Pulsed Power system

⓪ * Prerequisite courses:

Electric Circuits.

Engineering Mathematics / Phys Mathematics (ODE)

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② * No office hour, please feel free to stop by my office whenever my door is open & nobody is in my office. Or you may email me to schedule a meeting.

2018 (三) 14:10 ~ 17:00

③ * class time : 9:10 ~ 12:00 2016 English ~~chinese~~. with 10 mins br

→ 9:10 ~ 11:30 ~~ch Man~~ Mandarin for gr

11:30 ~ 12:00 2017

④ *. Assignments : 70% → No roll call.

Presentations : 30%

Pulsed Power by Gennady A. Mesyats.

Foundations of Pulsed Power Technology by Jane Lehr & Prathap Ron

⑤ * References: Pulsed power systems by H. Bluhm.

Circuits analysis by Cunningham and Stuller

Pulse power formulary by Richard J. Adler

* Additional References:

Pulsed Power by Gennady A. Mesyats

J. C. Martin on Pulsed Power

* Class material: myweb.ncku.edu.tw/~pchang

* Course Outline: p2

- Introduction to pulsed-power system. - (9/14 2016) → 9/21 2017. 9/12 2018

- Review of circuit analysis - 9/21 2017. 9/12 2018   HW. of RLC circuits

2. Static and dynamic breakdown strength of dielectric material. - 9/28, 10/5 2017 (9/19 2018, 9/26)
   - Gas. → avalanche, townsend condition, Paschen Law.   * HW?
   - Liquid
   - Solid.

3. Energy storage. 10/12 - 10/19 2017 (10/3, 10/17 2018)
   - pulsed discharge capacitors
   - Marx Generators.   ← HW. of explaining Marx
   - Inductive energy storage.

4. Switches. 10/26 - ~~11/2~~. 11/9 2017   (10/24, 10/31 2018)   ← ~~calculating capacitors~~ solving poisson's eq.
   - Closing switches → gas switches
   - Opening switches →

5. Pulse-forming networks ~~11/9~~; ~~11/16~~ 11/23; 11/16 (2017)   (11/14, 11/21 2018)
   - Transmission Lines
   - RLC Networks

6. Pulse transmission and transformation ~~11/23~~ - ~~11/30~~ 12/7 2017; 11/30   (11/28, 12/5 2018)
   - self-magnetic insulation in Vacuum Lines
   - pulse transformers
   - High voltage power supply
   - Transformation lines

P3

§7. Power and voltage adding ~~T~~ 12/14 2017 12/12 2018

- Adding of power
- voltage adding

§9. Diagnostics. 12/21 . 12/28. 2017 (12/19 . 12/26) 2018

- Electromagnetic - Field sensors — Capacitive sensor / Inductive
- Current -viewing resistors (CVRs)
- Current measurements based on Faraday Effect.
- E-field - - - - - - - - Electro-optic effects.
- Magnetic ion energy analysers
- Vacuum voltage monitors.

§10. Applications of pulsed-power system 1/4 2017 1/2 2018

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§ Introduction to pulsed-power system

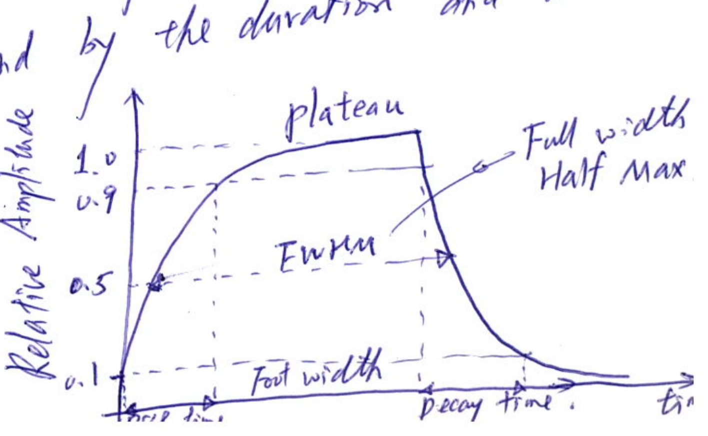
* Pulsed power is a scheme where stored energy is discharged as electrical energy into a load in a short pulse or ~~as~~ short pulses with a controllable repetition rate.

* Example of pulsed power in daily life:
  - Driven piles
  - Hammer.
  - making ~~sticky~~ rice cake. → great example of short pulses with a controllable repetition rate

* Pulsed power in general: — $P \sim 10^9 W$ (1GW) & $E \gtrsim kJ$

  The highest energy and power that have been achieved in a single pulse are in the order of 100MJ & few hund TW, respectively.
  - V : 10kV ~ 50MV
    I : 1kA ~ 10MA.

* A pulse is characterised by its shape, i.e., by its r ~~rise~~ & fall times and by the duration and flatness of its plateau region



- Pulse rise time – the time it takes the voltage to rise from 10% to 90%.

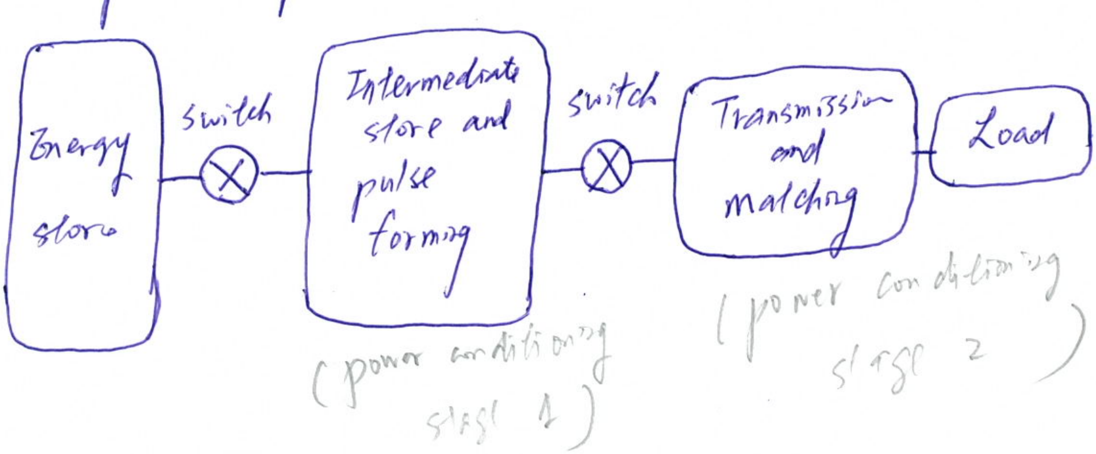
- Pulse {fall time / decay} – . . . . fall 90% to 10%.

- Both the fall and the rise time of a pulse depend on the evolution of the "Load impedance," which in most cases varies with time.

- pulse duration – no unique definition.
  → FWHM
  ② ~~Sometimes~~ It is defined as the duration at 90% of the peak amplitude.
  - Flatness of the plateau region is an important requirement for driving some ~~for~~ loads, such as Pockels cells.

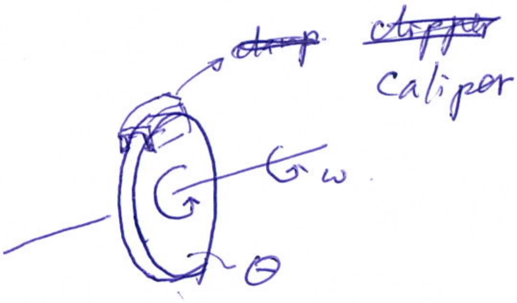
- A ~~general~~ generator scheme for the production of high-power electrical ~~pl~~ pulses is always based on an energy store that is charged slowly at a relatively low charging power and ~~by~~ is discharged rapidly by acting a switch.

- To achieve the desired power magnification factor and to shape the pulse, the above process can be repeated several time.



* The energy can be stored either chemically, mechanically, or electrically. P6.

Ex: Mechanical energy:



$$W_{kin} = \frac{1}{2}\Theta\omega^2$$

moment of inertia — angular frequency

For a massive cylinder: $\Theta = \frac{1}{2} M r^2$ (mass, radius)

$\Rightarrow W_{kin} = \frac{1}{2}\cdot\frac{1}{2} M r^2 \cdot \omega^2$

$\Rightarrow$ Stored energy density: $w = \frac{W_{kin}}{M} = \frac{1}{4} r^2 \omega^2$

- The ultimate energy density is limited by the tensile strength of the material used to construct the rotor.

$d\Sigma = \frac{dF}{A} = \frac{(r d\theta\, \delta\, dr\, \rho)\cdot r\omega^2}{r d\theta \cdot \delta} = \rho\omega^2 r\, dr$

$\Sigma = \int_0^R \rho\omega^2 r\, dr = \frac{1}{2}\rho\omega^2 R^2$

$\Sigma = \rho\omega^2 r\, dr$

$\Sigma = \rho\,\omega_{max}^2 \frac{r^2}{2}$ (tensile strength) — centrifugal accel.

$\Sigma \propto \rho\,\omega_{max}^2 r^2$

for a stainless steel cylinder or radius 1m.

$\omega_{max} = \cancel{400}\ 300/sec$ — AISI 302 stainless steel

$\Sigma = 520 / 860$ MPa (yield strength / ultimate tensile strength)

$\rho = 8.19\ g/cm^3 = 8190\ kg/m^3$

$\Rightarrow \omega \approx \sqrt{\frac{2\Sigma}{\rho r^2}} = \sqrt{\frac{2\times 860\times 10^6}{8190\times 1}} = 324 \quad 300 \quad \cancel{458 \sim 400}/s$

$w_{kin} = \frac{1}{4} r^2\omega^2 = \frac{1}{4}\cdot 1^2 \times \cancel{400}^2\ 300 = \cancel{4\times 10^4} \sim 2\times 10^4\ J/kg \Rightarrow \sim 1.6\times 10^8\ J/m^3$

High strength alloy ASTM A514 steel

$\rho = 7.8\ g/cm^3$ $\quad \Sigma = 690 / 760$ MPa (yield strength / ultimate tensile strength)

$\omega = \sqrt{\frac{2\times 690\times 10^6}{7800\times 1^2}} = 420 \sim 400/sec$

$w_{kin} = \frac{1}{4} r\omega^2 = \frac{1}{4}\times 1\times 400^2 = 4\times 10^4\ J/kg = 3.1\times 10^8\ J/m^3$

- The problem with mechanical storage is to release the energy in a sufficiently short time.

→ Several electrical compression stages are needed in combination with the mechanical storage to achieve the desired power level.

Ex: Electrical energy can be stored either capacitively in an <u>electric field</u> or inductively in a <u>magnetic field</u>.

Ex1: Electric field:

$$W_e = \frac{1}{2}\varepsilon\varepsilon_0 E^2$$

for oilimpregnated paper: $\varepsilon = 6$, breakdown strength $E = 0.78\times10^{8}\ \mathrm{V/m}$

$$\Rightarrow W_e = \frac{1}{2}\times 6\times 8.85\times10^{-12}\times(0.78\times10^{8})^2 = 161\ \mathrm{kJ/m^3}$$

With the finite packing density:

$E\ \ E_e = \frac{1}{2}CV^2,\quad C = \varepsilon\varepsilon_0\frac{A}{d}$

$\Rightarrow d\downarrow,\ E_e\uparrow$ → space is ~~occp~~ occupied by the electrode.

⇒ to estimate the energy storage in space

$$W_e' \approx \frac{1}{2}\times W_e \approx 80\ \mathrm{kJ/m^3}$$

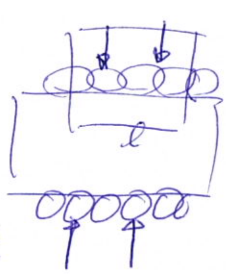
Ex2: Magnetic field:

$$W_B = \frac{B^2}{2\mu\mu_0}$$

The maximum energy density is limited by the onset of melting at the conductor surface or by the mechanical strength of the storage inductor.

$$C_v\cdot\rho\cdot T = \cancel{\frac{B^2}{2\mu_0}\cdot 2\vartheta}\ \frac{1}{2\mu_0}B^2\vartheta$$

C_v: heat capacitor per unit mass; ρ: mass density; T: surface temperature; ϑ: a factor of order unity depending on the form of the pulse



$B \cdot l = \mu_0 N I$

$\Rightarrow B = \mu_0 n I \propto I$ resistor.

$\cancel{R}\; E = P \cdot t = I^2 \cdot R \cdot t \propto B^2 \cdot R \cdot t$

$\Rightarrow C_v \rho T = \frac{1}{2\mu_0} B^2 \vartheta \approx \frac{B^2}{2\mu_0}$ take $\vartheta = 1$

$B \approx \sqrt{2\mu_0 \cdot C_v \cdot \rho \cdot T} = \sqrt{2 \times 4\pi \times 10^{-7} \times \frac{0.385\ J}{10^{-3}\ kg \cdot K} \times 8960 \times (1085-25)}$

Copper: $C_v = 0.385\ J/g \cdot K$ $= 96\ T \approx \underline{100\ T}$

melting: T: $1085\ °C$.

$\rho = 8.96\ g/cm^3 = 8960\ kg/m^3$

$\cancel{B}\; P_B \leq \Sigma$ ← yield strength $\Sigma = 70\ MPa$ for Cu

$\Rightarrow \frac{B^2}{2\mu_0} \Rightarrow B \leq \sqrt{2\mu_0 \Sigma} = \sqrt{2 \times 4\pi \times 10^{-7} \times 70 \times 10^6}$

$= \underline{13\ T}$

$\cancel{\Rightarrow W_B = \frac{1}{2}\mu\mu_0 B^2 = \frac{1}{2} \times 4\pi \times 10}$ $\Rightarrow w_B = \frac{1}{2} \frac{B^2}{\mu\mu_0}$

$\cancel{\Rightarrow W_B = \frac{1}{2}\mu\mu_0 B^2 = \frac{1}{2}}$ $= \frac{1}{2} \frac{13^2}{4\pi \times 10^{-7}} = \underline{6.7 \times 10^7\ J/m^3}$

$= \underline{67000\ kJ/m^3}$

⇒ The energy density stored in a magnetic field can be about 2 orders of magnitude higher than that storable in an electric field!!

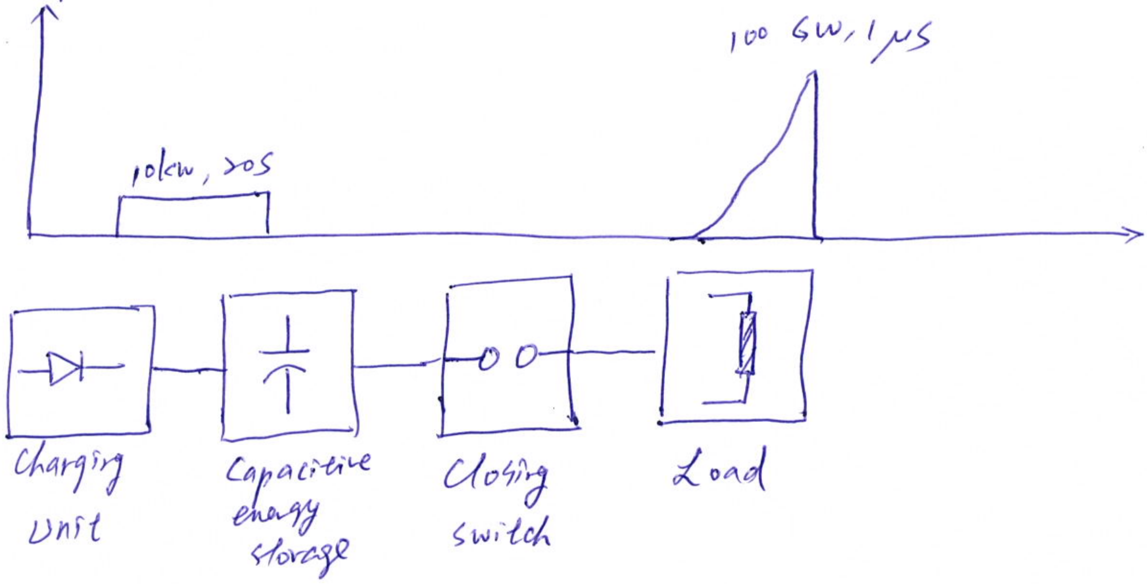
* Capacitive storage – requires one or more <u>closing switches</u> which remain open during charging and hold the charging voltage.

- power multiplication is done by current amplification.

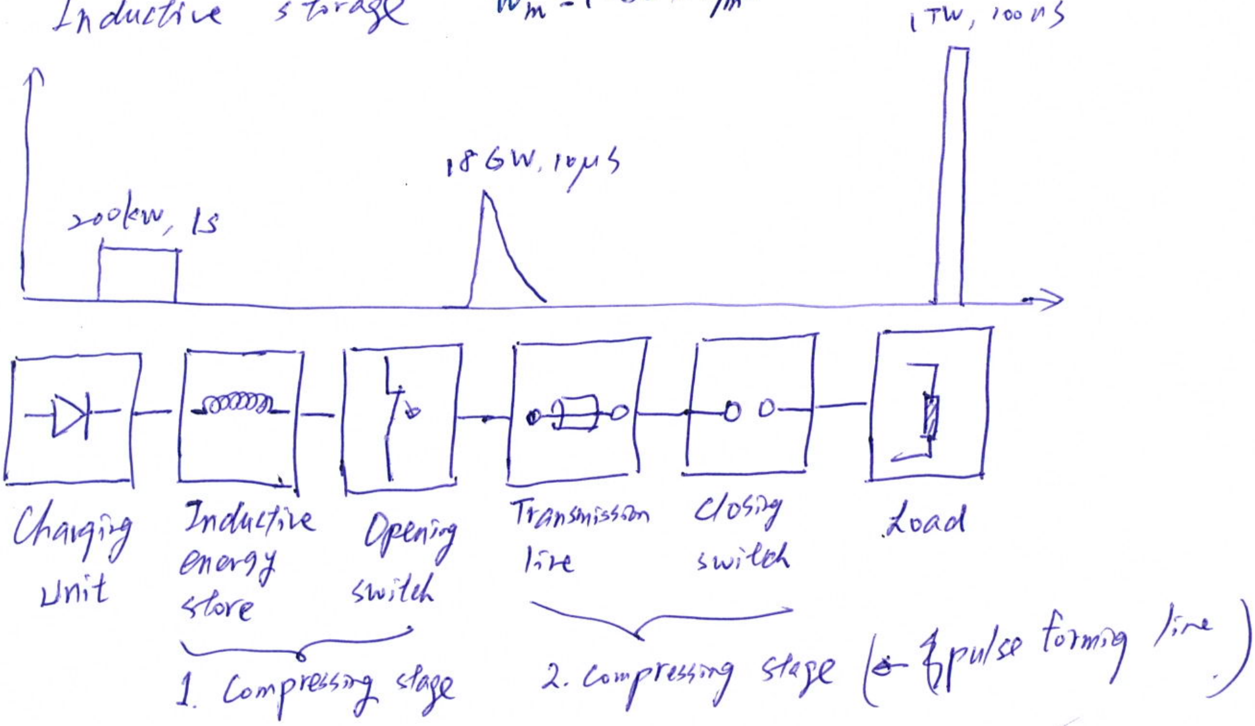
* Inductive storage – requires an <u>opening switch</u> which is closed during charge-up, carrying a large current at this stage.

- power multiplication is done by <u>voltage amplification</u>.

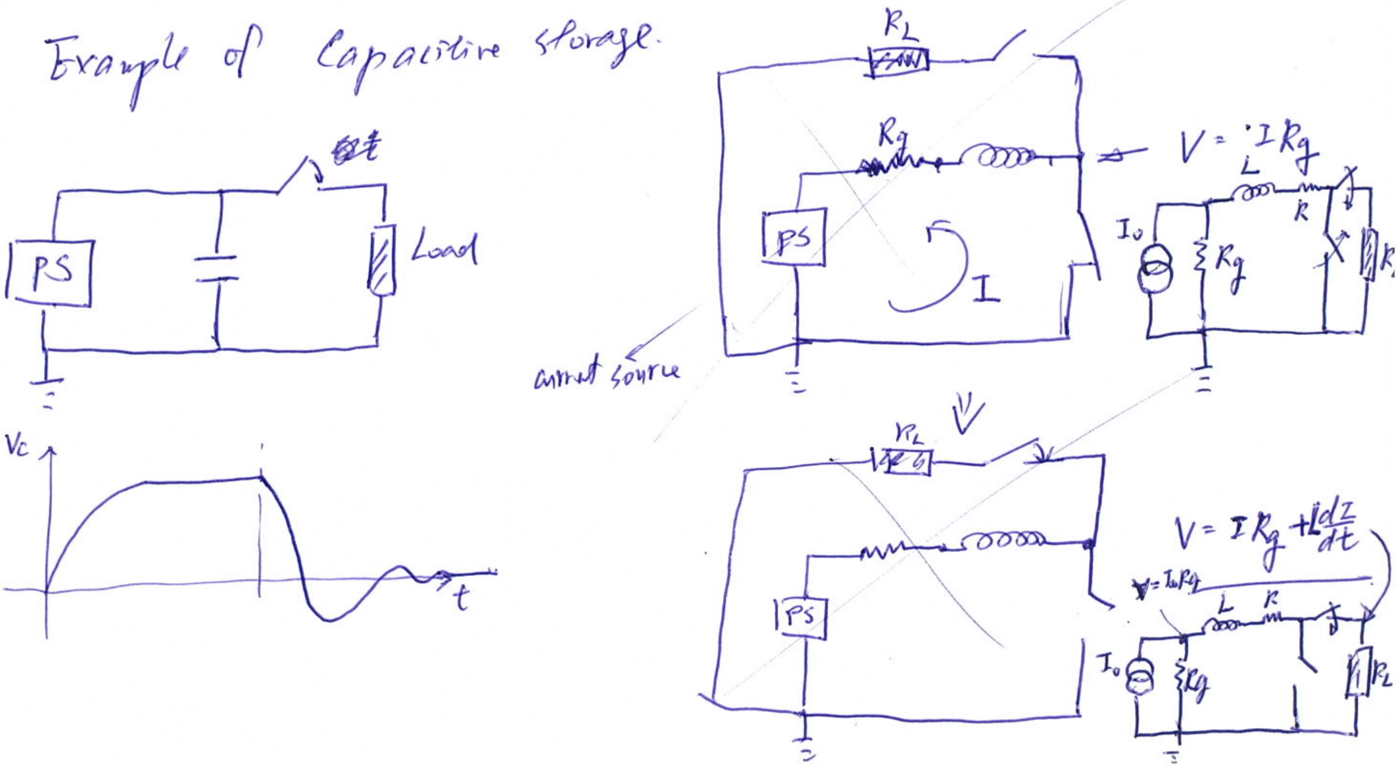
Capacitive storage $w_e = 10 \sim 80\ kJ/m^3$



Inductive storage $w_m = 1 - 50\ MJ/m^3$



Example of Capacitive storage.



Review of circuit analysis

* Kirchhoff's Current Law.

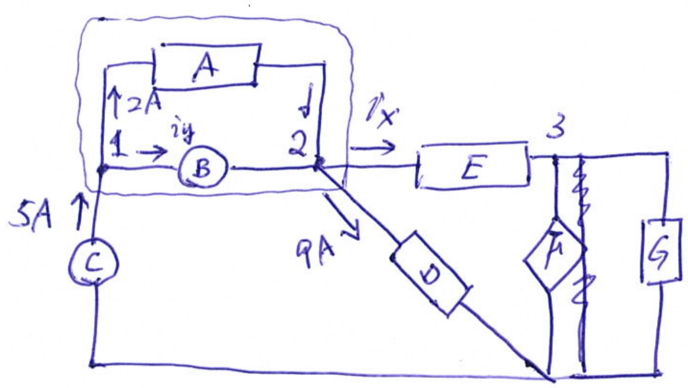
- At any instant in time, the algebraic sum of all currents leaving any closed surface is zero

$$i_1 + i_2 + \cdots \cdots + i_N = 0,$$

or in abbreviated notation:

$$\sum_{k=1}^{N} i_k = 0$$

where i_k is the k^{th} current of the N currents leaving the closed surfaces.



$i_y + 2 - 5 = 0$

$\Rightarrow i_y = 3\ (A)$

$-5 + i_x + 9 = 0$

$\Rightarrow i_x = -4\ (A)$

* Kirchhoff's Voltage Law.

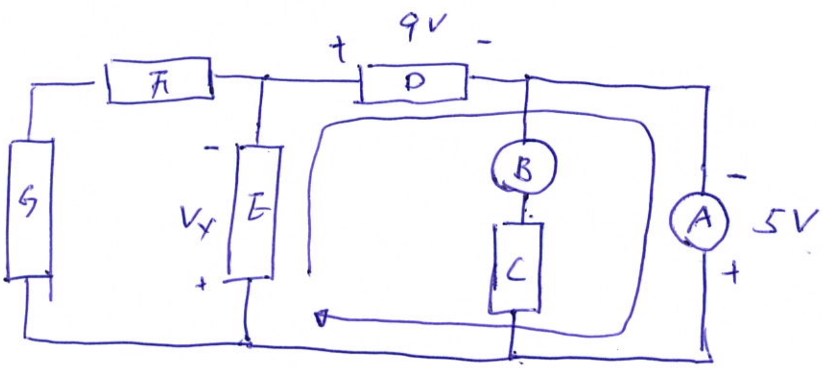
- At any instant in time, the algebraic sum of all voltage drops taken around any closed path is 0:

$$V_1 + V_2 + \cdots \quad V_N = 0.$$

or in abbreviated notation:

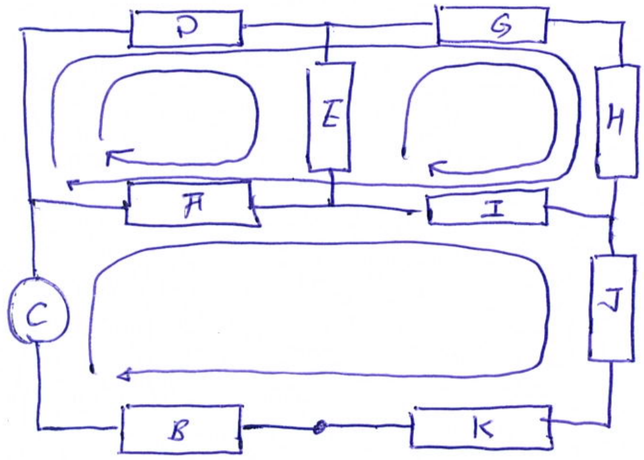
$$\sum_{k=1}^{N} V_k = 0$$

where V_k is the voltage drop, taken in the direction of the path along the k^{th} segment of the N segments in the closed path.

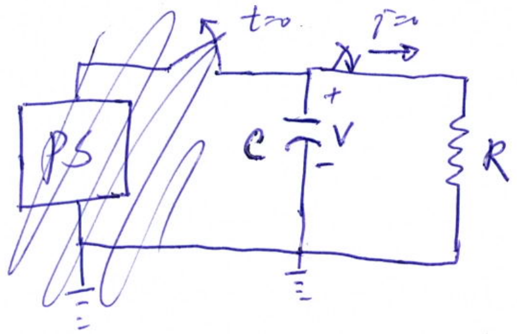


$$-V_x - 9 + 5 = 0 \Rightarrow \underline{V_x = -4\ V}$$

* Loops, Meshes, and Planar Networks



* Source-free RC circuit.



~~* Assume~~

⇒ Assume that the capacitor is fully charged to V_0. At $t=0$, the switch is opened.

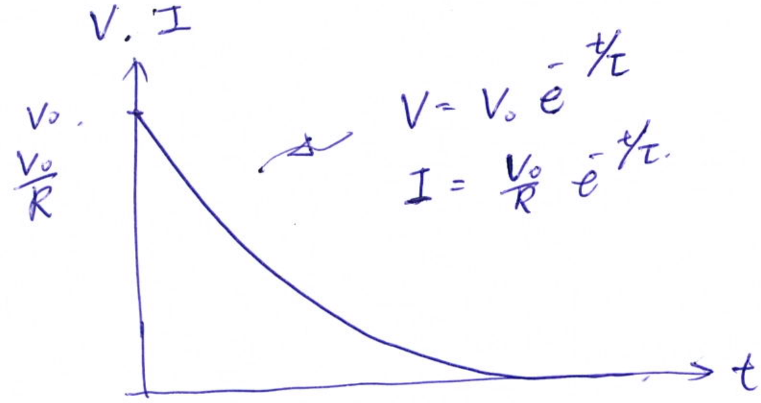
$$V_C - IR = 0 \qquad I = \frac{dQ}{dt} = -C\frac{dV}{dt} \qquad C = \frac{Q}{V}$$

$$\Rightarrow V_C + RC\frac{dV}{dt} = 0 \quad \text{or} \quad \frac{dV}{dt} + \frac{1}{RC}V = 0$$

$$\Rightarrow \int_{V_0}^{V}\frac{dV}{V} = -\frac{1}{RC}\int_0^t dt \Rightarrow \ln\frac{V(t)}{V(0)} = -\frac{t}{RC}$$

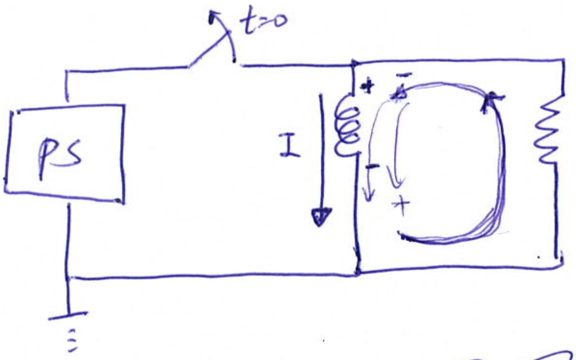
$$\Rightarrow V(t) = V_0 e^{-t/RC} = \underline{V_0 e^{-t/\tau_c}}, \quad \underline{\tau_c \equiv RC}$$

$$I = -C\frac{dV}{dt} = +V_0 C\left(+\frac{1}{\tau}\right)e^{-t/\tau_c} = \underline{\frac{V_0}{R}e^{-t/\tau_c}}$$



$$V = V_0 e^{-t/\tau}$$
$$I = \frac{V_0}{R} e^{-t/\tau}$$

* Source-free RL circuit



* Assume the current is at steady state for $t \leq 0$, $I(0) = I_0$

At $t=0$, the switch is opened

$$\cancel{V_L = IR + V_L = 0 \qquad V_L = L\frac{dI}{dt}}$$

$$-IR - V_L = 0 \qquad V_L = L\frac{dI}{dt}$$

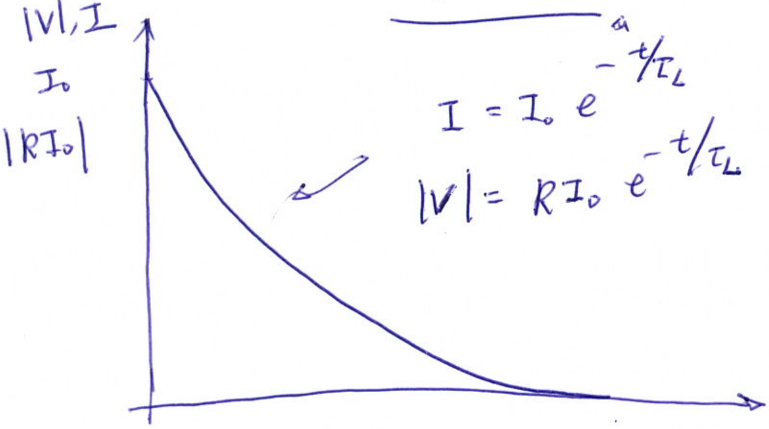
$$\Rightarrow IR + L\frac{dI}{dt} = 0 \Rightarrow \frac{dI}{dt} + \frac{R}{L}I = 0$$

$$\Rightarrow \int\frac{dI}{I} = -\frac{R}{L}\int dt \Rightarrow \ln\frac{I(t)}{I(0)} = -\frac{R}{L}t \equiv -t/\tau_L \qquad \tau_L = L/R$$

$$\Rightarrow I(t) = I_0 e^{-\frac{R}{L}t} = I_0 e^{-t/\tau_L}$$

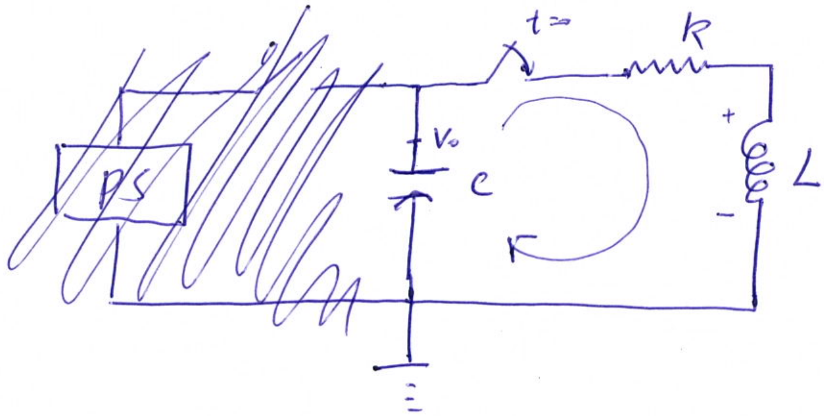
$$V(t) = L\frac{dI}{dt} = L \cdot I_0 \cdot \Big(-\frac{1}{\underbrace{\tau_L}_{=L/R}}\Big) e^{-t/\tau_L}$$

$$= \underline{-RI_0 e^{-t/\tau_L}}$$



$$I = I_0 e^{-t/\tau_L}$$
$$|V| = RI_0 e^{-t/\tau_L}$$

* Series RLC circuit



Assuming that the capacitor is fully charged to V_0, $I(0)=0$

At $t=0$, the switch is opened,

$$V_c - IR - L\frac{dI}{dt} = 0 \qquad I = \frac{dQ}{dt} = -C\frac{dV}{dt}$$

$$\Rightarrow V + RC\frac{dV}{dt} + LC\frac{d^2V}{dt^2} = 0$$

$$\frac{d^2V}{dt^2} + \frac{R}{L}\frac{dV}{dt} + \frac{1}{LC}V = 0$$

$$D^2 + \frac{R}{L}D + \frac{1}{LC} = 0 \Rightarrow D = \frac{-\frac{R}{L} \pm \sqrt{\left(\frac{R}{L}\right)^2 - \frac{4}{LC}}}{2}$$

$$= -\frac{R}{2L} \pm \sqrt{\left(\frac{R}{2L}\right)^2 - \frac{1}{LC}}$$

$$\Rightarrow \cancel{V = \alpha e}$$

$$V = e^{-\frac{R}{2L}t}\left(\alpha e^{\sqrt{\left(\frac{R}{2L}\right)^2 - \frac{1}{LC}}\,t} + \beta e^{-\sqrt{\left(\frac{R}{2L}\right)^2 - \frac{1}{LC}}\,t}\right)$$

1) $\left(\frac{R}{2L}\right)^2 - \frac{1}{LC} < 0 \Rightarrow V = e^{-\frac{R}{2L}t}\left(\alpha e^{i\sqrt{\frac{1}{LC} - \left(\frac{R}{2L}\right)^2}\,t} + \beta e^{-i\sqrt{\quad}\,t}\right)$

$$= e^{-\frac{R}{2L}t}\left[\alpha\cos\left(\sqrt{\frac{1}{LC} - \left(\frac{R}{2L}\right)^2}\,t\right) + \beta\sin\left(\sqrt{\frac{1}{LC} - \left(\frac{R}{2L}\right)^2}\,t\right)\right]$$

$$V(t=0) = V_0 = \cancel{e^{-\frac{R}{2L}t}}\,\alpha$$

$$\Rightarrow \cancel{V = V_0 e^{-\frac{R}{2L}t} V_0 \cos\sqrt{\frac{1}{LC} - \left(\frac{R}{2L}\right)^2}\,t}$$

$$V = e^{-\frac{R}{2L}t}\left[V_0\cos\left(\sqrt{\frac{1}{LC} - \left(\frac{R}{2L}\right)^2}\,t\right) + \beta\sin\left(\sqrt{\frac{1}{LC} - \left(\frac{R}{2L}\right)^2}\,t\right)\right]$$

$$I = -C\frac{dV}{dt} = -C\left\{-\frac{R}{2L}e^{-\frac{R}{2L}t}\left[V_0\cos(\sqrt{\ }\,t) + \beta\sin(\sqrt{\ }\,t)\right]\right.$$

$$\left. + e^{-\frac{R}{2L}t}\left[-\sqrt{\ }\,V_0\sin(\sqrt{\ }\,t) + \sqrt{\ }\,\beta\cos(\sqrt{\ }\,t)\right]\right\}$$

$$I(0) = 0 = \cancel{-C}\left\{-\frac{R}{2L}\cdot V_0 + \sqrt{\ }\,\beta\right\}$$

$$\Rightarrow \beta = \frac{R}{2L}V_0\cdot\frac{1}{\sqrt{\ }} = V_0\frac{R/2L}{\sqrt{1/LC - \left(\frac{R}{2L}\right)^2}}$$

$$= \frac{V_0}{\sqrt{\frac{4L^2}{R^2}\cdot\frac{1}{LC} - 1}} = \frac{V_0}{\sqrt{\frac{4L}{R^2C} - 1}}$$

$$V(t) = V_0 e^{-\frac{R}{2L}t}\left[\cos\left(\sqrt{\frac{1}{LC} - \left(\frac{R}{2L}\right)^2}\,t\right) + \frac{R/2L}{\sqrt{\frac{1}{LC} - \left(\frac{R}{2L}\right)^2}}\sin\left(\sqrt{\frac{1}{LC} - \left(\frac{R}{2L}\right)^2}\,t\right)\right]$$

$$\cancel{I(t) = -C\left\{-\frac{R}{2L}e^{-\frac{R}{2L}t}\left[V_0\cos(\sqrt{\ }\,t) + \beta\sin(\sqrt{\ }\,t)\right] + e^{-\frac{R}{2L}t}\left[-\sqrt{\ }\,V_0\sin(\sqrt{\ }\,t)\right.\right.}$$

$$I(t) = -C\left\{-\frac{R}{2L}e^{-\frac{R}{2L}t}\left[V_0\cos(\sqrt{\ }\,t) + \frac{V_0\cdot R/2L}{\sqrt{1/LC - (R/2L)^2}}\sin(\sqrt{\ }\,t)\right]\right.$$

$$\left. + e^{-\frac{R}{2L}t}\left[-\sqrt{\ }\,V_0\sin(\sqrt{\ }\,t) + \cancel{\sqrt{\ }}\,\frac{V_0 R/2L}{\cancel{\sqrt{\ }}}\cos(\sqrt{\ }\,t)\right]\right\}$$

$$= -CV_0 e^{-\frac{R}{2L}t}\left\{\left(\cancel{-\frac{R}{2L}V_0 + V_0\frac{R}{2L}}\right)\cos(\sqrt{\ }\,t) - \left(\frac{(R/2L)^2}{\sqrt{\ }} + \sqrt{\ }\right)\sin(\sqrt{\ }\,t)\right\}$$

$$= +CV_0 e^{-\frac{R}{2L}t}\,\frac{\cancel{\left(\frac{R}{2L}\right)^2} + \frac{1}{LC} - \cancel{(R/2L)^2}}{\sqrt{\ }}\sin(\sqrt{\ }\,t)$$

$$= \frac{V_0}{L}\frac{1}{\sqrt{\left(\frac{1}{LC}\right) - \left(\frac{R}{2L}\right)^2}}e^{-\frac{R}{2L}t}\sin(\sqrt{\ }\,t) = \frac{V_0}{\sqrt{\frac{L}{C} - \left(\frac{R}{2}\right)^2}}e^{-\frac{R}{2L}t}\sin\left(\sqrt{\frac{1}{LC} - (R/2L)^2}\,t\right)$$

$$I(t) = -\frac{V_0}{2} C e^{-\frac{R}{2L}t} \left\{ \left(1+\frac{R/2L}{\sqrt{\ }}\right)\left(\sqrt{\ } - \frac{R}{2L}\right) e^{\sqrt{\ }\, t} - \left(1-\frac{R/2L}{\sqrt{\ }}\right)\left(\sqrt{\ } + R/2L\right) e^{-\sqrt{\ }\, t} \right\}$$

$$= -\frac{CV_0}{2} e^{-\frac{R}{2L}t} \left\{ \frac{(\sqrt{\ })^2 - (R/2L)^2}{\sqrt{\ }} e^{\sqrt{\ }\, t} - \frac{\sqrt{\ }^2 - (R/2L)^2}{\sqrt{\ }} e^{-\sqrt{\ }\, t} \right\}$$

$$\cancel{= -\frac{V_0}{2} \frac{e}{\sqrt{(R/2L)^2 - 1/LC}} \left\{ -\frac{1}{LC} e^{\sqrt{\ }\, t} \right.}$$

$$= + \frac{CV_0}{2} e^{-\frac{R}{2L}t} \cdot \frac{+1/LC}{\sqrt{(R/2L)^2 - 1/LC}} \left[e^{\sqrt{(R/2L)^2 - 1/LC}\; t} - e^{-\sqrt{(R/2L)^2 - 1/LC}\; t} \right]$$

$$= V_0 e^{-\frac{R}{2L}t} \frac{1}{\sqrt{(\frac{R}{2})^2 - L/C}} \left[\frac{e^{\sqrt{(R/2L)^2 - 1/LC}\; t} - e^{-\sqrt{(\frac{R}{2L})^2 - 1/LC}\; t}}{2} \right]$$

$$= \frac{V_0}{\sqrt{(\frac{R}{2})^2 - L/C}} e^{-\frac{R}{2L}t} \sinh\left(\sqrt{(\tfrac{R}{2L})^2 - \tfrac{1}{LC}}\; t \right)$$

Plot 3 conditions !!

P11

2) $\left(\frac{R}{2L}\right)^2 - \frac{1}{LC} = 0 \quad \Rightarrow D = -\frac{R}{2L}$

$$V = (\alpha + \beta t)\, e^{-\frac{R}{2L}t}$$

$$V(0) = V_0 = \alpha \quad \Rightarrow V = (V_0 + \beta t)\, e^{-\frac{R}{2L}t}$$

$$I(t) = -C\frac{dV}{dt} = -C\left[\beta e^{-\frac{R}{2L}t} - \frac{R}{2L}(V_0 + \beta t)\, e^{-\frac{R}{2L}t}\right]$$

$$I(t=0) = 0 = -C\left[\beta - \frac{R}{2L}V_0\right] = 0 \quad \Rightarrow \beta = \frac{R}{2L}V_0$$

$$\Rightarrow V = \left(V_0 + \frac{R}{2L}V_0 t\right) e^{-\frac{R}{2L}t} = \underline{V_0\left(1 + \frac{R}{2L}t\right) e^{-\frac{R}{2L}t}}$$

$$I = -C\frac{dV}{dt} = -C\left[\cancel{\frac{R}{2L}V_0 e^{-\frac{R}{2L}t}} - \cancel{\frac{R}{2L}V_0 e^{-\frac{R}{2L}t}} - \frac{R}{2L}\cdot\frac{R}{2L}V_0 t e^{-\frac{R}{2L}t}\right]$$

$$= C\cdot\left(\frac{R}{2L}\right)^2 V_0 t e^{-\frac{R}{2L}t} = C\cdot\frac{1}{LC} V_0 t e^{-\frac{R}{2L}t}$$

$$= \underline{\frac{V_0}{L}\cdot t\cdot e^{-\frac{R}{2L}t}}$$

3) $\left(\frac{R}{2L}\right)^2 - \frac{1}{LC} > 0$

$$V = e^{-\frac{R}{2L}t}\left(\alpha e^{\sqrt{\left(\frac{R}{2L}\right)^2 - \frac{1}{LC}}\,t} + \beta e^{-\sqrt{\left(\frac{R}{2L}\right)^2 - \frac{1}{LC}}\,t}\right)$$

$$\cancel{= e^{-\frac{R}{2L}t}\left(\alpha \cosh(\sqrt{\ }\ t) + \beta \sinh(\sqrt{\ }\ t)\right)}$$

$$V(t=0) = V_0 = \alpha + \beta$$

$$I = -C\frac{dV}{dt} = -C\left\{-\frac{R}{2L}e^{-\frac{R}{2L}t}\left[\alpha e^{\sqrt{\ }t} + \beta e^{-\sqrt{\ }t}\right] + e^{-\frac{R}{2L}t}\left[\alpha\sqrt{\ }\, e^{\sqrt{\ }t} - \beta\sqrt{\ }\, e^{-\sqrt{\ }t}\right]\right\}$$

$\cancel{\Rightarrow}$ $-C$

$$I(t=0)=0 = -\cancel{C}\left\{-\frac{R}{2L}[\alpha+\beta]+(\alpha\sqrt{\ } - \beta\sqrt{\ })\right\} = 0$$ p16

$$\Rightarrow \left(\sqrt{\ } - \frac{R}{2L}\right)\alpha - \left(\sqrt{\ } + \frac{R}{2L}\right)\beta = 0$$

$$\Rightarrow \begin{cases} \alpha + \beta = V_0 \\ \left(\sqrt{\ } - \frac{R}{2L}\right)\alpha - \left(\sqrt{\ } + \frac{R}{2L}\right)\beta = 0 \end{cases} \Rightarrow \alpha = \frac{\sqrt{\ } + R/2L}{\sqrt{\ } - R/2L}\,\beta$$

$$\beta\left[\underbrace{1 + \frac{\sqrt{\ } + R/2L}{\sqrt{\ } - R/2L}}_{\circ}\right] = V_0$$

$$\frac{\sqrt{\ } - \cancel{R/2L} + \sqrt{\ } + \cancel{R/2L}}{\sqrt{\ } - R/2L} = \frac{2\sqrt{\ }}{\sqrt{\ } - R/2L}$$

$$\Rightarrow \beta = \frac{V_0}{2}\,\frac{\sqrt{\ } - R/2L}{\sqrt{\ }} = \frac{V_0}{2}\left(1 - \frac{R/2L}{\sqrt{\ }}\right)$$

$$\alpha = \frac{\sqrt{\ } + R/2L}{\cancel{\sqrt{\ } - R/2L}}\cdot\frac{V_0}{2}\,\frac{\cancel{\sqrt{\ } - R/2L}}{\sqrt{\ }} = \frac{V_0}{2}\,\frac{\sqrt{\ } + R/2L}{\sqrt{\ }} = \frac{V_0}{2}\left(1 + \frac{R/2L}{\sqrt{\ }}\right)$$

$$= \frac{V_0}{2}\left(1 + \frac{R/2L}{\sqrt{(R/2L)^2 - 1/LC}}\right) = \frac{V_0}{2}\left(1 + \frac{1}{\sqrt{1 - \frac{1}{LC}\frac{4L^2}{R^2}}}\right)$$

$$= \frac{V_0}{2}\left(1 + \frac{1}{\sqrt{1 - \frac{4L}{R^2C}}}\right)$$

$$\Rightarrow V(t) = e^{-\frac{R}{2L}t}\cdot\frac{V_0}{2}\left[\left(1 + \frac{1}{\sqrt{1 - \frac{4L}{R^2C}}}\right)e^{+\sqrt{(R/2L)^2 - 1/LC}\,t} + \left(1 - \frac{1}{\sqrt{1 - \frac{4L}{R^2C}}}\right)e^{-\sqrt{(R/2L)^2 - \frac{1}{LC}}\,t}\right]$$

$$I(t) = -Ce^{-\frac{R}{2L}t}\left\{-\frac{R}{2L}\left[\alpha e^{\sqrt{\ }t} + \beta e^{-\sqrt{\ }t}\right] + \alpha\sqrt{\ }\,e^{\sqrt{\ }t} - \beta\sqrt{\ }\,e^{-\sqrt{\ }t}\right\}$$

$$= -Ce^{-\frac{R}{2L}t}\left\{\alpha\left(\sqrt{\ } - \frac{R}{2L}\right)e^{\sqrt{\ }t} - \beta\left(\sqrt{\ } + \frac{R}{2L}\right)e^{-\sqrt{\ }t}\right\}$$

§2 Static and Dynamic Breakdown Strengths of Dielectric Materials

§2.1 Introduction

- We will ~~speed~~ to talk about the gas, liquid, and solid dielectric

* Dielectric substances serve both as "insulators" in generator components such as capacitors, HV transmission lines, & transformers, and as "working media" in switches.

* The properties of these devices are strongly depend on
  - electric breakdown strength.
  - dielectric constant.

* The dielectric strength of an insulant can be defined as "the maximum field stress that the material can ~~with~~ withstand for a given time".

skip

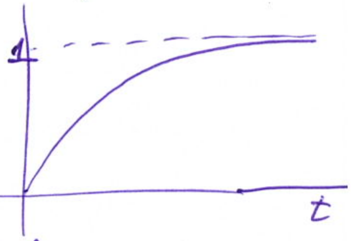
* Integrated field-time action:

  failure probability: $\ln\left[1-F(E,t)\right] = -\alpha \int_0^t E^b t^a \, dt$

  $F(E,t)$: probability of ~~fail~~ failure after time t.

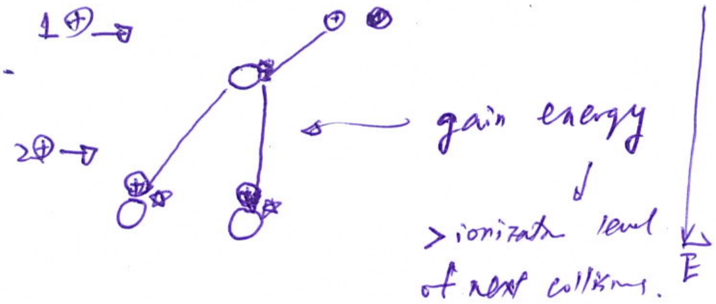
  $\alpha, a, b \to$ determined experimentally.

  $$F(E,t) = 1 - \exp\left[-\alpha \int_0^t E^b t^a \, dt\right]$$



* Electric strength also depends on the sample "geometry", the "pressure", the "temperature", and the "electrode material".

* At the microscopic level, breakdown requires the presence of sufficiently energetic charge particles that have acquired enough energy from the applied electric field between two energy-dissipating collisions to ionise the material and to create more charge particle.



* In most cases, electrons dominate the breakdown process since the mobility is much larger than that of ions.

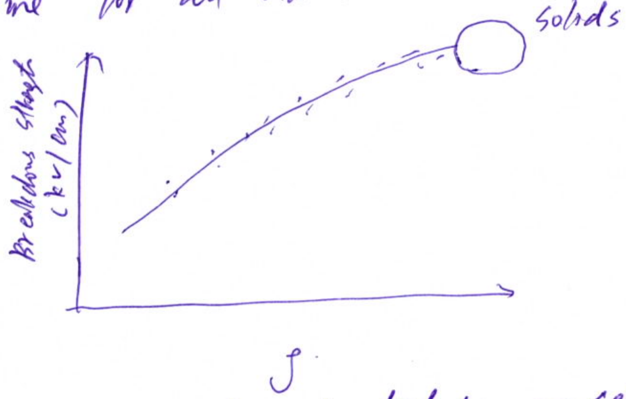
$$E_k = \frac{1}{2}mv^2 \Rightarrow v = \sqrt{\frac{2E_k}{m}} \Rightarrow s = vt \Rightarrow t = \frac{s}{v}$$

$$\Rightarrow t = \frac{s}{\sqrt{2E_k/m}} \propto n^{-1/3} \sim \frac{n^{-1/3}}{\sqrt{2E_k}}\sqrt{m}$$

$$n = \frac{\#}{V} \sim \frac{\#}{s^3} \Rightarrow s \sim n^{-1/3}$$

* In order for an electron to acquire enough energy between collisions, its mean free path in the material must be sufficient large.

* Mean free path depends essentially on the density of the material, the electric breakdown strength should be the same for all materials with the same density.



* Gaseous or liquid dielectric – self-repairing after a breakdown
Solid dielectric – remains irreversibly destroyed.
Liquid dielectric – preffered if large heat losses have to be removed

~~G # Gas~~

§2.2 Gases

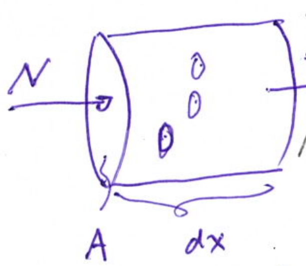
§2.2.1 Static Breakdown.

* the electric strength of a gas is determined by the magnitude of its atomic and molecular reaction cross-section. for electron collisions. → ionisation and attachment cross-sections.

σ: cross section of each atom.

n: # atom per unit volume

have not collided on anything



$N \pm dN$ # $= n \cdot A \cdot dx$

total cross sect: $\sigma_{tot} = \sigma \cdot n \cdot A \cdot dx$

$N' = N + dN < N$

$dN < 0$

A dx

probability of a particle causing an interaction in this layer: (dx)

$$P = \frac{\sigma_{tot}}{A} = \frac{\sigma n A dx}{A} = \underbrace{\sigma n}_{\Sigma} dx \equiv \Sigma dx$$

$P = N \Sigma \Delta x$

$$dN = -N \cdot P = -\Sigma N dx \Rightarrow \frac{dN}{N} = -\Sigma dx$$

$N' < N$, "−"

# of collisions $= NP$

$-(N' - N) = N \Sigma \Delta x$

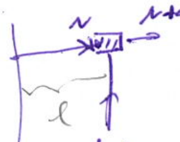
$\Delta N \Rightarrow -\Delta N = N \Sigma \Delta x$

$\frac{dN}{N} = -\Sigma dx$

$$N(x) = N_0 e^{-\Sigma dx}$$

# of particle NOT colliding atoms

Mean free path – a average length of a particle that can move without a collision is:



$dN = -\Sigma N dx$

or there are $\Sigma N dx$ particle stay on this range, i.e. l is the collision length

X dx

# of particles stay here

$$\lambda = \frac{\int x \, dN'}{\int dN'} = \frac{1}{N_0} \int x \cdot \Sigma \cdot N(x) \, dx$$

$\equiv \Sigma N(x) \cdot dx$

sum

$dN' = -dN = \Sigma N dx$

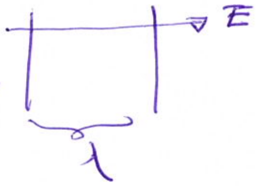
$$= \frac{\Sigma}{N_0} \int_0^\infty x N_0 e^{-\Sigma x} dx$$

$u = x \quad dv = e^{-\Sigma x} dx$

$du = dx \quad v = -\frac{1}{\Sigma} e^{-\Sigma x}$

$$= \Sigma \left[-\frac{1}{\Sigma} x e^{-\Sigma x} \Big|_0^\infty + \frac{1}{\Sigma} \int e^{-\Sigma x} dx \right] = -\frac{1}{\Sigma} e^{-\Sigma x} \Big|_0^\infty = \frac{1}{\Sigma}$$

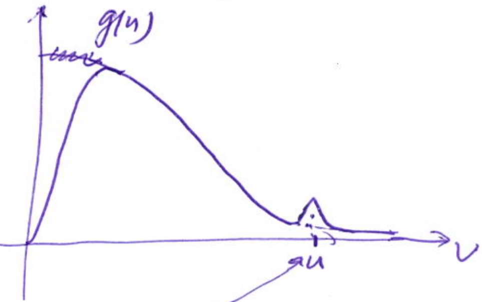
Between each collision,
the kinetic energy increase:



$$\lambda \cdot eE = \frac{1}{2} m u^2$$

$$\Rightarrow u = \sqrt{\frac{2eE\lambda}{m}}$$

velocity distribution



- Mean time between ionising collisions for electron with velocity u

mfp of ionising collisions

$\tau_i = \frac{\lambda_i}{u}$ ⇒ the rate of ionisation is:

$$\frac{1}{\tau_i} = \frac{u}{\lambda_i} = \Sigma_i u.$$

to p>1a →
(showing different cross section)

- # of ionising collisions per second leading to growth of the swarm

equilibrium velocity distribution function

$$\cancel{\frac{dN_e}{dt} \approx \frac{N_e}{\tau}}$$

$$\left\langle \frac{dN_e}{dt} \right\rangle = \int_0^\infty \frac{N_e \cdot g(u)\,du}{\tau} = N_e \int_0^\infty (\Sigma_i u)\, g(u)\,du$$

Skip

$$\frac{dN_e}{dt} = \frac{\delta N}{\delta t} \quad \frac{\partial N}{\partial t} + \frac{\partial x}{\partial t}\frac{\partial N}{\partial x} = \frac{\partial N}{\partial t} + u\frac{\partial N}{\partial x}$$

Skip all

Assume that the swarm does not spread

i.e. $\frac{\partial N}{\partial t} = 0$ → $N(x,t) = N(x)$

and introduce a mean swarm velocity $\langle u \rangle$

$$\Rightarrow \frac{dN_e}{dt} = \frac{\partial N}{\partial t} + u\cdot\frac{\partial N}{\partial x} \to \langle u\rangle \frac{\partial N}{\partial x} \stackrel{\delta}{=} N \int \Sigma_i u\, g(u)\,du$$

& assume $\frac{\partial N}{\partial x} = N_e \alpha$

Mean swarm velocity $\langle u \rangle$:

$$\alpha = \frac{\int_0 \Sigma_i(u)\cdot u \cdot g(u)\,du}{\langle u \rangle}$$

α: ionisation coefficient, — # of ionisation events performed by an electron in a unit length

$\Delta N = N_e \cdot \alpha \cdot \Delta x$

$\frac{\Delta N}{N_e} = \alpha \Delta x$

$\ln N_e / N_0 = \alpha x$

$$\Rightarrow N_e(x) = N_0 \exp(\alpha x)$$

the same @ p>1e

Notice that $\frac{\alpha}{p}$ is a unique function of E/p where p is the gas pressure under normal conditions.

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

☆ come back after p>e

* cross section → collisional cross section:
  - elastic collisions — NO energy exchanges. Momentum is redistributed.
  - inelastic collisions — energy exchanged between the collision partners → production of molecules & particles

* Elastic collisions:

* Inelastic collisions: a portion of the kinetic energy before collision is converted to potential energy of one of the particles in the system.

  - Ionization: $A + B \rightarrow A + B^+ + e^-$

The process of ionization is dominated by e^- acceleration in an electric field and is greatly aided by the appearance of initiatory electrons.

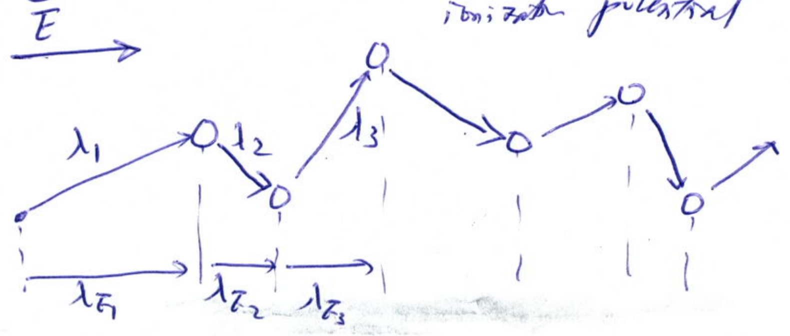
electrons $\begin{cases} \text{ionization in the gas.} \\ \text{emission from the cathode.} \end{cases}$

e^- impact ionization : $A + e^- \rightarrow A^+ + e^- + e^-$ ← dominated.

The most important process in the breakdown of gases but is not sufficient alone to result in breakdown.

$$q_e E \cdot \lambda_{Ei} \geq q_e V_i$$ ← requirement.

V_i: ionization potential



- Photoionization & collisions w/ excited molecules

$A + B \rightarrow A^* + B$ metastable production (1 ~ 10 ms life time)

A^* ← excited molecule

$A + e^- \rightarrow A^* + e^-$ electron impact excitation.

$A^* + e^- \rightarrow A^+ + e^-$ step ionization.

$A^* + e^- \rightarrow A + e^- + h\nu$ de-excitation

$h\nu$ ← photon.

$A^+ + e^- \rightarrow A + h\nu$ radiative recombination.

$A^* + e^- \rightarrow A^{**}$ dielectronic excitation

$A^{**} \rightarrow A^+ + e^-$ autoionization

$A^{**} \rightarrow A + h\nu$ dielectronic recombination.

$A^* + h\nu \rightarrow A^+ + e^-$ step photoionization

$A + h\nu \rightarrow A^+ + e^-$ photoionization.

photoionization is very complex:

$h\nu$ w/ $\lambda = 125$ nm (UV) @ 9.9 eV can ionize almost all gases despite that almost all molecules & atom have ionization energy > 9.9 eV. !!

- dust or water vapor → emit e^- through $h\nu$ absorption
- All photoionization occurs between 6 ~ 30 eV

→ Penning ionization:

$$A^* + B^* \rightarrow A^+ + B + e^-$$

- May be from impurities or Engineered mixture → Penning mixture

A penning mixture is a mixture of an inert gas w/ a small amount of a quench gas.

↑ lower ionization potential than the 1st excited state of the inert gas.

Ex: Neon lamp: Ne + <2% Ar

plasma display: He/Ne + Xe.

Gas ionization detector: Ar/~~X~~e, Ne/Ar, Ar/Acetylene

↑ 乙炔

* More complex collisions:

$A^+ + e^- + e^- \rightarrow A^* + e^-$ 3-body collision

$A^+ + B \rightarrow A^+ + B^{*} + (e^-)$ ion impact excitation

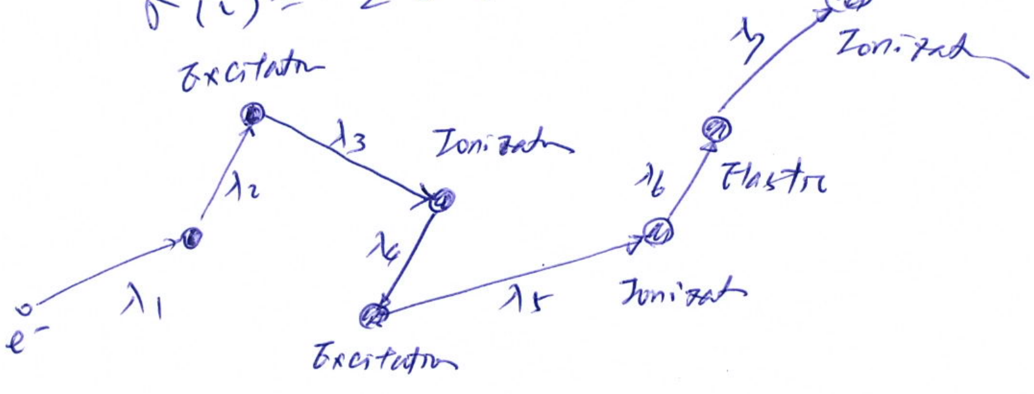
$A^+ + B + e^- \rightarrow A^* + B$

$A^+ + B \rightarrow A^+ + B^+ + e^-$ ion impact ionization.

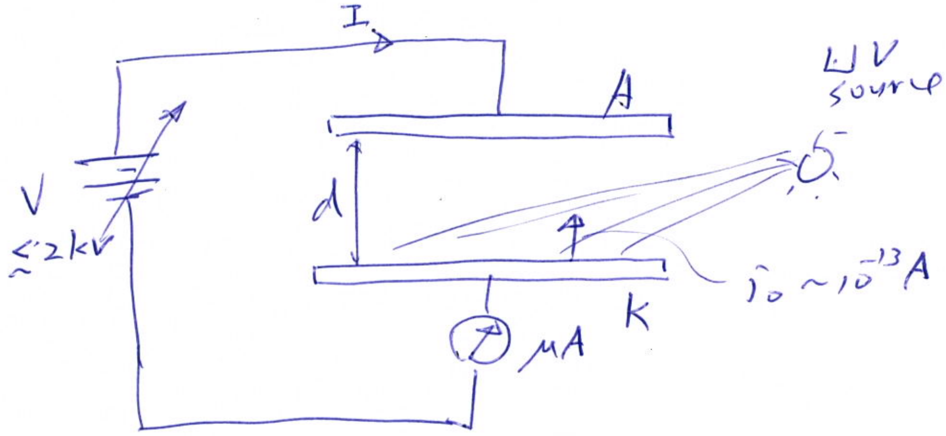
* Total collisional cross section:

$$\sigma(v) = \underset{\substack{\uparrow \\ \text{electron impact ionization}}}{\sigma_{el}} + \underset{\substack{\uparrow \\ \text{excitation}}}{\sigma_{ex}} + \underset{\substack{\uparrow \\ \text{step ionization}}}{\sigma_{ion}} \leftarrow \text{dominated.}$$

$$\sigma(v) = \sum \sigma.$$



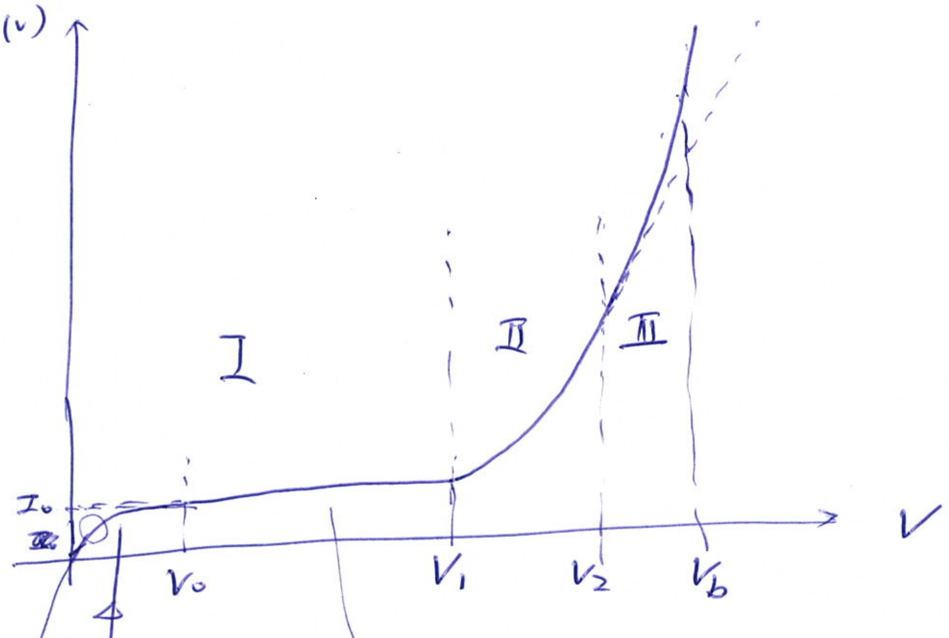
* Electric breakdown - Townsend's Experiments



$p < 100$ Torr.

$i_0 \sim 10^{-13}$ A initial current.

$V \uparrow \Rightarrow I(V) \uparrow$ till spark was produced.



I: photoemission from UV.

∵ e^- emitted from K are scattered in Random directions colliding w/ gas molecules

the directed average drift velocity > average random velocity component

II: The Townsend 1st ionization region

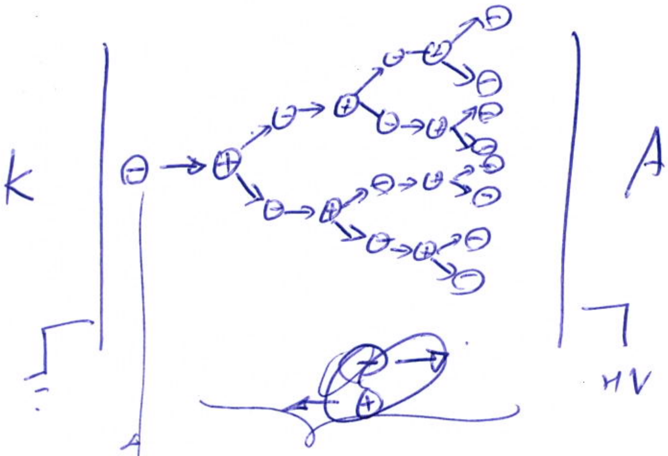
$$I(d) = i_0 e^{\alpha d}$$

α: Townsend primary (1st) ionization coefficient

III: The Townsend 2nd ionization region

- single-electron avalanche is not sufficient to carry the circuit-limited current
- successor avalanches are formed by positive ions, resulting from ionization collisions w/ primary e^-, bombarding K, and liberating e^-

* Electron Avalanche.



present naturally.
or photon
or cosmic rays
static charge

cascade ionization

$$I = q_e \cdot n \cdot V_d$$

$\uparrow$ e^- drift velocity

go back to p21. w/ ☆

$$dn = n(x) \cdot \alpha \cdot dx$$

ionization coefficient

$$\Rightarrow \int \frac{dn}{n} = \alpha \int dx \Rightarrow n(x) = n_0 e^{\alpha x}$$

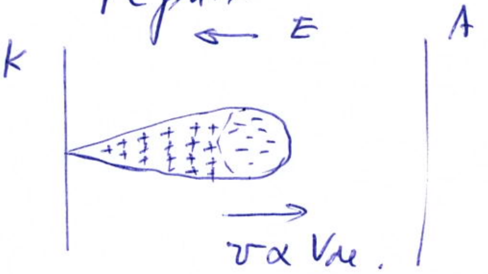
- electron drift toward Anode. $V_{de} \sim 10^7$ cm/sec
- ion — cathode $V_{di} \sim 10^5$ cm/sec.

$\Rightarrow$ separation of charges.

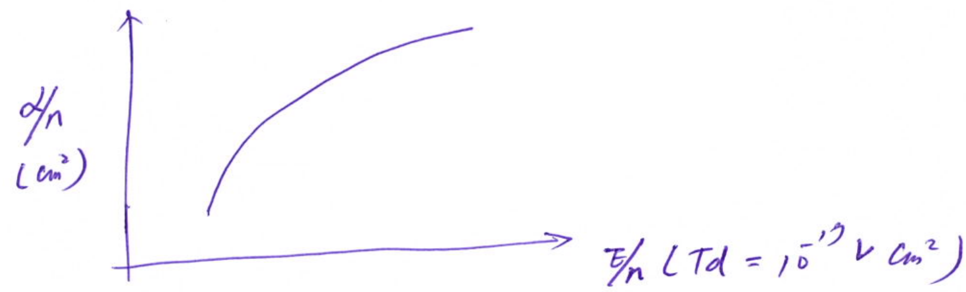
Additionally, e^- in the avalanche head diffuse $\because$ repulsion of like charges.

space charge effect

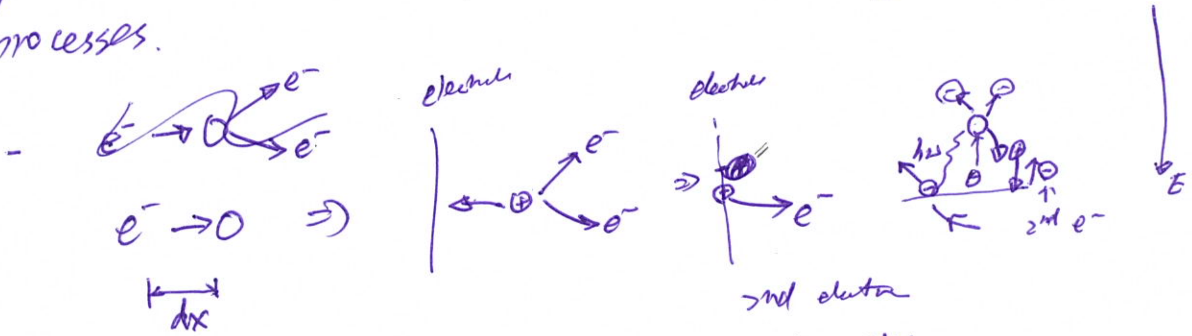
$\Rightarrow$

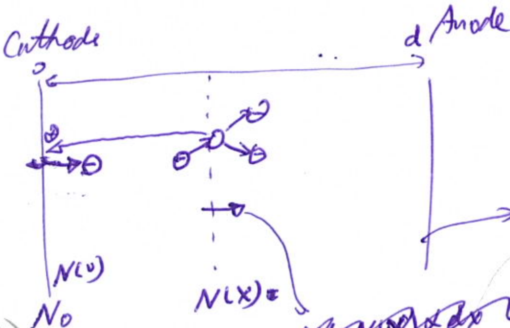


→ α/p or α/n can be determined experimentally.



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





$N(d) = N_0 \exp(\alpha d)$ ← # of electrons reach the anode

# of generated e^-

$\cancel{dN = N(x)\alpha dx}$ ⇒ $N(x) = N(0)\exp(\alpha x)$

coefficient of generating secondary e^- from the # of total e^- (generated 1st)

$$N(0) = \underset{\uparrow\ 1^{st}\text{ electrons}}{N_0} + \omega \underbrace{\boxed{\int_0^d N(x)dx}}_{2^{nd}\text{ electrons}} = N_0 + \omega N(0)\int_0^d \exp(\alpha x)\,dx$$

$$= N_0 + \omega N(0)\frac{1}{\alpha}e^{\alpha x}\Big|_0^d$$

$$\Rightarrow N(0) = N_0 + \frac{\omega}{\alpha}N(0)\left(e^{\alpha d}-1\right)$$

$$\Rightarrow N(0) = \frac{N_0}{1-(\omega/\alpha)(e^{\alpha d}-1)}$$

$$\Rightarrow N(d) = \frac{N_0\, e^{\alpha d}}{1-\frac{\omega}{\alpha}(e^{\alpha d}-1)}$$

N_0 : is the # of electrons released from the cathode by external processes.

* Avalanche grows oceans when the denominator equals to 0

$$1 - \frac{w}{\alpha}(e^{\alpha d} - 1) = 0 \quad \text{or} \quad \frac{w}{\alpha}(e^{\alpha d} - 1) = 1$$

This is called the "Townsend condition" for ignition.

→ In this case, the insulation of the cathode-anode gap breaks down and a self-sustained discharge is created.

To p239 →

* Experiments show that w/p is also a function of E/p

i.e. $\frac{w}{p} = f\left(\frac{E}{p}\right)$, $\frac{\alpha}{p} = F\left(\frac{E}{p}\right)$

$$\Rightarrow \frac{w}{\alpha}(e^{\alpha d} - 1) = 1 \Rightarrow \frac{w/p}{\alpha/p}(e^{\frac{\alpha}{p} pd} - 1) = 1$$

$$\Rightarrow \frac{f(E/p)}{F(E/p)}\left(e^{F(E/p) \cdot pd} - 1\right) = 1$$

~~⇒ pd can be determined if $f(E/p)$ & $F(E/p)$ are known~~

$\because E = \frac{U}{d}$, i.e. $\frac{E}{p} = \frac{U}{pd}$

$\therefore U$ can be ~~set~~ solved for ~~a~~ given pd if $f(E/p)$ & $F(E/p)$, i.e., $f\left(\frac{U}{pd}\right)$ & $F\left(\frac{U}{pd}\right)$, are known.

$$\Rightarrow U_b = \Pi(pd)$$

Paschen Law: The breakdown voltage U_b of a uniform-field gap is a unique function Π of pd.

* In certain region ~~$\frac{\alpha}{p} \approx A e^{B E/p}$~~ $\frac{\alpha}{p} = A e^{-B \underbrace{p/E}_{= pd/U}}$

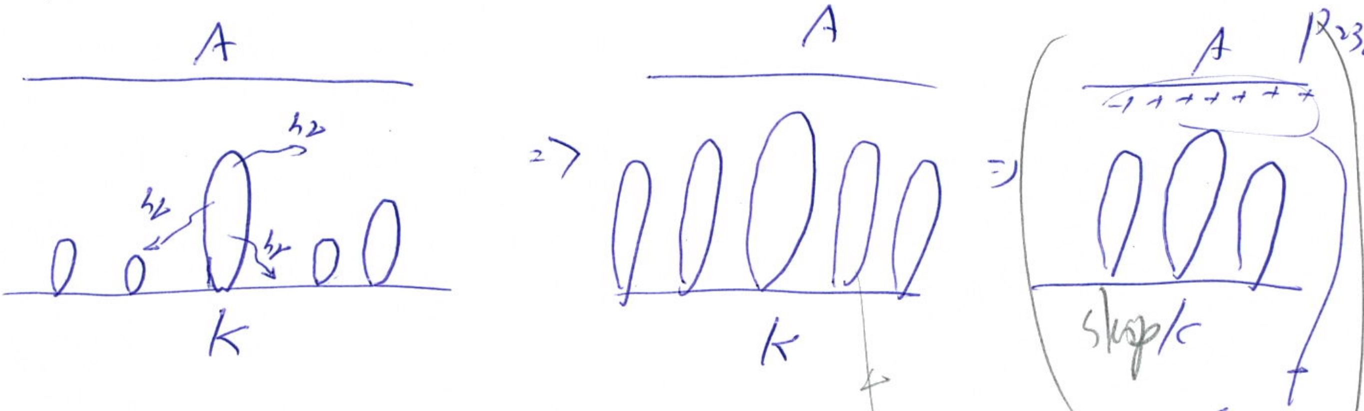
A & B are constants for a given gas.

let $\gamma \equiv \frac{w}{\alpha} = \frac{f(E/p)}{F(E/p)} = \gamma(E/p)$, which is a slowly varying function of E/p over a wide range.

$$\Rightarrow \gamma(e^{\alpha d} - 1) = 1 \Rightarrow \gamma(e^{\frac{\alpha}{p} \cdot pd} - 1) = 1 \Rightarrow e^{\frac{\alpha}{p} \cdot pd} = \ln[1 + \tfrac{1}{\gamma}]$$

$$\frac{\alpha}{p} \cdot pd = \ln(1 + \tfrac{1}{\gamma}) \Rightarrow A e^{-Bpd/U} = \frac{\ln(1 + 1/\gamma)}{pd} \Rightarrow e^{Bpd/U} = \frac{Apd}{\ln(1 + 1/\gamma)}$$

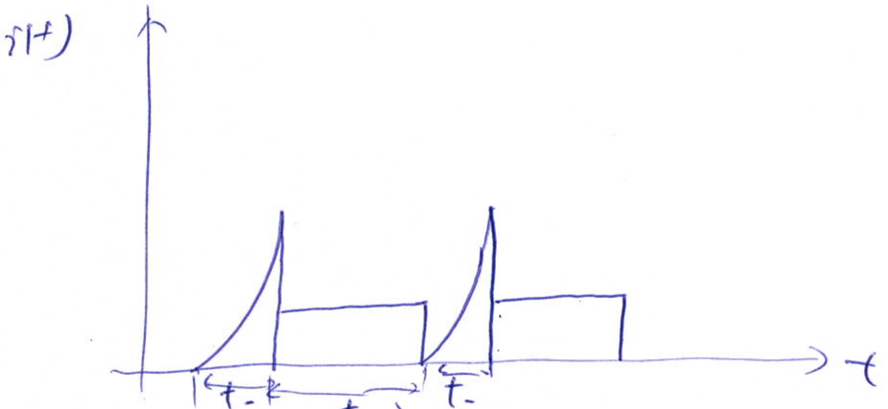
$$\Rightarrow \frac{B \cdot pd}{U} = \ln[Apd / \ln(1 + 1/\gamma)] \Rightarrow U_b = \frac{B \cdot pd}{\ln[A \cdot pd / \ln(1 + 1/\gamma)]}$$



untill the current is limited by the p system

space charge

* Multiple 2nd Mechanisms



from photon

from photon ~10^{10} cm/sec

from ion bombardmet.

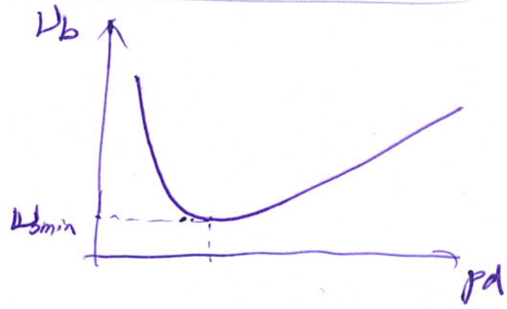
slow ∵ ion drift velocity is slow. ~10^5 km/sec.

* 2nd electrons generation are strongley dependent on the cathode material.

back to p23

Gas	A (1/(mm bar))	B (kV/(mm bar))	Range of E/p for validity (kV/(mm bar))
Air	1130	27.4	11-45
N_2	977	25.5	8-45
H_2	376	9.8	11-30
He	210	2.6	2-11
Ar	1020	13.5	8-45
CO_2	1500	34.9	37-75

$$U_b = \frac{B\cdot pd}{\ln[A\cdot pd / \underbrace{\ln(1+1/\gamma)}_{C}]}$$



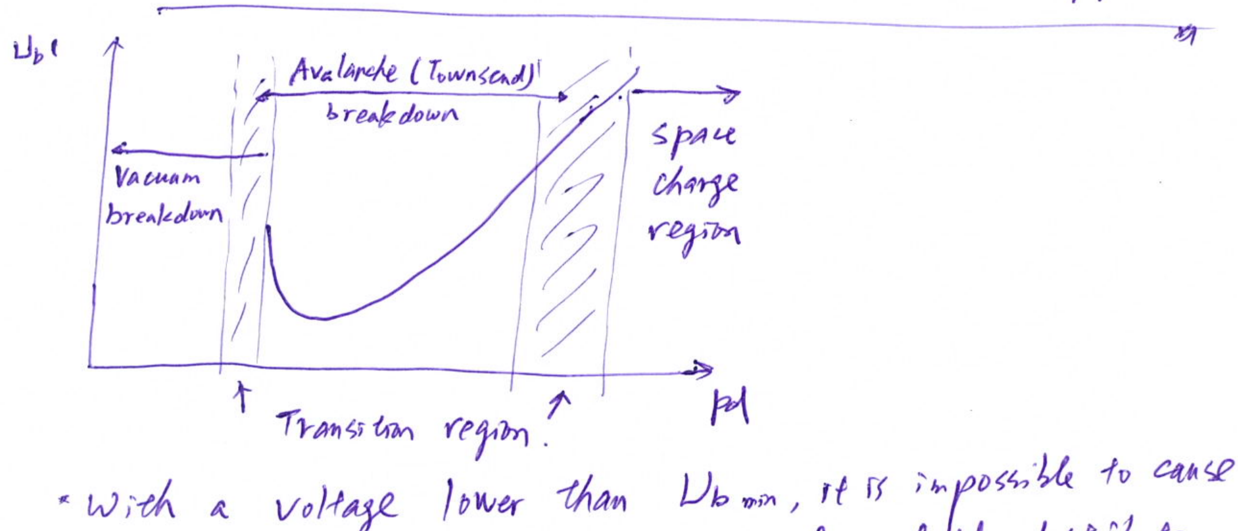
$$U_b = \frac{B\cdot x}{\ln[A\cdot x/C]} \qquad x \equiv pd$$

$$\frac{dU_b}{dx} = \frac{B\cdot\ln[A\cdot x/C] - Bx\cdot\frac{A/C}{A\cdot x/C}}{\ln[A\cdot x/C]^2} = \frac{B[\ln(A\cdot x/C)-1]}{[\ln(A\cdot x/C)]^2} = 0$$

$$\Rightarrow \ln(A\cdot x/C) - 1 = 0 \Rightarrow \underline{x = e\cdot\frac{C}{A}}$$

$$U_b = \frac{B\cdot x}{\ln[e\cdot\frac{C}{A}\cdot\frac{A}{C}]} = \frac{B\cdot x}{\ln e} = B\cdot x = e\cdot C\cdot\frac{B}{A}$$

$$\Rightarrow U_{b\,min} = e\cdot\ln[1+\tfrac{1}{\gamma}]\cdot\frac{B}{A} \quad (9) \qquad pd_{Bmin} = e\,\frac{\ln(1+\frac{1}{\gamma})}{A}$$



* With a voltage lower than $U_{b\,min}$, it is impossible to cause the breakdown of a gap with a uniform field distribution.

* At very high field strengths, field emission of electrons from the electrodes occurs. (for left & far right of Paschen curve)

* the most commonly used high-strength gas is <u>SF_6</u>.

SF_6 belongs to a group of "electronegative gases", which are characterised by the ability to attach electrons to the molecule, which then becomes a "negative ion".

⇒ attachment coefficient : η – attachment ~~coefficient~~ probability of an electron per unit path length.

* other electronegative : compounds containing Halogens (Cl, F, I, .. & O_2.

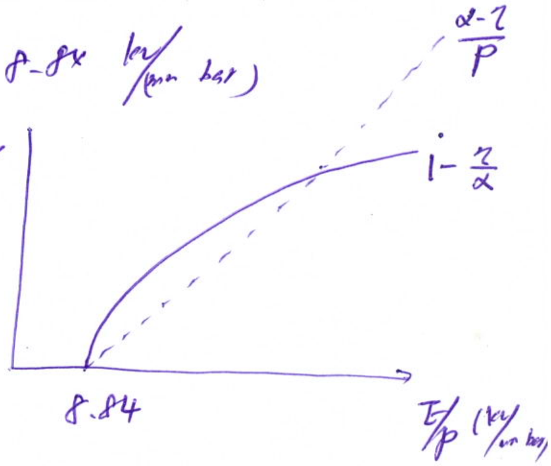
Effective ionisation coefficient: $\alpha_e = \alpha - \eta = p\, f\left(\frac{E}{p}\right)$

⇒ Electron avalanche formation becomes possible only if $\alpha_e > 0$. S_x: $\frac{E}{p} > 8.84$ kV/(mm bar) is needed for SF_6

$$\frac{\alpha - \eta}{p} = k\left[\frac{E}{p} - \left(\frac{E}{p}\right)_0\right]$$

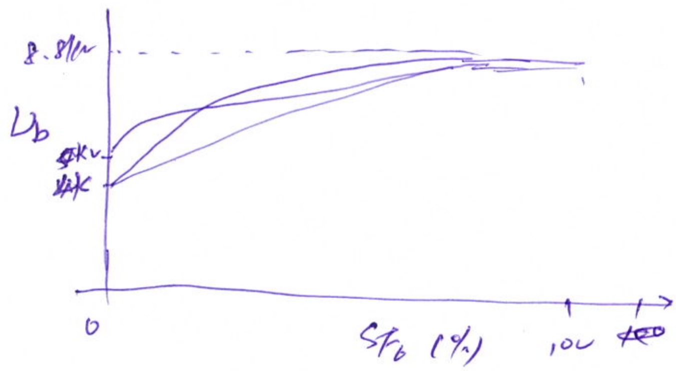
Skip

for SF_6: $k = 27.7$ kV. $\left(E/p\right)_0 = 8.84$ kV/(mm bar)



20. ⇒ $U_b = pd \cdot 8.84\,[\text{kV}/(\text{mm bar})] + 0.5\,\text{kV}$
derivation see next page.

* SF_6 maintains a high electric strength even if it is diluted with another gas.



* Vapours of higher strength than SF_6 are known, but most of them liquefy at atmospheric pressure and room temperature.

eq 2.8: $\gamma(e^{\alpha d}-1)=1 \Rightarrow \alpha d = \ln(1+\frac{1}{\gamma})$

eq 2.15: $\frac{\alpha_e}{p} = \frac{\alpha-\eta}{p} = k\left[\frac{E}{p} - \left(\frac{E}{p}\right)_0\right] = k\left[\frac{U}{pd} - \left(\frac{E}{p}\right)_0\right]$

$\Rightarrow \alpha_e d = \frac{\alpha_e}{p}\cdot pd = pd\cdot k\left[\frac{U}{pd} - \left(\frac{E}{p}\right)_0\right] = \ln(1+1/\gamma)$

$\Rightarrow U_b = pd\left(\frac{E}{p}\right)_0 + \frac{1}{k}\ln(1+1/\gamma)$

skip

$= pd \cdot 8.84\,(kV/mm\,bar) + 0.5\,kV$ for SF_6

- Quadratic ansatz → for gas are not electronegative or are only weakly so:

$\frac{\alpha}{p} = A\left[1 - \frac{Bp}{E} + \frac{1}{2}\left(\frac{Bp}{E}\right)^2\right]$

$\frac{\alpha_e}{p} \sim \left[\frac{E}{p} - \left(\frac{E}{p}\right)_0\right]^2$

$\Rightarrow \frac{\alpha_e}{p} \sim \left[\frac{U}{pd} - \left(\frac{E}{p}\right)_0\right]^2$

$\alpha_e d = \frac{\alpha_e}{p}\cdot pd = pd \cdot \left[\frac{U}{pd} - \left(\frac{E}{p}\right)_0\right]^2 = \ln(1+1/\gamma)$

$\Rightarrow \sqrt{pd}\left[\frac{U}{pd} - \left(\frac{E}{p}\right)_0\right] = \sqrt{\ln(1+1/\gamma)}$

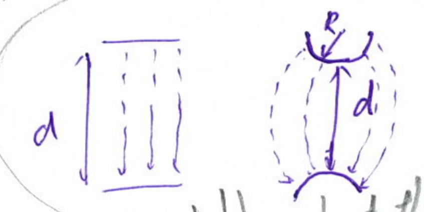
$U = \left(\frac{E}{p}\right)_0 \cdot pd + \sqrt{\ln(1+1/\gamma)}\cdot\sqrt{pd}$ → eq 2.18

plot to compare to paschen curve.

Gas	$(E/p)_0$ (kV/mm bar)	C (kV/$\sqrt{\text{bar mm}}$)
CO_2	3.21	5.88
Air	2.44	2.12
N_2	2.44	4.85
H_2	1.01	2.42

skip

(*) The mean breakdown strength can change considerably if a gap is bounded by spherical or cylindrical electrodes especially $d > R$



$U_b = \frac{U_{b0}}{\delta}$

$U_b = \frac{(E/p)_0\, pd + c(pd)^{1/2}}{\delta}$

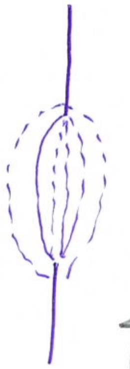
talks about the plot

- Concentric cylinders $\delta = (R/r - 1)/\ln(R/r)$
- Equal spheres $\cancel{\delta \approx X/2r}$ $\cancel{X}$ $\cancel{X/2r}$ $\cancel{X}$

$\delta \approx X/2r$ for $X/r \gg 1$ where $X = d-2r$

- Equal parallel cylinders $\delta \approx \frac{X}{2r\ln(X/r)}$ for $X/r \gg 1$ where $X = d-2r$

→ For very inhomogeneous field configurations (needle geometries) p27



$E_{needle} > E_{flat}$

$U_b = \left(\frac{E}{P}\right)_0 pd + c(pd)^{1/2}$ ← can ~~only~~ be used

but with d_{eff}

d_{eff} : It's defined as the distance where the field has dropped to about 80% of its maximum value

keep this

* For spheroid and cylindrical electrodes,

$d_{eff} = 0.115\,r$ & $0.23\,r$

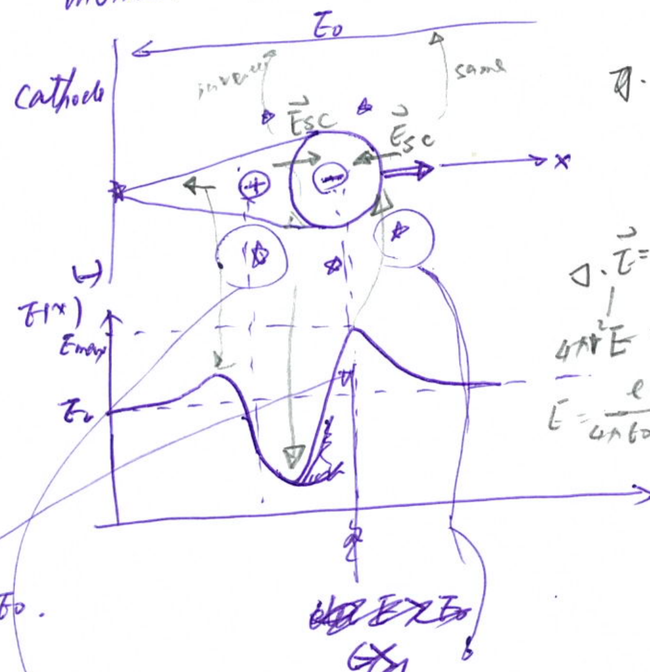
p28a

2.2.1.1 Space charge effects.

* The space charge ~~was neglected~~ that is created in the electron ~~avan~~ avalanche was neglected!! But it can not be neglected if there are $10^6 \sim 10^8$ particles in a gas at atmosphere pressure.

p28e

* immobile ions stay behind in the avalanche tail. mobile electrons form the spherical avalanche head.



If there are N charged particles

since the charge density grows by a factor of e over a distance $(1/\alpha)$ ← α: ionization events performed by an e^- in a unit length.

$\nabla \cdot \vec{E} = \frac{\rho}{\varepsilon_0}$

$4\pi r^2 E = \frac{eN}{\varepsilon_0}$

$E = \frac{eN}{4\pi\varepsilon_0 r^2}$

$E_{sc} = \frac{eN}{4\pi\varepsilon_0 (1/\alpha)^2} = 1.5\times10^{-7} \frac{N}{(1/\alpha)^2}$ V/cm

For $N = 10^7$, $\alpha^{-1} = 10^{-2}$ cm

$E_{sc} = 15$ kV/cm ≈ applied field.

ionisation caused by electron is more efficient ∵ $E > E_0$.

⇒ "Streamer mechanism"

UV light emitted in recombination and de-excitation.

⇒ creates electrons by "photoionisation" ahead & behind the avalanche

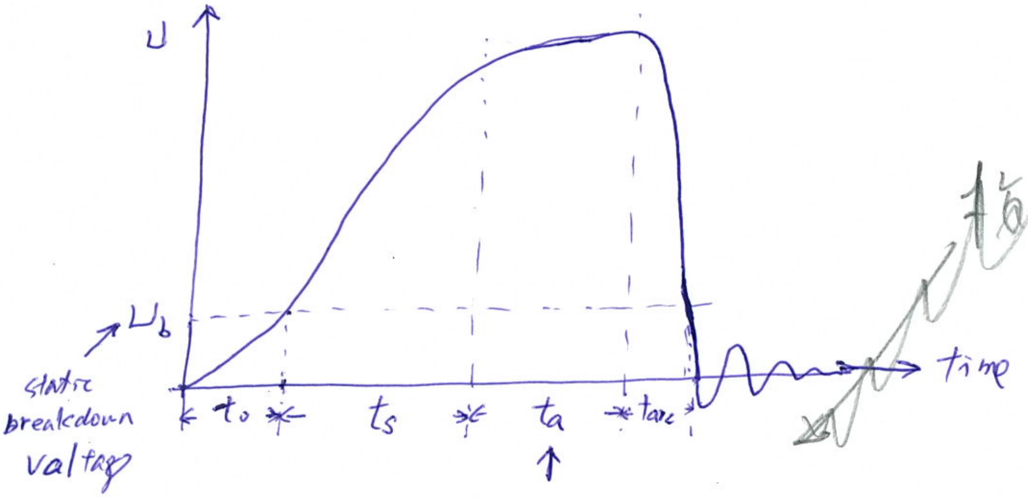
⇒ form a conducting bridge between anode & cathode

* Creating photoelectrons at larger distances from the main streamer can advance the growth of the breakdown ~~ch~~ channel rapidly.

add slide · ⇒ $v = 100 - 1000$ cm/μs was observed at atmosphere pressure

§ 2.2.2. Pulsed breakdown.

* If a fast-rising pulse across the gap, we must take account into the fact that it takes a finite time before breakdown can occur



t_0: the time until the static breakdown U_b is exceeded.

t_s: statistical delay time until an electron able to create an avalanche occurs.

t_a: the avalanche build-up time until the critical charge density is reached.

t_{arc}: the time required to establish a low-resistance arc across the gap.

→ results from the statistics of electron appearance.

* Free electrons can be created by illuminating the gap volume or the cathode surface with electromagnetic radiation, in particular UV light, x-rays & γ-radiation.

goto p32 after this page

* Streamer Mechanism.

- For long, atmospheric air gaps → can't be explained using Towesend's model

Ex① $d \sim 1\,cm$ ⇒ short delay time ($< 1\,\mu s$)

For Towesend's model : successive avalanches ~~develop~~ determined by ion drifting velocity

⇒ $\Delta t \sim \frac{1\,cm}{10^5\,cm/sec} \sim \underline{10\,\mu s}$

Ex②: breakdown appears to be independent of cathode material.

Ex③: Townsend discharge: broad development from the cathode.

However, existence of narrow, luminous discharges originating from either the anode or from the middle of the gap may happen !!

⇒ streamers - evocative of a thin band of bright light, attached at one end to an electrode and floating toward the other -

"kanals", channel in German.

* Cathode-directed (positive) streamers (from A → K)

Anode-directed (negative) streamers (from K → A

* single-electron avalanche → streamer.

~~when~~ Streamers develop when the charge density at the head of the avalanche becomes so large that it distorts the applied electric field.

i.e. space charge in the avalanche head generates a self-electric field that is on the order of the applied electric field.

* Criterion for streamer Onset: p28 b

$E_r \sim E_0$

↑

generated by the space charge at the head of the avalanche.

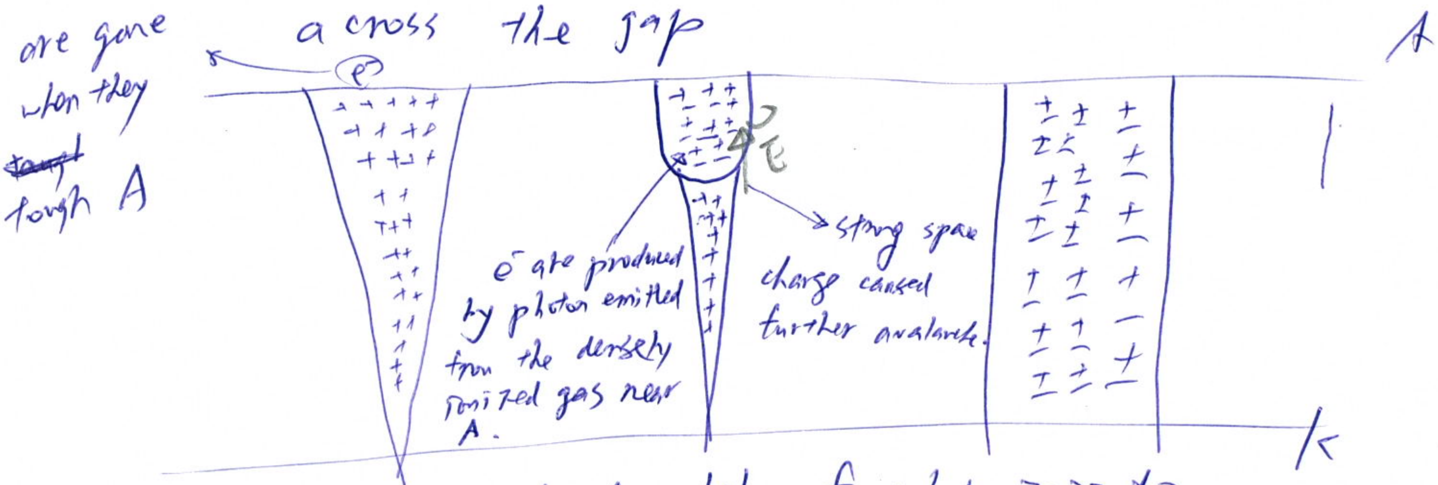
space charge or $N_{cr} \sim 10^8$ cm^{-3}

↑

of e^- in

made to p27 (~~p.12~~)

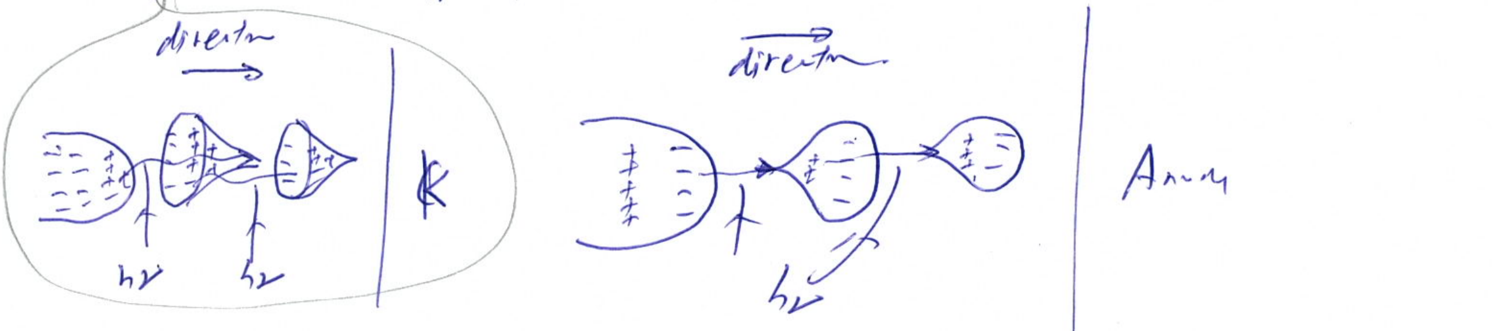
* Cathode-directed (Positive) streamer. from A → K
- When the avalanche has crossed the gap, the e^- are swept into the anode, the positive ions remaining in a cone-shaped volume extending across the gap



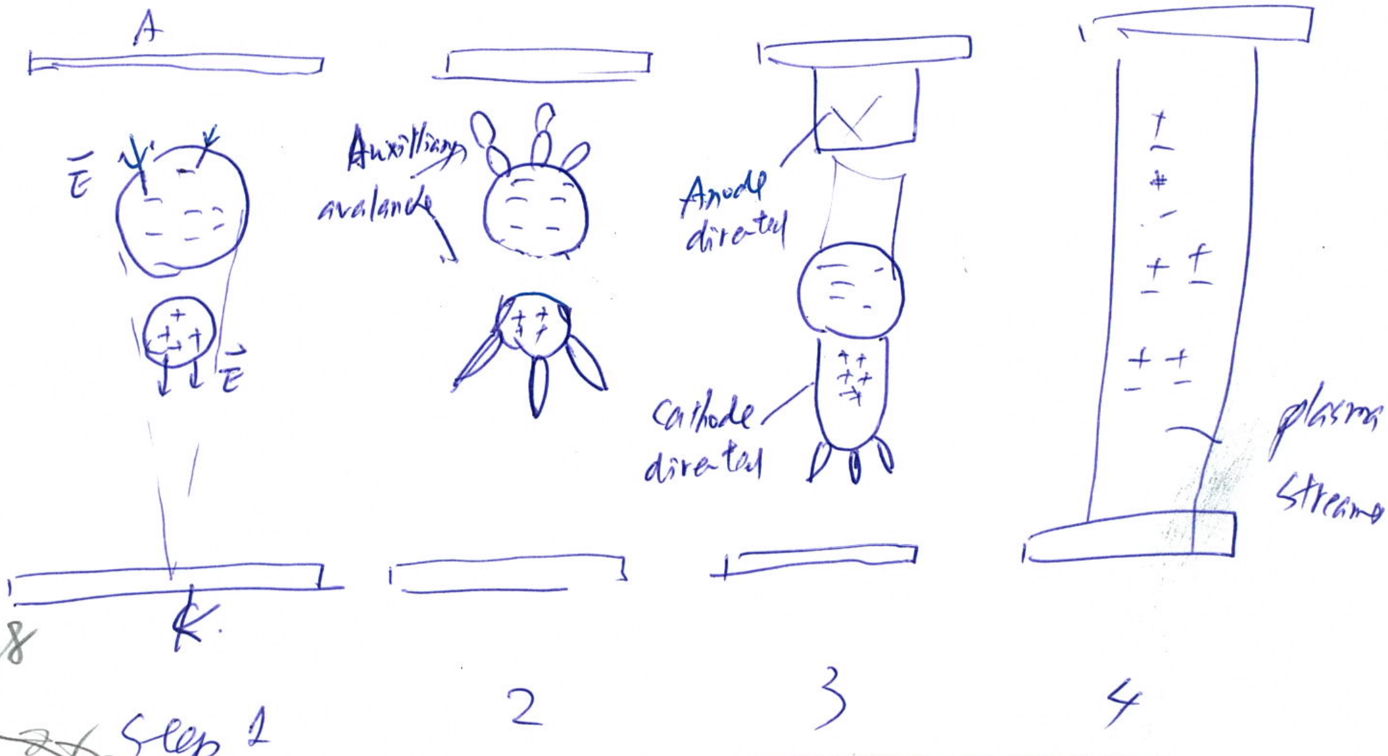
- grows w/ the help of photoionization

* Anode-directed (Negative) streamer: from K → A
- When the primary avalanche becomes sufficiently strong before reaching the anode.

of $e^- \sim 10^8$.



* Overvolted streamer:



* The Corona discharge.

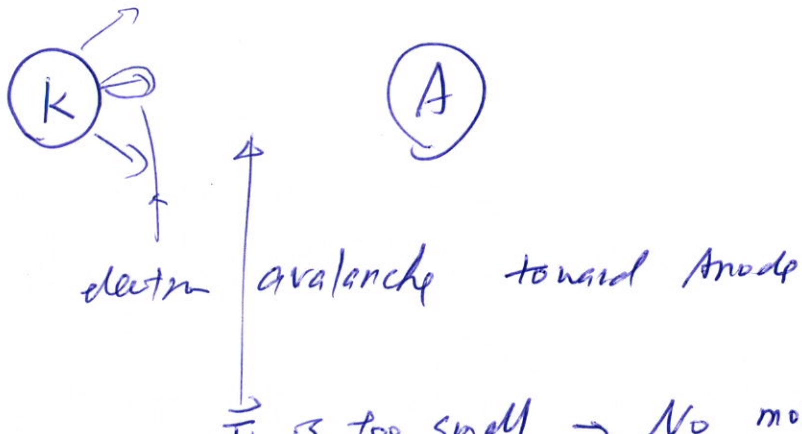
- Corona is a luminous, audible discharge that occurs when an excessive localized electric field gradients causes ionization in the ~~sur~~ surrounding gas.

  It manifests easily in highly nonuniform E field geometries

  → • colored glow frequently visible in darkened environment
  • subtle hissing sound. Volume ↑ w/ V ↑
  • O_3 can be generated → rubber can be distroyed
    ~~NO_3~~
    → NO_3 can be generated w/ moisture.

-

- Negative point corona (Trichel pulses)



$\vec{E}$ is too small → No more ionization

⇒ e^- are slowed down ∴ ⊕ ions left behind

⇒ attach to gas molecules, forming ⊖ ions

⇒ E field cancel the external E field

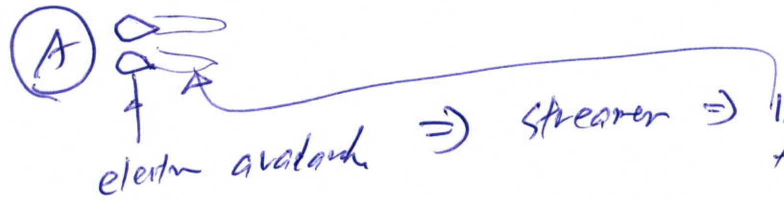
⇒ ⊕ & ⊖ ions drift to each electrode (current)

⇒ No more cancel E field

⇒ corona again

⇒ steady-state corona current when V is high enough

- Positive point corona



⇒ streamer ⇒ lateral avalanches fee into the streamer core

⇒ streamer growth

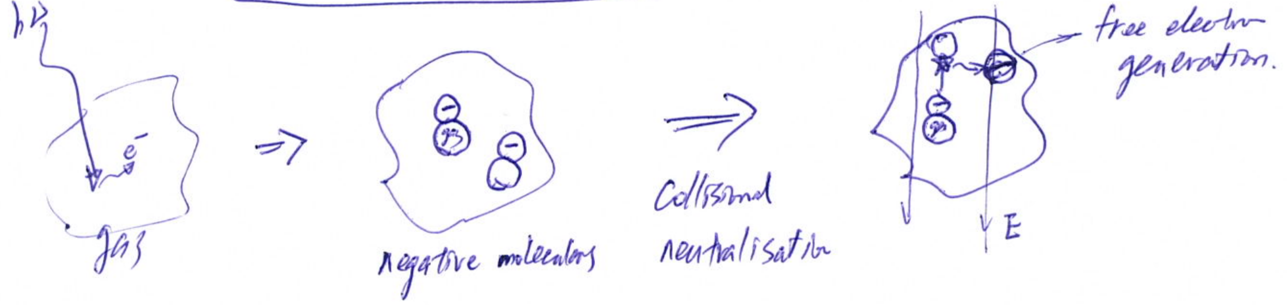
* Corona – power loss

– RF interference

– service life ↓

go back to p36 a9

* Natural radioactivity & cosmic radiation
  - → 0.1 ~ 10 free electron / cm^3-s in a gas at atmosphere.
  - → the electron can attach to the gas molecules
  - → few thousand negative moleculars / cm^3 - few minutes
    (SF_6 : 2500 SF_6^- ions / cm^3 in 5 minutes was measured)
  - → With electric field → e^- can be liberated through
    collisional neutralisation → free electron generation



$$\dot{n}_\delta(t) = \delta \cdot n_n \cdot u_n$$

$$u_n = \mu_{mix} \cdot E$$

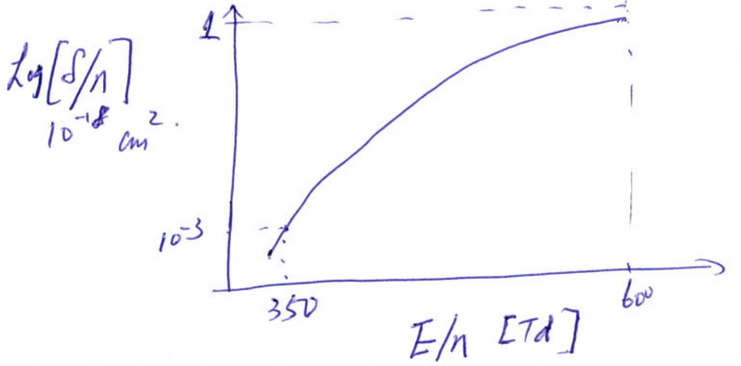
$\dot{n}_\delta$: rate of electron detachment / unit volume

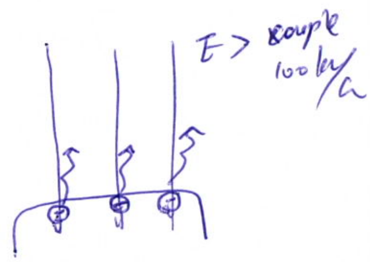
n_n : density of negative ion

δ : coefficient of collisional electron detachment

u_n : ion drift velocity

μ_{mix} : mobility - depends on < the kind of ions / gas composition.





* If E > few times 100 kV/cm → more electrons can leave the metal surface through the tunnel effect

The current density (Fowler-Nordheim eq. 1928)

$$j = \frac{1.54\times10^{-6}\,\beta^2 E^2}{\phi}\exp\left\{-\frac{6.83\times10^{7}\,\phi^{3/2}\,\theta(y)}{\beta E}\right\}$$

$\theta(y) = 0.956 - 1.06\,y^2$

$y = 3.8\times10^{-4}\,\frac{\sqrt{\beta E}}{\phi}$

j : A/cm^2

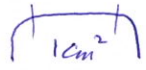
E : V/cm

β : Enhancement factor - take into account the special conditions at localised emission centers on the metallic surface.

ϕ : work function, eV

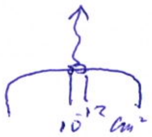
* The importance of localised emission site

To generate 10^6 $\bar{e}$/sec. from a flate metallic surface of area $1cm^2$,



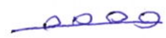
$E \geq 1.2 \times 10^7$ V/cm is needed

For a localised emission site possessing a field enhancement of $\beta = 100$



$\Rightarrow E \geq 2.4 \times 10^5$ V/cm is needed for an area of 10^{-12} cm²

* Most important emission centre:
  - dielectric inclusions
  - metallic microprotrusions (whiskers)
  - absorbed gases



* Total number of electrons in the gap:

$$\dot{N}(t) = \dot{N}_{on} + \dot{N}_F(t) + \dot{N}_g(t)$$

$\dot{N}_{on}$: # of naturally occuring electrons in the gap, independent of time

$\dot{N}_F(t)$: ~~#~~ rate of ~~field emission~~ field-emitted electrons

$\dot{N}_g(t)$: rate of electron detachment.

* Note that not every electron released ~~from~~ into the gap is able to initiate an avalanche even if the voltage is above the static breakdown value !!

→ Avalanches can grow only in those ~~di~~ parts of the gap volume where the local field strength exceeds a certain critical value

→ For electronegative gases, E_{cr} is when the ionisation coefficient $\alpha > \eta$ — the electron capture coefficient.

~~* An electron~~

* The probability for a single electron to initiate an avalanche:

$$g\left(\frac{E}{P}\right) = 1 - \frac{\eta}{\alpha}$$

(for greater α, smaller η, $g\left(\frac{E}{P}\right)$ is larger) - - -

$$\dot{N}(t) \to \dot{N}_a(t) = \int_F g\left(\tfrac{E}{p}\right) \cdot \dot{N}_{F1}(t)\, dA + \int_V g\left(\tfrac{E}{p}\right) \left[\dot{N}_g(t) + \dot{N}_{ion} \right] dV$$ P31

probability that a breakdown has occured before time t:

$$F(t) = 1 - e^{-\int_0^t \dot{N}_a\, dt}$$ (Conditional probability)

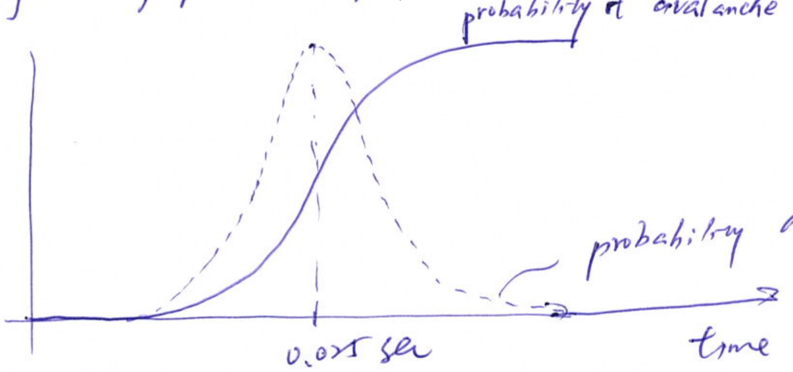
or probablity density:

$$f(t) = \dot{N}_a\, e^{-\int_0^t \dot{N}_a\, dt}$$

Ex: 1 cm gap w/ 1 bar dry N_2

⇒ static breakdown voltage : 31 kV

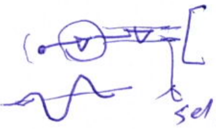
If the gap is ramped at 6 MV/sec



Slop

⇒ $0.025_{sec} \times 6\, MV/sec = \underline{150\, kV \gg 31\, kV}$!!

→ After the 1st electron avalanche there are two ways to break down.

- Townsend breakdown  ⇒ [quasi-stable glow discharge / glow-to-spark transition.
- streamer mechanism :  self-propagatn of the avalanch

t_a are very diffent betwn two

→ assumes that ~~of~~ secondary e^- are released fm cathode through interactn with photons & ions ⇒ ~~discharge~~ distribut the discharge over a larger ~~so~~ volume

→ The overvoltage must be sufficiently large such that the critical electron number N_{cri} is established in the gap during a single avalanche.

~ 15-20% > ~~of~~ static breakdown level U_b

§ 2.2.3 Spark Formation

* A conducting channel exists between the anode and the cathode after a streamer has bridged the high-voltage gap.

conducting channel. (low resistance)

→ An intense current starts to heat the channel and to ionise it further until a low-resistance channel is established

{ Toepler's model (1924, 1927)

* { Pfeiffer's model (1971):

Assuming that a weakly conducting column exists and that its conductivity is increased by collisional ionisation:

($\sigma \uparrow$ as ionisation $\uparrow$)

$$dn_e = n_e \cdot \alpha \cdot dx$$ → electron ~~spreading speed~~ drift velocity

$$= n_e \cdot \alpha \cdot u_e dt$$ → electron mobility

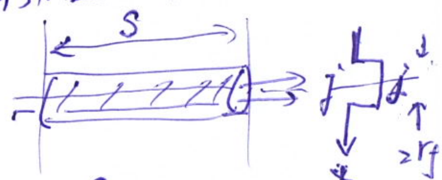
$$= n_e \cdot \alpha \cdot \mu_e E \cdot dt$$ → mean electric field in the spark channel.

$u_e = \mu_e E$, mobility

$$j = n_e \cdot \mu_e \cdot e \cdot E \ \left(= n_e \cdot u_e \cdot e\right)$$

$$\Rightarrow dn_e = \alpha \cdot \frac{j}{e} \cdot dt \Rightarrow n_e = \frac{\alpha}{e}\int_0^t j\, dt$$

Assuming a homogeneous current density distribution in the column



spark resistance

$$R_f(t) = \frac{U}{I} = \frac{E \cdot S}{j \cdot \pi r_f^2}$$

$$= \frac{E \cdot S}{(n_e(t) \cdot \mu_e \cdot e \cdot E)\, \pi r_f^2} = \frac{S}{\frac{\alpha}{e}\underbrace{\int j\, dt\, \mu_e \cdot e \cdot \pi r_f^2}_{=I}}$$

$$= \frac{S}{\alpha \cdot \mu_e \int_0^t I\, dt}$$

S: channel length

r_f: radius of the spark channel.

* ~~This~~ This model (Toepler) says that:

$$R \propto \frac{1}{\int I\,dt} = \frac{1}{Q}$$ ← charge that has been flowing through the channel.

* The colum expands when it is heated by the current flow.
  ⇒ It is not considered in the model
  ⇒ It is only valid for a limited time after the channel is formed, ~10ns in a gas at atmosphere.

* Weized & Rompe (1944, 1949) model
  - Channel expansion is ignored as well.

skip

$$R_f(t) = \frac{S}{\sqrt{2\frac{a}{P}\int_0^t I^2 dt}}$$

a → constant
p → gas pressure

→ * Braginskii (1958)
  - consider the thermal expansion of the plasma channel

  - assuming a time independant specific conductivity for the plasma channel.

$$R_f(t) = \frac{S}{\pi \sigma b^2 \int_0^t I^{2/3} dt}$$

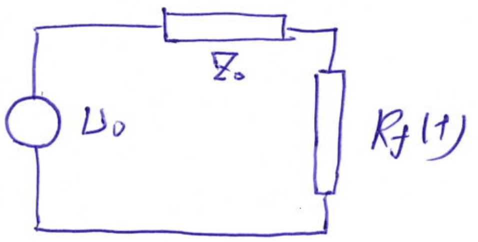
b: a constant depend on density, conductivity & the thermodynamic properties of the plas.

σ: mean plasma conductivity.

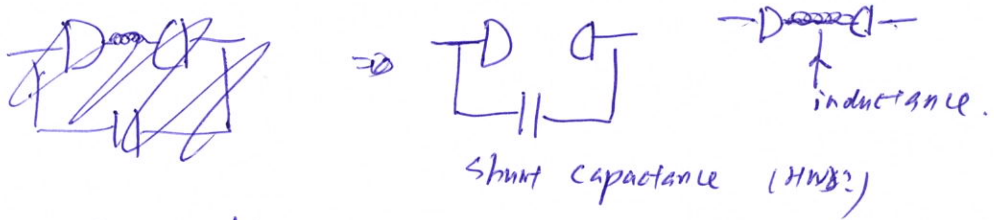
Gas	$k_T = 1/\alpha \mu e$ (10^{-4} V s/cm)	a atm cm^2/V^2s	σb^2 (10^4 $A^{1/3}$cm/V s)
Air	0.5-0.6		3.5
N_2	0.4	1.1	
CO_2	0.5	1.0	3
Argon	0.085	25	10

goto p35a after here

* Let's determine the current increase and the voltage decrease across the spark using Toepler's relationship.



* Inductance of the spark & shunt capacitance are neglected.



U_0 : ignition voltage

Z_0 : impedance of the driving source.

$$I_{max} = \frac{U_0}{Z_0 + R_f} \simeq \frac{U_0}{Z_0} \quad (\text{generally, } Z_0 >> R_f)$$

$$I = \frac{U_0}{Z_0 + R_f} = \frac{U_0}{Z_0 + \frac{s}{\underbrace{\alpha\mu_0}_{= 1/k} \int_0^t I\,dt}} = \frac{U_0}{Z_0 + \frac{s\,k}{\int_0^t I\,dt}}$$

$$\frac{I}{I_{max}} \equiv y = \frac{U_0}{Z_0 + \frac{s\,k}{I_m \int_0^t \frac{I}{I_{max}}dt}} \cdot \frac{Z_0}{U_0} = \frac{1}{1 + \frac{s \cdot k}{Z_0 \cdot \frac{U_0}{Z_0} \int_0^t y\,dt}}$$

$$\Rightarrow \quad y = \frac{1}{1 + \frac{k}{E_0 \int y\,dt}} \quad \Rightarrow \quad \underbrace{\frac{1}{y} - 1}_{= \frac{1-y}{y}} = \frac{k}{E_0 \int y\,dt}$$

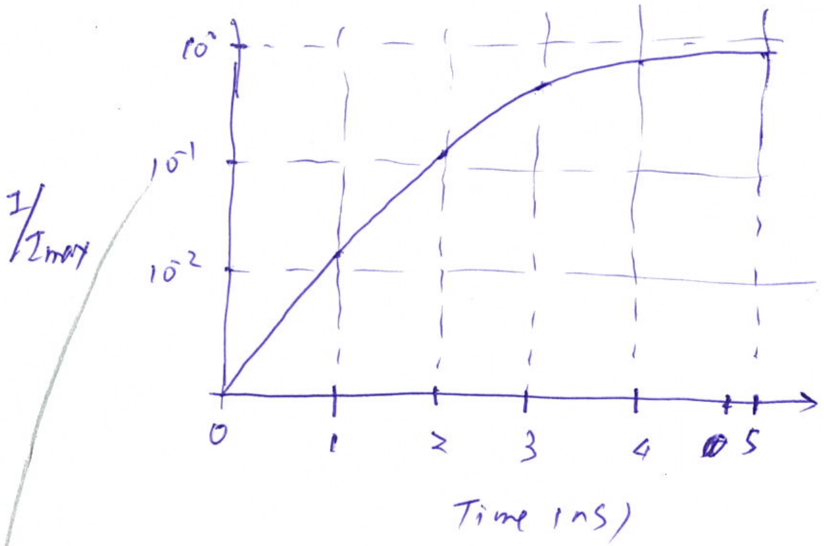
$$\Rightarrow \quad \int y\,dt = \frac{k}{E_0}\frac{y}{1-y} \quad \xrightarrow{\frac{d}{dt}} \quad y = \frac{k}{E_0}\frac{dy}{dt} \cdot \frac{(1-y)+y}{(1-y)^2}$$

$$\Rightarrow \quad dt = \frac{k}{E_0}\frac{dy}{y(1-y)^2} \quad \Rightarrow \quad t = \frac{k}{E_0}\left[\ln\left(\frac{y}{1-y}\right) + \frac{1}{1-y} + C\right]$$

Assuming that spark current begins with $y = \frac{I}{I_{max}} = 10^{-3}$

$\Rightarrow \quad C = 5.906.$

P35



$K = 0.4 \times 10^{-4}$ Vs/cm

$E_0 = 10^5$ V/cm

N_2.

rise time: $\tau_{0.1-0.9} = 13.2 \frac{K}{E_0}$

efolding time: $\tau_r = 6.84 \frac{K}{E_0}$

Slow * J. C. Martin's (1996) formula:

$$\tau_r = \frac{88}{Z_0^{1/3} E_0^{4/3}} \sqrt{\frac{\rho}{\rho_0}} \quad (\text{ns})$$

Z_0: impedance driving the channel.

E_0: the field at the beginning of breakdown.
in unit of 10 kV/cm

ρ: the density of the gas

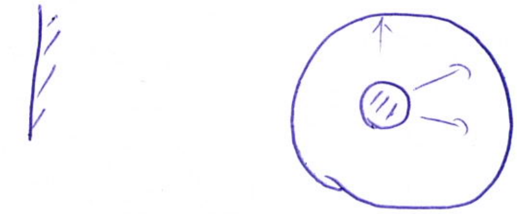
ρ_0: - - - - - - - ~~air~~ under normal condition.
(atmosphere)

7) The corona discharge.

corona – a luminous, audible discharge that occurs when an excessive localized electric field gradient causes ionization in the surrounding area.

- It manifests easily in highly nonuniform electric field geometries

a



⇒ colored glow ~~oi~~ frequently visible in darkened environment.

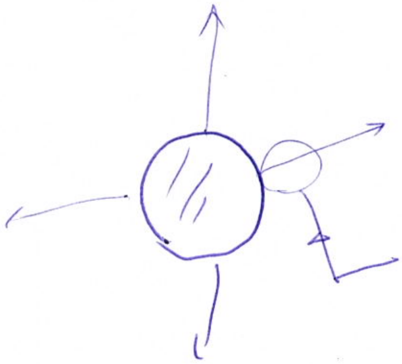
⇒ a subtle hissing sound, ↑ w/ ↑ V

⇒ Ozone is generated.

⇒ rubber is destroyed, by O_3

NO_3^+ is generated w/ moisture

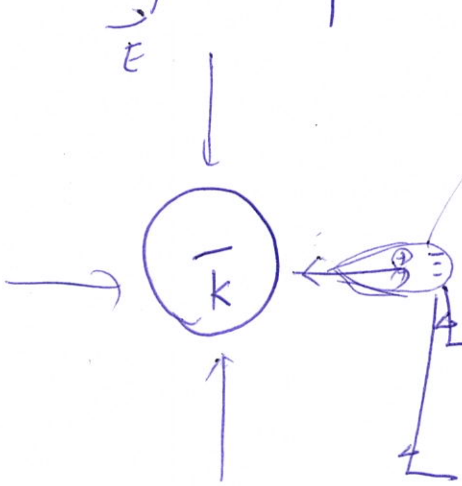
$$E \propto \frac{1}{r^2}, \quad V \propto \frac{1}{r}$$



Townsend breakdown occurs in small region only
⇒ luminous glow w/ hissing noise.

current pulses — randomly / regularly

- Negative point corona - Trichel pulses



avalanche toward Anode

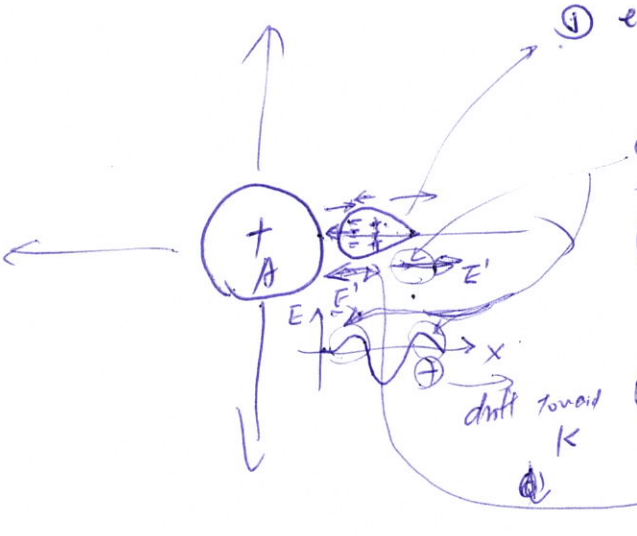
low field region ⇒ no further ionization.

slow down by ⊕ ions behind,
⇒ attach to gas molecules forming "⊖ ions"
⇒ reduce the E field point to cathode
⇒ discharge extinguish

drift toward Anode (current),
⇒ away from cathode
⇒ original E field is re-established
⇒ Another Trichel current pulse.

- Trichel pulses are regularly placed and only appear in gases exhibiting some e^- attachment, notably air & sulfur hexafluoride (SF_6)

- Positive point corona



① e^- avalanche initiated near the high-field region propagating toward A.

② streamers is developed

③ Lateral avalanches feed into the streamer core.

④ negative ion cloud is formed

p 28 ①

Corona
- power loss
- RFI interference.
- reduce the service life of solid & liquid insulation via initiating partial discharge.
- chemical decomposition

↓

go to p38C.

2.3 Liquids. (Lecture 4)

p36b first

2.3.1 Basic Electrical Processes

* Breakdown initiation in the liquid can be divided into two categories: ~~bulk liquid~~
  - those associated with the bulk liquid
  - those occurring at the electrodes.

* Lewis 1985, 1987, 1993, 1994a.b.c, 1996, 1998.

2.3.1.1

* Charge in the bulk liquid can arise from
  1. molecular dissociation (分子离解)
  2. injection at an electrode.
  - → no net charge in the liquid
  - → leads to either an excess or a deficiency of e⁻ in the bulk.

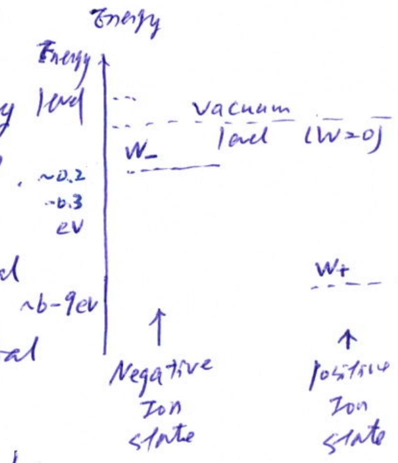
  excess: 过多 deficiency: 不足

* Charge transport occurs through
  1. molecular electronic state
  2. collective states of clusters of short-range order appearing in the liquid

  排列次序

* In atom:

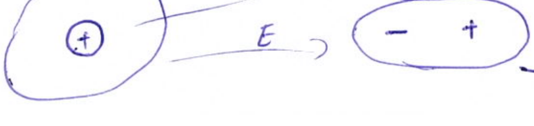
⇒ Energy Level



Positive ion state: W_+ → ionisation potential

Negative ion state: W_- → detachment potential

* In Liquid: ionised states are modified by the collective polarisation response of the ~~surr~~ surrounding ~~mole~~ molecules, and the energy levels corresponding to the fully polarised states shift to $W_+(\infty)$ and $W_-(\infty)$, respectively.

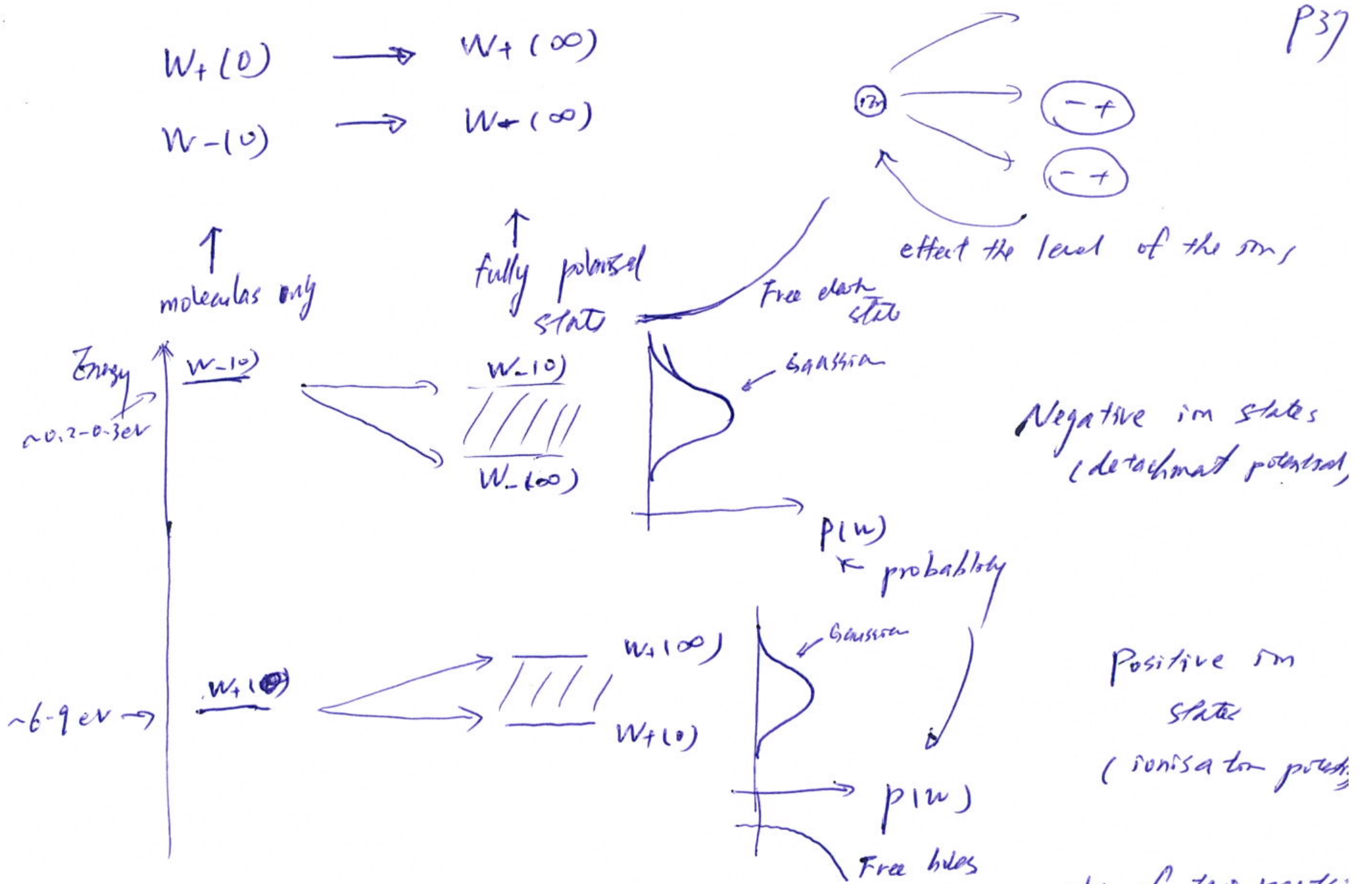


← polarised states in liquid.

* To creat an electrical discharge in liquid: P36 b

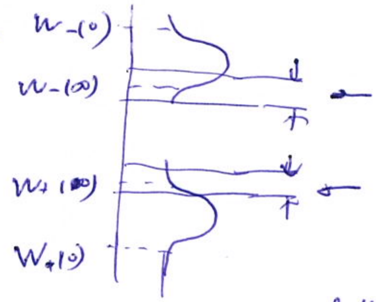
① a discharge in gas which occurs in gas bubbles that either are initially present in the liquid and on the electrodes or are formed under the action of voltage.
(electrolysis, boiling, degassing of the electrode surfaces, etc.)

② a consequence of the avalanche multiplication of free ~~ch~~. charge carriers in the liquid like the model in gas.

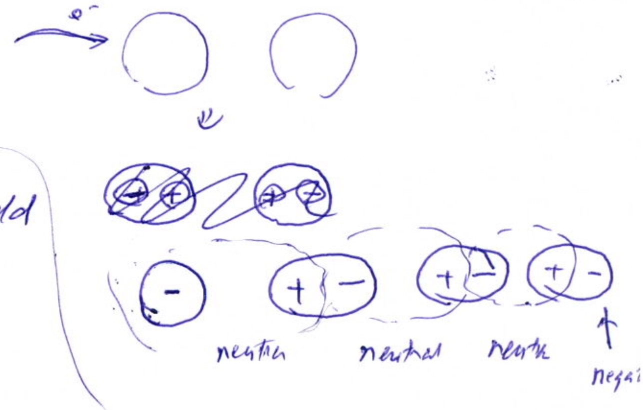


* The energy associated to the shift " $W(0) - W(\infty)$ consists of two parts:
  1) polarisability of the molecular orbitals
  2) collective dielectric response of the more remote molecules.
* when the state of an ion changes by gaining or loss of an electron, molecular reorganisation occurs on a much slower timescale than that needed to relocate the electron.
* (∵ thermal agitation → Gaussian distribution.)
* Electron & hole transport in the bulk liquid can be described (of negative / positive ion states) similar to by a band model that for amorphous solids. ← no crystalized structure like liquid.
* (Excess) charge carriers can stay in
  - localised
  - quasi-localised
  - quasi-free mobile states in the conduction band.
* Quasi-free: e^- energy > $W_-(0)$
  hole energy < $W_+(0)$
  ↳ carriers can be considered free if they move through a sequence of states in the bands without staying long enough to induce the full electronic polarisation. → mobilities > 10^{-3} $m^2/V\cdot sec$ (× volt.)

* Quasi-localized state:

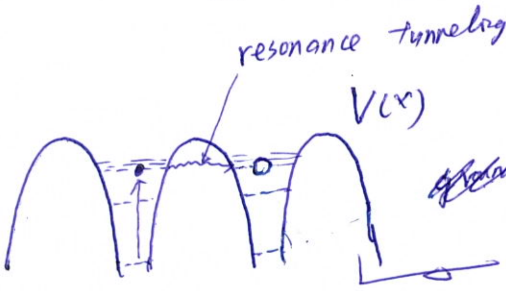


* Electrons and holes which have become fully localised drift as ions with their accompanying polarisation shells (polarons), mobility $< 10^{-5}$ $m^2/V \cdot s$



* Incident radiation & high electric field → can free the charge.

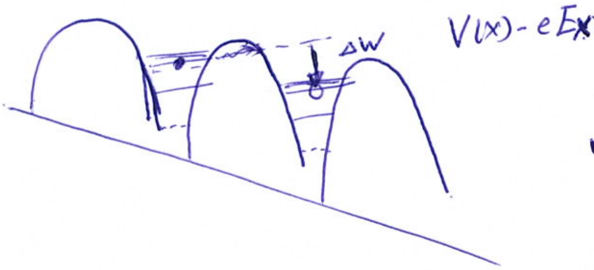
between quasi-local & quasi-free



~~special state~~

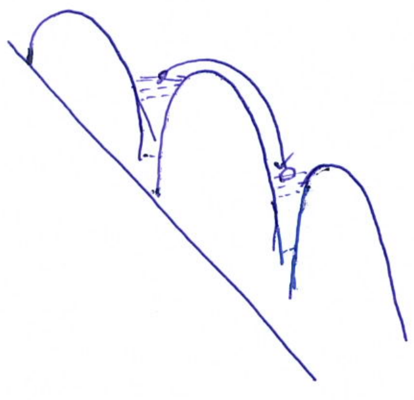
periodic potential in a molecular cluster.

~~dissipated as phonon energy → heating of the molecules along the electron path.~~



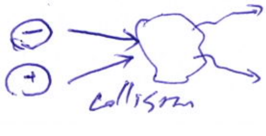
~~Higher electric field:~~

with electric field: ΔW is predominantly dissipated as phonon energy ⇒ heating of the molecules along the electron path



High electric fields: electron will be able to "jump over" the potential well. (hopping process) ⟹ dissipated as heat or emission of photons.

* In the quasi-free state: the mobility of electrons (holes) is determined by scattering collisions with the liquid molecules.
⇒ excite vibrational modes & loss their energy from the E field



vibration modes.

* ~~electron can be in quasi-free state sometime & in local~~

* During transit through a liquid, electrons can thus exist for some time in quasi-free and for some time localised states.

⇒ effective mobility:

$$\mu_{eff} = \frac{\mu_f t_f + \mu_t t_t}{t_f + t_t}$$

f: free state

t: trapped state.

μ: mobility.

$$t_t = t_0 \exp\left(\frac{E_t}{kT}\right)$$

⇐ the time in the trap is determined by the thermal activation energy E_t necessary to liberate the electrons.

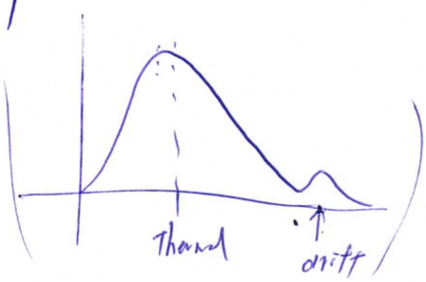
↑ reciprocal of an attempt-to-escape frequency (-1)

For hydrocarbons: $E_t \sim 0.3x$ eV.

* With high E field ⇒ $t_t \downarrow$
* Most of the time, electron transit in conduction ~~band~~ band

⇒ drift velocity ~~...~~ is limited by collision process (as mentioned in the last page)

* At very high field ⇒ drift velocity > thermal velocity



⇒ energy acquisition from the field can become quite high

In hydrocarbon (C_xH_y), the rate is 10^{14} eV/sec

⇒ energy is dissipated by stimulating various molecular vibrational modes with typical quantum energies $h\nu$ of a few tens of an eV

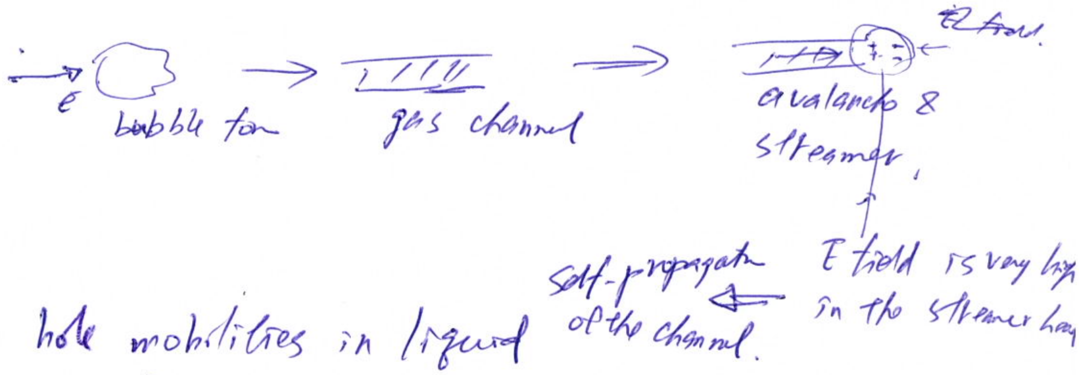
⇒ $E_{k.e} > h\nu$ ⇒ cross-section for inelastic collisions ~~↓~~ drops rapidly ⇒ electron can gain sufficient energy to excite the next mode in terms of energy, up to molecular dissociation and ionisation.

⇒ Ionisation is very important in the context of breakdown, since it generates a second electrons and a positive ion or hole, and an avalanche can build up in the liquid.

* ~100 meV is needed to heat the liquid to ~~to~~ its boiling ~~pto~~ point ⇒ a <u>region of low density (RLD)</u> may have been created before avalanching occurs in the liquid & normal density

⇒ In RLD, electron avalanches can build up at much lower electric field ⇒ ~~cause~~ form a growing <u>gas channel</u>

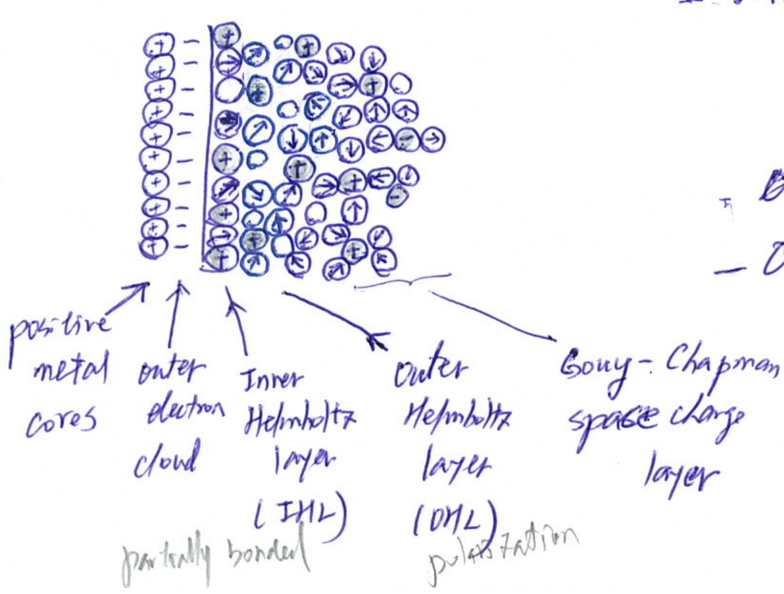
⇒ starting point of <u>a streamer</u> similar in gases



* The reported hole mobilities in liquid are typically a factor of 10 smaller than the electron mobility at equal field strength.

7. 2.3.1.2 Electrode Processes

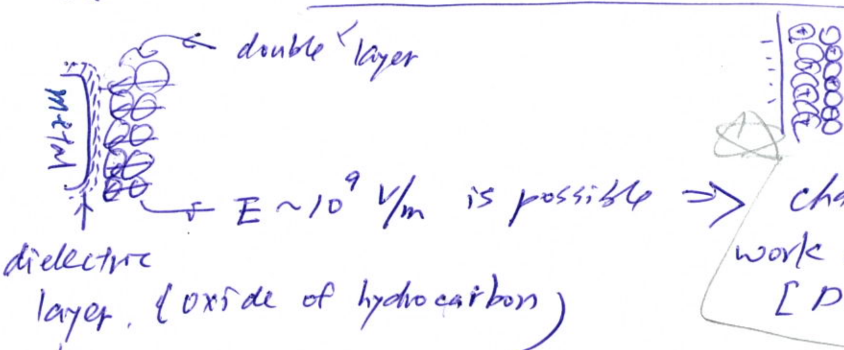
* Electrode processes play a dominant role in the <u>initiation of breakdown</u> in liquid
* Excess electrons (or holes) may be <u>injected from metallic electrodes</u> into the liquid.
* metal - dielectric interface



- IHL: a monolayer of ions and molecules chemically or physically bonded. → very different from bulk liquid
- ~~OHL:~~
- OHL: ions approach the equilibrium polarisation in the bulk liquid.

* Gouy-Chapman space-charge layer – a diffuse region. P41
→ the ions attracted into the Helmholtz layers are not sufficient to compensate all of the charge on the electrode, and the residual E field results in an additional charged layer. → may extend far into the liquid with low ion.

* IHL → may become double layer if the ions moving to the surface are not neutralized immediately.



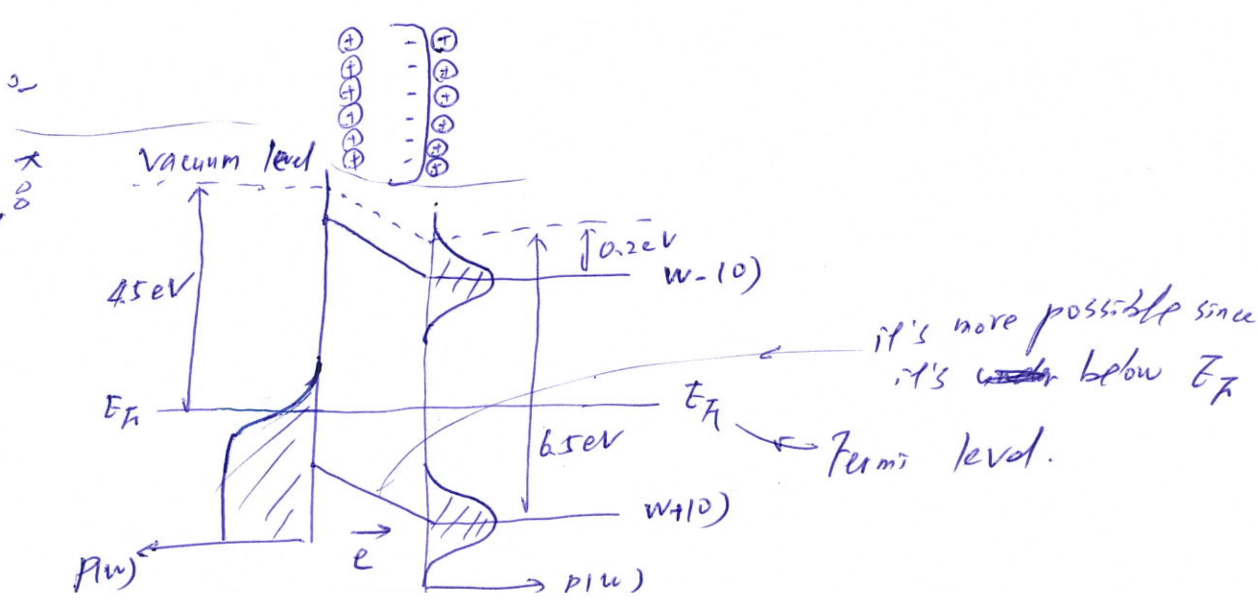
⇒ changes the effect work function of the met. [Dekker 1964]

dielectric layer

* If the charge transfer through the metal interface is difficult; ions can not be neutralized at the electrodes, the electrodes will become increasingly polarized. ⇒ increase in the resistance of the overall system

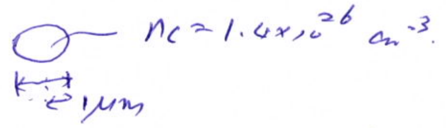
?? △.

doesn't fit the flow



* Less energy is required to expand the nucleation site to a critical size with sufficient low density ($n < n_c$) such that electron impact ionisation can take place and a gas streamer can grow to the critical size.

For water, ~~r_c~~ $r_c = 10^{-6}$ m, $n_c = 1.4\times10^{26}$ m^{-3}

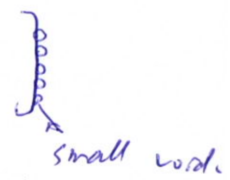


* It's still unclear how the large electron density can be injected to achieve the ~~super~~ required superheat.

⇒ An unrealistically large local field enhancement seems necessary to deliver the necessary electron tunnel current.

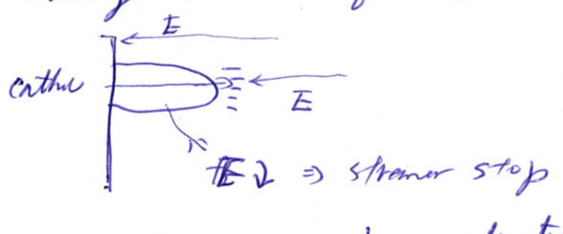
- Scenario 1: electrocapillarity

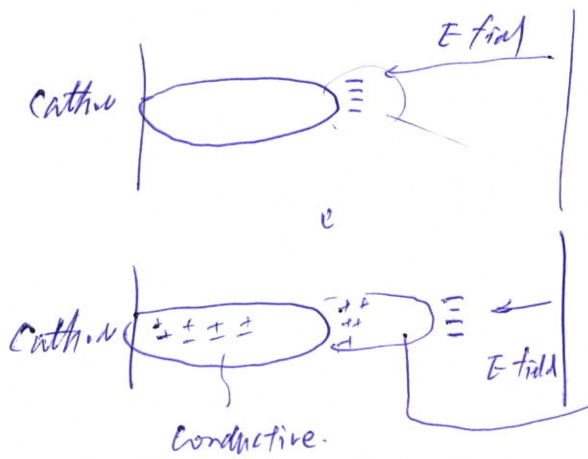
⇒ creates a tensile stress perpendicular to the applied field $\hat{E}$ and produce voids in the liquid & small crakes in the liquid boundary layer



- Scenareo 2: stimulated liberation of gas dissolved in the liquid.
  ⇒ preferentially at rough surfaces with crakes

* Streamer can stop because of the build-up of a negative space charge in the liquid. ~~front of the space~~





* Electron can be accelerated toward to the streamer tip into the liquid
  ⇒ form a new space charge and start another heating and evaporation cycle.

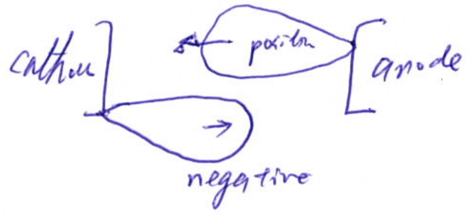
If it's heated and become a region of low density before the space charge build up ⇒ streamer die.

It helps maintaining the potential at the front closed to electrode by causing streamer die.

§ 2.3.2 streamer breakdown

→ ~~ppt~~ figure from power point.

* Positive and negative streamers propagate towards the cathode and anode respectively



* Schlieren diagnostics have shown that a streamer consists of a gaseous phase → breakdown strength should increase with pressure ← gas is not formed easily

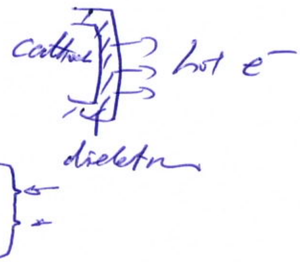
* Temperature has a minor effect.

§ 2.3.2.1 Cathode initiation (negative streamer)

* Primary process for the initiation of a negative streamer is the injection of hot electrons into the liquid. from

  - ① dielectric (oxide) emission

  ② metallic microprotusion. 돌출
    - A) on the electrode surface
    - B) contaminant particle in the liquid. ← most of the cases

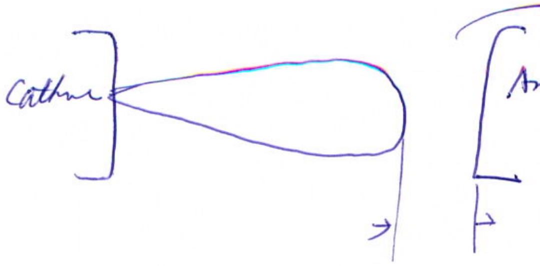


* If sufficiently large electron current density is injected into the liquid, a gas bubble of critical size & density may form at the electrode surface.

  → $> 10^9\ J/m^3$ (for water) must be deposited adiabatically in the liquid to create enough superheating
  [Jones and Kunhardt, 1995.]

→ when it gets closed to anode, pry

*



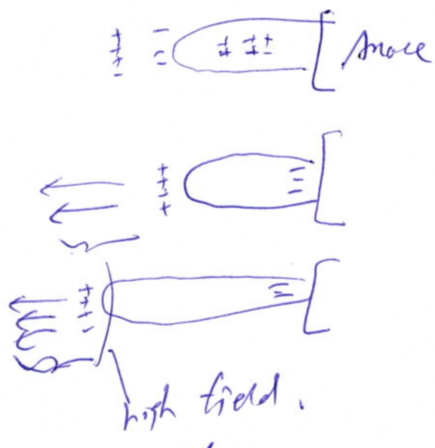
$E\uparrow \because d\downarrow$

⇒ ~~cause~~ initiate a secondary or tertiary streamer.

7.2.3.2.2 Anode initiation (positive streamer)

* Initiated by hole injection from an oxide microregion on the anode surface. → liquid-metal interface
  └ liquid-plasma boundary of a stream

* Liberation of electrons from traps, quasi-localised states, or molecules with a low ionisation potential through field ionisation in the vicinity of a microprotrusion on the anode.



7.2.3.2.2 Water:

* Important dielectric liquid in pulsed-power application
  - ✓ - High electric breakdown strength (up to 3×10^{7} V/m) for μs electric stress
  - ✓ - High permittivity (80) → store large energy densities for short time.
  - water molecules → simple structure,
    └ intramolecular electron transport is unimportant
  - possess large dipole moment
  - property @ metal-liquid boundary layer ≈ bulk liquid
  -

- much greater density for the 1st layer than in bulk water p45

⇒ strong impact on electron transfer

⇒ — — — the formation of gaps in the boundary layer due to electrocapillarity

- ~~[illegible]~~ small fraction ($\sim 10^{-7}$) dissociated into H^+ & OH^-

⇒ a residual conductivity 4×10^{-6} S/m

⇒ Inadequate for DC-insulation

↳ ionic currents do not contribute to the initiation of breakdown for submicrosecond pulses.

- can dissolve a lot of gases (N_2, O_2, CO_2) ⇒ lead to formation of gas bubbles and thus facilitate the appearance of a streamer.

- pressure ↑ ⇒ dynamic breakdown strength ↑

- time lag to breakdown ~~[illegible] water~~ in "doubly distilled ~~wat~~ water" without gas ↑ 50%

★ Transformer oil for insulation: (insulating)

- The natural moistening of insulating oils does not change their pulsed electric strength at voltage action times of 10^{-8} s even if the dc breakdown voltage changes three times!!

- Requirements to the purity of the insulating liquids used in pulsed power systems can be moderated.

3. 2.4 Solids

The phenomenon of ~~the~~ dielectric breakdown in solids is linked ~~separately~~ inseparably to the progressive distruction of the dielectric medium by electronic or ionic charge carriers that have acquired sufficient energy from the electric field.

Insulator material	Dielectric Constant ε	Breakdown strength (MV/m) kV/mm
Air	1	3.0
kapton	3.6	275
Mylar	2.5	~~200~~ 20
Polyethylene (PE, 聚乙烯)	2.2	~~177~~ 17.7
Polypropylene (PP, 聚丙烯)	2.5	~~378~~ 37.8
Polysulphone (聚砜)	3.1	~~315~~ 31.5
Pyrex glass	4~6	20
SF_6	1.0	8 (per atm)
Teflon	2.0	59.
Transformer oil	2.2	10-40
Water	80	20 (for $t < 10\,\mu s$)

* Strong binding energies in solid ~ several eV

impact ionisation 10 - 20 eV

Solid insulators : Breakdown strength ~100 MV/m.

* $\frac{10\ eV}{100\ MV/m} = 0.1\ \mu m$ ⇒ ~~distant betw electron gain 10eV in a field of 100MV/m~~
↑ required MFP

⇒ distant between (0.1~1 μm) each collision (Mean free path) such that electron can gain 10 eV of energy in a field of 100 MV/m

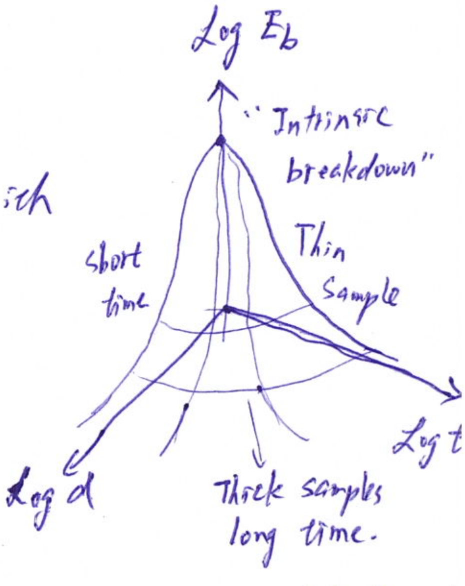
Typically, mean free path of 0.1 ~ 1 μm is required to ~~beak~~ ~~breakdown~~ break bonds and ionise material at the observed breakdown field strength.

* The chance of inducing electron avalanches in 2D or 1D lattices such as those of polymers is very small.

☆ * Damage can be done only if either the damage threshold is reduced ~~or~~ or electrons are allowed to move over significantly longer free paths.

* Magnitude of the breakdown field depend on:
  - time dependence of the electric field.
  - geometry of the sample.
  - nature of the electrode.

* Breakdown strength reduces ~~with~~ with
  - increasing thickness
  - longer time



* "Intrinsic" breakdown strength is where the material is without defects & without external influences.
~ 2~3 orders of magnitude above the design stress in technological application

* Breakdown strength is temperature-independent between cryogenic temp & critical temp. in most insulating materials, but drops drastically after critical temp.

* The final result of a breakdown is always the formation P40
of a narrow plasma channel.

* Electronic charge carrier injection from the electrodes accelerates the breakdown.

* The presence of macroscopic defects in the material (e.g. void or conducting inclusions) shorten the time to breakdo

* The ageing of the electric strength of a material is strongly affected by charge carrier injection & trapping.

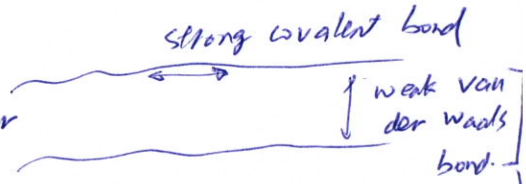
* Damage is done continuously to the material prior to the onset of the final breakdown.

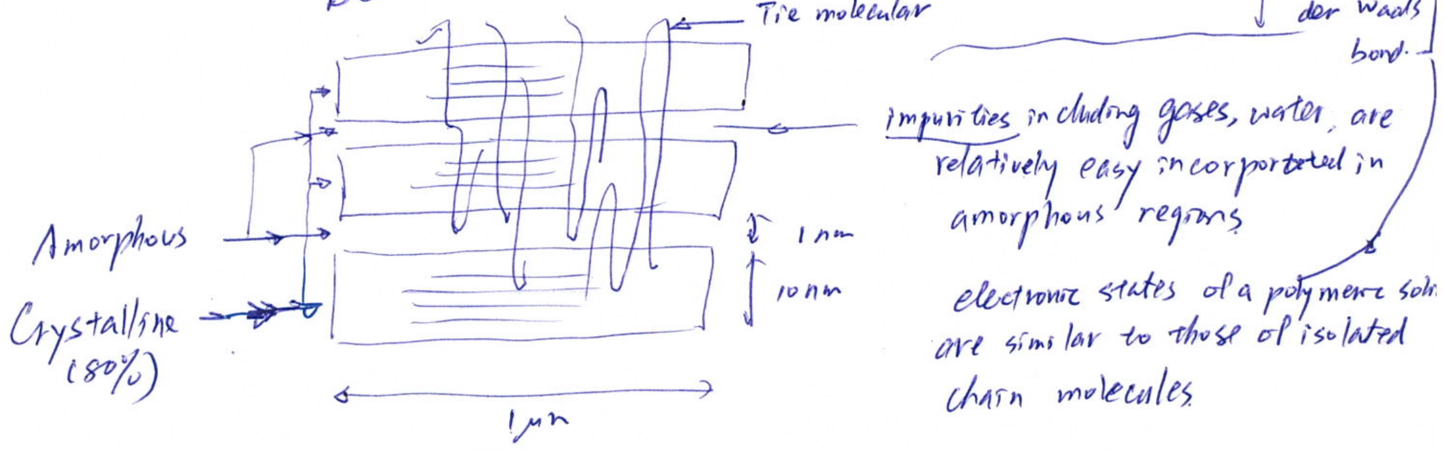
* Electrical breakdown must at least ~~start~~ begin at a molecular level →
  - charge transport
  - charge injection
  - breakdown.

2.4.2-1. Charge transport.

* The most important solid insulators in pulsed-power technology are organic polymeric dielectrics such as polyethylene (PE) or cast epoxy.

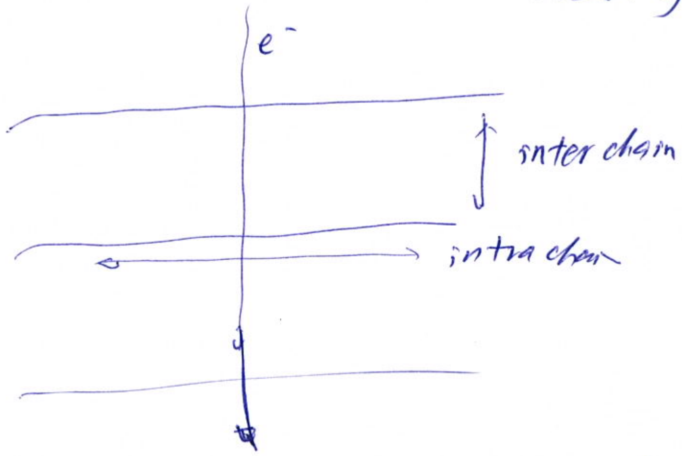
→ long-chain molecules with strong covalent bonding in the chains and weak Van der Waals bonding between chains.



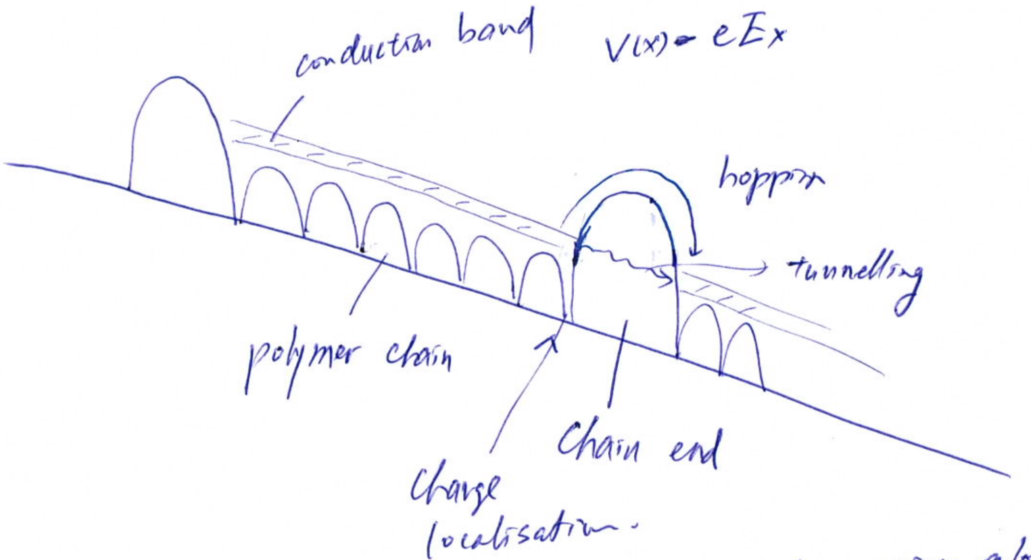


(* ??) Free-electron transport will follow interchain (鏈間) rather than intrachain (鏈中)

conflict ??



→ Electrons will move in the ~~perior~~ periodic potential along chain surface.



* ~~Electrons~~ Free electrons & Holes transport easier along chains that happen to lie in the field direction.

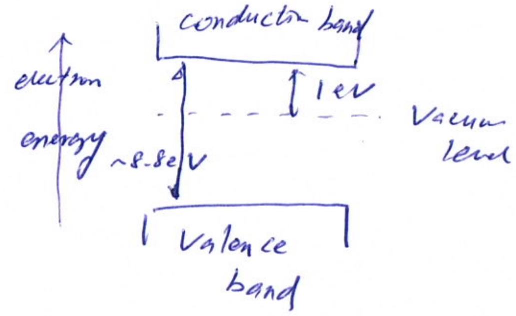
Chain ends, folds, kinks, and branching will interrupt the periodicity and lead to charge localisation.

→ hopping & tunnelling.

* electrons & holes can become trapped at dopant impurities.

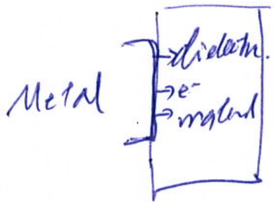
2.4.2.2 Metal - Dielectric Contact.

* The large band gap of insulating polymers (> 8 eV) makes it very unlikely that mobile charge carriers can be created thermally.

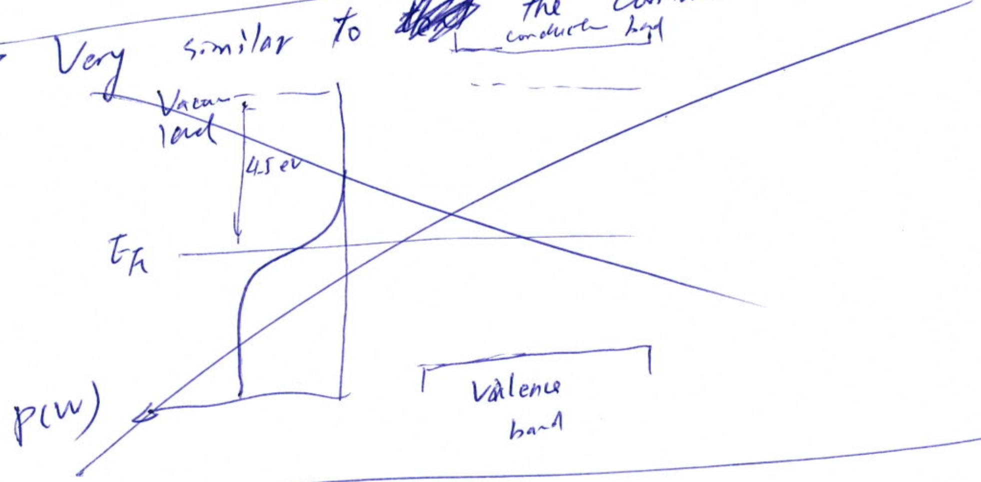


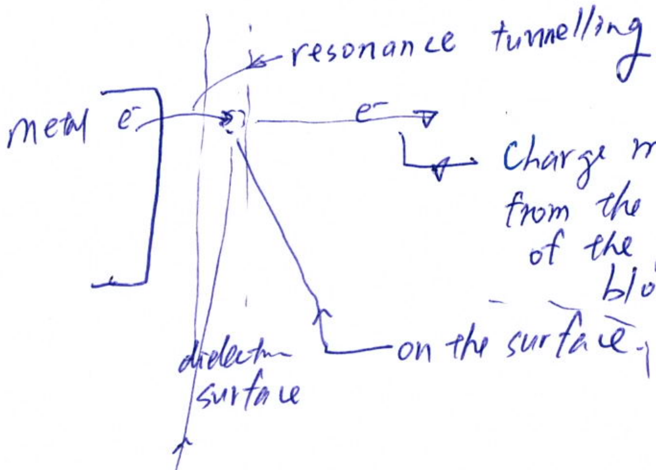
→ appropriate dopants or by injection of electron or holes from metallic electrodes.

→ A metal electrode in contact with a dielectric solid will transfer charge into the solid.



→ Very similar to ~~the~~ the contact between metal & liquid.





Charge may be transferred away from the interface into the interior of the polymer ⇒ reducing the blocking action.

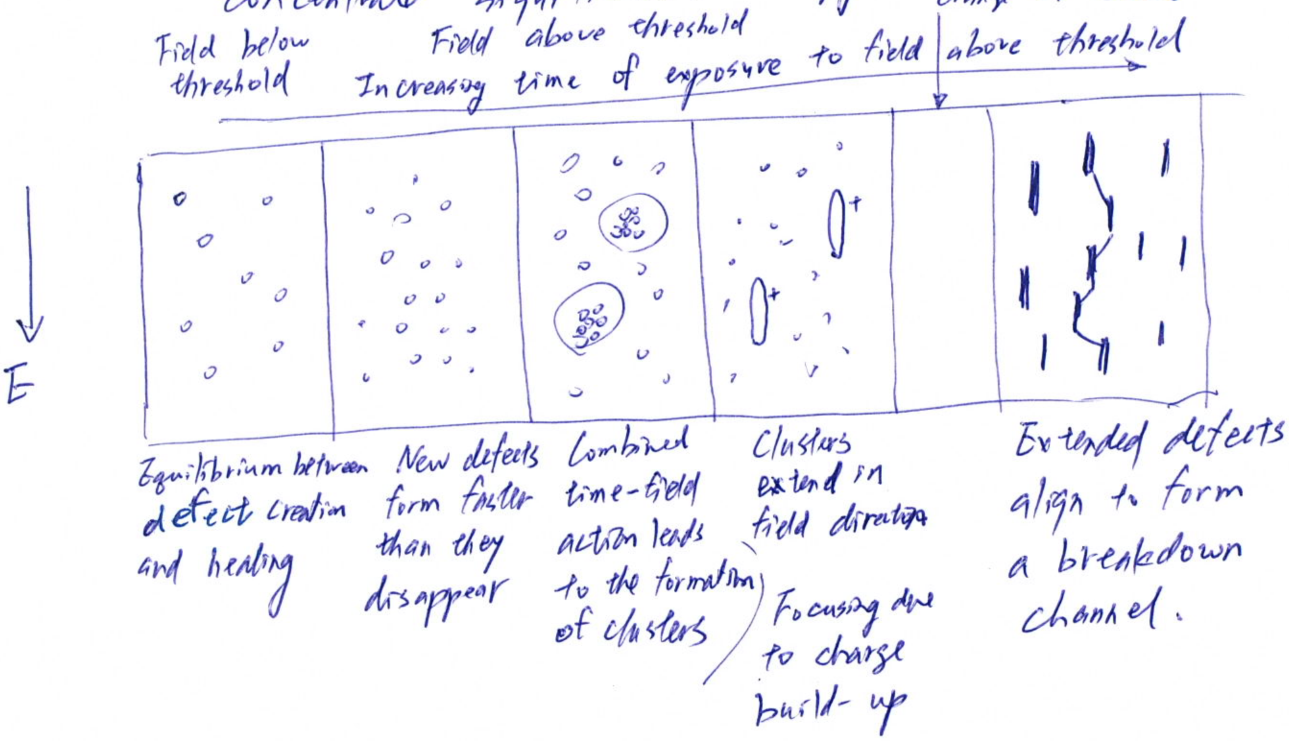
If the charge remains at surface states, further tunnelling will stop and current flow across the surface will become blocked.

* At even ~~higher~~ larger electric field
  → electrons can reach excited states.
  → Decay from excited states will remove the energy from electrons to the molecular and heat it

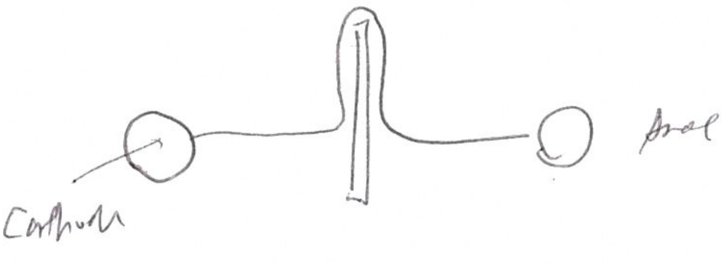
* At the highest fields
  → electrons can reach the band of extended conduction states.
  → energy-dissipating mechanism becomes scattering from lattice vibrations → kinetic energies sufficient for ionisatn can be reached.
  * Note that it is still restricted that the chain is parallel to the field direction.

§ 2.K.2.3 Breakdown.

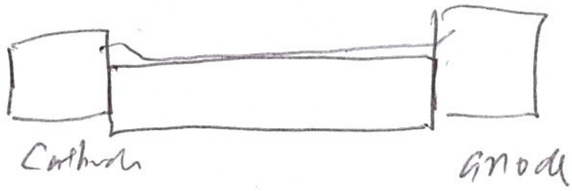
* Electrons and holes injected from metal electrodes or liberated from shallow traps and subsequently stored in states can concentrate significant energy densities.



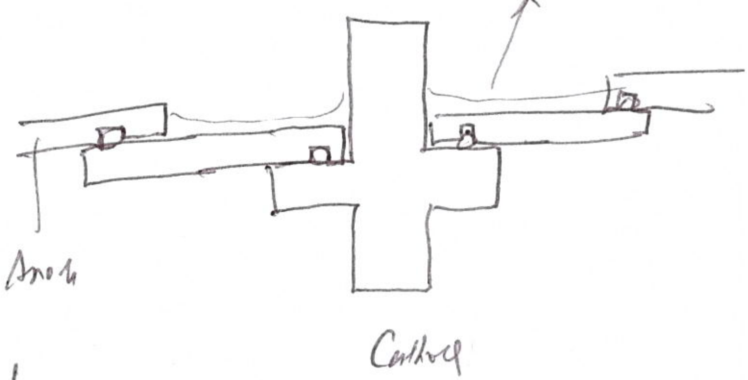
7. Surface Flashover of solid dielectric



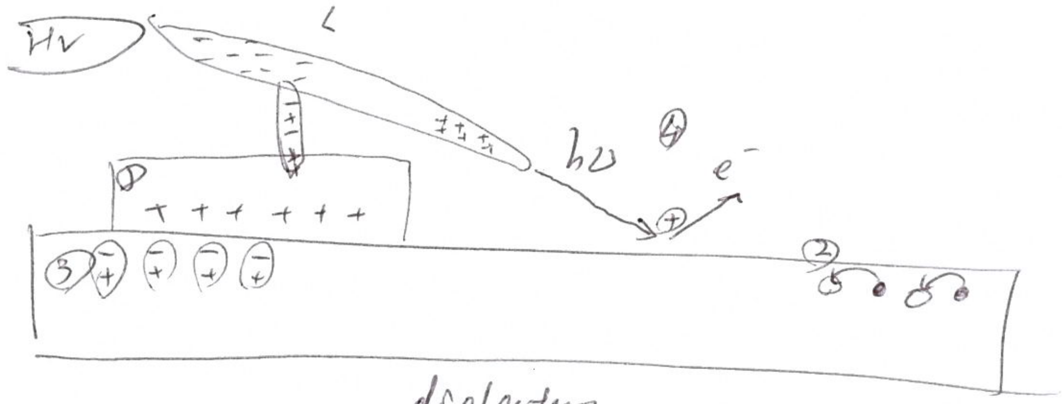
or



or



- Charge carriers formation near the dielectric.
- Surface can be a source for the discharge plasma.
- Generality of mechanisms of surface discharges in different mediums is in interaction of sparks and streamers w/ the surface of dielectrics



dielectron

1: surface charge

2. surface conductivity

3. polarization of the insulator

4. photoemission & thermionic emission

* 2nd electron emission from the dielectric surface → surface is +

* degas:

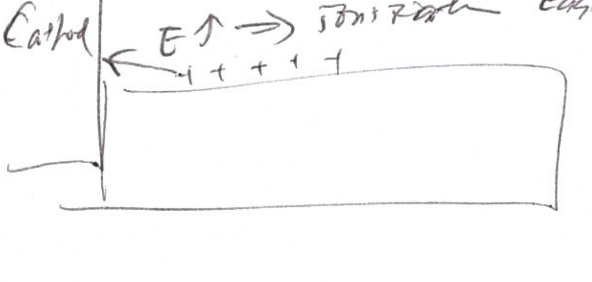
e⁻

~~degas~~ desorbed gas

↓

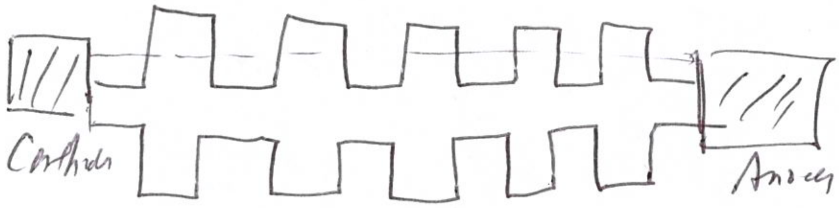
ionized by electron

* Cathod E ↑ ⇒ ionization easier.



~~7c~~ p51c

Solution:



"No line of sight"

Breakdown in solid.

- Solid insulators function as mechanical supports, enclosures, and feed through.
- Thin films of solid insulation are used in energy storage capacitors & pulse-forming line (PFLs) for high energy density storage, and advances in metalized films w/ their self-healing properties are revolutionary.

- Common solid film insulators:

paper, polypropylene (PP), Mylar (PET) polyethylene terephthala, & kapton (polyimide), Teflon, Acrylic, polyvinylidene fluoride ~~FPV~~ (PVDF)

- Outdoor installations: operate in humid & polluted environment.
- For repetitive pulsed power systems: thermal considerations such as effective ~~cot~~ cooling becomes important.

breakdown Mechanisms in Solids

- Solids are usually permanently damaged ~~after~~ when breakdown occurs.
  - intrinsic breakdown
  - thermal breakdown
  - electromechanical breakdown
  - partial discharges
  - electrical trees

§ Intrinsic breakdown.

- The highest values of breakdown strength when other sources of imperfections in the materials and testing are elimated.

- The timescale ~ in the order of 10 ns

- 

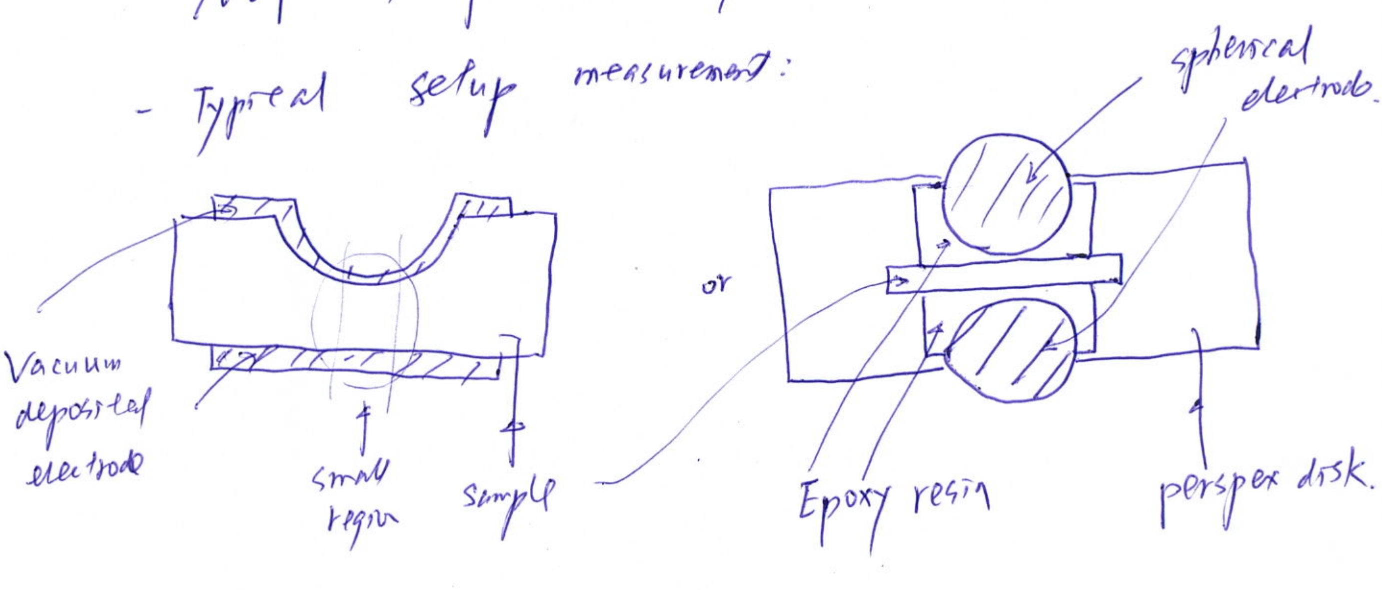
  when it gains enough energy from a high electric field.

- w/ sufficient e^- in the conduction band, intrinsic breakdown occurs

- In the range of 5-10 MV/cm.
- In Lab.: it is measured via eliminating all imperfections:
  - field non uniformity
  - internal discharges from imperfections (foreign particles or voids)
  - external discharges - from weak ambient surrounding the solid dielectric.
  - mechanical damage.
  - field induced chemical attacks.

  NOT in practical systems.

- Typical setup measurement:



- Very thin specimens of solid dielectric are used. p3
  - reasonable V ($E = V/d$)
  - probability of imperfections (forgein particles & void) ↓
- proper mechanical support is needed, to avoid electromechanical force.
- Short duration pulses w/ high voltage rising speed.
  → avoid other breakdown mechanism, such as thermal breakdown from joul heating.

• Frohlich criterion:

high-energy criterion. (Energy gain $\propto E_c^{3/2}$ > Energy loss $\propto E_c^{-1/2}$)

~~high energy e⁻ dominates the breakdown~~

If the net energy gained by an (conduction) electron ~~[illegible]~~ from the electric field is greater than the energy lost to the lattice, the electron is continuously accelerated, resulting in a state of instability and intrinsic breakdown occurs.

→ does not depend on the specimen thickness or wavefront, or duration of applied field.

• Avalanche Kriterion

low-energy criterion.

Conduction electrons gain sufficient energy from the applied field to release further electrons from the lattice, similar to impact ionization in gas.

→ depends on thickness, electrode geometry "time to breakdown" would depends on the overvoltage applied to the specimen.

3. Thermal breakdown. p.

- happen when rate of generating heat > dissipates rate

due to conduction or dielectric losses (AC)

diffuse to the surrounding.

→ depends on Voltage

- If heat gain > loss ⇒ thermal equilibrium is unstable.

⇒ thermal runaway. (熱失控)

$$HG_{DC} = \sigma E^2 \leftarrow \text{joul heating} — DC$$

conductivity, electric field.

$C_v \frac{dT}{dt}$ ← Rate of heat accumulation.

$\frac{\partial}{\partial x}\left(K_{th} \frac{\partial T}{\partial x}\right)$ ← heat lost to a surface A.

$$\Rightarrow HG_{DC} = \sigma E^2 = \underbrace{C_v \frac{\partial T}{\partial t}}_{\text{heat accumulation}} + \underbrace{\frac{\partial}{\partial x}\left(K_{th} \frac{\partial T}{\partial x}\right)}_{\text{diffusion (lost)}}$$

source.

For AC, dielectric losses from dipole rotation. & joul heating.

$$HG_{AC} = E^2 \cdot 2\pi f\, \varepsilon_0 \cdot \varepsilon_r \tan\delta$$

dielectric loss tangent

$$\Rightarrow HG_{AC} = E^2 2\pi f \cdot \varepsilon_0 \cdot \varepsilon_r \tan\delta = C_v \frac{\partial T}{\partial t} + \frac{\partial}{\partial x}\left(K_{th} \frac{\partial T}{\partial x}\right)$$

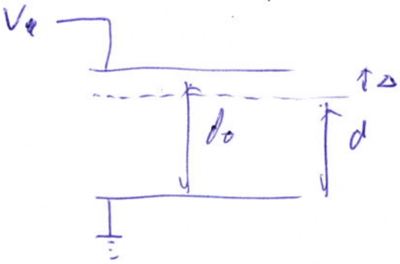
- Generally, the thermal breakdown need not be considered for DC,
∵ low (electric) conductivity of good insulator.

- For pulsed high electric field, w/ high dielectric losses → HG_{AC} is important.

Sr: Thermal breakdown @ room temperature. ~10 MV/cm

w/ ~ , ~100 kV/cm 2 order less!!

Electromechanical breakdown

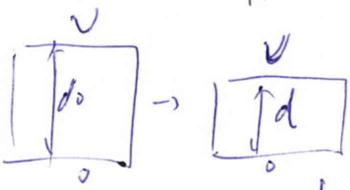


Δ ← due to the compression from the attraction between electrode.

Compressive force : $P_c = \frac{1}{2}\varepsilon_0 \varepsilon_r E^2 = \frac{1}{2}\varepsilon_0\varepsilon_r\left(\frac{V}{d}\right)^2$

Hooke's law : $P_c = Y \ln\left(\frac{d_0}{d}\right)$

↑ Young's modulus

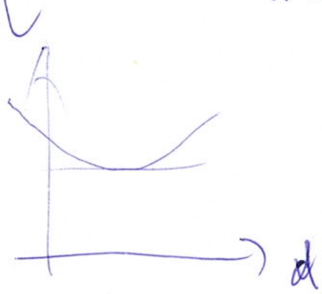


$$\Rightarrow \frac{1}{2}\varepsilon_0\varepsilon_r\left(\frac{V}{d}\right)^2 = Y\ln\left(\frac{d_0}{d}\right)$$

$$V^2 = \frac{2Y}{\varepsilon_0\varepsilon_r} d^2 \ln\left(\frac{d_0}{d}\right)$$

$\frac{d}{dd}$: $$2V\cdot \underset{0}{\underset{\shortparallel}{\frac{dV}{dd}}} = \frac{4Y}{\varepsilon_0\varepsilon_r} d \ln\left(\frac{d_0}{d}\right) + \frac{2Y}{\varepsilon_0\varepsilon_r} d^2 \cdot \frac{d}{d_0}\left(-\frac{d_0}{d^2}\right)$$

$$= \frac{2Y}{\varepsilon_0\varepsilon_r}\left[2d\ln\left(\frac{d_0}{d}\right) - d\right]$$



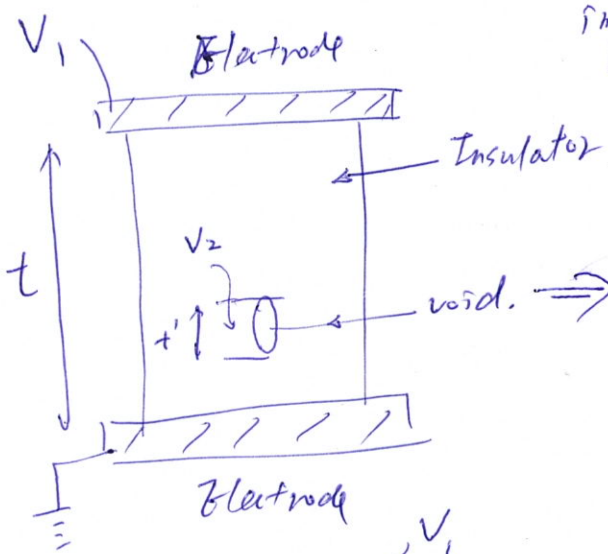
$$\Rightarrow \ln\left(\frac{d_0}{d}\right) = 0.5 \Rightarrow d = d_0 e^{-0.5} = 0.6\, d_0$$

* $V \uparrow \Rightarrow d \downarrow \Rightarrow$ exceeds the strength of the material

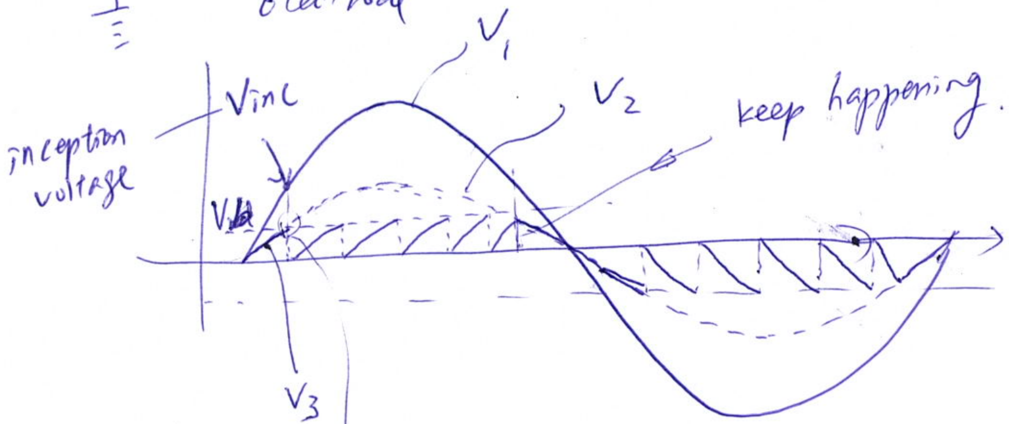
$\Rightarrow$ mechanical damage.

3) Partial discharges (PD)

- A PD occurs inside voids embedded in solid dielectrics
  ↑ imperfections.



⇒ a breakdown may occur!!

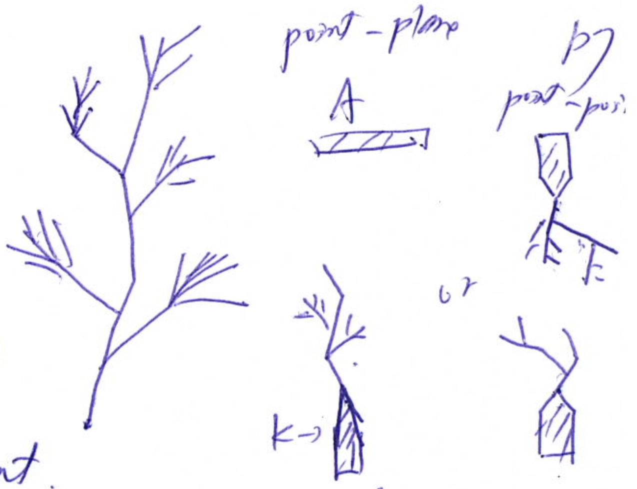


a spark forms in the void
⇒ V collapses to a low value.

V_b is determined by the Paschen curve where $d = t'$, p is p in the void.

- The energy dissipated in the void causes erosion, tracking, treeing and electrochemical deterioration.
- It takes a time period of years.

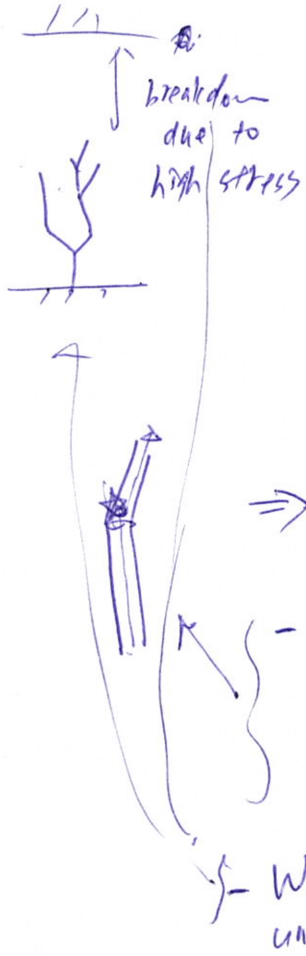
Electrical Trees



- dry trees
- water trees

- depends on the properties of dielectric & the environment.
- Over a period of time, may extend to few years, the trees cause the total breakdown.

- Dry trees: — hollow tubes, resembling the branches of trees, which are formed inside a dielectric due to electrical stress
  ↳ filled w/
- diameters: 10 ~ 500 μm, mixtures of gases from the decomposition of dielectric material.
- Nucleation sites (seed): — localized field enhancements, ex: asperities on electrodes, embedded foreign particles, voids.



- Initiation: mostly due to electromechanical force
  → fissures, microscopic cracks,

⇒ ~~or~~ cause erosion, tracking, gas evolution, decomposed products

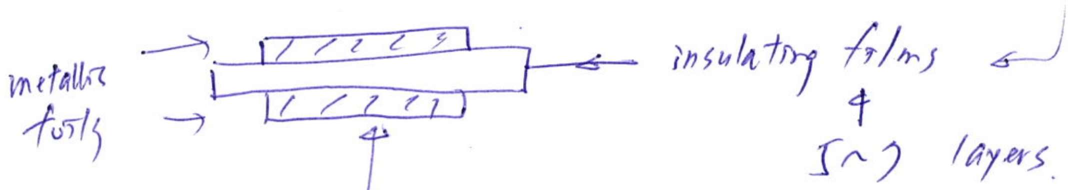
- The accelerated charged particles impact the walls of the cavities w/ high velocities, leading to their growth
- When a tree occupy a major length of the insulator, the remaining unbridged portion of the insulator will be subjected to extremely high stresses, leading to disruptive breakdown

* Water Trees
  - If dielectric is hydrophilic (親水) & is immersed in water → tree channels filled w/ water.
  - when electric stress is removed, water is reabsorbed in the solid dielectric. the channel becomes dry & hollow.
  - The electrical conductivity of water ~~stress~~ trees compared to dry trees is high
    ⇒ rapid growth.

  underground cable !!

7. Methods of improving solid insulator performance.
   - layers of insulating films instead of single layer w/ the same thickness
   - improving the contact area @ the interface between electrodes & dielectric - metallization & oil impregnation
   - controlling a nonuniform field - corona guards / equipotential rings.
   - modifying insulator shapes & surface profiles.
     → reduce the interaction of charge carriers at the surface.

Ex: - Insulation in energy storage capacitors

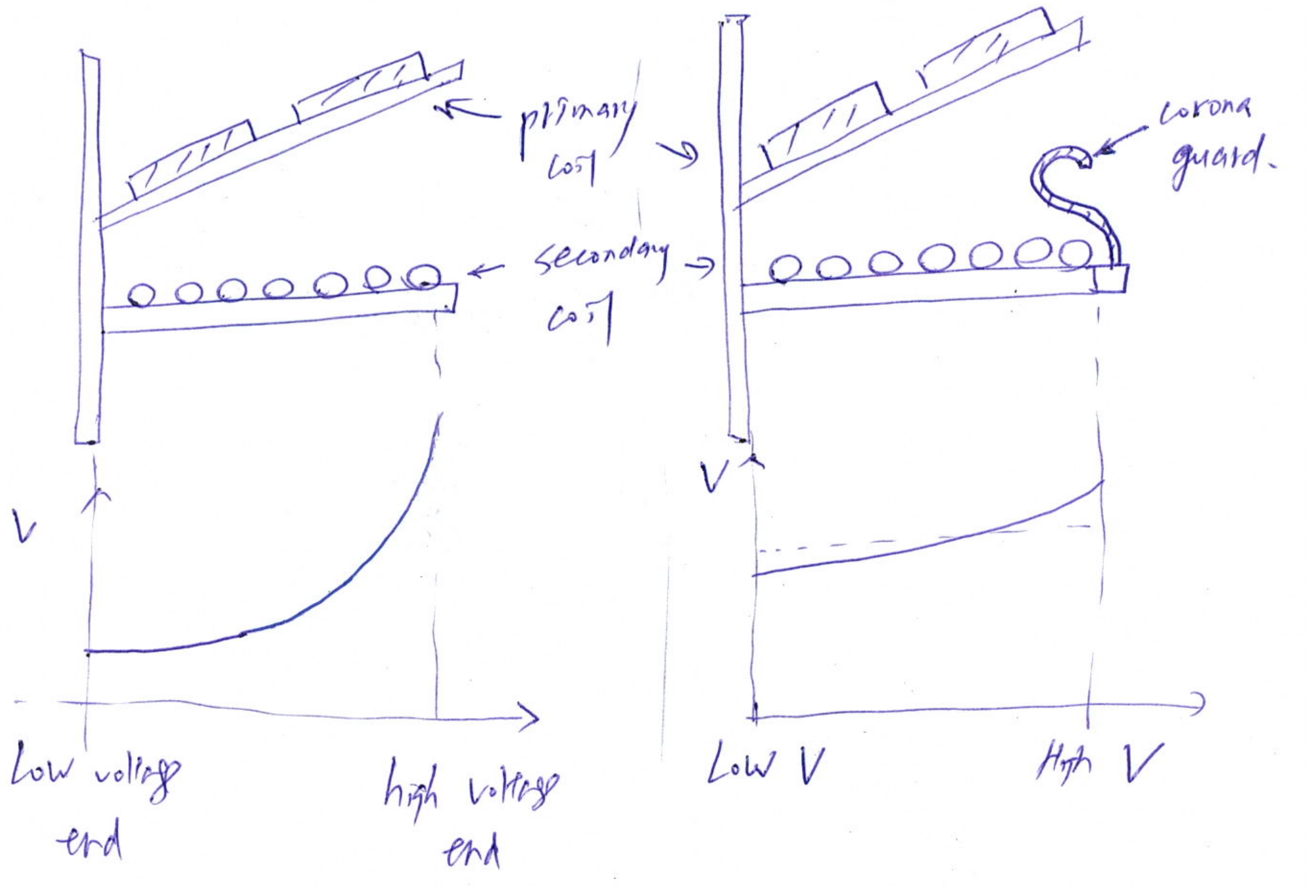


recently: use vapor deposition of Al or Zinc w/ $\delta = 0.0003\,\mu m$

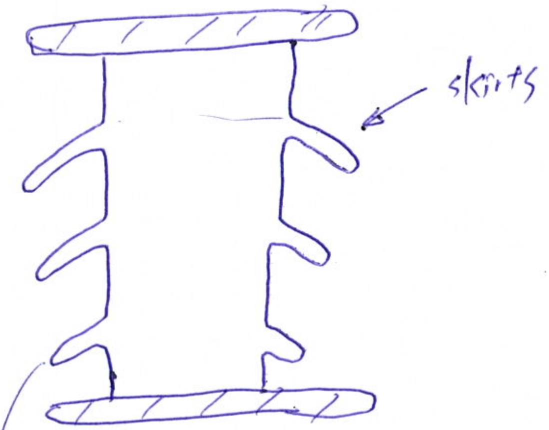
more layers can be packed ⇒ higher ~~de~~ energy density

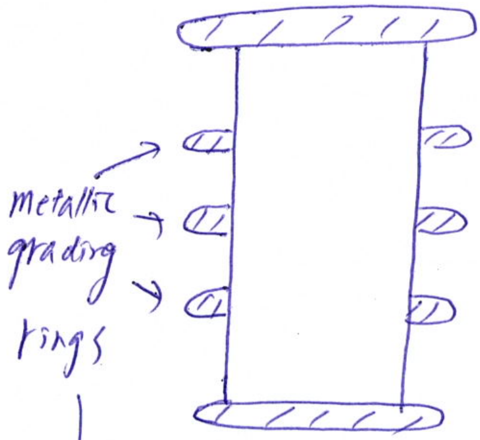
→ metallization → operate under higher field strength !!

- Surge voltage distribution in a Tesla Transformer



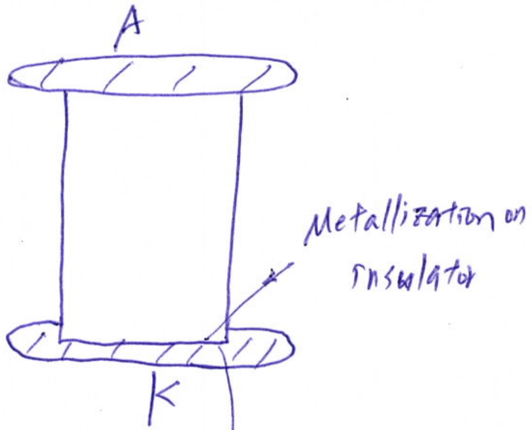
⊚ surface flashover in standoff insulators

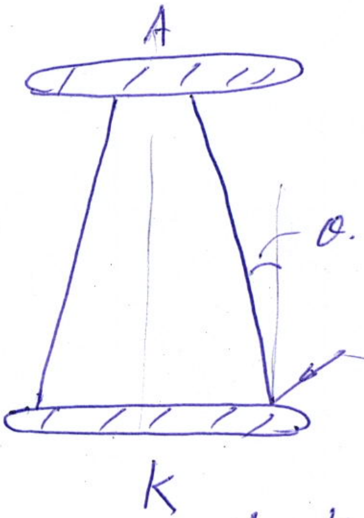




for humid & polluted environment.
→ increase the effective length of the insulator

make field distribution more uniform.

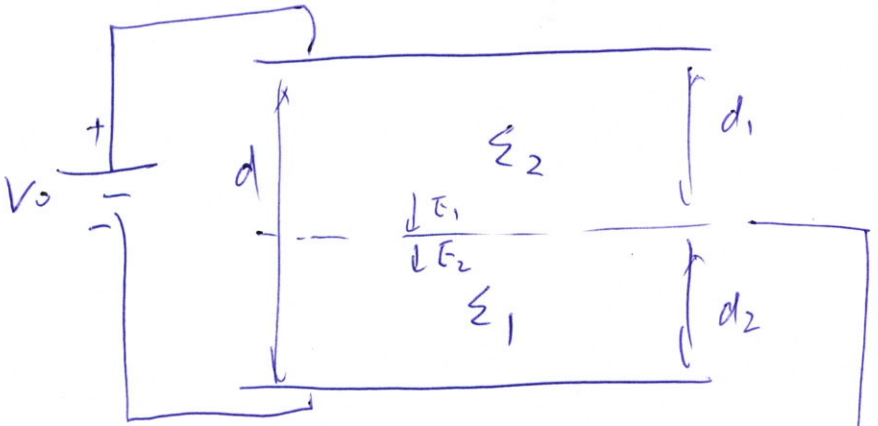




eliminating the voids & inclusions @ the surface

decreasing the role of triple junction & 2nd e^- emission from the insulator surface

3 Composite dielectrics:



B.C.:

$$\varepsilon_1 E_1 = \varepsilon_2 E_2$$

$$E_1 = \frac{V_1}{d_1}, \quad E_2 = \frac{V_2}{d_2}$$

$$\varepsilon_1 \frac{V_1}{d_1} = \varepsilon_2 \frac{V_2}{d_2}, \qquad V_0 = V_1 + V_2$$

$$\Rightarrow \quad V_1 = \frac{\varepsilon_2}{\varepsilon_1} \frac{d_1}{d_2} V_2$$

$$V_0 = \frac{\varepsilon_2}{\varepsilon_1} \frac{d_1}{d_2} V_2 + V_2 = \frac{\varepsilon_2 d_1 + \varepsilon_1 d_2}{\varepsilon_1 d_2} V_2$$

$$V_2 = V_0 \frac{\varepsilon_1 d_2}{\varepsilon_2 d_1 + \varepsilon_1 d_2} \qquad E_0 \equiv \frac{V_0}{d}$$

$$\begin{cases} E_2 = \dfrac{\varepsilon_1}{\varepsilon_2 d_1 + \varepsilon_1 d_2} V_0 = \dfrac{1}{d_2 + \frac{\varepsilon_2}{\varepsilon_1} d_1} V_0 \\ E_1 = \dfrac{\varepsilon_2}{\varepsilon_1} E_2 = \dfrac{\varepsilon_2}{\varepsilon_2 d_1 + \varepsilon_1 d_2} V_0 = \dfrac{1}{d_1 + \frac{\varepsilon_1}{\varepsilon_2} d_2} V_0 \end{cases}$$

if $\frac{\varepsilon_2}{\varepsilon_1} > 1 \quad d_1 + \frac{\varepsilon_1}{\varepsilon_2} d_2 < d_1 + d_2 = d$

$$\Rightarrow \underline{E_1 > E_0}$$

3. Liquids

- "All-liquid" pulsed-power system is feasible.

Ex: Oil-filled Max - oil/water-filled PFL

- oil or water spark gap.

Marx: high dielectric strength

PFL: - - - - - - +

high dielectric constant +

low conductivity

Spark gap: - - - - - +

high thermal conductivity +

minimum decomposition products +

self-healing properties.

properties:

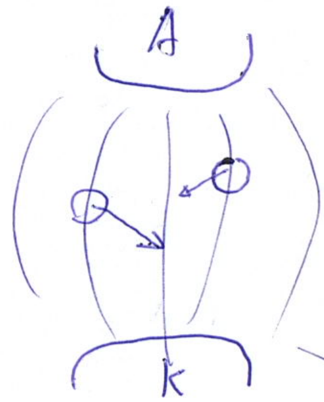
1. good thermal properties.
2. low viscosity.
3. low flammability
4. good chemical & thermal stability.
5. ~~good~~ works in low temperature
6. environmental considerations
7. low cost.

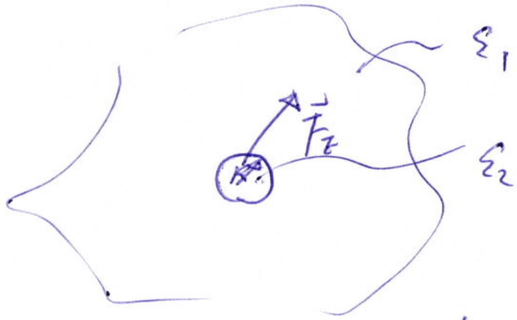
* Breakdow in liquid:

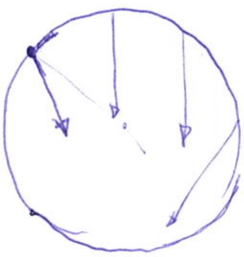
- particle alignment.
- electronic breakdown.
- streamers in bubbles.

* particle alignment - Solid impurities always exists in a liquid

- convection currents are set ~~up~~ up in a liquid dielectric due to particle movements even at low applied voltage.







$$\vec{F}_E = \frac{\varepsilon_2-\varepsilon_1}{\varepsilon_1+2\varepsilon_2} \cdot R^3 \left(\vec{E}\cdot\nabla\vec{E}\right)$$

- The ~~abo~~ force tends to concentrate the solid impurities to the region of the center of the electrodes where the field is fairly uniform.

- $\vec{F}_D$ - diffusion force.

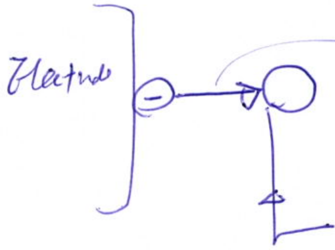
If $\vec{F}_E > \vec{F}_D$, the alignment of the particles takes place along the center of the electrode and breakdown in the liquid takes place along the aligned particles.

* Electronic breakdown.

- very similar to breakdown in gas.

$\vec{E}$

gain energy from $\vec{E}$.



lose energy to the molecules in the form of "nonionizing collisions" ⇒ NOT possible for e^- to reach ionization energy.

- elastic, vibration, excitation process

→ At elevated 升高 temperatures & high field strength near an asperity 粗糙 of an electrode.

→ energy loss ↓

⇒ continuous acceleration

⇒ energy > ionization energy.

⇒ more e^- due to impact ionization of the molecule

⇒ avalanche of e^- ⇒ breakdown.

* streamers in bubbles - propagation of streamers in the low-density vapor or bubbles

the process is very similar to that in gases

⇒ streamer mechanism of liquid breakdown is similar to the growth of electric trees in a solid due to discharge in a void.

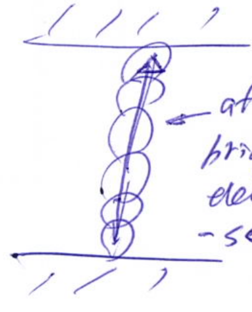
low-density vapor

high field due to space charge. ⇒ shockwave & thermal dissipation

⇒ more low-density vapor.

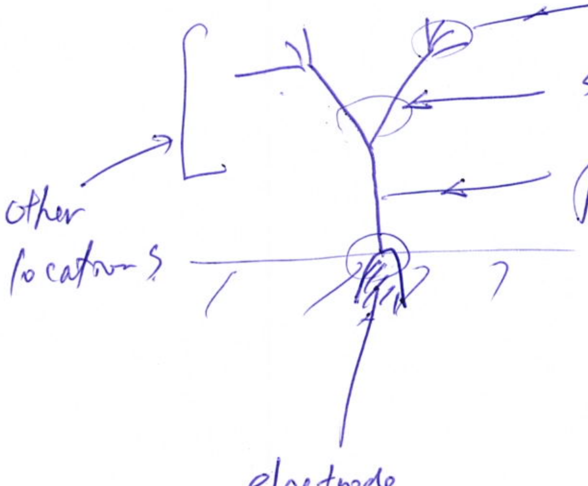
⇒ more ionization!

⇒



after streamer bridge the electrodes full-scale breakdown

Structure.



results of space charge distortion due to the high-density streamer @ front of the primary.

* Effect of hydrostatic process.

- breakdown voltage ↑ w/ p↑

~~stream~~ streamer grow at higher field @ p↑

Ex: transformer oil, V_{break} × 3~4 @ 4 MPa (~40 Atm)

Mechanisms of bubble formation.

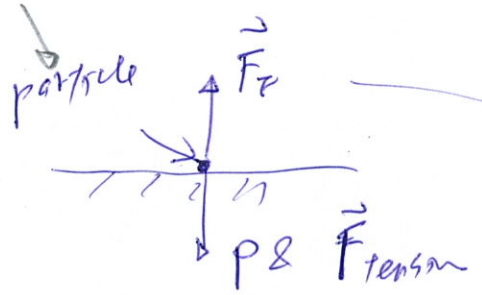
(1) foreign particles
(2) asperities on electrode causing field emission.
(3) chemical interaction w/ molecules causing their dissociation.
(4) release of the already existing gas dissolved in the liquid.

- Krasucki's hypothesis:
  - a vapor bubble grew continuously & when a critical size was reached.
    → breakdown ~~takes~~ took place.

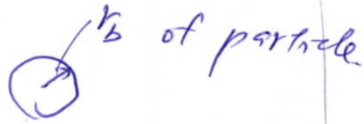
  - when V is gone → collapse faster than air bubble
    ⇒ p inside the bubble is "zero"

- w/ impurity particle → bubble grows preferentially on the particles
- w/o — — — → near the electrode surface.

seed of bubble



→ balance ⇒ causes a zero pressure

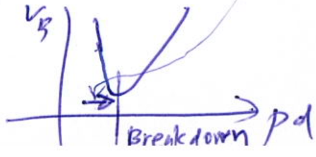


- $V_b \uparrow$ as $r_b \downarrow$
  - $\gamma_s \uparrow$ surface tension
  - $P \uparrow$ hydrostatic pressure

- Kao's hypothesis
  - bubble onced created starts elongating in the direction of the field. keeping its volume const.

$P \uparrow \Rightarrow r \downarrow$
$\Rightarrow V_B \uparrow$

→ paschen curve



* Sharbaugh & Watson hypothesis

⇒ asperity of K ⇒ field emission ↑

⇒ high current

∵ λ is short

∴ energy deposite in small region.

⇒ low-density vapor locally

⇒ breakdown in the bubble

For a pulse w/ few μs ⇒ enough energy from field emission to vaporize a small mass of liquid ahead of an asperity into a bubble

P ↑ ⇒ boiling point T_b ↑

⇒ more field is required to form the bubble.

☆ Water:

($\varepsilon_r = 80$)

(1) high energy density. in energy storage

(2) low impedance in PFL

(3) self-healing post breakdown

(4) easy maintenance.

(5) low cost

(6) ease of disposal

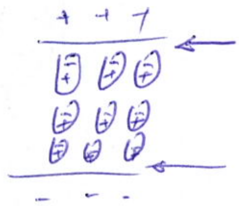
PMa

- for pulse w/ short duration (7-30 ns)
submegavolt, the E field ~~strength~~ is ≈ ×2 for longer ~~pu~~ duration (30ns~1ms)

3×10^7 V/m for μs electric stress

- dependence of breakdown voltage on Polarity (?)

- E field intensification.
  - enhanced field intensification at the asperities due to collective orientation of the dipolar water molecules @ liquid-electrode interface



field enhancement

- ~~For~~ water ($\varepsilon_r = 80$)
  propylene carbonate ($\varepsilon_r \approx 65$) ⇒ $V_{B,\mathrm{water}} < V_{B,\mathrm{PC}}$

* Methods of improving Liq. dielectric performance.
  — New composition:

In PFL: (vegetable oil): castor oils ($\varepsilon_r = 4.7$)
v.s. mineral oil ($\varepsilon_r = 2.4$)

hygroscopic (吸湿性)
sealing is important.

Synthetic oil e.g. PAO (poly-alpha-olefin),

a silicone oil → good for closing SW.

1) resistance to oxidation.

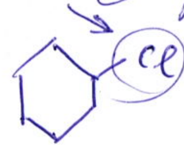
2) lower viscosity, ok @ low temperature

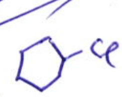
3) good lubrication, ok w/ hydraulic pump

forced flow @ high P & velocity removes the gases evolved by molecular dissociation & erosion from electrodes

— Electron scavengers — to ~~absorb~~ ~~electron~~ absorb

Ex: chlorocyclohexane

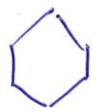




streamers go x10 faster than

v.s

cyclohexane



or adding CCl_4, more streamer !! (??)

∵ detrapping of e^- @ high field.

— Liquid mixture.

gas: $SF_6 + N_2$

solid: paper + polypropylene.

liquid: In PFL: water ($\varepsilon_r = 80$) + ethylene glycol ($\varepsilon_r = 40$)

⇒ increasing intrinsic time const.

* Impregnation

when putting insulating films & metallic foils in liquid dielectric:

① @ high temperature ⇒ removal of air
③ @ vacuum trapped @ electrode-liquid interface.

- purification
  - freed of foreign particles & ions.
    ⇒ filter ⇒ deionizer.
  - low temperature ⇒ R ↑
    ↳ chiller unit.

3 Vacuum.

- NO medium → NO breakdown, however
- breakdown does take place ∵ charge ~~particles~~ carriers being injected
  ⇒ desorbed gas, metal vapors from the electrode.
- "Surface flashover" across the solid insulator, the insulator surface is an electrically weaker medium than vacuum

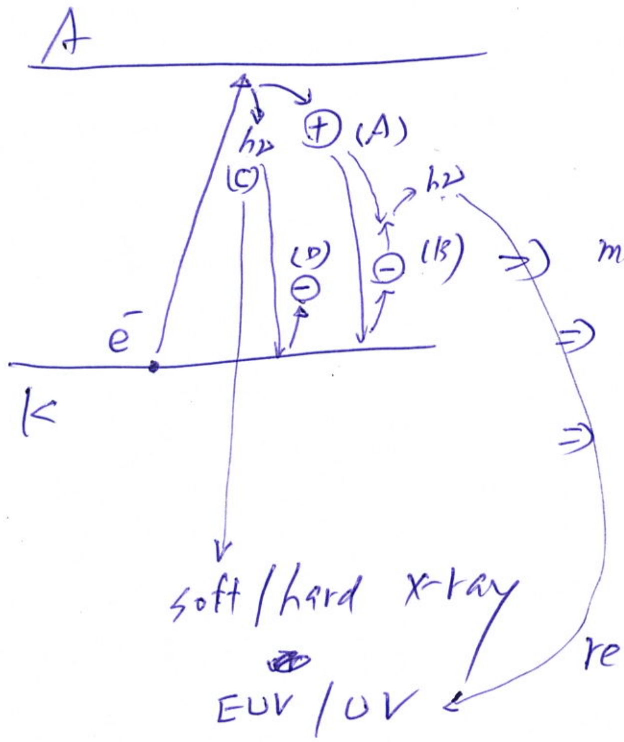
Ex: ① spark gap sw
② diodes for particle beams, X-rays, microwaves
③ transmission lines for feeding pulsed power into the load.

Vacuum breakdown mechanisms

- for $pd < 10^{-3}$ Torr cm → e^- cross the gap w/o colliding

however:

* ABCD mechanism



$$AB + CD \geq 1$$

⇒ more & more e^-

⇒ conductivity ↑

⇒ breakdown.

- high large impulse field intensity:
  1) high gas evolution from electrode
  2) metal vapor formation
  3) unfavorable μ-injection geometry

* field emission - initiated breakdown

Fowler - Nordheim (F-N) field emission formula

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

E field

$C_1 = \dfrac{1.54\times10^{-6}}{\varphi\, t^2(y)}$ ← work func.

$C_2 = 6.83\times10^{7} \cdot \varphi^{3/2} \nu(y)$

$y = 3.79\times10^{-4} \cdot \dfrac{\sqrt{E}}{\varphi}$

1) for $E_p = 10^6 - 10^8$ V/cm

$j_c = 10^8 - 10^{10}$ A/cm^2

→ leads to ABCD breakdown
or other

2) j_c → joul heating of microprojection

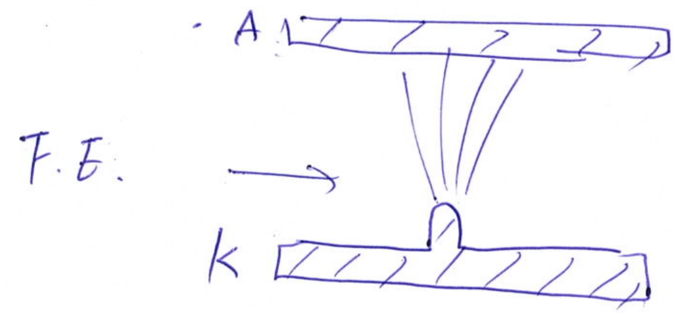
→ melting, vaporization, plasma forming

↓

ionization → breakdown.

③ high-energy e beam on anode

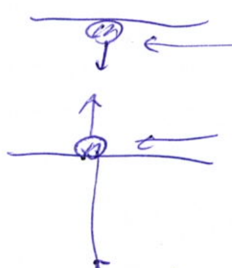
→ heating → metal vapor



④ low work function for K → high field emission

* Microparticle-initiated breakdown

①



← loosely adhering material being
← detached from electrode due to electrostatic force

② microprojections, made soft from joul heating by field emission

③ vaporization of anode

④ —— —— Cathode

(* plasma flare - initiated Breakdown)

7 Improving vacuum insulation performance

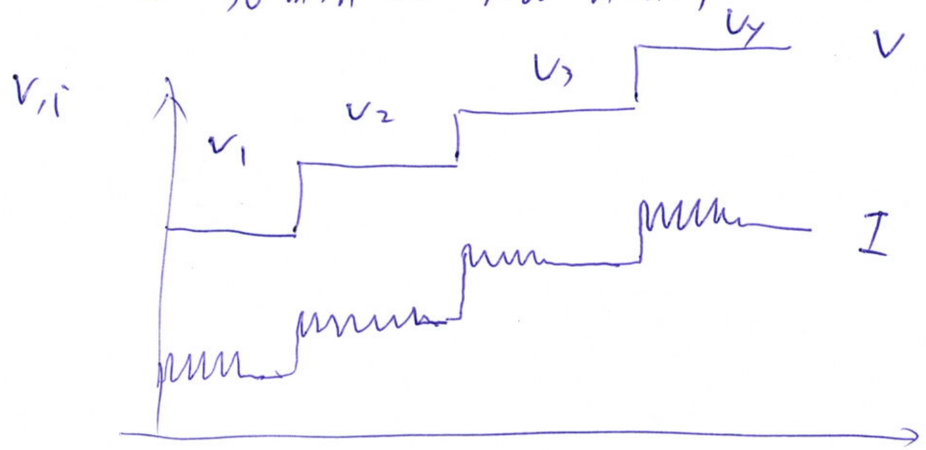
- conditioning:

~~Contra conditioned breakdown~~

w/ successive breakdown events, the breakdown voltage steadily increases ~~until~~ and attains a steady value

* Current conditioning:

- $I \sim 100s\ \mu A$
- A breakdown pulse removes a microprojection and the following pulse shifts to another microprojection site.
- 30 min ~ few hours



- AC / DC, start from 50% of expected V_b.

for both electrode.

* spark conditioning

Impulse voltages w/ width of 100s ns is used,

$I \lessapprox$ few A.

- chemical cleaning — reducing impurities
  - valence band e^- energy is changed
- residual stresses are changed — work hardened.

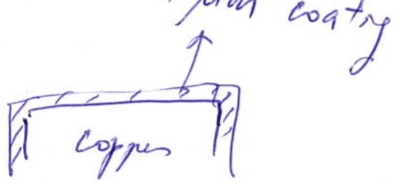
* Glow discharge cleaning

- H, He, Ar, N_2, SF_6, dry air
- sputter-cleaning
- a continuous flow of gas allowed the removal of impurities
- 30-60 mins using , then use Ar to remove O_2.

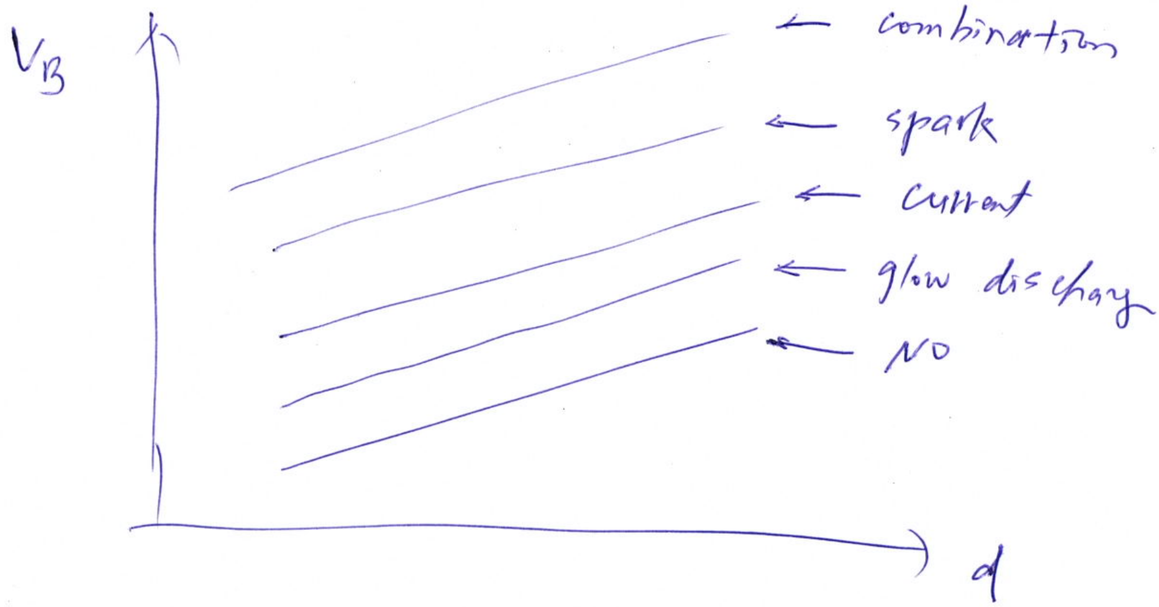
* Outgassing & annealing

- heating to T = 250 ~ 1500 °C for several hours for outgassing.

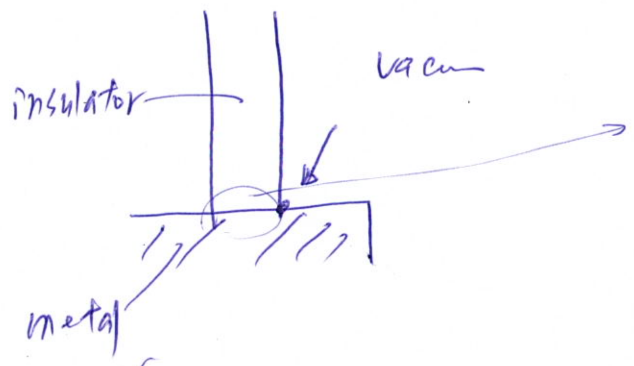
* Surface treatment & coating.



- cobalt-molybdenum 鈷鉬
  cobalt-tungsten 鈷鎢
- ion implantation → work hardening of the surface



3) Triple-Point Junction Modifications

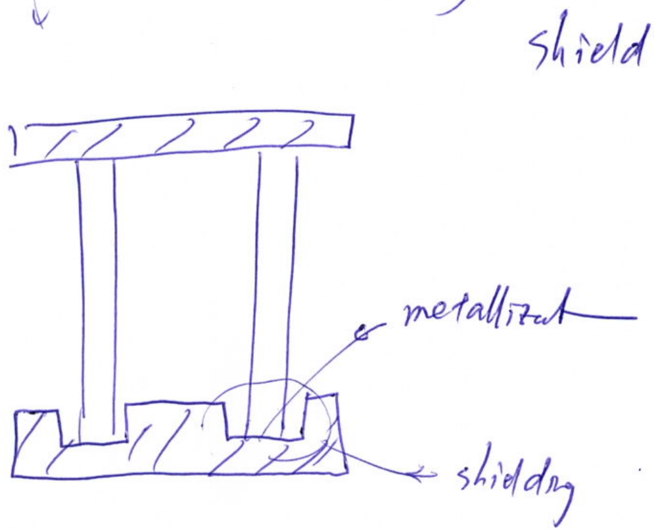


If imperfect
⇒ a void or a gap results
⇒ ↑ field enhancement
⇒ enhanced field emission

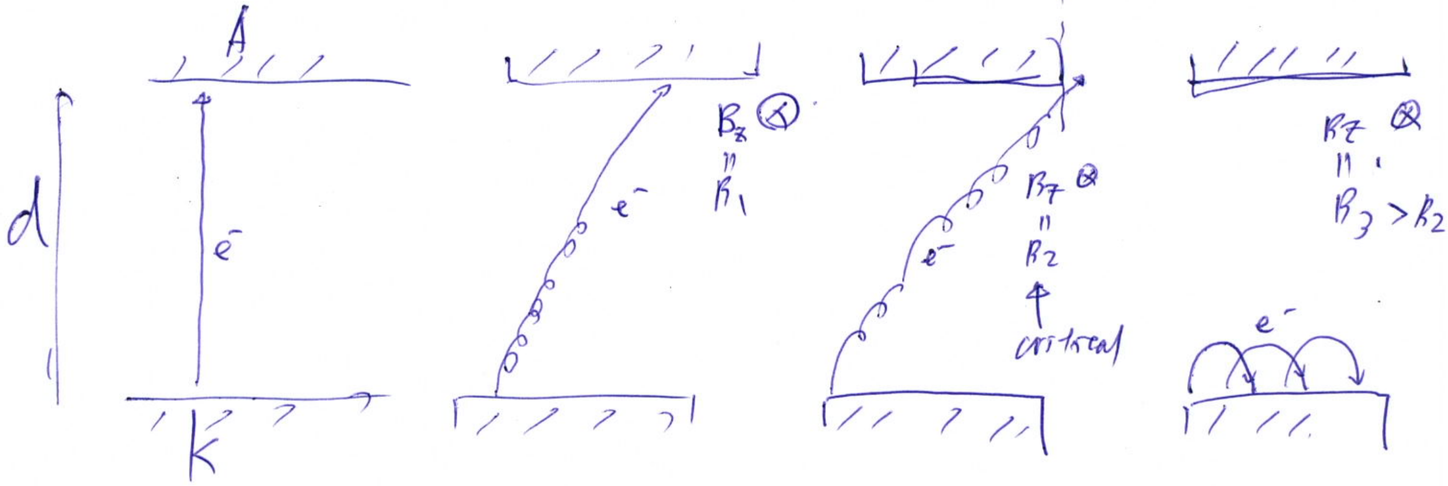
To improve: ① metalizing the insulator surface
③ contact ⇒ a firm contact.

② elimination of the void and the shielding of the emitted area by K.

Anode doesn't help



8. Vacuum magnetic insulation



- the crossed B field can be externally applied.

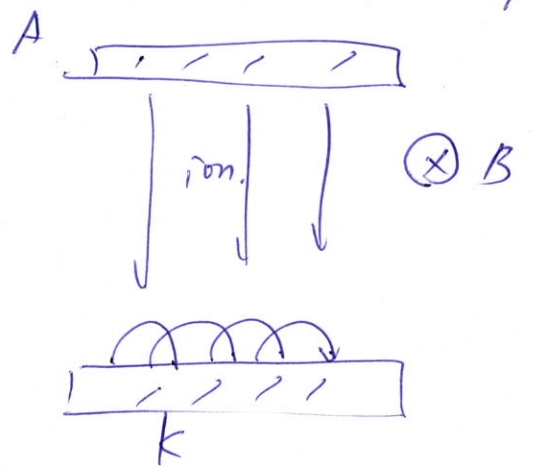
  but also self-generated

  ⇒ magnetic insulation transmission line (MITL)

  ------ insulated line oscillator (MILO) — high power μ wave source.

- Ion diode

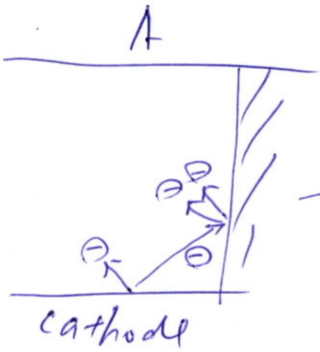
  $m_i > m_e$



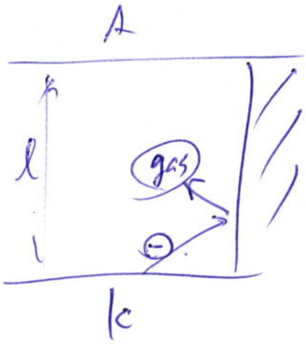
7) Surface flashover across solid in Vacuum

- V_B ↑ rapidly @ lower p ∵ lack of ionizing collisions partners

→ surface flashover



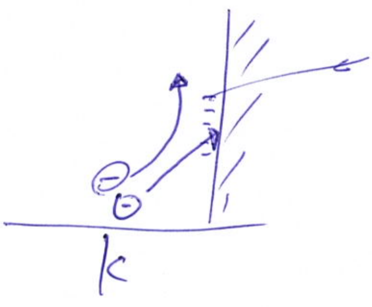
→ The dielectric surface is the source of electrons to feed the developing avalanche by a process known as 2^{nd} e^- emission.



→ electron-stimulated desorption.
e^- impacting the surface liberates gas trapped or adsorbed by the surface.

* 2^{nd} e^- emission from dielectric surface

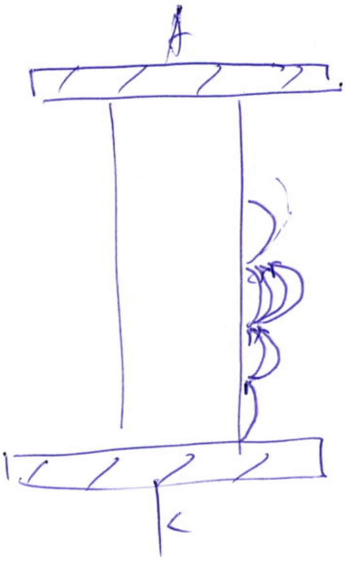
$E_k > E_0$ → to liberate e^-

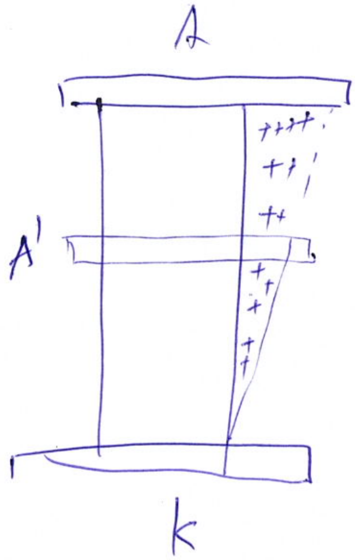


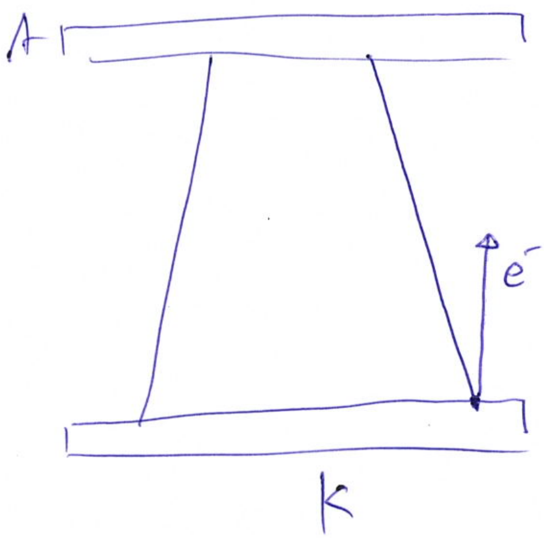
if $E_k < E_0$, charge build up, causing the following e^- away from the surface gaining more energy

⇒ $E_k \geq E_0$ → generating more e^-

$V_B \propto \sqrt{l}$.







← to improve V_B' or higher value of E_0 → less e^- generate