

Plasma and its Applications

Uwe Stöhr, chair of
process technology

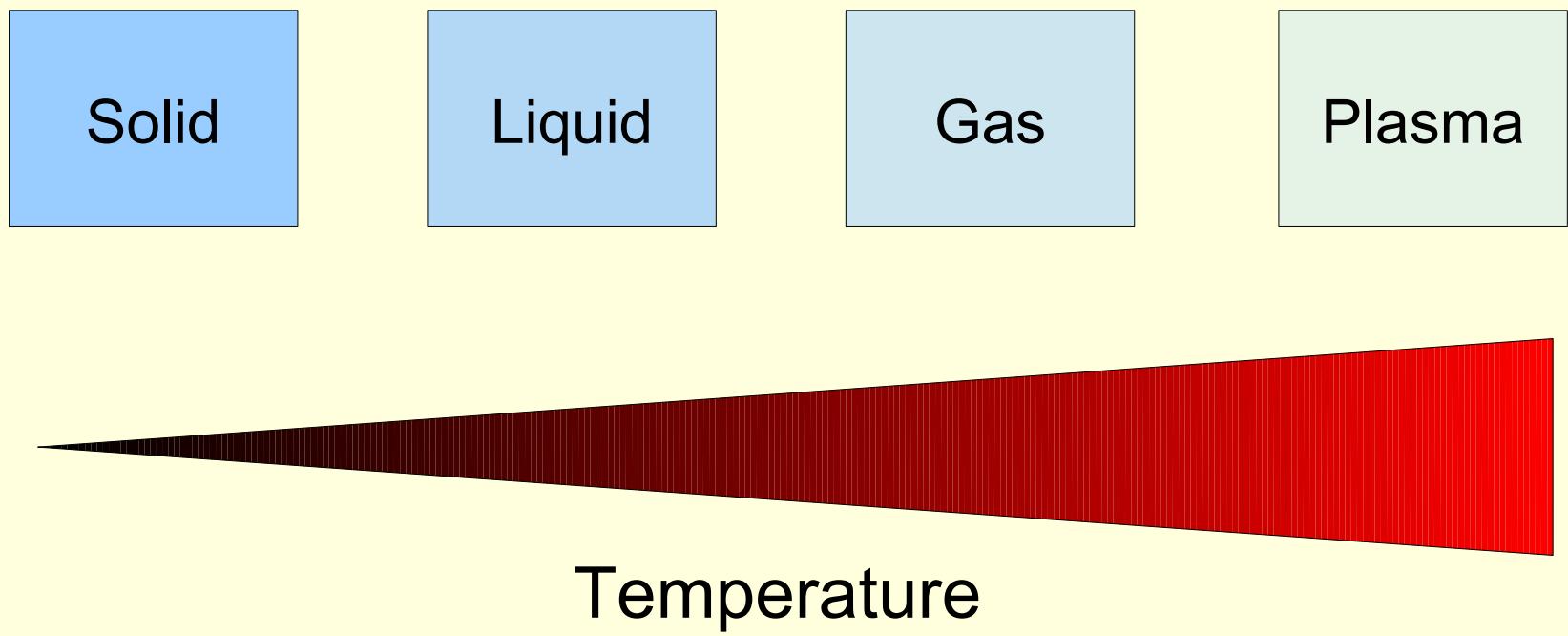
Overview

- Plasma fundamentals
- Kinetic theory of gases
- Plasma discharges
- Applications

**„plasma“ is Greek
„πλάσμα“
and means „shape“
(named by Irving Langmuir)**

What is a plasma?

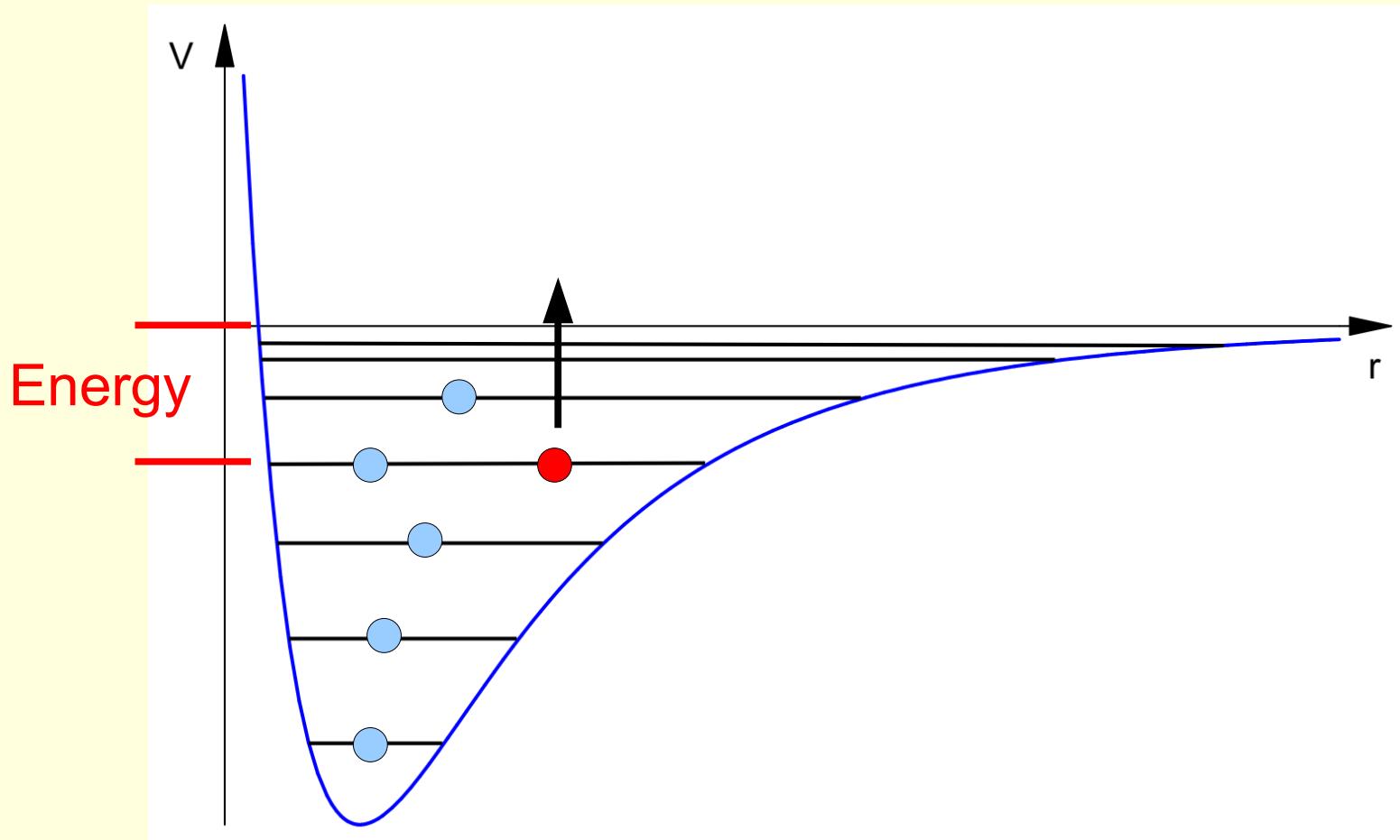
Plasma: fourth matter of state?



Plasma definition

**„quasi-neutral particle system
as mixture of free electrons,
ions, and neutral particles“**

Ionization



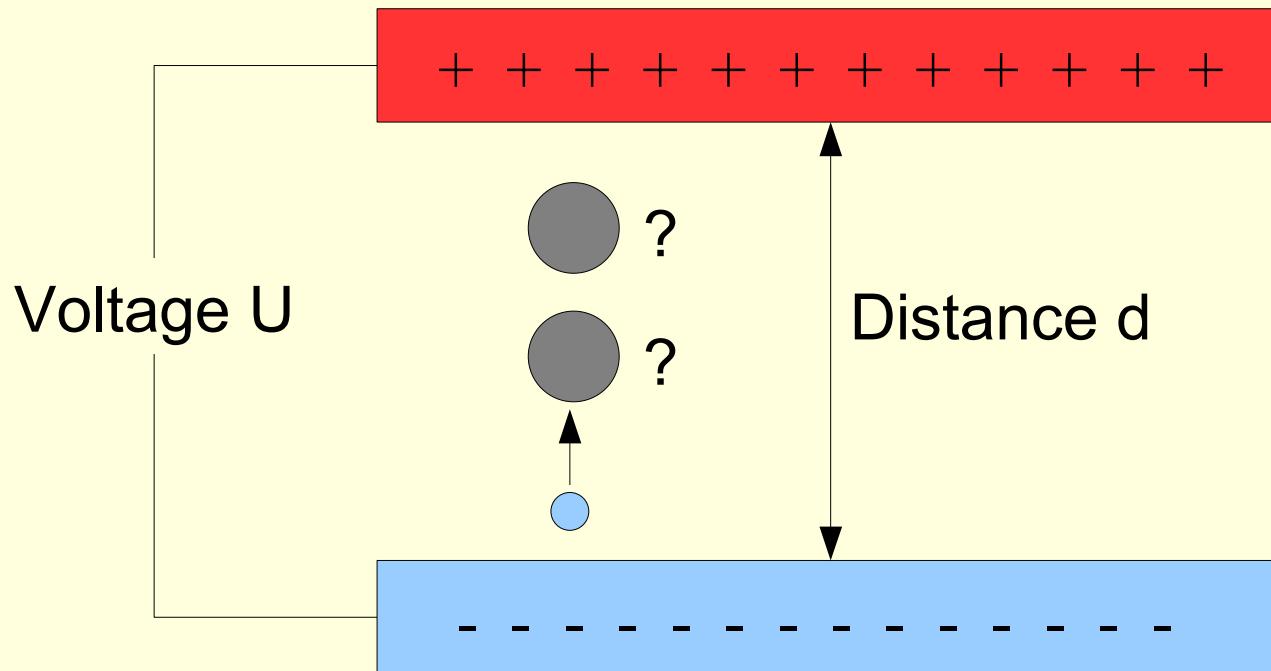
Plasma sources

- Capacity
- Inductivity
- Microwave
- Maser / Laser

Ionization types

- Impact ionization
- Photo emission

Impact ionization



Where is ionization more probable?

Impact ionization

$$F = q\mathcal{E} \quad \mathcal{E} = \frac{U}{d}$$

Impact ionization

$$F = q\mathcal{E} \qquad \mathcal{E} = \frac{U}{d}$$

$$W = \int \! F \, \mathrm{d}s$$
$$W_I = e \frac{U}{d} \cdot s_I$$

Impact ionization

$$F = q\mathcal{E} \qquad \mathcal{E} = \frac{U}{d}$$

$$W=\int\! F\,\mathrm{d}s$$
$$W_I=e\frac{U}{d}\cdot s_I$$

$$d\geq s_I$$

Photo effect

$$W_I = h f_I$$

- UV light
- Röntgen radiation
- Cosmic radiation

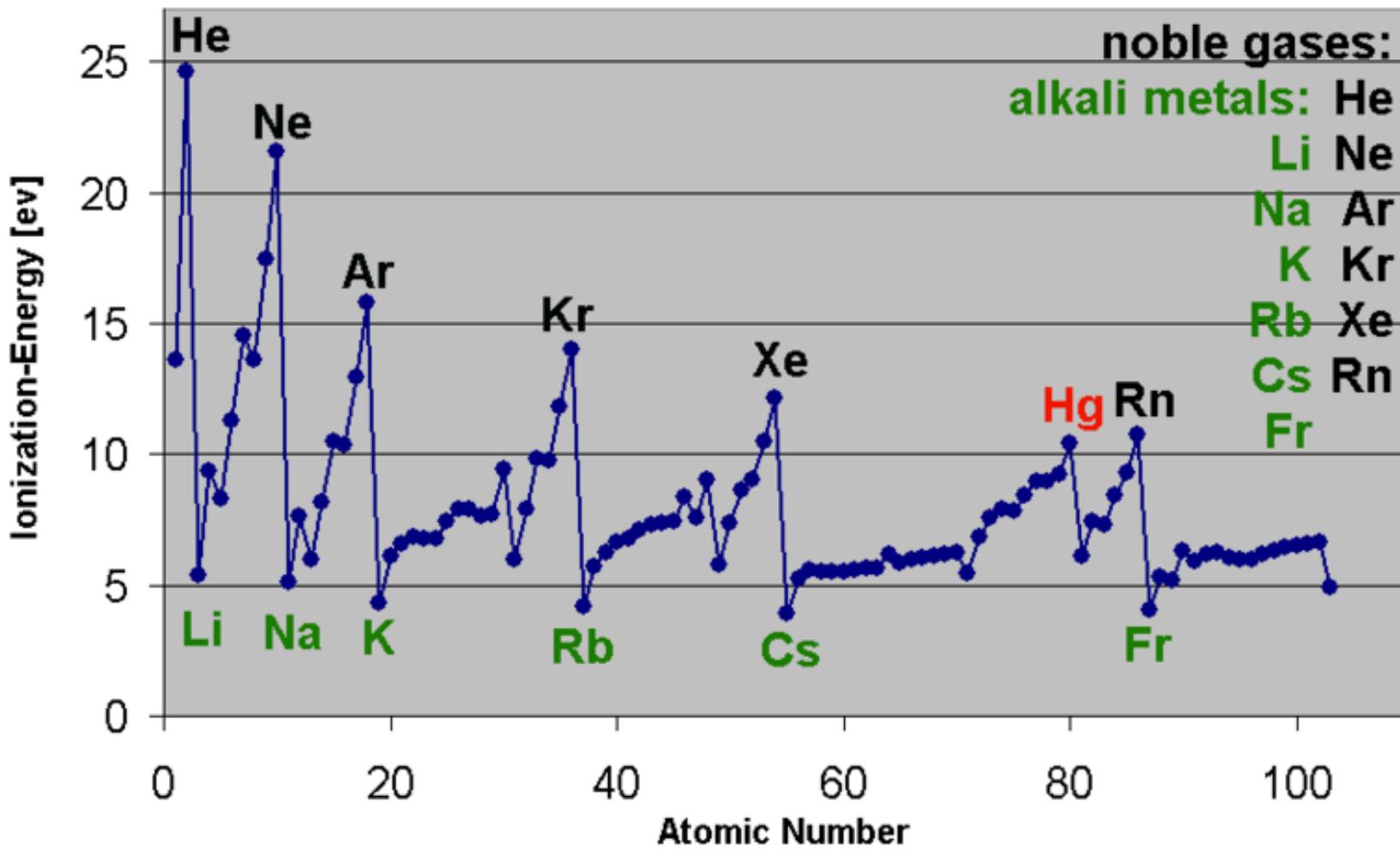
Photo effect

$$W_I = h f_I$$

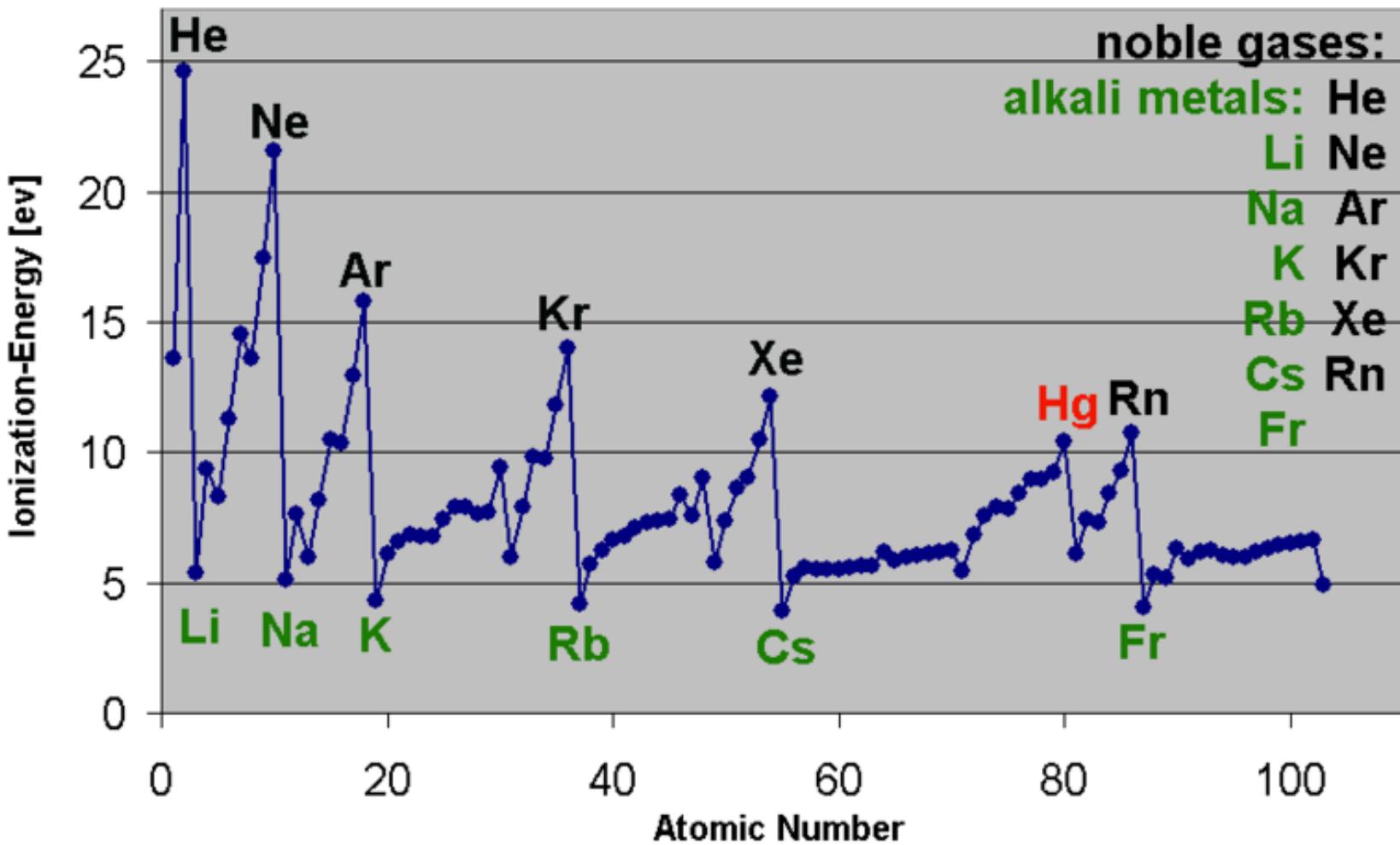
$$W_I = 4 - 25 \text{ eV}$$

- UV light, e.g. $\lambda = 300 \text{ nm} \rightarrow W = 4.1 \text{ eV}$
- Röntgen radiation,
e.g. $\lambda = 1 \text{ nm} \rightarrow W = 1.25 \text{ keV}$
- Cosmic radiation, $W = 10^9 - 10^{22} \text{ eV}$

Ionization-Energy



Ionization-Energy



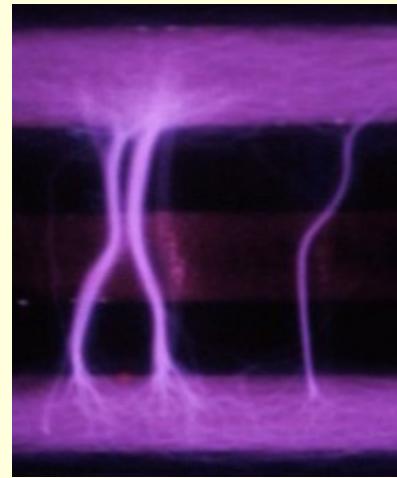
Coulomb law: $F = \frac{1}{4\pi\epsilon_0} \frac{q_1 q_2}{r^2}$

Ionization energy

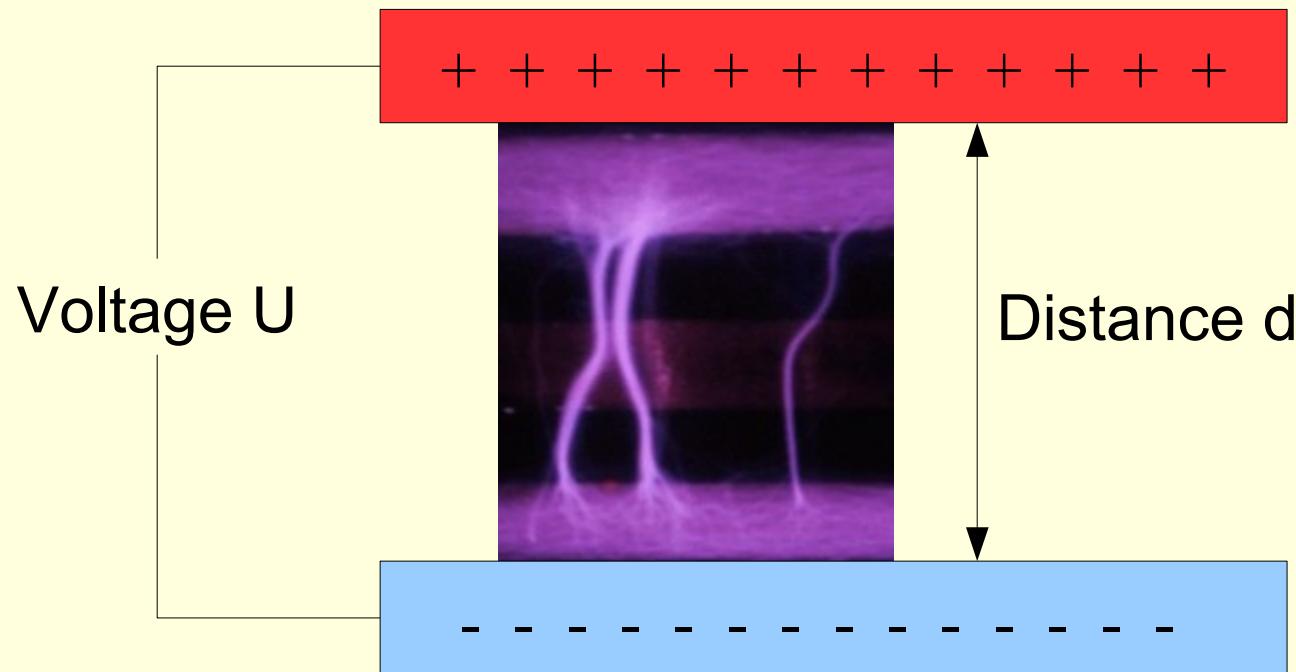
The following table shows the atomic number, element name, and symbol for each element in the periodic table. The elements are color-coded based on their group:

- Group 1 (Alkali metals):** H, Li, Na, K, Rb, Cs, Fr.
- Group 2 (Alkaline earth metals):** Be, Mg, Ca, Sr, Y, Ba, Ra.
- Groups 13-18 (Post-transition metals/Non-metals/Post-noble gases):** Al, Si, P, S, Cl, Ar, Ga, Ge, As, Se, Br, Kr, In, Sn, Sb, Te, I, At, Rn, Tl, Pb, Bi, Po, At, Uuo, Uup, Uuh, Uus, Uuo.
- Lanthanides (highlighted by a dashed orange box):** La, Ce, Pr, Nd, Pm, Sm, Eu, Gd, Tb, Dy, Ho, Er, Tm, Yb, Lu.
- Actinides (highlighted by a dashed orange box):** Ac, Th, Pa, U, Np, Pu, Am, Cm, Bk, Cf, Es, Fm, Md, No, Lr.
- Noble gases (highlighted by a black oval):** He, Ne, Ar, Kr, Xe.
- Transition metals (highlighted by a red circle):** Sc, Ti, V, Cr, Mn, Fe, Co, Ni, Cu, Zn, Tc, Ru, Rh, Pd, Ag, Cd, In, Sn, Sb, Te, I, At.

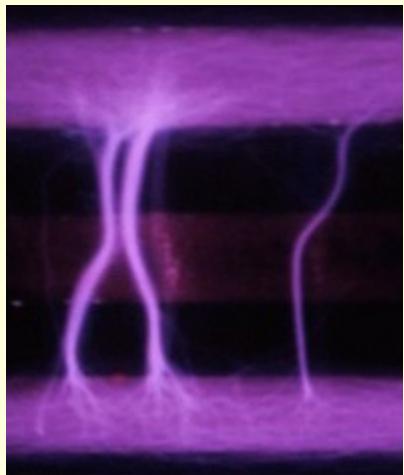
Well known plasmas



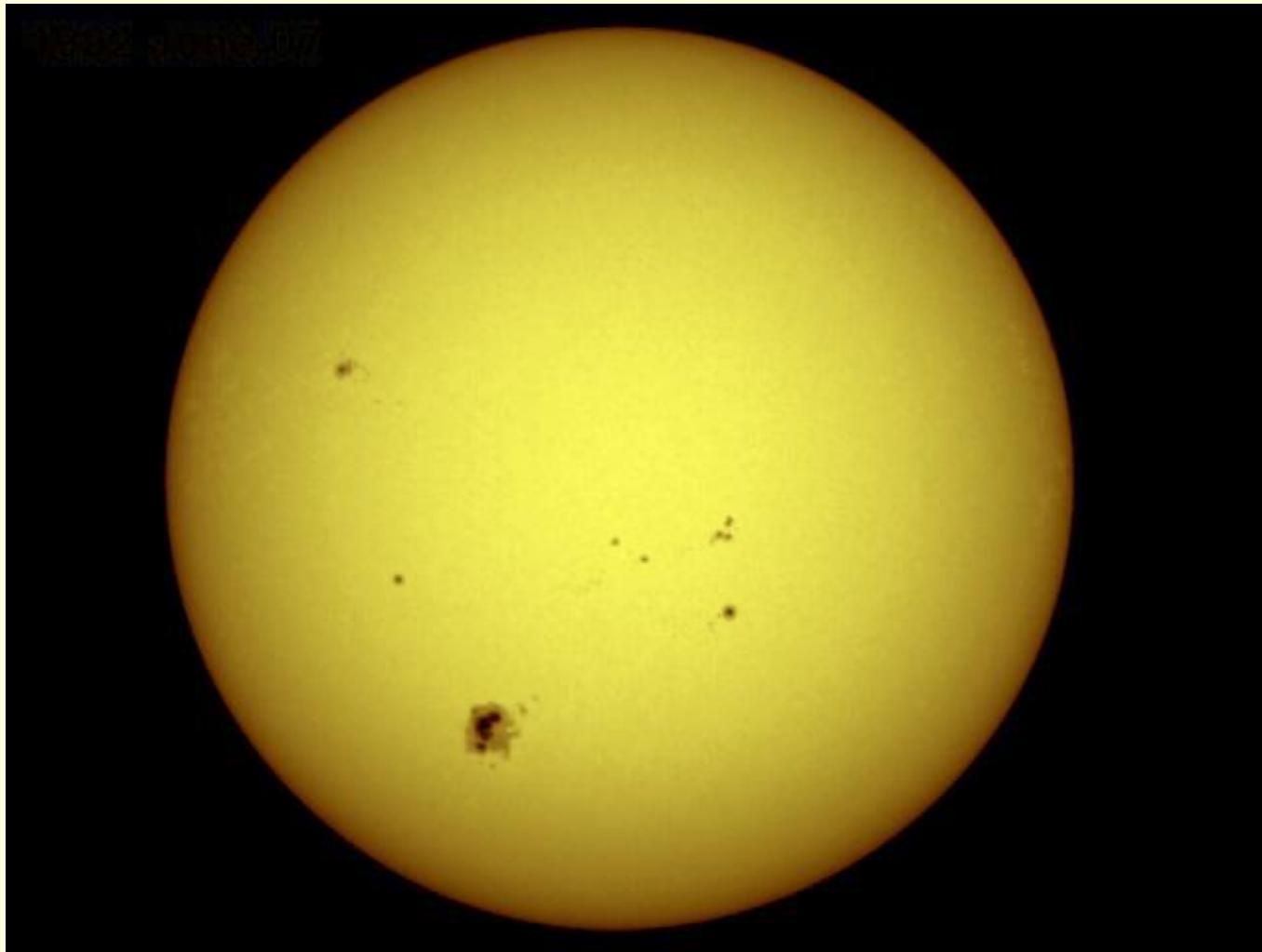
Well known plasmas



Well known plasmas



Well known plasmas



plasmas comprise 99% of the visible universe

Well known plasmas



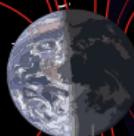
Magnetotail

Deflected solar
wind particles

Polar
cusp

Incoming solar
wind particles

Plasma sheet



Earth's
atmosphere

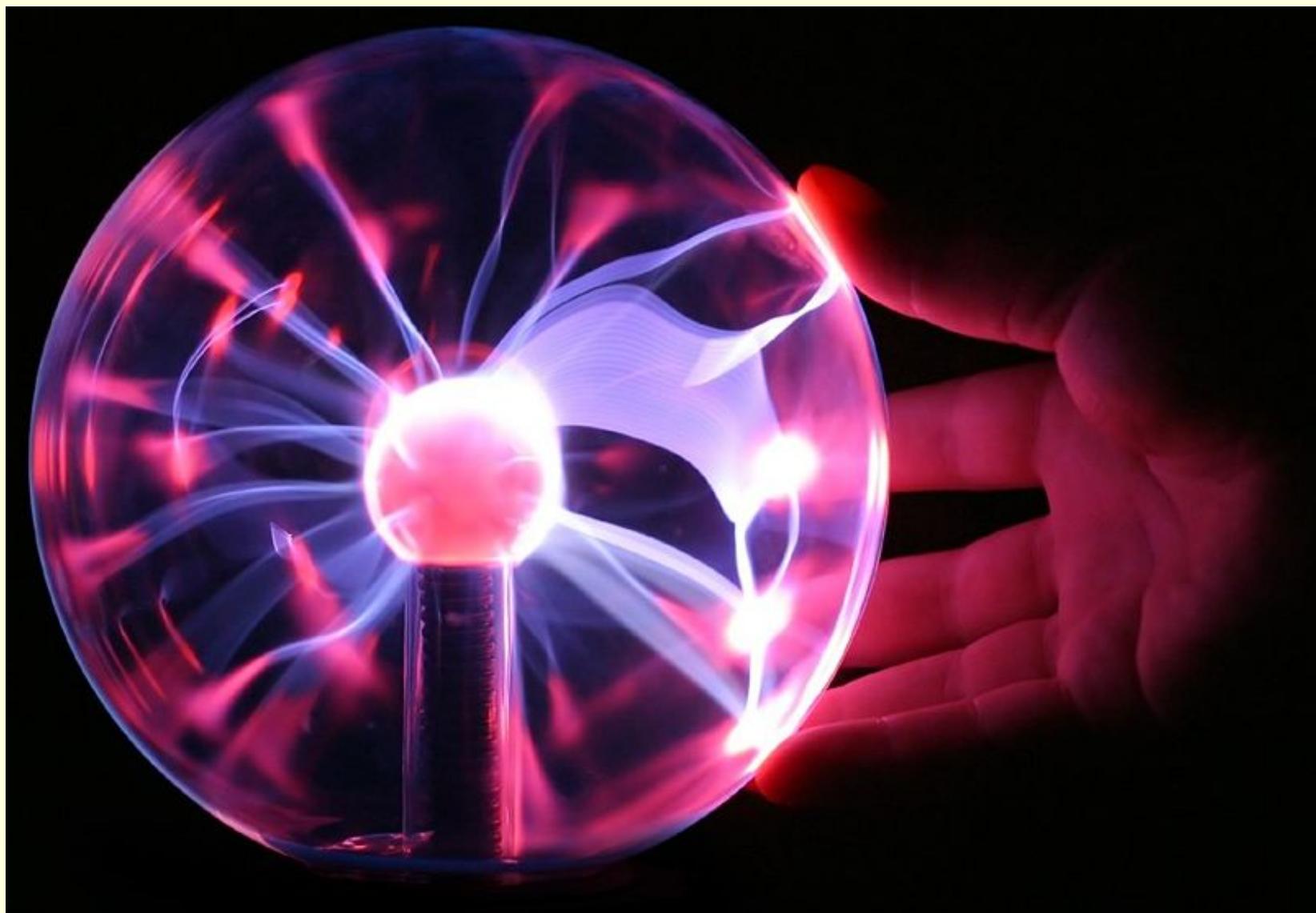
Neutral sheet

0 - 100 km

Bow
shock

Magnetosheath

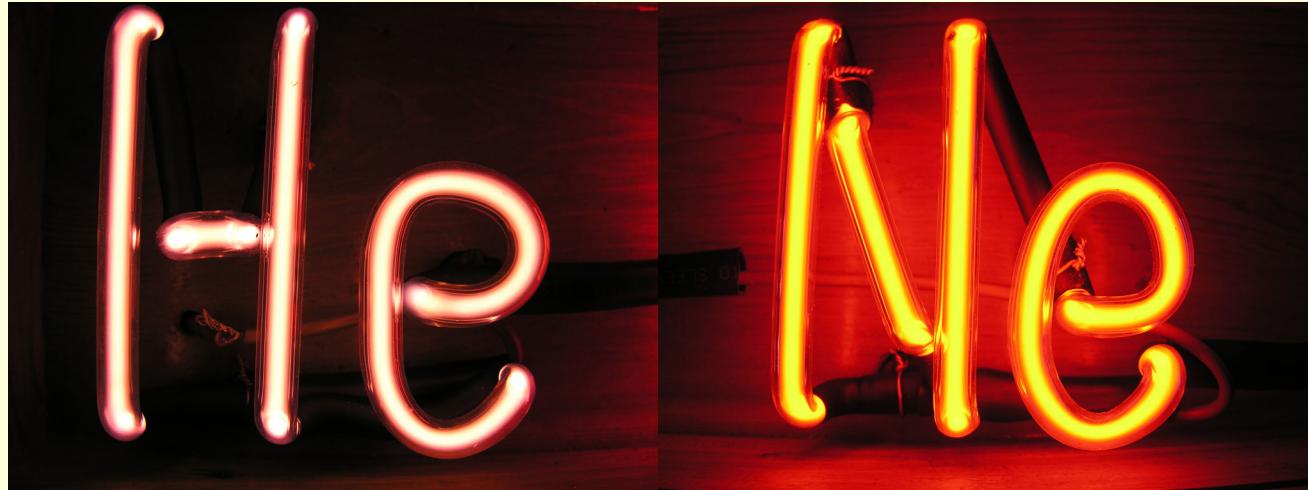
Well known plasmas



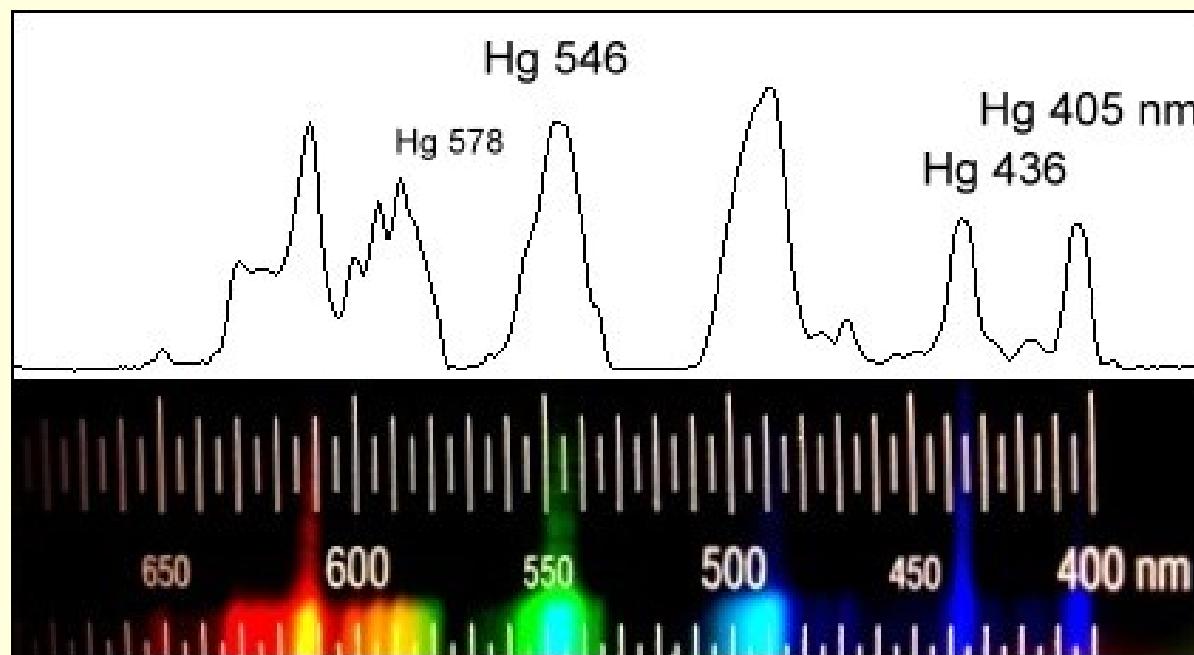
Well known plasmas



Gas discharges

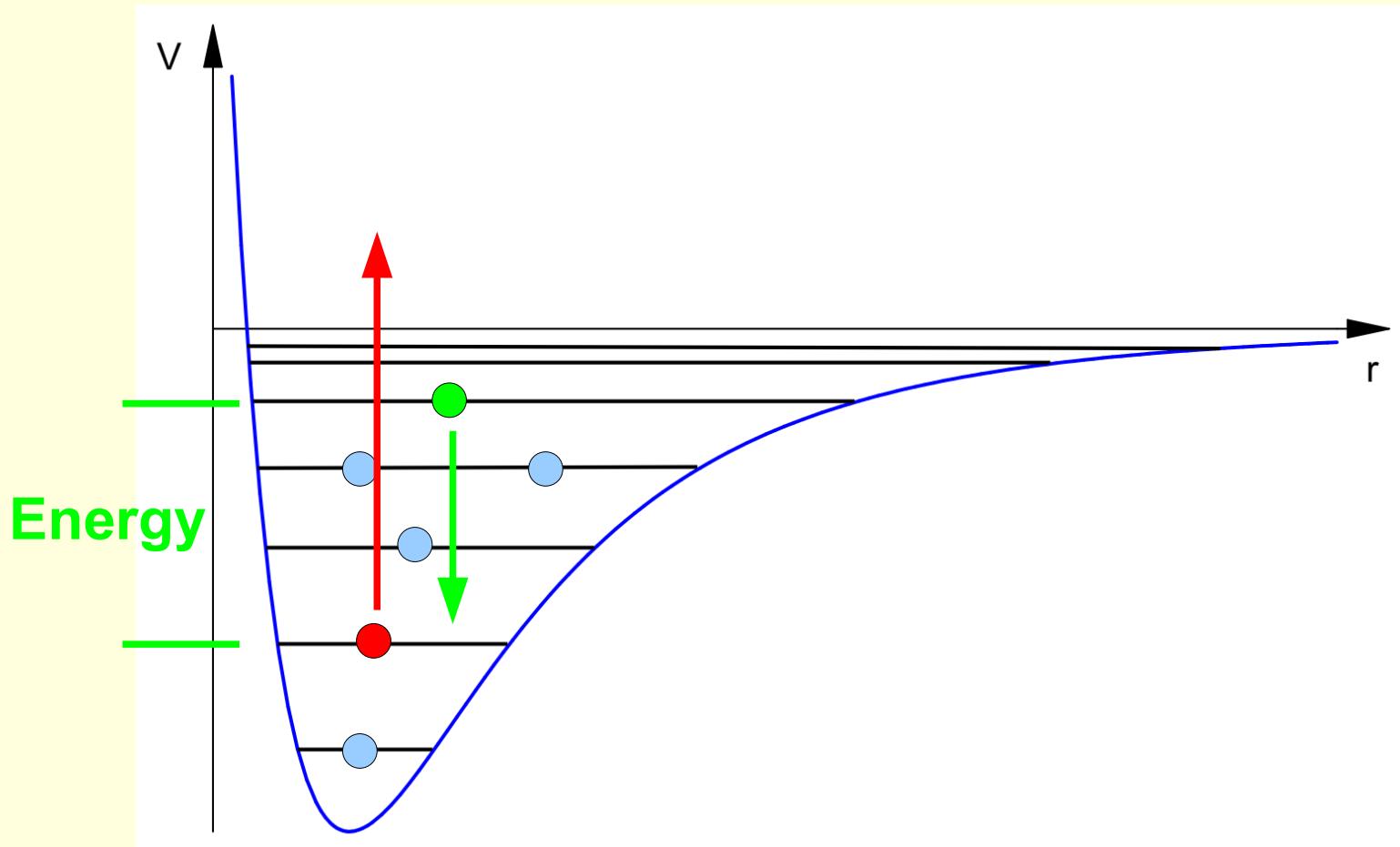


Gas discharges

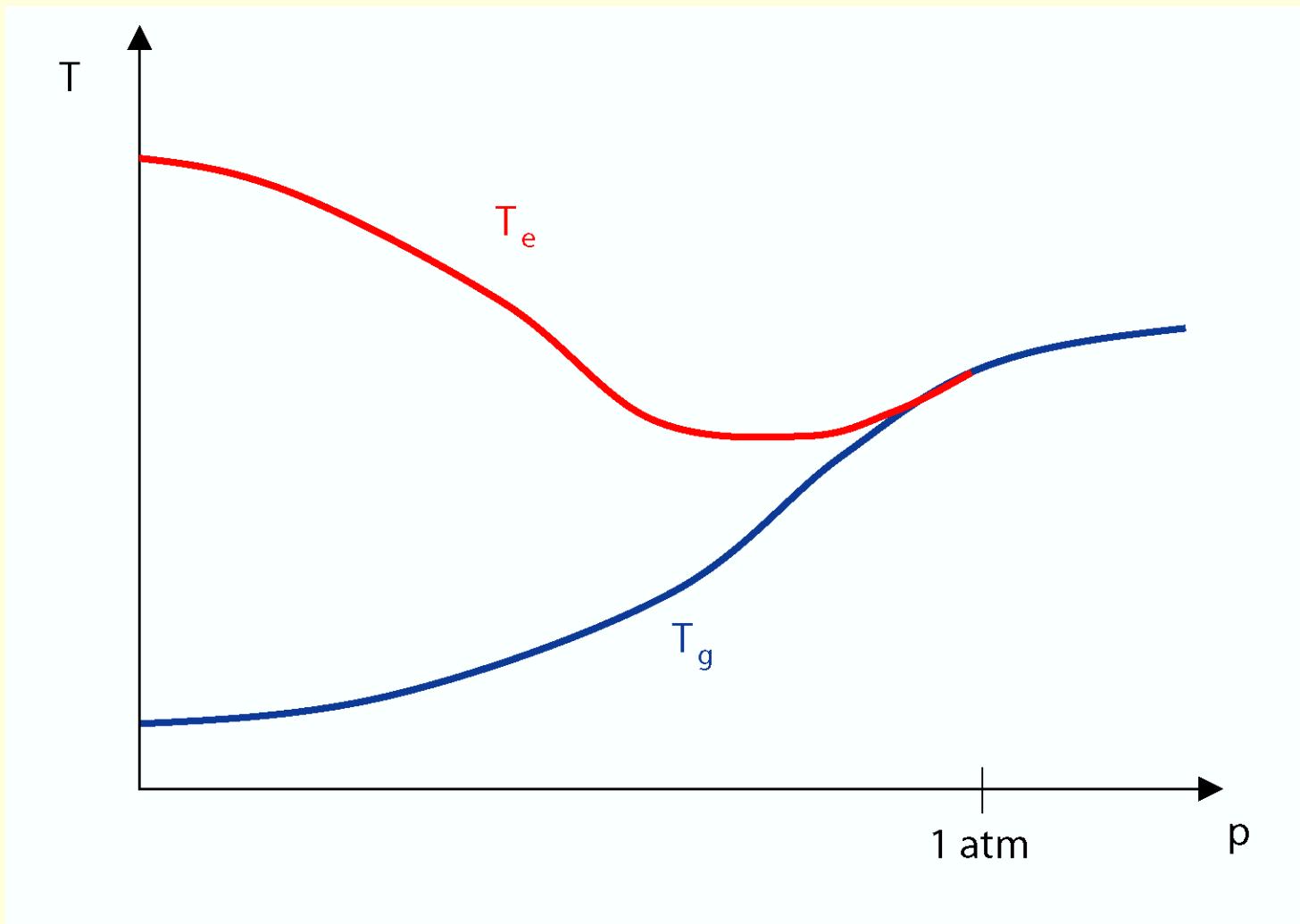


spectrum of a Hg lamp

Emission of energy



Plasma temperature



Plasma temperature

$$m_{\text{proton}} = 1.672 \cdot 10^{-27} \text{ kg}$$

$$m_{\text{neutron}} = 1.674 \cdot 10^{-27} \text{ kg}$$

$$m_{\text{electron}} = 9.109 \cdot 10^{-31} \text{ kg}$$

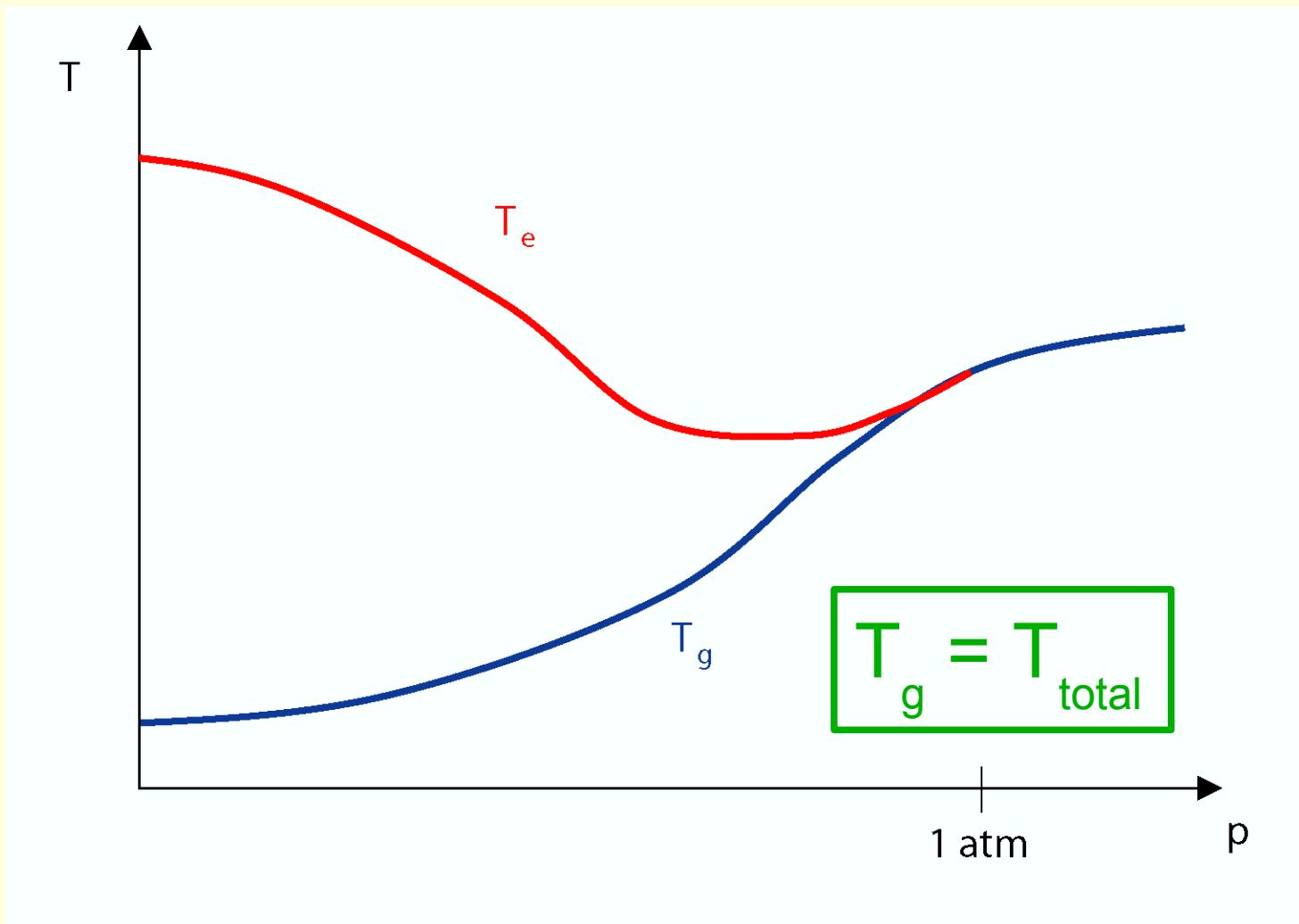
Plasma temperature

Helium:

$$m_{He^+} \approx 4m_p$$

$$m_{He^+}/m_e \approx 7347$$

Plasma temperature



Plasma temperature

$$E_{\text{kin}} = \frac{mv^2}{2}$$

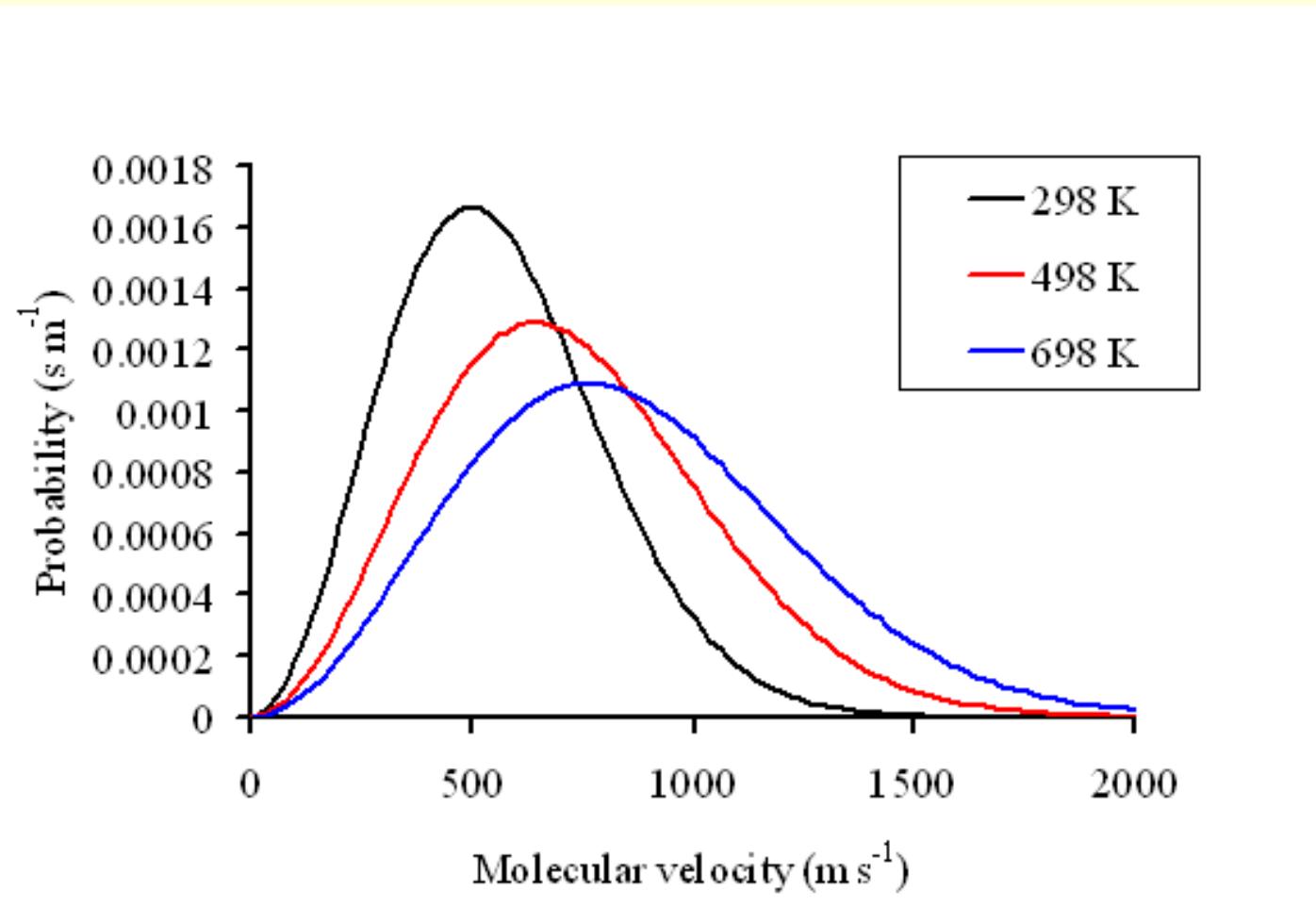
$$\overline{E_{\text{kin}}} = \frac{\overline{mv^2}}{2} \neq \frac{m\overline{v^2}}{2}$$

Plasma temperature

$$\bar{v} = \frac{v_1 + v_2 + \cdots + v_N}{N}$$

$$\overline{v^2} = \frac{v_1^2 + v_2^2 + \cdots + v_N^2}{N}$$

Maxwell-Boltzmann



velocity distribution

Plasma temperature

$$\bar{v} = \int_0^{\infty} v \cdot F(v) \, dv$$

$$\bar{v^2} = \int_0^{\infty} v^2 \cdot F(v) \, dv$$

Plasma temperature

$$\bar{v} = \int_0^{\infty} v \cdot F(v) \, dv$$

$$\bar{v^2} = \int_0^{\infty} v^2 \cdot F(v) \, dv$$

$$F(v) = \sqrt{\frac{2}{\pi}} \left(\frac{m}{k_B T} \right)^{1.5} v^2 \exp\left(-\frac{mv^2}{2k_B T}\right)$$

Plasma temperature

$$\bar{v} = \int_0^\infty v \cdot F(v) \, dv$$

$$\bar{v^2} = \int_0^\infty v^2 \cdot F(v) \, dv$$

$$F(v) = \sqrt{\frac{2}{\pi}} \left(\frac{m}{k_B T} \right)^{1.5} v^2 \exp\left(-\frac{mv^2}{2k_B T}\right)$$

$$\bar{v^2} = K \int_0^\infty v^4 e^{-av^2} \, dv$$

Plasma temperature

$$\bar{v} = \int_0^\infty v \cdot F(v) \, dv$$

$$\bar{v^2} = \int_0^\infty v^2 \cdot F(v) \, dv$$

$$F(v) = \sqrt{\frac{2}{\pi}} \left(\frac{m}{k_B T} \right)^{1.5} v^2 \exp\left(-\frac{mv^2}{2k_B T}\right)$$

$$\bar{v^2} = K \int_0^\infty v^4 e^{-av^2} \, dv$$

$$\int_0^\infty x^n e^{-ax^2} \, dx = \begin{cases} \frac{1}{2} \Gamma\left(\frac{n+1}{2}\right) / a^{\frac{n+1}{2}} & (n > -1, a > 0) \\ \frac{(2k-1)!!}{2^{k+1} a^k} \sqrt{\frac{\pi}{a}} & (n = 2k, k \text{ integer}, a > 0) \\ \frac{k!}{2a^{k+1}} & (n = 2k + 1, k \text{ integer}, a > 0) \end{cases}$$

Plasma temperature

$$F(v) = \sqrt{\frac{2}{\pi}} \left(\frac{m}{k_B T} \right)^{1.5} v^2 \exp\left(-\frac{mv^2}{2k_B T}\right)$$

$$\overline{v^2} = K \frac{3}{8a^2} \sqrt{\frac{\pi}{a}}$$

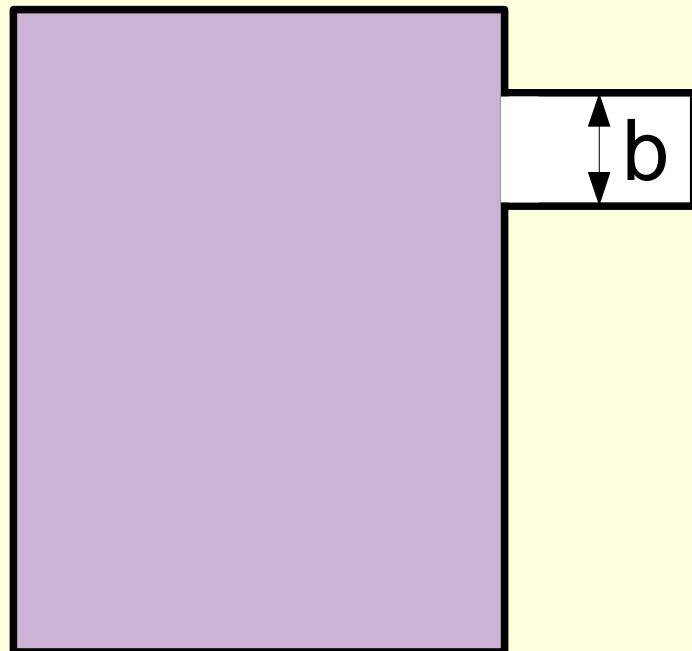
Plasma temperature

$$\overline{v^2} = \frac{3k_B T}{m}$$

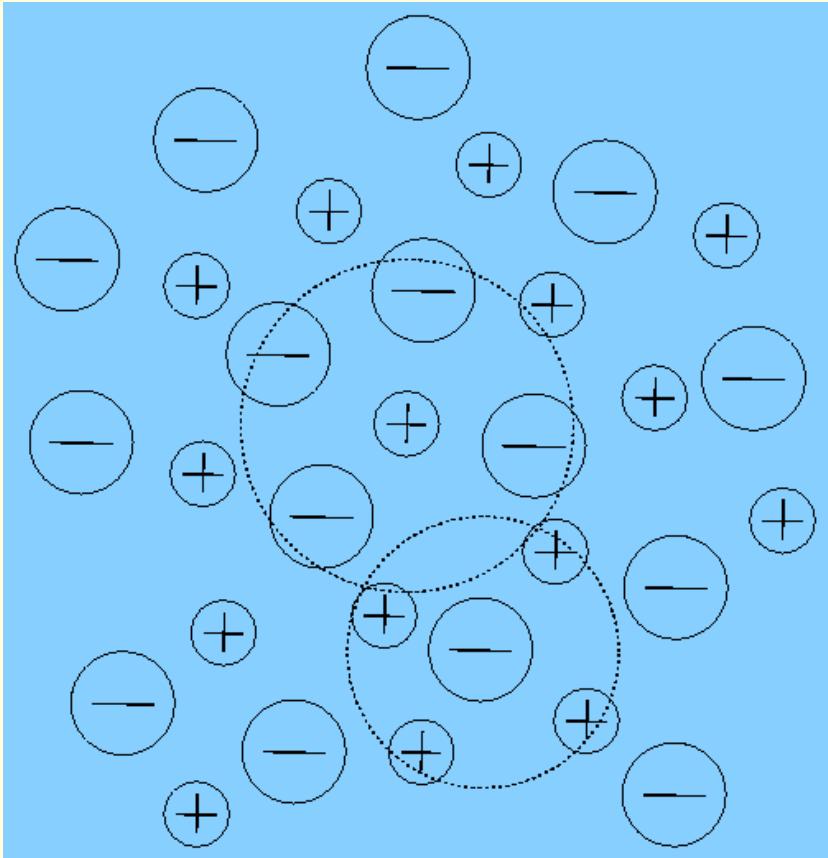
$$\begin{aligned}\overline{E_{\text{kin}}} &= \frac{mv^2}{2} \\ &= \frac{3}{2}k_B T\end{aligned}$$

Plasma chamber design

Plasma or not?



Electric shielding



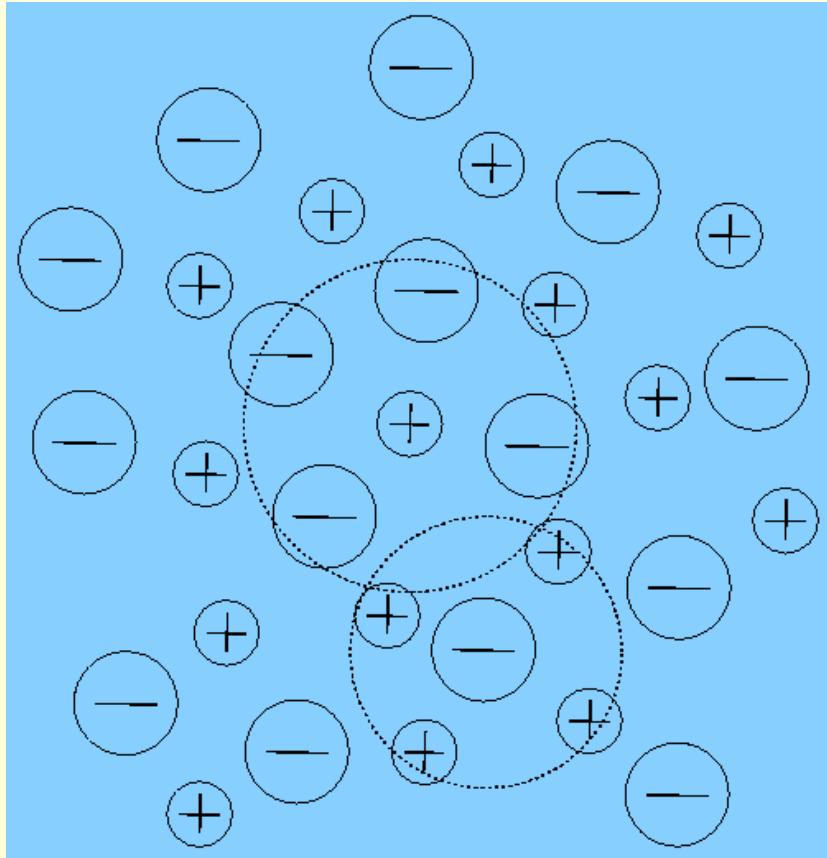
global: neutral

local: charged

Plasma definition

„**quasi-neutral** particle system
as mixture of free electrons,
ions, and neutral particles“

Electric shielding



global: neutral

local: charged

Distance where electric potential is decreased to $1/e$ of its maximum?

Electric shielding

$$\mathcal{E} = \frac{U}{s} \implies \mathcal{E} = \frac{dU}{dr} = \nabla U$$

Electric shielding

$$\mathcal{E} = \frac{U}{s} \implies \mathcal{E} = \frac{dU}{dr} = \nabla U$$

$$\rho = \nabla D = \epsilon_0 \nabla \mathcal{E} = \epsilon_0 \nabla \nabla U = \epsilon_0 \Delta U$$

Electric shielding

$$\mathcal{E} = \frac{U}{s} \implies \mathcal{E} = \frac{dU}{dr} = \nabla U$$

$$\rho = \nabla D = \epsilon_0 \nabla \mathcal{E} = \epsilon_0 \nabla \nabla U = \epsilon_0 \Delta U$$

$$\rho = qN$$

Electric shielding

$$\mathcal{E} = \frac{U}{s} \implies \mathcal{E} = \frac{dU}{dr} = \nabla U$$

$$\rho = \nabla D = \epsilon_0 \nabla \mathcal{E} = \epsilon_0 \nabla \nabla U = \epsilon_0 \Delta U$$

$$\rho = qN$$

$$N(E) = N_0 \exp\left(\frac{-E}{k_B T}\right)$$

Electric shielding

$$\mathcal{E} = \frac{U}{s} \implies \mathcal{E} = \frac{dU}{dr} = \nabla U$$

$$\rho = \nabla D = \epsilon_0 \nabla \mathcal{E} = \epsilon_0 \nabla \nabla U = \epsilon_0 \Delta U$$

$$\rho = qN$$

$$N(E) = N_0 \exp\left(\frac{-E}{k_B T}\right)$$

$$E = qU$$

Electric shielding

$$\mathcal{E} = \frac{U}{s} \implies \mathcal{E} = \frac{dU}{dr} = \nabla U$$

$$\rho = \nabla D = \epsilon_0 \nabla \mathcal{E} = \epsilon_0 \nabla \nabla U = \epsilon_0 \Delta U$$

$$\rho = qN$$

$$N(E) = N_0 \exp\left(\frac{-E}{k_B T}\right)$$

$$E = qU$$

$$N(U) = N_0 \exp\left(\frac{-qU}{k_B T}\right)$$

Electric shielding

$$\epsilon_0 \Delta U = q (N_{\text{ion}} - N_{\text{electron}})$$

$$\epsilon_0 \Delta U = e N_0 \left(\exp \left(\frac{eU}{k_B T} \right) - 1 \right)$$

Electric shielding

$$\epsilon_0 \Delta U = e N_0 \left(\exp\left(\frac{eU}{k_B T}\right) - 1 \right)$$

$$\exp(x) = \sum_{n=0}^{\infty} \frac{x^n}{n!} = 1 + x + \frac{x^2}{2!} + \cdots$$

Electric shielding

$$\epsilon_0 \Delta U = e N_0 \left(\exp\left(\frac{eU}{k_B T}\right) - 1 \right)$$

$$\exp(x) = \sum_{n=0}^{\infty} \frac{x^n}{n!} = 1 + x + \frac{x^2}{2!} + \cdots$$

$$U = U_0 \exp\left(-\frac{|x|}{\lambda_D}\right)$$

Electric shielding

$$\epsilon_0 \Delta U = e N_0 \left(\exp\left(\frac{eU}{k_B T}\right) - 1 \right)$$

$$\exp(x) = \sum_{n=0}^{\infty} \frac{x^n}{n!} = 1 + x + \frac{x^2}{2!} + \dots$$

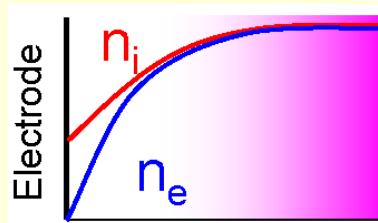
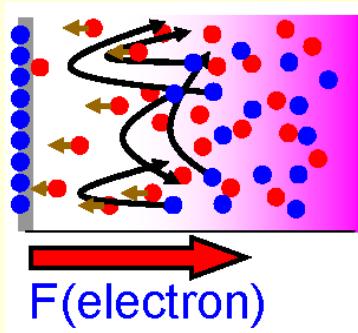
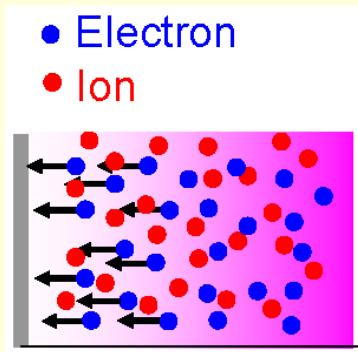
$$U = U_0 \exp\left(-\frac{|x|}{\lambda_D}\right)$$

Debye length: λ_D

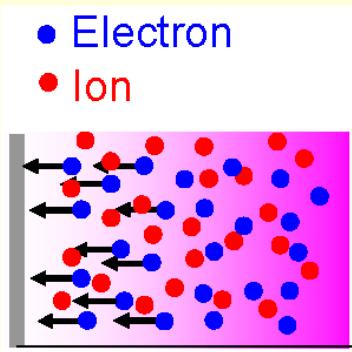
$$\lambda_D = \sqrt{\frac{\epsilon_0 k_B T}{e^2 N_o}}$$

typical values:
about 100 μm

Plasma sheath

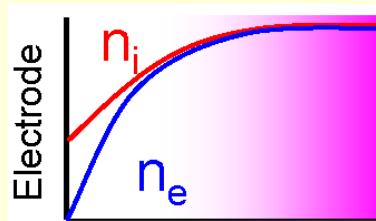
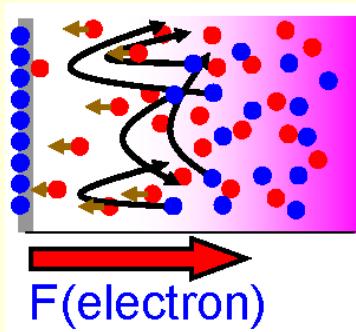


Plasma sheath

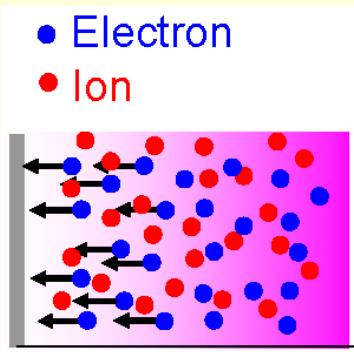


sheath distance: s

$$s \propto \lambda_D$$

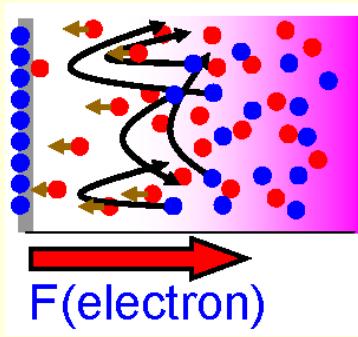


Plasma sheath

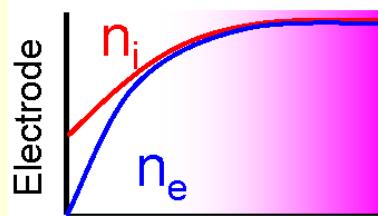


sheath distance: s

$$s \propto \lambda_D$$



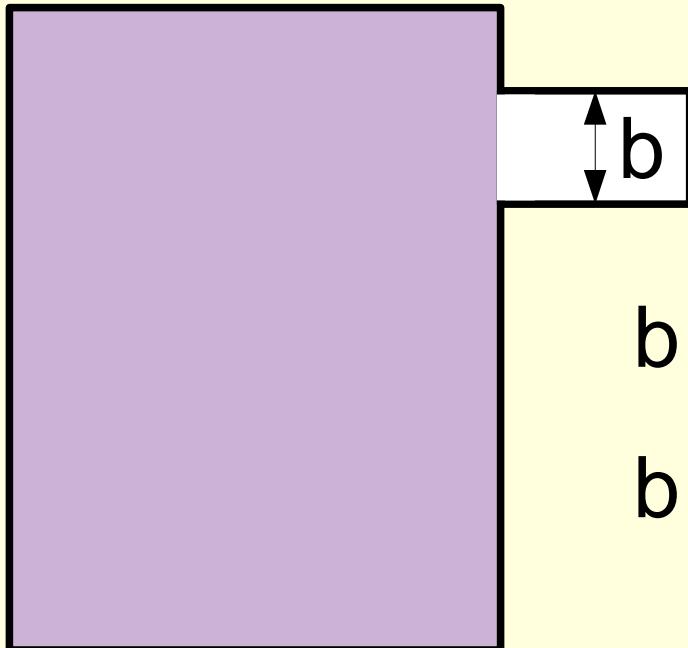
$$s \approx 1.1\lambda_D \left(\frac{eU_{sh}}{k_B T} \right)^{3/4}$$



$$U_{sh} = \frac{k_B T}{2e} \ln \left(\frac{m_+}{2\pi m_e} \right)$$

Plasma chamber design

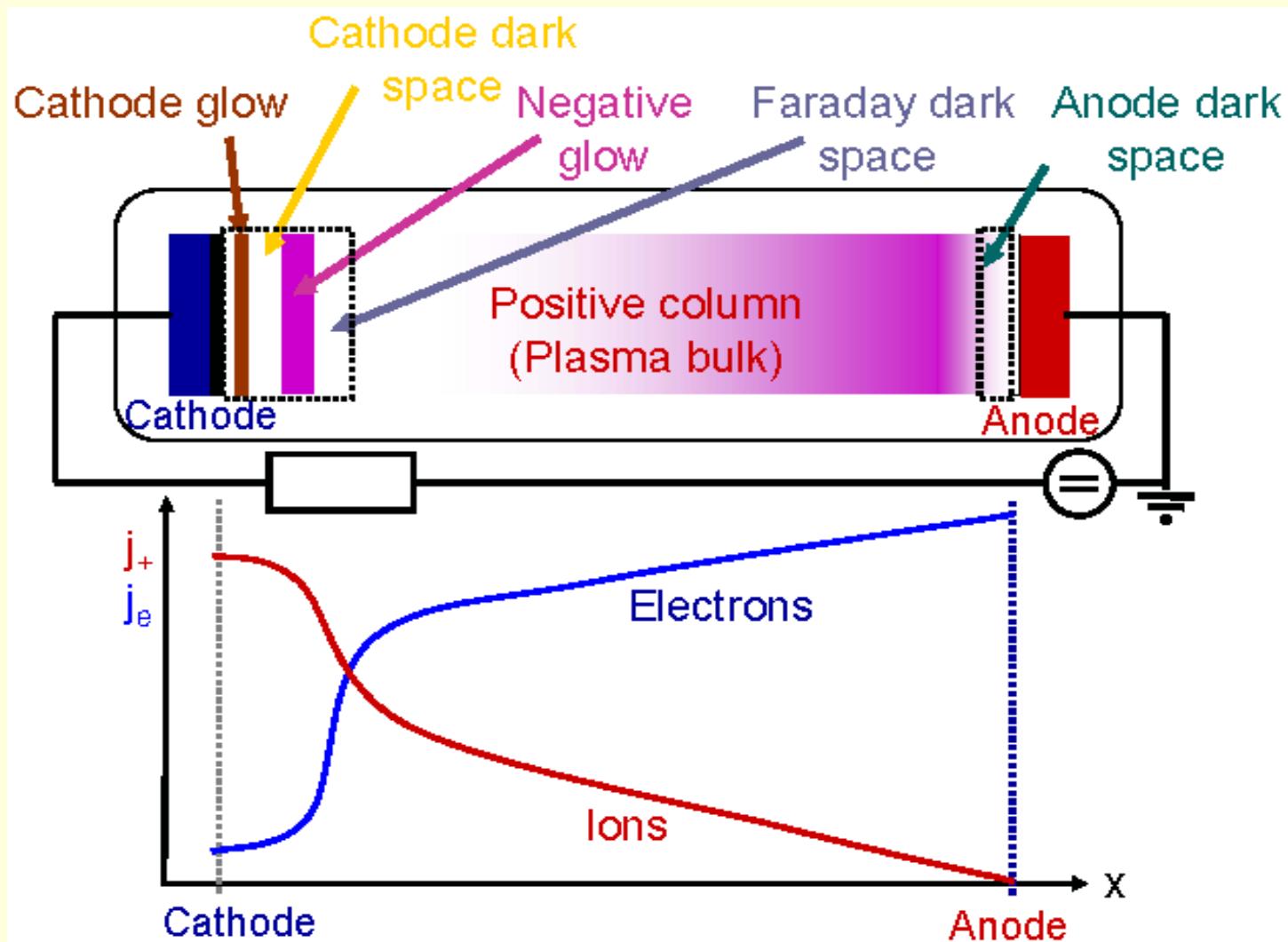
Plasma or not?



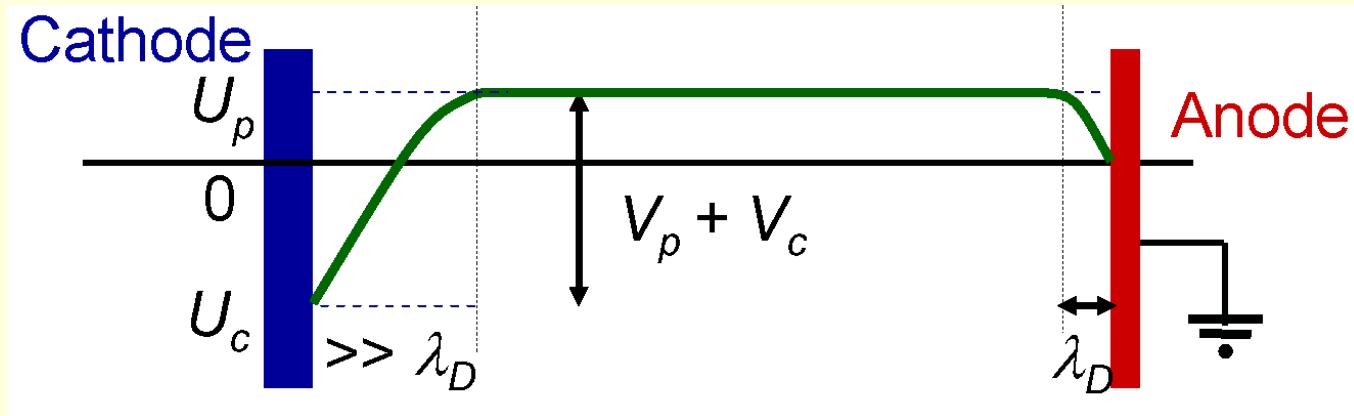
$b > 2s$: plasma

$b < 2s$: no plasma

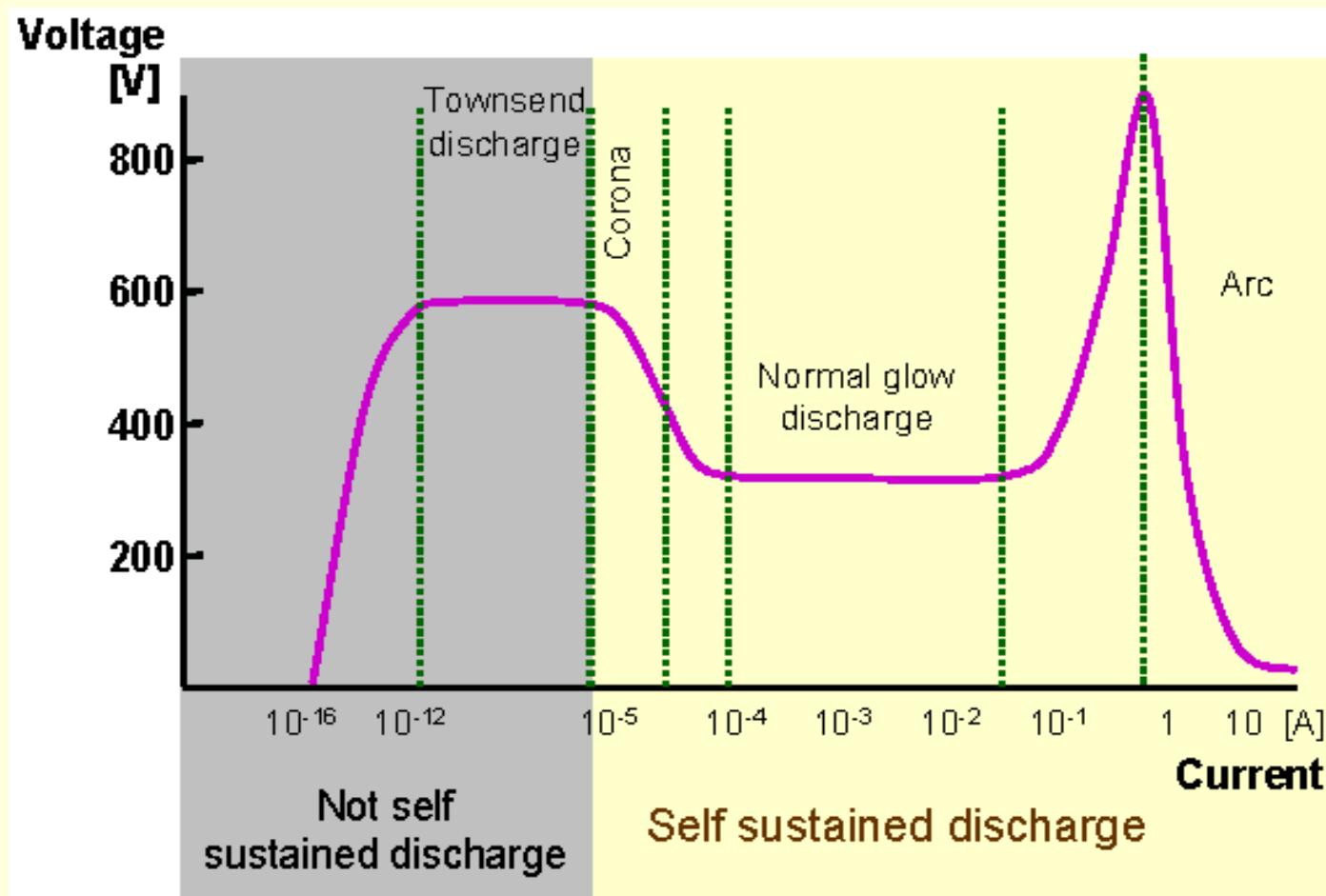
DC discharge



DC discharge

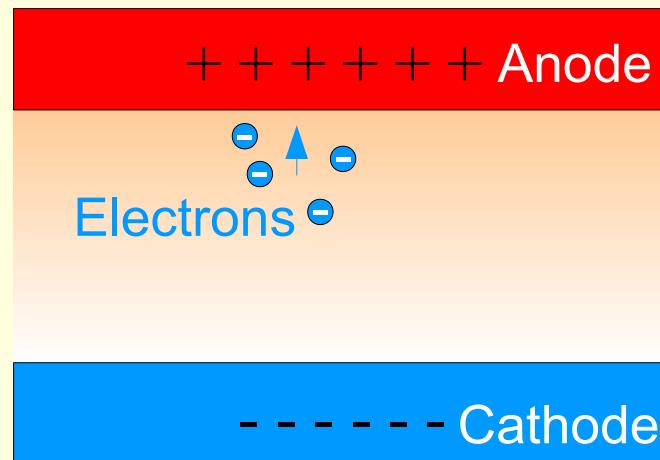
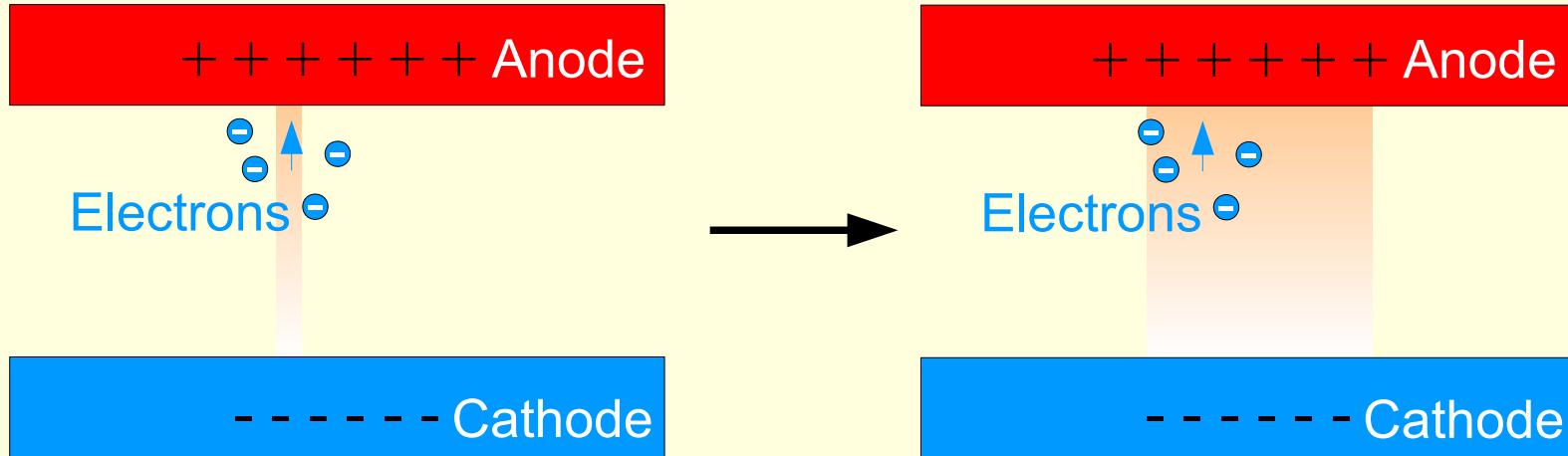


DC discharge



$$R = U/I$$

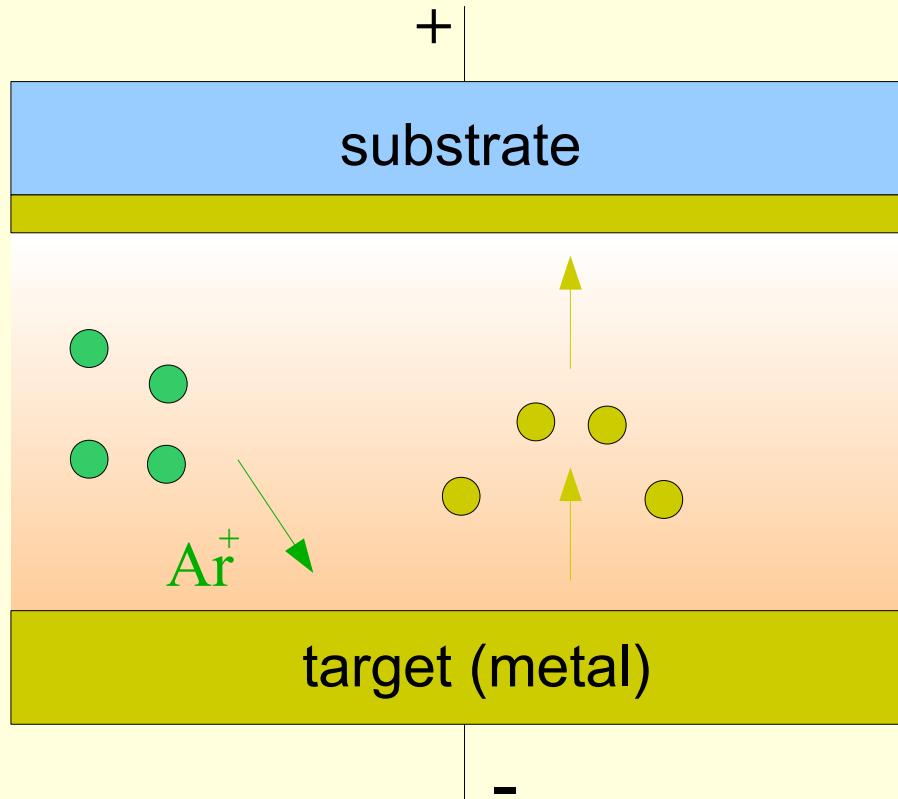
DC discharge



Plasma applications

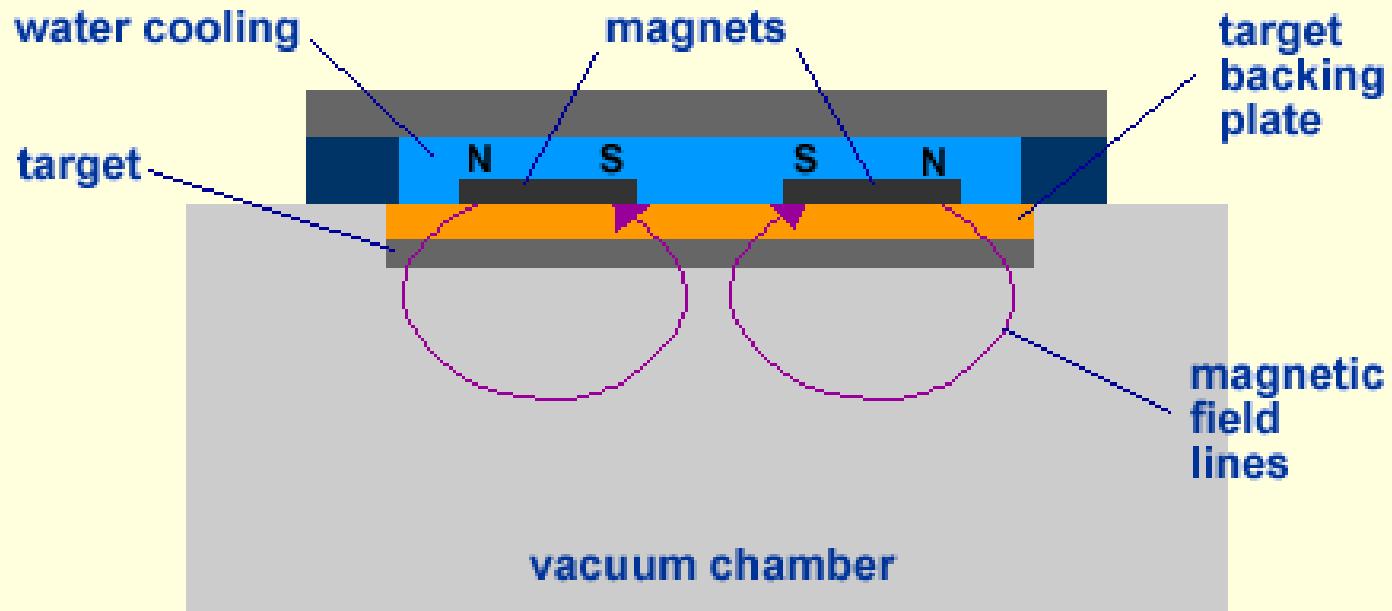
- Sputtering
- Etching / cleaning
- Surface activation
- Plasma displays

Sputtering



layer thickness homogeneity $\approx 5 \text{ nm}$

Magnetron sputtering

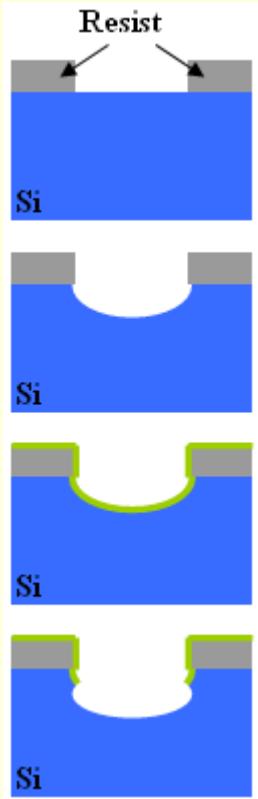


$$\vec{F} = q\vec{v} \times \vec{B}$$

electrons travel on a cycloide

Etching

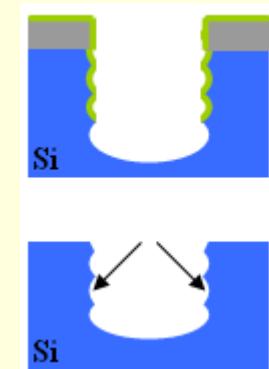
reactive ion etching



etching: plasma + SF₆

passivating: C₄F₈

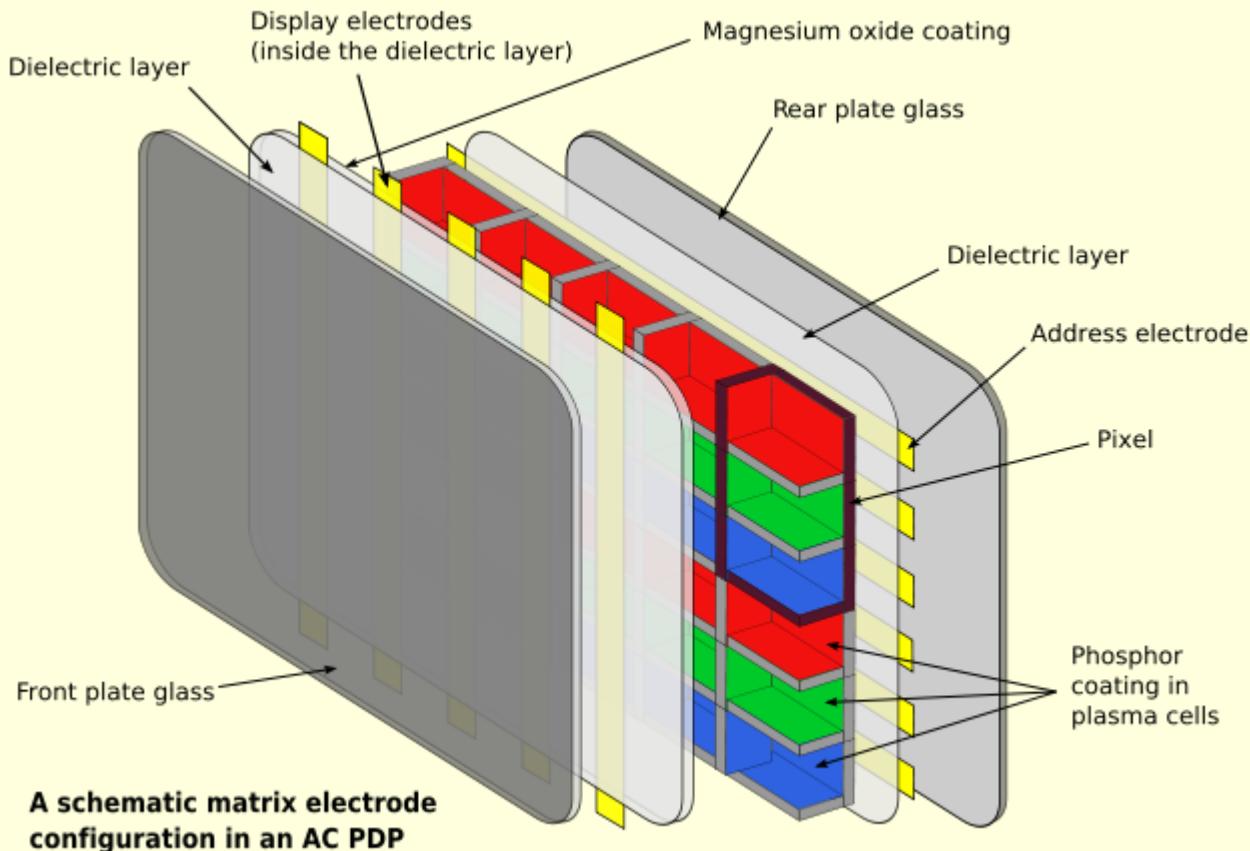
etching: plasma + SF₆



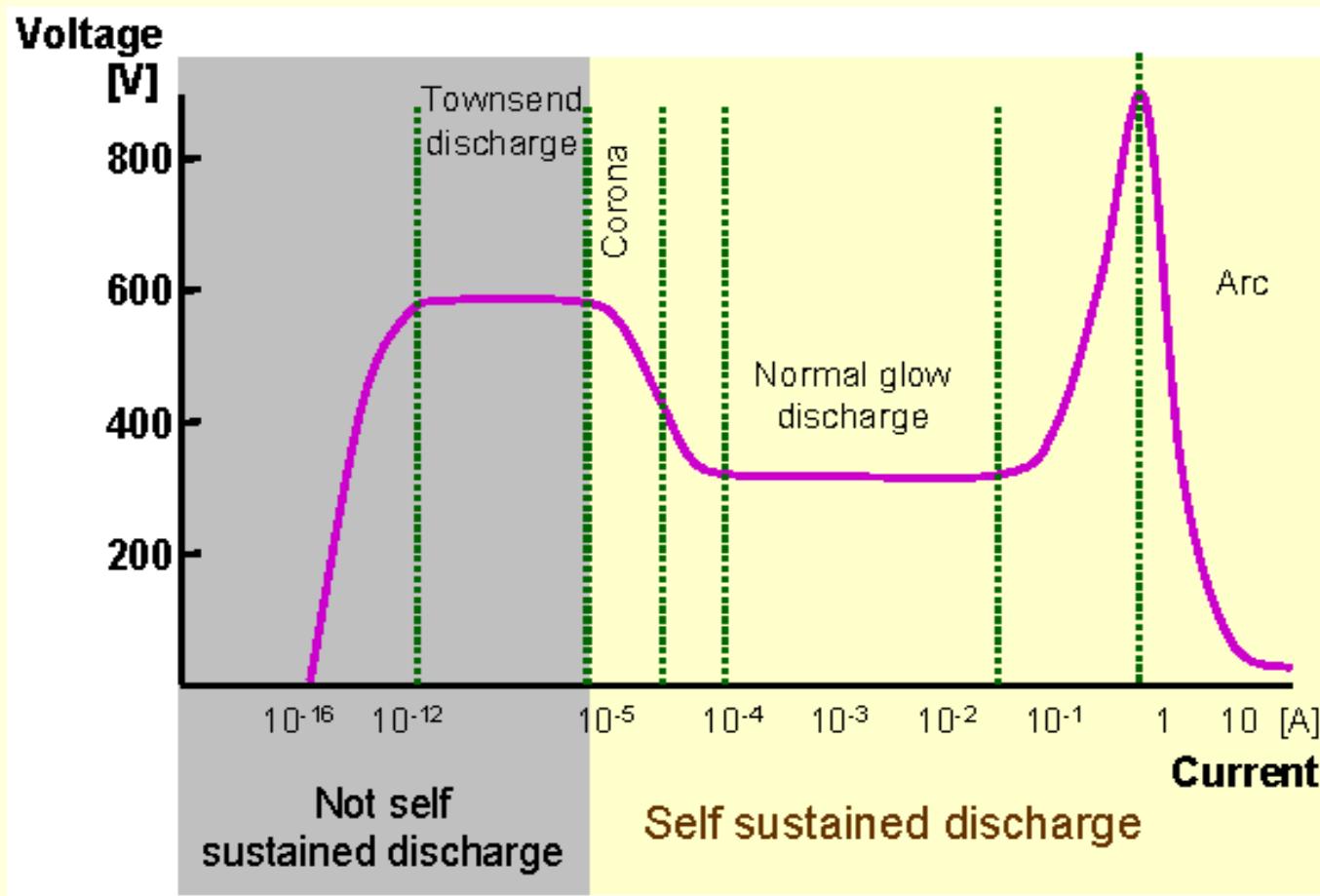
Activation

- 1) chemical bonds cracked
on the substrate surface
- 2) chemical reaction of ions
on the surface

Display

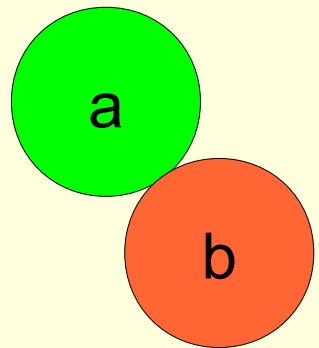


DC discharge



Needed voltage to ignite a plasma?

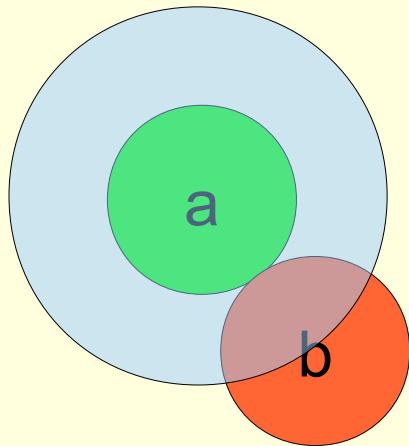
Mean free path



Mean free path

cross section: σ

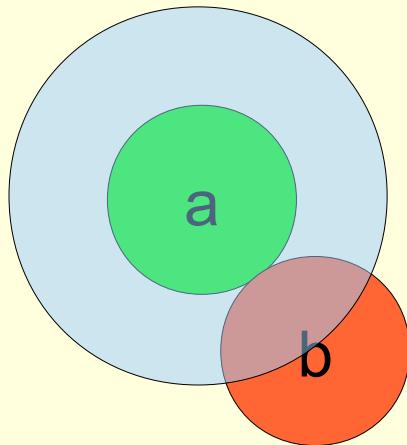
$$\sigma = \pi (r_a + r_b)^2$$



Mean free path

cross section: σ

$$\sigma = \pi (r_a + r_b)^2$$



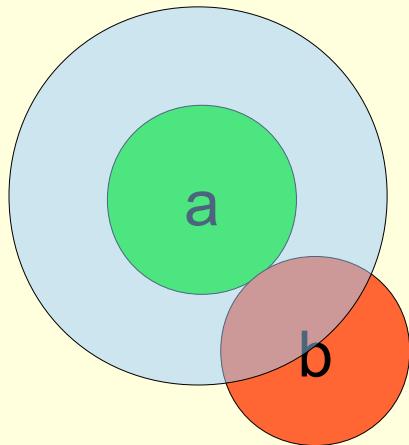
impact probability: P

$$P = \frac{N\sigma}{A} = \frac{x}{\lambda}$$

Mean free path

cross section: σ

$$\sigma = \pi (r_a + r_b)^2$$



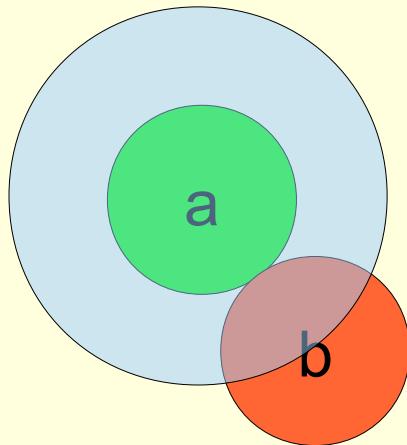
impact probability: P

$$P = \frac{N\sigma}{A} = \frac{x}{\lambda}$$

ideal gas law

$$pV = Nk_B T$$

Mean free path



cross section: σ

$$\sigma = \pi (r_a + r_b)^2$$

impact probability: P

$$P = \frac{N\sigma}{A} = \frac{x}{\lambda}$$

ideal gas law

$$pV = Nk_B T$$

mean free path: λ_e

$$\lambda_e = \frac{k_B T}{p\pi r^2}$$

Impact probability

particle current: Γ

$$d\Gamma(x) = -\Gamma(x) \frac{dx}{\lambda_e}$$

Impact probability

particle current: Γ

$$d\Gamma(x) = -\Gamma(x) \frac{dx}{\lambda_e}$$

$$\Gamma(x) = \Gamma(0) \exp\left(-\frac{x}{\lambda_e}\right)$$

$$P(\lambda > x) = \frac{\Gamma(x)}{\Gamma(0)} = \exp\left(-\frac{x}{\lambda_e}\right)$$

Impact probability

number of ionizations per length λ_e : α
(1st Townsend coefficient)

$$\alpha = \frac{P(\lambda > \lambda_I)}{\lambda_e} = \frac{1}{\lambda_e} \exp\left(-\frac{\lambda_I}{\lambda_e}\right)$$

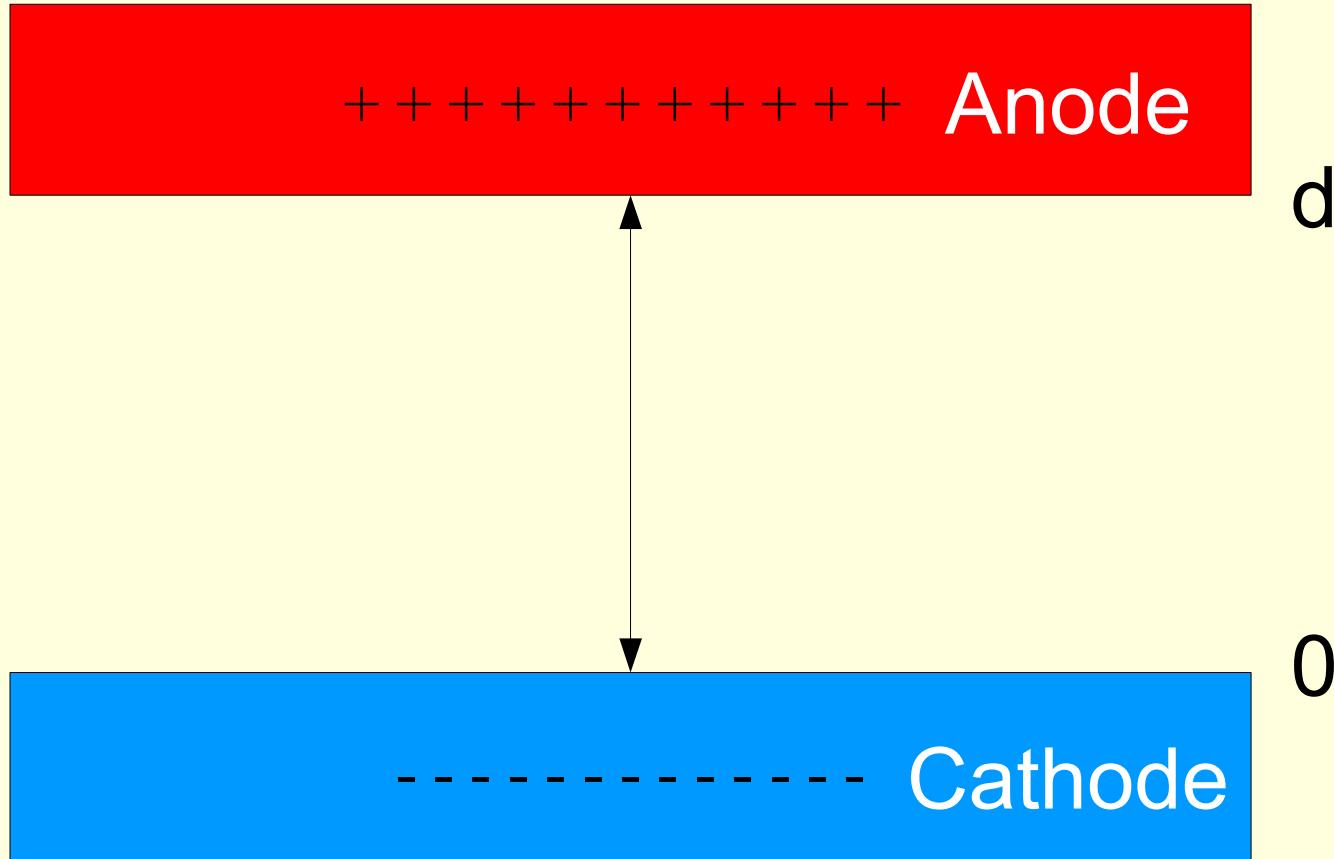
Impact probability

number of ionizations per length λ_e : α
(1st Townsend coefficient)

$$\begin{aligned}\alpha &= \frac{P(\lambda > \lambda_I)}{\lambda_e} = \frac{1}{\lambda_e} \exp\left(-\frac{\lambda_I}{\lambda_e}\right) \\ &= \frac{1}{\lambda_e} \exp\left(-\frac{E_I}{E_e}\right)\end{aligned}$$

$$E_I = \lambda_I q \mathcal{E}$$

Ignition voltage



Ignition voltage

$$\Gamma_e(x = d) = \Gamma_e(x = 0) e^{\alpha d}$$

number of electrons = number of ions

$$\Gamma_e(d) - \Gamma_e(0) = \Gamma_e(0) (e^{\alpha d} - 1)$$

$$\Gamma_i(d) = 0$$

Ignition voltage

$$\Gamma_e(x = d) = \Gamma_e(x = 0) e^{\alpha d}$$

number of electrons = number of ions

$$\Gamma_e(d) - \Gamma_e(0) = \Gamma_e(0) (e^{\alpha d} - 1)$$

$$\Gamma_i(d) = 0$$

$$\Gamma_e(0) = \gamma \Gamma_i(0)$$

number of secondary electrons per ion: γ
(2nd Townsend coefficient)

Ignition voltage

$$\alpha d = \ln \left(1 + \frac{1}{\gamma} \right)$$

Ignition voltage

$$\alpha d = \ln \left(1 + \frac{1}{\gamma} \right)$$

$$\begin{aligned}\alpha &= \frac{1}{\lambda_e} \exp \left(-\frac{E_I}{E_e} \right) \\ &= L \cdot p \exp \left(-\frac{L \cdot p \cdot d \cdot E_I}{eU} \right)\end{aligned}$$

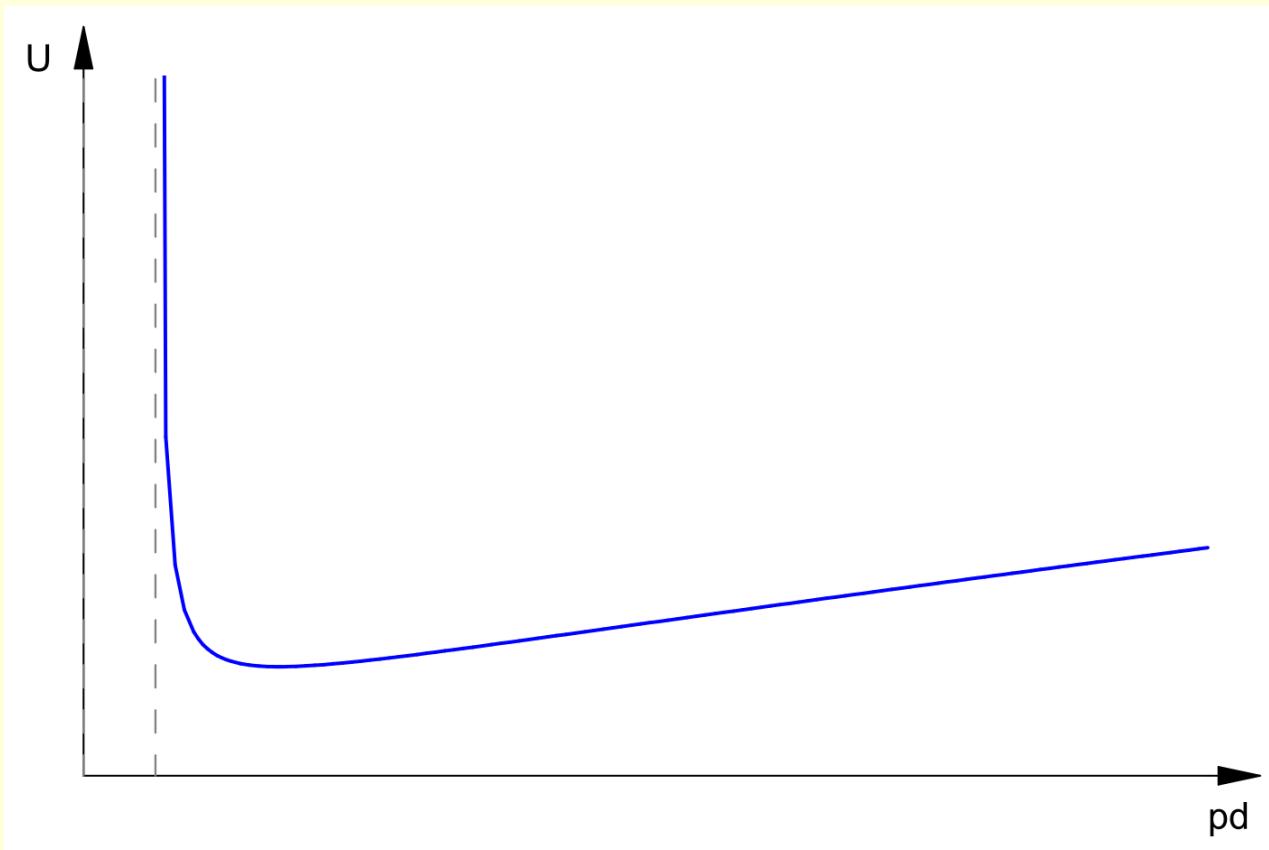
$$\lambda_e = \frac{k_B T}{p \pi r^2}$$

Ignition voltage

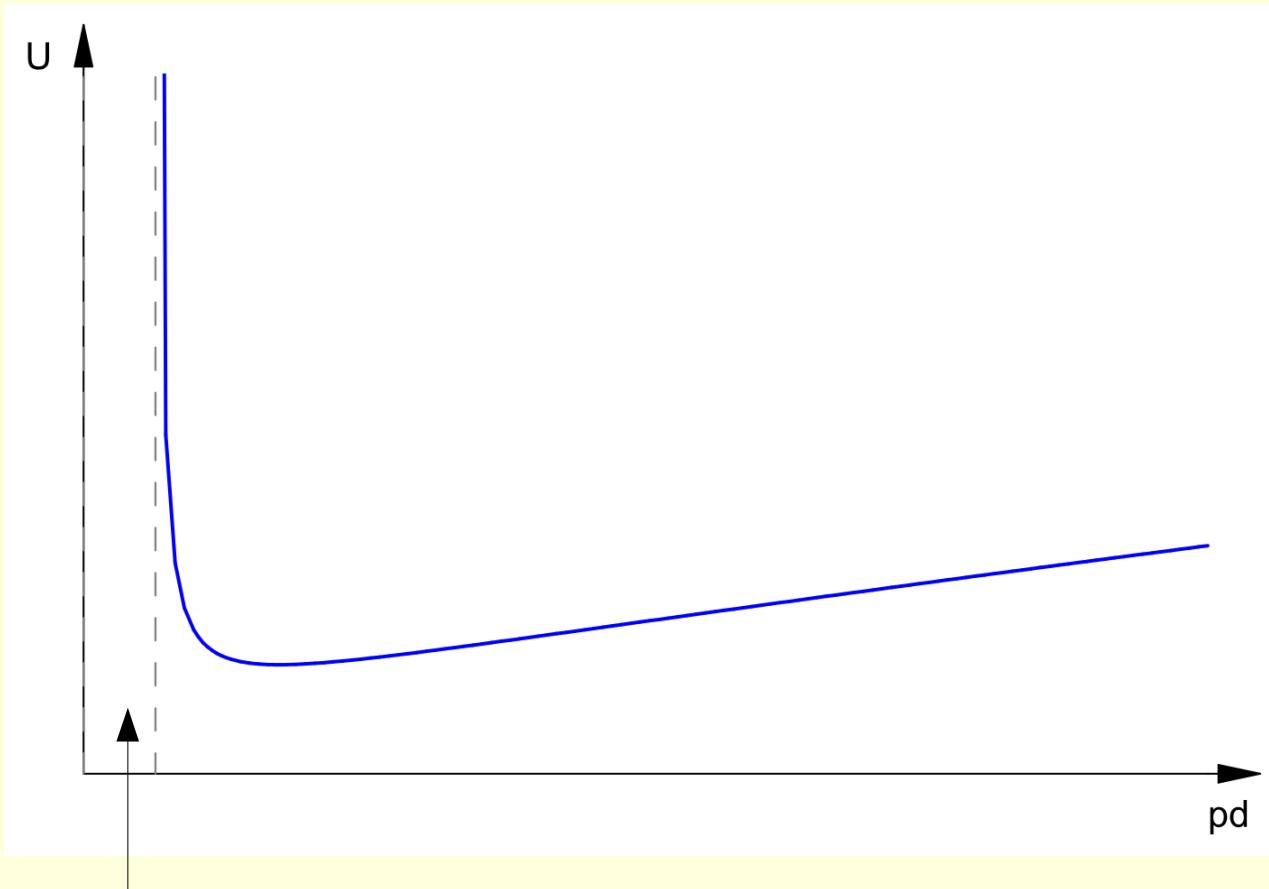
Paschen-Townsend law

$$U = \frac{L \cdot p \cdot d \cdot E_I}{e \left(\ln(L \cdot p \cdot d) - \ln \left(\ln \left(1 + \gamma^{-1} \right) \right) \right)}$$

Ignition voltage



Ignition voltage



no plasma

Ignition voltage

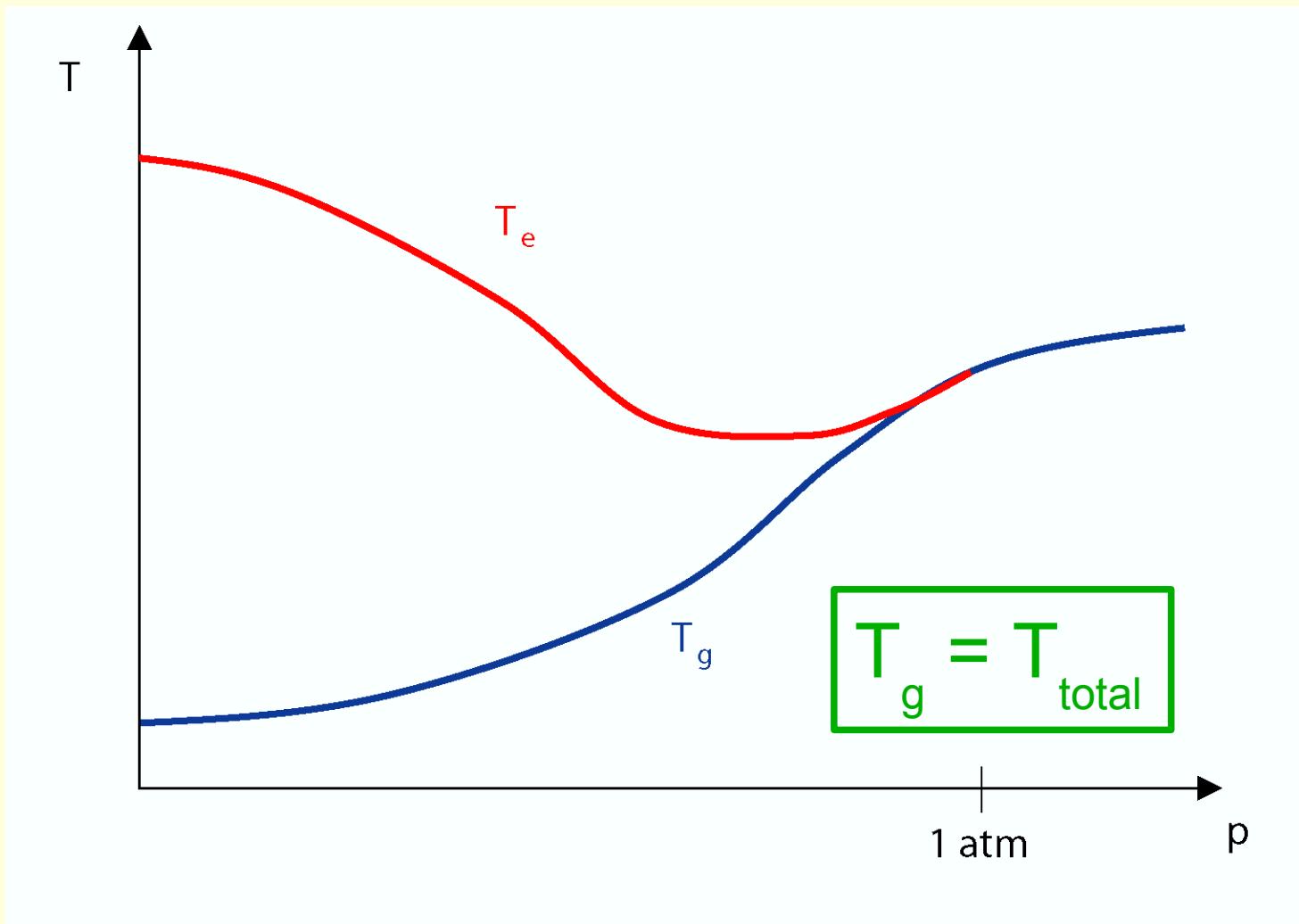
$$U = \frac{L \cdot p \cdot d \cdot E_I}{e \left(\ln(L \cdot p \cdot d) - \ln \left(\ln \left(1 + \gamma^{-1} \right) \right) \right)}$$

Ignition voltage

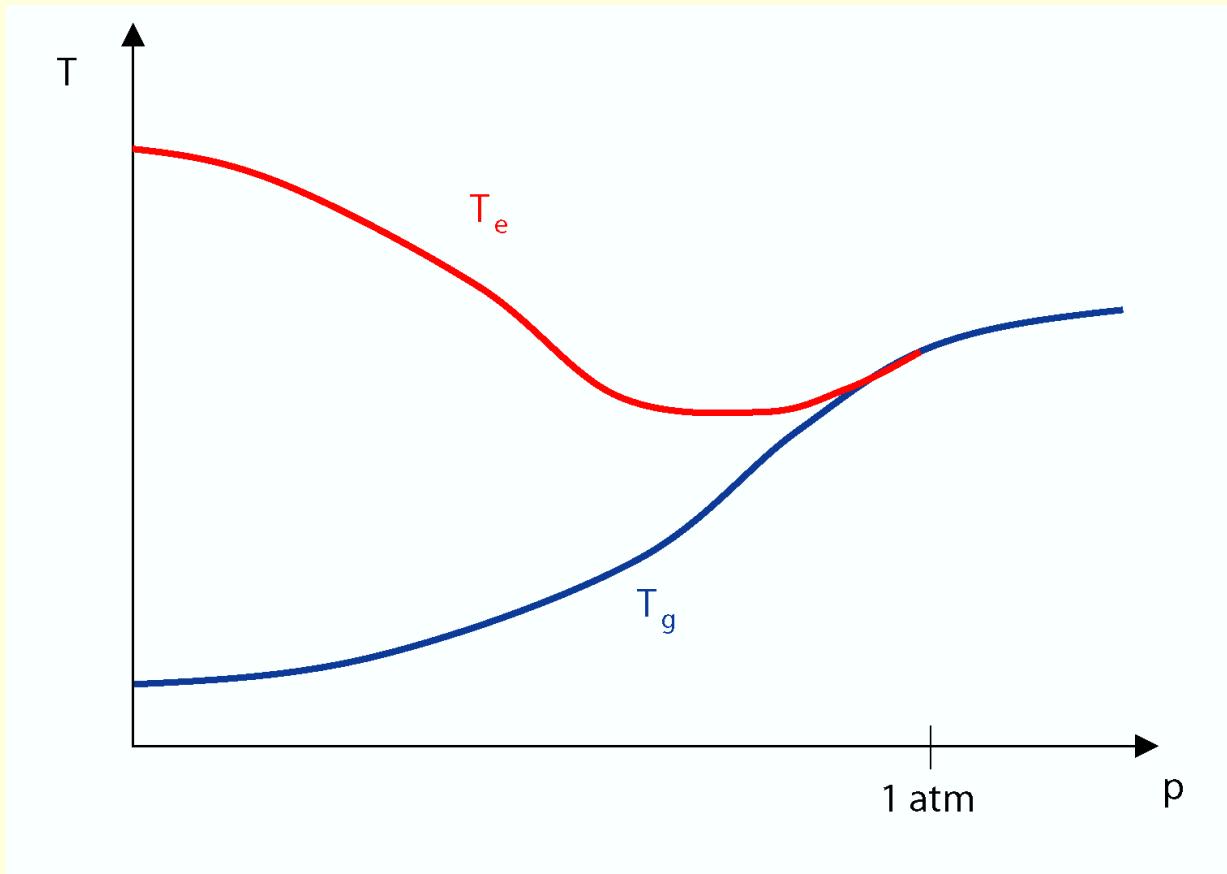
$$U = \frac{L \cdot p \cdot d \cdot E_I}{e \left(\ln(L \cdot p \cdot d) - \ln \left(\ln \left(1 + \gamma^{-1} \right) \right) \right)}$$

no plasma when $d \leq \lambda_e$

Plasma temperature

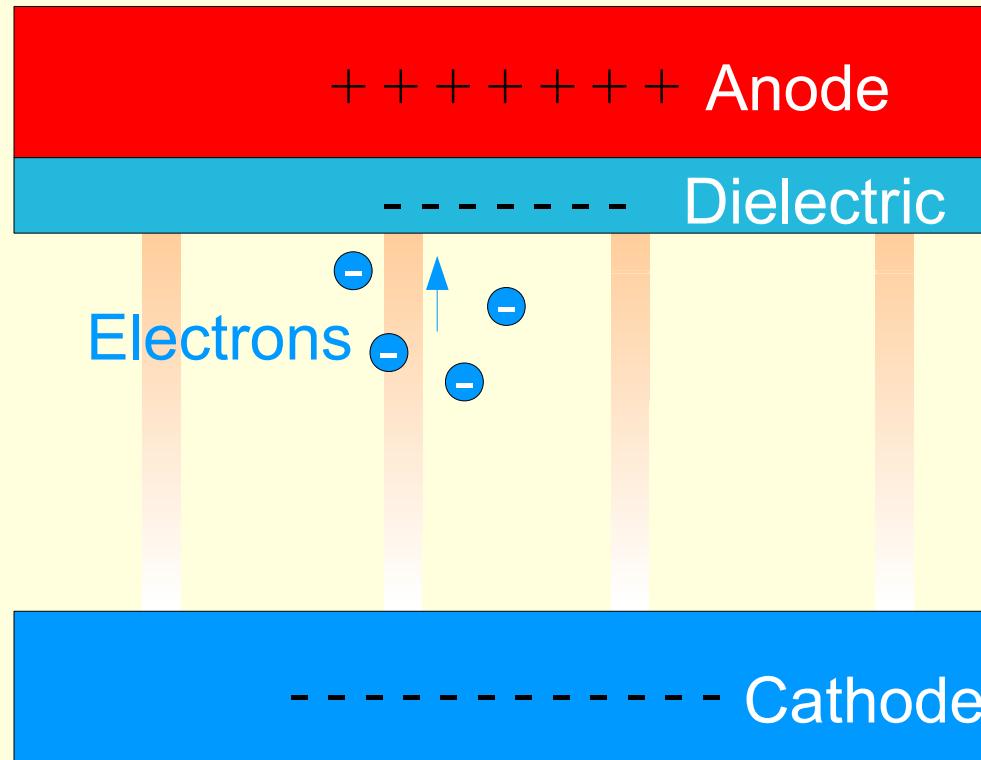


Plasma temperature



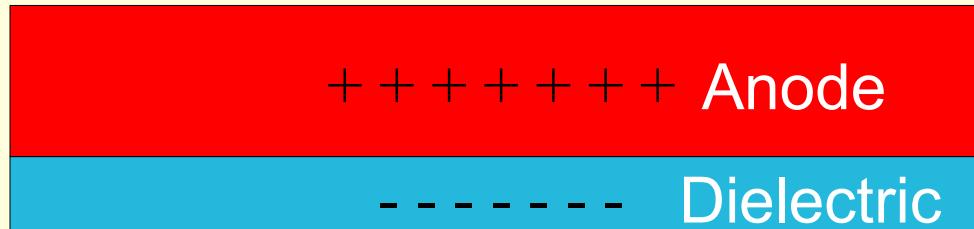
Cold plasma at atmospheric pressure?

Dielectric barrier discharge

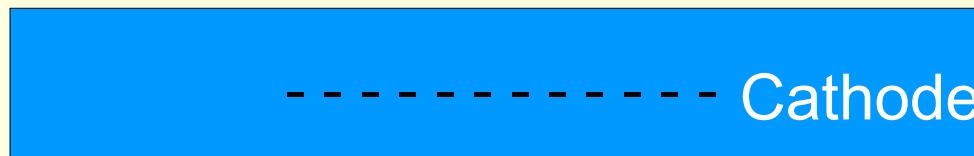
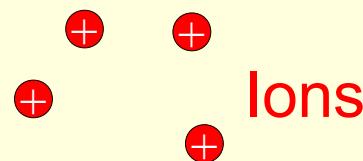


plasma streamers

Dielectric barrier discharge

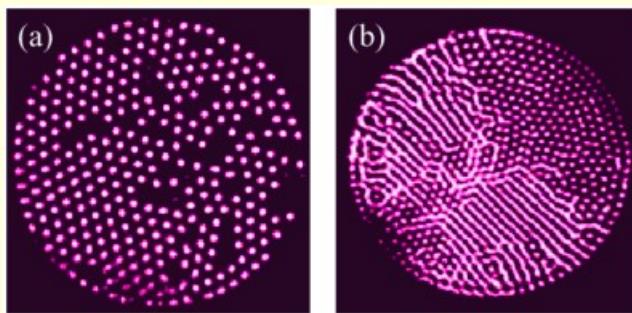
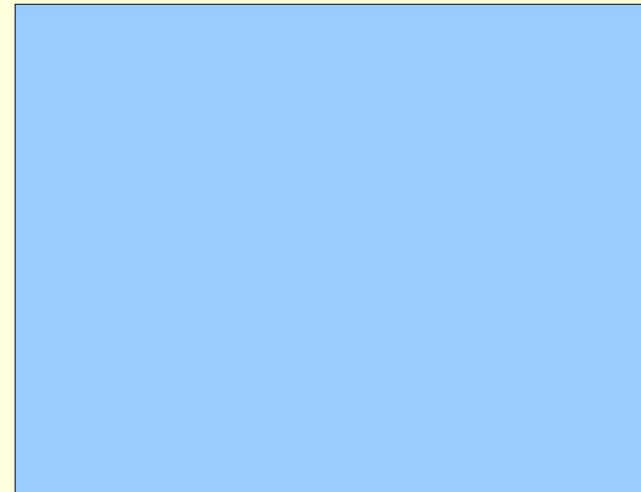
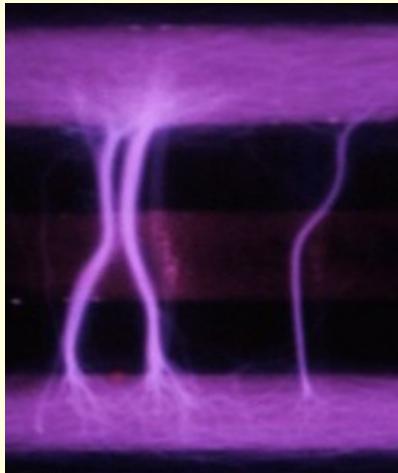


no plasma



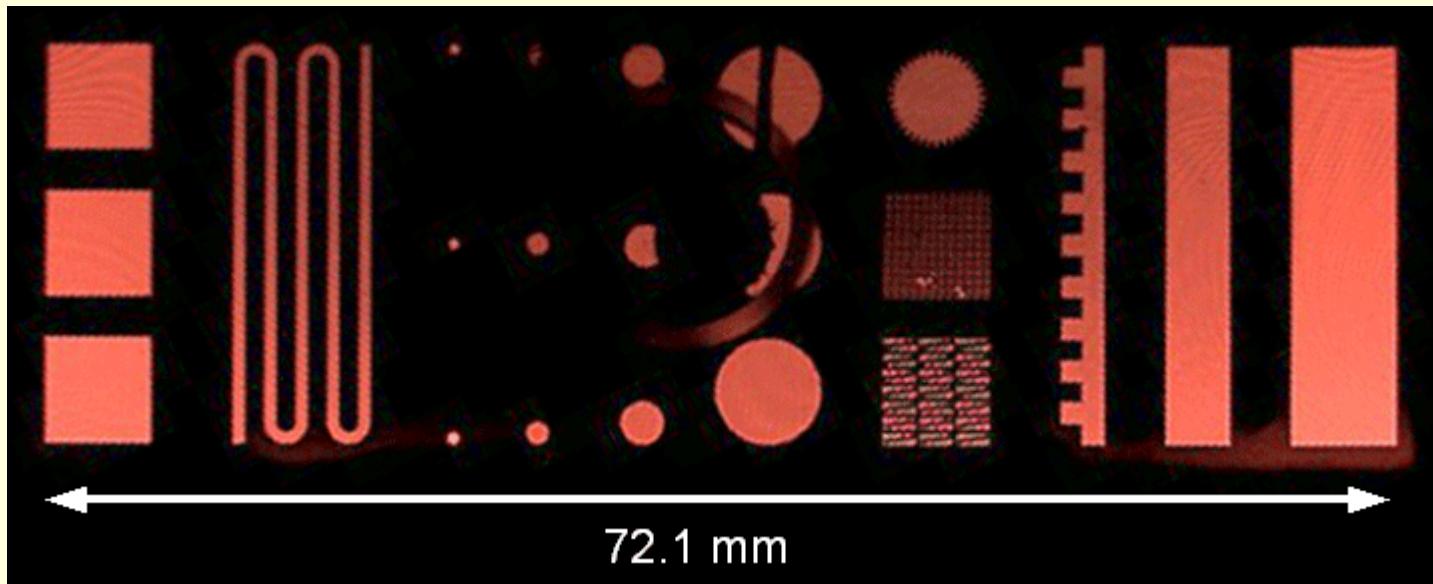
ions cannot follow →
plasma keeps cold

Dielectric barrier discharge



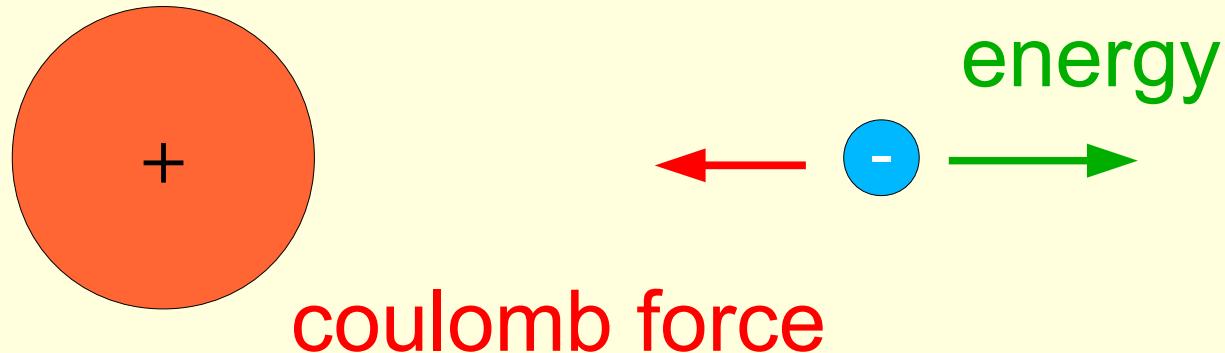
plasma streamers

Dielectric barrier discharge

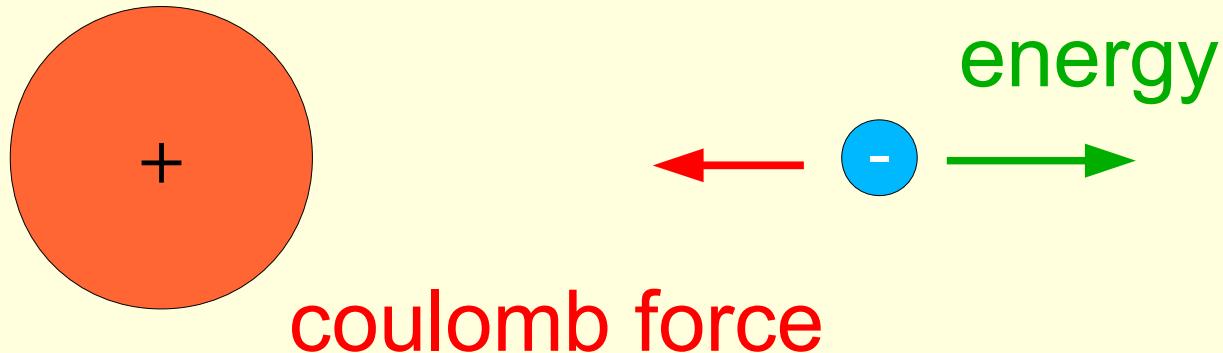


plasma printing

Plasma frequency

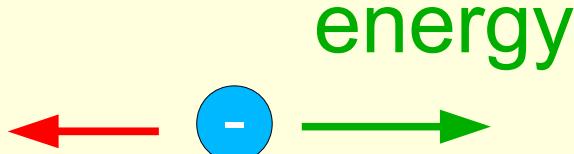
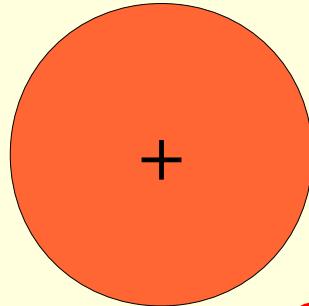


Plasma frequency



$$F = m \frac{d^2x}{dt^2} = -q\mathcal{E}$$

Plasma frequency



coulomb force

$$F = m \frac{d^2x}{dt^2} = -q\mathcal{E}$$

$$\epsilon \nabla \mathcal{E} = \rho = ne$$

$$\mathcal{E} = \frac{ne \cdot x}{\epsilon}$$

$$m \frac{d^2x}{dt^2} = -\frac{ne^2 x}{\epsilon}$$

Plasma frequency

$$\omega_p = \sqrt{\frac{ne^2}{m\epsilon}}$$

When ω above ω_p , plasma transparent,
otherwise reflecting.

Plasma frequency

$$\omega_p = \sqrt{\frac{ne^2}{m\epsilon}}$$

When ω above ω_p , plasma transparent,
otherwise reflecting.

UV: metal transparent
IR or VIS: metal reflecting

Frequency propagation

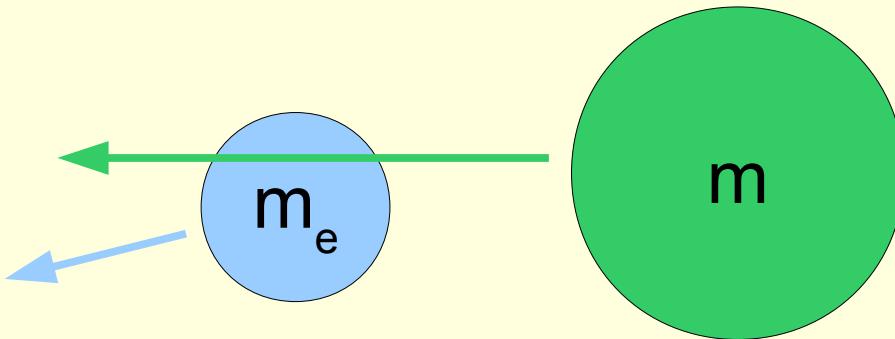
When ω above ω_p , plasma transparent,
otherwise reflecting.

$$E = hf = h\frac{\omega}{2\pi} = mc^2$$

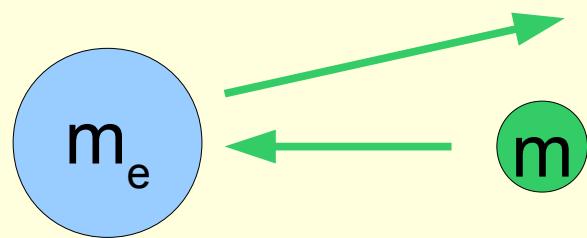
$$\omega \gg \omega_p \rightarrow m \gg m_e$$

$$\omega \ll \omega_p \rightarrow m \ll m_e$$

Frequency propagation



$$\omega \gg \omega_p \rightarrow m \gg m_e$$



$$\omega \ll \omega_p \rightarrow m \ll m_e$$



thanks for your attention