Plasma Parameter Measurement with a Langmuir Probe in a Weakly Ionized Plasma

Ibnul Farid, Shivajyoti Sarma and Homeswar Kakati#

Department of Physics, B. Borooah College, Ulubari, Guwahati-7, Assam, India

#Email: kakatidr@gmail.com

Abstract

The present work is aimed at studying the plasma production technique by hot cathode filament discharge method, Langmuir probe diagnostic technique to calculate different plasma parameters e.g. plasma density \(n_e\), electron temperature \(T_e\), plasma potential \(V_P\) etc. and to find out the variation of the above mentioned plasma parameters with discharge current \(I_d\). Plasma parameters define various characteristics of plasma. Factors like plasma density \(n_e\), electron temperature \(T_e\), plasma potential \(V_P\) has a great significant impact on study of plasma. It is observed in our project that plasma density is \(5-10 \times 10^{15} \text{ m}^{-3}\) and electron temperature is 2.4 - 3 eV. It is also observed that the plasma density increases linearly with the discharge current due to the increase of primary electrons which ionizes the neutral gas atoms.

1. Introduction

Plasma is a distinct phase of matter, separate from the traditional solids, liquids, and gases. It is a collection of charged particles that respond strongly and collectively to electromagnetic fields, taking the form of gas-like clouds or ion beams. Since particles in plasma are electrically charged, it is frequently described as an “ionized gas”.

The term “Plasma” was first used by American physicist Irving Langmuir and Tonks in 1923 to describe the ionized gas. By definition, plasma is a quasineutral gas of charged and neutral particles which exhibits collective behavior. Quasineutral means, the number density of positive ions and electrons are nearly equal, \(n_e \approx n_i\) and by the term collective behaviour means the motions that depend not only on local conditions but also on the state of plasma in remote region as well. In plasma, particles experience Columbic force which is a long range force in nature and becomes weaker at very large distance. On the other hand, in neutral gases the force between two particles is governed by the Van der-Walls’ force which is a short range force. Almost 99% of the matter in the universe e.g., the Sun, stars, nebula, the Milky Way etc. are in plasma state. Plasma phenomena near our earth are rare due to its low temperature and density. One can produce plasma on earth only by experimental means. In our everyday lives we encounters with plasmas are limited to a few examples: the flash of a lightning bolt, the soft glow of the Aurora Borealis, the conducting gas inside a fluorescent tube or neon sign and the slight amount of ionization in a rocket exhaust.
In order to convert a gas into plasma state, it is very necessary to tear away at least some of the electrons from the atoms. By these we convert the atoms into ions. This de-attachment of electrons from atom is called “ionization”. In the laboratory, ionization can be produced by various methods. The most important of these are (a) ionization by electric discharge (b) ionization by heat (c) ionization by radiation.

The most widely used method in laboratory for obtaining plasma is the electrical gas discharge method. When we apply electric field to a gas in the double plasma device in between two charged conductors i.e. one positively charged and one negatively charged, it is necessary that the electric field applied to the gas is large enough so that energy imparted to the electrons is sufficient to knock out at least one electron from an atom on impact. These primary electrons, after accelerated by the applied electric field will collide with the neutral particles and will generate new free charge carries. In this way, electrons multiplication proceeds. Thus ionization of an entire gas occurs and turns into plasma.

All substance became ionized if they are heated sufficiently to a very high temperature. This process is known as “thermal ionization”. It is necessary that the temperature be close to the energy of the most weakly bound electron i.e. almost equal to the lowest ionization energy of an atom or molecule. In atom the valance electron is in the outer orbit. By heating, we de-attach the electron and ionize the gas. Thus we obtain thermal plasma in laboratory. The radiation emitted by the sun, hot stars causes ionization in the surrounding gases, vapors and interstellar gas and in this way also plasma gets produced. In order to sustain plasma in a gas, the conditions are: \( \lambda_D < L, N_D \gg 1, \omega \tau > 1 \), where, \( \lambda_D \) is the Debye length, \( L \) is dimension of chamber, \( N_D \) is number of particles in a Debye sphere, \( \omega \) is frequency of oscillation and \( \tau \) is mean time between two collisions of charged particles with neutral atom.

The basic parameters of plasma are-

a) The particle density \( n \) which is measured in particle per cubic meter.

b) The temperature \( T \) of each species which is usually measured in electron volt (eV).

c) The steady state magnetic field \( B \) which is measured in Tesla.

Other subsidiary plasma parameters e.g. Debye length, Lamoure radius, plasma frequency, cyclotron frequency etc. can be derived from the above mentioned three plasma parameters.

### 3. Experimental

#### 3.1. Description of the experimental set-up

Figure 1 shows the photograph of the existing double plasma device in Centre of Plasma Physics- Institute for Plasma Research (CPP-IPR), Sonapur, Assam. The cylindrical shaped chamber, made of stainless steel (SS 304L), is 1.2 m long and 0.3 m in diameter. The chamber is connected to a vacuum unit consisting of a diffusion pump backed by a rotary pump. Penning and Pirani gauges are connected in the pumping lines to measure the diffusion and rotary pump created pressure readings respectively.

![Figure 1: Photograph of the existing double plasma device in Centre of Plasma Physics - Institute for Plasma Research (CPP-IPR), Sonapur, Assam.](image-url)
Plasma is produced in the source magnetic cage by hot cathode filament discharge method. In this method, initially the filament (usually of Tungsten) is heated sufficiently by passing current to emit electrons. These electrons are called primary electrons. Simultaneously the filament (cathode) is biased negatively with respect to the source magnetic cage (anode) and the latter is connected to ground. The primary electrons after emitting from the surface of the filament gain energy due to their acceleration towards the source magnetic cage and on their way they will suffer successive collisions with the neutral hydrogen gas molecules and atoms. If the electron energy is sufficiently high compared to the ionization energy of the hydrogen gas atom, then ionization occurs and thus plasma is produced inside the chamber. After production in the source cage, plasma diffusion takes place to the target magnetic cage through the transverse magnetic field.

![Schematic diagram of the experimental set up.](image)

Fig. 2: Schematic diagram of the experimental set up. The different parts labeled are (1) Filament voltage power supply ($V_F$), (2) Discharge voltage power supply ($V_D$), (3) Hydrogen gas cylinder, (4) Resistance, (5) Power supply, (6) Tungsten filament, (7) Cylindrical Langmuir probe, (8) Transverse magnetic field (N- North Pole, S- South pole), (9) Multi-dipole magnetic cage, (10) Diffusion pump, (11) Rotary pump.

### 3.3. Langmuir probe

Langmuir probe is the simplest and most frequently used tool for measuring different plasma parameters e.g. plasma density ($n_e$), electron temperature ($T_e$), plasma potential ($V_p$), floating potential ($V_f$), electron distribution function etc. Irving Langmuir (1881-1957) first developed this technique about fifty years ago. A Langmuir probe is basically a metal conductor which is inserted into plasma and electrically biased with respect to any reference electrode to collect electron or ion current. From this $I$-$V$ characteristic one can easily calculate different plasma parameters. Figure 3.3 shows an ideal Langmuir probe characteristic.

An ideal Langmuir probe characteristic can be divided into three parts viz. ion saturation region (A), transition region (B) and electron saturation region (C). When the probe is at the same potential ($V_p$) with its surrounding plasma ($V_S$), the existing electric field between the probe and plasma vanishes immediately. In this situation, the electrons whose mobility is higher due to their lower mass compared to the ions strikes the probe. Therefore, the current collected by the probe is predominantly electron current. Now, if the probe is biased positively with respect to the plasma potential ($V_S$), the electrons are accelerated whereas the ions are repelled by the probe.

![I-V Characteristics of Langmuir Probe](image)

Fig. 3: I-V Characteristics of Langmuir Probe

For a sufficiently high positive probe potential the ion current to the probe vanishes and a space charge layer of electrons build up near the surface of the probe. Because of this space charge layer the electron current to the probe saturates. When the probe potential is negative with respect to the plasma potential, the probe repels the electrons and accelerates the ions. Now, if the electron distribution is Maxwellian, the shape of the probe current curve in the transition region would be exponential. At a certain probe potential, the ion and electron flux to the probe becomes same. This potential is called the floating potential ($V_f$). At a large value of negative probe potential, a space charge layer of positive ions develops and the probe collects only the positive ions.

When the probe voltage $V_p$ is sufficiently negative with respect to the plasma potential $V_S$, the probe collects the ion saturation current ($I_{si}$). For a Maxwellian ion distribution at temperature $T_i$, the dependence of the ion current $I_i(V_p)$ on $V_p$ is given by-
When $T_e > T_i$, the ion saturation current can be written as:

$$I_{is} = 0.6 \times e \times n_e \times A_p \times \left(\frac{kT_e}{m_i}\right)^{1/2}$$  \hspace{1cm} (3)

where, $e$ is elementary charge, $n_e$ is electron density, $A_p$ is the probe surface area, $T_e$ is the electron temperature, $k$ is Boltzmann’s constant and $m_i$ is the mass of the atom (H atom in our case).

For $V_p >> V_S$, the probe collects electron saturation current $I_{es}$. The electron current as a function of $V_p$ can be expressed as:

$$I_e(V_p) = -I_{es} \exp\left(\frac{e(V_e-V_p)}{kT_e}\right) \text{ when } V_p \leq V_s$$  \hspace{1cm} (4)

$$I_e(V_p) = I_{es} \text{ when } V_p > V_s$$  \hspace{1cm} (5)

The electron saturation current $I_{es}$ is given by:

$$I_{es} = \frac{e}{4} n_e v_{e,th} A_p$$  \hspace{1cm} (6)

where, $v_{e,th} = \sqrt{\frac{8kT_e}{\pi m_e}}$ is the average velocity of the electron.

Now taking the semi log of equation (4), we get:

$$\ln I_e(V_p) = -\frac{e(V_e-V_p)}{kT_e} + \ln I_{es}$$  \hspace{1cm} (7)

or, $$\ln I_e(V_p) = \frac{eV}{kT_e} + \ln I_{es}$$  \hspace{1cm} (8)

where, $V = (V_p-V_S)$ equation is straight line. If $\ln I_e(V_p)$ is plotted against $V$, equation will give a straight line with a slope equal to $e/kT_e$ which gives a good measure of electron temperature.

For the present project, at first voltage applied to the filament and the filament voltage and current are kept constant at 7V and 12A. The discharge voltage and current are fixed at 80 V and 0.5 A. The Langmuir probe, which is in the source region, is biased from -80 V to +80 V to obtain the $I-V$ characteristics. After that the discharge current is varied from 0.5 A to 2 A by changing the filament voltage and in each time the Langmuir probe $I-V$ characteristics are obtained.

4. Results and discussion

The density of the neutral hydrogen atom is $n_a = \frac{P}{kT_g}$, where $T_g$ is the temperature of the neutral gas; $P$ is the neutral gas pressure, $k$ is Boltzmann const. For $P = 5 \times 10^{-4}$ mbar and $T_g = 300$ K, $n_a = 1.2077 \times 10^{19}$ m$^{-3}$. For $I_d = 1.5$ A, we get $n_i = 9.016 \times 10^{15}$ m$^{-3}$. We obtain $n_i/n_a = 7.465 \times 10^{-4}$. Thus only 0.074% of the neutral atoms are ionized. From our calculation we have found that the plasma inside the chamber is weakly ionized.

Figure 4 shows the $I-V$ characteristics of Langmuir probe for 0.5 A discharge current. For collision mean free paths, $\lambda = \frac{1}{n_a\sigma}$ where $\sigma$ is the cross-section area of collision and its value for H is $0.88 \times 10^{-20}$ m$^2$. So $\lambda = 9.40$ m. Thus the relatively long mean free path explains the relatively low value of the ionization percentage i.e. electrons that are energetically capable of ionizing atoms are more likely to make it to the wall before ionizing an atom. Since, mean free path > chamber dimension so the plasma is collision less.

Figure 5 shows the plot of $\ln I_P$ vs. $V_p$. The electron temperature can be calculated from the slope of the straight line which is drawn in the transition region of the probe characteristics. It is found that the electron temperature for 0.5 A discharge current is $\sim 2.5$ eV.
plasma density with respect to the discharge current. The plasma density linearly increases with respect to the discharge current. In our experiment the discharge current is increased by increasing the filament current. As the filament current increases the thermionic emission from the filament also increases. The electrons emitted from the filament are called the primary electrons and their energy is equivalent to $eV_d$. So, for 80 V discharge current, the primary electron energy would be around 80 eV. And the number density of this electron is a function of filament voltage. These primary electrons are responsible for the ionization of the background neutral gas and as their number density increases with discharge current, more ionization occurs. Therefore, the plasma density increases with respect to the discharge current.

![Figure 6: I-V characteristics of Langmuir probe for $I_d=0.5$ A, 1 A, 1.5 A and 2 A](image)

Figure 8 shows the variation of electron temperature with respect to the discharge current and it is observed that like plasma density, the electron temperature also increases as we increase the discharge current. As the discharge current increases the number of primary electrons emitted from the filament also increases and these primary electrons increase the average energy of the plasma.

![Figure 8: Variation of electron temperature with respect to the discharge current](image)

5. Conclusion:
From the above study, we have observed that the hot filament discharge technique is an efficient method for the production of cold plasma. The plasma density and electron temperature are calculated from the I-V characteristics of Langmuir probe and we have obtained these as $5-10\times10^{15}$ m$^{-3}$ and 2.4 - 3 eV. We have also observed that the plasma density increases linearly with the discharge current due to the increase of primary electrons that ionizes the neutral gas atoms. Because of these primary electrons the average temperature of the electrons inside the chamber also goes up.

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7. References

