MEASUREMENT OF ELECTRON TEMPERATURE AND ELECTRON DENSITY IN LOW DENSITY MAGNETISED PLASMA BY PROBE METHOD

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The measurement of electron temperature and electron density in low temperature plasmas in air, hydrogen, oxygen and nitrogen magnetised by either a transverse or a longitudinal magnetic field have been carried out by the probe method. The limitations of the probe theory and the precise method in measuring electron temperature and electron density both in the absence and in presence of the magnetic field have been discussed and the experiments have been performed under the conditions in which the assumptions of the probe theory are strictly valid. The general conclusion arrived at is that in case of transverse field, the electron temperature increases whereas the radial electron density decreases and in case of longitudinal field, the electron temperature decreases and the radial electron density increases. The results are also quantitative in agreement with the theoretical deductions of Beckman (1948) and Sen and Gupta (1971) in case of transverse magnetic field and that of Sen and Gupta (1969) and Sen and Jana (1977) in case of longitudinal magnetic field. Further, it is noted that in case of molecular gases the electron energy distribution is Maxwellian in presence of or in the absence of magnetic field but in the former case it becomes a function of (H/P) where H is the magnetic field and P is the pressure.

INTRODUCTION

THE Langmuir probe method is one of the standard methods of measuring the plasma parameters such as electron density and electron temperature in a gaseous discharge. The theory of the probe in zero magnetic field rests on two assumptions : (*a*) The dimensions of the probe; and (*b*) the thickness of the space-charge sheath surrounding the probe is small compared with the mean free path of the electrons and ions. In connection with the probe theory, a parameter $\xi_p = r_p/\lambda_d$ has been introduced by Chen, Etievant and Mosher (1968) where r_p is the radius of the probe and λ_d the Debye Shielding length for the repelled species. For cylindrical probe, the computations of Laframboise (1966) show that the orbital motion theory of Langmuir is accurate for $\xi_p > 5$. In our experimental set up, this condition is satisfied.

The limitations as well as the validity of these assumptions have been discussed by a large number of workers. Nevertheless, the values of the parameters obtained by this method compare very favourably with the values obtained by other standard methods. In our present programme of work in determining the momentum transfer cross section in a transverse magnetic field and the voltage current relation in a longitudinal magnetic field (Sen & Jana, 1977) or in studying the diffusion of electrons in a magnetic field, it has been assumed in explaining the observed experimental results that both the electron temperature and electron 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 the discharge current.

It has been deduced by Sen and Gupta (1971) that the electron temperature T_{eH} in presence of the magnetic field is given by

$$T_{eH}=T_e\left[1+C_1\frac{H^2}{P^2}\right]^{1/2}, \qquad \ldots (1)$$

when (H/P) is small and $C_1=\left(\frac{e}{m}\cdot\frac{L}{v_r}\right)^2$, where L is the mean free path of the electron in the gas at a pressure of 1 torr and v_r, the random velocity of the electron. The validity and limitation of the deduction has been discussed in a number of papers (Sen & Gupta, 1971; Sen *et al.*, 1972; Sen & Das, 1973). Further, it has been shown by Beckman (1948) and Sen and Gupta (1971) that in a transverse magnetic field the radial electron density at a distance r from the axis is given by

$$n_H = n\exp\left[\frac{-eHr}{4\sqrt{2mk}}\sqrt{\frac{R}{T_e}}\right], \qquad \ldots (2)$$

where R is the fraction of energy lost by an electron due to either elastic or inelastic collision. No direct experimental evidence of the validity of these deductions has been provided so far.

The situation is completely different when the direction of the magnetic field is along the direction of the discharge current. This problem has not been quantitatively studied so far but a detailed experimental analysis of the positive column in a longitudinal magnetic field has been provided by Bickerton and Von Engel (1956). Regarding the variation of radial electron density, Bickerton and Von Engel (1956) have obtained conclusive evidence that the radial electron density increases in a longitudinal magnetic field. Sen and Jana (1977) have shown that in case of molecular gases as well, the radial electron density increases when the plasma is confined by a longitudinal magnetic field, and deduced that

$$\frac{n_H}{n_0} = \frac{J_0\left[\frac{r}{\Lambda}\left\{\frac{\nu_{iH}}{\nu_i}\,\frac{T_e}{T_{eH}}\right\}^{1/2}\right]}{J_0(r/\Lambda)} \qquad \ldots (3)$$

where ν_i is the ionization frequency and Λ is the diffusion length. It is thus evident that the alignment of the magnetic field with respect to the direction of discharge current has a distinct effect on the plasma parameters specially the electron temperature and electron density distribution.

Aikawa (1976) has studied the anisotropy of the electron distribution function of a magnetised plasma by measuring the electron temperature ($T_{e\pi}$) in the direction of the magnetic field as well as in the perpendicular direction (T_{e1}). He has observed that in strong magnetic field (H = 350 G), electron temperature increases linearly with the magnetic field but for low values of the magnetic field the experimental results deviate from the linear curve. Kaneda (1977) has measured the electron temperature of a positive column with a transverse magnetic field and observed an increase of electron temperature with the increase of the magnetic field and the effect is more pronounced at lower gas pressure.

As most of the effects of magnetic field on a plasma depend on the manner in which these parameters are affected by the field itself, it is proposed in the present investigation to make an experimental study of the nature of the variation of these parameters by the probe method. This will enable us to put to a direct experimental test the theoretical deductions regarding electron temperature and electron density variation in both the longitudinal and transverse magnetic fields.

A magnetic field H applied to the plasma effectively reduces the free paths of the charged particles perpendicular to H to less than the radius of curvature $\rho = \frac{mv}{eH}$, v being the velocity and m, the mass of the particle and hence for a probe collecting across the magnetic field assumption (*a*) becomes invalid in moderate magnetic field. For this purpose the magnetic field used in the present experiment has been kept below 100 gauss. The validity of assumption (*b*) depends upon the sheath thickness and thus on the plasma density, the type of the gas and on the magnetic field. In our experiment the plasma density has been kept relatively low (10^8/c.c.) and the magnetic field is below 100 gauss. Under these conditions, the electron temperature and electron density can be obtained as has been shown by Bohm *et al.* (1949) as in the case without the field.

MEASUREMENT OF T_e AND n IN ABSENCE OF MAGNETIC FIELD

The probe theory as developed by Langmuir gives the electron current as

$$I_e = I_{re} \exp(-eV_p/KT_e), \qquad \dots (4)$$

where I_{re} the random electron current and in the range $\xi_p \gg 1$ the sheath is thin and Langmuir obtained for positive potential the saturation electron current

$$I_{re} = \tfrac{1}{4} A_e ne \left(\frac{8 KT_e}{m\pi}\right)^{1/2}, \qquad \dots (5)$$

where A_e is the effective electron collection area of the probe, n is the unperturbed electron density. By eqn. (4) the electron temperature T_e corresponding to the assumed Maxwellian distribution is calculated by measuring the slope of the Boltzmann line in a semilogarithmic plot of I_e versus V_p. It is observed that I_e is never saturated. Increase in current with increasing positive potentials is expected due to growth of effective collecting area as the sheath expands.

A plot of log I_e against V_p (shown in the figs.) indicates that instead of a sharp knee a round knee is obtained. As such the true space potential is not well defined. This is due to the disturbance of the plasma when the probe is drawing large electron current near the space potential. The convention of the linear extrapolation of the curves at space potential was adopted to determine the space potential. 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 in this region that the distribution is expected to be more Maxwellian (Schott, 1968). The other line is drawn in such a manner that it passes through the maximum number of points and lies below the points for which there is a departure from the semi log plot points. At first the total probe current was plotted against the probe voltage and an approximate value of space potential was obtained by the above procedure. Then I_e was determined by substracting I_i from the probe current. To get the value of I_i a linear extrapolation of I from highly negative probe potential to $V_p = 0$ has been adopted as suggested by Schott (1968); log I_e was finally plotted against V_p and electron temperature is obtained from the slope of the curve. The current corresponding to the space potential has been taken to be the electron saturation current from which the electron density can be obtained from eqn.(5).

MEASUREMENT IN MAGNETIC FIELD

The same procedure for the measurement of electron temperature and electron density has been adopted in both the transverse and longitudinal magnetic fields the probe being always placed at right angles to the magnetic field. In case of magnetic field following Uehara *et al.* (1975) the effective probe area A_e has been taken to be 4 al, where a is the radius and l the length of the probe.

It is worthwhile to mention that almost all previous determination of electron density has been made from ion saturation current but recently it has been mentioned by Chang and Chen (1977) that measurements made from ion saturation current are liable to be in error due to secondary emission from the probe surface and are not consistent with the values obtained by microwave method. They have shown that calculation of electron density from electron saturation current are in agreement with microwave measurements within 50 per cent. Hence in the present investigation electron density calculations have been made from electron saturation current.

EXPERIMENTAL ARRANGEMENT

The experiment in which electron temperature and electron density have been measured has been performed in two parts : (*a*) when the magnetic field is transverse; and (*b*) when the magnetic field is longitudinal, both with respect to the direction of the discharge current. Measurements have been made in d.c. glow discharges in air, hydrogen, nitrogen and oxygen on the assumption that electron energy distribution functions in these gases are expected to follow a Maxwellian distribution.

Pure and dry air was passed through phosphorus pentoxide and calcium hydroxide to remove traces of water vapour. Hydrogen and oxygen were prepared by the electrolysis of a strong solution of barium hydroxide. Hydrogen was passed through heated copper turnings, phosphorus pentoxide and calcium hydroxide and oxygen through concentrated sulphuric acid before being introduced into the discharge tube. Nitrogen gas was supplied by Indian Oxygen Company and the gas was passed through heated copper turnings and concentrated sulphuric acid.

Magnetic field was generated by an electromagnet energised by a stabilised power supply and the field was uniform between the pole pieces. For transverse field, the lines of force were exactly perpendicular to the axis of the discharge tube made of a pyrex glass tube 22 cm long and 4 cm in diameter. The field was introduced in the positive column of the plasma. For longitudinal measurements the discharge tube of length 8.5 cm. and 2.5 cm in diameter was placed between the pole pieces of the electromagnet which have the diameter of 3.5 cm which ensures that the magnetic field is uniform throughout the length of the tube because it is essential that the magnetic field should be free from radial components. The probes were of cylindrical tungsten wire of 0.5 mm diameter. In case of transverse field, it was 4 mm long and placed at a distance of 2.5 cm from the anode where the magnetic field was applied. In case of longitudinal field it was 2 mm long and was placed 1.3 cm from the anode. Both the probes were inserted into the discharge tube by a glass jacket. The pressure was varied between 0.4 to 1 torr for different gases and was kept constant for a particular set of experiments by a needle valve and was measured by a Mcleod gauge. The stationary discharge was made by a stabilized d.c. power supply and the discharge current was between 9 to 12 mA.

Probe voltages were supplied by a continuously varying dry battery and voltages were measured with respect to anode. The magnetic field was measured by a calibrated fluxmeter. Keeping the pressure constant for fixed discharge current the probe potential was varied from a high negative value to positive values and the corresponding probe current was noted in the microammeter. The procedure is repeated for different values of the transverse and longitudinal magnetic fields whose value has been allowed not to exceed 100 gauss in conformity with the limitations that should be observed for the validity of the probe theory in magnetic field.

RESULTS AND DISCUSSION

In conformity with the method of analysis of the probe data as reported earlier in the paper, semilog plot of current voltage characteristics has been obtained for air, hydrogen, oxygen and nitrogen in case of transverse field and the representative curve for hydrogen is shown in Fig. 1. It is observed that the plot is a straight line with two different slopes for both with and without magnetic field which shows that probe theory can be applied to find the electron density and electron temperature in presence of magnetic field as well, provided the magnetic field and the main discharge current are kept at a low value. From the slope of the straight line drawn through the highly negative probe voltages the electron temperature has been determined for all the four gases, with and without magnetic field, and the results are entered in Table I.

To vertify whether the theoretical expression previously deduced by Sen and Gupta (1971) that $T_{eH} = T_e\left[1 + c_1 \frac{H^2}{P^2}\right]^{1/2}$ is valid the values of $\left[\frac{T_{eH}^2}{T_e^2} - 1\right]$

TABLE I

Values of electron temperature in electron volt with and without magnetic field

Magnetic field in gauss	Air P = 0.4 torr	Hydrogen P = 0.7 torr	Oxygen P = .5 torr	Nitrogen P = 0.5 torr
0	7.63	7.829	7.898	8.025
13		8.163	8.165	
20	7.95			
27		9.116	8.737	8.643
40	8.228	9.527	9.34	9.34
60	8.886			

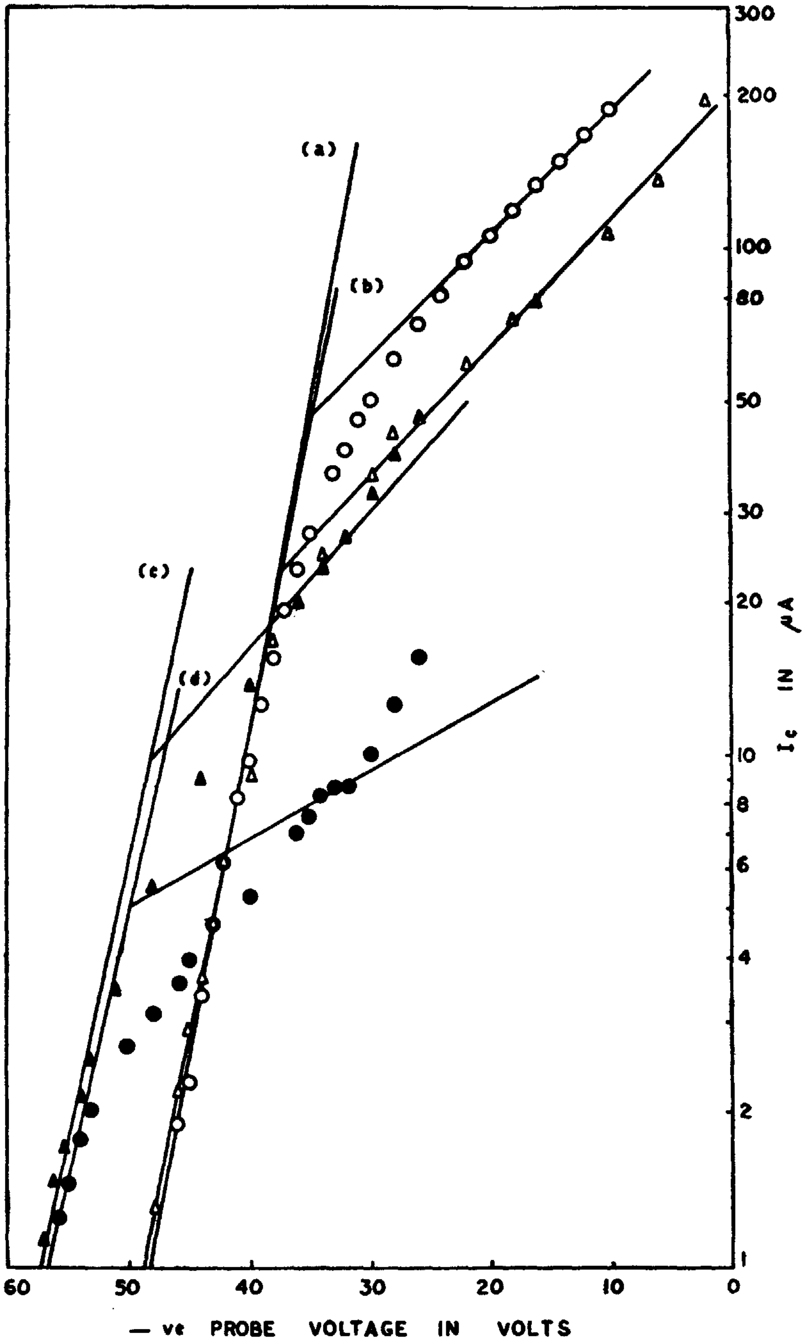

FIG. 1. Log I_e — V_p curves for hydrogen in transverse magnetic field. (*a*) B = OG (*b*) B = 13G (*c*) 27G (*d*) B = 40G.

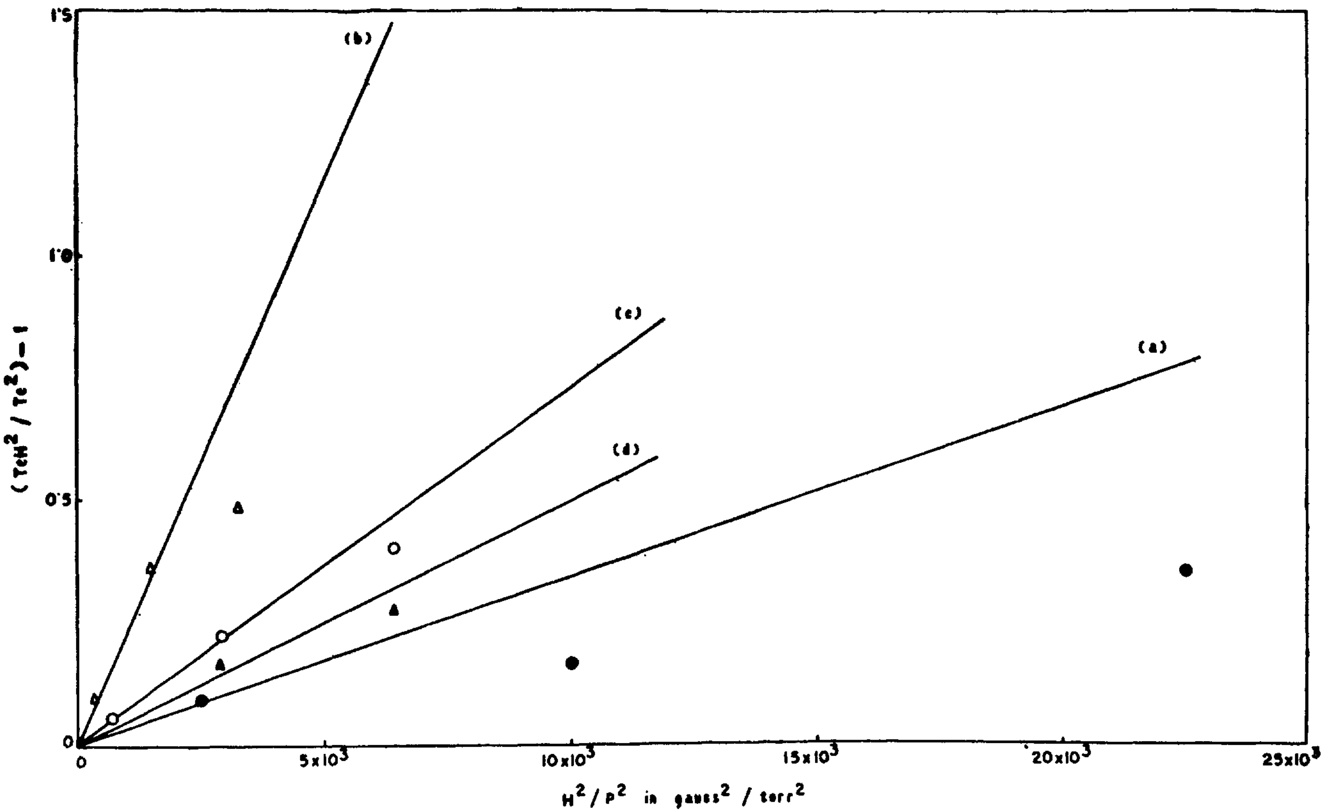

FIG. 2. Variation of $\left[\frac{T^2{}_{eH}}{T^2{}_e} - 1\right]$ against H^2P^2

(*a*) Air (*b*) Hydrogen (*c*) Oxygen (*d*) Nitrogen in Transverse magnetic fields.

have been plotted against H^2/P^2 for all the gases studied and are represented in Fig. 2.

It is observed that curves are all straight lines for the gases studied in conformity with eqn. (1) but with different slopes from which the values of $C_1 = \left(\frac{e}{m} \cdot \frac{L}{v_r}\right)^2$ have been calculated and entered for different gases in the second column of Table II.

TABLE II

Values of C_1 as calculated for different ionised gases for transverse and longitudinal magnetic fields

Gas	C_1 from transverse magnetic field measurement	C_1 from longitudinal field measurement.
Air	3.4×10^{-5}	4.3×10^{-5}
Hydrogen	2.31×10^{-4}	2.48×10^{-4}
Oxygen	7×10^{-5}	12.5×10^{-5}
Nitrogen	5×10^{-5}	5.6×10^{-5}

The value of C_1 as obtained here for different gases are of the same order as obtained previously by microwave and diffusion methods.

Besides electron temperature, the electron density with and without magnetic field has been determined experimentally. From the theoretical deduction (eqn. 2) it is evident that if $\log \frac{n}{n_H}$ is plotted against H the curve should be a straight line as is actually observed from the curve (Fig. 3) for different gases. The experimental results after analysis thus indicate that Beckman's theoretical expressions as further modified by Sen and Gupta with regard to electron temperature and radial distribution of electron density are valid specially for low values of (H/P).

LONGITUDINAL MAGNETIC FIELD

The variation of the semi log plot of electron current and probe voltage in case of all the four gases has been obtained and a representative curve has been shown in Fig. 4. As in the case of transverse magnetic field the curves are straight lines with two different slopes and the electron temperature and electron density have been determined as before for all the gases. The values of electron temperature have been entered in Table III. It was previously deduced by Sen and Gupta (1969) in case of longitudinal magnetic field that

$$T_{eH} = T_e + \frac{2T_e^2 \log \left[\frac{1}{[1 + c_1 H^2/P^2]^{1/2}}\right]}{\left[T_e + \frac{2e\,V_i}{k}\right]} \quad \ldots (6)$$

and from these results the values of C_1 have been calculated by plotting $e^{(T_e - T_{eH})\alpha}$ against H^2/P^2 (Fig. 5)

where $$\alpha = \frac{T_e + \frac{2\,eV_i}{K}}{2T^2_e}.$$

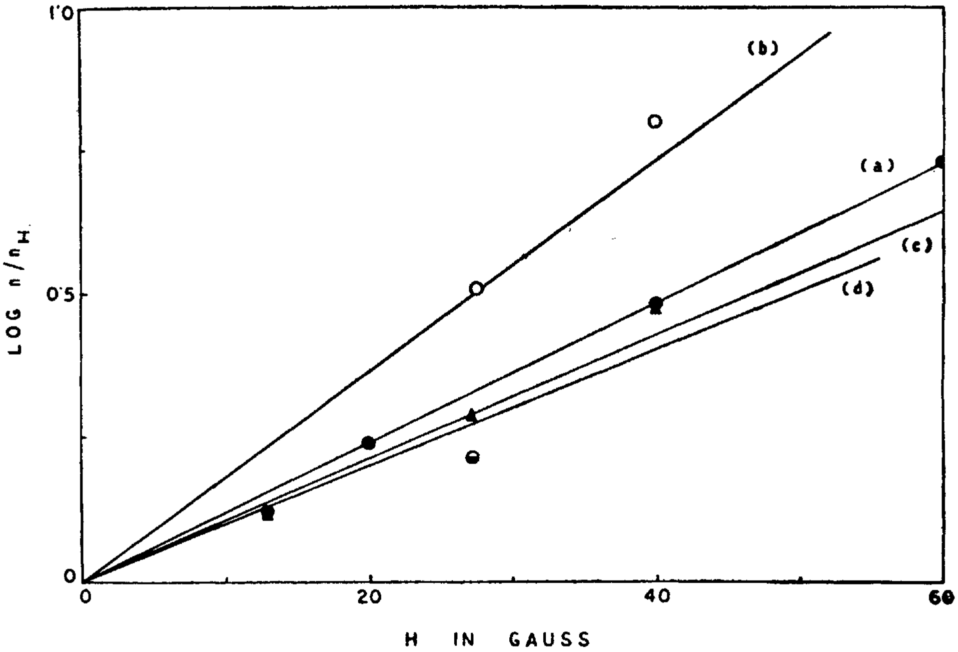

FIG. 3. Variation of log (n/n_H) against H for (*a*) Air (*b*) Hydrogen (*c*) Oxygen (*d*) Nitrogenin Transverse Magnetic field.

From the slope of the curves, the values of C_1 have been calculated for all the gases and results thus obtained have been entered in the last column of Table II, for comparison. It is thus evident that the values of C_1 obtained quite independently from the two sets of measurements agree very well in case of hydrogen and nitrogen. In case of air and specially in case of oxygen the agreement is not very close and this is definitely due to the fact that calculation for C_1 in case of longitudinal magnetic field involves the knowledge of an accurate value of V_i the ionization potential. In the case of air, there is uncertainty in the accepted value of V_i whereas in case of oxygen as has been shown by Thomson (1961) in their mass spectrographic measurements there are present in an oxygen discharge not only O_2^+ but also O^- which form 90 per cent of the ions and are present in equal amount and the value of V_i taken equal to that of oxygen introduces an element of uncertainty in the value of C_1.

To calculate theoretically the variation of n_e with the magnetic field and compare it with the experimental results, we have utilized the theoretical expression for n_H eqn. (3) as deduced by Sen and Jana (1977). The theoretical and experimental results are shown in Table IV. Λ the diffusion length is given by

$\frac{1}{\Lambda^2} = \left(\frac{\pi}{h}\right)^2 + \left(\frac{2.405}{R}\right)^2$, h is the distance between the electrodes and

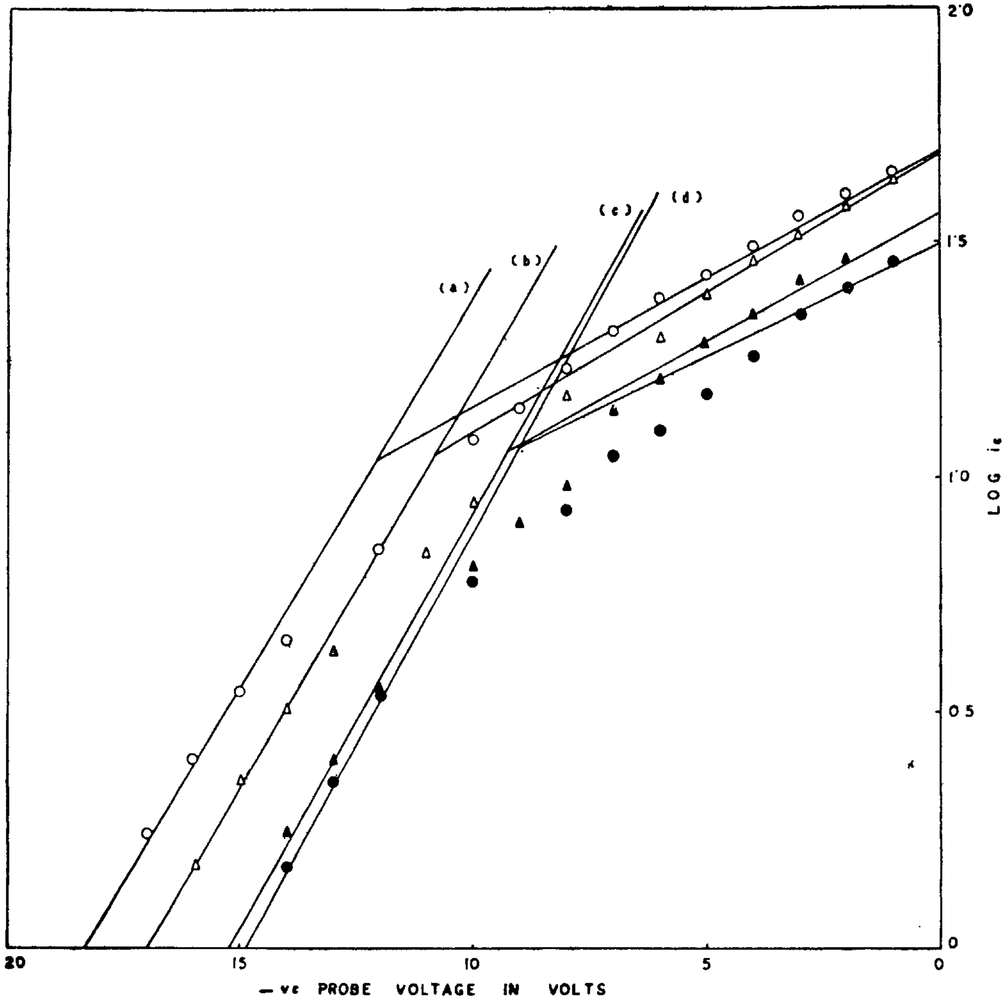

FIG. 4. Log I_e — V_p curves for Hydrogen in Longitudinal Magnetic field. (*a*) B = OG (*b*) B = 13G (*c*) B = 40G (*d*) B = 54G

TABLE III

Values of electron temperature in electron volt in longitudinal magnetic field

Magnetic field	Air $P = 0.6$ torr	Hydrogen $P = 1$ torr	Oxygen $P = 0.4$ torr	Nitrogen $P = 0.6$ torr
0	5.263	6.026	4.126	6.787
13		5.937		6.696
27	5.165		3.863	6.589
40		5.684	3.652	
54	5.141	5.501	3.423	6.277
82	4.917			

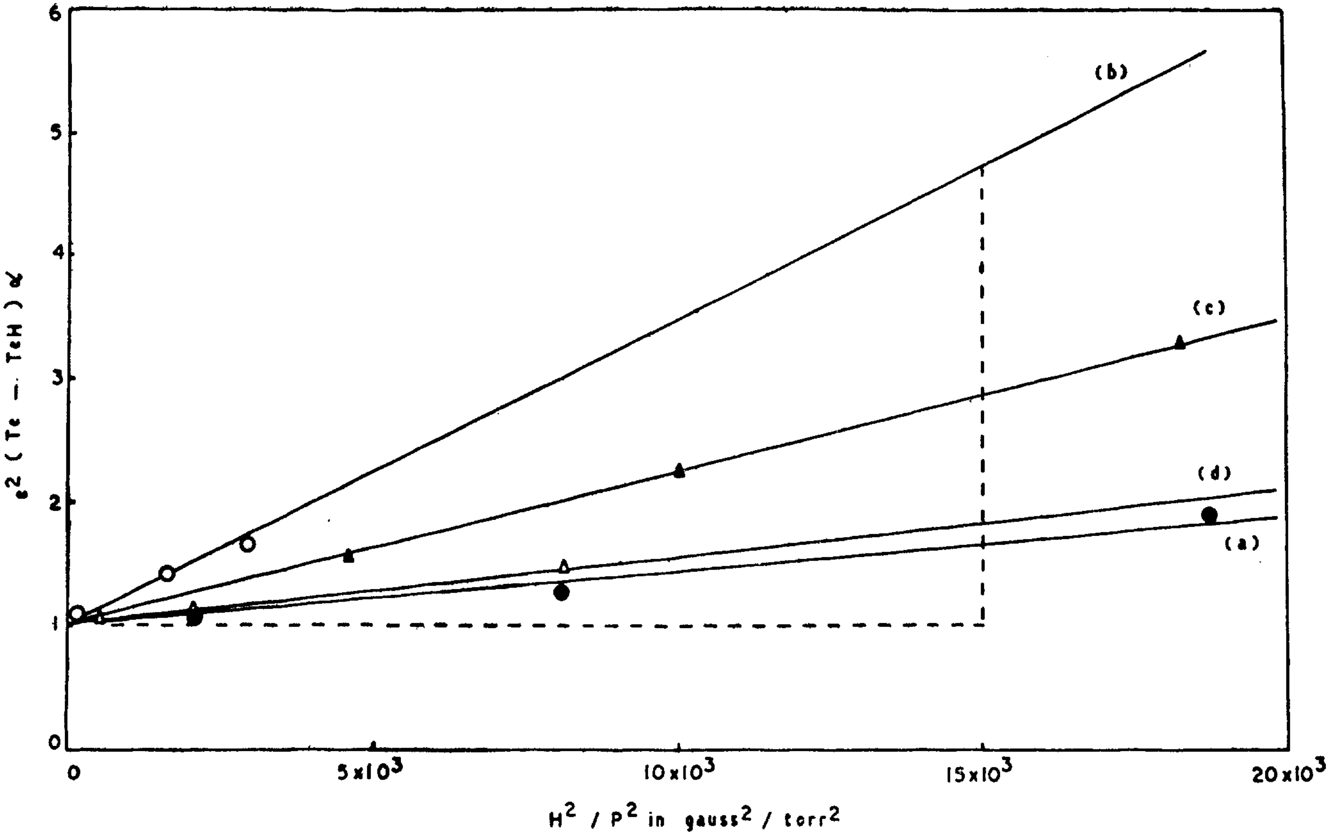

FIG. 5. Variation of $e^2 (T_e - T_{eH}) \alpha$ against H^2/P^2 for
(*a*) Air (*b*) Hydrogen (*c*) Oxygen (d) Nitrogen in Longitudinal Magnetic Fields.

TABLE IV

Value of n_H/n in longitudinal magnetic field.

Magnetic field in gauss	Air		Hydrogen		Oxygen		Nitrogen	
	Theor.	Experiment.	Theor.	Experiment.	Theor.	Experiment.	Theor.	Experiment.
13			1.0005	1.017			1.0002	1.025
27	1.001	1.016			1.004	1.047	1.0006	1.058
40			1.002	1.054	1.005	1.1		
54	1.003	1.047	1.0034	1.097	1.011	1.16	1.002	1.109
82	1.007	1.097						

R is the radius of the discharge tube and $\frac{1}{\Lambda^2} = 4.0671 \text{ cm}^{-2}$ and r has been taken to be 0.2 cm. the average distance of the probe from the axis.

Further

$$\frac{\nu_{iH}}{\nu_i} = \left[\frac{\exp\left(-\frac{ev_i}{KT_{eH}}\right)}{\exp\left(-\frac{ev_i}{KT_e}\right)}\right]\left[\frac{1+\frac{ev_i}{KT_{eH}}}{1+\frac{ev_i}{KT_e}}\right]$$

Thus all the terms in the right hand side of eqn. (3) can be evaluated and values of n_H/n can be calculated.

The agreement between the theoretical and experimental results is not very satisfactory but nevertheless the results do indicate that the axial electron density increases with the magnetic field. The quantitative disagreement arises due to the fact that whereas the theoretical expression expresses the electron density at a point distant r from the axis, in actual calculation we have taken an average value of r for the finite length of the probe because the whole area of the probe is effective in collecting the electrons. We can thus conclude that the alignment of the magnetic field with respect to the direction of the discharge current has a decisive effect on the values of the plasma parameters, and thereby we can bring out the difference in the behaviour of a swarm of electrons and their associated properties in transverse and longitudinal magnetic fields. In case of a transverse magnetic field as postulated by Beckman (1948) and further deduced by Sen and Gupta (1971) the electron temperature increases whereas radial electron density decreases up to a certain distance from the axis and our direct measurements of these two parameters by the probe method show not only qualitative but also quantitative agreement for small values of (H/P). In case of longitudinal magnetic field the electron temperature decreases whereas the radial electron density increases and the direct measurements of these two parameters in longitudinal magnetic field indicates quantitative agreement with theoretical predictions.

The problem investigated here is to be clearly distinguished from some experimental studies performed recently (Aikawa, 1976) in which anisotropy of electron temperature and electron distribution function in a magnetised plasma has been studied, What has been measured in the present investigation is the average electron temperature and its variation with the alignment of the magnetic field with respect to the direction of the discharge current. Throughout our investigation, it has been assumed that the electron energy distribution is Maxwellian in character and is hence tempeature-dependent though in general the distribution is non Maxwellian. However, in case of molecular gases the excitation levels are widely spread out up to ionization potential and inelastic losses set up at low energies and these are so distributed so as to produce an approximately Maxwellian distribution. The present investigation thus clearly indicates that though the nature of electron energy distribution remains Maxwellian in character in presence of magnetic field also it becomes a function of the magnetic field and is dependent upon the alignment of the magnetic field with respect to the discharge current.

REFERENCES

Aikawa, H. (1976). The measurement of the anisotropy of electron distribution function of a magnetised plasma. *J. phys. Soc. Japan*, **40,** 1741.

Beckman, L. (1948). The influence of a transverse magnetic field on a cylindrical plasma. *Proc. phys. Soc. London*, **61**, 515.

Bickerton, R. J., and Von Engel, A. (1956). The positive column in a longitudinal magnetic field. *Proc. phys. Soc.*, **B69,** 468.

Bohm, D., Burhop, E. H. S., Massey, H. S. W., and Williams, R. W. (1949). *The Characteristics of Electrical Discharges in Magnetic field.* McGraw Hill Bk. Co. Inc., New York.

Chang, J. S., and Chen, S. L. (1977). Electrostatic probe measurements of low-density medium-pressure magneto plasma. *J. Phys. D. appl. Phys.*, **10,** 979.

Chen, F. F., Etievant, C., and Mosher, D. (1968). Measurement of low plasma densities in a magnetic field. *Phys. Fluid*, **11**, 811.

Kaneda, T. (1977). The electron temperature of a positive column with a transverse magnetic field. *Japan, J. appl. Phys.*, **16**, 1887.

Laframboise, J. (1966). *UTIAS Report No.* 100. Institute of Aerospace Studies, University of Toronto.

Schott, L. (1968). *Electrical Probes in plasma Diagnostics*, North Holland Publishing Co., Amsterdam.

Sen, S. N., and Gupta, R. N. (1969). Plasma parameters from r. f. conductivity measurements. *Indian J. pure appl. Phys.* **7**, 462.

———(1971). Variation of discharge current in a transverse magnetic field in a glow discharge. *J. Phys. D. appl. Phys.*, **4,** 510.

Sen, S. N., Das, R. P., and Gupta, R. N. (1972). Spectral line intensity in a glow discharge in a transverse magnetic field. *J. Phys. D. appl. Phys.*, **5**, 1260.

Sen, S. N., and Das, R. P. (1973). Voltage current characteristics and power relation in arc plasma in a transverse magnetic field. *Int. J. Electron.*, **34,** 527.

Sen, S. N., and Jana, D. C. (1977). Current voltage characteristics of glow discharge in longitudinal magnetic field. *J. phys. Soc. Japan*, **43,** 1729.

Thompson, J. B. (1961). Electron energy distribution in plasma, IV. Oxygen & Nitrogen, *Proc. R. Soc.*, **A262,** 503.

Uehara, K., Yatsu, K., Hagiwara, S., and Kojima, S. (1975). Ion saturation current of a plasma having two electron temperatures. *Japan J. appl. Phys.*, **14,** 1761.