Langmuir probes for low temperature plasma diagnostic

Laboratory Instructions (Lab. project)

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How Langmuir probes operate?

The collecting Langmuir probes are metallic electrodes with a well defined geometry (planar, cylindrical or spherical) immersed in the plasma.

The external surface is exposed to the plasma and externally biased to the potential $V_p$, different from the local plasma potential $V_{sp}$.

According with the difference $V_p - V_{sp}$ the electrons (or ions) are attracted (or repelled).

The plasma is locally perturbed by the probe.

An electric current composed of ions and electrons is drained from the plasma.

$$I(V_p - V_{sp}) = I_i + I_e$$

- $V_p - V_{sp} \ll 0 \quad I_p \approx I_i$
- $V_p - V_{sp} \gg 0 \quad I_p \approx I_e$

The electron temperature $K_B T_e$, the local plasma potential $V_{sp}$ and the electron density $n_e$ are calculated from the current-voltage characteristic curves $I(V_p)$.
How are collecting Langmuir probes connected?

The connections for a *glow discharge*, the reference electrode is usually the anode:

\[ V_{dis} \approx 400 - 500 \text{ V} \]
\[ I_{dis} \approx 10 - 100 \text{ mA} \]

In plasmas produced by *boiling electrons* we have more possible choices:

\[ V_{dis} \approx 50 - 80 \text{ V} \]
\[ I_{dis} \approx 0.1 - 5 \text{ A} \]
The plasma sheath represents the extension of the perturbation in the plasma caused by the probe potential $V_p$. The spatial plasma potential profile is non monotonic (sheath and presheath) and its typical extents is roughly 1-10 Debye lengths.

How repelled (or attracted) particles contribute to the drained current?

This is the key question of Langmuir probe theory.

The space plasma potential profile around the probe is unknown and affected by particle collisions?, magnetic field, ...etc. ... This is not fully solved yet.

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The idealized voltage-current curve

In collisionless unmagnetized plasmas, according to the difference \( V_p - V_{sp} \) the ions and electrons could be attracted or repelled

\[
\begin{align*}
V_p - V_{sp} &< 0 & \text{Electrons are repelled and ions are attracted: C-D} \\
V_p - V_{sp} &> 0 & \text{Ions are repelled and electrons are attracted: A-C}
\end{align*}
\]

The idealized voltage-current curve \( I(V_p) = 0 \) defines the floating potential \( V_F \)

\( I_{es} \) defines the electron saturation current (for \( V_p >> V_{sp} \))

\( I_{is} \) defines the ion saturation current (for \( V_p << V_{sp} \))

In B-C the increment in the collection of repelled electrons is exponential
The collection of repelled charges

Because of the finite electron (or ion) temperature $K_B T_e \neq 0$ ($K_B T_i \neq 0$) a repelled electron (or ion) group has energy enough to reach the probe surface.

Thus, along B-C the electrons with kinetic energy $E$ over the probe potential $E > -e (V_p - V_{sp}) > 0$ reach the probe surface and are collected. The effective collection surface is the metallic surface of the probe: *no sheath effect for repelled particles.*
The results from the simplified theory

The elementary theory applies for collisionless and unmagnetized plasmas and assumes that, both electrons and ions, have a Maxwellian energy distribution function with finite temperatures: $K_B T_e \gg K_B T_i \approx K_B T_a$

$$I_{BC} = I_s \exp \left( \frac{e(V_p - V_{sp})}{K_B T_e} \right)$$

$$v_{th} = \left( \frac{8 K_B T_e}{\pi m_e} \right)^{1/2}$$

$$I_{es} = \frac{1}{4} Sn_e v_{th} \begin{cases} S=4 \pi r_p^2 \\ S=2 \pi r_p \ L \end{cases}$$

The second derivative of the current for repelled particles is proportional to the electron energy distribution function $g(E)$

$$\frac{d^2 I}{dV_p^2} = -\left( e^2 \pi r_p^2 \right) g(E) \sqrt{\frac{2e}{m_e V_p}}$$

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The actual experimental data in linear scale

![Graph showing electron and ion saturation points as well as plasma potential.](image)

- **Electron Saturation**
- **Ion Saturation**
- **Plasma potential**
The experimental data in logarithmic scale

Electron saturation current
Currents over 2.0 mA

Exponential growth of the electron current

Noise: currents below 5 x 10^{-5} Amp = 0.05 mA

Probes current (Amp.)

Probe voltage $V_p$ (volts)
The analysis of the current voltage curve

![Graph showing the current voltage relationship with labels for Electron saturation current, Exponential increase of the electron current, and Plasma potential.](image)
The actual collecting and emissive Langmuir probes employed in the experiments
The plasma chamber with the probe support

The support for the collecting and emissive Langmuir probes in the plasma chamber

The probes immersed into a glow discharge plasma in an actual experiment.
Laboratory Project: Objectives.

The main objective is to calculate the plasma parameters using actual experimental data of collecting and emissive Langmuir probes.

Check if the measured plasma properties are independent of the geometry of the collecting probe.

To verify if the collecting probes operate in the thick sheath-orbital motion limited-approximation (see the notes) using the experimental data.

Determine the electron emission current for different emissive probe temperatures from the voltage current characteristic curves.

Check if the floating potential of the emissive probe approaches the plasma potential as the probe is heated.