CHAPTER VIII

VARIATION OF ELECTRON TEMPERATURE AND ELECTRON DENSITY IN IONISED GASES IN TRANSVERSE AND LONGITUDINAL MAGNETIC FIELD

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 are small in comparision with the mean free paths of the ions and electrons. This means that the probe can be assumed to collect only a small number of charged particles in the plasma around the sheath so that outside the sheath the plasma to a close approximation may be assumed to be undisturbed by the presence of the probe.

(b) The thickness of the space charge sheath surrounding the probe is small compared with the mean free path of the electrons and ions which means that the ions and electrons can move in this region undisturbed by collisions.

These limitations and the validity of these assumptions have been discussed by a large number of workers (Bickerton and Von Engel, 1956) and recently by Uemera, Yatsu, Hagiwara and Kojima (1975). Nevertheless the values of the parameters obtained by this method compare very favourably with the values obtained by other standard methods such as microwave or the spectroscopic method. In our present programme of work in determining the momentum transfer cross section, voltage current relation in a longitudinal magnetic field or in studying the diffusion of electrons in a magnetic field it has been assumed that both the electron temperature and electron density 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 that is with the direction of the unperturbed motion of the electrons. Beckman (1948) who quantitatively studied the phenomena showed that the axial electric field increases in a transverse magnetic field and from these calculations Sen and Gupta (1972) deduced that the electron temperature T_e in presence of the magnetic field is given by

$$T_{eH} = T_e\left[1 + C_1 \frac{H^2}{P^2}\right]^{1/2} \tag{8.1}$$

where (H/P) is small and $C_1 = \left(\frac{e}{m} \cdot \frac{L}{\vartheta_r}\right)^2$ where L is the mean free path of the electron in the gas at a pressure of 1 torr and ϑ_r the random velocity of the electron. This expression has been utilised in explaining the variation of discharge current in a transverse magnetic field in the positive column of a glow discharge (Sen and Gupta, 1971), the variation of current and voltage in an arc plasma (Sen & Das, 1972) and the spectral line intensity variation in a magnetic field (Sen, Das & Gupta, 1973) and has thus led to indirect verification of the expression given by equation (8.1). 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

$$n_H = n \exp\left[\frac{-eHr}{4\sqrt{2mK}}\sqrt{\frac{k}{T_e}}\right] \tag{8.2}$$

where k 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; when the magnetic field is longitudinal it reduces the outward flow of electrons by diffusion. Their number can then be maintained by a lower rate of ionization and hence a smaller gradient E. The outward flow of ions is made to balance that of electrons by a readjustment of radial electric field. As the axial electric field is reduced, the electron temperature which is directly proportional to the reduced field should therefore decrease instead of increasing as in the case of transverse magnetic field. This problem has not so far been quantitatively studied but a detailed experimental analysis of the positive column in a longitudinal magnetic field has been provided by Bickerton and Von Engel (1956) where radial electron density, axial electric field and electron temperature have been measured in a helium plasma at a pressure 0.048 torr and a magnetic field varying from zero to 500 gauss. From the analysis of their results the authors have deduced a semi-empirical relation of the form

$$\frac{E_H}{E} = \frac{T_{eH}}{T_e}\sqrt{\frac{k_H}{k}} \qquad (8.3)$$

where E_H and E are the axial electric fields in the presence and absence of magnetic field and k is the fractions of energy lost by collision either elastic or inelastic. They further showed that as no new process arises from the application of the magnetic field the results can fairly be represented by a simpler expression

$$\frac{E_H}{E} = \frac{T_{eH}}{T_e} \qquad (8.4)$$

Regarding the variation of radial electron density the authors (Bickerton and Von Engel, 1956) have obtained conclusive evidence that the radial electron density increases in a longitudinal magnetic field. In chapter V while studying the voltage current characteristics in glow discharge in longitudinal magnetic field, we have shown that in case of molecular gases as well, ~~as~~ the radial electron density increases when the plasma is confined by a longitudinal magnetic field, and a theoretical expression for the electron density variation in terms of ionization frequency ν_i diffusion length Λ and axial electric field E has been derived

$$\frac{n_H}{n} = \frac{J_0\left[\frac{r}{\Lambda}\left(\frac{\nu_{iH}}{\nu_i}\cdot\frac{E}{E_H}\right)^{1/2}\right]}{J_0\left(\frac{r}{\Lambda}\right)} \qquad (8.5)$$

It is thus evident that the direction of the magnetic field with respect ~~of~~ to the direction of motion of the electrons has a distinct effect on the plasma parameters specially the electron temperature and electron density in as much as that when the field is transverse the ~~k~~ electron temperature increases and the electron density decreases whereas when the magnetic field is longitudinal it leads to a decrease of electron temperature and increase in electron density. As most of the effects of magnetic field on a plasma depend on the manner in which these parameters are affected, it is proposed in the present investigation to put to an experimental test by the probe method of the theoretical deductions regarding electron temperature and electron density variation in both the longitudinal and transverse magnetic fields.

The question as to whether the Langmuir probe method can be utilized to determine the electron temperature and electron density in presence of the magnetic field has been discussed by many workers. 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 $\rho = mv/eH$, v being the velocity and m the mass of the particle. Thus 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 assumptions (b) depends upon the sheath thickness and thus on the plasma density, the type of gas and on the magnetic field. In our experiment the plasma density has been kept relatively low $(n \approx 10^8/cc)$ and the magnetic field is below 100 gauss. Under these conditions, to a first approximation the net flow of electrons across the sheath can be neglected and the spatial distribution of electrons follows Boltzmann law for particles diffusing in a potential field and hence from the slope of the semilog plot of probe current against probe voltage, the electron temperature can be obtained as has been shown by Bohm et al (1949) as in the case without the field.

In absence of magnetic field the electron density is obtained from the saturation probe current from the relation $I_e = A_e n_e v_e e$ where A_e is the area of the probe, v_e the random velocity of the electron, and it has been shown by Bickerton (1954) that the number of electrons striking per unit area per second of a ~~xk~~ solid plane parallel to H decreases as H rises but the recent analysis of Uemera et al (1975) has shown that for probes in a magnetic field it may be permissible to use equation (8.6) by substituting approximate value for A_e. If the magnetic field is weak, A_e can be expressed very approximately by '4 aℓ' where a is the radius of the probe and ℓ is the length.

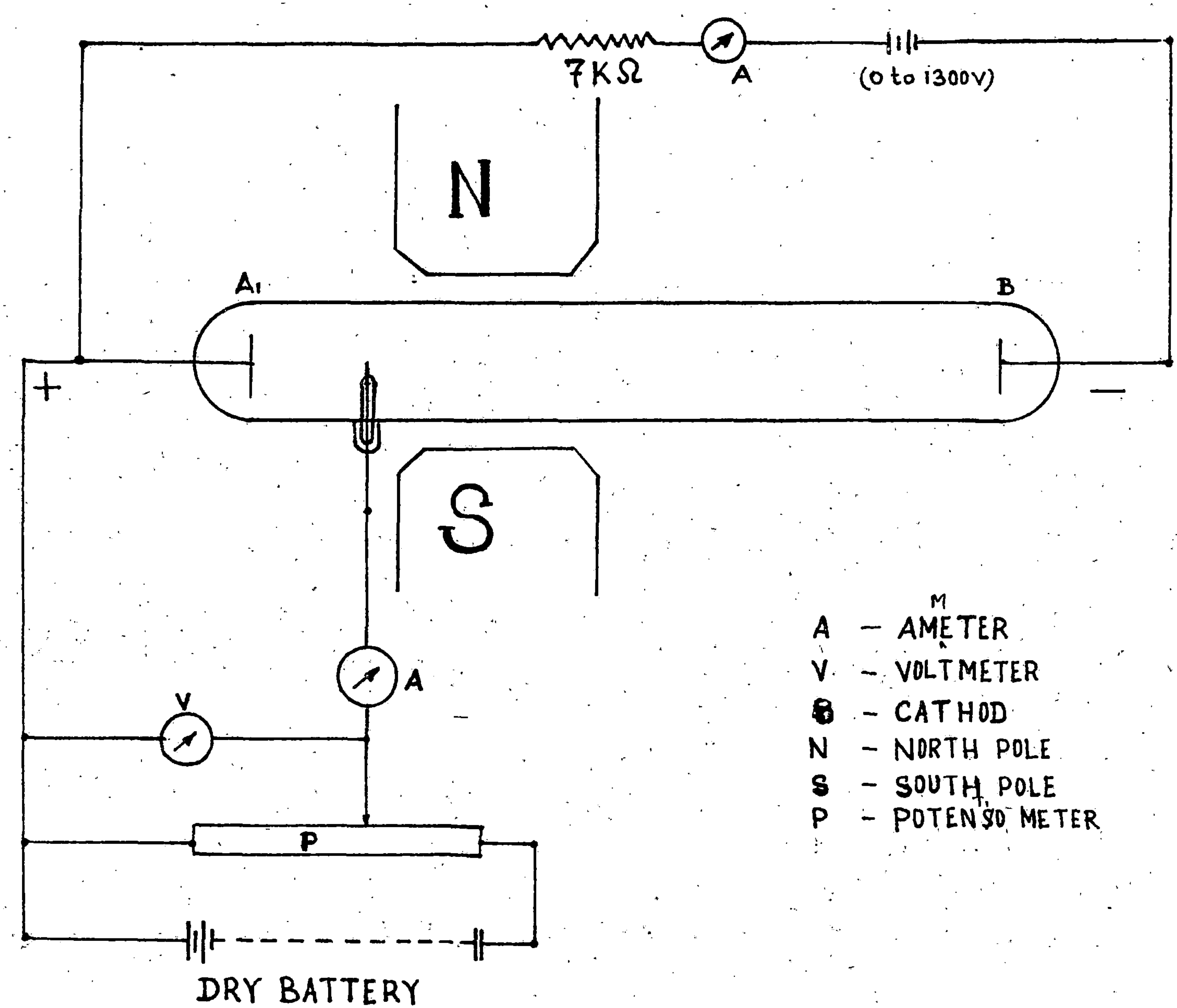
Taking these precautions in the design of the probe and keeping the electrons density and the magnetic field at a low value it is proposed to investigate in the present chapter the variation of electron temperature and electron density in the plasma when the magnetic field is either transverse or longitudinal.

EXPERIMENTAL ARRANGEMENT

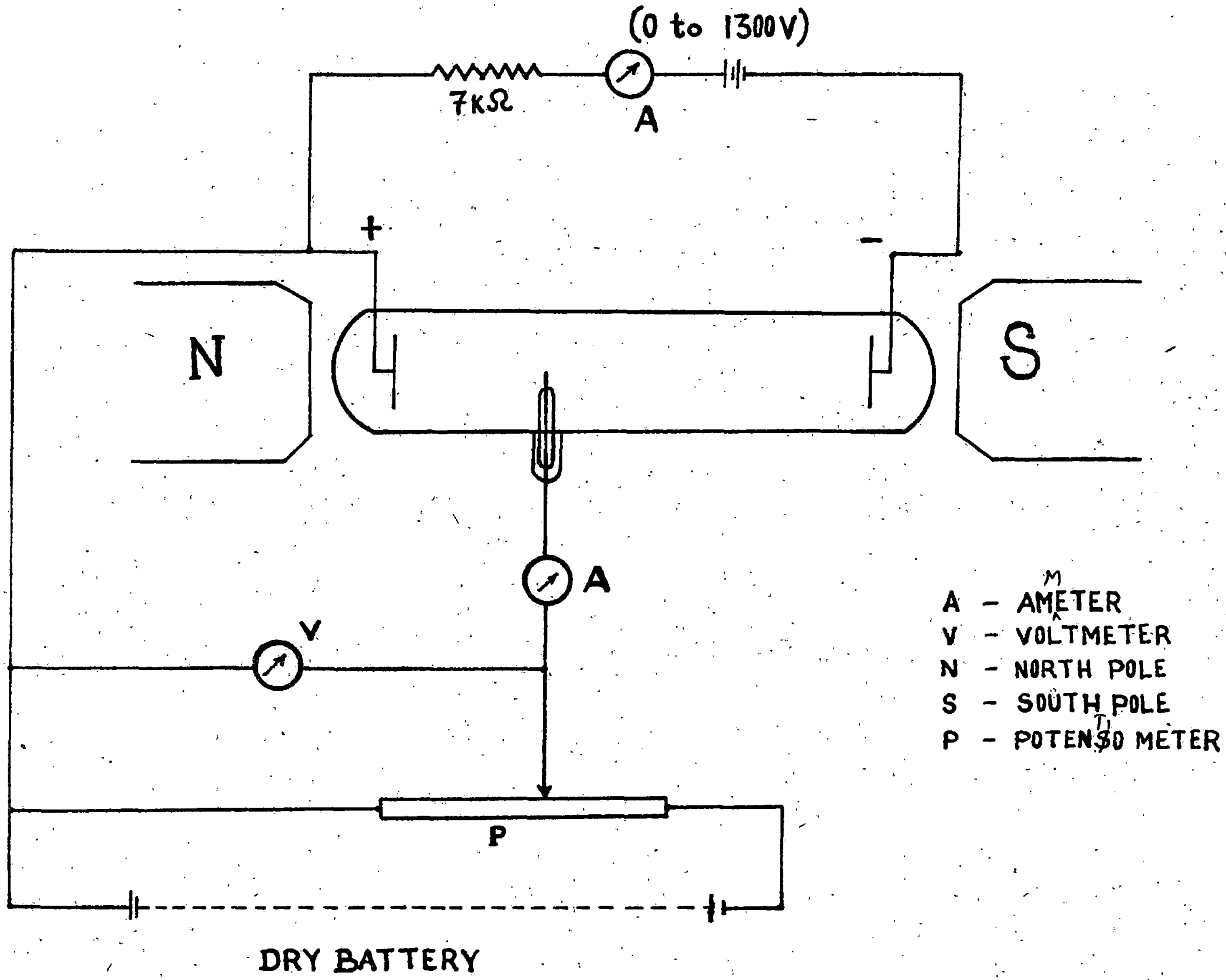
The experimentm has been performed in two parts (a) when the magnetic field is transverse and when it is (b) longitudinal. Pure & dry air has been used which was ~~pka~~ passed through phosphorus pentoxide to remove traces of water vapour. A schematic diagram of the experimental arrangement is shown in fig. (8.1). The plasma is produced by the breakdown of air in a cylindrical chamber of diameter 4.2 cm. and 24.3 cm. long fitted with two brass electrodes of 3.2 cm. diameter. The transverse magnetic field is placed at the positive column of the discharge. Measurements are made by a tungsten probe of diameter 0.05 cm. diameter and 0.4 cm. long and located at a distance of 2.5cm. from the anode. The experiment has been carried out at a pressure of 400 μ and the magnetic field has been kept at a low value below 100 gauss. The pressure has been measured by a Mcleod gauge and the magnetic field by a calibrated gaussmeter. The magnetic field has been provided by an electromagnet and the magnetic lines of force are perpendicular to the direction of the discharge current.

(b) Longitudinal magnetic field:

The experimental arrangement is shown in fig.(8.2) The discharge tube is cylindrical of radius 1.4 cm. and fitted with two brass electrodes at a distance of 5.5 cm.



SCHEMATIC DIAGRAM OF THE EXPERIMENTAL APPARATUS FIG:-8.1



SCHEMATIC DIAGRAM OF THE EXPERIMENTAL APPARATUS

FIG :- 8.2

The probe is a tungsten wire of diameter 0.05 cm. and length 0.03 cm. The tube is thoroughly cleaned and dried ~~by~~ and placed within the pole pieces of an electromagnet so that lines of force are parallel to the length of the discharge tube. The pole pieces 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 discharge is excited by an electronically stabilized power supply which is capable of delivering 1300 volts at an output current of 40 milliamps.

The variable probe potential has been supplied by a series of dry batteries in conjuction with a potentiometer as shown in the figure. Keeping the pressure constant and for a fixed discharge current the probe potential is varied from a high negative value to positive values and the corresponding probe current is noted in the microammeter. The experiment is repeated for different values of transverse and longitudinal magnetic fields.

RESULTS AND DISCUSSION

The experiment has been performed in two parts: (a) The magnetic field is transverse to the direction of the discharge current (b) The magnetic field is in the same direction as the direction of the discharge current.

Transverse field:

The variation of the probe current with various probe voltages has been plotted in figure (8.3) first without magnetic field and then at the magnetic fields H = 20 g, 40 g, and 60 g, the pressure has been kept constant at 400 μ . It is observed that the probe current gradually increases from a negative value with the increase of the probe potential and then assumes positive value and rises very rapidly. With the further increase of the probe potential the probe current shows a tendency to assume a limited value which is nearly independent of the probe potential. This saturation current is determined by the charge transported by the electrons that strike the surface of the probe due to their thermal agitation. It is further observed that with the application of the magnetic field the general nature of the curve remains unchanged but the rate at which the current increased after assuming the positive value gradually decreases with the application of the magnetic field. This is further observed in case of magnetic fields H = 40 g, as well as in the case of H = 60 g. The saturation current also shows a tendency to decrease with the increase of the magnetic field.

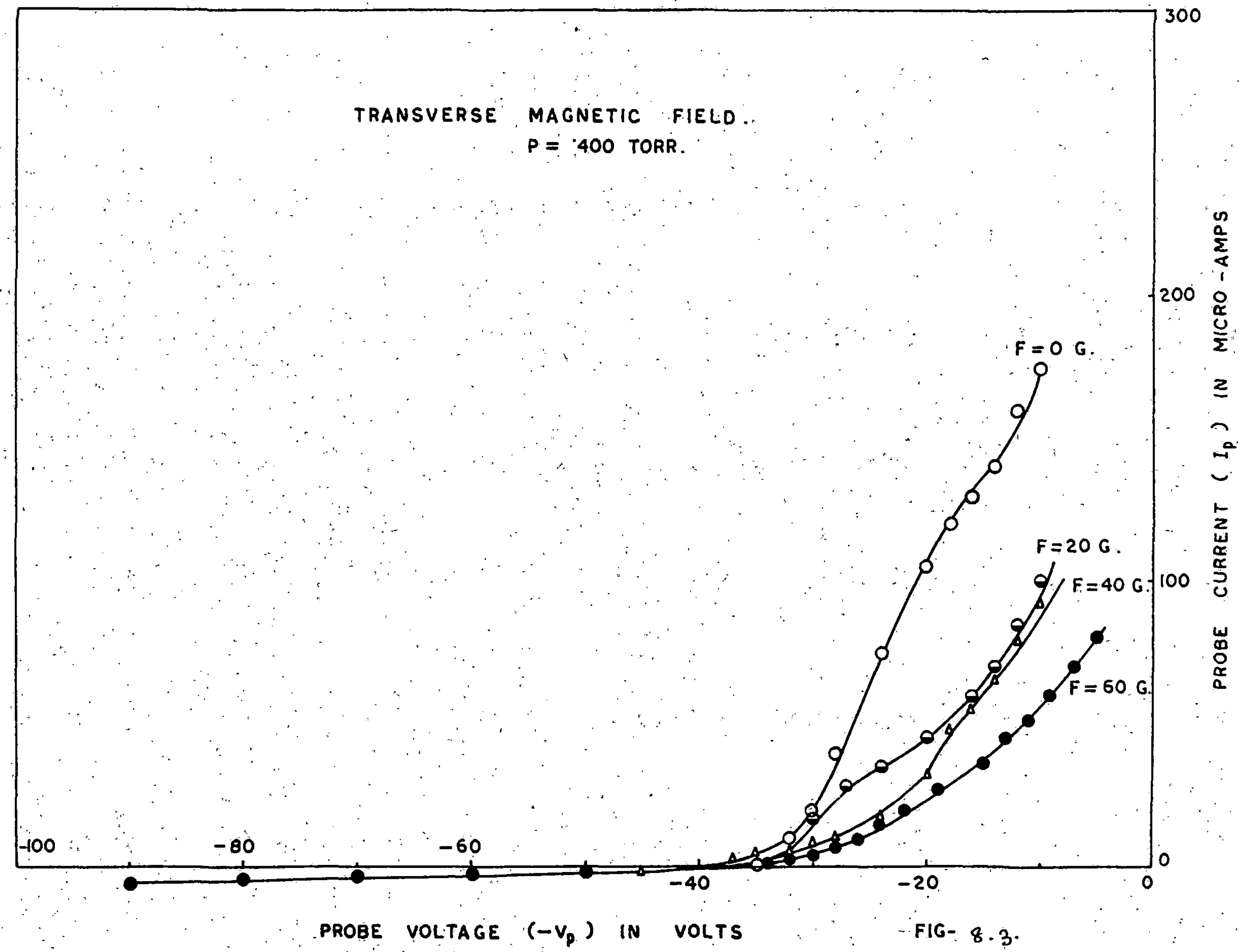

TRANSVERSE MAGNETIC FIELD.
P = ·400 TORR.
F = 0 G.
F = 20 G.
F = 40 G.
F = 60 G.
300
200
100
0
PROBE CURRENT (I_p) IN MICRO-AMPS
-100
-80
-60
-40
-20
0
PROBE VOLTAGE ($-V_p$) IN VOLTS

FIG- 8.3.

It is thus observed that so long as magnetic field is not large so that the Larmour radius is not reduced to a great extent, the simplified theory of probe may be utilized to calculate the parameters of the discharge in presence of the magnetic field as well. This is in accordance with the results obtained by earlier workers, (Bickerton and Von Engel, 1956).

In conformity with the probe data analysis the semilog plot of the current voltage characteristics is shown in the figures (8.4) where it is observed that the plot is a straight line with two different slopes both without and with magnetic field. From the slope and intersection of these straight lines it is possible to find the saturation current by drawing the tangent to the probe current, probe voltage curve as it approaches the saturation value. From the two straight line portions of the curve it is possible to find the electron temperature and saturation current by the same method as has been adopted by Uemera et al (1975), in the region in which the probe has a negative potential with respect to the plasma. In this region the probe repels the electrons and the surface of the probe can only be reached by those electrons in the Boltzmann distribution which

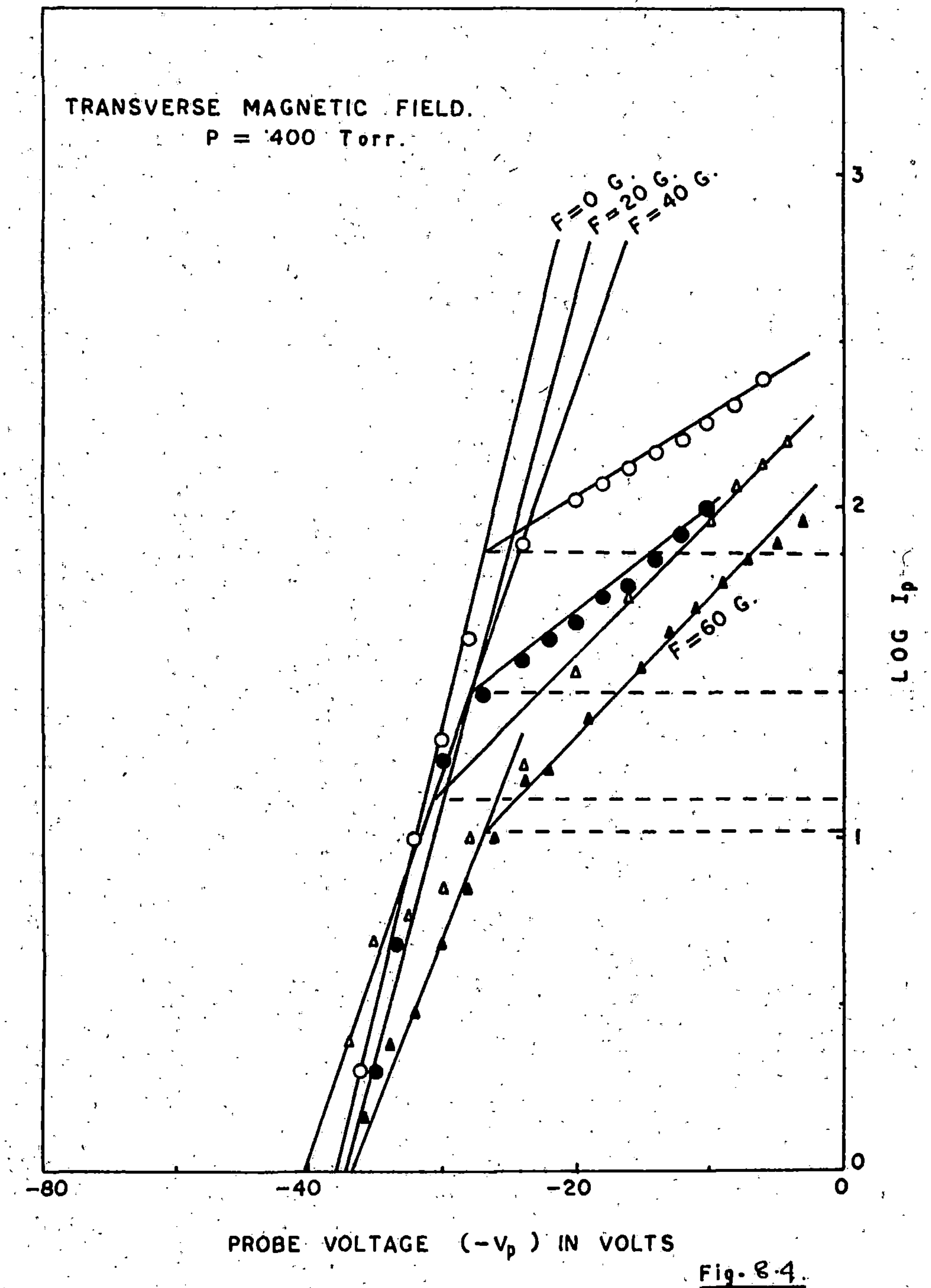

TRANSVERSE MAGNETIC FIELD.
P = 400 Torr.
F=0 G.
F=20 G.
F=40 G.
F=60 G.
3
2
1
0
LOG I_p
-80
-40
-20
0
PROBE VOLTAGE ($-V_p$) IN VOLTS

Fig. 8.4.

have energies sufficient to overcome the potential difference $(V - V_0)$ where V is the probe potential and V_0 the plasma potential; with the well known result in probe current probe voltage analysis we get

$$\log i_p = \frac{eV}{kT_e} + \text{const.}$$

Hence from the slope of the curve the electron temperature can be obtained

$$T_e = \frac{e}{k} \cdot \frac{1}{\text{slope}}$$

Where e is the electronic charge and K the Boltzmann constant.

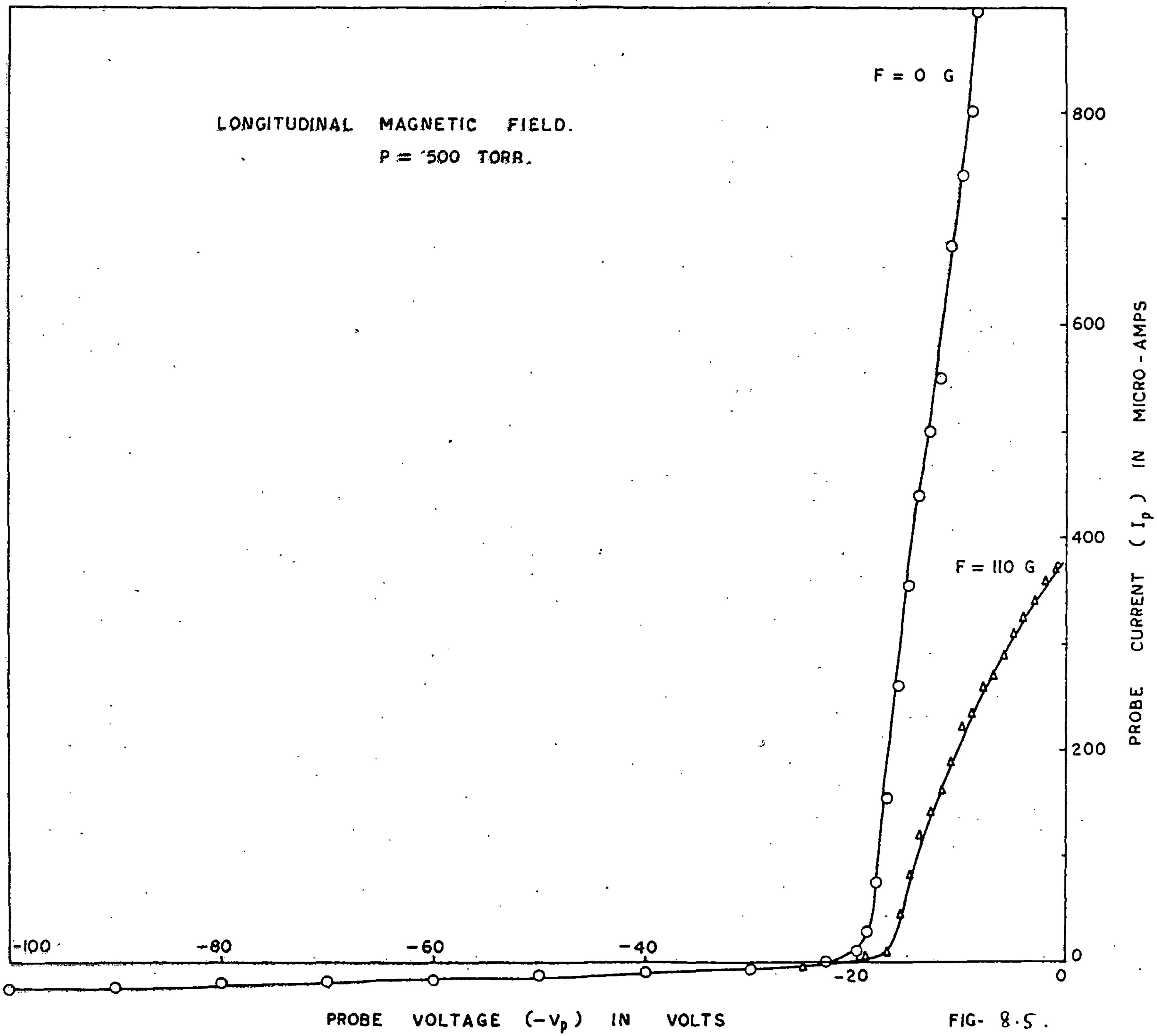
In accordance with the analysis carried out by Uemera et al (1975) the saturation current is taken to be that corresponding to the intersection of the second straight line with the first, and as the saturation current is given by $i_s = A_e n_e v_e e$ where A_e is the effective area of the cylindrical probe and as has been shown by Uemera et al (1975) A_e can be approximately represented by $A_e = 4a\ell$ where a is the radius and ℓ the length of the probe, because the probe is inserted perpendicular to the magnetic field and the magnitude of the magnetic field satisfies the condition $\rho_i >> a >> \rho_e$ where ρ_i and ρ_e

are the Larmour radii of the ions and electrons respectively n_e is the electron density and v_e is the random velocity of the electron and is given by $v_e = \left(\frac{8kT_e}{m\pi}\right)^{1/2}$ where m is the mass of the electron.

(b) Longitudional magnetic field:

The variation of probe current with probe voltage in a longitudinal magnetic field is shown in fig. (8.5) where the variation in a longitudinal magnetic field (H = 110 gauss) is also presented. The semilog plot of current with voltage both with and without magnetic field is shown in fig. (8.6). It is observed that a major portion of the curve can be represented by a straight line and from the slope of this portion the electron temperature can be obtained. The remaining portion of the curve approaching the saturation value is curved and ~~ax~~ according to the analysis of Uemera et al (1975) the intersection of the tangent to the other straight line gives the saturation value of the current from which the electron density can be obtained.

The method of analysis described enables~~x~~ us to calculate the electron temperature and electron density in both the transverse and longitudinal magnetic fields and the results are entered in tables I and II.



LONGITUDINAL MAGNETIC FIELD.
P = ·500 TORR.
F = 0 G
F = 110 G
-100
-80
-60
-40
-20
0
800
600
400
200
0
PROBE CURRENT (I_p) IN MICRO-AMPS
PROBE VOLTAGE ($-V_p$) IN VOLTS

FIG- 8·5.

TABLE 8.1

P = 0.400 torr.

TRANSVERSE MAGNETIC FIELD.

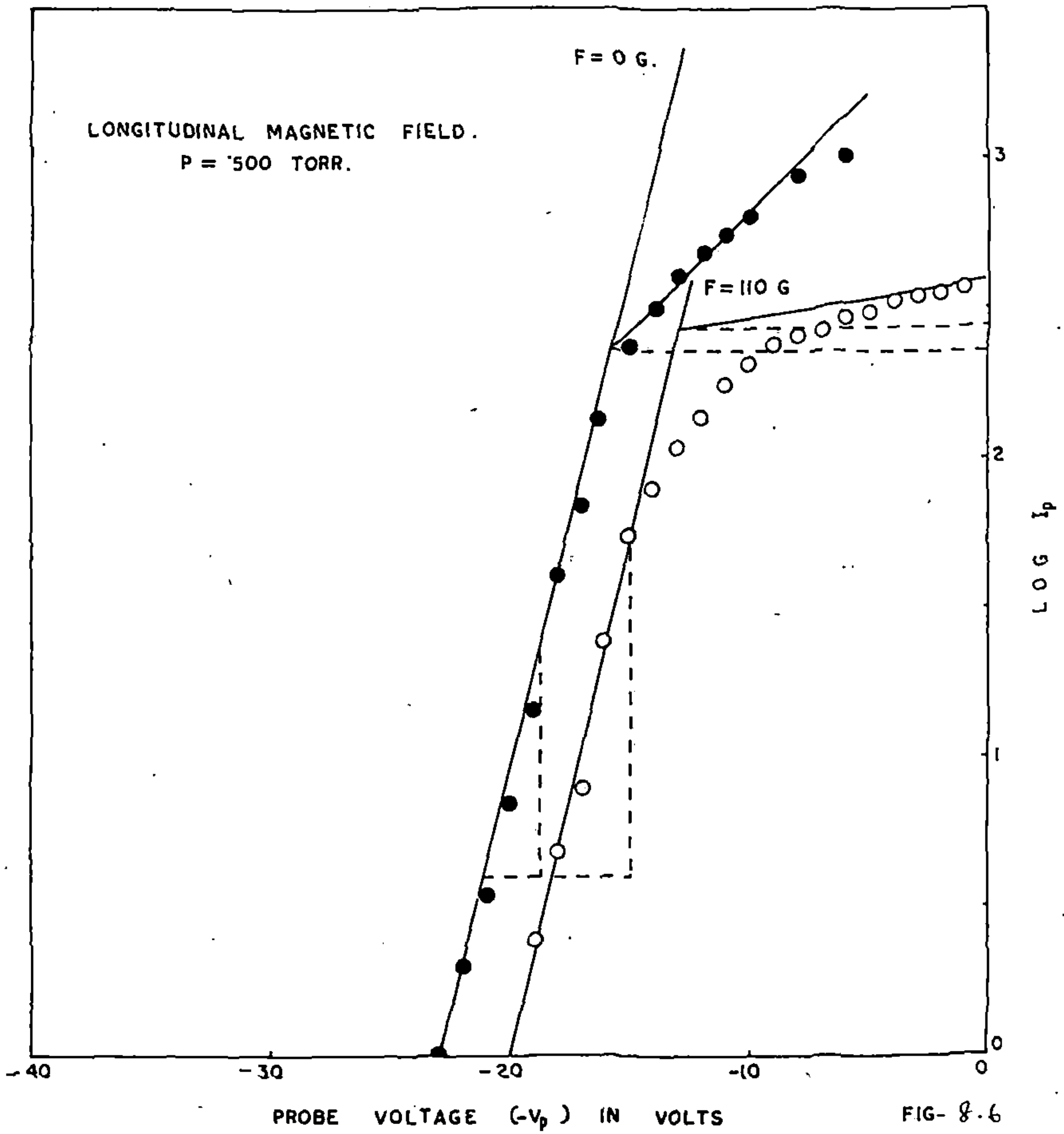
Magnetic field in gauss.	Electron temp. $T\,^{o}K$	Electron density n_e
0	7.007×10^4	6.879×10^8
20	7.92×10^4	2.459×10^8
40	9.42×10^4	1.186×10^8
60	11.02×10^4	0.5811×10^8

TABLE 8.2

P = 0.500 torr

LONGITUDINAL MAGNETIC FIELD

Magnetic field in gauss.	Electron Temp. $T\,^{o}K$	Electron density n_e
0	3.38×10^4	4.185×10^8
110	3.16×10^4	5.198×10^8



LONGITUDINAL MAGNETIC FIELD.
P = ·500 TORR.
F = 0 G.
F = 110 G
-40
-30
-20
-10
0
1
2
3
PROBE VOLTAGE (-V_p) IN VOLTS
LOG I_p

FIG- 8.6

From equation (8.1) it is evident that its validity can be tested by plotting ($T_{eH}^2/T_e^2 - 1$) against H^2/P^2 and similarly from equation (8.2) it is seen that

$$\log \frac{n}{n_H} = C\,H.$$

and a plot of ($T_{eH}^2/T_e^2 - 1$) against H^2/P^2 and that of log n/n_H against H should both be straight lines. Taking the experimental data from table (8.1) such curves are plotted in figures (8.7) and (8.8). The curves are straight lines indicating the validity of Beckman's deduction with regard to electron temperature and radial electron density variation in a transverse magnetic field within the values of H/P investigated here. The value of $C_1 = \left(e/m \cdot L/\nu_r\right)^2$ has been obtained from the slope of the curve (fig. 8.7) and is equal to (7.05×10^{-5}) in fair agreement with the value obtained from breakdown and microwave measurement.

Though only a single measurement could be made in the longitudinal field the results ~~mk~~ clearly indicate that electron temperature decreases in a longitudinal field and there is corresponding increase in radial electron density in confermity with the results obtained quite independently in chapter V.

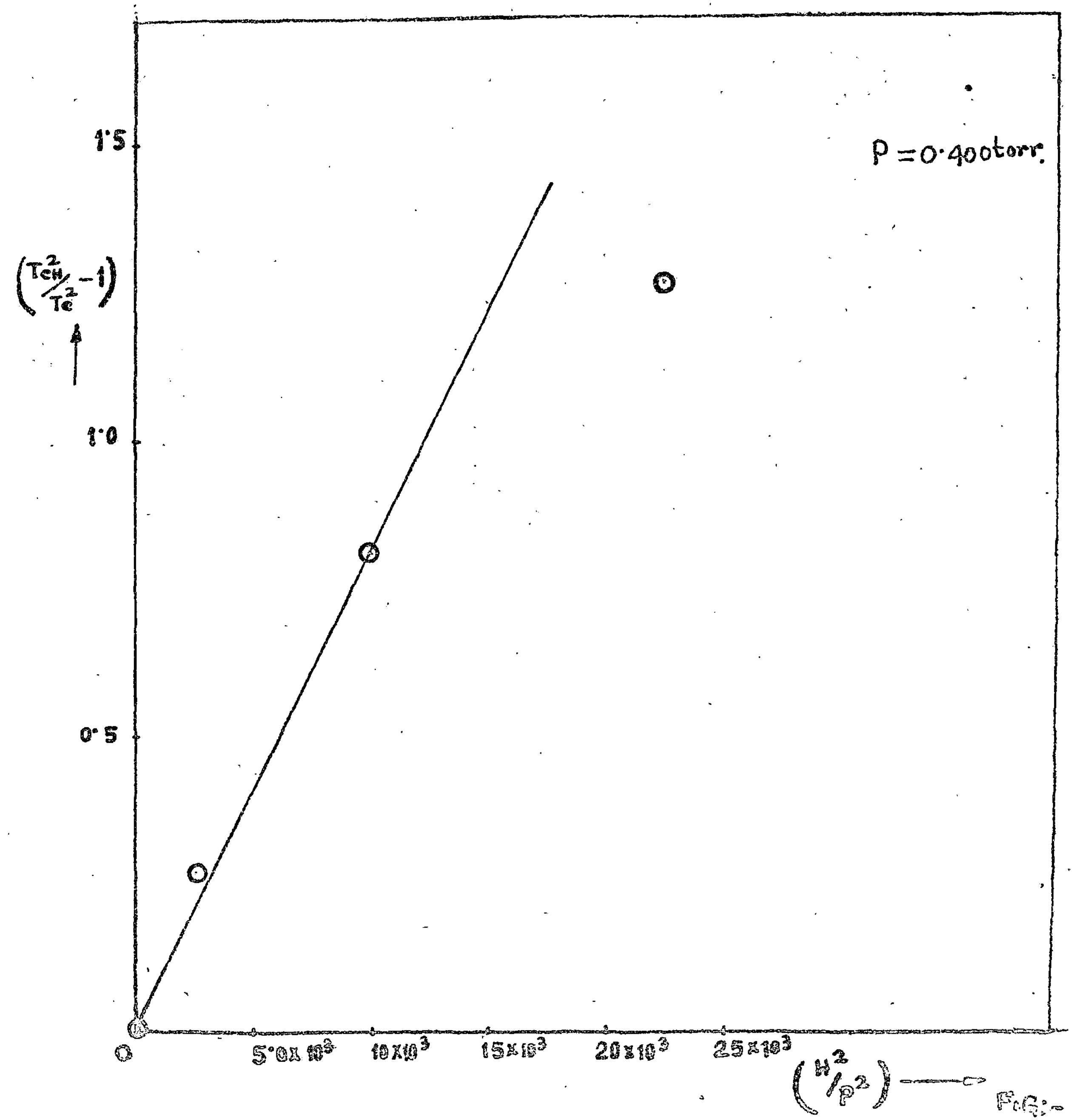

P = 0·400 torr.
1·5
1·0
0·5
0
5·0 x 10^3
10 x 10^3
15 x 10^3
20 x 10^3
25 x 10^3
$\left(\frac{T_{cH}^2}{T_c^2} - 1\right)$
$\left(H^2/P^2\right)$

FIG:- 8.7

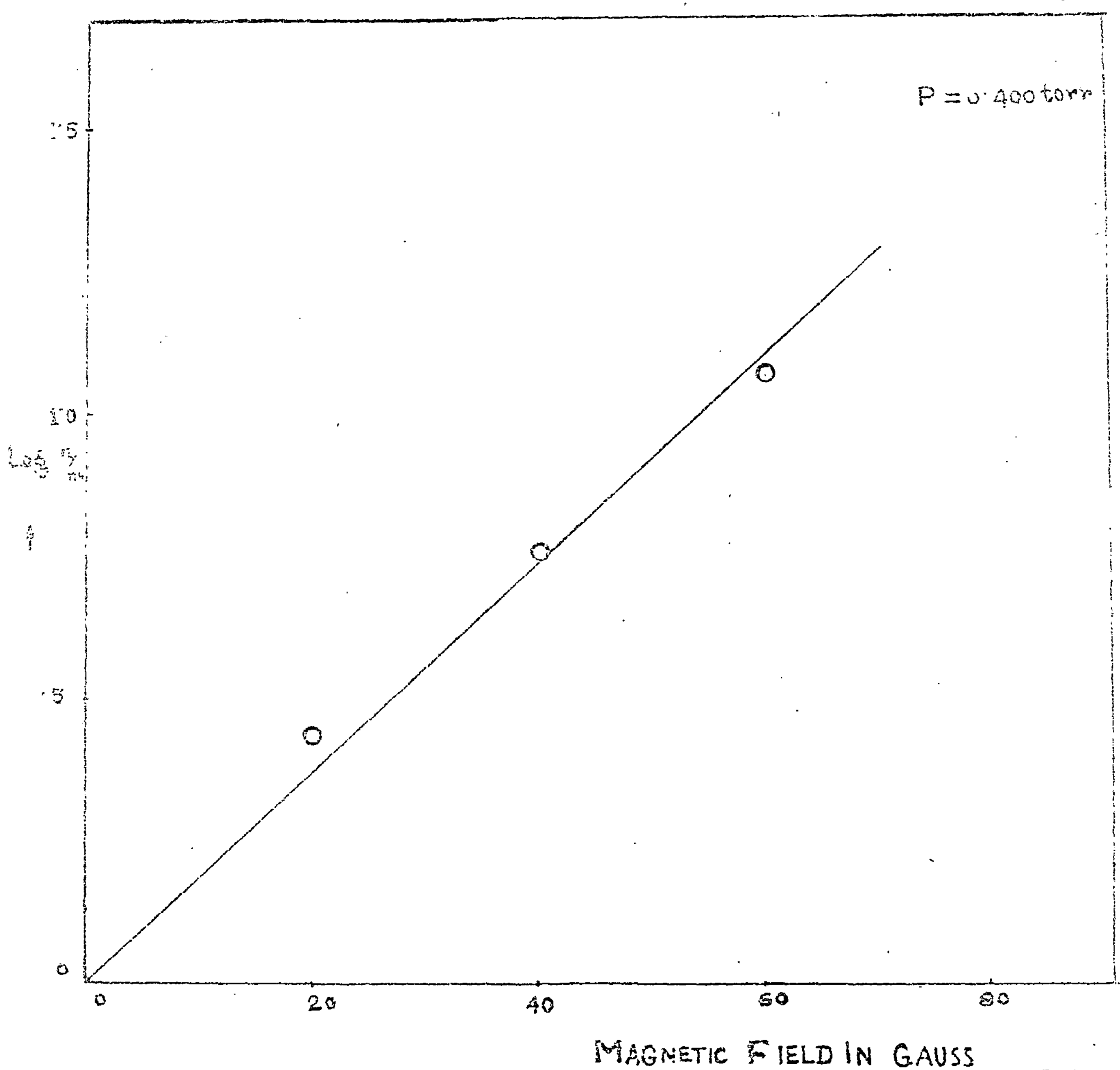


FIG:- 8·8

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 change in plasma parameters. The experimental data from probe measurements thus prove that while in a transverse magnetic field the electron temperature increases and radial electron density diminishes, in longitudinal field the electron temperature decreases and the radial electron density increases. The quantitative verification of Beckman's deduction is also obtained at least for the range of (H/P) values used in the present investigation.

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