Federal University of Santa Catarina
Graduate Program in Engineering and Mechanical Sciences

Plasmas and electrical discharges in gases

(ECM410054)

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SUMMARY
Plasmas and electrical discharge in gases

- Kinetic theory of gases
- Atomic structure
- Ionization
- Deionization
- Electron emission
- ~~Behavior of charged particles in a gas in electric fields of low E/p~~
- Behavior of charged particles in a gas in electric fields of high E/p
- Glow discharges
- Plasmas

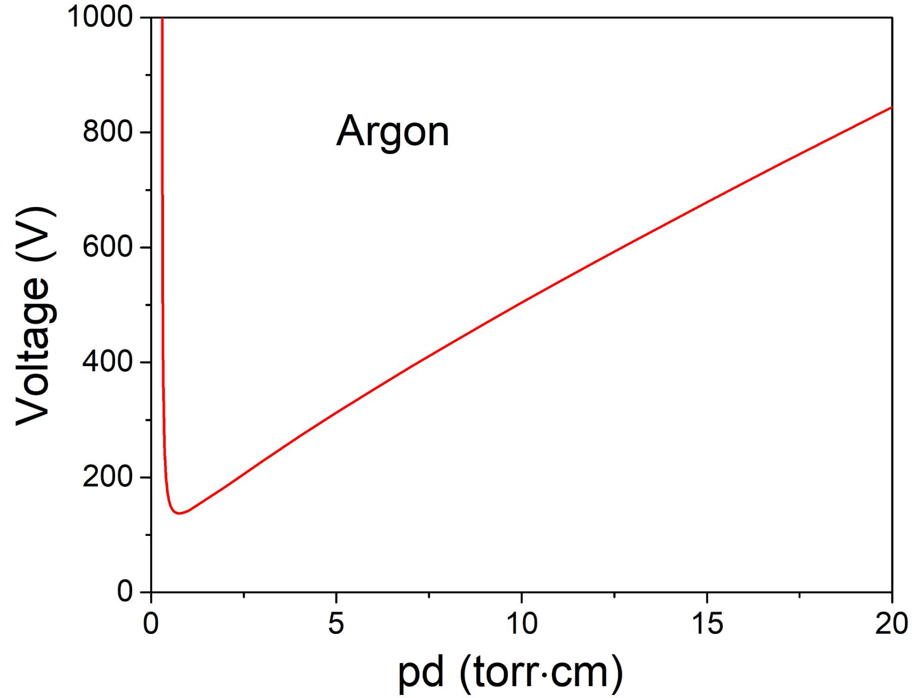
PLASMAS AND GLOW DISCHARGES
Secondary electron emission and Paschen's law

The breakdown voltage is given by

$$V_b = \frac{Bpd}{\ln\left[\frac{Apd}{\ln\left(1+1/\gamma\right)}\right]}$$

where A and B are constants for each gas, p the gas pressure, d the interelectrode distance and γ the **secondary electron emission** or the **second Townsend coefficient of ionization**.

The **secondary electron emission** is the number of electrons emitted from the cathode by positive-ion impact, gas-produced photons etc.



Gas	*A* ionizations/cm-torr	*B* V/cm-torr	*E*/*p* Validity Range V/cm-torr
Air	15	365	100–800
N_2	12	342	100–600
H_2	5.1	138.8	20–600
He	3	34	20–150
Ne	4	100	100–400
A	14	180	100–600
Kr	17	240	100–1000
Xe	26	350	200–800

PLASMAS AND GLOW DISCHARGES
Remote Glow Discharge Experiment (RGDX)

PPPL PRINCETON PLASMA PHYSICS LABORATORY

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Remote Glow Discharge Experiment (RGDX)

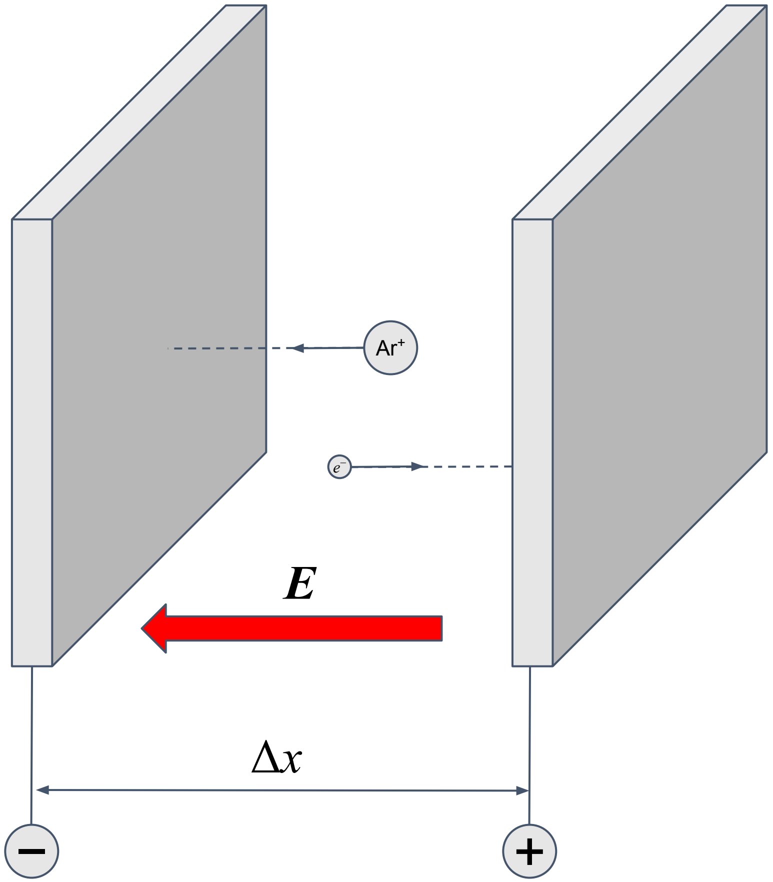
Controlling a lab from home

The Remote Control Glow Discharge (RGDX) is a plasma that you can control from the comfort of your browser. **YOU** have control of the entire experiment including the gas pressure inside the tube, the voltage produced by the power supply that makes the plasma, and the strength of an electromagnet surrounding the plasma. You can perform experiments from any computer anywhere in the world!

In 2002, we began developing plasma sources for educational purposes and one of our devices won 2nd place in the National Apparatus Competition sponsored by the American Association of Physics Teachers. In 2003, we began controlling our plasma sources by computer for a plasma exhibit in a science museum. The progression of this has led to remote control of a plasma from any location by anyone with an internet connection. This type of control could serve as an experimental component of an online physics class or for a school that typically does not have plasma physics equipment.

PLASMAS AND GLOW DISCHARGES
Electron and ion temperature

- Due to the presence of electrons and ions, the plasma state is moldable upon application of external fields.



- Electrons and ions presents their own velocity distribution.
- The work done on each particle is given by:

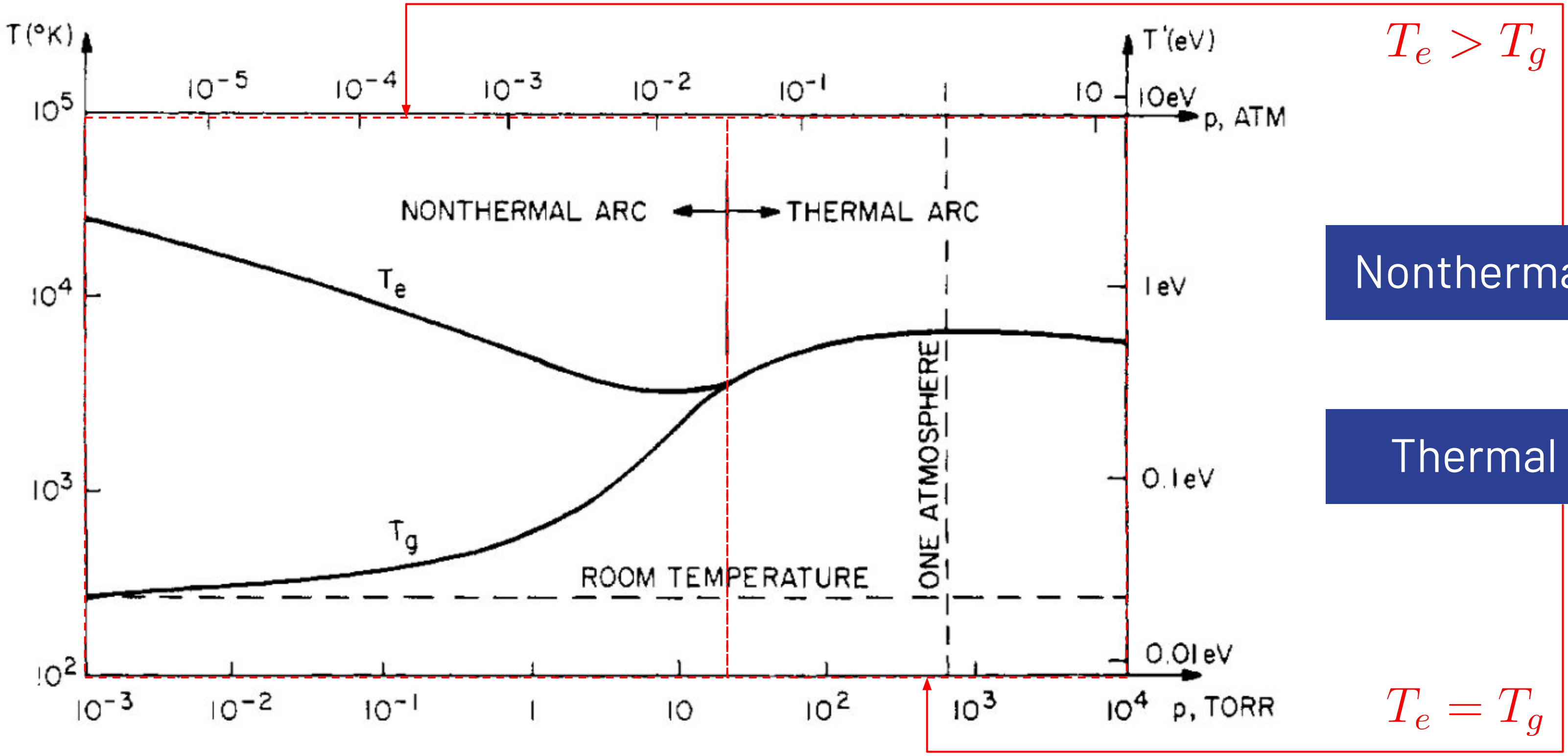
$$W = F\Delta x = eE\Delta x = eE\left(\frac{eE}{2m}t^2\right) = \frac{(eEt)^2}{2m}$$

- This equation states that the action of the electric field is primarily to give energy to the electrons.
- For low pressure gases, electrons can have higher average kinetic energy, with 2-8 eV typically.
- Electrons with kinetic energy of 2 eV present a temperature of 23,200 K! (most probable: 2 eV = $k_B T_e$).

Electronic temperature

PLASMAS AND GLOW DISCHARGES
Thermal and nonthermal plasmas

- Ions can receive some energy from the external electric field, but their temperature is a little higher than the gas (room) temperature; 500 K is representative.



Nonthermal plasmas

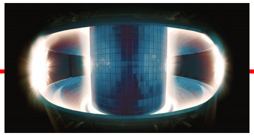
Thermal plasmas

Figure 10.2 The operation of arcs as a function of pressure.

PLASMAS AND GLOW DISCHARGES

Scope

https://www.iter.org/mag/2/18



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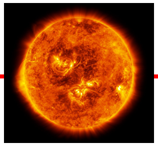
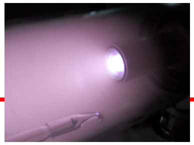


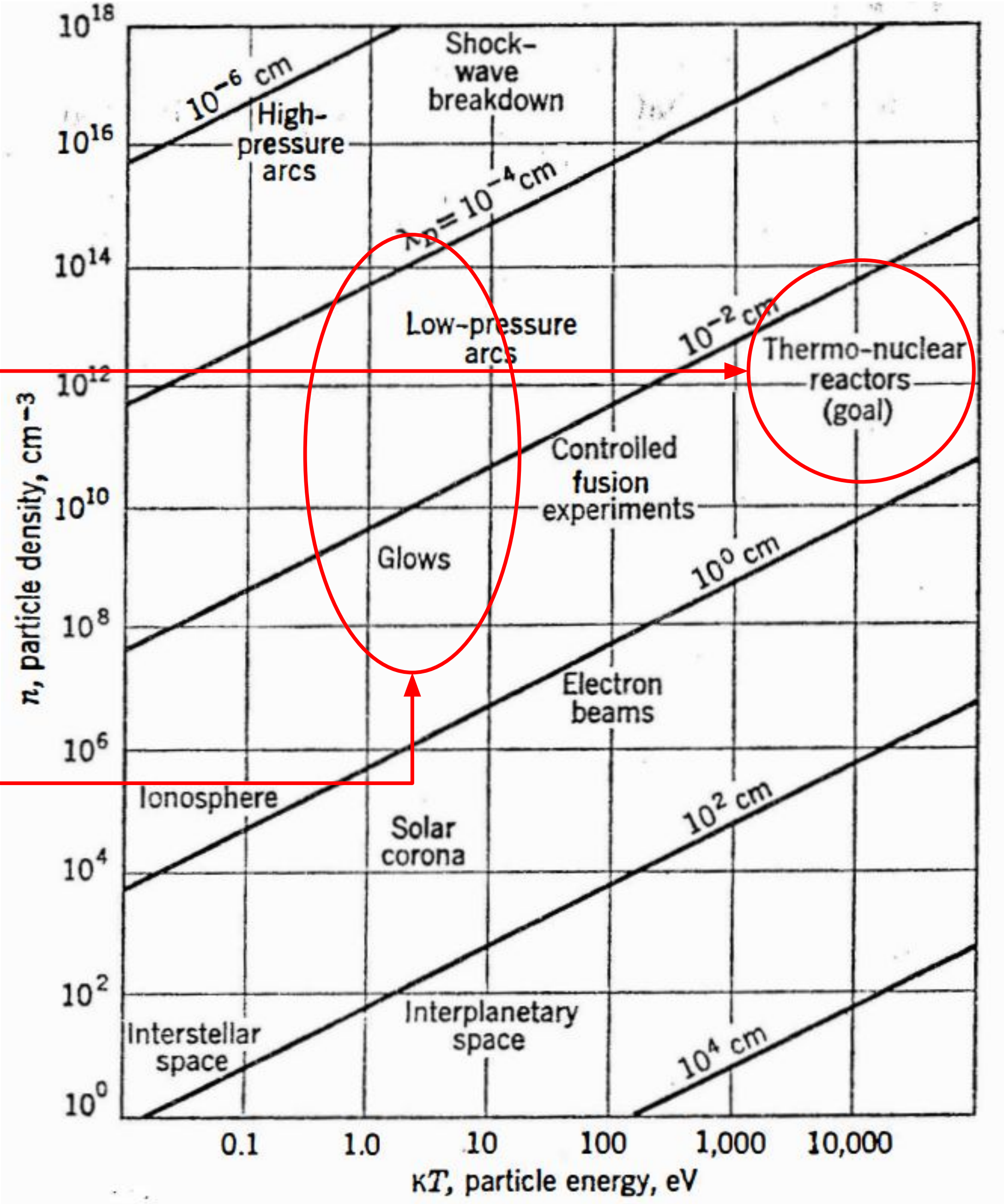
Hot plasmas: high ionization degree (nearly fully ionized)



http://www.inpe.br/webelat/homepage/menu/infor/relampagos.e.efeitos/solo.php

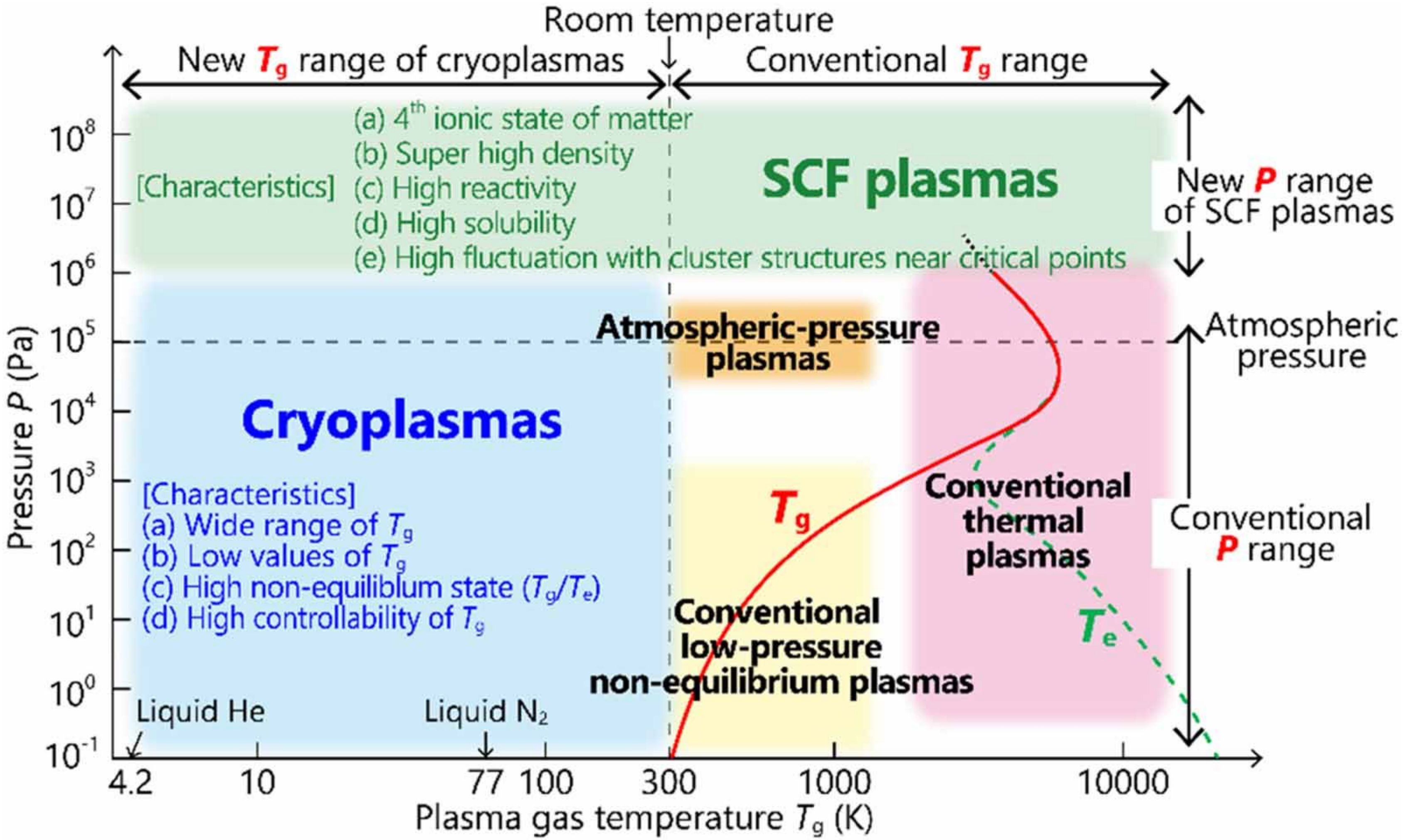
Cold plasmas: low ionization degree (<< 1%)

Ionization degree: $\alpha = \dfrac{n_i}{n_i + n}$



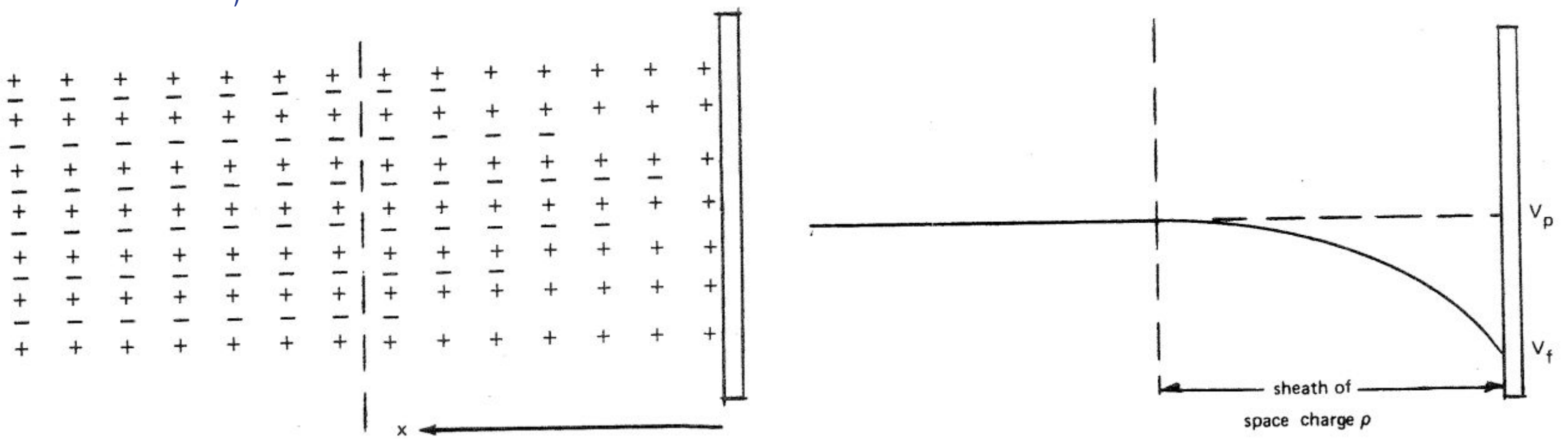
PLASMAS AND GLOW DISCHARGES

Scope



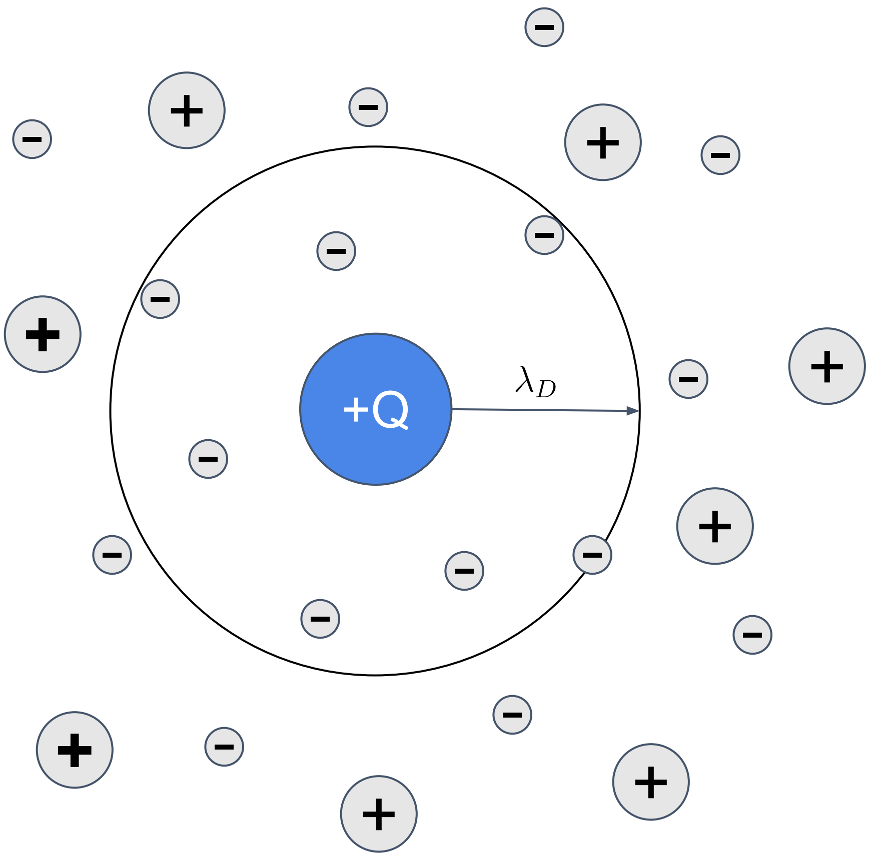
PLASMAS AND GLOW DISCHARGES
Plasma potential and sheath formation

- The presence of electrons and ions define the plasma density (n^- and n^+).
- As electrons are lighter and faster than ions, they move faster from plasma bulk, leaving a more positive potential in this region known as **plasma potential** V_p. In this case, the plasma bulk is defined by the so-called quasi-neutrality condition: $n_e \approx n_i$.
- If the plasma border is defined by chamber walls, a negative potential, with respect to the plasma bulk, will be formed. This property is called **floating potential** V_f.



PLASMAS AND GLOW DISCHARGES
Debye (electrostatic) shielding

- Plasma is an equipotential region with V_p. If this the region is perturbed with an external charge, the medium reacts to oppose that change.



- The amount of charges responsible for neutralize the electric field of the test charge are inside of the so-called Debye sphere, where its radius λ_D (known as Debye length) is given by:

$$\lambda_D = \left(\frac{k_B T_e \epsilon_0}{n_e e^2}\right)^{1/2}$$

- For a typical glow discharge ($k_B T_e$ = 2 eV and n_e = 10^{16} m^{-3}):

$$\lambda_D = \left[\frac{(1.38 \times 10^{-23})(23200)(8.86 \times 10^{-12})}{(10^{16})(1.6 \times 10^{-19})^2}\right]^{1/2}$$

$$\boxed{\lambda_D = 10^{-2}\ \text{cm} = 0.1\ \text{mm}}$$

PLASMAS AND GLOW DISCHARGES
Debye (electrostatic) shielding

- Other examples:
  - Tokamaks (nuclear fusion):

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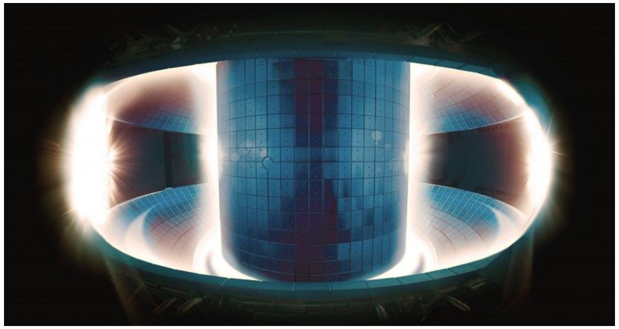


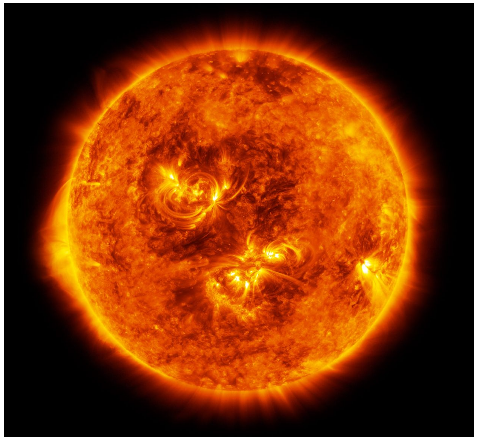
$$\lambda_D = \left[\frac{(1.38 \times 10^{-23})(10^8)(8.86 \times 10^{-12})}{(10^{20})(1.6 \times 10^{-19})^2}\right]^{1/2}$$

$$\boxed{\lambda_D = 69\ \mu\mathrm{m}}$$

  - Solar corona:

$$\lambda_D = \left[\frac{(1.38 \times 10^{-23})(10^6)(8.86 \times 10^{-12})}{(10^{12})(1.6 \times 10^{-19})^2}\right]^{1/2}$$

$$\boxed{\lambda_D = 69\ \mathrm{mm}}$$



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Debye (electrostatic) shielding: Plasma criteria

- To keep the charge neutrality in a plasma region, the following criteria must be satisfied:
  - The plasma dimensions L must be larger than the Debye length:

$$L \gg \lambda_D \qquad \#1$$

  - The number of electrons inside the Debye sphere n_D must be larger than unit:

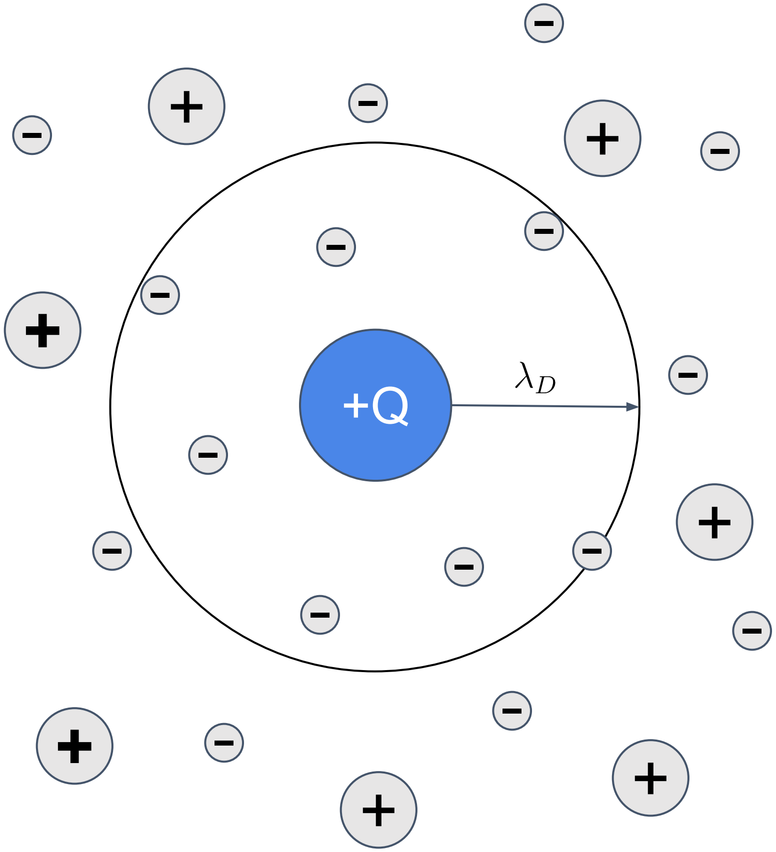
$$n_D = \frac{4}{3}\pi\lambda_D^3 n_e \gg 1 \qquad \#2$$

- These criteria also defines the difference between ionized gases (gas discharges) and plasmas.

PLASMAS AND GLOW DISCHARGES

Oscillations: plasma frequency

- If a plasma is perturbed, electrons will move faster than ions; then, restoring forces of the ions will act on the electrons:



- From Newton's 2nd law and Poisson equation:

$$\frac{d^2x}{dt^2} + \left(\frac{n_e e^2}{\epsilon_0 m_e}\right) x = 0$$

where x is the electron displacement by the external force. The oscillation frequency of the electrons, known as **plasma frequency**, is given by:

$$f_e = \frac{1}{2\pi}\left(\frac{n_e e^2}{\epsilon_0 m_e}\right)^{1/2}$$

$$f_e = \frac{1}{2\pi}\left[\frac{(10^{16})(1.6 \times 10^{-19})^2}{(8.86 \times 10^{-12})(9.11 \times 10^{-31})}\right]^{1/2}$$

n_e (m^{-3}) $\rightarrow$ $\boxed{f_e = 9.0\sqrt{n_e} = 9.0 \times 10^8 \text{ Hz}}$

PLASMAS AND GLOW DISCHARGES
Oscillations: plasma frequency

- Other examples:
  - Tokamaks (nuclear fusion):

$$f_e = 9.0\sqrt{n_e} = 9.0\sqrt{10^{20}} = 90 \text{ GHz}$$

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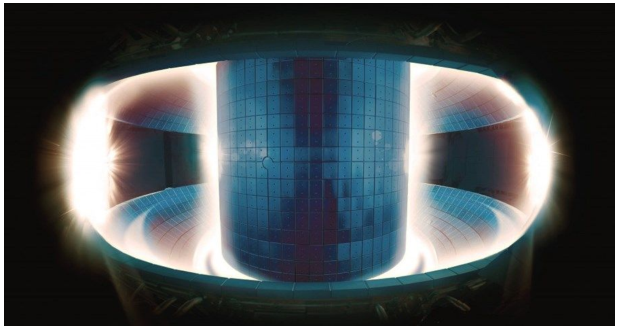
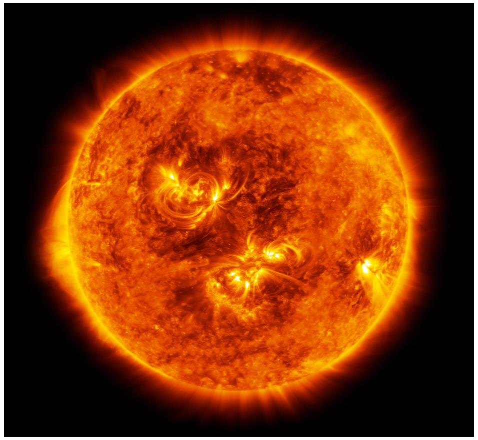


  - Solar corona:

$$f_e = 9.0\sqrt{n_e} = 9.0\sqrt{10^{12}} = 9 \text{ MHz}$$



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PLASMAS AND GLOW DISCHARGES

Oscillations: collision frequency and plasma criterium

- Plasma oscillations are a result of plasma trying to maintain the charge neutrality. Here, we define another condition for plasmas:
  - Oscillations can only be developed if the mean collision frequency f_c is much lower than plasma frequency f_e :

$$f_e \gg f_c$$

#3

DC GLOW DISCHARGES
Architecture of the discharge

- Consider two metallic plates face-to-face:

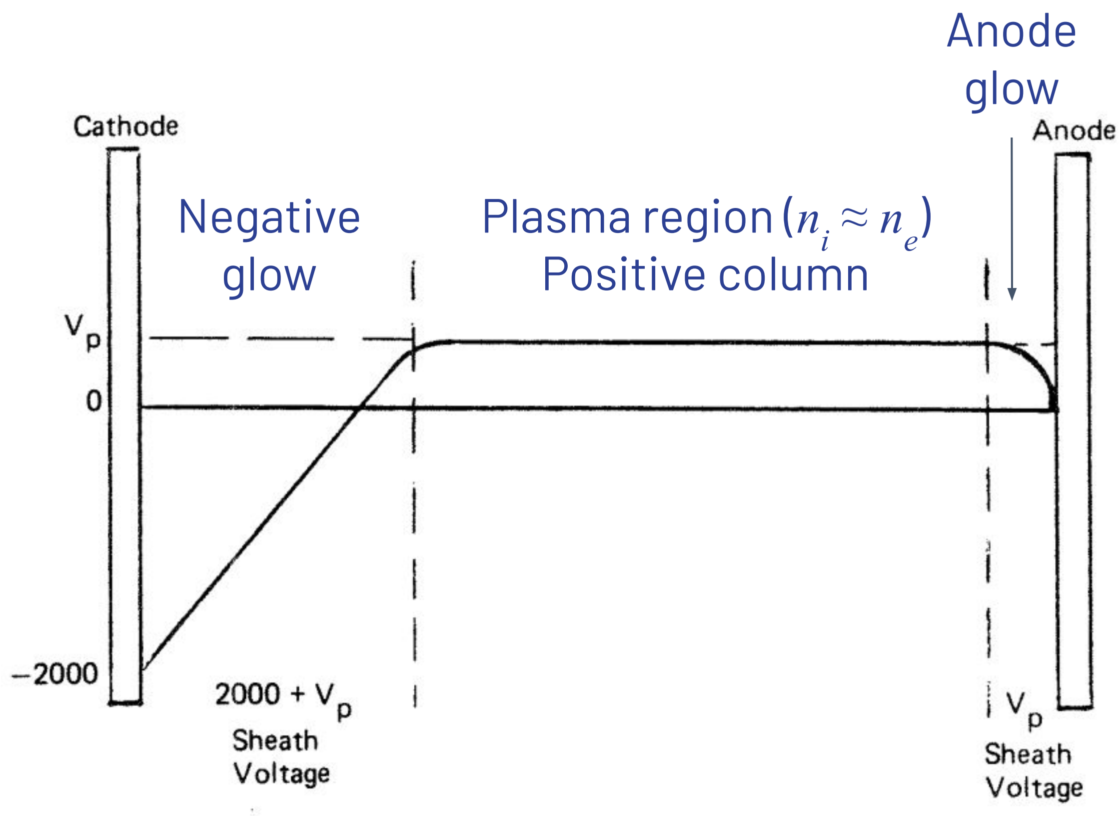
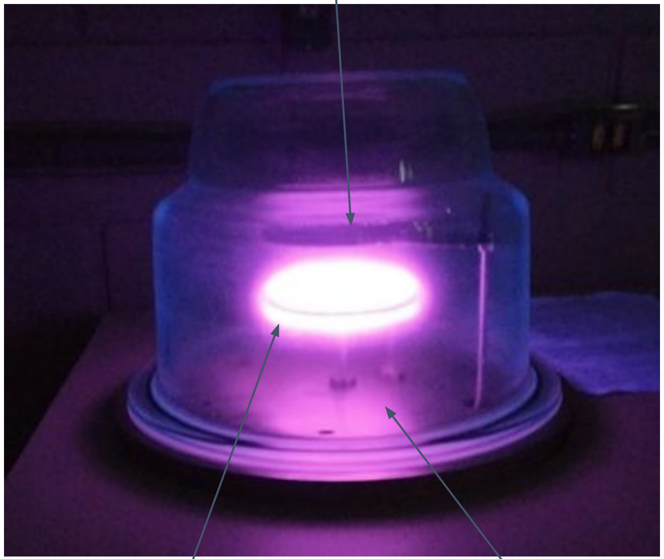


Figure 4-4. Voltage distribution in a dc glow discharge process



B. Chapman, Glow Discharge Processes: Sputtering and Plasma Etching, New York: Wiley, 1980

DC GLOW DISCHARGES

Maintenance of the discharge: I-V characteristics

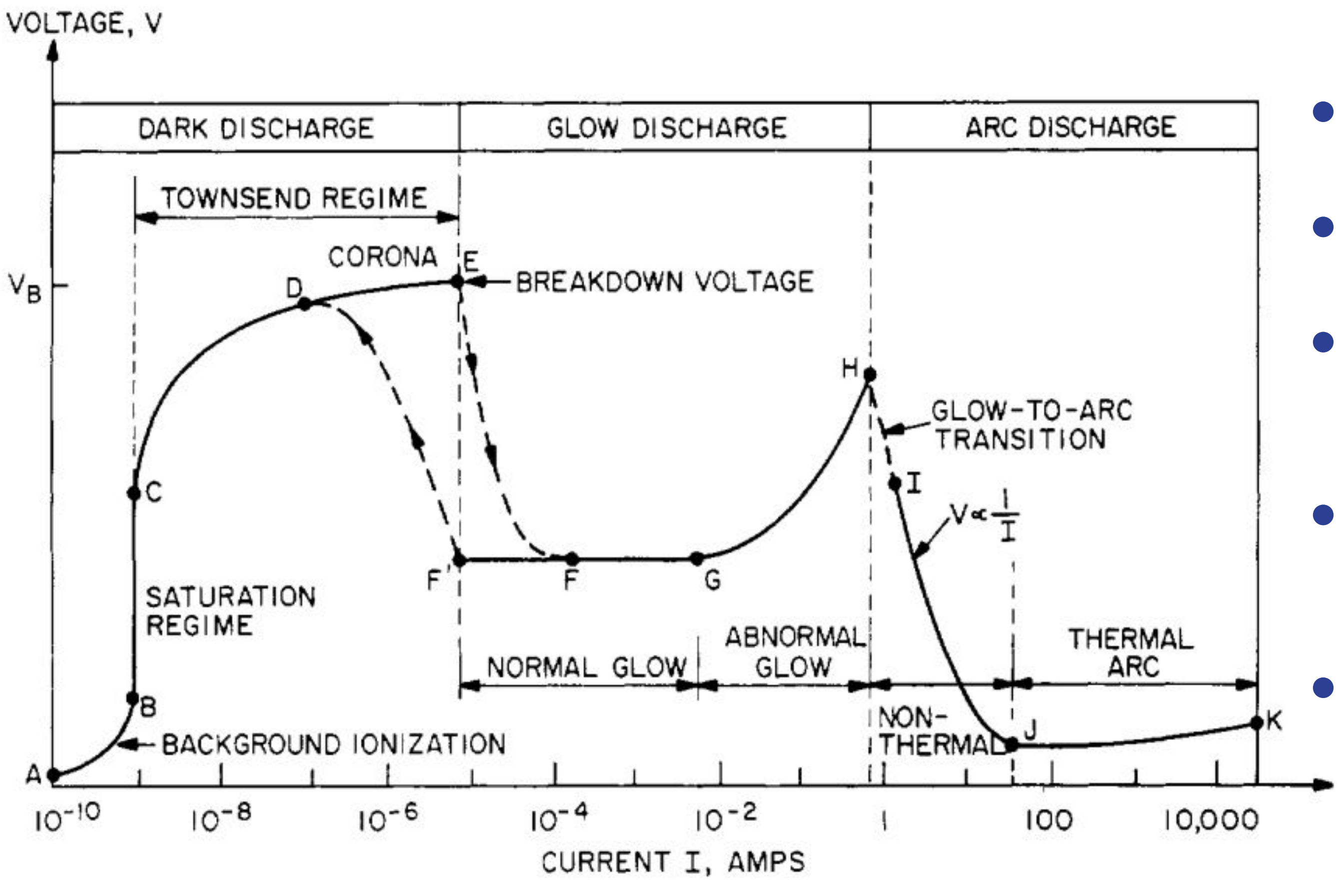


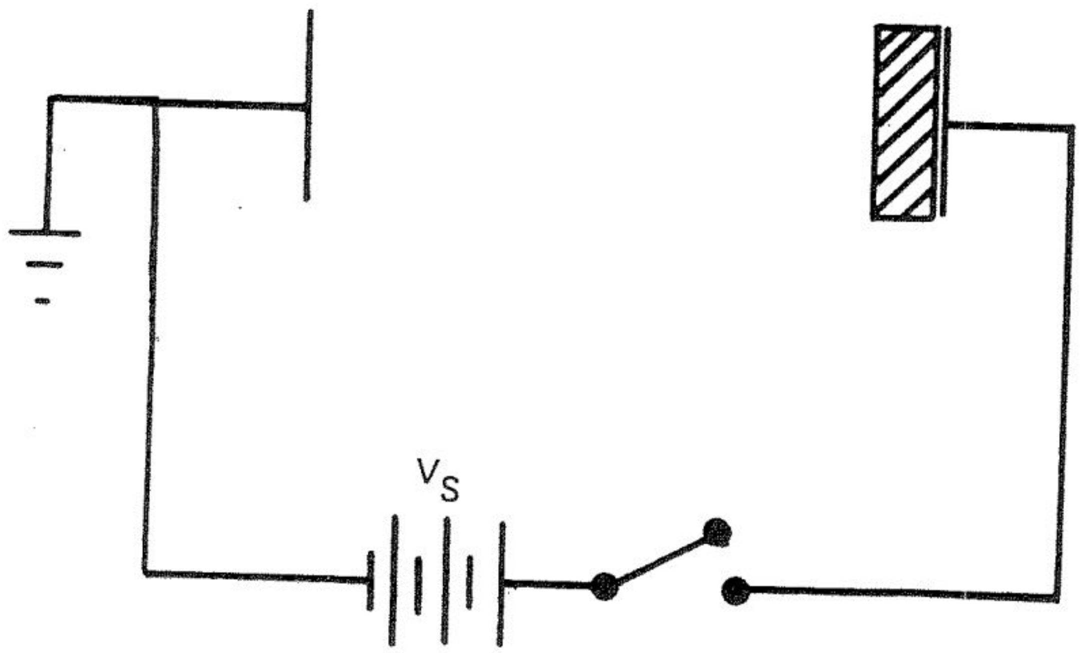
Figure 4.12 Voltage–current characteristic of the DC low pressure electrical discharge tube.

- Primary electrons
- Inelastic collisions
- Cathode bombardment
- Secondary electron emission
- Sputtering, thermionic emission, photoemission

J. R. Roth, Industrial Plasma Engineering - Principles, vol. 1, IOP Publishing, 1995.

AC DISCHARGES
Charging of insulator surfaces

- What happens with a DC discharge if the cathode is an insulator?
- Consider two face-to-face electrodes with 1 cm^2 area each, 1 mA/cm^2 current density, 1 kV across electrodes, with the cathode made in glass (C = 1 pF/cm^2).



$$C = \frac{Q}{V} = \frac{it}{V} \;\therefore\; t = \frac{CV}{i}$$

$$t = \frac{(1.0 \times 10^{-12})(1 \times 10^{3})}{1 \times 10^{-3}}$$

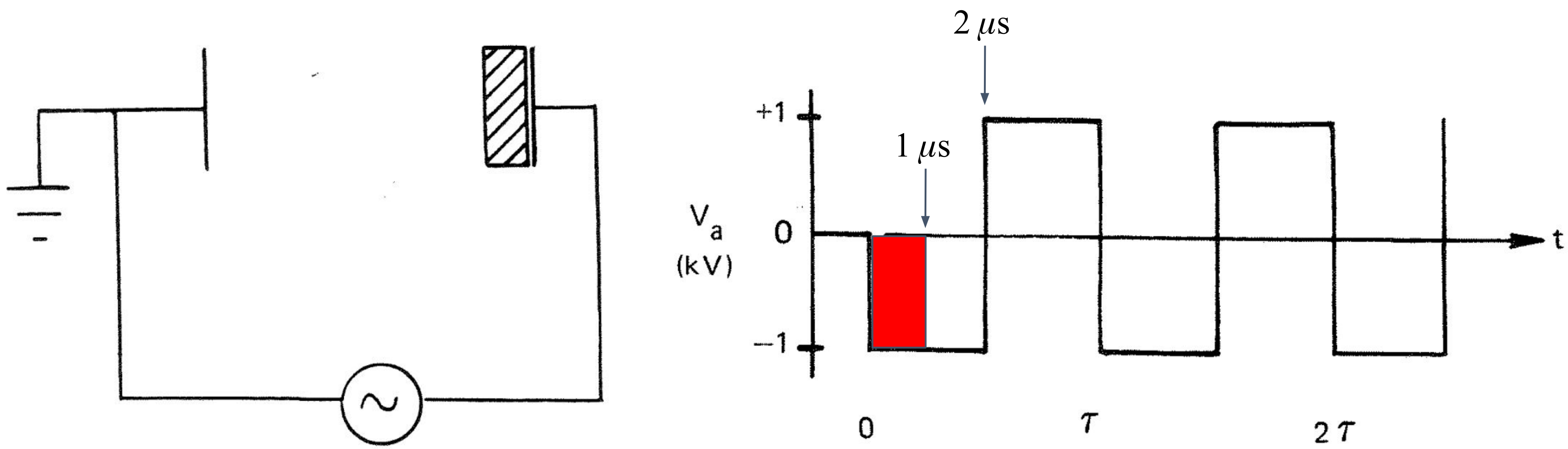
$$\boxed{t = 1.0\ \mu\text{s}}$$

Interval to charge the cathode!

- The discharge will be off after the cathode charges up!

AC DISCHARGES
"Low" frequency sources

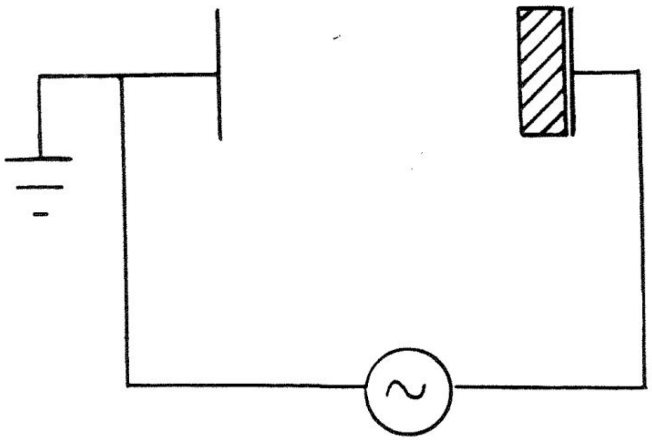
- Replacing the DC by an AC source is possible to neutralize the positive charge accumulated on the cathode during the half-cycle:

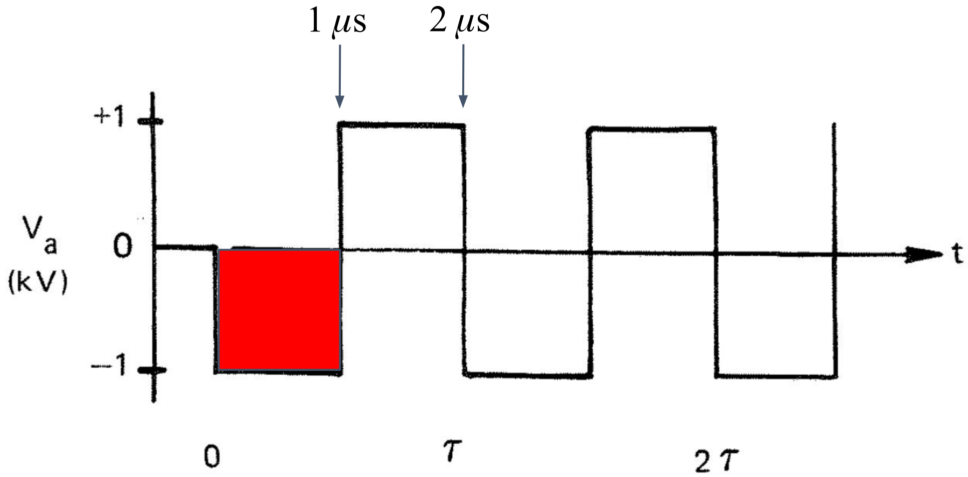


- Suppose a square wave wave voltage supply with 4 μs period, *i.e.*, 250 kHz frequency.
- In the first period quarter, the capacitor charges up and in the second one it is extinguished. In the second half-cycle, the electrode polarity is changed and the same phenomena with electrons is observed! **That's why low frequency sources, such as 60 Hz, are often inefficient to produce discharges**!

AC DISCHARGES
“High” frequency sources

- Increasing the frequency of the voltage supply we are able to avoid interruptions and produce discharges continuously:





- Suppose a square wave wave voltage supply with 2 μs period, *i.e.*, 500 kHz frequency.
- The electrode polarity is changed at the same time interval required for the complete electrode charging, keeping the discharge working. **That’s why high frequency sources, such as RF, are often efficient to produce discharges!**

AC DISCHARGES

Frequency source and electron amplitude

- Consider an electron oscillating along the x-axis in an AC field E of amplitude E_0 and angular frequency ω in a **collisionless region**. From the Newton's 2nd law, the force acting on the electron is given by:

$$m_e \frac{d^2x}{dt^2} = -eE_0 \cos \omega t$$

- The electron's amplitude is obtained by double integration: $x = \dfrac{eE_0}{m_e \omega^2}$
- Assuming an inter-electrode distance of 100 cm for the previous example and two different AC sources (RF and 60 Hz), we obtain:

$$x_{13.56\ \mathrm{MHz}} = \frac{eE_0}{m_e\omega^2} = \frac{(1.6\times10^{-19})(10^3)}{(9.11\times10^{-31})(2\pi\times13.56\times10^6)^2} = \boxed{2.4\ \mathrm{cm}}$$

Particle oscillates between electrodes without hit the anode.

$$x_{60\ \mathrm{Hz}} = \frac{eE_0}{m_e\omega^2} = \frac{(1.6\times10^{-19})(10^3)}{(9.11\times10^{-31})(2\pi\times60)^2} = \boxed{1.2\times10^9\ \mathrm{m}}$$

Unrealistic! Particle hits the anode before. Phew! ;)

- High frequency improves the confinement!

DC GLOW DISCHARGES
Experiment

- Let’s produce some plasmas!

PLASMAS AND GLOW DISCHARGES
Reading

- Chapter 4 - B. Chapman, Glow Discharge Processes (pages 77-82).
- Chapter 5 - B. Chapman, Glow Discharge Processes (pages 139-151).
- Chapter 8 - E. Nasser, Fundamentals of Gaseous Ionization and Plasma Electronics (pages 245-248).
- Chapter 14 - E. Nasser, Fundamentals of Gaseous Ionization and Plasma Electronics (pages 426-433).

Thanks!

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