Gas Breakdown and Gas-filled Detectors

Fall, 2017

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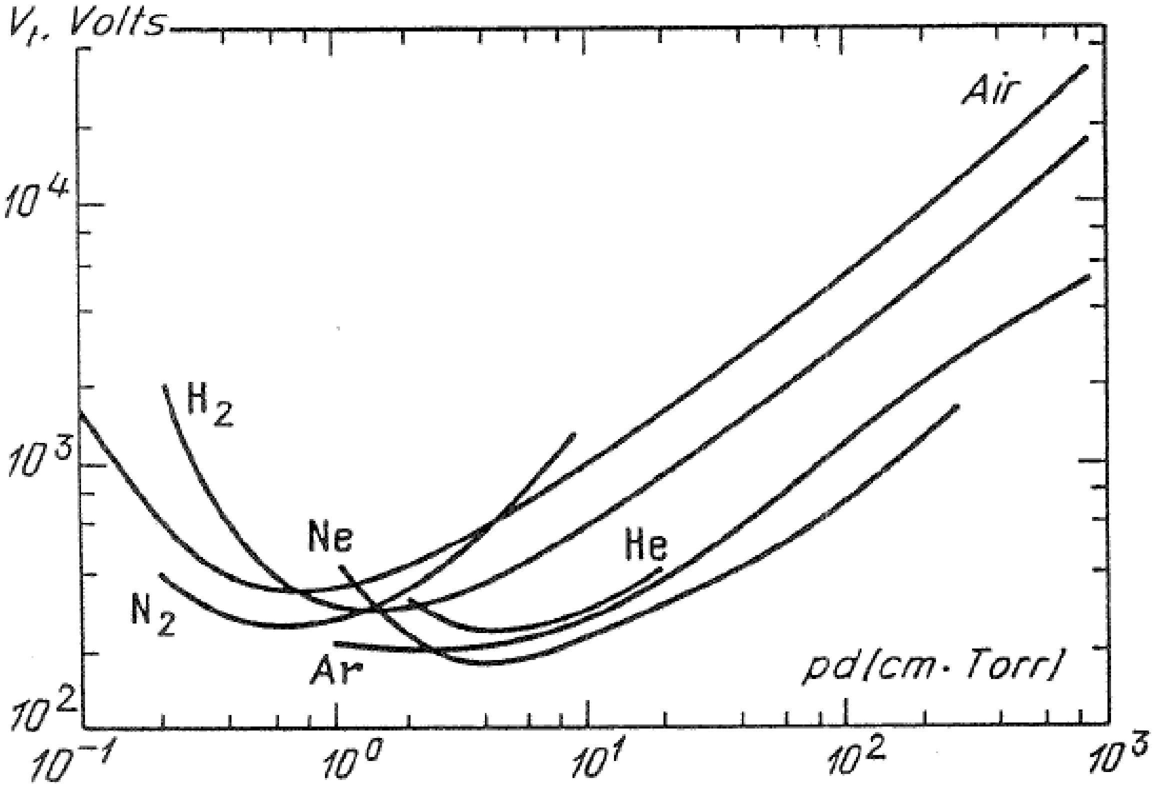
Paschen's curves for breakdown voltages in various gases

- Friedrich Paschen discovered empirically in 1889.

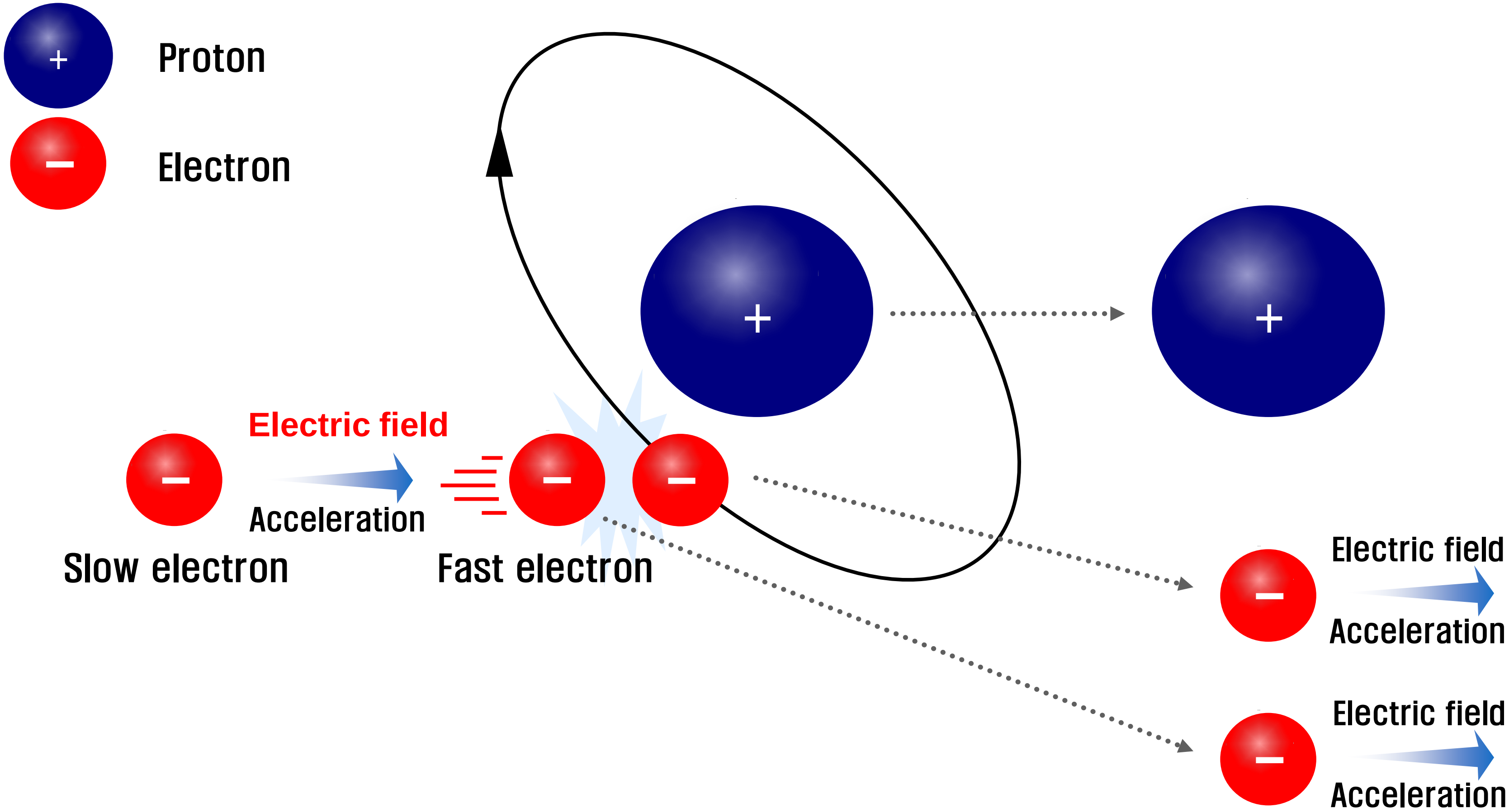
Left branch



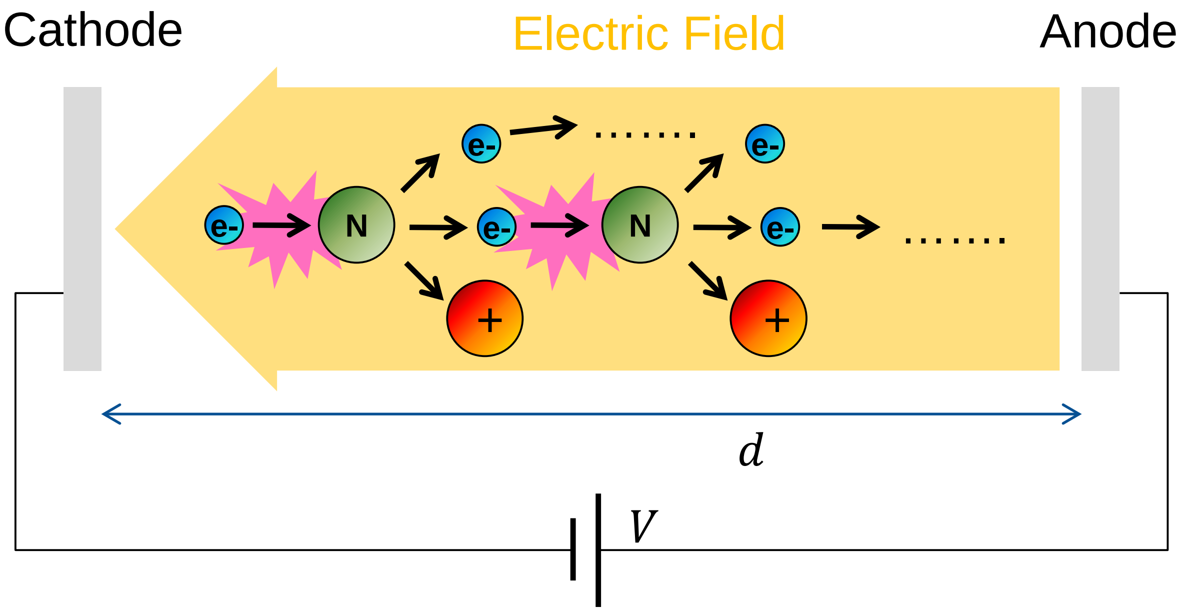
Right branch

Paschen minimum

Generation of charged particles: electron impact ionization



Townsend mechanism: electron avalanche



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

- Townsend ionization coefficient (α) : electron multiplication

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

$$\frac{dn_e}{dx} = \alpha n_e$$

$$\boxed{n_e = n_{e0}\exp(\alpha x)}$$

$$M = \frac{n_e}{n_{e0}} = e^{\alpha x}$$

Townsend 1st ionization coefficient

- Townsend related the ionization mean free path ($\lambda_i = 1/\alpha$) to the total scattering mean free path (λ) by treating it as being a process activated by drift energy gained from the field ($E\lambda$), with an activation energy eV_i.

$$\alpha = \frac{1}{\lambda_i} \propto \frac{1}{\lambda} \exp\left(-\frac{V_i}{E\lambda}\right)$$

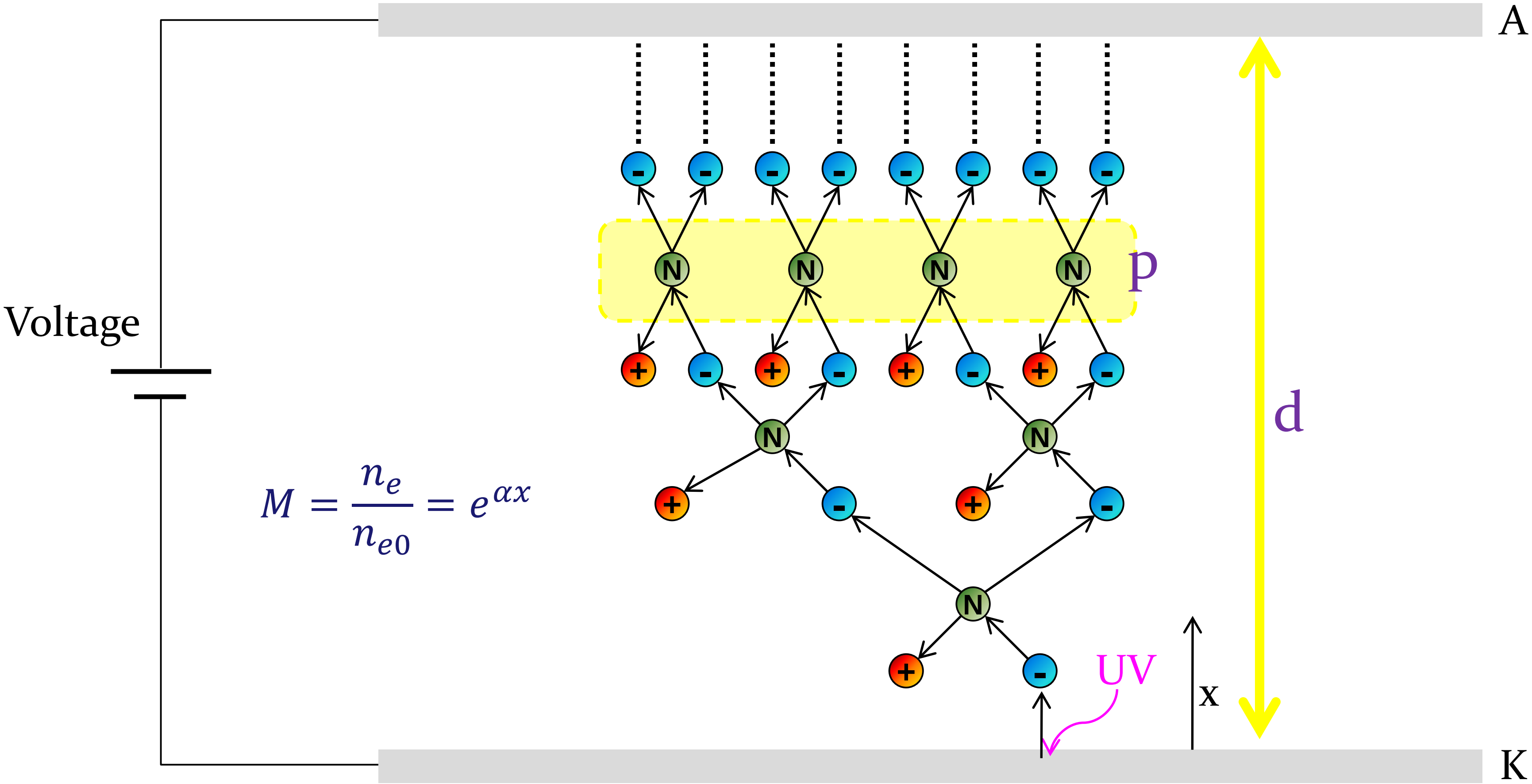
- Semi-empirical expression for Townsend first ionization coefficient

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

- A and C must be experimentally determined for different gases

Gas	A(ion pairs/mTorr)	C(V/mTorr)
He	182	5000
Ne	400	10000
H_2	1060	35000
N_2	1060	34200
Air	1220	36500

Townsend’s avalanche process is not self-sustaining



$$M = \frac{n_e}{n_{e0}} = e^{\alpha x}$$

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

Breakdown: Paschen's law

- 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

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

Townsend 2nd ionization coefficient

- Paschen's law

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

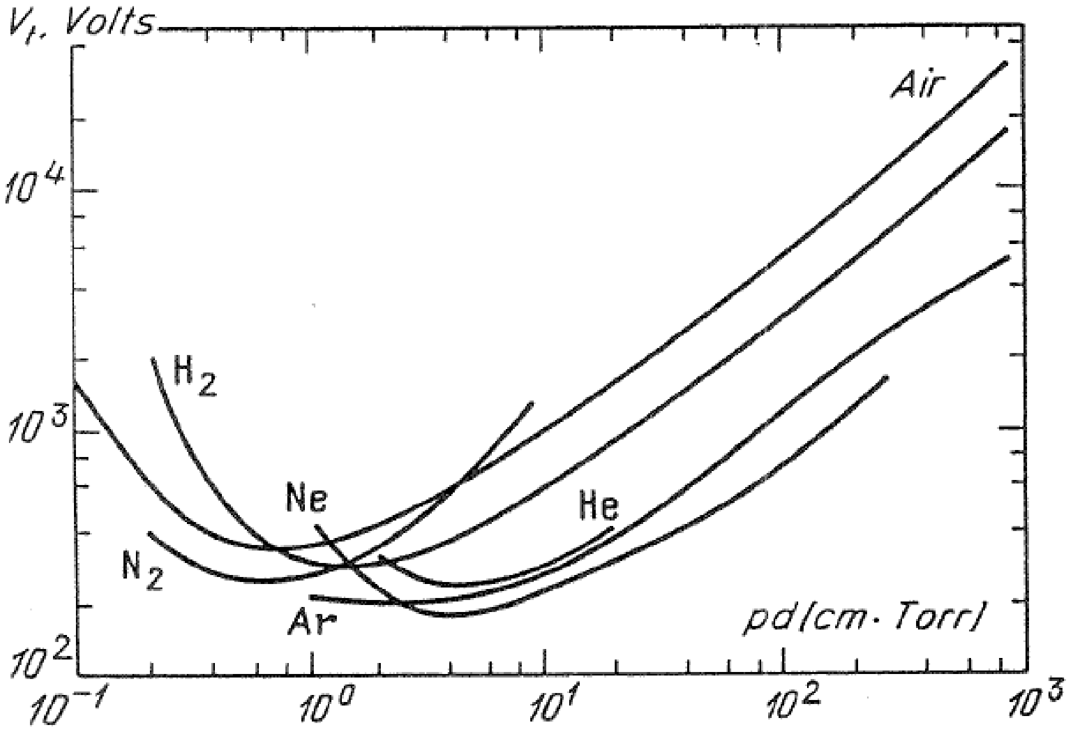
$$\boldsymbol{\alpha d = APd\exp\left(-\frac{B}{E/P}\right) = APd\exp\left(-\frac{BPd}{V_B}\right) = \ln\left(1+\frac{1}{\gamma}\right)}$$

$$\boxed{\boldsymbol{V_B = \frac{BPd}{\ln[APd/\ln(1+1/\gamma)]} = f(Pd)}}$$

Paschen curve

- Minimum breakdown voltage

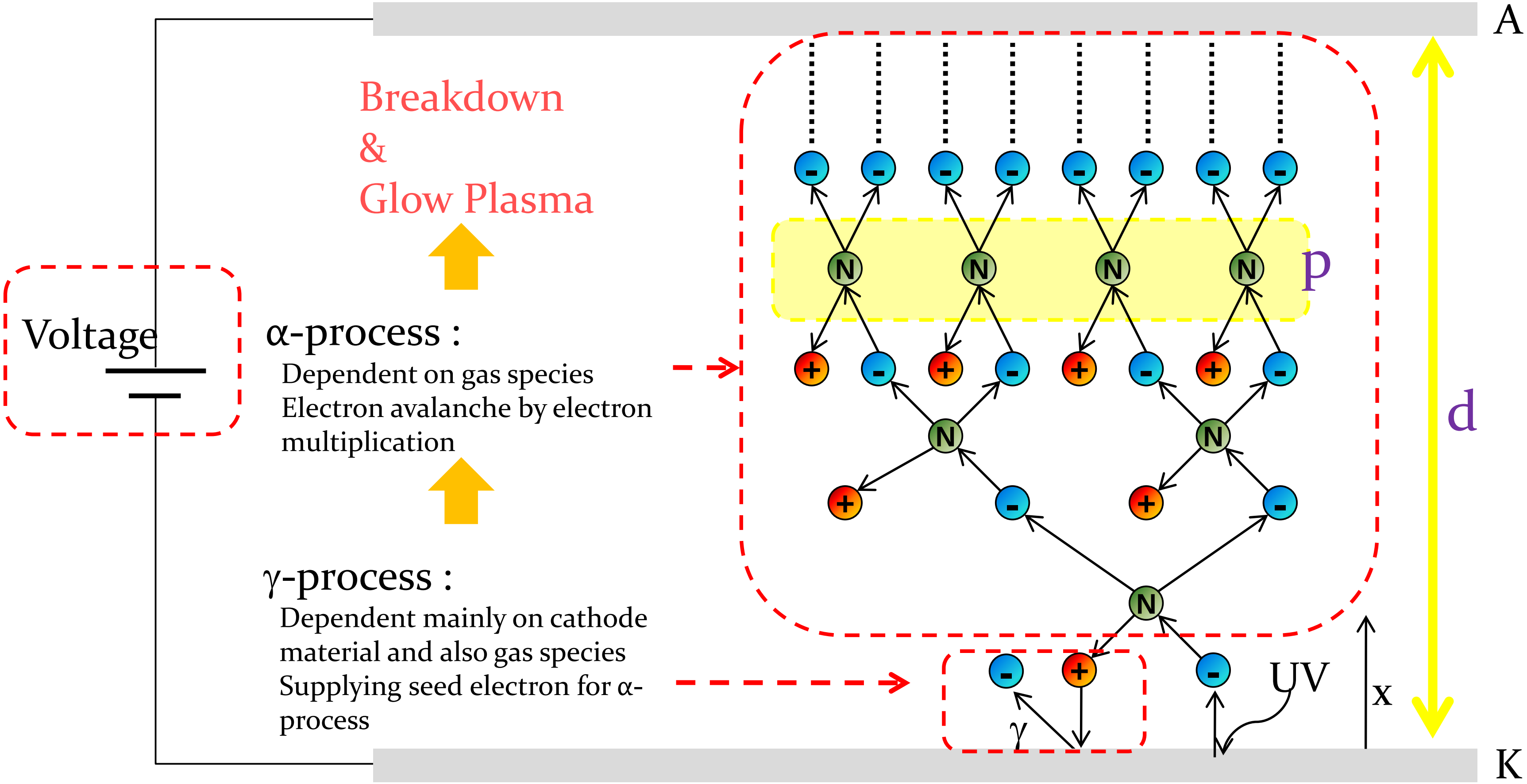
$$V_{B,min} = \frac{eB}{A}\ln\left(1+\frac{1}{\gamma}\right) \qquad \text{at} \qquad (pd)_{min} = \frac{e}{A}\ln\left(1+\frac{1}{\gamma}\right)$$



- 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



Voltage

Breakdown
&
Glow Plasma

α-process :

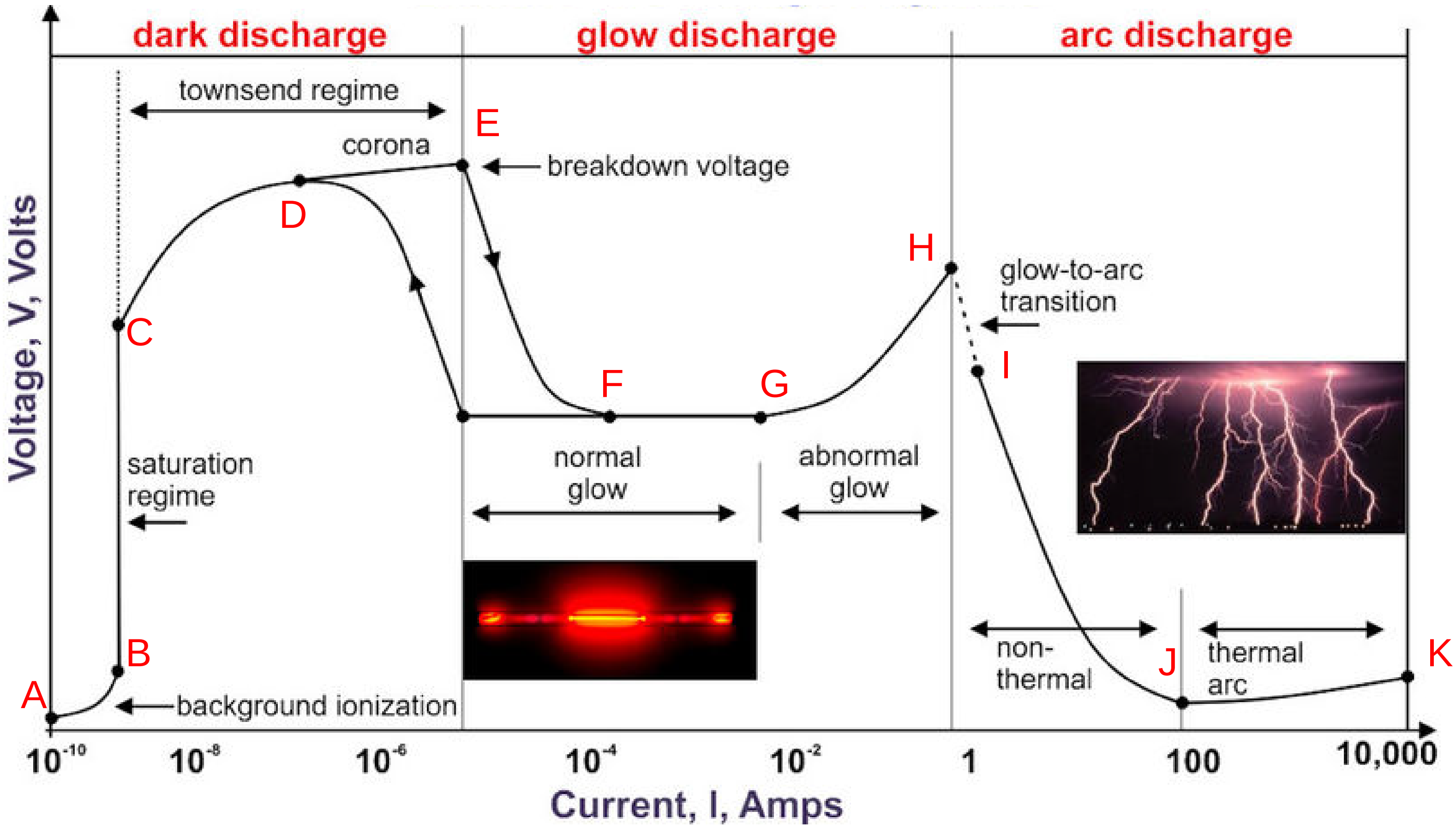
Dependent on gas species
Electron avalanche by electron multiplication

γ-process :

Dependent mainly on cathode material and also gas species
Supplying seed electron for α-process

- Two processes (α and γ) are required to sustain the discharge.

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.

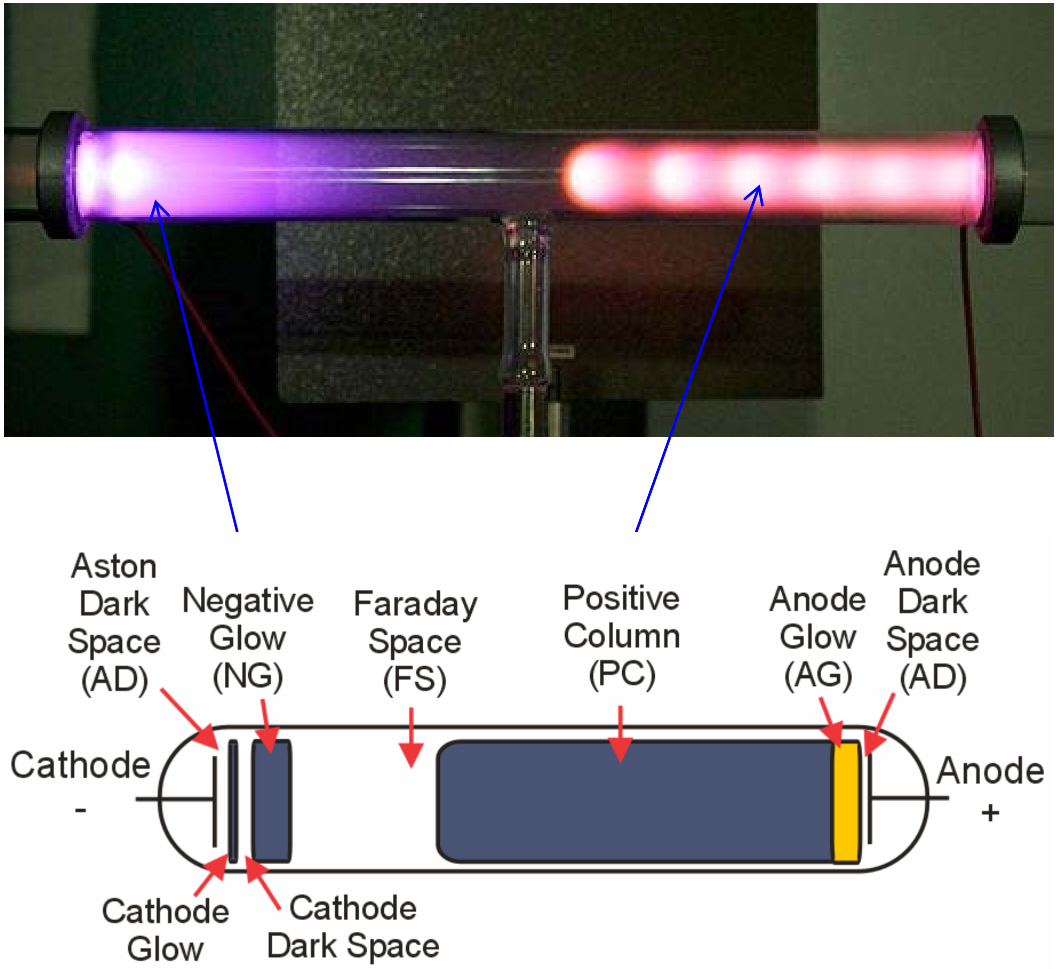
- Arc discharge
  - **H – K** At point H, the electrodes become sufficiently hot that the cathode emits electrons thermionically. If the DC power supply has a sufficiently low internal resistance, the discharge will undergo a glow-to-arc transition, H-I. The arc regime, from I through K is one where 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.

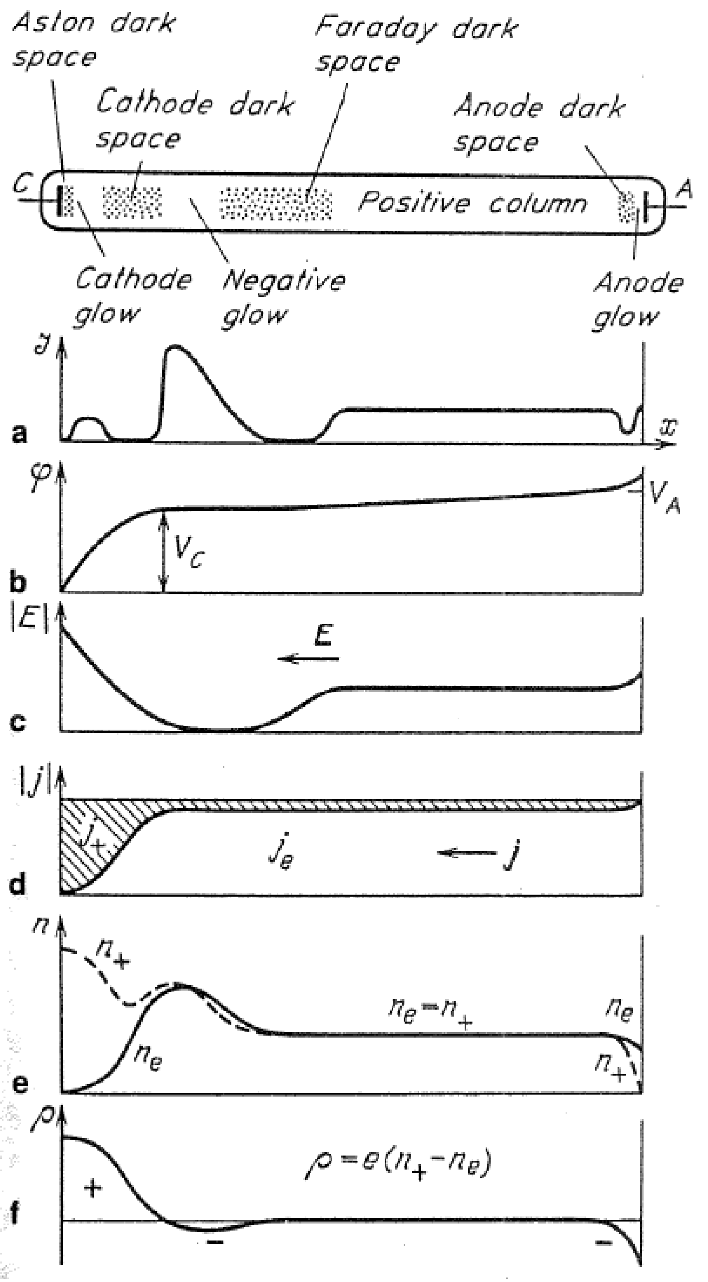
Glow discharge

- The glow discharge regime owes its name to the fact that the plasma is luminous.
- The gas glows because the electron energy and number density are high enough to generate visible light by excitation collisions.
- The applications of glow discharge include fluorescent lights, dc parallel plate plasma reactors, magnetron discharges used for depositing thin films, and electro-bombardment plasma sources.

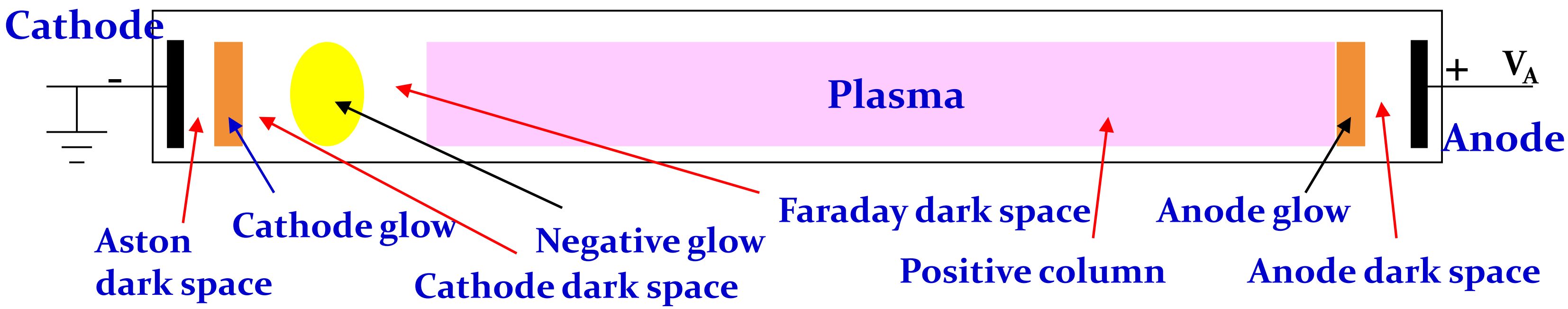
Parameter	Typical value
Discharge tube radius (cm)	0.3 – 3
Discharge tube length (cm)	10 – 100
Plasma volume (cm^3)	~ 100
Gas pressure (Torr)	0.03 – 30
Voltage between electrodes (V)	100 – 1000
Electrode current (A)	10^{-4} – 0.5
Power level (W)	~ 100
Electron temperature in positive column (eV)	1 – 3
Electron density in positive column (cm^{-3})	10^9 – 10^{11}

Structure of glow discharge





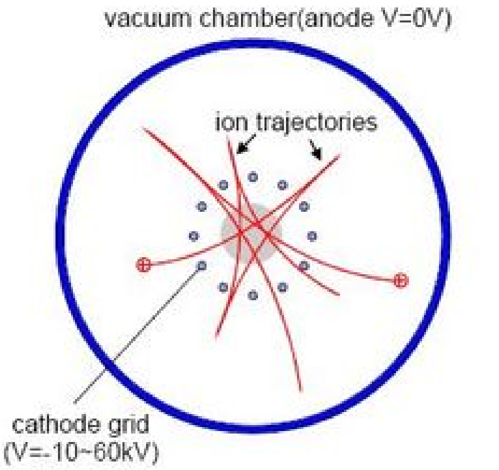
Structure of glow discharge



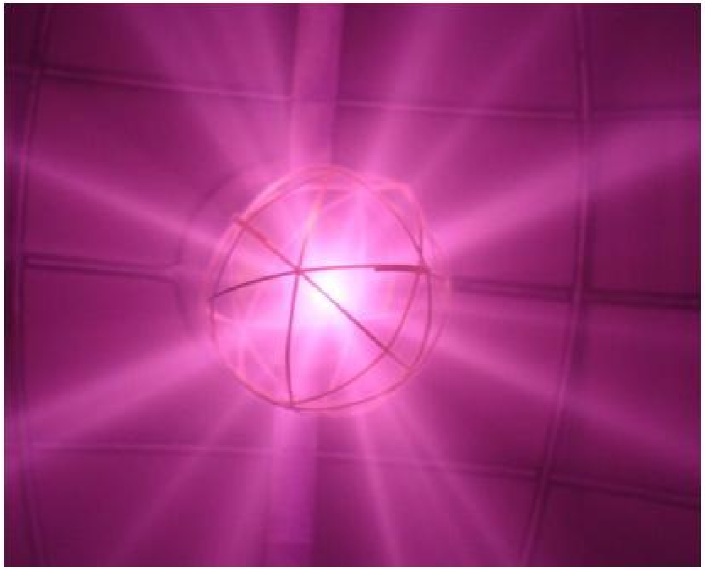
- **Cathode** : cathode material, secondary electron emission coefficients
- **Aston dark space** : a thin region with a strong electric field, and a negative space charge. Electrons are too low density and/or energy to excite the gas
- **Cathode glow** : reddish or orange color in air due to emission 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

Neutron source using DC glow discharge: IEC

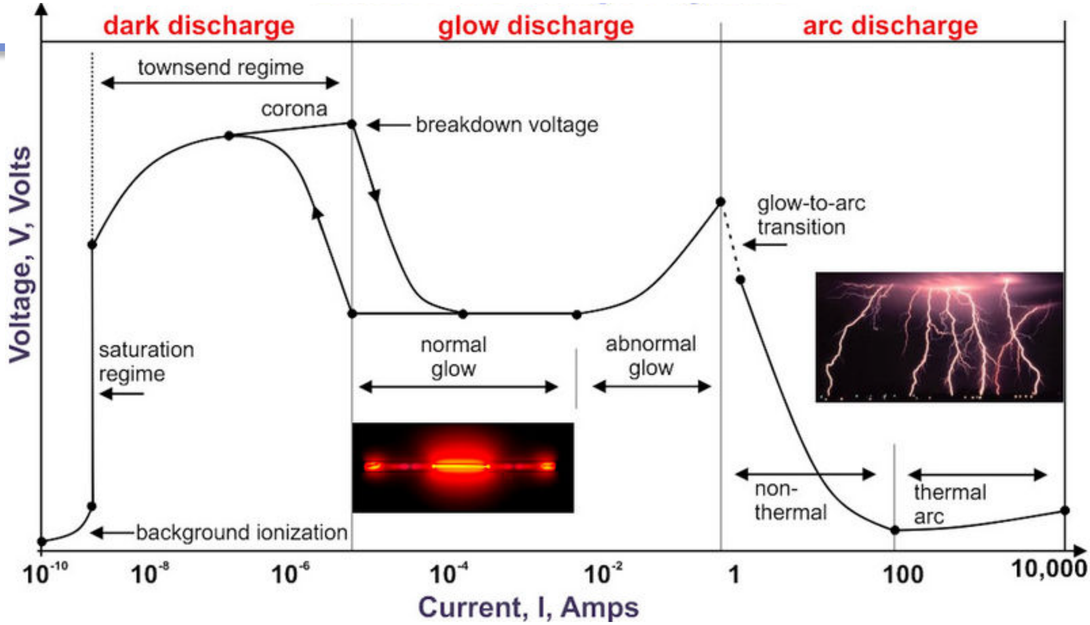
- An Inertial-Electrostatic Confinement Fusion (IECF) neutron/proton source is a compact device of simple configuration based on the properties of the glow discharge. It basically consists of a transparent hollow cathode at the center of a spherical vacuum chamber (serves as an anode), usually filled with a D_2 fuel gas, and a glow discharge takes place between them. The resulting high-energy ions interact with the background gas (beam-background collisions) and themselves (beam-beam collisions) in a small volume around the center spot, resulting in a high rate of fusion reactions.



An IECF configuration with a hollow cathode.



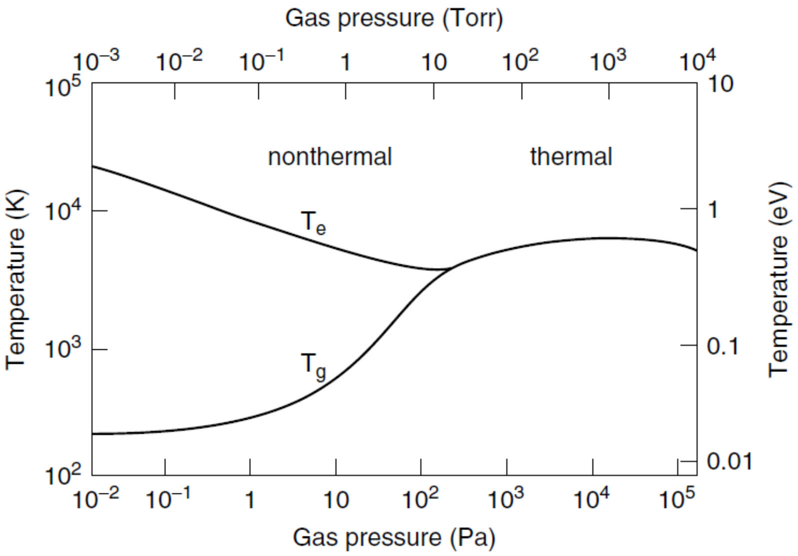
Arc discharge



- 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.

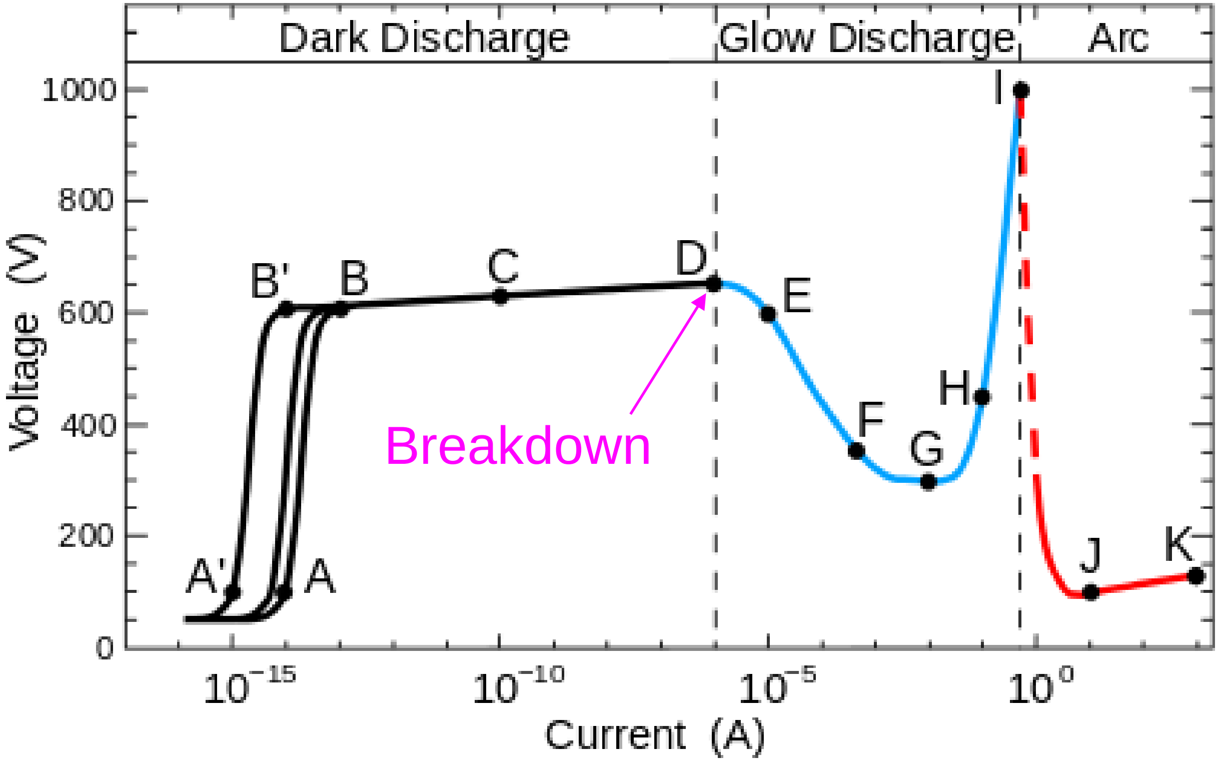
Operating regime of arc discharge



Parameter	Thermal arc	Nonthermal arc
Gas pressure	0.1 – 100 atm	10^{-3} – 100 Torr
Arc current	30 A – 30 kA	1 – 30 A
Cathode current density	10^4 – 10^7 A/cm^2	10^2 – 10^4 A/cm^2
Voltage	10 – 100 V	10 – 100 V
Electron density	10^{15} – 10^{19} #/cm3	10^{14} – 10^{15} #/cm3
Gas temperature	1 – 10 eV	300 – 6000 K
Electron temperature	1 – 10 eV	0.2 – 2 eV
E/p	Low	High

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

Non-self-sustaining ← → Self-sustaining



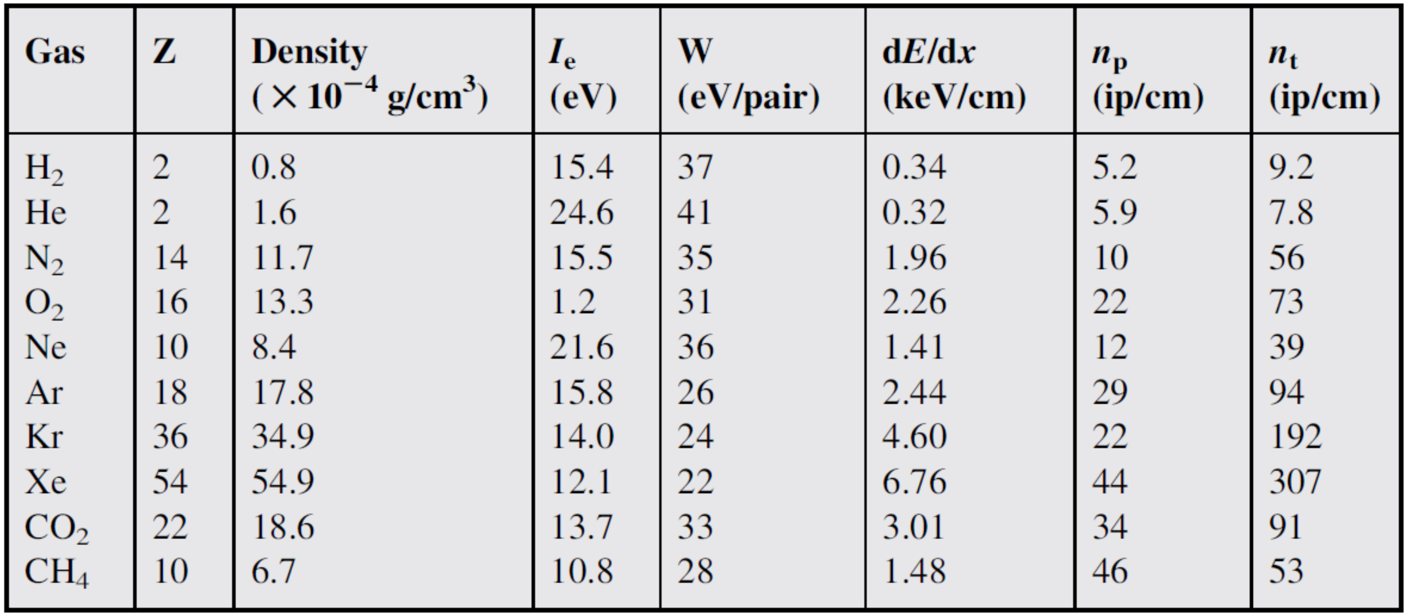
Radiation detection ← → Plasma generation

Introduction to radiation detection by gas-filled detectors

- Radiation passing through a gas can ionize the gas molecules, provided the energy it delivers is higher than the ionization potential of the gas. The charge pairs thus produced can be made to move in opposite directions by the application of an external electric field, resulting in a measureable electrical pulse. This process has been used to construct the so-called gas-filled detectors.
- A typical gas-filled detector consists of a gas enclosure and positive and negative electrodes. The electrodes are kept at a high potential difference that can range from less than hundred volts to a few thousand volts depending on the design and mode of operation of the detector.
- The creation and movement of charge pairs due to the passage of radiation in the gas perturbs the externally applied electric field, which results in an electrical pulse at the electrodes. The resulting charge, current, or voltage pulse at one of the electrodes can then be measured, which together with proper calibration gives valuable information about the particle beam, such as its energy and intensity.
- It is apparent that such a system would work efficiently if a large number of charge pairs are not only created but are also readily collected at the electrodes before they can recombine to form neutral molecules.

Production of electron-ion pairs

- W-value: the average energy needed to create an electron-ion pair in a gas. It significantly higher than the first ionization potential for gases, implying that not all the energy goes into creating electron-ion pairs.
- The charges created by the incident radiation are called primary charges to distinguish them from the ones that are indirectly produced in the active volume. The production mechanisms of these secondary charge pairs are similar to those of primary charges except that they are produced by ionizations caused by primary charge pairs and not the incident radiation.



Gas	Z	Density ($\times 10^{-4}$ g/cm^3)	I_e (eV)	W (eV/pair)	dE/dx (keV/cm)	n_p (ip/cm)	n_t (ip/cm)
H_2	2	0.8	15.4	37	0.34	5.2	9.2
He	2	1.6	24.6	41	0.32	5.9	7.8
N_2	14	11.7	15.5	35	1.96	10	56
O_2	16	13.3	1.2	31	2.26	22	73
Ne	10	8.4	21.6	36	1.41	12	39
Ar	18	17.8	15.8	26	2.44	29	94
Kr	36	34.9	14.0	24	4.60	22	192
Xe	54	54.9	12.1	22	6.76	44	307
CO_2	22	18.6	13.7	33	3.01	34	91
CH_4	10	6.7	10.8	28	1.48	46	53

Total number of electron-ion pairs produced

- For a particle that deposits energy ΔE inside a detector, the W-value can be used to determine the total number of electron-ion pairs produced:

$$N = \frac{\Delta E}{W}$$

- In terms of stopping power:

$$N = \frac{1}{W}\frac{dE}{dx}\Delta x$$

- The number of electron-ion pairs produced per unit length of the particle track:

$$n = \frac{1}{W}\frac{dE}{dx}$$

- For a gas mixture

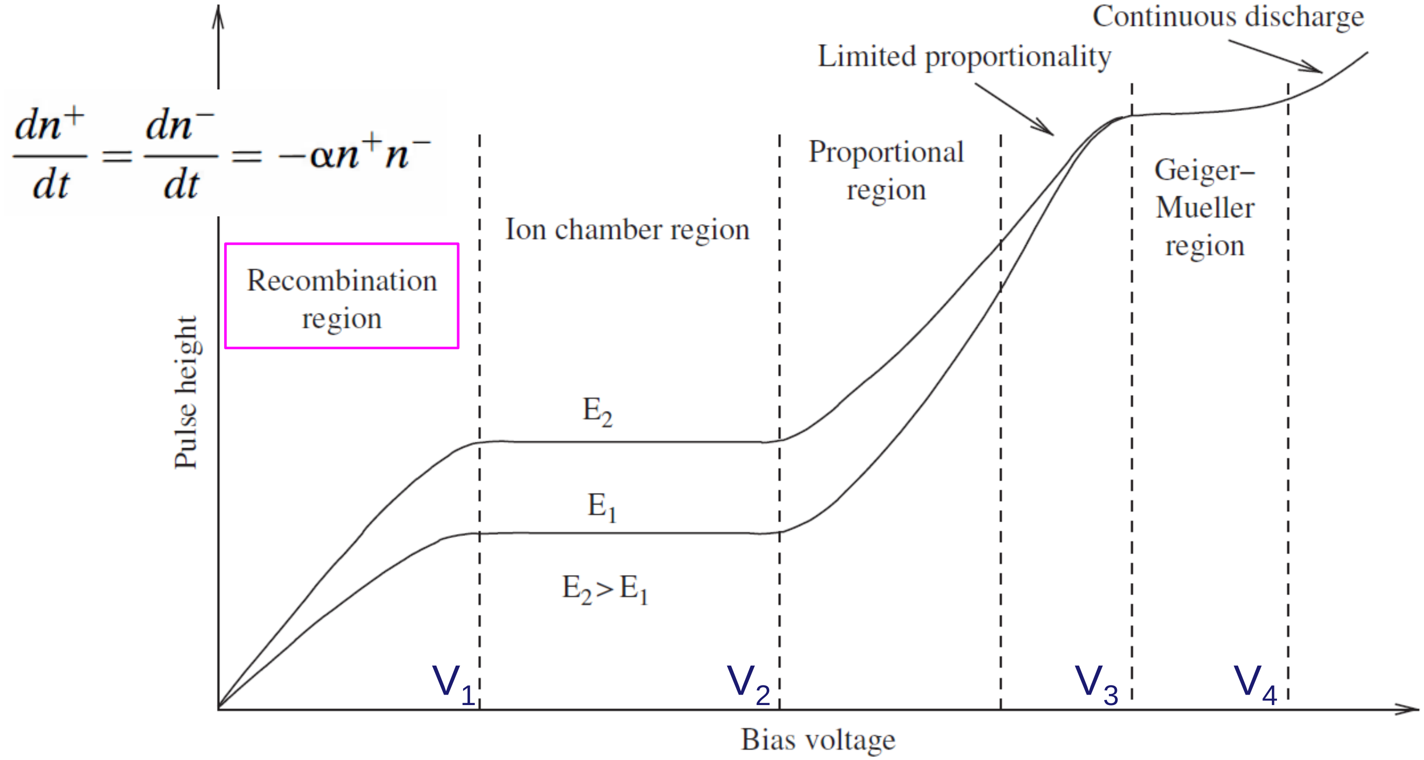
$$n = \sum_i x_i \frac{1}{W_i}\left(\frac{dE}{dx}\right)_i$$

For example, if a 3-MeV particle deposits all its energy in the detector, it will produce, on the average,

$$N = \frac{\Delta E}{W} \approx \frac{3\times 10^6}{30} \approx 10^5 \text{ electron} - \text{ion pairs}$$

Operation regions of gas-filled detectors

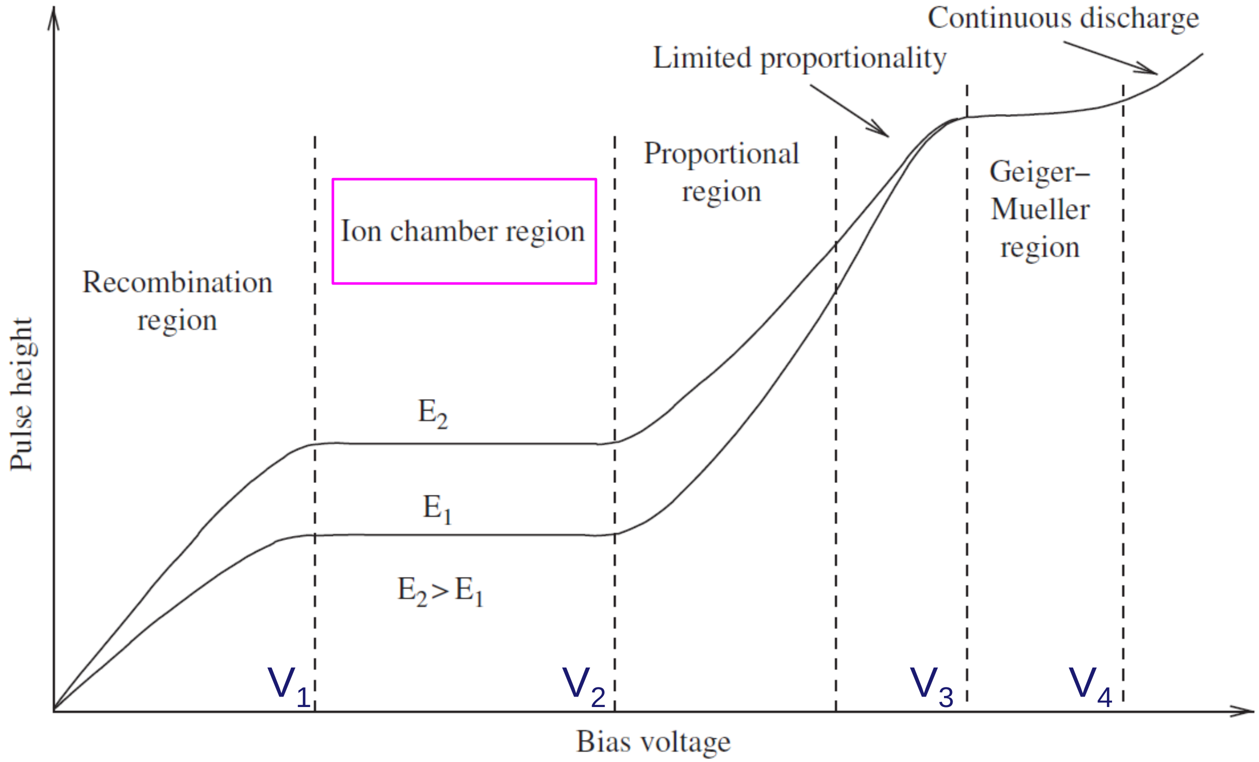
- Recombination region: When the voltage is very low, the electric field in the detector is not strong, electrons and ions move with relatively slow speeds, and their recombination rate is considerable. As V increases, the field becomes stronger, the carriers move faster, and their recombination rate decreases up to the point where it becomes zero. Then, all the charge created by the ionizing radiation is being collected ($V = V_1$).



$$\frac{dn^+}{dt} = \frac{dn^-}{dt} = -\alpha n^+ n^-$$

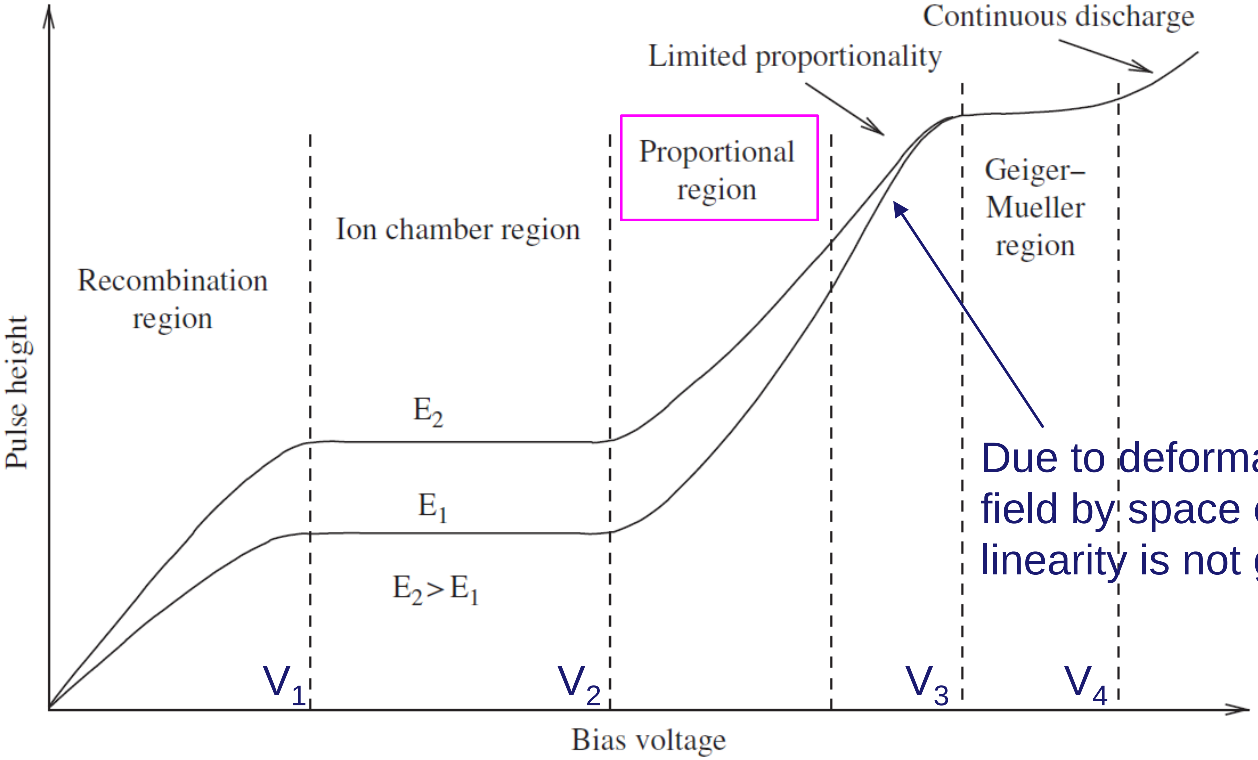
Operation regions of gas-filled detectors

- Ion chamber region: In this region further increasing the high voltage does not affect the measured current since all the charges being produced are collected efficiently by the electrodes. The current measured by the associated electronics in this region is called the saturation current and is proportional to the energy deposited by the incident radiation. The detectors designed to work in this region are called ionization chambers.



Operation regions of gas-filled detectors

- Proportional region: The collected charge starts increasing because the electrons produce secondary ionization that results in charge multiplication. The charge multiplication factor—the ratio of the total ionization produced divided by the primary ionization—is, for a given voltage, is independent of the primary ionization. Thus the total number of charges produced after multiplication is proportional to the initial number of charges.



Due to deformation of electric field by space charge, the linearity is not guaranteed

Avalanche multiplcation

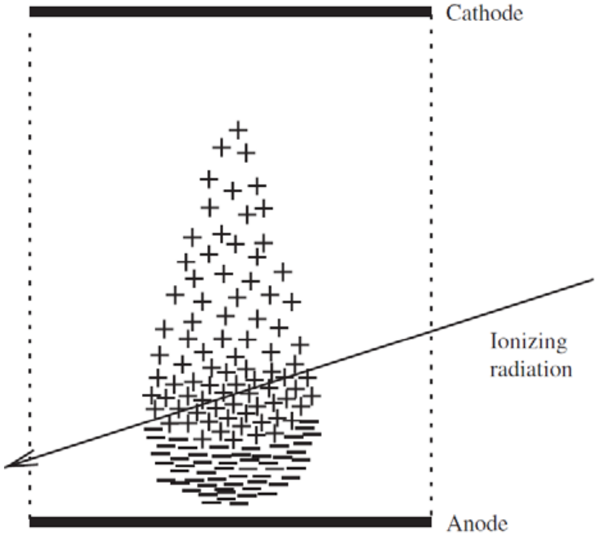
- Avalanche multiplication: Due to the high electric field between the electrodes, the charges quickly gain energy between collisions. If the total energy of an electron or an ion becomes higher than the ionization potential of the gas atoms, it can ionize an atom, thus creating another charge pair.
- In uniform electric field, the change in the number of charge pairs per unit path length is simply proportional to the total number of charge pairs:

$$\frac{dN}{dx} = \alpha N$$

$\alpha = \frac{1}{\lambda_{iz}}$: Townsend 1st ionization coefficient

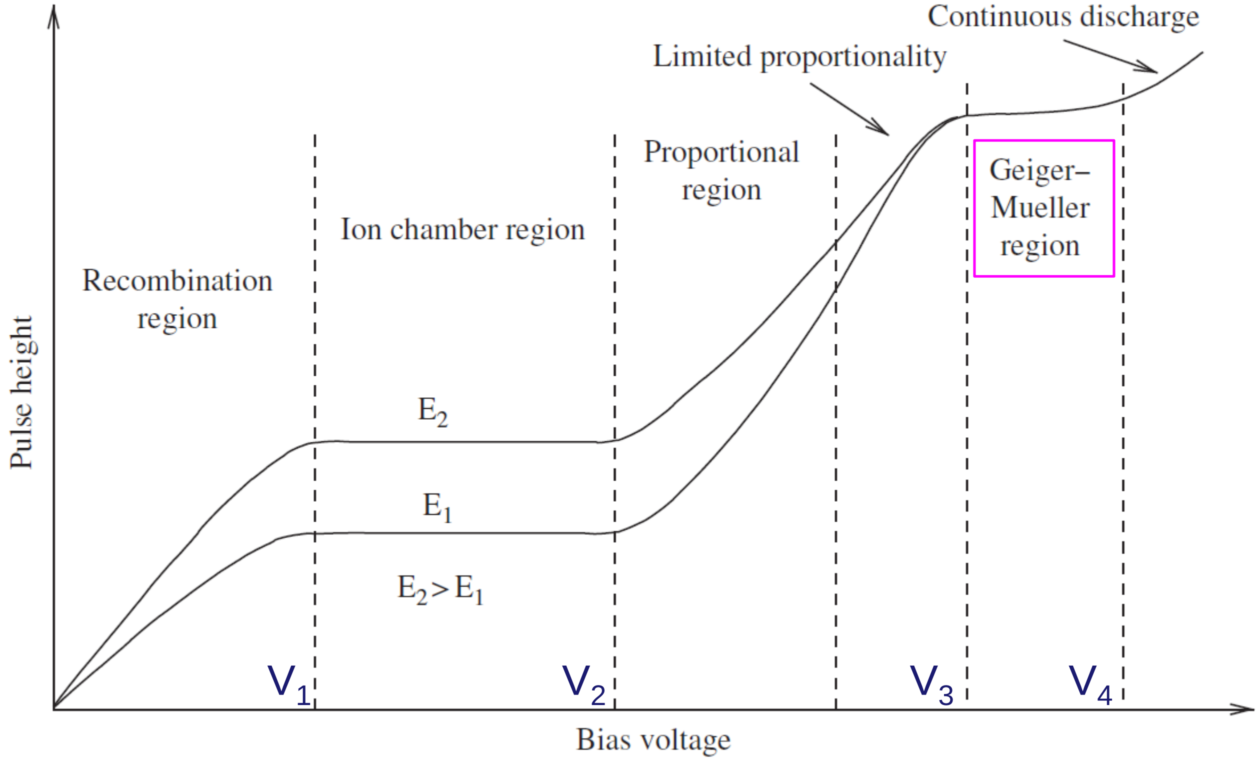
- Multiplication factor: $M = \frac{N}{N_0} = e^{\alpha x}$
- For non-uniform field, $M = \exp\left[\int_{r1}^{r2} \alpha(x)dx\right]$
- The first Townsend coefficient is given by

$$\frac{\alpha}{p} = f\left(\frac{E}{p}\right) = A\exp\left[-\frac{Bp}{E}\right]$$



Operation regions of gas-filled detectors

- Geiger-Mueller region: In this region, the electric field inside the detector is so strong that a single electron–ion pair generated in the chamber is enough to initiate an avalanche of electron–ion pairs. This avalanche will produce a strong signal with shape and height independent of the primary ionization and the type of particle, a signal that depends only on the electronics of the detector. Thus, the detectors operated in this region are not appropriate for spectroscopy.



Various types of gas-filled detectors

- **Ionization chambers**: No charge multiplication takes place. The output signal is proportional to the particle energy dissipated in the detector; therefore, measurement of particle energy is possible. Since the signal from an ionization chamber is not large, only strongly ionizing particles such as alphas, protons, fission fragments, and other heavy ions are detected by such detectors. The voltage applied is less than 1000 V.
- **Proportional counters**: Charge multiplication takes place, but the output signal is still proportional to the energy deposited in the counter. Measurement of particle energy is possible. Proportional counters may be used for the detection of any charged particle. Identification of the type of particle is possible with both ionization and proportional counters. An alpha particle and an electron having the same energy and entering either of the detectors will give a different signal. The alpha particle signal will be bigger than the electron signal. The voltage applied to proportional counters ranges between 800 and 2000 V.
- **GM counters**: Simple and provides a very strong signal. They can be used with any kind of ionizing radiation. The disadvantage of GM counters is that their signal is independent of the particle type and its energy. Therefore, a GM counter provides information only about the number of particles. Another minor disadvantage is relatively long dead time. The voltage ranges are 500 ~ 2000 V.