Characterisation of a toroidal plasma in a magnetic field by the floating double probe technique for hydrogen

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Abstract:
In the present work, the floating double probe technique was used to determine the plasma parameters by using the equivalent resistance method [1,2,3,4,5] for hydrogen in toroidal discharge. Measurements were done for transverse and longitudinal positions of the probes to the axial toroidal magnetic field. The experiment was carried out in a 13.56 MHz inductively coupled radio frequency plasma discharge at different pressures of 0.07 torr to 0.20 torr and magnetic fields of 0G to 75G and observed the differences of plasma temperature and particle number density on the discharge axis of the torus. It is also observed that the plasma temperature decreases whereas the plasma radial density increases for axial positions but for transverse positions of the probes, the plasma temperature increases and the radial density decreases with the magnetic field and changes with pressure also. The results were compared with nitrogen and argon as well as with direct current glow discharge plasmas with identical input magnetic field [6]. The validity of the probe method for measurement of plasma temperature and density in a toroidal discharge has been discussed.

1. Introduction:
An equivalent resistance method [1,2,3,4,5] was adopted to determine plasma temperature and density with magnetic fields on the Langmuir probe technique. The applied magnetic field reduces the free paths of these charged particles which are perpendicular to the field to less than the radius of curvature $r = \frac{mv}{eH}$ where v being the velocity, m the mass of the particle. Hence the probe dimensions become invalid in moderate magnetic field and that is why we keep the field below 100 Gauss. This paper very briefly exhibits the study of Low Pressure Laboratory built Inductively Coupled Plasma (LPLB-ICP) [7,8] produced in hydrogen excited by a 13.56 MHz RF power source within an electrode less toroidal chamber with different filling pressures and magnetic fields which seem to yield plasma temperature and density and a comparison with that of argon and nitrogen.
2. Experimental set up:

2.1 A schematic diagram of the low-pressure laboratory built inductively coupled plasma experimental set up is shown in figure 1.

Figure 1: Circuit diagram for parameters studies

(1) Annular coils for axial magnetic field,
(2) Annular H type solenoid coil generated by a stabilized power supply
(3) Gas inlet with measurement of filling pressure by a calibrated perani gauge
(4) Radio frequency power source of frequency 13.56 MHz
(5) The toroidal vacuum chamber of major radius 13.18 cm & minor radius 3.18 cm
(6) Cylindrical double probes of 0.2 mm diameter & 5 mm length having spacing of 1.5 cm for transverse & 3.25 cm for longitudinal to the axial magnetic field
(7) A ripple free D.C Voltage source (Ni-Cd cel) for probes
(8) Single resistor for measuring positive ion current or electron current
(9) D.C voltmeter of sensitivity 0.1 Volt for measuring probe voltage
(10) D.C µ ammeter of sensitivity 100nA for measuring probe current
(11) Tuning coil with Primary and Secondary
2.2 The floating double probe:

Here double probe mechanism has been carried out with an inductively coupled radio frequency source discharge. At first sight it might be thought that both probes would follow any fluctuations in the plasma potential. Although, plasma oscillations in this source are small, therefore the probe trace distortion is minimal [8,9,10].

3. Results and discussions:

A floating double probe was used to determine the plasma temperature and subsequently the particle number density of the laboratory built LP-ICP, with and without magnetic field. In this method, the variation of the probe current-voltage characteristics ($I_p$ Vs $V_d$) for constant torus breakdown voltage, filling pressure, with and without magnetic fields for hydrogen is shown in figure 2. In absence of the magnetic field, the expression of the plasma electron temperature ($T_e$) is given by [4],

$$T_e = \frac{e}{K} \sum \left( \frac{dI_p}{dV_d} \right) s - 0.82s \tag{1}$$

Where, $T_e$ is the electron temperature, $e$ is the charge of an electron, $K$ is the Boltzmann constant, $\Sigma I_p0 = I_{p10} + I_{p20}$ illustrated in fig.2, $V_d$ is the probe potential in terms of differential voltage, $I_p$ is the associated current in the circuit, $\left( \frac{dI_p}{dV_d} \right)_s$ is the slope of the current-voltage characteristics at the inflection point, $s$ is the slope of the positive ion saturation characteristics.

Again in absence of magnetic field, the expression of plasma density in terms of random ion current ($i_s$) passing through an area ($A$) in the plasma related to the ion density ($n_s$) and mean kinetic ion velocity ($v_{th}$) [11] can be formed as

$$n_s = \frac{4I_{sat}}{Aev_{th}} \tag{2}$$

Where, $n_s$ is the ion density, $I_{sat} \approx i_s$, the random ion current) at low-slope part of the V-I curve, $A$ is the effective area of the probe, $v_{th} = (2KT_i / m_s)^{1/2}$ is the mean kinetic ion velocity, $m_s$ is the ion mass.

Equation (2) holds only when $T_i > T_e$. If this situation does not obtain, the ions arrive at the probe with a velocity that corresponds to approximately $I/2KT_e$ [12]. When $T_e < T_i$ the saturation ion current is modified. Again when $T_i \rightarrow T_e$, which is not usually of great interest in processing discharge [12,23]. It is observed that $I_{sat}$ is never saturated. Increase in current with increasing negative potential is expected due to growth of effective collecting area as the sheath expands. The linear extrapolation was made in such a way that the ‘Boltzmann line’ was drawn through more points of highly negative probe potential as it is this region that the distribution is expected to be more Maxwellian [13]. To get the value of $I_{sat}$ a linear extrapolation of $I_p$ from highly negative probe potential to $V_d = 0$ has been adopted as suggested by Schottky [13]. This is illustrated in figure 2 which shows the results by using inductively coupled hydrogen plasma operating at 13.56 MHz. The probes are correctly driven when the ion current is minimum for any fixed voltage between the probes.
By equation (1) the plasma temperature ($T_e$) corresponding to the assumed Maxwellian distribution is calculated by measuring the slope of the current-voltage characteristics at the inflection points.

The current corresponding to the space potential has been taken to be the ion saturation current from which the ion density ($n_i$) can be obtained from equ. (2). The maximum error of these equations is about 0.6%.

The same procedure for the measurement of plasma temperature and density has been adopted in both the transverse and axial modes of magnetic fields.

In case of magnetic field, following Uehara et al. [14] the effective probe area ‘A’ has been taken to be $4al$, where ‘a’ is the radius and ‘l’ the length of the probe. It is worthwhile to mention that previously almost all determination of plasma density were made from ion saturation current. The accuracy of using the ion saturation current to measure the plasma density depends on the closeness of the electron to an assumed Maxwellian at the probe sheath edge and therefore to the type of plasma beam diagnosed[14,23]. But it was mentioned by Chang and Chen [15] that measurements made from ion saturation current are liable to be in error due to secondary emission from the probe surface and are not at all consistent with the values obtained by microwave method. They have shown that calculations of plasma density from ion saturation current are agreed with microwave measurement within 50%. Hence in the present investigation plasma density calculations have been made from ion saturation current.

From the result (figure 2) it is observed that at weak fields the I-V curves are approximately symmetric, but by increasing the field strength they become asymmetric. Argon and nitrogen also show the similar nature of variation. The magnetic field can have considerable effects on the ion current collection even though the ion gyro radius is much larger than the probe sizes. The lack of ion saturation is slowly increasing due to an expansion of sheath thickness as the probe goes increasingly negative with respect to the plasma.

As a whole the experimental results show that the I-V characteristics curve is symmetrical because the probes have the same cross section. The maximum current that circulates for the double probe is similar to the ion saturation current and, therefore, the maximum current is lesser than that of the single probe and can assure a smaller plasma perturbation.

These results imply that plasma particles correspond well with the Maxwellian distribution by using the theoretical curve to determine the basic parameters of the plasma. This method is applicable to the plasma with a weak magnetic field when Larmour radii of electrons ($r_L$) are larger than the probe radius($r_p$) and Debye length ($\lambda_D$) [16,17]. We can use existing theories of ion collection in a collision less plasma without a magnetic field. In the limit $\xi_p (= r_p / \lambda_D) << 1$, where as the probe current for a Maxwellian plasma is given by Langmuir’s orbital – motion theory[18].

The result of calculation, all the present discharge conditions satisfies sufficiently the situation of “zero magnetic field” solution. The path of the discharge current was deflected from the tube axis of the torus due to presence of a magnetic field; each probe within the torus was located in such a way that they have the same gradient in the ion saturation current range of the double probe characteristics.

In addition, the double probe produces a small current drain from the plasma that leads to less erroneous results; also, a double probe is preferred when a magnetic field is present because the ion current is much less affected by the magnetic field. The variation of plasma temperature ($T_e$) with magnetic field at fixed pressures for
hydrogen, nitrogen and argon are shown in figure 3(A) when probes are transverse and in figure 3(B) when probes are longitudinal to the axial toroidal magnetic field. The variation of $n_H/n$ with magnetic field at fixed pressures for hydrogen, nitrogen and argon are shown in figure 4(A) when probes are transverse and that of $n/n_H$ in figure 4(B) when probes are longitudinal to the magnetic field. For fixed pressure, the plasma temperature increases and radial plasma density decreases with transverse to the magnetic field and plasma temperature decreases and radial plasma density increases with axial to the magnetic field. Similar nature of variations was observed for three different sets of pressures for hydrogen, nitrogen and argon.

In some experiments of gaseous discharge, the variation of plasma temperature and particle distribution function of a magnetized plasma in molecular gases was studied by Sadhya et al. [6]. From the results, it is evident that the plasma temperature increases with transverse to the magnetic field where as decreases with axial to the magnetic field. It is shown that these effects are more remarkable at low gas pressures and low magnetic field (< 30 Gauss). Therefore, the increase of plasma temperature transverse to the magnetic field with the particle diffusion to a tube wall causes the deflection of discharge current from the tube axis [13].

On the other hand, decrease of plasma temperature axial to the magnetic field with the decrease of particle diffusion to a tube wall causes the confinement of discharge current to the tube axis. Such an effort is strengthened in lower gas pressure because of the rich amount of particle diffusion to the tube wall. Thus the dependence of the discharge pressure on the plasma temperature is considered as a cumulative ionization effect [19]. The cumulative effect became prominent with the increase in plasma density.

In studying the diffusion of plasma particles in a magnetic field, it was assumed to explain the observed experimental results that both the plasma temperature and density distribution are affected by the magnetic field and the nature of the variation is different according to the alignment of magnetic field with respect to the direction of discharge current.

It is also observed that magnetic field does not change the radial distribution of plasma particles from the normal Bessel function. Cummings and Tonks [20] & Sen and Jana [21] came to the same conclusion from a detailed theoretical and experimental analysis. We can thus bring out the difference in the behavior of a swarm of electrons and their associated properties in transverse and axial position of magnetic fields. More over the experimental results obtained in transverse mode of magnetic field satisfies the theory developed by Beckman [19].
**Figure 2:** Variation of Probe current ($I_P$) with Probe voltage ($V_d$) for hydrogen at Pressure ($P$) = 0.1 Torr and Magnetic Field (i) $H = 0$ G, (ii) $H = 25$ G, (iii) $H = 50$ G, (iv) $H = 75$ G in (Fig. 2A) axial & (Fig. 2B) transverse to the toroidal magnetic field.

1. Slope ($S$), 2. Inflection Point, 3. $I_{P10}$, 4. $I_{P20}$, 5. Slope ($\frac{dI_P}{dV_d}$), $\sum I_{P0} = I_{P10} + I_{P20}$

**Figure 3:** Variation of plasma temperature ($T_e$) with magnetic field ($H$) when probes are axial (fig.3A) and probes are transverse (fig.3B) at sets of pressures of (I) $P=0.07$ Torr, (II) $P=0.09$ Torr, (III) $P=0.1$ Torr for hydrogen; (IV) $P=0.07$ Torr, (V) $P=0.09$ Torr, (VI) $P=0.1$ Torr for nitrogen and (VII) $P=0.07$ Torr, (VIII) $P=0.09$ Torr, (IX) $P=0.1$ Torr for argon.
Figure 4: Variations of $n_H/n$ with magnetic field (H) when probes are axial (fig.4A) and variations of $n_e/n_{eH}$ with magnetic field (H) when probes are transverse (fig.4B) at sets of pressures of (I) P=0.07 Torr, (II) P=0.09 Torr, (III) P=0.1 Torr for hydrogen; (IV) P=0.07 Torr, (V) P=0.09 Torr, (VI) P=0.1 Torr for nitrogen and (VII) P=0.07 Torr, (VIII) P=0.09 Torr, (IX) P=0.1 Torr for argon

4. Conclusion:

It is concluded that the electron temperature and electron density of low-pressure inductively coupled plasma were measured by a double Langmuir probe. It was noticed that for the same filling pressure, electron temperature and the radial electron density of the toroidal discharge column decreases and increases respectively when the probes are axial to the magnetic field but shows the reverse nature when transverse to the magnetic field. This indicates that a significant amount of electrons had enough energy to excite and ionize almost all elements by a collision energy transfer process. The problem investigated here is to be clearly distinguished from some experimental studies performed by Sadhya et al [6]. There the nature of electron energy distribution remains Maxwellian in character in presence of magnetic field. It also becomes a function of the magnetic field, and depends upon the alignment of the magnetic field with respect to the direction of the discharge current. It has a decisive effect on the values of the plasma parameters, and thereby we can bring out the differences in the behavior of a swarm of electrons and their associated properties when the probes are held transverse and as well as axial to the applied magnetic field.
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