Electrical Breakdown in Gases

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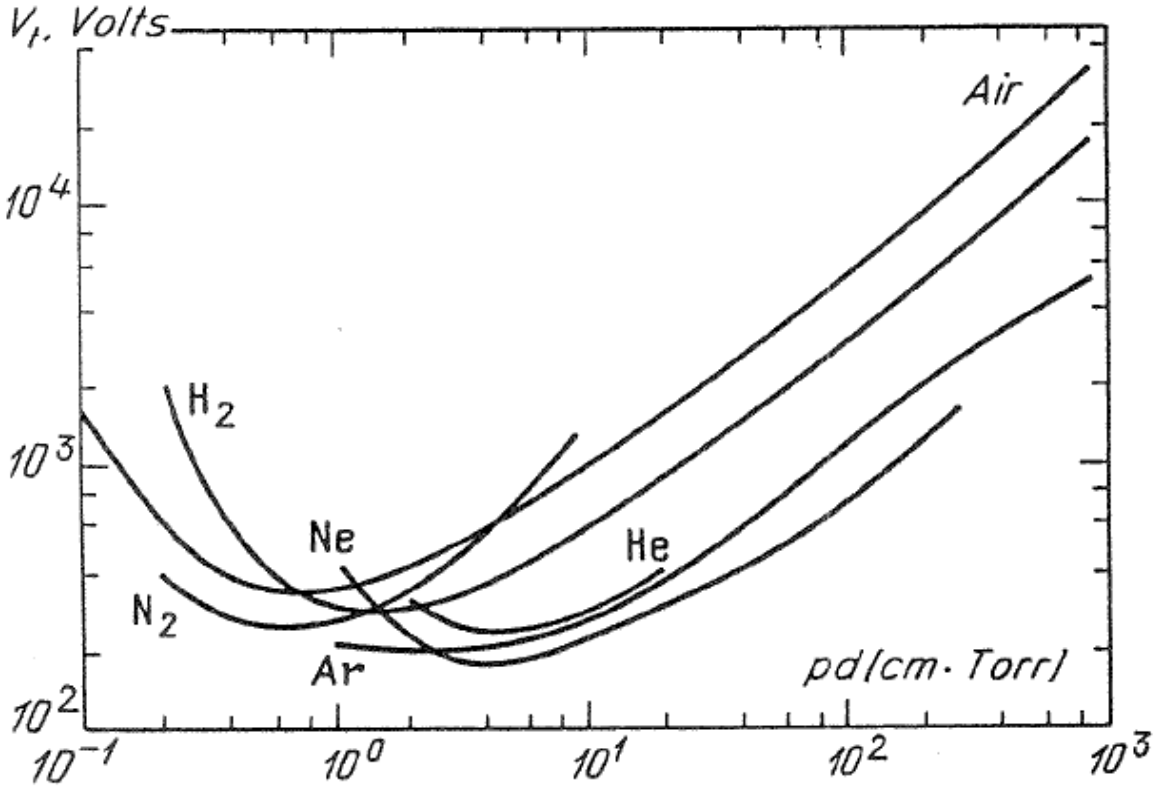
Gas breakdown: Paschen's curves for breakdown voltages in various gases

- Friedrich Paschen discovered empirically in 1889.

Left branch

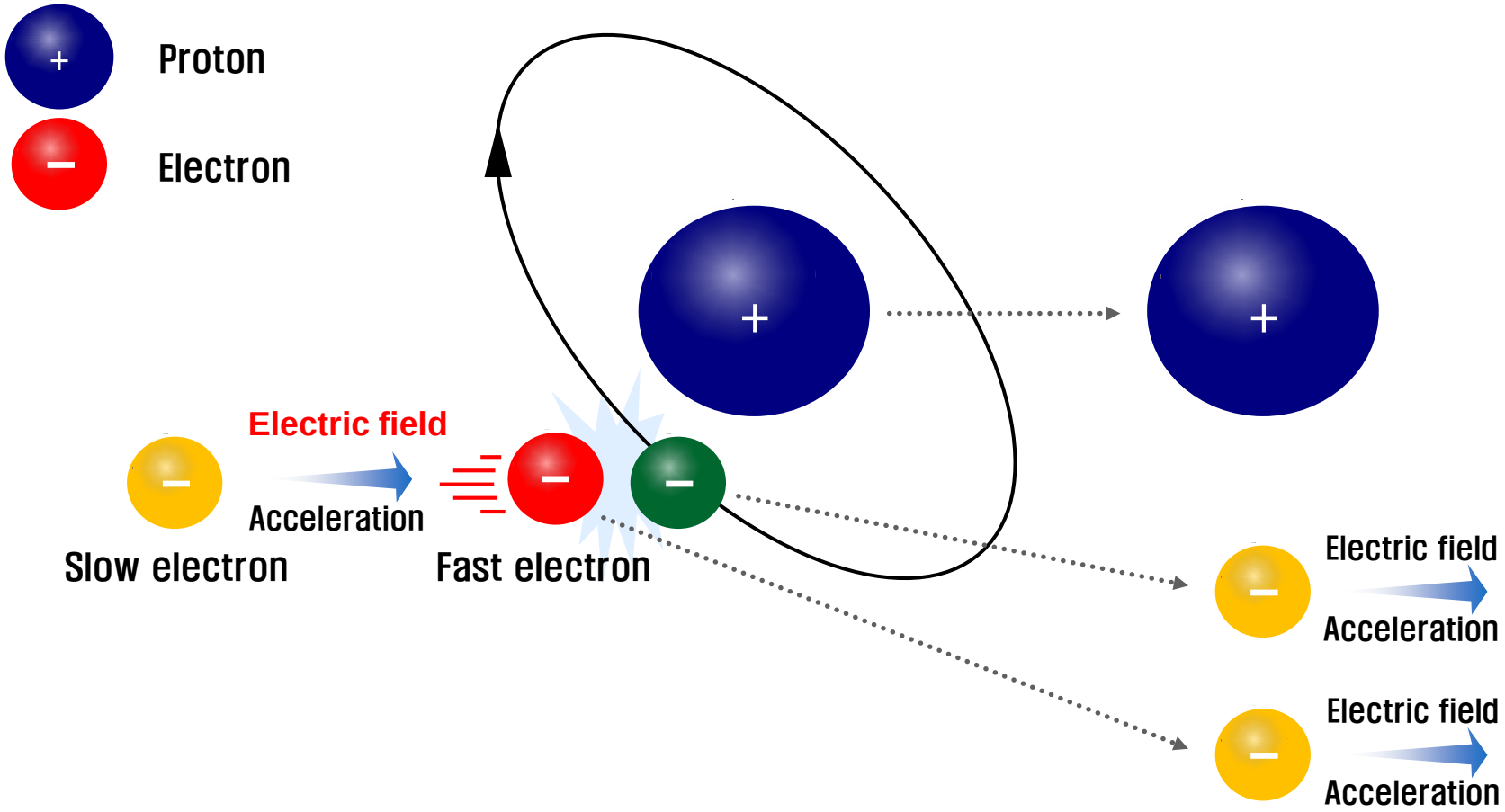


Right branch

Paschen minimum

F. Paschen, Wied. Ann. 37, 69 (1889)]

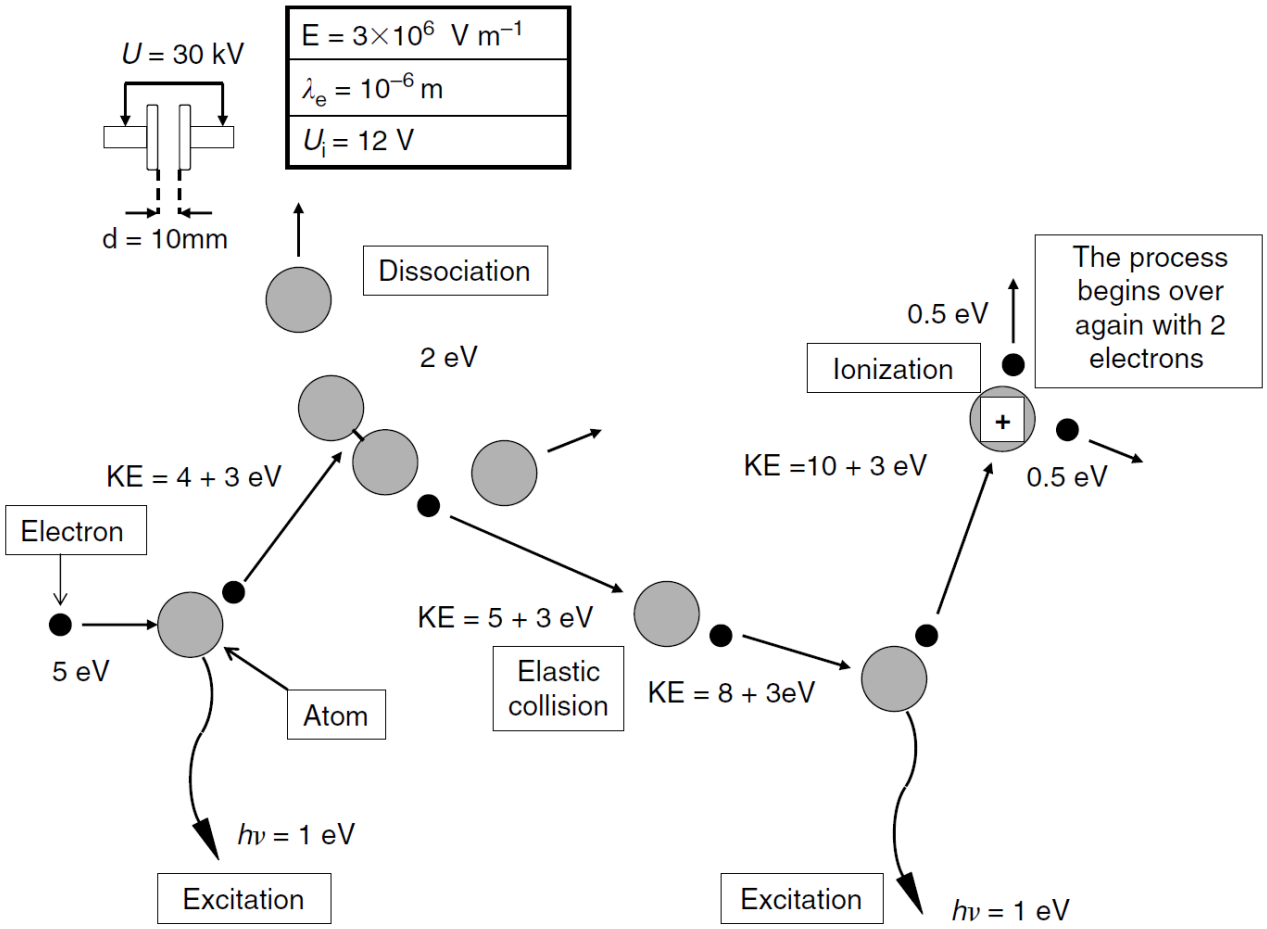
Generation of charged particles: electron impact ionization



Ionization energy of hydrogen: 13.6 eV

Behavior of an electron before ionization collision

- Electrons moving in a gas under the action of an electric field are bound to make numerous collisions with the gas molecules.

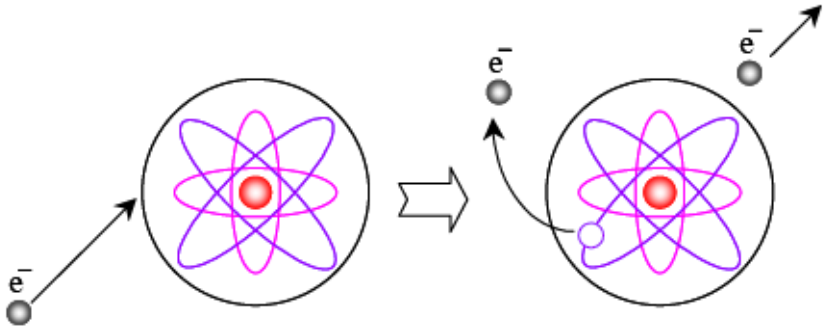


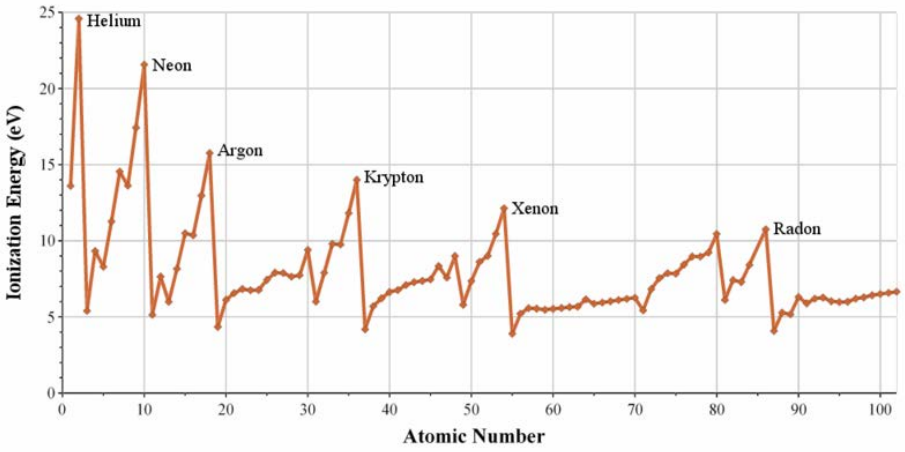
Electron impact ionization

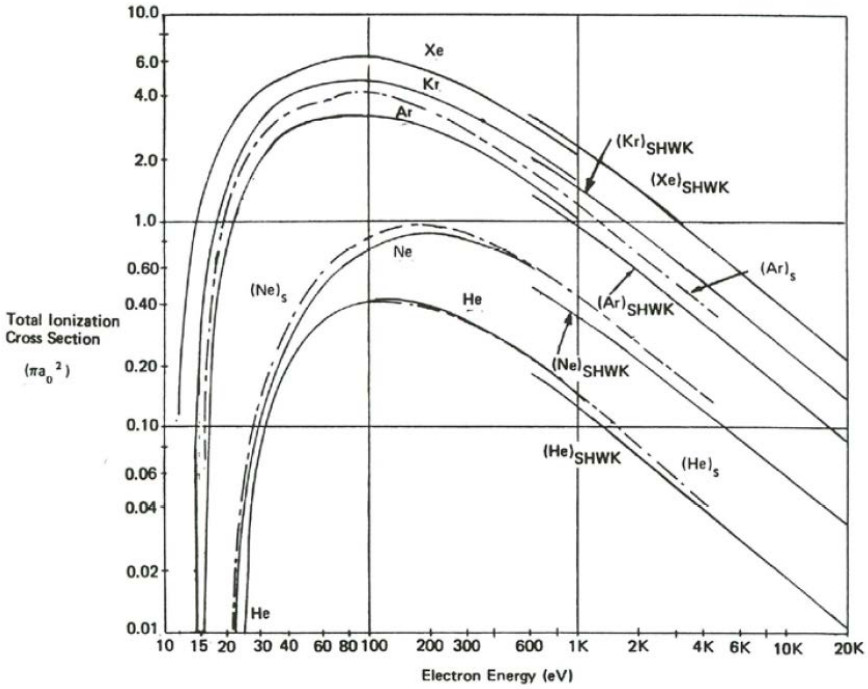
- Electron impact ionization

$$e + A \rightarrow 2e + A^{+}$$

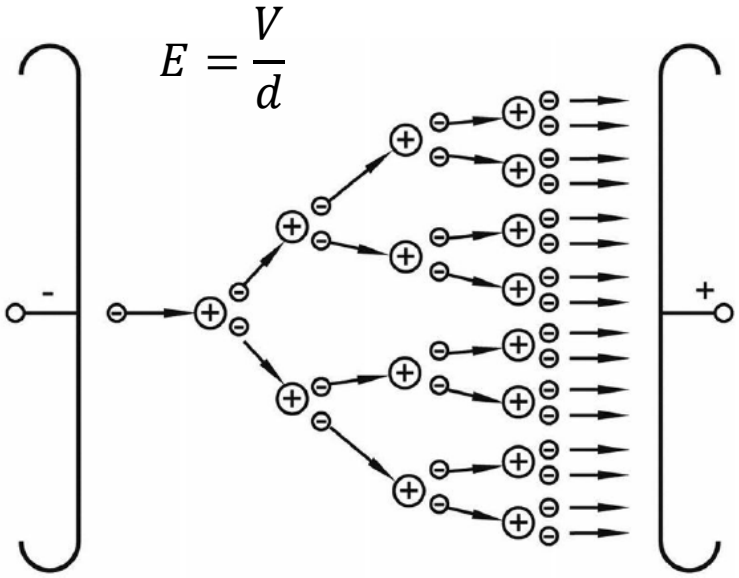
Electrons with sufficient energy (> 10 eV) can remove an electron from an atom and produce one extra electron and an ion.

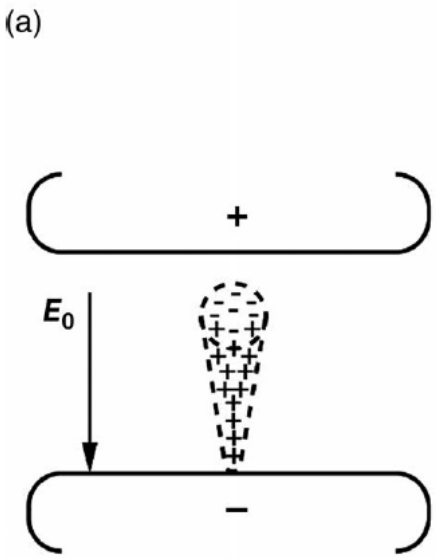


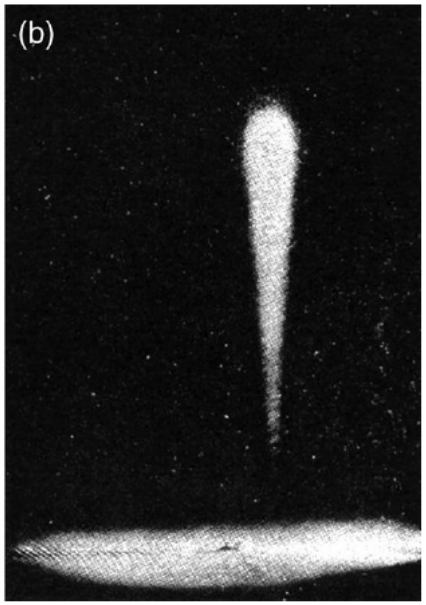




Townsend mechanism: electron avalanche







- Townsend ionization coefficient (α) : electron multiplication

  : production of electrons per unit length along the electric field (ionization event per unit length)

$$\frac{dn_e}{dx} = \alpha n_e \qquad \boxed{n_e = n_{e0}\exp(\alpha x)} \qquad M = \frac{n_e}{n_{e0}} = e^{\alpha x}$$

Townsend 1st ionization coefficient

- When an electron travels a distance equal to its free path λ_e in the direction of the field E, it gains an energy of $eE\lambda_e$. For the electron to ionize, its gain in energy should be at least equal to the ionization potential V_i of the gas:

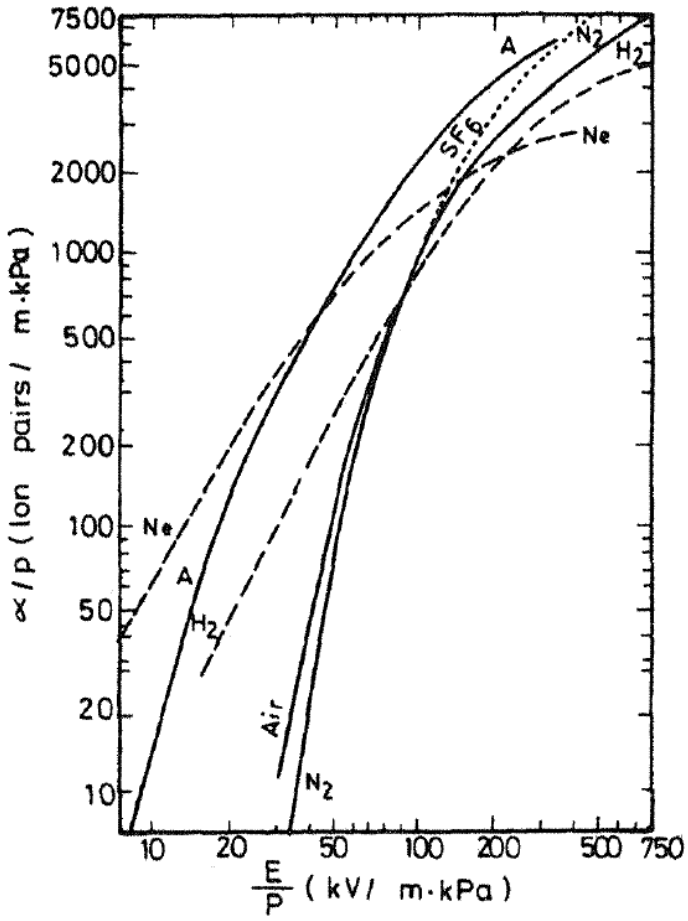
$$e\lambda_e E \geq eV_i \qquad \lambda_e = \frac{1}{n\sigma} \propto \frac{1}{p}$$

- The Townsend 1st ionization coefficient is equal to the number of free paths ($= 1/\lambda_e$) times the probability of a free path being more than the ionizing length λ_{ie},

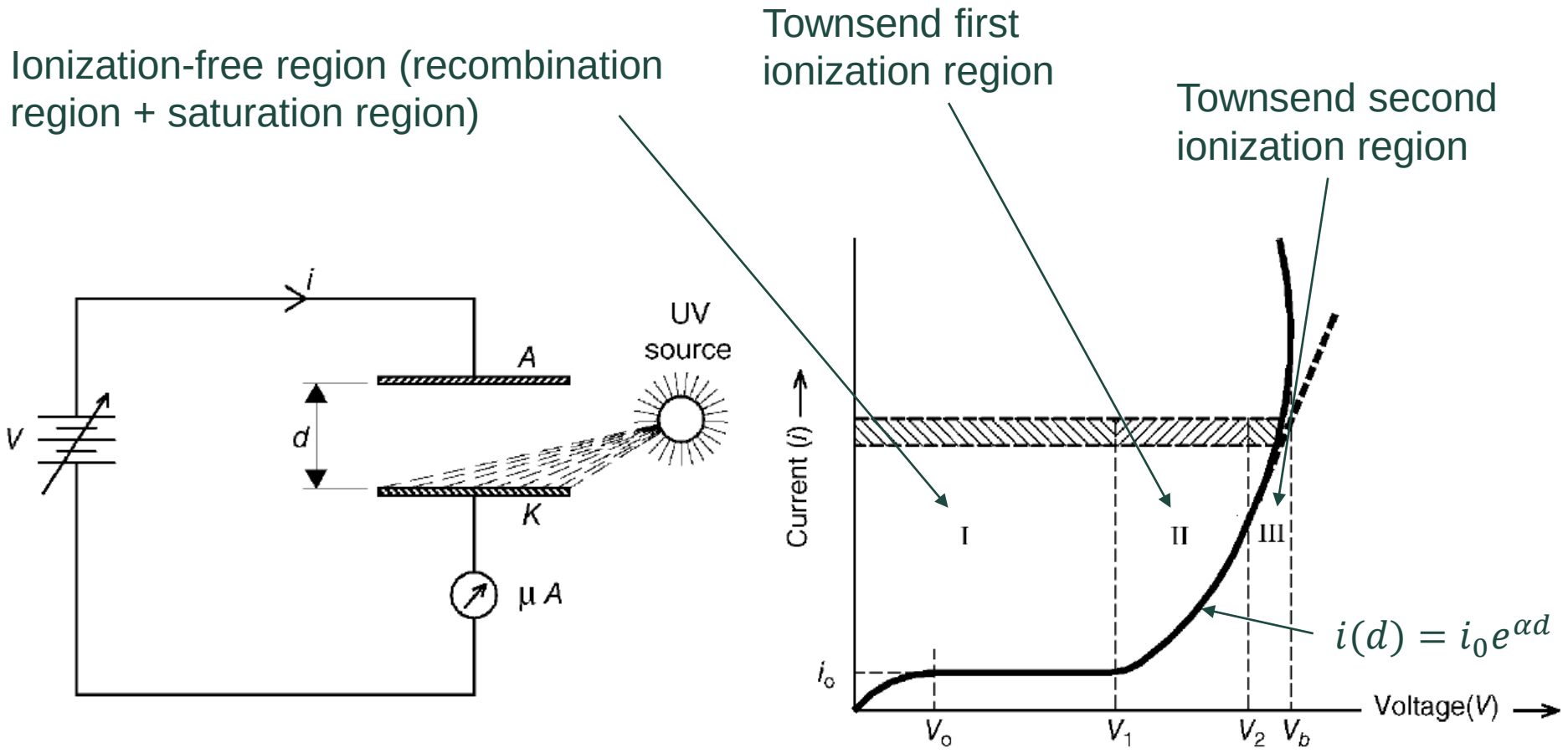
$$\alpha \propto \frac{1}{\lambda_e}\exp\left(-\frac{\lambda_{ie}}{\lambda_e}\right) \propto \frac{1}{\lambda_e}\exp\left(-\frac{V_i}{\lambda_e E}\right)$$

$$\boldsymbol{\alpha/p = A\exp\left(-\frac{B}{E/p}\right)}$$

- A and B must be experimentally determined for different gases.



Townsend's avalanche process is not self-sustaining



- Townsend's avalanche process cannot be sustained without external sources for generating seed electrons.

Townsend's criterion for breakdown

- Secondary electron emission by ion impact: when heavy positive ions strike the cathode wall, secondary electrons are released from the cathode material.
- The self-sustaining condition is given by

$$M = \frac{e^{\alpha d}}{1 - \gamma(e^{\alpha d} - 1)} \to \infty \qquad \alpha d = \ln\left(1 + \frac{1}{\gamma}\right)$$

γ: Townsend 2nd ionization coefficient

- Paschen's law

$$\boldsymbol{\alpha/p = A\exp\left(-\frac{B}{E/p}\right)} \quad + \quad \boldsymbol{\alpha d = \ln\left(1 + \frac{1}{\gamma}\right)}$$

$$\boldsymbol{\alpha d = Apd\exp\left(-\frac{B}{E/p}\right) = Apd\exp\left(-\frac{Bpd}{V_B}\right) = \ln\left(1 + \frac{1}{\gamma}\right)}$$

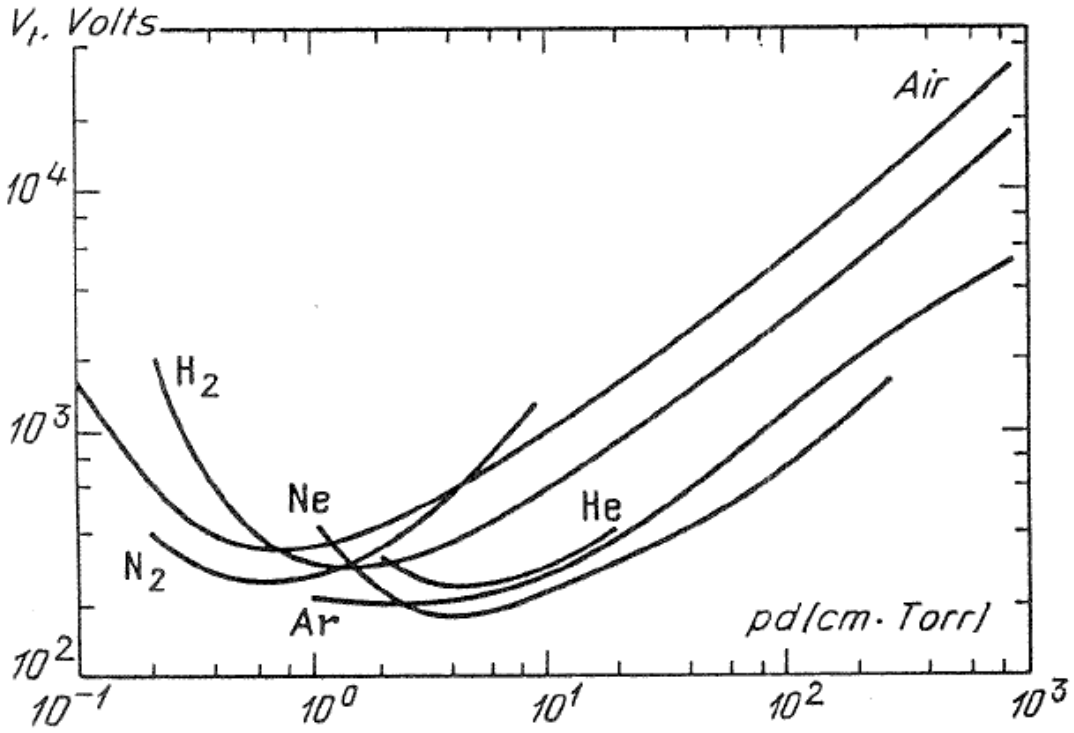
$$\boldsymbol{V_B = \frac{Bpd}{\ln[Apd/\ln(1 + 1/\gamma)]} = f(pd)}$$

Paschen curve

- Minimum breakdown voltage

$$V_{B,min} = \frac{eB}{A}\ln\left(1+\frac{1}{\gamma}\right)$$

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

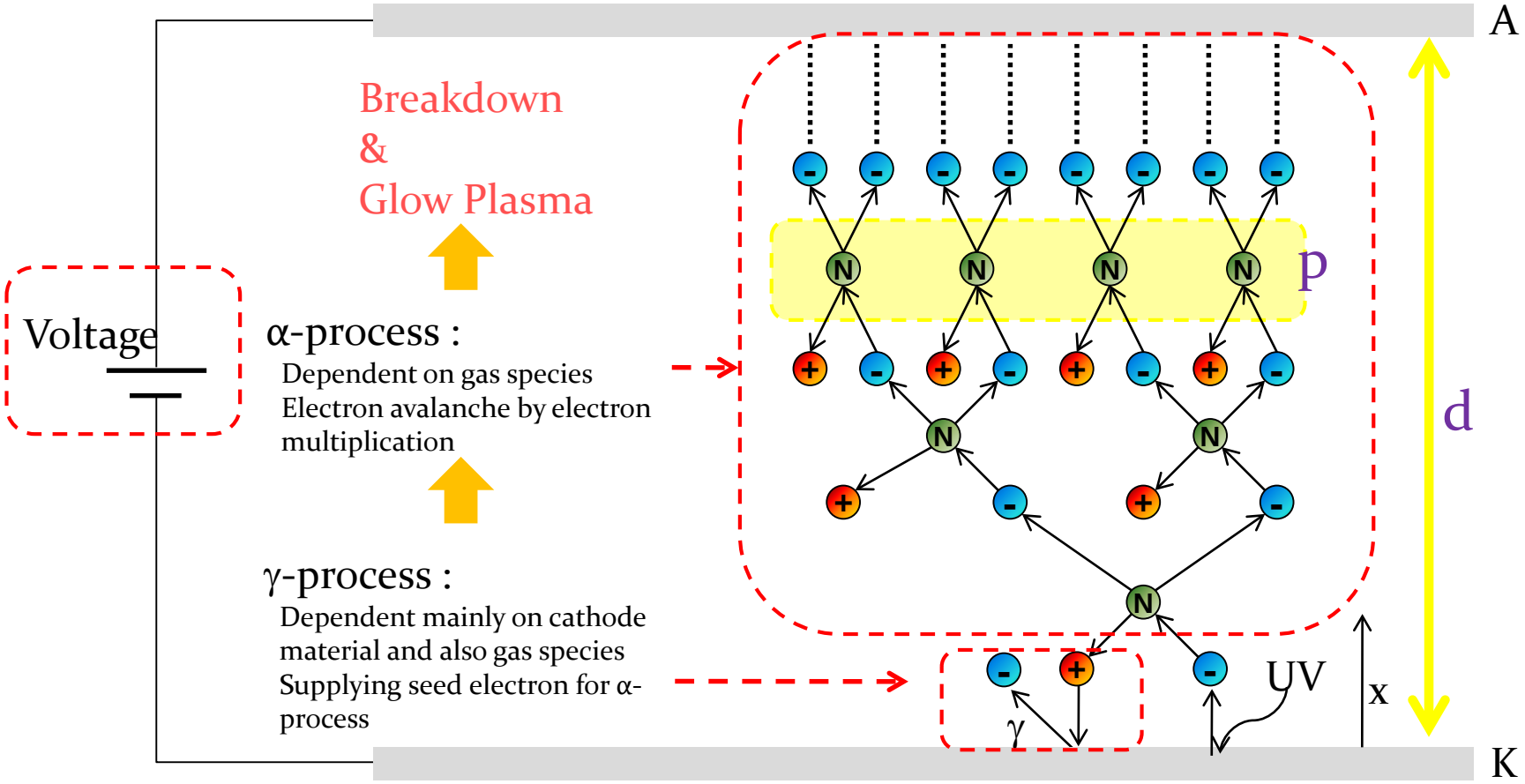


Gas	$V_{s,\min}$ (V)	$(pd)_{\min}$ (torr-cm)
Air (dry)	327	0.567
A	137	0.9
H_2	273	1.15
He	156	4.0
CO_2	420	0.51
N_2	251	0.67
O_2	450	0.7

- Main factors:
  - Pressure
  - Voltage
  - Electrode distance
  - Gas species
  - Electrode material (SEE)

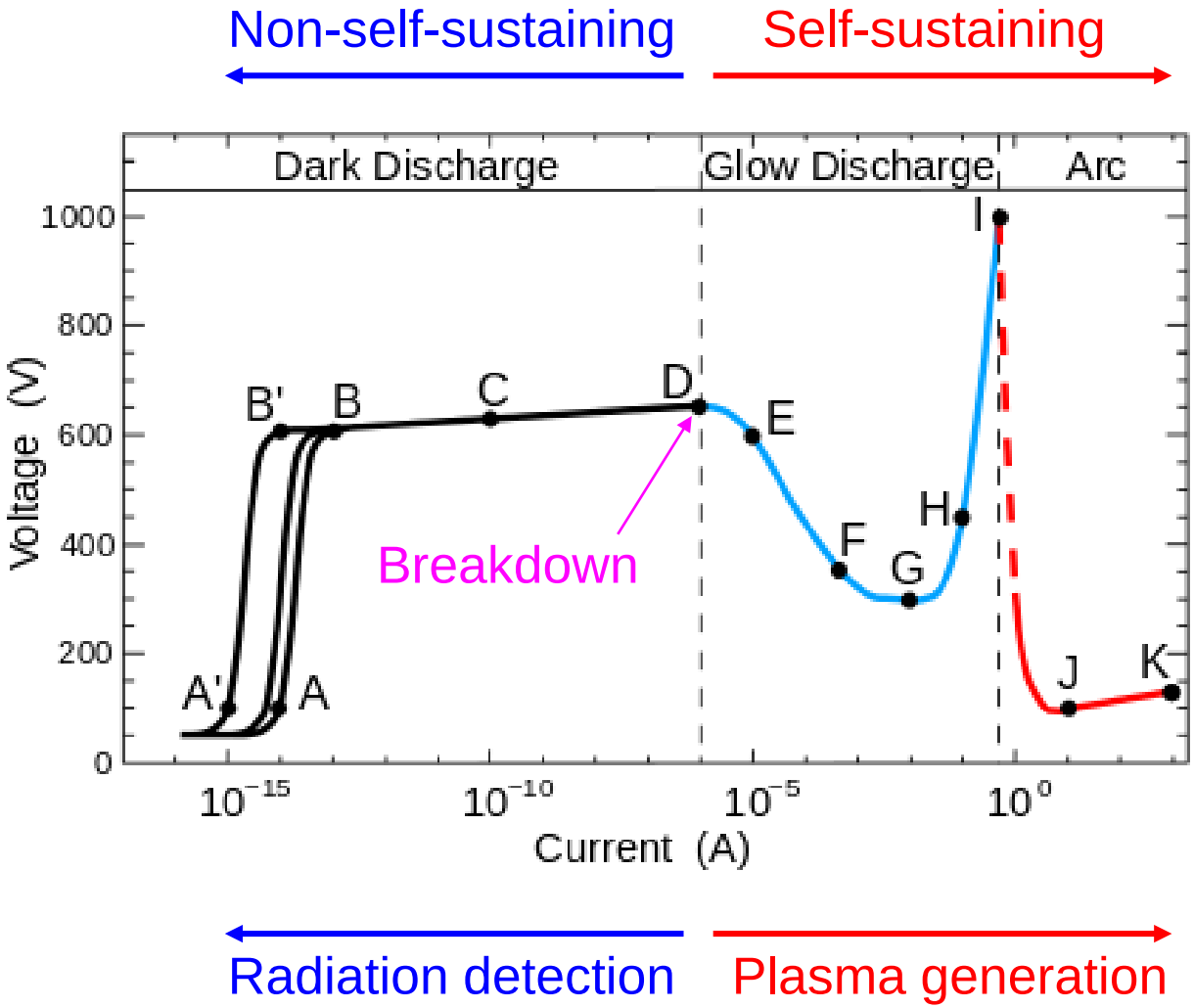
- Small *pd* : too small collision
- Large *pd* : too often collision

Summary of Townsend gas breakdown theory

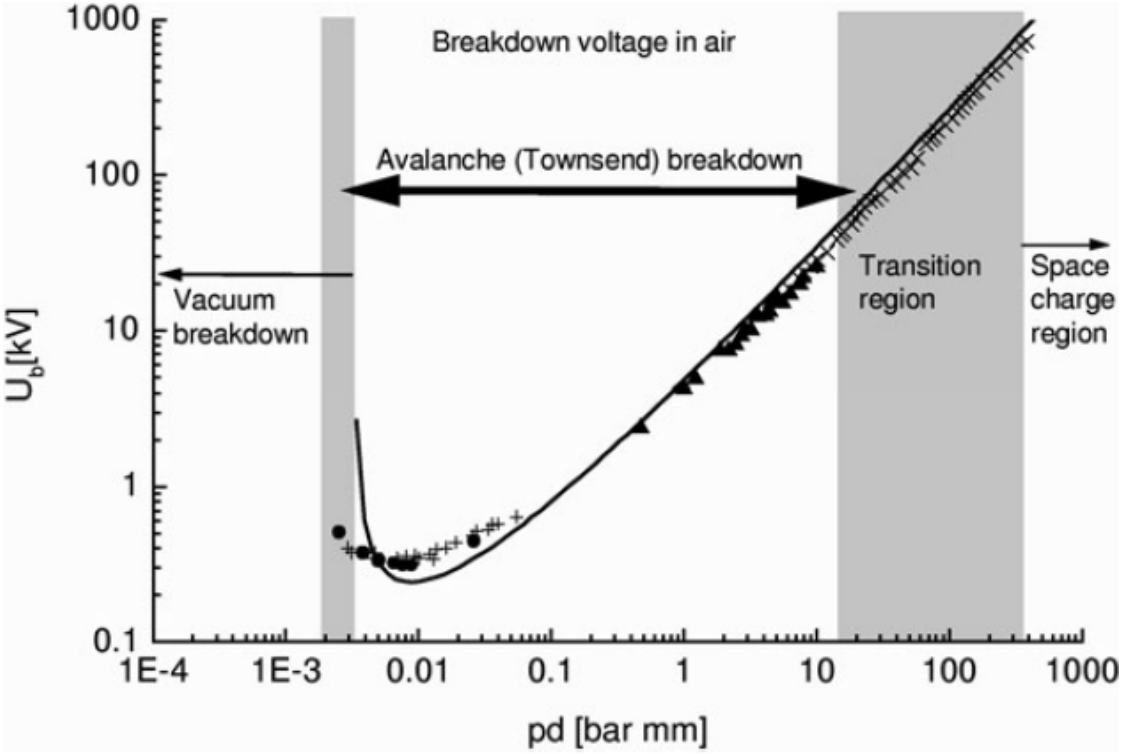


- Two processes (α and γ) are required to sustain the discharge.
- How about electronegative gases (e.g. SF6) which are widely used for gas insulation?

Typical characteristic curve for gas discharges: self-sustaining or non-self-sustaining



Limitation of Townsend theory



The Townsend quasi-homogeneous breakdown mechanism can be applied only for relatively low pressures and short gaps (pd < 200 Torr · cm).

1. The spark breakdown at high *pd* and considerable overvoltage develops much faster than the time necessary for ions to cross the gap and provide the secondary emission. → γ process fails.
2. The spark channel is observed to have a zig-zag shape at high *pd* regime.
3. The discharge at high *pd* is independent of electrode material.

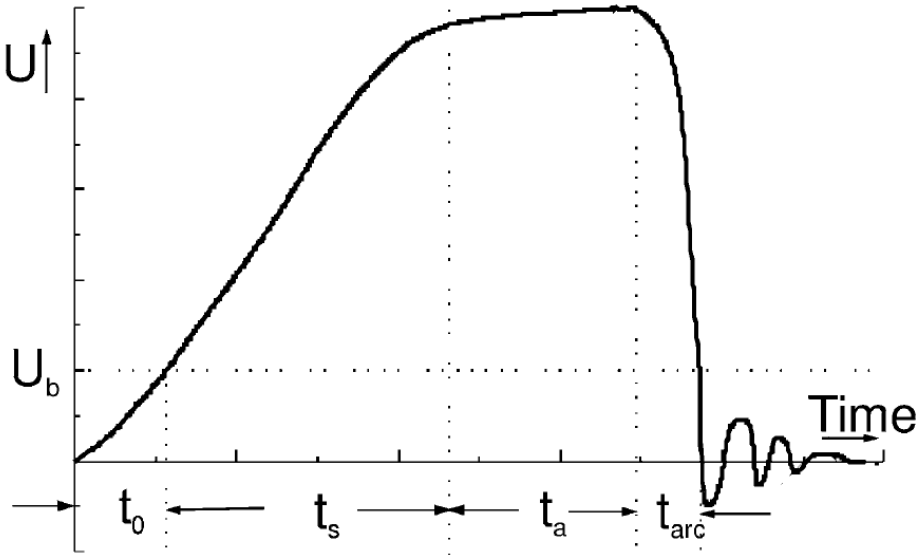
Pulsed breakdown

- Static characteristics : slowly-varying voltage

  → Townsend mechanism

- Dynamic characteristics : fast rising pulse

  → Overvoltage breakdown & discharge time lag



- t_0 : the time until the static breakdown voltage is exceeded
- t_s : the statistical delay time until an electron able to create an avalanche occurs
- t_a (t_f) : the avalanche build-up time until the critical charge density is reached (formative time)
- t_{arc} : the time required to establish a low-resistance arc across the gap

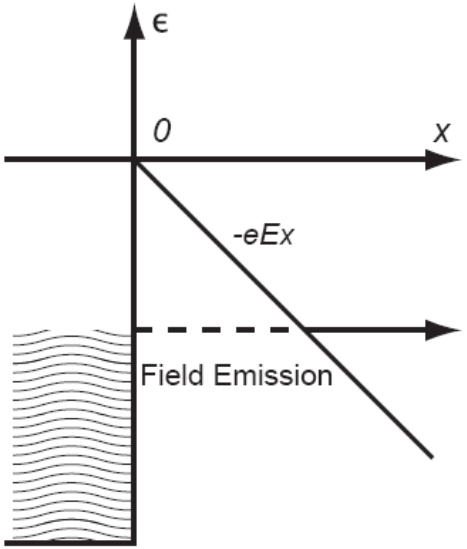
Breakdown delay time = statistical delay time + formative time

Statistical delay time

- The statistical delay time results from the statistics of electron appearance in the gap.
- The sources of electrons that initiate the self-breakdown of a gap
  - Natural radioactivity and cosmic radiation
    - ✓ They produce 0.1 ~ 10 free electrons per cm^3 per second in a gas at atmospheric pressure
  - Field emission by tunneling
    - ✓ Fowler-Nordheim eq.

$$J = C\frac{E^2}{W}\exp\left(-D\frac{W^{3/2}}{E}\right)$$

  - Electron detachment from molecules



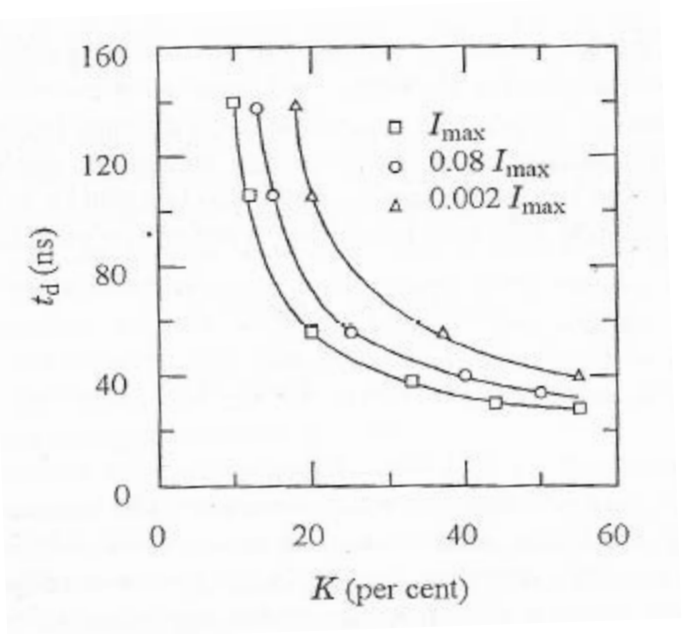
- Total number of electrons appearing in the gap

$$\dot{N}(t) = \dot{N}_{0n} + \dot{N}_F(t) + \dot{N}_\delta(t)$$

Natural occurrence **Field emission** **Electron detachment**

Formative time measurements

- The statistical delay time can be neglected if the gap is intensely irradiated with the light of an auxiliary spark. Then the measured delay time will be equal to the formative time.
- In an early experiment with 30% overvoltage for air gap, Rogowski found that the formative time was 10^{-8} sec, order of the drift time of the electrons in the gap.
- Many experiments confirmed that the formative time depends on the overvoltage and the intensity of irradiation.

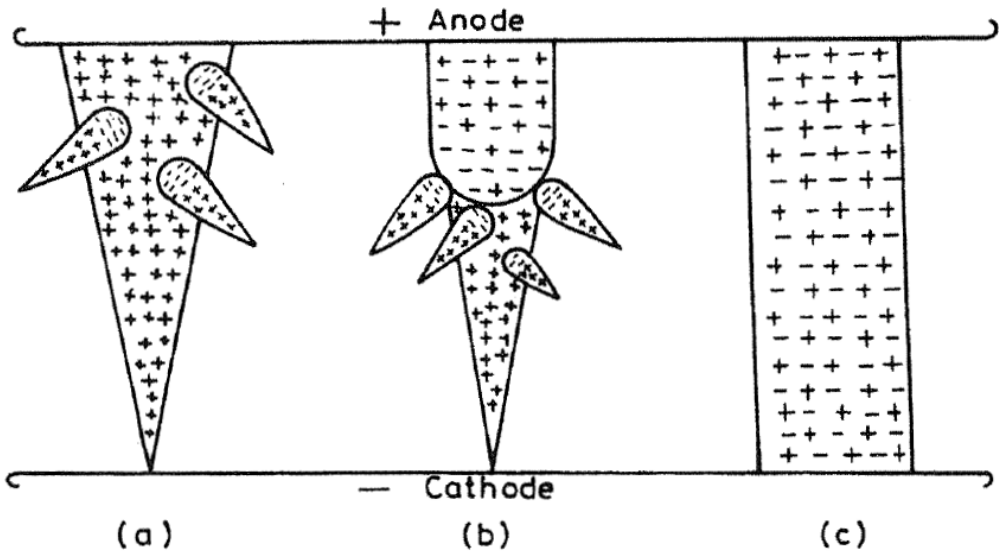


- Need for new theory → Streamer mechanism

Streamer mechanism

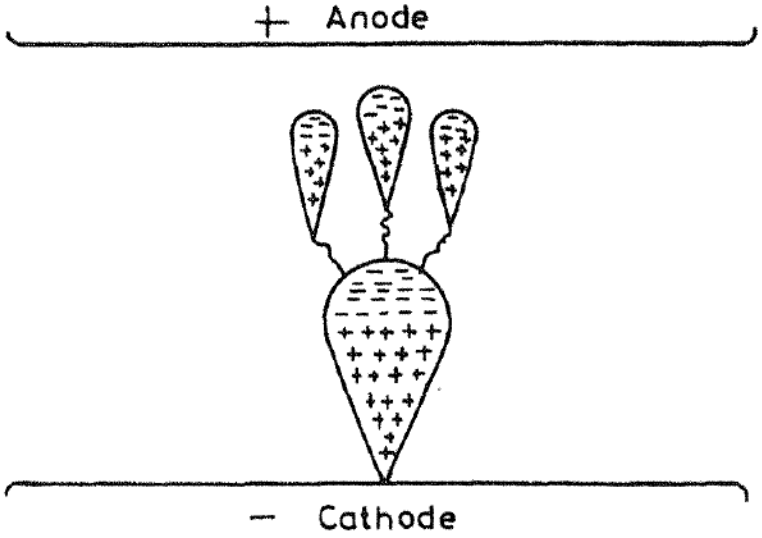
- The streamer concept was proposed by Loeb and Meek for the positive streamer and, independently by Raether for the negative streamer.
- Basic idea is that at a certain stage in the development of a single avalanche, photoionization of the gas in the inter-electrode space becomes the most important mechanism in determining the breakdown of the gap.

Meek & Loeb



Cathode-directed streamer

Raether



Anode-directed streamer

Effect of space charge

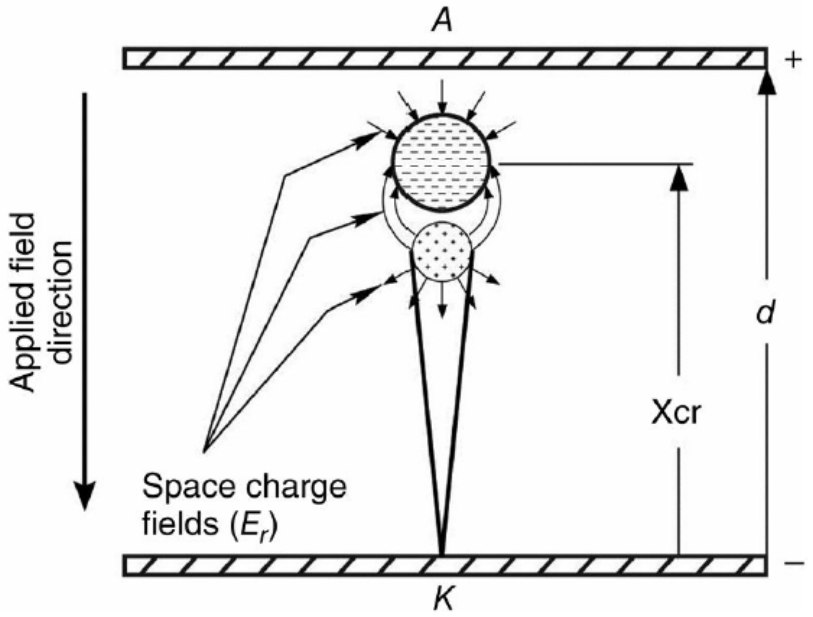
- A distinctive feature of Townsend breakdown mechanism is that the space charge of a single electron avalanche does not distort the electric field in the gap.

$$e^{\alpha d} < N_{cr} \qquad \gamma\left(e^{\alpha d} - 1\right) \geq 1$$

- When the number of electrons reaches N_{cr}, the avalanche acquires some characteristic features that may be favorable for a streamer discharge to occur.

$$e^{\alpha d} \geq N_{cr}$$

- Then, small-diameter, weakly conducting filaments (streamers) propagate from the avalanche toward the anode and cathode. As a result, the gap is bridged by a narrow channel.
- The energy deposited in this channel increases its conductivity, which results in the formation of a spark discharge.



Formative time for a streamer breakdown

- The time from the onset of the streamer stage to the formation of a high-conductivity channel is often shorter than the time needed for an avalanche with the charge-carrier number N_{cr} to develop (formative time for streamer breakdown).

- Raether's criterion for the avalanche-to-streamer transition: The avalanche-to-streamer transition takes place at the time t_{cr} when the resulting electric field $E = E_0 + E'$ vanishes at the point $d = X_{cr} = v_e t_{cr}$ on the avalanche axis.

- Formative time: The time for an initial electron avalanche to build up a space-charge field comparable to the applied filed.

$$N_{cr} = e^{\alpha X_{cr}} \sim 10^8 \quad \Longrightarrow \quad \alpha X_{cr} = \ln N_{cr} = 18\sim20$$

$$t_f = t_{cr} = \frac{X_{cr}}{v_e} = \frac{1}{\alpha v_e} \ln N_{cr}$$

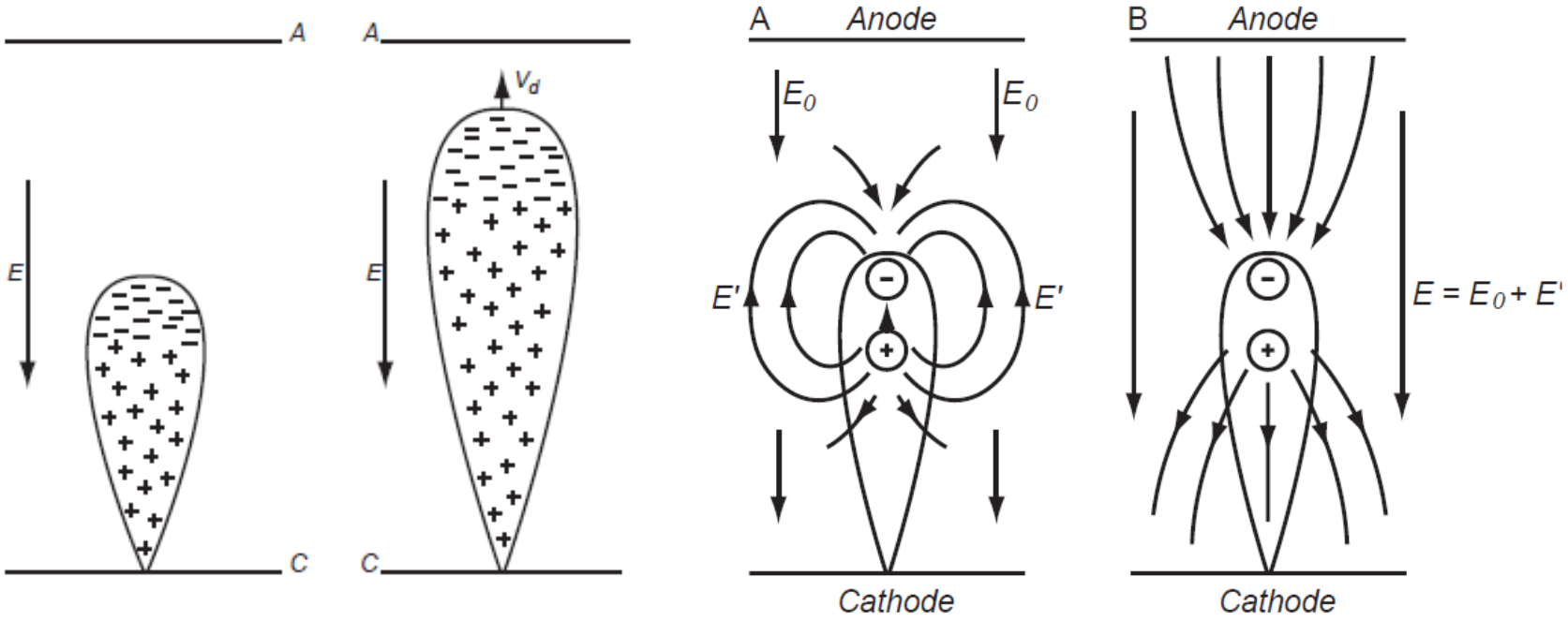
Streamer mechanism: Raether's criterion

- Raether observed that streamers developed when

$$\alpha X_{cr} \approx 20$$

$$E_{sc} \sim \frac{eN}{4\pi\epsilon_0 (1/\alpha)^2} \sim 15\ kV/cm$$

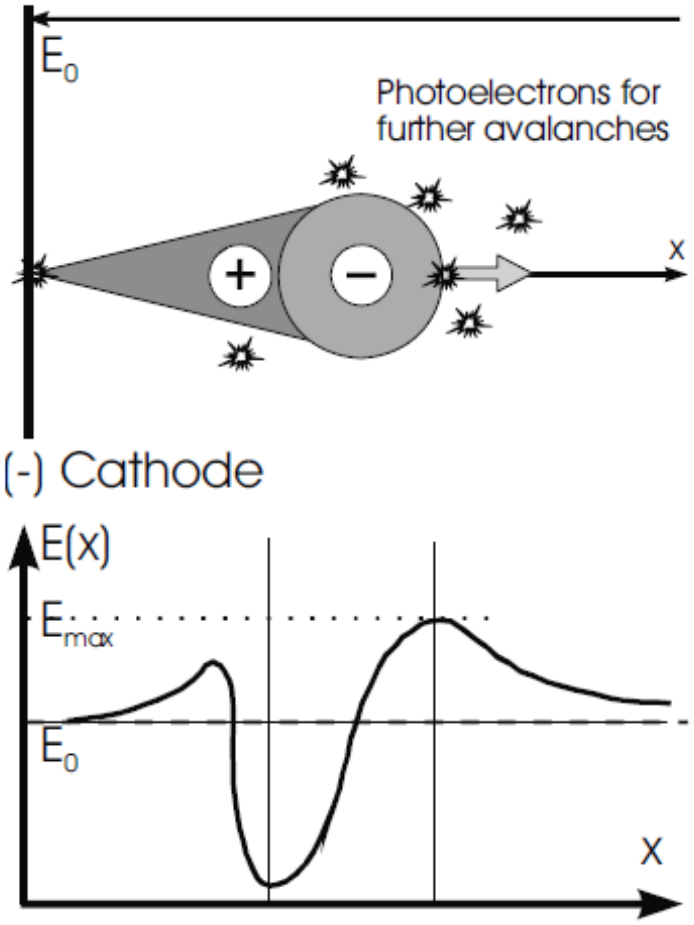
$$for\ N = 10^7\ and\ \alpha^{-1} = 10^{-2} cm$$



- The avalanche-to-streamer transformation takes place when the internal field of an avalanche becomes comparable with the external one.

Formation of space-charge electric field

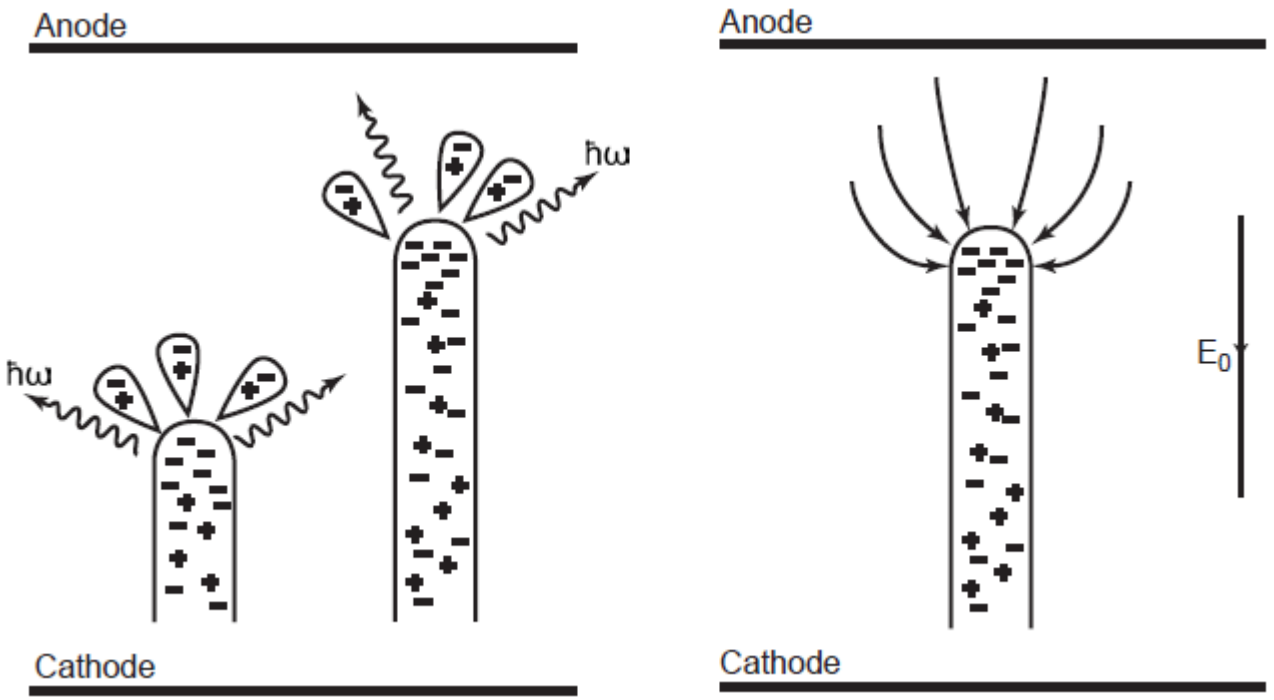
$N_{cr} \sim 10^8$
$(n_e \sim 10^{14}\ cm^{-3})$



- Ions are rather immobile and form a dipole field together with the electrons removed from the ions.
- This field will enhance the initially applied electric field E_0 at the avalanche head.
- UV light emitted in recombination and de-excitation events creates electrons by photoionization ahead of and behind the avalanche, initiating further avalanches.

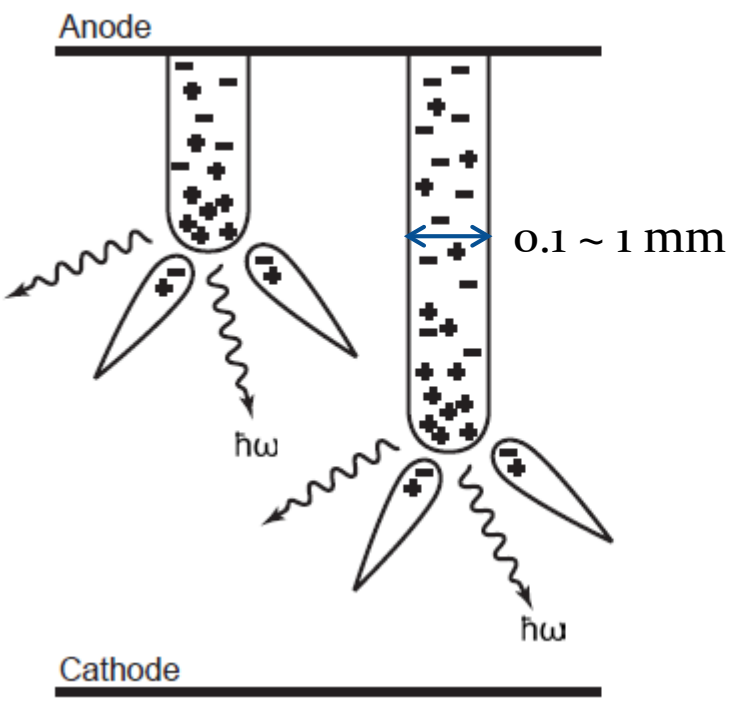
Negative streamer (anode-directed streamer)

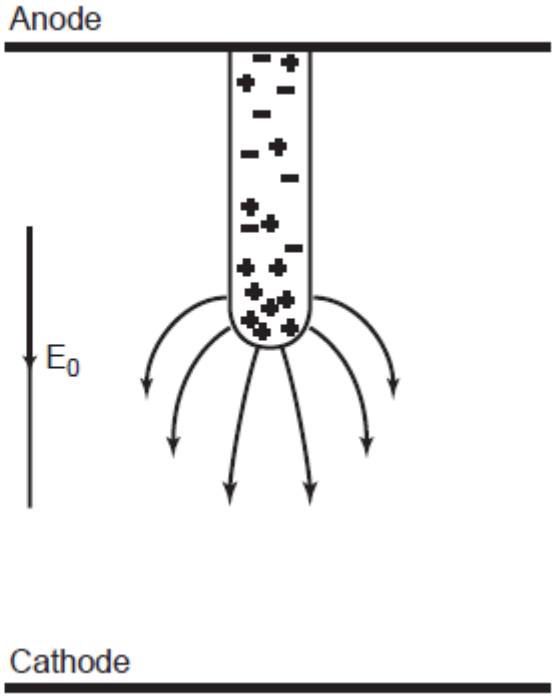
- If the gap and overvoltage are large, the avalanche-to-streamer transformation can take place far from the anode, and the anode-directed or negative streamer grows toward both electrodes.



Positive streamer (cathode-directed streamer)

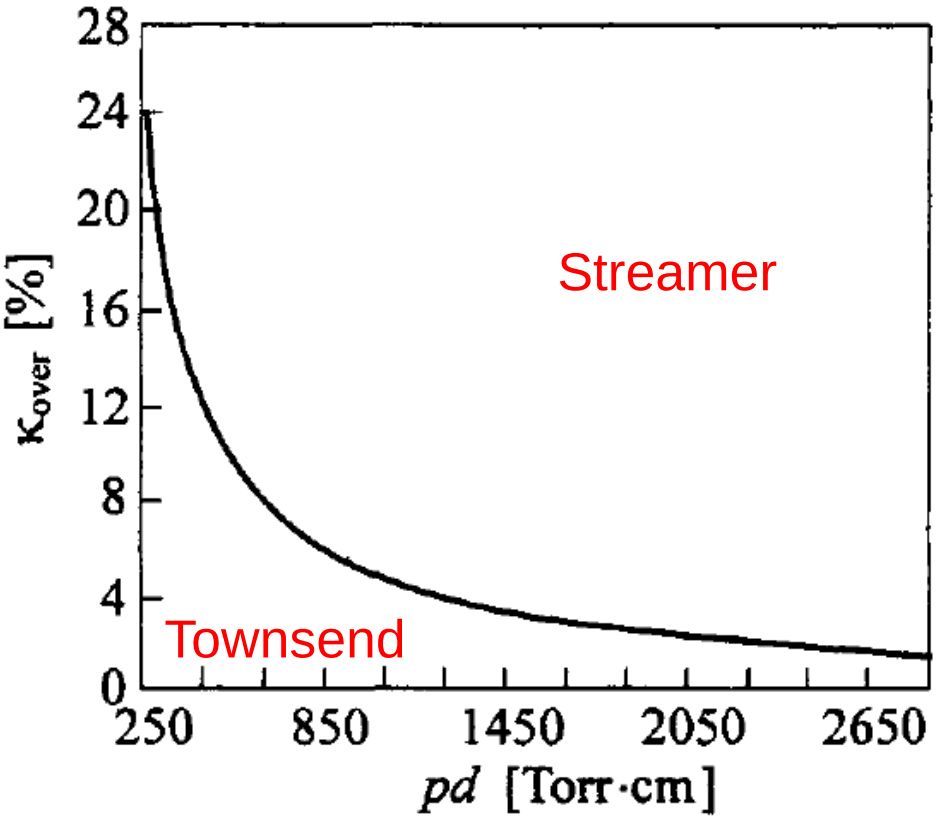
- If the gap is short, the transformation occurs only when the avalanche reaches the anode. Such a streamer that grows from anode to cathode and called the cathode-directed or positive streamer.



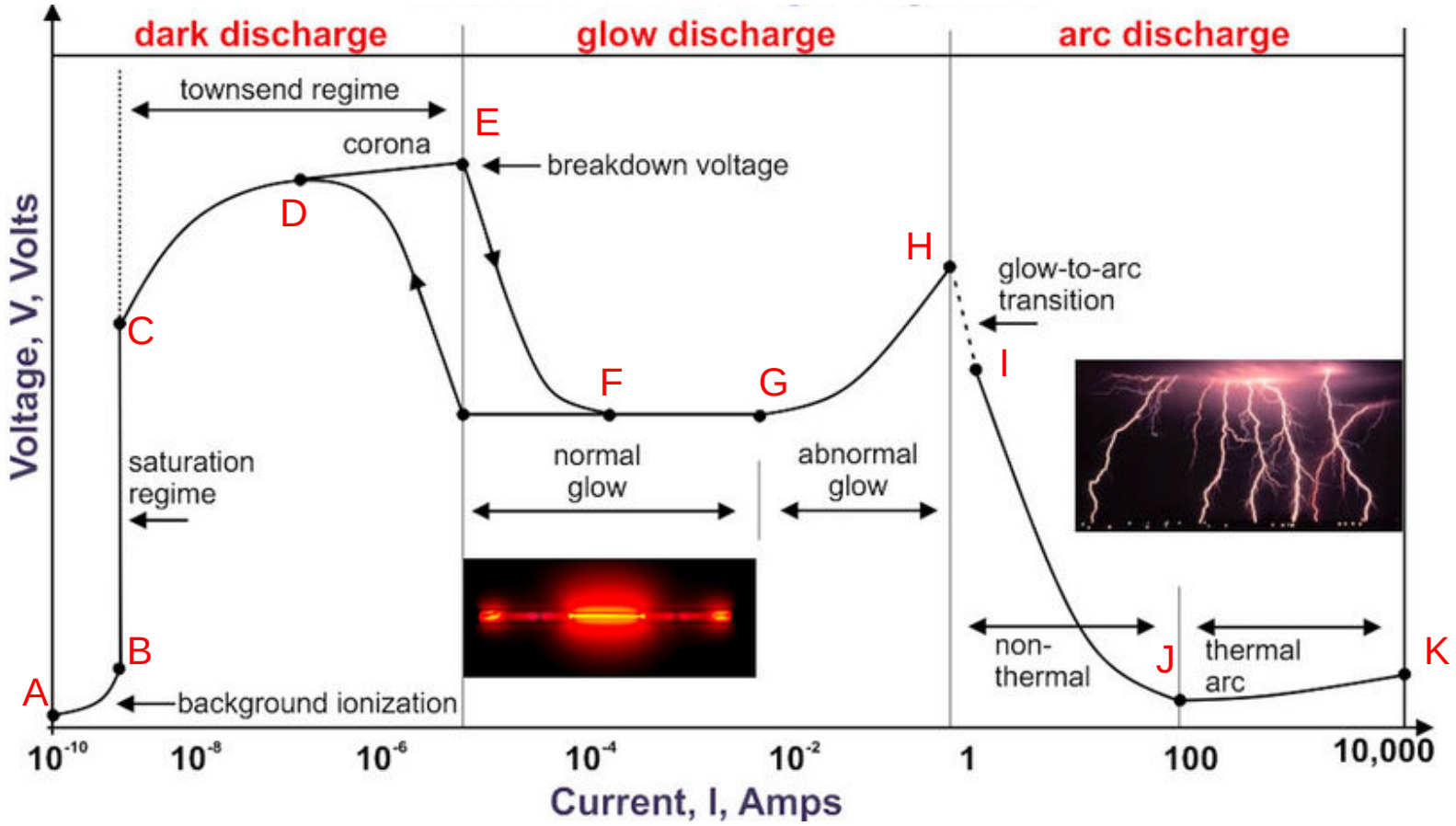


Limits of occurrence for the Townsend and streamer breakdown mechanisms

- The overvoltage coefficient plays a decisive part for a transition from the Townsend to the streamer mechanism.
- Depending on the conditions in the prebreakdown stage, the discharge may develop by the Townsend or streamer mechanism.



Typical current-voltage characteristics for electrical discharge of gases



Electrical discharge regime

- Dark discharge

- **A – B** During the background ionization stage of the process the electric field applied along the axis of the discharge tube sweeps out the ions and electrons created by ionization from background radiation. Background radiation from cosmic rays, radioactive minerals, or other sources, produces a constant and measurable degree of ionization in air at atmospheric pressure. The ions and electrons migrate to the electrodes in the applied electric field producing a weak electric current. Increasing voltage sweeps out an increasing fraction of these ions and electrons.
- **B – C** If the voltage between the electrodes is increased far enough, eventually all the available electrons and ions are swept away, and the current saturates. In the saturation region, the current remain constant while the voltage is increased. This current depends linearly on the radiation source strength, a regime useful in some radiation counters.
- **C – D** If the voltage across the low pressure discharge tube is increased beyond point C, the current will rise exponentially. The electric field is now high enough so the electrons initially present in the gas can acquire enough energy before reaching the anode to ionize a neutral atom. As the electric field becomes even stronger, the secondary electron may also ionize another neutral atom leading to an avalanche of electron and ion production. The region of exponentially increasing current is called the Townsend discharge.
- **D – E** Corona discharges occur in Townsend dark discharges in regions of high electric field near sharp points, edges, or wires in gases prior to electrical breakdown. If the coronal currents are high enough, corona discharges can be technically "glow discharges", visible to the eye. For low currents, the entire corona is dark, as appropriate for the dark discharges. Related phenomena include the silent electrical discharge, an inaudible form of filamentary discharge, and the brush discharge, a luminous discharge in a non-uniform electric field where many corona discharges are active at the same time and form streamers through the gas.

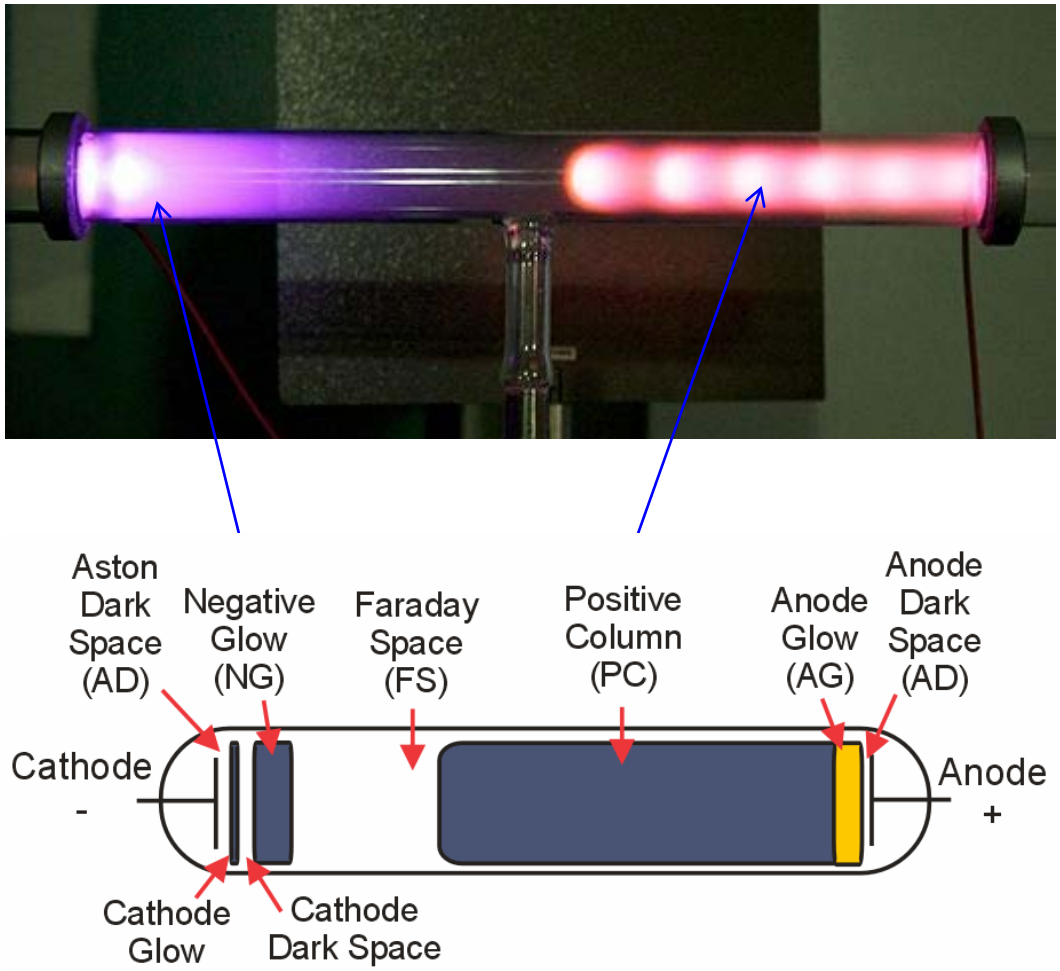
Electrical discharge regime

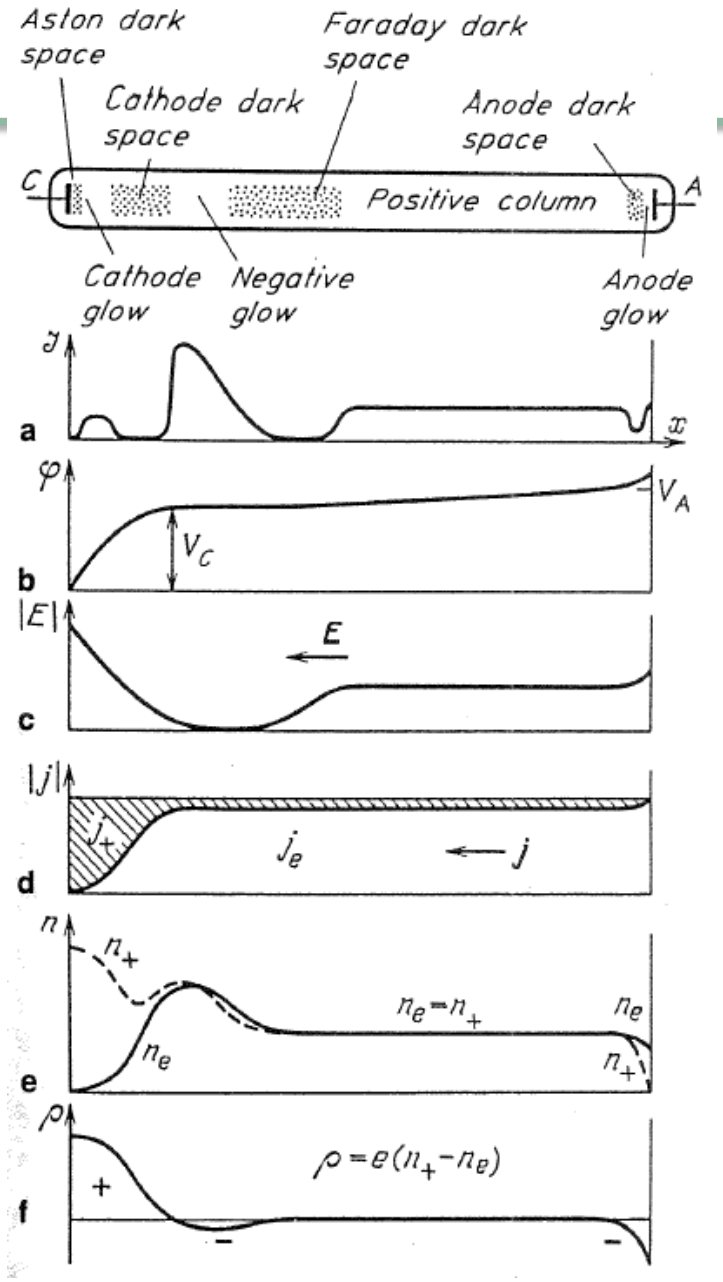
- Breakdown
  - **E** Electrical breakdown occurs in Townsend regime with the addition of secondary electrons emitted from the cathode due to ion or photon impact. At the breakdown, or sparking potential V_B, the current might increase by a factor of 10^4 to 10^8, and is usually limited only by the internal resistance of the power supply connected between the plates. If the internal resistance of the power supply is very high, the discharge tube cannot draw enough current to break down the gas, and the tube will remain in the corona regime with small corona points or brush discharges being evident on the electrodes. If the internal resistance of the power supply is relatively low, then the gas will break down at the voltage V_B, and move into the normal glow discharge regime. The breakdown voltage for a particular gas and electrode material depends on the product of the pressure and the distance between the electrodes, pd, as expressed in Paschen's law (1889).

- Glow discharge
  - **F – G** After a discontinuous transition from E to F, the gas enters the normal glow region, in which the voltage is almost independent of the current over several orders of magnitude in the discharge current. The electrode current density is independent of the total current in this regime. This means that the plasma is in contact with only a small part of the cathode surface at low currents. As the current is increased from F to G, the fraction of the cathode occupied by the plasma increases, until plasma covers the entire cathode surface at point G.
  - **G – H** In the abnormal glow regime above point G, the voltage increases significantly with the increasing total current in order to force the cathode current density above its natural value and provide the desired current. Starting at point G and moving to the left, a form of hysteresis is observed in the voltage-current characteristic. The discharge maintains itself at considerably lower currents and current densities than at point F and only then makes a transition back to Townsend regime.

- Arc discharge
  - **H – K** At point H, the electrodes become sufficiently hot that the cathode emits electrons thermionically. If the DC power supply has a sufficiently low internal resistance, the discharge will undergo a glow-to-arc transition, H-I. The arc regime, from I through K is one where the discharge voltage decreases as the current increases, until large currents are achieved at point J, and after that the voltage increases slowly as the current increases.

Structure of glow discharge





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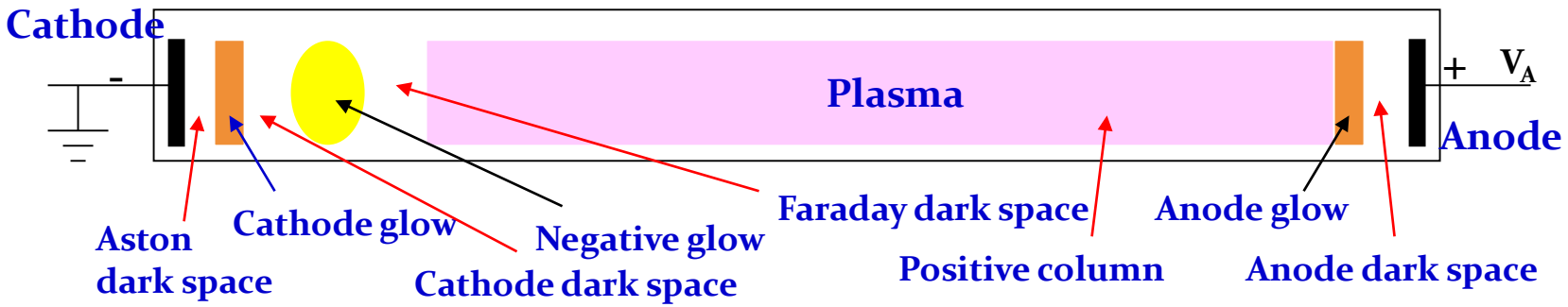
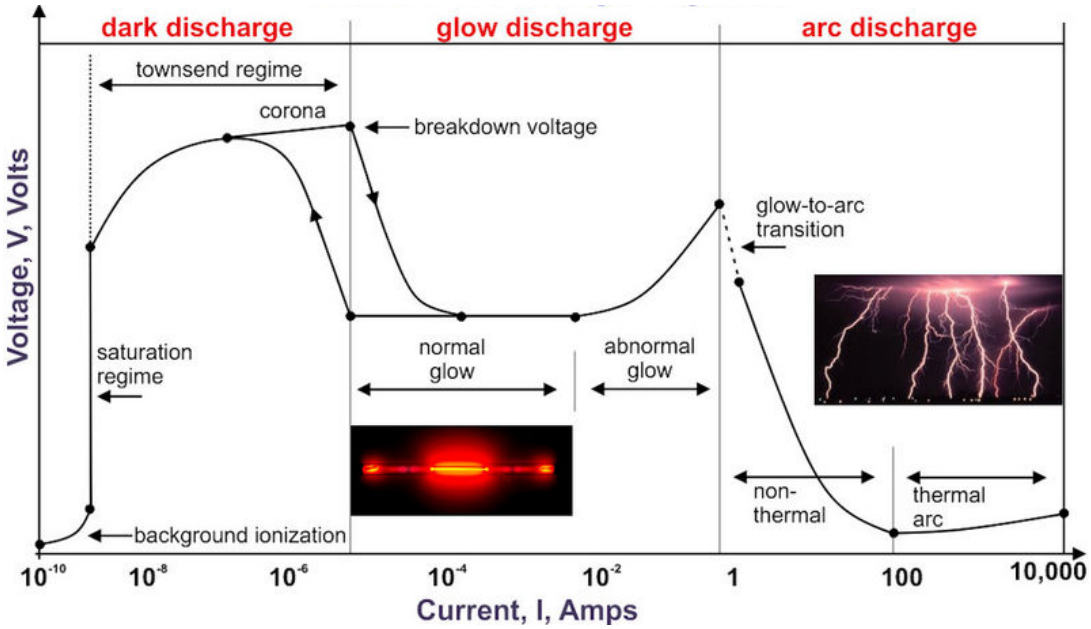
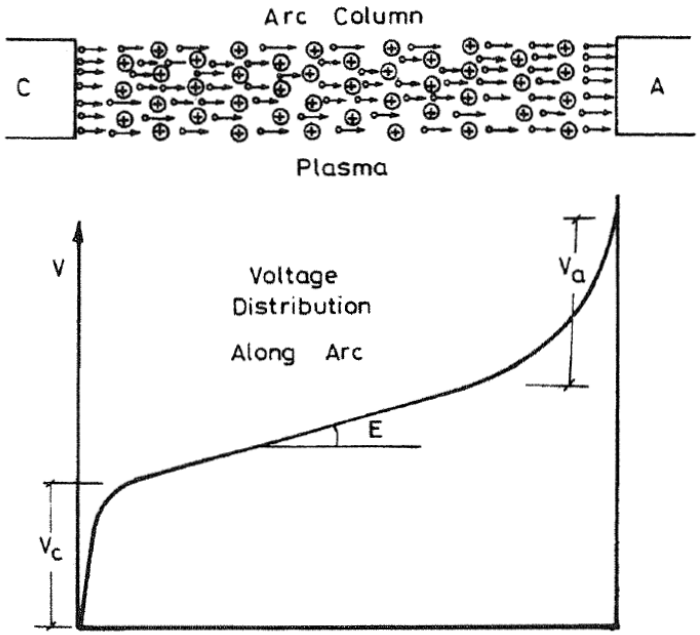


- **Cathode** : cathode material, secondary electron emission coefficients
- **Aston dark space** : a thin region with a strong electric field, and a negative space charge. Electrons are too low density and/or energy to excite the gas
- **Cathode glow** : reddish or orange color in air due to emission by excited atoms sputtered off the cathode surface, or incoming positive ions. High ion number density
- **Cathode (Crookes, Hittorf) dark space** : moderate electric field, a positive space charge and a relatively high ion density
- **Cathode region** : Most of the voltage drop, known as cathode fall V_c, most of the power dissipation, electrons are accelerated in this region, the axial length of the cathode region determined by Paschen minimum
- **Negative glow** : accelerated electrons produce ionization and intense excitation, hence brightest light intensity, relatively low electric field, longer than cathode glow, typical electron density of 10^{16} electrons/m^3
- **Faraday dark space** : low electron energy due to ionization and excitation, electron number density decreased by recombination and radial diffusion
- **Positive column** : quasi-neutral plasma, small electric field of 1V/cm, electron number density of 10^{15}-10^{16} electrons/m^3, temperature of 1-2 eV, long uniform glow
- **Anode glow** : bright region at the boundary of the anode sheath
- **Anode dark space** : anode sheath, negative space charge, higher electric field than positive column

Arc discharge

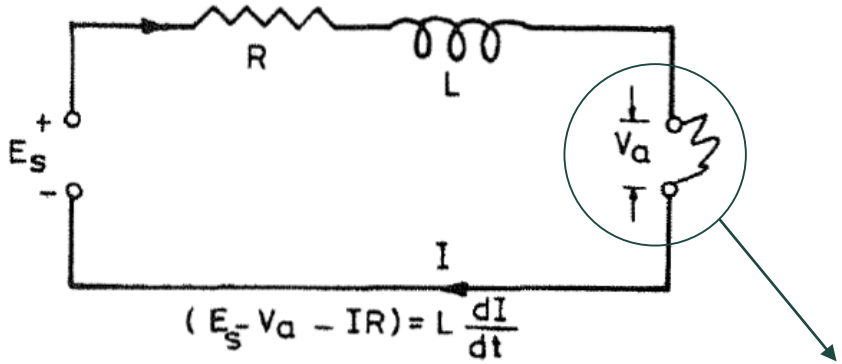
- Electrons emitted from the cathode spot can be produced mainly by thermionic emission if the cathode is made of a high-melting-point metal (e.g., carbon, tungsten, or molybdenum). With cathodes of low melting point, electrons can be supplied by field emission from points of micro-roughness where the electric field is highly concentrated.
- An additional important source of electrons at the cathode is ionized metal vapor.

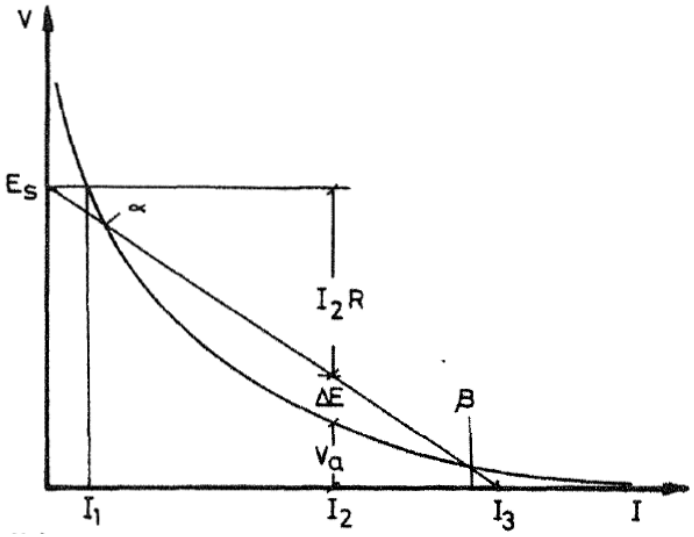


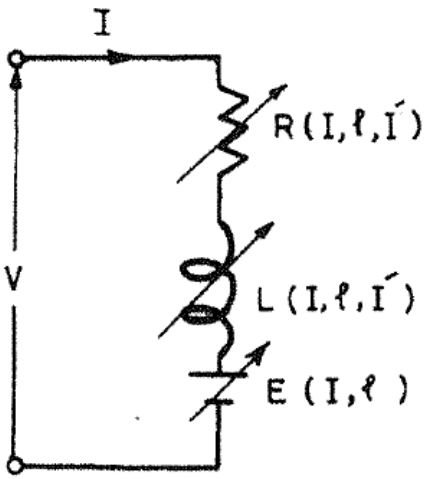


Arc as a circuit element

- The arc equivalent resistance varies with the current and dV/dI is negative. Therefore, a stabilizing impedance must be included in series with the arc in both AC and DC circuits.







Arc erosion

- Erosion of the contacts by arcing is caused partly by evaporation of metal from electrode spots during the arc.
- The energy of the arc, rather than its charge, is the deciding factor for arc erosion. The current wave shape also has an effect on the rate of arc erosion.
- For otherwise similar conditions, the rate of contact erosion is lower for contact metals with high melting points, greater latent heats of evaporation, and higher thermal conductivities.

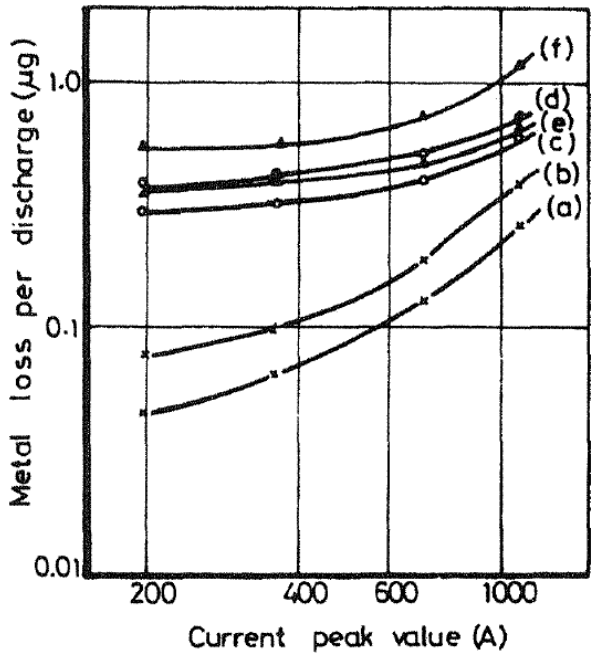
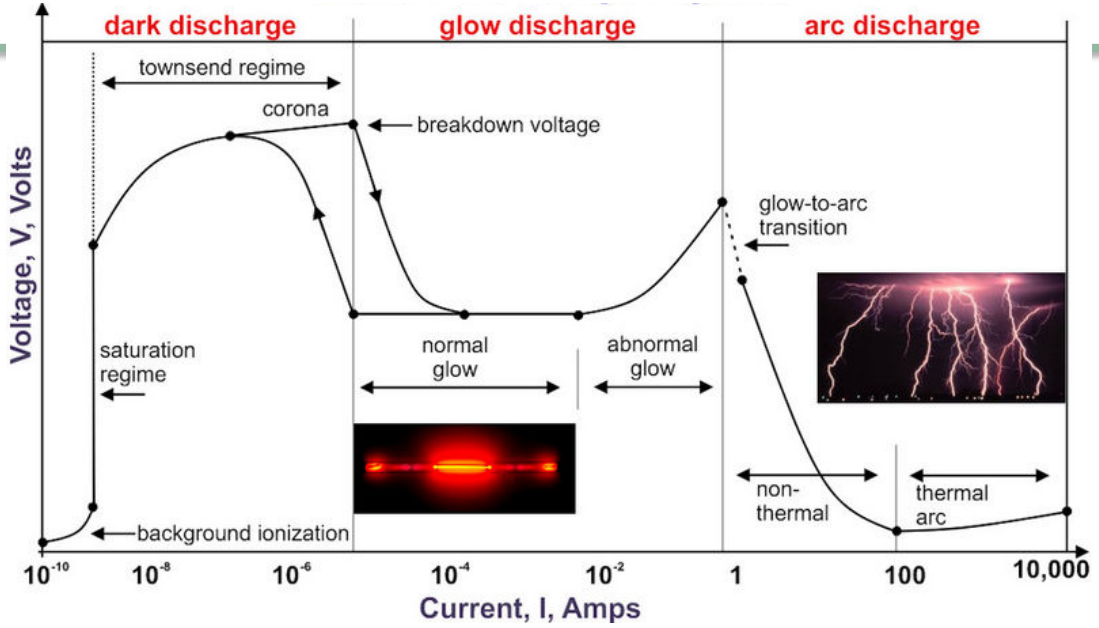


Figure 6.12 Rates of arc erosion from electrodes of different materials. DC arc charge, 73 mC; arc length, 1 mm: (a) anode and (b) cathode of molybdenum, (c) anode and (d) cathode of steel, (e) anode and (f) cathode of W–Cu sintered mixture.

Arc vs. glow

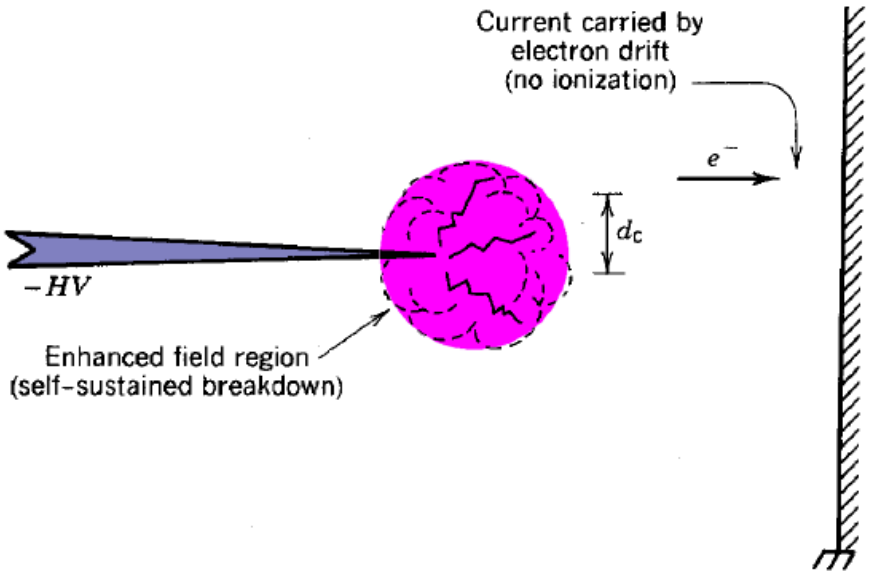


- Glow discharge
  - 전극간 전압 : 수백 V
  - 전류 : 수 mA
  - 양이온이나 광자에 의한 음극에서의 이차전자 방출에 의하여 방전이 지속되며 기체 중에 전극물질의 증발성분을 포함시키지 않는다.

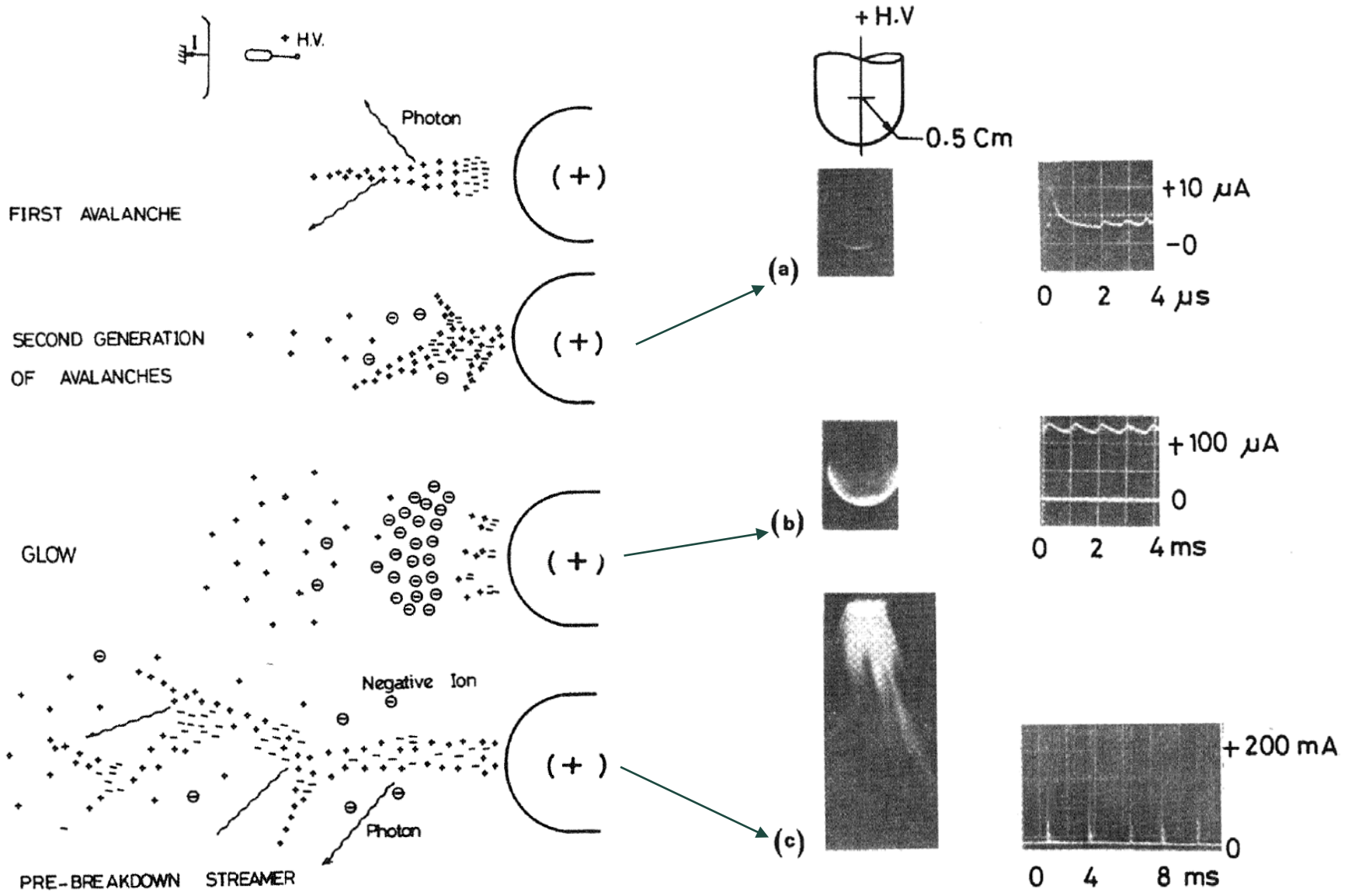
- Arc discharge
  - 전극간 전압 : 수십 V
  - 전류 : 수 A 이상
  - 음극의 2차 기구로서 열전자 방출 및 자계 방출이 중요한 역할을 하고 증발한 전극 물질은 기체분자와 더불어 방전의 형성과 유지에 관계한다.

Corona discharges

- Corona discharges appear in gases when electrodes have strong two-dimensional variations.
- Corona (crown in Latin) is a pattern of bright sparks near a pointed electrode. In such a region, the electric field is enhanced above the breakdown limit so that electron avalanches occur.



Positive corona



Positive corona

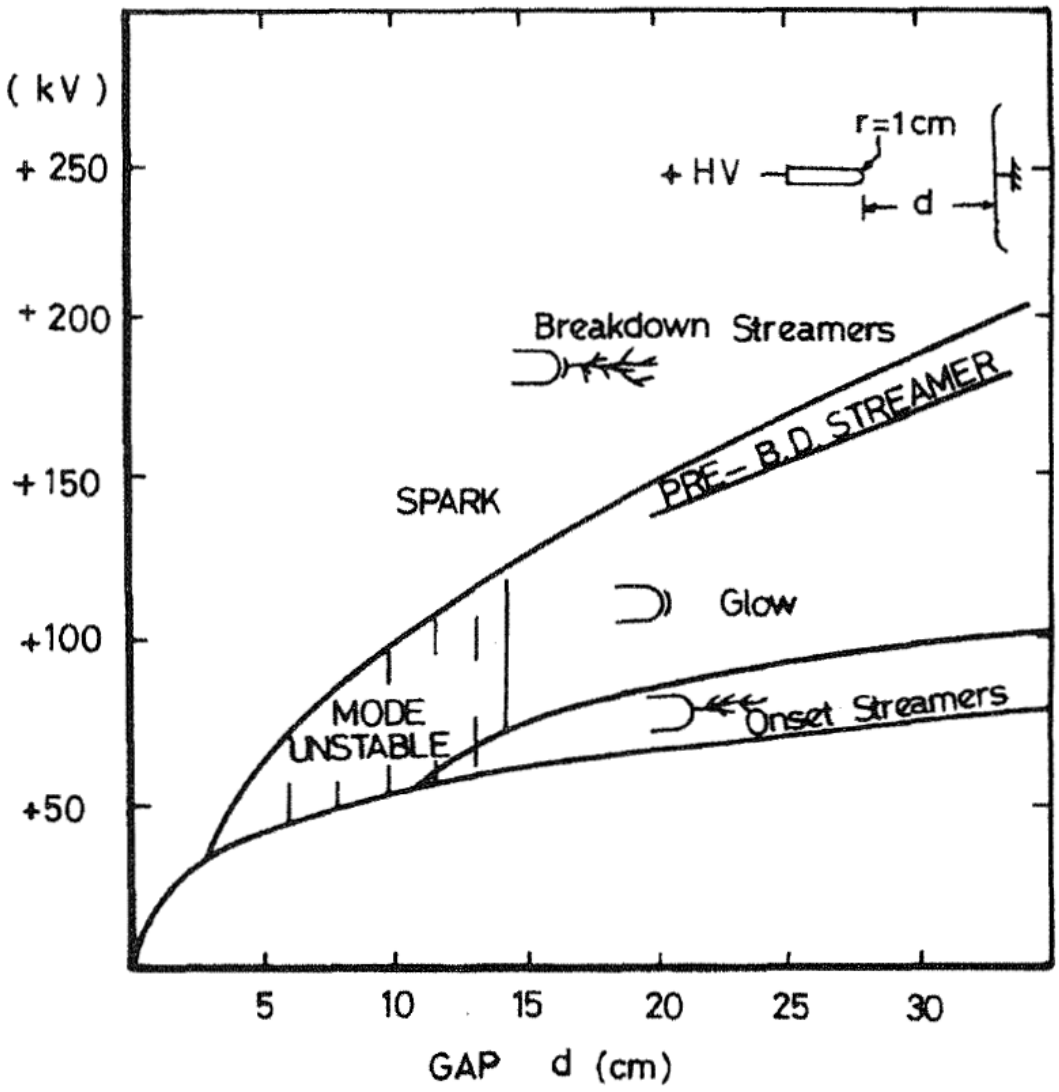
- Mechanism depending on the applied voltage level

  a. At the onset level: When a free electron is driven by the field toward the anode, it produces an electron avalanche. The cloud of positive ions produced at the avalanche head near the anode forms an eventual extension to the anode. Secondary generations of avalanches get directed to the anode and to these dense clouds of positive ions. This mode of corona consists of what are called onset streamers.

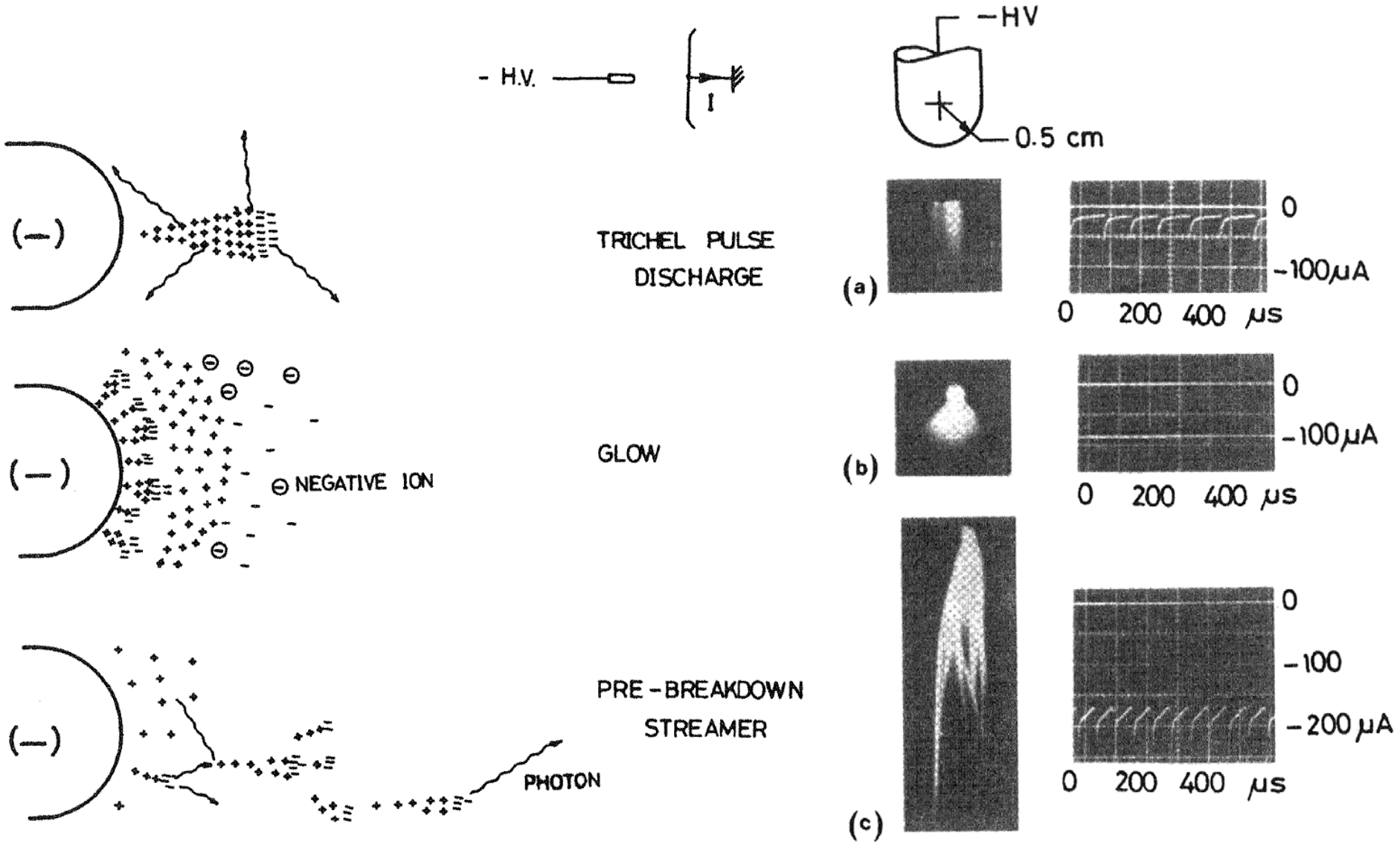
  b. At slightly higher voltages: A cloud of negative ions may form near the anode surface such that the onset-type streamers become very numerous. They are short in length, overlap in space and time, and the discharge takes the form of a ‘glow’ covering a significant part of the HV conductor surface. The corresponding current through the HV circuit becomes a quasi-steady current.

  c. At still higher voltages: The clouds of negative ions at the anode can no longer maintain their stability and become ruptured by violent pre-breakdown streamers, corresponding to irregular, high-amplitude current pulses. If we continue to raise the voltage, breakdown eventually occurs across the air gap.

Onset voltage of various positive corona modes



Negative corona



Negative corona

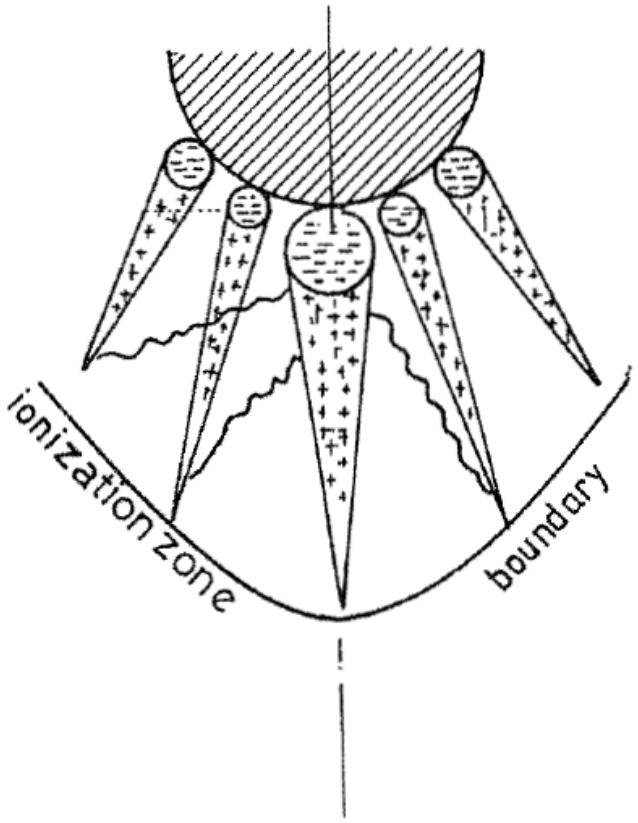
- Mechanism depending on the applied voltage level

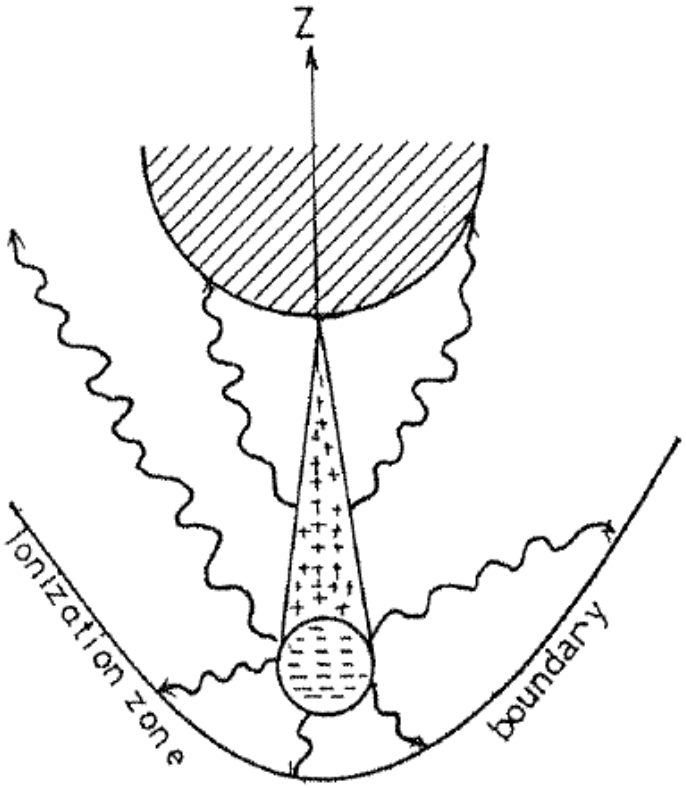
  a. At the onset level: The corona at the cathode has a rapidly and steadily pulsating mode; this is known as Trichel pulse corona. Each current pulse corresponds to one main electron avalanche occurring in the ionization zone. Drifting away from the cathode, more and more of the avalanche electrons get attached to gas molecules and form negative ions which continue to drift very slowly away from the cathode. During the process of avalanche growth, some photons radiate from the avalanche core in all directions. The photoelectrons thus produced can start subsidiary avalanches that are directed from the cathode.

  b. At slightly higher voltages: The Trichel pulses increase in a repetition rate up to a critical level at which the negative corona gets into the steady “negative glow” mode.

  c. At still higher voltages: Pre-breakdown streamers appear, eventually causing a complete breakdown of the gap.

Positive corona vs. negative corona





Positive space charge

electrons

photons

Positive space charge

electrons

photons