HIGH VOLTAGE ENGINEERING

Electrical Strength

Insulation systems

- Insulating materials
  - Gases
  - Liquids
  - Solid
- Classification of insulating materials according to insulating abilities
  - Self-renewable
  - Non-renewable

Electrical Strength of Gases

- Ionisation
  - Ionization is the process by which an electron is removed from an atom, leaving the atom with a positive charge (positive ion)
  - First ionization potential is energy required for removing of electron from its normal state in atom to a distance well beyond the nucleus

Ionisation Processes

- Ionization by simple collision

$$\frac{1}{2}m_e v^2 > E_i$$

$$M + e^- \longrightarrow M^+ + 2e^-$$

- Excitation (excited molecule)

$$M + e^- \longrightarrow M^* + e^-$$

*Excited molecule M*can give out a photon of emitted energy h*ν

$$M^* \longrightarrow M + h\upsilon$$

Ionisation Processes

- Double electron impact

$$M^* + e^- \longrightarrow M^+ + 2e^-$$

- Photo-ionization
  - Ionization by photon of frequency v with energy hv greater then ionization energy of the molecule

$$M + h\upsilon \rightarrow M^+ + e^-$$

- Thermal, electron Attachment/detachment

Breakdown in Gases

- Electron Avalanche Mechanism (Townsend Breakdown Process)
  - One free electron between electrodes is supposed and electrical strength is sufficiently high
  - Simple collision of free electron produce 2 free electrons and one positive ion
  - Electrons and positive ions create electron avalanche

Townsend’s first ionization process

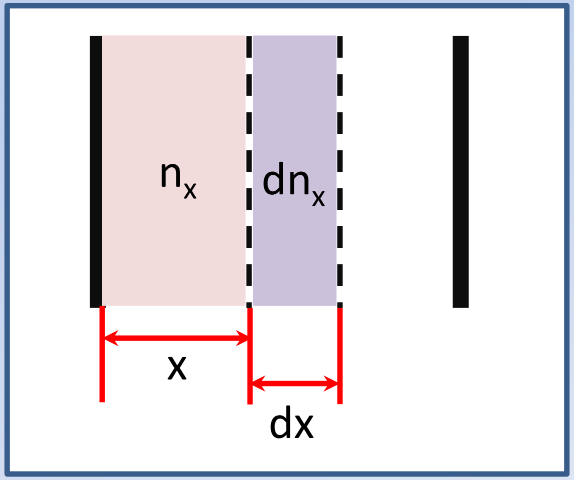
- Towsend’s first ionization coefficient α
  - Number of electrons produced by an electron per unit length of path in the direction of the field
- n_x is number of electrons at a distance x from the cathode

Number of electrons at distance x:

$n_x = \alpha\, n\, x$

Number of electrons in dx element:

$dn_x = \alpha\, n_x\, dx$



Townsend’s first ionization process

After adjustment we are integratin on both sides of equation:

$$\int_{n_0}^{n_x} \frac{dn_x}{n_x} = \alpha \int_0^x dx$$

with the result:

$$\ln\left(\frac{n_x}{n_0}\right) = \alpha x$$

Which can be rewrited to final form:

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

Townsend's first ionization process

- If the anode is at distance x=d from cathode, the number of electrons nd striking the anode per second is:

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

- On the average each electron leaving the cathode produces $\frac{(n_d - n_0)}{n_0}$ new electrons.

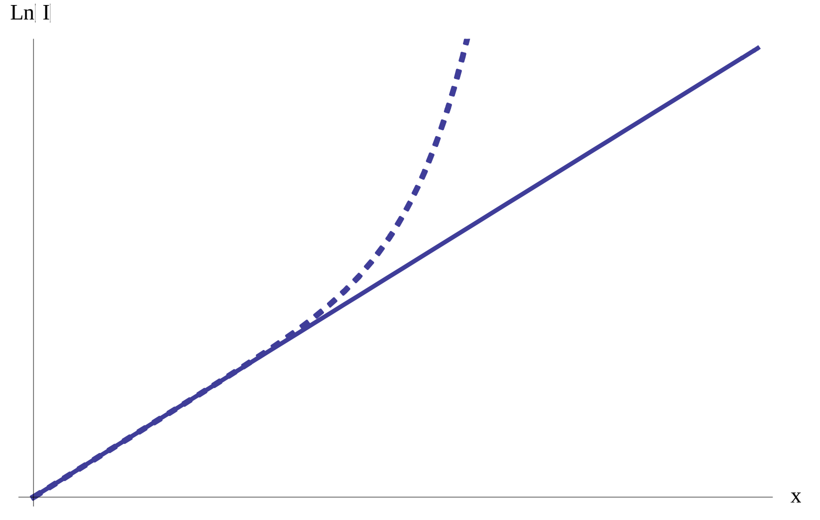
In terms of current:

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

Townsendův první ionizační proces

Make the log on both sides of previous equation:

$$\ln(I) = \ln(I_0) + \alpha x$$



- From observations the real current increased more rapidly (dashed curve)

Townsend's second ionization process

- The additional current is given by presence of positive ions and photons
- The positive ions release the electrons by collisions with gas molecules and bombardment of the cathode
- The photons also release electrons after collisions with gas molecules or after impact on cathode

Townsend's second ionization process

- Let n_0 be the number of electrons released from the cathode by UV radiation and n_+ the number of electrons released from cathode by positive ion collisions
- Townsend second ionization coefficient γ
  - number of electrons released from cathode per incident positive ion

The number of electrons reaching the anode is then:

$$n = (n_0 + n_+)e^{\alpha d}$$

Townsend's second ionization process

Then the number of electrons released from gas is:

$$n - (n_0 + n_+)$$

- Each electron has one positive ion and it is assumed that each positive ion releases γ electrons from the cathode

The number of electrons released from cathode:

$$n_+ = \gamma[n - (n_0 + n_+)]$$

$$n_+ = \frac{\gamma(n - n_0)}{1 + \gamma}$$

Townsend's second ionization process

Substituting n_+ in the previous expression for n :

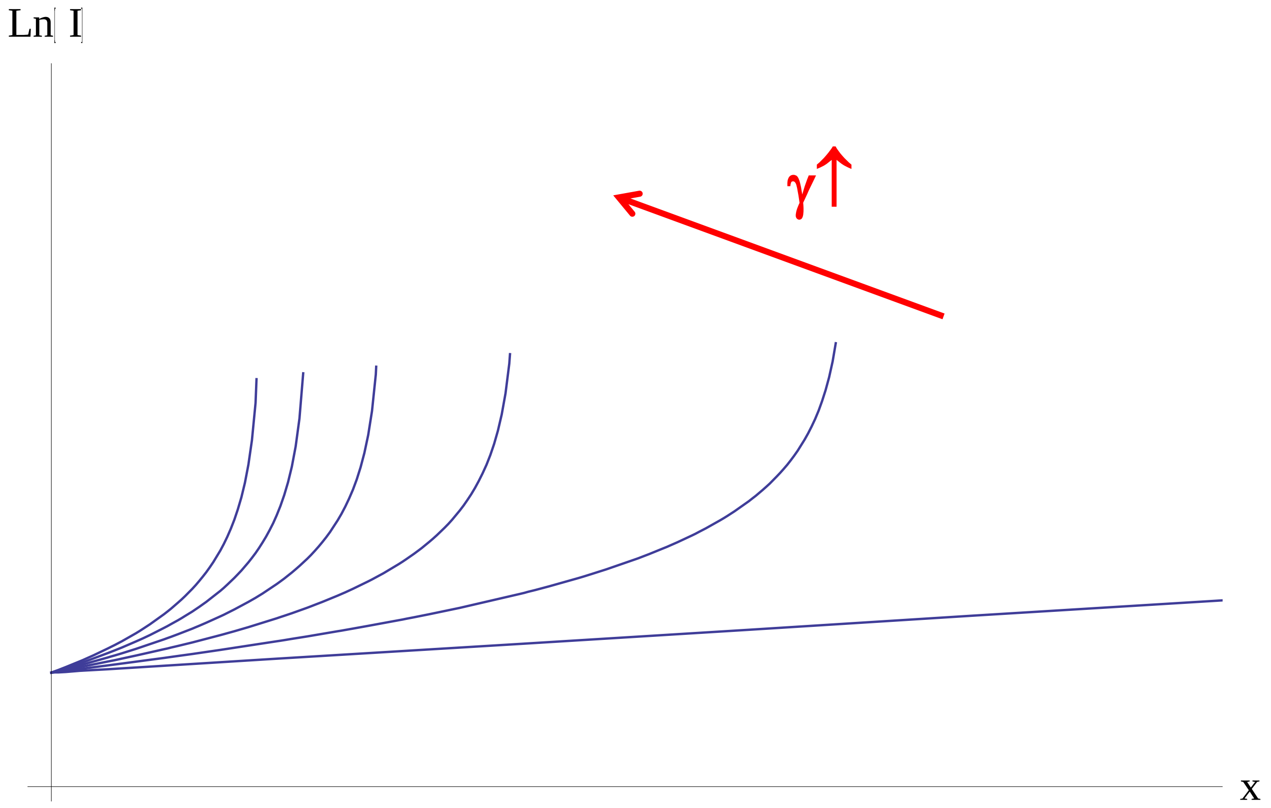
$$n = \left[n_0 + \frac{\gamma(n - n_0)}{1 + \gamma} \right] e^{\alpha d} = \frac{n_0 + \gamma n}{1 + \gamma} e^{\alpha d}$$

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

In terms of current:

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

Townsend’s second ionization process



- Increasing the coefficient γ the current rise is more faster

Townsend Breakdown Mechanism

- If the voltage between electrodes increase the current at the anode is given as:

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

The breakdown is characterized by “infinite“ current:

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

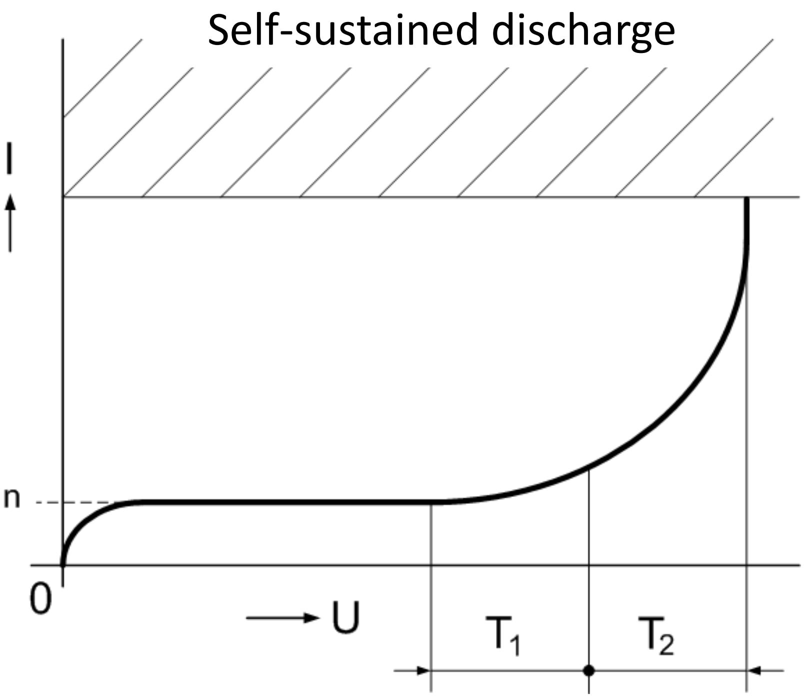
$$\gamma\left(e^{\alpha d} - 1\right) = 1$$

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

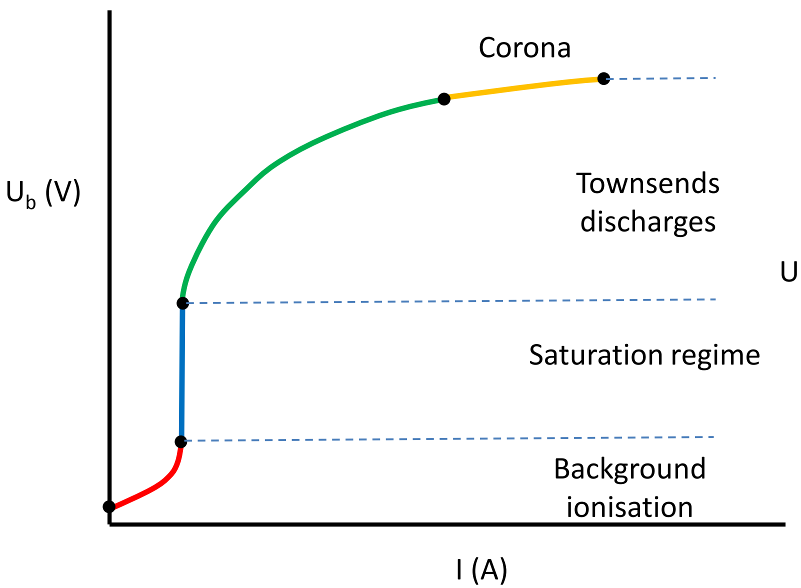
Townsend Breakdown Criterion

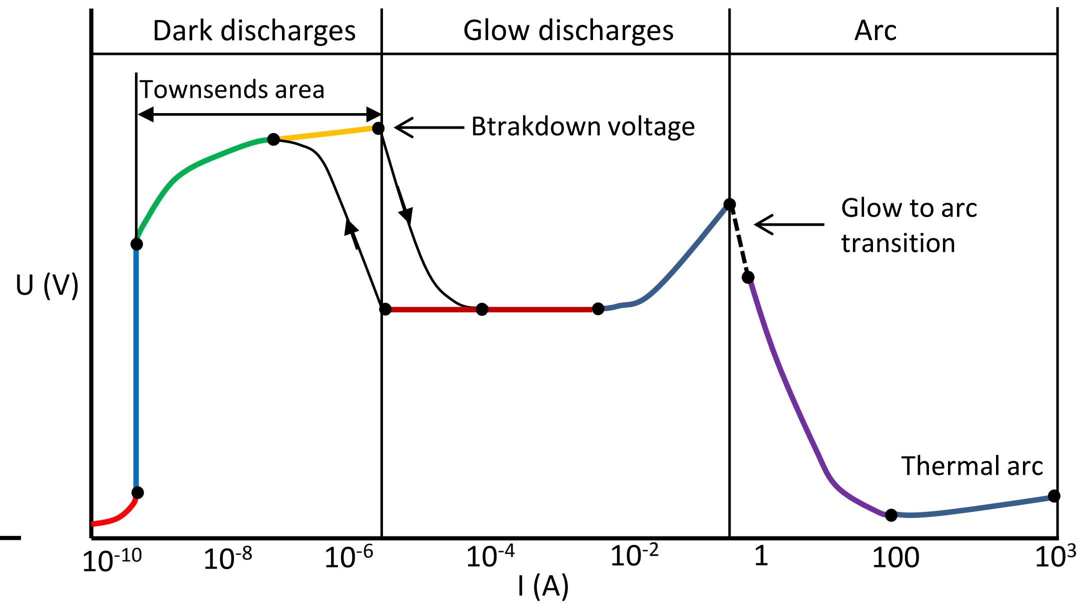
- The condition $\gamma e^{\alpha d} = 1$ is known as Townsend criterion or Townsend breakdown criterion

- Townsend criterion defines the threshold sparking condition, if $\gamma e^{\alpha d} < 1$ the current I is not self-sustained



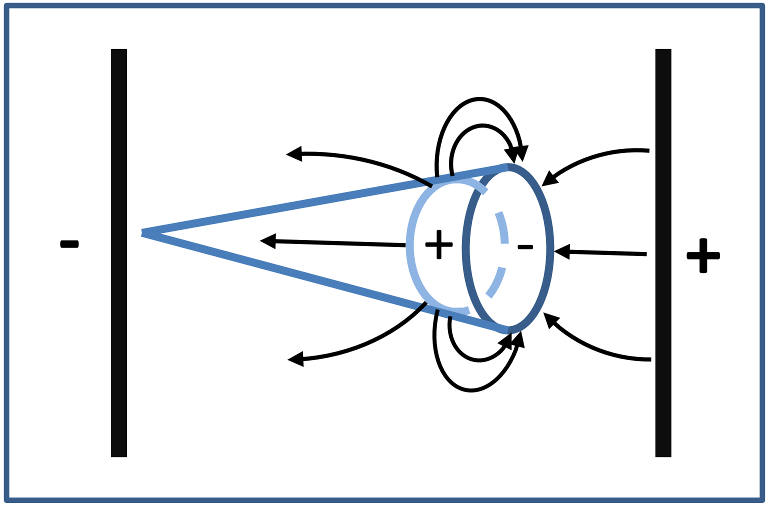
Voltage-current Characteristics of Electrical Discharges in Gases



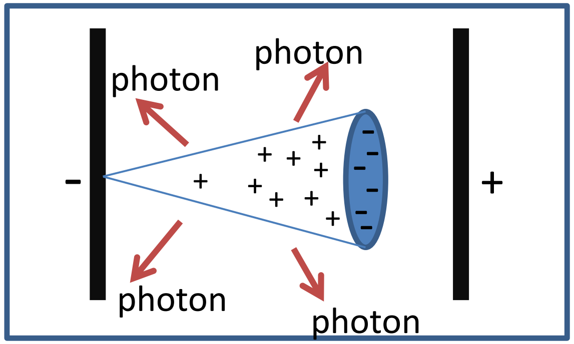


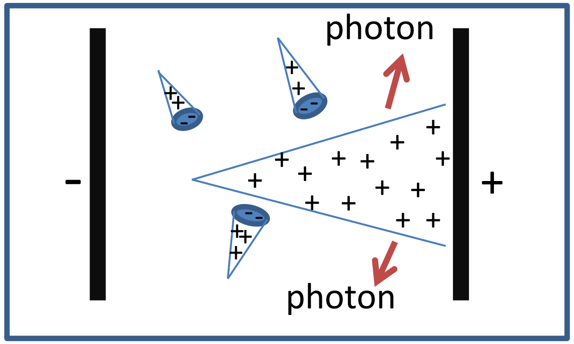
Kanal Mechanism

- Townsend’s theory can not explain all processes which are observed e.g. shape of the discharge or shorter formation time of the discharge
- Space discharges which are created by avalanches and photoionization processes have to be taking into account (Raether, Meek)



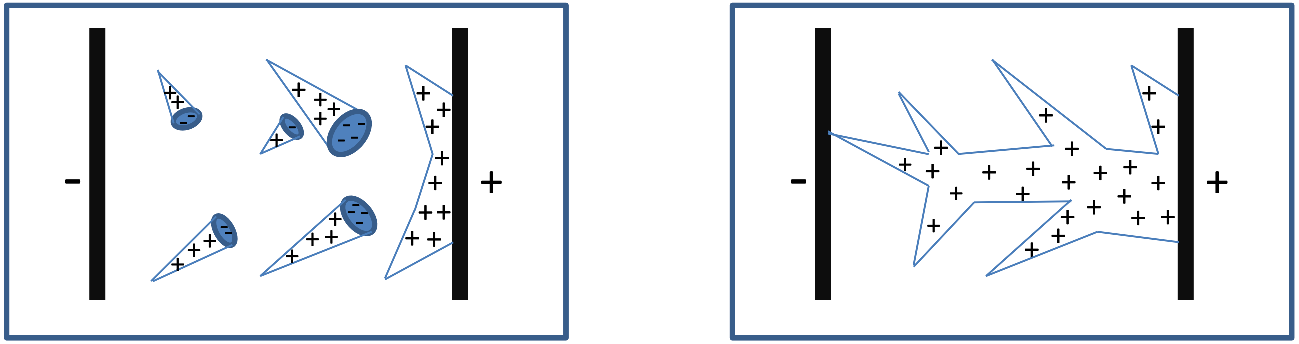
Kanal Mechanism





- An electron avalanche consists of fast electrons and slower positive ions. At the point, where higher concentration of positive and negative charges overlaps the recombination processes occurs. Photons are then emitted in different directions and absorbed by molecule causes photoionization process and releasing of electrons.
- Photoelectrons are then sources of new avalances in front and behind of primary avalanche, where the electrical strengts is higher than the value of main field (at concentration of 10^8 electrons in the head of avalanche are the electrical fields equal). The new avalanches propagate much faster in the direction of electrical field whis is deformed by space discharge.

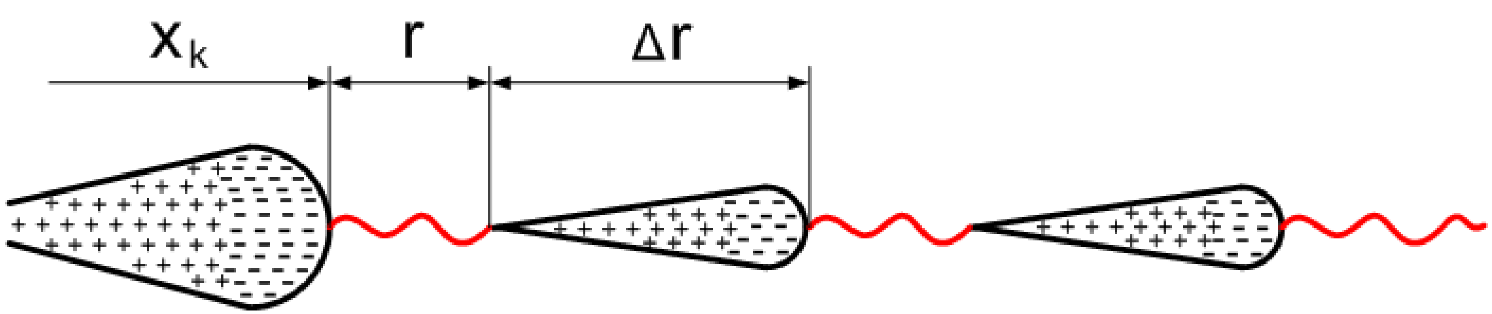
Kanal Mechanism



After the primary avalanche is passed through the area between electrodes the ionized channel remains and the main discharge then occurs.

Streamer Development

- An intensive ionization and emission of photons in the head of avalnche causes photoionization in the r distance from the head of avalanche
- Due to the higher electric field intensity the secondary avalanches are created much faster than original avalanche in the distance Δr



The velocity of electrons propagation is then $\frac{r+\Delta r}{\Delta r}$ times higher than the velocity of electrons in avalanche

Paschen's Law

- From Towsend's criterion can be derived the relation between the breakdown voltage, pressure and electrode distance
- Coefficients α and γ depend on the value of electric field E and pressure p (at constant temperature!)

These dependencies can be expressed as:

$$\frac{\alpha}{p} = f_1\left(\frac{E}{p}\right) \;\; a \;\; \gamma = f_2\left(\frac{E}{p}\right),$$

where f_1 and f_2 are general functions

Paschen’s Law

Assuming the uniform field the electric intensity is given by the formula :

$$E = \frac{U}{d}$$

After the substitution to the functions for α and γ :

$$\alpha = pf_1\left(\frac{U}{pd}\right) \;\; a \;\; \gamma = f_2\left(\frac{U}{pd}\right)$$

And after the substitution to the Townsend’s criterion formula:

$$f_2\left(\frac{U}{pd}\right)\left[e^{pdf_1\left(\frac{U}{pd}\right)} - 1\right] = 1$$

- Exists only one value of voltage U at given value of product (pd) and temperature T when the equation is true → breakdown voltage

Breakdown Voltage in Uniform Field

Suppose that γ=const. (i.e. doesn't change with pressure and electric field intensity) and temperature T=const. From the self sustained discharge condition:

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

Further it is assumed that the function $f_1 = Ae^{-\frac{Bpd}{U_p}}$, where A and B are constants and U_p is the breakdown voltage. Then

$$pdAe^{-\frac{Bpd}{U_p}} = Ln\left(1 + \frac{1}{\gamma}\right)$$

After the modification the breakdown voltage can be expressed as :

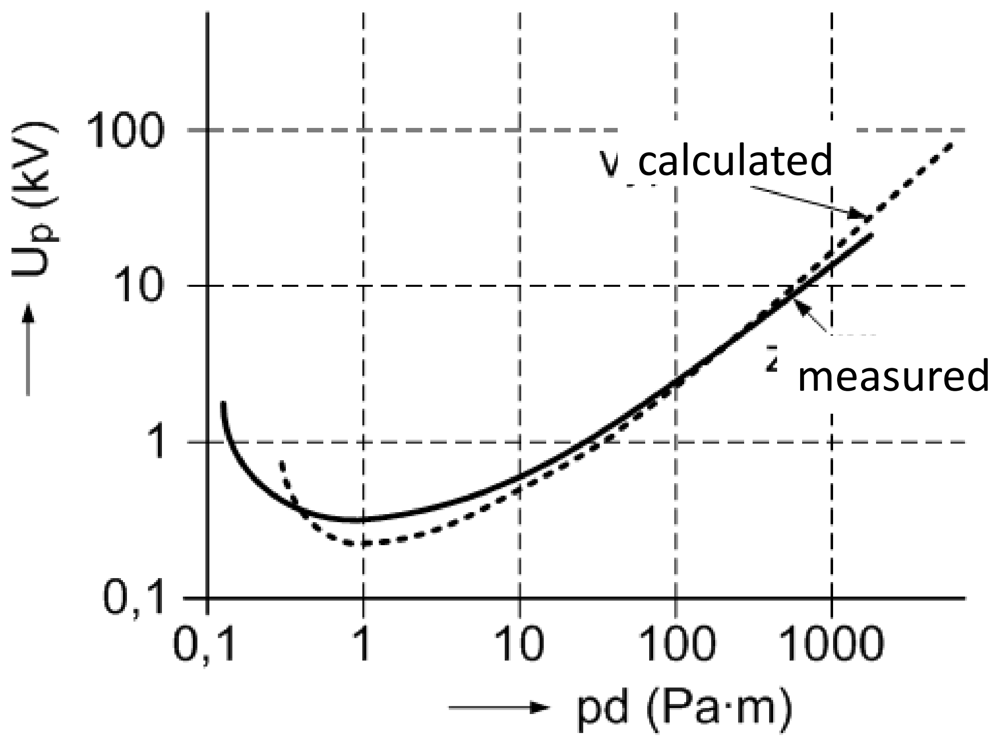
$$U_p = \frac{Bpd}{Ln\left(\frac{Apd}{Ln\left(1 + \frac{1}{\gamma}\right)}\right)}$$

This function has a minimum at (pd) value of:

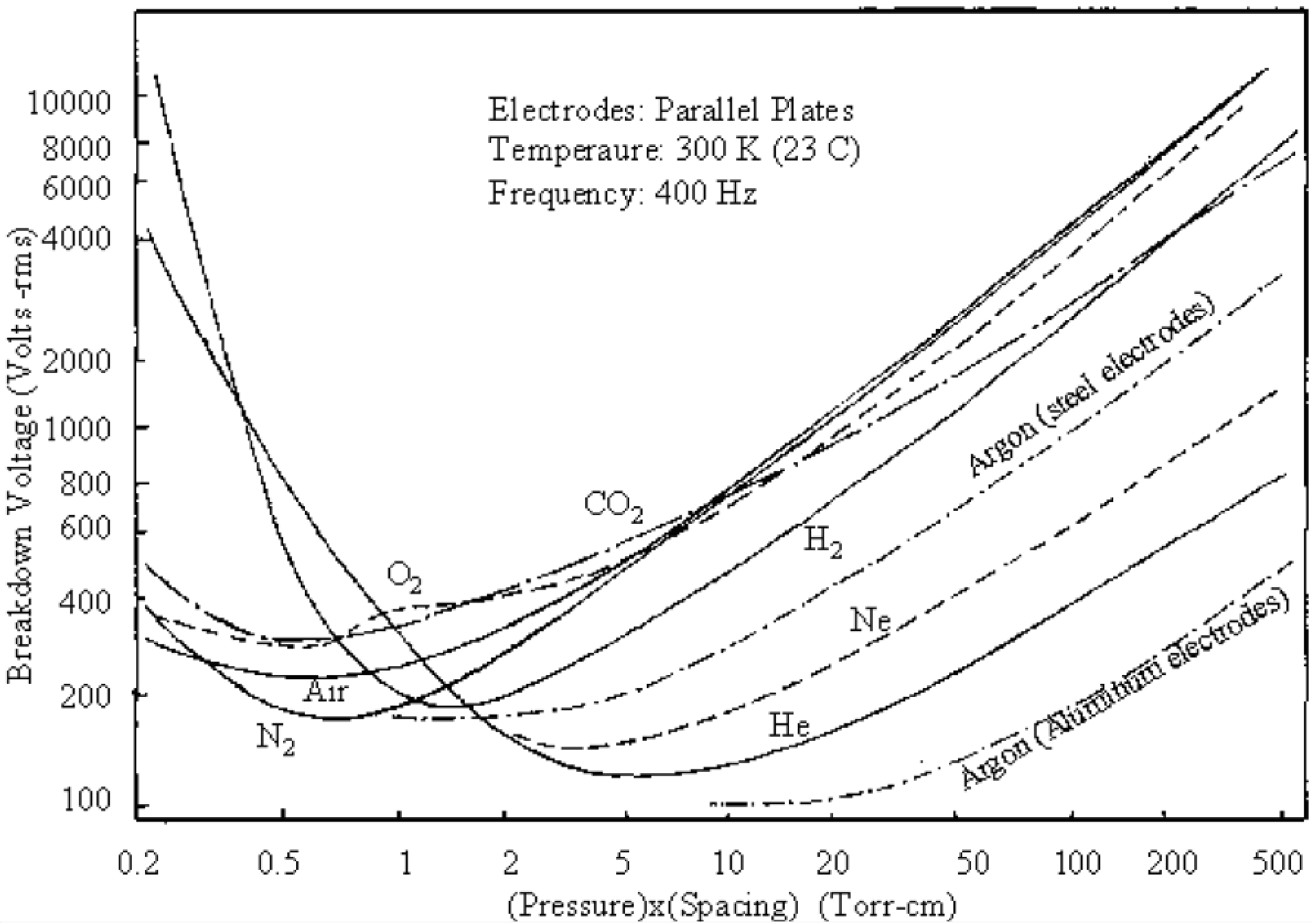
$$(pd)_{min} = \frac{e}{A} Ln\left(1 + \frac{1}{\gamma}\right)$$

Breakdown Voltage in Uniform Field

- An example of experimentaly determined and theoretically calculated dependency $U_p=f(pd)$. ($A=109{,}5\ cm^{-1}kPa^{-1}$, $B=2738\ Vcm^{-1}kPa^{-1}$, $\gamma=0{,}025$)



Breakdown Voltage for Gases



Breakdown Voltage in Non-Uniform Field

- The electric field intensity and the first ionization coefficient α change between electrodes

The Townsen's criterion of selfsustained discharge can be for low pressures expressed as:

$$\gamma\left(e^{\int_0^d \alpha\, dx} - 1\right) = 1$$

The integration path is along the field line with highest intensity of electric field

Breakdown Voltage in Non-Uniform Field

- For general case the criterion can be determined from exceeding of critical concentration of electrons

$$e^{\int_0^{x_c<d} \alpha \, dx} = N_{kr}$$

where N_{kr} is the critical concentration of electrons in avalanche which leds to the streamer initiation ($\approx 10^8$) and x_c is the path which is needed to reach such concentration.
The criterion can be rewritten as:

$$\int_0^{x_c<d} \alpha \, dx = Ln\,(N_{kr}) \approx 18 - 20$$

Field Efficiency Factor

- The quantification of electric field nonuniformity

Efficiency factor:

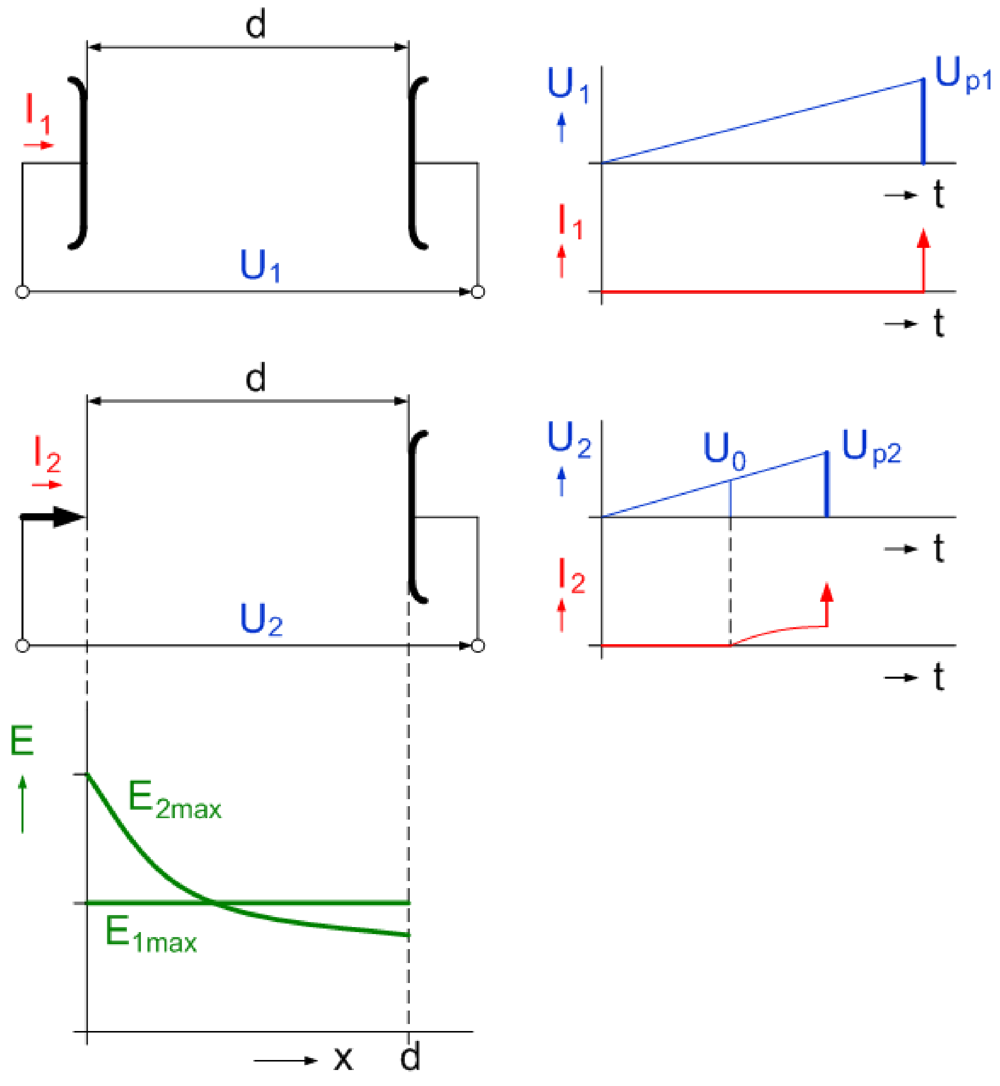
$$\eta = \frac{E_o}{E_{max}}$$

where E_0 is the mean value of electric field intensity and E_{max} is the maximal value of electric field intensity

Obviously the $E_o = \frac{U}{d}$ then:

$$\eta = \frac{U}{dE_{max}}$$

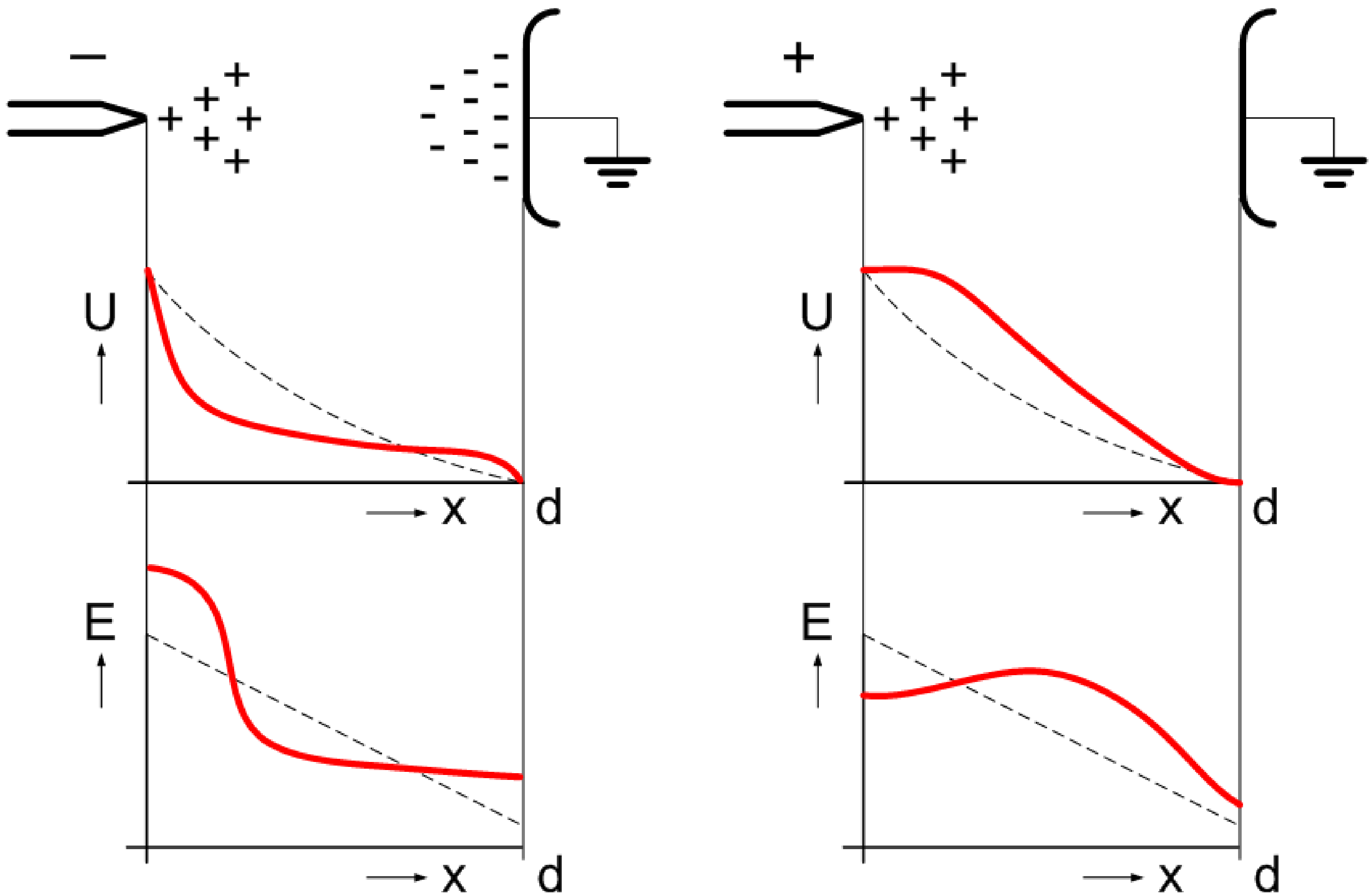
Field Efficiency Factor



Polarity Effect

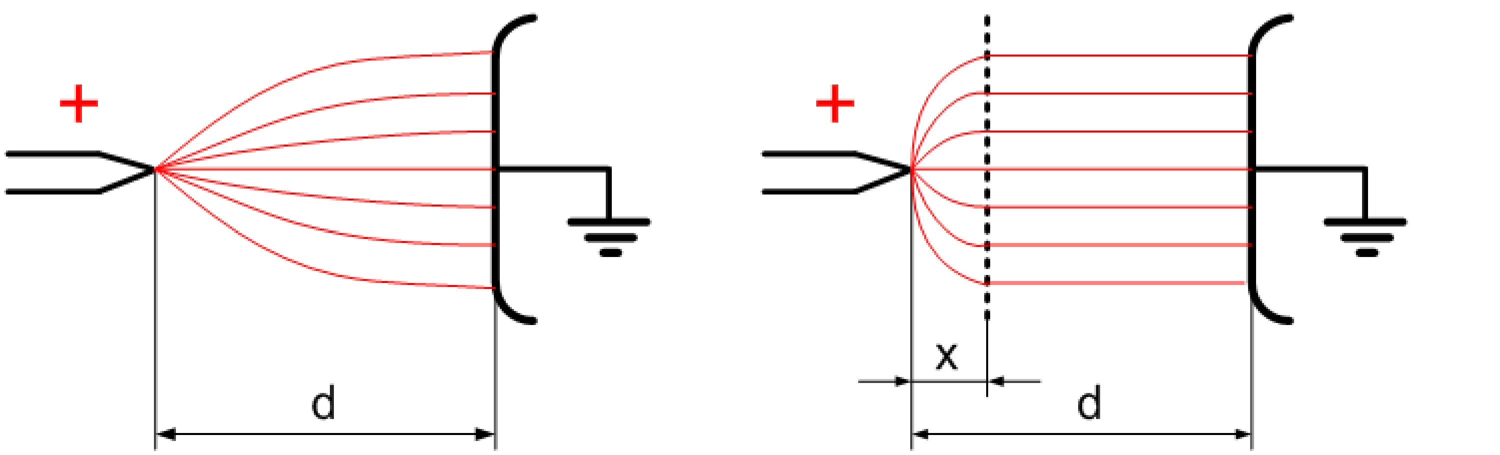
- There is a difference in the field strength between negative and positive polarity in nonuniform field
- In case of positive polarity the very high electric field area is present around the electrode. The very fast electrons are transported to the anode and positive ions slowly move to the cathode. This disproportion causes the dominance of positive charge around the anode and decrease of
- The process is opposite in the case of negative polarity. The barrier in the area around the electrode is created and the electrical strength is increased (main electric field is reduced).

Polarity Effect

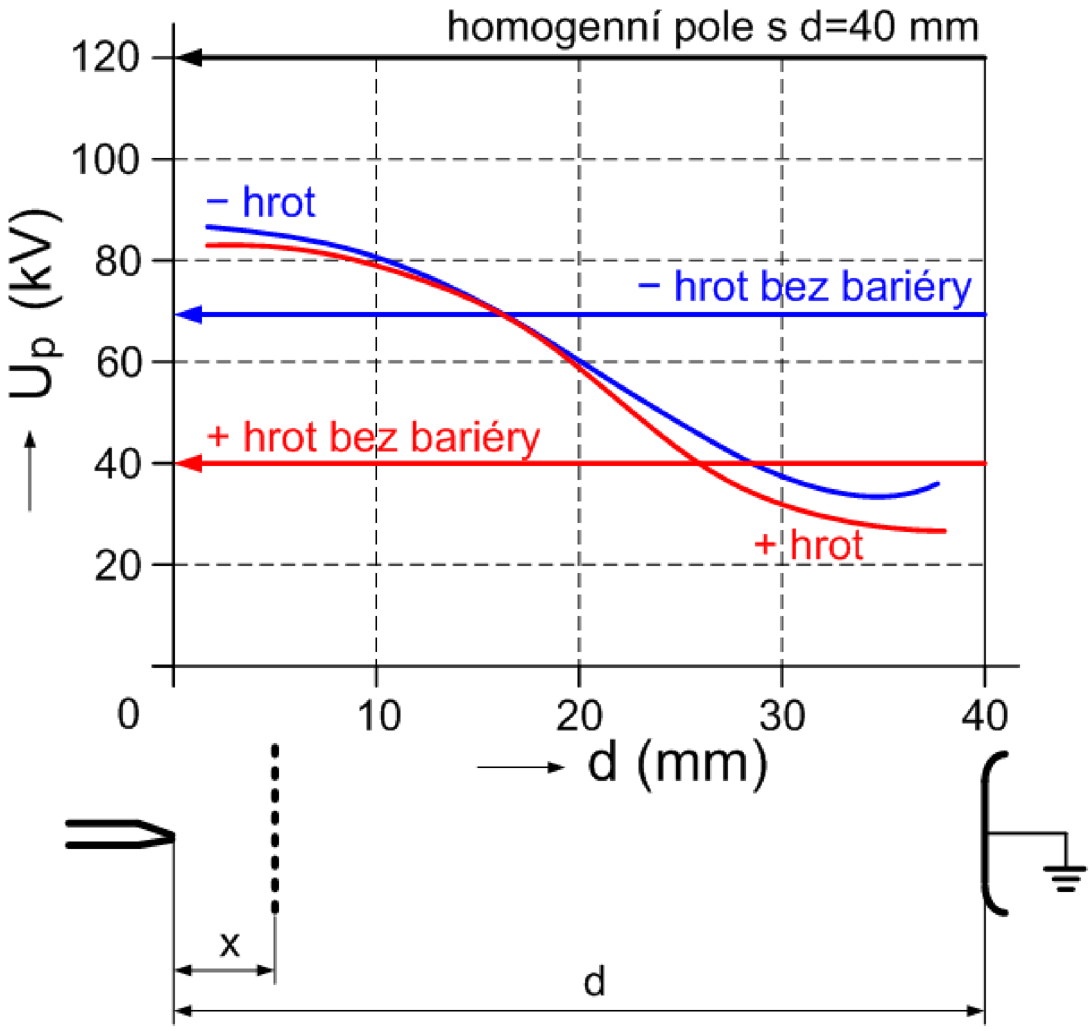


Influence of Barrier

- The electrical field close to the sharp electrode is homogenized by application of barrier
- An optimal location of barrier exists, when the electrical strength is maximal



Optimal Location of Barrier



Overview of Insulation Gases

- The most used insulation gases for high voltage apparatus are air and SF_6

Name	Formula	Boiling point (°C)	Dielectric strength
Hexafluoro-2-butyne	C_4F_6	−25	2.2
Trifluoromethyl sulfur pentafluoride	CF_3SF_5	−20	1.55
Trifluoromethane sulfonyl fluoride	CF_3SO_2F	−22	1.49
Thionyl fluoride	SOF_2	−44	1.42
Trifluoronitromethane	CF_3NO_2	−31	1.34
Perfluoro-n-butane	C_4F_8	2	1.5
Chloropentafluoroethane (F-115)	C_2F_5Cl	−39	1.13
Perfluoro-butane	C_4F_{10}	−2	1.06
Sulfur dioxide	SO_2	−10	1.0
Sulfur hexafluoride	SF_6	−64	1.0
Dichlorodifluoromethane (F-12)	CCl_2F_2	−30	0.99
Octofluoropropane (F-218)	C_3F_8	−37	0.98
Perfluorodimethyl ether	C_2F_6O	−59	0.84
Hexafluoroethane (F-116)	C_2F_6	−78	0.79
Bromotrifluoromethane (F-1381)	$CBrF_3$	−58	0.75
Chlorotrifluoroethylene (CTFE)	C_2F_3Cl	−28	0.69
Nitrous oxide	N_2O	−89	0.5
Carbon tetrafluoride (F-14)	CF_4	−128	0.42
Air	$N_2 + O_2$		0.37
Nitrogen	N_2	−196	0.37
Carbon dioxide	CO_2	−79	0.32

Liquid Insulators

- Insulating oil
  - Natural
  - Synthetic
- Mineral oil
  - The most used liquid insulation medium, good insulation properties, aging (oxidation, moisturing), flammable, slow biological decomposition
  - Periodical condition inspection, potential oil regeneration
- Silicone oil
  - Excelent insulation properties, nonflammable, oxidation resistant up to 150 °C, the main disadvantage is worst gas absorption and high water absorption
- Esters
  - Nonflammable, fast biological decomposition

Liquid Insulators

Property	Unit	Mineral oil	Silicone oil
Breakdown field strength	kV/mm	28	10
Volume resistivity (ρ)	Ω-m	$10^{11} \sim 10^{13}$	10^{13}
Dielectric constant ε_r	—	2.2	2.8
Dissipation factor at 25°C (1 MHz) tan δ	—	0.001	0.0002
Density	g/cm^3	0.91	0.96
Thermal conductivity	W/K°m	0.14	0.16
Specific heat (C_p)	cal/g/°C	0.53	0.36
Thermal stability limit	°C	90	150
Flash point	°C	145	>300
Neutralization number (acidity)	mg KOH/g	<0.03	—
Pour point	°C	−40	−55
Dielectric impulse breakdown, negative needle to sphere (25.4 mm gap)	kV	145	—
Water content	ppm	25	50

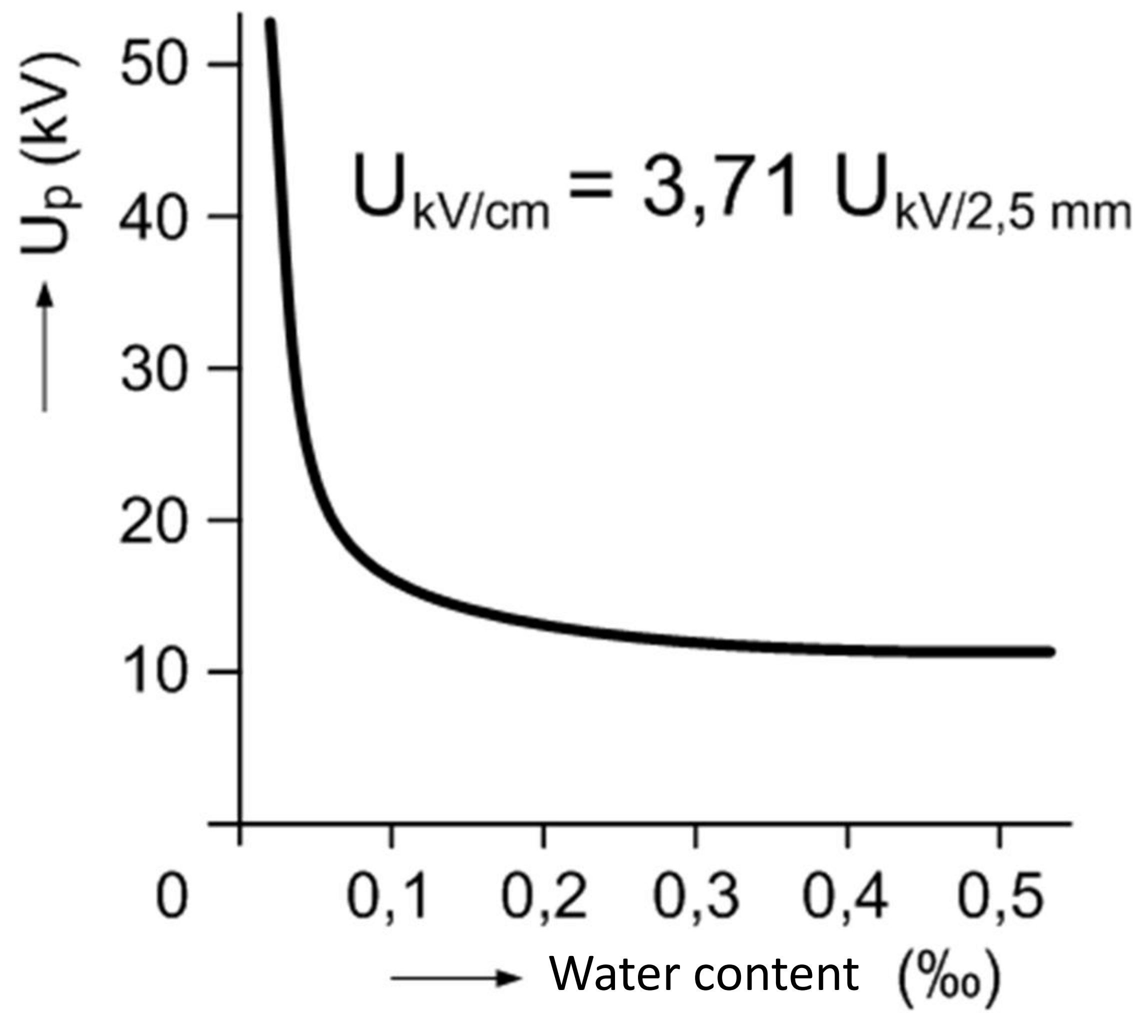
Current Conduction in Insulation Liquids

- Generally two kind of insulation liquids: polar and nonpolar
- The polar liquids are characterised by fixed dipoles (separation of positive and negative discharge center) without presence of electric field
- Nonpolar liquids doesn’t form any dipoles without presence of external electric field. Created dipoles are not fixed and disapear after the electric field is finished.
- Most of the insulation liquids are nonpolar

Current Conduction in Insulation Liquids

- The crutial influence to liquid conductivity has dissociation of impurities (ions generation) and solid particles of impurities
- Positive and negative ions, which don’t recombine, travel towards electrodes and creates current
- The charge carriers are generated mainly by electro-chemical processes on the boundary of liquid insulator and metal electrode at mean value of electric field

Influence of Water Content to Breakdown Voltage



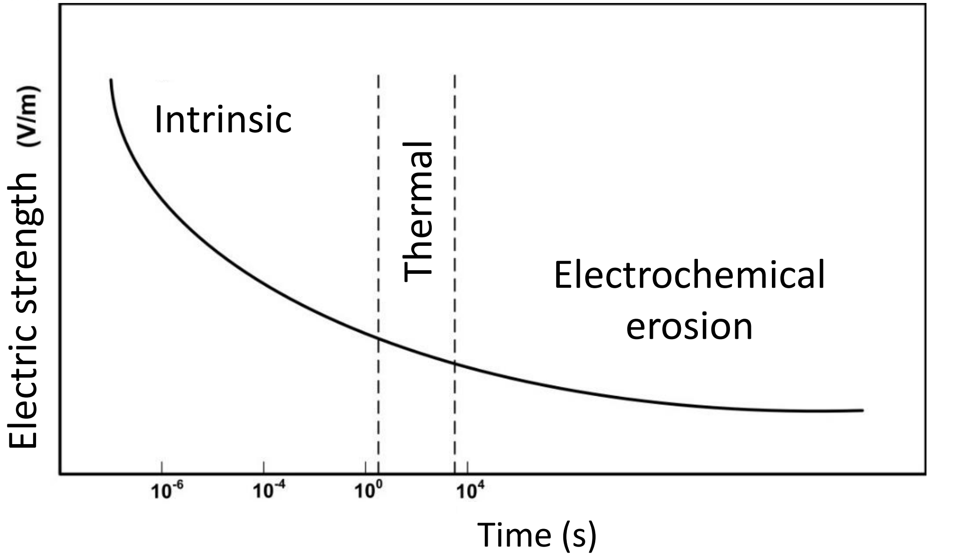
Solid Insulators

- Fundamental classification
  - Organic
    - Natural
    - Synthetic
      - Thermoplast
      - Termosetts (reaktoplast)
      - Elastomers
  - Anorganic
    - Amorphous
    - Crystalic

Breakdown of Solid Insulation

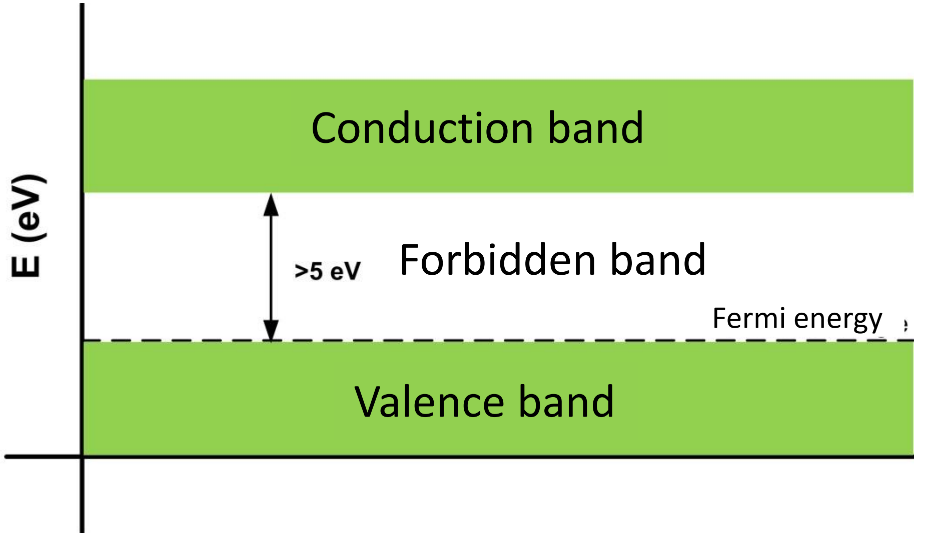
- The breakdown mechanism is complex phenomennon dependent on time of voltage aplication

- The three mechanisms are usually recognised:
  - Intrinsic breakdown
  - Thermal breakdown
  - Erosion, electrochemical



Intrinsic Breakdown

- Occures in very short time 10^{-8} s at high electric field intensities MV/cm of electric field
- Electrons cross the forbidden energy gap from the valence to the conduction band where they can freely go through the crystal lattice

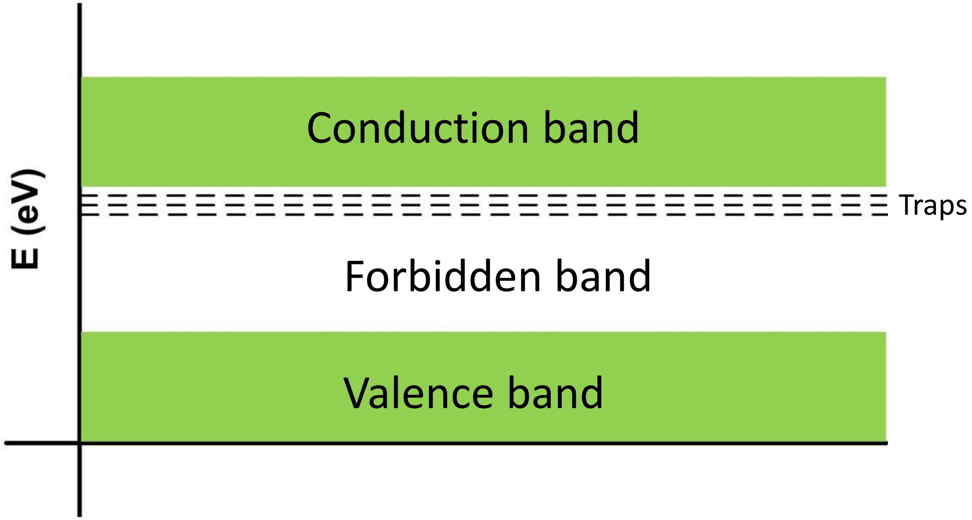


Influence of Impurities

- The valence band is separated from conduction band by large energy trap in pure uniform dielectrics
- Electrons can not reach enough energy to cross forbidden band at common temperatures $\rightarrow$ zero conductivity
- Practically, all crystals contain various impurities and lattice defects

Influence of Impurities

- Atoms of impurities act the role of traps for free elctrons in energetic levels below conduction band
- Electrons are catched in traps at lower temperatures, ther the transit to coduction band is more easy when the temperature is increased



Thermal Breakdown

- The heat is generated when the insulation is stressed by voltage due to conductive current and dielectric losses (polarization)
- The conductivity increases with temperature – positive feedbacka

Dielectric Losses

The active power is given as:

$$P_d = UIcos\varphi$$

From the vector diagram it is clear that:

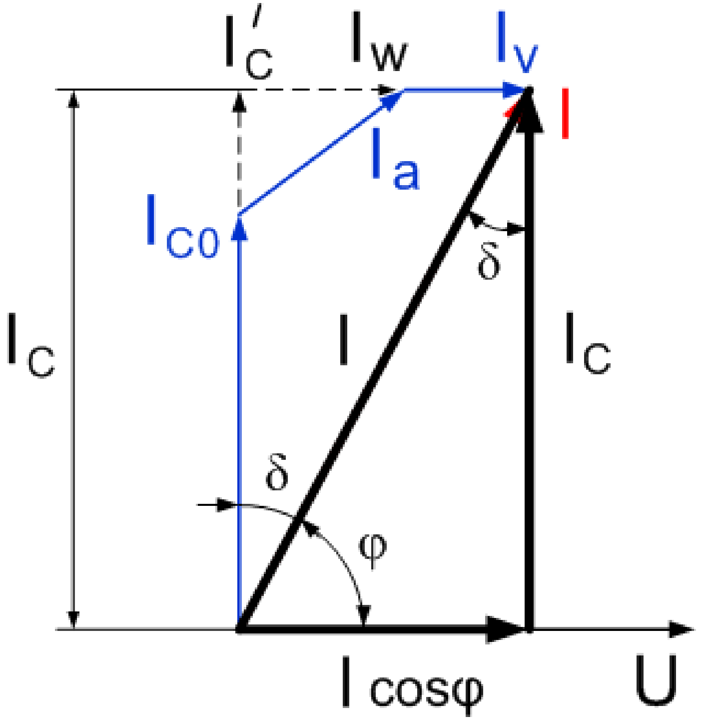
$Icos\,\varphi = Isin\,\delta$ a $I = \frac{I_c}{\cos\delta}$

The capacitive current can be expressed as:

$$I_c = U\omega C$$

After the substitution:

$$P_d = U^2\omega Ctg\,\delta$$



Thermal Breakdown

Fourier's law

$$q = -\lambda \, grad \, T$$

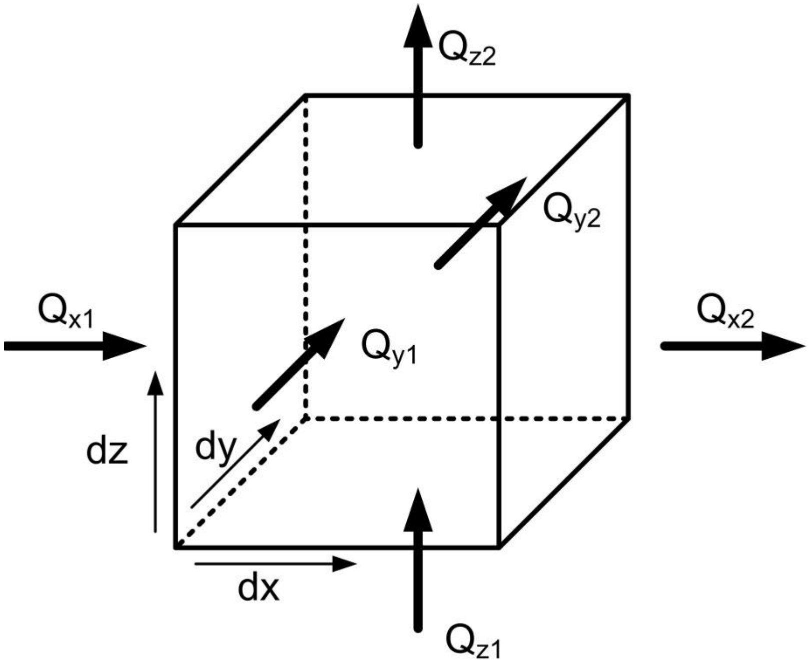
Heat flow in the direction of the X-axis element dxdydz during dt

$$Q_{x1} = -\lambda \frac{\partial T}{\partial x} dydzdt$$

$$Q_{x2} = -\lambda \frac{\partial}{\partial x}\left(T + \frac{\partial T}{\partial x} dx\right) dydzdt$$

$$dQ_x = dQ_{x1} - dQ_{x2} = \lambda \frac{\partial^2 T}{\partial x^2} dxdydzdt$$

In the direction of the axes y and z it is obtained analogously relations



Thermal Breakdown

Total shared heat in element dxdydz during time dt is:

$$Q = dQ_x + dQ_y + dQ_z = \lambda\left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2}\right) dxdydzdt$$

From the law of conservation of energy:

Generated heat = absorbed heat + teplo odvedené

Assume, the heat source is the current flow:

$$\sigma E^2 = c_v \frac{dT}{dt} + \lambda\left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2}\right)$$

- Experiments show that the breakdown voltage depends on time of voltage application $\rightarrow$ two limit states: impulse and a steady state thermal breakdown

Impulse Thermal Breakdown

- The heat increase is very steep $\rightarrow$ neglecting of heat transfer to the boundary is assumed

$$\sigma E^2 = c_v \frac{dT}{dt} = c_v \frac{dT}{dE}\frac{dE}{dt}$$

The linear increase of electric intensity is assumed:

$$E = \frac{E_p}{t_p} t,$$

where E_p is maximal intensity at time t_p when the breakdown will occure.

The dependency of electric conductivity can be described as:

$$\sigma = \sigma_0 e^{-\frac{W}{kT}},$$

where W is activation enegy and k je Boltzman constant

Impulse Thermal Breakdown

$$\sigma_0 e^{-\frac{W}{kT}} E^2 = c_v \frac{dT}{dE} \frac{E_p}{t_p}$$

$$\sigma_0 e^{-\frac{W}{kT}} E^2 dE = c_v \frac{E_p}{t_p} dT$$

$$\frac{\sigma_0 t_p}{c_v E_p} \int_0^{E_p} E^2 dE = \int_{T_0}^{T_p} e^{\frac{W}{kT}} dT$$

Suppose W>>kT a T_p>T_o, the integral on the right side can be rewrited as: $T_0 \frac{k}{W} e^{\frac{W}{kT_0}}$, then the final formula for E_p is:

$$E_p = \left(\frac{3 c_v k T_0^2}{\sigma_0 W t_p}\right)^{0,5} e^{\frac{W}{2kT_0}}$$

Thermal Breakdown in Steady-State

- Dielectrics is placed between two large electrodes which have an ambient temperature
- High gradient of temperature between the temperature inside dielectric and electrodes causes that all generated heat is transferred to the surroundings
- The part $c_v \frac{dT}{dt}$ in equation of conservation can be neglected

Thermal Breakdown in Steady-State

$$\sigma E^2 = k\frac{d^2T}{dx^2}$$

$$\sigma\left(-\frac{dU}{dx}\right)^2 = k\frac{d^2T}{dx^2}$$

$$-\sigma\frac{dU}{dx}\int\frac{dU}{dx}dx = k\int\frac{d^2T}{dx^2}dx$$

In case of uniform electric field $\frac{d^2U}{dx^2} = 0$

$$-\sigma\frac{dU}{dx}U = k\frac{dT}{dx} + konst.$$

For the simplicity let konst.=0, start point x=0 is placed in the middle, between electrodes and applied voltage on electrodes is $\pm 1/2U_a$

Thermal Breakdown in Steady-State

If T_{max} is the maximal temperature in x=0, $\left.\frac{dT}{dx}\right|_{x=0} = 0$, then:

$$\int_0^{\frac{U_a}{2}} U dU = -\int_{T_{max}}^{T_0} \frac{k}{\sigma} dT$$

$$U_a^2 = 8\int_{T_0}^{T_{max}} \frac{k}{\sigma} dT$$

- The applied voltage reach the breakdown voltage U_p if T_{max} is equal to critical temperature T_k
- The unstable case is set when $T_c \rightarrow \infty$ a $U_a \rightarrow U_p$

$$U_p = \sqrt{8\int_{T_0}^{T_c\rightarrow\infty} \frac{k}{\sigma} dT}$$

Electromechanical Breakdown

- The electrostatic forces are generated when the solid dielectric material is exposed to strong electric field. This effect can lead to deformation of the material.

Assume d_0 the initial thickness of material, which is compressed to the thickness d at applied voltage U_p, then the compression strength is in balance if :

$$\varepsilon_0 \varepsilon_r \frac{U^2}{2d^2} = Y ln\left(\frac{d_0}{d}\right)$$, where Y is Young's modulus

Usually the mechanical instability occurs at $\frac{d}{d_0} = 0.6$, then the maximal electric intensity is :

$$E_m = \frac{U}{d_0} = 0.6\left(\frac{Y}{\varepsilon_0 \varepsilon_r}\right)$$