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.

\[ F = E \cdot e = m_i \cdot \ddot{a} \]

\[ W = \overline{F} \cdot x = \overline{E} \cdot e \cdot x \]

\[ x = \frac{\ddot{a} \cdot t^2}{2} \]

\[ \text{Work done} = \overline{E} \cdot e \cdot \frac{1}{2} \frac{\overline{E} \cdot e}{m_i} t^2 \]

\[ = \frac{(\overline{E} \cdot e \cdot t)^2}{2 \cdot m_i} \quad (IV.1) \]
2. Electron and ion temperature

Work done = \( \frac{(E_e t)^2}{2m_i} \)

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

\( T_e \) and \( T_g \) depends upon pressure
3. Plasma parameters

A plasma is characterized by the following parameters:

- Density of neutral particles, $n$
- Densities of the electrons and ions, $n_e$, $n_i$.
  \[ n_i = n_e = n = \text{plasma density} \]
- Energy distribution of the neutral particles, ions and electrons.
- Degree of ionization
  \[ \alpha = \frac{n_i}{n_{\text{Tot}}} \quad (IV.2) \]
- Plasma density
  \[ = \alpha \cdot \frac{N}{V} \quad (IV.3) \]

### Ranges of parameters for various low pressure plasmas

<table>
<thead>
<tr>
<th>Plasma Type</th>
<th>Pressure (torr)</th>
<th>Ion density (cm$^{-3}$)</th>
<th>$\alpha$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Deposition/etching</td>
<td>$&lt; 10$</td>
<td>$&lt; 10^{10}$</td>
<td>$10^{-6}$</td>
</tr>
<tr>
<td>Reactive Ion Etching</td>
<td>$10^{-2}$-$10^{-1}$</td>
<td>$10^{10}$</td>
<td>$10^{-6}$-$10^{-4}$</td>
</tr>
<tr>
<td>Magnetron sputtering</td>
<td>$10^{-3}$</td>
<td>$10^{11}$</td>
<td>$10^{-4}$-$10^{-2}$</td>
</tr>
<tr>
<td>ECR</td>
<td>$10^{-4}$-$10^{-2}$</td>
<td>$10^{12}$</td>
<td>$10^{-1}$</td>
</tr>
</tbody>
</table>

Rem:

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

- $n_e \approx 10^{10}$ cm$^{-3}$, to be compared with $3 \times 10^{19}$ 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.

\[ \text{Cold plasma terminology is related to heat transferred by electrons.} \]
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.

$$J_i = \alpha \cdot n_e \cdot e$$  \hspace{1cm} (IV.4)

with

$$n_e = \frac{\tilde{N}}{4} \cdot \langle V \rangle$$

We have:

$$J_e = \frac{e \cdot n_e}{4} \cdot \langle V_e \rangle$$

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

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

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

$J_i = 25 \mu\text{A/cm}^2$

$J_e = 60 \text{ mA/cm}^2$

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.

Electrons are subsequently repelled and ions attracted.

The surface negative potential decreases.

Rate of electron flux = ion flux.

No net current but $V\rightarrow$
4. Plasma potential

\[ V(x) = V_0 \cdot e^{\frac{x}{\lambda_D}} \]  \hspace{1cm} (IV.5)

- \( V_0 \) is the initial potential relative to the plasma at \( x = 0 \)
- \( \lambda_D \) is the Debye length.
- \( \lambda_D \) is the characteristic dimension of regions in which the breakdown of neutrality can occur in a plasma.

\[ \lambda_D (cm) = 6.93 \left( \frac{T_e (^\circ K)}{n_e (cm^{-3})} \right)^{1/2} \]  \hspace{1cm} (IV.6)

\[ \lambda_D (cm) = 743 \left( \frac{T_e (eV)}{n_e (cm^{-3})} \right)^{1/2} \]

- If \( T_e = 1 \) eV, \( n_e = 10^{10} \) cm\(^{-3} \), \( \lambda_D = 74 \) μm.
- \( \lambda_D \downarrow \) when \( n_e \uparrow \).
- If \( \lambda_D \geq D \) (dimension of a system),
  
  \( \therefore \) 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.

\[ V_{ps} = \frac{k T_e}{2e} \]  
\[ V_s \text{ (planar surface)} = \frac{k T_e}{2e} \ln\left(\frac{m}{2.3 \times 10^7}\right) \]  
\[ V_s \text{ (spherical surface)} = \frac{k T_e}{2e} \ln\left(\frac{\pi m}{2 \times 10^7}\right) \]

\(v_B\): Bohm speed

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 $\lambda \approx d_s$

$$d_s = \eta^{2/3} \lambda_D$$

with

$$\eta = \frac{e(V_p - V_f)}{kT_e}$$

(IV.10)

If $\lambda >> d_s$

$$d_s = 1.1 \eta^{3/4} \lambda_D$$

(IV.11)

- If $T_e = 1$ eV, $n_e = 10^{10}$ cm$^{-3}$,  
  $\lambda_D = 74 \mu$m.
- $d_s = 0.87$ cm.

No glow over 0.87 cm

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:

$$J_i = 27.3 \left( \frac{40}{m} \right)^{1/2} \frac{V_s^{3/2}}{d^2}$$

(IV.12)

$J_i$: mA/cm$^2$, $V$: kV, $d$: mm, $m_i$: molecular weight (amu).

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

$$J_i = 9.95 \times 10^5 \mu_i \frac{V_s^2}{d_s^3}$$

(IV.13)

$\mu_i$: the ion mobility (Ar$^+$ in Ar: 1200 cm$^2$/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

\[ f_p = \left( \frac{n_e e^2}{m_e \varepsilon_0} \right)^{1/2} = 9.000 \sqrt{n_e} \text{ (Hz)} \]  \hspace{1cm} (IV.14)

If \( n_e = 10^{10} \text{ cm}^{-3}, f_p = 9\times10^8 \text{ Hz} \)

We also have:

\[ \lambda_D f_p = \left( \frac{k T_e}{m_e} \right)^{1/2} \approx <v_e> \]  \hspace{1cm} (IV.15)

**Other very important stuff**

- Electrons can move a distance \( \lambda_D \) in a time \( 1/f_p \).
- \( 1/f_p \) is the maximum reaction time to re-establish the neutrality of the plasma (1.1x10^{-9} \text{ s}).

If incident EM of \( f_i \):
- If \( f_i < f_p \): EM can give its energy to \( e \) in the plasma
- If \( f_i > f_p \): EM is transmitted (\( e \) = too much inertia) without energy absorption
- If \( f_i = f_p \): depends on \( n_e \) in the plasma (\( n_e \))

**Figure 4.7** Electromagnetic radiation from a source with frequency \( f = f_{\text{ref}} \) incident on plasma slab with number density \( n_e \) and electron plasma frequency \( f_{\text{pe}} \). 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.
6. Sheath summary

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 $T^\circ$ are equals. They exist only in stars.

**Plasmas in local thermodynamic equilibrium**
- Heavy particles very energetic ($10^2 \rightarrow 10^4$ eV), thermonuclear fusion
- Atmospheric pressure ($T_e = T_g \approx 20.000K$)

**Cold plasmas**

$T_e \gg T_i \approx T_g$

9. Electrostatic probes

How to measure the plasmas characteristics like $T_e$, $T_i$, $V_e$, $V_i$, $\lambda_D$, ...

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:

$$I_+ = AeN_+\sqrt{\frac{kT_+}{2\pi M}}$$  \hspace{1cm} (IV.16)

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

$$I_-= AeN_-\sqrt{\frac{kT_-}{2\pi M}} \gg I_+$$ \hspace{1cm} (IV.17)

$$V_n = \frac{kT_e}{2e} \ln\left(\frac{\pi m_e}{2m}\right)$$

10. Particles in magnetic field

The orbiting frequency is called the gyro or cyclotron frequency

$$f_c \ (Hz) = \frac{eB}{2\pi m} \quad m: \text{kg}; B: \text{T}$$  \hspace{1cm} (IV.18)

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

$$r_L \ (m) = \frac{mV}{eB} \quad m: \text{kg}; B: \text{T}, V \text{ m/s}$$ \hspace{1cm} (IV.19)

- For magnetic confinement, $r_L$ must be $\ll D$.
- $r_L$ 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:

\[ f_c \ (Hz) = 2.8 \times 10^{16} \cdot B \ (Gauss) \]  \hspace{1cm} (IV.20)

\[ r_L \ (cm) = 3.37 \cdot \frac{[T_e \ (eV)]^{1/2}}{B \ (Gauss)} \]  \hspace{1cm} (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 \( \parallel \) to B: electrons are accelerated along the field lines.
- When E is also present and \( \perp \) to B: electrons are drifted \( \perp \) to plane (E,B).

\[ \frac{v_e \ (cm/s)}{10^8} = \frac{E_\perp \ (V/cm)}{B \ (Gauss)} \]  \hspace{1cm} (IV.22)

The drift of electrons along B is also depending on \( \nabla B \):

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