# PULSED POWER SYSTEM
# 脈衝功率系統

**Po-Yu Chang**

**Institute of Space and Plasma Sciences, National Cheng Kung University**

**2024 Fall Semester**

**Thursday 9:10-12:00**

**Lecture 4**

**http://capst.ncku.edu.tw/PGS/index.php/teaching/**

**Online courses:**

**https://nckucc.webex.com/nckucc/j.php?MTID=mf87b10f22c1e36d5c4b2337e60d8a847**

2024/10/24 updated

# Reference

- **Foundations of pulsed power technology, by Jane Lehr & Pralhad Ron**
- **Pulsed power systems, by H. Bluhm**
- **Pulsed power, by Gennady A. Mesyats**
- **J. C. Martin on pulsed power, edited by T. H. Martin, A. H. Guenther, and M. Kristiansen**
- **Pulse power formulary, by Richard J. Adler**

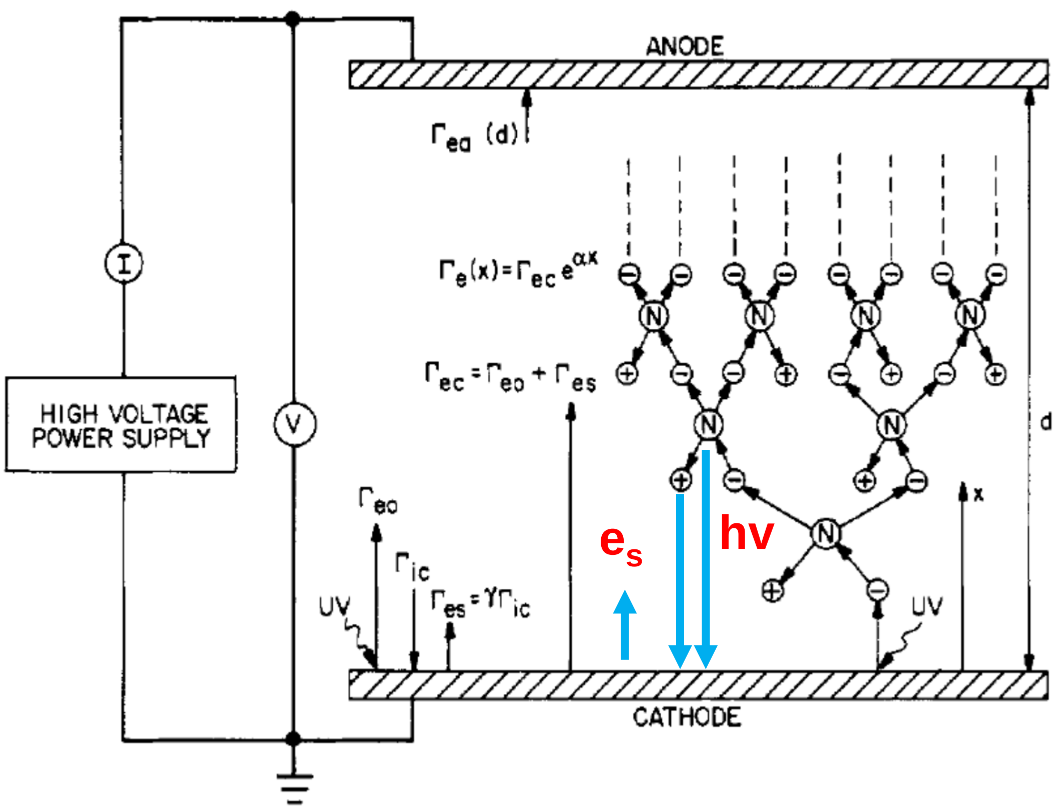
- **Circuit analysis, by Cunningham and Stuller**

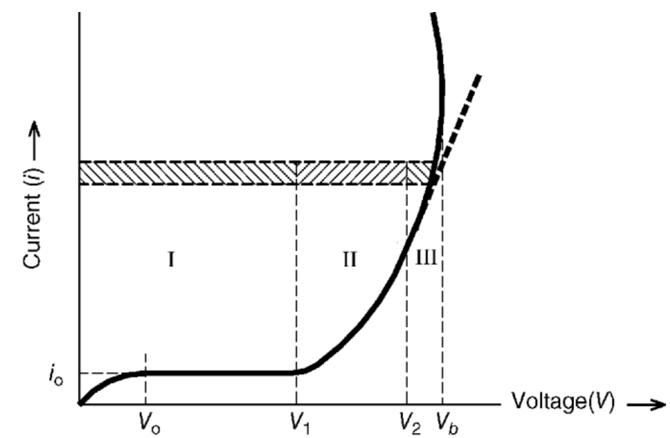
# Outlines

- Introduction to pulsed-power system
- Review of circuit analysis
- Static and dynamic breakdown strength of dielectric materials
  – Gas – Townsend discharge (avalanche breakdown), Paschen's curve
  – Liquid
  – Solid
- Energy storage
  – Pulse discharge capacitors
  – Marx generators
  – Inductive energy storage

# More electrons, secondary electrons, are needed to cause the breakdown

- **Secondary electrons – electrons released from the cathode by ions that have drifted to the electrode as well as by light quanta created by recombination and de-excitation processes.**



# Secondary electrons lead to more electron avalanche

$$n(0) = n_0 + \omega \int_0^d n(x)\,\mathrm{d}x$$

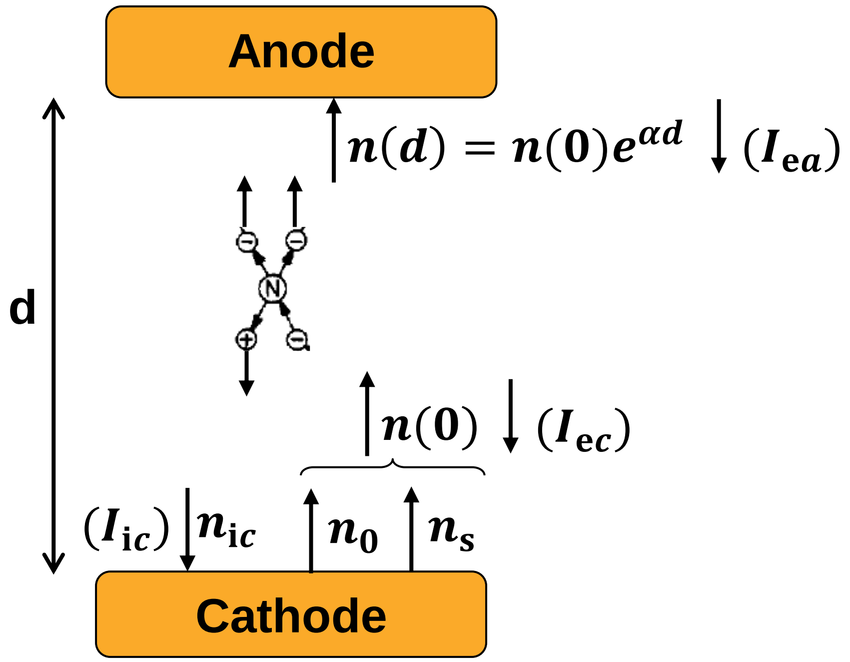
$$= n_0 + \omega n(0) \int_0^d e^{\alpha x}\,\mathrm{d}x$$

$$= n_0 + \omega n(0) \frac{1}{\alpha} e^{\alpha x} \Big|_0^d$$

$$n(0) = n_0 + \frac{\omega}{\alpha} n(0)\left(e^{\alpha d} - 1\right)$$

$$n(0) = \frac{n_0}{1 - \frac{\omega}{\alpha}\left(e^{\alpha d} - 1\right)}$$

$$n(d) = \frac{n_0 e^{\alpha d}}{1 - \frac{\omega}{\alpha}\left(e^{\alpha d} - 1\right)}$$




- $n_0$: the #/ of electrons released from the cathode by external process.
- $\omega$: coefficient of generating secondary electrons from the #/ of total generated primary electrons.

# Townsend condition for ignition

- When the denominator equals to zero, the breakdown happens.

$$n(d) = \frac{n_0 e^{\alpha d}}{1 - \frac{\omega}{\alpha}\left(e^{\alpha d} - 1\right)}$$

$$1 - \frac{\omega}{\alpha}\left(e^{\alpha d} - 1\right) = 0 \qquad \frac{\omega}{\alpha}\left(e^{\alpha d} - 1\right) = 1$$

- The insulation of the cathode-anode gap breaks down and a self-sustained discharge is created.
- Experiments show that ω/p is also a function of E/p, i.e., $\frac{\omega}{p} = f\left(\frac{E}{p}\right)$

$$\frac{\omega/p}{\alpha/p}\left(e^{\frac{\alpha}{p}\text{pd}} - 1\right) = 1 \qquad \frac{f(E/p)}{F(E/p)}\left(e^{F(E/p)\text{pd}} - 1\right) = 1 \qquad E = \frac{V}{d} \qquad \frac{E}{p} = \frac{V}{\text{pd}}$$

- V can be solved for given pd if f(E/p) and F(E/p), i.e., f(V/pd) and F(V/pd) are known.

# Paschen's law: the breakdown voltage $V_b$ of a uniform-field gap is a unique function Π of pd

$$V_b = \Pi(\mathrm{pd})$$

- In certain region, A and B are constants for a given gas.

$$\frac{\alpha}{p} = \mathrm{A}e^{-\mathrm{BP}/E} \equiv \mathrm{A}e^{-B\frac{\mathrm{pd}}{V}} \qquad \gamma \equiv \frac{\omega}{\alpha} = \frac{f(E/p)}{F(E/p)} = \gamma\left(\frac{E}{p}\right)$$

- Γ is a slowly varying function of E/p over a wide range.

$$\frac{\omega}{\alpha}\left(e^{\alpha\mathrm{d}} - 1\right) = 1$$

$$\gamma\left(e^{\alpha\mathrm{d}} - 1\right) = 1$$

$$\gamma\left(e^{\frac{\alpha}{p}\mathrm{pd}} - 1\right) = 1$$

$$\frac{\alpha}{p}\mathrm{pd} = \ln\left(1 + \frac{1}{\gamma}\right)$$

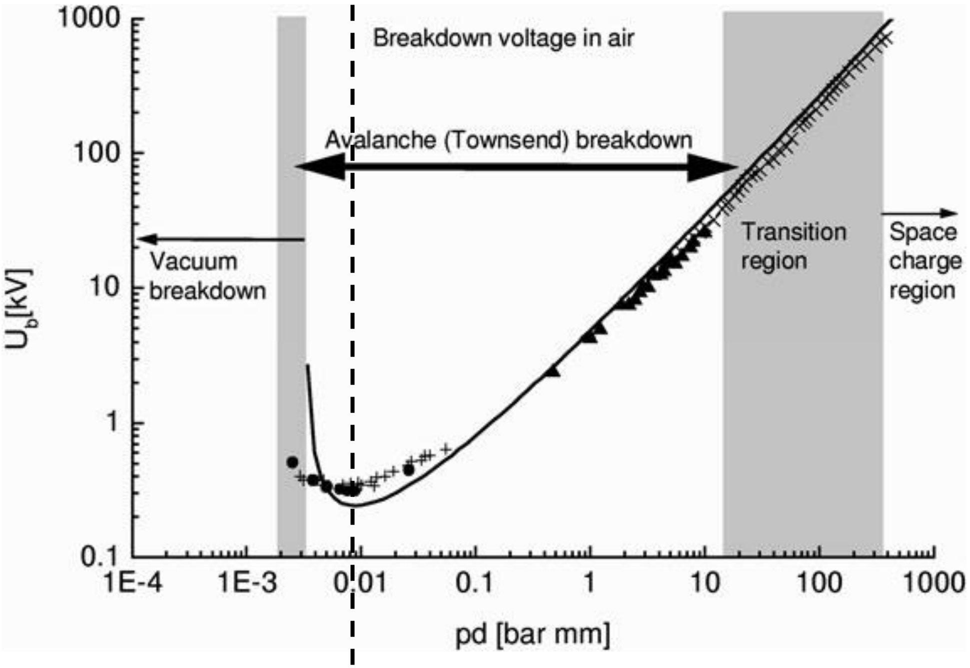
$$Ae^{-B\frac{\mathrm{pd}}{V}} = \frac{\ln\left(1 + \frac{1}{\gamma}\right)}{\mathrm{pd}} \qquad e^{B\frac{\mathrm{pd}}{V}} = \frac{\mathrm{Apd}}{\ln\left(1 + \frac{1}{\gamma}\right)}$$

$$\frac{Bpd}{V} = \ln\left[\frac{\mathrm{Apd}}{\ln\left(1 + \frac{1}{\gamma}\right)}\right]$$

$$V_{\mathrm{B}} = \frac{\mathrm{Bpd}}{\ln\left[\frac{\mathrm{Apd}}{\ln\left(1 + \frac{1}{\gamma}\right)}\right]}$$

# With a voltage lower than $V_{B,min}$ it is impossible to cause the breakdown of a gap with a uniform field

$$V_B = \frac{\mathbf{Bpd}}{\ln\left[\frac{\mathbf{Apd}}{\ln\left(1+\frac{1}{\gamma}\right)}\right]}$$

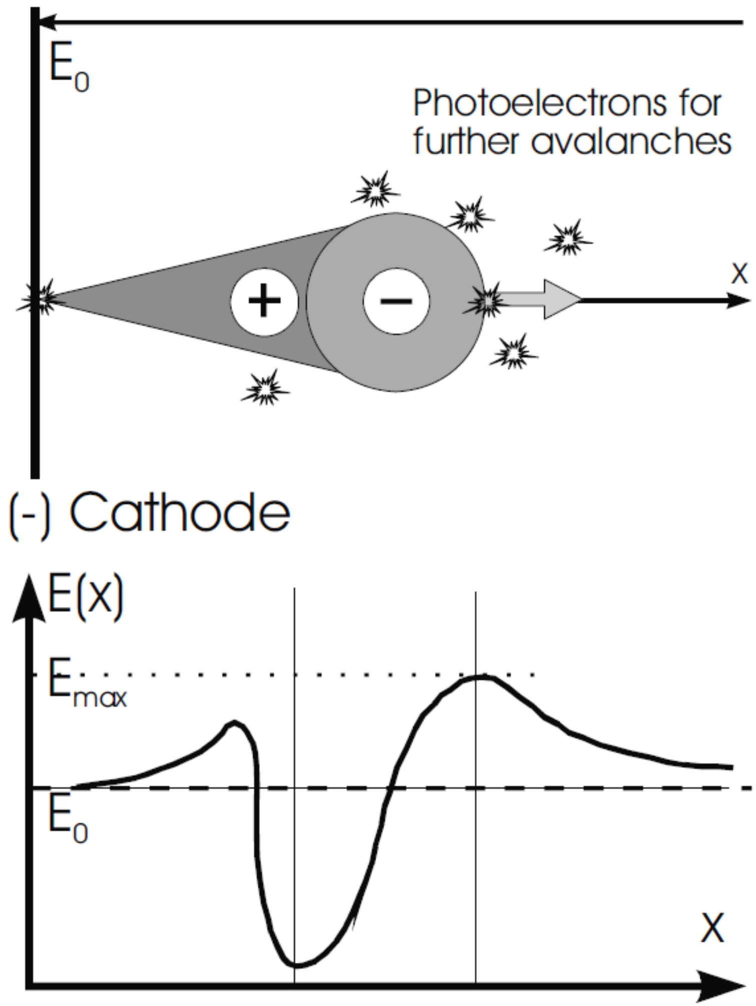



- **Collision is not frequent enough even the electrons gain large energy between each collision.**

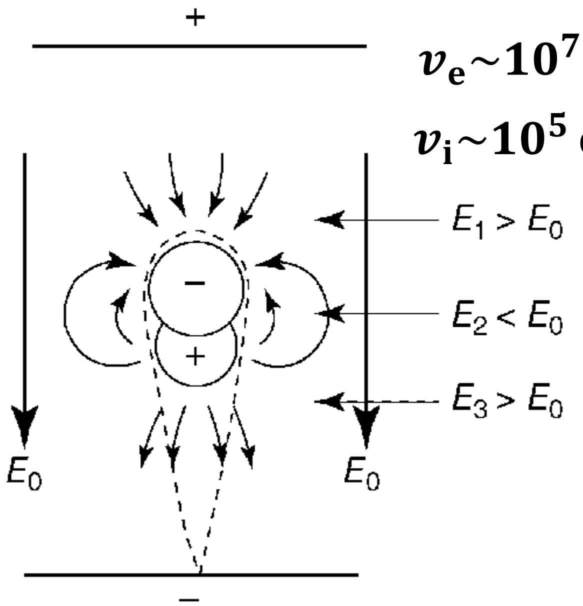
- **Electrons do not gain enough energy between each collision even collisions happen frequently.**

- **The minimum of the Paschen's curve corresponds to the Stoletow point, the pressure at which the volumetric ionization rate is a maximum.**

# Space charge effect

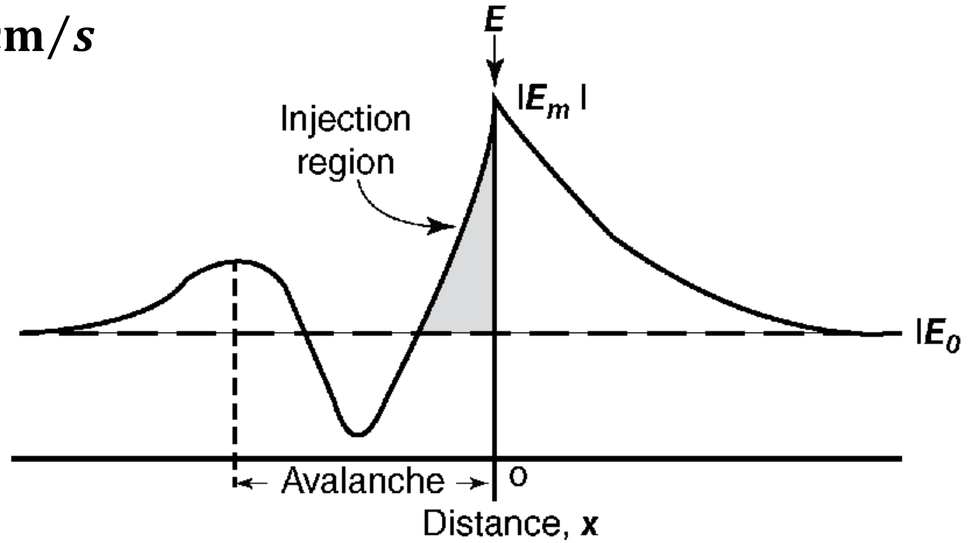


# Electrons moving much faster than ions leads to space charge effort which will enhance the avalanche




$v_e \sim 10^7\ \mathrm{cm}/s$

$v_i \sim 10^5\ \mathrm{cm}/s$




- **Criterion for streamer onset:**

**$E_r \sim E_0$ where $E_r$ is generated by the space charge at the head of the avalanche.**

**or $N_{cr} \sim 10^8$ where $N_{cr}$ is the #/ of electrons in the head of the avalanche.**

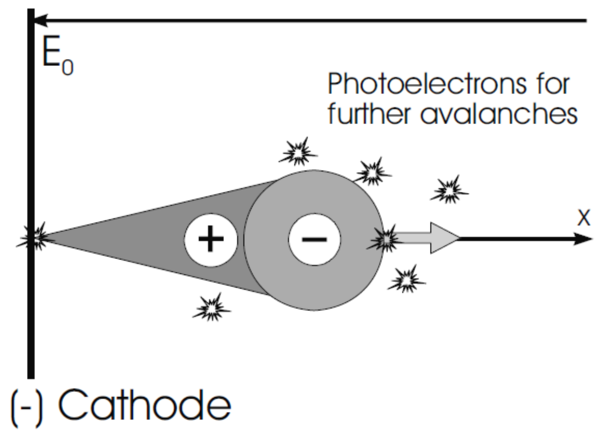
$$E_{SC} \sim \frac{eN}{4\pi\epsilon_0 r^2} = 1.5 \times 10^6 \frac{N}{(1/\alpha)^2}\ V/\mathrm{cm}$$

**For** $N = 10^7, \alpha = 10^{-2}\mathrm{cm}$

$$E_{SC} \sim 15\ \mathrm{kV/cm}$$

# Streamers

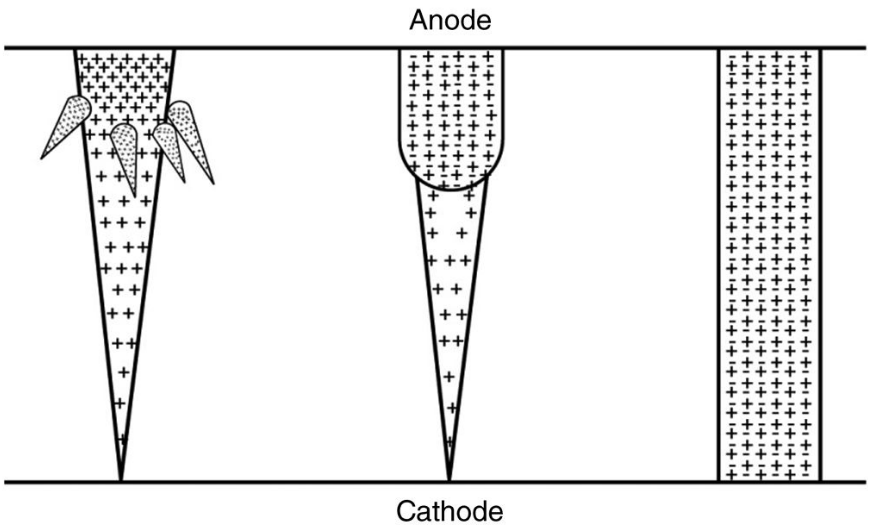
- UV light emitted in recombination and de-excitation creates electrons by "photoionization" ahead and behind the avalanche so that a conducting bridge between anode and cathode is formed.
- Creating photoelectrons at larger distances from the main streamer can advance the growth of the breakdown channel rapidly.
  - *v* =100-1000 cm/μs at atmospheric pressure was observed.

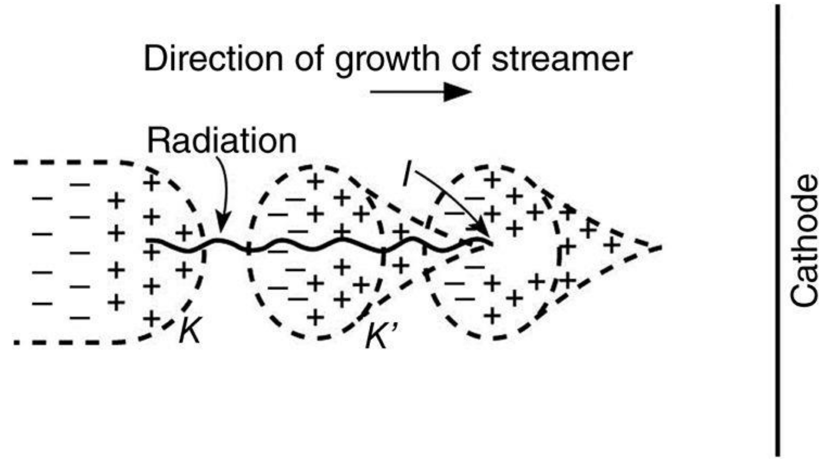


# Streamers

- **Streamers - evocative of a thin band of bright light, attached at one end to an electrode and floating toward the other – "kanals". (Channel in German)**
- **Cathode – directed (positive) streamers, from anode toward cathode.**
- **Anode – directed (negative) streamers, from cathode toward anode.**
- **Single-electron avalanche -> streamer – Streamers develop when the charge density at the head of the avalanche becomes so large that it distorts the applied electric field, i.e., space charge in the avalanche head generates a self-electric field that is on the order of the applied electric field.**

# The cathode-directed (positive) streamer (A → K)

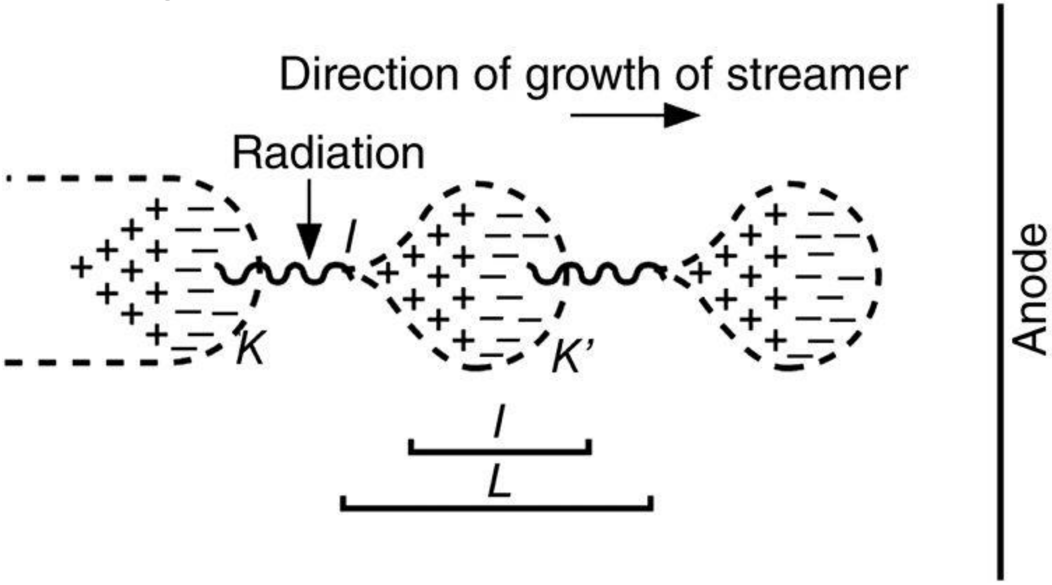


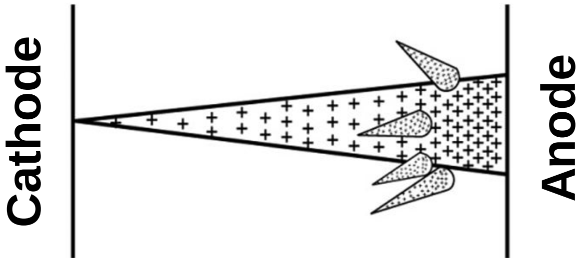

- **When the avalanche has <u>crossed the gap</u>, electrons are swept into the anode, the positive ions remaining in a cone-shaped volume extending across the gap.**
- **The streamer grows with the help of photonionization.**

# The anode-directed (negative) streamer (k → A)

- **Negative streamer**

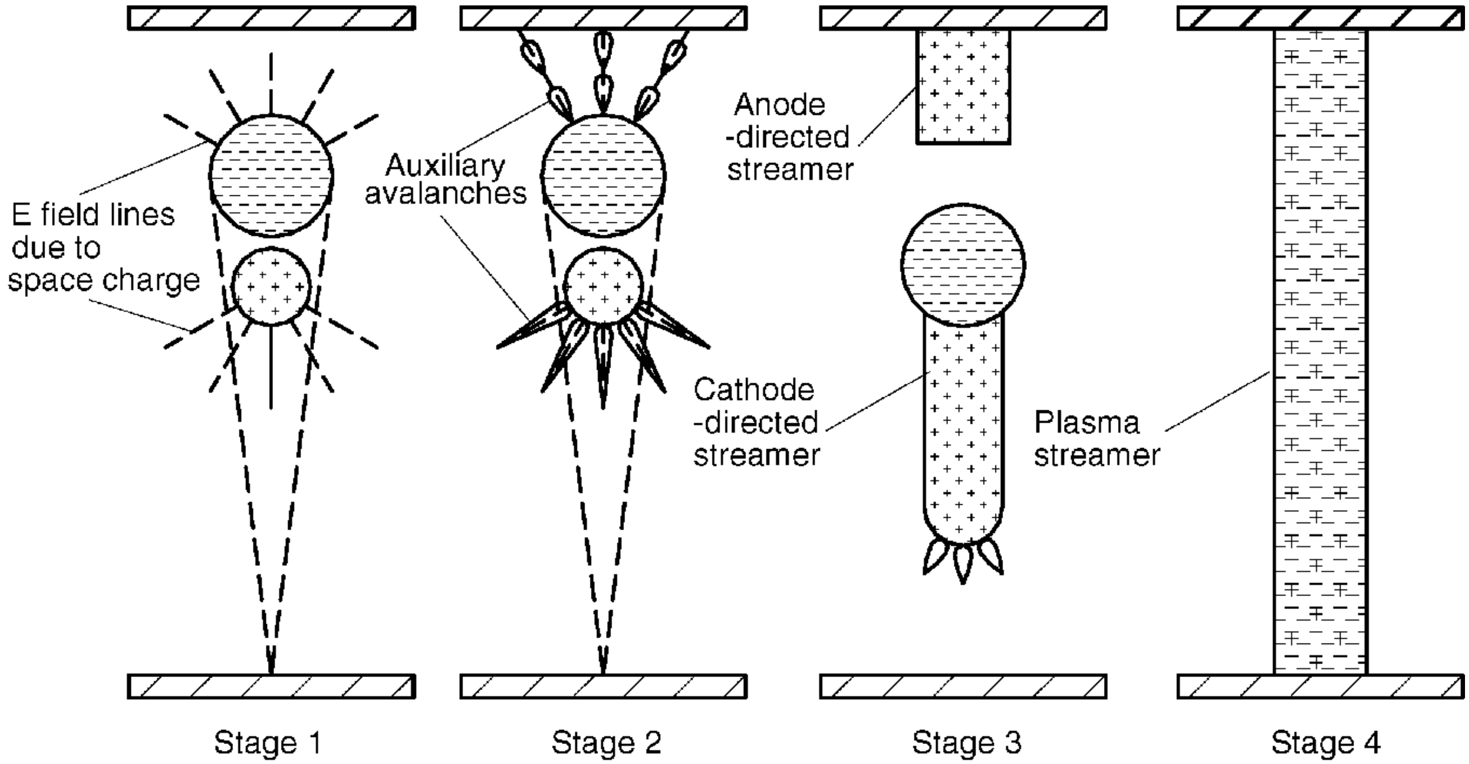



- **Positive streamer**



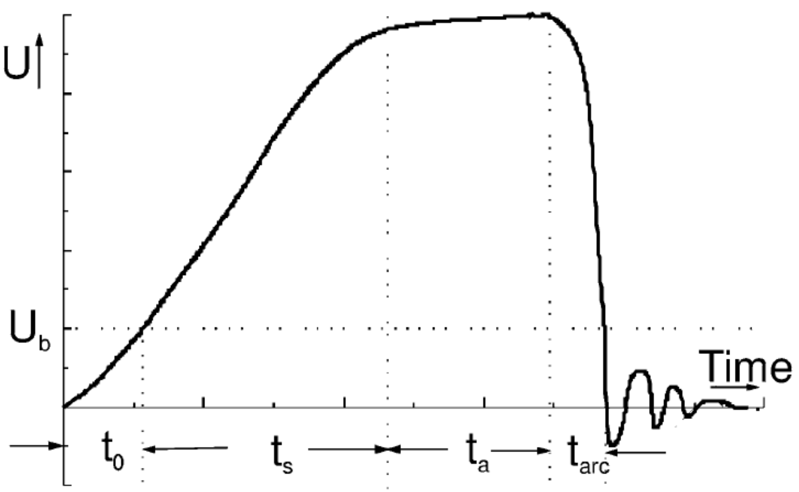

- **The negative streamer happens when the primary avalanche becomes sufficiently strong <u>before reaching the anode</u>.**
  - **$N_{cr}$~$10^8$ where $N_{cr}$ is the #/ of electrons in the head of the avalanche.**

# The overvolted streamer



# A voltage cross the gap higher than the static breakdown voltage occurs in a pulsed breakdown

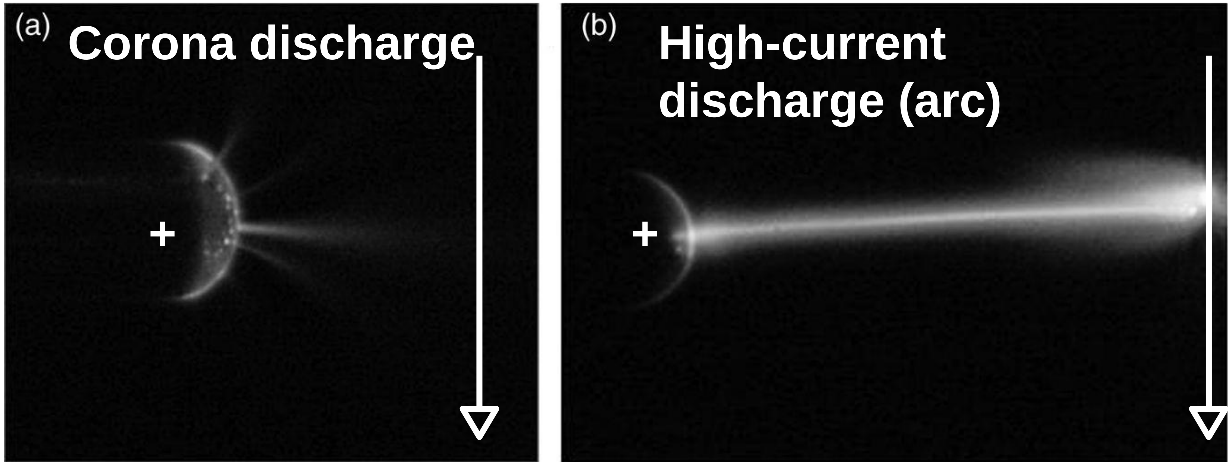
- If a fast-rising pule across the gap, we must take into account the fact that it takes a finite time before a breakdown can occur.
- Free electrons can be created by illuminating the gap volume or the cathode surface with electromagnetic radiation, in particular UV light, x rays and γ radiations.



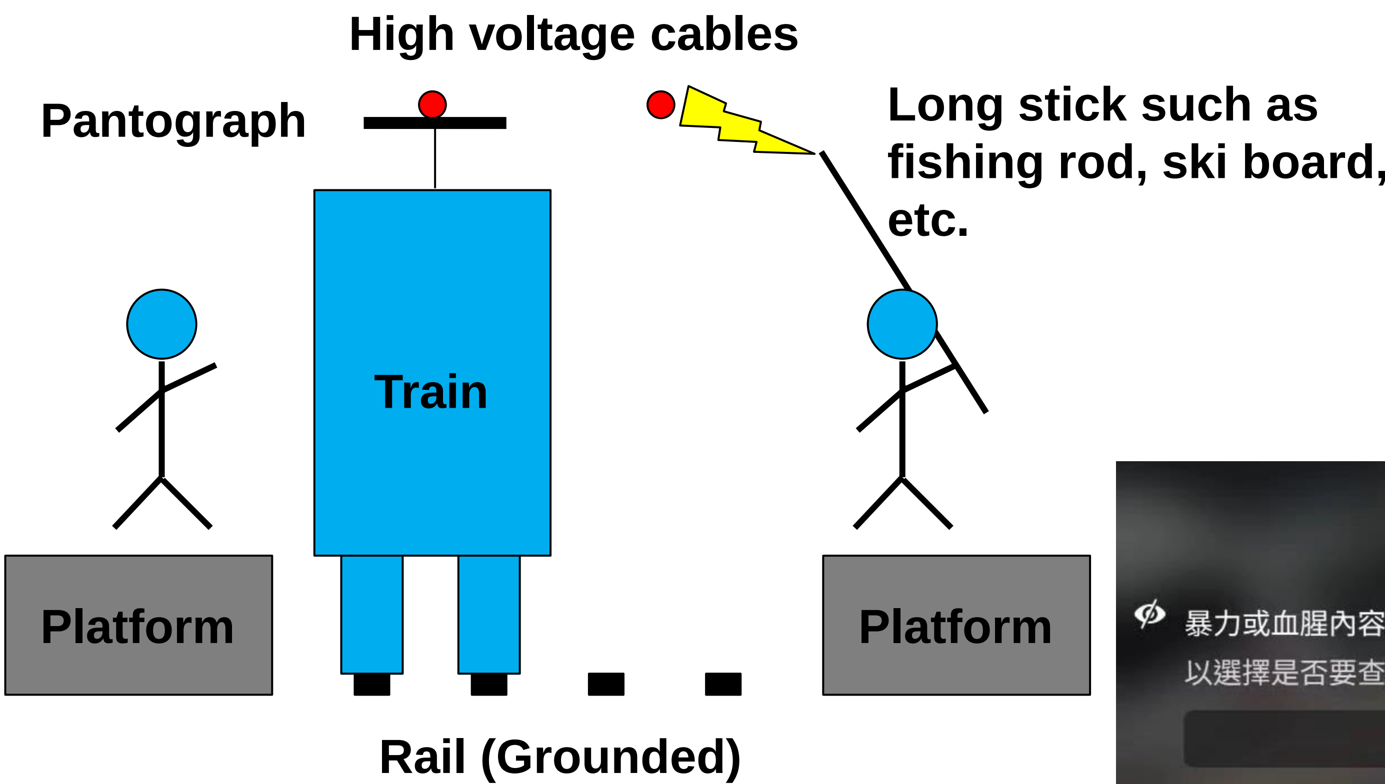

- $U_b$: The static breakdown voltage.
- $t_0$: the time until the static breakdown $U_b$ is exceeded.
- $t_s$: statistical delay time until an electron is able to create an avalanche resulting from the statistics of electron appearance.
- $t_a$: the avalanche build-up time until the critical charge density is reached.
- $t_{arc}$: the time required to establish a low-resistance are across the gap.

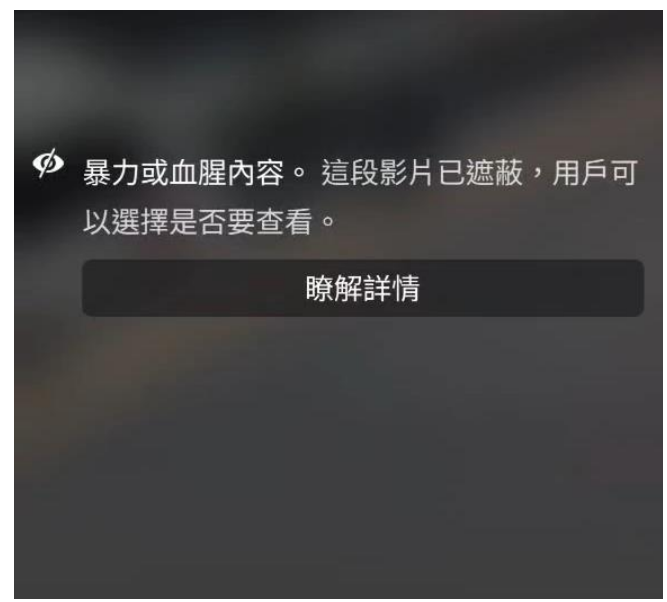
# The corona discharge – a small current leakage across a gap before a breakdown happens

- Corona is a luminous, audible discharge that occurs when an excessive localized electric field gradient causes ionization in the surrounding gas.
  - Luminous discharge: colored glow, frequently visible in darkened environment.
  - Audible discharge: a subtle hissing sound, louder with high voltage.
- It manifests easily in highly nonuniform electric field geometries, such as point-to-plane electrodes or cylindrical geometries with inner conductors made of wire.

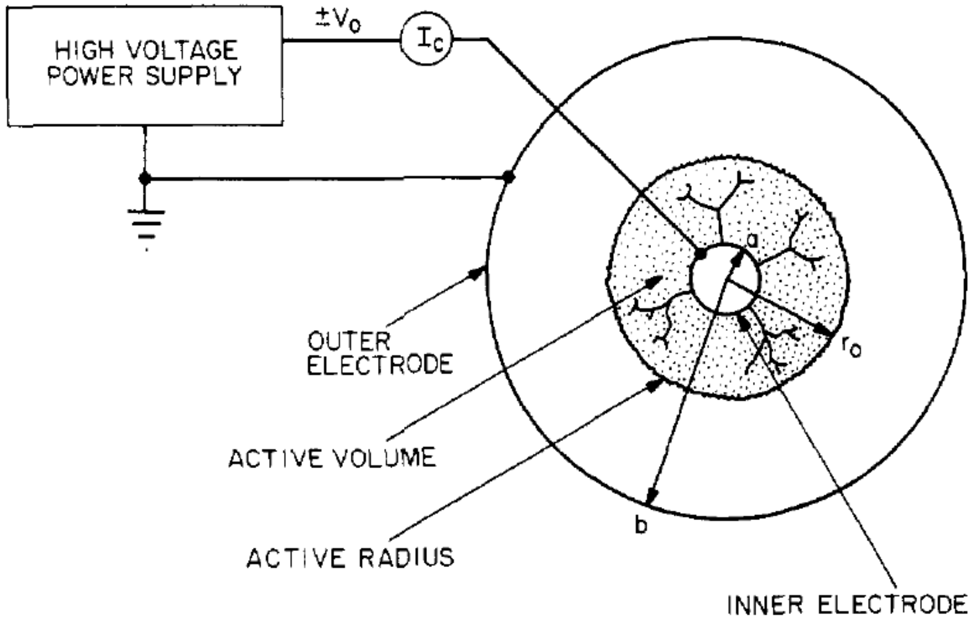


# Don’t bring a long stick to a train station



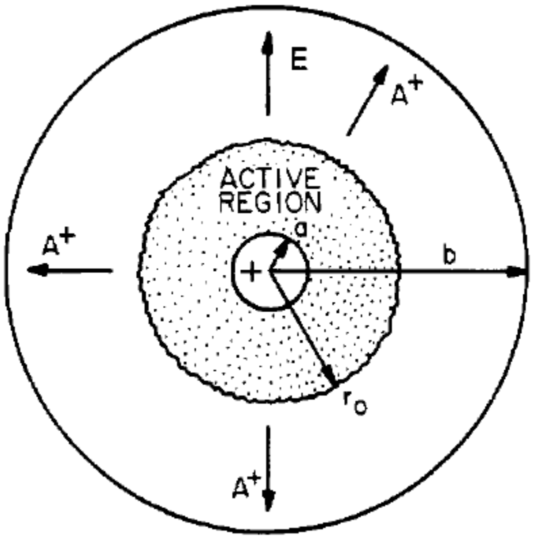
# The corona discharge happens when the electric field is not uniform



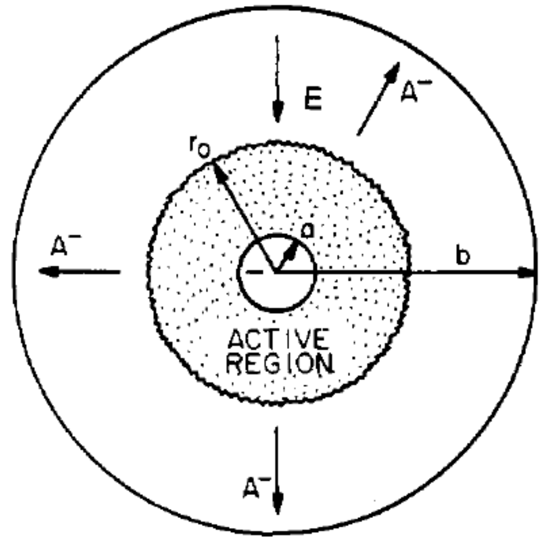

- **The point of corona initiation is that point at which the voltage on the inner conductor of radius a is high enough that corona is just detectable.**
- **The electric field will drop off to the breakdown value at a radius $r_0$ called the active radius.**
- **Electrons are attached to molecular forming negatively charged ions to close the current loop. No additional avalanche can happen.**

# Corona can occur for both positive and negative polarity

- **Positive polarity**

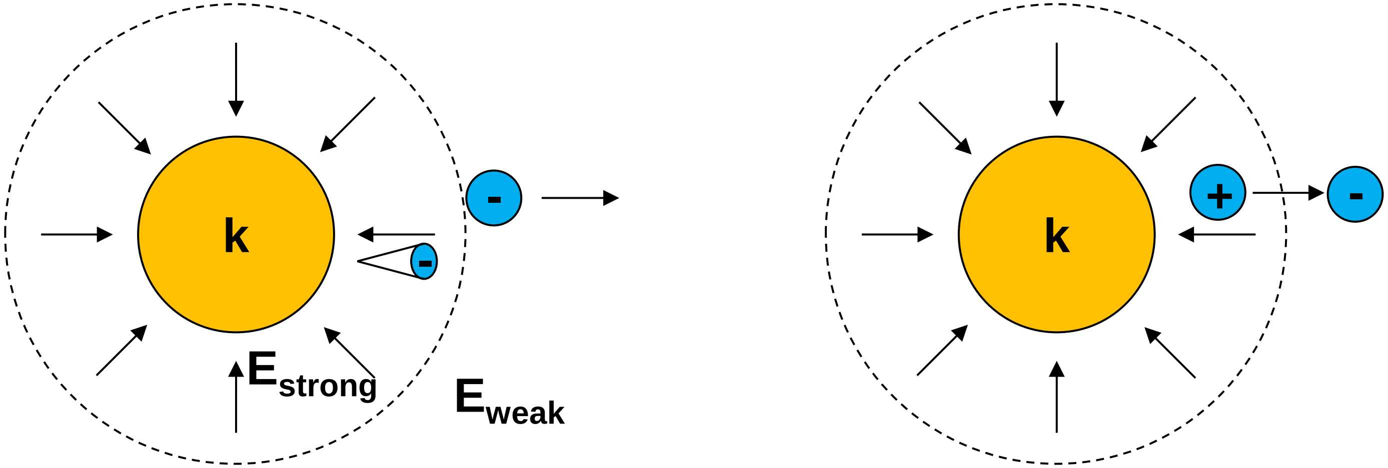



- **Negative polarity**



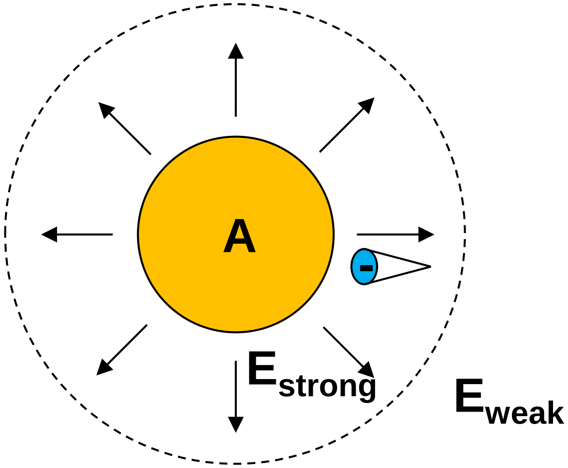

- **The initiation voltages or coronal current are slightly different between positive and negative polarity.**
- **A continuous (positive polarity, DC) or intermittent (negative polarity, usually) current, usually in the order of uA ~ mA per decimeter of length will flow to the power supply.**

# Negative point corona, also known as Trichel pulses




- Avalanche toward anode occurs in the strong electric field region.
- No further ionization occurs in the weak field region.
- Electrons are slow down by positively charged ions (ion+) behind.
- Electrons attach to gas molecules forming negatively charged ions (ion-).
- The presence of the negative ions reduces the electric field at the point electrode and the discharge extinguishes.
- When positively/negatively charged ions drifted away, the original high-field conditions are re-established

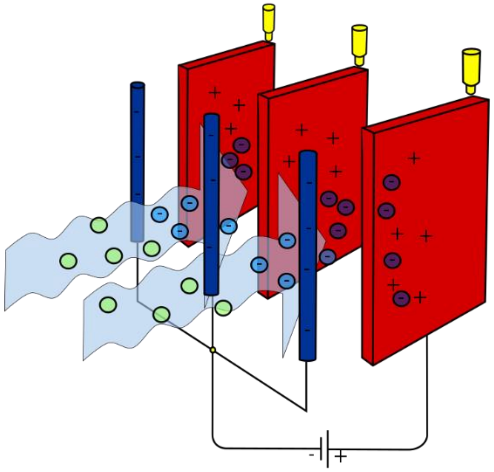
# Positive point corona




- Electron avalanche initiated near the high-field region propagating toward anode.
- Streamer is developed.
- Lateral avalanches feed into the streamer core.
- Negative ion cloud is formed

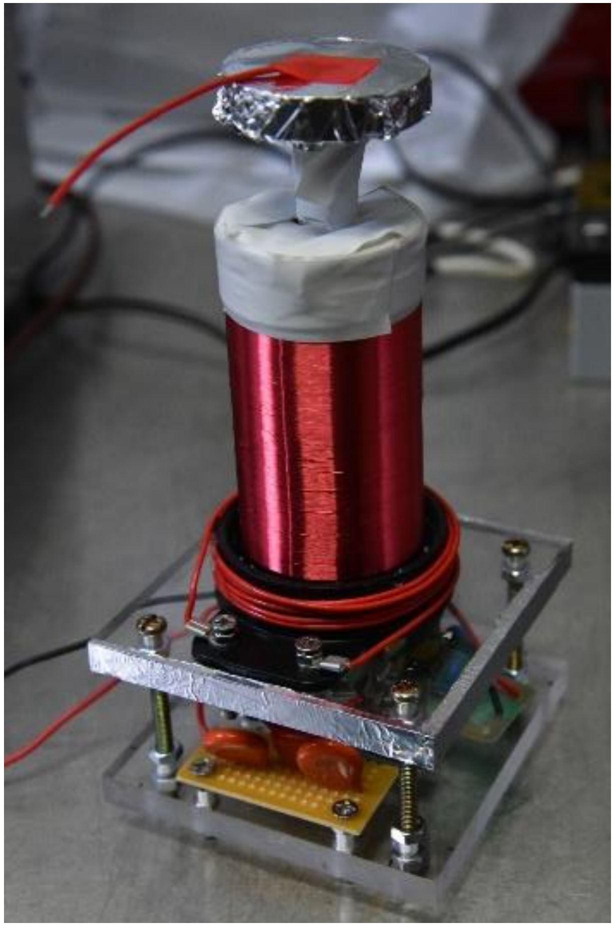
# A corona discharge causes some problems even no breakdown occurs

- Ozone ($O_3$) is generated.
- Rubber is destroyed by $O_3$.
- $NO_3^+$ is generated with moisture.
- Disadvantage:
  - Power losses.
  - Radio frequency (RF) interference.
  - Reduce the service life of solid and liquid insulation via initiating partial discharge.
  - Chemical decomposition.
- Advantage:
  - Pseudospark discharge – fast switch.
  - Electrostatic precipitator (dust remover) using corona discharge.
  - Hair dryer

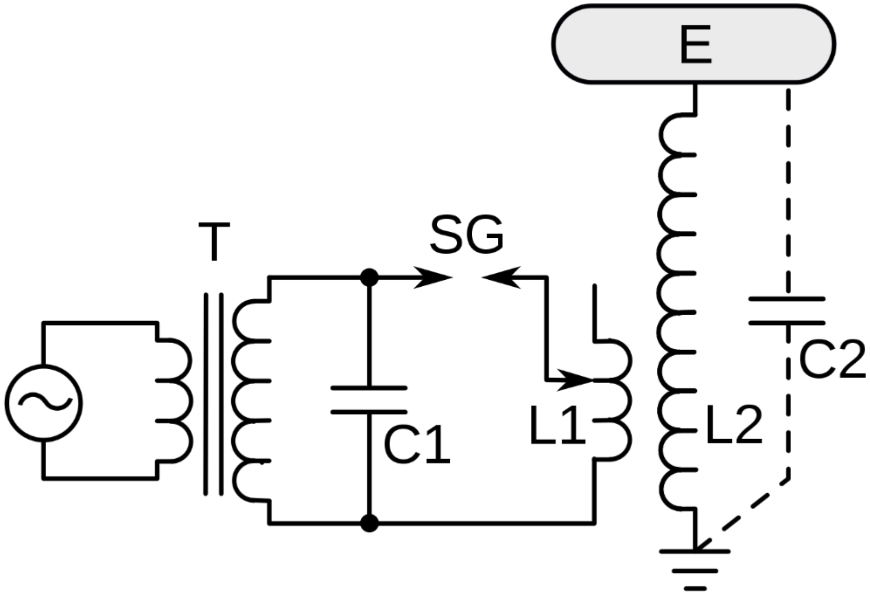


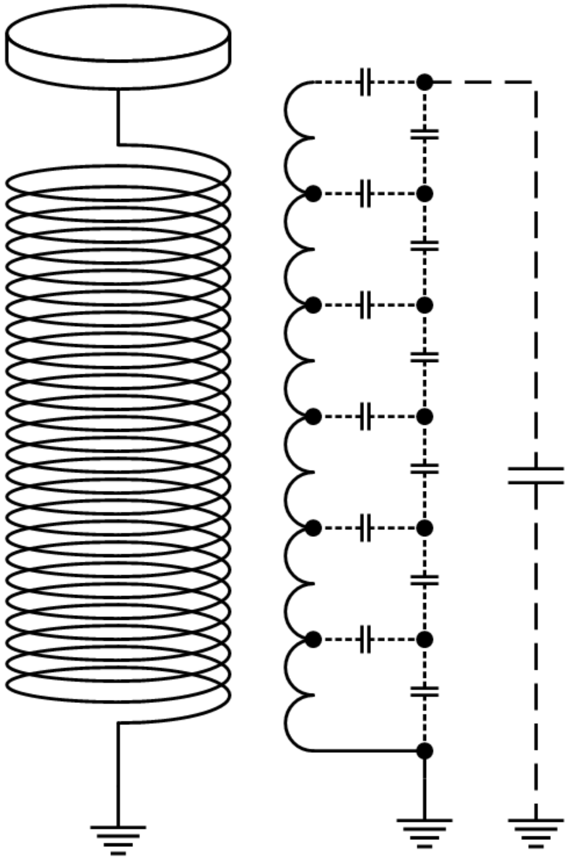
https://zh.wikipedia.org/wiki/%E9%9D%99%E7%94%B5%E9%99%A4%E5%B0%98

# Tesla coil can generate high voltage



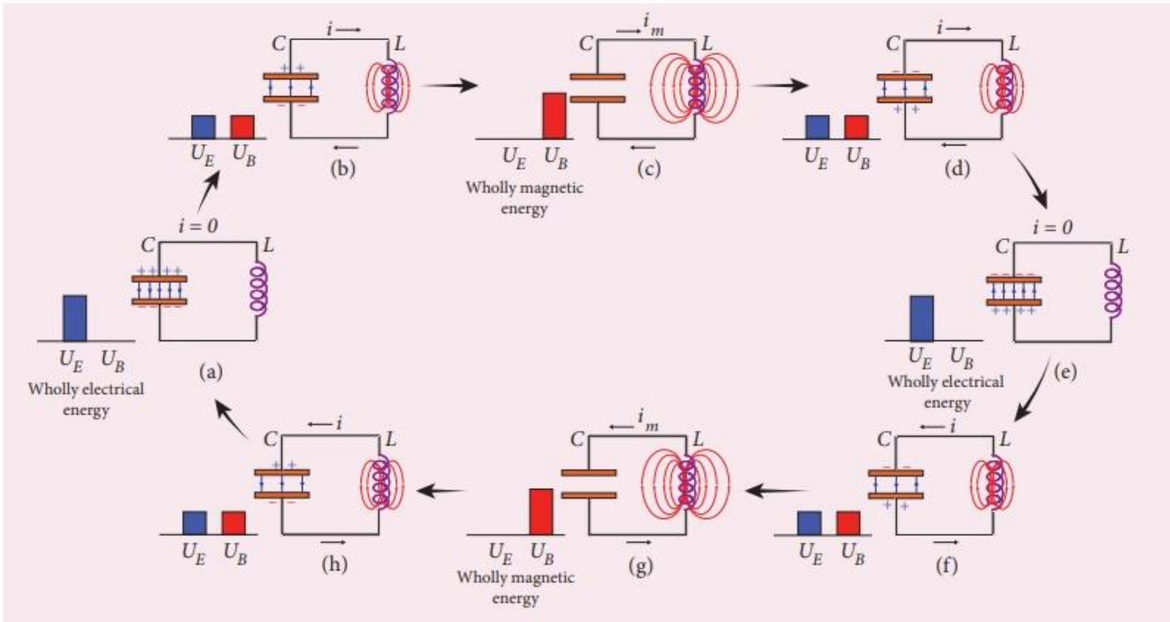
# The high voltage is generated by two resonant LC circuits

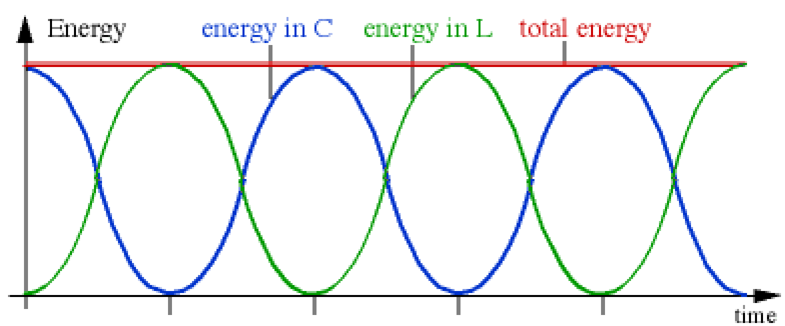


https://en.wikipedia.org/wiki/Tesla_coil

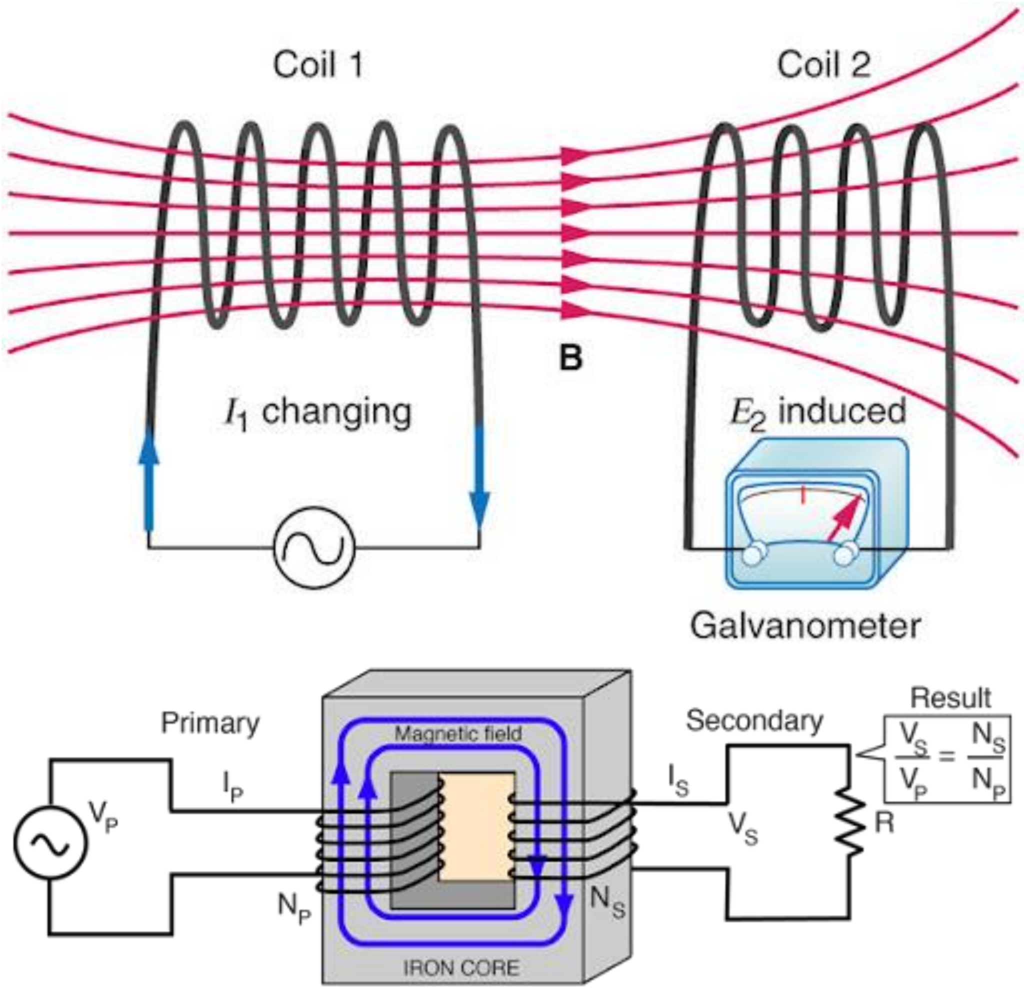
# Energy is oscillating between the capacitor and the inductor



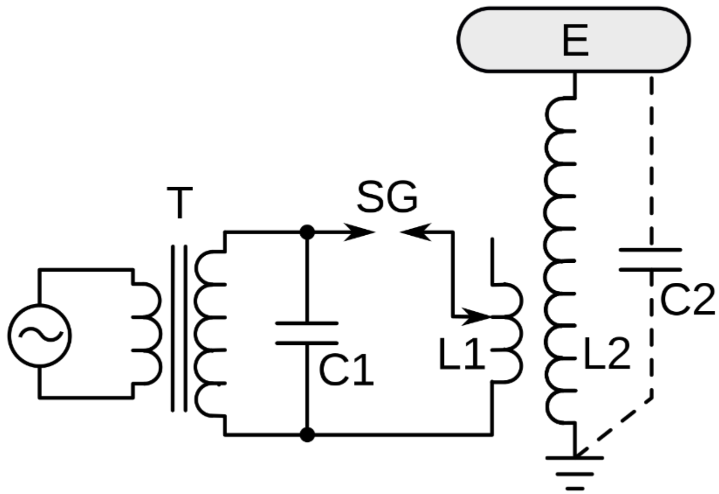

https://www.brainkart.com/article/Energy-conversion-during-LC-oscillations_38532/
http://ffden-2.phys.uaf.edu/webproj/211_fall_2016/Mark_Underwood/mark_underwood/Primary.html

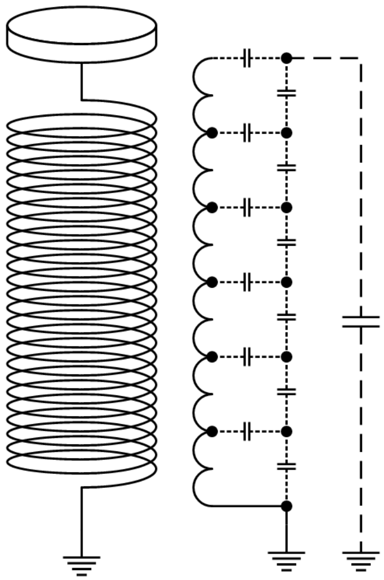
# Voltage of two separated coils can be transferred by mutual inductance between two coils

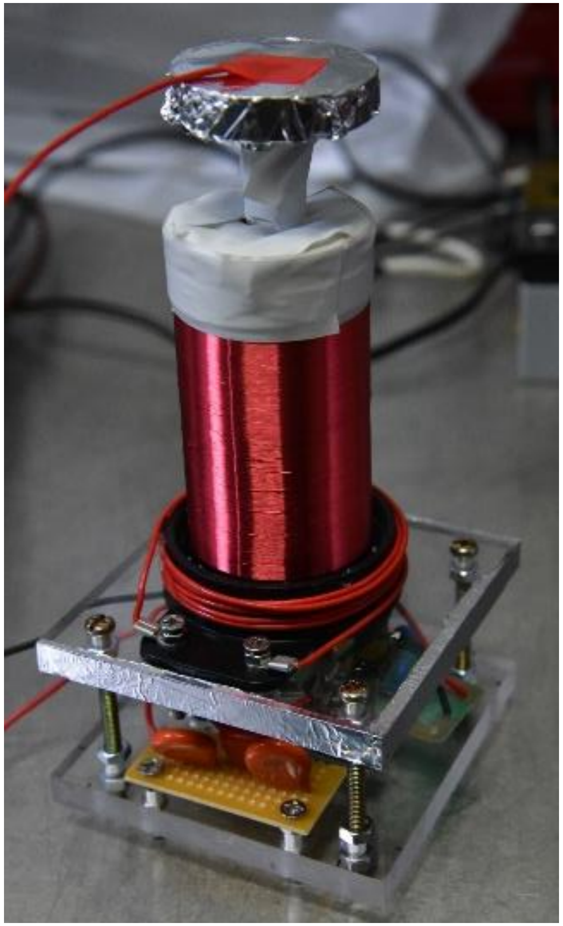



http://www.physics.louisville.edu/cldavis/phys299/notes/mag_mutualind.html
http://hyperphysics.phy-astr.gsu.edu/hbase/magnetic/indmut.html

# The high voltage is generated by two resonant LC circuits

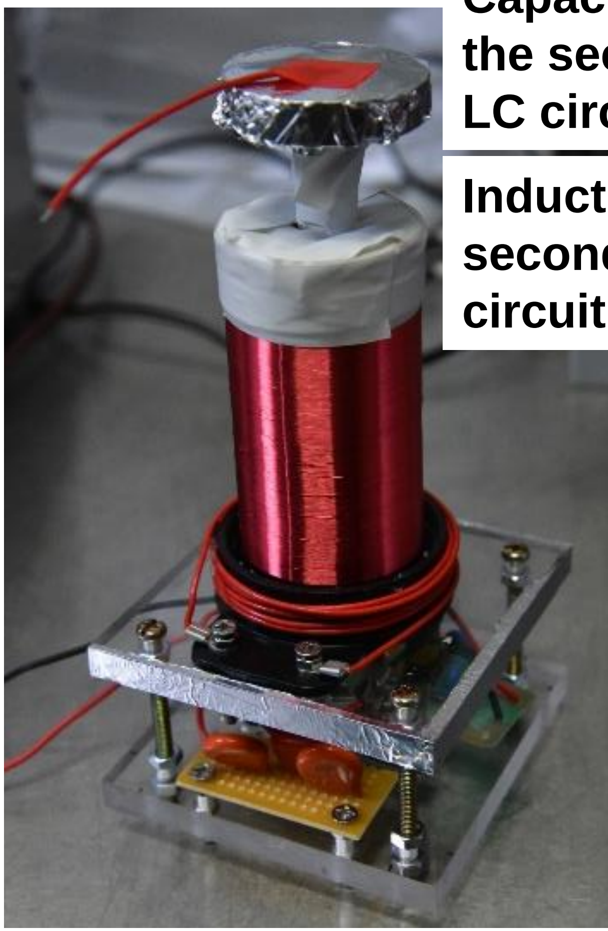




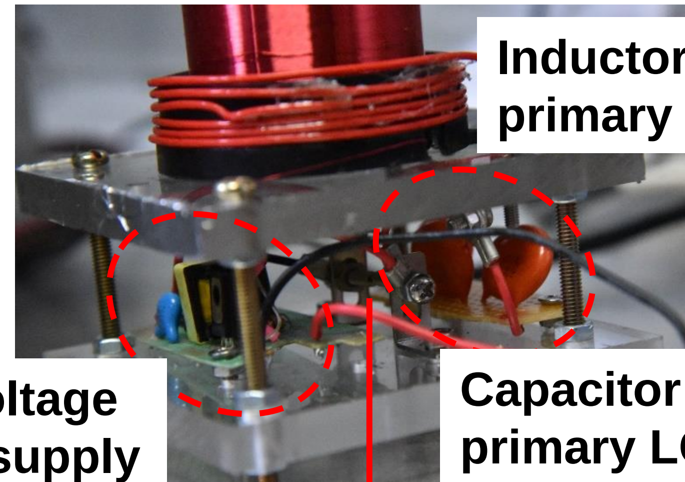
https://en.wikipedia.org/wiki/Tesla_coil

# Components of the tesla coil



Capacitor of the secondary LC circuit

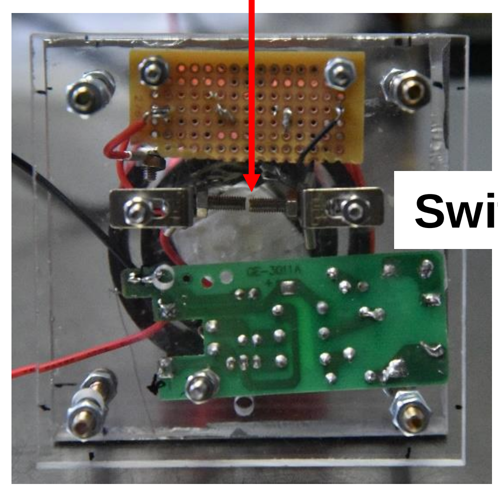
Inductor of the secondary LC circuit



Inductor of the primary LC circuit

High voltage power supply

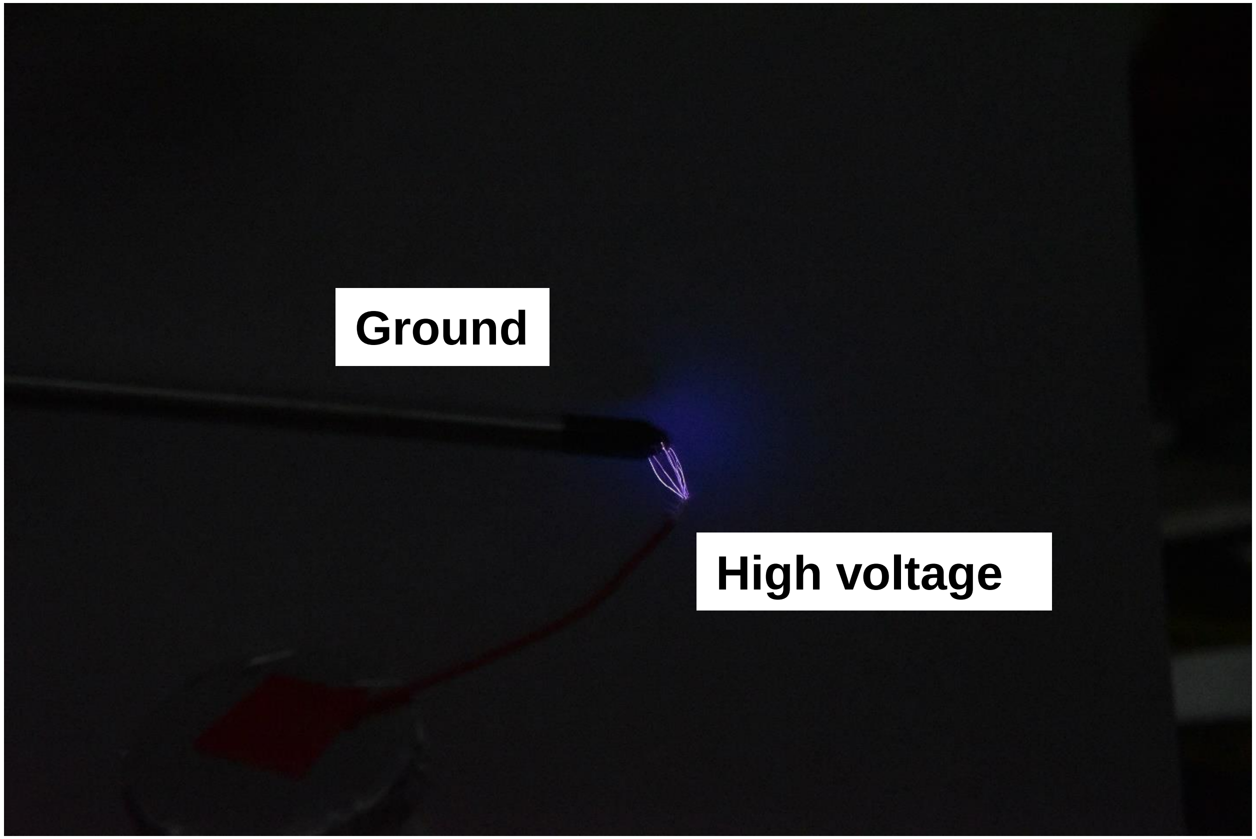
Capacitor of the primary LC circuit



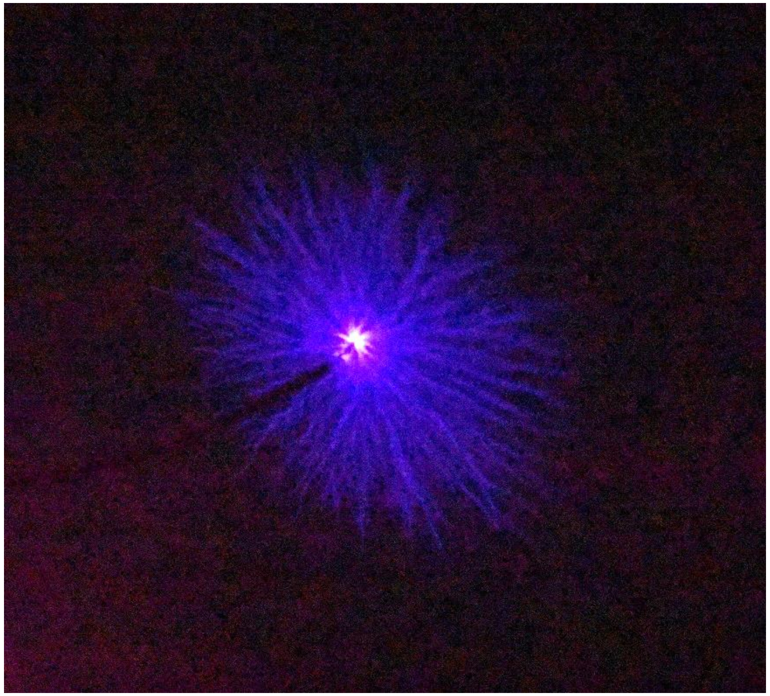
Switch

Show video.

# Arc discharge occur between the high voltage and a grounded electrode



# Corona discharge occurs when the electric field drops below a certain value



# Outlines

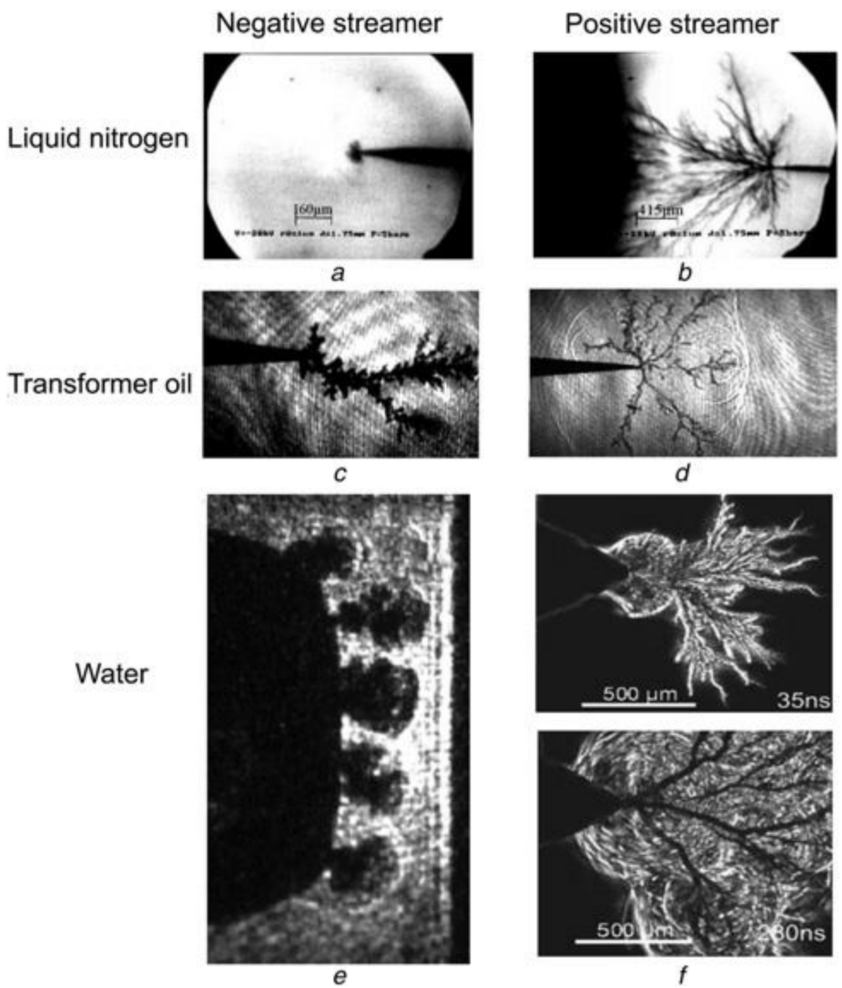
- Introduction to pulsed-power system
- Review of circuit analysis
- **Static and dynamic breakdown strength of dielectric materials**
  - Gas – Townsend discharge (avalanche breakdown), Paschen's curve
  - **Liquid**
  - Solid
- Energy storage
  - Pulse discharge capacitors
  - Marx generators
  - Inductive energy storage

# Liquids – "all liquid" pulsed-power system is feasible

- Oil-filled Marx – oil/water filled pulse-forming line (PFL).

  – oil/water spark gap.
- Marx: high dielectric strength. (output in the order of 1 MV is generated)
- PFL: high dielectric strength, high dielectric constant, low conductivity.
- Spark gap: high dielectric strength, high thermal conductivity, minimum decomposition products, self-healing properties.
- Properties of liquid needed for high voltage:
  - Good thermal properties
  - Low viscosity
  - Low flammability
  - Good chemical and thermal stability
  - Works in low temperature
  - Environmental considerations
  - Low cost

# Shadowgraphy of negative (left column) and positive (right column) streamers in different liquids



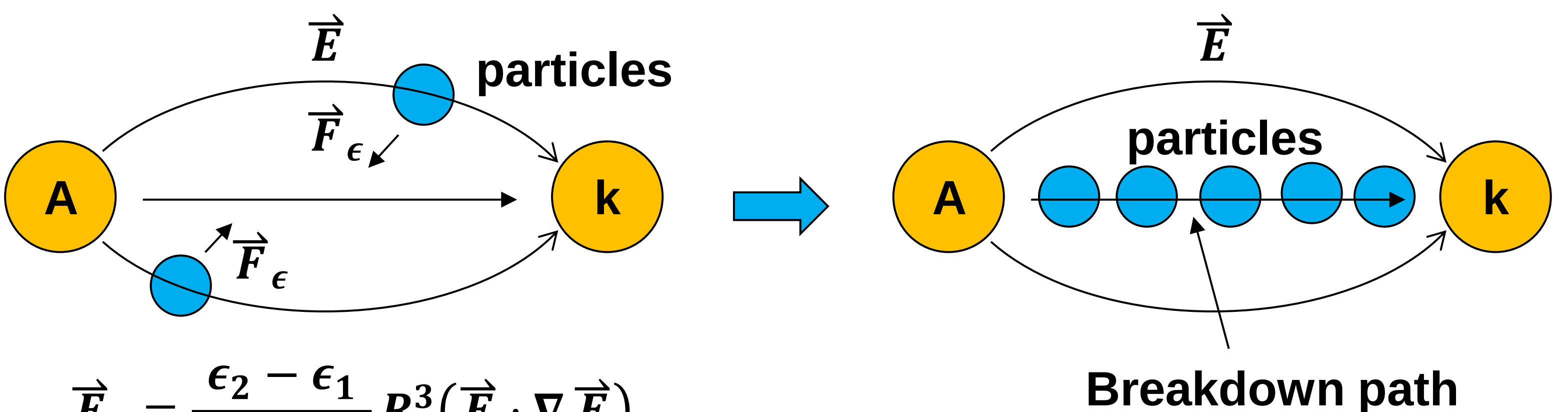

A. Sun *etc.*, High Volt., **1**, 74, 2016

# Breakdown in liquid

- **Particle alignment**
- **Electronic breakdown**
- **Streamers in bubbles**

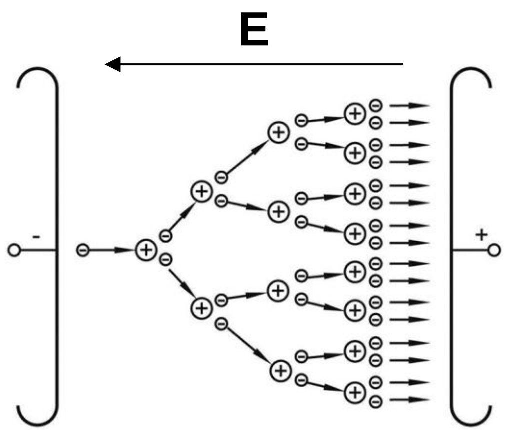
# Solid impurities always exist in a liquid leading to breakdown due to particle alignment

- Convection currents are set up in a liquid dielectric due to particle movements even at low applied voltage.
- The force tends to concentrate the solid impurities to the region of the center of the electrodes where the field is fairly uniform.
- Let $\vec{F}_D$ be the diffusion force. If $\vec{F}_\epsilon > \vec{F}_D$, the alignment of the particles takes place along the center of the electrode and breakdown in the liquid takes place along the aligned particles.




$$\vec{F}_\epsilon = \frac{\epsilon_2 - \epsilon_1}{\epsilon_1 + 2\epsilon_2} R^3 \left(\vec{E} \cdot \nabla \vec{E}\right)$$

# Electronic breakdown is very similar to breakdown in gas




- Electrons emitted from cathode lose energy to the molecules in the form of "nonionizing collisions" such as elastic, vibration, excitation process.
- Normally, not possible for electrons to reach ionization energy.
- At elevated temperatures and high field strength near an asperity of an electrode, energy losses reduce.

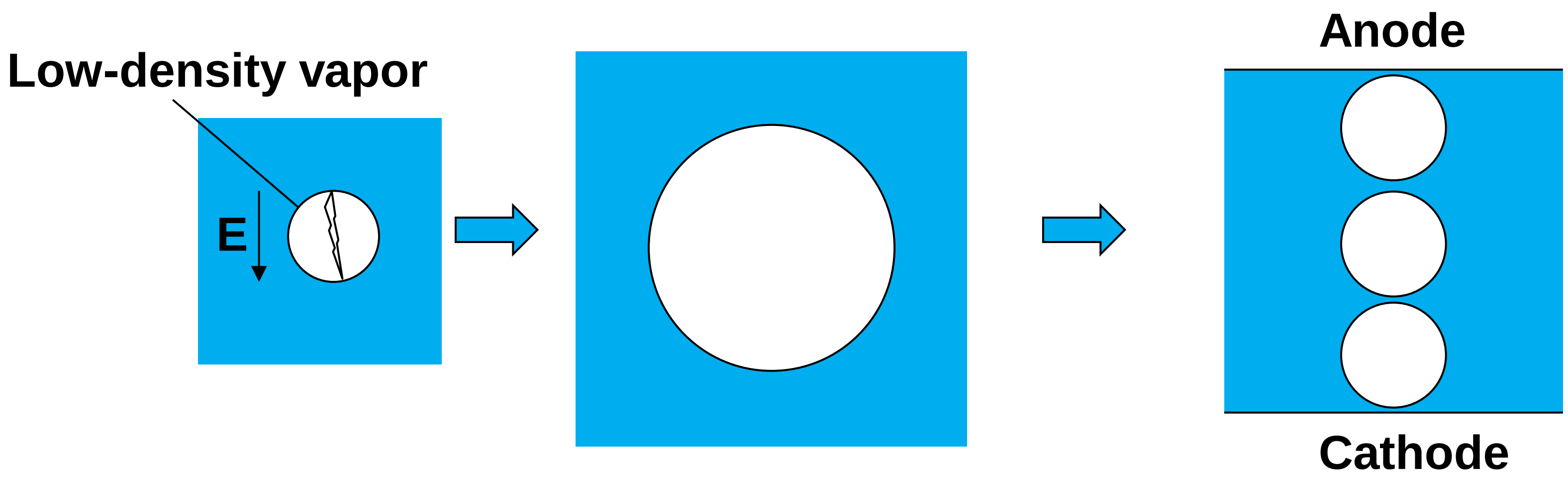
→ continuous acceleration → energy > ionization energy

→ more electrons due to impact ionization of the molecule

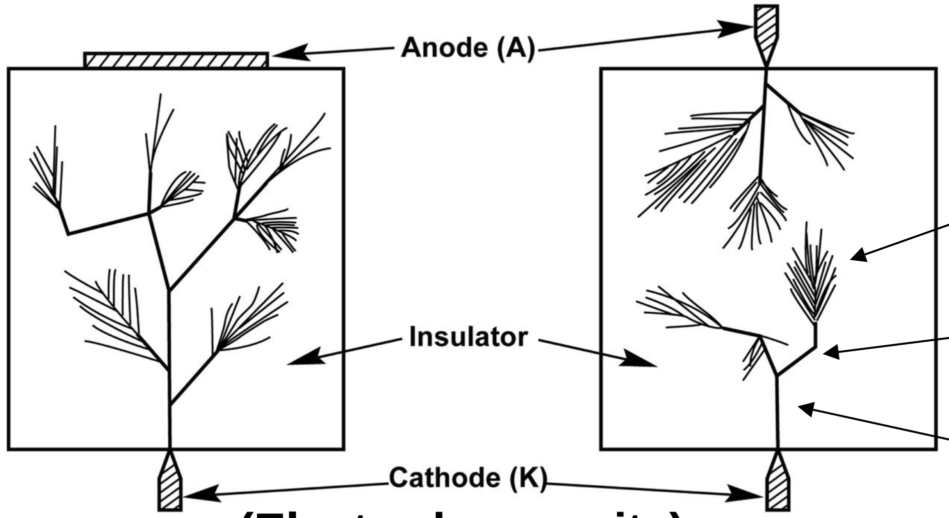
→ avalanche of electrons → breakdown

# Bubbles in liquid are formed so that a breakdown similar to that in gas occurs

- **Propagation of streamers in the low-density vapor or bubbles occurs.**
- **Streamer mechanism of liquid breakdown is similar to the growth of electric tress in a solid due to discharge in a void.**
- **Discharge in vapor → shockwave & thermal dissipation (heat) → more low-density vapor → more ionization**



# Structures of arcing in liquid is like a tree




(Electrode asperity)

**Tertiary streamer:**
**~ 5 um**

**Secondary structure:**
**various direction**

**Primary structure:**
**60-90 um**

- **Secondary and tertiary structures are results of space charge distortion due to the high-density streamer at the front of the primary structure.**
- **Effect of hydrostatic process:**
  - **Breakdown voltage increases with higher pressure.**
  - **Streamer can only grow/be initiated at higher field with higher pressure.**
  - **Ex: for transformer oil, $V_{break}$ is x3~4 at 4 MPa (~40 Atmosphere).**

# Mechanisms of bubble formation

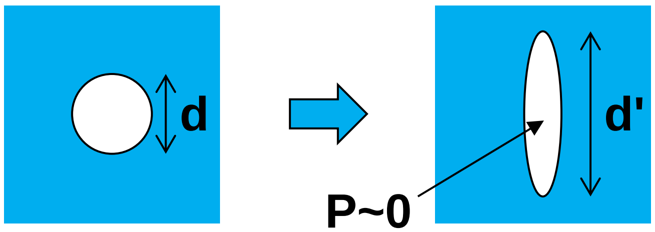
- **Foreign particles.**
- **Asperities on electrode causing field emission.**
- **Chemical interaction with molecules causing their dissociation.**
- **Release of the already existing gas dissolved in the liquid.**

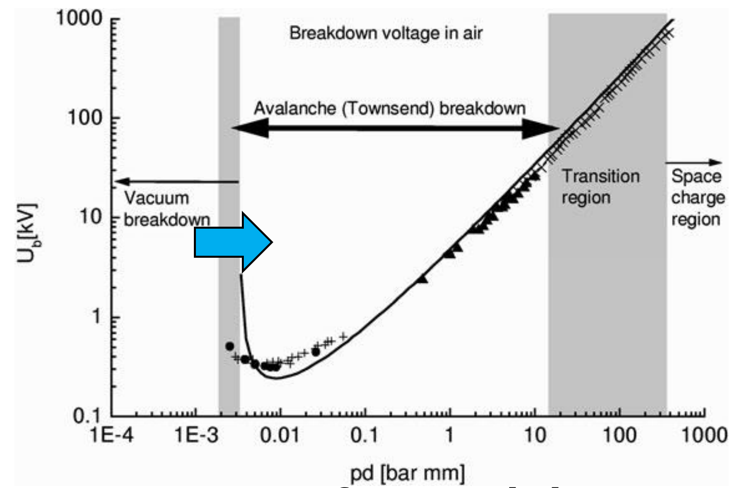
# Pressure in a bubble is "zero"

- **Krasucki's hypothesis:**
  - **A vapor bubble grows continuously when a critical size is reached → breakdown takes place.**
  - **When applied voltage is gone → collapse faster than air bubble. → pressure in the bubble is "zero".**
  - **With impurity particles – bubble grows preferentially on the particles.**
  - **W/o impurity particles – bubble grows preferentially near the electrode surface.**
  - **$V_{break}$ ↑ as radius of bubble ($r_b$) ↓ , surface tension ($\gamma_s$) ↑, and hydrostatic pressure (P) ↑**

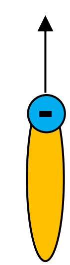
# Breakdown tempts to occur easier when the bubble becomes elongated

- **Kao's hypothesis – bubble once created starts elongating in the direction of the field keeping its volume remains constant.**



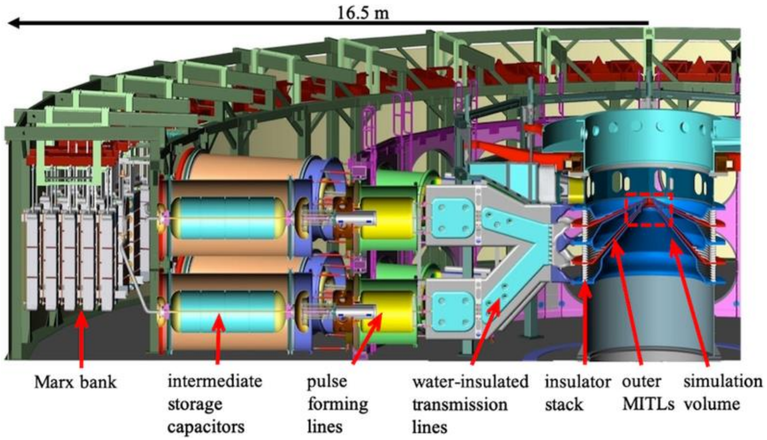

- **Sharbaugh and Watson hypothesis**
  - **Asperity of cathode → field emission occurs → mean free path is short → energy is deposited in small region → low-density vapor is generated → breakdown in the bubble.**
  - **For a pulse with few us, enough energy from field emission to vaporize a small mass of liquid ahead of an asperity into a bubble.**
  - **P↑ => boiling point $T_b$↑ => more field is required to form bubbles.**



# Water is a very special dielectric material

- Breakdown voltage is dependent on the polarity.
- Electric field is enhanced at the asperities due to collective orientation of the bipolar water molecules. $V_{break}$ of water ($\varepsilon_r$=80) is lower than that of propylene carbonate (PC, $\varepsilon_r$=65).
- However,
  - For sub-Mega volt pulse with short duration (7~30 ns), the dielectric strength is x2 of that with long duration (50 ns ~ 1 ms).
  - The $V_{break}$~$3\times10^7$ V/m for us electric stress.
  - High energy density ($\varepsilon_r$=80) in energy storage.
  - Low impedance in PFL.
  - Self-healing post breakdown.
  - Easy maintenance.
  - Low cost.
  - Ease of disposal.

$$E_{\mathrm{ene}} = \frac{1}{2}\epsilon_0\epsilon_r {E_f}^2$$



# Methods of improving liquid dielectric performance

- **New composition:**
  - **Vegetable oil (used in PFL): castor oil (蓖麻油, $\varepsilon_r$=4.7) vs mineral oil (礦物油, $\varepsilon_r$=2.4). However, castor oil is more hygroscopic (吸濕性). Therefore, sealing is important.**
  - **Synthetic oil (合成油), e.g., PAO (poly-alpha-olefin), a type of silicone oil. Good for closing switches.**
    - **Resistance to oxidation.**
    - **Lower viscosity, ok at low temperature.**
    - **Good lubrication, ok with hydraulic pump. The pump is used for forced flow at high pressure and velocity for removing gases evolved by molecular dissociation and erosion from electrodes.**
  - **Electron scavengers, e.g., chlorocyclohexane vs cyclohexane**

# Methods of improving liquid dielectric performance

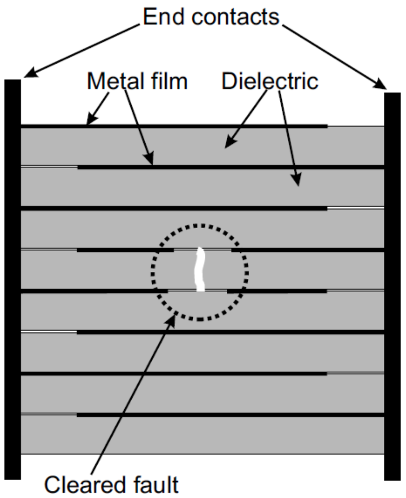
- **Mixture of materials improve performances**
  - **Gas: $SF_6$ + $N_2$**
  - **Liquid: in PFL, Water ($\varepsilon_r$=80) + ethylene glycol ($\varepsilon_r$=44)**

    **→ increasing intrinsic time constant.**
  - **Solid: paper + polypropylene**
- **Impregnation: when putting insulating films and metallic foils in liquid dielectric for removing of air trapped at electrode-liquid interface :**
  - **High temperature**
  - **Vacuum**
- **Purification**
  - **Freed of foreign particles using filter and ions using deionizer.**
  - **Low temperature using chiller unit to reduce resistance.**

# Outlines

- Introduction to pulsed-power system
- Review of circuit analysis
- **Static and dynamic breakdown strength of dielectric materials**
  - Gas – Townsend discharge (avalanche breakdown), Paschen's curve
  - Liquid
  - **Solid**
- Energy storage
  - Pulse discharge capacitors
  - Marx generators
  - Inductive energy storage

# Breakdown in solid



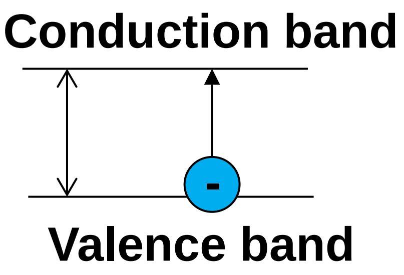

- **Solid insulators function as**
  - **Mechanical supports.**
  - **Enclosures.**
  - **Feedthrough.**
  - **Energy storage.**
- **Thin films of solid insulation are used in energy storage capacitors and pulse-forming line (PFLs) for high density storage. Advances in metalized films with their self-healing properties are revolutionary.**
- **Common solid film insulators: paper, Mylar (polyethylene terephthalate, PET), Kapton (polyimide), Teflon, Epoxy, polypropylene (PP), Acrylic, Polyvinylidene fluoride (PVDF)**
- **Outdoor installations: operate in humid and polluted environment.**
- **For repetitive pulsed power systems, thermal considerations such as effective cooling becomes important.**

# Breakdown mechanisms in solids

- Solids are usually permanently damaged when breakdown occurs.
  - Intrinsic breakdown.
  - Thermal breakdown.
  - Electromechanical breakdown.
  - Partial discharges.
  - Electrical trees.

# The highest breakdown values when other sources of imperfections in the materials and testing are eliminated

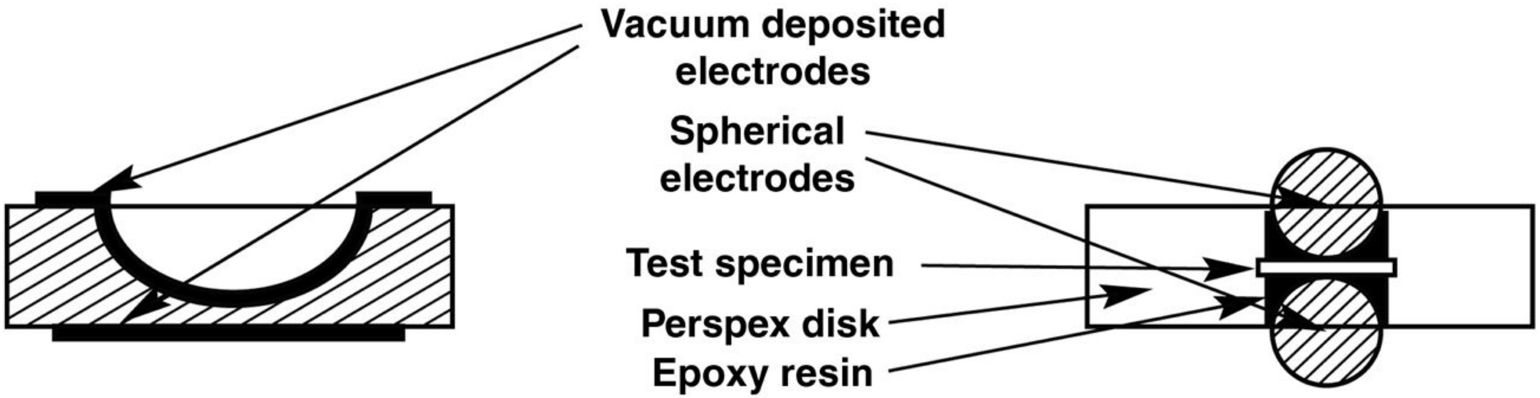
- The timescale of the intrinsic breakdown is in the order of 10 ns.
- Electrons jump from valence band to conduction band when it gains enough energy from a high electric field.




- With sufficient electrons in the conduction band, intrinsic breakdown occurs.
- $V_{break}$ is in the range of 5-10 MV/cm.

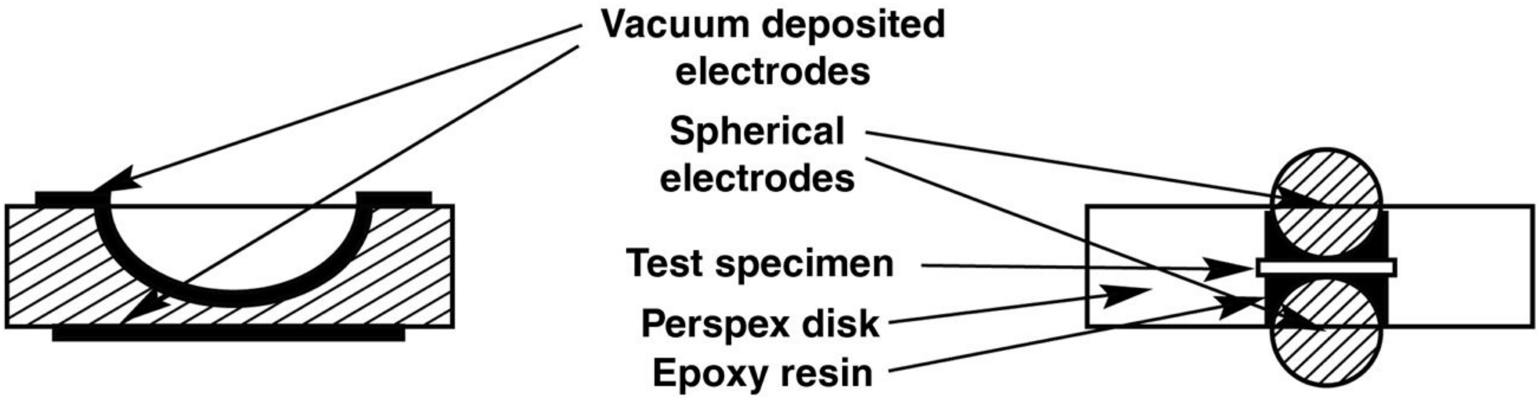
# In laboratory, it is measured via eliminating all imperfections

- **Field non uniformity.**
- **Internal discharges from imperfections (foreign particles or voids).**
- **External discharges from weak ambient surrounding the solid dielectric.**
- **Mechanical damage.**
- **Field induced chemical attacks.**



# In laboratory, it is measured via eliminating all imperfections

- Very thin specimens of solid dielectric are used.
  - Reasonable V (E=V/d).
  - Probability of imperfections (foreign particles and void)
- Proper mechanical support is needed to avoid electromechanical force.
- Short duration pulses with high voltage rising speed → to avoid other breakdown mechanism, such as thermal breakdown from joule heating.



# Criterion of intrinsic breakdown of a solid

- **Frohlich criterion (high-energy criterion):**
  - **If the net energy gained by an conduction electron from the electric field is greater than the energy lost to the lattice, the electron is continuously accelerated, resulting in a state of instability and intrinsic breakdown occurs.**
  - **Is not dependent on the specimen thickness, wave front, or duration of applied field.**
- **Avalanche criterion (low-energy criterion):**
  - **Conduction electrons gain sufficient energy from the applied field to release further electrons from the lattice, similar to impact ionization in gas.**
  - **It is dependent of thickness and electrode geometry. "Time to breakdown" is dependent on the overvoltage applied to the specimen.**

# It happens when rate of generating heat is greater than dissipate rate to the surrounding

- Generated heat is due to conduction (DC) or dielectric losses (AC). It is dependent on voltage.
- If heat gain > losses → thermal equilibrium is unstable → thermal runaway.
  - DC: $$HG_{\mathrm{DC}} = C_v \frac{\mathrm{dT}}{\mathrm{dt}} + \frac{\partial}{\partial x}\left(\kappa \frac{\partial T}{\partial x}\right) = \sigma \mathrm{E}^2$$
  - AC: $$HG_{\mathrm{AC}} = C_v \frac{\mathrm{dT}}{\mathrm{dt}} + \frac{\partial}{\partial x}\left(\kappa \frac{\partial T}{\partial x}\right) = E^2 2\pi \mathrm{f} \epsilon_0 \epsilon_r \tan\delta$$

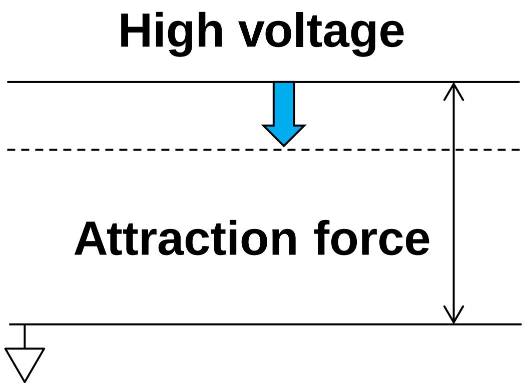
  Heat accumulation diffusion source

- Generally, the thermal breakdown need not be considered for DC due to low electric conductivity of good insulator.
- For pulsed high electric field with high dielectric losses, $\mathrm{HG_{AC}}$ is important.

Ex: Thermal breakdown @ room temperature ~ 10 MV/cm. With pulsed-high electric field, ~100 KV/cm, 2 order less!

# Breakdown occurs due to the compression from the attraction between electrodes

- **Compressive force:** $P_c = \frac{1}{2}\epsilon_0\epsilon_r E^2 = \frac{1}{2}\epsilon_0\epsilon_r\left(\frac{V}{d}\right)^2$

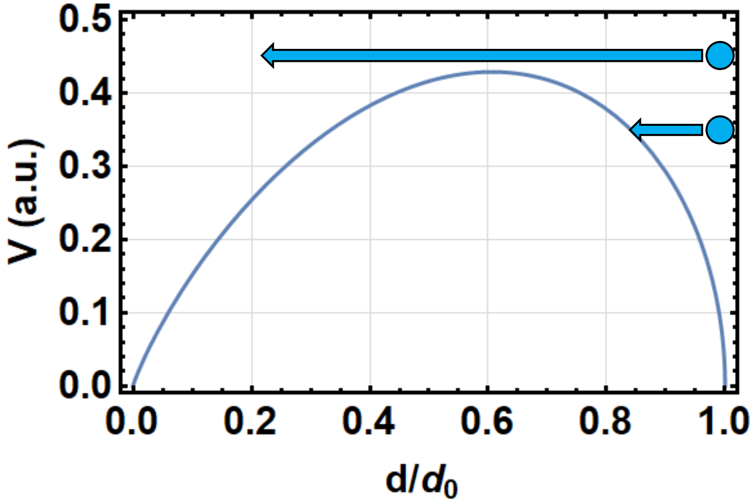



- **Hooke's law** $P_H = Y\ln\left(\frac{d_0}{d}\right)$

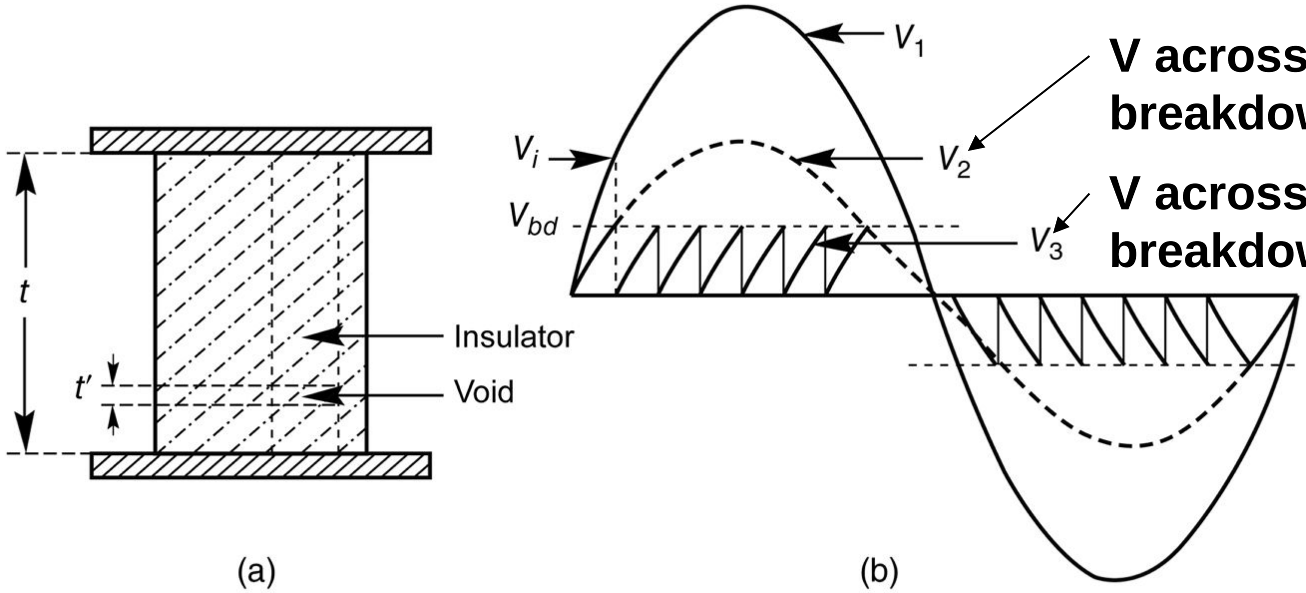
- **Force balanced:** $P_C = P_H$

$$\frac{1}{2}\epsilon_0\epsilon_r\left(\frac{V}{d}\right)^2 = Y\ln\left(\frac{d_0}{d}\right) \qquad V^2 = \frac{2Y}{\epsilon_0\epsilon_r}d^2\ln\left(\frac{d_0}{d}\right) \qquad V = d\sqrt{\frac{2Y}{\epsilon_0\epsilon_r}\ln\left(\frac{d_0}{d}\right)}$$

- **V ↑ => d↓. If exceeds the strength of the material => mechanical damage.**



# A partial discharge occurs inside voids embedded in solid dielectrics

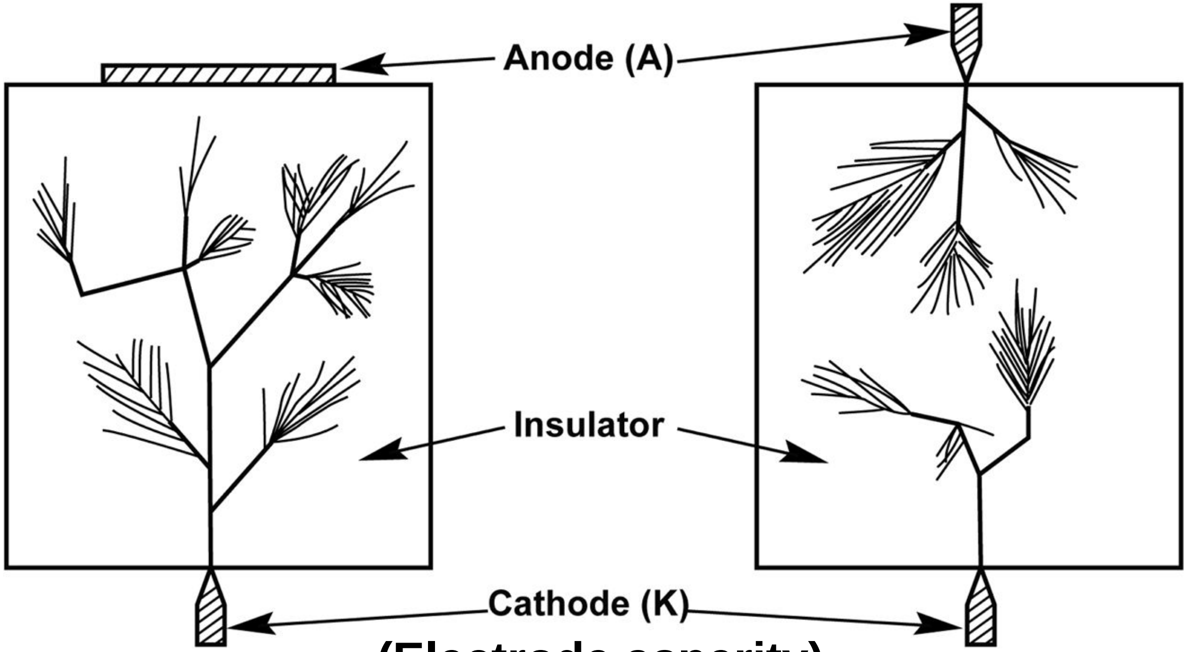



V across the void w/o breakdown.

V across the void w/ breakdown.

- $V_{bd}$ is determined by the Paschen's curve where d=t', p is pressure in the void.
- The energy dissipated in the void causes erosion, tracking, treeing and electrochemical deterioration.
- It takes a time period of years for causing breakdown through the whole insulator.

# There are two kinds of electrical trees: dry trees vs water trees.

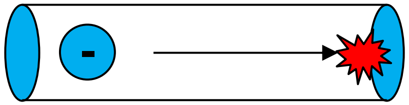



(Electrode asperity)

- It is dependent on the properties of dielectric and the environment.
- Over a period of time, may extend to few years, the trees cause the total breakdown.

# Dry trees – hollow tubes, resembling the branches of trees, which are formed inside a dielectric due to electrical stress

- Diameter: 10 ~ 500 um, mixtures of gases from the decomposition of dielectric material.
- Nucleation sites (seed) – localized field enhancements, e.g., asperities on electrodes or embedded foreign particles, or voids.
- Initiation: mostly due to electromechanical force → fissures, microscopic cracks.
- Erosion, tracking, gas evolution, decomposed products are produced.
- The accelerated charged particles impact the walls of the cavities w/ high velocities, leading to their growth.
- When a tree occupy a major length of the insulator, the remaining unbridged portion of the insulator will be subjected to extremely high stresses, leading to disruptive breakdown.

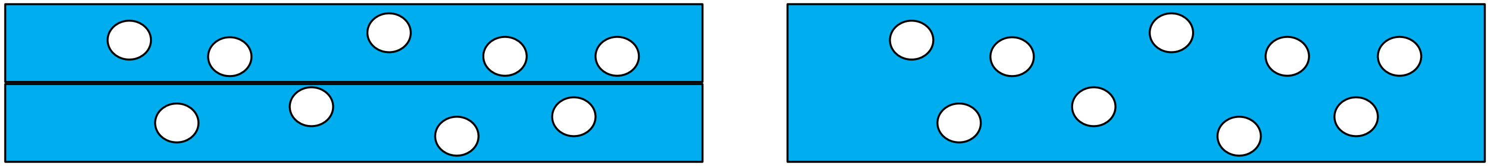


# Water trees – hollow filled with water

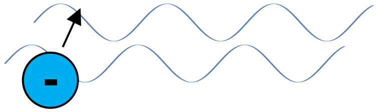
- **If dielectric is hydrophilia (親水) and is immersed in water → tree channels are filled with water. It happens in underground cable.**
- **When electric stress is removed, water is reabsorbed in the solid dielectric. The channel becomes dry and hollow.**
- **The electric conductivity of water tress compared to dry trees is high leading to a rapid growth compared to the dry trees.**

# Methods of improving solid insulator performance

- Layers of insulating films instead of single layer with the same total thickness.
- Improving the contact area at the interface between electrodes and dielectric – metallization and oil impregnation.
- Controlling a nonuniform field – corona guards / equipotential rings.
- Modifying insulator shapes and surface profiles – reduce the interaction of charge carries at the surface.
- Ex:



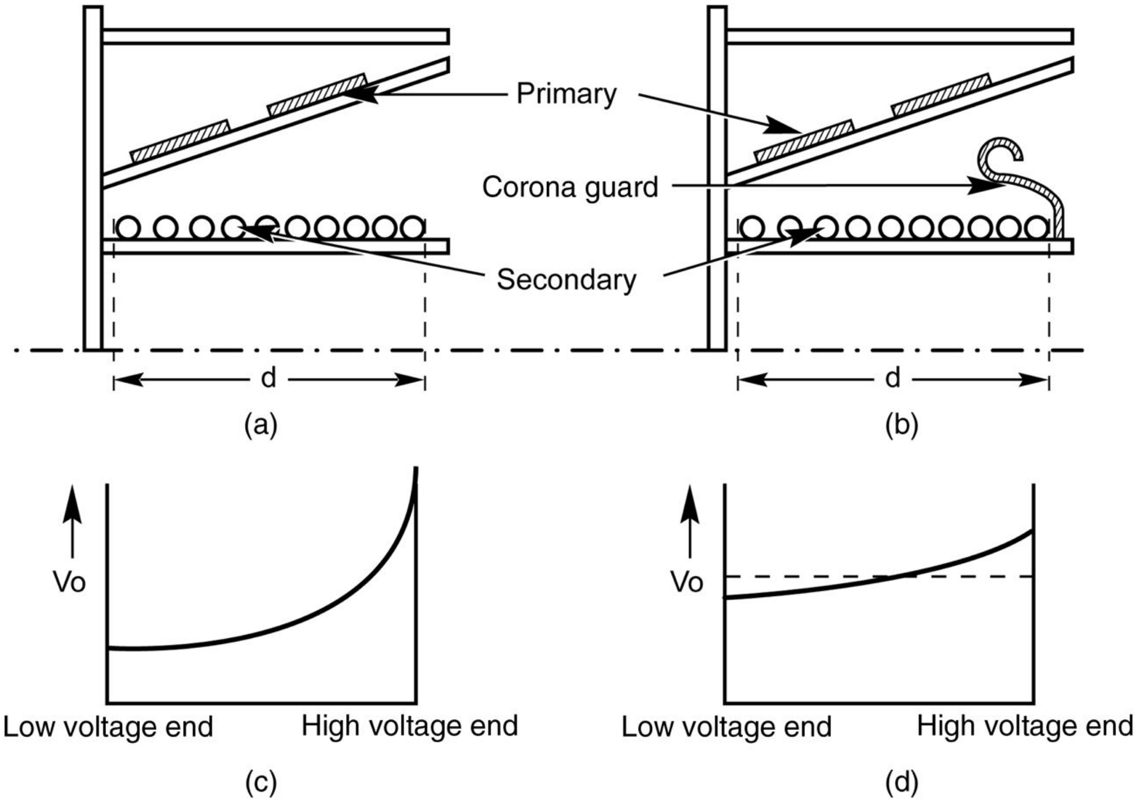
- Ex: insulation in energy storage capacitors

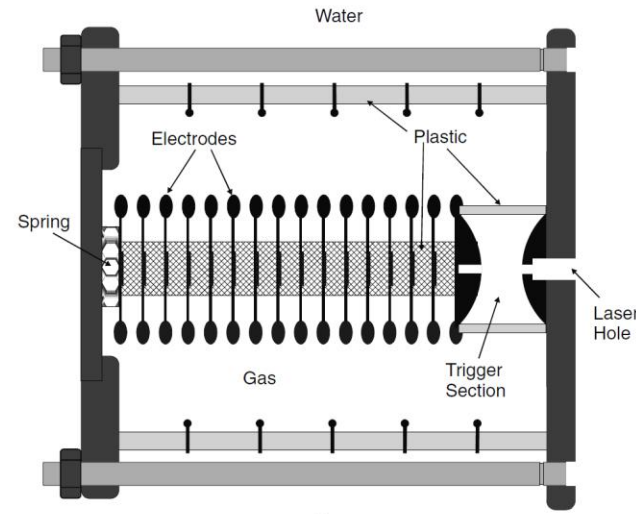



5~7 layers of dielectric films.

Metallization: vapor deposition of Al or Zinc w/ δ=0.3 nm => more layers can be packed leading to higher energy density.

# Surge voltage distribution help reducing the chance of breakdown



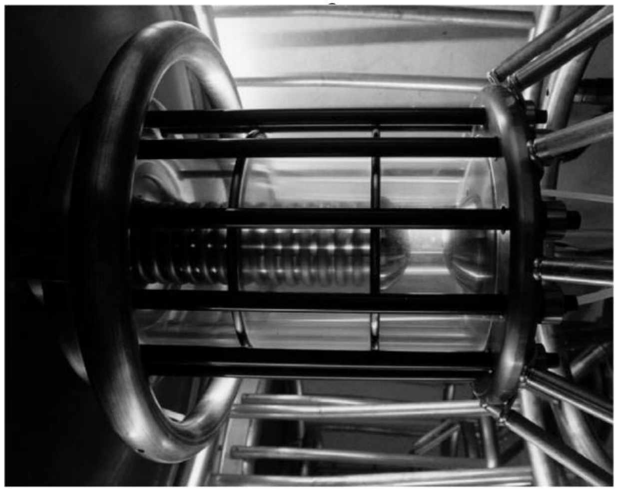



**Fig. 4.13.** A 4 MV version of a multigap spark switch

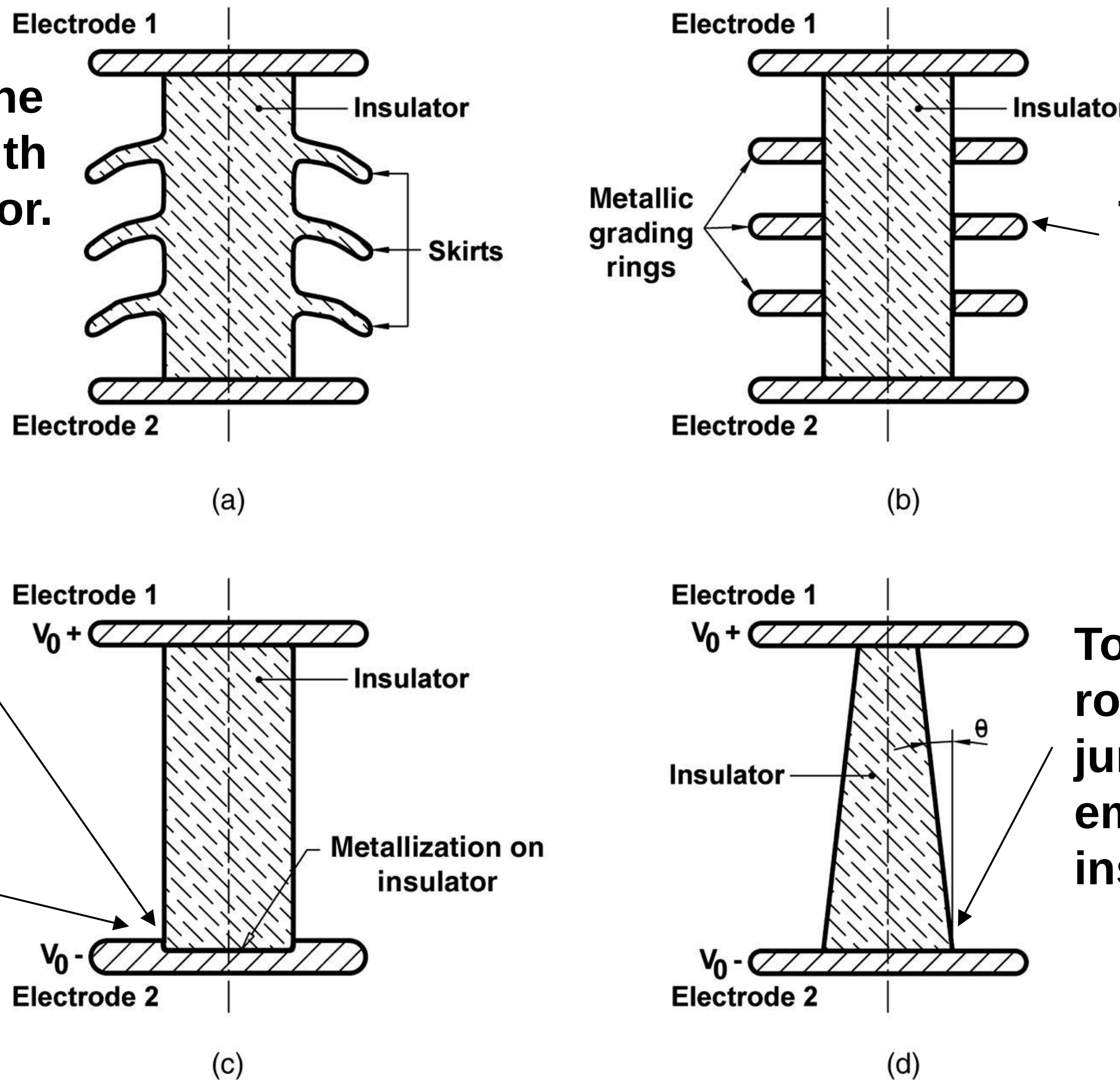
# Surface flashover in standoff insulators

To increase the effective length of the insulator.

To make field distribution more uniform.

Metallization on insulator

To decrease the role of triple junction & 2[nd] $e^-$ emission from the insulator surface.

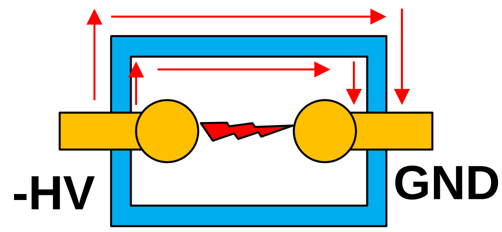


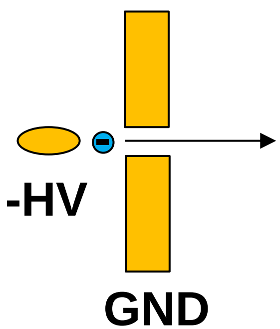
# Breakdown in Vacuum

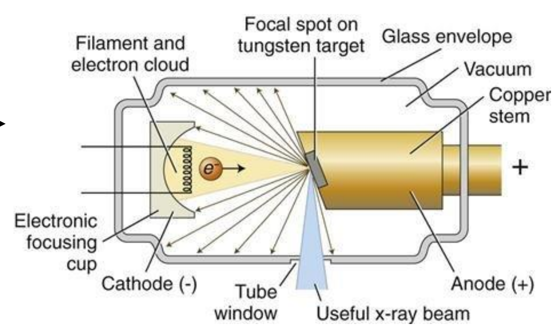
- **If there is no medium, there is no breakdown.**
- **However, breakdown does take place since charge carriers can be injected from desorbed gas, metal vapors from the electrode.**
- **The insulator surface is an electrically weaker medium than vacuum, i.e., “Surface flashover” across the solid insulator is more possible.**

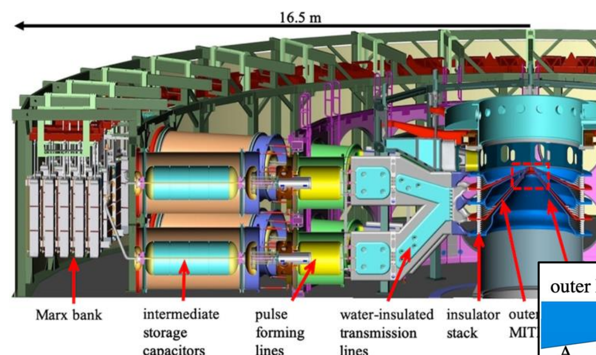
# Examples

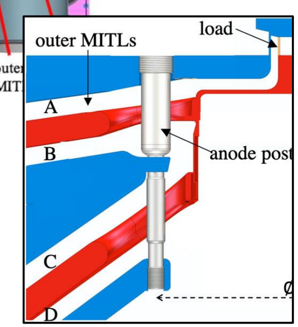
- **Spark gap switch.**
- **Diodes for particle beams, x-rays, magnetron.**
- **Transmission lines for feeding pulsed power into the load.**

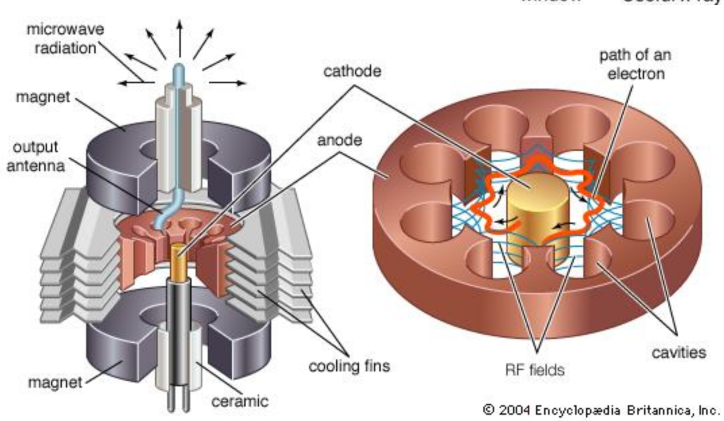


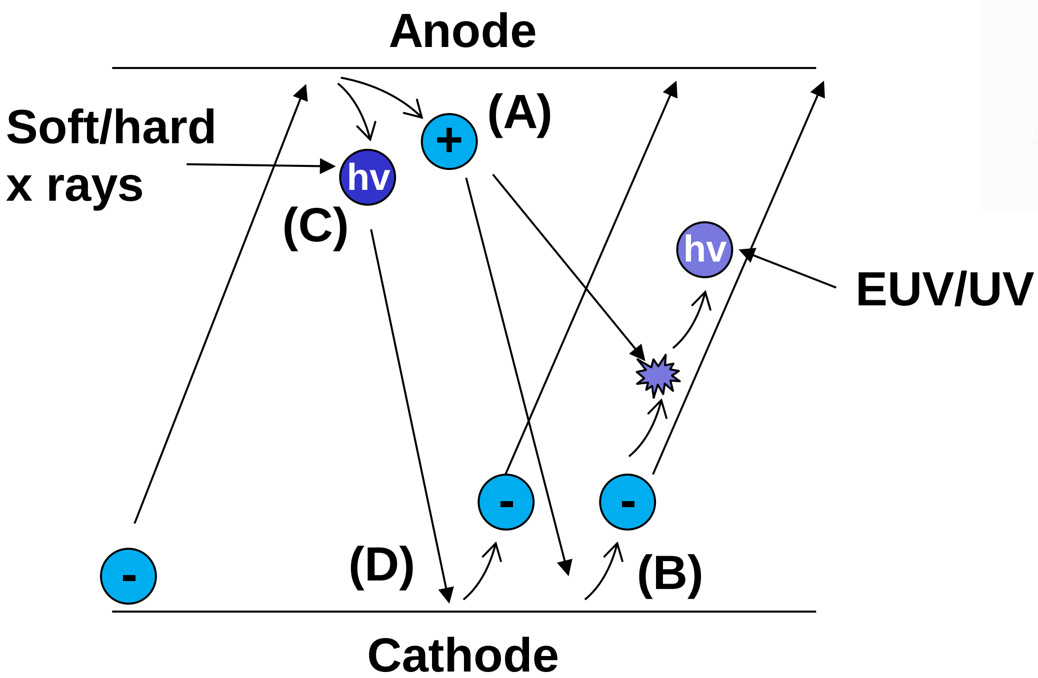

- https://www.researchgate.net/publication/327816840_X-ray_imaging_using_100_mm_thick_Gas_Electron_Multipliers_operating_in_Kr-CO2_mixtures
- http://www2.ee.ic.ac.uk/ngai-han.liu08/yr2proj/magnetron.htm
- N. Bennett, etc., Phys. Rev. Acc. Beams., 22, 120401 (2019)

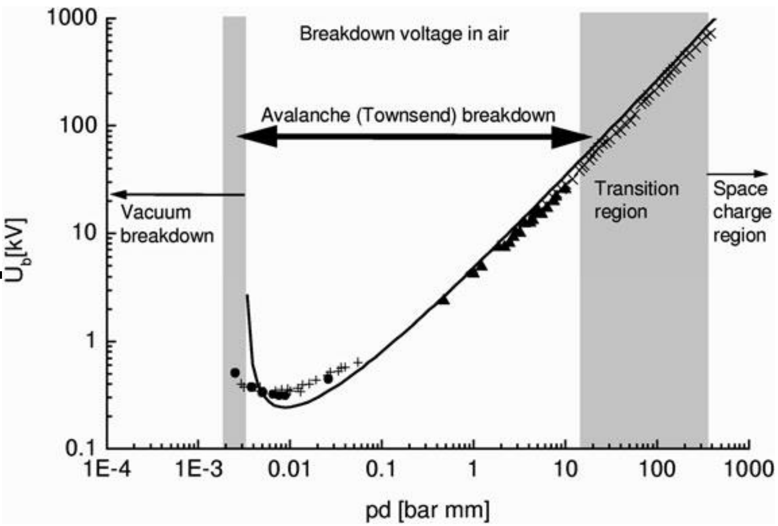
# Vacuum breakdown mechanisms – ABCD mechanism

- **For pd < $10^{-3}$ Torr-cm, electrons cross the gap without colliding gas molecular.**
- **ABCD mechanism: AB+CD ≧ 1**

**More and more electrons are generated**

**=> conductivity increases => breakdown.**



# Characteristics of ABCD breakdown

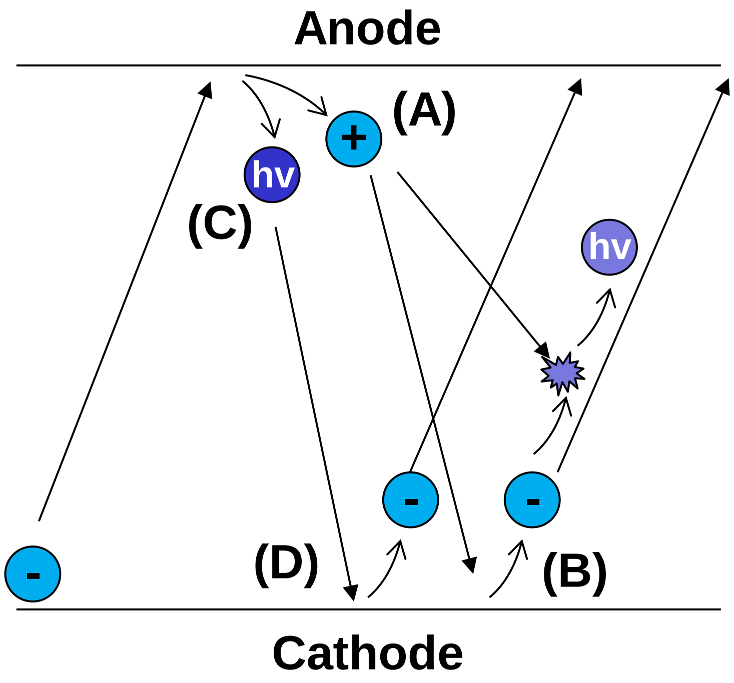
- The probability of ABCD breakdown is high at large impulse field intensity:
  - High gas evolution from electrode due to desorption.
  - Metal vapor formation.
  - Unfavorable micro-injection geometry.
- Field emission initiated breakdown:
  - Fowler-Nordheim (FN) field emission:

$$j_c = C_1 {E_p}^2 e^{-C_2/E_p} \ A/\mathrm{cm}^2$$

$$C_1 = \frac{1.65 \times 10^{-6}}{\psi \, t^2(y)} \quad \psi\text{: work function}$$

$$y = 3.79 \times 10^{-4} \frac{\sqrt{E_p}}{\psi}$$

$$C_2 = 6.83 \times 10^7 \psi^{3/2} v(y)$$



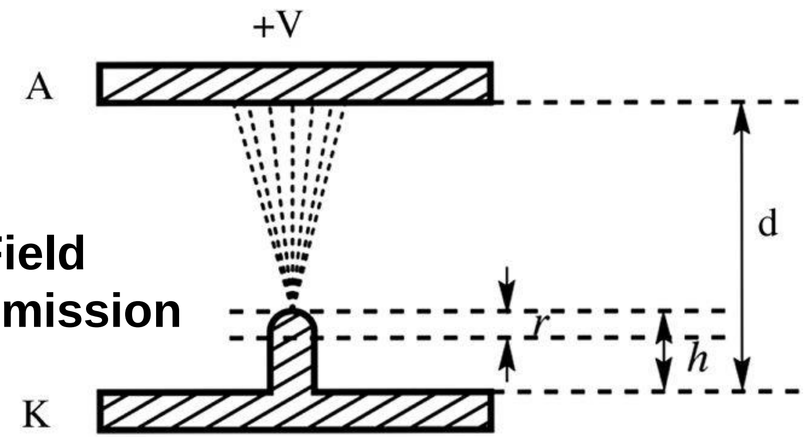
# Potential breakdown conditions

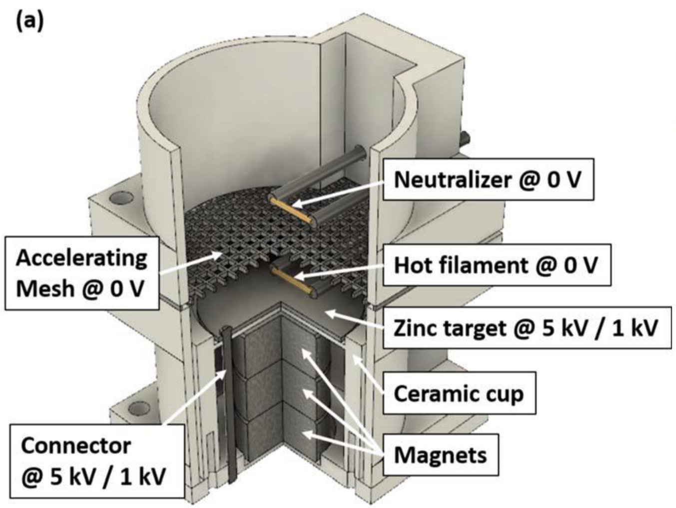
- For $E_p = 10^6 - 10^8$ V/cm, $j_c = 10^8 - 10^{10}$ A/cm$^2$ => leads to breakdown.

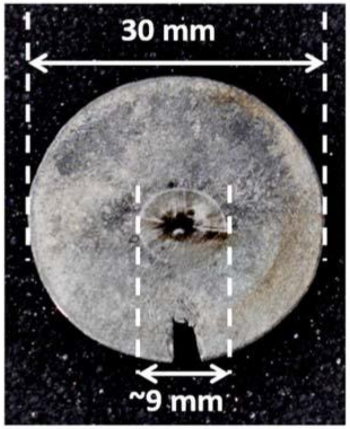
$$j_c = C_1 {E_p}^2 e^{-C_2/E_p}\ A/\mathrm{cm}^2$$

- $j_c$ => joul heating of microprojection => melting, vaporization, plasma forming => ionization/breakdown.
- High-energy electron beam on anode => heating => metal vapor
- Low work function for cathode => high field emission.

**Field emission**



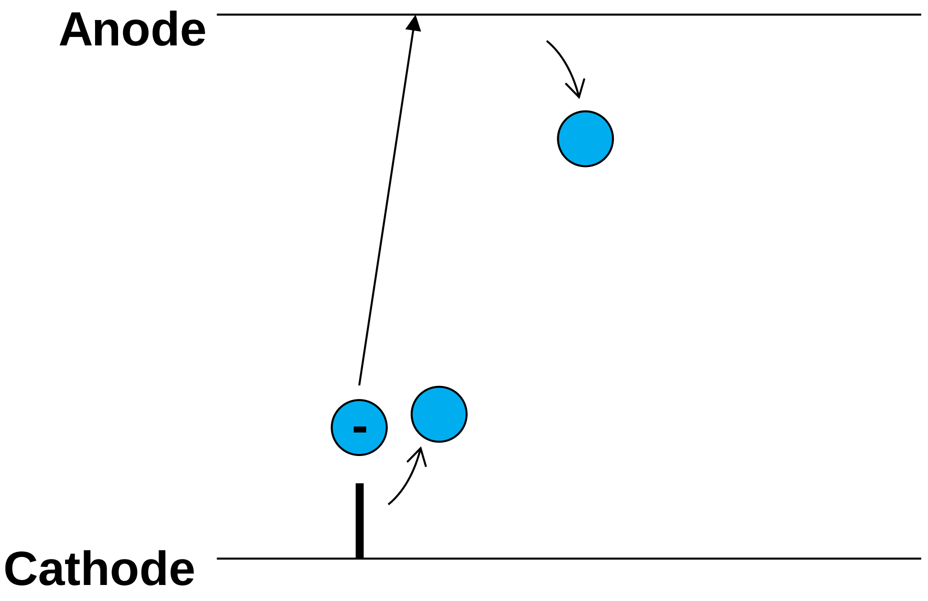




- K.Y. Chen, P.-Y. Chang, and W.-Y. Lin, Plasma Source Sci. Technol., 29, 065021 (2020)

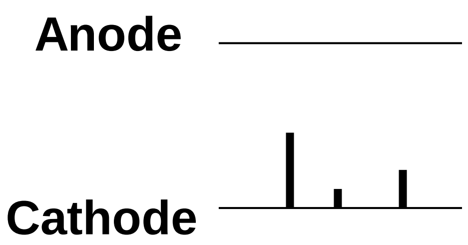
# Microparticle-initiated breakdown

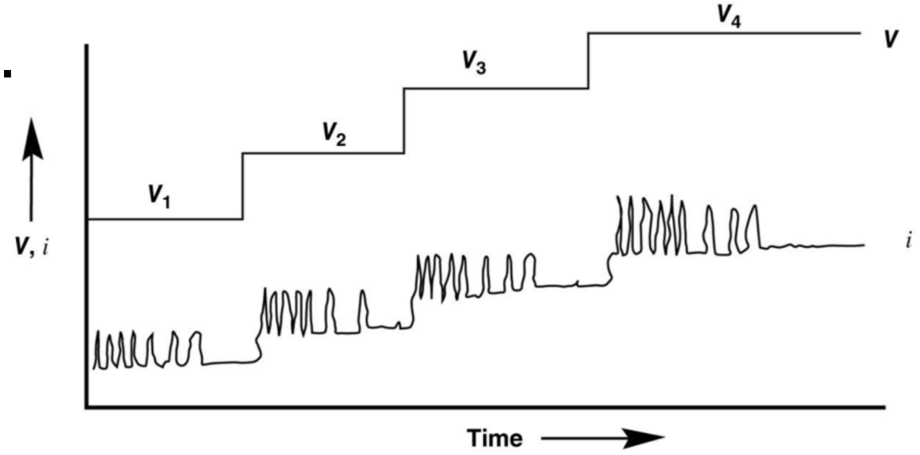
- **Loosely adhering material being detached from electrode due to electrostatic force.**
- **Micro projections are made from joule heating by field emission current.**
- **Vaporization of the anode material by pulsed heating by accelerated electron beam.**
- **Vaporization of the cathode material by joule heating.**



# Improving vacuum insulation performance

- Conditioning: with successive breakdown events, the breakdown voltage steadily increases and attain a steady value.
- Current conditioning:
  - I ~ 100s μA.
  - A breakdown pulse removes a microprojection and the following pulse shifts to another microprojection site.
  - 30 mins~ few hours.
- AC/DC are employed for both electrodes.
- Start from 50% of expected $V_{breakdown}$.



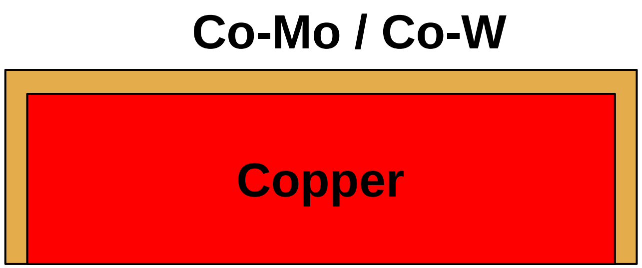



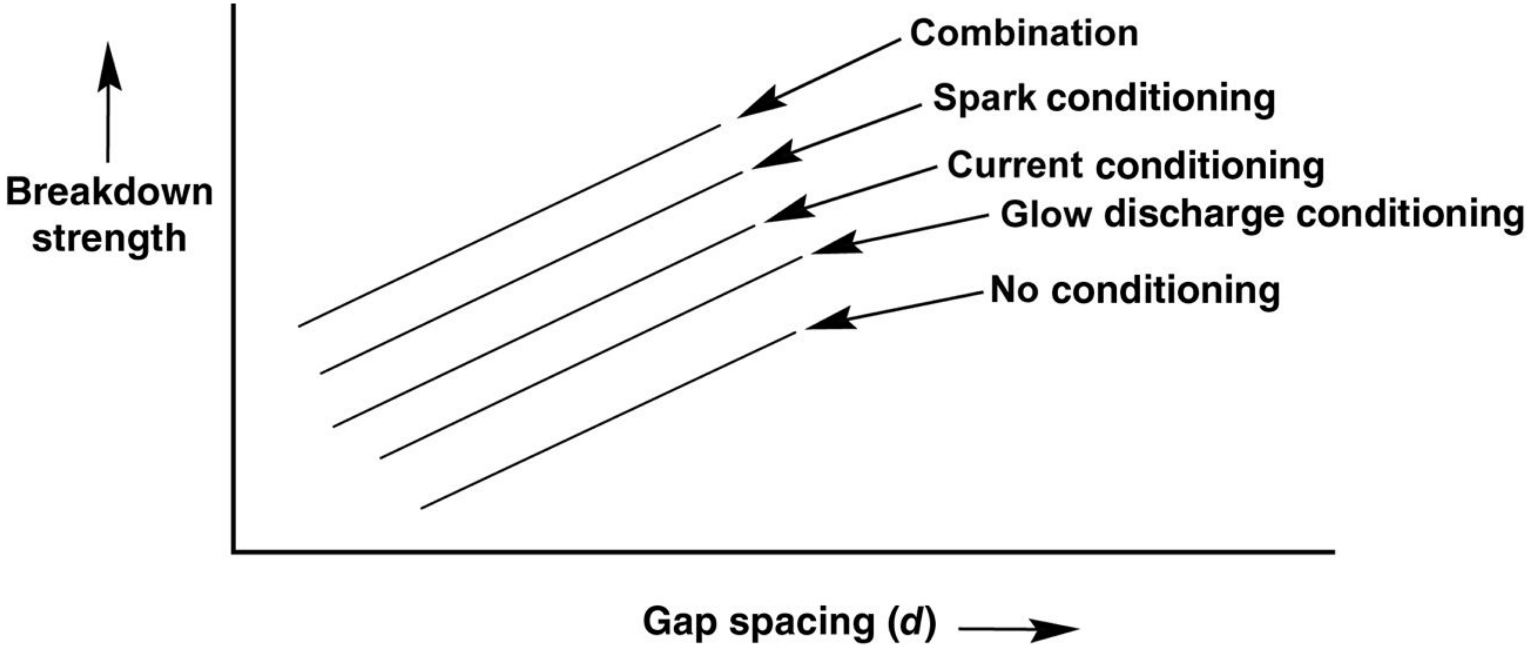
# Improving vacuum insulation performance

- **Spark condition: impulse voltages with width of 100s ns is used.**
  - **I ≦ few Ampere.**
- **Chemical cleaning:**
  - **reducing impurities.**
  - **Valence bend energy is changed. (changing work function.)**
- **Glow discharge cleaning:**
  - **Sputter cleaning.**
  - **A continuous flow of gas allowed the removal of impurities.**
  - **30-60 mins using H, He, Ar, $N_2$, $SF_6$, dry air, then use Ar to remove $O_2$.**
- **Outgassing and annealing: heat to T=250 ~ 1500 ℃ for several hours for outgassing.**

# Improving vacuum insulation performance

- **Surface treatment and coating**
  - **Cobalt-molybdenum (鈷-鉬)**
  - **Cobalt-tungsten (鈷-鎢)**
  - **Ion implantation – work hardening of the surface.**

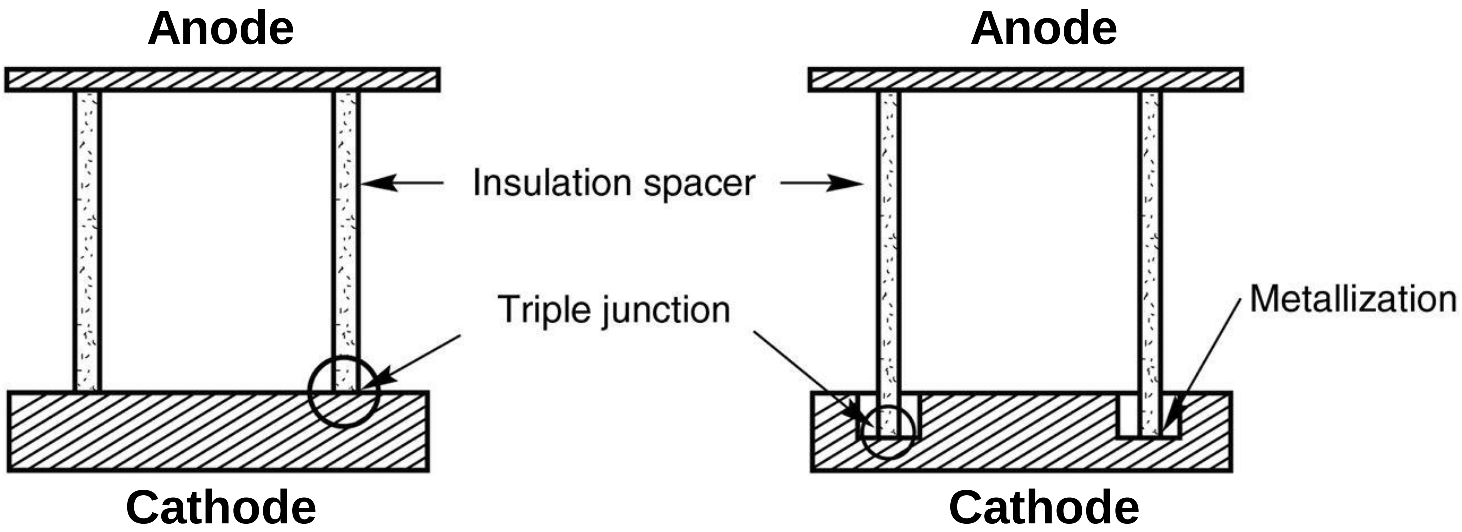


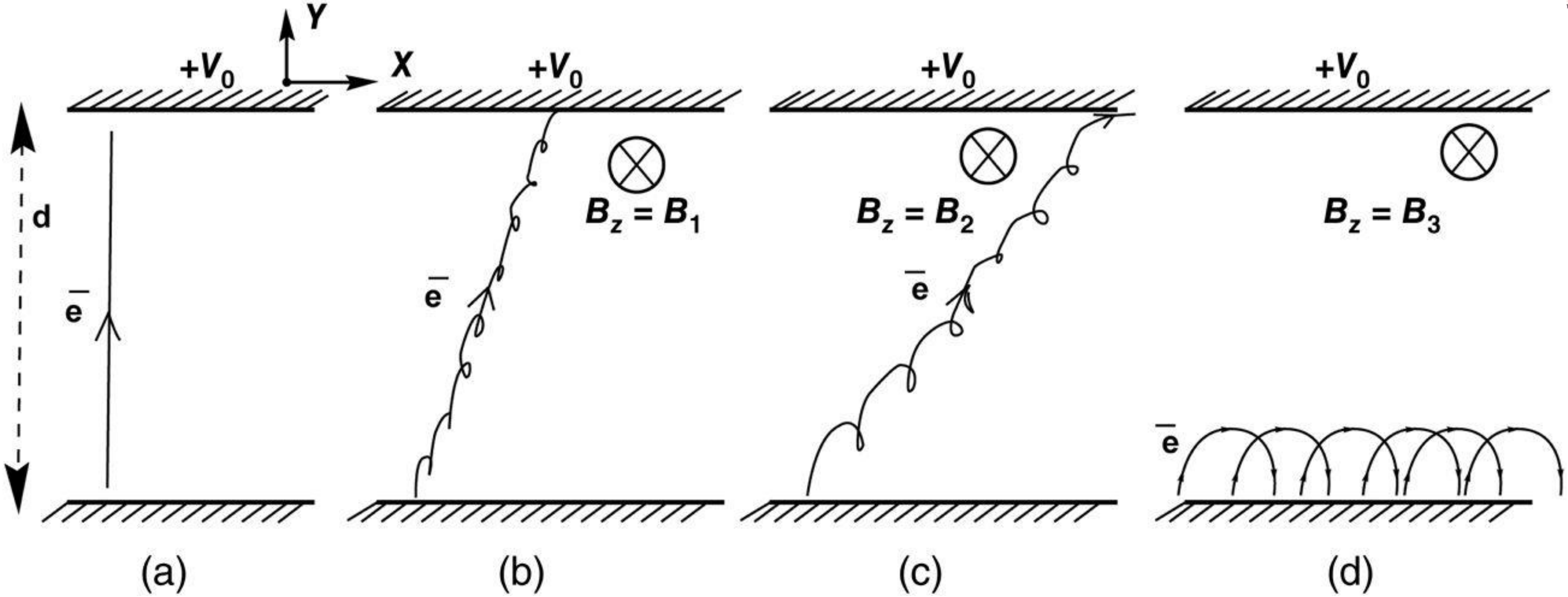
# Triple-point junction modifications

- If imperfect at the triple-point junction, there may be voids or gaps.

  => E field enhancement => enhanced field emission.
- To improve:
  - Metalizing the insulator surface at contact => a firm contact.
  - Elimination of the void and the shielding of the emitted area by cathode. Anode doesn't help!

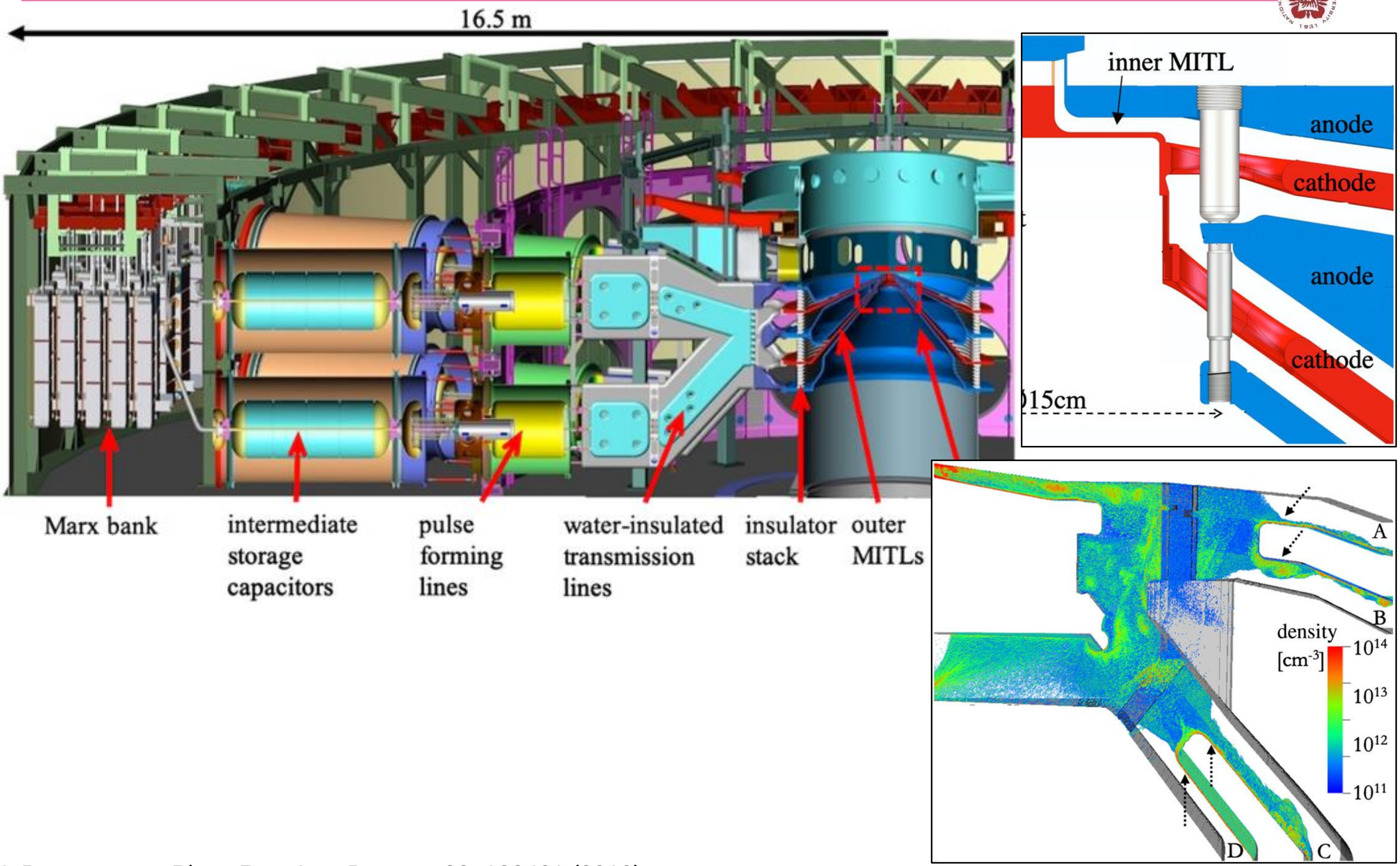


# Vacuum magnetic insulation



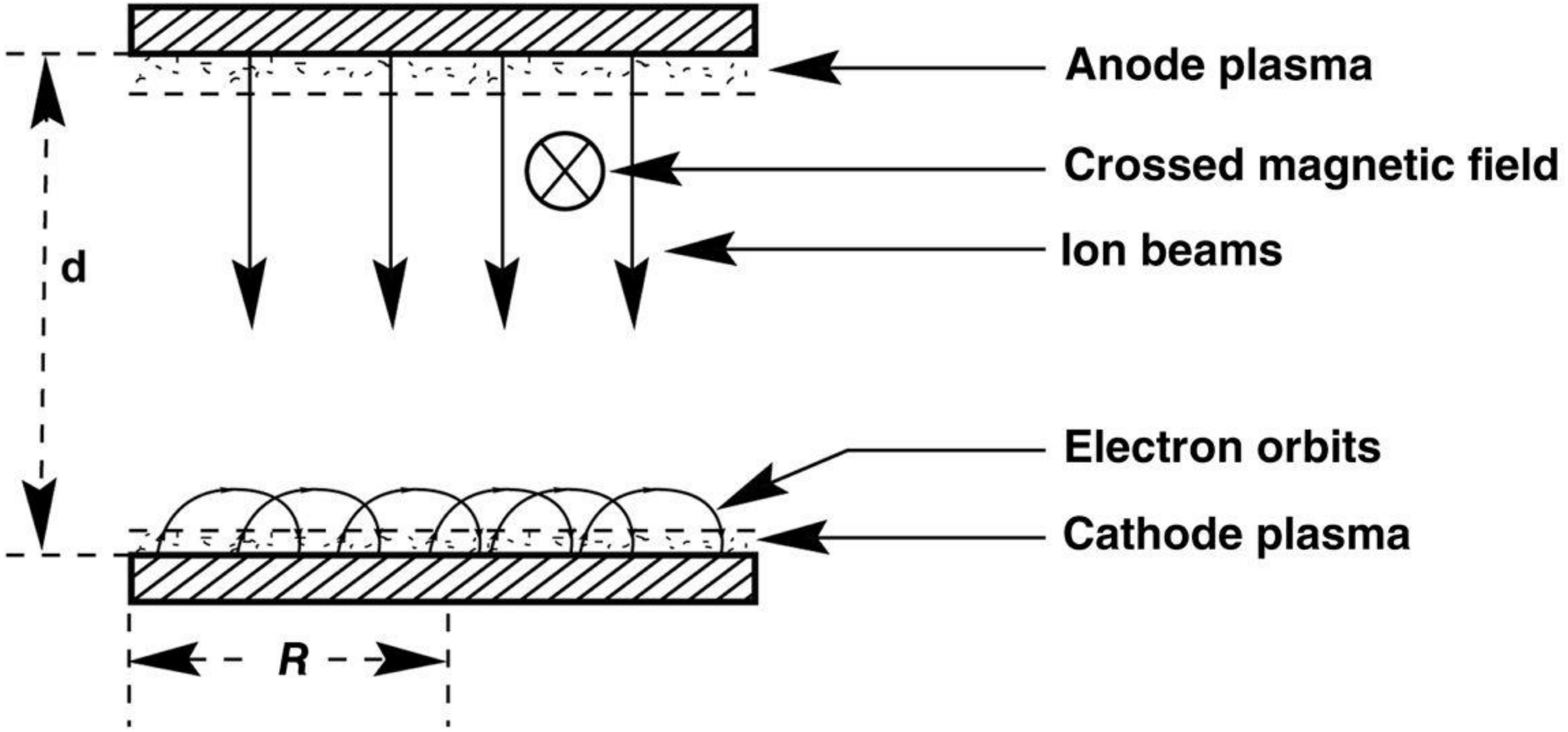

- **The crossed magnetic field can be externally applied.**
- **Self-generated magnetic field is also possible when current is high enough:**
  - **Magnetic Insulation Transmission Line (MITL).**
  - **Magnetic Insulation Line Oscillator (MILO) for high power microwave source.**

# Magnetic Insulation Transmission Line is commonly used in transmitting high current in vacuum




- N. Bennett, etc., Phys. Rev. Acc. Beams., 22, 120401 (2019)

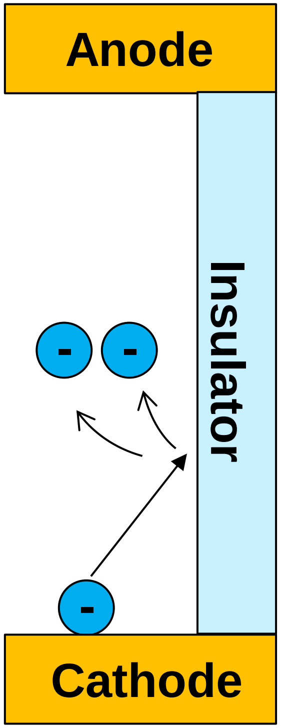
# Ion diode using vacuum magnetic insulation




- $m_i > m_e$ .

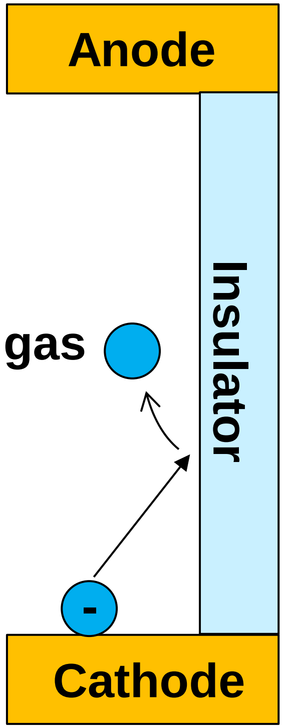
# Surface flashover across solid in vacuum

- $V_B$ increases rapidly at lower pressure due to lack of ionizing collisions particles.
- Process of surface flashover
  - The dielectric surface is the source of electrons to feed the developing avalanche by a process known as $2^{nd}$ electron emission.
  - Electro-stimulated desorption: e- impacting the surface liberates gas trapped or adsorbed by the surface.
- $2^{nd}$ $e^-$ emission from dielectric surface requires $E_k > E_0$ to liberate $e^-$.
- If $E_k < E_0$, charge builds up causing the following $e^-$ are away from the surface and gain more energy till $E_k > E_0$ and generate more $e^-$.
- $V_B \sim \sqrt{l}$



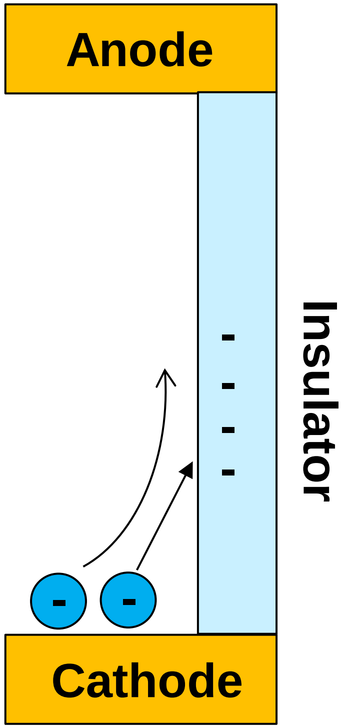
# Surface flashover across solid in vacuum

- $V_B$ increases rapidly at lower pressure due to lack of ionizing collisions particles.
- Process of surface flashover
  - The dielectric surface is the source of electrons to feed the developing avalanche by a process known as 2nd electron emission.
  - Electro-stimulated desorption: e- impacting the surface liberates gas trapped or adsorbed by the surface.
- 2nd $e^-$ emission from dielectric surface requires $E_k > E_0$ to liberate $e^-$.
- If $E_k < E_0$, charge builds up causing the following $e^-$ are away from the surface and gain more energy till $E_k > E_0$ and generate more $e^-$.
- $V_B \sim \sqrt{l}$

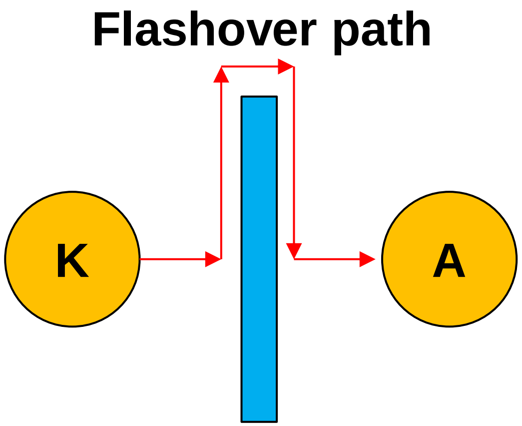


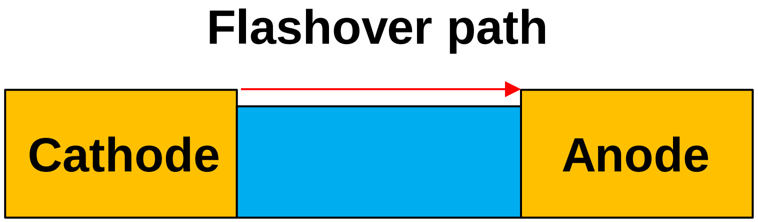
# Surface flashover across solid in vacuum

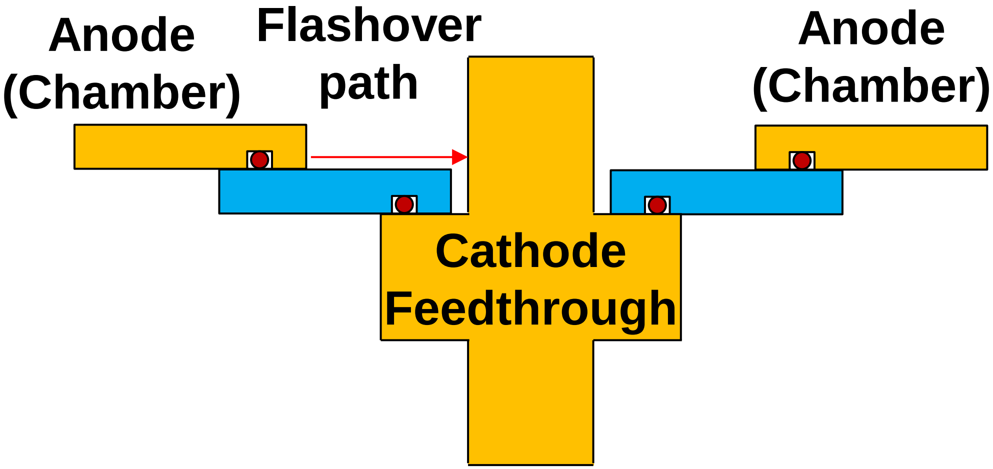
- $V_B$ increases rapidly at lower pressure due to lack of ionizing collisions particles.
- Process of surface flashover
  - The dielectric surface is the source of electrons to feed the developing avalanche by a process known as $2^{nd}$ electron emission.
  - Electro-stimulated desorption: e- impacting the surface liberates gas trapped or adsorbed by the surface.
- $2^{nd}$ $e^-$ emission from dielectric surface requires $E_k > E_0$ to liberate $e^-$.
- If $E_k < E_0$, charge builds up causing the following $e^-$ are away from the surface and gain more energy till $E_k > E_0$ and generate more $e^-$.
- $V_B \sim \sqrt{l}$



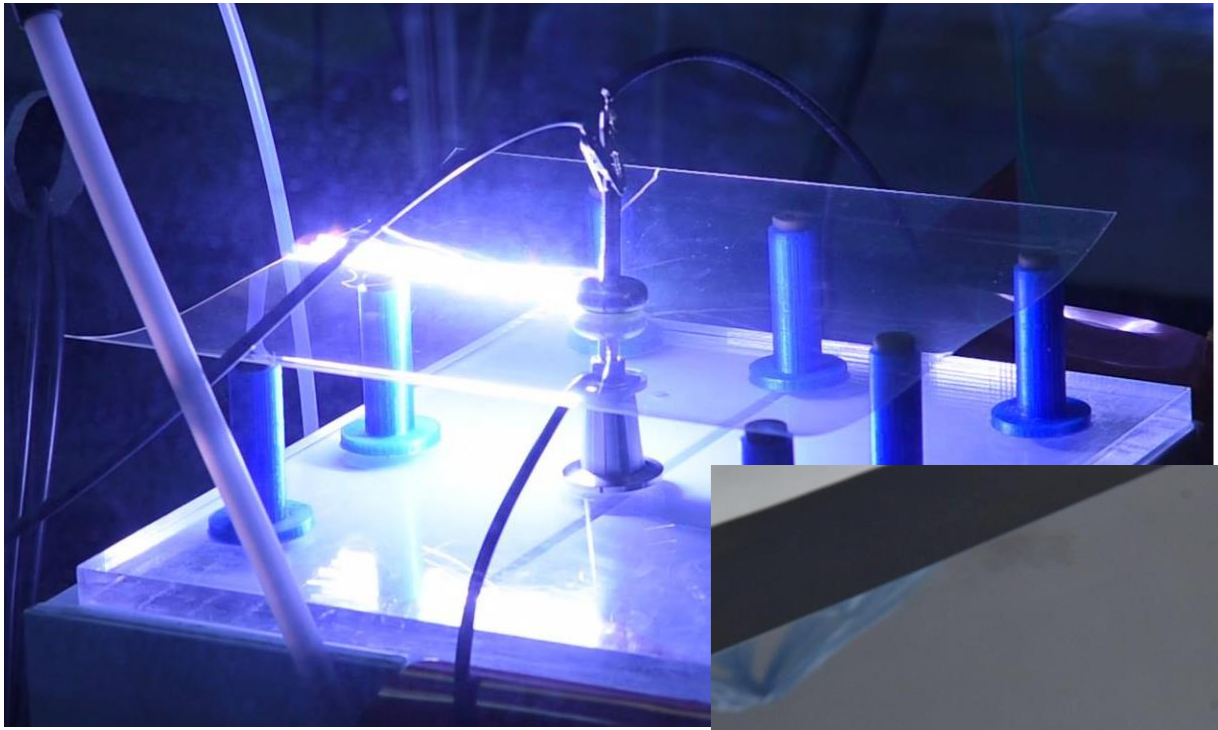
# Some examples of surface flashover of solid dielectric

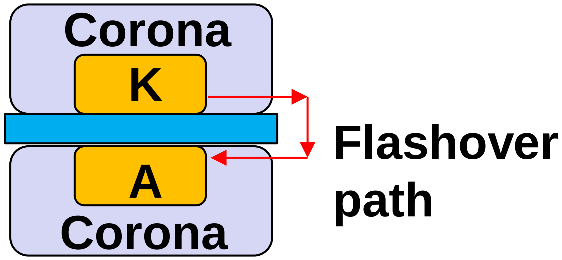


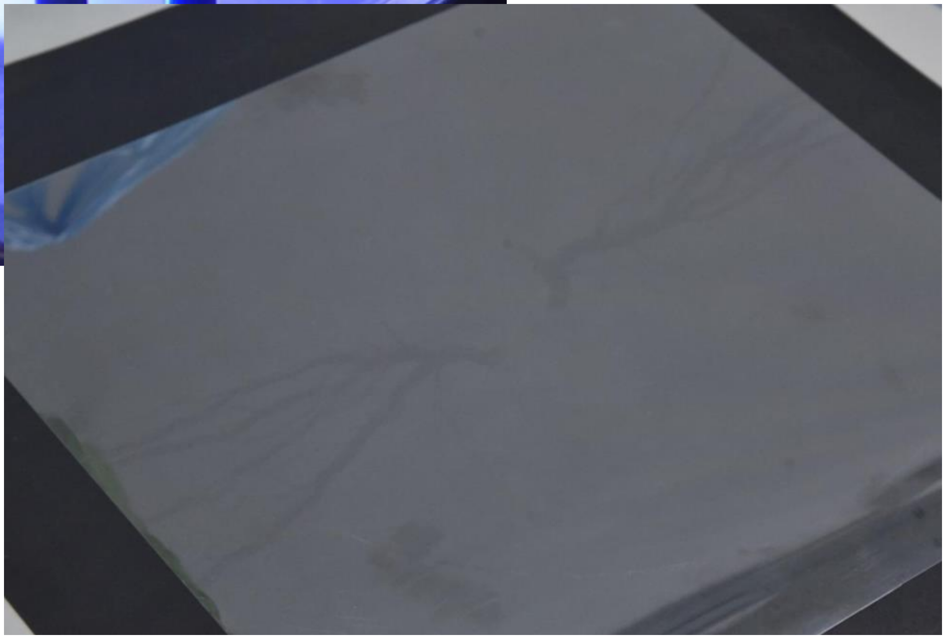



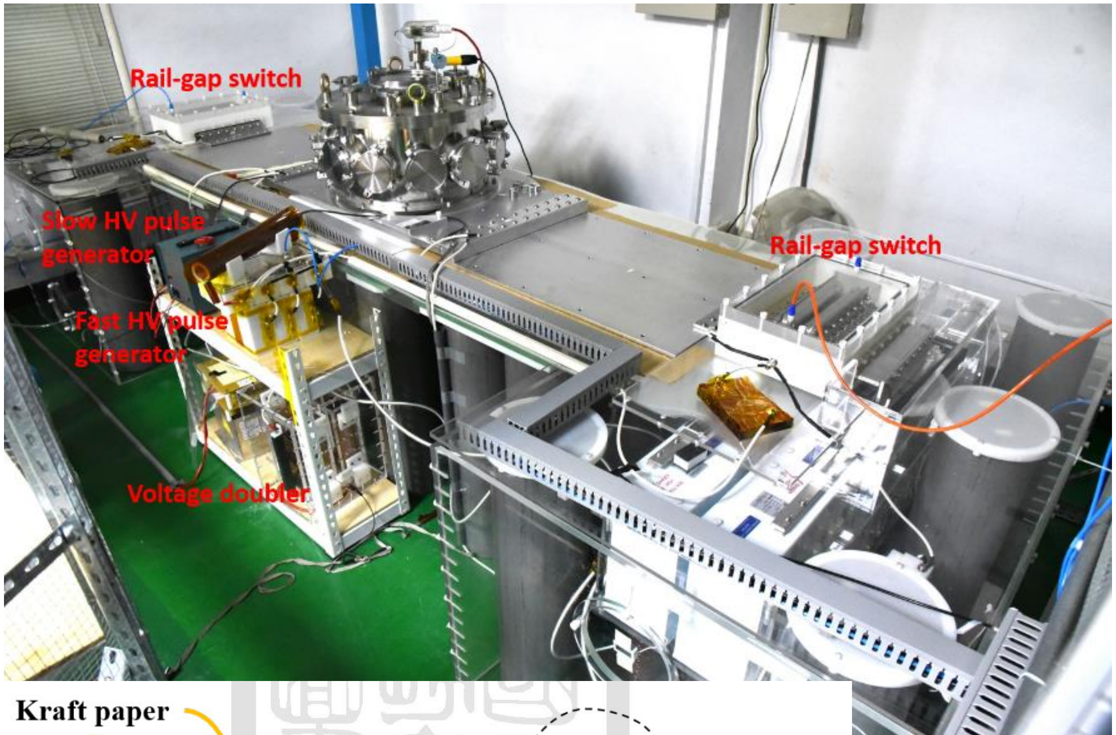
# Some examples of surface flashover of solid dielectric

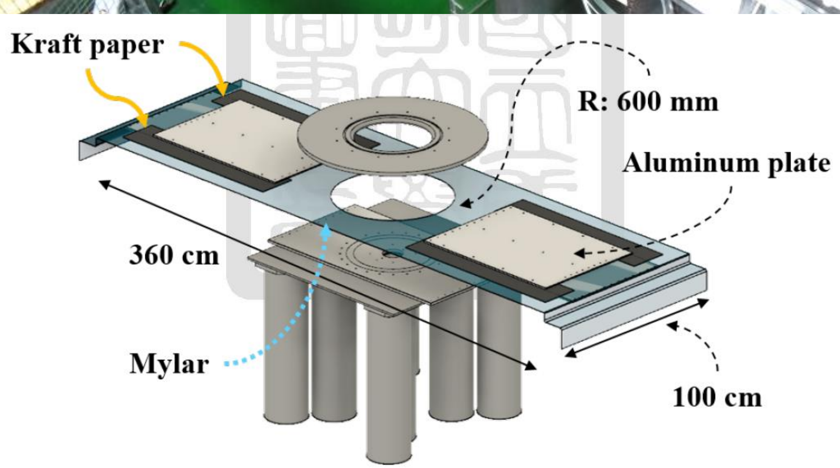




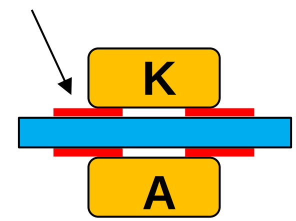



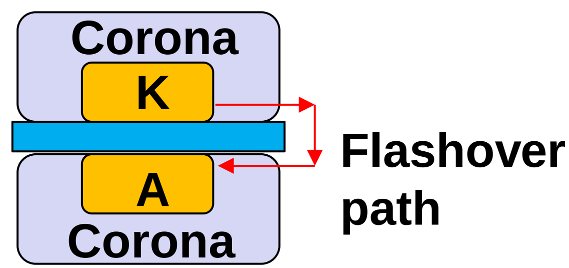
# A kraft paper with high resistivity can kill the corona



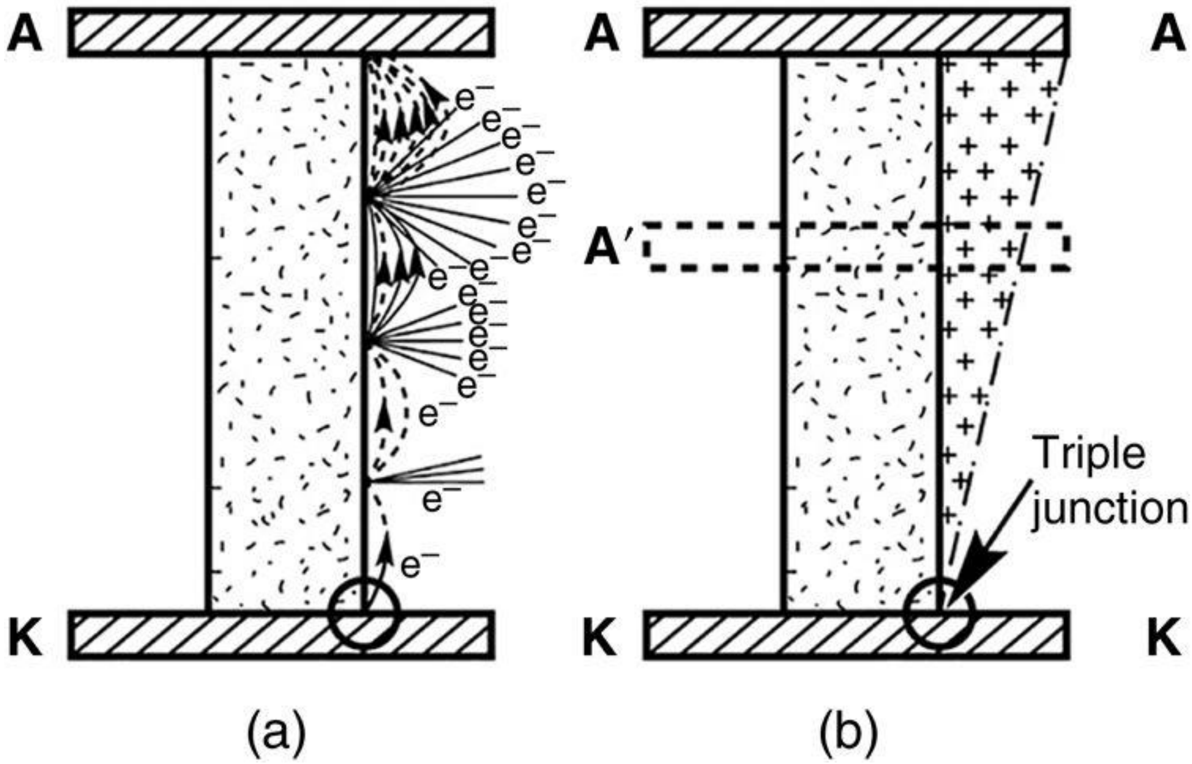




- High but finite resistivity will bring the charge away from the electrodes. Corona is harder to be initiated.



# To avoid flashover, need to avoid avalanche on the insulator surface



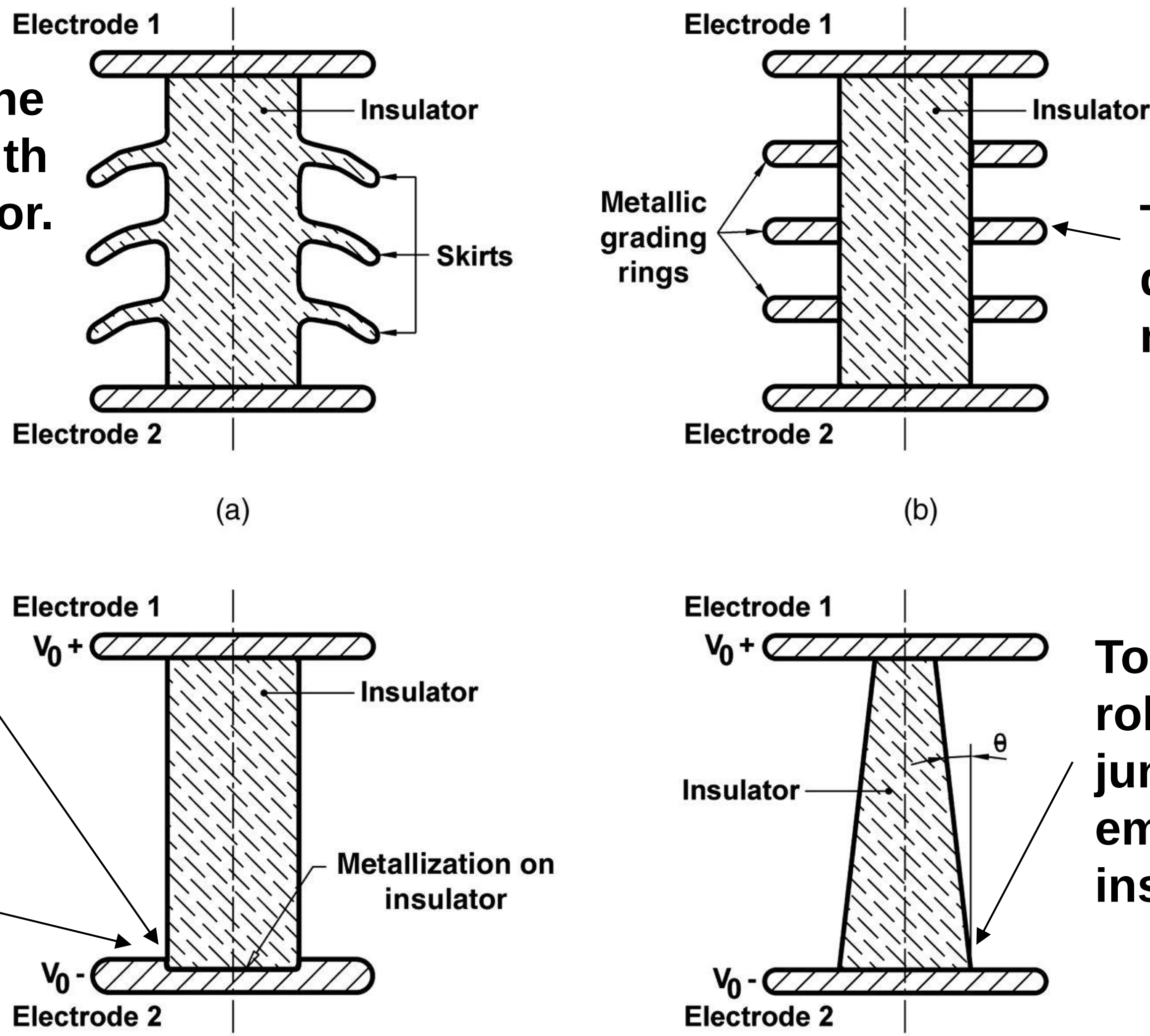
# Ways to avoid surface flashover in standoff insulators

To increase the effective length of the insulator.

To make field distribution more uniform.

Metallization on insulator

To decrease the role of triple junction & 2$^{nd}$ $e^-$ emission from the insulator surface.




• No line of sight!

# Composite dielectrics

$$\epsilon_1 E_1 = \epsilon_2 E_2 \qquad E_1 = \frac{V_1}{d_1}, E_2 = \frac{V_2}{d_2}$$

$$\epsilon_1 \frac{V_1}{d_1} = \epsilon_2 \frac{V_2}{d_2}, \qquad V_0 = V_1 + V_2$$

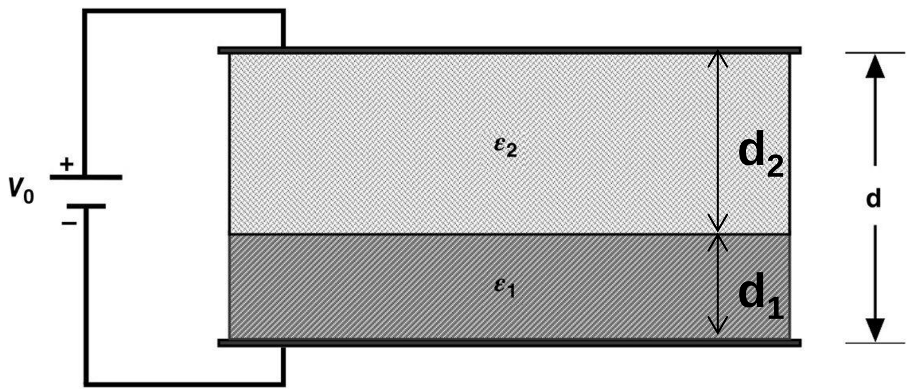
$$V_1 = \frac{\epsilon_2}{\epsilon_1}\frac{d_1}{d_2} V_2$$

$$V_0 = \frac{\epsilon_2}{\epsilon_1}\frac{d_1}{d_2} V_2 + V_2 = \frac{\epsilon_2 d_1 + \epsilon_1 d_2}{\epsilon_1 d_2} V_2$$

$$V_2 = \frac{\epsilon_1 d_2}{\epsilon_2 d_1 + \epsilon_1 d_2} V_0$$

$$E_2 = \frac{\epsilon_1}{\epsilon_2 d_1 + \epsilon_1 d_2} V_0 = \frac{V_0}{\epsilon_2/\epsilon_1\, d_1 + d_2}$$

$$E_1 = \frac{\epsilon_2}{\epsilon_1} E_2 = \frac{\epsilon_2}{\epsilon_2 d_1 + \epsilon_1 d_2} V_0 = \frac{V_0}{d_1 + \epsilon_1/\epsilon_2\, d_2}$$




$$E_0 \equiv \frac{V_0}{d} = \frac{V_0}{d_1 + d_2}$$

$$\text{if } \frac{\epsilon_2}{\epsilon_1} > 1, d_1 + \frac{\epsilon_1}{\epsilon_2} d_2 < d_1 + d_2 = d$$

$$\frac{\epsilon_2}{\epsilon_1} d_1 + d_2 > d_1 + d_2 = d$$

$$E_1 > E_0, E_2 < E_0$$

- **The lower dielectric constant of the material creates a higher electric field.**

# Outlines

- Introduction to pulsed-power system
- Review of circuit analysis
- Static and dynamic breakdown strength of dielectric materials
  - Gas – Townsend discharge (avalanche breakdown), Paschen's curve
  - Liquid
  - Solid
- **Energy storage**
  - **Pulse discharge capacitors**
  - **Marx generators**
  - **Inductive energy storage**

# Electric energy storage requirements

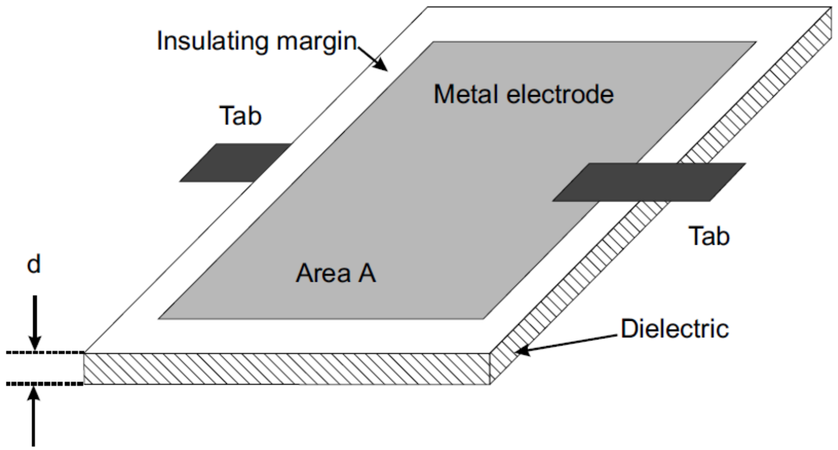
- **High energy density.**
- **High breakdown strength.**
- **High discharge current capability.**
- **Long storage time (low rate of energy leakage).**
- **High charging and discharging efficiency.**
- **Large power multiplication**

  **(≡ power during discharge / power during charging).**
- **Repetition rate capability and long lifetime.**
- **Low specific cost.**

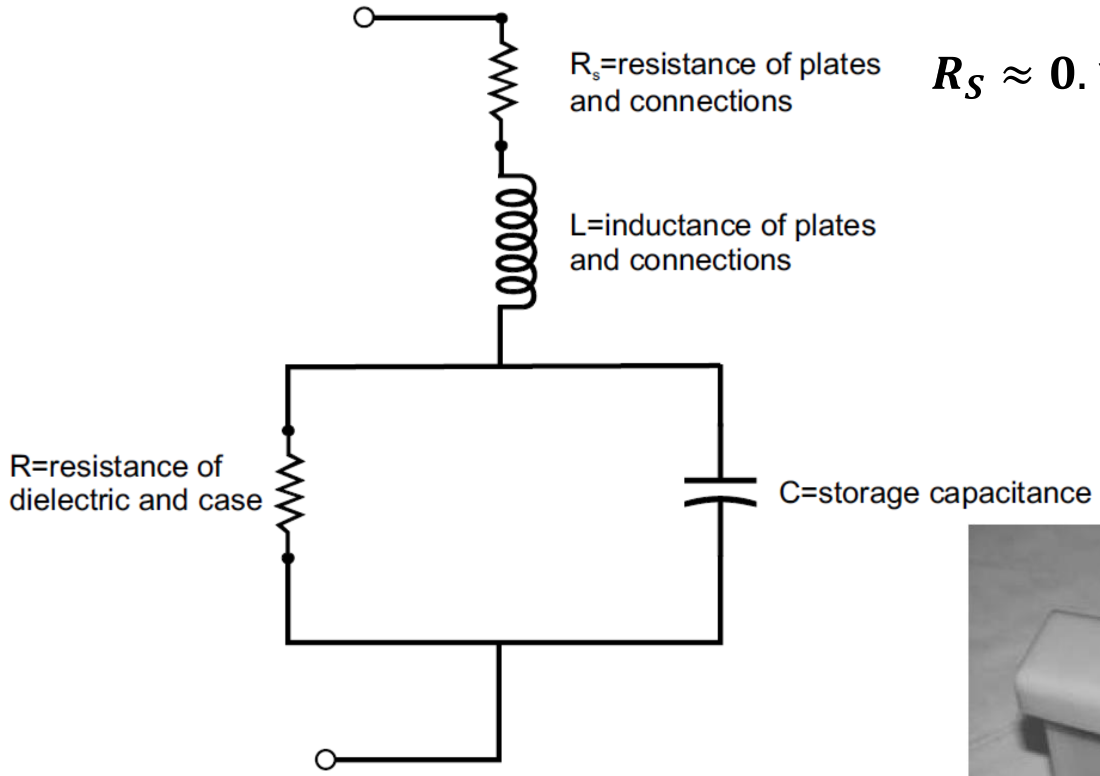
# Pulse discharge capacitors

- **Pulsed power systems are still based on high-voltage energy-storage capacitors due to: reliability, repetition, fast closing switches, and the energy hold time is longer than inductive storage devices.**
- **An insulating margin around the metal electrodes prevents flashover between the electrodes.**

$$W_c = \frac{1}{2} \mathrm{c} \mathrm{V}^2$$



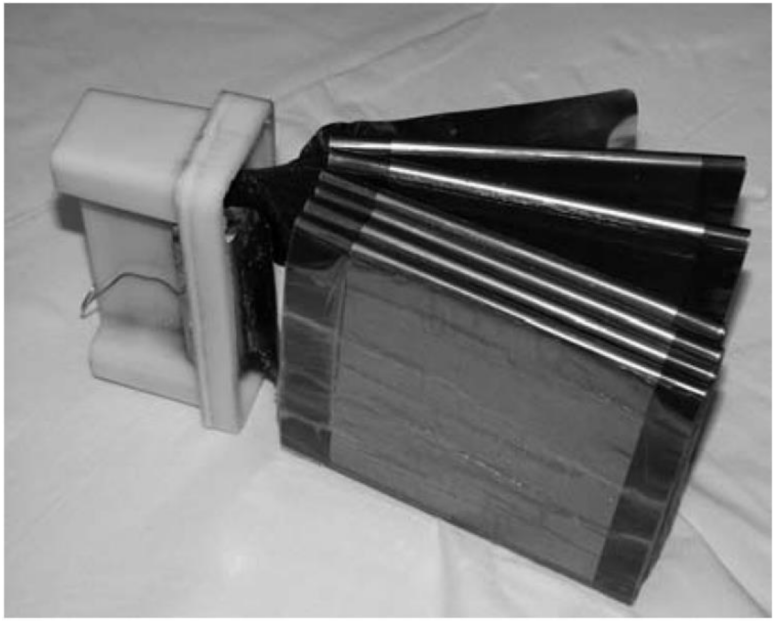
# Lumped circuit model of a capacitor



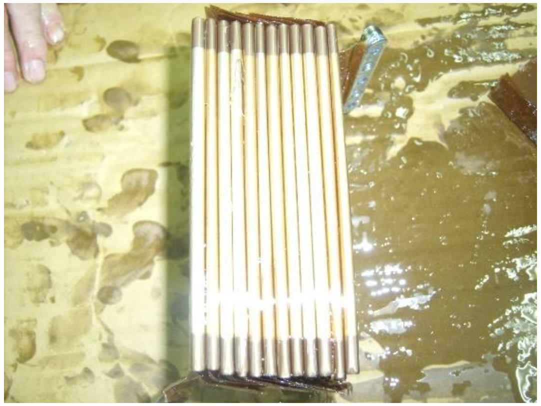

$$R_S \approx 0.1\ \Omega$$

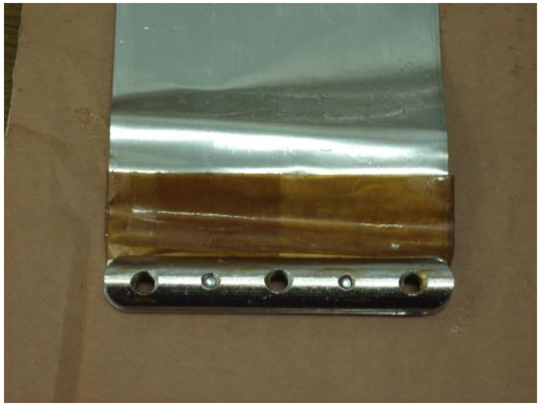
$$I_{\text{peak}} = \frac{V}{\sqrt{L/C}}$$

**Impedance ≡ L/C**

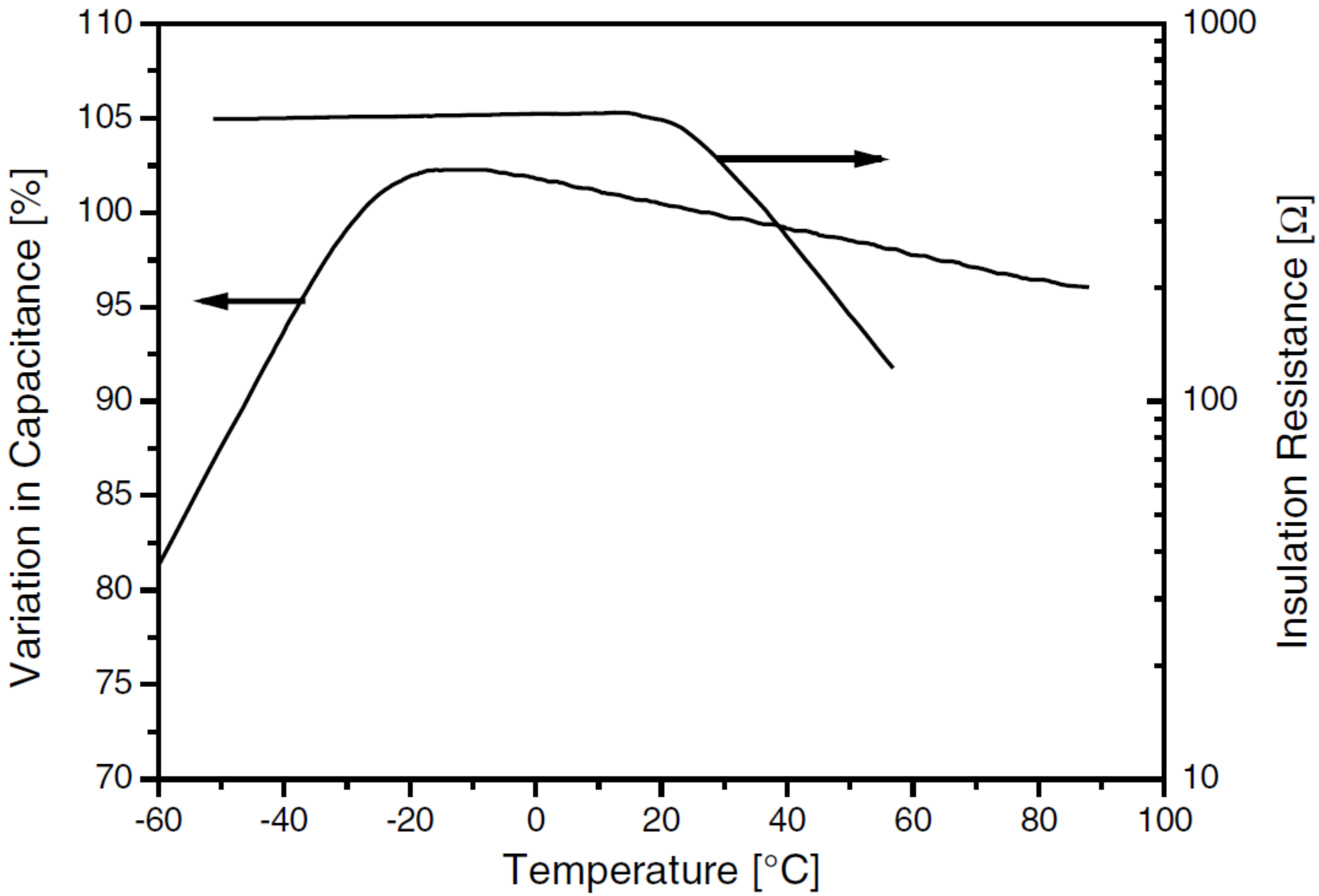


# High voltage super capacitor



# Oil-impregnated paper as the dielectric



# Properties of some dielectric materials used for the insulation of high-voltage capacitors

| Material | E | $E_{DB}$ (kV/cm) | Tan(δ) |
|---|---|---|---|
| Impregnated paper | 3-4 | 200-800 | 0.01-0.03 |
| Epoxy | 3.5 | 320 | 0.014 |
| Mylar | 3 | 400 | 0.001 |
| Polypropylene | 2.55 | 256 | 0.0005 |
| Teflon | 2.1 | 216 | 0.0002 |
| Kapton | 3.4 | 2800 (25 μm) | 0.01 |
| Plexiglas | 3.3 | 200 | 0.009 |
| Transformer oil | 3.4 | 400 | 0.0002 |
| Aluminiumoxide | 8.8 | 126 | 0.01 |
| Bariumtitanate | 1143 | 30 | 0.01 |
| Glass (borosilicate) | 4.84 | 157 | 0.0036 |

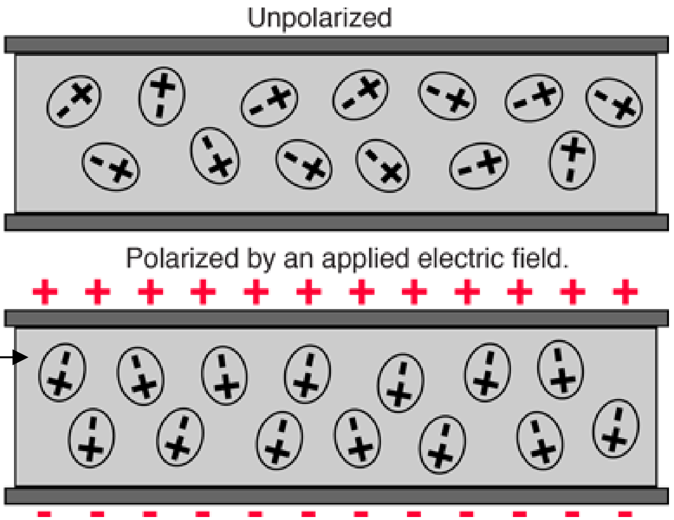
# Properties of dielectric materials

- **Electric strength (dielectric strength), influenced by**
  - **Conditions of operations.**
  - **Temperature.**
  - **Pressure.**
  - **Humidity.**
  - **Voltage reversal.**
- **Dielectric constant ε.**
- **Loss factor tan(δ).**

# Characteristics of capacitors

- Dependence of the high-voltage strength of a capacitor
  - Breakdown strength of the dielectric.
  - Shape, area, metal of the terminals.
  - Bonding to the insulator that fills the case.
- The instantaneous capacitance differs from the static value when a capacitor is charged or discharged quickly. It is the result from the finite relaxation time of the polarization, which is also responsible for the dielectric losses.

Polar molecules rotate if the electric field oscillates. The rotation of the polar molecules causes the energy loss.




http://hyperphysics.phy-astr.gsu.edu/hbase/electric/dielec.html