

CHAPTER I

(A)

REVIEW OF THE PREVIOUS WORK

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- (A) REVIEW OF THE PREVIOUS WORKS:
- (1) DETERMINATION OF PLASMA PARAMETERS WITH SPECIAL EMPHASIS ON RADIO FREQUENCY CONDUCTIVITY MEASUREMENT.

The study of the electric discharge phenomena in the steady state by means of a radio frequency signal as a probe was first suggested by Vonder Pol (1919). If a r.f. voltage not sufficient to cause the breakdown, be applied to an ionised gas, then the r.f. current I_{rf} that flows through the gas is given by

$$I_{rf} = \frac{e^2 n x_0}{m} \left[\frac{\omega_c}{\omega_c^2 + \omega^2} - j \frac{\omega}{\omega_c^2 + \omega^2} \right] \quad (1.1)$$

where n is the number of electrons per c.c. of the ionized medium, e and m , the charge and mass of the electron respectively; ω the angular frequency of the applied r.f. field and ω_c the collisional frequency of the electrons. Hence the complex conductivity σ_c is given by

$$\sigma_c = \frac{I_{rf}}{x_0} = \frac{e^2 n}{m} \left[\frac{\omega_c}{\omega_c^2 + \omega^2} - j \frac{\omega}{\omega_c^2 + \omega^2} \right] \quad (1.2)$$

Assuming $\sigma_c = \sigma_r - j\sigma_i$, we have

$$\sigma_r = \frac{e^r n \nu_c}{m [\nu_c^r + \omega^r]} \quad \text{and} \quad \sigma_i = \frac{e^r n \omega}{m [\nu_c^r + \omega^r]}$$

It is then seen that both σ_r and σ_i are functions of

- (i) frequency ω
- (ii) electron density n and
- (iii) the collision frequency ν_c which is itself a function of pressure. The value of σ_r is maximum when $\nu_c = \omega$, i.e.,

$$(\sigma_r)_{\max} = \frac{ne^r}{2\nu_c m} \quad .$$

Thus by measuring the conductivity of an ionised gas in a high frequency field the electron concentration can be obtained. The conductivity of ionized air was measured by Childs in (1932) by substitution of a resistance of known value for the leakage resistance of the ionized gas, the oscillation frequency being 1 MHz. The variation of the radio frequency conductivity of ionized air with pressure at frequencies of the order of 1000 MHz using a lecher wire system coupled to the condenser within which the discharge tube was placed was studied by Appleton and Chapman (1932), the radio frequency current being rectified by means of a galena crystal and detected by the galvanometer. As the conductivity increases, the galvanometer deflection falls and Appleton and Chapman observed that the conductivity attains a maximum value at a certain pressure and then decreases in accordance with the theory; but they did not report any absolute value of the conductivity for the gas investigated, namely air. Similar

study was made in case of sulphur dioxide and xenon by Imam and Khastgir (1937) in the pressure range 10 - 120 cm of mercury using radio waves of $\lambda = 481$ cm and a lecher wire system. The above simple theory has been modified by Margenau (1946) by taking into consideration the distribution of velocities and employing Boltzmann transfer equation. The modified expression for σ is given by

$$\sigma = \frac{4}{3} \frac{ne^2 \lambda_e}{\sqrt{2\pi m k T_e}} \cos \omega t + \frac{ne^2 \lambda_e^2 \omega}{3 K T_e} \sin \omega t. \quad (1.3)$$

for values of $\nu_c \gg \omega$

Dowson and Oberman (1962, 1963) developed an elementary model to calculate the high frequency electrical conductivity of plasma. Berk (1964) showed how the plasma model of Dowson and Oberman can be adopted to yield a kinetic description of electrical transport processes, which is uniformly valid for high and low frequencies, as well as for finite wave lengths.

The theory of the electrical conductivity of a gas which is either fully ionized or weakly ionised has been well established for a number of years. Although the conductivity of a partially ionized gas is qualitatively well understood, very little quantitative information exists, principally because of the mathematical complications which arise when the electron-electron interaction is included in the Boltzmann equation for the electron velocity distribution function. Johnson (1967) calculated the electrical conductivity for a variety of assumed

electron-molecule collision frequencies. The results differ only by a few percent from those obtained using an approximation suggested by Frost (1964). A simple procedure, requiring no numerical integrations has been given relating electron temperature to electrical conductivity for a partially ionized gas. Sen and Ghosh (1966) studied the properties of ionized gases experimentally by using radio frequency probe. The r.f. conductivity (σ_r) of the ionised air and nitrogen has been determined at various pressures and also at various values of discharge current. They observed that σ_r increases with pressure and attaining a maximum value gradually decreases. The maximum value of σ_r occurs at the same pressure for different discharge currents for the same gas. The experiment was carried out specially at low pressure (a few microns).

Nagata (1966) presented a simple technique for measuring the plasma conductivity. The method is based on the observation that Hall current and Hall voltage are related simply to an electrical resistance. This method may also be applied to the measurement of electron density in high pressure plasma. An improved probe method of measuring the electrical conductivity of low temperature plasma is set out by Khozhablow and Yarin (1966). They presented experimental data regarding the effect of layers near the electrode, on the probe readings. Ciampi and Talint (1967) measured the average plasma conductivity by r.f. probe for a cylindrical plasma assumed radially inhomogeneous. They obtained the average conductivity of 75 to 100 mho/m with a Q -factor ^{frequency} ranging

from 0.5 to 1.5 MHz. The probe used is calibrated with electrolytic solution (H_2SO_4) of standard conductivity.

From the study of the complex conductivity of mercury vapour at microwave frequencies, Adler (1949) has shown plots of σ_r and σ_i with current or pressure when the other is fixed. Using the theoretical expression of Margenau, Adler calculated values of the electron density in the discharge space and compared the value obtained with those obtained experimentally using Langmuir probe measurements. Adler found that the theoretical and experimental values agree closely and that σ varies linearly with the discharge current. Aleksardrov and Yalsenko (1965) studied the complex conductivity of neon plasma by the Q meter method. The results are given regarding the measurements of the active and reactive components of the conductivity of the parallel-plate-capacitor containing between its electrodes of the plasma of a positive gas discharge column. The frequency range was 0.5 to 25 MHz, the discharge currents were 5 to 100 mA, and various gas pressures were used. Experimental results are in good agreement with the theoretically calculated values.

The effect of Magnetic field on the Conductivity of ionised gas.

As the various characteristics of a discharge change due to the presence of a magnetic field, it is clear that the conductivity of an ionised gas will also change in presence of a magnetic field. The conductivity of an ionised gas such as air, nitrogen and hydrogen in a magnetic field was measured

by Ionescu and Mihul (1932) for pressure greater than 10^{-3} mm of Hg., who found that maxima other than those due to free electrons could be obtained. With very intense fields, only the variation due to free electrons remained, the others disappearing and the values of the magnetic field giving maxima conductivity varied with pressure.

A theory regarding the variation of r.f. conductivity with magnetic field was proposed by Appleton and Boohariwala (1935) who showed that the real part of r.f. conductivity in a magnetic field is given by

$$\sigma_{RH} = \frac{ne^2}{m} \frac{\nu_c (\omega^2 + \omega_b^2 + \omega_c^2)}{(\omega^2 + \omega_b^2 + \omega_c^2)^2 - 4\omega^2\omega_b^2} \quad (1.4)$$

where n is the number of electrons per unit volume and ν_c the collision frequency ω is the angular frequency of the applied field and $\omega_b = \frac{eH}{m}$

A general theory regarding the variation of r.f. conductivity of ionized gases and its variation with pressure and magnetic field has been worked out by Gilardini (1959) who derived the expression for the conductivity of an ionized gas under the following assumption:

(a) When the distribution function is predominantly spherically symmetrical in velocity space but not necessarily Maxwellian.

(b) When the electron collision frequency is an arbitrary function of electron velocity. The value of the complex conductivity is given by

$$\sigma = \frac{e^2 n}{m} \frac{1}{\nu_c + j\omega}$$

In presence of magnetic field he defined two conductivities; a conductivity σ_c for the right handed polarization and conductivity σ_o , for the left handed polarization where

$$\sigma_c = \frac{e^2 n}{m} \left[\frac{1}{\nu_c + j(\omega - \omega_b)} \right]$$

and

$$\sigma_o = \frac{e^2 n}{m} \left[\frac{1}{\nu_c + j(\omega + \omega_b)} \right]$$

and the conductivity in the direction of the field is given by

$$\sigma_H = \frac{1}{2} (\sigma_c + \sigma_o) = \frac{e^2 n}{m} \left[\left\{ \frac{\nu_c}{\nu_c^2 + (\omega - \omega_b)^2} + \frac{\nu_c}{\nu_c^2 + (\omega + \omega_b)^2} \right\} - j \left\{ \frac{\omega - \omega_b}{\nu_c^2 + (\omega - \omega_b)^2} + \frac{\omega + \omega_b}{\nu_c^2 + (\omega + \omega_b)^2} \right\} \right]$$

$$\therefore \sigma_{rH} = \frac{e^2 n}{m} \left[\frac{\nu_c}{\nu_c^2 + (\omega - \omega_b)^2} + \frac{\nu_c}{\nu_c^2 + (\omega + \omega_b)^2} \right]$$

and after simplification it reduces to the result obtained earlier by Appleton and Bochariwalla.

Later on several authors (WU, 1965; Oberman and Shure, 1963; Schweitzer and Milchner, 1967; Green et al, 1965) studied the ionized gas in presence of magnetic field and developed the theory considerably.

In 1967 the complex conductivity of a plasma in a steady magnetic field was studied by Prodhan and Dasgupta (1967). They derived an expression for the complex conductivity tensor

of a homogeneous classical plasma in an external uniform magnetic field using the Kubo theory of transport phenomena and obtained exact relations between the conductivity tensor in the presence of the magnetic field and in its absence.

The experimental determination of radio frequency conductivity has been carried on in presence of a transverse magnetic field by Sen and Gupta (1969), Gupta and Mandal (1967) and Gupta (1968) from which variation of plasma parameters in a magnetic field have been measured. The method is useful due to the fact that from the r.f. conductivity measurement it is possible to calculate the plasma parameters such as collision frequency, electron density, electron temperature, Debye shielding distance and the dielectric constant of the plasma. A precise knowledge of these parameters, their variation with pressure, discharge current and magnetic field is essential for the proper understanding of the mechanism operating in the discharge. Through there have been some measurements of these parameters in the microwave region the corresponding data in the r.f. range has been comparatively little reported. Between 1966 to 1969 alternative method has been developed in this laboratory for measurement of r.f. conductivity and measurements have been made in case of helium, neon, argon, hydrogen, air and carbondioxide and the plasma parameters and their variation with pressure, discharge current and magnetic field have been studied by Sen, Gupta and Mandal.

2. MEASUREMENT OF MOMENTUM TRANSFER COLLISION CROSS-SECTION WITH AND WITHOUT MAGNETIC FIELD.

The measurement of momentum transfer cross section of electrons for elastic scattering has been carried out in a large number of atomic and molecular gases for a wide range of electron energies by various standard methods (1) Swarm^{km} experiment, (2) Microwave after-glow method and (3) Cyclotron resonance method with and without magnetic field.

In Swarm experiments Townsend and Bailey (1922) and Ramsayer^u (1921) carried out the comparison of momentum transfer (diffusion) cross-section with total collision cross-section for He, Ne and A in the wide range of electron energies by measuring the drift velocity electron shutter method.

The operation of shutter principle consists of two shutters S_1 , S_2 placed at different levels in the diffusing electron swarm. At regular intervals of these shutters open for short interval of times so that electrons may pass through. They are synchronized in phase so that both are open at the same time. Electrons will succeed in passing through both shutters only if they traverse the distance between them in an integral number of cycles. By observing the variation of the current passing through S_2 as a function of the frequency of shutter operation, the drift velocity may be determined. The method was adopted by Bradbury and Nielsen (1936) (1937), Loeb and Cravath (1929, 1935) and has been further modified.

by Phelps, Pack and Frost (1960) Pack and Phelps (1961) with and without d.c. bias covering the higher values of (E/P) from 10^{-4} to $40 \text{ V cm}^{-1} \text{ torr}^{-1}$.

Secondly Hornbeck (1951) measured the drift velocities of positive ions and Bowe (1960) measured the drift velocities of electron in various rare gases using different methods. The methods of Hornbeck's were further developed by Lowke(1962).

Bortner, Hurst and Stone (1957) have developed a pulse method, which was originally suggested by Stevenson (1952) for measuring the drift velocities of electrons, which is particularly suitable for studying gases commonly used in ionization chambers and counters.

The microwave after glow method was used for measuring the complex conductivity of a plasma by Margenau (1946), Phelps, Fundingsland and Brown (1951). The other related parameters were measured and their variation with wide range of pressure was measured by many workers Margenau and Adler (1950), Varnerin (1951) Gould and Brown (1953, 1954) and Chen (1964), specially for Neon and Helium.

A theory was developed by Allis and Allen (1937) in a combined electric (E) and Magnetic field (H) and it has been shown that the angle of deflection is given by

$$\theta = \arctan(\beta H U / E)$$

where $\beta \approx 1$ depends on the variation of momentum transfer cross-section with velocity and $\beta = 1.06$ the cross-section

independent of velocity

u = drift velocity.

Huxley and Zaazou (1949) modified the procedure of Townsend and Bailey (1922) and their collaborators measured the drift velocities using the modern vacuum techniques in a number of gases. This method has been developed particularly by Jory (1965) who has used the same apparatus as that of Compton and Elford and Gaseoigue (1965) in the measurement of D/u , the ratio of Diffusion coefficient to the drift velocity.

In the Cyclotron resonance method a uniform steady magnetic field H and a Microwave electric field $E \cos \omega t$ are applied at right angles and then the variation of absorbed power by the electron in the resonance form is measured about the cyclotron angular frequency $\omega_H = \frac{eH}{m}$ of the electron and the width of the resonance curve varied with the collision frequency of the electron in the plasma.

In presence of a magnetic field the interaction between a microwave field and a plasma has been formulated by Allis(1956), in terms of high frequency conductivity tensor, whose component transverse to the field was

$$\sigma_t = \frac{4\pi ne^2}{3m} \int_0^\infty \frac{\nu + i\omega}{\omega_H^2 + (\nu + i\omega)^2} \frac{\partial f_0}{\partial \nu} \nu^3 d\nu \quad (1.5)$$

and the imaginary part of σ_t

$$= -\frac{4\pi ne^2}{3m} \int_0^\infty \frac{\omega(\nu^2 + \omega^2 - \omega_H^2)}{\nu^2 + (\omega + \omega_H)^2 \{ \nu^2 + (\omega - \omega_H)^2 \}} \frac{\partial f_0}{\partial \nu} \nu^3 d\nu$$

(1.6)

considering ν to be independent of ω it can be shown that

$$\omega_H^\nu = \nu + \omega^\nu \quad (1.7)$$

Thus the collision frequency of the plasma can be determined knowing the values of resonance frequency with magnetic field in presence of discharge plasma and the resonance frequency ω is equal to that of the cavity in the absence of plasma.

Hirshfield and Brown (1958) determined the momentum transfer cross section in helium using this method and Fehsenfeld (1963) studied the collision frequencies in helium, argon, CO_2 and oxygen by the cyclotron resonance method.

3. VOLTAGE CURRENT CHARACTERISTICS IN A GLOW DISCHARGE IN LONGITUDINAL MAGNETIC FIELD.

In the absence of space charge effects the motion of a swarm of electrons moving in electric and magnetic fields was worked out by Townsend (1912) who showed that the coefficient of diffusion D_H perpendicular to the magnetic field and the mobility μ_H parallel to the field are reduced according to the equations

$$D_H = \frac{D}{1 + \frac{\omega^2}{\nu^2}} \quad \text{and} \quad \mu_H = \frac{\mu}{1 + \frac{\omega^2}{\nu^2}} \quad (1.8)$$

where $\omega = \frac{eH}{m}$, the cyclotron frequency and ν is the frequency of collision of electrons, for momentum transfer with neutral molecules.

In the Townsend experiment Lorentz method was applied to the combined drift and diffusion of the electron stream and the Zeroth = order approximation was considered for the detailed calculation. Allis and Allen (1937) applied the same method to the drift of electrons in crossed electric and magnetic fields. It was found by Allis and Allen (1937) that the magnetic field changes the energy distribution as well as the direction of drift.

For electrons which, like arc plasma electrons have a Maxwell distribution to a first approximation, the first order correction to the distribution function which arises from the drift motion was calculated by Tonks and Allis (1937) and from this exact averaging of component velocities was

carried out. Tonks also pointed out that the drift speed is the same as would occur if the components of concentration gradient and electric field perpendicular to it as well as the magnetic field itself did not exist, is found to hold within twelve percent.

The condition in a cylindrical plasma under the influence of transverse homogeneous magnetic field was treated by Beakman (1948) in a manner analogous to that given by Von Engel and Stejneger (1934) for the case without magnetic field. The general effect of a transverse magnetic field on the positive column of a glow discharge has been theoretically studied by Beekman (1948) who showed that the current is forced ~~to~~ towards the tube wall thereby increasing the loss of electrons and ions. In order to compensate this loss the axial electric field increased, thus increasing the ionization and the electron temperature. Based on these assumptions the variation of discharge current in a glow discharge in air, carbon dioxide, helium, hydrogen and neon in a variable transverse magnetic field has been satisfactorily explained by Sen and Gupta (1972). They showed that the current gradually rises with the increase of the magnetic field, attains a maximum value at a particular value of the magnetic field which is the same for all the gases and independent of pressure for the same initial discharge current and then gradually decreases. The value of the magnetic field at which the discharge current is maximum is found to be proportional to the square root of the initial discharge current and the maximum value of the current is

inversely proportional to pressure in all the gases. Utilizing Beekman's expression for the axial electric field and the radial electron density distribution in a transverse magnetic field, a mathematical expression for the discharge current and its variation with magnetic field was deduced and is given by

$$i_{\max} = \frac{A(n_H)_{\max} E}{P} \left(1 + \frac{C_1}{A_1^2} \right)^{1/2} \quad (1.9)$$

where n_H = radial electron density in presence of magnetic field.

E = axial electric field .

C_1, A, A_1 = constants, P = pressure.

When a magnetic field parallel to the axis of the +ve column of a discharge was applied this was known to impart a rotary component on the radial motion of electrons. As a result ~~the flow~~ of both positive ions and electrons ^{flow} to the wall, causing a corresponding decrease in the radial and longitudinal components of the electric field and in the electron temperature.

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27 MAR 1981



4. RADIO FREQUENCY BREAKDOWN IN MOLECULAR GASES IN LONGITUDINAL MAGNETIC FIELD.

The secondary effects in a d.c. discharge with electrodes made of different elements have been studied quite extensively by Townsend and others from as early as 1904. The mechanism of discharge excited by a transformer is however substantially the same as that of a d.c. discharge, Townsend (1902) in his ionization theory derived an expression for the ionisation current flowing in a gap (d) when the cathode is irradiated as

$$i/i_0 = e^{\alpha d} \quad (1.10)$$

where i_0 = initial current, α = number of ion pairs produced per unit length per primary electron. It suggests that the plot of $\log (i/i_0)$ against d would be a straight line. But it was found that the current terminates abruptly to a value producing a spark. This indicates that another source of ionisation has arisen other than ionisation by electron collision. Townsend's obvious choice was a relation of the form

$$i/i_0 = \frac{e^{\alpha d}}{1 - \beta/d e^{\alpha d}} \quad (1.11)$$

where β = ionisation coefficient due to positive ions.

The positive ion theory was criticised by Thomson (1912) Bohr (1913) and others. The mechanism was however studied by many workers; Sultan and Muzon (1930, 1931), Muzon (1932),

Becék (1930, 1934). Nordmeyer (1933), Varney (1935), 1936, 1938); Rastagin (1934). These results have been discussed by Loeb (1947). However Fetz and Medicus (1948) have given strong support to the mechanisms as a possible process of ionisation.

RADIO FREQUENCY BREAKDOWN OF GASES.

(a) Without Magnetic field:

The mechanism of the breakdown of gases for an alternating voltage at 50 cycles/sec is substantially the same as that for d.c. voltage. However, under the influence of a high frequency alternating field, free electrons in a gas may acquire energies sufficient to excite and to ionise the neutral gas molecules, when the electric field is sufficiently large, the ionisation process is cumulative and the gas breaks down into a luminous glow discharge. The exciting field may be applied directly by electrodes connected to the source of high frequency potential. Alternatively the gas may be excited by a h.f. current flowing in a nearby conductor. The first type of discharge is called E discharge and second type H discharge. The mechanism of E & H discharges are fundamentally the same and division into two types is justified only when the wavelength of the exciting voltage is large compared with the linear dimension of the discharge tube. Comparatively little study has been made of H-discharge. The reason is probably to be found in the difficulties experienced in making precise measurements as the path of the discharge current is closed and there are no electrodes between which current and p.d. may be measured.

The breakdown mechanism in E-discharge and the magnitude of the breakdown voltage V_b of a gaseous discharge in an a.c. field depend upon the nature and the pressure of the gas, the frequency of the applied field and the linear dimension of the discharge tube. The general characteristics of the breakdown curves have been studied by many workers and it has been reviewed by Darrow (1932, 1933). One of the earliest workers, Thomson (1930, 1934) enunciated two conditions for breakdown in high frequency field. Assuming the electron under the influence of an a.c. field, the first criterion was that in time 't' the electron must acquire sufficient energy from the field so that the energy is either equal or greater than the ionisation energy of the gas; consequently the first condition states that

$$\frac{1}{2} m \left[\frac{E}{\omega} \cdot \frac{e}{m} \sin \omega t \right]^2 \gg e V_i \quad (1.12)$$

where V_i = ionisation potential of the gas. The second condition was the distance transversed by the electron in the time 't' must be either equal to or smaller than the mean free path of the electron in the gas.

$$\text{Hence } \frac{E}{\omega^2} \cdot \frac{e}{m} \cdot (1 - \cos \omega t) \leq \lambda_e \quad (1.13)$$

combining these two conditions he obtained an equation for the breakdown voltage which is a function of pressure and frequency and shows that at a certain pressure the breakdown voltage becomes a minimum. Thomson (1937) next studied the starting potential for hydrogen within the pressure range (0.25 mm to 9.5 mm) and for frequency 1.8 MHz to 99 MHz. In case of a

lower frequency (below 2.83 MHz) he obtained double minima and above this frequency single minima. Double minima was also observed by Gittons (1928) who concluded that these were due to resonance phenomena in the gas; Gill and Donaldson (1931) found that the double minimum disappeared if the discharges were away from the walls of the tube. To explain this, Thomson (1937) attempted to modify his theory. In order that a typical electron may acquire the maximum energy at a time, it is assumed that the electron begins to move at a time $t = 0$, when the electric field is $E \cos(-\phi)$. Then the ionising velocity will be most quickly attained if it is acquired in a time t , such that the electric field at time t , is $E \cos(+\phi)$ for under this condition

$$\int_0^t \cos(2\pi ft - \phi) dt \quad \text{is a maximum.}$$

Gill and Donaldson (1931) showed that when the excitation was by a field at right angles to the long axis of the tube, double minima appear and when the field was along the axis one minimum (that at higher pressure) disappears.

The explanation is seen by considering a cloud of electrons oscillating in the gas under the influence of the field. At a fixed pressure, as the field is increased the rate of ionization increases and when this is just greater than the rate of loss, due mainly to diffusion, the glow appears. Now if the pressure is reduced the electrons

acquire more energy from the field owing to their increased free path and the critical force required for breakdown is less. However as the pressure is reduced the amplitude of oscillation of the electrons also increases and when this becomes of the same order as the distance apart of the walls, rate of loss of electrons increases rapidly and the breakdown voltage is increased. The calculations of Gill and Donaldson relating to their conditions of experiments are in agreement with their views.

Breakdown in hydrogen for frequencies 5 to 11 MHz for $p \times d = 0.2$ to 30 mm Cm. of Hg. was studied by Githens(1940) who attempted to correlate the appearance of the minima of $(V_s, p \times d)$ curves with the position of the walls of the discharge tube relative to the electrodes. He concluded that the breakdown of the h.f. discharge occurred through three different processes^{es} which he denoted by modes, a,b,c, each of which gave rise to a minimum in $(V_s, p \times d)$ curve.

Similar results were observed by Pim (1948, 1949) using small gaps in air at pressures from 59 mm to 764 mm for frequencies ranging from 100 MHz to 300 MHz.

^aHope (1948) tried to explain his measurements in argon and xenon over the range of frequencies 5 MHz to 50 MHz and at gas pressure 20 - 50 microns by assuming that the breakdown potential for h.f. field is determined by those electrons in the gas which succeed in acquiring ionising energy in

one mean free path; there is considerable divergence of the theoretically calculated breakdown voltage with experimental results in case of lower frequencies. The value of the mean free path of the electron used was that given by kinetic theory which can hardly be correct. As is known, the mean free path of the electron varies with the energy of the electron and as the energy of the electron varies between zero and ionising energy, what is needed is an effective mean free path. Also the assumption that the probability of ionization becomes a maximum when the electron acquires the ionising energy is not supported by experimental results because it has been shown by Smith (1930) that efficiency of ionisation increases quite rapidly with increasing electron energies slightly above the ionising energy.

The extent of the influence of the discharge in the walls and electrodes upon breakdown mechanism depends upon the relative magnitudes of p , f and d , where p is the pressure, f is the frequency and d is the electrode separation. Llewellyn Jones and Margan (1951) showed that when ' f ' and ' p ' are sufficiently high the amplitude of motion of the electron cloud is small, and it can be much less than the linear dimension of the discharge tube, V_g is independent of the nature of electrode surfaces and secondary electron production at the electrode surfaces does not appear to play ^{an} important part. However at very low pressure, experiments of Gill and Von Engel (1948, 1949) and also

those of Chenoo (1948) show that a discharge can be started, provided the frequency is greater than a critical value, at quite a low potential which is independent of the pressure of the gas. In this case Gill and Von Engel have assumed that a single electron strikes the opposite glass surface and releases the secondary electrons which move in phase with the applied electric field and release further electrons from the walls.

Applicability of similarity principle in h.f. discharge has been studied by Llewellyn Jones (1951, 1953) and his co-workers. Townsend and Williams (1958) studied the breakdown condition in air and hydrogen using a pair of geometrically similar electrode system and measurements were made for values of $p.d = 15\text{mm. cm. of Hg.}$ and frequency 5 MHz to 70 MHz for $f = 10$ MHz or more double minima appeared.

The first minimum was not very sensitive to change of frequency but the second minimum moved to higher values of V_g and p as the frequency is decreased. The similarity theorem was found to be obeyed within the frequency range investigated. They have concluded that the multiple minima in $(V_g, p.d)$ curves at high frequency can be interpreted on the basis of a single breakdown mechanism involving electron generation by collision with gas molecule and loss by diffusion and drift to the electrodes and to the walls of the discharge tube. The first published results for breakdown in ultrahigh frequency region, appear to be those of Cooper(1947) who made

measurements of the breakdown in air, in co-axial lines and wave guides for gaps between 0.1 and 0.3 cm at gas pressure 20 - 760 mm. at the two wave lengths (10.7 cm and 3.1 cm) and the breakdown gradient was found to be 70% of the d.c. breakdown value. Similar measurements were made by Posin (1948) who found that for 3 cm. wave, breakdown voltage for a 0.043cm. gap in air under atmospheric condition is substantially independent of pulse duration provided that duration exceeds 4 sec. The nature of spark mechanism in a cavity resonator~~at~~ at the ^{se}wavelengths has been studied by Prowse and Cooper (1948) and by Prowse and Jasinski (1947) using photographic and spectroscopic methods.

Series of investigations on microwave breakdown in gases in cylindrical cavities and between co-axial cylinders at a wavelength of 9.6 cm have been made by Brown and his colleagues (1948, 1949, 1958, 1959). The gaps studied range from 0.06 to 7.6 cm in air at pressure from 0.1 to 100 mm. of Hg. The results are discussed in terms of a new theory for ultra high frequency breakdown, which is based on the criterion that at the point of breakdown, ionisation rate equals the rate of loss due to diffusion. Other processes of removal of electrons, such as attachment and recombination are considered to be negligible for the type of the discharges studied; when the gap length is small compared with the wavelength the electronic mean free path and the amplitude of oscillation, the breakdown condition is obtained from consideration of the continuity equations for electrons as

$$\frac{\delta n}{\delta t} = \nu n - \nabla \Gamma \quad (1.14)$$

when 'n' is the electron density, γ is the net production rate of electrons per electron and denotes the differences between the ionisation rate and the attachment rate. Γ represents the electron current density lost to the walls by diffusion.

The threshold for breakdown is considered to occur when $\frac{\delta n}{\delta t}$ goes through zero. The breakdown is then the characteristic value of the electric field obtained from the solution of the equation.

$$\gamma n - \nabla \Gamma = 0. \quad (1.15)$$

with the boundary condition that the electron density varies at the cavity surface. A high frequency ionisation coefficient can be defined as

$$\rho = \frac{\gamma}{DE} \quad (1.16)$$

where D = diffusion coefficient.

Values of ρ have been calculated by Brown and others from the breakdown measurements under parallel plate condition in cylindrical cavity and are expressed as function of E/p and $p\lambda$, where λ is the wavelength. The data are then used to calculate breakdown voltages in air between co-axial cylinders and results are found to be in close agreement with the experimentally determined values. If the applied frequency is greater than the frequency of inelastic collision and less than the frequency of elastic collision, Holstein (1946) showed that the energy distribution of electrons in h.f. field is ^{essentially} easily the same as that of

electrons in a static field equal in magnitude to the r.m.s. value of h.f. field. Holstein deduced the breakdown condition that the rate of production of electron by ionization must exceed the rate of loss due to diffusion for non attaching gases. In case of a uniform field between parallel plates the calculated relation between the breakdown gradient E , the gap length 'd' and the gap pressure 'p' is

$$(p.d)^2 = \frac{\pi^2 k T_e}{e (E/p)^\alpha / p} \quad (1.17)$$

is α is the Townsend's first ionisation coefficient.

In a series of theoretical papers on h.f. discharge, Margan^{au} and Hartman (1948) have discussed methods for determining the electron energy distribution and have shown how such functions can be used in the calculation of the breakdown fields on the assumption that the only mechanism for electron removal is recombination with positive ions. The calculated values are appreciably lower than the measured values and the discrepancy is explained by the consideration that electron must also be removed by other mechanisms.

Kihara (1952) assuming a proper model for collision processes in the molecular kinetic theory of electrical discharge and modifying the Boltzman's transport equation obtained expressions for the fundamental parameters involved in the discharge phenomena of gases. Dividing the whole problem into different parts, Kihara obtained absolute expression for mobility coefficient, diffusion coefficient and electron temperature in terms of some molecular constants, and some measurable parameters. The processes by which these molecular constants for different gases and vapours are to be

calculated have also been provided. Starting from Boltzmann distribution of charged particles in a gap with uniform temperature and pressure and nonuniform density and applied external electric field, Kihara (1952) also obtained the well known relation, diffusion coefficient = $\frac{KT_e}{e}$ x mobility where T_e = electron temperature and K the Boltzmann constant.

Assuming that the coefficient of elastic scattering between gas molecules and electron or ion is inversely proportional to the relative speed between the colliding particles an expression for the difference of gas temperature and electron temperature in terms of applied field and frequency has been obtained by Kihara. Extending this idea, the mobility coefficient of electron in gases is given by

$$\bar{k} = \frac{e}{m N \lambda} \quad (1.18)$$

where N = number of molecules per c.c. and λ is a molecular constant introduced by Kihara in this theory (dimension cm^3/sec). Kihara accounted for the excitation by electron with the help of a model giving cross section of excitation as $Q(c, c_0) = f \frac{c^3}{c_0^2}$ i.e. which involves a process such that the speeds of electrons decrease from

c_0 to values below C because of inelastic collisions. Here f is a molecular model constant which has the dimension of area divided by velocity. According to this model the total cross section $Q(c, c_0) = f c$ is proportional to the speed of colliding electrons. For high

frequency field, the electron temperature is obtained as

$$kT_e = \left(1 + \frac{\omega^2}{N^2 \lambda^2}\right)^{-\frac{1}{2}} \frac{1}{(3\lambda\rho)^{1/2}} \cdot \frac{e E_0}{N\sqrt{2}} \quad (1.19)$$

and the dielectric constant

$$\epsilon = 1 - \frac{\omega_0^2}{(\omega^2 - j\omega N\lambda)} \quad (1.20)$$

The process of ionisation by collision with electron was explained assuming a model cross section.

$$Q = \begin{cases} \sigma (c^2 - c_i^2)^{3/2} / c_i c^2 & (c > c_i) \\ 0 & (c < c_i) \end{cases} \quad (1.21)$$

where σ is a molecular constant with the dimension of area and c_i corresponds to electron velocity at first ionization potential. Since a few electrons with exceptionally large energies usually take the main part of ionisation, Kihara considered that the velocity distribution of electrons is not disturbed by the ionisation process so that it can be taken as Maxwellian. From this reasoning he obtained the expression for the first Townsend coefficient α as

$$\alpha/p = A_0 \exp(-B_0 p/E) \quad (1.22)$$

where

$$A_0 = \frac{N}{P} \frac{\sigma}{c_i} \left(\frac{3\lambda}{P}\right)^{1/2}$$

and

$$B_0 = \frac{N}{P} \frac{m c_i^2}{2e} \left(3\lambda\rho\right)^{1/2}$$

When the gas is excited by Microwaves and the pressure is high the loss of electrons is generally attributed to diffusion but in case of excitations by radio frequencies the loss is due both to mobility and diffusion and the continuity equation in one dimensional treatment is given by

$$\frac{\delta n}{\delta t} = \nu n + D \cdot \frac{\delta^2 n}{\delta z^2} - [\bar{K} E_0 \cos \omega t] \frac{\delta n}{\delta z} \quad (1.23)$$

where \bar{K} is the mobility coefficient of electron. The breakdown condition for r.f. discharge is

$$\frac{1}{\pi^2} \left[L - 2 \bar{K} \frac{E_0}{\omega} \right] \nu_D = 1 \quad (1.24)$$

On the assumption that electrons velocity distribution is Maxwellian, the solution of equation (1.24) is

$$\exp(B_0 \frac{P}{2E}) = A_1 P L \left(1 - \frac{E}{C_2 \frac{L}{\lambda}} \right) \quad (1.25)$$

where A_1 , and C_2 are two derived molecular constants introduced by Kihara, λ is the wavelength of the applied r.f. field. This theoretical expression is in agreement with the experimental observations upto a certain limited range. Taillet and Brunet (1965) in their conference paper investigated the physical mechanism of high frequency discharge maintained by resonance. It was concluded that when a radio frequency discharge is excited with a frequency $\frac{\omega}{2\pi}$ higher than the collision frequency ν , a resonance due to the

dispersible properties of the plasma can control the steady state of the discharge and determine the value of the electron density for a given geometry and frequency. Besides the two general type of loss of electrons in high frequency discharge namely mobility and diffusion, there may be a third type of loss mechanism which becomes very prominent in case of certain gases. This is the loss by formation of ~~an~~ negative ions. Negative ions appear in gases under two circumstances (a) they may be created in the gas largely through attachment of free electrons to atoms and molecules or by dissociation of molecules in the polar phase by electron impact (b) they may be introduced in the gas by interaction of fast particles of atomic mass with surfaces or by liberation from hot surfaces. Attachment of electrons causes loss of the former as ionising agents and leads to delayed and undesirable electronic ionising events in assymetrical field breakdown. It may further act to increase the rate of loss of carriers by recom^bination.

This loss of electron by attachment is a very predominant factor in case of certain types of gas e.g. O_2 , CO_2 , SO_2 , halogens, some organic vapours etc. which have a strong affinity to attach the electrons to neutral atoms or molecules to form negative ion directly or by dissociation. The electron is bound to the molecule with an energy E_a which is called the electron affinity. The phenomenon of electron attachment to neutral atom is a common ~~xxx~~ occurrence for gases whose outer electronic shells are nearly filled. The measurement

of the ease with which an electron can attach to a neutral atom or molecule is given by the electron affinity energy which varies from about 4 volts for gases like F_2 and O_2 to nearly zero for those gases which exhibit small attachment and is -ve for those which do not. Atoms characterised by closed electronic shells are inert to extra atomic electrons. Molecules in a Σ ground state are characterised by ~~with~~ no resulting spin or angular momentum. An electron that makes ν_c impacts per sec. and under the action of the field 'E' moves μE centimeters per second and takes $\frac{1}{\mu E}$ seconds to go one centimeter. Starting with n electrons, the number dn out of 'n' that attach in going dx centimeters will depend on 'n' $\nu_c/\mu E$ and on dx . If h is the proportionality constant, then $dx = -hn \nu_c \frac{dn}{\mu E}$ and h is called the probability of attachment and is the reciprocal of the average number of impacts an electron makes to attach and μ is the mobility coefficient. Another quantity β may be defined as the probability of attachment per cm. travel in analogy to ionisation coefficient α and like wise β/ρ is a function of E/p . These two attachment coefficients are related by $h = \beta \frac{\mu E}{\nu_a}$. Hence another coefficient ν_a may be defined in analogy to ν_c , ionisation frequency, and may be called the attachment frequency and it is related to h by $h = \nu_a/\nu_c$. Taking into consideration this new mechanism, the conductivity equation for number of electrons/c.c. may be modified by putting

$[(\nu_i - \nu_a) n]$ in place of $(\nu_i n)$ as the frequency of

production of electrons, when the breakdown condition in case of high frequency discharge with Maxwellian velocity distribution of electron can be given by

$$\alpha/p = \beta/p + \frac{2}{3} \frac{\pi^{\nu} U_{ave}}{(E_e/p)(pd)^{\nu}}$$

where E_e = effective field, U_{ave} = average electron energy in e.v. The quantities α/p , β/p and U_{ave} are all functions of E_e/p , and depend on the energy distribution function. Different authors measured the variation of α/p and β/p with E/p . Considering different possibilities of energy dissipation of electron after attachment to the molecules and atoms and applying continuity equation Harrison and Geballe (1953) obtained the expression for d.c. current for applied d.c. voltage E as

$$i = i_0 \left[\frac{\alpha}{\alpha - \beta} \right] \exp [(\alpha - \beta)d] - i_0 \beta / (\alpha - \beta) \quad (1.26)$$

where d = distance between the electrodes. Variation of d.c. current with different electrode separation for values of $E/p = 60$ to $E/p = 25$ volts/cm/mm. of Hg. were obtained. Variations of β/p with α/p were obtained for air, Freon, CF_3 , SF_3 . Measurements of variation of h with E/p were made by Brodhury and Talel (1939) for gases, SO_2 , N_2O , H_2S , NH_3 , H_2O , Hcl , Cl_2 and different mixtures of attaching gases. Burch and Geballe (1957) measured the variation of β/p with E/p of oxygen. Measurements of cross section of attachment of halogens Cl_2 , Br_2 , I_2 for different energy of the electron by Healay (1958) show a maximum near 2 volts at energy of electrons for all three gases. These are some of the observations of variation of β/p with E/p .

These measurements of variation of β/p and α/p with E/p help to compare the breakdown voltage data observed in high frequency discharge of attaching gases taking the effective high frequency fields as the applied d.c. field. Harlin and Brown (1948) measured the breakdown voltage in air at 3000 MHz with the distance varying from 0.635 cm to 0.158 cm and the pressure varying from 70 mm Hg. to 2 mm Hg. Similar measurements were done by Pim (1949) at 200 MHz with the gap length varying from 0.08 cm to 0.06 cm and the pressure varying from 760 mm Hg. to 160 mm Hg. The discrepancy between these observations and theoretical plot of breakdown curve, obtained by taking help of measurements of Healey and Reed (1941) for average electron energy as function of E/p was of the order of 10%. However with increased purity of air by taking observations with fresh air after exhausting all air of the previous observation the experimental curve shows much better agreement with the theoretical curve. The data of microwave breakdown measurements in oxygen at 3000MHz with gap length 0.635 cm over a range of pressure from 70 to 2 mm Hg. are in good agreement with the theoretical value calculated with the help of measurement of α/p and β/p for oxygen from the work of Harrison and Gebballe (1953) and taking the value of $\nu_m = 3.5 \times 10^9$ p. obtained from mobility measurements of Nicl^osen Bredby^{ur} (1937) and the relation for the a.c. mobility, ω^e to get the value of E given by

$$E_e^2 = \frac{E_p^2}{2} \frac{\nu_m^2}{\nu_m^2 + \omega^2} \quad (1.27)$$

where $E_p \exp(j\omega t)$ is the applied field (high frequency) and ν_m is the collision frequency.

(b) BREAKDOWN IN PRESENCE OF MAGNETIC FIELD:

Breakdown of a high frequency discharge in a gas in presence of magnetic field has been studied previously by some workers. Townsend and Gill (1937) calculated the effect of a magnetic field on the breakdown potential of a gas under r.f. excitation and showed that the mobility of the electrons in the direction of the electric field is reduced and is given by the equation

$$\bar{K}_H = \frac{k}{1 + \omega_H^2 \tau^2} \quad (1.28)$$

where $\omega_H = \frac{eH}{mC}$, the cyclotron frequency, and τ is the time between successive collision. The diffusion coefficient D is reduced in a direction perpendicular to the magnetic field in the ratio,

$$D_H = \frac{D}{1 + \omega_H^2 \tau^2} \quad (1.29)$$

From these considerations, they observed that if the electric and magnetic fields are parallel, the diffusion perpendicular to the field is reduced and hence a smaller breakdown field is necessary. If the fields are perpendicular not only the breakdown voltage is reduced but for certain value of the magnetic field and the applied frequency resonance will occur when

$$f_{\text{applied}} = \frac{eH}{2\pi mC} \quad (1.30)$$

They carried out experiments in air for two frequencies namely 48 MHz and 30 MHz and the range of pressure varying from a few mm. Hg. to 24 mm. Hg. A decrease of the starting potential was noted for values of pressure less than the minimum without field and increase of starting potential for values of pressure greater than that at which the breakdown voltage becomes minimum when the magnetic field is applied. The values of the magnetic field were so chosen that the resonance condition was satisfied. The work has further been extended by Brown (1940) to the case of hydrogen who obtained almost similar results.

Lex, Allis and Brown (1950) carried out experiments on the breakdown voltage of a gas excited by a microwave field in presence of a transverse magnetic field. The gas used was helium containing a small admixture of Hg. vapour and they obtained breakdown curves for different values of pressure. The breakdown voltage becomes a minimum for a magnetic field (1125 gauss) for all values of the pressure, the effect of resonance being most marked at low values of pressure.

Ferritti and Vercesi (1955) performed experiments in air for frequencies ranging from 10 MHz to 30 MHz in air, the magnetic field varying from 0 to 600 gauss. They used cylindrical electrodes and observed a lowering of breakdown potential in presence of magnetic field.

Most of the work in this line was done in resonance magnetic field such that the frequency of the applied and the magnetude of the magnetic field are of such a value that

$$\left\{ \begin{array}{l} \text{applied} \\ \text{frequency} \end{array} \right. = \frac{e H}{2\pi m c} \quad \text{was satisfied.}$$

So far practically little work has been done in which the magnetic field is far removed from the resonance value. Sen and Ghosh (1963) studied the breakdown in air and nitrogen x in crossed non-resonance magnetic field applying the radio frequency voltage of frequency 8.1 MHz and 7.15 MHz respectively in the pressure range of a few microns Hg. to 500 microns Hg. They obtained a family of curves for different steady magnetic fields whose value lies within 100 gauss. It was observed that each curve for a steady crossed magnetic field has got a minimum breakdown voltage at a certain pressure which shifts to higher pressure as the magnetic field is increased. An increase of breakdown voltage was also observed on the application of transverse magnetic field within the range of pressure for which the measurements were taken. Following the theory of Kihara (1952) for breakdown of gases by radio frequency field and equivalent pressure concept introduced by Blevin and Haydon (1950) with the variation of mobility and diffusion coefficient in a magnetic field, an expression for the breakdown voltage of gases by r.f. field was developed to explain their experimental results. It was observed that the theoretical results are in fairly good agreement with experimental results. The discrepancy was attributed to uncertainties in the values of molecular constants introduced

by Kihara in his theory. They also considered the effect of attachment loss to the breakdown condition and obtained the modification in their breakdown voltage expression as

$$E_0 = (E_0^a) \cdot b + \frac{L\omega(1-b)}{2\bar{K}} \quad (1.31)$$

where

$$b = \left[\frac{\gamma_i - \gamma_a}{\gamma_i} \right]^{1/2} = \left[\frac{\alpha/p - \beta/p}{\alpha/p} \right]^{1/2}$$

and \bar{K} = mobility coefficient;

L = length of the gap, $\omega \hat{=}$ applied frequency.

E_0^a = Breakdown voltage without consideration of attachment.

E_0 = Breakdown voltage with consideration of attachment.

This new modification with the consideration of attachment loss showed a better agreement between theoretical and experimental breakdown voltage.

Bagnall and Haydon (1965) studied the pre-breakdown ionization in molecular nitrogen to establish whether the influence of a transverse magnetic field is equivalent to an increase in the gas pressure from p to $p_c = p \left(1 + \frac{\omega^2}{\gamma_i}\right)^{1/2}$ where ω is electron cyclotron frequency and γ_i a constant, which is the effective electron molecular collision frequency. When the value of E/p_c lies within the range $150 < E/p_c < 250$ $V \text{ cm}^{-1} \text{ torr}^{-1}$, γ_i has a constant value equal to $8.3 \times 10^9 \text{ p. sec.}^{-1}$ but when $E/p_c < 150$, γ_i/p must decrease with increasing E/p_c for satisfactory agreement \pm

to be maintained. The possibility of extending the concept to account for the changes in secondary ionization and the breakdown potential in nitrogen are also discussed. Considering the different complex situations of pre-breakdown ionisation at different E/P_c , they observed that the complex situation is not restricted to nitrogen so that an approach to the problem of breakdown in terms of an equivalent increase in gas pressure is by no means simple and at least for nitrogen the equivalent pressure concept is valid within a limit range of E/P values.

(5) PLASMA DIFFUSION IN A MAGNETIC FIELD.

Ordinary diffusion of electrons and ions across a magnetic field is caused by collisions. The classical binary collision diffusion theory (Normal diffusion theory) which is based upon the equation of motion of charged particles is Boltzmann's equation which predicts a greatly reduced diffusion rate in the direction across a strong magnetic field. The theory has been confirmed by experiments with low temperature plasmas, only under restricted conditions.

The development of this subject during the past decade has been highly influenced by the pioneer work of Bohm, Burhop, Massey and Williams and their collaborators (1949).

Earlier reviews of this topic have been given by Simon (1958), Lust (1960), by Paulikas (1962), by Hoh (1962), by Roesshoten (1964) and by Granoveskii (1966). An extensive discussion on these problems is also due to Lehnert (1961).

The binary collision diffusion coefficient of charged particles perpendicular to a homogeneous magnetic field B_z^H has been given by Townsend (1937)

$$D_{i\perp} = \frac{D_i}{1 + \omega_i^2 \tau_i^2} ; D_{e\perp} = \frac{D_e}{1 + \omega_e^2 \tau_e^2} \quad (1.32)$$

where $\omega_i = \frac{e H_z}{m_i}$; $\omega_e = \frac{e H_z}{m_e}$

and where D_i is the diffusion coefficient of ions in the absence of a magnetic field, e the electronic charge, m_i the ion mass, ω_i the gyrofrequency of ions, and τ_i the collision time between ions and neutrals. The same notations are valid for electrons where e is used as subscript. Here we mainly confine the discussion to a weakly and singly ionized gas in which only collisions with neutral particles are important. A rigorous treatment of diffusion coefficient (eqn. 1.32) in such a gas has been given by Chapman and Cowling (1958). Golent (1960) has extended their calculation to include the effect of electron ion interactions.

DIFFUSION IN ARC CHAMBERS:

An arc of some amperes is struck between the filament and the anode. Ionization takes place in arc column continuously, and the produced charged particles diffuse radially outwards. These form a secondary plasma body, having a temperature upto 2 e.v. around the arc, In general, electron neutral and ion neutral collisions dominate.

The secondary plasma body is kept in a steady state, partly by its diffusion at the walls and partly by radial diffusion across the magnetic field. Obviously, the characteristic folding length λ_0 , by which the plasma density decays radially, depends upon the ratio between the

diffusion rate at the secondary plasma along and across the magnetic field. The values χ_0 can be obtained by measuring the ion density distribution with probes. With these values, the transverse diffusion coefficient of ions can be determined and compared to that given in eqn. (1.32).

A correct approach of the "Normal Diffusion Theory" seemingly is simple, but in reality a very complicated, problem and was first given by Simon (1958) and then by Zharinov (1960). A more detailed analysis of this problem has been given by Tonks (1929) who approached the problem by assuming an approximate Boltzman equilibrium for the electrons along the magnetic field, but allowed a small deviation in the potential.

With a cylindrical geometry Neidigh and Simon (1958) were able to show that $\chi_0 \propto \frac{1}{H_z}$ and that $\chi_0 \propto P_0$ is in accordance with the theory of Simon. At lower pressure, $\chi_0 \propto P_0^{1/2}$ was found in agreement with the results of Tonks. As calculated from equation (1.32), Simon claimed a satisfactory agreement. Further, we found similar agreement from Bohms' data. Simon (1958) concluded that plasma oscillations have little effect on diffusion and that no drain diffusion mechanism need be proposed.

Later, Boeschten and Schwirzke (1961) studied the transverse diffusion of electrons and ions in a large drift

tube inserted in a magnetic mirror field with a small mirror ratio. The dependence $\chi_0 \propto 1/B_2$ was found in agreement with the observation by Simon and Neidigh.

Instead of inserting probes into the plasma body, Zharinov (1960) mounted his probes outside the plasma. Through holes in the anode, electron and ion currents along the corresponding lines of force could be collected. He found that the electron currents to the probes were much larger than that predicted from the electron diffusion coefficient in equation (1.32). They also found that the electron probable current suddenly increased by an order of magnitude at a certain critical magnetic field, where as the ion current remained unaltered.

DIFFUSION IN POSITIVE COLUMN:

In contradiction to the arc plasma, the radial density distribution in a cylindrical positive column immersed in a strong axial magnetic field is independent of the magnetic field. Nevertheless, the particle flux to the wall greatly decreases as a consequence of eqn. (1.32). The reduced particle loss reflects itself in the diminished rate of ions electron pair production. This decreased the axial electric field. Thus, the transverse diffusion coefficient can be estimated from the measured axial electric field.

Schottky's theory of positive column has been extended by Tonks (1934) and by Bickerton and Von Engel (1956) to include the influence of an axial magnetic field. Later Lehnert (1958) rigorously re-examined various aspects of the theory, starting from the macroscopic equations of the motion of charged particles. The corresponding extension of Langmuir and Tonk's theory has been carried out by Bickerton and Von Engel, who also experimentally verified their theory. Hoh (1960) made the same initial assumptions as those listed by Lehnert, to write the basic equations in a suitable form.

The electron temperature necessary to produce the required ionization rate $Z(T_e)$ may be obtained from a relation given by Von Engel and Steenbeck (1955). On the other hand, the axial electric field E_z is also connected with electron temperature through the energy balance relation; i.e. the energy gain of an electron in the field E_z between two collisions should, on the average, compensate the energy loss of the electron in a collision. Denoting the average fractional energy loss of the electron in one collision by $K_e(T_e)$, it was found that

$$E_z = \left(\frac{64}{\pi}\right)^{1/4} \left[K_e(T_e) \right]^{1/2} \frac{kT_e}{e \lambda_e} \quad (1.33)$$

where λ_e is the electron mean free path. The above equation is plotted by using $K_e(T_e)$ function given by Lehnert (1958)

Lehnert (1958) and by Hoh and Lehnert (1960) and Wajaizek (1960). The diffusion coefficient $D_{a\perp}$ is now expressed as a function of E_z via the functions $Z(T_e)$ and $K_e(T_e)$. Essentially the effect of an axial magnetic field B_z is to decrease $D_{a\perp}$, T_e and hence also E_z .

The use of the axial electric field as a measure of the radial diffusion has been criticized. Firstly it has been pointed out that the axial electric field is a rather insensitive measure of the particle losses (Lehnert, 1958; Eckers G. 1961). Secondly, both $Z(T_e)$ and $K_e(T_e)$ were calculated assuming a Maxwellian distribution of the electrons (Lehnert 1958, Von Engel 1955, Ecker 1961). It has been suggested that use of the radial potential distribution provides a more sensitive method for the study of radial diffusion.

In spite of these facts, experiments with a helium positive column in a magnetic field showed good agreement with the theory. Actually, in 1961 probe measurements in the experiments of Von Gierke and Wohler showed that the electron velocity distribution in a helium positive column is very nearly Maxwellian and does not change very much with the magnetic field.

Early experiments by Rohklin (1939), by Cummings and Tonks (1941) and by Reichrudel and Spivač (1941) of the positive column in magnetic fields available were found to give

results in agreement with the theories (Tonks and Langmuir 1929, 1939, Schottky, 1924); Latzer, Bickerton and Von Engel (1956) showed that the positive column behaves in accordance with the normal-diffusion theory in an axial magnetic field upto 500 gauss.

In extending these experiments to stronger magnetic fields and to longer tube lengths, Lehner^t (1958) made the important discovery that the positive column suddenly became unstable and that the transverse diffusion increased greatly when the axial magnetic field exceeded a certain critical value.

Hoh and Lehnert (1960) measured the axial electric field by the probes, as a function of the magnetic field and when compared with the normal diffusion theory, the theory fits the experimental values quantitatively upto a certain critical magnetic field.

The dependance of the critical magnetic field on the pressure, tube radius, different gases, and the end effects has been explored systematically (Hoh and Lehnert, 1960). From the currents collected by probes inside the plasma, Wasileva and Granowakki (1959) found some kind of anomalous diffusion by using probe techniques.

With stereo-streak photo graphs, Allen, Panlikes and Pyle (1966) found that the current in the positive column concentrated in a rotating screw shaped channel when the magnetic field just passed its critical value. The rotational

frequency and the wavelength of the helix, as well as the critical magnetic field measured thereby, were of decisive importance in checking and confirming the theoretical predictions made by Kadomtsev and Nedospasov (1960). The critical field measured under various conditions was in good agreement with previous experimental results (Hoh and Lehner, 1969). Further, the radial potential observed also seems to agree with theoretical predictions (Hoh, 1962), ~~Man~~ Johnson and Jerde, 1962).

In a low pressure PIG discharge, Bonnal, Brifford, Gregoire and Manus (1961) found that the radial anomalous diffusion decreased again with increasing magnetic field at magnetic fields much larger than the critical field.

Further, no rotating screw shaped current channel was observed in contrast to other experiments (Allen et al, 1960; Johnson and Jerde, 1962).

Von Gierke and Wohler (1961) have extended the experiments to include the effects of additional r.f. ionization (4 MHz), helical multipolar magnetic field^d, and a pure azimuthal magnetic field. Johnson and Jerde (1962) studied the screw instability in a magnetic field κ that smoothly rose to its full value in a time of the order of ^a few milliseconds. It was found that the critical magnetic field observed κ was three times higher than the corresponding static critical magnetic field. They ^{suggested} that the rising magnetic field induced an azimuthal electric field which depressed the onset of the

instability. Further, if the static axial electric field were replaced by an a.c. field (Paulikar, 1961), the instability disappears when the frequency of the a.c. field was higher than some tens of KHz. All these observations seem to be comparative with the screw instability theory (Kadantzer, 1960, Hoh, 1961, 1962, Johnson, 1962) although a detailed proof has not yet been given. The screw instability also seems to be operative in heavily distorted geometries (Ekman, Hoh and Lehnert, 1960) and seems to be observed in connection with microwave measurements of the electron temperature of a positive column in magnetic fields (Brown et al, 1962).

A new method for obtaining electron diffusion coefficient has been introduced by Jurst and his co-workers (1963) at the Oak Ridge National Laboratory. This method differs from Townsend's (1915) in that it requires pulsed rather than steady state operation. The technique differs from the Townsend and electrical shutter methods in that it permits the simultaneous independent evaluation of both the drift velocity and diffusion coefficients.

The theory and mechanism was however, further studied by many workers, Granovskii and Wrazokov (1964), Moushasn (1965), Granovskii (1966), Schowirzki (1966) and others.

Bulanin, Zhilinskii, Smirnov (1970) showed that the speed of enormously fast diffusion of plasma transverse to a homogeneous magnetic field found under certain conditions, does not

depend upon the type of gas (such as helium, argon, hydrogen, caesium and mercury) or pressure of neutral particles.

Takeda (1970), Takeda, Kando (1970) showed a diffusion of plasma particles in helium gas by measuring the decay time of the electron density in decaying plasma using microwave techniques. The measured decay time constants are compared with values predicted theoretically and seen to indicate a change from ambipolar diffusion to Bohm diffusion with increasing magnetic field, although the variation of the time constants with pressure is greater than expected for Bohm diffusion. An oscillation of the plasma density with a frequency of the order of tens of Kilohertz has been also detected.

Vahal (1972) has carried out calculation regarding the relation between the transverse spatial diffusion and conductivity coefficients considering a generalized Einstein relation. These coefficients have both a $1/B$ (volume dependent) terms (with B uniform magnetic field as well as $1/B^2$ (volume independent) term for a finite plasma. For an infinite plasma, the coefficients have a 'classical' $1/B^2$ dependence.

Taylor (1973) investigated diffusion in two dimensional plasmas and showed that at high magnetic fields it is always proportional to $1/B$. When this investigation is extended to three dimensions a 2D-like contribution to diffusion is found which dominates the classical ($1/B^2$) diffusion at high fields. This 2D-like contribution diminished slowly with the size of the system and is

susceptible to shear.

The plasma transport rates in the d.c. octapoles device was measured by Ohkawa, Tamako, Prater (1973) for various values of collision frequency. The diffusion rates are proportional to the inverse square of the magnetic field strength, independent of collision frequency. For short mean free path regime, the experimental results agree with the Pfirsch-Schluter theory in magnitude of the coefficient and dependence on temperature and density. For long mean free path regime, the results agree with the neoclassical theory. Okuda, Dawson (1973) has carried out calculation on the plasma diffusion across a magnetic field considering three regions; for sufficiently weak magnetic fields the diffusion coefficient is the classical one with D_1 going like B^{-2} for moderate magnetic fields ($\omega_{ce} \approx \omega_{pe}$) the diffusion rate is enhanced and D_1 is almost independent of B ; finally for very large fields ($\omega_{ce} \approx \omega_{pe}$) the diffusion coefficient gets like B^{-1} . The enhanced diffusion at moderate and high magnetic fields is dominated by collective models, i.e. by thermally excited convective modes. They have also shown that the diffusion coefficient behaves essentially the same way for a three-dimensional plasma when the magnetic field lines are closed.

The diffusion coefficient of the electrons across a magnetic ^{field} (with strength B) was also calculated by Ichimaru,

Tange (1974), in terms of the spectral function of the electric field fluctuations. For a Maxwellian plasma it is found that the diffusion coefficient contains an anomalous term D_1^* in addition to the usual classical term, D_1^* is proportional to B^{-1} when $\omega_e^2 (1 + T_e/T_i) \geq \Omega_e^2$ and to $B^{-2} \log B$.

when $\omega_e^2 (1 + T_e/T_i) \leq \Omega_e^2$, where ω_e is the electron plasma frequency, and Ω_e the electron cyclotron frequency.

The contributions of the like-particle interactions vanish identically in the diffusion coefficient.

(6) ELECTRON TEMPERATURE AND ELECTRON DENSITY MEASUREMENT
IN IONIZED GASES IN MAGNETIC FIELD.

The simple single wire Langmuir probe is undoubtedly the most widely used diagnostic tool in plasma (i.e. measurement of Electron temperature and electrondensity etc.) even to-day. Such probes, through indeed rather simple mechanically, are quite the opposite in regard to the theory of current collection. In fact in most probe applications with plasma immersed in magnetic fields, rigorous theory does not exist. Nevertheless probes continue to receive wide use since they can yield measurements with a degree of localization difficult to achieve by other methods. Even when operating in domains where approximations can not be made to reduce the theory to a tractable ^{on} form they provide relative measurements that show a great deal of the structure of the usual non-quietescent plasma.

The single probe characteristics rely on establishment of a firm plasma potential that serves as a reference for the probe voltage. In some discharges a good reference point does not exist and in others fairly large electron currents are drawn to establish the probe characteristics, which cause perturbation sufficient to alter the plasma conditions. The double ^{probe} system was proposed to alleviate this difficulty. Two probes are spaced sufficiently close to ensure uniform plasma in the intervening region. The probe system is allowed to float relative to the plasma so that no net current is

drawn from the system. The resulting potential is the "floating potential" which is sufficiently negative with respect to the plasma to repel enough ~~part~~ of the higher mobility electrons to maintain $I_e = I_+$ where I_e is the electron current and I_+ that due to ions.

Between the probes one placed a bias $V = V_1 - V_2 > 0$. positive current flows in the external circuits from probe-2 to probe-1. If the probe areas are such that $A_1 \approx A_2$ both probes are negative relative to plasma but V_1 is less negative and V_2 more negative. Thus more electrons flow to 1 and fewer to 2. For large positive V , probe 2 will draw only ion saturation current while probe 1 collect just enough net electron current to cancel the ion current to 2. The double probe characteristics is thus symmetric when $A_1 = A_2$ and the total current to either probe can not be greater than the ion saturation current. This condition has the advantage of minimizing the plasma perturbation since the current flow is small; at the same time however only the electrons in the tail of the distribution enter the probe current.

The classical theory of probe measurements in gas discharge [Langmuir (1923), Langmuir and Mott-Smith (1924) and Langmuir (1926)] contains the basic assumption that the potential difference between a probe and the plasma in which it is immersed, is confined to a space charge region or "Sheath" which surrounds the probe, i.e. it is postulated

that the plasma outside the sheath, is unperturbed by the presence of the probe. However, during the course of their researches on the low pressure mercury arc, Langmuir and his colleagues found that the potential difference existing between the axis of the discharge tube and the wall was not entirely associated with the wall sheath. The effect of this field, penetration of probe measurements was ignored until the study of Bohm, Burhop and Massey (1949). The subject has been discussed by several writers (Bayd, 1950; 1954) Wenzl, 1950, Allen and Thonemann, 1954.

Bohm et al (1949) showed that the ion current depends on the electron temperature, and not ^{on} the ion temperature because the electron temperature determines the strength of the electric field which draws the ions towards the sheath. However, their theory does not deal with the potential distribution within the sheath, nor with the increase in ion current which is observed as a probe is made more negative. Allen, Bayd and Reynolds (1956) presented a treatment which gives potential distributions both for the plasma and the sheath, together with the positive ion current voltage characteristics. This work presents a method suitable for the computation of the characteristics of electrostatic probes in case where collisions are negligible. The method is applicable only to probe of such symmetry that the charged

particle orbits can be characterized in terms of explicit time independent constant of motion. Bernstein, Irving and Rabinowitz (1959) used spherical and cylindrical probes to the collection of positive ions. The method is completely self consistent and requires no a priori separation of the discharge into plasma and sheath. They formulate the theory of spherical cylindrical probes immersed in plasma of such low density that collisions can be neglected. Medicus (1956), Boyd and Twiddy (1959) developed the practical techniques for extracting and displaying the second derivative of current by voltage to the distribution function in connection to the theory of Mott-Smith and Langmuir (1926). A simple and accurate ~~electric~~ electronic device for reducing the probe data and displaying the results on an oscilloscope is described by Harp (1963). The circuit employs commercially available plug in amplifiers to provide maximum ease of construction and high accuracy is obtained with a minimum of calibration adjustments. The probe characteristics of electron and ion currents for ~~single~~ single electrode (cylindrical and plain) and for two, three and four electrode plane probes are studied by Ionov and Tongogode (1964). They found that the most complete and correct data on electron and ion distribution in a plasma can be obtained using three and four electrode probes. A four electrode probe should be used when photo and secondary emission occurs under the action of fast particles, i.e. when studying low density cosmic plasma. Application of magnetic

field B has the immediate effect of decreasing the ratio of electron to ion saturation currents. This ratio which for $B=0$ is $(\tau_e m_+ / \tau_i m_e)^{1/2} \approx 100$ can decrease by an order of magnitude when the magnetic field is such that the probe radius and Debye length are large compared to the electron Larmor radius r_e but still small compared to the ion Larmor radius r_+ whereas the electron current that is normally available with $B=0$ is that due to diffusion into a surface surrounding the probe of radius equal to one mean free path, electrons in the magnetic field can move ~~in~~ into the probe only along the direction of the field. Electron motion along the field is essentially unhindered whereas across the field the diffusion coefficient is ~~re~~ reduced (classically) by the ratio

$$D_{\perp}/D_{\parallel} = \frac{1}{(1 + \omega_{ce}^2 \tau^2)} \quad (1.34)$$

where $\omega_{ce} \tau \approx (eB/m) (1/n\sigma v)$ is the product of the electron cyclotron frequency and mean collision time with ions or neutrals whichever is dominant. For even very low fields $\omega_{ce} \tau \gg 1$, hence classical diffusion varies as $1/B^2$ and becomes extremely small. Classical diffusion is seldom observed in practice, the cross field diffusion being given rather by Bohm expression which varies as τ_e/B .

Nevertheless ^e electron collection is mainly along the flux tube of radius $a + r_e$ with diffusion across the entire tube boundary maintaining the particle flux.

When a steady uniform positive column of a low pressure discharge is acted upon by a longitudinal magnetic field the charged particles having velocity components in all directions, spiral about the magnetic lines of force. Because of their small mass, only the electrons are appreciably affected by magnetic field. The spiralling parallel to the axis of the tube between collisions reduces the radial diffusion of electrons and thus a smaller radial electric field is required to maintain the equality between the numbers of ions and electrons arriving at the non-conducting tube wall. Since their radial velocities are the same, the radial flow of both charges will decrease. A longitudinal magnetic field should thus reduce the electron temperature and the electric field in the column.

In an attempt by Tonks (1939) to formulate a quantitative theory, use was made of theoretical results (Townsend, 1959) for the effect of a magnetic field on electron diffusion in the absence of space charge. This result was confirmed in experiments with electron swarms for photo electric currents (Bailey, 1930). It holds also for large currents ($\leq 10^{-6}$ amp) when allowance is made for the space charge. Other experiments (Cummings and Tonks, 1941) with a positive column in mercury vapour were inconclusive because of the

difficulty of interpreting probe characteristics taken in the presence of a magnetic field. Davies (1953) used the spectroscopic method to investigate the ~~fxnk~~ influence of a magnetic field on the electron temperature in a low pressure positive column in cæsium vapour. Instead of a large reduction, however, a small increase in the electron temperature was observed. The effect of a magnetic field on the loss of charges from a plasma to the walls of a closed conducting box has been shown by Simon (1955) to be controlled by currents in the plasma which are flowing essentially along the field and not by plasma oscillations as previously suggested. These arguments do not apply here because the plasma of a positive column is uniform in the direction of the magnetic field. Bickerton and Von Engel (1956) presented a probe (movable probe) measurement in a positive column in helium in longitudinal magnetic fields and the effect of such fields on the column is discussed theoretically. Bertotti (1961) developed a theory of probe characteristics in presence of a strong magnetic field; Virmant (1963) studied the Langmuir probe in presence of magnetic field, Nobata (1963) studied the characteristics of Langmuir probe in presence of a strong magnetic field. The mechanism of the collection of charged particles by Langmuir probe in a strong magnetic field has been theoretically investigated by him. The magnetic field is assumed to be sufficiently strong i.e. the electron cyclotron frequency exceeds the collision frequency of electron with neutral gas molecules,

and he obtained the following results (1) when the length of the probe in the direction of magnetic field is larger than the average gyration diameter of electrons, the probe current is determined by the gyration diameter. Whereas when the probe length is smaller, the probe current is free from the effect of magnetic field. Experimental results concerned with the saturation electron current, agree with the calculated values. From a 24 probe azimuthal Array Bol (1965) has produced a beautiful display of density fluctuations occurring for given operating conditions of the Etude Stellarator.

Uchida, Yatsu, Hagiwara, Kojima (1975) have developed the probe theory of the positive ion saturation region for a plasma having two electron temperature according to Bohm's criterion of ion sheath formation. They have checked this theory experimentally by measuring the floating potential and two electron temperatures, appearing on the probe characteristics and showed their variation with pressure and discharge current.

(B) SCOPE AND OBJECT OF THE PRESENT INVESTIGATION.

The properties of ionised gases under the action of either a longitudinal or a transverse magnetic field have been investigated by a large number of workers. Starting from the study of ionosphere and that of auroraborealis and Van Allen radiation belt where the interaction of earths magnetic field with an ionised gas is taken into consideration, the subject has assumed considerable importance due to the utilization of the magnetic fields in various geometrical shapes and forms for the confinement of plasma for thermonuclear power generation. In the present work the following properties have been investigated.

(a) Plasma conductivity in a magnetic field:

It has been shown in previous communications [Sen and Ghosh (1966), Gupta and Mandal (1967) and Sen and Gupta (1969)] that the measurement of radio frequency conductivity of an ionised gas and its variation with pressure enables us to calculate the various parameters such as electron density collision frequency and electron temperature of the gas. The application of the magnetic field enables us to study the variation of electron temperature with magnetic field also. In the interpretation of these results the only effect that has been taken into consideration is the introduction of the concept of equivalent pressure as was deduced by Blevin and Haydon (1958), namely

$$P_e = P \sqrt{1 + C_1 H^2 / P^2}$$

and it has been observed that the theoretical deduction can explain the experimental results only for small values of (H/P) . Beckman (1948) has theoretically calculated the effect of a transverse magnetic field in an ionised gas and has shown that the magnetic field (i) changes the radial electron density distribution and (ii) increases the axial electric field of the discharge. The incorporation of these deductions has enabled us to explain satisfactorily the variation of current in a glow discharge (Sen and Gupta, 1971) variation of current voltage and power in an arc plasma (Sen & Das, 1973) and the variation of intensity of line spectra in a glow discharge (Sen, Das and Gupta, 1972). It is thus worth while to study and ~~ak~~ analyse the experimental results regarding the variation of radio frequency ^{conductivity} of ionised gases in a transverse magnetic ~~field~~ field taking into consideration the theoretical deduction of Beckman. The plain of the present work is to derive the variation of r.f. conductivity from theoretical consideration and predict results for ~~some~~ some specified cases. The experimental results obtained in the present work in the radio frequency range will be compared with the theoretical calculation.

(b) Momentum Transfer Collision Cross-Section for slow electrons in magnetic field from radio frequency conductivity measurements

It has been well established that the measurement of radio frequency conductivity of an ionised gas and its va-

riation with pressure can enable us to calculate the electron density, collision frequency and electron temperature of the gas. It is the purpose of this section to show that from these measurements it is possible to obtain the momentum transfer collision cross-section of electrons with neutral molecules and to study its variation with the energy of the electrons. The measurement of the momentum transfer cross section of electrons for elastic scattering has been carried out in a large number of atomic and molecular gases for a wide range of electron energies by various standard methods such as swarm ~~xxx~~ experiments, microwave after glow method and the cyclotron resonance method. A comprehensive review of these methods and the analysis of these results has been provided by Massey and Burhop (1969). The effect of a magnetic field on the collision cross-section of electrons with atoms and molecules is important not only for understanding the nature of interaction of magnetic field with ionised gases but is also necessary for explaining the phenomena of breakdown in a magnetic field. In the present section experimental measurement of momentum transfer collision cross section ~~law~~ of low energy electrons in some molecular gases will be reported and a theoretical analysis of the experimental results will be presented.

electron temperature, radial electron density and the axial field by the probe method in case of a glow discharge in helium under a longitudinal magnetic field has been carried out by Bickerton & Von Engel (1956). The experimental results are in general agreement with the theoretical predictions. It however remains to be examined whether the application of the magnetic field changes the radial distribution of electrons from the normal Bessel function. In order to study the effect of a longitudinal magnetic field k on the glow discharge and hence to bring out clearly the salient differences from the case when the magnetic field is transverse it is proposed to study the variation of current and voltage in a glow discharge in air, hydrogen and oxygen in presence of a longitudinal magnetic field at different pressures. From the analysis of the experimental results it will be possible to obtain the axial variation of the distribution of electrons with the magnetic field and this study will enable us to understand more clearly the generation and loss mechanism of electrons in a longitudinal magnetic field.

(d) Validity of diffusion theory in radio frequency breakdown in molecular gases in longitudinal magnetic field:

It is experimentally well established that when a gas under reduced pressure is excited by means of a high frequency electric field then the electrons generated due to ionization of the gas are lost by diffusion and mobility and

if the gas is an electron attaching one then electrons are lost by attachment as well. It has further been shown by Herlin and Brown (1948) that if the gas pressure is high (a few millimeters of mercury) and the exciting frequency lies in the microwave region then the electrons are lost mainly by diffusion, starting from a molecular model, Kihara (1952) developed a method to calculate theoretically the breakdown voltage of a gas under a high frequency field taking both mobility and diffusion losses into consideration. It has been clearly demonstrated by a series of experimental work in this laboratory (Sen & Ghosh, 1963; Sen & Bharracharjee, 1965, 1966, 1967; Sen & Gupta, 1969) that both the diffusion and mobility are responsible for losses when the pressure is of the order of a few millitorr and the exciting frequency of the order of a few Megahertz. To test the limitations of the diffusion theory it is proposed here to undertake some breakdown measurement experiments when the exciting frequency is of the order of a few megahertz and the pressure of the gas is of the order of a few torr. The effect of attachment will also be taken into consideration by studying the breakdown in electron attaching gases as well.

The effect of magnetic field on the loss due to diffusion is also of considerable interest not only from the theoretical stand point but also from the consideration that

diffusion loss is also effected in a plasma which is confined by a magnetic field. Considerable experimental work has been done in this line by Lax et al (1950), Ferrithi and Veronesi (1955), Brown (1956), Sen and Bhattacharjee (1969). The object is also to test the validity of the diffusion theory in presence of the magnetic field.

(e) Diffusion of a Plasma in a Magnetic Field:

The problem of plasma diffusion in a magnetic field has been a subject of both theoretical and experimental investigation by a large number of workers. Townsend and Gill (1937) calculated that if D_H represents the diffusion coefficient in a magnetic field then

$$D_H = D / \left\{ 1 + \frac{\omega_H^2}{\nu_c^2} \right\}$$

where D is the diffusion coefficient in absence of the magnetic field and ω_H the electron cyclotron frequency and ν_c the collision frequency of the electrons with neutral molecules. It has however been shown by Bohm, Burhop, Massey and Williams (1949) that some drain diffusion mechanism enabled an arc plasma to escape across the magnetic field at a speed much faster rate than that expressed by the normal diffusion theory. Bickerton and Von Engel (1956) showed however that the positive column behaved in accordance with the normal diffusion theory upto a magnetic field of 500 gauss. In extending these results to stronger magnetic fields and to longer tube lengths Lehnert (1958) made the important observation that the positive column suddenly becomes unstable and the transverse diffusion increased greatly when the axial magnetic field exceeded certain critical value.

Hence it is thought worthwhile to undertake some experiments to measure the diffusion length in presence of magnetic field quite independent of breakdown measurements and the method of measurement proposed here involves the measurement of the d.c. conductivity of the plasma in presence of magnetic field. The results are expected to indicate the limit of the values of magnetic field and pressure under which the normal diffusion theory remains valid.

(f) Electron Temperature and Electron Density

Measurement in an Ionized gas in Transverse and Longitudinal Magnetic Fields:

The single and double probe measurement of electron temperature and electron density in an ionised gas have been the most widely used methods of determining these parameters. When a magnetic field is present of such strength that the electron cyclotron radii are comparable to the probe dimension the situation is significantly altered. Since the effective mean free paths are now comparable to probe dimensions the electron space charge saturation current is considerably reduced. It is only the mobility transverse to the field which is altered and electrons may flow along the lines κ essentially unimpeded. Thus if the magnetic field is not very large the same probe technique can be utilized to calculate the electron temperature and electron density in presence of a magnetic field.

The object of this section of the present work is to find out the essential difference between the effect of a transverse and longitudinal field in changing the electron temperature and electron density. It has been shown by Beckman (1948) that the effect of a transverse magnetic field is to increase the axial electric field and hence as has been shown by Sen and Gupta (1971) it will lead to an increase of electron temperature which is given by

$$T_{eH} = T_e \left(1 + C_1 \frac{H^2}{P^2} \right)^{\frac{1}{2}}$$

whereas it leads to a decrease in the radial electron density by the equation

$$n_H = n \exp \left[\frac{-e H r}{4 \sqrt{2 m k}} \sqrt{\frac{k}{T_e}} \right]$$

An indirect verification of the above deductions has been obtained in explaining in a satisfactory manner the variation of discharge current in the positive column in a magnetic field (Sen and Gupta, 1971) and in variation of intensity of spectral lines in a transverse magnetic field (Sen, Gupta & Das, 1972). To put the above deductions to a direct experimental test it is proposed to measure these parameters directly with the probe method in presence of the transverse magnetic field. It has been shown by the probe method (Bickerton and Von Engel, 1956) that a converse effect is observed in a longitudinal field. The electron temperature decreased and the

radial electron density increases in presence of the longitudinal magnetic field. We have also obtained similar results when we studied the variation of current and voltage in a glow discharge in presence of a longitudinal magnetic field. To have a direct experimental support of this result it is proposed to measure by the probe method the electron temperature and electron density in presen^{ce} of longitudinal field. This will help us to understand not only the interaction of the magnetic field with an ionised gas but will clearly elucidiate the difference regarding the effect of transverse and longitudinal magnetic field on these ~~xxx~~ parameters.

(c)

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