CHAPTER III

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

3.1. Introduction

The measurement of electron temperature and radial electron density in low density plasma in molecular gases magnetised by either a transverse or a longitudinal magnetic field have been carried out by Langmuir probe method. The probe method is one of the standard methods of measuring plasma parameters. The theory of Langmuir probe in zero magnetic field rests on two assumptions: (a) the dimension of probe and (b) the thickness of space-charge sheath surrounding the probe is small compared to the mean free path of the electrons and ions. The limitations as well as the validity of these assumptions have been discussed by a larger number of workers. Nevertheless, the values of the parameters obtained by this method compare very favourably with the values obtained by other standard methods.

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, an experimental study of the nature of variation of these parameters by probe method has been reported. This will enable us to put to a direct experimental test the theoretical deductions regarding electron temperature and electron density variation in both longitudinal and transverse magnetic fields.

A magnetic field B applied to the plasma effectively reduces the free paths of the charged particles perpendicular to B to less than the radius of curvature $\rho = mv/eB$, v , m and e being the velocity, mass and charge of the particle and hence for a probe collecting across 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 G. The validity of assumption (b) depends upon the sheath thickness and thus on plasma density, type of gas and on B. In our experiment the plasma density has been kept relatively high ($> 10^9/cm^3$) and the magnetic field below 100 G. Moreover in the experiment, molecular gases have been utilised and the electronic energy in the molecular gases is supposed to be much lower than in atomic gases because of the ability of the molecules to absorb energy from the electrons by vibrational and rotational excitation in collisions at low energies. Such excitation is not possible in monatomic gases. In this way the sheath thickness which is assumed to be of equal value to Debye length given by the expression (Krall and Trivelpiece, 1973),

$$\lambda_D = 4 \cdot 9 \left(T_e / n_e \right)^{1/2} \text{ cm.} \qquad (3.1)$$

where n_e and T_e are the number density (cm^{-3}) and temperature (°K) of electrons, will be much less so that assumption (b) holds even when a magnetic field is present. Under these conditions, the electron temperature and electron density can be obtained as has been shown by Bohm et al (1949) and by Kagan and Perel (1969) as in the case without the field.

3.2. 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, & (b) when the magnetic field is longitudinal, both with respect to the direction of the discharge current which is along the axis of discharge tube. Measurements have been made in d.c. glow discharges in air, hydrogen, nitrogen and oxygen. For molecular gases the excitation levels are widely spread out upto ionization potential and inelastic losses set up at low energies and these are so distributed so as to produce an approximate Maxwellian distribution.

For transverse field, the lines of force were exactly perpendicular to the axis of the discharge tube and the field was introduced in the positive column of plasma. For longitudinal magnetic field, the discharge tube was placed in between the pole pieces of electro-magnet, producing an uniform field without any radial component at the location of discharge tube. The probes were of cylindrical tungsten wire of 0.019 cm. diameter. In case of transverse magnetic field it was 4.1 mm. long, hence the ratio $l/r_p \approx 43$ (l is the length and r_p is the radius of the probe) and was placed at a distance 2.5 cm. away from the anode. In case of longitudinal magnetic field the probe was 2.2 mm. long, $l/r_p \approx 23$ and was placed 1.3 cm. from the anode. The pressure of the gases in the experiment have been measured as described in chapter II and entered in Table 3.1.

Probe voltages were supplied by a dry battery and voltages were measured with respect to anode. Keeping the pressure constant, the magnetic field was introduced and the probe potential was changed from negative values with respect to plasma potential to positive values far into electron attraction region. Other details of the experimental arrangement have been given in chapter II.

TABLE 3.1

Pressure of discharge in different gases.

Gas	Pressure in torr in Transverse magnetic field.	Pressure in torr in Longitudinal magnetic field.
Air	0.4	0.6
Hydrogen	0.7	1.0
Oxygen	0.5	0.4
Nitrogen	0.5	0.6

The discharge currents were varied between 9 and 12 mA.

3.3. Results and Discussions

3.3.1. Probe data analysis and methods of measurements ~~ka~~ of T_e and n_e

In figs. 3.1 through 3.5 probe currents and probe voltages with respect to anode have been plotted for different gases when either transverse or longitudinal magnetic field was present. Then the logarithm of probe current and probe voltage was plotted. The characteristics have three distinct part: the region of positive ion saturation current, the region of partial electron current known as the electron temperature regime and the electron saturation current regime. It is observed that electron current I_e is never saturated. Increase in electron current with increasing positive potentials is expected due to growth of effective collecting area as the sheath expands. In principle the space potential (or the plasma potential) may be determined from the characteristic. When the two distinct parts in the electron attraction region of the characteristic have a sharp crossing known as knee of the characteristic, the voltage corresponding to knee or break off point is the space ~~pa~~ potential. In our experiment a sharp knee was not obtained, instead a round knee was observed. The possible reason may be either a deviation from Maxwellian distribution or drain diffusion. So, two tangents have been drawn to the

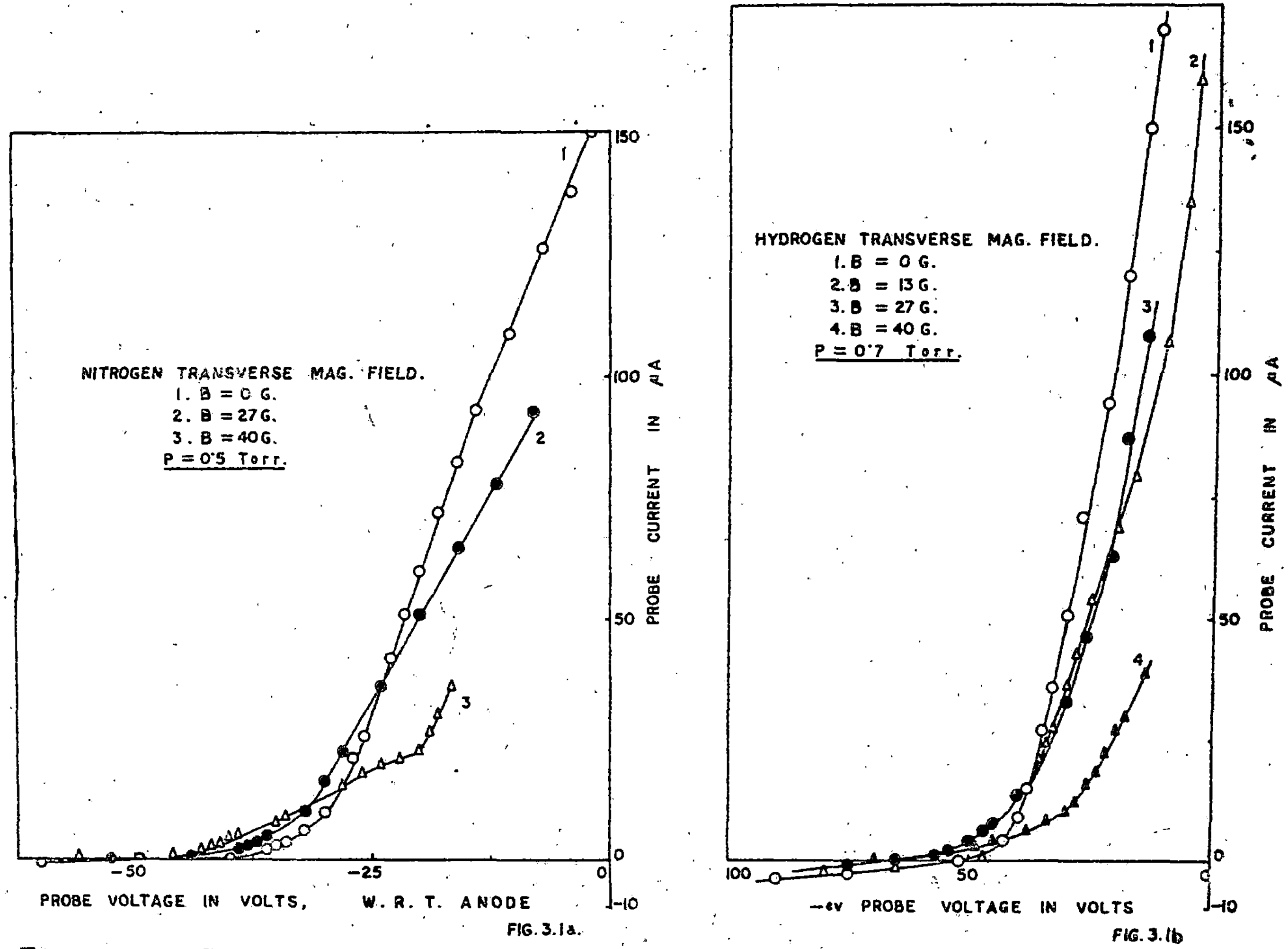

Fig. 3.1. Current-voltage characteristic of probe with and without transverse magnetic field for (a) nitrogen, (b) hydrogen.

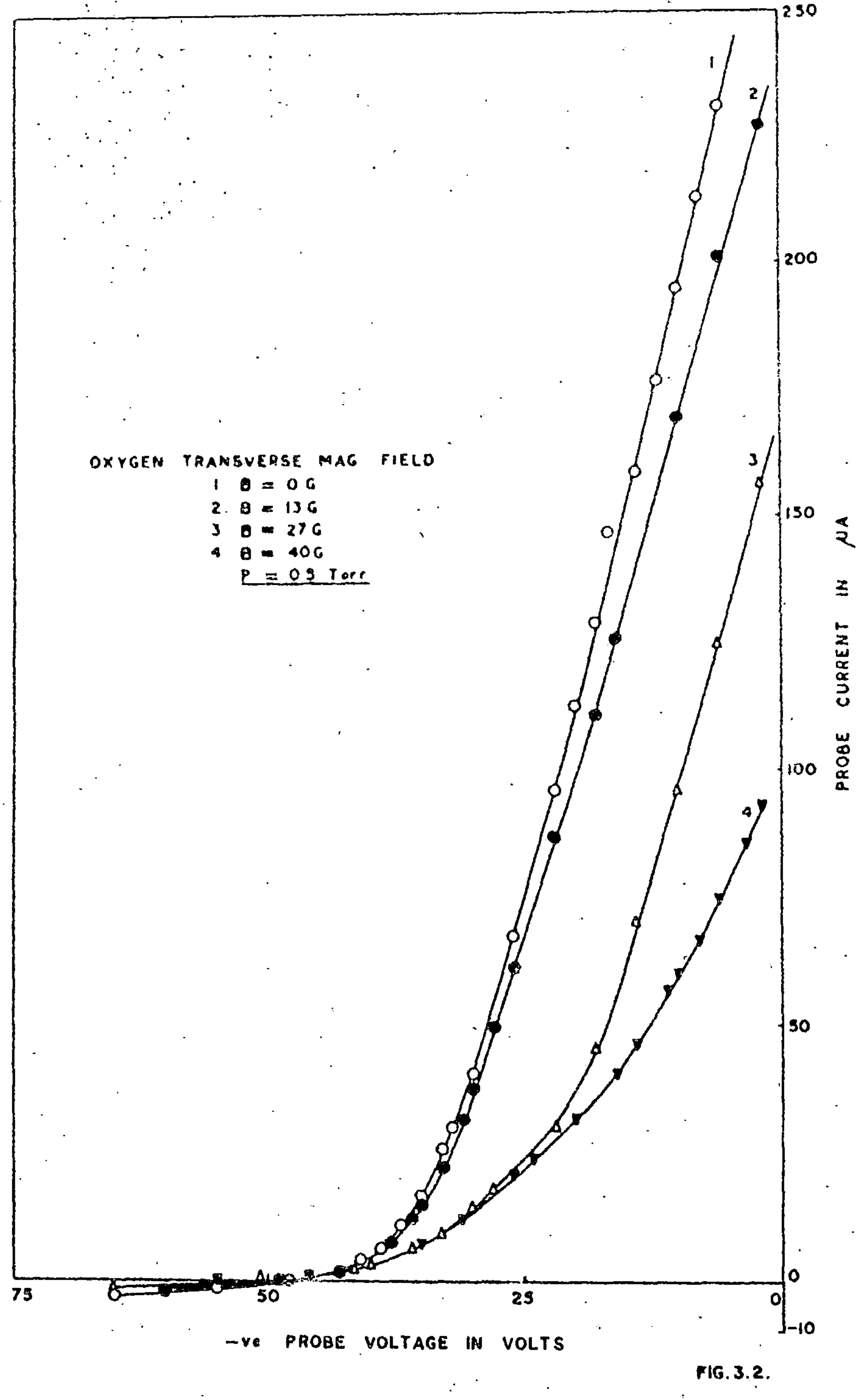

Fig. 3.2. Current-voltage characteristic of probe in oxygen in transverse magnetic field.

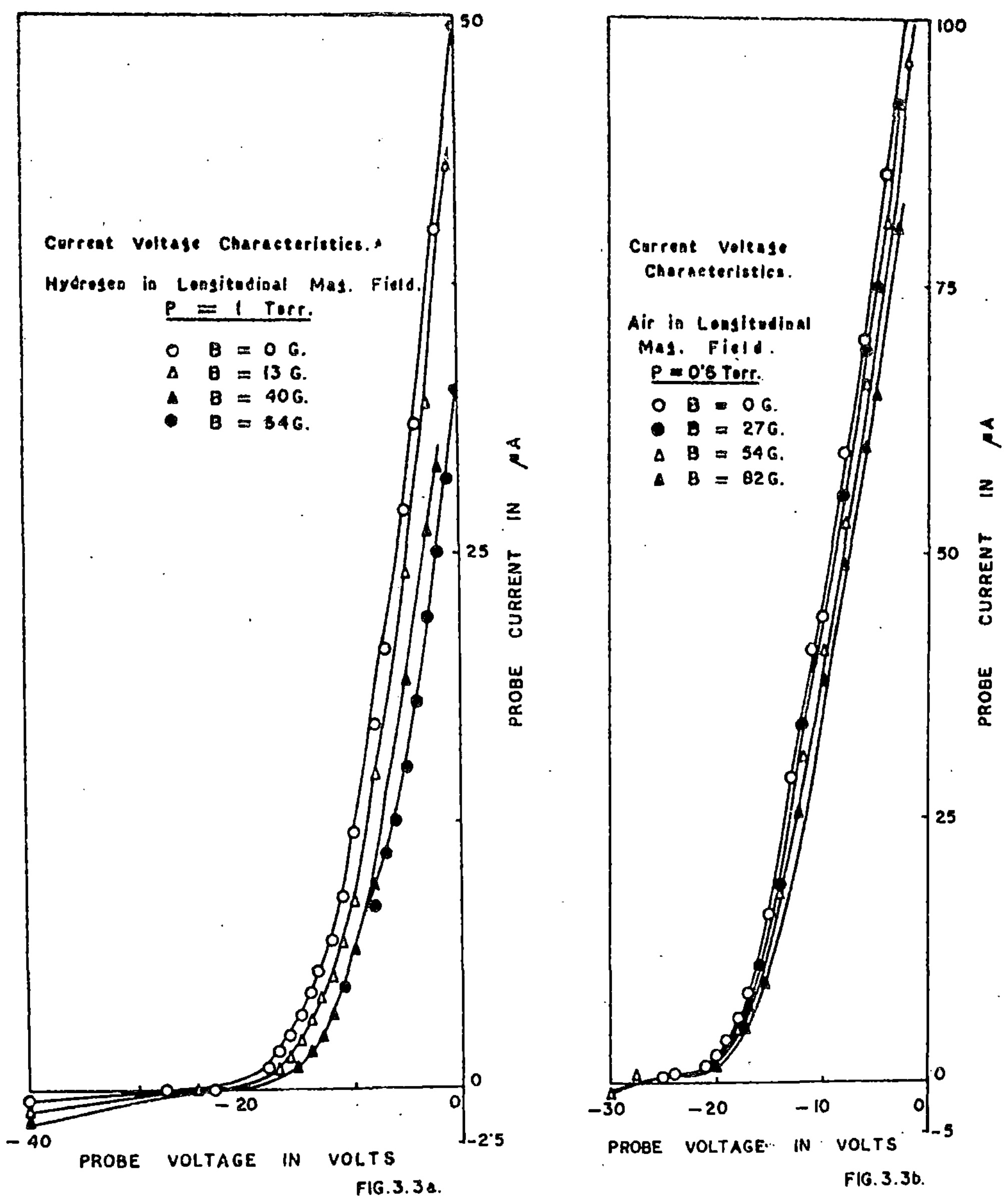

Fig. 3.3. Current-voltage characteristic of probe in longitudinal magnetic field in (a) hydrogen, (b) air.

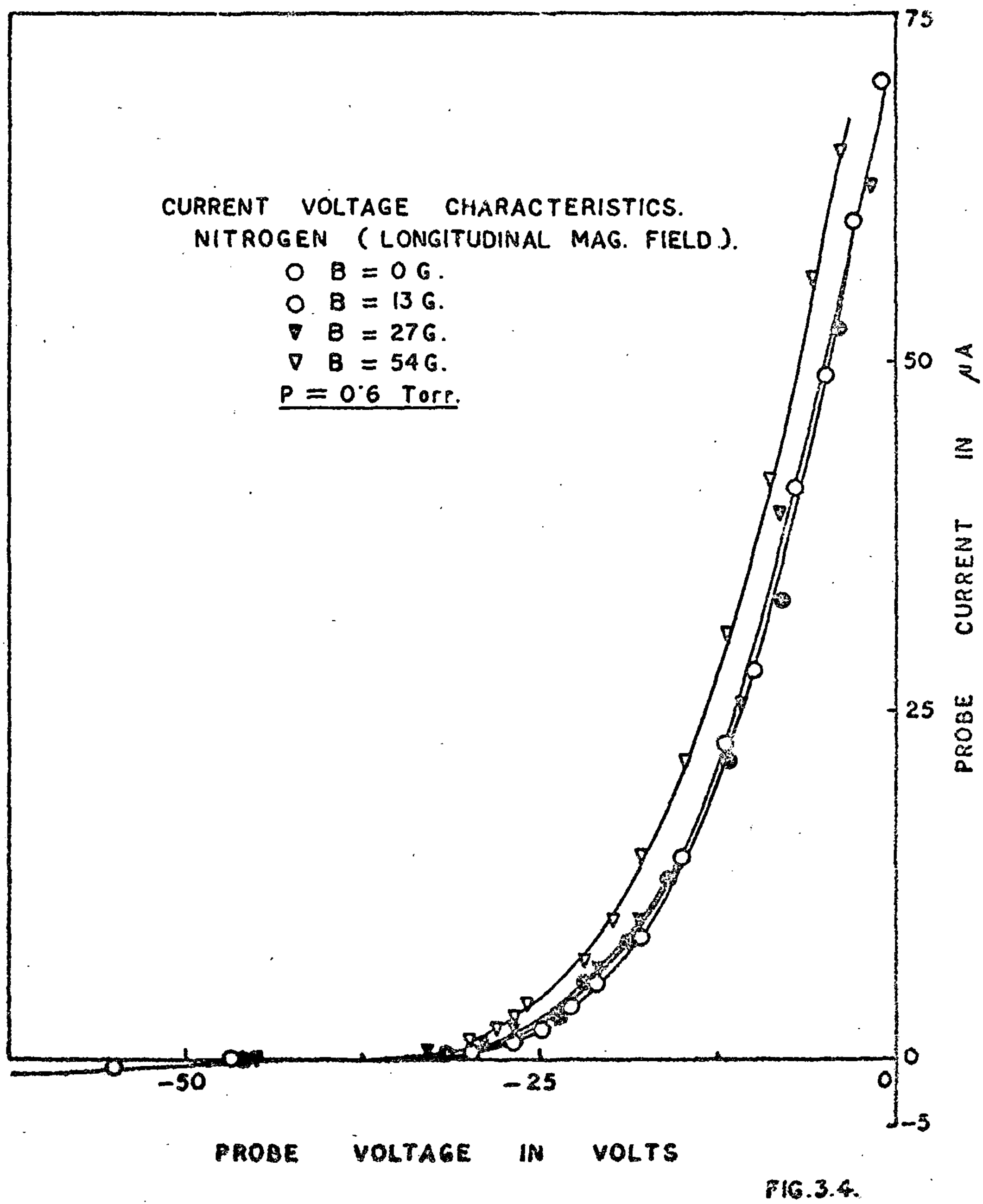

Fig. 3.4. Current-voltage characteristic of probe in nitrogen in longitudinal magnetic field.

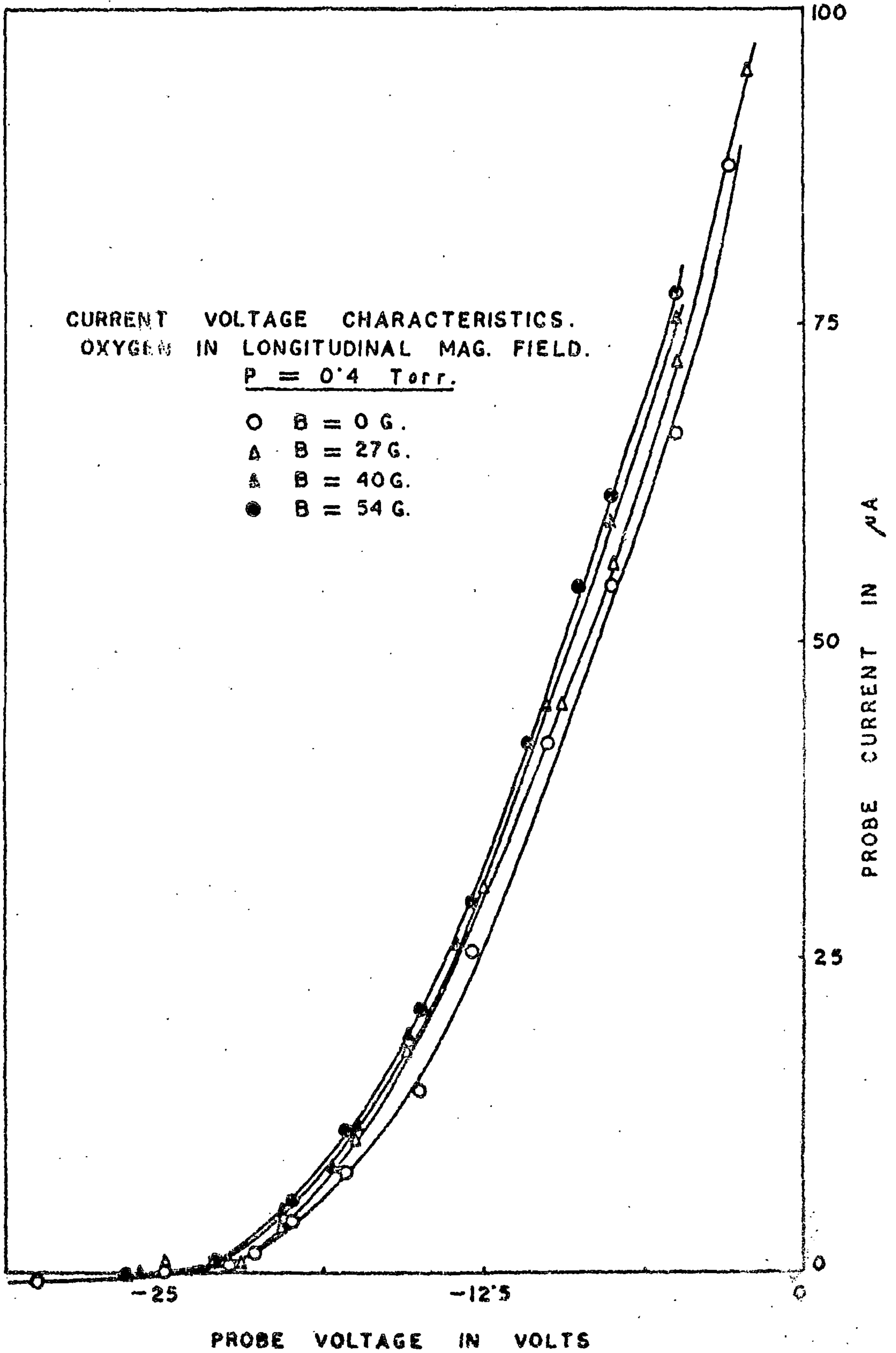

FIG.3.5

Fig. 3.5. Current-voltage characteristic of probe in oxygen in longitudinal magnetic field.

electron temperature regime and electron saturation current regime on the semilogarithm plot of the characteristic and the crossing point of the two tangents represented the space potential. When space potentials have been determined, the saturated ion current at the space potential is determined by extrapolating the ion currents graphically from high negative probe potentials, linearly to the space potential. Such extrapolations have been shown in fig. 3.6 for air and oxygen in transverse magnetic field. The electron current I_e is determined by subtracting I_i from the probe current (eqn. 2.6). Log I_e has been finally plotted against probe potential (V_p) and the characteristics have been obtained. The characteristics of gases with and without magnetic fields have been shown in figs. 3.7 to 3.14. In figs. 3.7 to 3.10, the gases were subjected to transverse magnetic field and for figs. 3.11 through 3.14, longitudinal magnetic fields were used.

For the analysis of the probe characteristics, the domain of the probe operation is to be determined. The four parameters, probe radius (r_p), Debye length (λ_D), mean free path of electrons and ions (λ_e and λ_i) effectively determines the domain. In our experiment, $r_p = 9.5 \times 10^{-3}$ cm. λ_D is determined from equation (3.1). For typical glow discharges, T_e varies from 1-5 eV and n_e from 10^8-10^{10} cm^{-3}. In determining λ_D, we considered $T_e = 5$ eV and $n_e = 10^{10}$ cm^{-3} as it will be seen later that experimental values obtained from probe characteristic in general are of these orders.

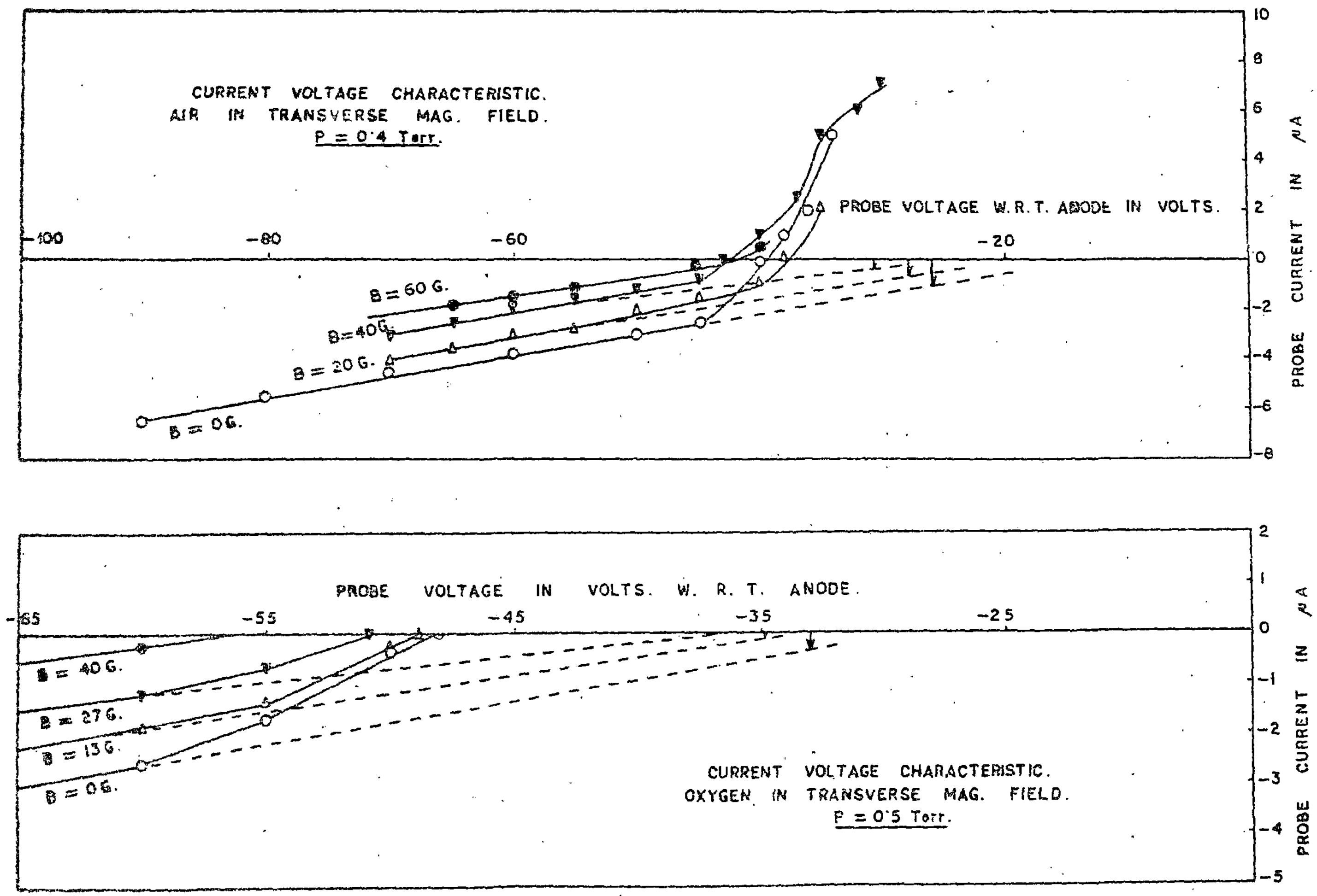

FIG. 3.6.

Fig. 3.6. Current-voltage characteristic of probe in air and oxygen and determination of saturation ion current at space potential by method of linear extrapolation.

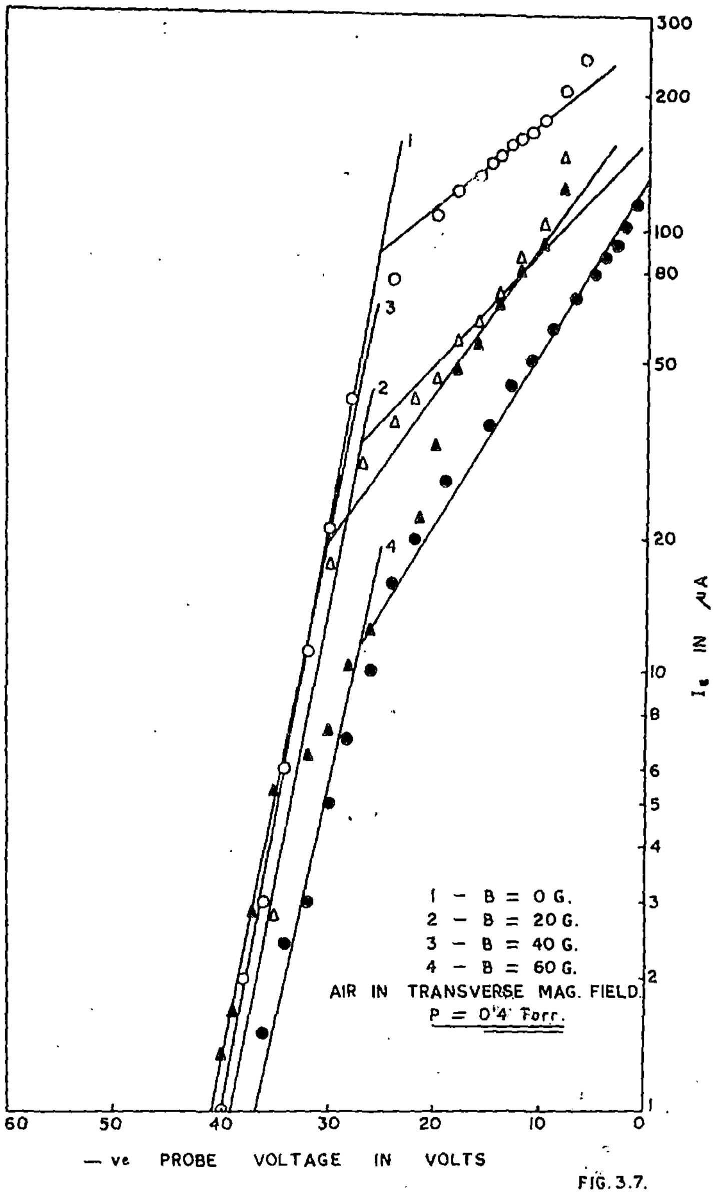

Fig. 3.7. Log I_e - V_p curves for air in transverse magnetic field.

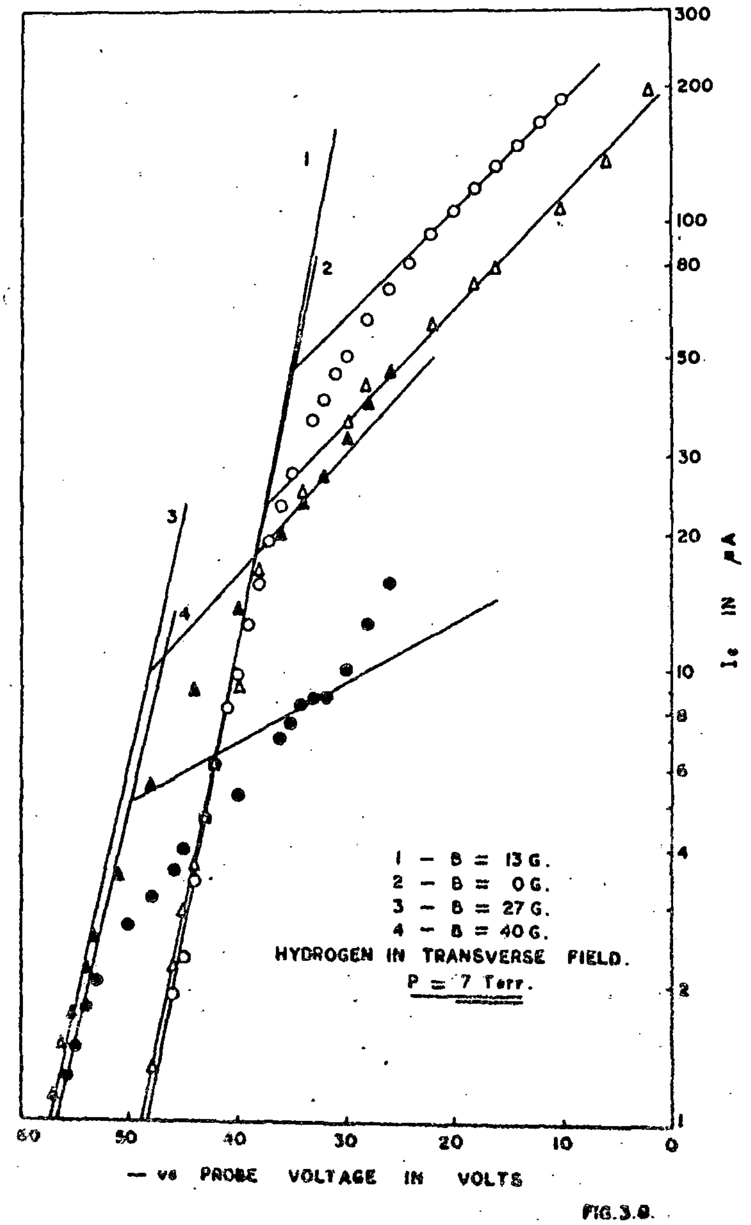

Fig. 3.8. Log I_e - V_P curves for hydrogen in transverse magnetic field.

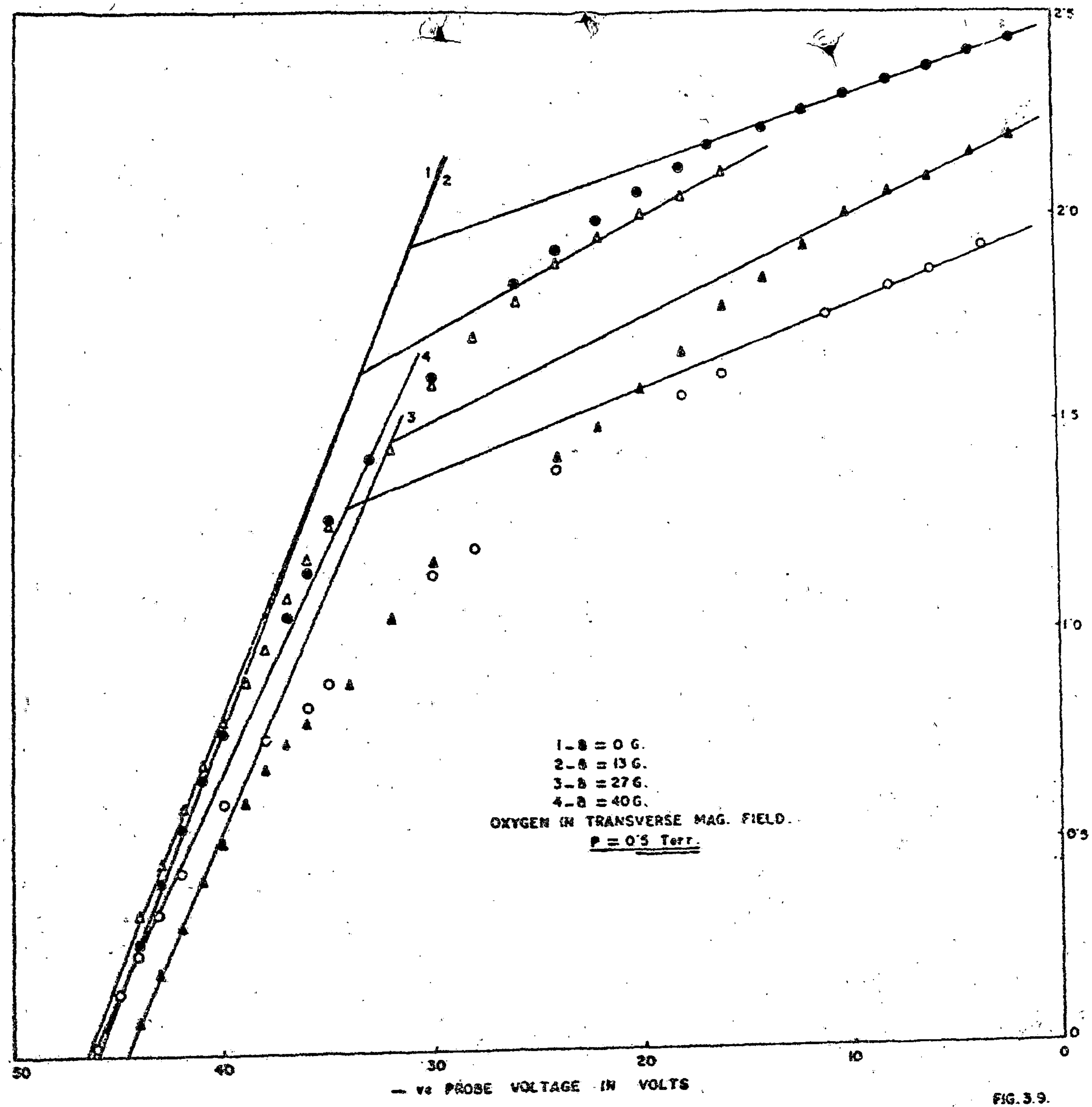

Fig. 3.9. Log I_e-V_p curves for oxygen in transverse magnetic field.

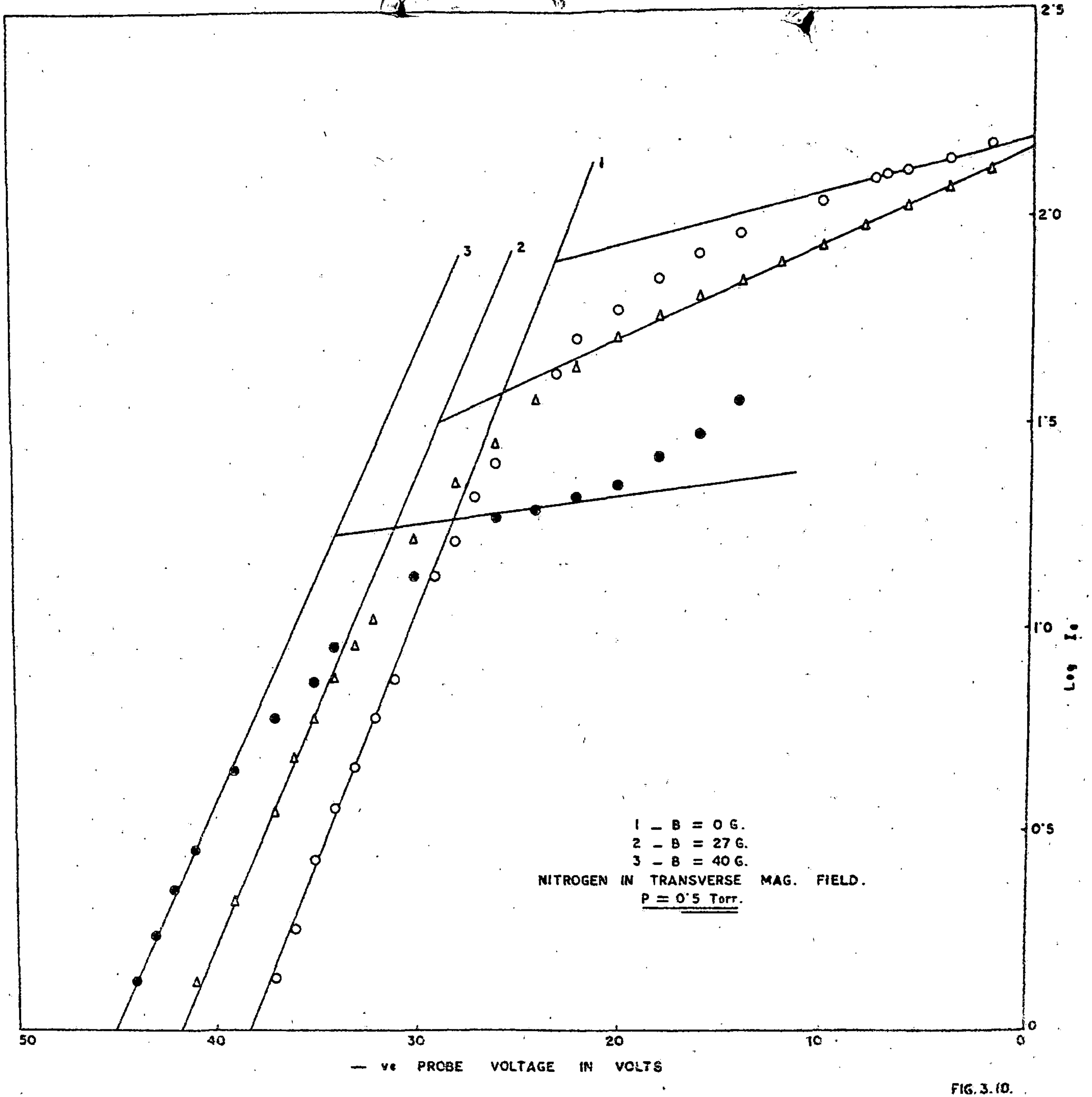

Fig. 3.10. Log I_e-V_p curves for nitrogen in transverse magnetic field.

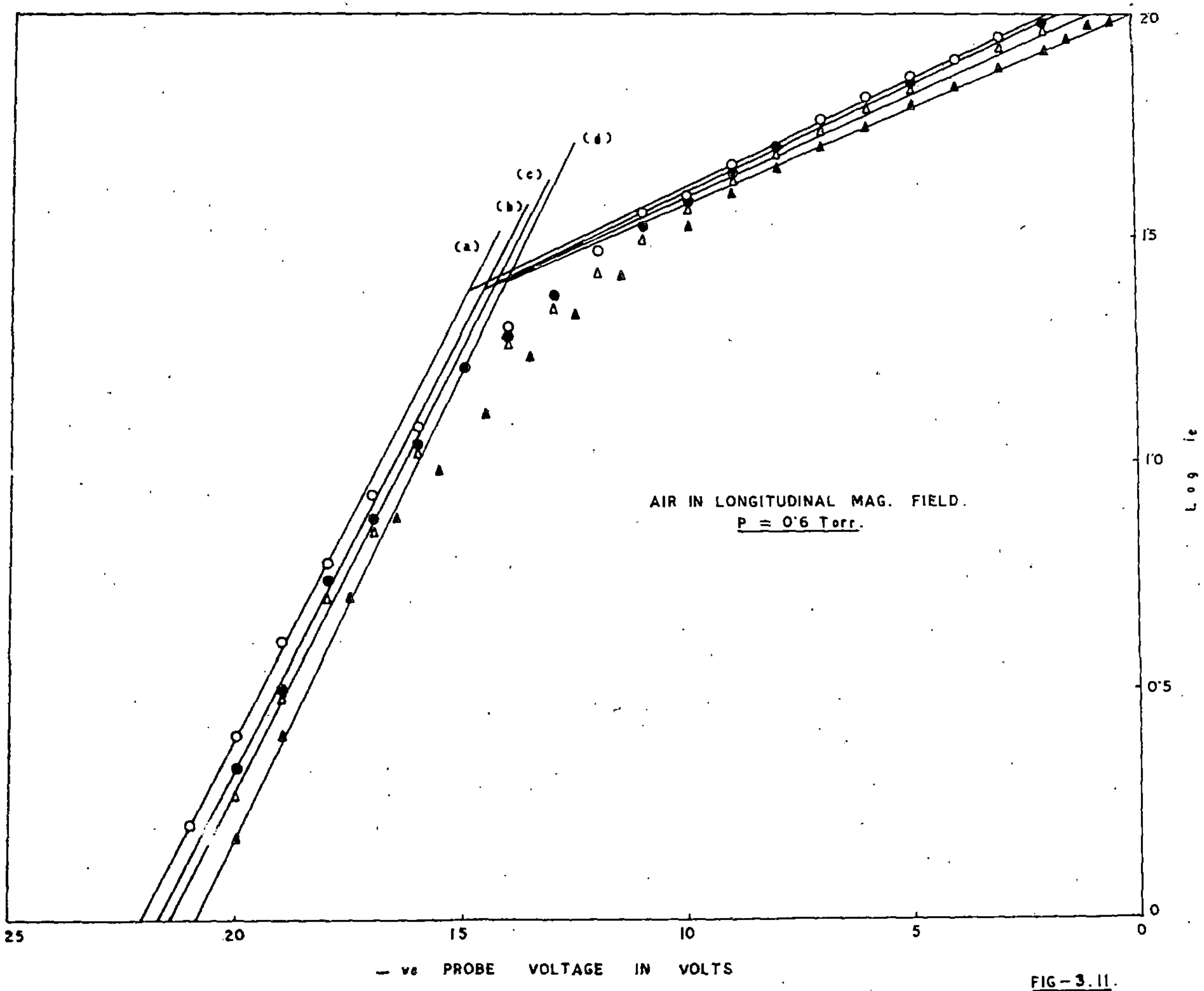

Fig. 3.11. Log I_e-V_p curves for air in longitudinal magnetic field (a) B =0G, (b) B = 27G, (c) B = 54G, (d) B = 82G.

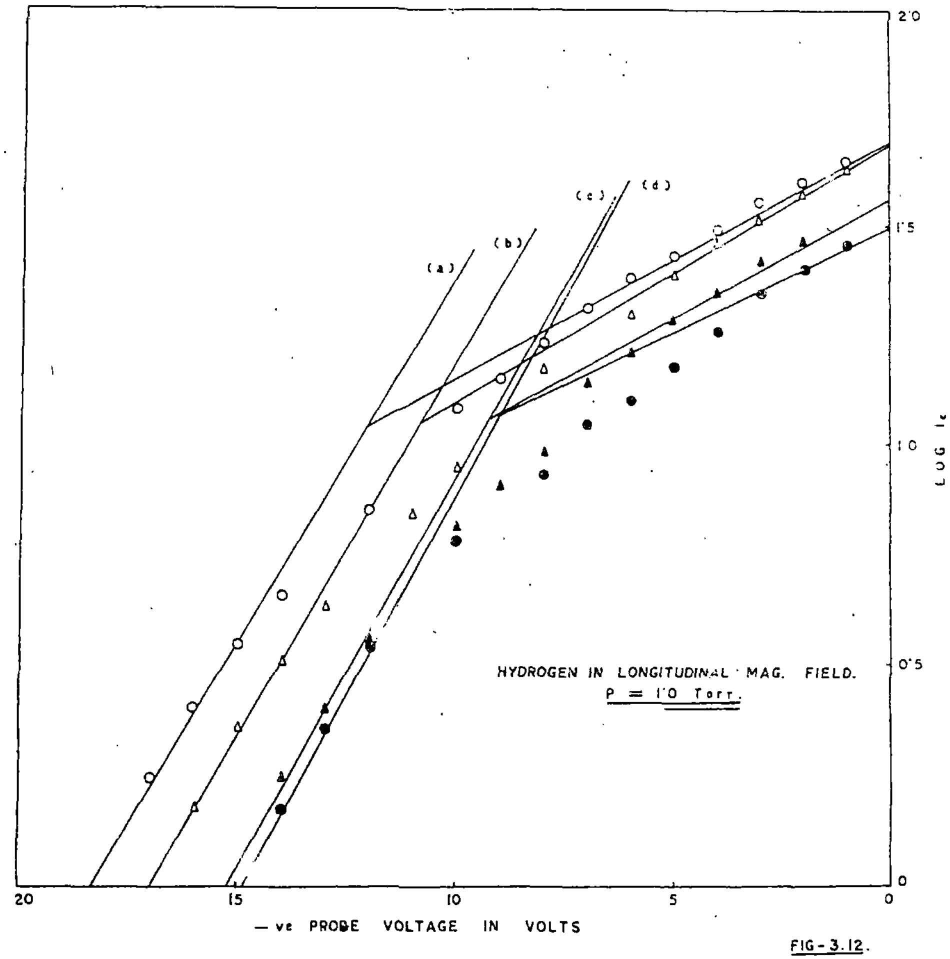

Fig. 3.12. Log I_e-V_p curves for hydrogen in longitudinal magnetic field (a) B = 0G, (b) B = 13G, (c) B = 40G, (d) B = 54G.

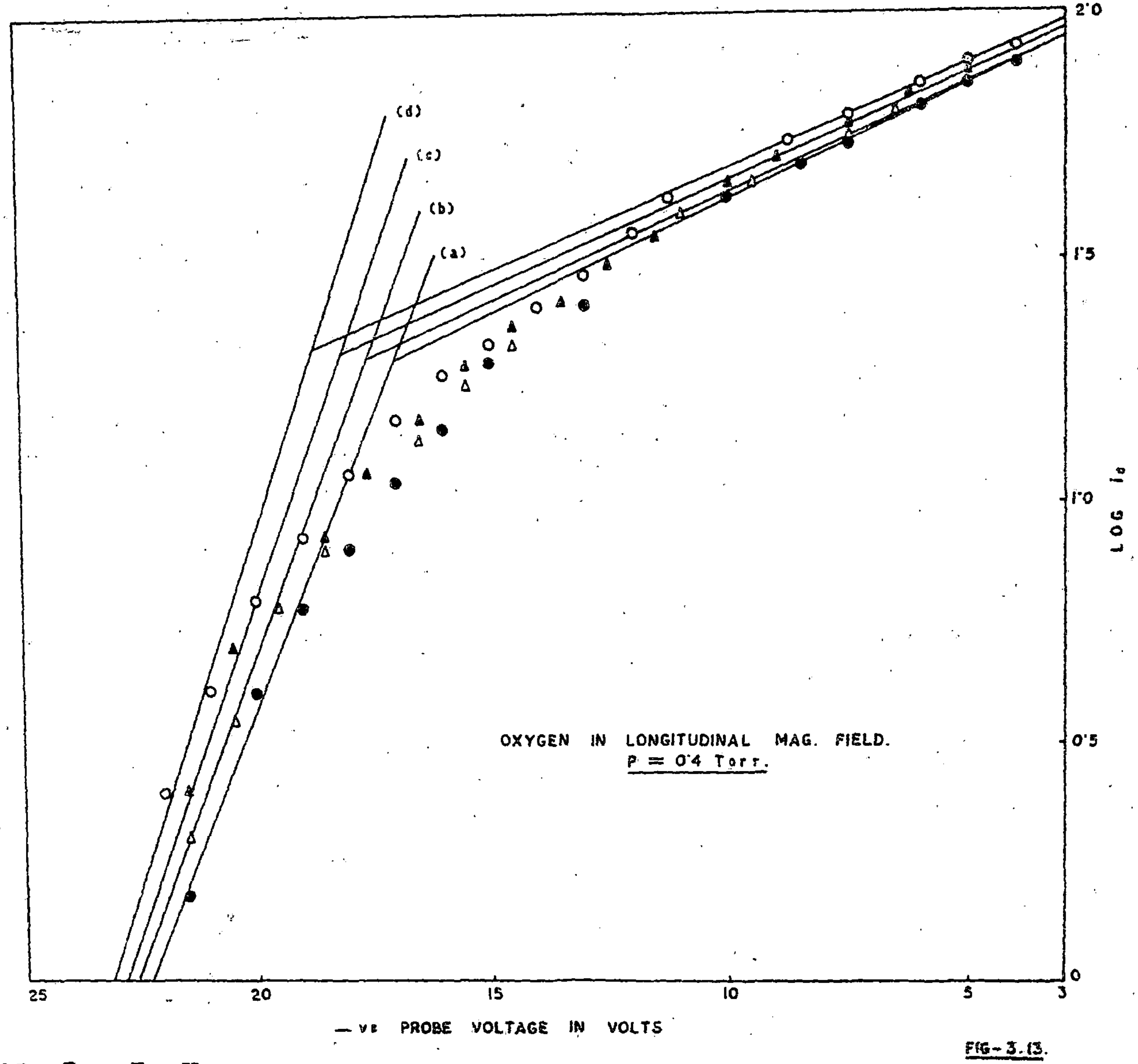

Fig. 3.13. Log I_e-V_P curves for oxygen in longitudinal magnetic field (a) B = 0G, (b) B = 13G, (c) B = 27G, (d) B = 54G.

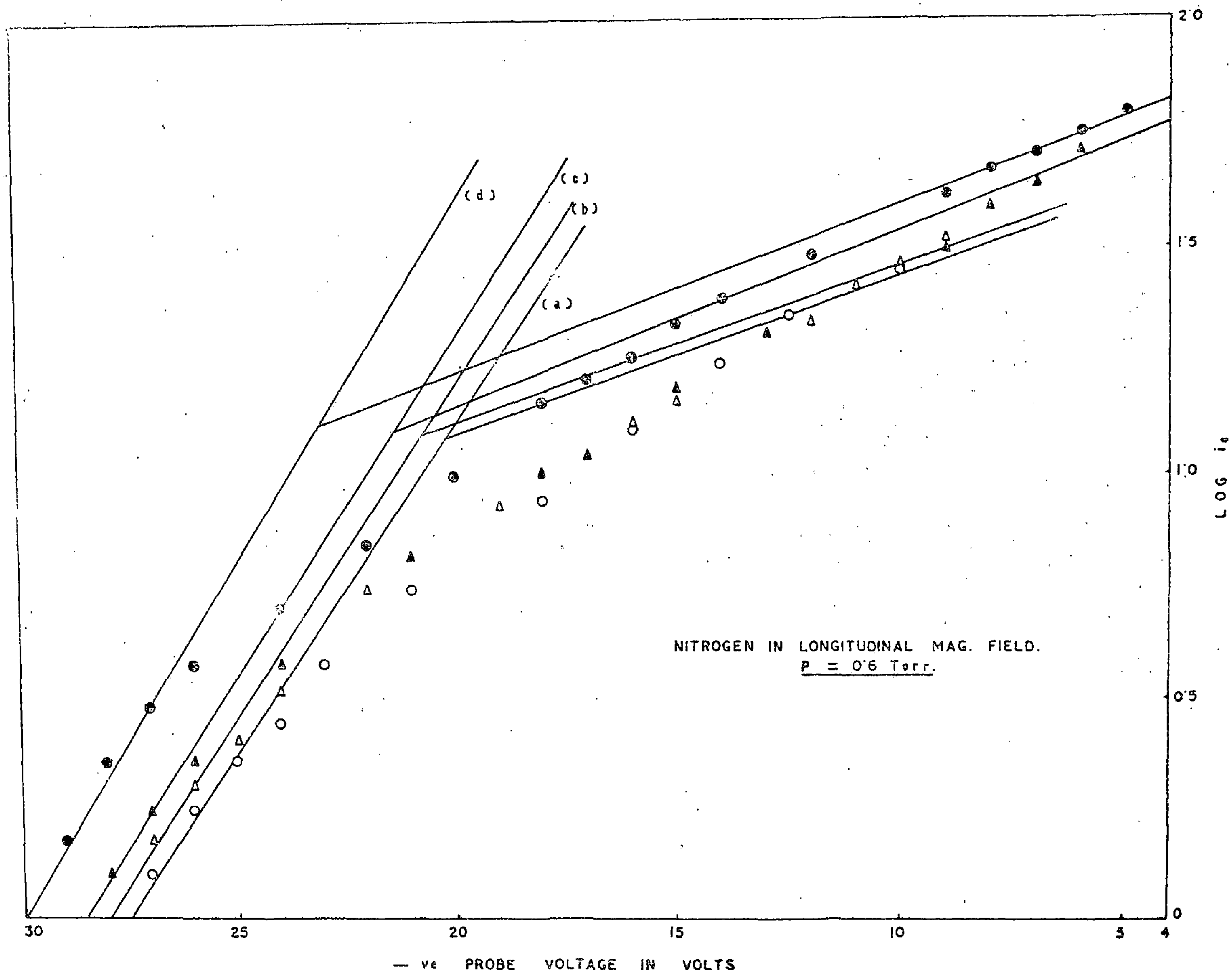

Fig. 3.14. Log I_e-V_p curves for nitrogen in longitudinal magnetic field (a) B = 0G, (b) B = 13G, (c) B = 27G, (d) B = 54G.

λ_D , thus calculated was 1.1 x 10^{-2} cm. The mean free path of electrons λ_e may be estimated from values of collisions cross section (q_m). But collision cross section is a function of electron energy. Huxley & Crompton (1974) have shown that $q_m(v)$ may be replaced by an effective mean value q_m^* corresponding to a value of E/N. When the electron energy is greatly in excess of the mean energy of the gas molecules, and when inelastic collisions (like vibrational and rotational excitation) are important q_m^* becomes a function of E/N where E is the electric field intensity and N is the number density of molecules. For a Maxwellian distribution of electron energy,

$$q_m^* = 2.23 \times 10^{-10} \frac{E/N}{W\,(D/\mu)^{1/2}} \quad cm.^2 \qquad (3.2)$$

where E/N is expressed in townsend, W, the drift velocity at corresponding E/N is expressed in cm/sec. and (D/ μ), the energy corresponding to E/N is in volts. For the values of E/N in our experiments, for different gases, the values of W and (D/ μ) are not available in literature for air, oxygen and nitrogen, so a model calculation for hydrogen gas for which datas are available (Huxley and Crompton, 1974) have been made. The cathode fall and anode fall for brass electrodes in hydrogen gas

(Francis, 1960) have been subtracted from total voltage drop across the discharge tube (1000 V). The potential thus obtained when devided by the length between the electrodes, gives E. E when devided by pressure of the hydrogen gas reduced to 20°C (temperature of gas in the discharge tube was nearly 50°C), gives E/N corresponding to T = 293°K and taking values of W and D/μ corresponding to 293°K, q_m^* is determined from equation (3.2). q_m^* N which is the inverse of λ_e is determined by finding N from pressure of the discharge reduced to 0°C, and λ_e thus calculated ~~from~~ for hydrogen at 0.7 torr pressure was 6.3 x 10^{-2} cm. λ_i has been determined from data given by von-Engel (1965), corrected by Sutherland constant. Actually the datas given by von-Engel determines classical mean free path λ of hydrogen molecule in its own gas. But $\lambda \leq \lambda_i \leq \sqrt{2}\lambda$. The factor $\sqrt{2}$ applied only when $\vartheta_{ion} >> \vartheta$ molecule. Considering $\lambda = \lambda_i$, for hydrogen λ_i has been calculated to be 2.1 x 10^{-2} cm. for pressure 0.7 torr. So it is found for hydrogen gas that $\lambda_m >> r_p$, $\lambda_m >> \lambda_D$ and $\xi_p (= r_p/\lambda_D) < 5$. λ_m is the smallest free path for collision between the charged and other particles of which plasma is composed. It is evident from Table 3.1 that for hydrogen, the pressures were comparatively larger than for other gases. So it is expected that for other gases λ_m would be greater so that above condition is fulfilled. In this condition the orbital motion theory of Langmuir is valid.

The probe theory as developed by Langmuir gives electron current as

$$I_e = I_{re} \exp\left(-eV_p / kT_e\right) \tag{3.3}$$

where I_{re} is the random electron current, and k is the Boltzmann constant

$$I_{re} = \frac{1}{4} A_s n_e e \left(\frac{8kT_e}{m\pi}\right)^{1/2} \tag{3.4}$$

A_s is the effective electron collection area of the probe and n_e is the unperturbed number density of electrons. From equation (3.3), electron temperature T_e corresponding to the assumed Maxwellian distribution is calculated by measuring the slope of the line in partial electron attraction region in a semilogarithmic plot of I_e versas V_p. I_{re} corresponds to the electron current to the probe at space potential which is determined from crossing point of the two tangents in the characteristics. The tangents were drawn in the following manner:

1. The tangent in the partial electron attraction region was drawn through more points of highly negative probe potential as it is in this region that the distribution is expected to be Maxwellian and equation (3.3) is valid for electron currents which are small compared to I_{re} (Schott,1968).

2. The line in electron saturation current regime was drawn in such a manner that it passes through maximum number of points. The electron saturation current regime may be divided into two parts: one corresponding to a linear increase of I_e with V_p due to the growth of effective collecting area, as the sheath expands. When V_p is made more positive, a breakaway from this linear increase is observed. In this region the probe becomes very hot and the sheath expands so much that for a large potential drop across the sheath, the electrons can further ionise in their way to probe and a luminous region is created surrounding the probe. While drawing the tangent the points just below the breakaway point were utilised so that all points after breakaway limit are above the tangent.

Since the ratio l/r_p was very much greater than unity, the effective electron collection area A_s was considered to be equal to $2\pi r_p l$. Thus from equation (3.4) number density of electrons was determined.

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

3.3.2. Results

With the method of analysis of the probe data as reported in section 3.3.1, semilog plot of current voltage characteristics has been obtained for air, hydrogen, oxygen and nitrogen in transverse and longitudinal magnetic fields. It has been observed that the plots ~~is~~ are straight lines with two different slopes for both with and without magnetic field.

From the slope of the straight lines electron temperature has been determined for all the gases and from the point of intersection of two tangents I_{re} has been determined from which electron density has been obtained. Table 3.2 shows the values of electron temperature and electron densities thus obtained, for transverse magnetic fields. The values of these parameters when a longitudinal magnetic field is present have been entered into Table 3.3.

TABLE 3.2

Values of T_e and n_e with and without transverse magnetic field.

Magnetic field (G)	Air $p = 0.4$ torr		Hydrogen $p = 0.7$ torr		Oxygen $p = 0.5$ torr		Nitrogen $p = 0.5$ torr	
	T_e eV	$n_e \times 10^{-9}$ cm^{-3}	T_e eV	$n_e \times 10^{-9}$ cm^{-3}	T_e eV	$n_e \times 10^{-9}$ cm^{-3}	T_e eV	$n_e \times 10^{-9}$ cm^{-3}
0	7.63	4.87	7.83	2.53	7.90	4.52	8.03	4.19
13			8.16	1.92	8.17	3.50		
20	7.95	2.78						
27			9.12	0.78	8.74	2.17	8.64	2.57
40	8.23	1.59	9.53	0.39	9.34	1.52	9.34	1.35
60	8.89	0.91						

TABLE 3.3

Values of T_e and n_e with and without longitudinal magnetic field.

Magnetic field (G)	Air $p = 0.6$ torr		Hydrogen $p = 1.0$ torr		Oxygen $p = 0.4$ torr		Nitrogen $p = 0.6$ torr	
	T_e eV	$n_e \times 10^{-9}$ cm^{-3}	T_e eV	$n_e \times 10^{-9}$ cm^{-3}	T_e eV	$n_e \times 10^{-9}$ cm^{-3}	T_e eV	$n_e \times 10^{-9}$ cm^{-3}
0	5.26	4.74	6.03	2.05	4.13	4.85	6.79	2.13
13			5.94	2.09			6.70	2.18
27	5.15	4.82			3.86	4.91	6.59	2.25
40			5.68	2.16	3.65	5.02		
54	5.14	4.97	5.50	2.25	3.42	5.14	6.28	2.36
82	4.92	5.20						

It is evident from Table 3.2 and 3.3 that plasma parameters change with magnetic field. In case of transverse magnetic field the electron temperature increases where as radial electron density at some region near the axis decreases and in case of longitudinal magnetic field, the electron temperature decreases and the axial electron density increases.

3.3.3. Discussion of the results

In the case of longitudinal magnetic field, for cylindrical probe perpendicular to magnetic field, the electron temperature and electron density can be determined from the characteristic as in the case of zero field. Not much distortion in the probe characteristics was observed in the range of magnetic fields used. But distortion was present in the case of transverse magnetic field. In transverse field the knee becomes more and more round and the space potential undefined. In case of longitudinal magnetic field, from experimentally measured values of rf conductivity, Sen and Gupta (1969) have shown λ_D decreases with the increase of field. This is also in accordance with equation (3.1) as in the axial region T_e decreases and n_e increases. From the stand-point of probe measurements, a decrease in λ_D is welcome. For transverse field equation (3.1) predicts an increase of λ_D in the axial region. If λ_D increases, the sheath and hence the effective probe collection area increases. When λ_D is comparable to λ_i , an increase of λ_D means collisions in the sheath. So when λ_D will be high, diffusion of particles have to be considered and the probe current would fall. So a rounded knee is expected in magnetic field for a probe perpendicular to the magnetic field and to discharge current mutually as the diffusion becomes anisotropic. Nevertheless we have utilised standard probe theory in this case in the anticipation that $\lambda_D \ngtr \lambda_e$ and we are utilising the electron attraction region of the probe characteristic.

While investigating the effect of transverse magnetic field on glow discharges, Beckman (1948) observed that the longitudinal electric field increases with the increase of magnetic field and the radial electron distribution becomes asymetric. From Beckman's analysis Sen, Das and Gupta (1972) obtained that ~~t~~ electron temperature when a magnetic field B is present is related to the zero field value by the relation

$$T_{eB} = T_e \left[1 + C_1 \frac{B^2}{p^2} \right]^{1/2} \qquad (3.5)$$

where p is the pressure of the discharge and C_1 is a constant for a particular gas given by

$$C_1 = \left(\frac{e}{m} \cdot \frac{\lambda_{e1}}{v_r} \right)^2 \qquad (3.6)$$

e, m, λ_{e1} and v_r are the charge, mass, mean free path at a pressure of 1 torr in 0°C and random velocity of the electrons respectively. Equation (3.5) is valid for conditions (i) in the domain where Schottky's ambipolar diffusion is valid (ii) the ionisation is mainly by electron impact ionisation collisions of the ground state molecules (iii) when B/p i.e. the value of reduced magnetic field is comparatively small. The experimental values of $\left[(T_{eB}/T_e)^2 - 1\right]$ have been plotted against B^2/p^2 for all the gas studied in fig. (3.15). It is observed that the curves are straight lines for the gases studied at low values of B/p in conformity with equation (3.5). The slopes of the curves are the value of C_1 for the gases. Slopes are of different values, so that C_1 is dependent on nature of the gas. From the slopes, the calculated values of C_1 for different gases have been entered in second column of Table (3.4).

Sen and Gupta (1971) have shown that the ratio of the electron density at a distance r from the axis when the transverse magnetic field is present, to the value in the absence of the magnetic field is given by

$$n_{eB}/n_e = \exp(-aB) \qquad (3.7)$$

where $a = e E C_1^{1/2} r / 2 k T_e p$.

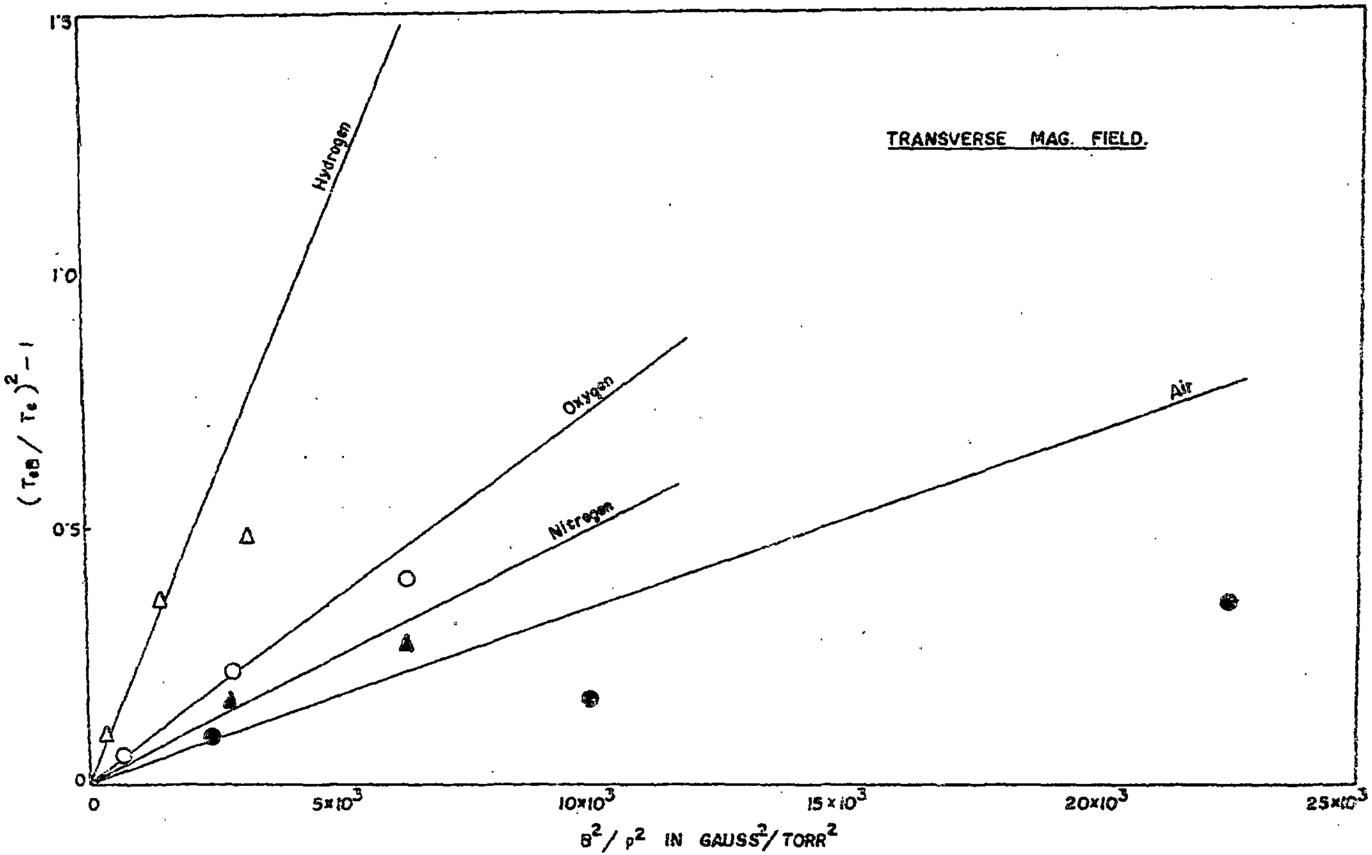

FIG. 3.15.

Fig. 3.15. Variation of $((T_{eB}/T_e)^2 - 1)$ against B^2/p^2 in transverse magnetic field.

From equation (3.7) it is evident that there will be a reduction of electron density and log (n_e/n_{eB}) will be proportional to B/p . From the experimentally obtained electron density, log (n_e/n_{eB}) has been plotted with B/p for different gases in fig. (3.16) and straight lines have been obtained. The experimental results after analysis thus indicate that Beckman's theoretical expressions as further modified by Sen et al (1971, 1972) with regard to electron temperature and radial distribution of electron density are valid for low values of B/p.

For longitudinal magnetic field Sen and Gupta (1969) obtained

$$T_{eB} = T_e + \frac{2T_e^2 \log\left[\frac{1}{\sqrt{1+C_1 B^2/p^2}}\right]}{T_e + 2eV_i/k} \tag{3.8}$$

V_i is the ionisation potential of the molecule. Equation (3.8) is also valid when Schottky's ambipolar diffusion theory is valid and ion pairs are created by electron collisions with the ground state molecules. From equation (3.8), it may be shown

$$1 + C_1\frac{B^2}{p^2} = \exp\left[2(T_e - T_{eB})\alpha\right] \tag{3.9}$$

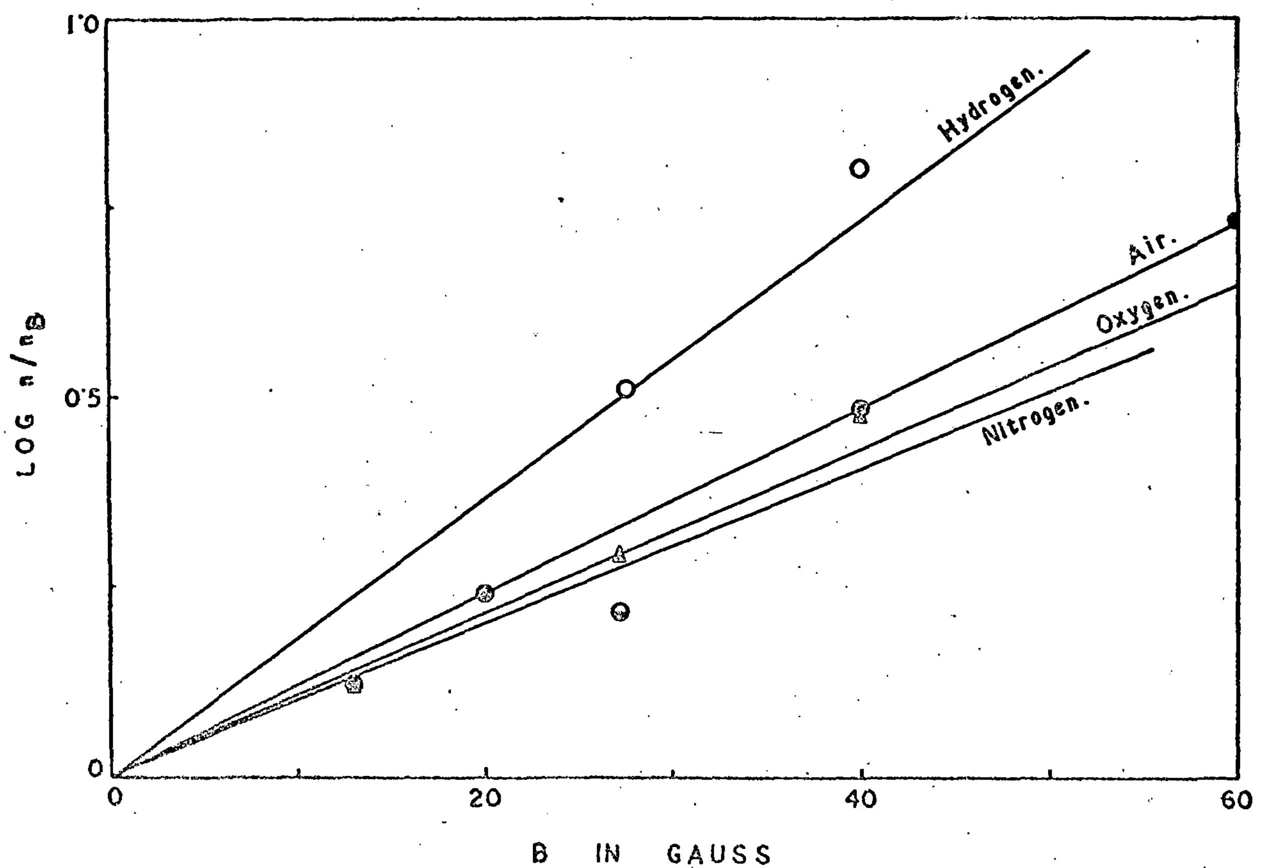

Fig. 3.16. Variation of log (n/n_B) against transverse magnetic field.

where

$$\alpha = \left[T_e + \frac{2eV_i}{k} \right] / 2T_e^2 \qquad (3.10)$$

From equation (3.10) α for different gases may be calculated if ionisation potentials are known. Ionisation potentials for hydrogen, oxygen and nitrogen molecules are 15.4, 12.5 and 15.8 eV respectively. Ionisation potential for air has been calculated from values of coefficients A and B defined by von-Engel (1965). These coefficients are defined as

$$A = \frac{1}{\lambda_{e1}} \quad , \quad B = \frac{V_i}{\lambda_{e1}} \qquad (3.11)$$

where λ_{e1} is the value of λ_e at a pressure of 1 torr. From equation (3.11),

$$V_i = \frac{B}{A} \qquad (3.12)$$

values of B and A for air have been given by von-Engel (1965) and from these value V_i is calculated to be 24.33 V. For longitudinal magnetic field, from the experimentally obtained electron temperatures, $\exp.2(T_e - T_{eB})\alpha$ has been plotted against B^2/p^2 in fig. (3.17). The plots are straight lines with an intercept of unity as predicted by equation (3.9). From the slope of the lines C_1 have been

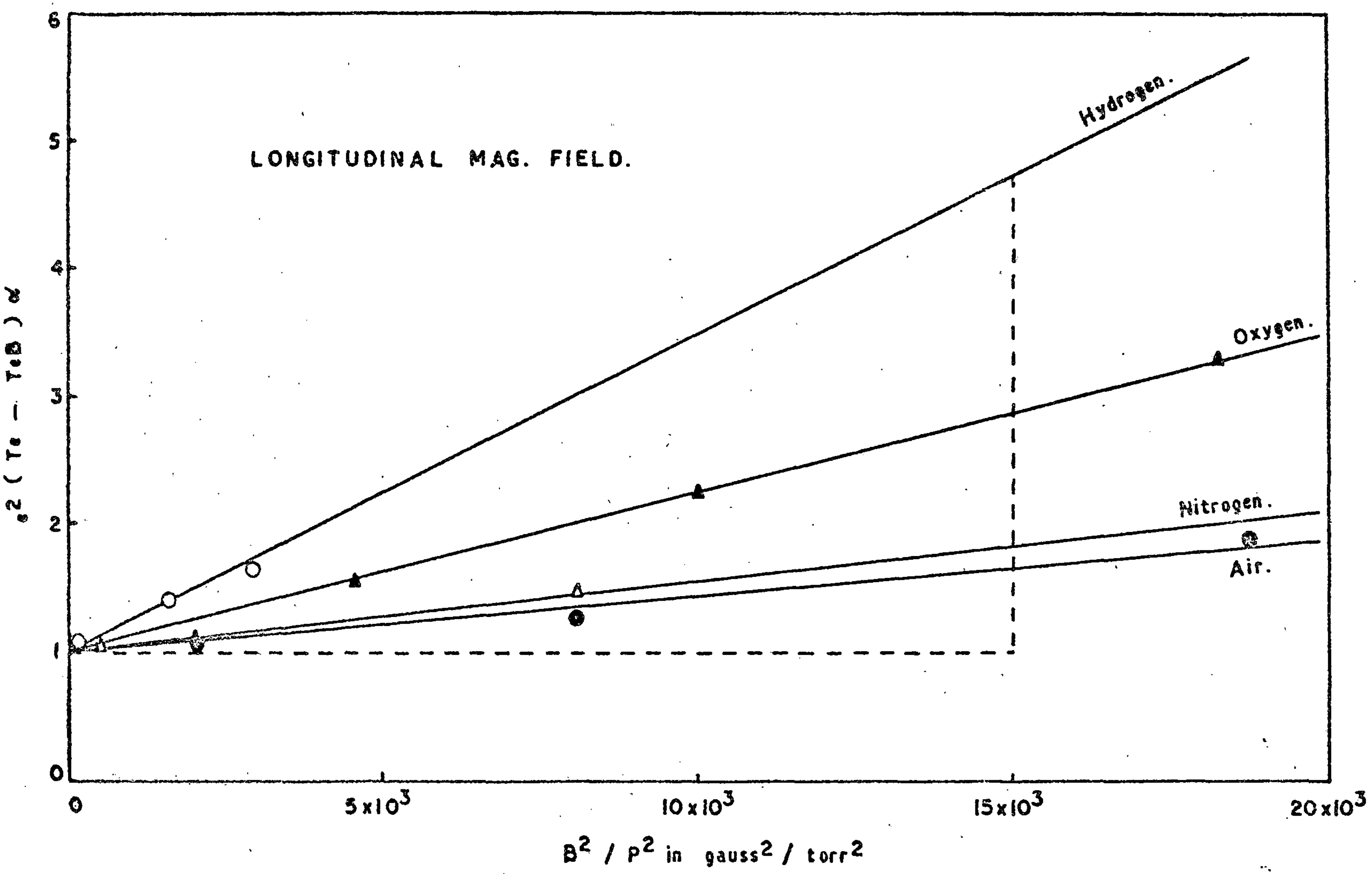

FIG.3.17.

Fig. 3.17. Variation of $e^{2(T_e - T_{eB})\alpha}$ against B^2/p^2 in longitudinal magnetic field.

calculated for all the gases and results thus obtained have been entered in the third column of Table 3.4.

TABLE 3.4

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

Gas	C_1 from transverse magnetic field measurement ($torr^2/gauss^2$)	C_1 from longitudinal magnetic field measurement ($torr^2/gauss^2$)
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}

It is evident that the values of C_1 obtained quite independently from 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 of C_1 in case of longitudinal magnetic field involves the knowledge of an accurate value of V_i, the ionisation 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 plasma O^-, O_2^-, O^+ and O_2^+ ions. O^- and O_2^+ concentration are about equal in magnitude and formed over 90% of the ions present. So the value of V_i taken equal to that of oxygen molecular ions introduces an element of uncertainty in the value of C_1.

Sen and Jana (1977) have discussed that in case of molecular gases the radial distribution of electrons in a cylindrical discharge tube where Schottky's ambipolar diffusion theory is valid, is governed by the normal Bessel function. The authors have shown that the radial electron density increases when the plasma is confined by a uniform longitudinal magnetic field and deduced that

$$\frac{n_{eB}}{n_e} = \frac{J_0\left[\frac{r}{\Lambda}\left\{\frac{\nu_{iB}}{\nu_i}\,\frac{T_e}{T_{eB}}\right\}^{1/2}\right]}{J_0\left(\frac{r}{\Lambda}\right)} \tag{3.13}$$

where n_e is the electron density at a distance r. ν_i and Λ are the ionisation frequency and diffusion length. The subscript B signifies a quantity when a magnetic field is present. The diffusion length Λ is given by

$$\frac{1}{\Lambda^2} = \left(\frac{\pi}{L}\right)^2 + \left(\frac{2.405}{R}\right)^2 \qquad (3.14)$$

L and R being the distance between electrodes and radius of the discharge and $1/\Lambda^2 = 4.067\ cm^{-2}$. Further,

$$\frac{\nu_{iB}}{\nu_i} = \frac{\exp(-eV_i/kT_{eB})\left[1 + eV_i/kT_{eB}\right]}{\exp(-eV_i/kT_e)\left[1 + eV_i/kT_e\right]} \qquad (3.15)$$

Considering a value of r, from equation (3.13) the values of n_{eB}/n_e may be calculated. Taking $r = 0.2$ cm., the length of the probe, the calculated values of n_{eB}/n_e from eqn. (3.13) and the experimentally obtained values from probe data have been entered in Table 3.5.

TABLE 3.5.

Values of n_{eB}/n_e in longitudinal magnetic field.

Magnetic field (G)	Air		Hydrogen		Oxygen		Nitrogen	
	Theo.	Expt.	Theo.	Expt.	Theo.	Expt.	Theo.	Expt.
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						

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 a longitudinal magnetic field. One of the reasons for quantitative disagreement between theoretical and experimental values is 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 probe is effective in collecting the electrons.

From experimentally obtained values of plasma parameter by probe method, it is thus evident that magnetic field influences a discharge column inconformity with observations of Beckman and Sen et al. In the analysis, the authors considered the plasma balance equation of the positive column. The magnetic field modifies the loss processes like ambipolar diffusion and mobility of charged particles and the plasma parameters change in magnetic field as the plasma adjusts to this new situation. The theoretical interpretations are in agreement with other models of positive column used. As ~~fa~~ for example we mention the ion fluid model discussed by Franklin (1976) when a longitudinal magnetic field is present. In this model a quantity δ , which measures particle collision frequency of momentum transfer relative to ionisation frequency, is of importance. Franklin discussed that when ionisation frequency $<<$ elastic collision frequency, the quantity δ_i / δ_e in a longitudinal magnetic field is changed by the relation

$$\left(\frac{\delta_i}{\delta_e}\right)_B = \frac{\delta_i}{\delta_e} \frac{1}{1 + C_1 \frac{B^2}{p^2}} \tag{3.16}$$

the subscripts i and e indicates ion and electron. C_1 has been already defined and it is the square of mobility at a pressure of 1 torr at 0°C. When T_e is not large

$$\delta_i / \delta_e = \mu_e / \mu_i \tag{3.17}$$

μ is the mobility of a particle. In the range $B/p < 0.5$ Tesla torr^{-1}, only μ_e is affected in a magnetic field so that,

$$\frac{\mu_e}{\mu_{eB}} = 1 + C_1 \frac{B^2}{p^2} \tag{3.18}$$

Equation (3.18) virtually speaks for an effective increase of pressure

$$\frac{p_B}{p} = \left(1 + C_1 \frac{B^2}{p^2}\right)^{1/2} \tag{3.19}$$

Equation (3.19) was utilised by Sen and Gupta (1969) in the plasma balance equation of positive column to reduce equation (3.8).

3.4. Conclusions

The 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 measured by probe method. Experiments have been performed under the condition in which assumptions of probe theory are valid. The alignment of 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 behaviour of a swarm of electrons and their associated properties in transverse and longitudinal magnetic fields. In case of transverse magnetic field, the electron temperature increases whereas radial electron density decreases upto a certain distance from the axis. Quantitative agreements for the variation of plasma parameters in transverse magnetic field have been obtained with existing theories for small values of ~~k~~ B/p. For longitudinal magnetic field, the electron temperature decreases whereas the radial electron density increases. This may be explained from an equivalent increase of pressure in longitudinal magnetic field as predicted by the theory.

For molecular gases, the excitation levels are widely spread out upto ionization potential and inelastic losses set up at low energies and these are so distributed so as to produce an approximate Maxwellin distribution for electron energy. The present investigation clearly indicates that ~~thxx~~ though the nature of electron energy distribution (in case of longitudinal magnetic field) remains Maxwellian in character in presence of or in absence of magnetic field, also it becomes a function of the magnetic field. For transverse magnetic field nothing specific about the electron energy distribution can be predicted owing to the distortion of the characteristics due to anisotropic diffusion. What has been measured in the present investigation is the average electron temperature and its variation with alignment of magnetic field.

References:

1. Beckman, L. (1948) Proc. Phys.Soc. 61, 515.
2. Bohm, D., Burhop, E.H.S., Massey, H.S.W. and Williams, R.W. (1949) The characteristics of Electrical Discharges in Magnetic fields (McGraw Hill, New York).
3. Francis, G. (1960) Ionization phenomena in gases (Butterworths, London).
4. Franklin, R.N. (1976) Plasma phenomena in gas discharges (Oxford University Press).
5. Huxley, L.G.H. and Crompton, R.W. (1974) The diffusion and drift of Electrons in gases, p. 530 (John Wiley,NY).
6. Kagan, Y.M. and Perel, V.I. (1969) Sov.Phys. Tech. Phys. 13 1348.
7. Krall, N.A. and Trivelpiece, A.W. (1973) Principles of Plasma Physics (McGraw Hill, New York).
8. Schott, L. (1963) in Plasma diognostics, (Ed.W. Lochte-Holtgreven, North Holland Publishing Co., Amsterdam).
9. Sen, S.N., Das, R.P. and Gupta, R.N. (1972) J.Phys. D. 5 1260.
10. Sen, S.N. and Gupta, R.N. (1969) Indian J.Pure Appl.Phys. 7, 462.
11. Sen, S.N. and Gupta, R.N. (1971), J.Phys.D.4, 510.
12. Sen, S.N. and Jana, D.C. (1977), J.Phys.Soc.Jap.43 1729.
13. Thomson, J.B. (1961) Proc.Roy.Soc. A262 503.
14. Uehara, K., Yatsu, K., Hagiwara, S. and Kojima, S. (1975) Japan J.Appl.Phys.14 1761.
15. von-Engel, A. (1965) Ionised Gases (2nd.Edn) p.31 & 181 (Oxford University Press).

Reprinted from the Proceedings of the Indian National Science Academy
Vol. 45 *Part A, No.* 4, (1979). pp. 309-321

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

S. K. SADHYA, D. C. JANA *and* S. N. SEN
Department of Physics, North Bengal University, Darjeeling

(*Received 27 July 1978; after revision 5 October 1978*)

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

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

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

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

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

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

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 $(T_{e\perp})$. 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

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

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

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

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			

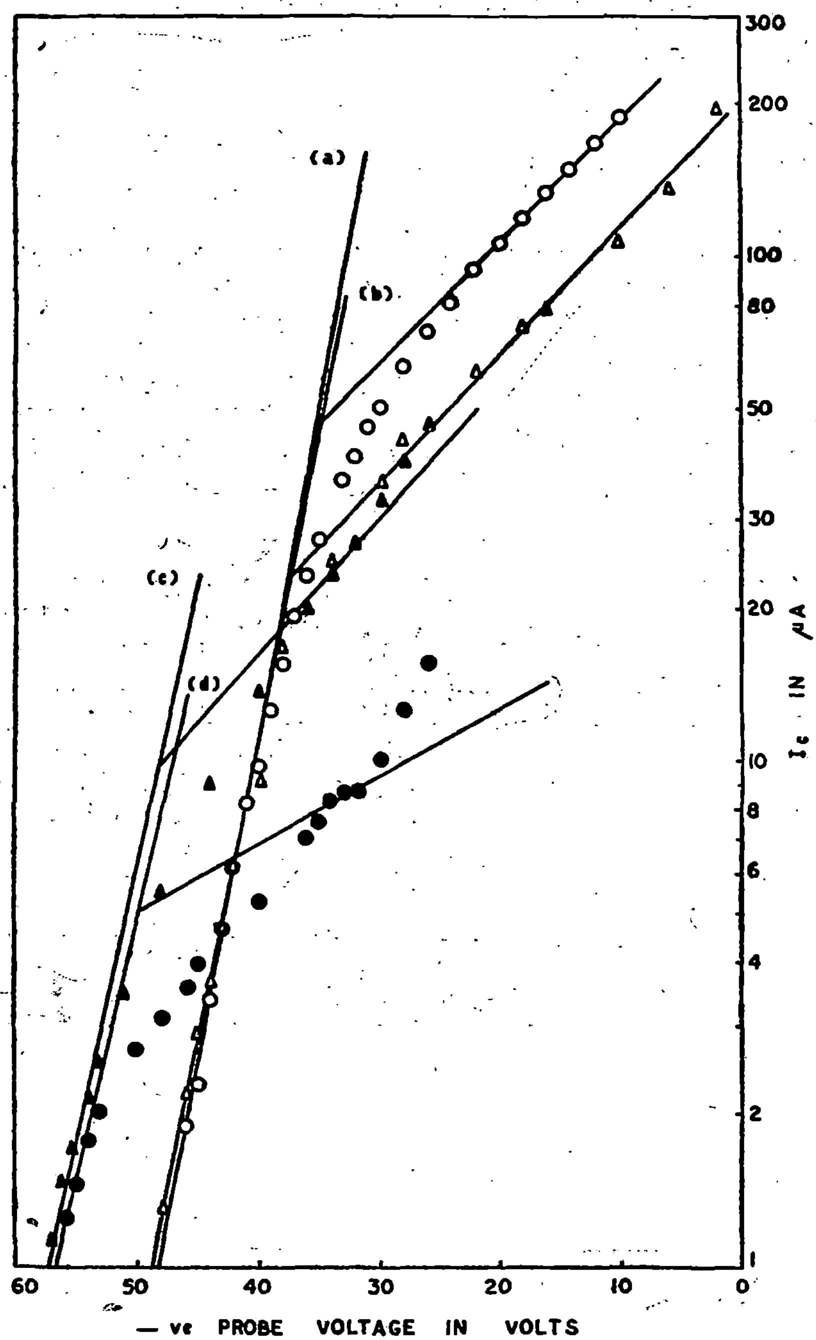

FIG. 1. Log I_e — V_p curves for hydrogen in transverse magnetic field. (*a*) B = OG (*b*) B = 13G (*c*) 27G (*d*) B = 40G.

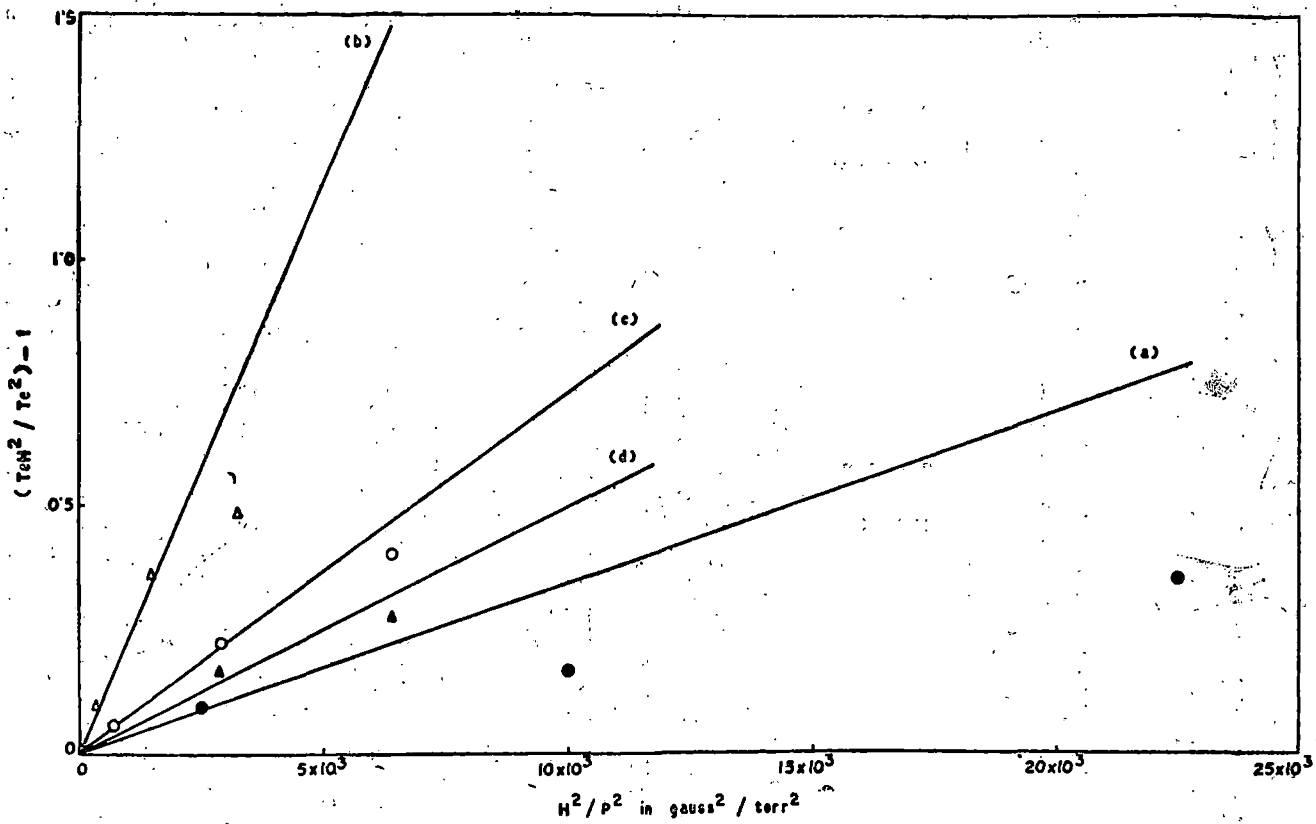

FIG. 2. Variation of $\left[\frac{T^2_{eH}}{T^2_{e}} - 1\right]$ against H^2P^2

(*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

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

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

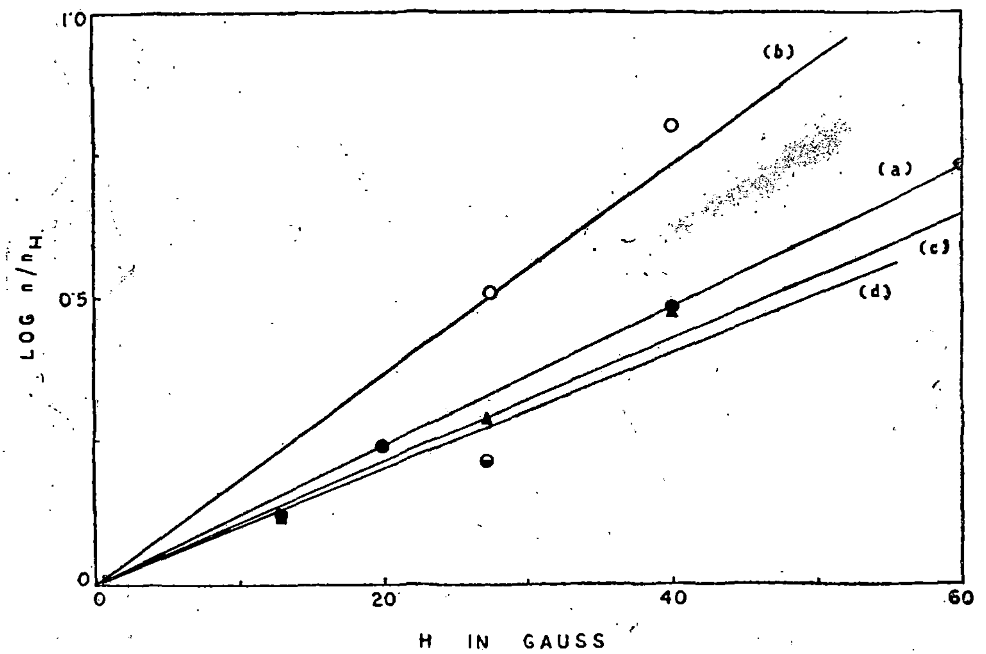

FIG. 3. Variation of log (n/n_H) against H for (*a*) Air (*b*) Hydrogen (*c*) Oxygen (*d*) Nitrogenin Transverse Magnetic field.

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

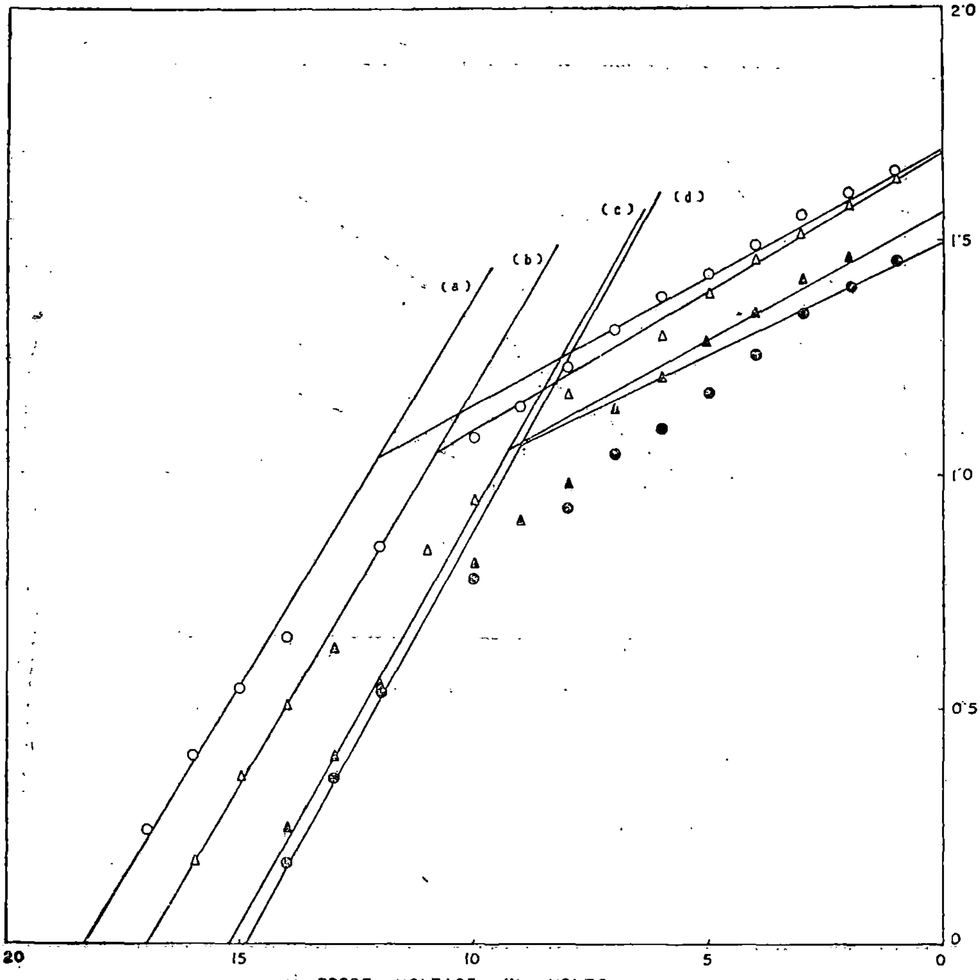

FIG. 4. Log I_e — V_p curves for Hydrogen in Longitudinal Magnetic field.
(*a*) B = OG (*b*) B = 13G (*c*) B = 40G (*d*) B = 54G

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			

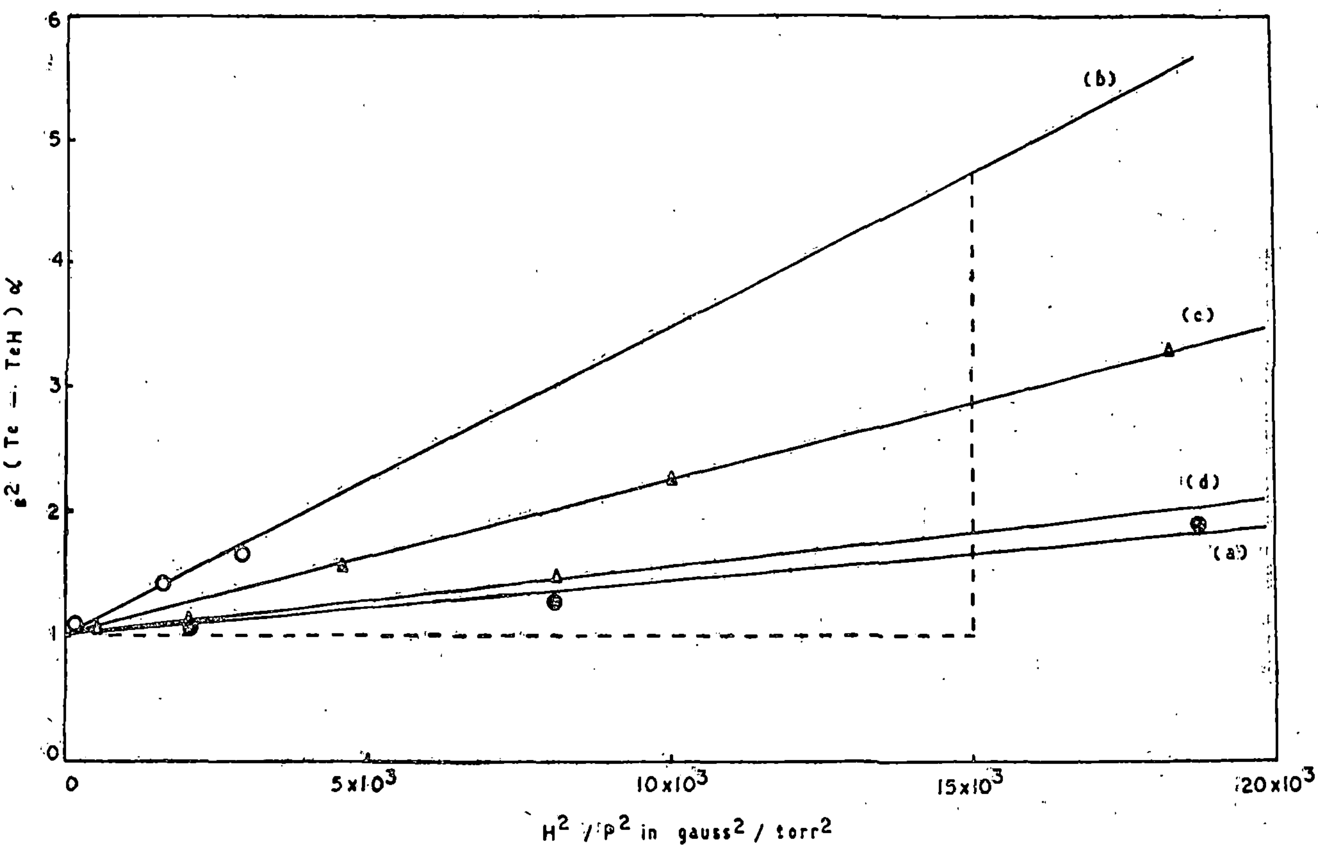

FIG. 5. Variation of $e^2 (T_e - T_{eH})\ \alpha$ against H^2/P^2 for (*a*) Air (*b*) Hydrogen (*c*) Oxygen (d) Nitrogen in Longitudinal Magnetic Fields.

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 $\frac{1}{\Lambda^2} = 4.0671$ 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.