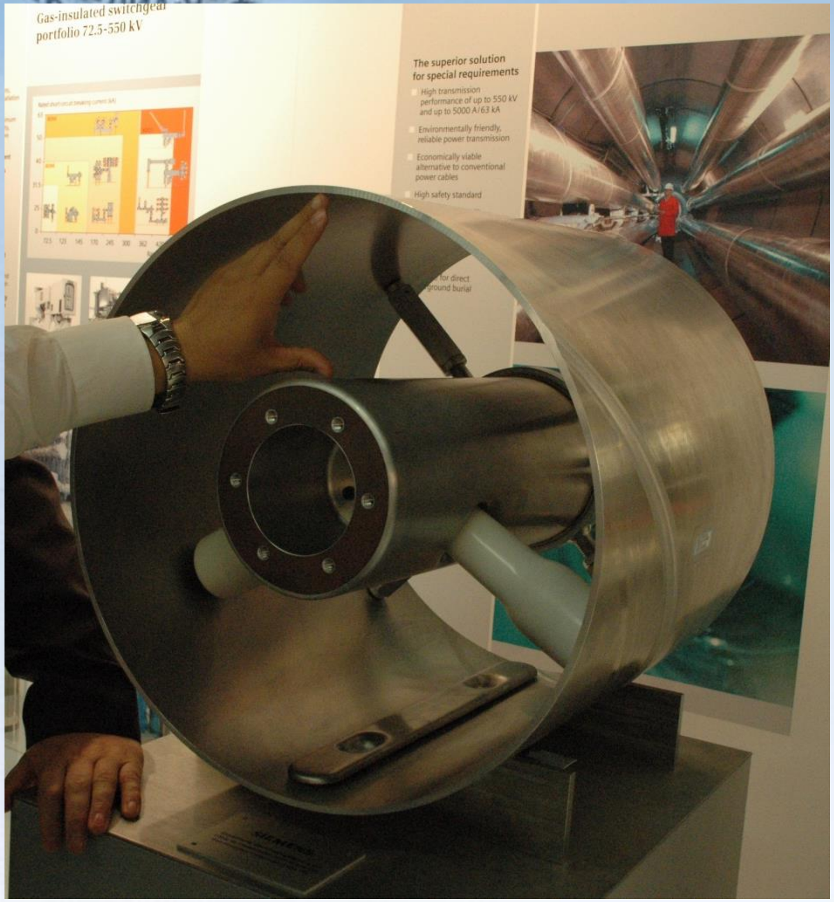

Slightly non-uniform field is widely used in Gas Insulated Substation and transmission Line (GIS & GIL)

1.4.5 Self-sustained discharge criterion and polarity effects of slightly non-uniform electric field

Sphere gap used for HV measurement is a slightly non-uniform field system

1.4.5 Self-sustained discharge criterion and polarity effects of slightly non-uniform electric field

A slightly non-uniform electric field will not produce corona before breakdown

Once the corona/streamer is started, it will penetrates the gap and breakdown

Self-sustained discharge criterion is the breakdown criterion;

The negative breakdown voltage U_b(-) is lower than that of positive polarity U_b (+). The polarity effect of breakdown voltage is opposite to that of non-uniform field

The prediction/calculation on U_b (-) for slightly non-uniform field is in Chapter 2