CHAPTER - VI.

VARIATION OF DISCHARGE CURRENT IN A TRANSVERSE MAGNETIC FIELD IN GLOW DISCHARGE.

INTRODUCTION.

When a magnetic field acts upon a flow discharge various changes such as increase of equivalent pressure, decrease in the length of the cathode dark space, a change in radial ion density in the positive column and marked changes in the voltage current characteristics of the discharge take place. Theoretical interpretation of these phenomena have been provided by Townsend (1938), Guntherschulze (1924) and also by Allis and Allen (1937) who have investigated the motion of electrons in presence of electric and magnetic field and a concentration gradient. Most of the experimental work in the line has been done in a longitudinal magnetic field. Penning (1936) studied the effect of a transverse magnetic field upon the voltage current characteristic curve in a discharge. The effect of a transverse magnetic field on the positive column as regards the electron temperature, electric field gradient and the new electron density has been calculated by Beckman (1948) on a theoretical basis and the results agree fairly well with the experimental results obtained in case of hydrogen, nitrogen, neon and helium. The general effects of the transverse magnetic field have been investigated by McBee and Dow (1953) on an unconfined glow discharge in air within the pressure range of 0.3 to 10 mm. of Hg. discharge current 0.05 to 2.5 amp. with H = 0 to 7000 gauss. They found with the probe measurements that the anode fall and the cathode fall first decrease and then increase and the positive column and the anode region become more luminous. Though there have been some measurements regarding the change of breakdown voltage in presence of taansverse magnetic field in a number of gases (Sen and Ghosh 1962 and references therein) the corresponding measurements regarding the variation of current in a steady state discharge have been little reported so far. The object of the present investigation is thus to study the variation of the discharge current in the positive column in a variable transverse magnetic field at different pressures; since the discharge current is a function of the electron density and the longitudinal electric field the present investigations are expected to show how these parameters are changed in a transeverse magnetic field and whether the previous theoretical derivations (Beckman 1948) agree with the experimental results. The present paper reports the results in case of air, carbondioxide, hydrogen neon and helium.

E X P E R I M E N T A L   A R R A N G E M E N T.

A d.c. source from a 2.5 K.V. regulated power supply has been used to ionise the gas and the discharge tube is a cylindrical tube of length 10 cm. and diameter 2.5 cm. fitted with two internal electrodes. The pressure has been measured by an Edward Pennin Pirani vacuum gauge which is provided with individual calibration curve for air, carbondioxide, helium, neon and hydrogen. Pure and dry air has been used and carbondiox ide has been prepared by letting a saturated solution ofoxalic acid in water fall drop by drop into a saturated solution of sodium bicarbonate. The evolved gas was passed through phosphorus pentoxide to remove water. Pure and dry hydrogen has been prepared by the electrolysis of strong barium hydroxide solution using nickel electrodes and passing the gas over heated copper and dried through phosphorus pentoxide. Spectroscopically pure neon and helium have been supplied and the British Oxygen Company.

The magnetic field has been provided by an electromagnet and the lines of force are perpendicular to the axis of the discharge tube. The magnetic field which has been varied from 0 to 300 gauss has been measured by a calibrated fluxmeter. Keeping the pressure of the gas constant at a particular value, the magnetic field has been varied and the d.c. discharge current between the two electrodes has been measured for various values of the magnetic field. The same procedure has been repeated for different values of the pressure (80 millitorr to 200 millitorr) and for different initial discharge currents. The experiments have been repeated a number of times and the results have been found to be consistant.

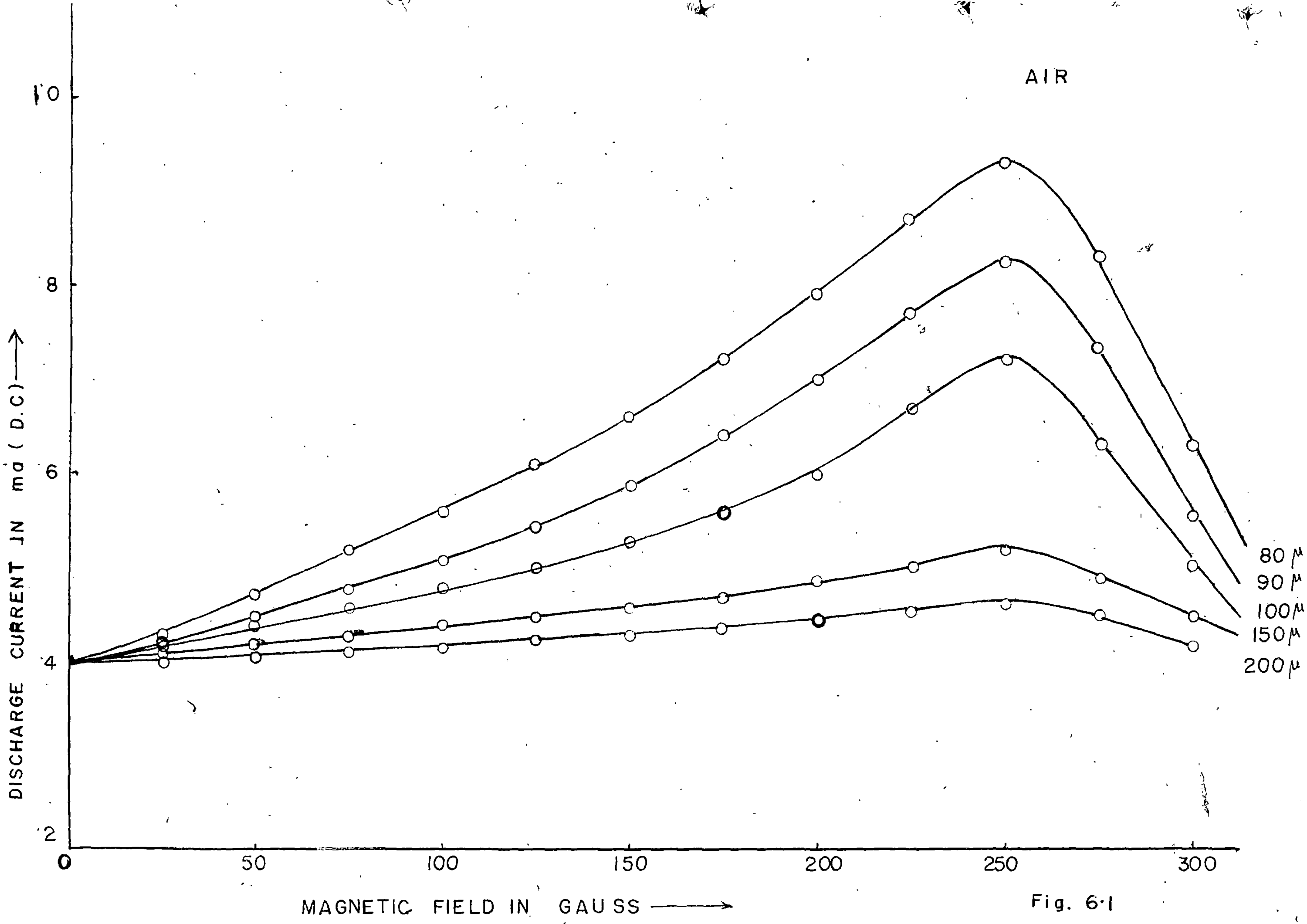
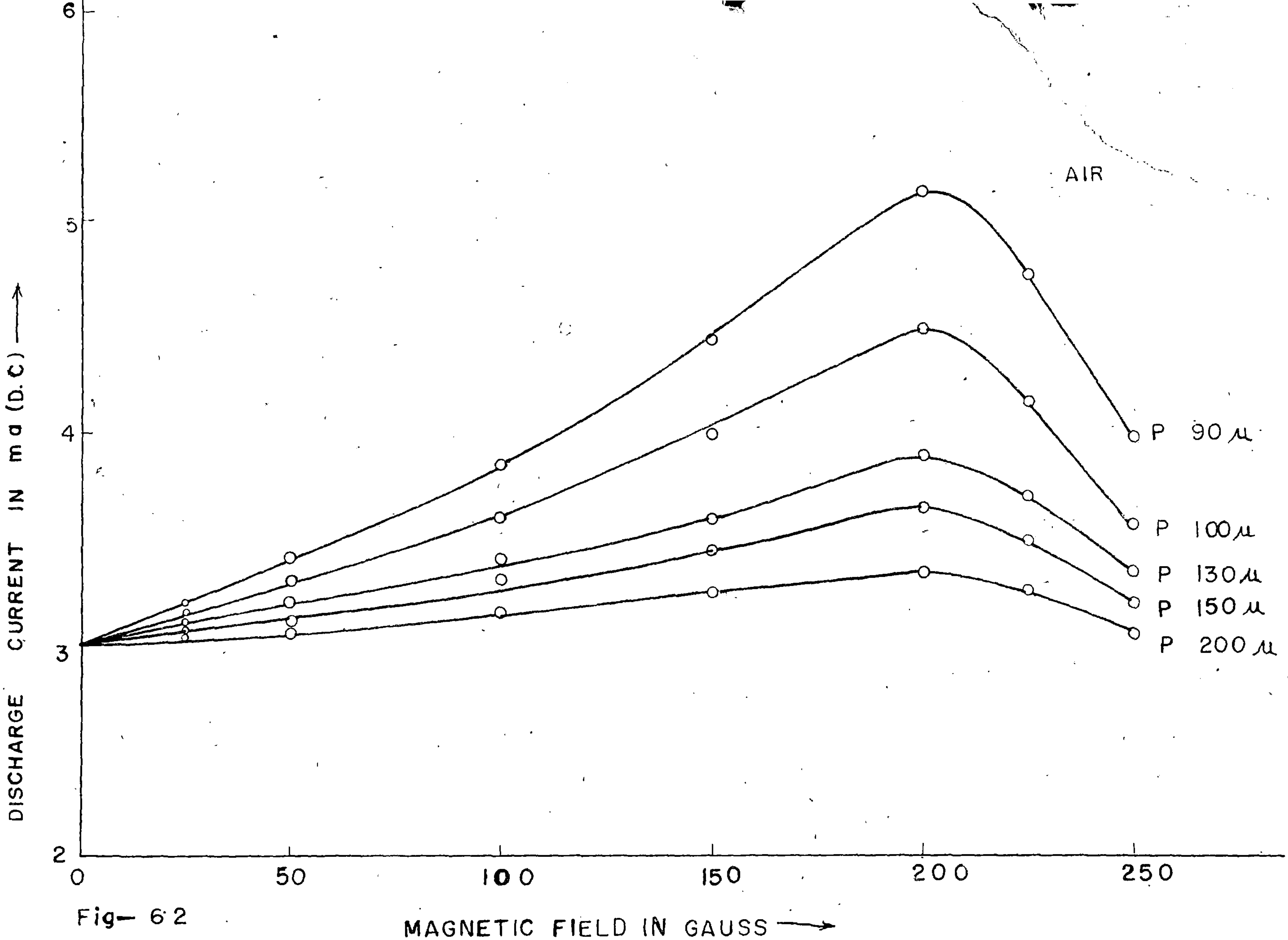
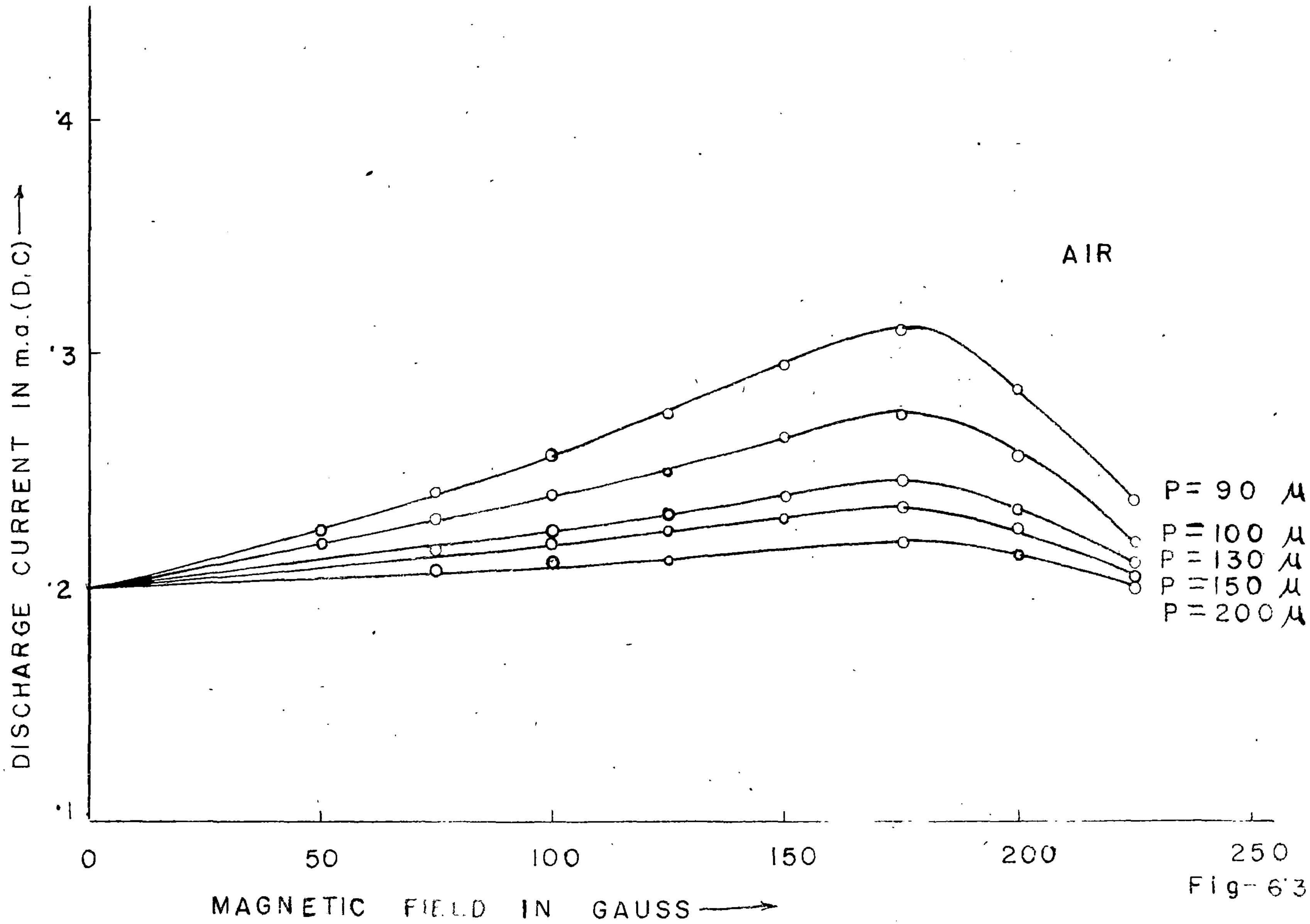

AIR
DISCHARGE CURRENT IN ma (D.C)
MAGNETIC FIELD IN GAUSS
80 μ
90 μ
100 μ
150 μ
200 μ
10
8
6
4
2
0
50
100
150
200
250
300

Fig. 6·1


AIR
DISCHARGE CURRENT IN ma (D.C)
MAGNETIC FIELD IN GAUSS
P 90 μ
P 100 μ
P 130 μ
P 150 μ
P 200 μ
6
5
4
3
2
0
50
100
150
200
250

Fig— 6·2



AIR
P= 90 μ
P = 100 μ
P = 130 μ
P = 150 μ
P = 200 μ
DISCHARGE CURRENT IN m.a.(D.C)
·1
·2
·3
·4
0
50
100
150
200
250
MAGNETIC FIELD IN GAUSS

Fig-6·3

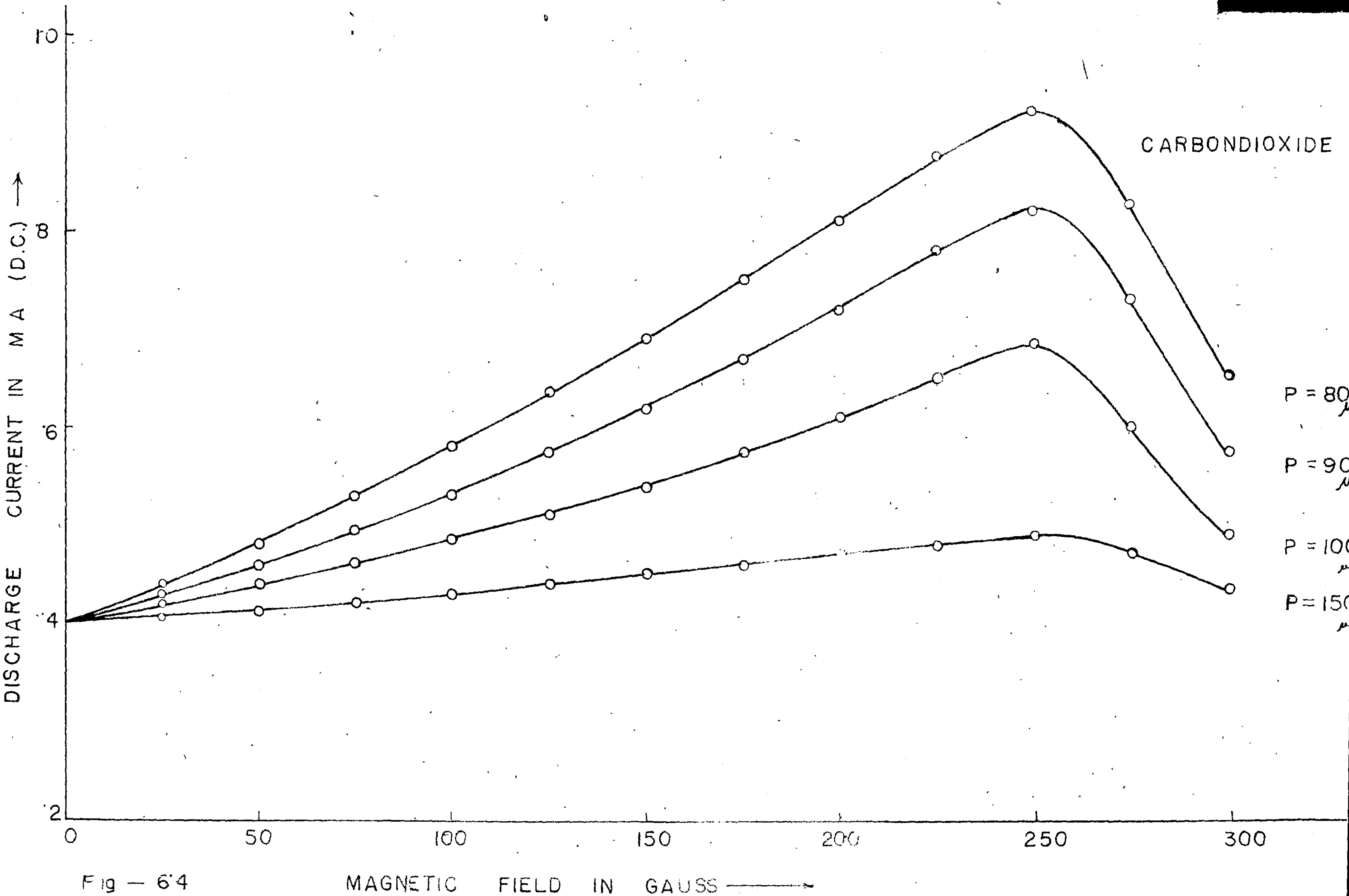

CARBONDIOXIDE
P = 80 μ
P = 90 μ
P = 100 μ
P = 150 μ
DISCHARGE CURRENT IN MA (D.C.) →
MAGNETIC FIELD IN GAUSS →
0
50
100
150
200
250
300
·2
·4
·6
·8
1·0

Fig — 6·4

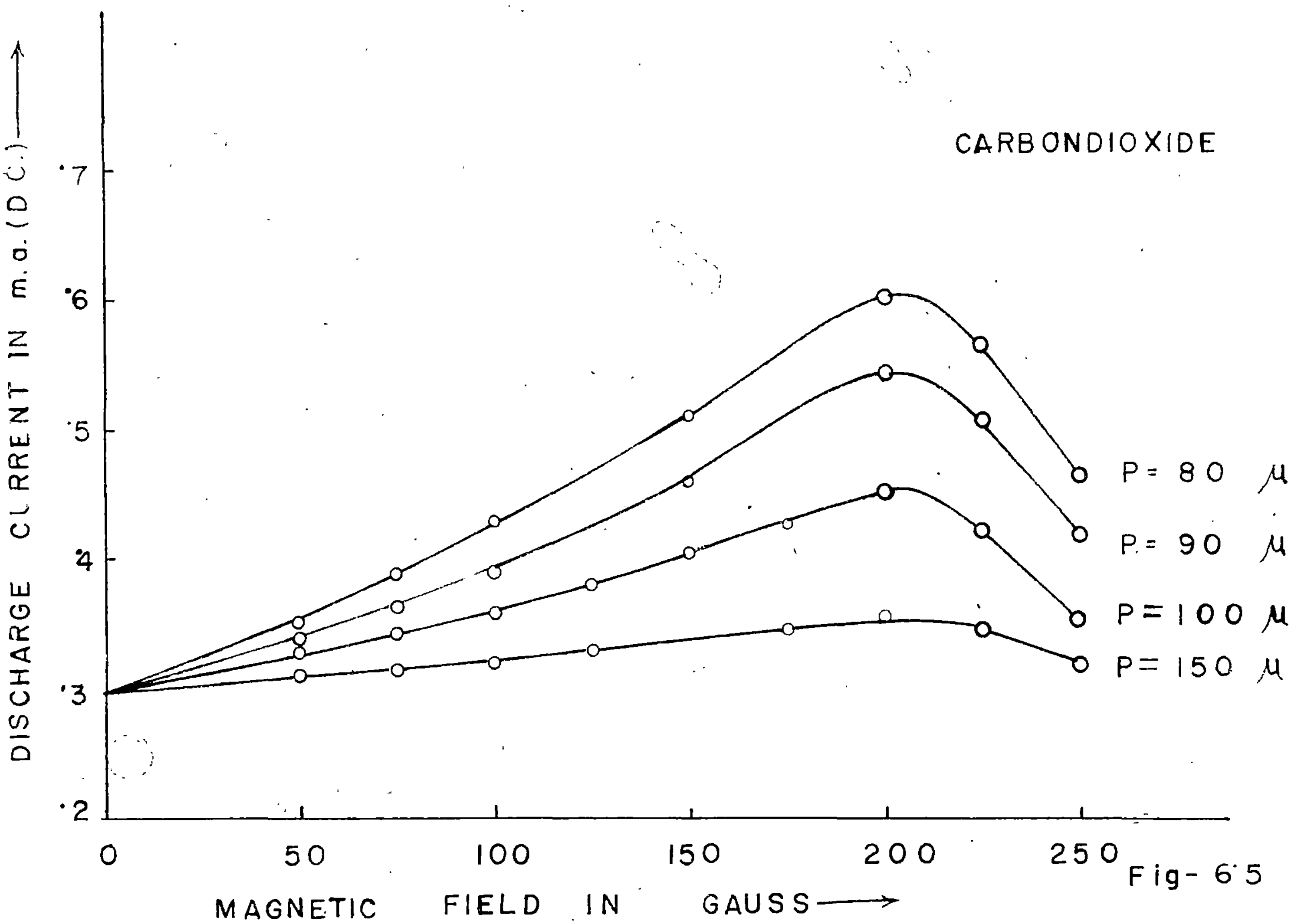
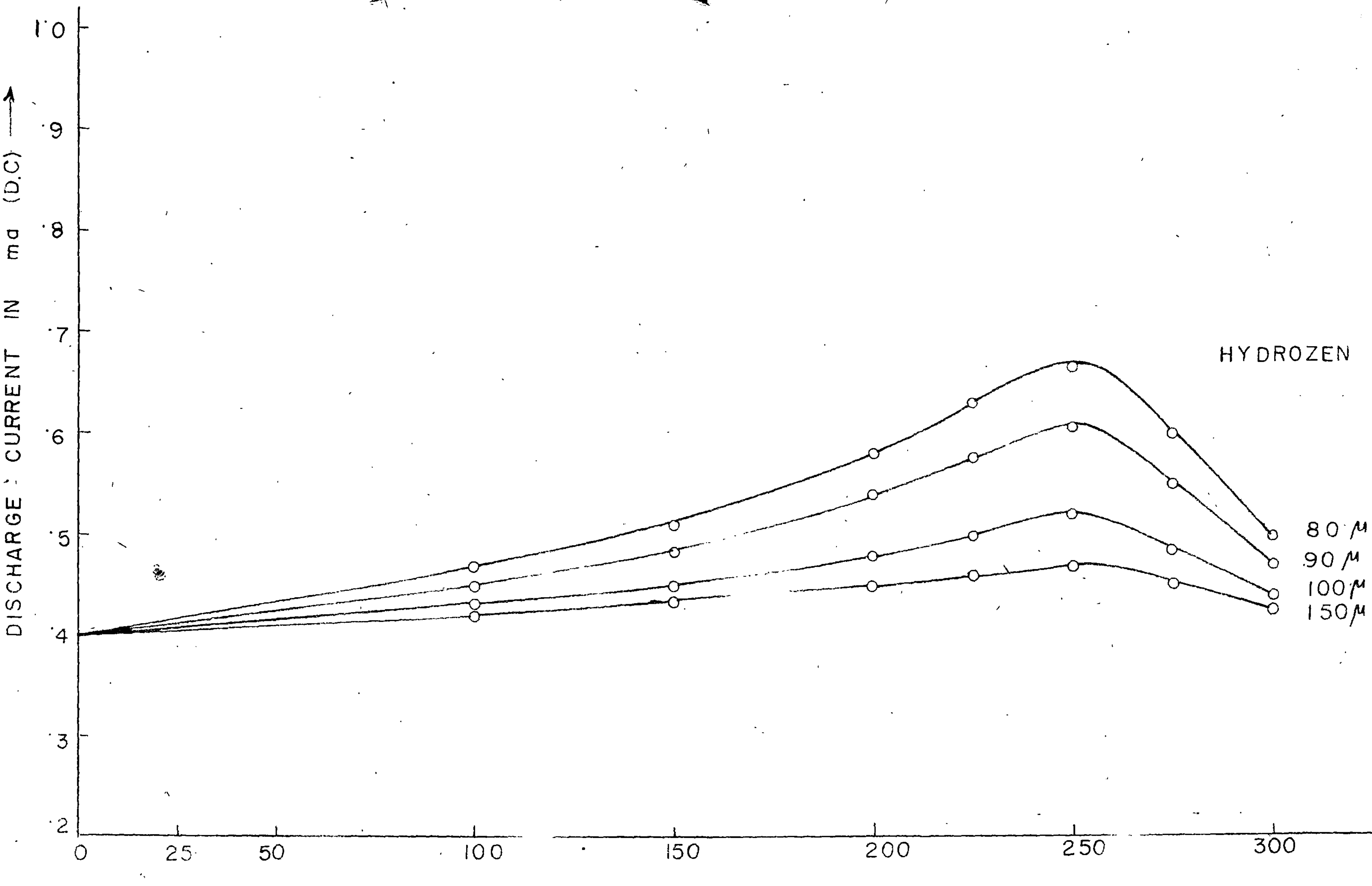

CARBONDIOXIDE
DISCHARGE CURRENT IN m.a. (D.C.)
·7
·6
·5
·4
·3
·2
0
50
100
150
200
250
MAGNETIC FIELD IN GAUSS
P= 80 μ
P= 90 μ
P= 100 μ
P= 150 μ

Fig- 6·5



DISCHARGE CURRENT IN ma (D.C)
1·0
·9
·8
·7
·6
·5
·4
·3
·2
HYDROZEN
80 μ
90 μ
100 μ
150 μ
0
25
50
100
150
200
250
300
MAGNETIC FIE. D IN GAUSS

Fig — 6·6

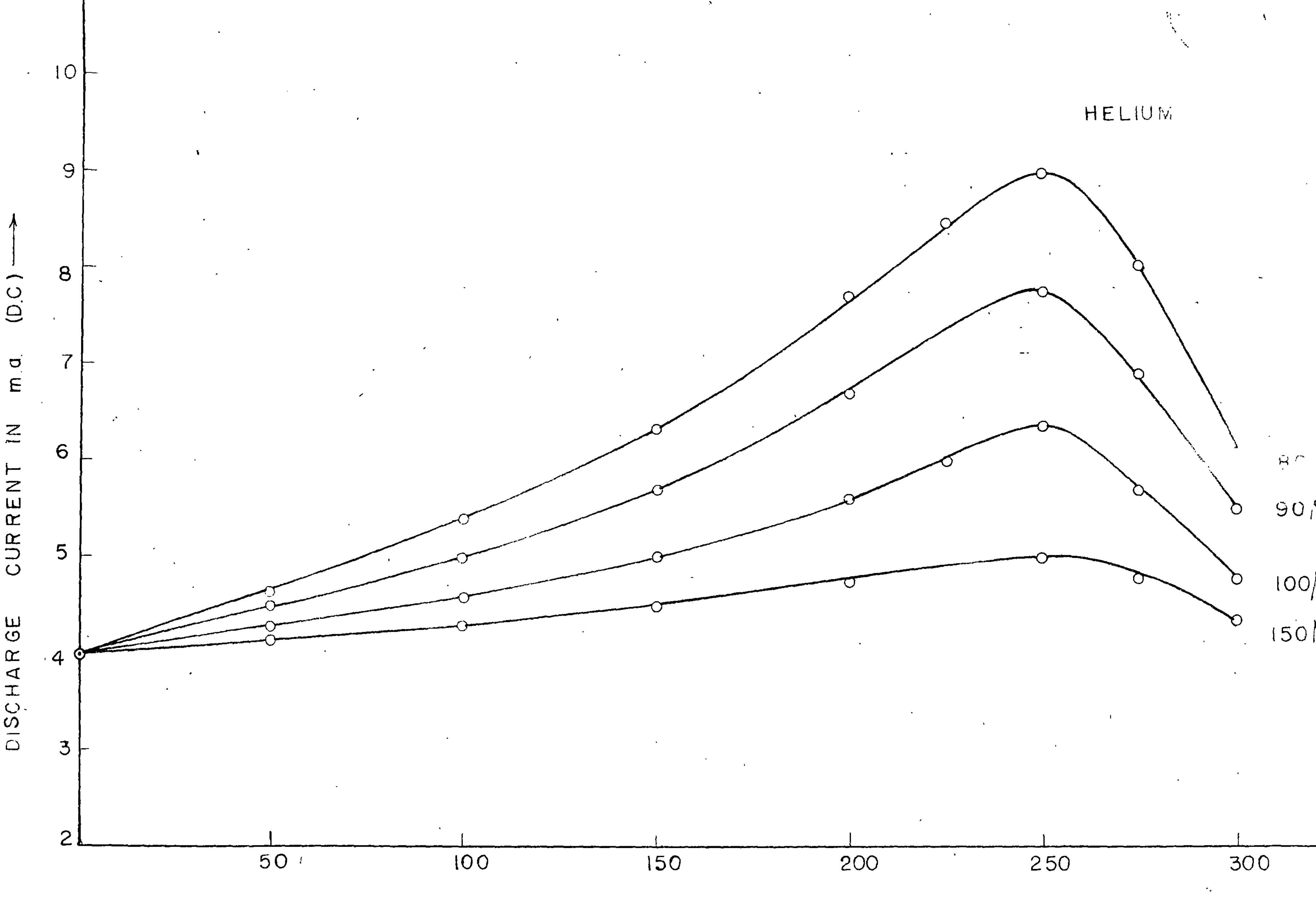

HELIUM
DISCHARGE CURRENT IN m.a. (D.C)
MAGNETIC FIELD IN GAUSS
90μ
100μ
150μ
2
3
4
5
6
7
8
9
10
50
100
150
200
250
300

Fig-6·7

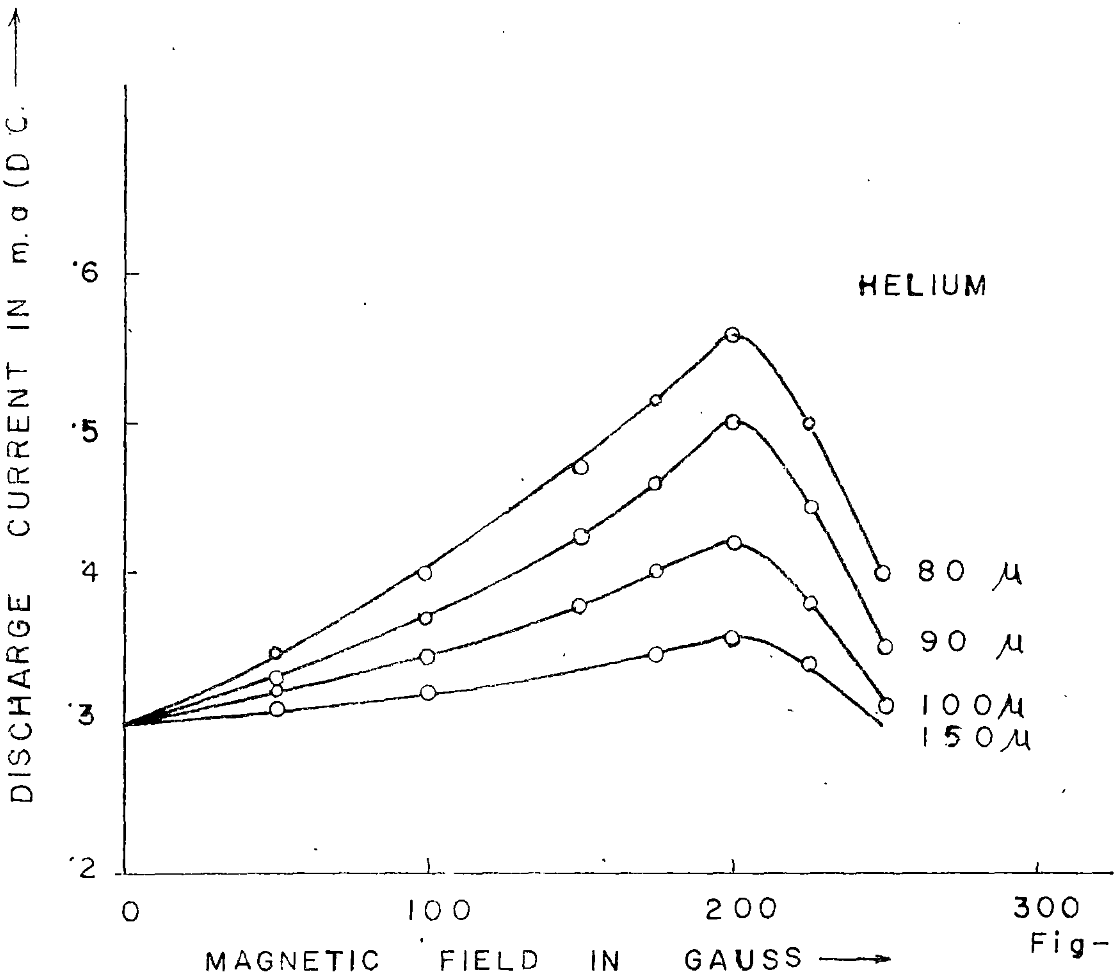
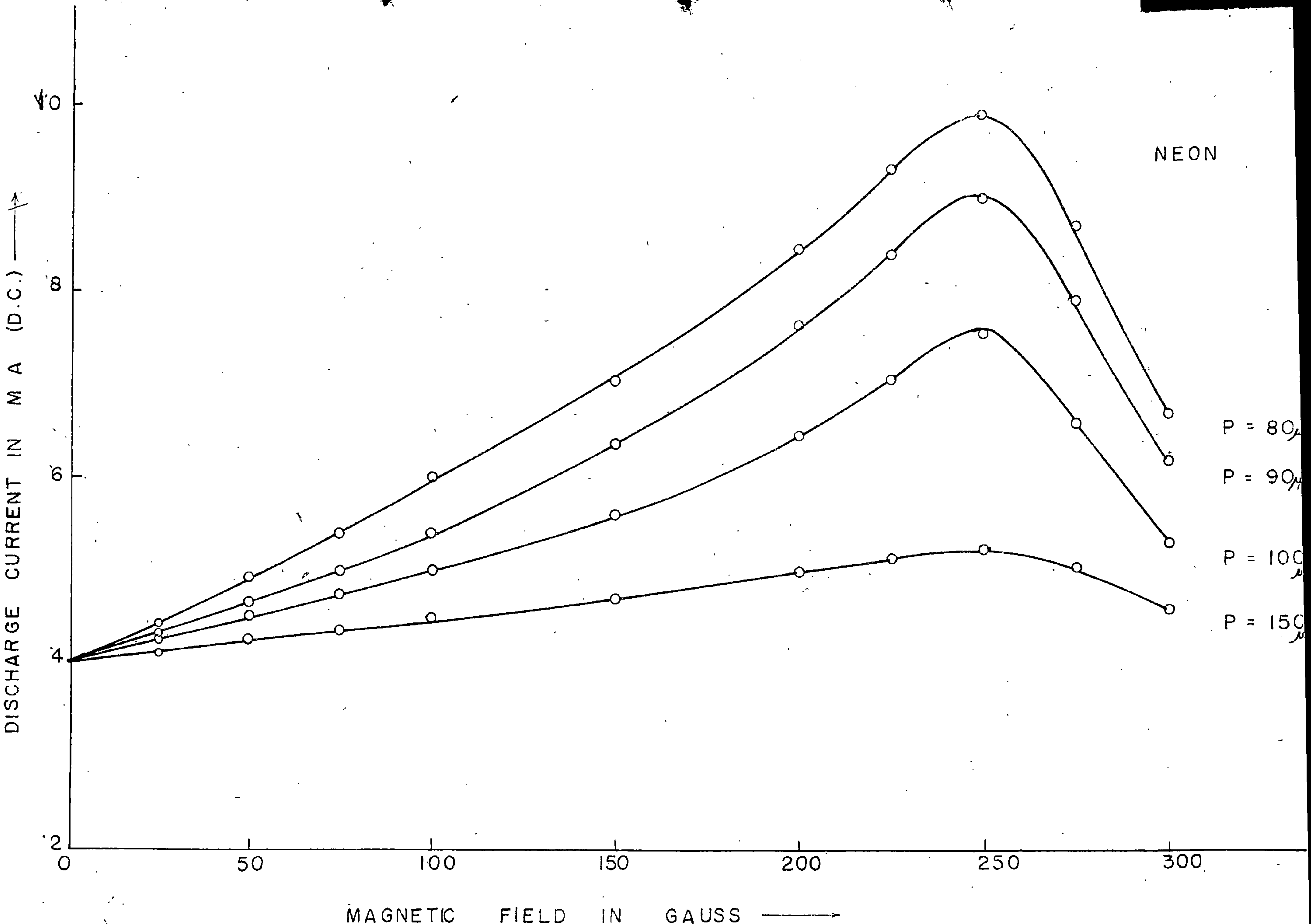
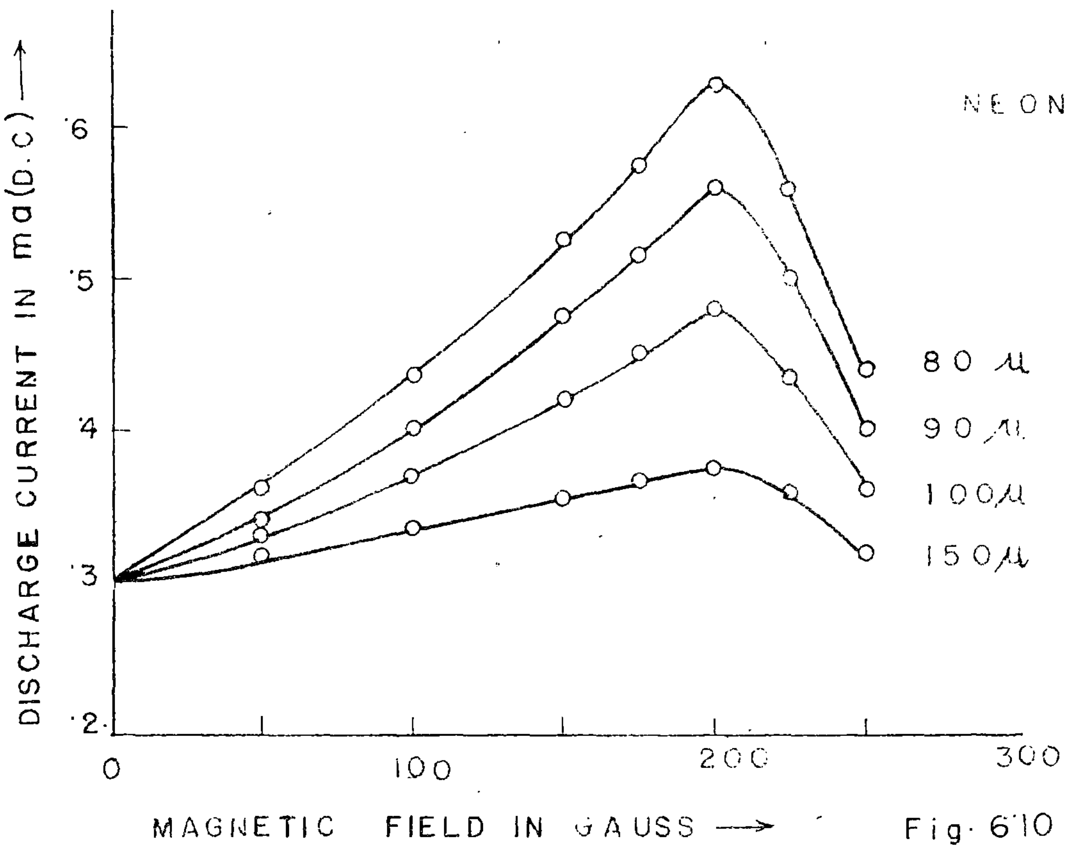

DISCHARGE CURRENT IN m.a (D.C.) →
·6
·5
·4
·3
·2
HELIUM
80 μ
90 μ
100μ
150μ
0
100
200
300
MAGNETIC FIELD IN GAUSS →

Fig-6·8



1·0
·8
·6
·4
·2
0
50
100
150
200
250
300
DISCHARGE CURRENT IN M A (D.C.)
MAGNETIC FIELD IN GAUSS
NEON
P = 80μ
P = 90μ
P = 100μ
P = 150μ

Fig – 6·9.



NEON
DISCHARGE CURRENT IN ma(D.C) →
·6
·5
·4
·3
·2
0
100
200
300
80 μ
90 μ
100μ
150μ
MAGNETIC FIELD IN GAUSS →

Fig· 6·10

RESULTS AND DISCUSSION.

The variaton of discharge current for different values of the magnetic field and for different initial discharge currents has been plotted for different gases in figures (6.1 to 6.10). The nature of the curve is the same for all the gases which shows a gradual rise of the discharge current with the magnetic field, which then attains a maximum value at a particular value of the magnetic field and then gradually decreases. The analysis of the experimental data is entered in table (6.1).

TABLE - (6.1).

Gas	Initial discharge current without mag. field. in mA	Pressure in millitorr	Mag. field at with discharge current is max. in gauss	i_{max} in mA	i_{max} X P
	.4	80	250	.93	74.4
	.4	90	250	.825	74.25
air	.4	100	250	.720	72.00
	.4	150	250	.51	76.5
	.4	200	250	.465	93.00
	.3	90	207.5	.515	46.35
	.3	100	207.5	.45	45.00
air	.3	130	207	.39	50.7
	.3	150	207.5	.365	54.75
	.3	200	207.5	.335	67.00
	.2	90	175	.31	27.9
	.2	100	175	.275	27.5
air	.2	130	175	.245	31.85
	.2	150	175	.235	34.25
	.2	200	175	.220	44.00

TABLE - (6.1 continued)

Gas	Initial discharge current without mag. field in mA.	Pressure in millitorr	Mag. field at which discharge current is max. in gauss	i_{max} in mA	i_{max} XP.
CO_2	.4	80	250	.92	73.6
	.4	90	250	.82	73.8
	.4	100	250	.68	68.0
	.4	150	250	.49	73.5
CO_2	.3	80	200	.60	48.0
	.3	90	200	.54	48.6
	.3	100	200	.45	45.0
	.3	150	200	.355	53.25
N_2	.4	80	250	.665	53.20
	.4	90	250	.605	54.45
	.4	100	250	.52	52.00
	.4	150	250	.47	70.50
Ne	.4	80	250	.99	79.2
	.4	90	250	.90	81.0
	.4	100	250	.755	75.5
	.4	150	250	.525	78.75
Ne	.3	80	200	.63	50.4
	.3	90	200	.56	50.4
	.3	100	200	.48	48.0
	.3	150	200	.38	57.0
He	.4	80	250	.90	72.0
	.4	90	250	.775	69.75
	.4	100	250	.635	63.5
	.4	150	250	.500	75.0
He	.3	80	200	.56	44.8
	.3	90	200	.50	45.0
	.3	100	200	.42	42.0
	.3	150	200	.36	54.0

From the analysis of the data it is evident that irrespective of the nature of the gas, the magnetic field at which the discharge current becomes a maximum is the same for all the gases provided that the initial discharge current is the same and is independent of pressure. The maximum value of i is a function of pressure and varies from gas to gas.

For an individual gas.

1. The current increases with the magnetic field and attains a maximum at a particular value of the field H_{max} and then decreases where H_{max} is the value of the magnetic field at which the discharge current becomes a maximum.

2. H_{max} is independent of the pressure of the gas.

3. H_{max} depends upon initial current; smaller the value of the initial current, smaller is the value of H_{max}. A relation can be established from the experimental data; which is $(H_{max})^2 \propto i_0$.

4. The value of i_{max} depends upon pressure. The experimental results show that to a first approximation ($i_{max} \times P$) is a constant.

General.

1. H_{max} isindependent of pressure and the nature of the gas.

2. For the same initial current the product ($i_{max} \times P$) is almost the same for all the gases and the value of the constant decreases with the initial discharge current.

The effect of a transverse magnetic field in a cylindrical plasma has been treated by Beckman (1948). When a transverse magnetic field is applied to a cylindrical plasma two effects are observed. (a) the magnetic field deflects the electrons and ions from the axis of the cylindrical plasma and pushes them towards the wall, thereby increasing the loss of electrons and ions. In order to compensate this loss it has been shown by Beckman (1948) that the axial electric field increases thus increasing th ionization and the electron temperature. It has been shown by Beckman that the axial electric field increases from E to E $(\alpha + \beta^2/\alpha)^{1/2}$ where

where

$$\alpha = 1 - h^2 + h^4 \exp h^2 \int_h^\alpha \frac{\exp(-h)}{h} dh$$

$$\beta = \frac{h}{2} \left[1 - 2h^2 + 4h^3 \exp h^2 \int_h^\alpha \exp(-h^2)\, dh \right]$$

$$h = eH\lambda / m\omega$$

Where H is the magnetic field, λ the electronic mean free path and ω is the most probable electronic speed which is given in terms of the electron temperature T_e by

$$\omega^2 = 2 K T_e / m$$

the electron velocity distribution is supposed to be Maxwellian.

Now $h = eH\lambda / m\omega$ and $\omega = \sqrt{2 K T_e / m}$

and $\upsilon_r = \sqrt{8 K T_e / m\pi}$ where υ_r is the random velocity.

then $h = \dfrac{eHL}{Pm\sqrt{\frac{2KT_e}{m}}} = \dfrac{2eHL}{m \cdot p \cdot \upsilon_r \cdot \sqrt{\pi}}$

where L is the mean free path of electron in the gas at a pressure of 1 mm. of mercury as h is a very small quantity $\beta = \frac{h}{2}\sqrt{\pi}$

then $\beta = \dfrac{1}{2} \cdot \dfrac{2eHL\sqrt{\pi}}{m p \upsilon_r \sqrt{\pi}} = \left(\dfrac{eL}{m\upsilon_r}\right) \cdot \dfrac{H}{P}$

and as h is very small $\alpha \approx 1$

then $E_H = E(1+\beta^2)^{1/2} = E\left(1 + c_1 H^2/P^2\right)^{1/2}$ ...(6.1).

where C_1 is a constant for a particular gas and is given by $C_1 = (eL/mv_r)^2$ That this equation represents the increase of the axial electric field with the increase of the transverse magnetic field has been verified by Beckman with the experimental results obtained by him in case of hydrogen, nitrogen, helium and neon. Utilizing this expression for the increase of axial electric field in the experimental results obtained by McBee and Dow (1953) regarding theincrease of electric field gradient in the positive column it has been found that the experimental results can be explained to a good degree of accuracy. It can thus be concluded that the above expression can be utilized as representating theincrease of axial electric field with the increase of the transverse magnetic field; further if n_H represents the electron density at a distance r from the axis when the magnetic field is present, then the discharge current is

$$i_H = n_H\, e\, b_i\, E_H = n_H \frac{e^2 L}{P\, v_r} E \left[1 + C_1 H^2/P^2 \right]^{1/2}$$

where n_H is a function of H and b_i is the electron mobility.

$$\text{or} \qquad i_H = \frac{A\, n_H\, E}{P} \left[1 + C_1 H^2/P^2 \right]^{1/2}$$

where A is a constant.

$$\text{then} \quad \frac{di_H}{dH} = A \frac{dn_H}{dH} \frac{E}{P} \left[1 + C_1 H^2/P^2 \right]^{1/2} + A\, n_H \frac{E}{2} \left[1 + C_1 H^2/P^2 \right]^{-1/2} \cdot \frac{2\, H\, C_1}{P^2}$$

$$\text{for maximising} \quad \frac{dn_H}{dH} \frac{1}{P} \left[1 + C_1 H^2/P^2 \right]^{1/2} = - \frac{n_H \cdot C_1 \cdot H}{P^3 \left(1 + C_1 H^2/P^2 \right)^{1/2}}$$

$$\text{or} \quad \frac{dn_H}{dH} = - \frac{n_H \cdot C_1 \cdot H}{P^2 + C_1 H^2}$$

or $$C_1 \frac{dn_H}{dH} H^2 + P^2 \frac{dn_H}{dH} + n_H C_1 H = 0$$

or $$H_{max} = - \frac{n_H C_1 \pm \sqrt{n_H^2 C_1^2 - 4 C_1 \left(\frac{dn_H}{dH}\right)^2 . P^2}}{2 C_1 \left(\frac{dn_H}{dH}\right)}$$

...(6.2).

Further it has been shown by Beckman (1948) that due to transeverse magnetic field the electron density at a distance r from the axis is given by

$$n_H = n_0 \exp\left(\frac{-C r \cos\phi}{2 D_a}\right) J_0 (2.405 r/R)$$

...(6.3).

where n_0 is the electrondensity at the axis, R the radius of the tube, $C = b_i E \beta/\alpha$ D_a is the ambipolar diffusion constant and J_0 is the Basel function of the zero order and of first kind. In absence of magnetic field the electron distribution in the positive column is given by Schottkey's formula so that

$$n = n_0 J_0 (2.405 r/R)$$

Then $$n_H / n = \exp(-C r \cos\phi / 2 D_a)$$

as $C = b_i E \beta / \alpha$ and $\beta = C_1^{1/2} H / P$ and $\alpha = 1$

$$n_H / n = \exp(-b_i E C_1^{1/2} H \cdot r / 2 D_a P) \quad \text{assuming } \phi = 0$$

or $$\frac{1}{n} \frac{dn_H}{dH} = \exp\left(\frac{-b_i E C_1^{1/2} H \cdot r}{2 D_a P}\right) . \left(\frac{-b_i E C_1^{1/2}}{2 D_a P}\right)$$

$$= \frac{-b_i E C_1^{1/2} r}{2 D_a} . \frac{1}{P} . \frac{n_H}{n}$$

or $$\frac{dn_H}{dH} = \frac{-b_i E C_1^{1/2} r}{2 D_a} . \frac{n_H}{P}$$

...(6.4).

Then from equation (6.2)

$$H_{max} = \frac{-n_H C_1 \pm \sqrt{n_H^2 C_1^2 - \frac{4 C_1 b_i^2 E^2 C_1 \gamma^2}{4 D_a^2} n_H^2}}{2 C_1 \left(\frac{dn_H}{dH}\right)}$$

$$= \frac{-n_H C_1 \pm \sqrt{n_H^2 C_1^2 \left(1 - b_i^2 E^2 \gamma^2 / D_a^2\right)}}{2 C_1 \left(\frac{dn_H}{dH}\right)}$$

Now $D_a = \frac{K T_e}{e} b_i$

Then $$H_{max} = \frac{-n_H C_1 \pm \sqrt{n_H^2 C_1^2 \left(1 - e E \gamma / K T_e\right)^2}}{2 C_1 \left(\frac{dn_H}{dH}\right)}$$

now $e E \ll K T_e$ and it becomes still smaller when multiplied by γ if γ corresponds the radius for unity cross section; then neglecting the second term within the radical in comparison with unity

$$H_{max} = \frac{-n_H C_1 - n_H C_1}{2 C_1 \left(dn_H / dH\right)} = \frac{n_H}{\left(dn_H / dH\right)}$$

Hence

$$H_{max} = \frac{2 D_a P}{b_i E C_1^{1/2} \gamma} = \frac{2 K T_e P}{e E C_1^{1/2} \gamma}$$

It has been shown by Von Engel (1955) that

$$K T_e = \frac{e E \lambda_e}{\sqrt{\mathcal{R}}}$$ where $\mathcal{R}$ is the fraction of energy lost by collision

Hence

$$H_{max} = \frac{2\,\lambda_e\,P}{C_1^{1/2}\sqrt{R}\cdot r} = \frac{2\,L}{\frac{e}{m}\cdot\frac{L}{\upsilon_r}\sqrt{R}\cdot r} = \frac{2\,m\,\upsilon_r}{e\cdot\sqrt{R}\cdot r}$$

as $\upsilon_r = \sqrt{8\,K\,T_e/m\pi}$

$$H_{max} = \frac{4\sqrt{2\cdot m\,K}}{e\,r\sqrt{\pi}}\sqrt{\frac{T_e}{R}}$$

now if we consider the current which passes through an unit area around the axis of the tube

$$\pi r^2 = 1 \quad \text{or} \quad r = 1/\sqrt{\pi}$$

and $$H_{max} = \frac{4\sqrt{2\times 9\times 10^{-28}\times 1{\cdot}37\times 10^{-16}}}{1{\cdot}6\times 10^{-20}}\sqrt{\frac{T_e}{R}}$$

...(6.5).

In verifying his theory Beckman (1948) has used the values of R as given by Von Engel and Steenbeck (1932, 1934). These values are derived from Townsend's observation which shows that R varies with electron temperature. To take representative cases as in the case of hydrogen, Von Engel (1955) has given thevalues of T_e for (E/P) values varying from 0 to 300 volts/cm. mm. of Hg. for various molecular gases and also the values of R. Thus for hydrogen for $T_e = 1.16\times 10^4$

$R = 2.17\times 10^{-3}$ and $\sqrt{T_e/R} = 2.312\times 10^3$

and $H_{max} = 12.4\times 10^{-2}\times 2.312\times 10^3 = 287.06$ gauss

for air, for $T_e = .116\times 10^4$, $R = 15\times 10^{-3}$

$\sqrt{T_e/R} = 1.978\times 10^3$. $H_{max} = 12.4\times 10^{-2}\times 1.978\times 10^3$

$= 245.7$ gauss.

As no data is available for carbondioxide either for electron temperature or for R calculation can not be made in this case.

Beckman has calculated the values of electron temperature in case of helium at zero magnetic field and has given the value of $\kappa = 3.4 \times 10^{-3}$ at T = 40,000 K and $\kappa = 9.3 \times 10^{-3}$ at T = 60,000 K and the values lie approximately on a straight line. From these values $\sqrt{T_e/\kappa} = 1.840 \times 10^3$ and $H_{max} = 228.2$ gauss.

For neon, Druyvestyn and Penning (1940) have given the values of electron energy losses in inelastic collisions from which κ can be calculated. Thus $\kappa = .058$ at 60000 K and $\kappa = .092$ at T = 80,000 K but if calculations are made for $\sqrt{T_e/\kappa}$ and the value inserted in inserted in equation (6.5)

$$H_{max} = 95.48 \text{ gauss}$$

where as if it is assumed that all the collisions are elastic then assuming an electron temperature of the order of 20000° and obtaining κ from the data given by Von Engel (1955), $\sqrt{T_e/\kappa} = 13.55 \times 10^3$, and the calculated value of $H_{max} = 1681$ gauss which is not in agreement with experimental results. It can thus be presumed that incase of neon both elastic and inelastic collisions are taking place.

Thequantitative agreement or disagreement of the theory with the experimental results should not be taken seriously because there are a number of uncertain factors which have entered into the calculation.

(a) The increase of axial electric field in presence of transverse magnetic field cannot be fully represented by the factor $E\,(1 + C_1 H^2/P^2)^{1/2}$ as has been shown also by Beckman and as in the case of equivalent pressure concept the equation has a limited applicability within a certain range of $(H/_p)$ values.

(b) The expression for distribution of electron density in a transverse direction in presence of magnetic field as has been deduced by Beckman has also not been experimentally verified and the degree of accuracy with which this holds has not been determined. Experiments are now under progress in this laboratory to verify the results by a prove method.

(c) The variation of $\mathcal{R}$ the fraction of energy lost by an electron during collision is a function of electron temperature as has also been noted by Beckman but though some experimental results are available in literature regarding the variation of $\mathcal{R}$ with small $(E/_p)$ values these relate to much smaller values of $(E/_p)$ than those used in the present experiment and an adequate comparison cannot be made.

(d) In the above discussion it has been assumed that all the electrons are moving with the same velocity and in his calculation Beckman has assumed the distribution to be Maxwellian; while this is true in case of molecular gases there is a definite departure from Maxwellian distribution in case of inert gases. The distribution of electron velocities specially in presence of magnetic field will modify the final result.

Inspite of these limitation the calculation shows that the order of magnitude of H_{max} is of the same order as has been found from the experiment and independent of pressure.

The theoretical results further show that the $H_{max} = 12.4 \times 10^{-2} \sqrt{T_e \mathcal{R}}$ and as $T_e \propto (E/p)$ and i_o the discharge current is $\propto (E/_p)$

$$H_{max} \Big/ (i_o)^{1/2} = \text{const.}$$

$$\text{or } H_{max}^{\ 2} \propto i_o$$

which is also observed experimentally. Further from the relation

$$i_H = \frac{A \cdot n_H \cdot E}{P} \sqrt{1 + C_1 H^2/P^2}$$

$$(i_H)_{max} = \frac{A\,(n_H)_{max}\,E}{P} \sqrt{1 + C_1 H_{max}^2/P^2}$$

$$\text{now} \quad H_{max} = \frac{n_H}{(dn_H/dH)} = \frac{n_H\,P}{A_1\,n_H} \quad \text{where } A_1 \text{ is a constant.}$$

$$(i_H)_{max} = \frac{A \cdot (n_H)_{max}\,E}{P} \sqrt{1 + C_1/A_1^2}$$

$$\text{or} \quad (i_H)_{max} \cdot P = \text{Constant}$$

which also follows the experimental results.

It can thus be concluded that the variation of current in the discharge in presence of a transverse magnetic field is a function of the radial electron density and also the axial electric field which are themselves function of the transverse magnetic field. The value of thedischarge current and its variation with themagnetic field as calculated agree at least qualitatively with the experimental results and lends indirect support to the theoretical calculation of Beckman (1948).

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