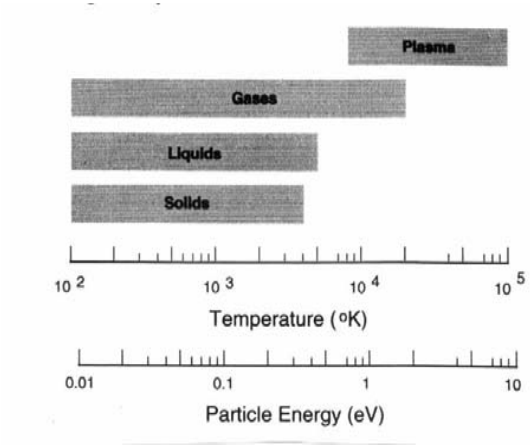
Chapter IV: Plasmas

1. Introduction and definition

Plasma is energetically the fourth state of the matter.

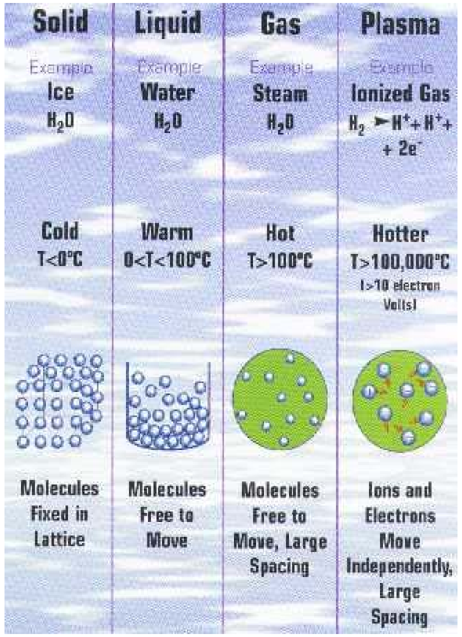


Plasma can be defined as a quasi-neutral gas of charged and neutral particles characterized by a collective behaviour.

Ion-electrons pairs are continuously created (ionization) and destroyed (recombination). Since these processes are always in pairs, the space remains neutral.

The total space is neutral, but local concentration of positive and negative charges arise.

1. Introduction and definition



2. Electron and ion temperature

• The essential mechanisms in the plasma are excitation, relaxation, ionization and recombination.
• To maintain a steady state of electron and ion densities, the recombination process must be balanced by an ionization process.

☞ An external energy source is required.

Suppose an electric field acting on m_i.
Work done by the electric field (W):

$$\vec{F} = \vec{E}.e = m_i.\vec{a}$$

$$W = \vec{F}.x = \vec{E}.e.x$$

$$x = \frac{\vec{a}\ t^2}{2}$$

$$\text{Work done} = \vec{E}.\ e.\ \frac{1}{2}\frac{\vec{E}.\ e}{m_i}t^2$$

$$= \frac{(\vec{E}.e.t)^2}{2.m_i} \qquad \text{(IV.1)}$$

2. Electron and ion temperature

$$\text{Work done} = \frac{(\vec{E}.e.t)^2}{2.m_i}$$

Similar relation holds for the electrons, but since $m_i >> m_e$, the energy transferred to the electrons is far more important.

- An electric field gives most energy to electrons:
  If mean $E_e \approx 2$ eV, $T_e \approx 23200$ K

- The atoms (ions) have an average energy slightly above the one of neutral molecules.
  $T_i \approx 500$ K

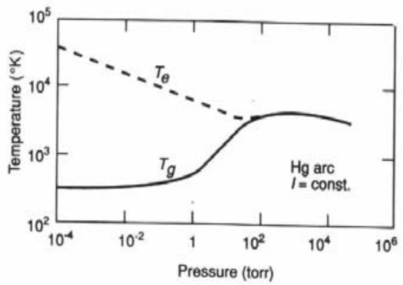
- Neutral molecules gain energy from collisions with themselves, ions and electrons, and remains essentially at room temperature.
  $T_g \approx 290$ K.

- In practice, we consider $T_i = T_g$ for cold plasma

2. Electron and ion temperature

T_e and T_g depends upon pressure

Electron and ion temperatures as a function of pressure (from [7], reprinted with permission from R.F. Baddour and R.S. Timmins, *The Application of Plasmas to Chemical Pressing*, MIT Press, © 1967).



3. Plasma parameters

A plasma is characterized by the following parameters:

- Density of neutral particles, n
- Densities of the electrons and ions, ne, ni.
  $n_i = n_e = n$ = plasma density
- Energy distribution of the neutral particles, ions and electrons.
- Degree of ionization

$$\alpha = \frac{n_i}{n_{Tot}} \qquad \text{(IV.2)}$$

- Plasma density

$$= \alpha . \frac{N}{V} \qquad \text{(IV.3)}$$

Ranges of parameters for various low pressure plasmas			
Plasma Type	Pressure (torr)	Ion density (cm^{-3})	α
Deposition/etching	< 10	< 10^{10}	10^{-6}
Reactive Ion Etching	10^{-2}-10^{-1}	10^{10}	10^{-6}-10^{-4}
Magnetron sputtering	10^{-3}	10^{11}	10^{-4}-10^{-2}
ECR	10^{-4}-10^{-2}	10^{12}	10^{-1}

3. Plasma parameters

Rem:

Even if Te = 10^4 K, plasma is still ***cold***:

- $n_e \approx 10^{10}$ cm^{-3} , to be compared with 3×10^{19} part cm^{-3} at atmospheric pressure.
- Due to their low heat capacity and low density, the amount of heat transferred to the gas and walls is very low.

☞ Cold plasma terminology is related to heat transferred by electrons.

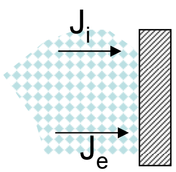
4. Plasma potential

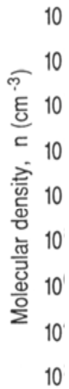
Suppose an isolated substrate suspended into the plasma: It is bombarded by charged particles which result in a current density J_i given by the product of the particle flux (chapter 1) and the charge

$$J_i = \alpha . n_c . e \qquad \text{(IV.4)}$$

with

$$n_c = \frac{\tilde{N}}{4} . \langle V \rangle$$





We have: $$J_e = \frac{e.n_e}{4} . \langle V_e \rangle$$

$$J_i = \frac{e.n_i}{4} . \langle V_i \rangle$$

At 5x10-3 Torr, in typical plasmas (Ar) we have:

$\tilde{N}_{gas} \approx 1.6 \times 10^{14}$ at/cm^3; $\langle v_i \rangle = 3.9 \times 10^4$ cm /s; $\alpha = 10^{-4}$;

→ $J_i = 25\ \mu A/cm^2$

$J_e = 60\ mA/cm^2$

4. Plasma potential

The ions, present at the same amount as the electrons are much heavier and have lower temperature than the electrons.

⇓

They have a much lower velocity.

⇓

An isolated surface charges up negatively: more electron, positive charge left in the plasma ***V----***

⇓

Electrons are subsequently repelled and ions attracted

⇓

The surface negative potential decreases ***V--***

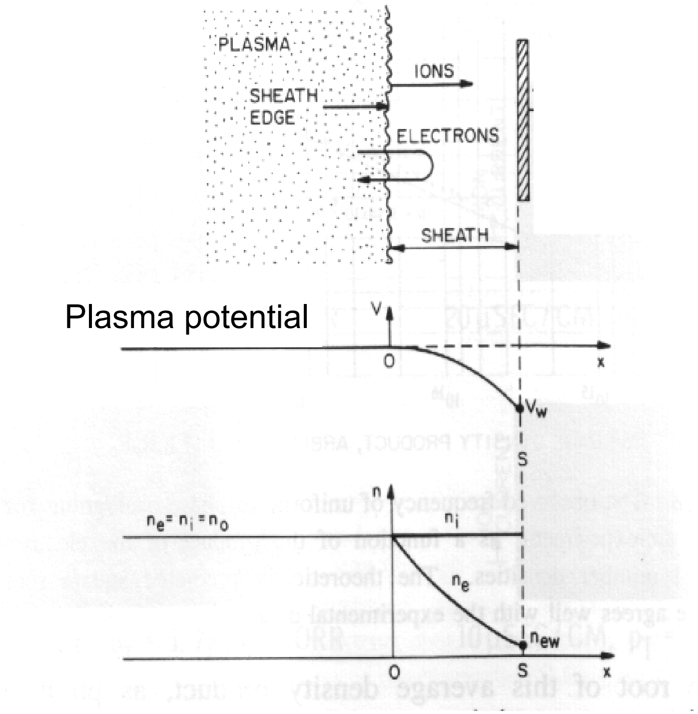
⇓

Rate of electron flux = ion flux

⇓

No net current but V--

4. Plasma potential



$$V(x) = V_0 \cdot e^{-\frac{x}{\lambda_D}} \qquad \text{(IV.5)}$$

• V_0 is the initial potential relative to the plasma at x= 0
• λ_D is the Debye length.
• λ_D is the characteristic dimension of regions in which the breakdown of neutrality can occur in a plasma.

4. Plasma potential

$$\lambda_D(cm) = 6.93 \left(\frac{T_e(°K)}{n_e(cm^{-3})} \right)^{1/2}$$

$$\lambda_D(cm) = 743 \left(\frac{T_e(eV)}{n_e(cm^{-3})} \right)^{1/2} \qquad \text{(IV.6)}$$

• If T_e = 1 eV, $n_e = 10^{10}$ cm^{-3}, ☞ λ_D = 74 µm.

• $\lambda_D \downarrow$ when $n_e \uparrow$.

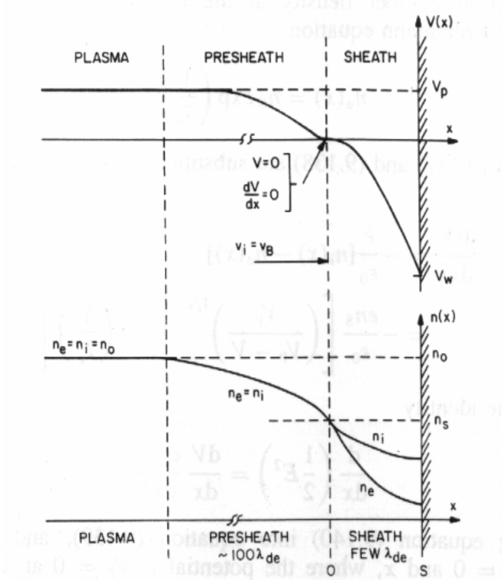
• ***If λ_D is $\geq$ D (dimension of a system),***

☞ no plasma can occur.

5. Sheath formation and bohm criterion

In point 4, we supposed an isolated substrate suspended in a plasma. Due to the difference in ion and electrons velocities, electrons leaves the plasma much faster than ions and leave the plasma with a positive charge, until an electric field develops close to the surface and balance the ion and electron current. As a result, the surface achieves a negative potential with respect to the plasma, and is therefore self-biased. The potential was decreasing monotonically from the plasma to the substrate.

In reality, before the sheath as defined in 4.3, there is a *quasi-neutral* transition region of low electric field that increase the ion velocity entering the sheath.



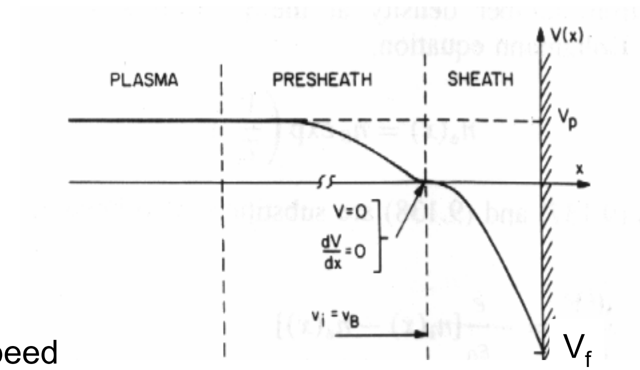
No é

No collisions

No glow

5. Sheath formation and bohm criterion

5.1 Self-Bias potential



v_B: Bohm speed

$$V_{ps} = \frac{k\,T_e}{2\,e} \qquad \text{(IV.7)}$$

$$V_s\,(\text{planar surface}) = \frac{k.T_e}{2e}\ln\left(\frac{m_e}{2.3\,m_i}\right) \qquad \text{(IV.8)}$$

m: kg, T: K

$$V_s\,(\text{spherical surface}) = \frac{k\,T_e}{2e}\ln\left(\frac{\pi\,m_e}{2\,m_i}\right) \qquad \text{(IV.9)}$$

Typical value of V_f ($V_{PS}+V_s$): -10 to -40 V

5. Sheath formation and bohm criterion

5.2 Sheath thickness (d_s)

If $\lambda \approx d_s$

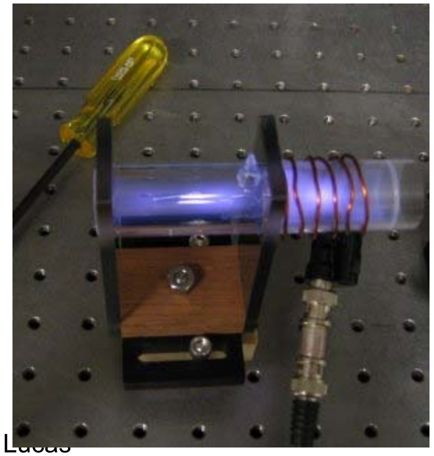
$$d_s = \eta^{2/3}\,\lambda_D \quad \text{with} \quad \eta = \frac{e\,(V_p - V_f)}{k\,T_e} \qquad \text{(IV.10)}$$

If $\lambda >> d_s$

$$d_s = 1.1\,\eta^{3/4}\,\lambda_D \qquad \text{(IV.11)}$$

• If T_e = 1 eV, $n_e = 10^{10}$ cm^{-3}, → λ_D = 74 µm.
→ d_s = 0.87 cm.

No glow over 0.87 cm



5. Sheath formation and bohm criterion

5.3 Ion current density

For low pressure plasma ($\lambda >> d_s$), the ion current density through the plasma sheath is given by the Child-Langmuir relation:

$$J_i = 27.3\left(\frac{40}{m_i}\right)^{1/2}\frac{V_s^{3/2}}{d_s^2} \qquad \text{(IV.12)}$$

J_i: mA/cm2, V: kV, d: mm, m_i: molecular weight (amu).

For high pressure plasma, where collisions are very frequent within the sheath:

$$J_i = 9.95\,10^{-5}\,\mu_i\,\frac{V_s^2}{d_s^3} \qquad \text{(IV.13)}$$

μ_i: the ion mobility (Ar^+ in Ar: 1200 cm2 /V.s).

6. Plasma frequency

When re-establishing plasma bulk neutrality from local perturbation (within the Debye sphere), electrons will respond through oscillations faster than ions to the local electric force. The frequency of these electron oscillations is called the plasma frequency

$$f_p = \left(\frac{n_e\, e^2}{m_e\, \varepsilon_0}\right)^{1/2} = 9.000\sqrt{n_e}\ \ (\mathrm{Hz}) \qquad \text{(IV.14)}$$

n_e: cm^{-3}

If $n_e = 10^{10}$ cm^{-3}, $f_p = 9 \times 10^8$ Hz

We also have: $$\lambda_D\, f_p = \left(\frac{k\, T_e}{m_e}\right)^{1/2} \approx \langle v_e \rangle \qquad \text{(IV.15)}$$

- Electrons can move a distance λ_D in a time $1/f_P$.
- $1/f_P$ is the maximum reaction time to re-establish the neutrality of the plasma (1.1×10^{-9} s).

6. Plasma frequency

- If the plasma density increases somewhere, the é will repel each other to be attracted by the associated net positive charge.

- As the electrons are moving to it, their reduce their potential energy and increase their kinetic energy
- They will overshoot the positive region mark, and will make “U turn”
- They oscillates around positive charges

Other very important stuff

If incident EM of f_i:

If $f_i < f_p$: EM can give its energy to é in the plasma
If $f_i > f_p$: EM is transmitted (é = too much inertia) without energy absorbtion
If $f_i = f_p$: depends on n_e in the plasma (n_c)

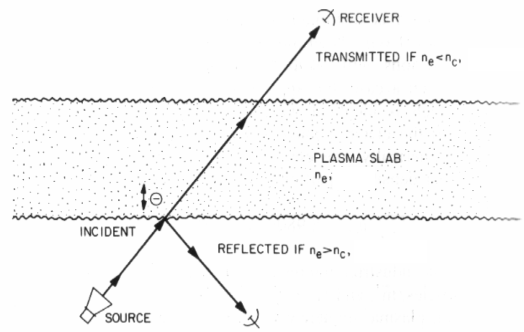


Figure 4.7 Electromagnetic radiation from a source with frequency $\omega = \omega_0$ incident on plasma slab with number density n_e, and electron plasma frequency ω_{pe}. The incident radiation will be reflected from, or transmitted through this slab, depending on the relation of the incident frequency to the electron plasma frequency in the slab.

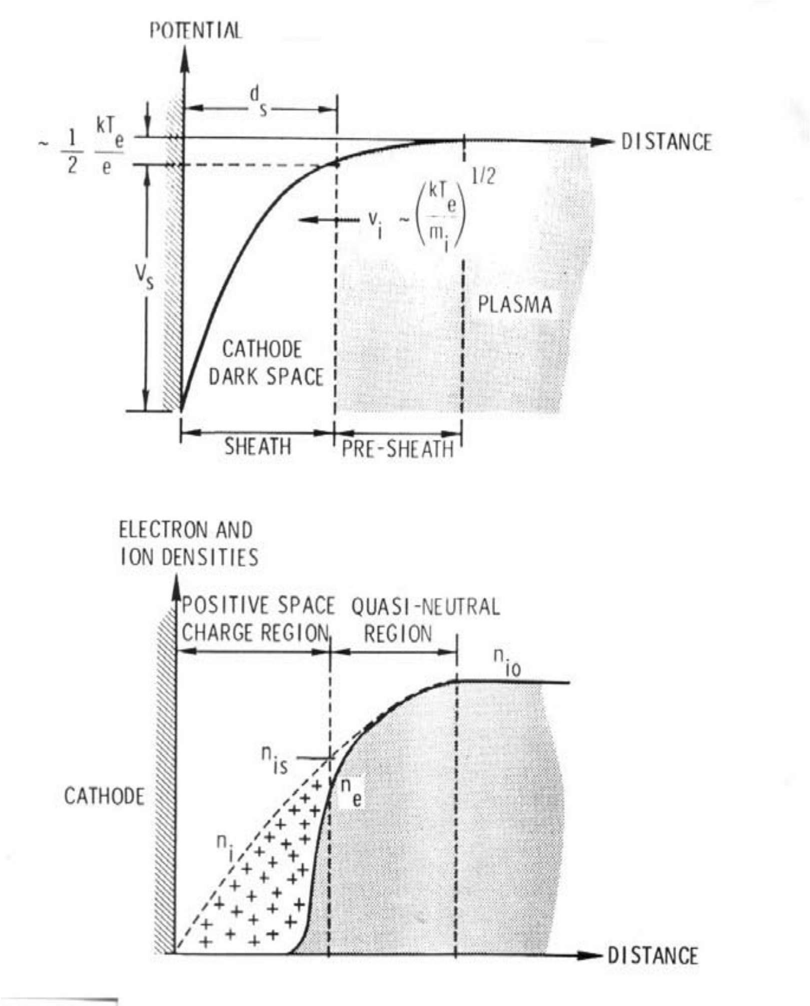
IV.14 $\rightarrow$

$$n_C\ (/cm^3) = 1{,}24 \times 10^{-8} . f_p^2$$

If f = 2.45 GHz,
$N_{e\text{-}refl} = 7.41 \times 10^{10}/cm^3$

If f = 13.56 MhZ
$N_{e\text{-}ref} = 2.28 \times 10^6/cm^3$

6. Sheath summary



Schematic representation of the positive space-charge sheath that develops over a cathode

7. Diffusion in the plasma

Any plasma has a density gradient of particles resulting in diffusion of particles to lower concentration.
In a plasma, the flux of charged particles is composed of two terms:
1- Flux associated with the motion induced by diffusion:

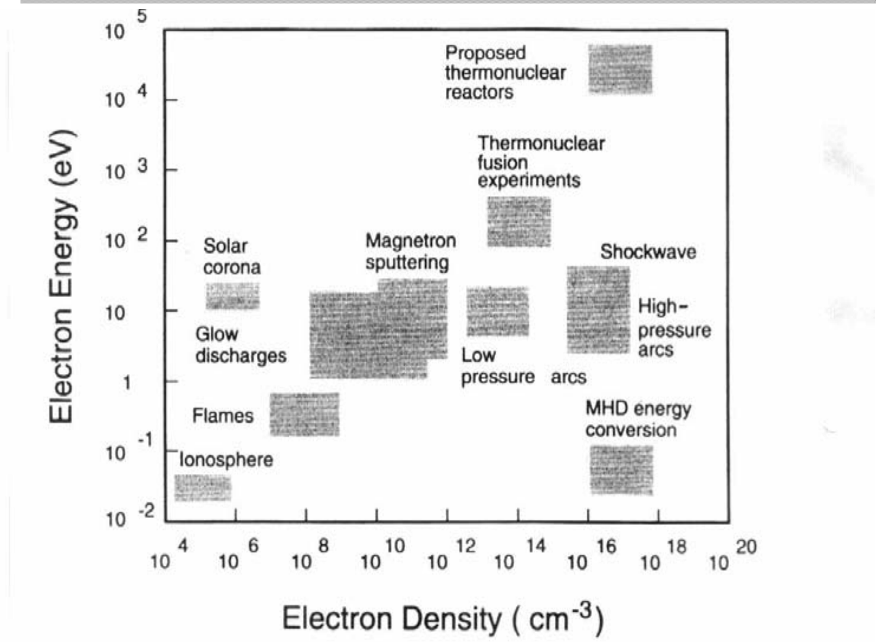
$$-D\nabla n,$$

2-Flux associated with the drift of the charged particles under the influence of an electric field:

$$\pm n\mu E$$

Since the movements of ions and electrons are interconnected, the diffusion is called ambipolar diffusion.

8. Plasma types



Plasmas in complete thermodynamic equilibrium

All T° are equals. They exist only in stars.

Plasmas in local thermodynamic equilibrium

- Heavy particles very energetic ($10^2 \rightarrow 10^4$ eV), thermonuclear fusion
- Athmospheric pressure ($T_e=T_g$=20.000K)

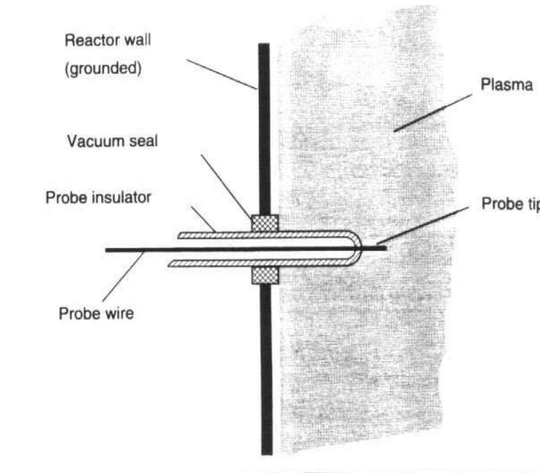
Cold plasmas

$T_e >> T_i \approx T_g$

9. Electrostatic probes

How to measure the plasmas characteristics like T_e, T_i, Vs, V_f, λ_{D}, ...

Langmuir introduced the electrostatic probe in 1920, that carries his name. It is now a science by itself, and a lot of developments have been done the last 20 years. For complete details, see [1].

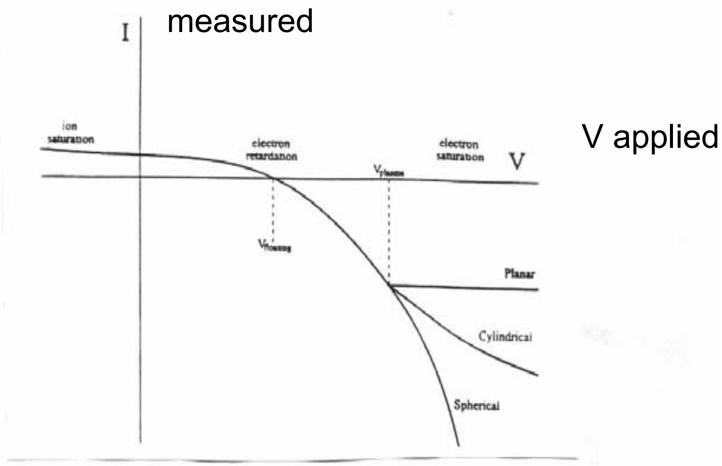


Probe tip: High melting point metal (W, Mo, Pt).

Depending of the sheath thickness and probe radius, different formulas have to be applied.

Depending of the geometry, electron collection will be different.

9. Electrostatic probes



Ion saturation: No electrons travel to the probe. The current is the positive current from the plasma:

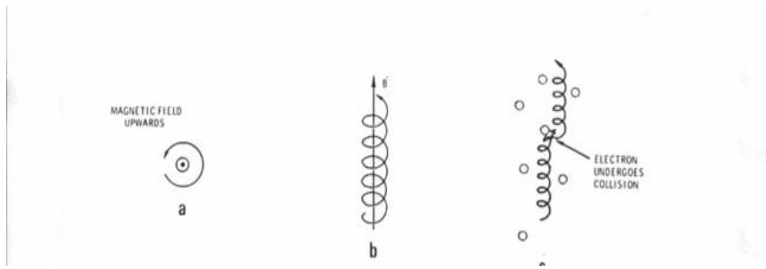
$$I_{+} = Ae N_{+} \sqrt{\frac{kT_{+}}{2\pi M}} \qquad \text{(IV.16)}$$

Electron saturation: Ion current is negligible, electrons stream freely to the probe

$$I_{-} = Ae N_{-} \sqrt{\frac{kT_{-}}{2\pi M}} \gg I_{+} \qquad \text{(IV.17)}$$

$$V_{fl} = \frac{k\,T_e}{2e} \ln\left(\frac{\pi\, m_e}{2\, m_i}\right)$$

10. Particles in magnetic field



The orbiting frequency is called the gyro or cyclotron frequency

$$f_c\ (\text{Hz}) = \frac{e\,B}{2.\pi.m} \qquad \text{m: kg; B: T} \qquad \text{(IV.18)}$$

The orbiting radius is called the gyro, cyclotron or Larmor radius:

$$r_L\ (\text{m}) = \frac{m\,V_{\perp}}{e\,B} \qquad \text{m: kg; B: T, V m/s} \qquad \text{(IV.19)}$$

- For magnetic confinement, r_L must be << D.
- r_L depends on m.
  - ☞ large B to influence ion motion
  - ☞ usually, B is chosen to confine electrons
  - ☞ ions are also confined due to electrostatic forces (ions will not move far away from electrons).

10. Particles in magnetic field

For electrons, we have:

$$f_c \text{ (Hz)} = 2.8x10^{16}.B(\text{Gauss}) \quad \text{(IV.20)}$$

$$r_L \text{ (cm)} = 3.37 \cdot \frac{[T_e \text{ (eV)}]^{1/2}}{B \text{ (Gauss)}} \quad \text{(IV.21)}$$

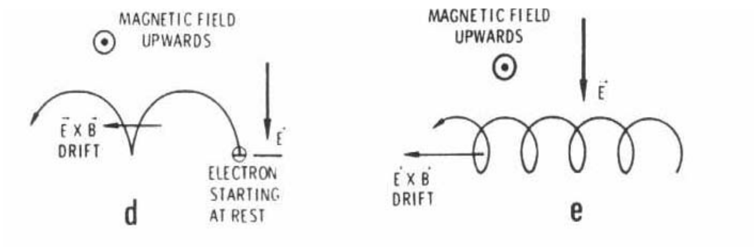
• Typical B in magnetron discharge: 50 < B < 400 G

• Electrons move from one field line to the other through collisions

• Electron travels distance with B ↗↗↗.

• When E is also present and // to B: electrons are accelerated along the field lines.

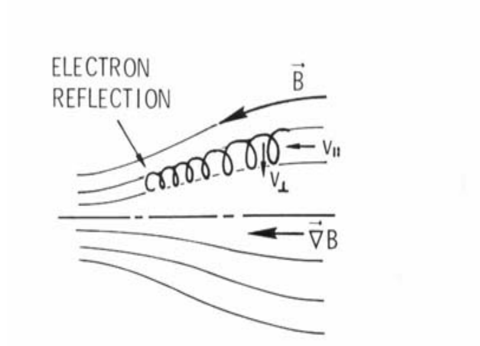
• When E is also present and ⊥ to B: electrons are drifted ⊥ to plane (E,B).



$$\vec{v}_e \text{ (cm/s)} = 10^8 \frac{E_\perp \text{ (V/cm)}}{B \text{ (Gauss)}} \quad \text{(IV.22)}$$

10. Particles in magnetic field

The drift of electrons along B is also depending on ∇B:



Due to the conservation of magnetic moments, electron will be reflected. ☞ electromagnetic lenses.