Elektrische Sonden im Plasma

Nikolas Abt (Matr.-Nr. 2712859)
Philipp Scheiger (Matr.-Nr. 2757623)
Universität Stuttgart, November 8, 2014

Plasma, often called the fourth state of matter, is a particle mixture whose components are (partially) split up into ions and electrons. There are some characteristic quantities like electron temperature and electron density, distinguishing the different types of plasma like glow discharge, lightnings or aurorae. Plasma is used to generate light or in surface technologies like reactive-ion etching. To determine important quantities, the Langmuir probe is the most important tool in plasma diagnostics. In this experiment, the single and the double probes are used to study plasma parameters in a glow discharge, depending on different initial conditions.

I. Basic plasma physics

I.1. Physical properties of plasma

There are several properties which are important for the characterization of plasma. At first of all, one major constraint is that the plasma has to be quasi neutral, i.e. the amount of positive (ions i) and negative (electrons e) charged particles is approximately equal,

$$n_e = \chi_j n_{i,j}, \tag{1}$$

where n_e and $n_{i,j}$ denote the density of electrons and ions, respectively, and χ_j is the degree of ionization. Potentially, there might be deviation from this condition, but they can only appear on scales small compared to the Debye-length.

I.2. Debye length

The Debye length is a characteristic length scale in plasma physics regarding variations in the electrical potential of charged particles which can be derived by means of the Debye"=Hückel"=Theory. If we consider a single negative charge, there will be statistically more positive charged particles shielding the negative one. Hence there will be a decrease in the electrical potential. The Debye length is the length, where the potential dropped on the value $1/e$. It is

$$\lambda_\mathrm{D} = \sqrt{\frac{\varepsilon_0 k_\mathrm{B}/e^2}{n_e/T_e + \chi_j n_{i,j}/T_j}}, \tag{2}$$

where T_α are the corresponding Temperatures of charged particles. A much more easier form of (2) is obtained if the ionic temperature is neglected, due to the marginal mobility of the ions. In this approximation,

$$\lambda_\mathrm{D} = \sqrt{\frac{\varepsilon_0 k_\mathrm{B} T_e}{n_e e^2}} \tag{3}$$

is valid. Since the Debye length is only property of electrostatic deviations, another quantity, the plasma frequency can be introduced.

I.3. Plasma frequency

A local compression is not a state of equilibrium, so the Coulomb interaction is acting on the electrons in such a way, that the equilibrium could be established. Due to the inertia of the electrons, they do not rest in their idle state but overshoot the mark which leads to another compression. This process of collective oscillation happens with the plasma frequency

$$\omega_\mathrm{p} = \sqrt{\frac{n_e e^2}{m_e \varepsilon_0}}. \tag{4}$$

Below ω_p incident electromagnetic waves are reflected, above ω_p incident waves are transmitted through the plasma.

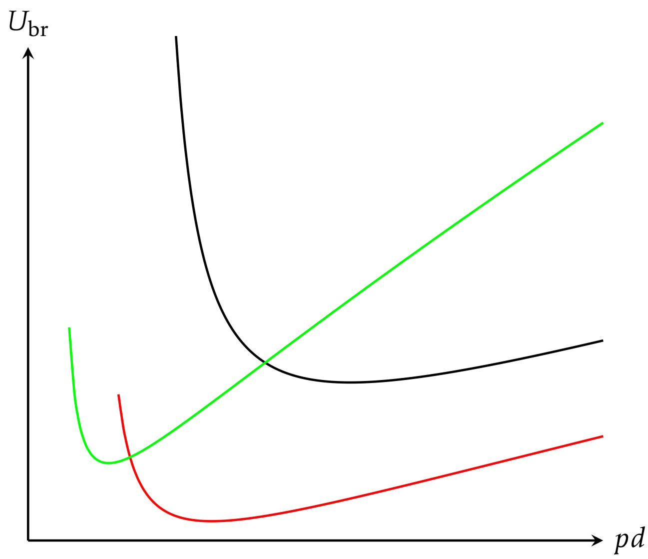

Fig. 1: *Possible Paschen curves.*

I.4. Glow discharge

The easiest way to create plasma in laboratories is the apply a voltage between to electrodes in a tube which is filled with a certain gas. Through random processes (for example ionization through cosmic radiation), there is finite number of free electrons and ions in each gas even at room temperature. These free charged particles are accelerated towards the electrodes. If the voltage is sufficiently high and the electrons ionize the atoms or the ions free another electron at the impact on the cathode, a gas charge will occur. This voltage is called the *breakdown voltage*. The breakdown voltage U_{br} depends on the gas pressure p and the distance d of the electrodes. These quantities are connected by the *Paschen law* and

$$U_{\mathrm{br}} = \frac{\alpha p d}{\ln(\beta p d) + \ln\left[\ln\left(1 + \gamma^{-1}\right)\right]} \tag{5}$$

holds with gas specific constants α and β. Figure 1 shows possible Paschen curves.

I.5. Langmuir probe

To measure plasma characteristics, the Langmuir probe is the most common device that is used. The probe consists of an electrode inserted into the plasma. Measured are the voltage between the electrode and a reference potential and the current flowing onto or off the probe. The experimental setup is displayed in figure 2 in configuration ①. Assuming that initially the potential of the probe and the plasma are equal, there will be higher electron flux onto the probe compared to the ion flux

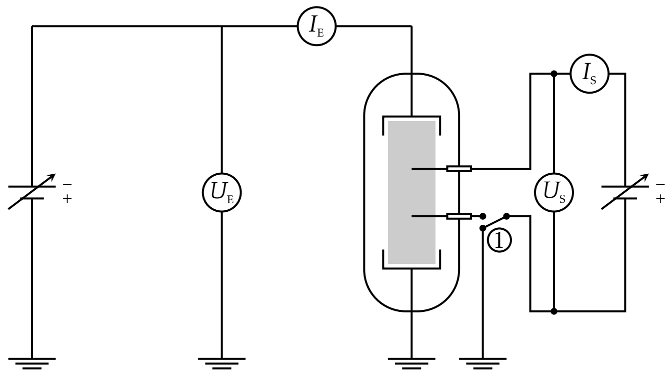

Fig. 2: *Experimental setup with the single and the double probe.*

due to the different mobilities. After a certain time when the potential is too negative to attract further electrons more ions move onto the probe. The state of equilibrium is when both fluxes are equal and the probe is on the so called *floating potential* U_{fl}.

By changing the applied voltage U_{s} between a reference potential (for example the cathode) and the probe the characteristic curve can be measured. For high negative voltages, only ions are attracted and the current is limited to the ion saturation current

$$I_{\mathrm{i,\,sat}} = 0.61 e n_e S \sqrt{\frac{T_e}{m_i}} \tag{6}$$

. where S is the probe surface and m_i the ion mass. If the voltage is increased, the probe reaches the floating point, where the current vanishes. A further increase will result in the electron retardation region where more and more electrons are drawn on the tip of the probe. The dependence is exponential and it is

$$I = I_{\mathrm{e,\,sat}} e^{-e(U_{\mathrm{fl}} - U)/T_e} + I_{\mathrm{i,\,sat}} \tag{7}$$

with

$$I_{\mathrm{e,\,sat}} = -e n_e S \sqrt{\frac{T_e}{2\pi m_e}}. \tag{8}$$

If the voltage is as large as the plasma potential all electrons in the surrounding are drawn and the current is limited to the electron saturation current $I_{\mathrm{e,\,sat}}$. Yet, there is a dependence on the surface of the probe tip that, in general, there will be no saturation due to the increasing boundary layer between probe and plasma and the higher electron flux coming along. A characteristic curve is plotted in figure 3. The electron temperature and density for the calculation of the degree of ionization, Debye length and plasma frequency are obtained by fitting the the exponential dependence (7) in the electron retardation regime to experimental data.

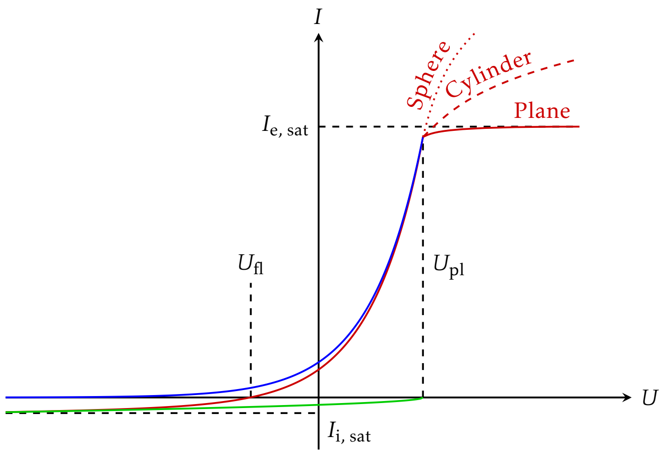

Fig. 3: *Typical characteristic curve of a single Langmuir probe. The green line is the ion current, the blue one is the electron current and the red one is the combined current.*

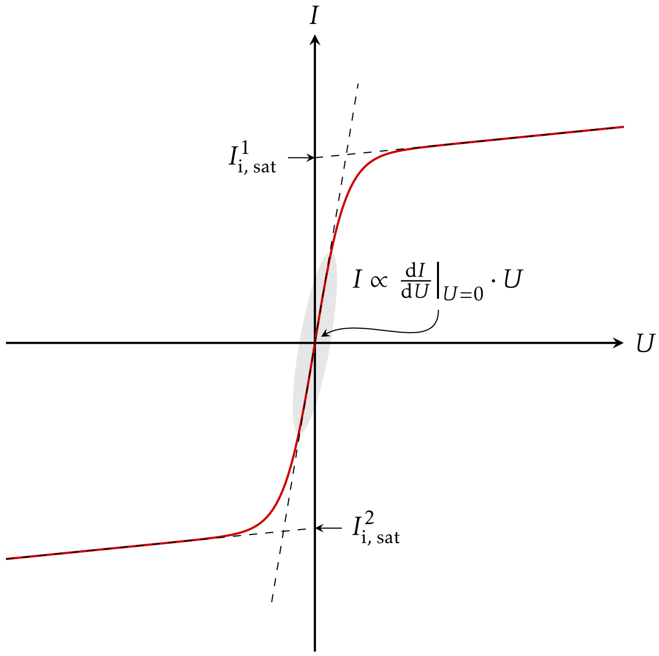

Fig. 4: *Typical characteristic curve of a single Langmuir probe. The green line is the ion current, the blue one is the electron current and the red one is the combined current.*

I.6. Double probe

Sometimes the single probe fails, for example when there is no well defined reference potential, the double probe is used. The mechanism is the same as for the single probe but the characteristic curve looks a little bit different. We define $U = U_1 - U_2$, so a negative voltage means that the second probe has a more negative potential to the plasma potential than probe 1, so its ion current will be increased. If it is sufficiently negative, only ions are attracted and the electron current is given by $I^2_{\text{i, sat}}$. When the point $I = 0$ (both probes are on the floating potential) is approached, the range of electron retardation is reached and the current depends linear on the applied voltage. If the probes are equal in size and shape, the characteristic curve is symmetric around $I = U = 0$. Figure 4 depicts a characteristic curve of a double probe. For the double probe, the electron temperature is obtained by extrapolation for the saturation currents $I^{1,2}_{\text{i, sat}}$ as depicted in figure 4. Further, the slope at $U = 0$ has to be determined by a linear fit. These three parameters are the input for the conditional equation for the electron temperature, namely

$$T_e = \left(\frac{\mathrm{d}I}{\mathrm{d}U}\bigg|_{U=0} \right)^{-1} e \frac{I^1_{\text{i, sat}} I^2_{\text{i, sat}}}{I^1_{\text{i, sat}} + I^2_{\text{i, sat}}}. \tag{9}$$

By using equation (6) the density can be calculated.

II. Experimental setup and procedure

The experimental setup is schematically drawn in figure 2. The voltages $U_{\text{E, S}}$ could be tuned by hand and both the current and the voltage of the probe was directly transmitted to a LabView program. Initially the characteristic of the single probe for Argon at five different gas pressures at constant discharge current I_{E} was measured. Only negative voltages were applied to avoid a too high current which would destroy the probe. Secondly the radial position of the tip of the probe was changed. This was done for $I_{\text{E}} = 5, 10$ and $20\,\text{mA}$. The third task was to measure the characteristic for the double probe, also at five different gas pressures. The last task was to measure the Paschen law. The whole procedure was repeated for Helium.

III. Auswertung

IV. Zusammenfassung

References