Vacuum Breakdown and Insulation Techniques

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Vacuum breakdown

H. Craig Miller, IEEE Transactions on Electrical Insulation 24(5) (1989) 765.
J. M. Wetzer, IEEE Transactions on dielectrics and Electrical Insulation 2(2) (1995) 202.

- If $pd < 10^{-3}\ \mathrm{Torr} - \mathrm{cm}$, an electron crosses the gap practically without collisions, so that there is no multiplication in the volume. This does not mean that a vacuum gap can be an ideal insulator.
- If high voltage is applied to a narrow gap, a high field is generated, capable of causing field emission from the cathode.
- The field is additionally enhanced in the vicinity of microscopic protrusions.
- Sputtering or desorption process → metal vapor.
- Discharge develops in vaporized electrode material.

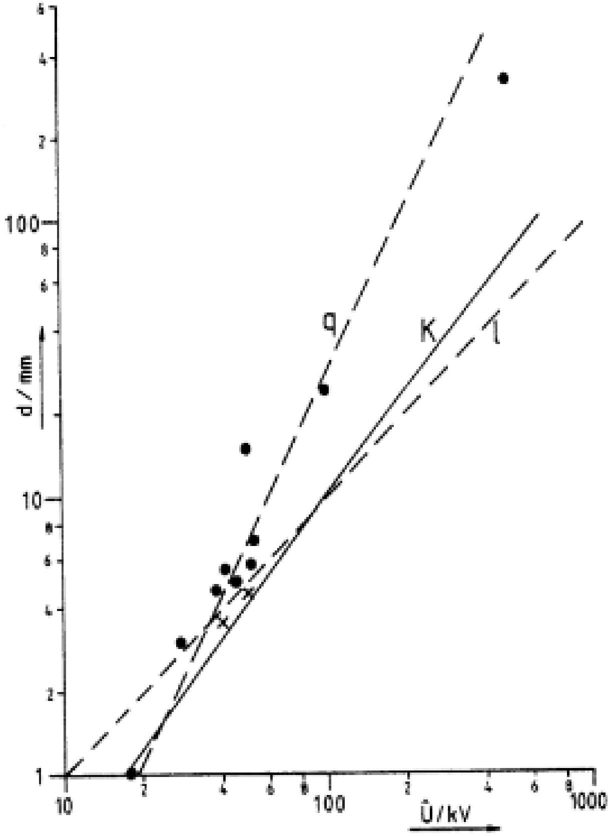


Fig. 3. Breakdown laws for extraction gaps. Û: breakdown voltage, d: gap width, q: quadratic law, K: Kilpatrick d.c. law, l: linear law. The filled circles indicate the limits d(Û) for existing or proposed systems, listed in [9]; the crosses show the limits for two widths of our second gap

Field emission-initiated breakdown

- The current density at a microprotrusion on the cathode electrode is described by the Fowler–Nordheim (FN) field emission equation:

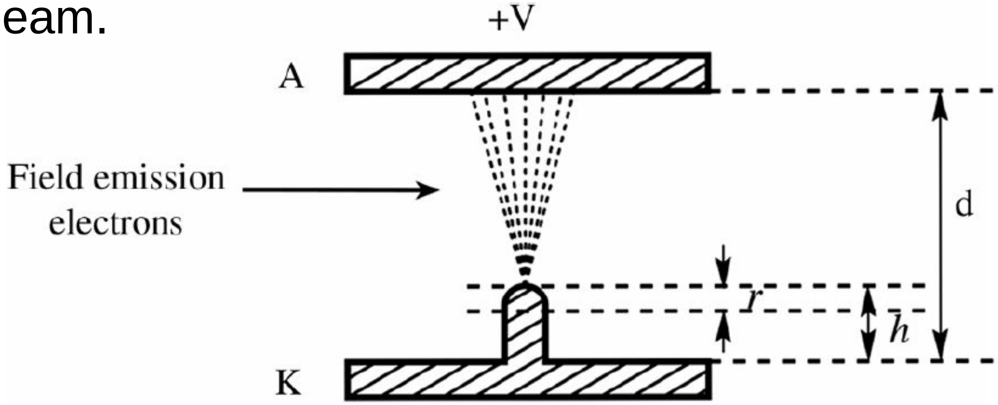
$$j_{FN} = C_1 E_p^2 e^{-C_2/E_p}$$

10^8-10^{10} A/cm^2

$$E_p = \beta E_{avg} = \beta \frac{V}{d} \approx \left(2 + \frac{h}{r}\right) \cdot \frac{V}{d}$$

10^6-10^8 V/cm

- The large current density would mean the emission of a large number of electrons n_e from the cathode.
- The large field emission current density would lead to Joule heating of the microprotrusion, resulting in melting, vaporization, and plasma formation.
- The metal vapor would also be produced by the heating of an anode spot by the impact of a high-energy electron beam.



Microparticle-initiated breakdown

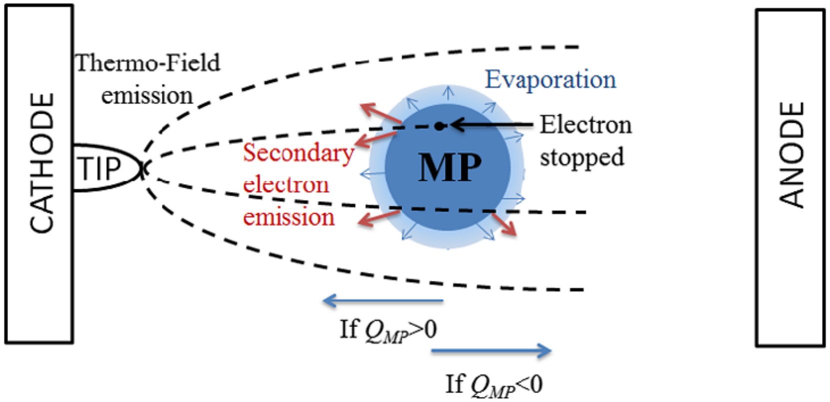
- The initiation of breakdown is due to detachment by electrostatic repulsion of a clump of material loosely adhering to one electrode, but in electrical contact with it; traversal by the clump of most or all of the high voltage gap, and impingement on an electrode at much lower, or at the lowest potential.

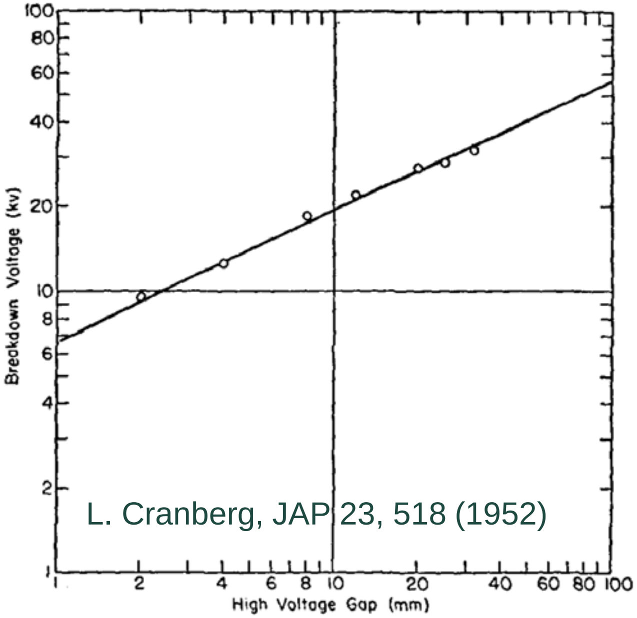
$Q_p \propto E$ (charge acquired by the particle)

$W_i = Q_p V \propto \frac{V^2}{d}$ (energy of the microparticle at the impact point on the anode)

- The breakdown will occur if the kinetic energy of the clump exceeds some critical value, then we obtain

$V_b \propto d^{1/2}$





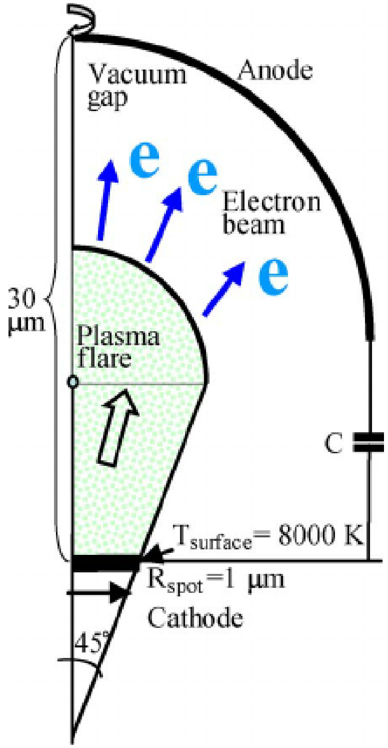
L. Cranberg, JAP 23, 518 (1952)

Plasma flare-initiated breakdown

- This type of breakdown takes place in a vacuum gap d on the application of a high-voltage, short-duration pulse.
- The high field intensity at a microprotrusion causes a large field emission current density, which results in a large field emission current at the tip. The mass of the tip explodes into a plasma flare if the Joule energy input (E_i) exceeds the boiling energy of the tip (E_c).

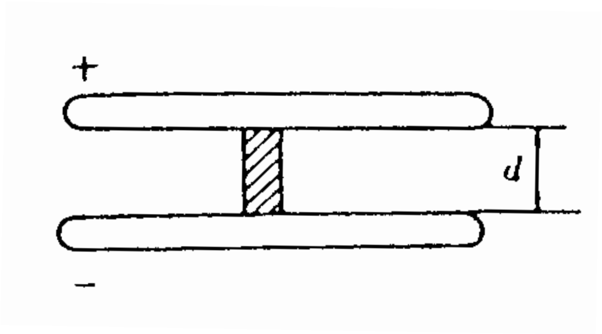
$$E_i = i_c^2 R\Delta t > E_c = m(C_p(T_m - T_0) + L_v)$$

- The higher the degree of ionization in the plasma flare, the higher the energy difference $E_i - E_c$. This plasma flare starts expanding toward the anode and the breakdown takes place when it bridges the gap.
- A plasma flare can also start from the anode when the electron emission from the cathode-initiated plasma front is high enough to explode the anode material at the impact point. The gap will be bridged by the plasma when the two plasma fronts meet.

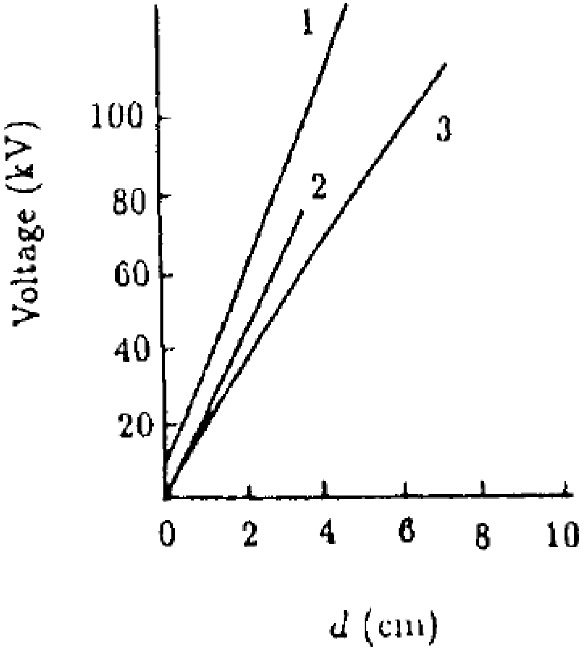


Effect of an insulator in the gap

- The general effect of the insulator in the gap is to lower the breakdown voltage.



(1) Breakdown voltage in the air
(2) Flashover voltage with a paraffin cylinder
(3) Flashover voltage with a ceramic cylinder



- Surface flashover is an electrical breakdown that occurs on or just above the surface of an insulator when a sufficiently high voltage stress is applied.

- This phenomenon is distinct from bulk breakdown which occurs within the insulating material or vacuum breakdown where the discharge develops in vaporized electrode material.

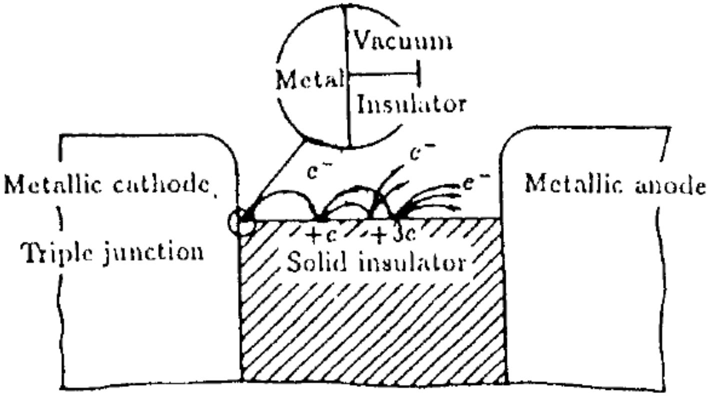
Mechanism of surface flashover

① Electrons are emitted at the triple junction of cathode, insulator, and vacuum due to field enhancement at microscopic irregularities and dielectric mismatch.

② The electrons are accelerated in the field between the cathode and anode. Some of these electrons impact the surface of the insulator. Depending on the particular material, the angle of incidence, and the impact energy, possibly more secondary electrons are emitted.

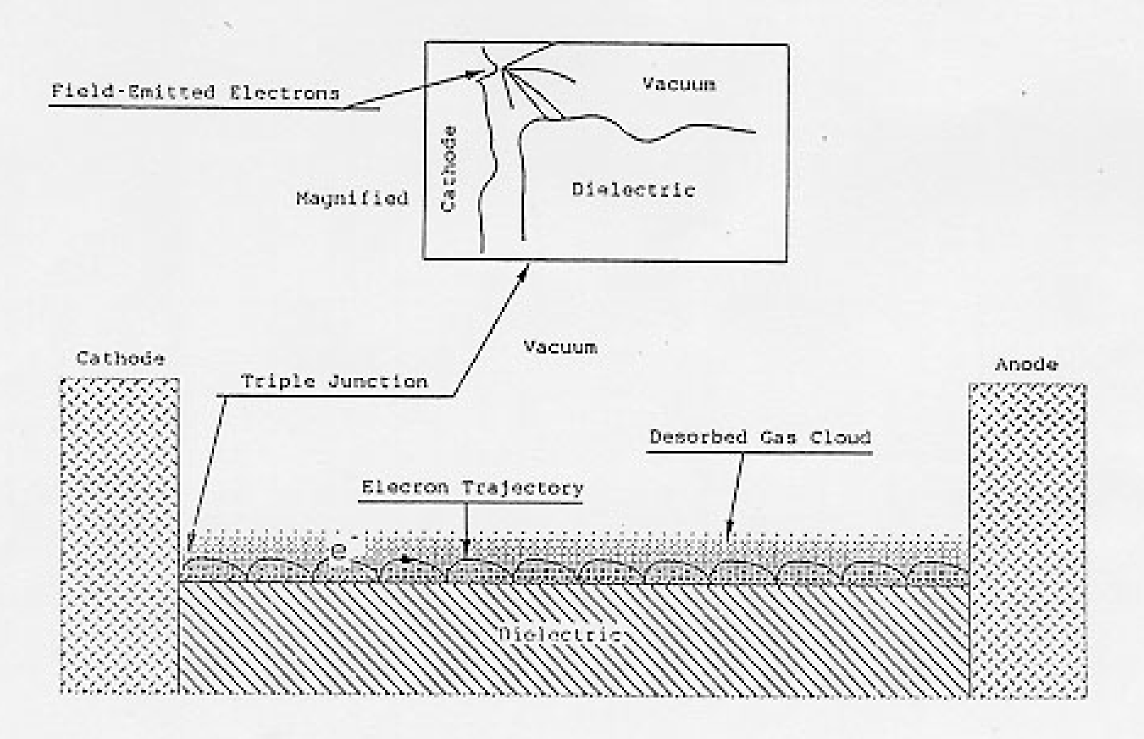
③ When more than one secondary electron is emitted, then that part of the insulator surface will acquire a positive charge.

④ Once the surface acquires a positive charge, the trajectories of the emitted secondary electrons are likely to reimpact the surface in such a way that more than one additional secondary is emitted for each impacting electron.



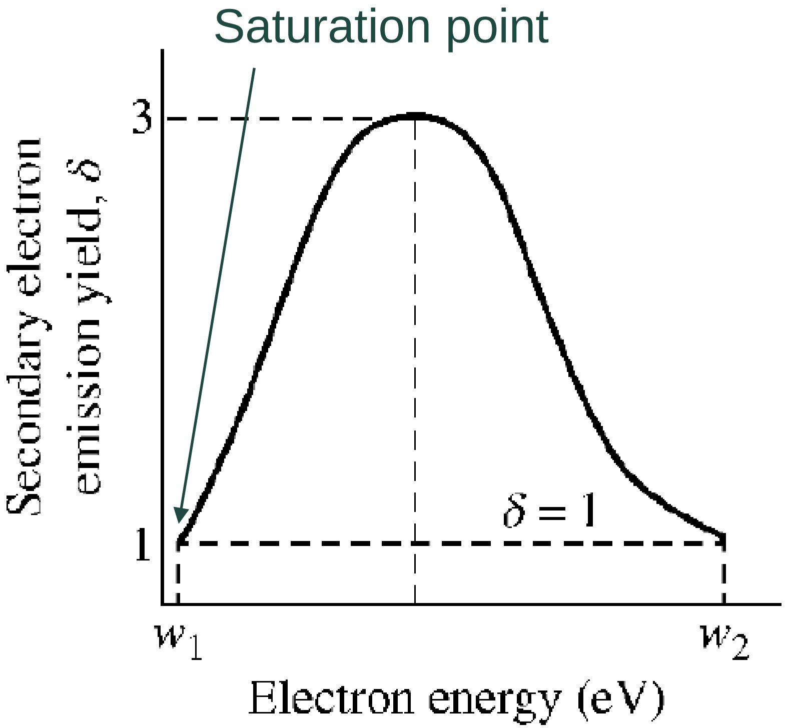
Mechanism of surface flashover

⑤ Thus, an avalanche of electrons hopping along the surface of the insulator toward the anode occurs. This avalanche knocks off gas molecules that were adsorbed on the insulator surface. When the pressure in this layer of gas reaches a critical value, ordinary gas phase breakdown due to electron impact ionization of the gas occurs.



Secondary electron emission from dielectric surfaces

- When energetic particles impinge on a solid, they can impart their energy, exciting electrons within the material. If this energy is sufficient to overcome surface energy barriers, such as the work function, electron affinity, or surface charge potential, electrons can escape from the material.
- For $w > w_1$, the insulator surface will attain a net positive charge. Then, electrons are less affected by the external electric field, driving the energy of the incident electron back toward w_1.
- For $w < w_1$, the insulator surface will attain a net negative charge. Then, electrons gain more energy from the external electric field, and the operation point will again tend toward w_1.
- After a period of time (~ns), the energies of all of the impacting electrons will converge to w_1. It is referred to as the saturated secondary electron avalanche condition.



Electron trajectories

A. S. Pillai and R. Hackam, JAP 53, 2983 (1982)

- The Pillai–Hackam model assumes that a secondary electron is emitted normal to the surface with an initial velocity v_0. The equation of motion gives the trajectories:

$$v_x(t) = \frac{e}{m}E_p t \qquad v_y(t) = v_0 - \frac{e}{m}E_n t$$

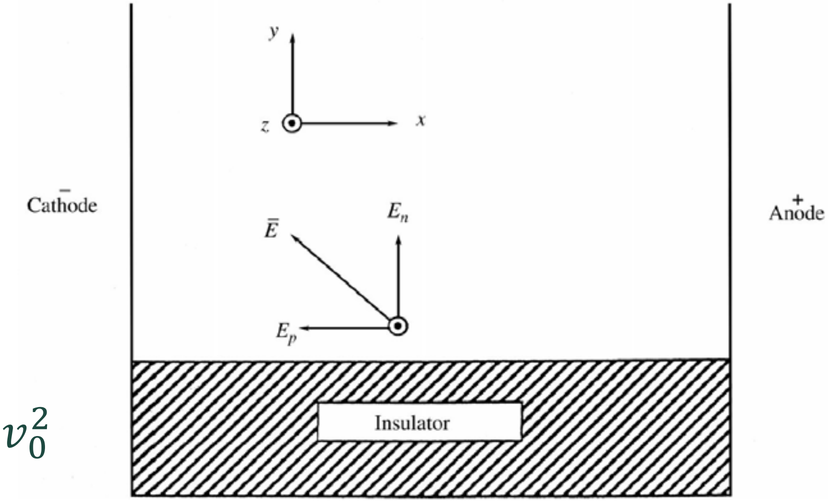
$$x(t) = \frac{e}{m}E_p \frac{t^2}{2} \qquad y(t) = v_0 t - \frac{e}{m}E_n \frac{t^2}{2}$$

- The trajectory of an electron emitted from the surface shows that the electrons are driven back into the surface at the time t_0 satisfying $y(t_0) = 0$. Then, we obtain the electron energy at impact:

$$w_i = \frac{m}{2}(v_x^2 + v_y^2) = \frac{m}{2}v_0^2\left(1 + 4\left(\frac{E_p}{E_n}\right)^2\right)$$

- After the secondary electron avalanche has saturated, $w_i = w_1$. This condition gives

$$\tan\varphi = \frac{E_n}{E_p} = \sqrt{\frac{2w_0}{w_1 - w_0}} \qquad w_0 = \frac{1}{2}mv_0^2$$



Saturated secondary electron emission avalanche

- Pillai and Hackam formulated a breakdown criterion for surface flashover in vacuum by incorporating electron-stimulated desorption of gas from the insulator surface.
- From the normal electric field component at saturation, an electron current density normal to the surface is given by

$$J_n = \frac{2\epsilon_0 v_1 E_p^2 \tan\varphi}{w_1} \qquad w_1 = \frac{1}{2} m v_1^2$$

- An electron-stimulated gas desorption rate is proportional to J_n as following:

$$D_0 = \frac{\gamma}{e} J_n = \frac{2\gamma\epsilon_0 v_1 E_p^2 \tan\varphi}{e w_1}$$

γ: gas desorption coefficient

- The density of desorbed gas is

$$N_d = \frac{D_0}{v_d}$$

v_d: velocity of the desorbed gas

- The amount of desorbed gas per unit area of the insulator is

$$M = N_d l = \frac{D_0}{v_d} l = \frac{2\gamma\epsilon_0 v_1 E_p^2 \tan\varphi}{e w_1 v_d}$$

l: length of the insulator

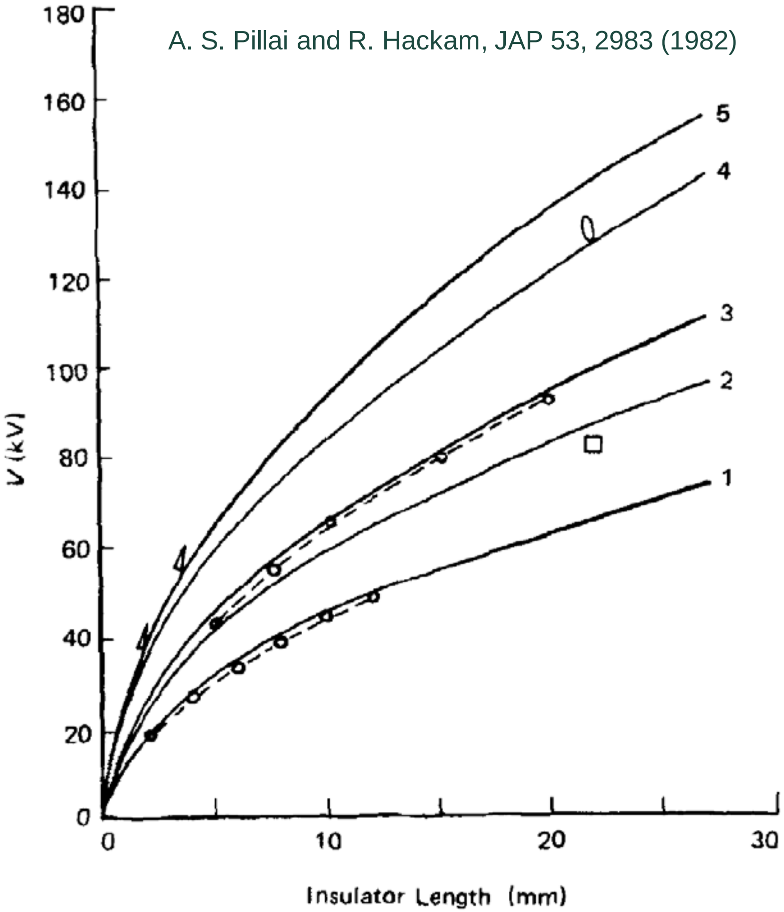
Saturated secondary electron emission avalanche

- As the quantity of gas above the insulator surface increases, the local gas density increases that lead to Paschen breakdown in the desorbed gas. It gives the breakdown electric field for a crucial amount of gas M_{cr}:

$$E_{br} = \sqrt{\frac{e w_1 v_d M_{cr}}{2\gamma\epsilon_0 v_1 l \tan\varphi}}$$

- The breakdown voltage under these uniform field conditions is given by

$$V_{br} = \sqrt{\frac{e w_1 v_d M_{cr} l}{2\gamma\epsilon_0 v_1 \tan\varphi}} \propto \sqrt{l}$$



A. S. Pillai and R. Hackam, JAP 53, 2983 (1982)

FIG. 6. Comparison of calculated and measured surface flashover voltage for different insulating materials as a function of insulator length. ($M_{cr} \approx 1.4\times10^{18}$ cm^{-2}) (1) Alumina Ceramic[18] ($\gamma = 8$, $A_1 = 20$ eV); (2) Quartz ($\gamma = 8$, $A_1 = 30$ eV); (3) Plexiglass[16] ($\gamma = 5$, $A_1 = 25$ eV); (4) Pyrex glass ($\gamma = 5$, $A_1 = 40$ eV); (5) Quartz ($\gamma = 5$, $A_1 = 50$ eV); (——) Calculated; (– – –) Measured; □, Quartz (Measured[19]); 0, Glass (Measured[19]); △, Quartz (Measured, this paper).

Electric field enhancement near “cathode triple junction”

- The presence of a small void strongly concentrates the equipotential lines, i.e. it greatly increases the local electric field.
- The degree of concentration depends upon the permittivity of the insulator.
- Incorporation of graded permittivity significantly reduces the concentration effect of a small void at the triple junction, thus improving the holdoff performance of the insulating system.

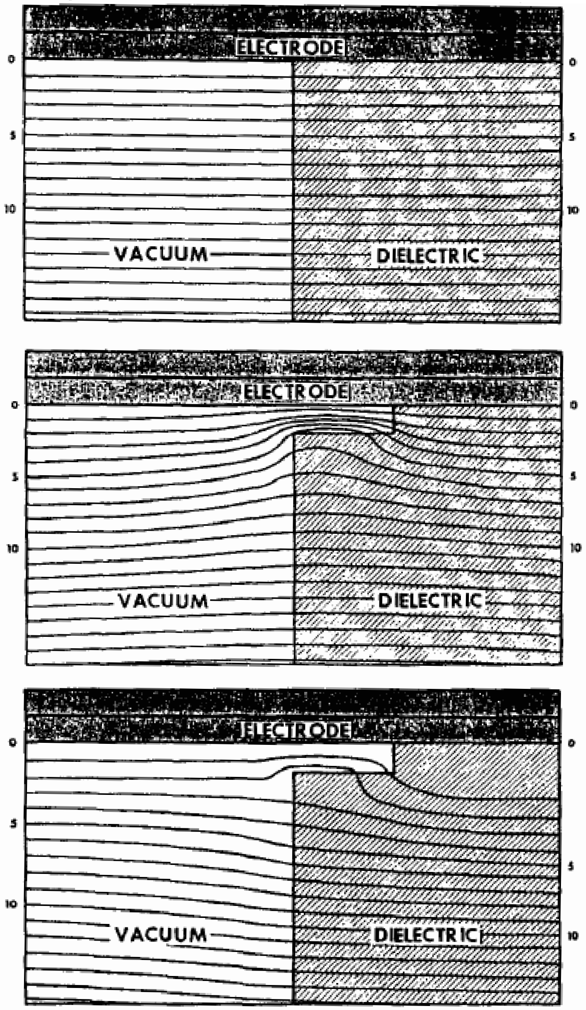
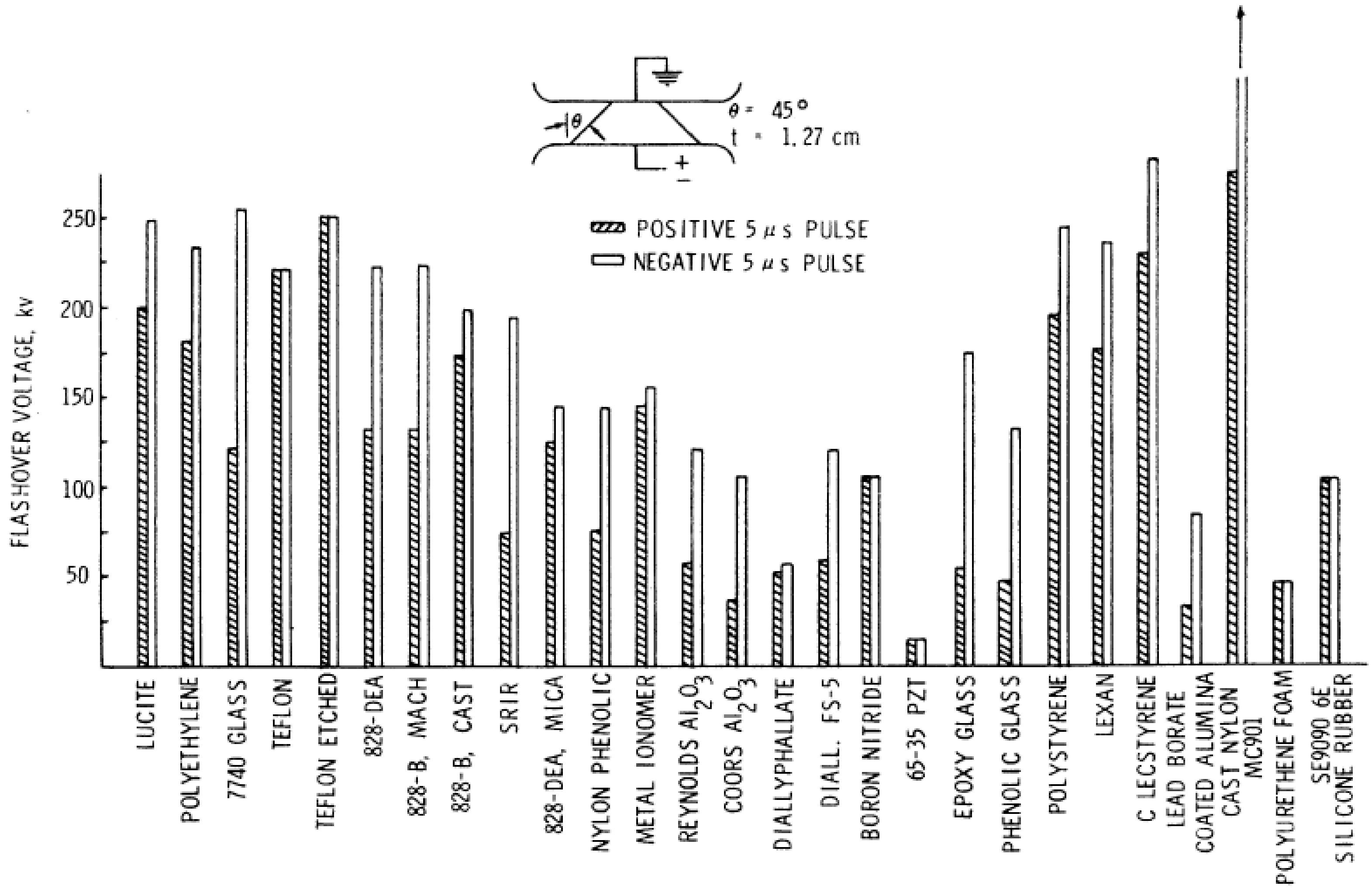


Figure 2.

Equipotential plot- triple junction region, (a): Perfect contact at junction, (b): void at junction, (c): effect of graded insulator permittivity.

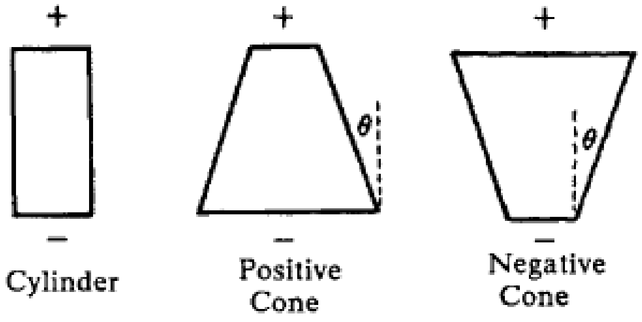
Effect of insulator material

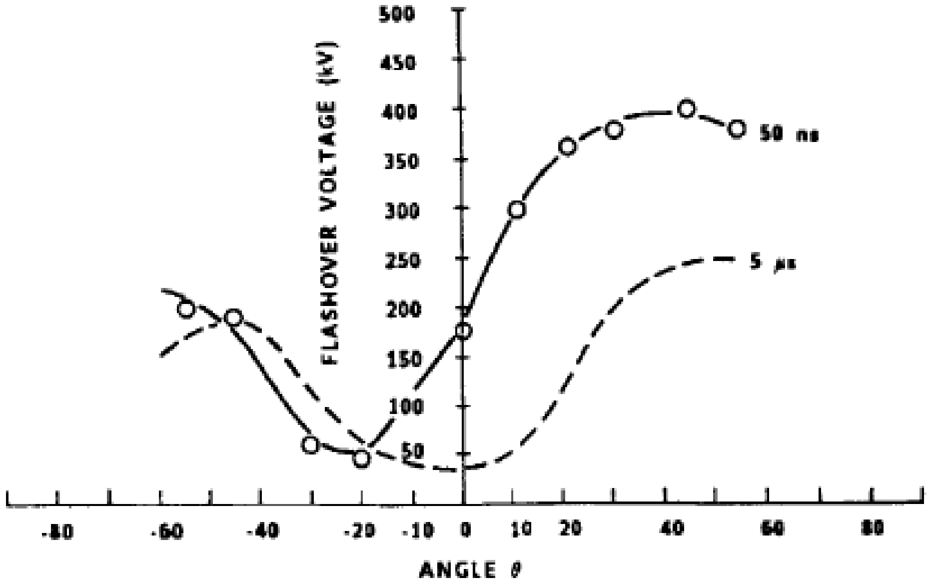


O. Milton, IEEE Trans. Electrical Insulation EI-7, 9 (1972)

Effect of insulator geometry

- The exact shape of an insulator can have a strong effect upon its surface flashover.





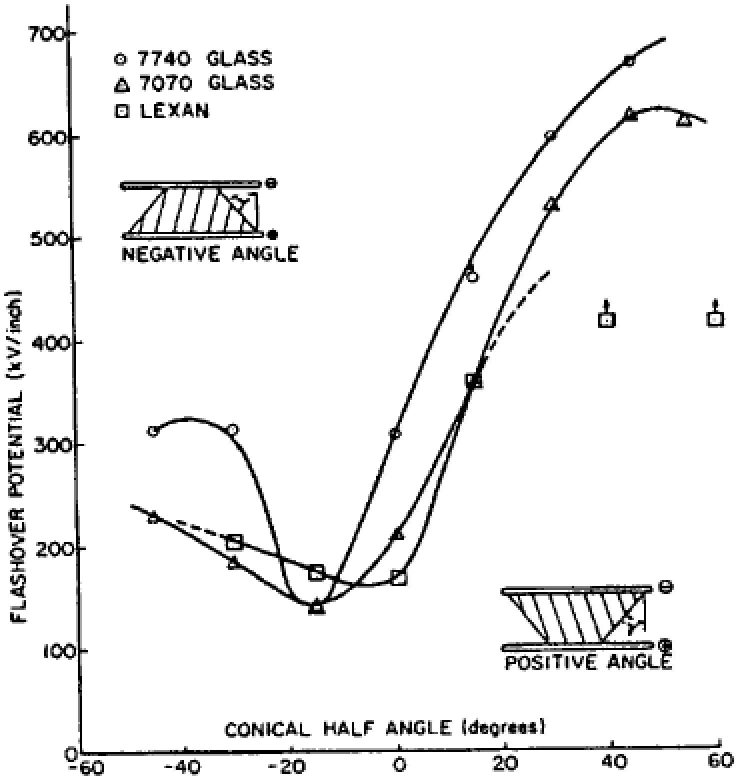


Figure 7.

Surface flashover field *vs.* insulator cone angle for 75 ns pulses. $d = 9.5$ mm (from Watson, [55])

Effect of insulator geometry

- The exact shape of an insulator can have a strong effect upon its surface flashover.

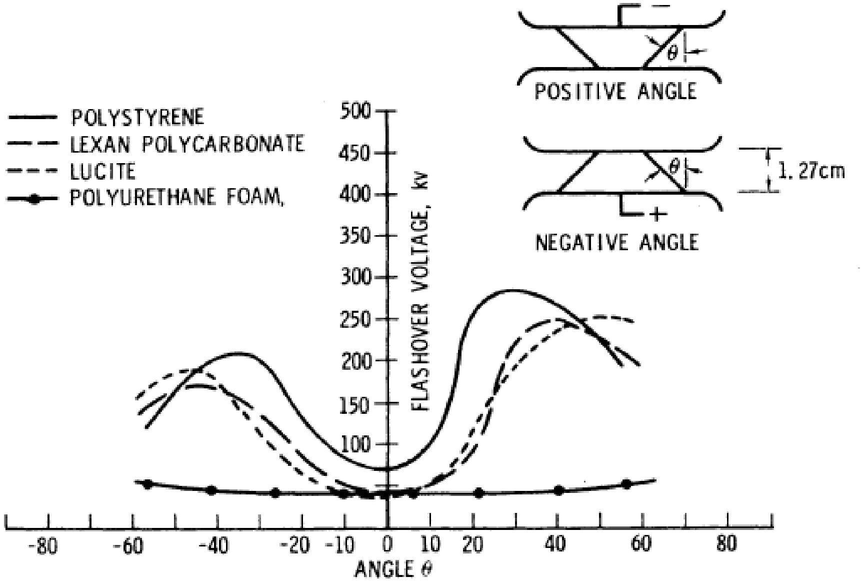


Fig. 8. Flashover voltage versus angle θ for some insulators. Pulse rise time about 5 μs.

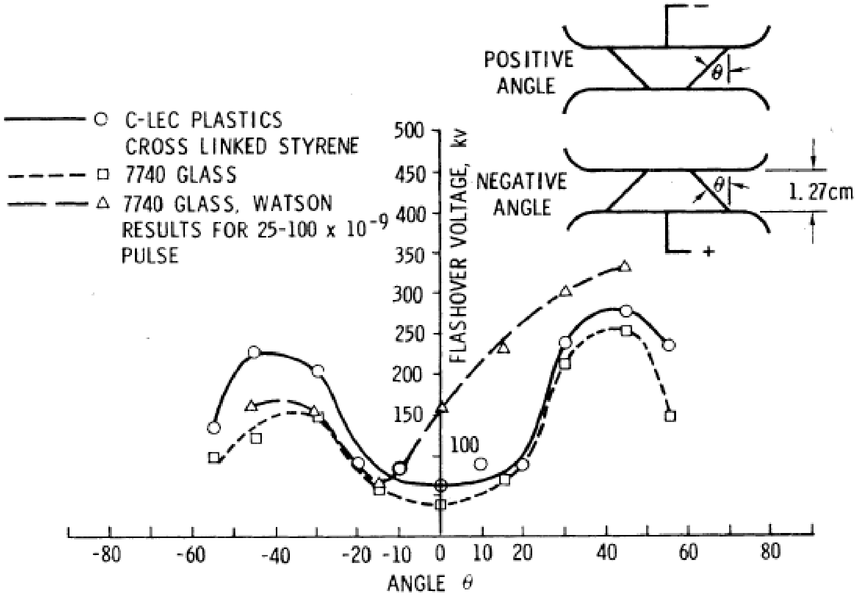


Fig. 9. Flashover voltage versus angle θ for 7740 glass and cross-linked styrene. Pulse rise time about 5 μs.

O. Milton, IEEE Trans. Electrical Insulation EI-7, 9 (1972)

Geometry effect of an insulator

- The initiation of a surface flashover is usually begun by the emission of electrons (generally by field emission or thermal-field emission) from the triple junction.
- Minimizing the electric field near the cathode triple junction is critical in the design of vacuum insulation system.

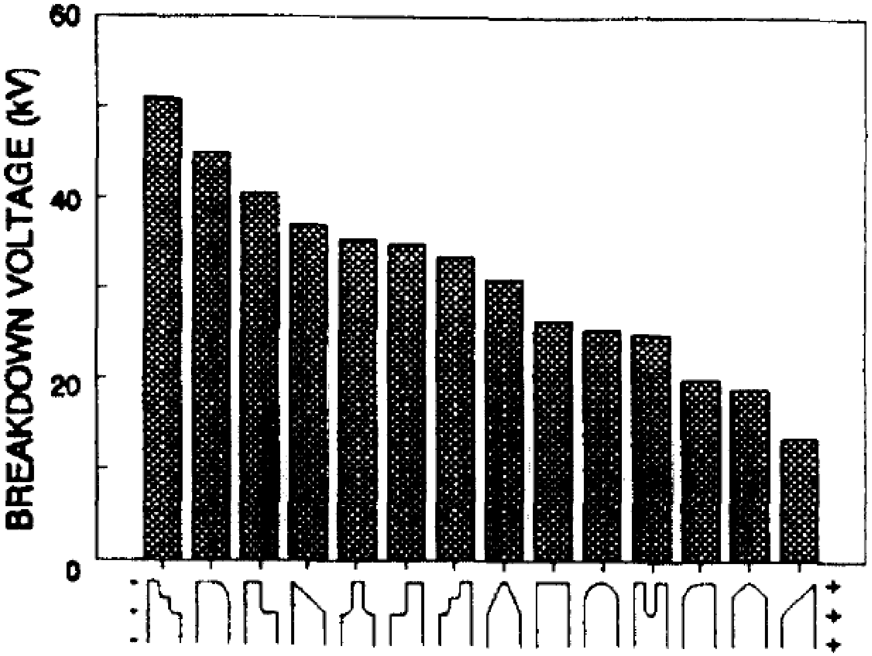


Figure 1.

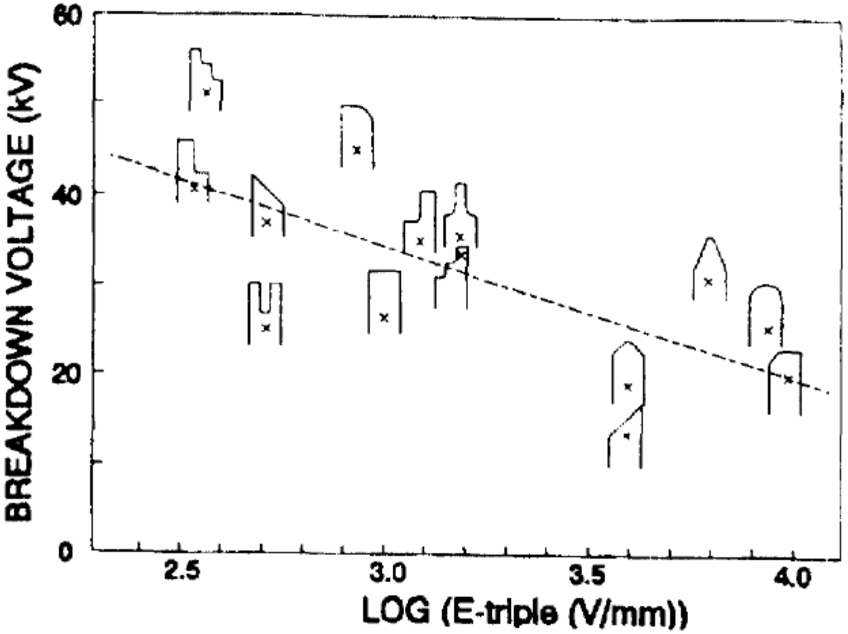


Figure 2.

- Other mechanisms also play a significant role.

Cathode recess effect: charge trap

- Chamfering the cathode end of the insulator can be effective in increasing its voltage hold-off performance. This probably occurs because electrons accumulating on the surface of the chamfer reduce the electric field at the cathode triple junction.

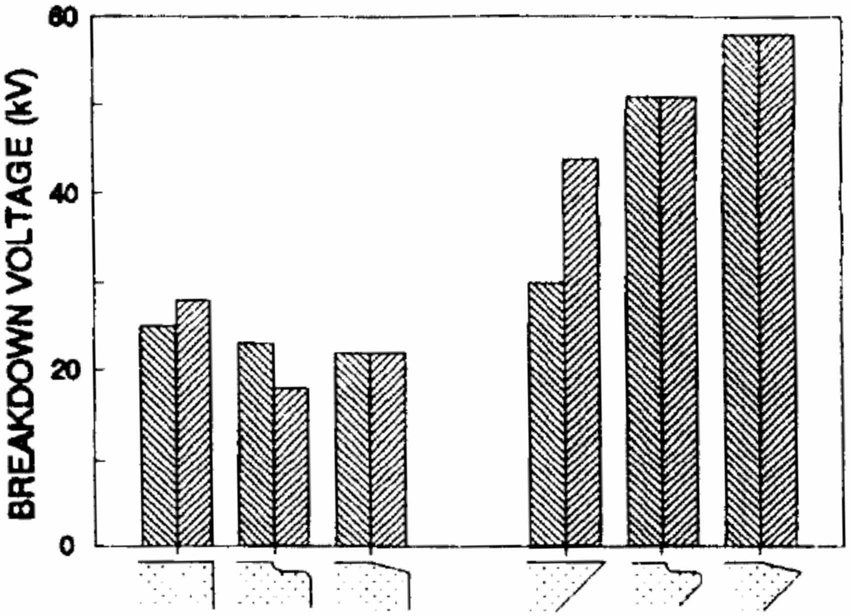


Figure 5.

Unconditioned breakdown voltages obtained for recessed insulators together with the reference shapes from which they are derived. Two samples of each geometry have been tested.

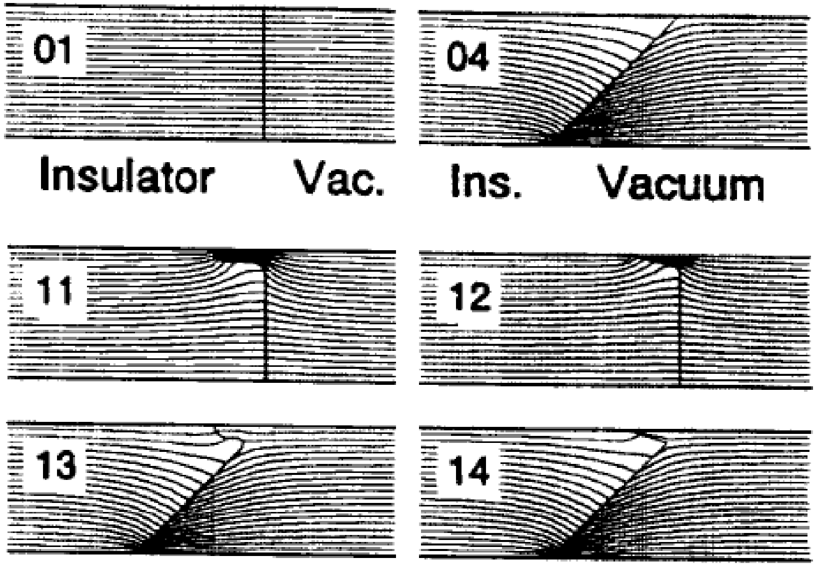
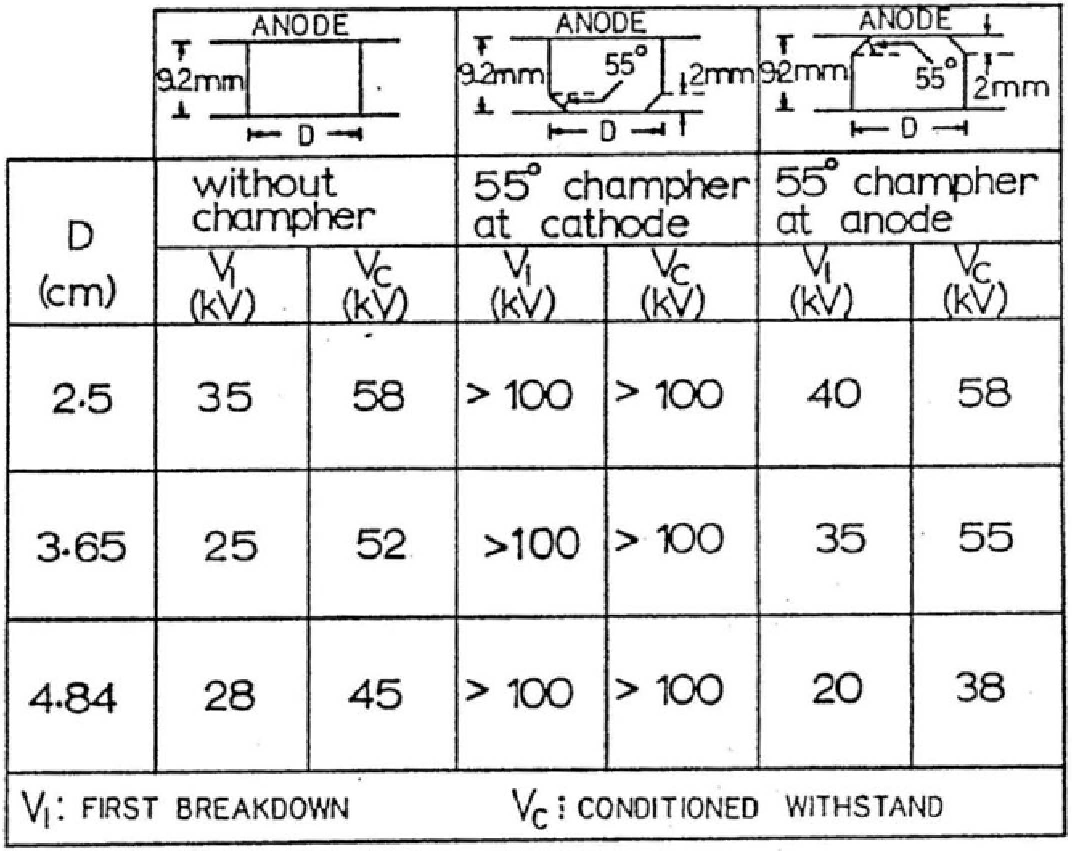


Figure 6.

Modification of electrostatic equipotential line plot caused by cathode recess (compare Figure 4). For the cylindrical insulator the cathode recess forces the electrons to move towards the insulator surface, whereas they are repelled in case of the conical insulator.

Cathode recess effect: charge trap

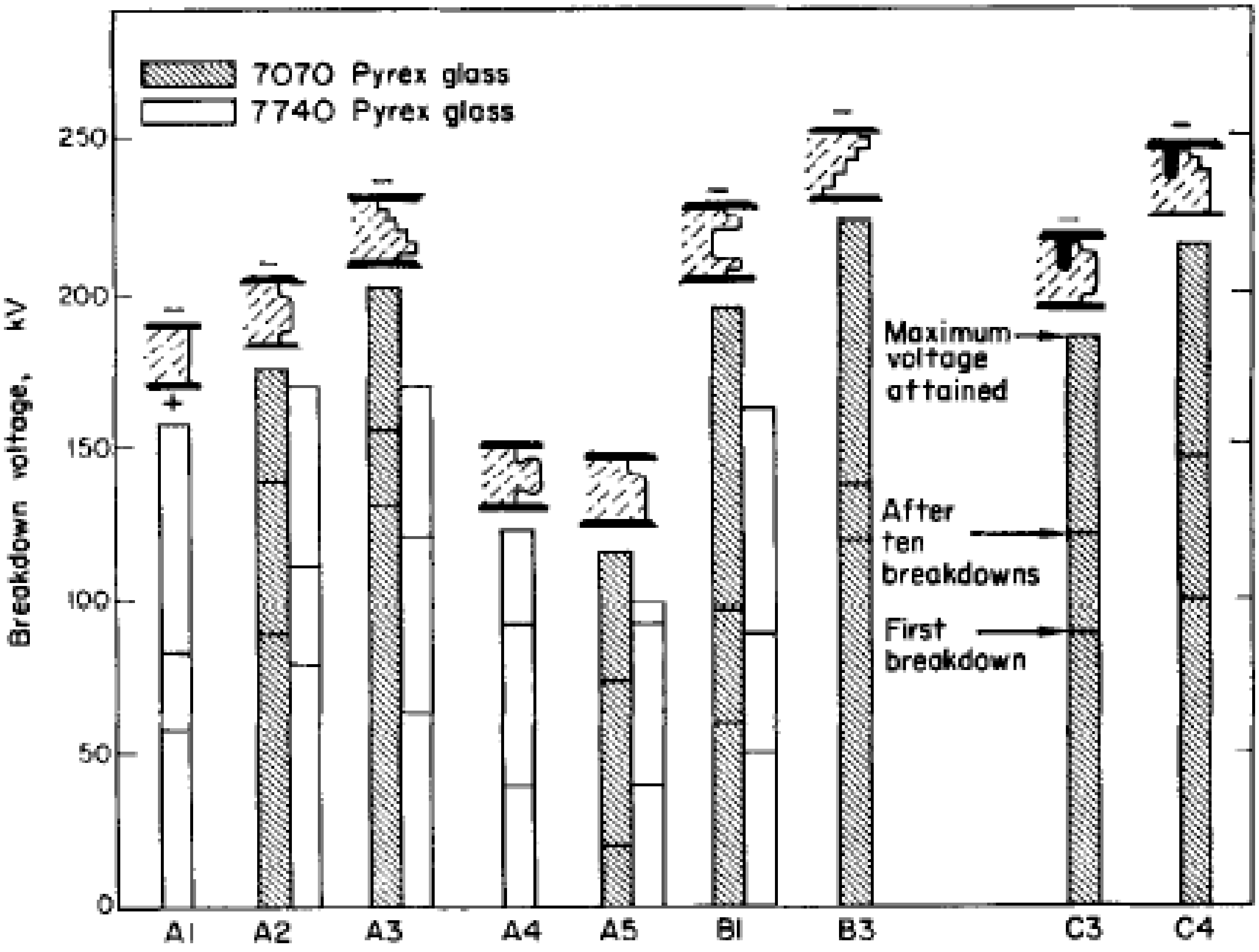
- Mechanism: high E field near the triple junction → electron emission → trapping of electrons in the chamfered surface → negative surface charging → stress relief at the cathode.



D (cm)	without champher V_I (kV)	without champher V_C (kV)	55° champher at cathode V_I (kV)	55° champher at cathode V_C (kV)	55° champher at anode V_I (kV)	55° champher at anode V_C (kV)
2·5	35	58	> 100	> 100	40	58
3·65	25	52	>100	> 100	35	55
4·84	28	45	> 100	> 100	20	38

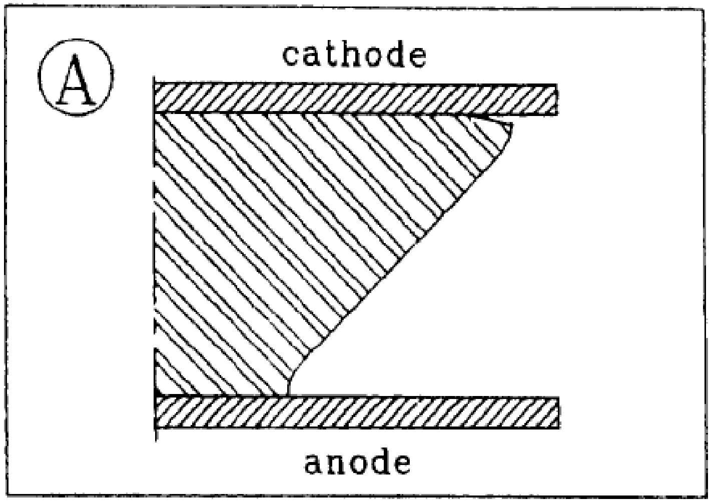
V_I: FIRST BREAKDOWN V_C: CONDITIONED WITHSTAND

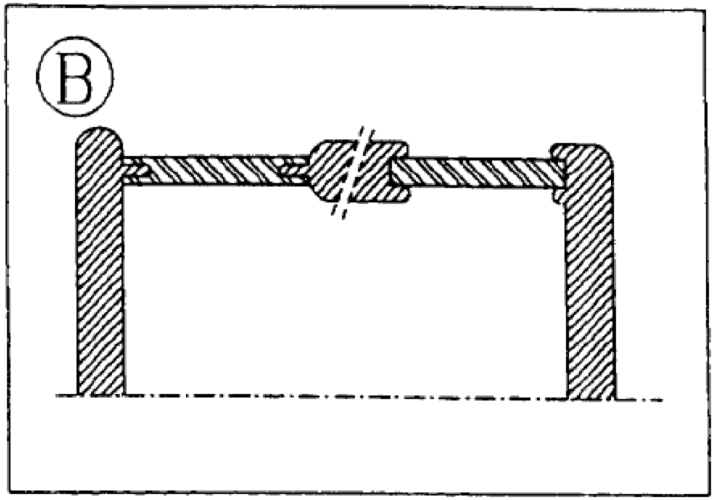
Effect of insulator geometry with charge trap

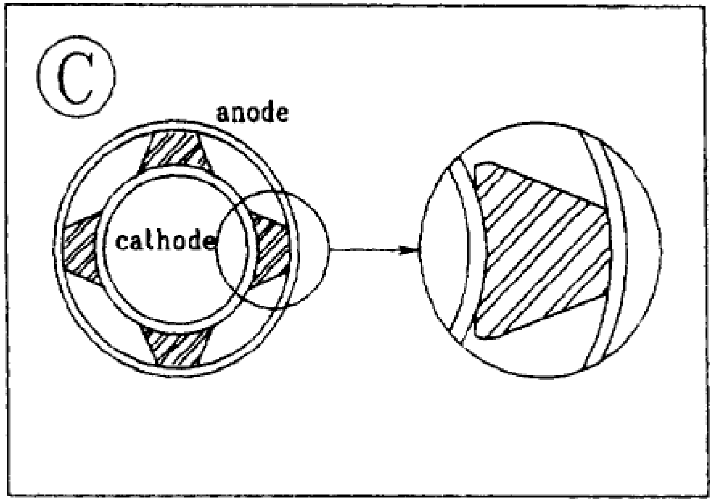


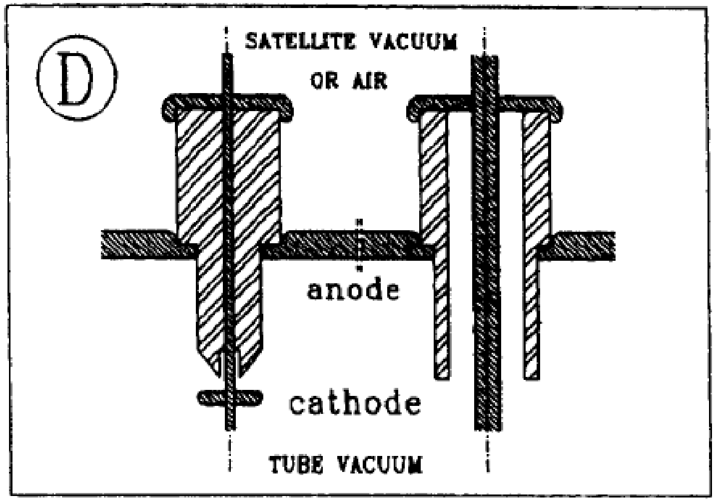
R. Hawley, Vacuum 18, 383 (1968)

Examples of optimized insulator designs

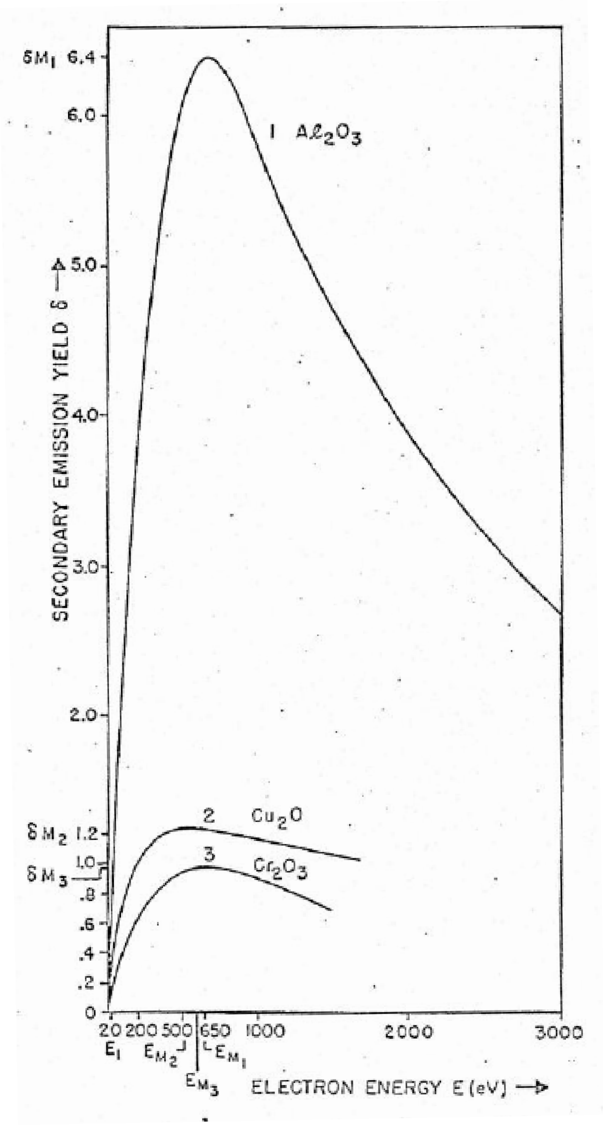


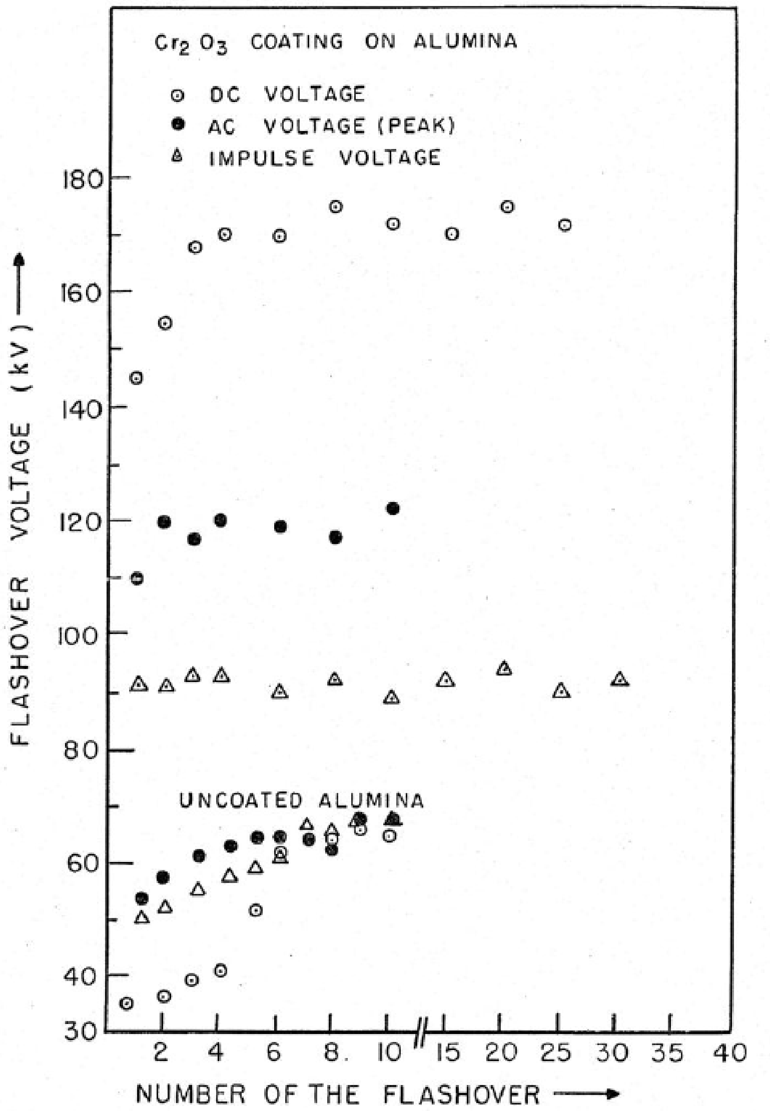




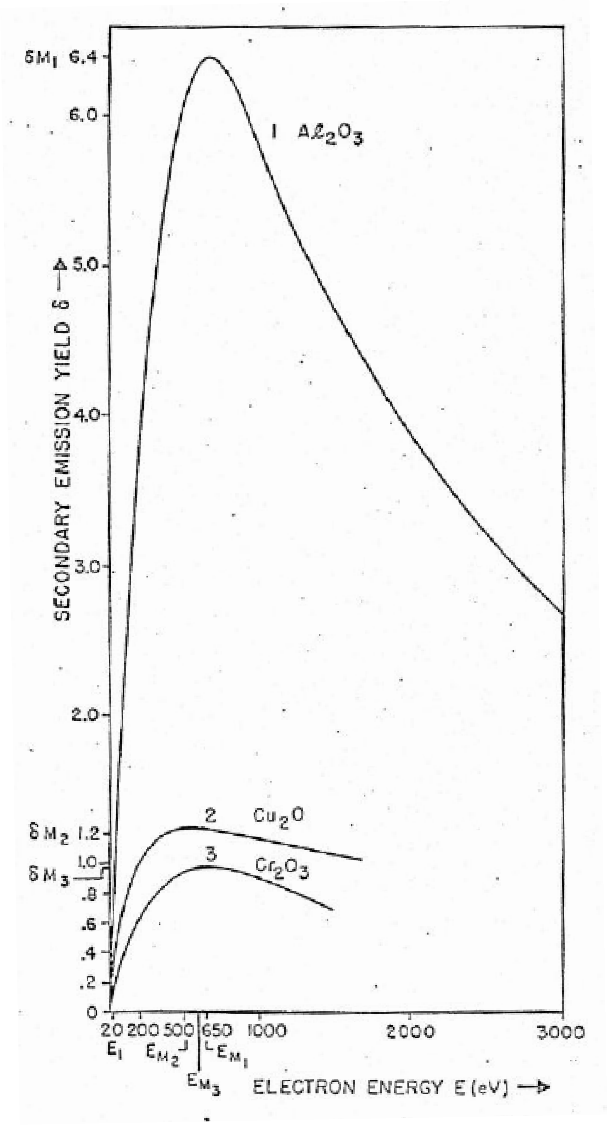


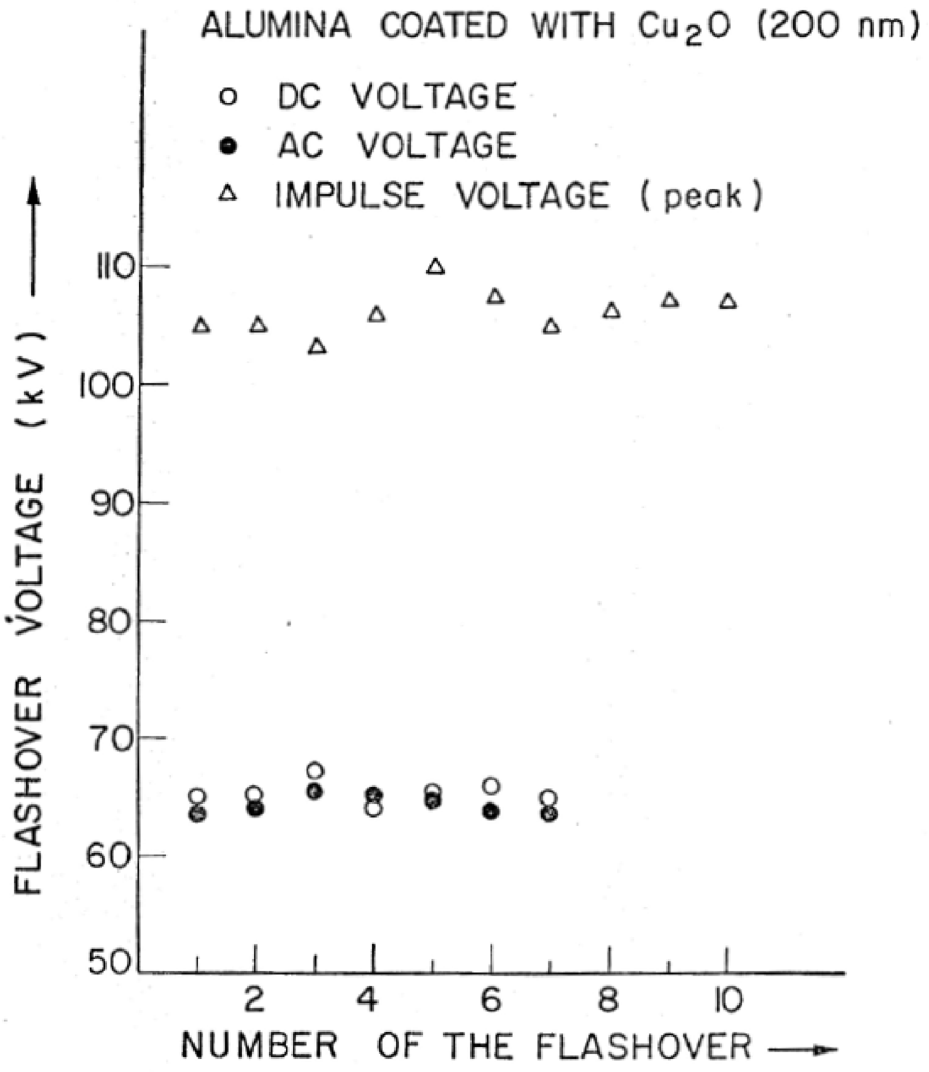
Effect of surface coating





Effect of surface coating





Conditioning

- Current conditioning: The current in the breakdown event is restricted to hundreds of microamperes by including a current limiting resistor in the high-voltage power supply. A breakdown pulse removes a microprojection and the following pulse shifts to another microprojection site.
- Spark conditioning: Impulse voltages with durations of hundreds of nanoseconds are used. The spark currents during breakdown are limited to a few amperes.
- Glow discharge conditioning: Various gases like hydrogen, helium, argon, nitrogen, SF_6, or dry air are used. (e.g.) Argon/oxygen mixture: The argon component of the discharge provides physical sputtering, whereas oxygen provides chemical combustion of heavy hydrocarbons into easily removable components such as CO, CO_2, and H_2O.
- Outgassing and annealing: Outgassing is minimized by heating the electrodes in a high-temperature vacuum furnace at temperatures ranging from 250 to 1500°C with time periods up to several hours. The electrodes can be annealed separately at the highest temperatures to achieve the full advantages of annealing such as the removal of residual stresses.

Effect of conditioning

- The insulator surface collects charge due to the application of breakdowns. The breakdown voltage gain of insulators obtained by conditioning with a number of breakdowns with limited energy, is partly due to surface charging.
- The faster rise in breakdown voltage in the second series of breakdowns shows that also a more permanent type of conditioning has taken place, which is ascribed to the removal of emission sites.
- The gain in breakdown voltage may be lost when the surface charge is lost.

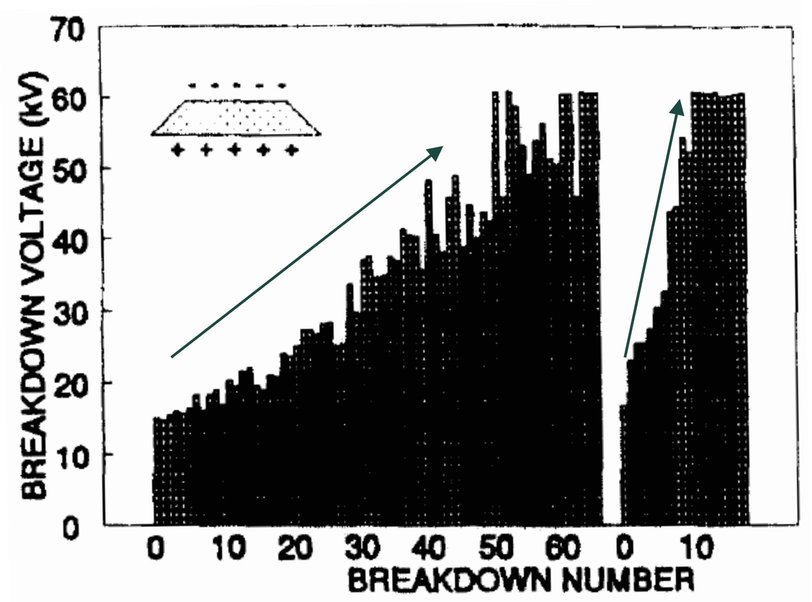
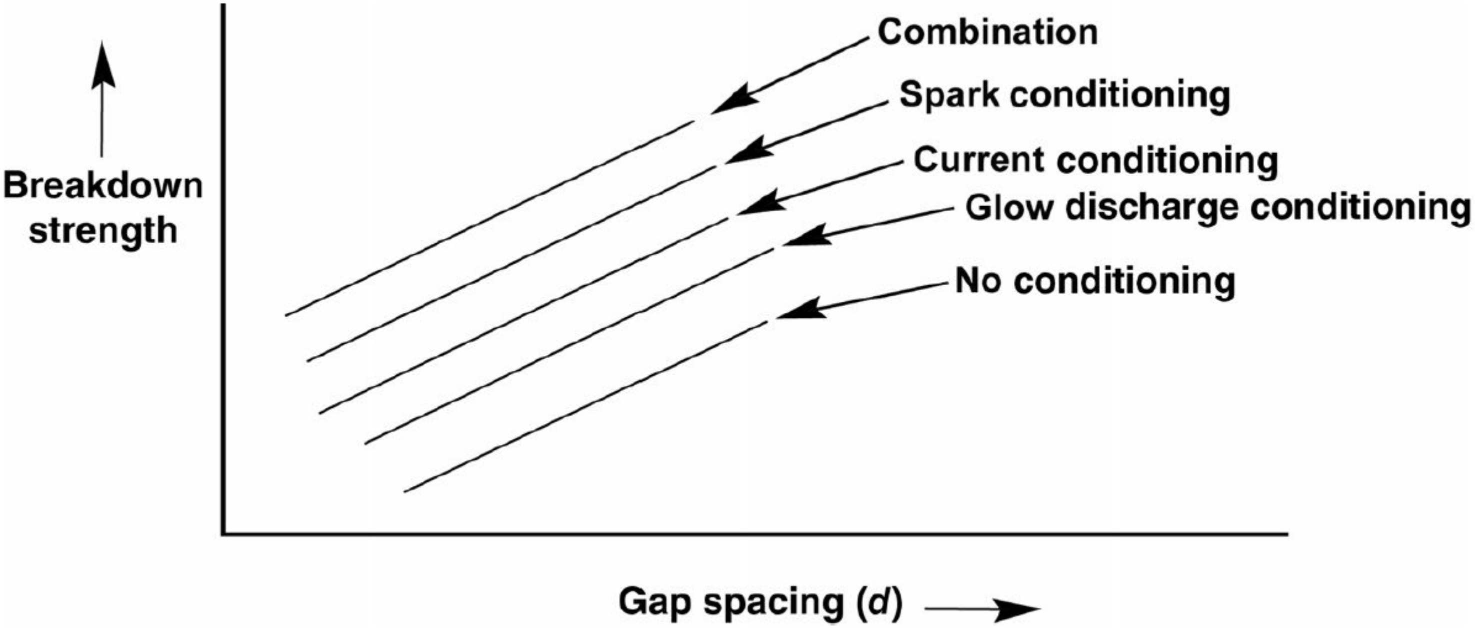


Figure 3.

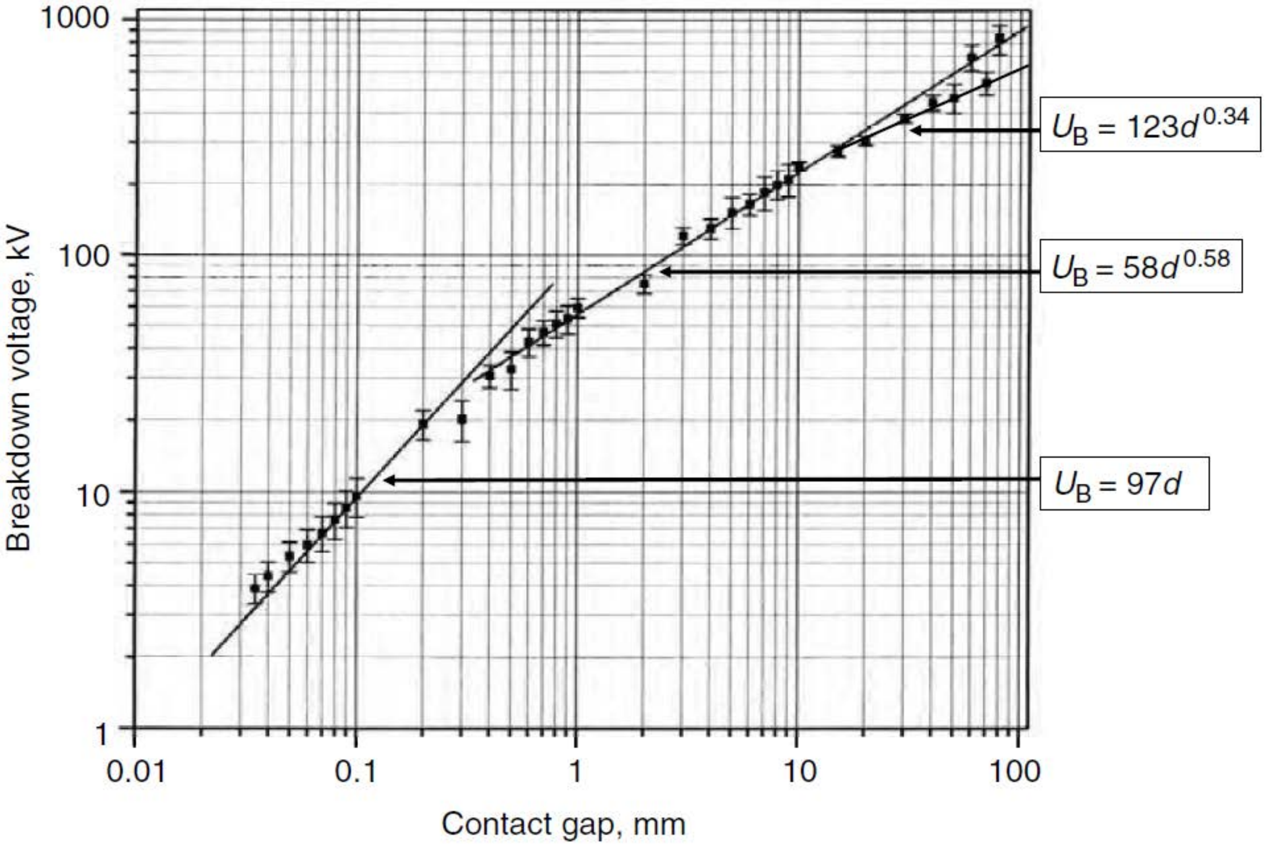
Example of measured breakdown voltage evolution. After 67 breakdowns the surface charge is removed with a low pressure nitrogen discharge (no voltage applied).

Effect of conditioning

- The best performance is obtained by employing a combination of conditioning techniques.



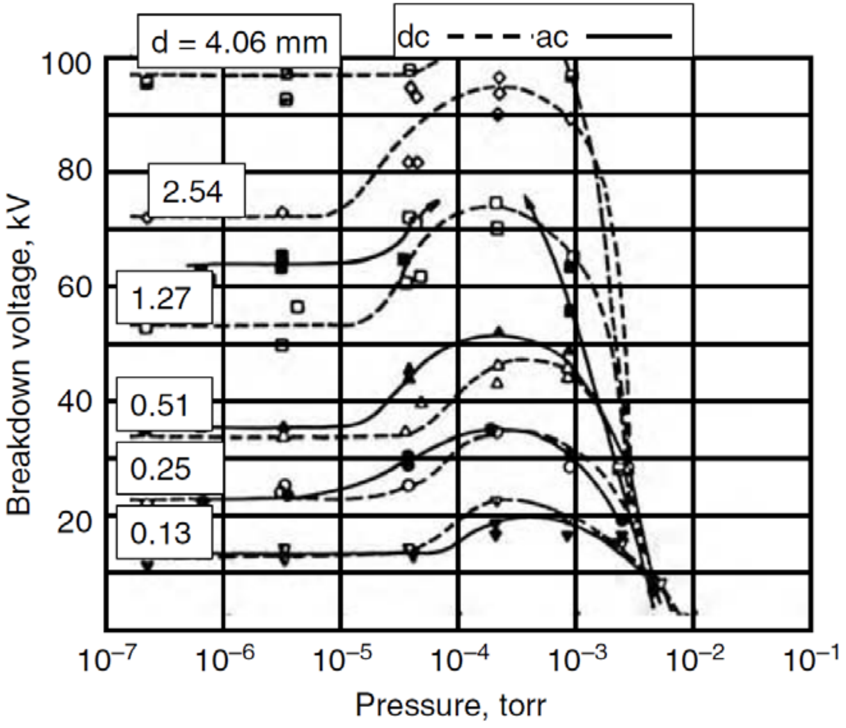
Effect of gap distance

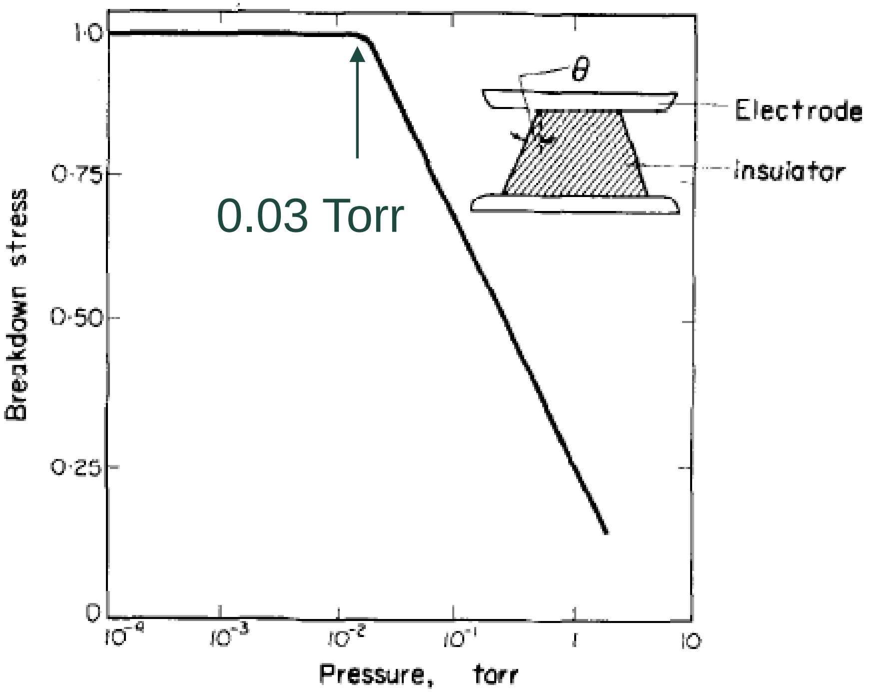


P. Slade, The Vacuum Interrupter (2008)

Effect of gas pressure

- For short insulators, variation of ambient pressure appears to have little or no effect on the breakdown voltage.
- For longer insulators, it is shown that there is a most definite dependence of the breakdown voltage on pressure.





0.03 Torr

Figure 4. Breakdown stress versus pressure (After Smith[17]) Insulator right cone 2.5 cm long oiled perspex with half angle of 25°. Voltage 30 ns pulses.

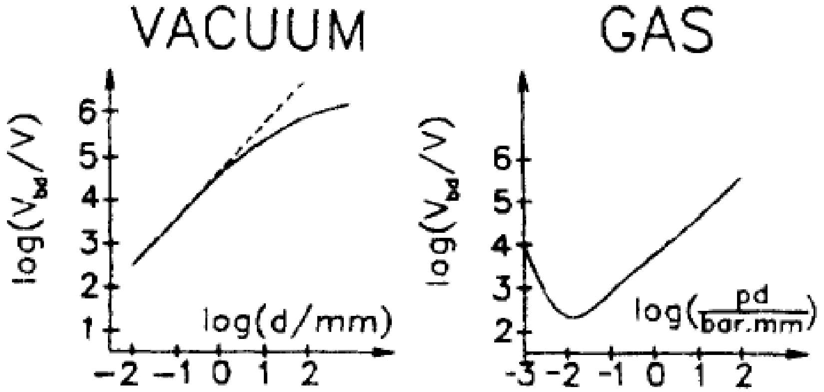
P. Slade, The Vacuum Interrupter (2008)

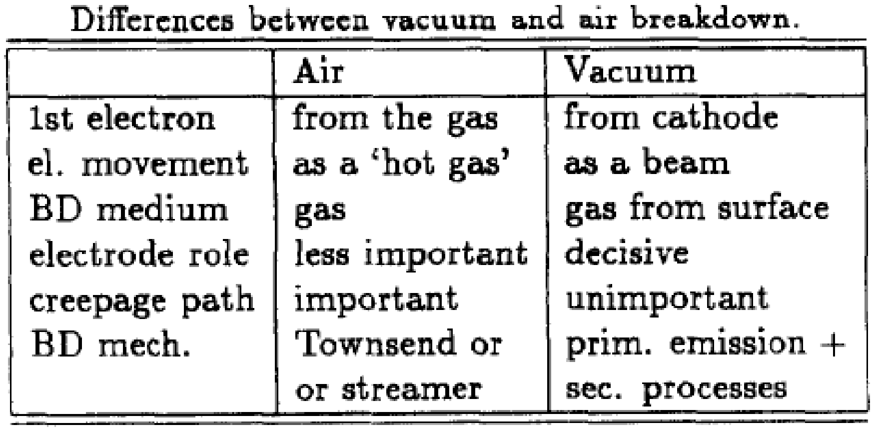
R. Hawley, Vacuum 18, 383 (1968)

Vacuum breakdown vs. gas breakdown

- In vacuum, breakdown is initiated by electron emission from microscopic protrusions or imperfections at the negative electrode, across the barrier of the work function. Secondary emission is caused by energetic electrons impinging on the insulator surface.

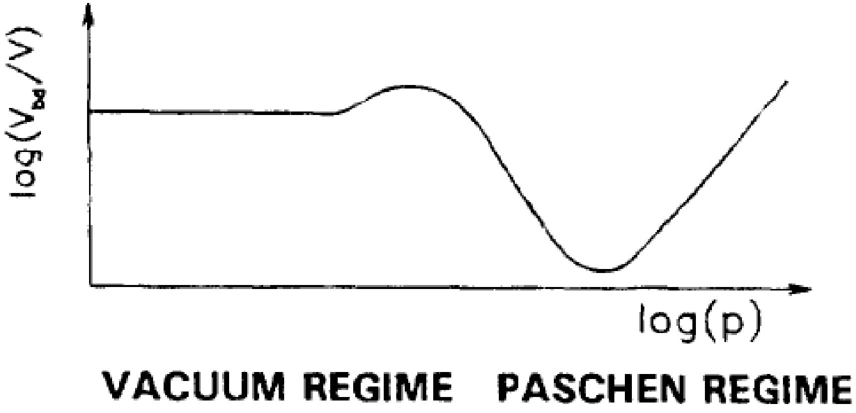
- In air, charge carriers are produced in an avalanche of a certain macroscopic distance. Microscopic field enhancements are not very important, provided their scale length is short compared to the avalanche length.





Differences between vacuum and air breakdown.

	Air	Vacuum
1st electron	from the gas	from cathode
el. movement	as a 'hot gas'	as a beam
BD medium	gas	gas from surface
electrode role	less important	decisive
creepage path	important	unimportant
BD mech.	Townsend or or streamer	prim. emission + sec. processes



Magnetic insulation

- The presence of a magnetic field greatly enhances the insulating properties of vacuum gaps. At sufficiently high magnetic field, the electron is trapped and orbits near the cathode. A large number of electrons emitted by the cathode thus form a cloud on the cathode.
- Above a critical value of magnetic field, electrons cannot cross to the anode and the gap is magnetically insulated. This phenomenon is called magnetic insulation.

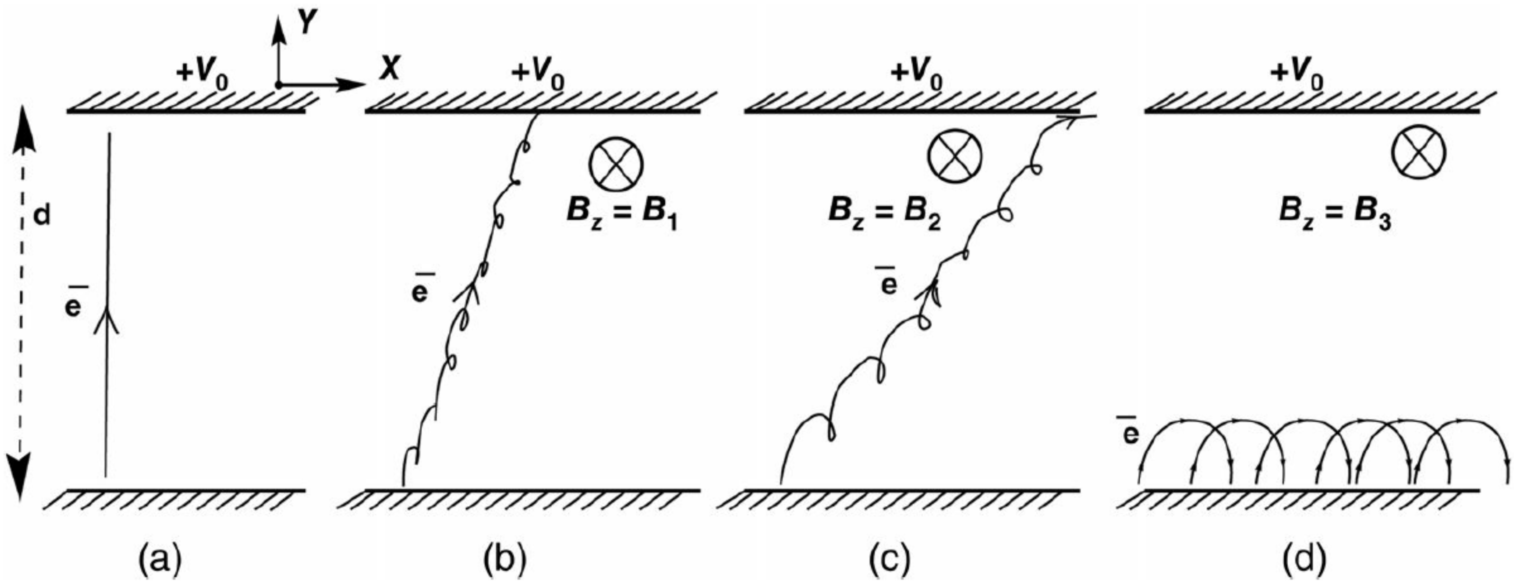


Figure 9.12 Electron trajectories in a vacuum gap with and without crossed magnetic field. (a) No Mag field. (b) Mag field = B_1. (c) Mag field = $B_2 > B_1$. (d) Mag field = $B_3 > B_2$.

Criterion for magnetic insulation: critical B field

- The canonical momentum in the x direction P_x is conserved because all forces are uniform along x.

$$P_x = \gamma(z) m_e v_x(z) - eA_x(z)$$

$$\boldsymbol{P} = m\boldsymbol{v} + q\boldsymbol{A}$$

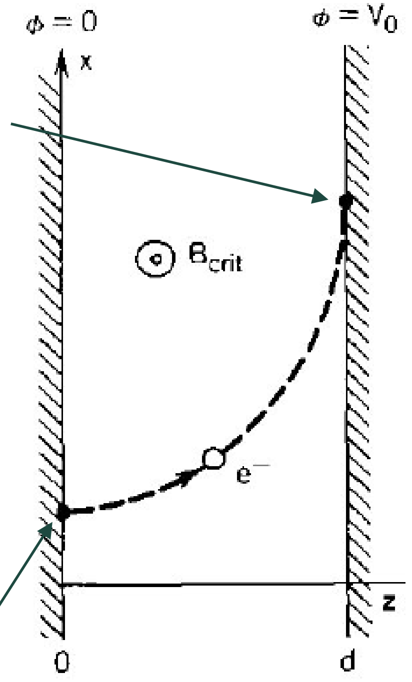
$$\boldsymbol{B} = \boldsymbol{\nabla} \times \boldsymbol{A}$$

- The vector potential can be calculated as

$$B_y = \frac{\partial A_x}{\partial z} \qquad A_x(d) = \int_0^d B_y(z)dz = B_0 d$$

- An applied magnetic field equal to B_{crit} gives electron orbits that just reach the anode. Conservation of total energy implies the electrons have a relativistic γ factor of

$$\gamma(d) = 1 + \frac{eV_0}{m_e c^2} \qquad v_x(d) = c\frac{\sqrt{\gamma(d)^2 - 1}}{\gamma(d)}$$



$v_z(d) = 0$

$v_z(0) = 0 \quad v_x(0) = 0$

$A_x(0) = 0 \quad P_x(0) = 0$

- The conservation of canonical angular momentum:

$$P_x(0) = P_x(d) = \gamma(d) m_e v_x(d) - eB_{crit} d = 0$$

- We obtain the critical magnetic field:

$$B_{crit} = \frac{m_e \gamma(d) v_x(d)}{ed} = \frac{m_e c}{ed}\sqrt{\gamma(d)^2 - 1} = \frac{m_e c}{ed}\left[\frac{2eV_0}{m_e c^2} + \left(\frac{eV_0}{m_e c^2}\right)^2\right]^{1/2}$$

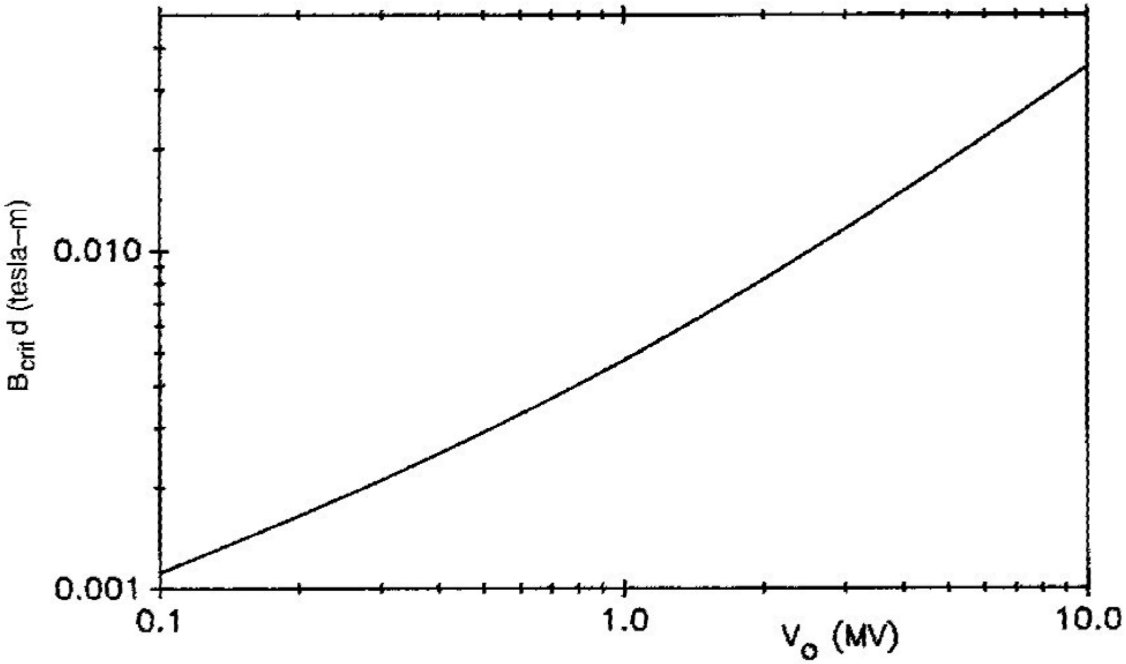
Moderate magnetic fields can insulate high-voltage gaps

- The critical magnetic field for electrons can be expressed as:

$$B_{crit} = \frac{m_e c}{ed}\left[\frac{2eV_0}{m_e c^2} + \left(\frac{eV_0}{m_e c^2}\right)^2\right]^{1/2} = B^* \underbrace{\left[1 + \frac{eV_0}{2m_e c^2}\right]^{1/2}}_{\text{Relativistic correction term}}$$

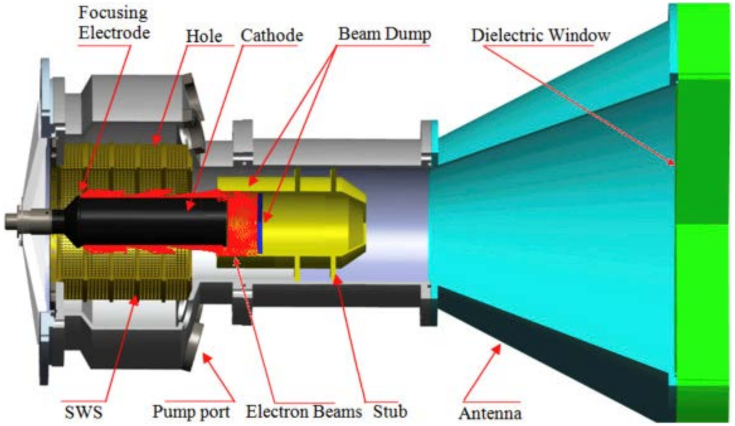
$$B^* = \frac{1}{d}\left[\frac{2m_e V_0}{e}\right]^{1/2}$$

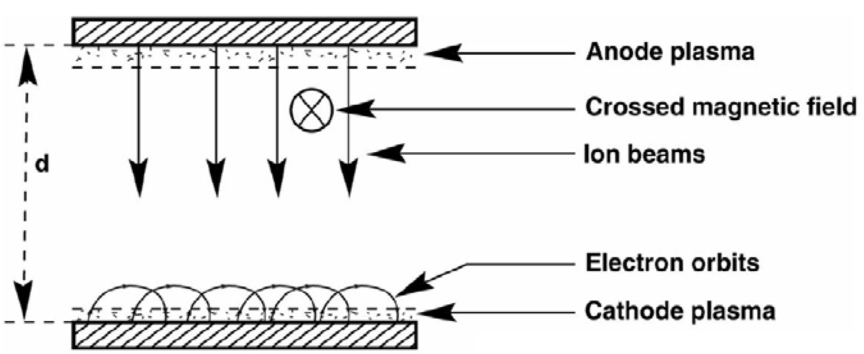
Non-relativistic factor

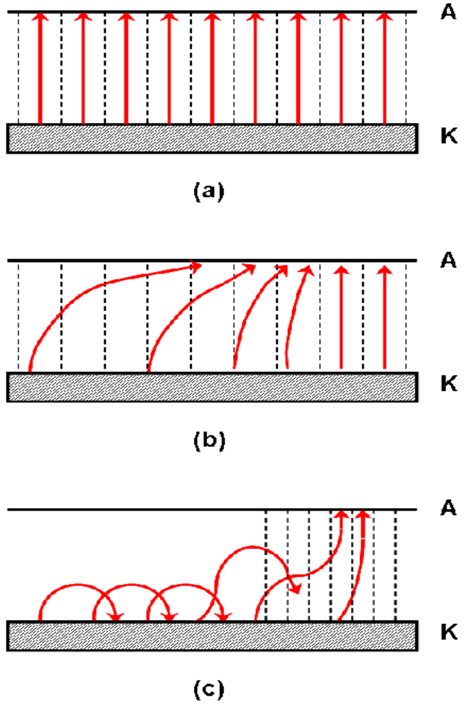


Implementation of magnetic insulation

- High current electron or ion beam source







- Magnetically insulated transmission line (MITL)