Chapter-4
Field-Dependent Electric Strength and Breakdown in Gaseous Dielectric and Vacuum

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Objective

- Properties of gaseous dielectrics
- Mechanism of the generation of charge carriers
- Development of Electron Avalanche
  - Townsend's current growth equation (Pr. And Sr. coefficients)
- Breakdown Mechanism in Uniform, weakly nonuniform, and extremely nonuniform Fields
  - Uniform Field with Space Charge

Introduction

- Fitting theories to experimental results.

- Common gaseous dielectrics and their properties:
  - Atmospheric air
  - SF_6
  - Vacuum technology

- Electropositive gasses Vs Electronegative gases

- Mass of electron Vs Mass of ion/molecule

- Speed of Electron Vs Speed of ion/molecule under Uniform Field

- What do you mean by Elastic and inelastic collision?

Introduction

- Air as an Dielectric
- Air constitutes of (Nitrogen, Oxygen, etc.):
- ***Electronegative or Electropositive ?***
- Why air is used as an "Model of Discharge"

Table 1 Composition of earth's atmosphere

Constituent	Percent by volume or by number of molecules of dry air
Nitrogen ()	78.084
Oxygen ()	20.946
Argon (A)	0.934
Carbon dioxide (CO_2)	0.031
Neon (N_e)	1.82×10^{-4}
Helium (H_e)	5.24×10^{-4}
Methane (CH_4)	1.5×10^{-4}
Krypton (K_r)	1.14×10^{-4}
Hydrogen (H_2)	5×10^{-5}
Nitrous oxide (N_2O)	3×10^{-5}
Xenon (Xe)	8.7×10^{-6}
Carbon monoxide (CO)	1×10^{-5}
Ozone (O_2)	upto 10^{-5}
Water (average)	upto 1

Introduction

- SF_6 as an electronegative gas
- High intrinsic strength
- Has favourable properties suitable for high-voltage power apparatus
  - Critical temperature
  - Triple point & sublimation point
  - Specific heat
  - Heat conductivity

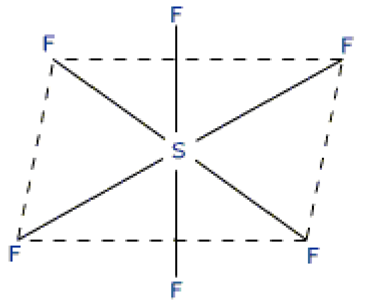

Fig. 1 Octahedral structure of SF_6

Table 2 Physical properties of SF_6

Property	Physical conditions	Symbol	Unit	Value
Relative Permittivity	0.1 MPa, 25°C - 51°C (liquid)	ε_r	--	1.002 1.81 ± 0.02
Dielectric Loss Tangent	0.1 MPa, - 51°C (liquid)	tan δ	--	< 5.10^{-6} < 5.10-6
Critical Temperature	--	θ_{cr}	^{0}C	45.5
Triple Point	p =0.22 MPa	θ_T	^{0}C	-50.8
Intrinsic Breakdown Strength	0.1 MPa, 25^o C		kV/cm	89
Sublimation Point	--	θ_s	^{0}C	-63.8
Specific Heat Capacity	at 10^0 C and constantp=0.1 MPa	C_p		5.13
Specific Heat Capacity	at 10^0 C and constant volume	C_v		4.06
Heat Conductivity	30^0 C	--		$0.82.10^{-5}$
Heat Transition No.	--	--		$0.44.10^{-5}$

Introduction

- What happens *if* applied voltage at electrodes increases?

- Ionization: ***The process of build-up of high currents in a breakdown, in which electrons and ions are created from neutral atoms or molecules, and their migration to the anode and cathode respectively leads to high current.***

- Streamer Theory or Townsend Theory: Explains Ionization and electric breakdown.

- Factors affecting ionization: Physical condition of gases, like temp, pressure, electrode field configuration, nature of electrode surface, and the availability of initial conducting particles.

Ionization Process

- Primary Ionization
  - Impact Ionization
  - Photoionization
  - Electron emission due to Photons

- Secondary Ionization
  - Electron emission due to Positive ion impact
  - Electron emission due to Metastable and Neutral Atoms
  - Thermionic emission/Thermal Ionization
  - Field emission

- Electron Attachment/ Recombination/Diffusion/Mobility

Generation of Charge Carriers in Gases

- In a gas, the electrons and ions are the electric charge carriers.
- Ions are produced from neutral molecules or atoms by ejection or attachment of an electron.
- The total energy of an electron can be divided into two types of energies:

Kinetic energy

$$W_{KE} = \frac{1}{2} m_e v_e^2 = \frac{1}{8\pi\varepsilon} \cdot \frac{e^2 z}{r_e}$$

Potential energy

$$W_{pot} = -\frac{1}{4\pi\varepsilon} \cdot \frac{e^2 z}{r_e} = -2W_{KE}$$

$r_e \rightarrow \infty$

$$W_{total} = W_{KE} + W_{pot} \quad = -\frac{1}{8\pi\varepsilon} \cdot \frac{e^2 z}{r_e}$$

$$= \frac{1}{2} W_{pot}$$

$$W_{total} = -13.6eV \cdot \frac{z^2}{n^2} = -W_I$$

- ***For a small gap distance between electrodes, ions can therefore be assumed not to have moved from the place where they are generated.***

Generation of Charge Carriers

During an Electric Breakdown: the insulating gas between the electrodes is bridged by a conducting discharge canal (channel).

In small gap distance the charge carriers required in order to build this discharge canal are not only produced within the gaseous dielectric across the gap (*primary or α- process*), but are also released from the electrode surfaces (*secondary or γ - process*).

From where initial charge particles will come?

- **Initial Electrons: Emission from cathode or in extreme case by cosmic rays/friction and movement/ultra-violet radiation /photoionisation, etc.**

Impact (or Collision) Ionization

- Impact or collision of particles amongst each other, *accelerated under electrical field*, leads to the formation of charge carriers from neutral gas molecules.
- The multiplication of charge carriers in gas takes place mainly by impact of electrons with neutral molecules known as α - process (also primary process).

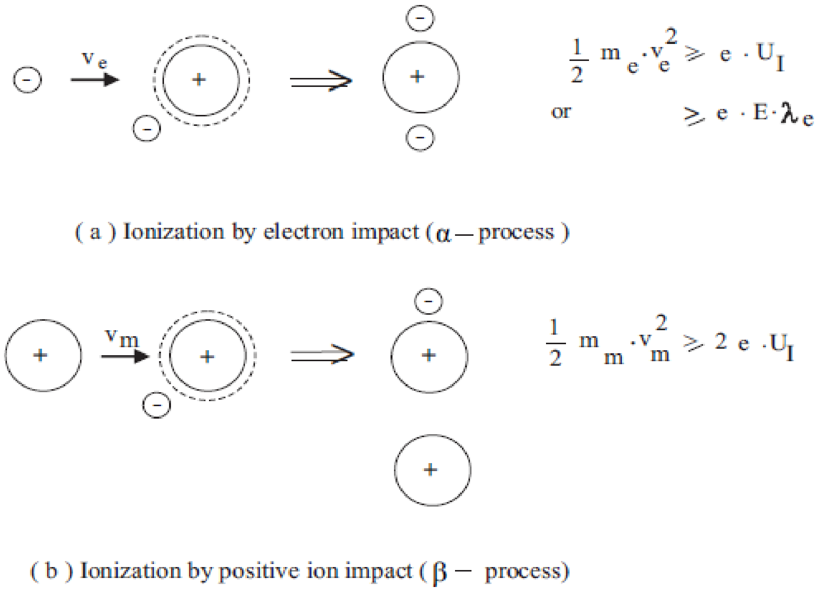

Fig. 2 Impact ionisation by electron and ion

Table 2 Ionisation energies for the first electron in various gases

Gas	First Ionization energy W_I (eV)
N_2	15.6
SF_6	15.6
H_2	15.9
O_2	12.1
H_2O (vapour)	12.7
CO_2	14.4
He	24.0

To cause ionization, the incoming electron must have a kinetic energy greater than or equal to the ionization energy of the molecule (eU_I).

Thermal Ionization

- If a gas is heated to sufficiently high temperature, to the order of 10,000 K and above, many of the gas atoms or molecules acquire high velocity to cause ionization on collision with other atoms or molecules.
- The molecules excited by photon radiation also affect the ionization process.
- Thermal ionization is the principal source of ionization in flames and arcs.
- Thermal ionization becomes significant only at temperatures above 10,000 K , as shown in Fig. 3 where theta is degree of ionization.

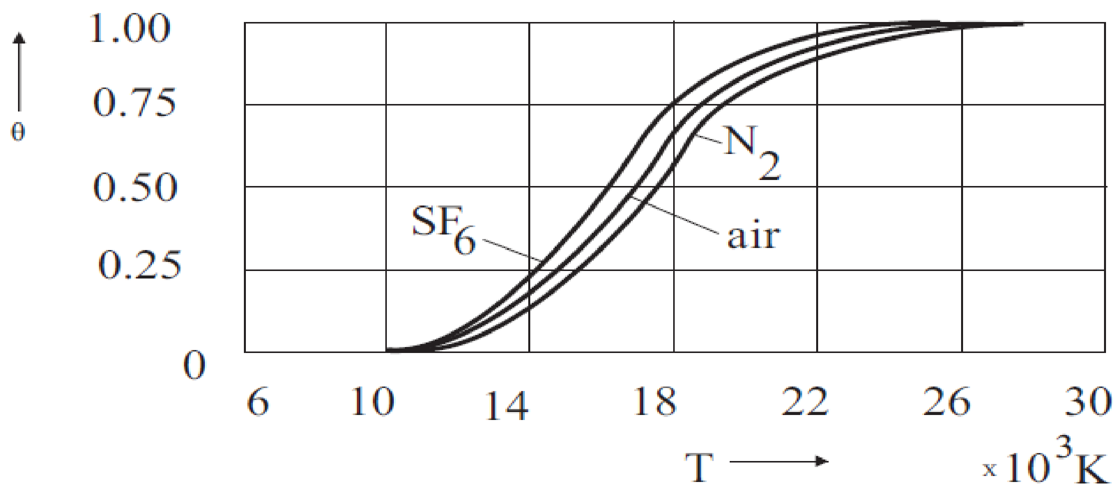

Fig. 3 Degree of ionisation of thermally ionised gases at 1 bar

During electrical breakdown in gases, thermal ionization has its *significance only towards the final stage of breakdown*. Because of the transformation of large amount of energy in the electrically conductive channel (known as 'leader') towards the final stage of breakdown, an exceptionally high temperature rise in this channel core is possible

Photoionization

- The phenomenon associated with *ionization by radiation*, which involves the interaction of *radiation with matter*.

- Phototionisation occurs when the *amount of radiation energy absorbed by an atom or molecules exceeds its ionization potential*.

- Continues absorption of direct excitation of the atom.

- Excitation of the atom to a higher energy state.

- The impact ionization process is possible only when the energy exchanged in collision is more than the energy required for ionization (eU_I). The electrons having energy lower than the ionization energy may excite the gas molecules to higher energy states on collision. Under this condition, *an electron is raised from a lower energy level to a higher one.*

- On recovering from the excited state of electron in 10^{-7} *to* 10^{-10} sec, a molecule radiates a quantum of energy of photon.

- This energy in turn may ionize another molecule whose ionization potential energy is equal to or less than the photon energy.

Electron Emission due to Photon (or secondary photoionization)

- To cause an electron escape from a metal, it should be given enough energy to overcome the surface potential barrier.

- Excited molecules in the avalanche may emit photons on returning to their ground state. This radiation falling on cathode may produce photo-emission of electrons.

Breakdown in Gaseous Dielectric in Uniform and Weakly Nonuniform Fields

- The first step which lead to breakdown is ‘ionisation’
- Initial process of ionisation in gaseous dielectric, caused by electric field also known as ‘electron avalanche’
- Dependent on the magnitude of applied voltage
- *Complete Breakdown of dielectric is the advanced* stage when an *unlimited growth of conduction current* caused
- This requires a *vigorous ionization process*
- Sustained and non sustained discharge
- The basic discharge process leading to breakdown in weakly and uniform field is similar

Development of Electron Avalanche

- Initially the electrons are originated in a gaseous dielectric gap space between two electrodes either by ionization of neutral molecules by photons from cosmic rays, or by ultraviolet illumination of cathode, or at a later stage by photons from the discharge itself when electric field is applied.

- The electrons thus generated accelerate towards the anode, gaining kinetic energy of movement from the applied electric field between the electrodes.

- The kinetic energy thus acquired by the electrons can be so high that on collision with neutral molecules it may ionize them (elastic collision) or render them to a higher excited or vibrational state (inelastic collision).

- When an electron gains more energy than required for ionization of the gas molecules (Table shown earlier), then it is capable of ionizing, that is, ejecting an electron from the neutral molecule, and leaving behind a positive ion.

- The new electron thus ejected along with the primary one repeat the process of ionization.

- Since a molecule is much heavier compared to an electron, it can be considered relatively stationary, making no contribution to the ionization process.

- On the contrary, the electrons move very fast under the influence of applied electric field and continue to release further electrons from the gas molecules.

Development of Electron Avalanche
“Swarm of Charged Particle”

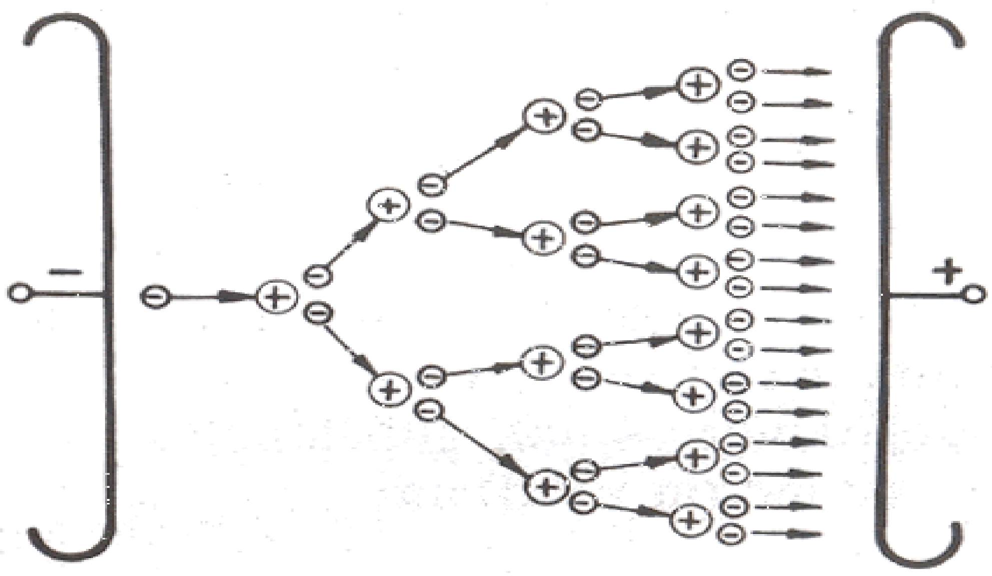

Fig. 4 Development of an electron avalanche in a uniform field

Development of Electron Avalanche by Townsend's Equation

- If only the process of electron multiplication by ***electron collision*** is considered in uniform field between two plates, then neglecting other processes ***(recombination and diffusion)***, the number of electrons produced by collision at an element dx, at distance x from the cathode is,

$$dn_x = n_x\, \alpha\, dx \qquad \ldots(1)$$

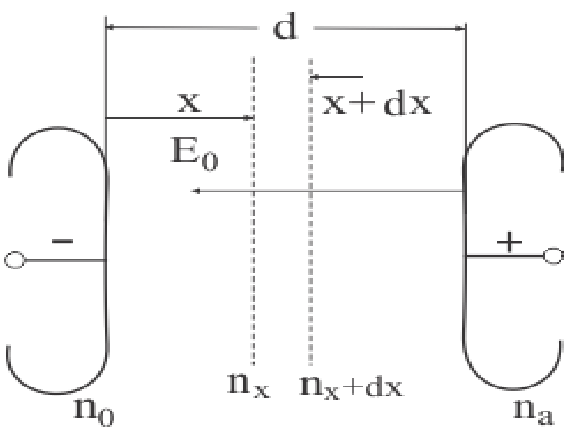

Fig. 5 Electrons in a uniform field

- x is the distance form the cathode,
- α is the average number of ionizing collisions produced by an electron in moving unit distance.
- n_0 the number of Pr. electrons set out from cathode
- n_x the number of electrons at distance x from the cathode.

Cont...

- In a uniform field where the field intensity *E* is constant, the ionization coefficient α can be considered constant. By integrating Equation (1) and applying the initial condition $n_x = n_0$ at x = 0, the following equation is derived for a uniform field,

$$n_x = n_0 e^{\alpha x}$$

- For a weakly nonuniform fields, where α is not constant, above equation can be written as

$$n_x = n_0 exp\left[\int_0^x \alpha dx\right]$$

- In case of very small gap distances, the number of electrons striking the anode per second (at x = d) are,

$$n_d = n_0 e^{\alpha d}$$

- The Townsend's first ionisation coefficient (α) is a function of electric field intensity (E), and at constant temperature it is dependent upon the gas pressure (p).

$$\frac{\alpha}{p} = f\left(\frac{E}{p}\right)$$

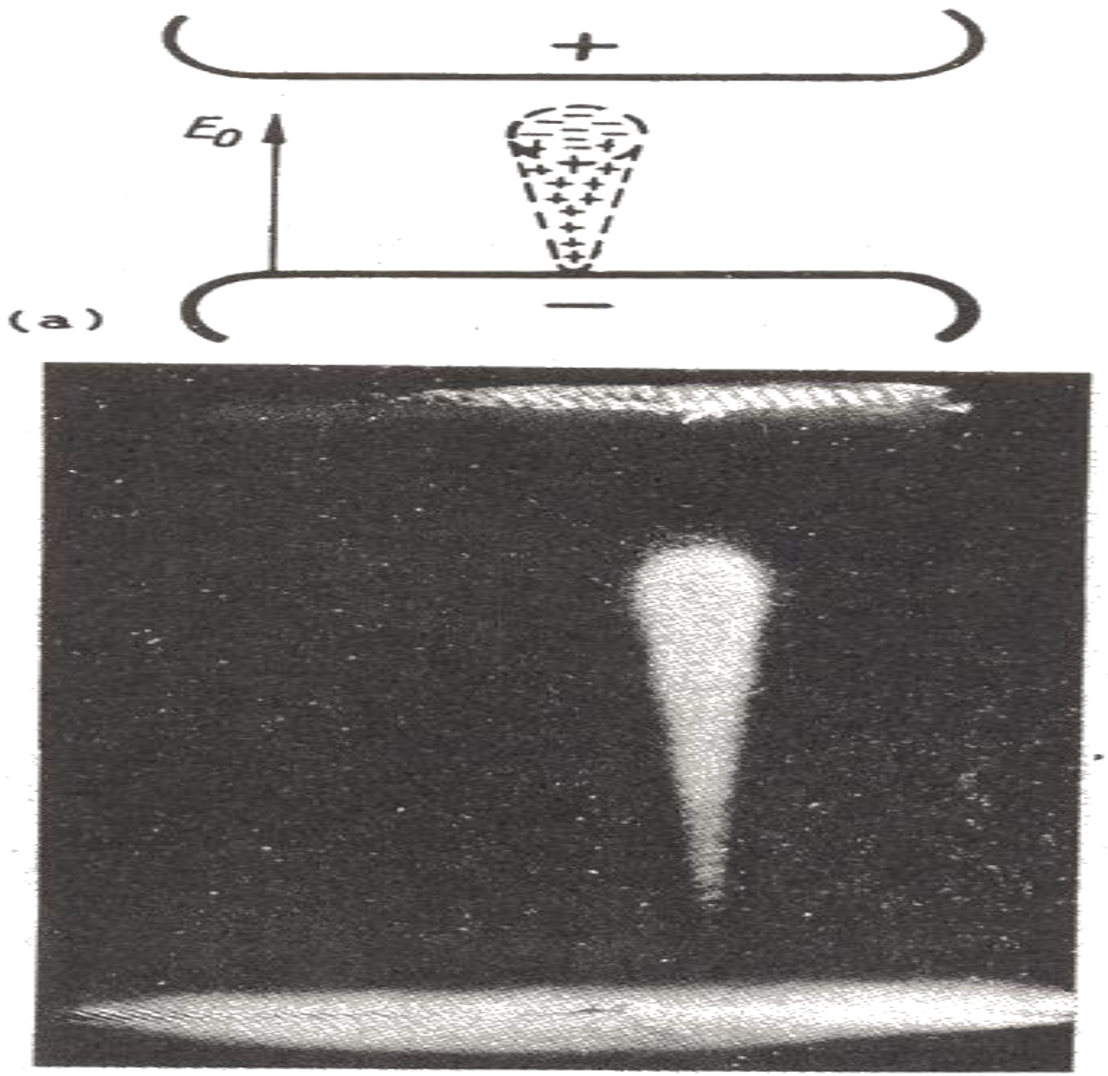

Fig. 6 An electron avalanche in a uniform field. (a) Distribution of charge carriers and the shape (b) Actual photograph by Raether

Breakdown Mechanism

1) Breakdown with Avalanche Discharge (Townsend Mechanism)
2) Breakdown with Streamer Discharge (Streamer or Kanal Mechanism)

Breakdown in Uniform Fields as Described by Townsend

•When the distance *d* between two electrodes in a uniform field is very small, α the Townsend's first ionization coefficient which is a function of field intensity *E*, may still have ***quite a low value*** even at the breakdown field intensity.

•Townsend has observed that *current increased more rapidly with increase in voltage* as compared to the one given by above equation.

•Production of sufficient number of charge carriers in the gap under such conditions is possible *only by secondary ionization process*,

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The three processes of cathode effect are described quantitatively by a coefficient " as follows,

$$\gamma = \gamma_{ion} + \gamma_p + \gamma_m$$

It is defined as the *mean number of secondary electrons released per +ve ion incident on the cathode*.

It strongly depends upon the *cathode material and is a function of field intensity and pressure* of the gas.

$$\gamma = f\left(\frac{E}{p}\right)$$

(Townsend secondary ionization coefficient) which he define as *the mean number of electrons release per positive ion incident on the cathode.*

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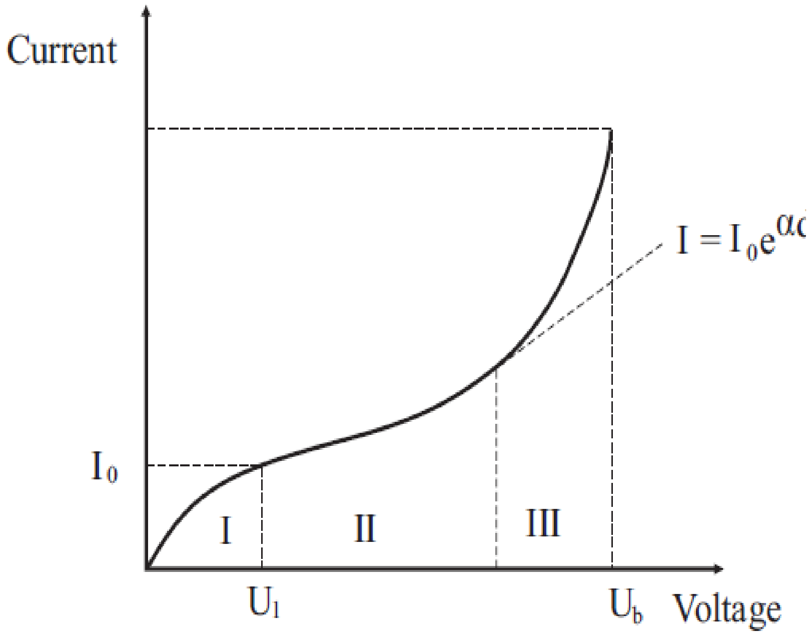

Fig. 7 General conduction current–voltage characteristics in gaseous dielectrics before breakdown

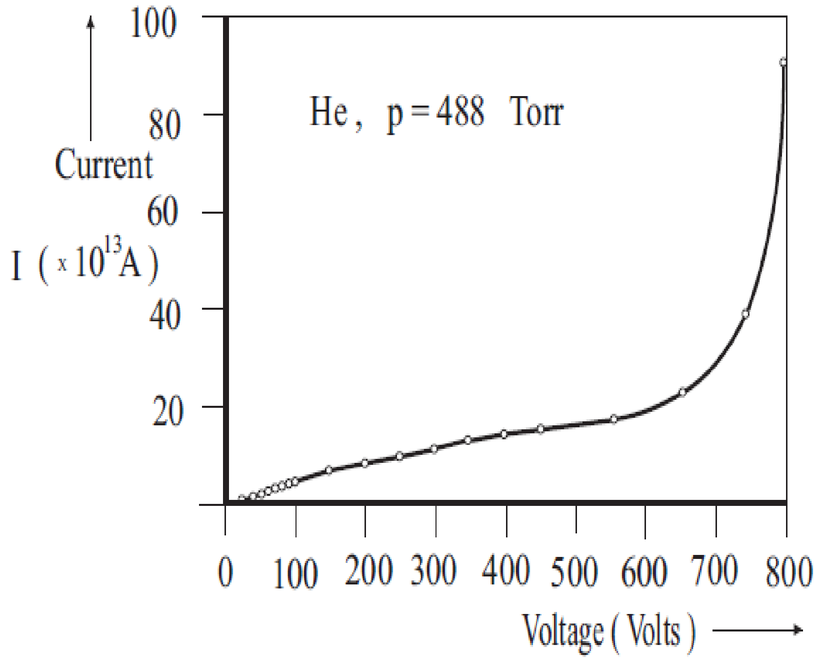

Fig. 8 Voltage-current (U-I) characteristics in Helium measured by Rees [4.8] in 1963.

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- The Townsend's current growth equation in this III region is derived as follows:

- Let, n_0 = the number of primary electrons (photo electrons) emitted from the cathode (at $x = 0$) per second.

- In other words, an avalanche in uniform field develops at the cathode with n_0 initial electrons.

n_0' = the number of secondary electrons produced at the cathode per second.

n_0'' = the total number of electrons leaving the cathode per second.

Thus $$n_0'' = n_0 + n_0'$$

Cont…

- Since each electron leaving the cathode makes on an average $(e^{\alpha d} - 1)$ collisions in the gap d, therefore, the total number of ionizing collisions per second in the gap will be $n_0''\ (e^{\alpha d} - 1)$.

- By definition, γ is the number of secondary electrons produced on an average at the cathode per ionizing collision in the gap, then,

$$n_o' = \gamma\, n_o'' \,(e^{\alpha d} - 1) \qquad \text{...(1)}$$

Substituting Equation (2) , we have

$$n_o'' = n_o + \gamma\, n_o'' \,(e^{\alpha d} - 1)$$

$$n_o'' = \frac{n_0}{1-\gamma(e^{\alpha d}-1)}$$

or

- The number of electrons arriving at the anode is given by,

$$n_d = n_o'' e^{\alpha d}$$

Cont…

By putting the value of n_0" in the above equation, we have

$$n_d = \frac{n_0 e^{\alpha d}}{1 - \gamma(e^{\alpha d} - 1)} \qquad (a)$$

•Under the steady state conditions, the current in the gap can therefore be given by,

$$I = \frac{I_0 e^{\alpha d}}{1 - \gamma(e^{\alpha d} - 1)} \qquad (b)$$

This equation describes the growth of average current in the gap before the breakdown.

Cont…

•According to Equation (b) , $\gamma\ (e^{\alpha d} - 1)$ in the denominator of Equation represents μ, **the mean number of secondary electrons produced per avalanche**.

•For $\mu \ll 1$, the secondary ionization, or γ - process is insignificant. Then equation reduces to $I \approx I_0\ e^{\alpha d}$, which represents the region II.

• The applied voltage and hence the field intensity is low in this region. This condition is also described as *'non-self-sustaining discharge'*, or ionization process, under which a breakdown would not be able to develop by itself.

•As the applied voltage, and thus the field intensity *E* is increased, the value of μ approaches 1. Then the denominator of this equation approaches zero and, therefore, the current I tends to rise unlimitedly.

•At this stage, the current is however limited by the impedance offered by the power supply and by the gas itself. Under these conditions, the discharge or ionization process becomes ***self-sustained*** to maintain the level of required charge carriers, described as a 'self-sustaining discharge'.

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The quantitative condition for breakdown can be expressed as,

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

This equation is known as the *'Townsend Criterion'* for spark breakdown in uniform field. At the final stage of breakdown, the electron amplification is normally much greater than one ($e^{\alpha d} >> 1$), so the criterion reduces to

$$\gamma e^{\alpha d} = 1$$

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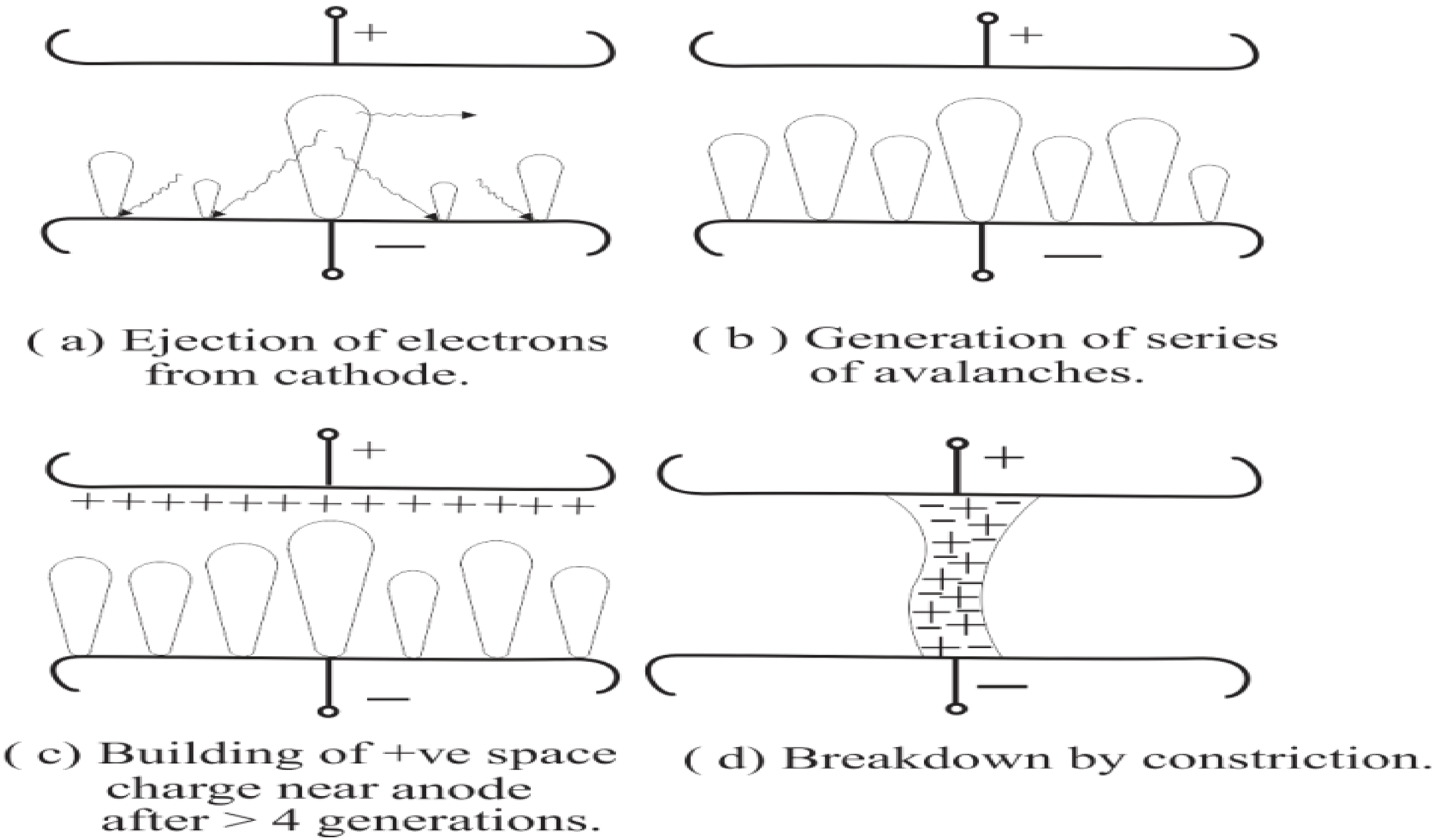

Fig. 9 Schematic showing Townsend breakdown mechanism

Development of Streamer Mechanism Leading to Breakdown

Transformation from avalanche to streamer processes began to develop from the head of an electron avalanche when the number of charge carriers increased near a critical value,

$$n_0 e^{\alpha x_c} \approx 10^8$$

For an avalanche initiated by a single electron (*n0 = 1) in a uniform field, this* corresponds to a value,

$$\alpha x_c = \alpha d_c = \ln 10^8$$
$$= 18.4$$

On the basis of experimental results and some simple assumptions, Raether developed the following empirical formula for the " streamer breakdown criterion"

$$\alpha x_c = 17.7 + \ln x_c + \ln \frac{E_a}{E_0}$$

$$\alpha x_c = 17.7 + \ln x_c$$ If (*Ea ≈E0).*

Cont…

•The interaction between the space charges and the polarities of the electrodes results in distortion of the uniform field.

•Field intensities towards the head and the tail of avalanche acquire a magnitude $(E_a + E_o)$, while above the positive ion region, just behind the head, the field is reduced to a value $(E_0 - E_a)$.

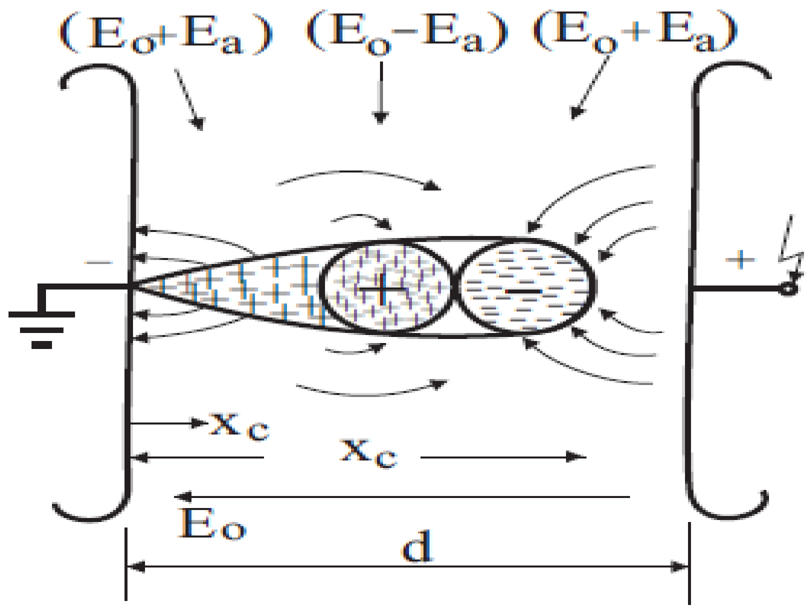

Fig. 10 Effect of eigenspace charge field E_a of an avalanche of critical amplification on the applied uniform field.

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The minimum value of αx_c *required for breakdown in a uniform field gap* by streamer mechanism is obtained on the assumption that the transition from avalanche to streamer occurs when an avalanche of critical size just extends across the gap d_c.

By incorporating this condition, the criterion for streamer breakdown takes the form:

$$\alpha d_c = 17.7 + \ln x_c$$
$$= 10^8$$
$$= 18.4$$

For $\alpha x_c = \ln 10^8$, x_c *works out to be equal to* 2.01 cm. Hence, a gap distance of 2 cm between the uniform field electrodes can be considered to be minimum or critical gap distance *dc for streamer phenomenon to* take place in atmospheric air.

The 'streamer breakdown criterion' can be therefore interpreted as a condition for the development of *significant field distortion* caused by stark space charge within a *single avalanche* so that its field intensity is *comparable* to the externally applied field.

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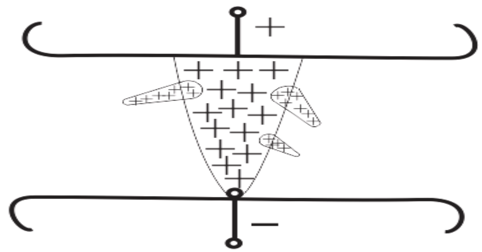
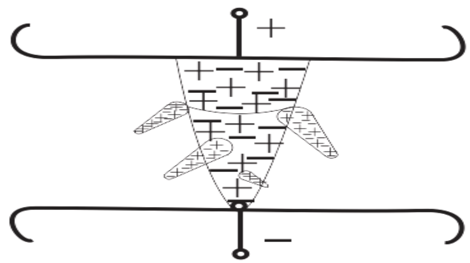
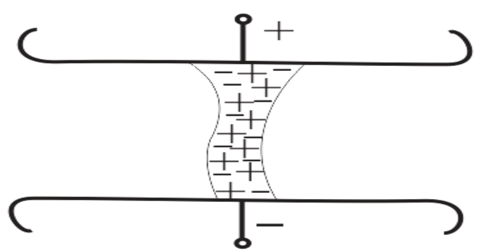


(a) Primary avalanche electrons swept into anode



(b) Secondary avalanche feed into primary.



(c) Self propagating streamer breakdown.

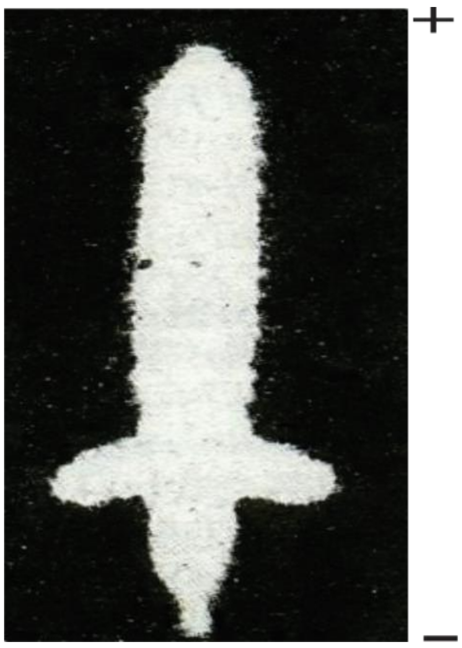


Fig. 11 shows the photograph of an avalanche where secondary avalanches are feeding into the primary avalanche, taken in a gap of 3.6 cm in air at 270 Torr and a field intensity of about 12,200 V/cm by Raether

Fig. 10 Schematic of a cathode directed streamer breakdown showing development stages.

Breakdown Voltage Characteristics in Uniform Fields (Paschen's Law)

In uniform fields, Townsend ' s criterion for breakdown in electropositive gases in given by equation

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

$$\alpha d = \ln\left(\frac{1}{\gamma} + 1\right)$$

where the coefficients α and λ are functions of E/p and are given as follows

$$\alpha = p f_1\left(\frac{E_o}{p}\right)$$

$$\gamma = f_2\left(\frac{E_o}{p}\right)$$

$$E_b = \frac{U_b}{d}$$

$$f_2\left(\frac{U_b}{pd}\right)\left\{\exp\left[pdf_1\left(\frac{U_b}{pd}\right)\right]-1\right\}=1$$

Cont..

•Paschen found experimentally that breakdown voltage depends upon the product of gas pressure and inter electrode spacing for uniform fields i.e.

$$U_b = f(pd)$$

•This is known as Paschen's law.

•The scientist, Paschen, established it experimentally in 1889 from the measurement of breakdown voltage in air, carbon dioxide and hydrogen.

•It can be shown that this law is also applicable to electronegative gases. The values of α depend upon the particular gas and of upon the electrode material.

•The breakdown voltage of a gas in uniform field is, therefore, a unique function of the product of gas pressure, *'p'* and the gap distance between electrodes '*d'* for a given electrode material and its condition.

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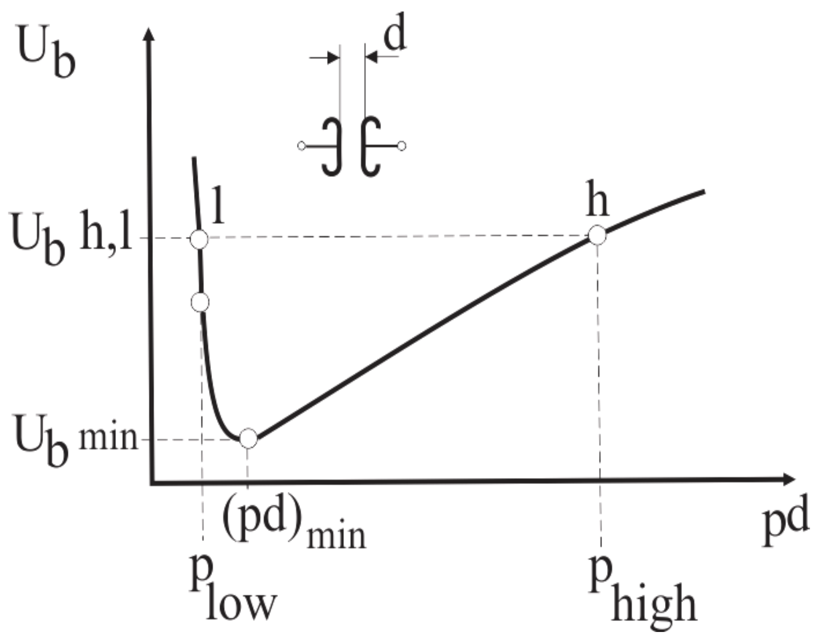

Fig. 12 Breakdown Voltage vs *pd* characteristics in uniform field (Paschen's curve)

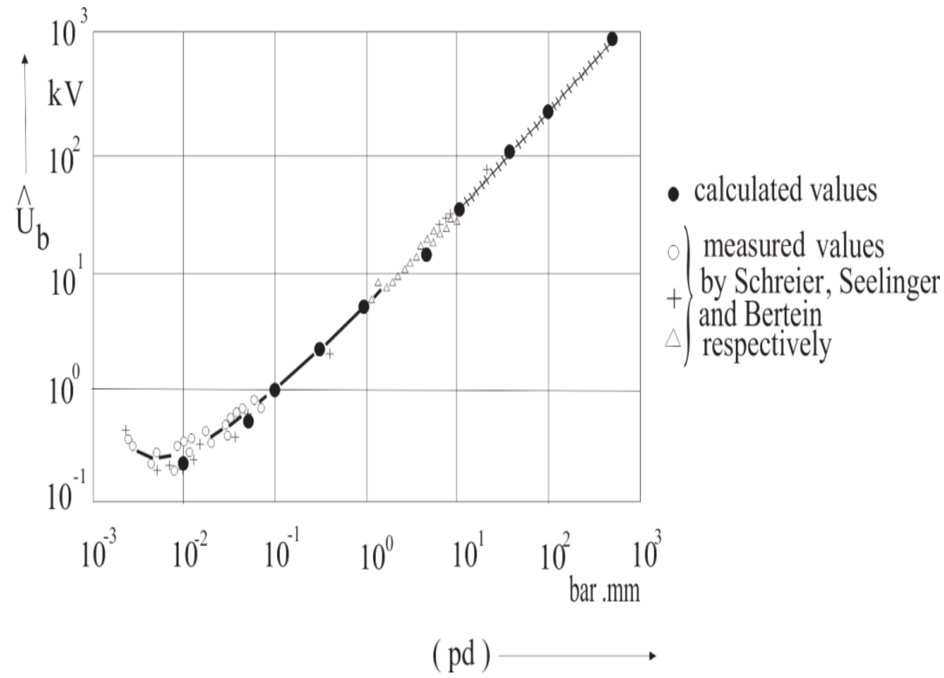

Fig. 13 Paschen's curve for air at temperature 20° C

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With the help of many scientists, Schumann, Sohst and Schröeder, the following equation for breakdown voltage of air in uniform field was derived.

$$\hat{U}_b = 6.72\sqrt{d} + 24.36\,d$$

or

$$\hat{E}_b = 24.36 + \frac{6.72}{\sqrt{d}} \qquad kV/cm$$

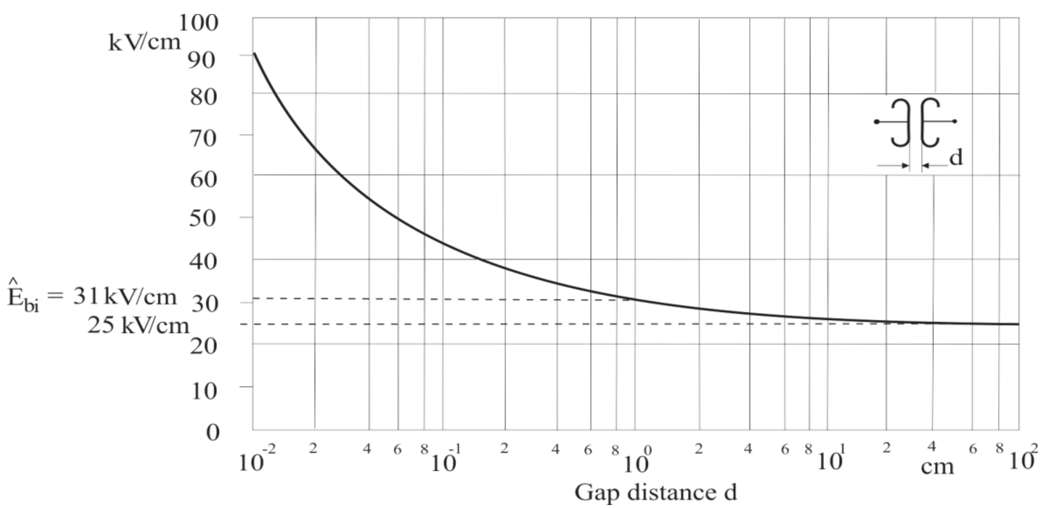

Fig. 14 Breakdown voltage characteristics of atmospheric air in uniform fields

- It is interesting to note that even in uniform field at constant pressure and temperature, the electric strength of air is not constant .
- It tends to 24 kV /cm for very long gaps.
- The value 31 kV/cm is applicable only for d = 1, that is for one cm gap at 760 Torr and 20°C.
- For gaps of a few mm, the electric strength is much higher than 31 kV/cm. It has been measured to rise to about 92 kV/cm for a gap of 0.1 mm.
- The electric field strength measured across 1 cm gap in uniform field at normal temperature and pressure is known as intrinsic strength of air E_{bi}.

Breakdown Voltage Gaseous Dielectric in Weakly Nonuniform Fields and the Limiting Value of Schwaiger Factor ‘η’

➢The breakdown mechanism in weakly nonuniform fields is similar to uniform fields. Like in uniform fields the PB inception, U_i , and the breakdown voltages in weakly nonuniform fields are equal, the breakdown voltage can be estimated from the following relationship given by Schwaiger:

$$U_i = U_b \approx E_{bmax} . d . \eta$$

- Knowing the dimensions, the factor η can be found out.
- It can be seen that as the gap distance d between the spheres is increased, the Schwaiger factor decreases, i.e. the field becomes more nonuniform.
- If the ***measured values of U_b-d characteristic are known***, E_{bmax}- d characteristic can be plotted. From these curves it is evident that E_{bmax} does not change much within a certain range of gap distance d, as also shown by the straight-line part of the U_b- d curve.
- For this particular electrode configuration, it is limited upto a *gap distance nearly equal to the radius of the sphere.*

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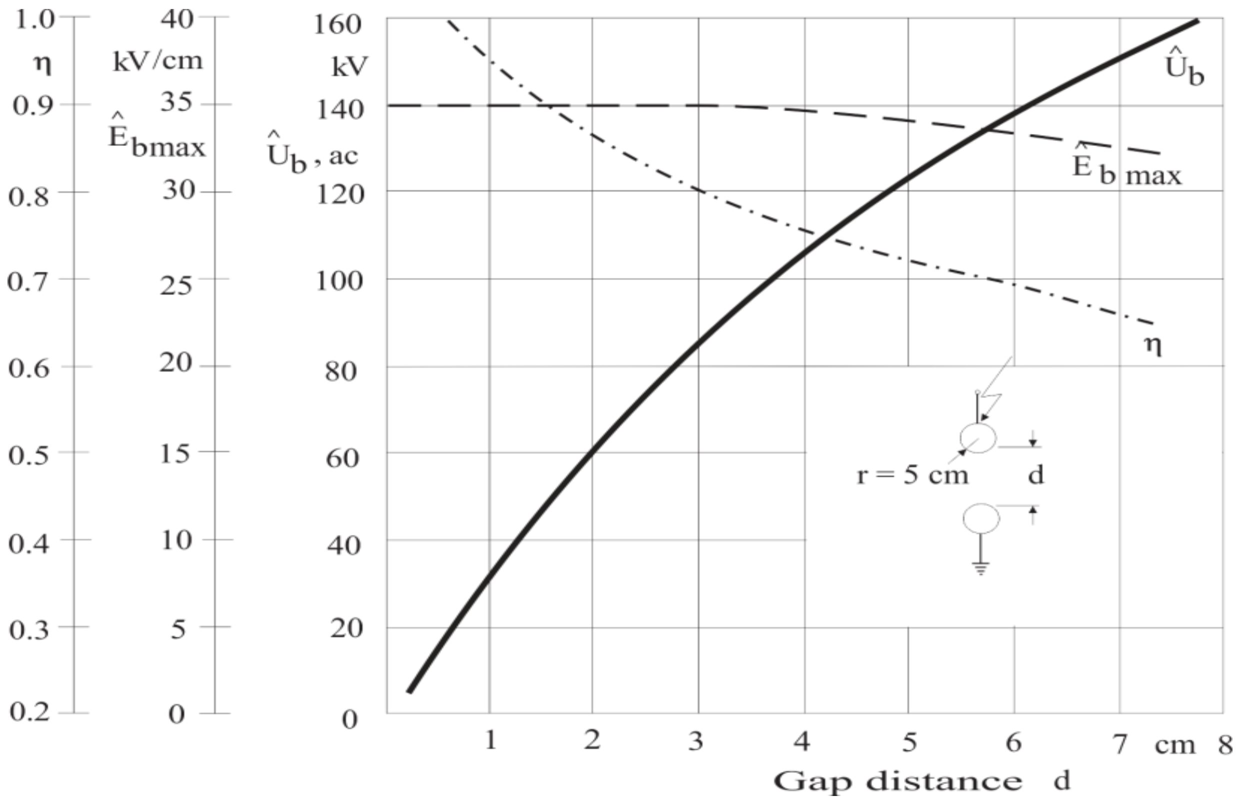

Fig. 15 ac Breakdown voltage in air, maximum breakdown field intensity at the electrode and factor of uniformity for different gap distances in weakly non-uniform field

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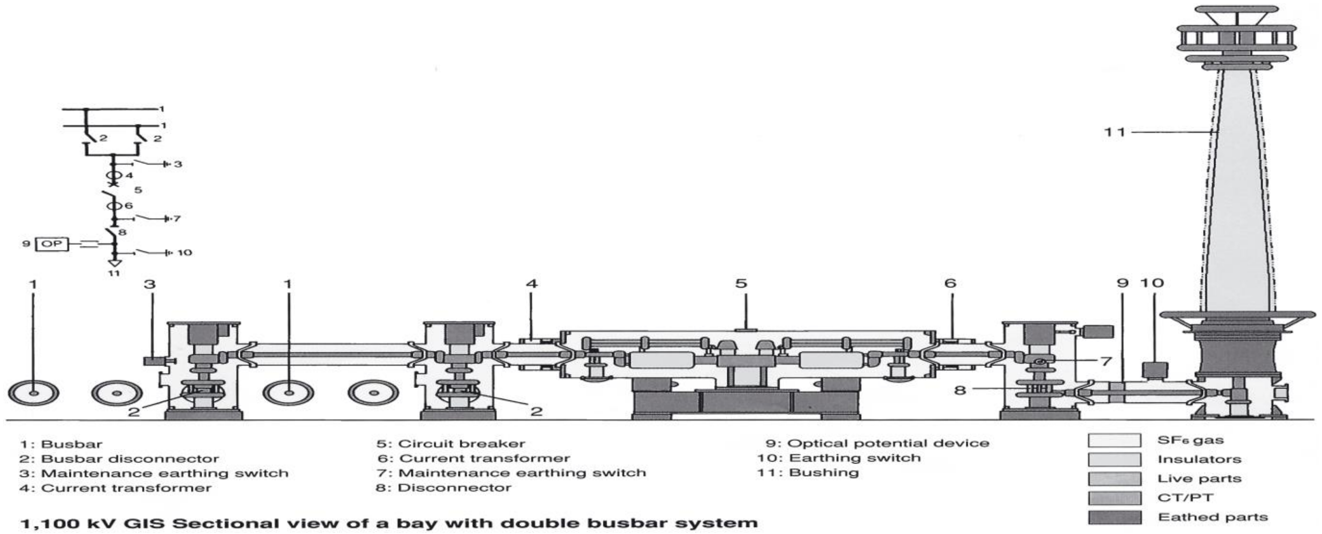
➢Breakdown Voltage Characteristics of SF6 Gas and its Mixtures in Weakly Nonuniform Fields

- The insulation systems with atmospheric air require very large dimensions and the electric field in these systems is mostly extremely non-uniform.
- The compressed SF_6 gas, found to be a suitable alternative to air and nitrogen, is widely used in power system apparatus since 1960s.
- The SF_6 gas made its breakthrough initially for high voltage circuit breakers, but very soon technologies for complete metal-clad substations with SF_6 gas were developed, known as 'gas insulated substations/systems', (GIS).

(a)



(b)

(c)

(d)

Fig. 16 (a) A 1100 kV, SF_6 gas insulated substation (GIS) (b) A sectional view of 1100 kV GIS bay with two bus-bar system, courtesy Toshiba, Japan (c) & (d) A 1200 kV SF_6 gas insulated circuit breaker, courtesy Siemens

Cont…

In order to bring down the cost and the required quantity of the costly insulating gas, the research led to the investigation of properties of mixtures of SF_6 gas with nitrogen N_2, carbondioxide Co_2, and helium, He.

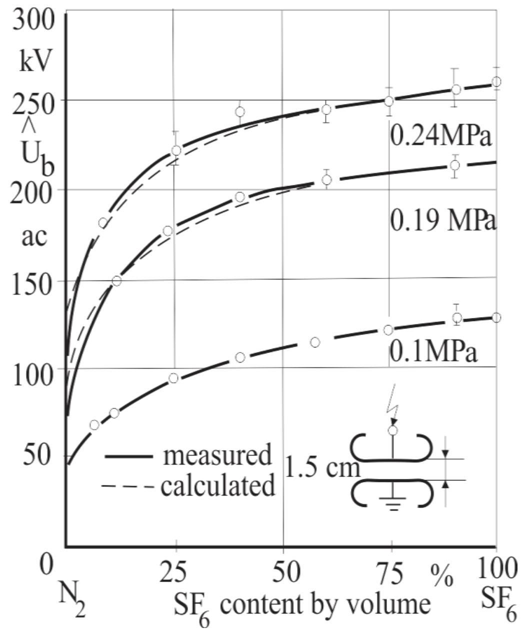


Fig. 16 Alternating voltage breakdown characteristics in uniform field for a mixture of SF_6 and N_2 at constant gas pressure

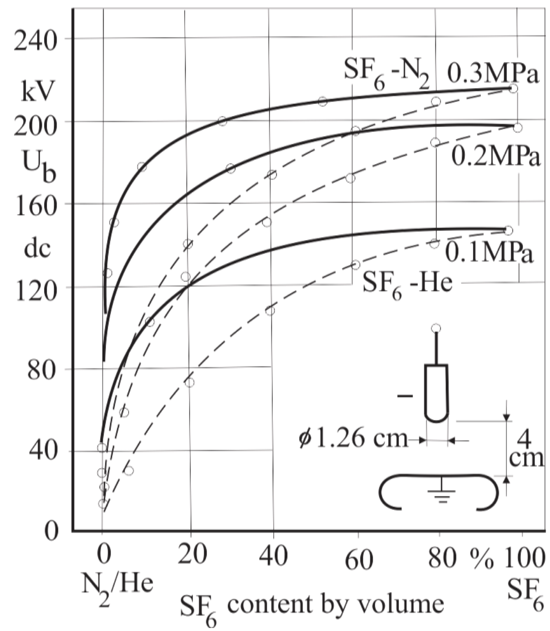


Fig. 17 Direct voltage breakdown characteristics for negative rod-plane electrode system with SF_6– N_2 and SF_6–He mixtures

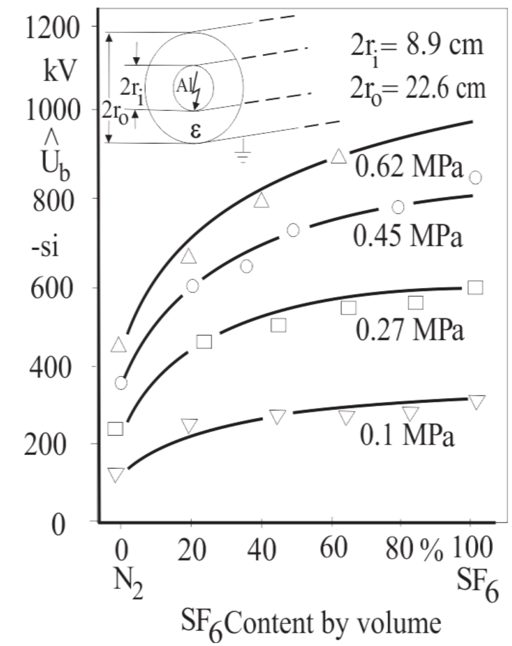


Fig. 18 Average negative switching impulse breakdown voltage characteristics for a coaxial cylinder electrode geometry with SF_6 – N_2 mixtures.

Cont…

Limiting value of η, the η_{lim}

- The value of η at which the transition from weakly non-uniform to extremely non-uniform field configuration takes place is termed as η_{lim}.
- The exact value of η_{lim} in gaseous dielectrics depends not only upon the field non-uniformity, but also upon the gas pressure and the type and polarity of the voltage since it is related with the inception of PB.

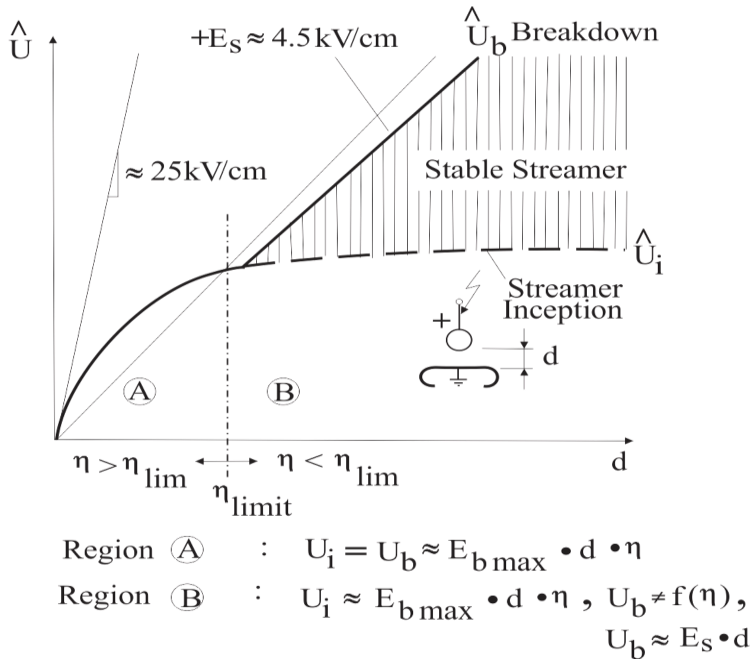


Fig. 19 Threshold curves showing breakdown with stable streamer for positive sphere–plane electrode configuration

Cont…

A breakdown when η is greater or equal to η_{lim} , that is, the region-A. The breakdown voltage for the region-A can be estimated by using either Eq.(1) or (2);

$$U_b = E_{bmax}.d.\eta_{lim} \qquad \text{….(1)}$$

The breakdown voltage for the region B is given by the equation;

$$U_b = E_s .d \qquad \text{….(2)}$$

The value of η_{lim} for atmospheric air can be determined as follows:

$$E_{bmax}.d.\eta_{lim} = E_s .d$$

$$\eta_{lim} = \frac{E_s}{E_{bmax}}$$

$$= \frac{4.5}{25} \approx 0.2$$

An ac power frequency voltage between two identical spheres of 9.92 mm diameter for increasing gap distance, *'d'* up to 70 mm shown in Fig. 20.

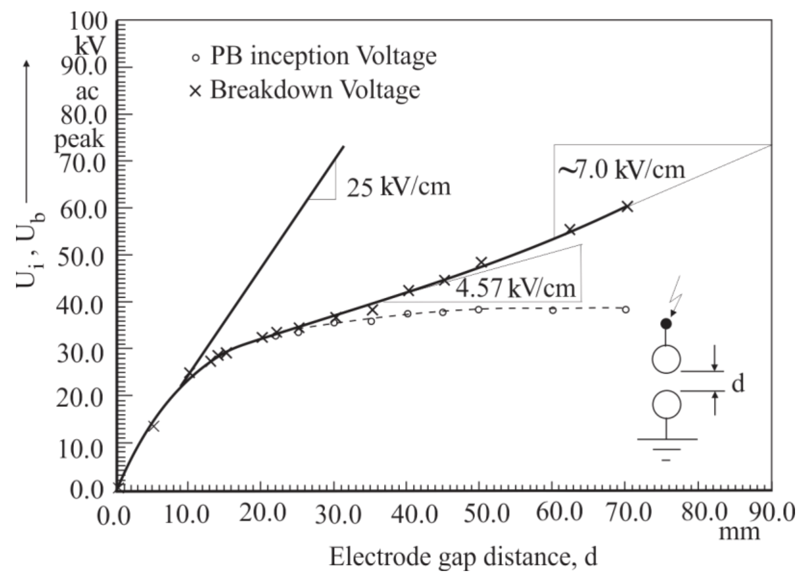


Fig. 20 PB inception U_i and breakdown voltage U_b characteristic for 9.92 mm diameter sphere–sphere electrodes, Arora et al.

Cont…

➢Pressure Dependency of Field Uniformly Factor Limit, η_{lim}

- Experimental investigations have revealed that in compressed gas insulated extremely non-uniform field electrode arrangements, the inception of PB not only depends upon the electrode geometry and the gap distance, but it is also strongly affected by the gas pressure.
- In the region ($\eta > \eta_{lim}$), no stable PB occurs since the field is weakly non-uniform. Whereas in the region ($\eta < \eta_{lim}$), being an extremely non-uniform field stable PB is observed before the breakdown.

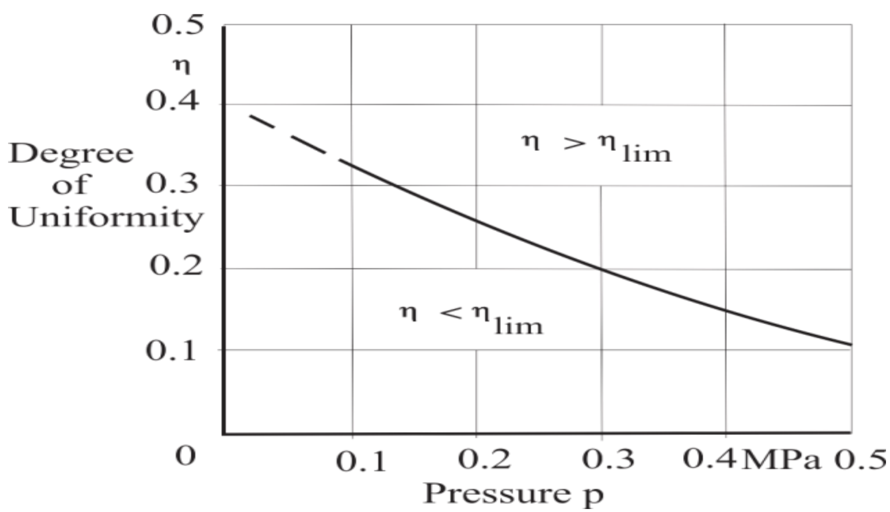


Fig. 21 Pressure dependent variation in limiting degree of uniformity ‘ ’for electrode configurations in SF_6

Breakdown in Extremely Nonuniform Fields and Corona

- In extremely nonuniform fields at voltages much below the breakdown, a ***stable partial breakdown*** in the gas, ***confined locally to the region*** of extreme field intensity, can be maintained.

- This phenomenon is known as '***Partial Breakdown***' (PB)

What Is Corona?

- Corona is a luminous discharge due to *ionization of the air surrounding an electrode*, caused by a voltage gradient exceeding a certain critical value.

- These discharges generate light, audible noise, radio noise, and energy loss among other things.

Types of Coronas

- ✓ **Star**
- ✓ **Streamer**
- ✓ **Leader**

Development of Star Corona
(Positive or Anode Star Corona)

- The process through which an avalanche is formed at a positive point electrode is analogous to the one in uniform field.
- However, the applied field intensity E in this case of electrode system falls sharply close to the point electrode. Beyond a short-distance Δx, the field intensity falls below the minimum filed required for partial breakdown, E_i .
- Thus the strong space charge formation process is able to extend itself to a maximum length of Δx in the gap, which is shorter than the ***critical amplification*** of length required by the avalanche.

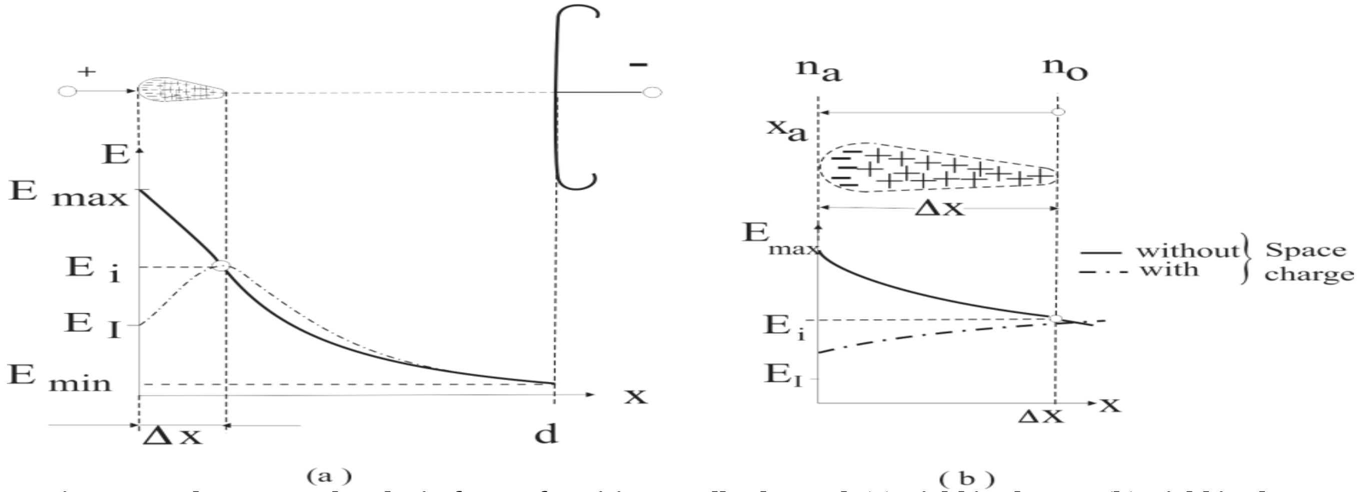


Fig. 15 An electron avalanche in front of positive-needle electrode(a) Field in the gap,(b) Field in the region of ionization

Cont…

- A positive space charge due to the heavy and slow ions remains at the back.
- It has a very slow movement, especially because of rapidly decreasing applied field at the tip of the anode. This results in weakening of the resultant electric field in the region in front of the tip due to like polarity space charge at the positive electrode, as shown by the dotted lines in Fig. 15.
- Inception of further partial breakdown is possible only when there is a drift of space charge away from the anode due to radial diffusion which re-establishes the applied electric field.
- This type of a *discontinuous process gives rise to an impulse form of discharge current* at voltages just above the inception of PB, inspite of applying a dc voltage.

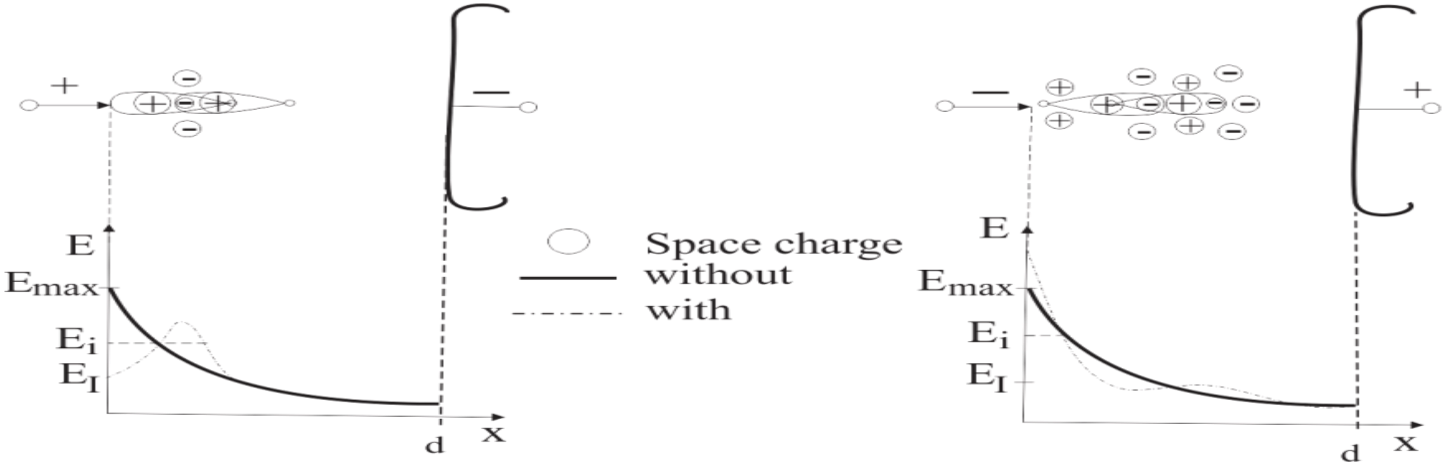


Fig. 16 Field intensity distribution between needle-plane electrodes with stable star corona

Negative Needle-Plane Electrode Configuration (Negative or Cathode Glow Corona)

- When a negative dc voltage, just sufficient for the inception of PB, is applied to a point (the cathode), the condition is similar to the one discussed in the previous slide.
- In this case also, the possibility of PB is limited to a short distance Δx because of a steep potential gradient fall from the point towards the plane. The ionization process adjacent to the point is able to extend the avalanche to a maximum length of Δx only.
- However, in this case the avalanche develops in the opposite direction, that is, the avalanche head is towards the plane (anode), as shown in Fig. (b).
- The avalanche does not acquire its critical length of amplification. Hence the PB process limits itself within a short region and it is not able to expand farther. Due to the high field, the electrons first drift very fast nearer to the point electrode but then slow down because of the steep fall in field intensity.
- *Since oxygen in the air is an electronegative gas, the slow electrons infront of the avalanche are absorbed by oxygen molecules forming negative ions*. Again, because of these heavy and slow ions, a negative space charge is developed leading to weakening of the field at a short distance away from the negative point electrode, preventing the avalanche hence the PB process from developing further. In the mean time, the positive space charge left behind , shifts towards the negative point electrode, increasing the field intensity there considerably, as shown in Fig. (17).
- After a certain time, even the negative space charge shifts away from the vicinity of point, diminishing the field weakening effect. New avalanche and PB processes are then possible. ***Under the influence of the +ve and -ve space charges, a less nonuniform field is resulted away from the gap, leading to a higher breakdown voltage.***

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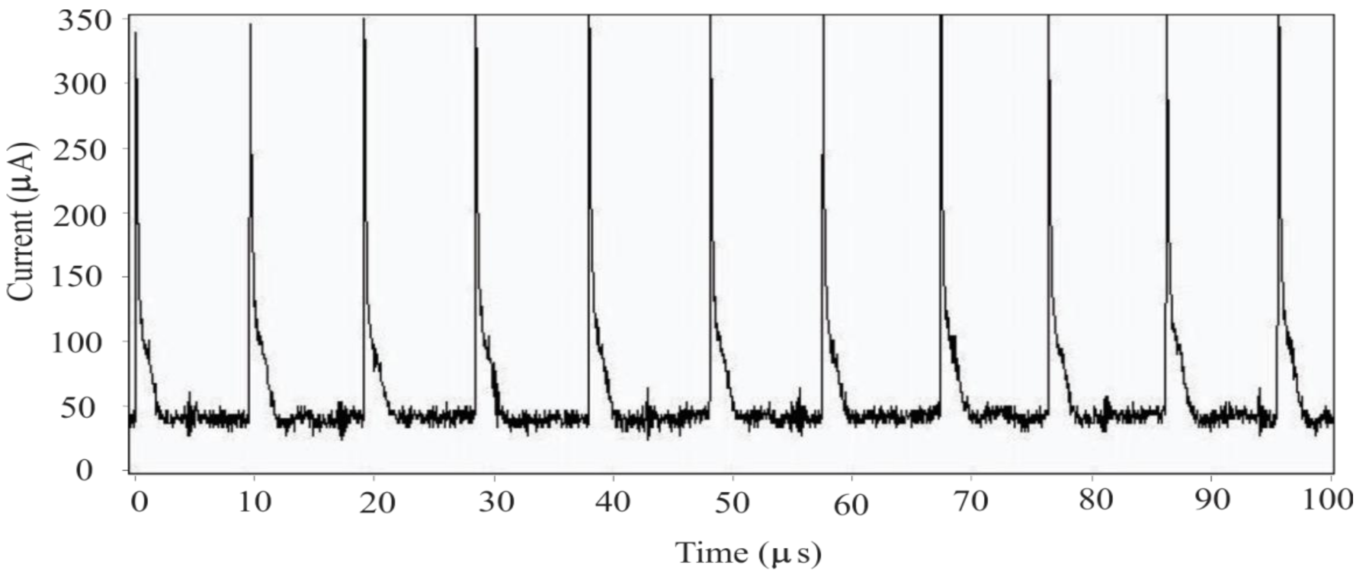

Fig. 17 Field intensity distribution between needle-plane electrodes with stable star corona

Development of Streamer Corona

- **Positive Rod-Plane Electrode (Positive Streamer Corona)**

- Consider a situation after the inception of an avalanche discharge in the region next to a positive rod electrode.
- when the avalanche has grown to its critical amplification level, the following equation must hold good:

$$\int_0^{x_c} \alpha dx = ln\frac{n_{xc}}{n_0} = 18.4 \approx 20$$

where x_c is the length of an avalanche when it acquires its critical amplification.

- Electrons at the head of the avalanche are absorbed immediately by the positive rod electrode (anode).
- The positive space charge left behind can lead to a weakening of the field next to the anode to such an extent that further discharges may not be possible in this region.
- Since the avalanche has acquired its critical amplification stage, there is a strong concentration of positive space charge till up to the tail end of the avalanche,

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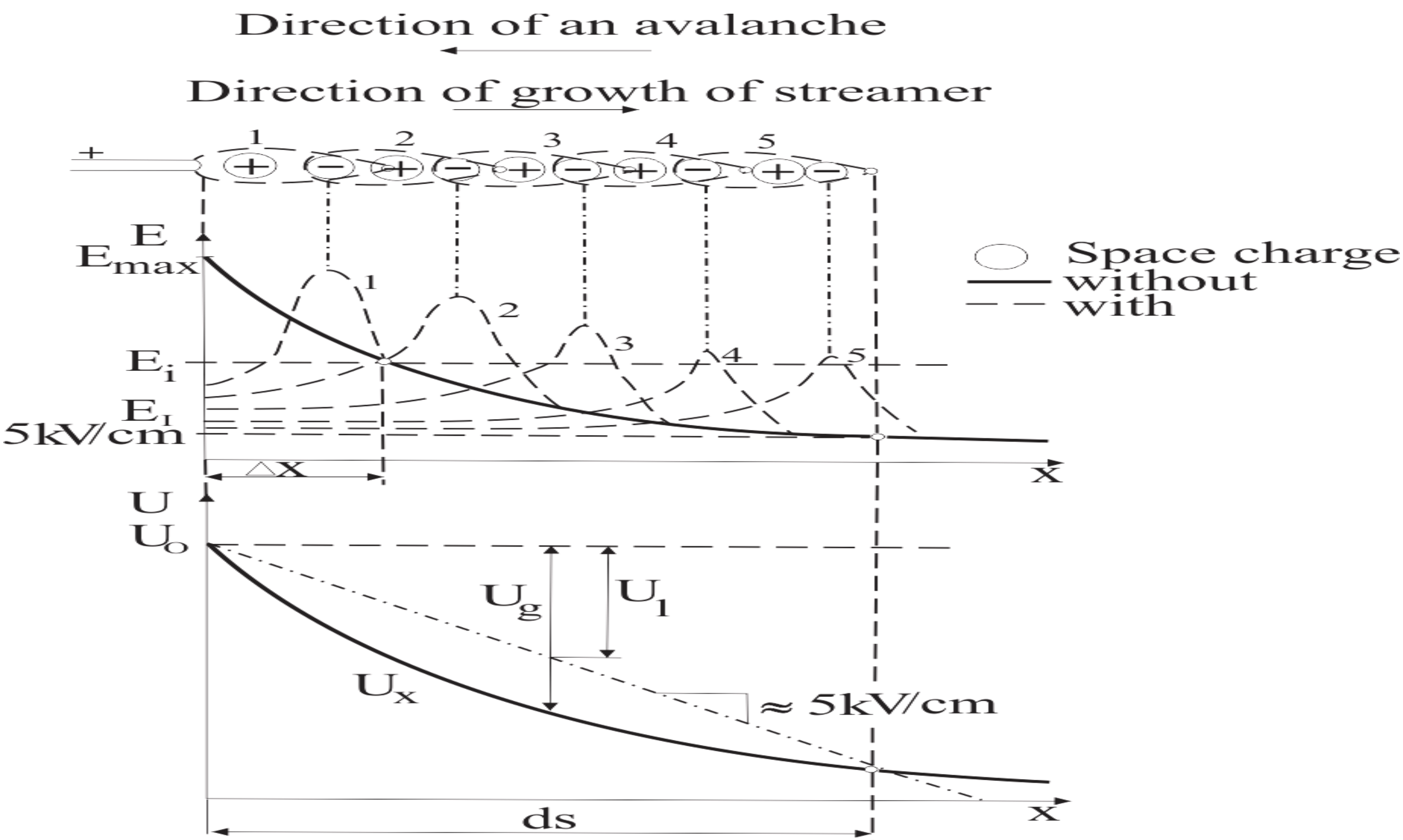

Fig. 18 Schematic of streamer discharge in front of a positive rod electrode with variation in field and potential as a consequence of space charge development

Cont..

This photograph was taken by Lemke on applying a long duration 1/5000 µs, 100 kV positive peak *impulse* voltage on a needle-plane electrode system having a gap distance of 20 cm. Similar photographs have also been taken by other authors and even on dielectrics other than gaseous, for example, in solids and liquid. A number of PB branches grow exponentially with increasing gap length.

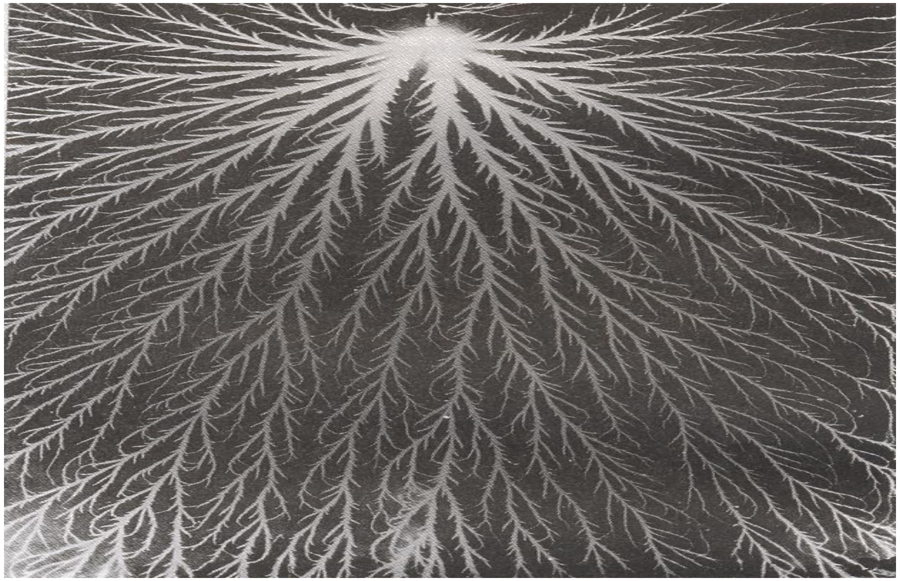

Fig. 20 Photograph of a positive streamer discharge by Lemke

Negative Rod - Plane Electrode (Negative Streamer Corona)

- As with positive rod - plane electrodes, the development of a streamer discharge in negative rods also begin with an avalanche of above critical amplification.

- The negative streamer mechanism is in principle comparable to the positive streamer except for the location of the formation of space charge.

- The direction of the avalanches in this case is, however, opposite; that is, their heads are away from the rod. A strong positive space charge is therefore built in front of the rod in the dielectric, increasing the field intensity right at the tip of the electrode.

- *The electrons form a negative space charge of their own and that of negative oxygen ions at the head of the avalanche slightly away from the tip of the electrode. The two like polarity charges weaken the field in the vicinity.*

- Higher basic field is required to be applied in this situation to enable the impact and the photo - ionizations as well as PB to continue farther in the gap.

Cont..

- When the PB process develops farther, a sort of " scattering " of negative space charge takes place by radial diffusion because of the high mobility of electrons.

- Consequently, weakening of the negative space charge takes place. The field intensity, which is affected by the concentration of the space charge, again increases to some extent.

- Because of this space charge effect on the field, the anode directed streamer corona is not able to grow in the gap to the extent compared to cathode directed corona at the same potential.
-
- The radial diffusion of electrons is also responsible for a comparatively lesser number of distinct trajectories of streamer corona able to develop at the rod.

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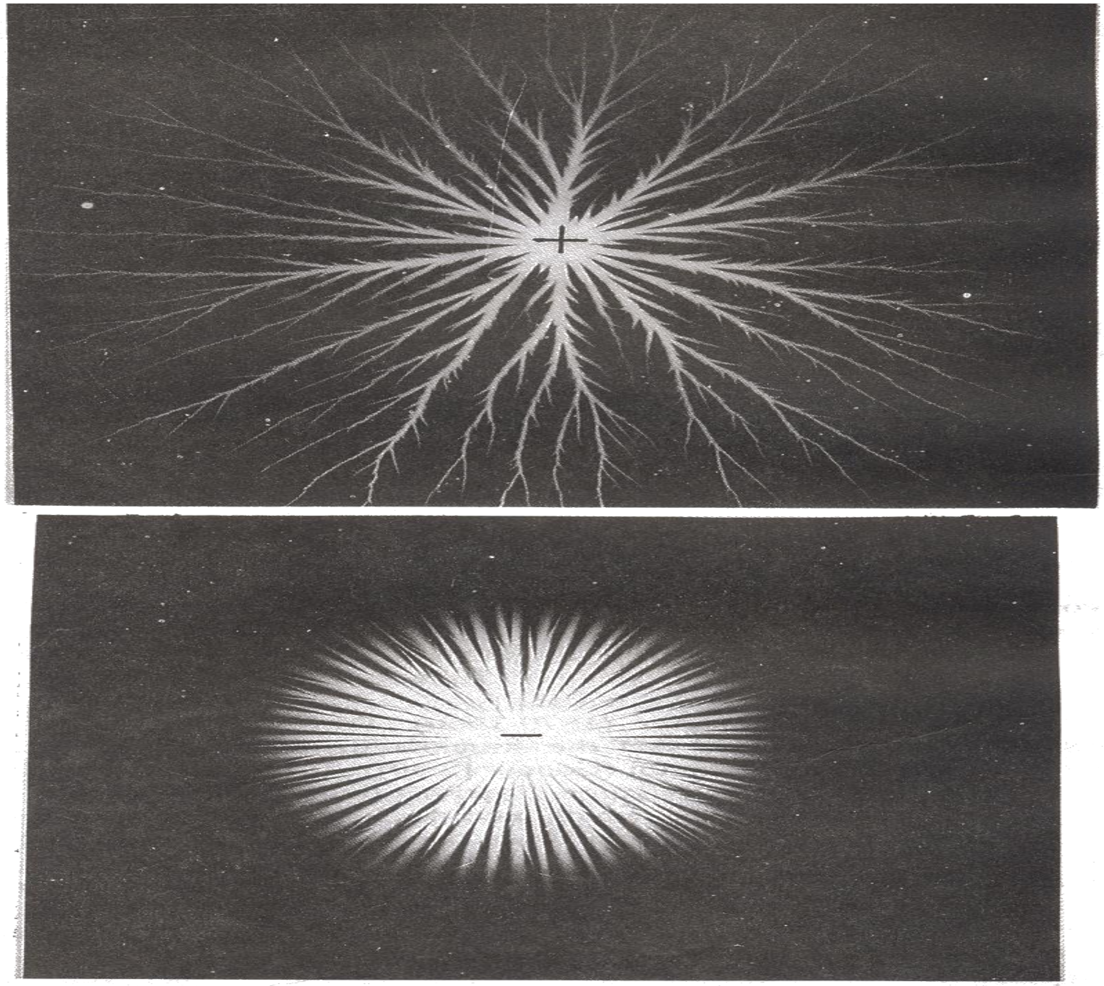

Fig. 21 Photographs of positive and negative streamer discharge, 'Lichtenberg Figures' taken by Toepler, TU Dresden

Development of Leader Corona

- If the gap distance between the rod and plane electrodes is increased above one meter and sufficient potential applied to the rod, ***after vigorous activity of streamer corona at the tip a 'constriction' of streamer trajectories takes place and a stem is formed***.

- On increasing the applied voltage further, the stem of this discharge grows in to a few bright, stepped trajectories in the gap towards the plane.

- This is described as 'Leader corona'. Much higher magnitude of the voltage is required to be applied on long gap distance as compared to star and streamer coronas.

- However, Leader corona can easily be produced as 'Surface Discharge' on a glass plate on applying quite low magnitude of voltage. Fig 22 shows (a) Leader corona as surface discharge on a glass plate and (b) Leader corona in free air.

- The mean axial potential gradient across stable leader corona channels is quite low due to high charge density or current. For stable positive leader it was estimated by Lemke to be about 1 kV/cm and for negative leader it is estimated to be 2-3 kV/cm.

- The audible noise produced by Leader corona is a loud cracking sound. The EMI produced by this corona extends to a band width upto 2 GHz. The leader corona can be seen to happen in nature. The cloud to cloud as well as cloud to ground lightning discharge phenomenon is accomplished with leader channels.

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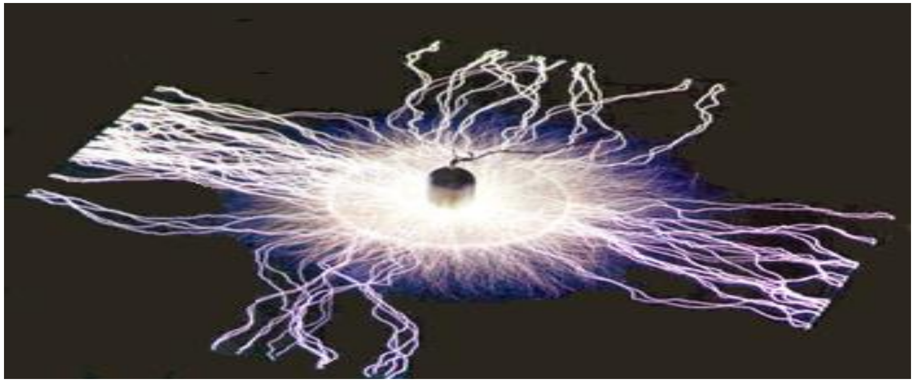

(a) Leader corona as surface discharges over a glass plate

(b) Leader corona in free air in very long gap distance, vertical & horizontal bolts

Fig. 22 Stable leader corona, (a) as surface discharge on a glass plate, and (b) in free air gaps, vertical and horizontal bolts, Courtesy DejanZakic taken at Novi Sad, Serbia and Ryan Phillips taken at Houston, United States.

Mechanism and Breakdown Characteristics of Atmospheric Air Extremely Nonuniform Fields

- In case of extremely non-uniform field configurations the breakdown strength strongly depends upon the development of the type of stable PB or corona, which precedes the complete breakdown.
- The stable corona in such fields continues to take place so long as applied voltage is above the PB inception but below the complete breakdown.
- Thus the breakdown strength/voltage measured is close to the respective potential gradient across the type of stable corona channel developed in the gap just before the complete breakdown, also known as 'spark breakdown' in gaseous dielectrics.
- The type of corona produced in the gap depends upon the shape of the electrodes and the gap distance between the two electrodes.

➢ ***Breakdown proceeded with Stable Star corona***

- Unlike uniform and weakly non-uniform fields, in case of extremely non-uniform fields, the process of avalanche formation at the tip of a sharp electrode is not able to grow deeper in the gap towards the opposite electrode.
- The partial breakdown process, in this case, restricts itself close to the tip of the sharp electrode.
- The avalanches are unable to acquire their critical amplification as these are able to extend to a very small gap length, of the order of a few mm to a few cm.

Cont..

- Such stable avalanche discharges are possible to be produced only with static dc or slow changing ac power frequency voltages.
- Under such conditions, the avalanches formed are not able to achieve their critical stage of amplification even before the breakdown. With the result, the mean breakdown voltage in the electrode gap acquires comparatively higher value, of the order of 10 to 20 kV/cm (peak) depending upon the polarity of the applied voltage.
- Breakdown voltage characteristics between a 30° needle and plane electrode configuration for increasing gap distance with positive as well as negative polarity dc voltages, shown in Fig. 24.

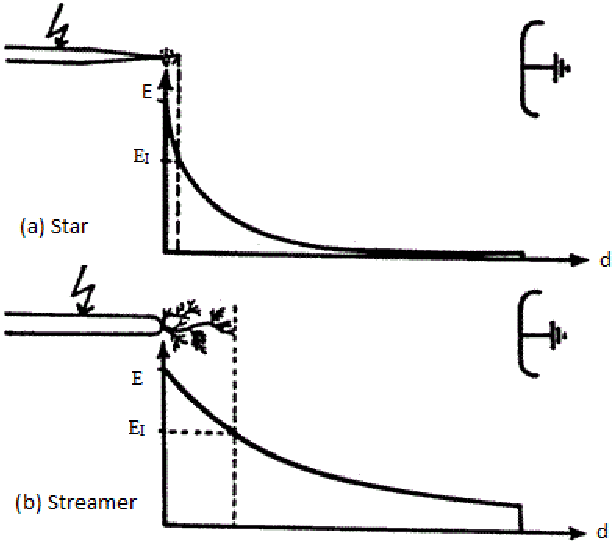

Fig. 23 Variation of field intensity at needle and rod-plane electrode configurations

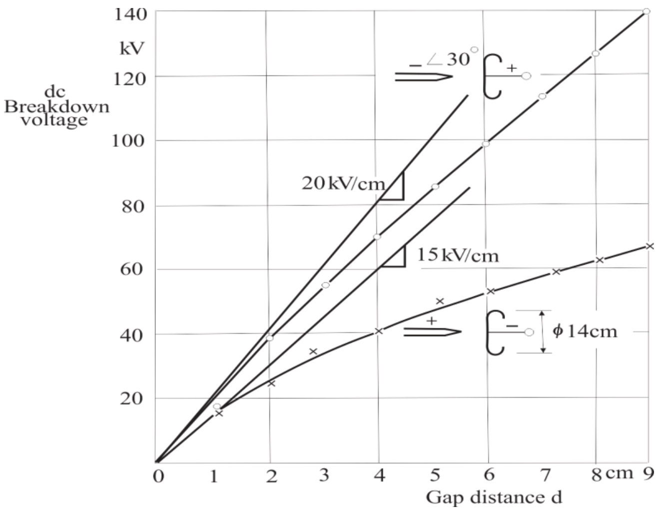

Fig. 24 dc breakdown voltage characteristics of a 30° needle and a plane of 14 cm diameter in air, with respect to increasing gap distance

Cont..

➢ *Breakdown proceeded with Stable Streamer Corona*

- In case of gap lengths not too long, say a few tens of cm but less than a metre, as soon as the streamer is able to extend itself upto the opposite electrode, the cathode, denser streamer discharge erupts from the anode because of 'cathode effect', also known as 'γ-effect' or secondary process
- Thermal ionization in front of the tip of the electrode is caused due to the ‘constriction’ of number of streamer channels. Subsequently, first a short bright 'stem' and then a 'stem-bunch' discharge outbreaks, turning into a thriving unstable leader.
- Breakdown is accomplished with a 'final jump' of the leader channel bridging the two electrodes.
- Ultimately an arc is produced, which conducts the short circuit current.
- A distinction between breakdown with stable and unstable streamers can be made in terms of the degree of uniformity of the field.
- Characteristics of breakdown with dc voltage for air gaps up to 2.5 m are shown in Fig. 26 with both, positive and negative polarities for sphere–sphere and rod–plane electrode configurations.

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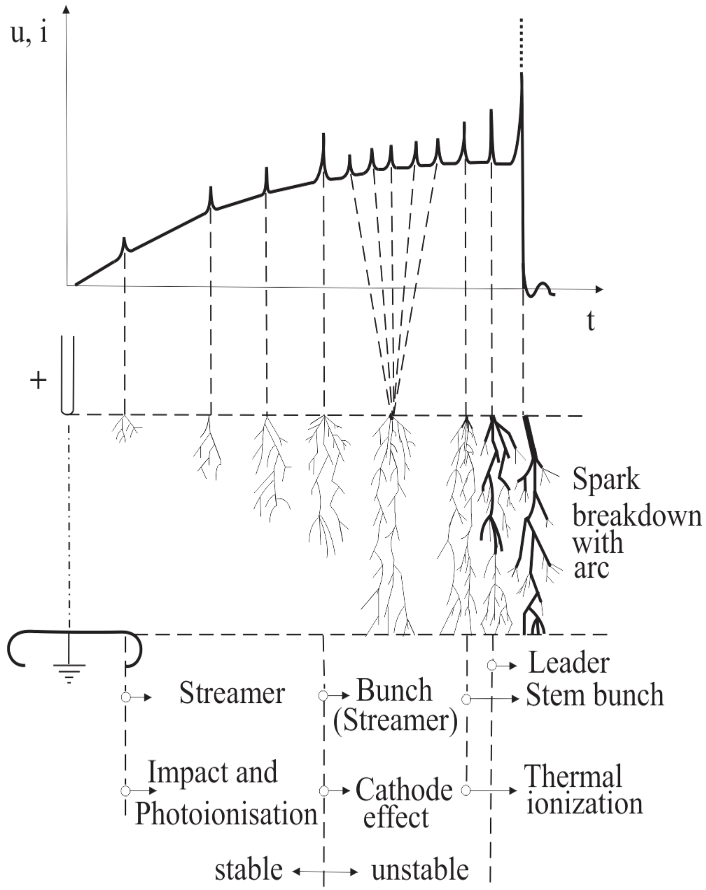

Fig. 25 Schematic of the development of breakdown mechanism with stable streamer corona

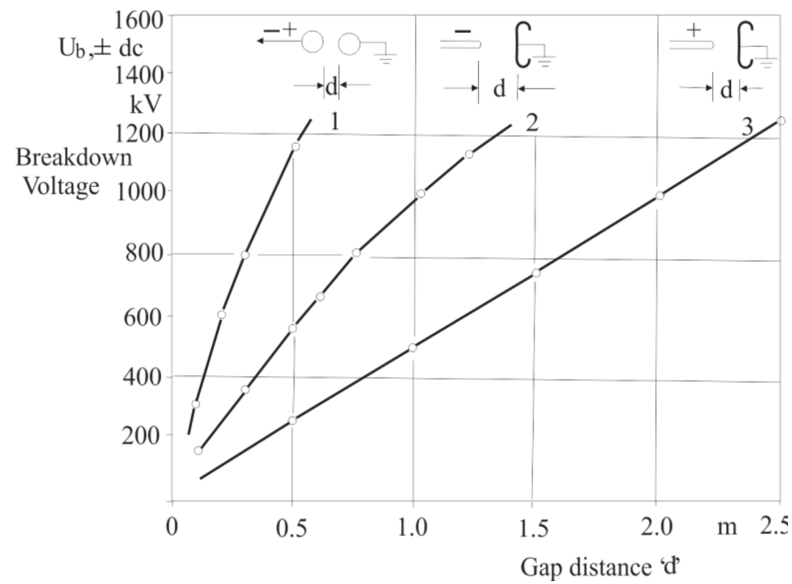

Fig. 26 Breakdown voltage characteristic with both polarity dc for 'sphere–sphere' and rod-plane medium length air gaps

Cont..

- ***Breakdown with Stable Streamer and Leader Coronas***
- Development of different breakdown characteristics strongly suggests that the magnitudes of the breakdown voltage depend upon the type of stable partial breakdown that occur in the gap before the final jump.
- The breakdown voltage characteristic for a rod-plane gap, shown in Fig. 27, with positive polarity 60/2500 μs shape of switching impulse voltages, represents stable partial breakdown (streamer corona) taking place up to a relatively small gap distance of 1 m.
- On increasing the gap distance, a lower average potential gradient was required for breakdown.
- An average potential gradient of 1 kV/cm was required for breakdown for the gap lengths above 4 m in this case.
- On applying dc or preferably a slow changing voltage, that is, ac or *si* of sufficiently large magnitude, at first a very strong and dense filamentary streamer corona appears at the high voltage electrode as shown in the schematic of breakdown in Fig. 28.

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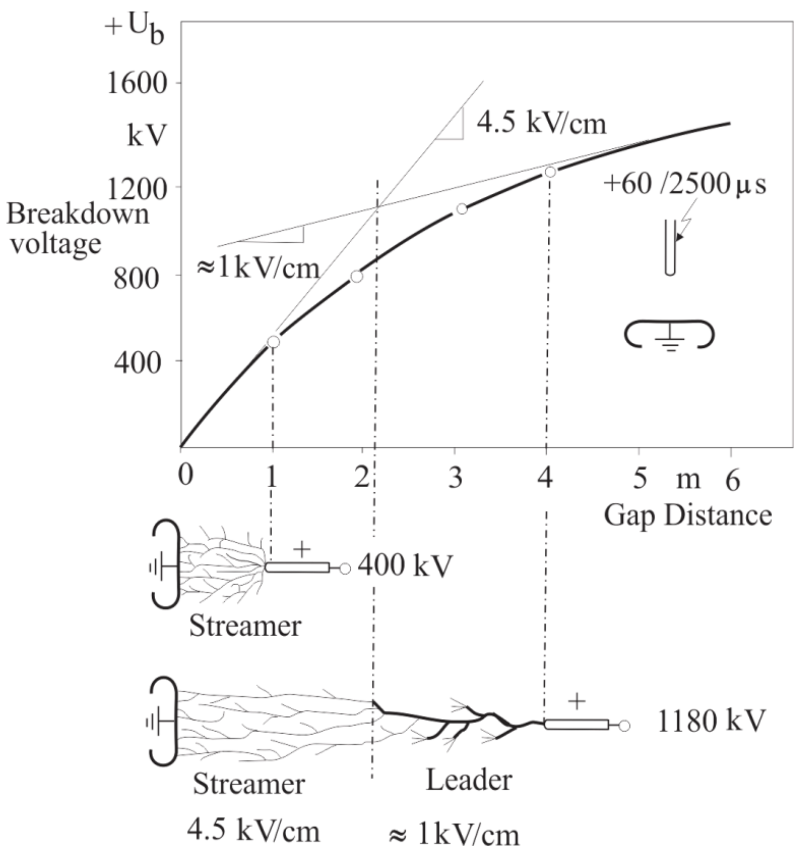

Fig. 27 Relationship between breakdown voltage characteristics and the mean potential gradient requirement for the propagation of stable streamer and leader coronas,

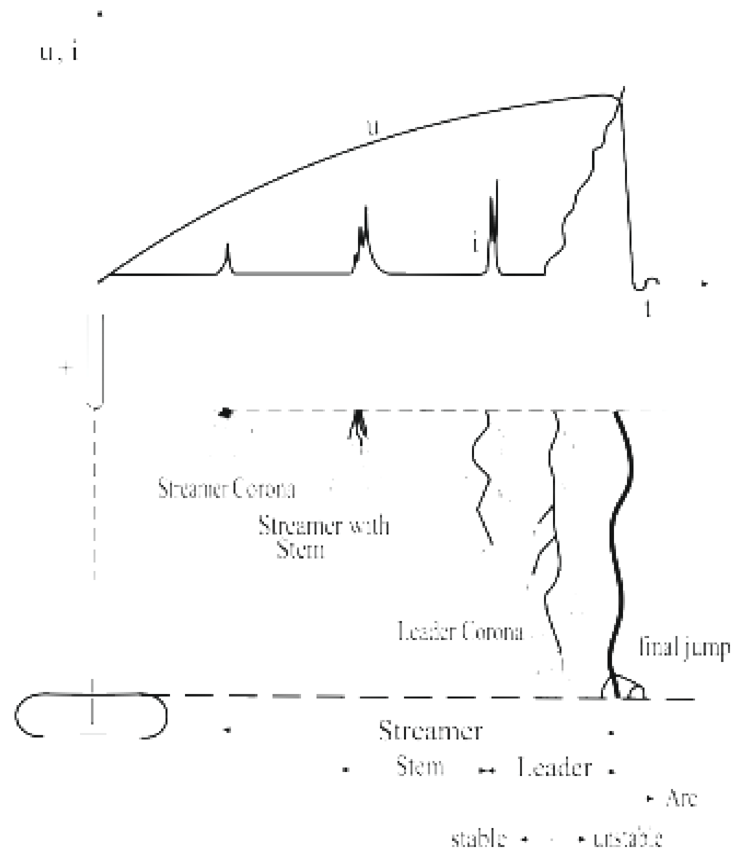

Fig. 28 Schematic of breakdown mechanism with stable leader and streamer coronas

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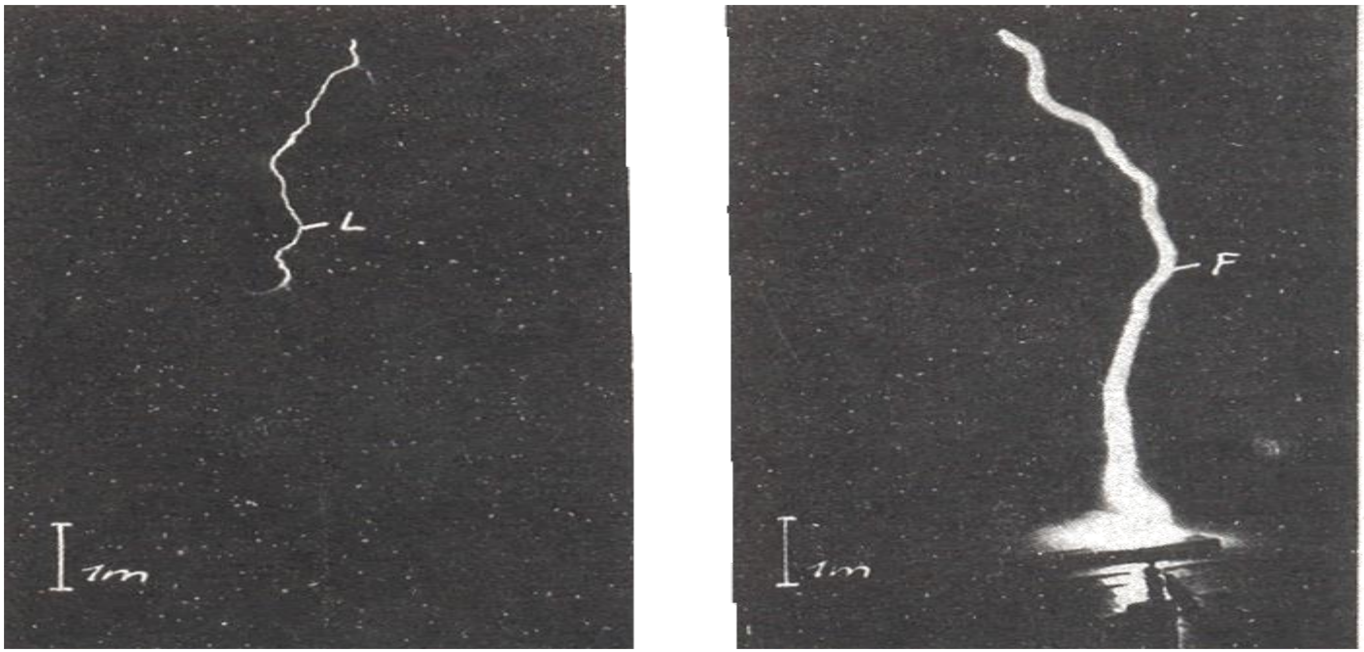

Fig. 29 Stable leader corona and breakdown with final jump for a 7 m gap with positive polarity si voltage, Lemke

Cont..

- **Summary of Breakdown in Extremely Non-uniform Fields in Air**

(a)

(b)

Fig. 30 (a) Photograph of a tree after 'Fall' in winter representing the stem, leader and streamer corona trajectories in long air gaps, (b) Shadow of such a tree on the ground

Breakdown in Vacuum as Electrical Insulator

- The source/location of micro-discharges are enlisted below :
- ✓ Semi-conductive surface oxides
- ✓ Impurity concentrations, such as, adsorbates, dust
- ✓ Organic vapours from, e.g., grease and rubber O-rings
- ✓ Porous oxide layers – H_2O and hydrocarbon adsorbates
- ➢ **Pre-breakdown Conduction Currents and Breakdown Voltage Characteristics in Vacuum**
- Pre-breakdown conduction currents and breakdown voltages measured with ac power frequency on needle and hemispherical rod-plane surface gap.

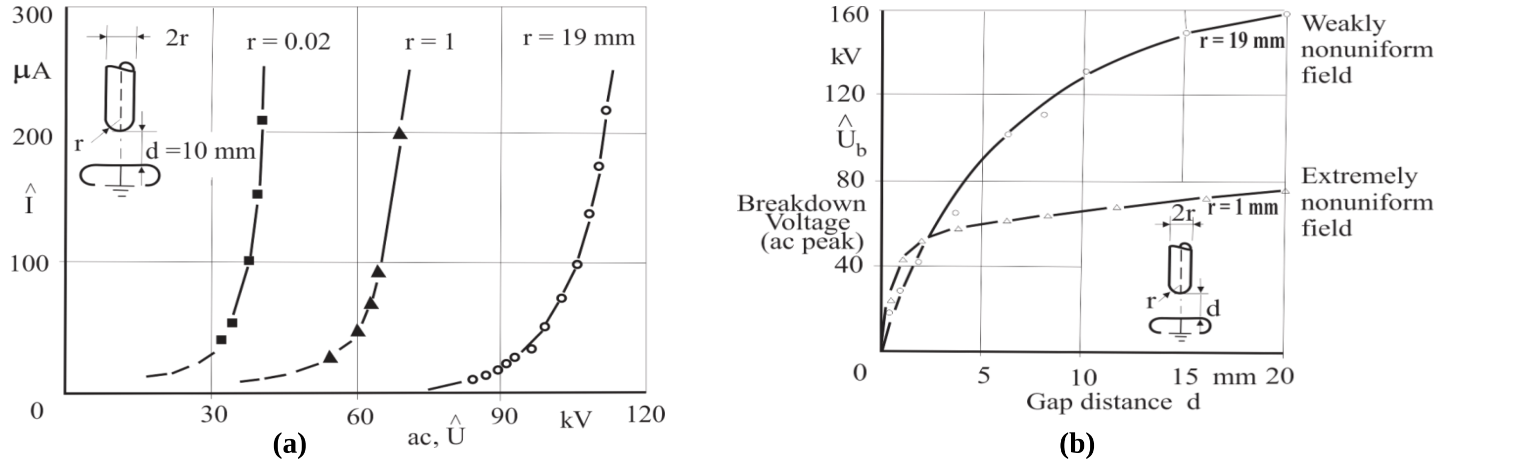

Fig. 31 (a) Pre-breakdown conduction current as a function of the applied ac voltage for copper needle and hemispherical rod-plane electrode system at constant gap distance, (b) ac Peak breakdown voltage for the same electrode systems with increasing gap distance at 1.0 mPa or 7.5×10^{-6} Torr

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- The breakdown strength of vacuum depends strongly upon the magnitude of pressure.
- Measured at different pressures for the same electrode system in weakly non-uniform field, the breakdown characteristics with ac power frequency voltage are shown in Fig. 32

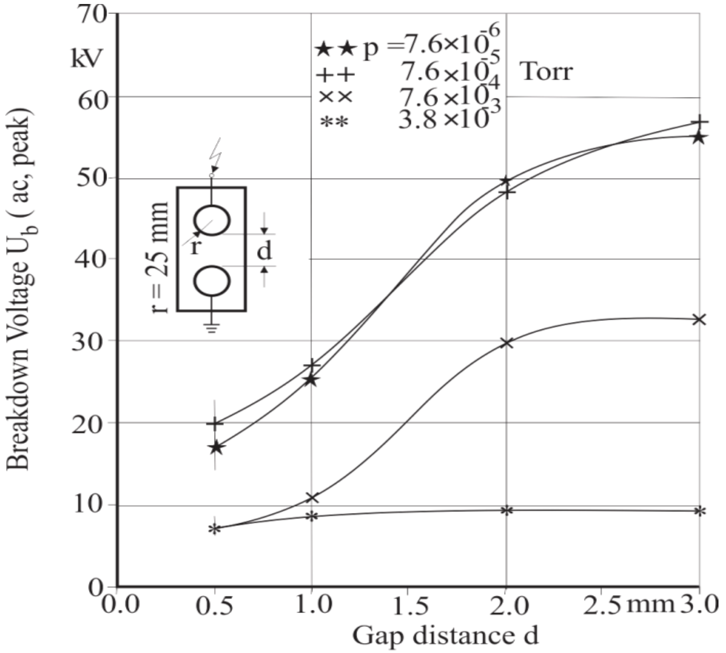

Fig. 32 Breakdown in vacuum at different pressures measured with ac power frequency voltage in a weakly non-uniform field between identical spheres of 50 mm diameter for increasing gap distance,

Summary

- The atmospheric air which constitutes 78 % of Nitrogen, has fairly good electrical insulation properties.
- The cheapest protection from high voltage is by maintaining adequate distance of clearance from the live conductors.
- The SF_6 gas has three times better insulating properties than air.
- Field dependent investigation of the breakdown process in atmospheric air has been made very extensively as it is most simple compared to experiment with any other dielectric. It reveals interestingly that the basic mechanisms leading to breakdown, such as, ionisation, avalanche, streamer and leader processes, are quite similar in all the dielectrics.
- In the beginning with the properties of the gaseous dielectrics, the process of generation of charge carriers and the development of breakdown mechanisms under different field conditions are discussed.
- Actual breakdown characteristics, measured under different conditions, are given so far it is possible since these compare the breakdown strengths of different dielectrics in a better way.
- Researchers have found a remarkable analogy in the development of breakdown mechanisms between all the three types of dielectrics, that is, gaseous, liquid, and solid.

Thank You
&
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