Basics of Plasma

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Outline

1. Ionisation
2. Plasma definition
3. Plasma properties
4. Plasma classification
5. Energy transfer in non-equilibrium plasma
6. *i-U* characteristic of DC discharge

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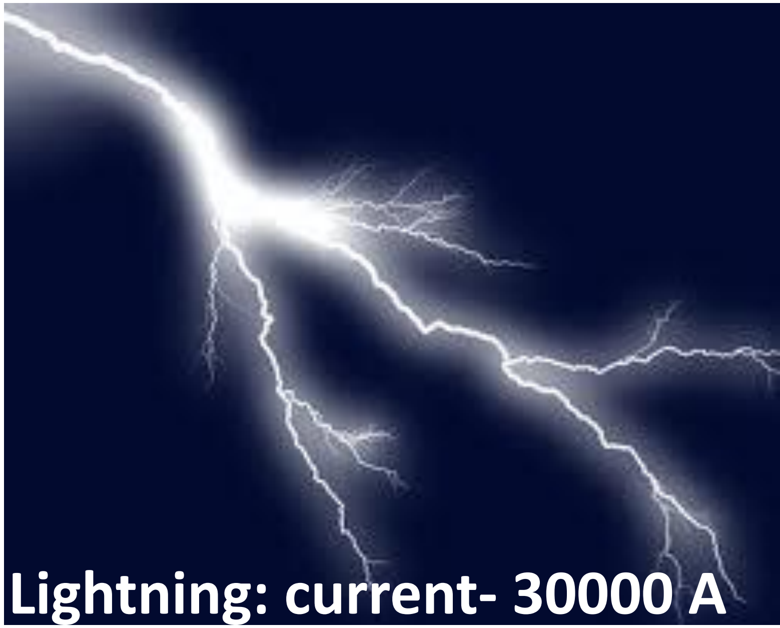
Air



Resistivity of air is $\sim 10^{28}$ times higher than that of copper

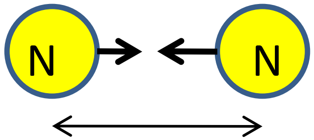
A good **insulator**
(properties are governed by neutral particles)

A good **conductor**
(properties are governed by charged particles)

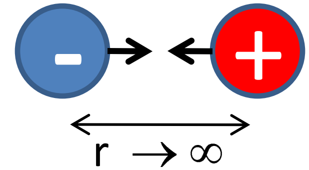
Two different states of matter?

Neutral versus ionised gas

1 nm = 10^{-9} m = 0.000000001 m



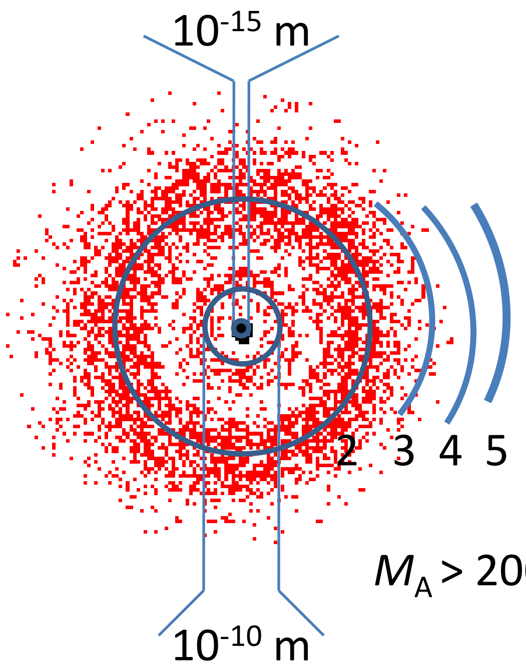
r = 0.2-10 nm



Short-range interaction $E_{NN} = -\frac{C_{NN}}{r^6}$

Long-range interaction $E_{qq} = -\frac{C_{qq}}{r}$

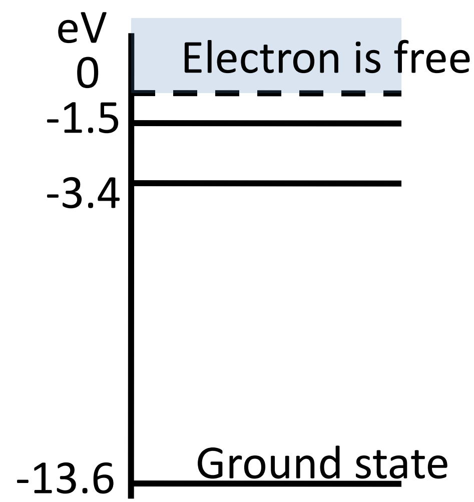
Atom

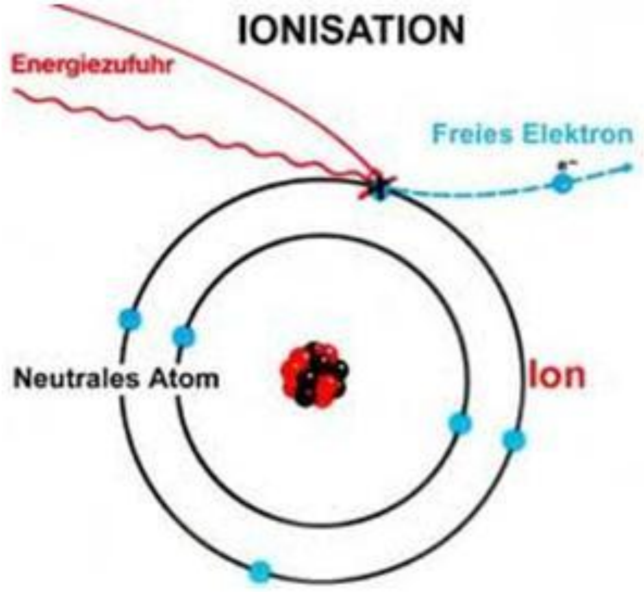


$M_A > 2000\ m_e$

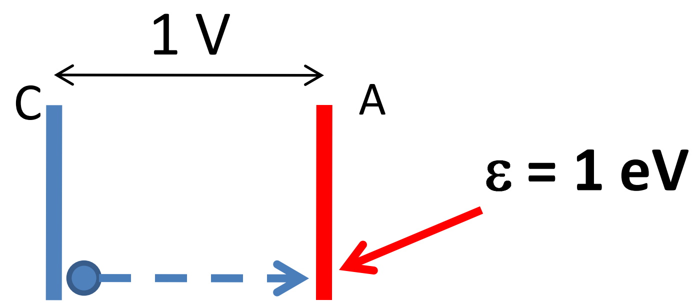
Binding energy decreases with the orbital number

Hydrogen: energy level plot

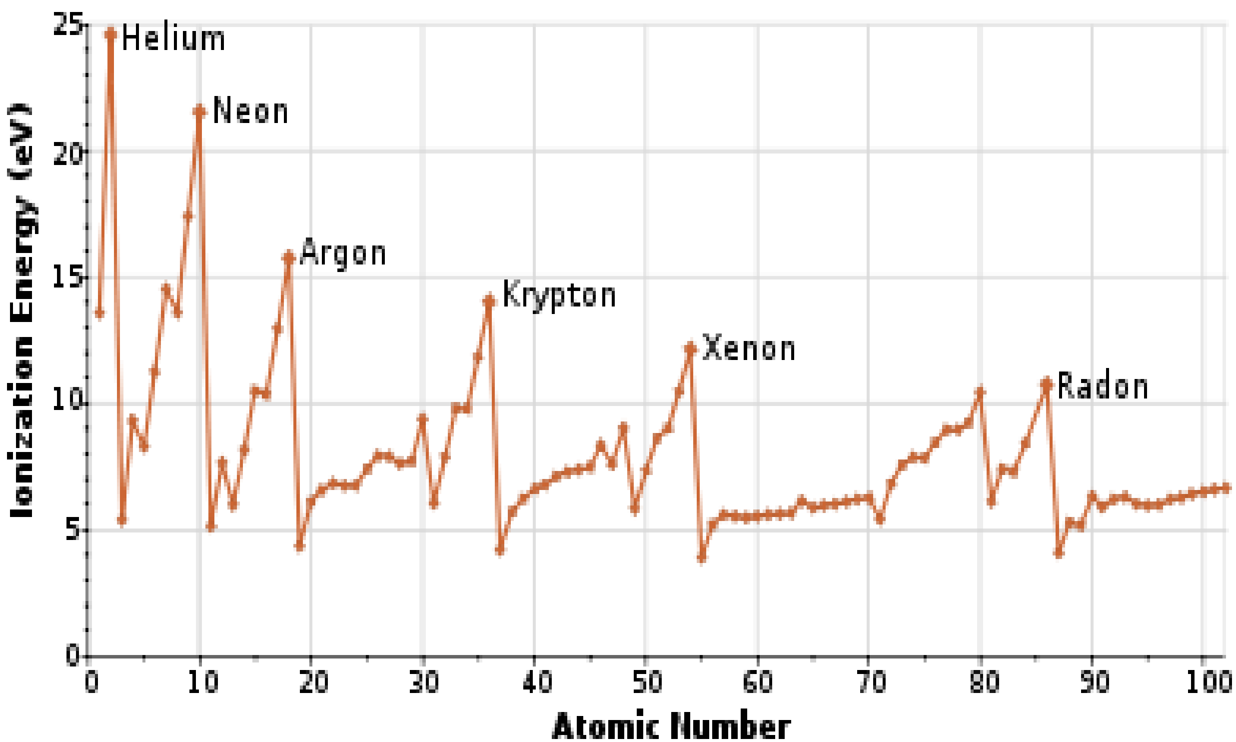




In the microworld instead of energy unit **Joule** (J) the unit **electronvolt** (eV) is used



$$1 \text{ eV} = 1.6\times10^{-19} \text{ J}$$



Let E_i = 10 eV

It is possible to ionise atoms
- by short-wavelength radiation (λ < 120 nm)
- by high-energy particles

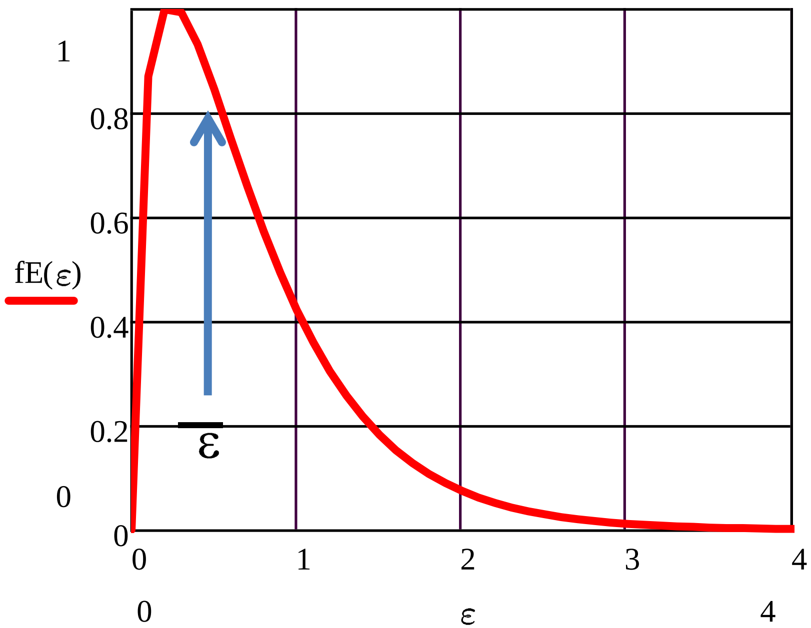
Cosmic rays, radioactive decay, hot gas

How hot the gas should be to have charged particles?

$$\bar{\varepsilon} = \frac{M\bar{v}^2}{2} = \frac{3}{2}k_B T$$

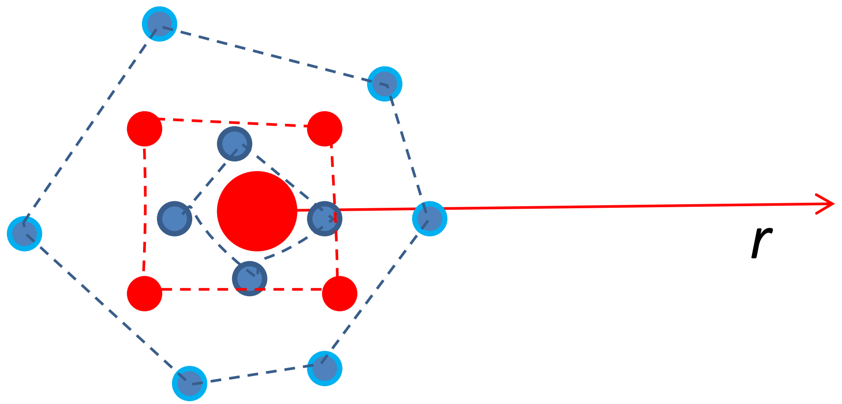
1 eV → 11 600 K

⇒ W boiling temperature T_W = 5550 K ⇒ $\bar{\varepsilon}$ = 0.48 eV



$$N_{\varepsilon i}/N_n < 10^{-8}$$

Effect of other charges

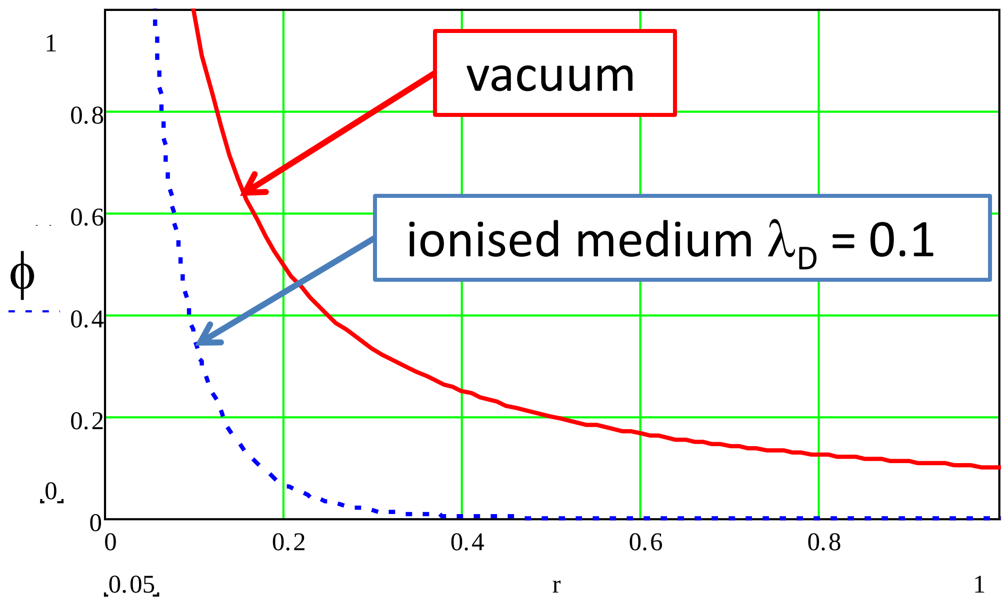


In vacuum the potential of charge Q changes as $\phi \propto$ **1/*r***

Because of other charges the **screening** of charge Q takes place

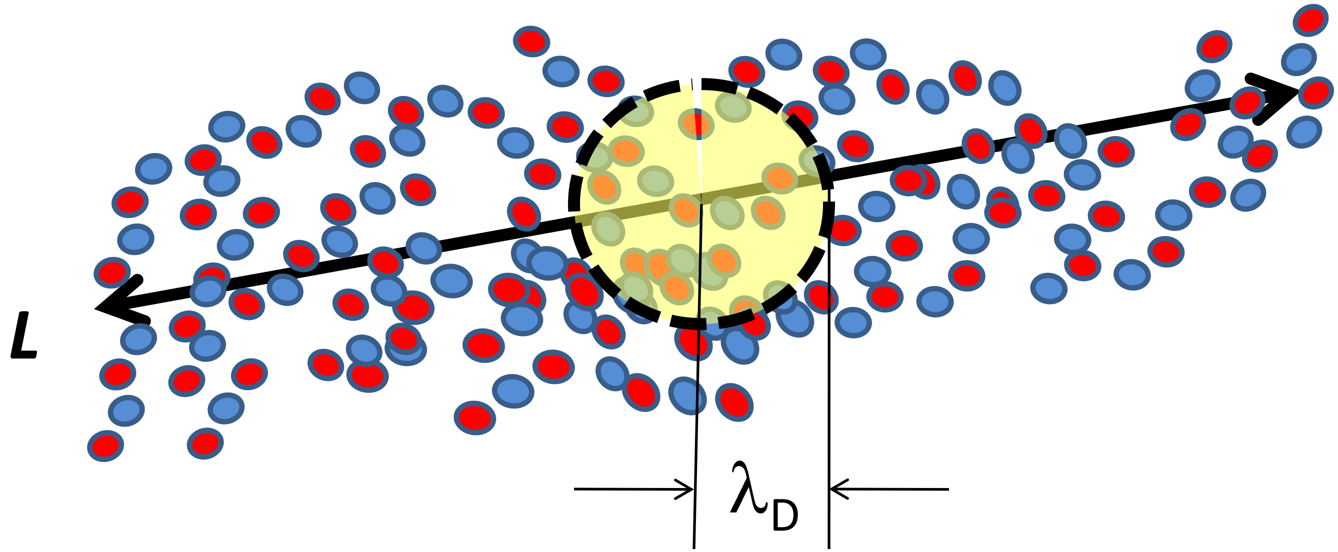
In an ionised medium the Q potential decreases exponentially

$$\phi \propto 1/r \times \exp(-r/\lambda_D)$$



Debye length (radius) λ_D gives is the characteristic screening distance

What is plasma? ($\pi\lambda\alpha\sigma\mu\alpha$ (Greek) $\rightarrow$ jelly)



Plasma is an ionised medium which linear dimensions are considerably larger than Debye length λ_D

In plasma a charged particle loses its individual properties, collective effects are at the foreground

Plasma: the most important characteristics

Quasineutrality

Considering only single-charged particles the concentration of **positive ions N_+** equals to the sum of concentrations of **electrons n_e** and **negative ions N_-**

$$N_+ \approx n_e + N_- = n$$

The quasineutrality means that inside plasma $E \approx 0$

Debye length

depends both on charged particles concentration and the mean energy

$$\lambda_D = \sqrt{\frac{k_B T \varepsilon_0}{n_e e^2}}$$

k_B – Boltzmann constant, ε_0 –dielectric constant, e- elementary charge

T – mean energy

n – plasma concentration

When T (K)& n (m^{-3}), then:

$$\lambda_D = 69\left(\frac{T}{n}\right)^{1/2} \text{(m)}$$

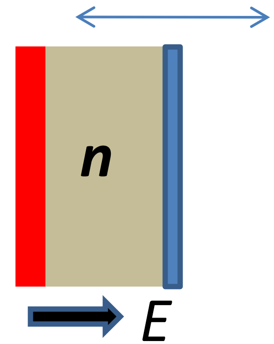
When T(eV) & n cm^{-3}, then:

$$\lambda_D = 743.\left(\frac{T'}{n}\right)^{1/2} \text{(cm)}$$

Plasma: the most important characteristrics

Plasma frequency

A distortion of quasineutrality leads to the rise of oscillations



$$\omega_p = \sqrt{\frac{ne^2}{m_e \varepsilon_0}}$$

SI: $\nu_P = 8{,}97\sqrt{n}$

ν_P^{-1} gives the time needed for elimination of distorsions

Some figures

	$n(m^{-3})$	$T(eV)$	$\omega_p(sec^{-1})$	$\lambda_D(m)$	$N_D = n\frac{4}{3}\pi\lambda_D^3$
Interstellar	10^6	10^{-2}	6×10^4	0.7	$\sim 10^6$
Solar Chromosphere	10^{18}	2	6×10^{10}	5×10^{-6}	
Solar Wind (1AU)	10^7	10	2×10^5	7	
Ionosphere	10^{12}	0.1	6×10^7	2×10^{-3}	
Arc discharge	10^{20}	1	6×10^{11}	7×10^{-7}	$\sim 10^2$
Tokamak	10^{20}	10^4	6×10^{11}	7×10^{-5}	$\sim 10^8$
Inertial Confinement	10^{28}	10^4	6×10^{15}	7×10^{-9}	

In the case of atmospheric-pressure plasmachemistry applications:
$n = 10^{16}$-10^{20} m^{-3}, T = 1-5 eV, $\lambda_D \sim 10$ μm (free path length: ~ 0.1 μm)

Classification of plasma

Classical plasma

Quantum plasma (e.g. metals)

Distance between particles is less than de Broglie wavelength ($n^{1/3} << h/p$)

Ideal plasma (C. potential energy << kinetic energy temperature))

Plasma of **low ionisation degree** $\frac{N_i}{N_i + N_A} \leq 10^{-4}$

(charge carriers collide mainly with neutral particles)

Fully ionised plasma (fusion reactors)

Low temperature plasma

(Gas temperature does not exceed 5000 K)

High temperature plasma

$T > 10$ eV, in the case of fusion reactors $T > 10$ keV (10^8 K)

Non-equilibrium plasma: (non-thermal) different plasma constituents have different mean energy (temperature)

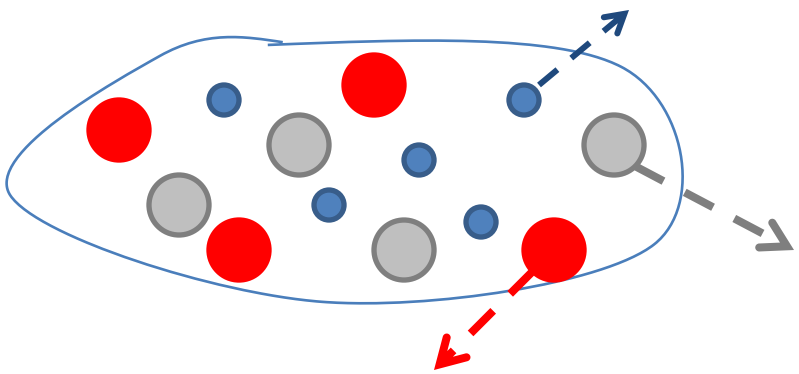
Energy transfer

Steady plasma

In **steady** conditions the concentrations of plasma components as well as their energy do not change with time

Plasma of electropositive gas:

- atoms/molecules in their ground and excited states
- positive ions
- electrons



Losses

1. Diffusion

2. Collisions – elastic and non-elastic

Non-elastic collisions lead to excitation, ionisation, dissociation, recombination and different other plasma-chemical reactions

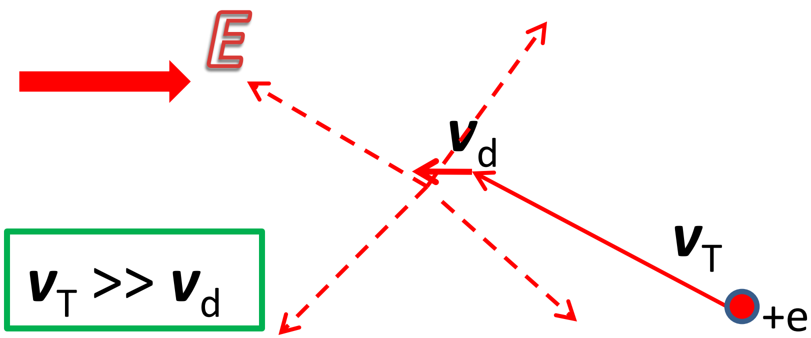
Energy transfer

Losses in plasma could be compensated by an external electric field

$T \rightarrow \boldsymbol{v}_{\mathrm{T}}$

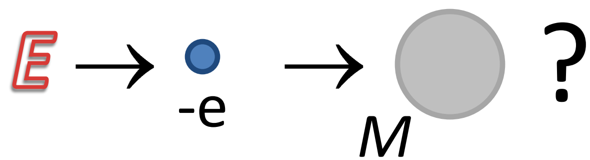
$\boldsymbol{E} \rightarrow \boldsymbol{v}_{\mathrm{d}}$

$\boldsymbol{v}_{\mathrm{T}} >> \boldsymbol{v}_{\mathrm{d}}$



As $M_{\mathrm{i}} \approx M_{\mathrm{A}} >> m_{\mathrm{e}}$,

the gain of energy from electric field occurs via electrons



Most of collisions in steady plasma are elastic as the amount of high-energy particles is small

In the case of elastic collisions:

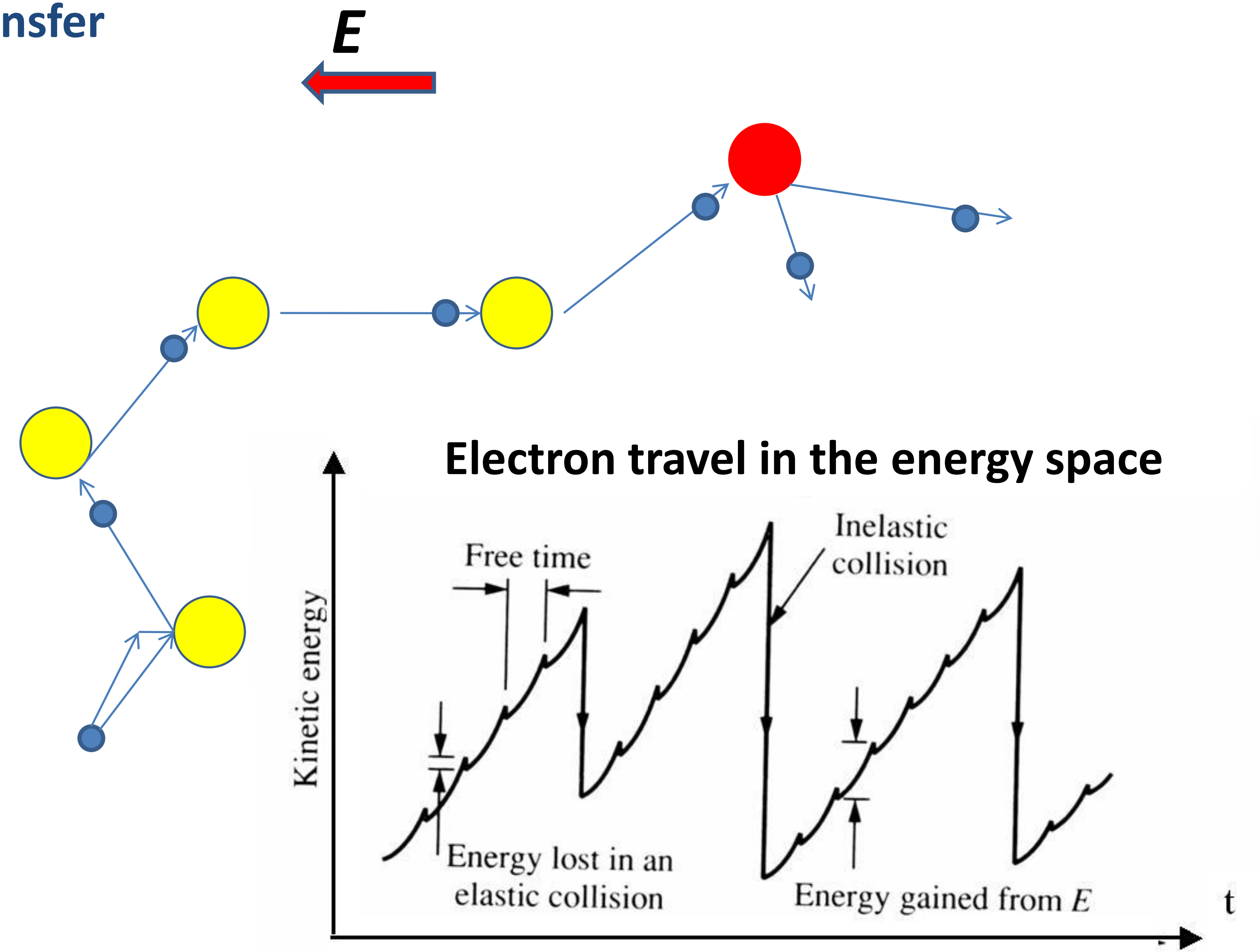
$$\frac{2m_1m_2}{(m_1+m_2)^2}$$

$\rightarrow$ $M_{\mathrm{A}} >> m_{\mathrm{e}}$ $\rightarrow$

Transferred energy:

$$\delta = 2m/M$$

Energy transfer



$\delta = 2m_e/M_A \rightarrow$ a chance to have $T_e >> T_g$!

Why the condition $T_e >> T_g$ is so important?

Example: ozone production

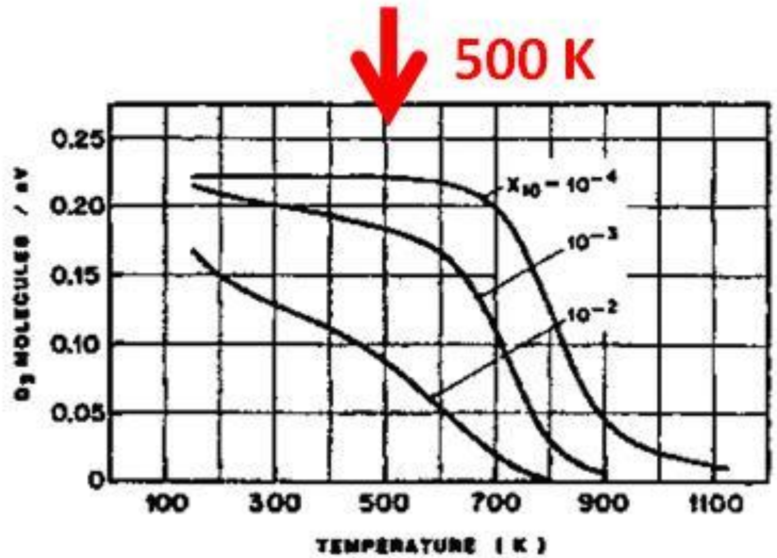
$$O + O_2 + M \rightarrow O_3^* + M \rightarrow O_3 + M$$

For efficient production of ozone precursors by reactions

$e + O_2 \rightarrow 2\,O(^3P) + e$	6.0 eV
$e + O_2 \rightarrow O(^3P) + O(^1D) + e$	8.4 eV

the mean energy of electrons should be ε_e = 6-9 eV (**9 eV → 104 000 K**)

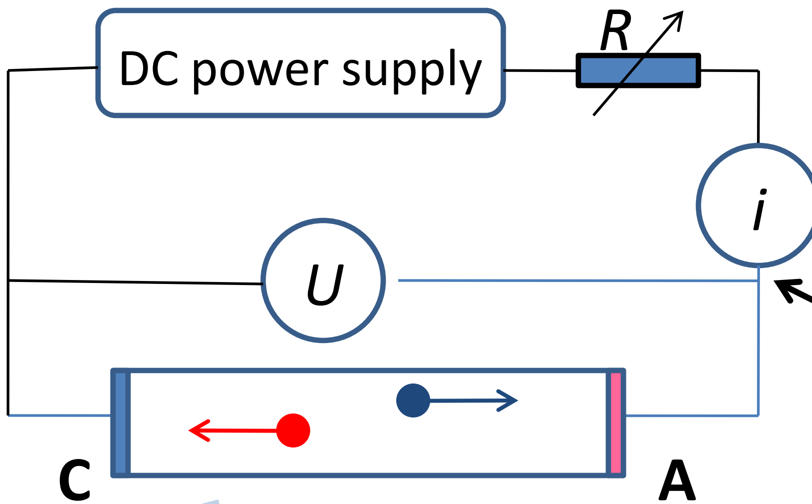
At the same time high gas temperatures lead to ozone decomposition



Thus: a high yield of O_3 production is achieved when $T_e >> T_g$

Production of plasma:

current- voltage, ***i-U***, characteristics of direct current , **DC,** discharge



Argoon

Pressure: 100 Pa

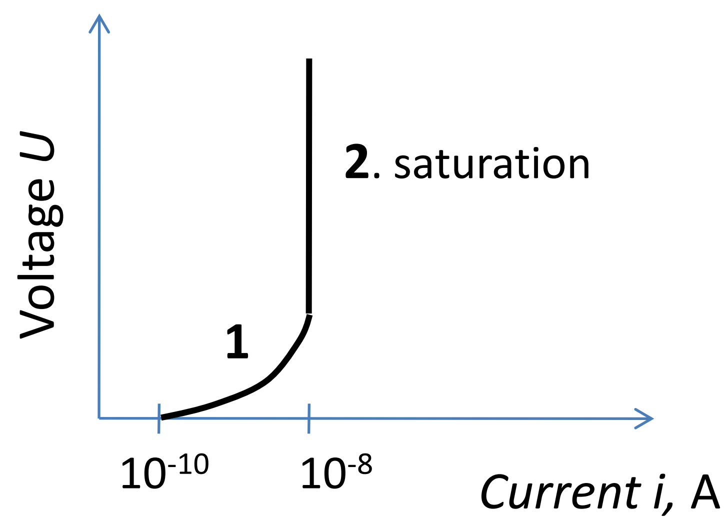
⟷ 1 cm

$U = U_0 - iR$

Background ionisation
(non-self-sustained discharge)

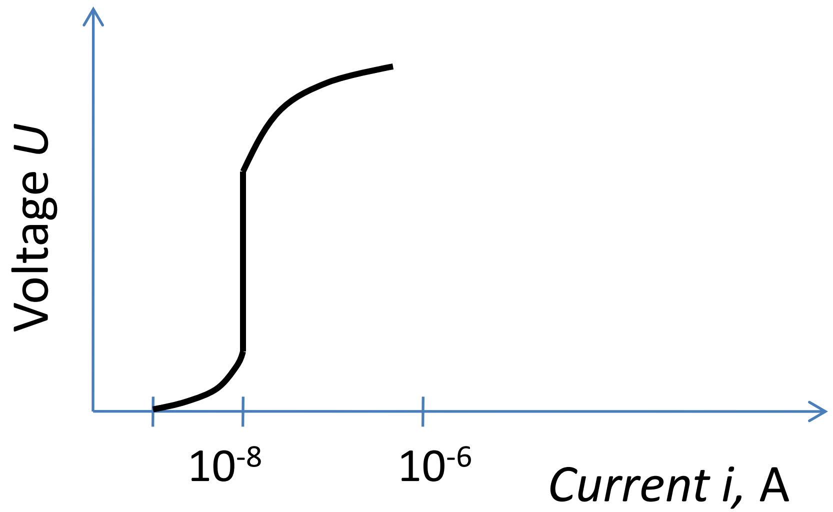
Low electric field

1. Only drift and recombination
2. The role of recombination is negligible

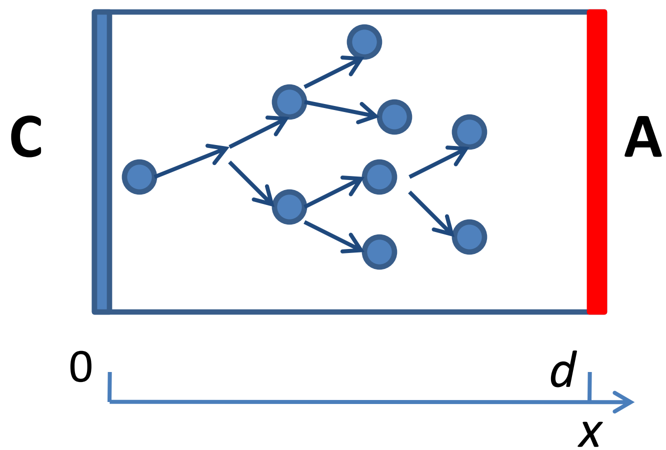


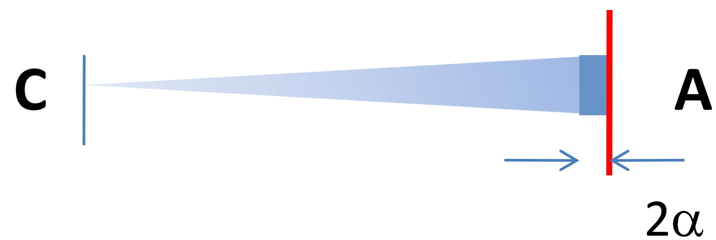
i-U characteristics of DC discharge

Non-self-sustained discharge



Strong electric field:
Excitation & ionisation





Electron avalanche: number of charge carriers increases exponentially

$$n_x = n_0 e^{\alpha x}$$

α - ionisation coefficient

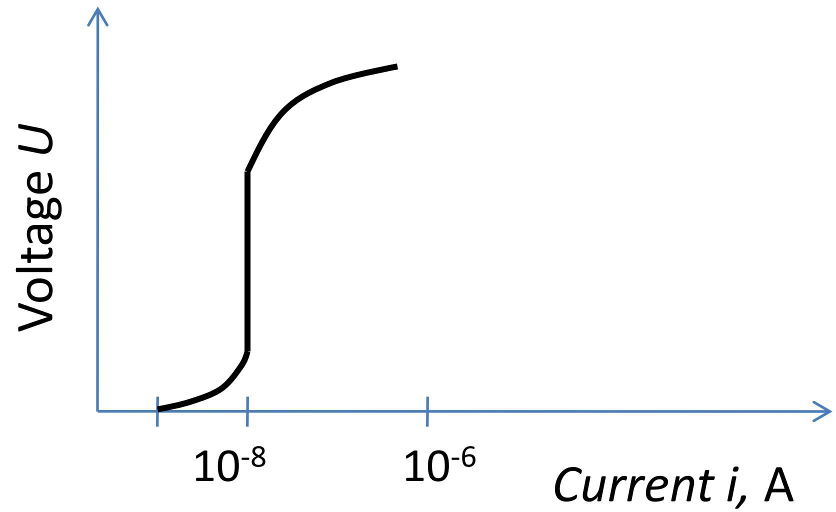
As $\alpha = f(E)$,

the current increases rapidly with voltage

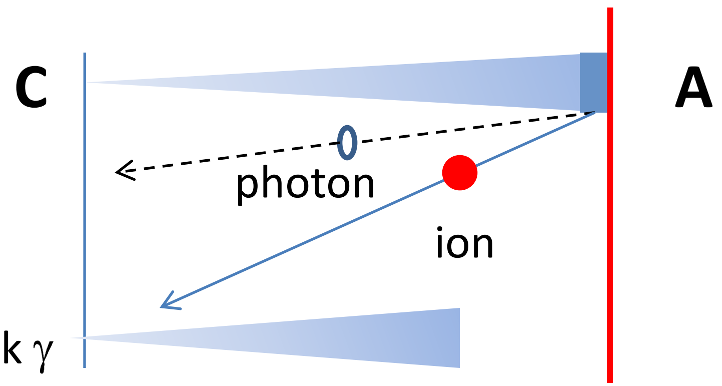
i-U characteristics of DC discharge

Non-self-sustained discharge

Strong electric field:
Excitation & ionisation



$$\boldsymbol{n_x = n_0 e^{\alpha x}}$$



Positive feedback γ

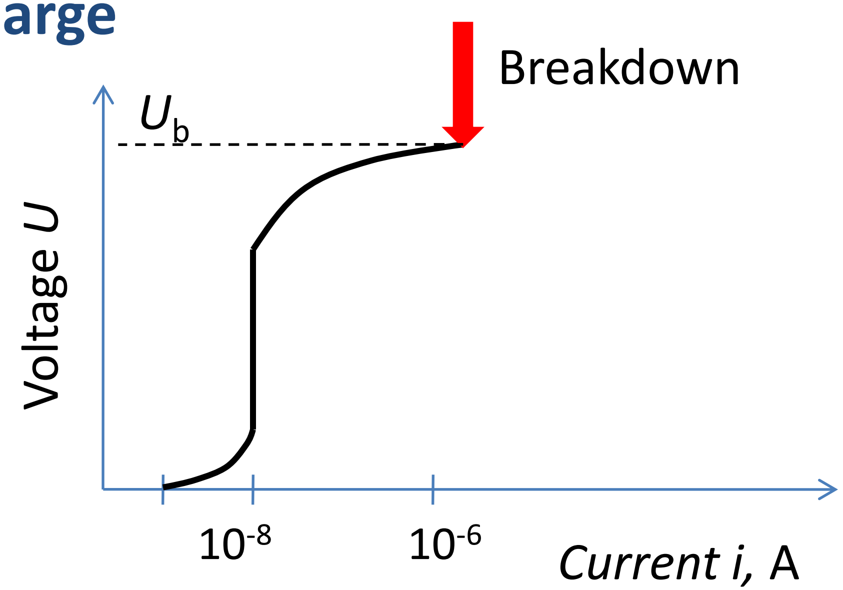
When the size of the secondary avalanche reaches that of the primary one the transition to

self-sustained discharge

takes place

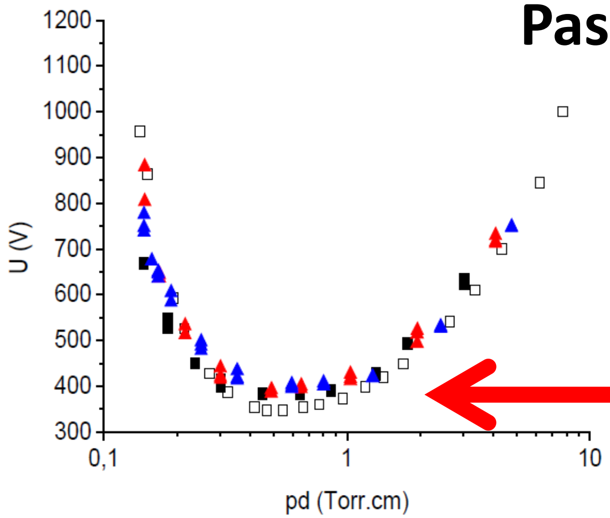
i-U characteristics of DC discharge

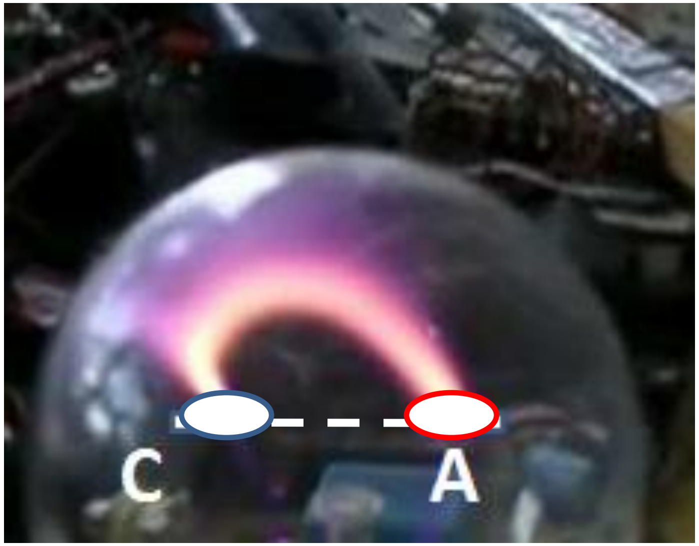
Transition to self-sustained discharge → **breakdown**



At certain gas mixture and cathode material
the breakdown voltage U_b depends on production *pd*

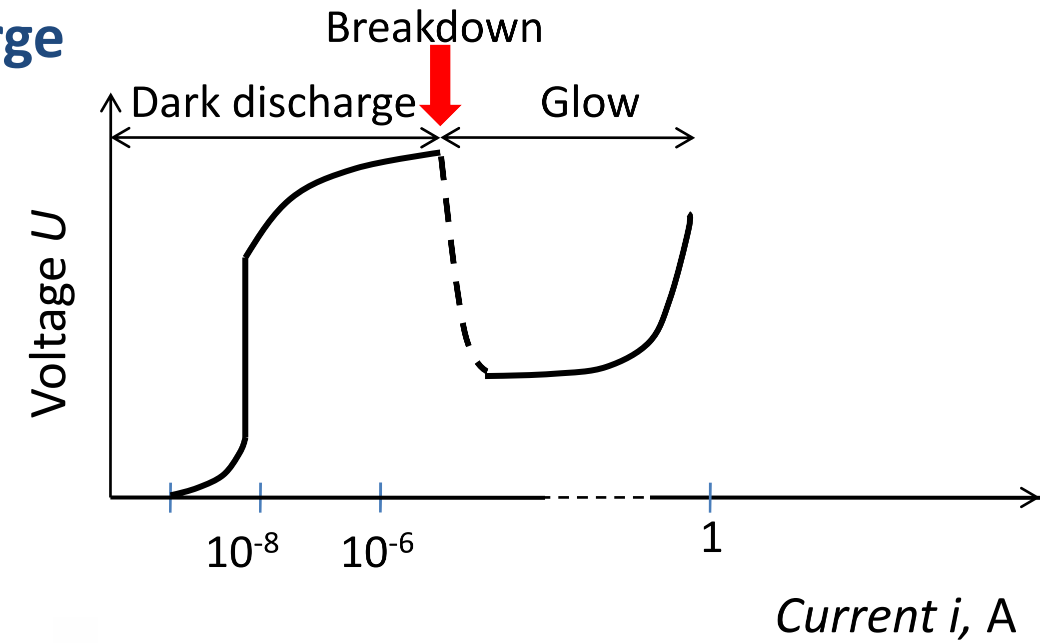
Paschen's law

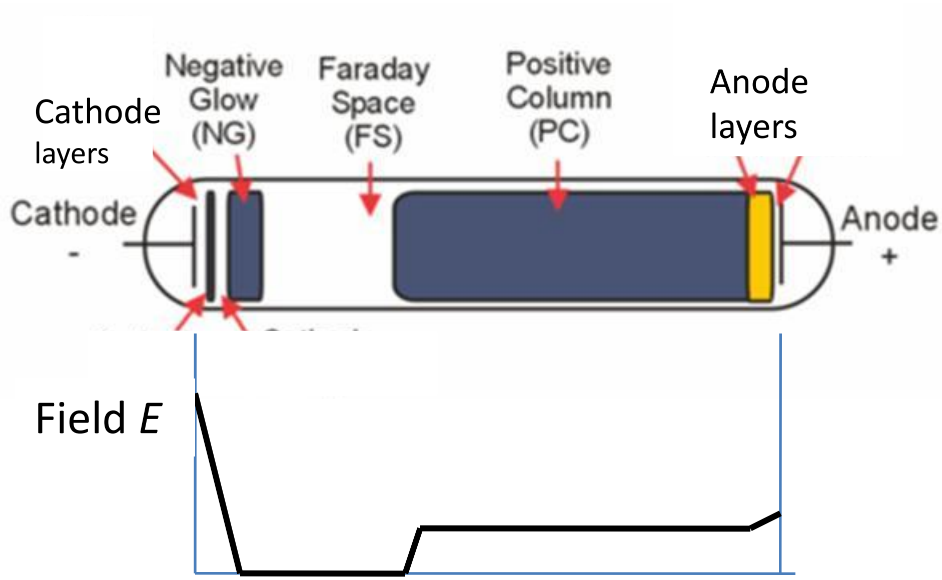




i-U characteristics of DC discharge

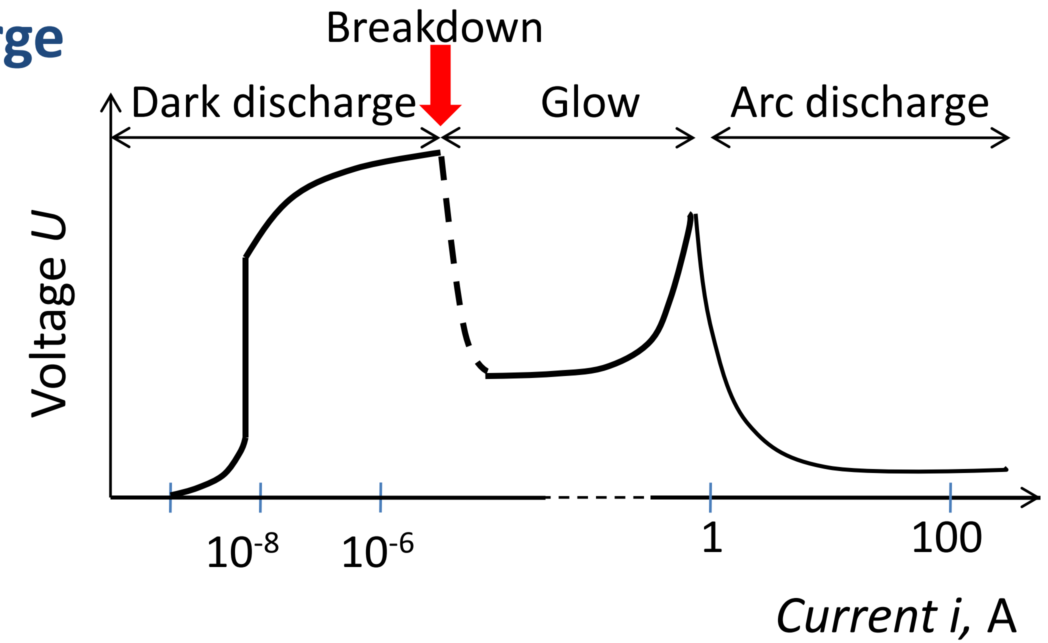
Depending on conditions the breakdown could be **diffuse or filamentary** and it could last from 10^{-3} to 10^{-9} s.



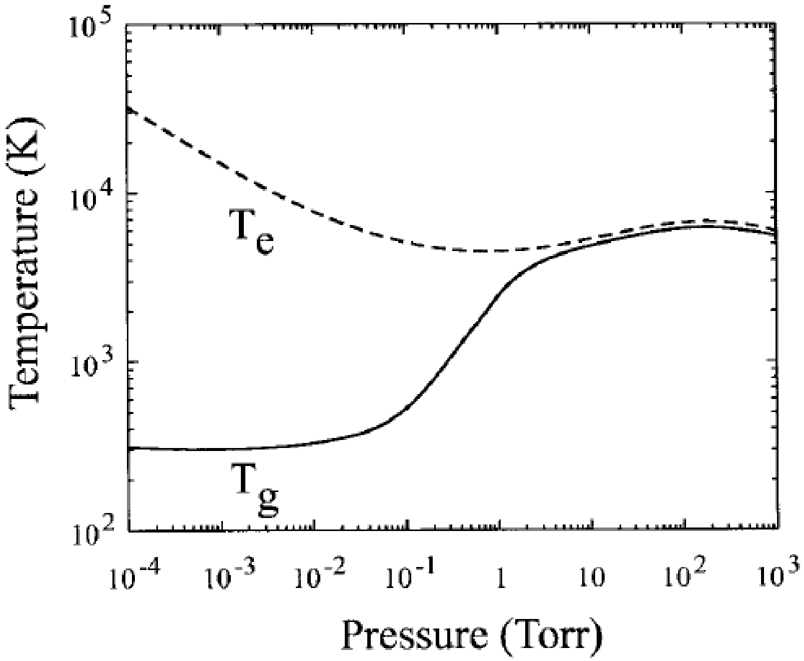


- Glow discharge emits intensive light
- Because of field distribution there is a number of characteristic luminous regions
- Light emitted by NG is caused by non-equilibrium (non-thermal) electrons
- PC- “true” plasma region

i-U characteristics of DC discharge



A growth of the current increases the power liberated in plasma and it finally leads to qualitative changes



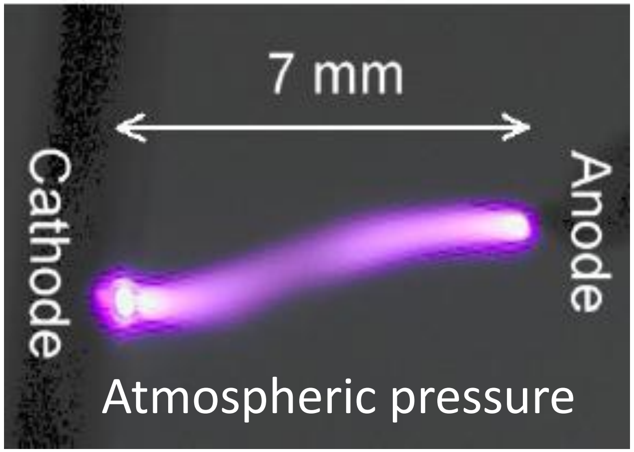
During each electron-atom elastic collision a energy fraction $2m_e/M_A$ is passed to the gas. A growth of the pressure increases the rate of collisions ν_{eA} and the difference between T_e and T_g diminishes

Growth of T_g warms up the cathode material and electrons are emitted due to thermoionic emission for which lower applied voltage is needed.

The glow transits to arc discharge.

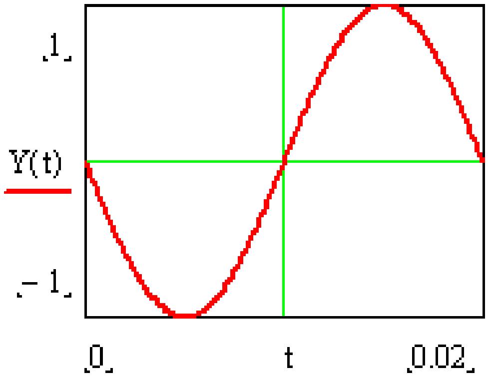
Importance of DC discharge

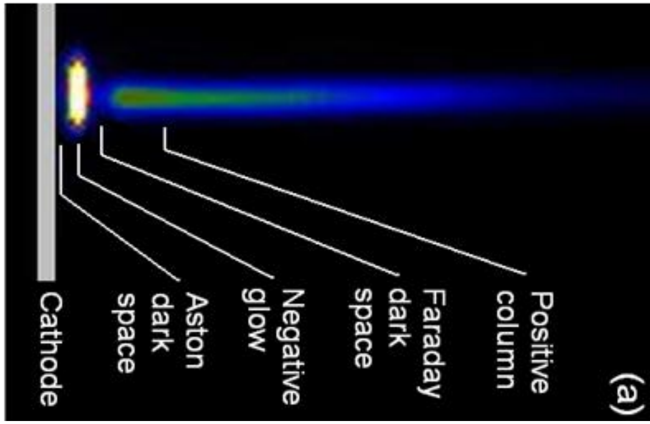
• Qualitatively, the desribed regularities are independent of gas pressure (1 – 10^6 Pa)



• The desribed regularities exist also in AC and HF discharges as well as in the case of pulsed nanosecond discharges

AC glow, negative half-cycle





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