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Review on Gradual Development and Successive Modification in the Langmuir Probe Technique for Measurement of Plasma Parameters Since 1924

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ABSTRACT

This paper briefly reviews the contributions of single Langmuir probe diagnostic method **[1]** and its further development **[1-11]** for the detection of plasma parameters a number of modifications to the conventional Langmuir probe technique have been developed with the objective of reducing the current drain from the plasma by the probe system. these include the floating double probe **[3,4,5]** and the triple probe **[4,8]**. In spite of these, studies were made keeping the probe in various orientation (transverse and longitudinal) and in presence of magnetic field **[7,10,11].** The variations of plasma temperature in different gases were also studied.

1. Introduction

In 1924 Langmuir [**1**], developed a technique for detection of plasma temperature using single probe. Later this method was modified experimentally to overcome some limitations. later double probe and triple probe techniques were developed to achieve those plasma parameters with better accuracy and subsequently studies were done in presence or in absence of magnetic field in longitudinal as well as well as transverse direction using toroidal discharge tube. our objective is to review the various techniques based on Langmuir single probe method developed since 1926 till date for detection of plasma temperature using single probe, double probe in various plasma environmental conditions .

2. Theoretical Review

1.1 In 1924 Langmuir and Smith [**1**], developed a technique for measurement of electron temperature by single probe method. In 1926 they **[2]** carried out the same experiment with different dimensions of probe and found that the cylindrical probe gives the best suitable result. When a cylindrical or spherical electrode immersed in an ionized gas and brought to a suitable potential, it becomes surrounded by a symmetrical space charge region of +ve or -ve ions. Assuming the gas pressure to be low and proportional to ions which collide with the gas molecules in space charge region is negligibly small, the current taken by the collector can be calculated in terms of the radii of the collector.

3. Results and Discussions

The results were approximated by neglecting some corrections like edge effects for a plane collector, end effects for cylindrical collector and the distributing effect of spherical collector so that it was assumed that current per unit area is uniform over the surface of the collector. It was found that the collector current is almost independent of the space charge region.

1.2 Langmuir and Smith described a single probe method for measuring electron temperature, electron densities etc but which was applicable to certain types of time-varying discharges. To overcome this in 1950 E.G. Johnson and Malter [3] had developed double probe method which seems to yield accurate electron temperature in all types of discharges, including decaying plasma. The DPM appears to be advantageous since the positive ion current is hundred times smaller than the electron current for single probe.

Methodology: The double probe method consists of two probes, each similar to single probe. They are interconnected as shown in Fig.1. The potential V_d is termed as differential voltage, and I_d the associated current. The electron temperature (T_e) was determined from the $V_d - I_d$ characteristics using the following relation.

$$\ln I_e = (e / kT_e) V + \ln Aj_0 - (eV_s / kT_e) \qquad (1)$$

But this eqn. is significant only when V_s ,T_e and j_0 do not change with V_p.

T_e is determined from I_d vs. V_d plots by using equivalent resistance method. The ultimate expression for electron temperature is given as:

$$Te = 11{,}600\,(G-G^2)\,R_o \sum I_p \qquad (2)$$

where $R_o = [\, dVd/dI_d \,]_{vd=O}$ The factor R_o is denoted as equivalent resistance.

Result and Discussion: Those electrons are being collected by the probes which have sufficient velocities to overcome the field at the probes. In this method electron temperature can be determined only if the electrons have Maxwellian distribution. The current voltage characteristics has been shown in Fig.2.

1.3 In double probe method done by Johnson and Malter [3], the probe characteristics have an effect on plasma which exceeds the saturation value of the ion current. To overcome this condition, Kenzo ,Yamamoto and Takayoshi Okuda [4] in 1956 proposed a floating triple probe method which is useful to measure energy distribution in electrodless or h.f discharge. The third probe is always held at the floating potential to measure the electron energy distribution.

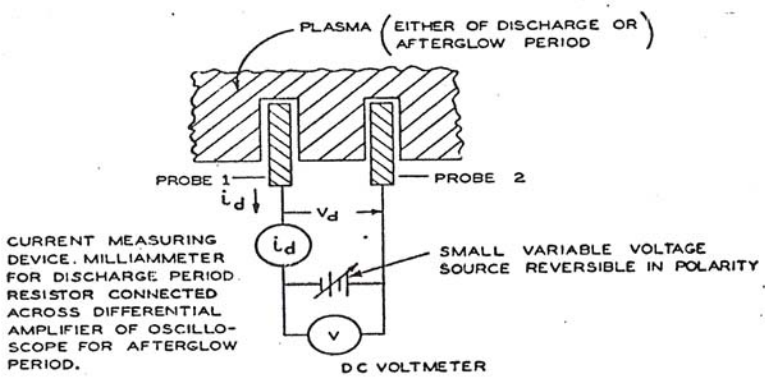

Fig. 1. The basic double probe arrangement

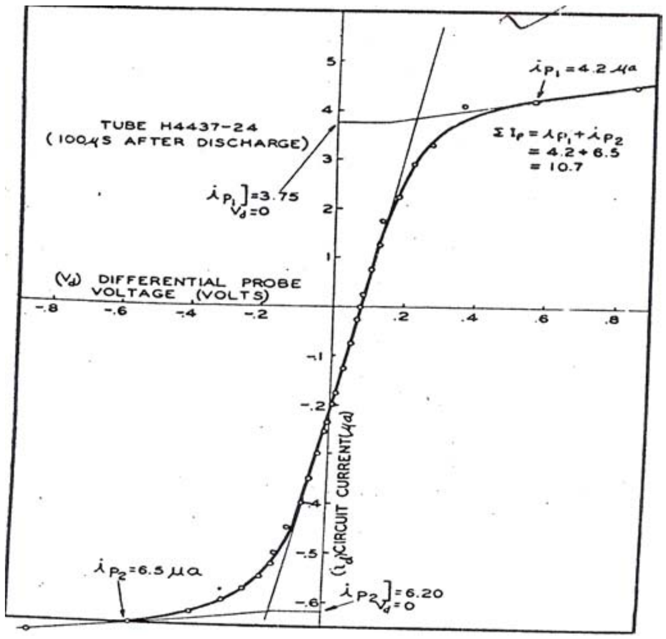

Fig. 2. The current voltage characteristics for double probe

Methodology: The arrangement is shown in fig. 3. The potential difference between No1. and No3 becomes equal to ΔV_1 and that between No.2 and No.3 to ΔV_2.

Result and Discussion: with increasing of pressure mean energy decreases as well as electron energy distribution becomes Maxwellian.

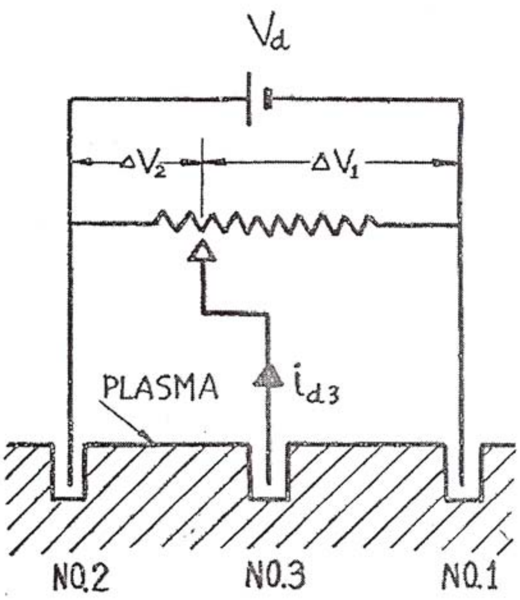

Fig.3 The basic circuit for triple probe

1.4 In 1968, T. Dote [5] proposed a new method for estimating the electron temperature under a more rigorous analysis of floating double probe characteristics to overcome some approximation of current-voltage characteristics as done by Johnson and Malter [3], Kenzo Yamamoto and Takayoshi Okuda [4] which yields incorrect estimation of the electron temperature.

Methodology: The formula (1) and (2) was modified by Dote by including the ratio α of the net positive ion current $\sum l_p=I_{p1}+I_{p2}$ to that at a starting point.
The ratio α can be calculated by using the slope S of the positive ion saturation characteristic. The slope dI_d / dV_d of the current voltage characteristics at the inflection point is expressed as:

$$dI_d / dV_d = 0.5\,S\{ \alpha / p + 4.6\, \alpha\, (1-q)+1\} \quad (3)$$

where $p=2SkT_e / e \sum l_{po}$ and $q= -(dI_{p2} /dV_2) / 2S$, where T_e is the electron temperature and $\sum I_{po}$ is shown in Fig.4. The final expression for electron temperature is given by Dote was

$$Te = e / k\{ \sum I_{po} / 4\{ (d_{Id}/d_{V d})_0 - O.\,82S\} \quad (4)$$

Result and Discussion: The percentage difference between the temperature obtained from the literature [3,4] are shown in fig.5.

1.5 From 1.1 to 1.4 it was seen that for the measurement of electron temperature and other characteristics the effect of external magnetic field was not incorporated. But in 1972 M SATO [6] first studied experimentally the effect of magnetic field in measuring the electron temperature using double probe technique in low pressure high density plasma. It was found that even if the ion gyro radius is very much larger than the probe size the ion current can be affected by the magnetic field.

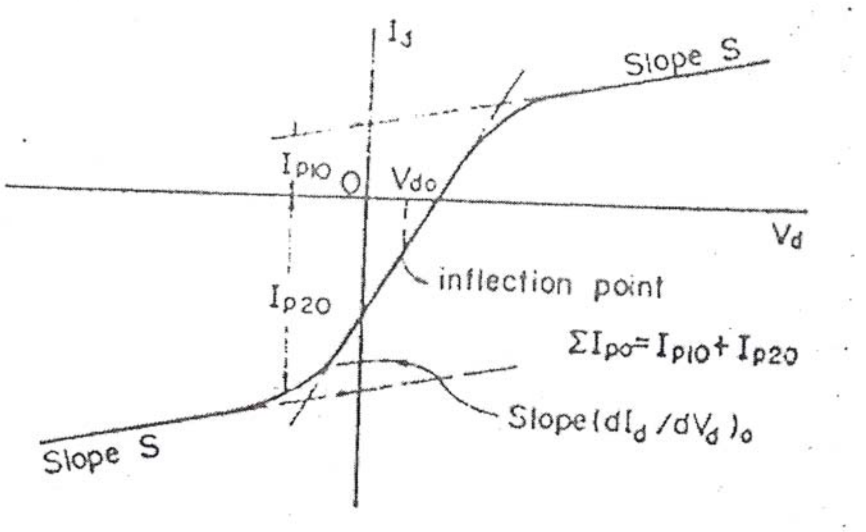

Fig. 4. Graphical representation of double probe characteristics

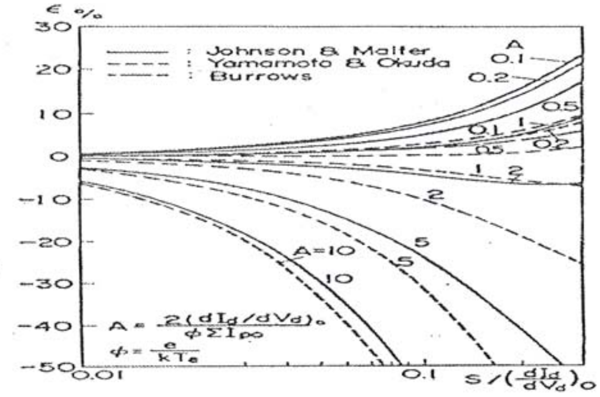

Fig. 5. Percentage difference between the electron temperature

Methodology : The plasma used was diffusion type argon arc discharge. The arc was formed by applying a DC potential between a hot cathode and an anode, and was confined in a channel of 6 mm diameter by an auxiliary coil of 3 k Gauss. The tube in which the diffused plasma was confined by axial homogeneous magnetic field was 110 cm long and 11 cm inner diameter was evacuated by oil diffusion pumps. Molybdenum disc probes of radii u=0.25 and 0.5 mm were used as symmetric double probes. The probes were held about 35 cm from the anode and 2.5 cm from the centre axis. The spacing of the two discs was such that no overlap of the two ion sheaths occurred and interception of the shadows was also avoided.

Results and Discussion: An example of the asymmetric double probe characteristics is presented in fig. 6 for a pair of double probes consisting of two discs of the same radius of 0.5 mm perpendicular to each other. At weak fields the I-V curves are approximately symmetric, but by increasing the field they become asymmetric. For such fields, where the electron gyro radius is equal to or smaller than the probe size, electrons might be constrained to move along the field, so that the effective collecting area of probes of any shape is reduced to the projection of the probe area on a plane perpendicular to the field; that is, the so-called channel effect appears. Therefore it can be concluded from the above that the magnetic field can have considerable effects on the ion current collection, even though the ion gyro radius is much larger than the probe size which contradicts to what had been assumed in the past.

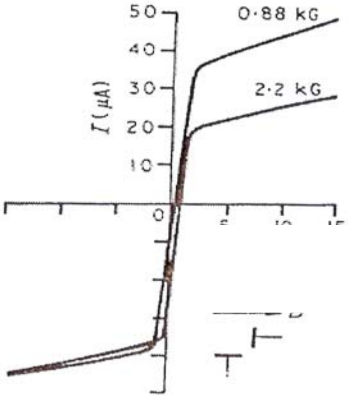

Fig.6. The I-V curves of a double probe of radius O.5 mm

1.6 In 1979, S.K. Sadhya, D.C. Jana and S.N. Sen **[7]** measured the electron temperature in low temperature plasma in presence of transverse or longitudinal magnetic field with different gases

Methodology : The experiment was carried out in dc glow discharge in presence of transverse and longitudinal magnetic field for air, hydrogen, nitrogen and oxygen. The energy distribution functions were assumed to be Maxwellian. The probes were inserted into the discharge tube by a gas jacket. The pressure was varied between 0.4 to 1 torr for different gases. The mathematical expression for calculating the electron temperature in transverse magnetic field is

$$T_{eH} = T_e [1 + C_1 (H^2 P^2)]^{1/2} \quad (5)$$

And for longitudinal magnetic field is

$$T_{eH} = T_{e+} 2T e^2 \log [\{1 / [1 + C_1 (H^2/P^2)]^{1/2}\} / [T_{e+} (2eVi / K)] \quad (6)$$

Results and discussion: The semilog plot of current voltage characteristics has been obtained for air, hydrogen and nitrogen for transverse and longitudinal magnetic field are shown in Fig.7 and 8. It is observed that the plots go straight with two slopes for both with and without magnetic field and for transverse and longitudinal magnetic field. The results show that the electron temperature increases where as radial electron density decreases with transverse magnetic field but reverse effects are obtained for longitudinal magnetic field.

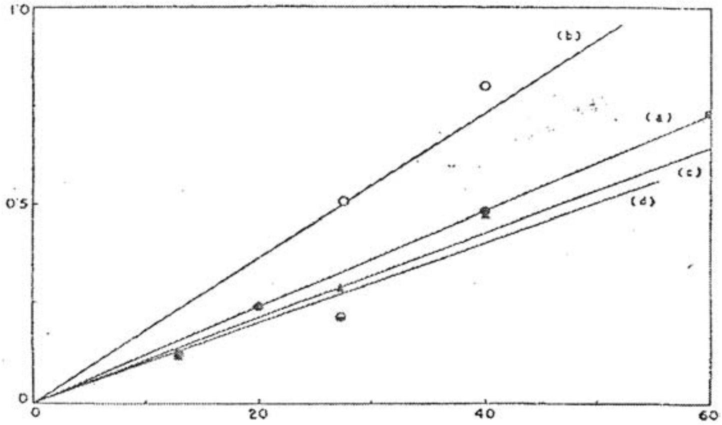

Fig. 7. (a) air , (b) hydrogen, (c) nitrogen in Transverse magnetic field

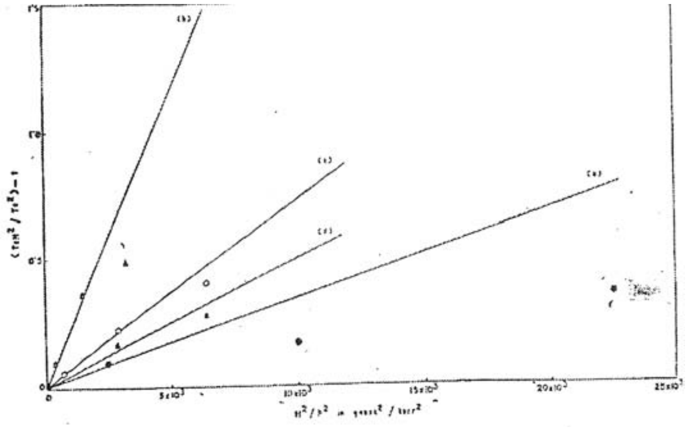

Fig. 8. (a) air, (b) hydrogen, (c) nitrogen in Longitudinal magnetic field

1.7 In 1992, H. Lin, G. X. Li, Roger D. Bengtson, Ch. P. Ritz, and H. Y. W. Tsui **[9]** made a comparison of Langmuir probe techniques for measuring electron temperature. Measurements using Langmuir probe techniques were difficult because of the fluctuation of electron temperature was at the same frequency as electron density and potential fluctuations and so it is technically difficult to make accurate temperature measurements. to overcome this, two methods were adopted so that the results are compared to estimate electron temperature variation. The two techniques were within the estimated error limits at a frequency of 100 kHz. They compared the level of electron temperature fluctuations measured in the same plasma, with the same probe array using the swept double probe and triple-probe techniques.

Methodology : These experiments were carried out on the ohmically-heated TEXT-U tokamak with major radius R_o= 1.05 m, minor radius a=0.27 m. The plasma conditions in the edge plasma and in the scrape-off layer were measured with the Langmuir probes. The electron temperature was varied from 5 to 50 ev and the density was from 1 to 4 X 10 m^{-3}. The radial scale lengths for both electron density and temperature were about 20 mm. Z. The data presented here were collected from a 4pin Langmuir probe array mounted on a pneumatically driven reciprocating probe drive located on the top of the tokamak. The probe array was made up of four O.5 mm diameter molybdenum pins of length 2 mm arranged in a square array of edge 2 mm.

The same probe array was used for both techniques of temperature fluctuation measurement. The probe alignment with magnetic field for both double and triple probe is shown in fig. 9

Fig.I3 Probe alignment with respect to the toroidal magnetic field (a) double-probe (b) triple-probe

Fig. 14 Relative fluctuation as a function of plasma radius for the double-probe and triple-probe technique.

Results and Discussion: The radial dependence of the density and temperature fluctuations from both techniques are shown in Fig. 10. The measured temperature fluctuations were consistent with the earlier observations. The double probe and triple-probe techniques measure the same level of temperature fluctuations within the same error limits in the same plasma, using the same probe tips. The triple probe has some operational advantages over the double-probe technique i.e. (1) The amount of data required for a statistically significant result for the swept double probe is a factor of 2-5 times larger than that of triple probe technique, (2) the triple probe produces spectral information, and (3) the triple probe technique provides the possibility of plasma potential measurements. The double probe technique produces a current-voltage characteristic, which could be useful in diagnosing non equilibrium plasmas.

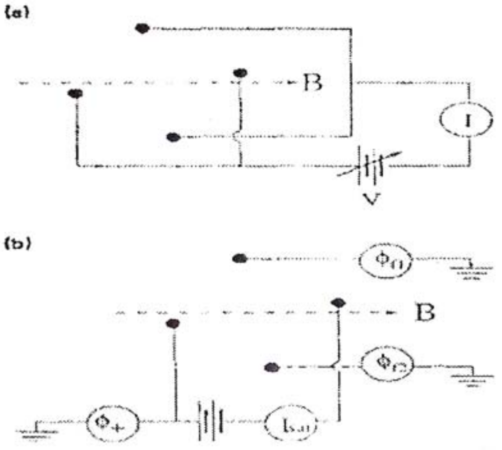

Fig. 9. Probe alignment with respect to the total magnetic field (a) double probe (b) triple probe.

1.8 In 2006 with reference to E.O. Johnson and Malter **[3]** D.C. Jana and S.S. Pradhan **[10]** studied the subnormal glow discharge region for molecular and rare gases using floating double probe technique. Equivalent resistance method was applied to measure the plasma parameters in sub normal glow discharge. The electron temperature was measured in both transverse and longitudinal magnetic field in low pressure for air, hydrogen and argon.

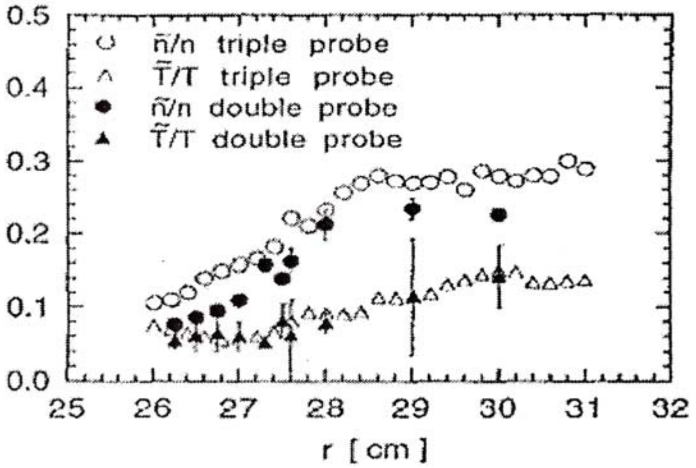

Fig. 10. Relative fluctuation as a function of plasma radius for the double probe and triple probe technique

Methodology: The experimental setup is shown in fig. 11. The gas was ionized by regulated DC power supply. Two cylindrical probes which were inserted to the discharge tube were held parallel to each other and were perpendicular to the axis of the tube. The gas pressure was measured by a Pirani gauge and the discharge current was measured by an ammeter. Using the same electromagnet both the transverse and longitudinal magnetic fields were applied to the gas discharge by rotating the tube. The electron temperature can be determined by the formula

$$Te = e / K[\sum l_{p0} / 4 \{(dld/dVd)_o -0.82S\}] \qquad (7)$$

Result and Discussion: It was observed that the electron temperature increases whereas the radial electron density decreases with transverse magnetic field and with longitudinal magnetic field the electron temperature decreases and the radial electron density increases. The electron temperature was determined from the way in which the probe current varies with the probe voltage, which was determined by Dote **[5]** and further modified by equivalent resistance method by Johnson and Malter **[3]**. It is also observed that electron temperature increases with the increase in transverse magnetic field and decreases with the increase in longitudinal magnetic field shown in fig. 12. The alignment of magnetic field with respect to the direction of the discharge current has an effect on the change in plasma parameters.

1.9 In 2006, C. Das and D. C. Jana **[11]** performed the same experiment as in 1.8 but within a toroidal chamber in low density plasma developed in air by a 13.56 MHz rf source with varying magnetic field.

Methodology: The experimental setup is shown in fig. 13. An H type solenoid coil was excited by 13.56 MHz rf power source in presence of magnetic field. The probe voltage was supplied by a constant DC source and the corresponding probe current was measured by a micro ammeter. The experiment was performed using air with pressures varying from 0.1 to 0.2 torr. Keeping the filling pressure constant for fixed plasma breakdown voltage, the probe potential was varied from high +ve to high -ve value and the corresponding probe current was measured. The same procedure was repeated by varying the magnetic field.

This experiment was carried out by changing the probe positions in both longitudinal and transverse direction of the plasma as shown in fig. 14.

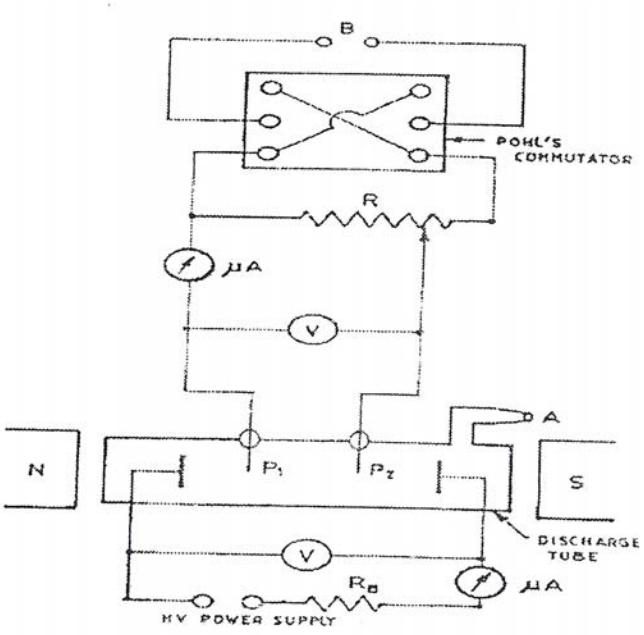

Fig. 11. Experimental arrangement

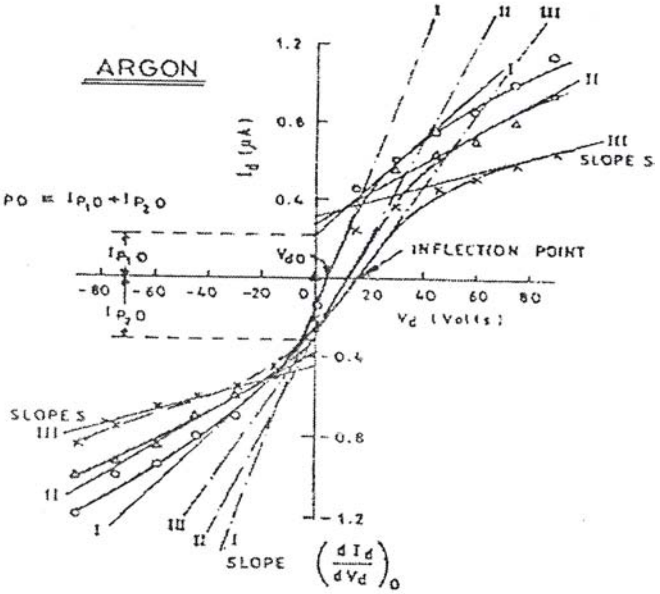

Fig. 12. Double probe characteristics

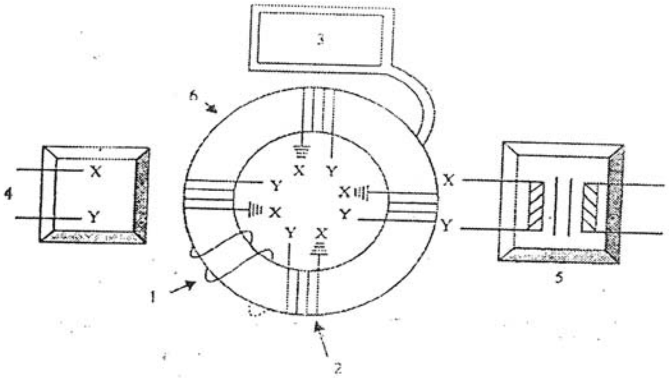

Fig. 13. Experimental set up for measurement of plasma parameters

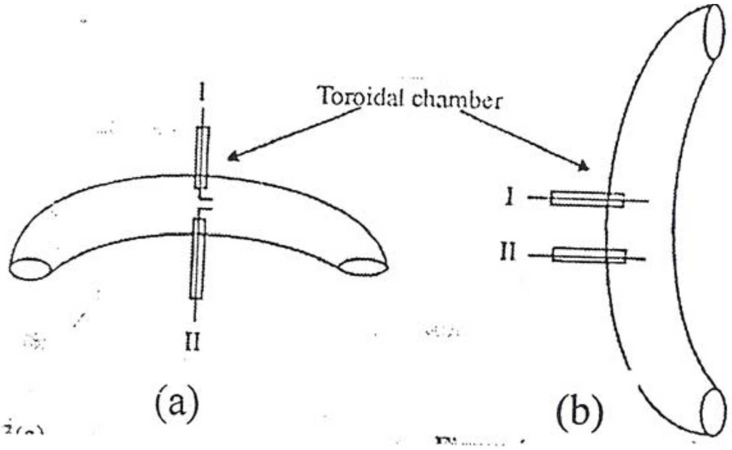

Fig. 14. (a) Alignment of the probes for transverse positions (b) Alignment of the probes the longitudinal positions

Result and Discussion: It has been observed that the electron temperature increases and the radial electron density decreases with the torodial magnetic field when double probe are aligned in transverse direction to the magnetic field whereas the reverse effect takes place for axial alignment of the probes with the magnetic field. This method is also applicable to the continuing discharge when it has the advantage over the single probe of exerting a negligible influence on the discharge. The probe characteristics for different toroidal magnetic field in transverse and longitudinal positions of the probes are shown in fig. 15 and 16.

4. Conclusion

The authors [1-10] herein discuss all the problems with reference to Langmuir single probe technique and show the ways to overcome the difficulties encountered in measurement of accurate plasma parameters. It has been shown that reasonably good agreement can be obtained between different probe methods under different circumstances. We have reviewed the various techniques based on Langmuir single probe method developed since 1924 till date for the measurement of plasma parameters and discussed their experiments with the results [1.1 - 1.9] so obtained by the authors.

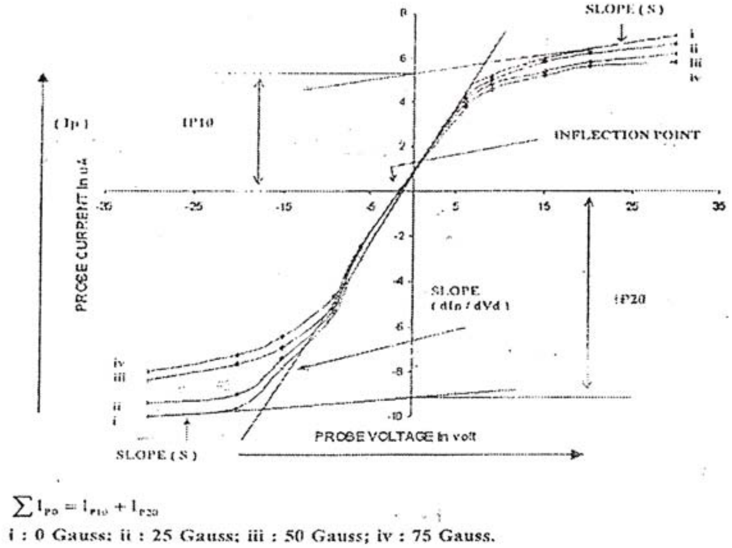

Fig. 15. Double probe characteristics in Transverse position of the probes for different mag. field

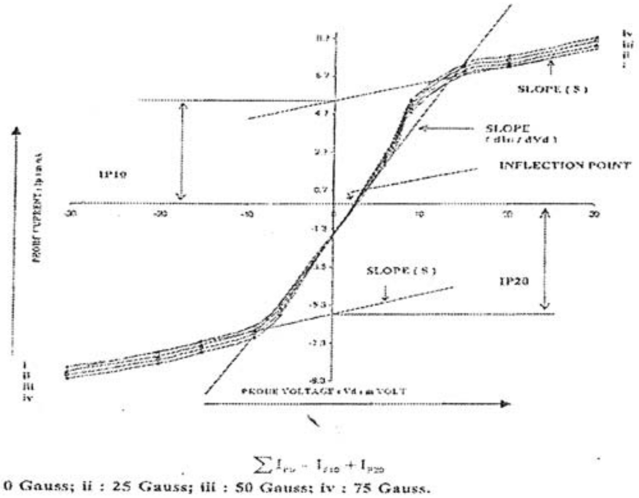

Fig. 16. Double probe characteristics in Longitudinal position of the probes for different mag. field

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