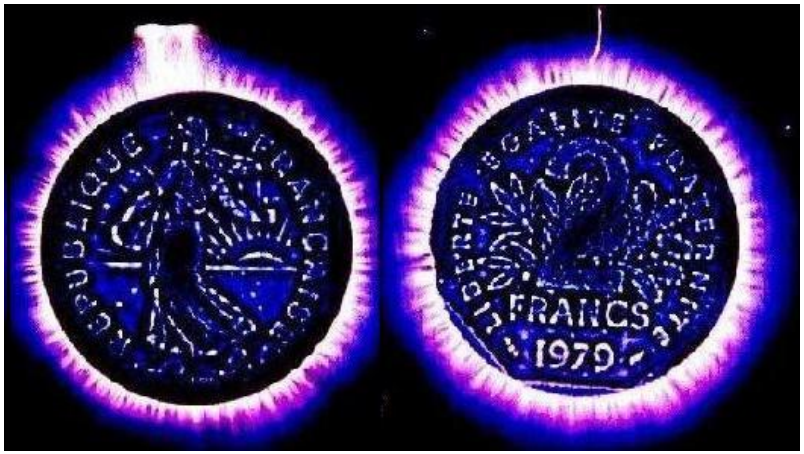
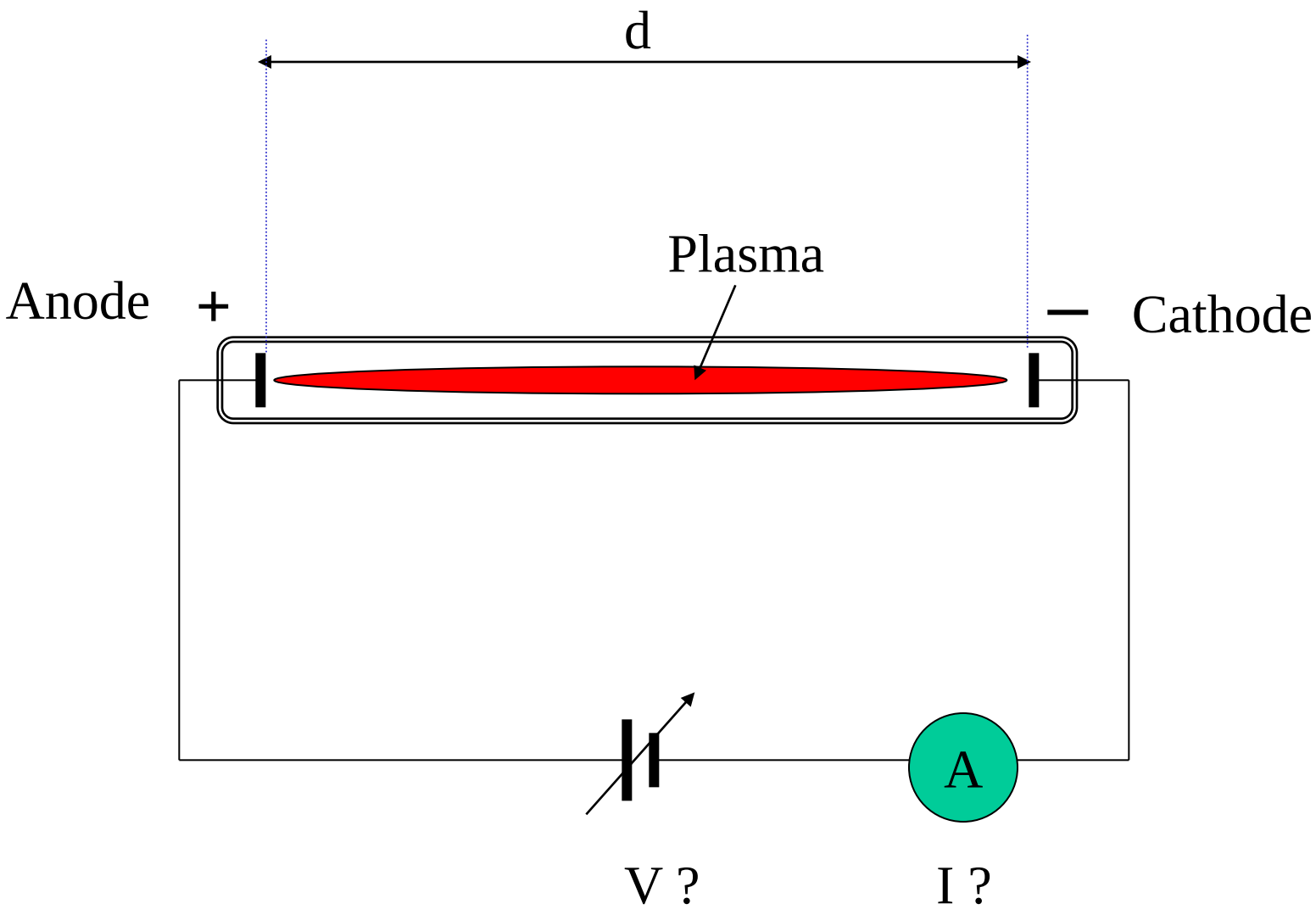
EE 403/503
Introduction to Plasma Processing

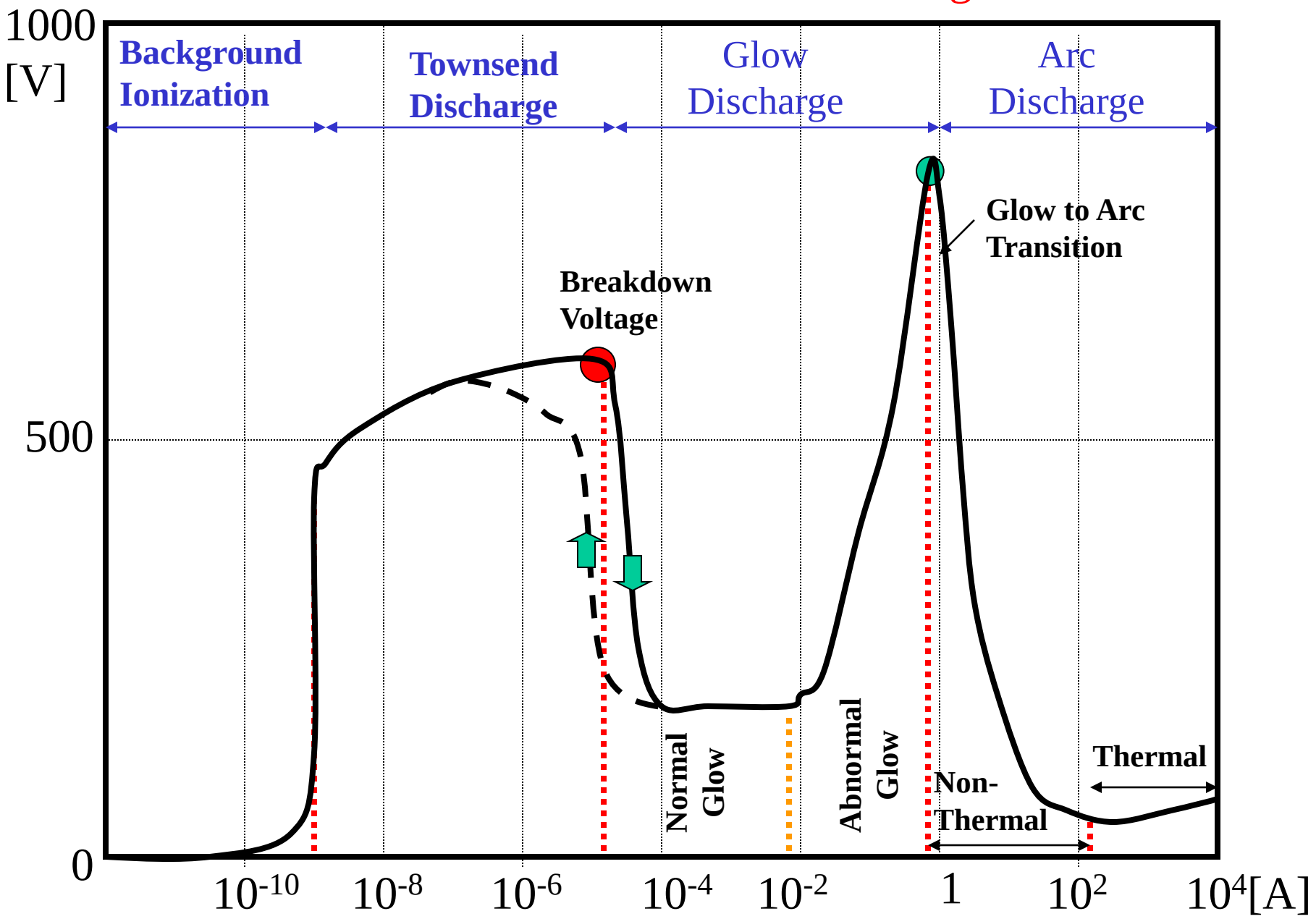
DC Discharge I



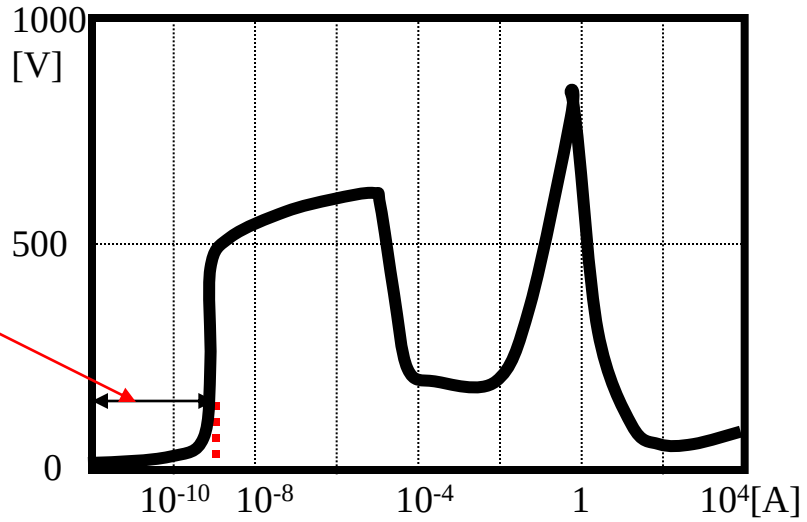
October 26, 2011


d
Plasma
Anode
+
–
Cathode
A
V ?
I ?

V-I Characteristic of DC Discharges



Background Ionization

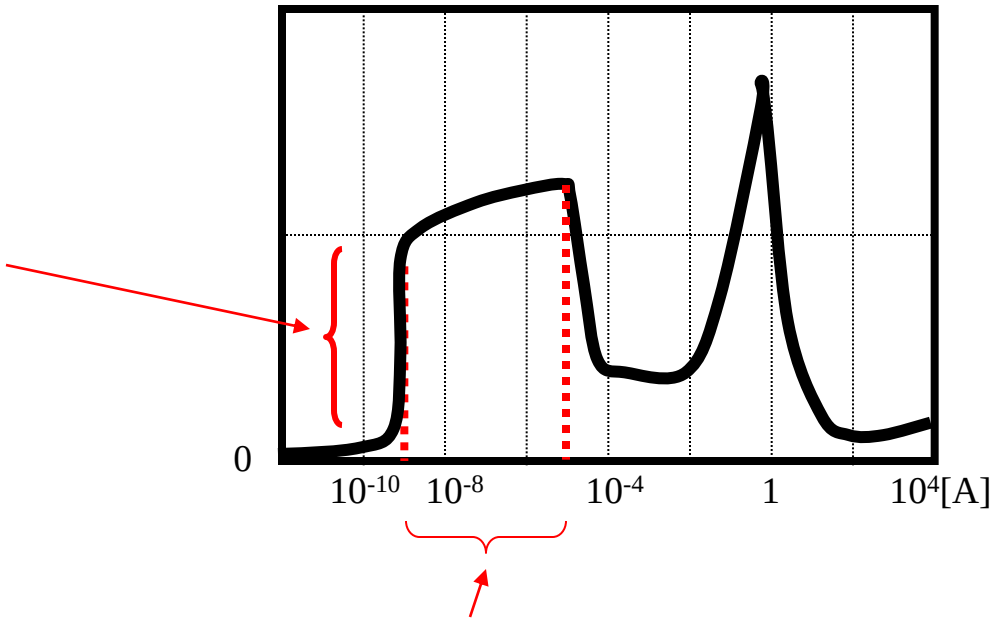


$$e \times d \times E = \frac{1}{2} m_e v_e^2 < \chi_{s,\min}$$

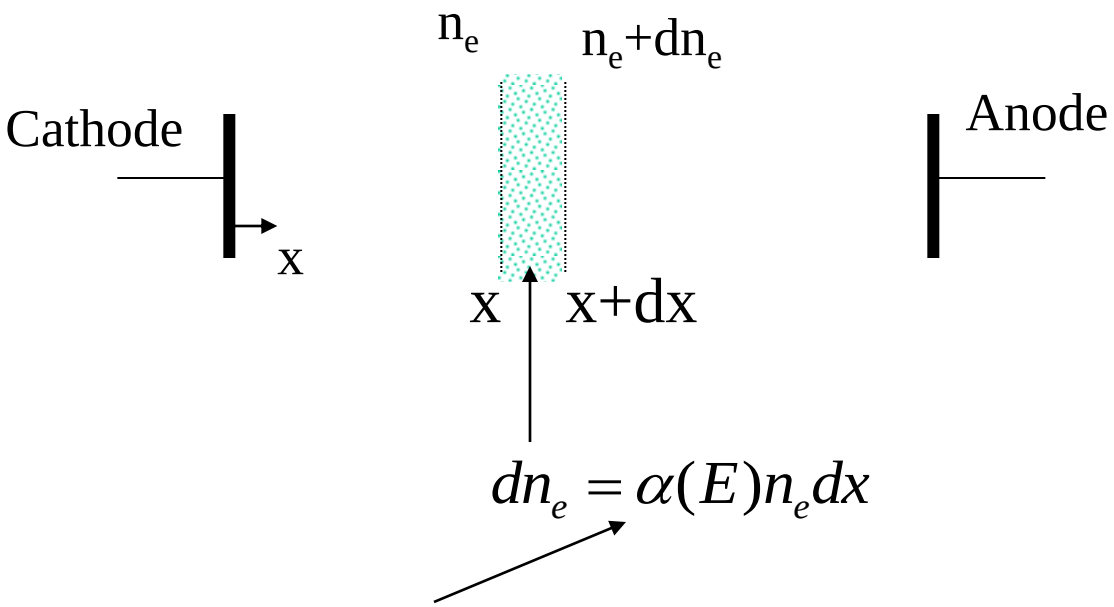
- e and A+ are generated by cosmic rays and other forms of background radiation
- No excitation take place
- Absolutely dark
- Non self substaining discharge

-Collection of all electrons and ions that are produced by external radiation.

- A dark current discharge emits very little light



Electrons pick up sufficient energy in a mean free path to make ionizing collisions with neutrals. ($e\lambda_e E > \chi_i$)



$$dn_e = \alpha(E) n_e dx$$

Ionization Coefficient (probable # of ionizing collision per meter)

Assuming E is constant
No Space Charge

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

$$j_e = j_{e0} e^{\alpha x}$$

First Townsend Coefficient (α)

λ Mean Free Path → 1/λ is number mean free path per unit length.

λ_x Mean free path that meets the minimum requirement for ionization.

$$f(\lambda_x) = e^{-\frac{\lambda_x}{\lambda}}$$

Fraction of λ_x among all the λ.

$$\alpha = \frac{1}{\lambda} e^{-\frac{\lambda_x}{\lambda}}$$

Number of λ_x that lead to ionization

Depends on T_e and Type of Gas

$$\lambda = \frac{A}{p}$$

$$\lambda_x = \frac{const}{E}$$

$$\alpha = \frac{p}{A} \exp\left(\left(\frac{-const}{E}\right) \div \left(\frac{A}{p}\right)\right)$$

First Townsend Coefficient (α)

$$\frac{\alpha}{p} = C_1 \times e^{\frac{-C_2}{\left(\frac{E}{P}\right)}}$$

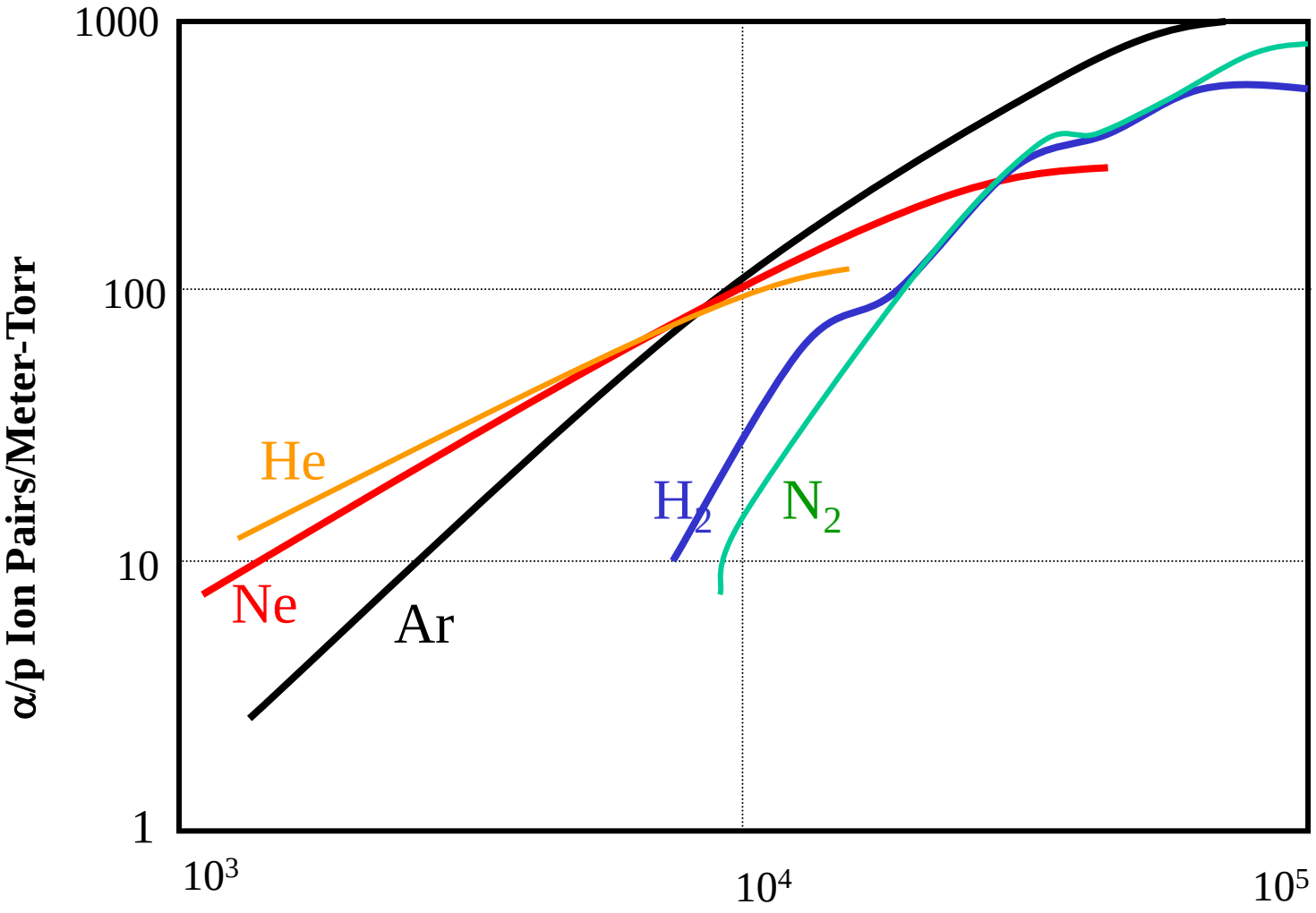
$$C_1 = \frac{1}{A}$$

$$C_2 = AV_i$$

Effective Ionization Potential

Gas	C_1 [ion pair/m-Torr	C_2 V/m-Torr
Ar	1200	20 000
Air	1220	36 500
CO_2	2000*	46 600
H_2	1060	35 000
HCl	2500*	38 000
He	182	5 000
Hg	2000	37 000
H_2O	1290*	28 900
Kr	1450	22 000
N_2	1060	34 200
Ne	400	10 000
Xe	2220	31 000

First Townsend Coefficient (α)



Cobine 1958

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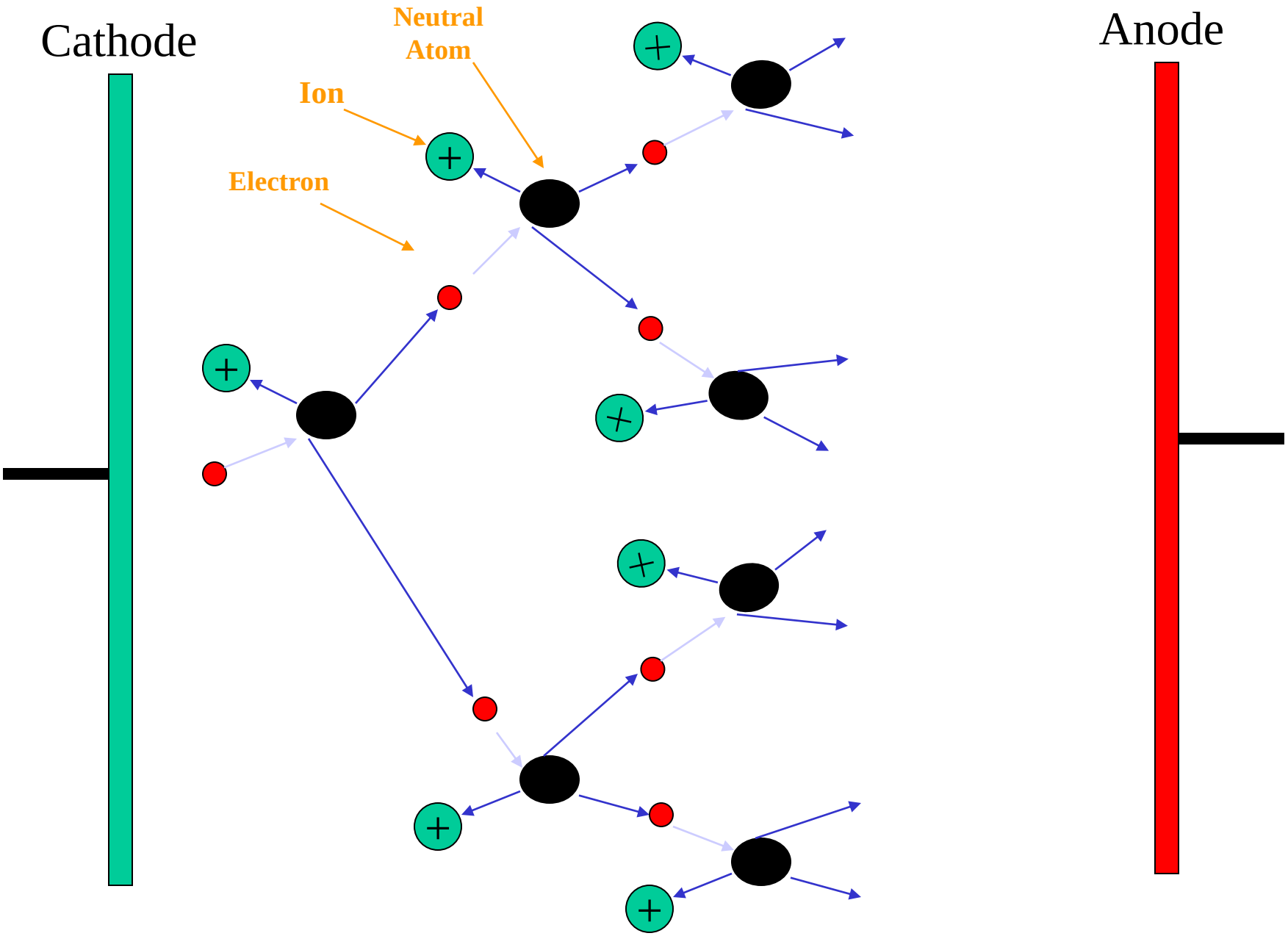
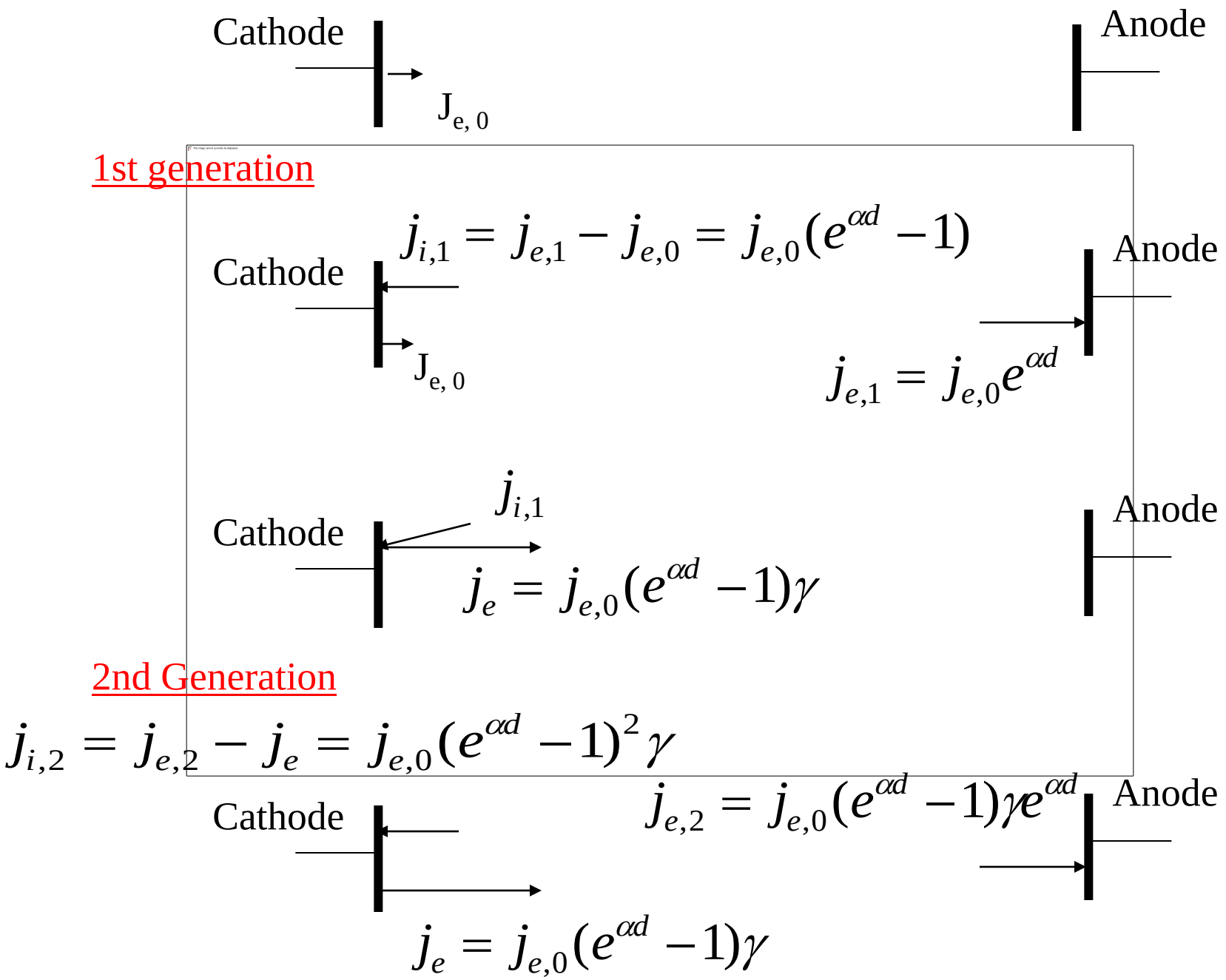
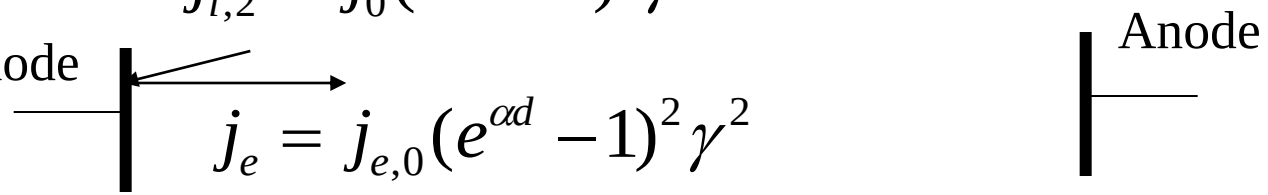

Cathode
Neutral Atom
Ion
Electron
Anode

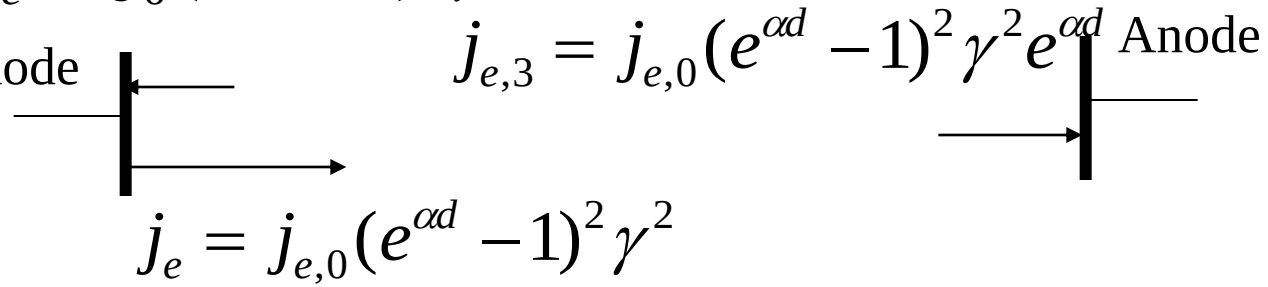

Cathode
Anode
$J_{e,0}$
1st generation
$j_{i,1} = j_{e,1} - j_{e,0} = j_{e,0}(e^{\alpha d} - 1)$
Cathode
Anode
$J_{e,0}$
$j_{e,1} = j_{e,0} e^{\alpha d}$
$j_{i,1}$
Cathode
Anode
$j_e = j_{e,0}(e^{\alpha d} - 1)\gamma$
2nd Generation
$j_{i,2} = j_{e,2} - j_e = j_{e,0}(e^{\alpha d} - 1)^2 \gamma$
Cathode
$j_{e,2} = j_{e,0}(e^{\alpha d} - 1)\gamma e^{\alpha d}$
Anode
$j_e = j_{e,0}(e^{\alpha d} - 1)\gamma$

$$j_{i,2} = j_0(e^{\alpha d} - 1)^2 \gamma$$



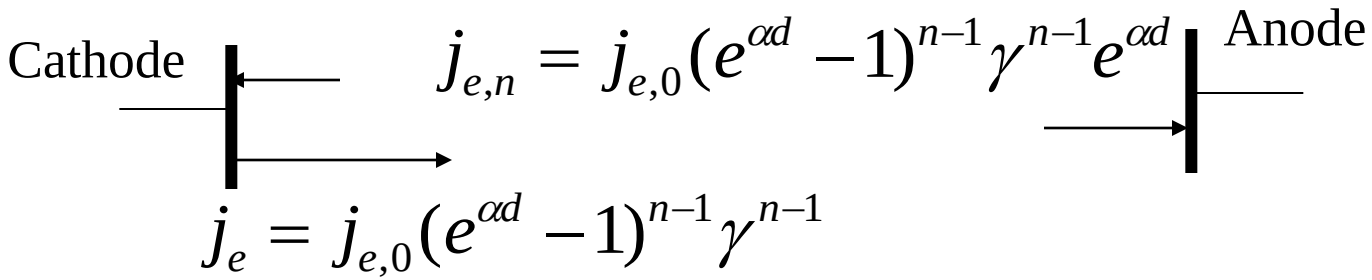
3rd generation

$$j_{i,3} = j_{e,3} - j_e = j_0(e^{\alpha d} - 1)^3 \gamma^2$$



nth generation

$$j_{i,n} = j_{e,n} - j_e = j_0(e^{\alpha d} - 1)^n \gamma^{n-1}$$



$$j_e = \sum_{i=1}^{\infty} j_{e,i} = j_0 e^{\alpha d} \sum_{i=1}^{\infty} \gamma^{i-1} (e^{\alpha d} - 1)^{i-1}$$

Geometric Series

If $\gamma(e^{\alpha d} - 1) < 1$

$$j_e = \frac{j_o e^{\alpha d}}{1 - \gamma(e^{\alpha d} - 1)}$$

Secondary Emission Coefficient

$$j_e = \frac{j_0 e^{\int \alpha dx}}{1 - \Gamma(e^{\int \alpha dx} - 1) - (1+\Gamma)\frac{\beta}{\alpha} e^{\int \alpha dx}}$$

First Townsend Coefficient:
(ionization by electron collision)

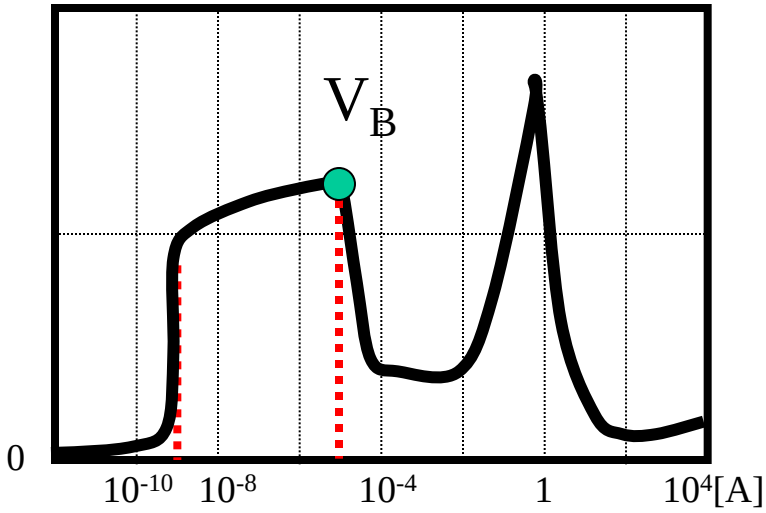
$$\alpha = C_1 \times p \times \exp\left(\frac{-C_2 \times p}{E}\right)$$

β is secondary Townsend coefficient: ionization rate by ion collisions

$$\Gamma = \gamma_i + \gamma_{photo} + \gamma_{meta} + \gamma_A$$

Breakdown Voltage

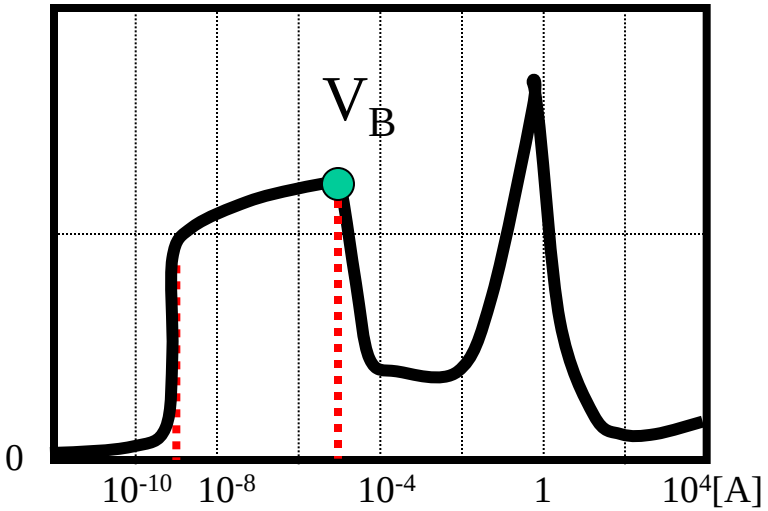
$$n_e = \frac{n_o e^{\alpha d}}{1-\gamma(e^{\alpha d}-1)}$$



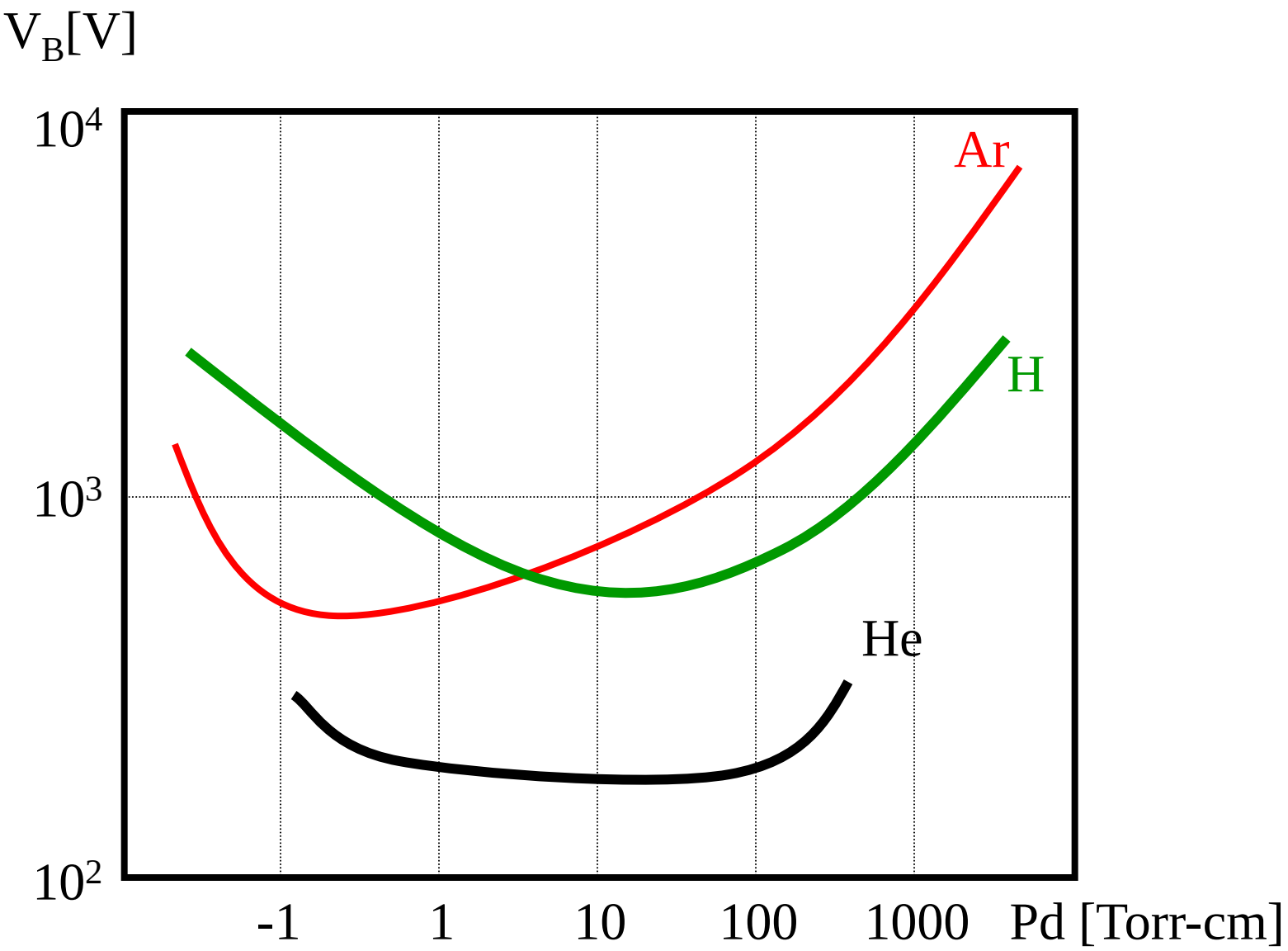
$$\gamma(e^{\alpha d}-1)=1$$ Townsend breakdown criterion

$$\alpha = C_1 \times p \times \exp\left(\frac{-C_2 \times p}{E}\right)$$

V=E x d



$$V_B = \frac{C_2(pd)}{\ln(pd) + \underbrace{\ln C_1 - \ln\left(\ln\left(\frac{1}{\gamma}+1\right)\right)}_{\text{Almost Constant}}}$$


V_B[V]
10^4
10^3
10^2
Ar
H
He
-1
1
10
100
1000
Pd [Torr-cm]

Minimum Breakdown Condition

$$(pd)_{\min} = \frac{2.718}{C_1} \ln\left(1 + \frac{1}{\gamma}\right)$$

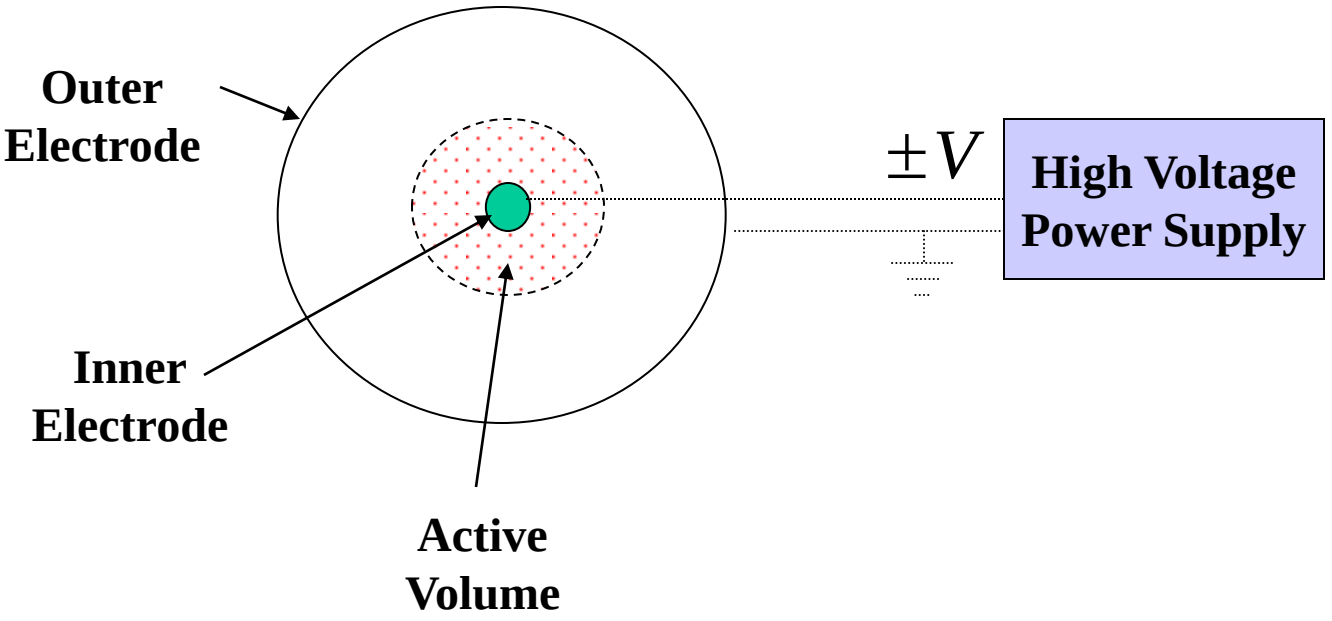
$$V_{b,\min} = 2.718 \frac{C_2}{C_1 \ln\left(1 + \frac{1}{\gamma}\right)}$$

Breakdown above ~100 Torr

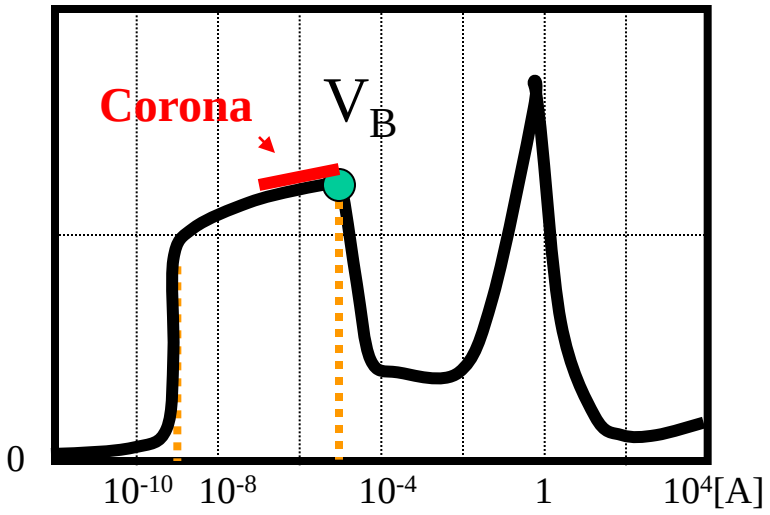
$V_b = 3000\ d + 1.35\ kV$ **for dry atmospheric air**

$E_b \sim 30\ kV/cm$

Corona Discharge



For dry Air for parallel electrodes:

$$V_B = 3000d + 1.35 \qquad [\text{kV}]$$

$$E_B = \frac{V_B}{d} = 3000 + \frac{1.35}{d} \qquad [\text{kV/m}]$$