I. Langmuir Probes
A. Diagnostic of Electron Temperature $T_e$ and Density $n_e$
1. Langmuir probes are small metal electrodes inserted into a plasma.
2. For a cool, low density plasma, it enables one to determine electron temperature $T_e$ and electron density $n_e$.

3. Sweep probe voltage from negative to positive and measure $I_p$.

- $I_p$ versus voltage $V$
  - Ion Saturation Electron Saturation Current $I_{es}$ regime
  - Plasma Potential $\phi_p = V = 0$
  - Defined as the reference for zero.
B. Ion Saturation Current

1. For a sufficiently negative probe potential, all electrons are prevented from reaching the probe, and you only get the ion current.

2. From our study of the plasma sheath, we know the ion current is constant across the sheath (from the ion continuity equation). The ion current is therefore determined by the conditions at the sheath edge:

\[ I_{is} = n_i e u_0 A, \text{ where the Bohm criterion specifies} \]
\[ U_0 = C_s = \sqrt{\frac{e U}{m_i}} \]

3. But we want to know the density in the unperturbed plasma, not the density at the sheath edge:

![Graph showing density distribution](image)

a. The ion momentum equation gives a conservation of energy condition where we can use to find \( n_i \) as a function of \( n_0 \):

\[ \frac{1}{2} m_i u_0^2 + e \phi(d) = \frac{1}{2} m_0 u_i^2 + e \phi_0 \]

Sheath edge \quad Unperturbed plasma

b. Taking \( \phi_0 = 0 \) as reference for potential (different from \( \phi(d) = 0 \)),

we get:

\[ \phi(d) = -\frac{1}{2} m_i u_0^2 = -\frac{1}{2} e \frac{T_e}{m_i} = -\frac{T_e}{2e} \]
Lecture 8 (Continued)

3. (Continued) c. In the sheath, \( n_i = n_e = n_0 e^{-\frac{\phi_s}{T_e}} \), where the density \( n_0 \) is unperturbed plasma density at \( \phi = \phi_s = 0 \).

d. Substituting \( \phi_s = -\frac{T_e}{2e} \), we get \( n_i(\phi) = n_0 e^{-\frac{T_e}{2e}} = n_0 e^{\frac{1}{2} \phi_s} \).

4. Therefore, \( I_{es} = 0.61 n_0 e^{\frac{T_e}{2e}} \). If we can find \( T_e \), this gives \( n_0 \).

C. Electron Saturation Current

1. For a probe voltage \( V \) is positive with respect to the plasma potential \( \phi_s = 0 \), electrons are not hindered from reaching the probe.

\[ \Rightarrow \text{There is no sheath formation.} \]

2. All electrons in the positive half-plane of a Maxwellian distribution will reach the probe.

\[ I_{es} = -eA \int_{V}^\infty \frac{V e^\frac{V-V_0}{T_e}}{\pi^2 V e^2} dV \]

\[ = -e \frac{A (2\pi)^{1/2}}{2 m_e^{1/2}} \frac{V e^\frac{V-V_0}{T_e}}{\pi^2 V e^2} \]

b. Component of velocity hitting probe, \( V \cos \theta \)

3. We must integrate over half-planes of distribution \( f_e(V) = \frac{n_0 e}{\pi^2 V e^2} \).

\[ I_{es} = -eA \int_{V}^\infty \frac{V e^\frac{V-V_0}{T_e}}{\pi^2 V e^2} dV \cos \theta \]

\[ = -e A (2\pi)^{1/2} \frac{V e^\frac{V-V_0}{T_e}}{2 m_e^{1/2}} \]

Thus \( I_{es} = -\frac{1}{2} n_0 e \left( \frac{2T_e}{\pi m_e} \right)^{1/2} A \).
Lecture 20 (Continued)

1. RC Circuit (Continued)

4. Notes: Ratio \( \frac{|I_{es}|}{I_{is}} = \frac{1}{2} \frac{m_{i}}{m_{e}} \frac{e}{(\frac{2\pi}{c})^2} \frac{E_{0}}{L_{0}} \frac{1}{0.66(0.1)^2 \sqrt{m_{i}}} \)

\( \text{Quasineutrality: } n_{e} = n_{i} \)

So \( \frac{|I_{es}|}{I_{is}} = 0.65 \left( \frac{m_{i}}{m_{e}} \right)^{1/2} \). Since \( m_{i} \gg m_{e} \), \( |I_{es}| \gg I_{is} \).

9. Electron Retardation Current

1. In this regime, it can be shown that:

\[ I_{e}(V) = I_{es} e^{\frac{e(V - \phi_{p})}{T_e}} = I_{es} e^{\frac{eV}{T_e}} \]

2. Taking the \( \ln \) of this equation, we find:

\[ \ln(|I_{e}|) = \ln(|I_{es}|) + \frac{e}{T_e} V \]

slope is inversely proportional to \( T_e \).

3. To determine the electron temperature:

a. Determine ion saturation current \( I_{is} \)

b. \( I_{e}(V) = I_{p}(V) - I_{is} \)

electron current \hspace{1cm} \text{probe current} \hspace{1cm} \text{ion current}

c. Plot a semi-log plot \( \ln(I_{e}) \)

\[ \text{Slope} = m = \frac{e}{T_e} \]

\[ I_{e} = \frac{e}{m} \text{ slope} \]
II. Atomic Collisional Processes

A. Cross-Sections

1. Collisions between charged particles (usually electrons) and neutral atoms can lead to ionization of the atom.

2. Such collisional ionization is an important way to generate plasma.

3. We quantify the probability of collisions as a cross-section, \( \sigma \).

4. For a gas of atoms with density \( N_a \),

   a. Mean free path \( \lambda_{fp} = \frac{1}{N_a \sigma} \).

   b. Collision frequency \( \nu_{coll} = \frac{\sigma}{\text{cross-section}} V_{Na} \).

B. Ionization Rate Coefficient

1. If we want to know the rate of ionization in a gas with electron temperature \( T_e \), we must average over velocity distribution,

\[
\langle f_e(v) \rangle = \frac{n_e}{\frac{4\pi}{3} v_{Te}^3} e^{-\frac{mv_{Te}^2}{2kT}}
\]

   \( V_{Te} = \frac{2T_e}{m_e} \).

2. Rate coefficient is defined as the average over distribution,

\[
\langle \sigma_{ion} v \rangle = \frac{1}{n_e} \int_0^\infty \sigma_{ion}(v) v f_e(v) \, dv
\]
Lecture 70 (Continued)

II. B. (Continued)

3. The ionization frequency is then \( \nu_{\text{ion}} = n_0 \langle \sigma \text{v} \rangle \)

4. Total ionization rate (per volume per second)
   \[ S_{\text{ion}} = n_e n_0 \langle \sigma \text{v} \rangle \]

C. Electron Impact Ionization

1. Typical low pressure gas discharges have \( T_e \sim 3 \text{ eV} \)

2. Ionization rate is determined by tail of distribution

3. For electron collisions with atoms, other processes can occur
   a) Elastic collisions
   b) Ionization
   c) Excitation

\[ \text{[Graph showing distribution functions for elastic collisions and ionization]} \]

[Graph showing energy distribution for Aron gas with peaks for elastic collisions and ionization]
Lecture #20 (Concluded)

III. Plasma Generation

A. General Types of Discharges
   1. DC Discharges
   2. Capacitive RF Discharges
   3. Inductively Coupled Discharges

B. DC Discharges

\[ \text{Discharge current} \]

\[ \begin{align*}
   \text{Power supply chosen high enough so breakdown occurs, } V \sim 600 \text{ V} \\
   \text{Resistor in series to limit current after breakdown.}
\end{align*} \]

2. Glow discharge in long glass tube: (Fluorescent or neon lights)

   - Cathode (-)
   - Anode (+)
   - Cathode layer
   - Negative glow
   - Positive column
   - Positive glow
   - Cathode region
     - Liberates electrons
   - From cathode to cause electron impact ionization
Lecture #20 (Continued)

III. C. Gas Breakdown

1. Electron avalanche

\[ \lambda_e = \text{Electron mean free path for ionization} \]

2. a. Ions released from ionization collisions impact the cathode
   b. These ion impacts can release more electrons to continue the process
   c. Breakdown occurs when enough electrons are released to maintain the avalanche.

3. Paschen Curve

\[ V_\text{bd}(V) \]

\[ p \text{d} \] (torr cm)

a. Minimum in breakdown voltage vs. (pressure x gap length)

b. Left of minimum, too few atoms for ionization

c. Right of minimum, energy gain per mean free path is too little for ionization

d. Hence, a higher electric field is required for breakdown.

4. Gas | Cathode | \( V_{\text{min}} \) (V) | (p*d)_{\text{min}} \) (torr cm)
---|---|---|---
He | Fe | 1.50 | 2.5
Ar | Fe | 2.65 | 1.5
Air | Fe | 3.30 | 0.57
Hg | W | 4.25 | 1.8
III. Thermionic Emitters

1. Cold cathodes require high voltages (300 - 3000V) to achieve breakdown.
2. Heated cathodes can release electrons more readily, requiring a smaller voltage drop.
3. Hot metal or oxide cathodes: W, LaB₆, BaSrO.

E. Capacitive Radio-Frequency (RF) Discharges

1. Parallel plate discharge; \( f = 13.56 \text{ MHz} \).
2. Electrons gain a thermal energy of \( \Delta E \) a few eV, enough to lead to ionization.
3. Frequency used for plasma processing: a) plasma etching,
   b) Plasma-enhanced chemical vapor deposition (PECVD).

4. RF electric fields result from surface charges on electrodes.

F. Inductively Coupled Plasmas

1. Can achieve higher plasma densities for plasma processing.
2. Semi-conductor industry.

a. Electric field in plasma is generated by a time-varying magnetic field.