Measurement of electron energy probability function in weakly magnetized plasma

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Abstract. Knowledge of the real EEDF is of great importance in understanding the underlying physics of processes occurring at the magnetized plasma, such as the formation of transport barriers, cross-field diffusion coefficients and plasma–substrate interactions. In the present experiment, the application of Langmuir probe to evaluate EEPF in presence of magnetic fields within the range 594–32 G is investigated. The data recorded for EEPFs in magnetic fields and in dust is acquired using current–voltage characteristics measured in low pressure hydrogen plasma. The values of plasma density, electron temperature and EEPF are evaluated with a single cylindrical Langmuir probe at different axial positions (1 cm to 6 cm) from the magnet. From the recent EEPF observations in presence of magnetic field, it shows a bi-Maxwellian EEPF structure at different magnetic fields. But at different magnetic field, it is observed that the low energy electron population changes whereas the high-energy electron population remains almost constant. EEPF measurement shows almost identical behaviour with the unmagnetized plasma when the larmour radius of electron is greater than or equal to 10 times of the probe radius.

1. Introduction
The importance of the knowledge of the electron energy distribution function (EEDF) is of great interest in different branches of plasma physics ranging from laboratory to fusion plasmas [1,2]. The EEDF is a measure of the number of electrons within a unit energy interval and provides information on other internal parameters of the plasma. The EEDF is obtained using the Druyvesteyn procedure [3] by the second derivative of I–V characteristic measured by the probe which is proportional to the electron energy probability function (EEPF) [4,5].

\[ F(\varepsilon) = \varepsilon^{1/2} \times f_p(\varepsilon) \] \hfill (1)

Here, \( \varepsilon \) is the electron energy in eV.

In most of the laboratory plasma devices, a magnetic field is practically observed in all situations either in ambient or is applied in the industrial/ fusion plasma research. It is known that the magnetic field can influence the anisotropy of the plasma properties. Hence, the magnetic field affects the plasma properties by altering the transport of ions and electrons to the chamber wall. However, due to many difficulties in measuring of the EEDF magnetized plasmas [6], the evolution of the EEDF and associated plasma parameters across magnetic fields still remains a topic of important research.

Also, the understanding of the dust behavior in plasma is of great importance for experimental and industrial applications [6,7]. The dust charging behaviour and its controlling in filamentary hydrogen...
plasma are reported by our group in our earlier publications [8-11]. The presence of dust (grains) changes the plasma parameters by redistributing the low and high energy electron populations [12]. The density of the plasma electrons in presence of dust particles decreases by capturing the low energy plasma electrons on the surface of the dust grain, which in turn increases the energy of the electrons. However, the study on EEPF for dust containing hydrogen plasma in presence of magnetic field is very rare [13].

The present experimental work is largely dealt with the study of the effect of external magnetic field on the plasma parameters such as plasma density, electron temperature, EEPF in absence/presence of dust in low pressure hydrogen plasma. Special emphasis is given on the measurement of EEPF by Langmuir probe for “high and low magnetic field case” for pristine and dust containing hydrogen plasma. The electron energy distributions functions measured in this work are presented in terms of electron energy probability function EEPF, in units of cm$^{-3}$V$^{-3/2}$ rather than the EEDF itself.

2. Experimental set up

The experiments are carried out in the existing dusty plasma device consisted of two stainless steel chambers placed one above the other as shown in figure 1. The lower chamber is the plasma chamber that is placed horizontally and vertical upper chamber facilitates the holding of dust dropper. The plasma discharge chamber was made out of a cylindrical stainless steel chamber of 100 cm in length and 30 cm in diameter. The dust unit consists of cylindrical stainless steel chamber of height 72 cm and 15 cm in diameter with a dust dropper, fitted inside the dust chamber. For the confinement of the plasma elements, a full line cusped magnetic cage made of strontium ferrite of 1.3 kG is used. Hydrogen plasma is produced by hot cathode filament discharge technique by striking a discharge between incandescent tungsten filaments and grounded magnetic cage. Here filaments are acting as cathode and the grounded chamber as an anode. A permanent magnet having magnetic field strength 1.2 kG is placed inside the plasma chamber to observe the effect of magnetic field on plasma parameters.

![Figure 1. Schematic diagram of the experimental device.](image-url)
Plasma parameters are measured by a single cylindrical Hiden Analytical Limited’s ESPION advanced Langmuir probe system, consisting of a tungsten wire of 0.15 mm in diameter and a length of 10 mm. For probe measurement validity in magnetic field, the probe tip is oriented normally to the magnetic field.

In general, the probe radius should be much smaller than the Larmor radius of the electron or ion. If the Larmor radius of the electron or ion is smaller than the probe radius, the electron or ion current to the probe is reduced, and as a result the data acquired in presence of magnetic field are not accurate. In presence of strong magnetic field, the charge collections by the Langmuir probe is limited due to orbital effect and the reduction of collected charged particle can be represented by a parameter $\beta$. The parameter $\beta$ is estimated by the ratio of the probe radius ($r_p$) to the mean Larmor gyroradius ($r_L$) of charged particle. In the present experiment for different magnetic field strength, the parameter $\beta$ is found out to be 1.16 (max) and 0.05 (min) for electron and for ion, it is 0.20 (max) and 0.009 (min). Thus the electron collection by the probe in presence of magnetic field is affected more compared to the ion collection.

In the present work, tungsten dust particles (having dia ~ 4-6 µm) are used to study the effect on EEDF in presence of dust grains which are dropped from the top of the dust chamber with the help of an electrically controlled dust dropper.

3. Results and Discussions

The presence of the magnetic field lines is generally thought to reduce the electron or ion current drawn from the plasma by a Langmuir probe because the charged particles tend to follow the magnetic field lines. As the magnetic field strongly restrict the motion of the electrons than the ions, so the electron density measured from the electron saturation current with the help of a Langmuir probe deviates from the ion density measurements. In presence of magnetic field, the electron saturation current takes the form of [14]

$$I_e = I_o \delta$$

where $I_o = -\frac{1}{4} n_{e0} \bar{v}_e e A_p$ is the undisturbed electron current, where $A_p$ is the probe surface area, $e$ is the elementary charge, $\bar{v}_e$ is the electron’s mean velocity, $n_{e0}$ is the electron density of the undisturbed plasma. The $\delta$ is the reduction factor due to the magnetic field which is given by;

$$\delta = \left( 1 + \frac{\pi r_p}{\lambda} \left[ 1 + \left( \frac{\lambda}{r_L^e} \right)^2 \right]^{1/2} \right)^{-1}$$

where $r_p$ is the probe radius, $\lambda$ is the Debye length and $r_L^e$ is the Larmor radius of the electron.

The reduction factor $\delta$ at different magnetic field strengths for our present experiment is shown in figure 2.
The maximum reduction factor $\delta$ is around 0.85 at magnetic field, $B = 594$ Gauss for $I_{\text{dis}} = 100$ mA and it reduces to 0.2806 at magnetic field, $B = 32$ Gauss for $I_{\text{dis}} = 300$ mA.

The influence of magnetic field on the plasma parameters are strongly deviates from the unmagnetized plasma [10]. The plasma parameters are calculated from the I-V characteristics of the Langmuir probe. Figure 3 shows the plasma density and electron temperature measurement at different magnetic field strengths for constant working pressure $\sim 2 \times 10^{-4}$ mbar. From figure 3, it is seen that as the magnetic field strength increases, the electron temperature decreases from $\sim 1.55$ eV to $\sim 1.10$ eV for discharge currents 300mA. Because, at higher field strength, only high energetic electrons are collected by the probe and the lower energetic electrons are trapped by the magnetic field lines. As the
field strength decreases, the electrons with lower energy can also reach the probe. Thus, the electron temperature decreases with the decrease in field strengths.

Also, the plasma density decreases with the increase of magnetic field strength because higher magnetic field constraints the motion of electrons and ions. Hence, the charge collection by the probe is reduced from the actual value. It is observed that the plasma density and the electron temperature measured by Langmuir probe shows almost consistent result at lower magnetic field strength (at $B \leq 37$) as the influence of magnetic field on the collection of charge particle is almost negligible. At this field strength, $r'_L$ and $r''_L \geq 10r_p$.

The shape of EEPF for molecular gases (like N$_2$, O$_2$) is completely different and complicated than atomic gases [8]. It is reported that the EEPF for molecular gases (N$_2$ and O$_2$) plasma shows nearly Maxwellian distribution whereas the atomic gases (like noble gases) shows Druyvesteyn distribution at low pressure. Godyak et al. [6] suggested that if the electron-electron collision frequency is of the order of $10^{10}$ (cmV$^{1/2}$)$^{-3}$, then the EEPF shows Maxwellian structure. The electron-electron collision frequency is proportional to the value of $N(<\varepsilon>/e)^{-3/2}$. It is found that the the value of $N(<\varepsilon>/e)^{-3/2}$ is very less compare to $10^{10}$ (cmV$^{1/2}$)$^{-3}$ at the operating pressure 2 x $10^{-4}$ mbar. Thus, a bi- Maxwellian EEPF is observed for the entire magnetic field range (figure 5). In the present work $N(<\varepsilon>/e)^{-3/2}$ is presented in the form of $n^*(<\varepsilon>/e)^{-3/2}$ (V$^{-3/2}$), where $n^* = n_e/n_i$. The value of $n^*(<\varepsilon>/e)^{-3/2}$ (V$^{-3/2}$) at different magnetic field is shown in figure 4.

![Figure 4](image_url)  
**Figure 4.** The values of $n^*(<\varepsilon>/e)^{-3/2}$ (V$^{-3/2}$) at different magnetic field strengths.

Figure 5(a) and (b) shows the EEPFs of hydrogen plasma, in absence and presence of dust, for higher field strength ($B = 594$G) and lower field strength ($B = 37$ G). A bi-Maxwellian EEPF is observed in both the cases for pristine and dust containing hydrogen plasma. From the observations, it is found that the low energy electron population changes whereas the high-energy electron population remains almost constant in presence of magnetic field. At higher magnetic field, the probe does not collect the lower energetic electrons due to the higher value of $\delta$. So, the probe collects mostly the higher energetic electrons. So, the peak of bulk electrons i.e. the low energy electrons are very small at higher magnetic field compared to the lower magnetic field. As the magnetic field reduces the bulk electron peak of the EEPF becomes steeper and reaches a saturated value. It reflects the decrease in electron temperature at lower magnetic field strength, which is also observed in the electron temperature measurements (figure 2).
Additionally, the EEPF is studied in presence of dust particles. Like pristine hydrogen plasma, a similar bi-Maxwellian EEPF is observed for dust containing hydrogen plasma in presence of magnetic field. It is observed that the bulk electron peak of the EEPF slightly decreases and the high-energy tail becomes slightly larger in presence of dust grains than the pristine plasma due to the collection of electrons and ions by the dust particles. It is seen from figure 5 that only the low energy electron populations are reduced and the high energy electrons are enhanced in presence of dust particles. Because of collection of the bulk electrons by the dust particles, the overall electron loss increases and the system then self-organizes to maintain a balance between the production and loss of electrons by increasing the number of high-energy electrons. As a result, the fraction of high-energy electrons in the EEPF tail enhances in presence of dust particles. The present observation shows similar EEPF for dust containing hydrogen plasma in absence of magnetic field [8].

4. Conclusion
From the observations, it is found that the plasma density and the electron temperature, shows consistent results at lower magnetic field strength. It is seen that the plasma density increases with the increase of magnetic field strength as the charge collection by the probe is highly restricted for higher field strengths and correspondingly the electron temperature gradually decreases with the reduction of magnetic field strength as both the higher and lower energetic electrons are collected by the probe. We have found from the measured EEPFs, a bi-Maxwellian behaviour at a very low pressure (≈ 2 \times 10^{-4} mbar) in presence of magnetic field. In the EEPF graphs, the peak of bulk electrons is very small at higher magnetic field compared to that of lower magnetic field. As the magnetic field decreases, the bulk electron peak in the EEPF increases as both the higher energetic and lower energetic electrons are collected by the probe. In presence of dust particles, the bulk electron peak of the EEPF slightly decreases due to the collection of electrons by the dust particles and the high-energy tail becomes slightly larger compared to pristine hydrogen plasma in presence of magnetic field.

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