CHAPTER - I.

A. REVIEW OF PREVIOUS WORK.

1. RADIO FREQUENCY BREAKDOWN OF GASES.

a) Without Superimposed Field.

Ionization and consequent breakdown of a gas subjected to uniform alternating electric field differ in several important respects from ionization and consequent breakdown by uniform d.c. field. When a high frequency or microwave electric field is applied across a gas, charged particles in the volume of the gas are accelerated. Due to cosmic radiations electrons are always present in a given volume of a gas and through these electrons the transfer of energy from the electric field to the volume of the gas starts. Since the masses of ions are much greater than that of electrons, electrons are accelerated much more than ions and the energy transferred from the applied field to the electrons is so much greater than to ions, that for the most part, we can ignore the motion of the heavier particles. When the direction of the field changes, the direction of the force on the electron changes and the electrons will oscillate within the volume of the gas provided the walls of the container are sufficiently far apart. This is the main characteristic that distinguishes high frequency or microwave discharges from low frequency or d.c. discharges. At low frequencies, the reversal of direction of acceleration does not take place before the electron strikes the walls of the containing vessel. The electron striking the walls may cause the release of other electrons or impurity atoms from the walls, thus introducing complicated wall surface mechanisms into the situation.

At high frequencies and in the absence of any gas atoms, the electrons would oscillate out of phase with the field and no energy would be transferred. But in presence of gas atoms electrons accelerated by the electric field collide frequently with the gas atoms, thus changing the phase condition. As a result, on the average, a net transfer of energy from the field to the electrons will take place. The electrons lose energy by collisions with the gas atoms. In a favourable situation, an electron may gain sufficient energy to exceed the excitation energy level of the atom and thus lose most of its energy. This energy subsequently becomes radiation when the atom returns to its ground state. Thus the electrons lose energy not only by elastic collisions but also by inelastic collisions. The resulting energy distributions of electrons may produce sufficient number of electrons having energy comparable to ionization energy of the gas atom so that they may ionize the atoms. When this happens we have multiplication of electrons and the process may be a cumulative one. At the same time the electrons may be lost by diffusion to the side walls, recombination with the positive ions, or by attachment to neutral atoms or molecules. The relative values of these production and loss rates determine the value of the electron concentration and this in turn determines the electrical behaviour of the system. If the electric field be sufficiently large, the electron concentration attains a very large value with a luminous glow in the volume of the gas, causing the breakdown of the gas. The production and loss rates are complicated functions of the nature and the density of the gas, electric field magnitude and frequency, and the geometry of the container.

Discharges have been classified according to their mode of excitation:

(i) The E, or electrostatic, mode which is excited by the field between two conductors, and

(ii) The H, or ring, mode where the discharge current forms a closed path in the gas and the glow then appears as a luminous ring.

The mechanism of E- and H- mode of discharges are fundamentally the same and division in two types is justified only when the wavelength of the exciting voltage is large compared with the linear dimensions of the discharge tube. Comparatively little study has been made of H- discharge. The reason is probably 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 potential difference may be measured. In E- discharge the high frequency field can be applied to the gas either by external or internal electrodes. With internal electrodes, some net motion, however, small, of ions and electrons to the metal takes place, and boundary layer sheaths are established.

The general characteristics of the breakdown curves have been studied by many workers. Mention may be made of the work of Gutton (1928) who measured the potentials, between external electrodes, required to initiate the discharge in hydrogen at low pressures with oscillations of wavelengths between 3 to 5620 metres. Krichner (1930) and others used internal electrodes. Thomson (1930) examined extensively the electrodeless ring discharge. The high frequency discharges have been reviewed by Darrow (1932, 1933) and Francis and von Engel (1953).

Several ideas are advanced to explain the mechanism of E- discharge. According to the first it is thought to be analogous to a d.c. glow discharge; each electrode or nearby end walls acts as a cathode in alternate half-cycle of the applied field, and produces negative glow and the cathode fall; while the positive column fills the centre of the discharge tube. Townsend and Gill (1938) considered only the motion of free electrons in the gas under the influence of an alternating electric field ignoring all wall and electrode processes and space charge effects. Thomson (1937) derived an elementary theory of this type, regarding each electron as oscillating about a mean position in the gas. In order to ionize the gas each electron must, at some point in its path, attain enough energy for ionization and, moreover, it must hit a molecule before it returns this energy again to the field. If $E_0 \cos \omega t$ be the applied field, the energy gained in time "t" by an electron from the field must be equal to or greater than the ionization energy eV_i of the gas atom,

$$\text{i.e. } \frac{1}{2} m \left[\frac{E_0}{\omega} \cdot \frac{e}{m} \cdot \sin \omega t \right]^2 \geqslant eV_i$$

where V_i is the ionization potential of gas atoms or molecules and "e" and "m" are the charge and mass of an electron respectively. According to the second criterion, the distance traversed by the electron in time "t" must be either equal to or smaller than the mean free path λ_e of the electron in the gas,

$$\text{i.e. } \frac{E_0}{\omega} \cdot \frac{e}{m} \left[1 - \cos \omega t \right] \leqq \lambda_e$$

Only electrons which start with zero initial velocity and in zero phase of the field can perform this motion. But if there be any initial velocity and phase - ϕ then in time "t" the phase must change to + ϕ to attain the ionizing velocity i.e. $\int_0^t \cos(\omega t - \phi)\,dt$ is maximum and these can only be a minute fraction of all the electrons present. From the conditions mentioned above the author obtained an equation for the breakdown voltage which is a function of pressure and frequency and the breakdown voltage attains a minimum at a certain pressure.

Several workers observed a double minimum in the starting potential as a function of pressure. According to Guttons (1928), the double minimum is due to resonance phenomena in the gas. Gill and Donaldson (1931) found that when the field is directed along the tube only one minimum appears, but when it is across the tube, another minimum, at higher pressure, appears. They gave the explanation that at high pressure the cloud of electrons oscillates with an amplitude less than the width of the tube, ionization in the gas being balanced by diffusion. As the pressure decreases, the electrons gain more energy from the field due to their long free paths, so the starting field slowly decreases. However, the amplitude of oscillation of the electron cloud increases and when it becomes approximately equal to the distance between the walls, the loss of electrons increases rapidly and a much greater field is required to start the discharge; this accounts for the minimum at higher pressure. Measurements of this kind was also made by Thomson (1937), Githens (1940), Zouckerman (1940), Chenot (1948) and Pim (1948, 1949).

Thomson (1937) measured the starting potential for hydrogen within the pressure range 0.25 mm. to 9.5 mm. Hg. and for frequencies 1.8 Mc/s. to 99 Mc/S. For frequencies lower than 2.83 Mc/s. double minimum appeared. Githens (1940) measured the breakdown voltage in hydrogen for a wide range of frequency and pressure. He attempted to correlate the appearance of minima in the curves of breakdown voltage V_s vs. p x d ("p" being the pressure and "d" being the distance between the electrodes) with positions of the walls of the discharge tube relative to the electrodes. He concluded that the breakdown of the high frequency discharge occurs through three different process which he denoted by modes, a,b,c, each of which give rise to a minimum in V_s vs. p x d curve. Pim (1948, 1949), using small gaps ($\lesssim 1$ mm) and air measured breakdown voltage for frequencies between 100 Mc/s. and 300 Mc/s. He also found that the breakdown voltage increases when the electrodes are brought closer than a critical distance depending on frequency.

Hale (1948) tried to explain his measurements in argon and xenon over the range of frequencies 5 Mc/s. to 50 Mc/s. and at gas pressures 20 to 50 microns by assuming that the breakdown potential for high frequency field is determined by those electrons in the gas which succeed in acquiring ionizing energy in one mean free path; there is considerable divergence of the theoretically calculated breakdown voltage with experimental results in 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 ionizing 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 ionizing energy is not supported by experimental results because it has been shown by Smith (1930) that efficiency of ionization increases quite rapidly with increasing electron energies slightly above the ionizing energy. It become clear that no theory can be adequate which considers only ionization in the gas caused by oscillating electrons hitting gas molecules, while ignoring all wall and electrode processes.

A new approach to the solution of these problems was made in the experiments of Gill and von Engel (1948), who measured the starting potential of a high frequency discharge as a function of the wavelength of the applied field, in gases at very low pressure, of the order of 10^{-3} mm. Hg. Cylindrical glass vessels were placed between two parallel plates in a uniform electric field directed along the axis of the vessel. The mean free path of the electrons at these pressures is much greater than the length of the vessels used. It is found that the starting field is independent of the gas and the pressure, but depend upon wavelength of the applied field, and the dimensions and material of of the vessel, although the fully developed discharge shows the spectrum of the gas. It is also observed that for a vessel of given length "d", there is a maximum (cut - off) wavelength beyond which no field, however large, can start a discharge.

From these results Gill and von Engel deduced a theory of the initiation of the discharge. They showed that an initial electron produced in the vessel by some chance process can be multiplied by secondary emission from the end (glass) walls. An electron which starts, say, near one end-wall must traverse the tube in half a cycle, and hit the opposite end-wall with a speed which is large enough to release more than one secondary electron. The secondary electrons then repeat this motion exactly in opposite direction. These two conditions - namely, that the transit time is equal to half a cycle and the final energy of impact greater than the critical value mentioned above - determine not only the field but also the phase in which the electron starts. As the wavelength increases, the phase in which an electron must start at one end-wall becomes steadily more negative, until a critical value λ_c

is reached when the secondary electrons, in spite of their small initial velocity, are driven back on to the wall and lost. Thus no multiplication or discharge can occur when $\lambda \geqslant \lambda_c$. Llewellyn-Jones and Morgan (1951) showed that when the frequency of the applied field and pressure of the gas are sufficiently high, the amplitude of motion of the electron cloud is small and it can be much less than the linear dimensions of the discharge tube. The breakdown voltage is then independent of the nature of electrode surface and secondary electron production at the electrode surfaces does not appear to play an important part. Therefore ionization can occur by collisions between electrons and molecules.

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 x d = 15 mm. cm. of Hg. and frequency 5 Mc/s. to 70 Mc/s. or more; double minima appeared. The first minimum was not very sensitive to breakdown voltage and gas pressure as 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_s vs. p x d curve 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.

Cooper (1947) was the first who made measurements in ultra-high-frequency breakdown of air in co-axial lines and wave guides for gaps between 0.1 cm. and 0.3 cm. at gas pressure 20 cm. to 760 cm. At the two wavelengths 10.7 cm. and 3.1 cm. the breakdown field was found to be 70% of the d.c. breakdown value. Similar measurements were made by Posin (1948) who found that for 3.0 cm. wave, breakdown voltage for a 0.043 cm. gap in air under atmospheric conditions is substantially independent of pulse duration provided that duration exceeds 4 secs. The nature of spark mechanism in a cavity resonator at these wavelengths had been studied by Prowse and Cooper (1948) and by Prowse and Jasinaki (1949) using photographic and spectroscopic methods.

In several papers Brown and his colleagues (1948, 1949) have discussed the theoretical interpretation and experimental investigation of breakdown of gases in cylindrical cavities and between co-axial cylinders at a wavelength of 9.6 cm. The gap studied range from 0.06 to 7.6 cm. in air at pressures 0.1 mm. to 100 mm. Hg. The theoretical interpretation of the results are in terms of a new theory for ultra-high-frequency breakdown, which is based on the criterion that at the point of breakdown ionization 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 discharge studied, when the gap length is small compared with the wavelength, the electronic mean free path and the amplitude of oscillation. The mechanism of discharge of this type have been reviewed by Bito and Antal (1973). The more common statistical descriptions and those by independent particles applied so far are outlined and refe reference is made regarding the sphere of validity of the approximations used by these descriptions.

Considering only the diffusion of electrons, the flow of electrons constitutes a current, and if $\vec{\Gamma}$ be the current density which is equal to the product of particle concentration "n" and diffusion coefficient "D" the continuity equation for electrons is

$$\frac{\partial n}{\partial t} + \nabla . \vec{\Gamma} - P = 0 \qquad \dots (1.1)$$

where "P" is a net production rate. If ν_i be the ionization frequency then "P" is equal to $n \nu_i$. So, the continuity equation becomes

$$\frac{\partial n}{\partial t} = n\nu_i - \nabla\cdot\vec{\Gamma} \qquad \ldots (1.2)$$

~~Amm~~ Assuming the gas between infinite parallel plates and approach to breakdown is so slow that $\frac{\partial n}{\partial t}$ can be ignored and solving eqn. (1.2) with the aid of boundary condition $n = 0$ at $x = \pm \frac{d}{2}$ we get the condition of breakdown as

$$D\left(\frac{\pi}{d}\right)^2 = \nu_i \qquad \ldots (1.3)$$

More generally, the solution for a vessel of any geometry in a uniform field is

$$\frac{D}{\Lambda^2} = \nu_i \qquad \ldots (1.4)$$

where Λ is a quantity known as characteristic diffusion length. By analogy with the first Townsend coefficient for d.c. ionization where the electron loss is controlled by mobility, a high frequency ionization coefficient where loss is controlled by diffusion, is defined as

$$\xi = \frac{\nu_i}{DE^2} = \frac{1}{\Lambda^2 E^2} \qquad \ldots (1.5)$$

Values of ξ have been calculated by Herlin and Brown (1948) and Mc Donald and Brown (1949). They are given as a function of E/p and λp where λ is the wavelength. The data are then used to calculate breakdown voltage in air between co-axial cylinders and results are found to be in close agreement with the experimentally determined values. The ratio of the two ionization coefficients may be written as

$$\frac{\eta}{\xi} = \frac{D}{\mu} \qquad \ldots (1.6)$$

which is a measure of the average energy of electrons. Thus, in principle, d.c. ionization coefficient η can be determined ~~fm~~ from the a.c. ionization coefficient if the average energy of electron as a function E/p is known. This can be done correctly only for those cases where the electron energy distribution functions are essentially the same. When 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 a h.f. field is closely the same as that of electrons in a static field equal in magnitude to the ~~xm~~ r.m.s. value of h.f. field. Holstein (1946) interpreted the breakdown criterion having a general character, given in relation (1.3), with the aid of the introduction of the direct current analogy. He then obtained a relation between the breakdown field "E", the gap length "d" and the gas pressure "p" as

$$(pd)^2 = \frac{\pi^2 k T_e}{e\left(\frac{E}{p}\right)\left(\frac{\alpha}{p}\right)} \qquad \ldots (1.7)$$

where α is the Townsend's first ionization coefficient, "e" is the electronic charge, T_e is the electron temperature and "k" is the Boltzmann constant.

In a series of theoretical papers on h.f. discharge, Morganau 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 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 discripancy is explained by the consideration that electron must also be removed by other mechanism.

Kihara (1952) adopting a proper molecular model for collision processes between gas molecules and charged particles such as ions or electrons introduced cross - sections of molecule for elastic, exciting and ionizing collisions into Boltzmann theory to establish the molecular kinetic theory. Dividing the whole problem into different parts Kihara obtained absolute expressions 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 gas with uniform temperature and pressure and nonuniform density and applied external field, Kihara also obtained the well known relation between mobility and diffusion coefficient viz.

$$D = \mu \cdot \frac{kT_e}{e}$$

Assuming the coefficient of elastic scattering between gas molecules and electrons or ions inversely proportional to the relative speed between the colliding particles Kihara obtained an expression for the difference of electron temperature and the gas temperature in terms of applied electric field and frequency. Since a few electrons with exceptionally large energies usually take main part in ionization, Kihara considered that the velocity distribution of electrons is not disturbed by the ionization process and remains Maxwellian. He then obtained the breakdown condition as

$$\exp\left(B_0 p/2E\right) = A_1 pL\left(1 - \frac{E/B_0 p}{CL/\lambda}\right) \qquad \ldots (1.8)$$

where A_1 and C are two molecular constants introduced by Kihara, λ is the wavelength of the applied r.f. field. This theoretical expression is in agreement with observations upto a certain limited range.

Taillet and Brunet (1965) in their conference paper investigated the physical mechanism of high frequency discharges maintained by resonance. It is concluded that when a r.f. discharge is excited with a frequency $\omega/2\pi$ higher than the collision frequency ν_c, a resonance due to dispersive 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 ~~fk~~ 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 negative ion. 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 and rarely by dissociation of molecules in a 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 an undesirable electronic ionising events in asymmetrical field breakdown. It may further act to increase the rate of loss of carriers by recombination.

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 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 $\mathcal{E}_a$ which is called the electron affinity. The phenomenon of electron attachment to neutral atom is a common occurance for gases whose outer electronic shells are nearly filled. The measure of the ease with which an electron can attach to neutral atom or molecule is given by the electron affinity energy which varies form 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 no resulting spin or angular momentum. Their electrons form closed groups and hence also show inertness to extra molecular electrons. Gases such as H_2 , N_2 and CO fall into this group and show no electron attachment.

The attachment of electrons in gases was not clearly perceived until about 1910 when the vacuum techniques and purification of gases led Franck and Pohl (1910) to study ion mobilities in inert gases and N_2 and they noted the presence of free electrons at higher pressures. The studies of Townsend (1914) and his co-workers Lattey, Tizzard (1912) had led to the recognition of the existence of free electrons at lower pressures in gases. The experimental works leading to the ultimate discerning of electron attachment were the studies of the variation of carrier mobilities in air as a function of pressure by A.F.Kovarick (1910) with the Rutherford A.C. method of mobility measurements using photo electrons and those of E.M.Wellisch (1915, 1916, 1917) using the same method but producing ions by α -particles from Po in an auxiliary field below a gauge following the method of Franck.

Loeb (1921, 1923, 1924) in a series of work investigated the possible theories of formation of negative ion from electron and neutral molecules proposed by J.J.Thomson and by Wellisch. Mobilities of the carriers formed by photo electrons liberated from one plate of a parallel plate condenser by a beam of ultra violet light, focussed on it at a glancing angle from a quartz lens, were determined at different pressures for air using the Rutherford a.c. method. The results in general confirmed the results of previous observers, yielding a single class of carriers whose mobilities became abnormal below 150 mm. pressure. The values of these mobilities were also found to be a function of the frequency of commutation in agreement with earlier results. The manner of introduction of ultraviolet light into the chamber reduces the stray light effect and it was found that the asymptotic feet of the curves observed below 200 mm. pressure were a real and important feature of the phenomemon. The mathematical theory of J.J.Thomson was adapted to fit these measurements and on the basis of the equation so deduced the chance of ion formation "n" was determined from experiment. Within the limits of accuracy of the method, "n" was found to be equal to about 2.5 x 10^5 for pure and dry air. The current voltage curves computed on the basis of the Thomson theory were compared with the observed curves and marked general similarities were noticed below 200 mm. pressures. The asymptotic feet of the computed and observed curves lie close together, which is significant in as ~~mm~~ much as it is these portions of the observed curves that yield the abnormal values of the mobility. Deviations of the observed curves from those computed at the higher and lower pressures are explained. Repetition of the Wellisch experiments shows that what he termed "free electrons" are the carriers of abnormally high mobilities observed by the earlier workers. It is shown that as the electrons do not attach to N_2 molecules, and that as the values of "n" obtained in pure O_2 and in N_2 with small quantities of O_2 in it agree with the values found for air on the basis of its oxygen content, one must conclude that it is to the O_2 molecules in air that the electrons attach. The value of "n" for O_2 molecules is then 5×10^4.

Most of the methods of measurements of "n", the attachment probability were handicapped due to different reasons. Because of the very low values of "n" in many gases, as well as the difficulty of achieving groups of electrons of narrow energy spread in gases of sufficient density for appreciable attachment, no significant studies on the appearance potentials of ions and energy of ion formation with indentification of ion species formed by mass spectrographs have been successful, until when Hickam and Fox (1954) applied their retarding potential difference method to the study of attachment of electrons to SF_6 combined with mass spectrograph revealing a new technique of investigation.

An electron that makes ν_c impacts per second and under the action of the field "E" moves μE centimeters per second takes $1/\mu E$ 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 $dn = -hn\nu_c dx/\mu E$. "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 ionization coefficient " α " and likewise β/p is a function of E/p. These two attachment coefficients are related by $h = \beta\mu E/\nu_c$. Hence another coefficient ν_a may be defined in analogy to ν_i, ionization 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 continuity 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

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

where E_e = effective field U_{avg} = average electron energy in eV. The quantities α/p, β/p and U_{avg} 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

$$i = i_0[\alpha/(\alpha-\beta)]\exp[(\alpha-\beta)d] - i_0\frac{\beta}{\alpha-\beta} \qquad \ldots (1.9)$$

where "d" is the 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 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 Bradbury and Tatel (1934) 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 (1938) show a miximum near 2 volts of energy of electrons for all the three gases. These are the 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 field as the applied d.c. field. Herlin and Brown (1948) measured the breakdown voltage in air at 3000 Mc/sec. 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 2000 Mc/sec. 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 curves, obtained by taking help ~~k~~ of measurements of Healey and Reed (1941) for average electron energy as a function of E/p was of the order of 10%. However, with increased purity of air - by taking every observation 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 measurement in oxygen at 3000 Mc/sec. with gap length 0.635 cm. over a range of pressures from 70 to 2 mm. Hg. often are in good agreement with the theoretical value calculated ~~xk~~ with the help of measurements of α/p and β/p for oxygen from the work of Harrison and Geballe (1953) and taking the value of $\nu_m = 3.5 \times 10^9\ p$ obtained from mobility measurements of Nielsen and Bradbury (1937) and the relation for the a.c. mobility to get the value of E_e given by

$$E_e^2 = \frac{E_p^2}{2} \cdot \frac{\nu_m^2}{\nu_m^2 + \omega^2} \qquad \ldots (1.10)$$

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

b) With Superimposed D.C. Electric Field.

The effect of a d.c. potential on the initiation of radio-frequency discharge was first made by Krichner (1925, 1947). He studied the r.f. potential necessary for the initiation and maintenance of a discharge in different gases with different frequencies. He found, that the application of a d.c. potential, plus or minus, to a r.f. discharge maintained by an a.c. potential caused the discharge to vanish completely. He stated the reason for the effect is that the displacement which the electrons responsible for ionization can attain during one period of oscillation is of the same order of magnitude as, or smaller than, the distance between the electrodes, and that therefore these electrons can oscillate between the electrodes and give rise to a cumulative generation of ions. When a d.c. voltage of the same magnitude is superimposed on the a.c. voltage, during one half of the complete cycle the voltage becomes nearly equal to zero and the continuous oscillation of electrons for production of ions and electrons ceases due to this effective nullification of accelerating voltage and hence discharge disappears.

Varela (1947) superimposed a d.c. field, less than ~~tx~~ that required to initiate the discharge on a r.f. potential in a discharge tube with the idea of hastening the discharge and obtaining a short deionization time. It is hoped that the intensity of the discharge should be increased by the direct current, but contrary to this ~~ks~~ it is observed that the application of a d.c. potential greatly impeded the formation of discharge and higher radio frequency potential is required for initiation of the discharge and also the admittance of the discharge is found to be lower than when the ~~bxx~~ bias is applied. Recovery is some what rapid as has been expected. It is observed that ionization occur through ~~xx~~ a small angle at the voltage peak of the radio frequency cycle when the voltage is above the ionization threshold, the remaining period being utilised for removal of the ions. So when a d.c. bias of about the same value as the r.m.s. value of the alternating potential is applied, the field exceeded the ionization threshold for only one period in each cycle and the ratio of ionization time to deionization time is considerably reduced. The increase in ionization rate due to higher potential during the ionization period is not sufficient to offset the increase in deionization time and so higher r.f. voltage is required to initiate the discharge; the same effects are present during the discharge and d.c. bias produces a reduction in intensity. Varela (1947) conducted experiment at a frequency of 120 Mc/Sec. with 5 micro sec. pulses at a rate of 60 per sec. The discharge tube had Al electrodes in an atmosphere of about 5 cm. of hydrogen with 20% Argon. No quantitative theory was formulated to explain these effects.

Varnerin and Brown (1950) obtained solutions for the energy distribution function of electrons in a gas showing a very close similarity between the distribution functions under the action of a.c. and of d.c. fields. From this similarity it is possible to compare quantitatively the first Townsend coefficient of a gas with the a.c. ionization coefficient in hydrogen in which collision frequency is constant at constant pressure. Taking the total electric field,

$$\vec{E} = \vec{E}_{d.c.} + \sqrt{2}\,\vec{E}_{a.c.}\exp(j\omega t) \qquad \ldots (1.11)$$

where $E_{d.c.}$ represents the d.c. field, $E_{a.c.}$ the r.m.s. value of the a.c. field and ω its radian frequency, an effective field is defined by

$$E_e^2 = E_{d.c.}^2 + \frac{\nu_c^2}{\nu_c^2 + \omega^2} \cdot E_{a.c.}^2 \qquad \ldots (1.12)$$

where ν_c is the collision frequency.

The breakdown of a gas in a cavity occurs when the losses of electrons to the walls of the cavity are replaced by ionization in the body of the gas. When an a.c. field alone is applied, electrons are lost by diffusion. When a small d.c. sweeping field is applied, electrons are lost both by diffusion and mobility. The mathematical formulation of the breakdown condition is obtained by the consideration of these processes. The flow of electrons $\vec{\Gamma}$ is given by

$$\vec{\Gamma} = -n\mu\vec{E}_{d.c.} - D\nabla n \qquad \ldots (1.13)$$

When the electrons that are lost are replaced by new ones resulting from ionization,

$$\nabla . \vec{\Gamma} = \nu_i n \qquad \ldots (1.14)$$

where ν_i is the ionization coefficient, 'D' and μ are the diffusion and mobility coefficients respectively and 'n' is the density of electrons. Then we have when $\vec{E}_{d.c.}$ is directed along the z-axis,

$$\nabla^2 n + \frac{E_{d.c.}}{D/\mu} \cdot \frac{\partial n}{\partial z} + \nu_i n = 0 \qquad \ldots (1.15)$$

The solution of this equation is obtained subjected to the condition

$$\frac{\nu_i}{D} = \frac{1}{\Lambda^2_{d.c.}} \qquad \ldots (1.16)$$

where $\Lambda_{d.c.}$ defines a modified diffusion length given by the relation

$$\frac{1}{\Lambda^2_{d.c.}} = \frac{1}{\Lambda^2} + \left[\frac{\mu E_{d.c.}}{2D}\right]^2 \qquad \ldots (1.17)$$

Λ is the characteristic diffusion length and is given by

$$\frac{1}{\Lambda^2} = \left(\frac{\pi}{L}\right)^2 + \left(\frac{2.405}{R}\right)^2 \qquad \ldots (1.18)$$

The only difference between the breakdown condition in the a.c. - d.c. case and the pure a.c. case is the substitution of a modified diffusion length $\Lambda_{d.c.}$ for the characteristic diffusion length Λ. The modified diffusion length of a cavity is smaller than the characteristic diffusion length which means that d.c. sweeping field is equivalent to reduce the cavity dimension.

When an a.c. field alone is applied the effective a.c. ionization coefficient ξ_e is given by

$$\xi_e = \frac{\nu_i}{DE_e^2} = \frac{1}{\Lambda^2 E^2} \qquad \ldots (1.19)$$

Varnerin and Brown (1950) then equated the value of ξ_e so obtained to $1/\Lambda^2_{d.c.}E_e^2$ for the appropriate value of E_e and obtained the value of $\Lambda_{d.c.}$. From the definition of $\Lambda_{d.c.}$ the value of D/μ is obtained from which they obtained the average electron energy and first Townsend ionization coefficient in hydrogen. A theoretical breakdown curve for an $(E/p)_{d.c.} =$ 12 volts cm.$^{-1}$ torr^{-1} has been obtained using proper distribution function and the modified diffusion length. The relative increase in a.c. breakdown field with superimposed d.c. field for air at pressure of 38 mm. Hg. had been obtained by Brown (1956) upto $E_{d.c.}$ = 200 volts/cm.

Yamanoto and Okuda (1955) made some study of high frequency discharge with a d.c. voltage applied perpendicular to high frequency field, The discharge tubes were filled with air and a fitted with internal electrodes made of several materials. A high frequency (77 Mc/sec.) voltage was applied to two parallel electrodes from outside the tube; perpendicular to the high frequency field, a strong d.c. field was applied to a set of parallel electrodes placed inside the tube. The d.c. source had maximum voltage of 20 KV and maximum current capacity of 20 mA. During the experiment, the pressure was varied from 10 mm. Hg. to 10^{-4} mm. Hg. Keeping the high frequency field constant, the d.c. voltage current characteristic curves were obtained. The system give rise to three type of discharge: a d.c. glow discharge, in which a small amount of ionization is produced by the h.f. field, a typical high frequency ("diffusion region") discharge in which the d.c. electrodes act as a double probe and collect current limited by space charges and an intermediate type in which the h.f. field produces enough ions to alter substantially the cathode fall to the glow discharge. In absence of high frequency field, the cathode region mechanism depends on the value of γ , the Townsend's second ionization coeffieient at the electrode. From the properties of the intermediate type, γ can be calculated.

Rasquin (1965) studied the breakdown behaviour of air under the influence of a direct inhomogeneous electric field with a superimposed alternating electric field. With an electrode configuration which produces an inhomogeneous field, breakdown in air can occur even if the applied d.c. field is much smaller than the d.c. breakdown voltage, if a high frequency alternating field is superimposed whose peak value, however, is still small compared with the d.c. reference field. For this breakdown to occur, the d.c. field must be applied so that the electrode of greater curvature is more positive than the other. A possible explanation is that negative space charge near the inner cylinder prevents breakdown from developing. In this connection it should be noted that the density of the negative space charge takes a definite value dependent on the applied voltage. Under stationary conditions, the negative space charge is rather greater than that is necessary for the establishment of an arc. If the voltage on the electrode is changed, the space charge cannot follow the voltage for an arbitrarily high rate of change. Thus for part of the time the space charge is less than the equilibrium value and during this time breakdown can occur.

Sen and Bhattacharjee (1965) measured the breakdown voltages in the case of some rare gases (He, Ne, A) and in oxygen at a constant pressure (10 mm. Hg.) when excited simultaneously by radio frequency field (frequency 10 Mc/S.) and a variable d.c. field. It is found in all cases that the breakdown voltage is higher when both the fields are present than when the gases are excited by the radio frequency field alone and the breakdown voltage gradually increases with the increase of the applied d.c. field. The variation of breakdown field with d.c. field is of the same nature in all ~~the~~ of the gases studied. A theoretical expression for the breakdown voltage in the presence of both the r.f. field and d.c. fields deduced from the theory of electrical discharge by Kihara (1952) together with the expression of equivalent length as deduced by Varnerin and Brown (1950). Sen and Bhattacharjee (1966) also measured the breakdown voltage in case of air, hydrogen, oxygen and carbondioxide at a pressure of a few millimeters of mercury when excited simultaneously by a radio frequency field (frequency 10.3 Mc/Sec.) and a variable d.c. field varying from 0 to 240 volts/cm. It is found that the breakdown voltage increases when the d.c. field is small, and when the field is further increased it shows a maximum and then gradually falls for all the gases studied, the maximum occuring at a d.c. voltage which differs from gas to gas. Sen and Bhattacharjee (1967) have shown that, when the d.c. field is small, the dominant factor is the loss of electrons by diffusion as well as by mobility which causes the breakdown voltage to increase, but when the d.c. field is increased, contribution due to d.c. ionization causes a decrease in the r.f. breakdown voltage. Stanskii and Fridrikhov (1972) have observed the presence of a region of instability when a constant electric field of 100 - 500 volts/cm. is applied to high frequency resonant discharge in the microwave region.

c) With Superimposed Magnetic Field.

The breakdown of gases by high frequency electric fields in presence of a constant magnetic field has been studied by Townsend and Gill (1938) and by Brown (1940). Townsend and Gill (1938) calculated the effect of magnetic field on the h.f. breakdown of a gas in a magnetic field. In presence of a magnetic field of intensity "H" the electrons move in spiral with angular frequency eH/m. When the electric force is in the direction of the magnetic force, the velocity of electrons are independent of the magnetic force, and the mean energy gained by the electrons from the electric field is the same as that gained in absence of magnetic force. But if the magnetic force be in a direction perpendicular to the electric force the velocity of electrons changed by a factor

$1/(1+\omega_b^2\tau^2)$ where $\omega_b = eH/m$, the cyclotron frequency and τ is the time between successive collisions. The diffusion coefficients is also changed in the same ratio. Hence if μ and "D" are the mobility and diffusion coefficients in absence of magnetic field and μ_H and D_H are the corresponding values in presence of a perpendicular magnetic field then

$$\mu_H = \frac{\mu}{1+\omega_b^2\tau^2} \qquad \ldots (1.20)$$

and

$$D_H = \frac{D}{1+\omega_b^2\tau^2} \qquad \ldots (1.21)$$

In discharge tubes where the electric and magnetic fields are in the direction of the axis of the tube, the rate of diffusion of electrons to the surface of the tube is diminished by the action of the magnetic force and hence a smaller breakdown field is required. The effect is most noticeable in gases at low pressures. If electric and magnetic fields are perpendicular to each other, not only is diffusion reduced, but for certain values of magnetic field and applied frequency resonance will occur when $\omega = \omega_b$. Physically, this means that the magnetic field reverses the direction of electrons, without loss of energy, as the applied electric field reverses, so that although the magnetic field supplies no energy to the electron, it so alters its direction that the electron can rapidly gain energy from the electric field, provided that the motion is not frequently interrupted by collisions with the gas molecules. Thus at low pressure a resonance condition occurs when

$$f_{applied} = \frac{eH}{2\pi m} \qquad \ldots (1.22)$$

giving very low breakdown fields. At high pressures the resonance will be masked by collisions, but the losses by diffusion will still be reduced by the presence of magnetic field.

Townsend and Gill (1938) tested experimentally the theoretical investigation by measuring the electric field required to start a discharge in dry air in a large spherical bulb 13 cm. in diameter. The oscillatory field was applied by means of two large parallel plates, between which the bulb was placed, which formed the condenser of a secondary circuit loosely coupled to a high frequency continuous wave generator. The magnetic field in a direction perpendicular to the electric field was maintained by a current in a large pair of Helmholtz coils. The frequency of the applied electric field was 48 Mc/sec. and 30 Mc/sec. and the range of pressure varied from few microns to 240 microns. The magnetic field varied from 0 to 30 e.m.u. A decrease of starting field was noted for values of pressure less than the minimum without magnetic field and increase of starting field for values of pressure greater than that at which the breakdown voltage became minimum when magnetic field was applied. Brown (1940) extended the work to the case of hydrogen and obtained almost similar results.

Lax, Allis and Brown (1950) carried out experiments and explained theoretically the breakdown voltage of a gas excited by a microwave field in presence of transverse magnetic field. The gas used was helium containing a small admixture of Hg. vapour (Heg) and they obtained breakdown curves for different values of pressure. The breakdown voltage becomes a minimum ~~x~~ for a magnetic field which is independent of pressure of the gas, the effect of resonance being most marked at low values of pressure.

Ferritti and Veronesi (1955) measured breakdown voltage in air using cylindrical electrodes. The frequency of applied field was 10 Mc/sec. to 30 Mc/sec. and magnetic field varied from 0 to 800 Gauss. The pressure of the gas was 0.1 mm., 0.5 mm. and 10 mm. Hg. and in all cases they observed a lowring of breakdown voltage in presence of magnetic field.

A theoretical investigation was made of the problem of electrical breakdown in a high frequency electrodeless discharge at low pressure in the presence of a steady transverse magnetic field by Deb and Goswami (1964). It was shown that with increase in α , the ratio of cyclotron frequency to the frequency of the applied field, the breakdown field tends to increase and the main region of the curve is displaced towards longer wavelengths. The effect of angle of arrival at the end-walls of the charged particles on the breakdown mechanism had also been considered.

Bengall 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 $p_e = p\left(1+\frac{\omega_b^2}{\nu_e^2}\right)^{1/2}$ where ω_b is the electron cyclotron frequency, and is a constant, effective electron molecule collision frequency. When the value of E/p_e lies within the range $150 < E/p_e < 250$ V cm.$^{-1}$ torr^{-1} ν_c has a constant value equal to 8.3×10^9 p sec.$^{-1}$, but when $E/p_e < 150$, ν_c/p must decrease with decreasing E/p_e for satisfactory agreement 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 ionization at different range of E/p_e , 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 limited range of E/p_e values.

A high frequency single electrode discharge was considered in a coaxial resonator in the presence of longitudinal magnetic field by Ivanov and Gavrilova (1972). Experiments which confirm the theory are discussed. Under certain conditions the losses due to high frequency single electrode discharge are large, being governed mainly by the secondary emission coefficient of the electrode material and by the ratio of frequencies ω and ω_b = eH/m. High frequency resonance discharge had also been studied by Grallean (1974) in hydrogen in static magnetic field. It was shown experimentally that the gas pressure, the amplitude of the electromagnetic field and the angle between the direction of the static magnetic field and the discharge axis are the most important parameters.

Most of the works in this line were done in resonance magnetic field such that the frequency of the applied field and magnitude of magnetic field are such that $f_{applied} = \frac{eH}{2\pi m}$ was satisfied. 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 in crossed non-resonant magnetic field applying the radio frequency voltage of frequency 8.1 Mc/sec. and 7.15 Mc/sec. respectively in the pressure range of few microns of Hg. to 500 microns of Hg. They obtained a family of curves for different steady magnetic fields whose value lie 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 ~~hgk~~ 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 measurement were taken. Sen and Gupta (1969) obtained the breakdown characteristics in non-resonant magnetic field varying from 0 to 120 gauss in helium, neaon and argon and obtained the same results as Sen and Ghosh (1963), the frequency of the applied h.f. field was 4 to 12 Mc/sec. Following the theory of Kihara (1952) for breakdown of gases by radio frequency field and equivalent pressure concept introduced by Blevin and Haydon (1958) with the variation of mobility and diffusion coefficients in a magnetic field, an expression for the breakdown voltage of gases by r.f. field was developed by Sen and Ghosh (1963) to explain their experimental results. They also considered the effect of attachment loss to the breakdown condition and obtained the modification in their breakdown voltage expression as

$$E_0 = (E_0^{a})b + \frac{L\omega(1-b)}{2\mu} \qquad \ldots (1.23)$$

where

$$b = \left[\frac{\nu_i - \nu_a}{\nu_i}\right]^{1/2} = \left[\frac{\alpha/p - \beta/p}{\frac{\alpha}{p}}\right]^{1/2} \qquad \ldots (1.24)$$

μ = mobility coefficient,

E_0 = breakdown voltage without consideration of attachment,

E_0^{a} = breakdown voltage with consideration of attachment.

Sen and Bhattacharjee (1969) calculated the values of α/p at different E/p values from the r.f. (17.6 Mc/s.) breakdown measurements in air, ~~k~~ oxygen and carbondioxide within the pressure range 1 to 6 mm. Hg. and in transverse magnetic field from 0 to 1800 gauss. It was found that the α /p values calculated from Brown's theory of diffusion controlled breakdown are in better agreement with the results obtained in the literature than those calculated from Kihara's theory. Kumar, et al (1971) studied the breakdown phenomena of air in presence of parallel low intensity magnetic field over the pressure range 5 to 115 m. torr, the frequency of the applied r.f. field was 55 Mc/sec. Appreciable reduction in diffusion loss of electrons beyond 80 gauss was observed.

Ram and Sarkar (1971) studied the r.f. (16 Mc/sec.) breakdown characteristic of argon in presence of a low intensity (0 to 180 gauss), longitudinal and a high intensity (100 to 1500 gauss), non-resonant transverse magnetic field over the pressure range of 0.5 to 100 mm. Hg. In the case of longitudinal magnetic field, breakdown potential was found to increase monotonously with increasing magnetic field. But in case of transverse magnetic field the breakdown voltage was found to increase upto a certain field and then decreased slightly with increase of field above 40 mm. Hg. Sen and Jana (1977) showed the validity of diffusion theory in radio frequency breakdown in molecular gases in longitudinal magnetic field.

2. GLOW DISCHARGE CURRENT IN PRESENCE OF MAGNETIC FIELD.

Townsend (1912) worked out the motion of a random swarm of electrons moving in electric and magnetic fields in absence of space charge effects. Later work by Townsend (1938) obtained the coefficient of diffusion and mobilities of electrons in a gas in presence of electric and magnetic fields. In a magnetic field of intensity "H" the electrons move in spirals about the axes parallel to the direction of magnetic field with angular velocity also called gyro-frequency, ω_b given by

$$\omega_b = \frac{e\,H}{m}$$

'e' and 'm' are the charge and mass of the electrons. The coefficient of free diffusion of electrons D_H perpendicular to the magnetic field is given by

$$D_H = \frac{D}{1+\omega_b^2\tau^2}$$

where "D" is the normal diffusion coefficient and τ is the mean time of flight of an electron between collisions. This equation was verified experimentally by Bailey (1930) who measured the lateral diffusion coefficient of a stream of electrons in parallel electric and magnetic fields. He used photo electric currents having negligible space charge. In perpendicular electric and magnetic fields the drift velocity and hence mobility in the field direction is reduced and is given by

$$\mu_H = \frac{\mu}{1+\omega^2\tau^2}$$

where μ is the mobility in absence of magnetic field.

When a magnetic field acts upon a glow 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 current voltage characteristics of the discharge takes 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 an electric field, a magnetic field and a concentration gradient. Penning (1936) studied the effect of a transverse magnetic field upon the current voltage characteristic curve in a discharge. Beckman (1948) has calculated in detail the relations between electric field gradient, electron temperature and magnetic field, and also the new electron density distribution when a cylindrical plasma is placed in a uniform transverse magnetic field. The results agree fairly well with measurements in H_2 , N_2 , He A, Ne . The general effects of the transverse magnetic field have been investigated by Mc Bee and Dow (1953) on an unconfined glow discharge in air within the pressure range 0.3 - 10 torr, discharge current 0.05 - 0.25 A, with the magnetic field varying from zero to 7000G. They found with probe measurements that the anode and cathode fall first decrease and then increase and the positive column and the anode region become more luminous.

The variation of discharge current in a transverse magnetic field varying from 0 to 300G has been studied by Sen and Gupta (1971) in the positive column of a glow discharge in air, carbondioxide, hydrogen, helium and neon within the pressure range of 80 to 200 m. torr. They found that the current gradually rises with the increase of the magnetic field, and then 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 the pressure in all the gases. Utilizing Beckman'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 has been deduced.

When the electric and magnetic fields are in the direction of the axis of the tube, the rate of diffusion of electrons to the surface of the tube is diminished by the action of the magnetic force so that the electric force is diminished since the rate of ionization required to balance the loss due to diffusion is diminished. The effect is most noticeable in gases at low pressures and may be observed either in the positive columns of direct current discharges, or in oscillatory discharges when the electric force is in the direction of the axis of the tube.

The outward flow of ions is made to balance that of electrons by a readjustment of the radial electric field. Nearly all workers have found results consistant with this general picture, but there is disagreement on one important point, namely whether or not the magnetic field changes the radial distribution of ions and electrons from the normal Bessel function. Cummings and Tonks (1941) in a detailed theory of positive column in a longitudinal magnetic field, concluded that no change in the radial distribution is to be expected. The radial potential distribution should also be unaltered in shape but reduces in scale, although they calculated that in large magnetic fields the radial electric field may become zero or even reverse i.e. the axis may become negative with respect to the walls. They believe that the apparent axial concentration of a discharge when placed in a uniform magnetic field is due entirely to a concentration being propagated from the cathode end. In the absence of a magnetic field this would have dispersed within a short distance. Tonks (1941) has calculated approximately the dispersal effect along a cylindrical column. The solution for the radial electron and ion distribution is the sum of a series of zero order Bessel functions. The first term, which is the normal distribution, is constant along the length of the column, while successive terms decrease with distance along the column at rates which are complicated funstions of the magnetic field intensity "H" and electron temperature.

Cummings and Tonks tested their theory by experiments on the positive column of a mercury arc, at a pressure of 5×10^{-3} mm. Hg., and a current of 4 amperes. The discharge tube, 60 cm. long, was placed entirely inside a solenoid wound in sections through which suitable currents could be passed to produce a magnetic field of any desired configuration. The required parameters were measured with suitably placed probes. The tube ~~and~~ had a cylindrical oxide coated cathode, divided into eight sections. It was found that the current flowing from the cathode was collimated into a luminous beam which clearly showed the pattern of the cathode. The beam changed abruptly into a glow which filled the tube at a distance of about 30 cm. from the cathode. This glow was more intense at the axis than in the absence of a magnetic field. Probe measurements showed an increased electron density at the axis which was thought to be propagated from the cathode because the distribution tended to be normal towards the anode.

Similar experiments were performed by Rokhlin (1939) who observed the effect of a magnetic field on the radiation from a mercury vapour discharge having pressure $\sim 10^{-3}$ mm. Hg. and current varying from 1.5 amperes to 4.0 amperes. This method avoids the disadvantages of probes, but indicated only the behaviour of fast electrons of energy greater than the excitation energy of the gas. He used two solenoids spaced a few cm. apart. The magnetic fields could be coincident, giving an almost uniform field between them, or opposite giving a distorted field having strong radial components. The image of a diameter section was observed in a spectroscope, and the intensities of resonance lines (1850 Å and 2537 Å) measured by the brightness of a fluorescent probe placed in the tube. With coincident fields the discharge is visibly constricted into a cord, at first rapidly and then more slowly with increasing "H". The cord follows the lines of magnetic force. The 'radius' of the constriction is derived arbitrarily by extrapolating the linear part of the curve, and it was compared with the theoretically calculated value following the method due to Stömer (1956). The intensity distribution of various spectral lines leads to the same values of this radius and also shows that the electron energy distribution is constant across a chord of the tube. The relative intensity of several lines at the centre of the discharge attains a maximum and then decreases with increasing magnetic field. The maximum is due to two opposing effects, the increased concentration of electrons at the centre, and the decrease in their energy.

Bickerton and von Engel (1956) have made measurements on the positive column in helium at low pressure, taking great care to eliminate end effects in the presence of a magnetic field. They found that the radial distribution of charges alter appreciably from the normal Bessel function, and concluded that even in a low pressure column where Langmuir's theory normally applies, the properties of column in a magnetic field of sufficient strength are best described by Schottky's theory of ambipolar diffusion. They discussed theoretically radial potential distribution and the decrease in the gradient and electron temperature. However, when the gas becomes highly ionized the effect of partial pressure of the electron gas may become important and both the gradient and the electron temperature should then be independent of magnetic field. This has actually been observed earlier by Davies (1953) who used a spectroscopic method to measure the electron temperature in the positive column of a low pressure ceasium discharge. He found, contrary to expectations, a slight increase in electron temperature when the magnetic field was applied.

The behaviour of the positive column was also studied in presence of strong longitudinal magnetic field by Toader (1969). The gas studied were helium and neon in the pressure range 0.5 - 4 mm. Hg. and the maximum applied magnetic field was 3600 Gauss. Good agreement was obtained between collision diffusion theory and experiment upto a certain critical magnetic field. For stronger field, the longitudinal electric fields indicated a much higher diffusion rate across the magnetic field than that expected for the binary collision theory. The dependence of the critical magnetic field on the kind of gas, pressure and the tube radius were in good agreement with the predictions made by the perturbation theory of Kadomtsev-Nedospasov (1960) and Hoh(s (1960) theory for a pressure range of 0.5 - 1.5 mm. Hg. For pressures over 1.5 mm. Hg. Hoh's theory was unacceptable, while the agreement of the Kadomtsev-Nedospasov theory with experiment detoriorated.

3. ELECTRICAL CURRENT IN GAS DISCHARGES EXCITED BY RADIO FREQUENCY ELECTRIC FIELD.

The current flowing through an ionized medium by the application of a small alternating electric field had been considered in many problems of microwave work and in the analysis of ionospheric problems. For low frequencies and high pressures, the current density set up by an alternating electric field is given by Langevin (1905) mobility formula. The current remains in phase with the applied field. But in presence of high frequency field and low pressure, on the other hand, the current is represented by the formula characteristic of free electrons and is in quadrature with the applied alternating field. The intermediate case between the two has been considered by Margenau (1946). Assuming the energy distribution of the electrons to be Maxwellian, Margenau (1946) obtained expressions for the current density which has two components; one in phase with the applied alternating field and the other in quadrature with the field. Sodha (1960) obtained expressions for the conductivity when a high power radio frequency wave is incident on the plasma. He has shown that for constant mean free path and energy loss factor and for low frequencies the distribution is Druyvesteyn. The conductivity obtained by Sodha has also two components i.e. the conductivity is complex. Everhart and Brown (1949) measured the admittance in the microwave region by measuring the discharge current by applying a high frequency electric field of sufficient amplitude in helium filled in the cavity of a magnetron.

When a discharge current is maintained between two parallel plates which are used to apply the high frequency electric field of sufficient amplitude, in addition to the two components of currents in the plasma between the plates, another current flows between the plates which act as a capacitor. The capacitative current is in quadrature with the applied high frequency field. Francis and von Engel (1953) have pointed out that the capacitative current is much greater than the discharge current. The current flowing through the discharge can be estimated by loading the circuit with a resistance or a capacity which induces the same voltage drop as the discharge. In order to measure the current it is necessary to discriminate one part of gas discharge current from the capacitative current. A differential method is therefore necessary to balance out the capacitative current flowing across the electrodes. Francis and von Engel (1953) considered the total current and no mention, however, be made about the individual part of the discharge current. In order to reduce the capacitative current they considered the electrodes as small as possible. The capacitative current flowing across the external electrodes was then balanced out by a bridge method. The bridge became unbalanced when current was flowing through the gas. The unbalanced component was proportional to the discharge current and was amplified, rectified and displayed on a oscilloscope. The voltage across the electrodes was measured by means of two diodes charging an electrostatic voltmeter (Gill and von Engel, 1948). The calibration of the circuit was made by replacing the gas discharge by a known impedance and observing the displacement of the trace on the screen. They considered the impedance of a coil because capacities of resistances vary considerably in different resistances.

Penfold and Warder, Jr. (1967) reviewed a number of methods commonly used for the measurement of radio frequency plasma discharge current. A common method of current measurement which is simple in principle, is to monitor the voltage across a capacitor or an inductive element. A capacitor tends to suppress harmonics, while the inductance emphasizes them. The voltage can be determined by the use of a high voltage probe with an oscilloscope readout. Penfold and Warder, Jr. measured the current by measuring the voltage drop across a specially constructed centre tapped inductor.

Clark, Earl and New (1970) measured the gas discharge current separating out the capacitative components by a bridge method similar in principle to that employed by Francis and von Engel (1953). They also measured the maintainance voltage and phase relation between the gas discharge current and maintainance voltage from which the discharge characteristic and the complex ~~index~~ impedance were obtained.

4. MEASUREMENTS OF PLASMA PARAMETERS USING ELECTRIC PROBES.

The electric probes have long been used as a fundamental diagnostic technique for measuring the local properties of plasma. In principle the technique of probe measurement is simple though the theory underlying the probe response is complicated. Since Langmuir (1923) first developed the electric probe technique, the probe have been used to measure electron densities and temperatures in a wide variety of gasious ionized media, such as electric discharges, afterglows, ionizing shock waves, flames, MHD, plasma-jet flows, etc. The electric probes consists of one or more small metallic electrodes inserted into a plasma. Two probe configurations are commonly employed. In the single probe configuration one inserts a small electrode into the plasma. The probe is connected to a variable power supply which is used to apply various potentials positive or negative in relations to the plasma. The current collected by the probe is measured as a function of its applied potential. The applied potential is measured with respect to some convenient reference point, this is often the cathode of the discharge. A double probe consists of two electrodes of equal area that come in contact with the plasma and the current passing through the plasma between the two electrodes is measured as a function of the applied voltage between them. Since the two electrodes and the power supply of the double probe system form an isolated closed circuit, in case of a double probe there is no charge drain from the plasma which actually occurs in case of a single probe. There are certain advantages associated with the use of each of the probe systems.

The first classical probe theory due to Langmuir (1923) assumed that the potential difference between the probe and the plasma was confined to a space charge 'sheath' adjacent to the probe and the plasma outside the sheath is unperturbed by the presence of the probe. Langmuir and Mott-Smith (1924) assumed that (a) the dimension of the probe is much smaller than the mean free path of ions and electrons, (b) the thickness of the space charge sheath surrounding the probe is small compared with the mean free path of ions and electrons. Thus the sheath can be treated as a region in which ions and electrons move as in vacuum undisturbed by the collisions. Langmuir and Mott-Smith (1926) introduced the idea of orbital motion limited current collected by a spherical and a cylindrical probe. The orbital motion limited current collected by a probe when none of the undisturbed plasma particles (at infinity) capable of reaching the probe on the basis of energy consideration is excluded from doing so by intervening barriers of effective potential. Thus for orbital motion limited current the particles are reaching the probe from a region for which $R/\lambda_D \to 0$, i.e. from an infinitely thick sheath, where R is the radius of the probe and λ_D is the Debye Shielding distance. Their calculations were for a sheath of finite dimension, and the limit for an infinite sheath was taken as a special case.

If the electrons have Maxwellian distribution the number of electrons striking the probe per unit area per second is given by

$$\nu_e = \frac{1}{4} n_e \bar{v} = \frac{1}{4} n_0 \bar{v} \exp\left(-\frac{eV_p}{kT_e}\right) \qquad \ldots (1.25)$$

where $\bar{v}$ is the mean velocity of the electrons, T_e is the electron temperature; V_p is the probe potential and n_0 is the electron concentration. Langmuir assumed that the number hitting an absorbing probe would essentially be the same. This clearly refers to the situation where the mean free path is large compared with the size of the probe. Thus electrons travel from region much further away than the boundary of the sheath without making a collision. Thus with an absorbing probe the current to the probe is given by

$$I = I_0 \exp\left(-\frac{eV_p}{kT_e}\right) \qquad \ldots (1.26)$$

where I_0 is the saturation current and is given by

$$I_0 = \frac{1}{4} n_0 e \bar{v} A_p = \frac{1}{4} n_0 e A_p \left(\frac{8kT_e}{\pi m} \right)^{1/2} \qquad \ldots (1.27)$$

A_p being the effective area of the probe. Hence

$$\log_e I = \text{Const.} - \frac{eV_p}{kT_e} \qquad \ldots (1.28)$$

and

$$\frac{d}{dV_p}\left(\log_e I\right) = -\frac{e}{kT_e} \qquad \ldots (1.29)$$

The logarithim of the probe current plotted against probe potential gives a straight line whose slope gives T_e .

Langmuir and Mott-Smith (1926) have calculated the orbital motion limited current for charged particles having both monoenergetic and Maxwellian velocity distribution. Lamframbois and Parker (1973) have re-examined the orbital-motion limited current regime, and rederived the results given above on the basis of energy considerations alone. Their results apply to probes not only to circular cylinders and spheres, but to any convex three-dimensional shapes. For a given probe, even if the considerations in a plasma do not correspond to the orbital-motion-limited regime, the results are still important because they provide an upper limit for the current collected by a probe under collisionless conditions. This is because the number of charged particles which are able to reach the probe are reduced by the potential barriers which occure at finite values of R/λ_D .

Bohm (1949), considering negligible ionization in the sheath, small electric field at the plasma edge and neglecting energy distribution of ions, i.e. for mono-energetic ions, have shown that the positive ions require a certain minimum energy before the sheath can be formed. Also 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. Allen, Boyd and Reynolds (1957) starting with the equations of Bohm et al (1949), which are the same as the equation later used by Bernstein and Rabinowitz (1959) have shown that in the limit $T_i / T_e = 0$ and in the case of an ion-attaching spherical probe, the ions move in a radially inward direction. The velocity of ions arises solely from the energy they acquire in the potential field of the probe. Radial motion model of collisionless ion collection introduced by Allen et al (1959) represents the correct limit for $T_i / T_e \rightarrow 0$ for a spherical probe, both for the monoenergetic ion approximation treated by Bernstein and Rabinowitz (1959) and Maxwellian ion distribution considered by Laframboise (1966). Chen (1965) derived an equation for the cylindrical probe using the radial motion assumption and from it computed a set of cylindrical probe characteristics.

Wasserstrom, Su and Probstein (1965) considered the effect of ion-neutral collisions on ion current collection by spherical and cylindrical probes. This was later followed by Chou, Talbot and Willis (1966), Self and Shih (1968) and Bienkowski and Chang (1968). The kinetic theory approach of Chou, Talbot and Willis is the most rigorous one. The calculations required in the Chou-Talbot-Willis analysis make this analysis difficult to use. Starting with general expression of Chou-Talbot-Willis an approximate forms of the results for spherical probe have been obtained by Talbot and Chou (1969). An even simpler approach was used by Schultz and Brown (1955), Sutten (1969) and later by Thornton (1971) gave some additional justification for the procedure.

The effect of electron neutral collisions, on electron saturation current to cylindrical and spherical probes in a stationary plasma has been examined by Peterson (1971) using the Talbot-Chou (1969) approach. In the electron retarding region of the probe characteristic, which is generally used to infer the electron temperature, the effect of electron neutral collisions on the probe current is not well understood. There is evidence, both theoretical and experimental, that the classical $I = n_0 e \bar{v} A_p \exp\left(-\frac{eV_p}{kT_e}\right)$ behaviour is sufficiently altered by collisions that the method for obtaining T_e from the slope of the plot of $\log_e I$ versus - probe potential V_p no longer holds. Kirchhoff et al (1971) have concluded on the basis of both theory and experiment that a double probe is less sensitive than a single probe to collisional effects, and hence a double probe may often be used to determine electron temperature under conditions in which single probe may give spurious results.

The presence of a magnetic field further complicates probe-data interpretation. The complications introduced are two-folds. First, particles are constrained by the magnetic field to move at different rates along and across the field lines. The problem thus becomes an anostropic one. Secondly charged parficles can travel only a distance of the order of their Larmor radii $r_{L_{i,e}}$ without making a collision and when either r_{L_e} or r_{L_i} is of the order of R or less collisions come into play even when the relevant mean free path λ is large compared to R.

The simplest and most straight forward case arises when $r_{L_{i,e}} \left(= \frac{m_{i,e}\bar{v}}{eH}\right)$ the gyro-or Larmor radii of electrons and ions, are both larger than the probe radius and the Debye length. The current voltage characteristics of the probe are identical in this case to the collision less magnetic field or collisional zero-magnetic field solutions. Bickerton (1954) have shown that the inverse gradient of semi-log plot of electron current in presence of magnetic field is proportional to electron temperature (as in zero magnetic field) in the region of high negative probe potential. Identical results have been obtained by Sugawara (1966) in a weakly ionized neon discharge under moderate magnetic field and similar conclusion was made theoretically by Sanmartin (1970).

Since the probe is of finite size, it draws some of its currents along and some across the magnetic field lines. The ion current to the probe is not effected by the magnetic field, since $r_{Li} \gg r_{Le}$. However, the slowest electrons of the electron velocity distribution are influenced by the magnetic field when they move perpendicularly to the lines of force to the probe. Thus the electron current will be decreased in particular when V_p is either positive or slightly negative with respect to space even if $r_{Le} > R, \lambda$. Hence the ratio electron-to-ion saturation current is decreased even at low magnetic fields. Bickerton and von Engel (1956) measured the density of electrons by measuring the relative changes in the saturation ion current to the probe for various magnetic fields ($\leq$ 600 gauss), and using them together with the values of plasma concentration found the electron saturation current in zero magnetic field.

Considering the classical diffusion coefficient of electrons $D_{e\parallel} = D_e = \frac{1}{3}\bar{v}\lambda$ and $D_{e\perp} = \frac{D_e}{1+\omega_b^2\tau^2}$ where $D_{e\parallel}$ and $D_{e\perp}$ are the diffusion coefficients along and perpendicular to the magnetic field lines and τ is the mean collision time, Chen (1965) obtained an approximate expression for the electron saturation current to the probe in presence of a magnetic field of moderate strength as

$$I_e = \left(\frac{1}{4} n_0 e \bar{v} A_p\right)\cdot \frac{4}{3}\cdot \frac{\lambda}{R}\sqrt{\frac{D_{e\perp}}{D_{e\parallel}}}$$

The resulting anisotropy for electron flux gives rise to three very interesting phenomena:-

a) Electron saturation current is decreased below its saturation value in the absence of a field. Experiments of Sugawara (1970) later predicted the decrease using kinetic theory approach for a fully ionized collisionless gas.

b) In the vicinity of plasma potential, near the probe surface, an overshoot of potential is predicted. As a consequence of the overshoot the usual sharp knee in the current voltage characteristics of the probe at space potential becomes blurred.

c) The variation in the cross section of the probe along the magnetic field becomes unimportant for electron collection because of channeling effect of the lines of force.

A swarm of electrons in an electric field may have mean energy (or temperature) far in excess of the thermal value associated with the gas molecules even in a weak field. There is, in many case, some doubt whether the use of Maxwellian velocity distribution is permissible and even to represent a good approximation for the velocity distribution of electrons. In some problems of ionosphere and in many problems of plasma physics we require a plasma which is quiscent, stationary, homogeneous, free of electric field and currents and in which the free electrons and ions have Maxwellian distribution of energy. But the conventional methods of producing plasmas are not free of electric fields and currents which complicate the analysis.

Phelps, Fundingsland and Brown (1951) used field free plasma to determine the ratio of the real and imaginary components of plasma conductivity. They considered a afterglow plasma in the cavity of a continuous wave tunable magnetron and measured the change in the cavity ~~indepan~~ impedance due to presence of free electrons by using a standing wave detector which is sensitive only for a period of a few microseconds during the afterglow. The afterglow plasma has steep potential gradients at the boundary and nonstationary.

The bush-cathode method of producing a stationary field-free plasma was used by Persson (1962) and obtained anosotropies in the electron velocity distribution. Fromhold and Biondi (1968) considered the plasma in an encloser with absorbing boundaries and calculated the spatial density distribution.

Ekbote, Schott and Whitfield (1970) have investigated theoretically and experimentally the source of plasma which is quiscent, homogeneous, stationary and free of electric field and current. The plasma was produced by a discharge in a region between two concentric cylinders. The inner cylinder which was the anode had perforations. Quiscent diffusion plasma, free of electric field and currents, was formed in its interior having densities bweteen 10^8 to 10 10^{11} cm^{-3} and electron temperature 0.3 to 0.5 eV.

A spherical source of plasma of diameter 69 cm. free of electric field and current was designed by de Hoog and Schott (1970). The electric field in the plasma was less than 10 mV/cm. The density of electrons were between 10^8 and 10^{10} cm^{-3} while the temperature were between 10^3 and 3×10^3 °K. The radial variation of plasma density was less than 10% over about two thirds of the plasma radius in argon at gas pressures between 10^{-2} and 10^{-4} Torr.

Brodskii and Voronehev (1970) produced a current-free cessium plasma by the irradiation of mixtures of ceasium and mercury vapours by the resonant line of mercury λ = 2537 Å. The ionization of the ceasium vapour occured on impact of the second type of excited mercury atoms with ceasium atoms. It was shown that the transformation coefficient of the radiation energy of 2537 Å source into ionization energy was close to unity.

B. SCOPE AND OBJECT OF THE PRESENT WORK.

Though various properties of glow discharge have been studied by many authors, yet there are certain problems which require more exhaustive theoretical and experimental treatment. The present work undertakes to investigate some of these problems.

1. Dielectric Breakdown of Gases in Crossed Radio Frequency and D.C. Electric Fields.

It was observed by Varela (1947) and Kirchner (1947) that the breakdown potential of a gas excited by a radio frequency field increases when a d.c. field is superimposed across the discharge tube. It was expected, however, that the presence of the d.c. field would hasten ionization and a smaller breakdown voltage would be necessary, but the results were contrary to what was expected. Varnerin and Brown (1950) calculated theoretically the distribution function of electrons in an ionized gas in presence of both radio frequency and d.c. fields and they suggested that when r.f. field alone is present, the electrons are lost mainly by diffusion, but when in addition a d.c. field is applied, the electrons are lost by mobility also. This increase in loss can be compensated by the increase in generation of electrons and consequently the value of the radio frequency breakdown voltage increases. The theory was verified by Varnerin and Brown (1950) in case of air at a pressure of ~~10~~ 38 torr. where a d.c. field upto 200 volt per cm. was applied.

In a series of paper Sen and Bhattacharjee (1965, 1966 and 1967) have shown, for different gases, that when a variable d.c. field is simultaneously applied parallel to r.f. exciting field, the r.f. breakdown potential increases and shows a maximum when the d.c. field is continuously increased keeping the gas pressure constant.

In order to extend the work further and to investigate whether a d.c. potential can cause a change in r.f. breakdown potential when the d.c. field is applied perpendicular to r.f. field, it has been proposed to study the variation of r.f. breakdown potential with pressure in presence of various values of d.c. field transverse to r.f. field. When the applied d.c. field is not of appreciable value to contribute significantly to ionization, then, according to analysis given by Varnerin and Brown (1950) the effect of transverse d.c. field is expected to increase the drift of electrons along the direction of d.c. field and consequently loss of electrons will increase. To compensate this loss, a higher rate of production of electrons is necessary to cause the breakdown and this will remain true for all gas pressure. The expression for effective diffusion length proposed by Varnerin and Brown (1950) will remain identical for all pressure values and hence the nature of variation of breakdown potential with pressure is expected to remain unaltered compared to when there is no d.c. field except that at all pressure the r.f. breakdown field will be larger in presence of d.c. field than when absent. The object of this part of work is thus to see whether the breakdown phenomena will follow this process and whether the experimental results agree with the theory developed.

2. Radio Frequency Electric Field Breakdown of Gases in Presence of Magnetic Field.

(i) The breakdown of a gas excited by a radio-frequency voltage in the presence of a magnetic field, either longitudinal or transverse, has been studied previously. Mention may be made of the works of Lax et al (1950) and Ferritti and Veronesi (1955). Brown (1956) had also discussed some of the microwave breakdown measurements in the presence of a magnetic field. Sen and Ghosh (1963), working in the present laboratory, obtained the breakdown potential of some molecular gases using r.f. voltage in presence of small transverse magnetic field.

The diffusion theory of electrical breakdown of gases as a function of gas pressure is found to be consistent with the experimental observations for microwave and radio frequency field. It is worth-while to investigate whether the above breakdown conditions with variation of gas pressure remain valid in case where a magnetic field, transverse to electric field, is applied. The mechanisms responsible for the loss of electrons and the gain of electrons in the gas are affected by the presence of magnetic field. So, it is proposed to study the variation of r.f. breakdown potential of gases with gas pressure at different values of magnetic field and attempts may be made to explain the results by modifying the diffusion theory of electrical breakdown of gases at high frequency with the expected changes in the different parameters in presence of magnetic field.

(ii) While studying the high frequency breakdown potential of gases in the presence of a magnetic field in this laboratory, it has been noticed that at some specific range of gas pressure and intensity of magnetic field, the discharge once established can be extinguished either by increasing the electric field or by decreasing the magnetic field. A similar observation was made previously in a very low-pressure discharge (Francis, 1960) where the pressure of the gas was about 10^{-5} torr and the magnetic field used was below 100 Gauss. No explanation either quantitative or qualitative was given for the observations.

To investigate in detail this phenomena and to study the variation of r.f. breakdown potential with change in magnetic field, transverse to electric field, for a wide range of magnetic field values (zero to a few K.gauss) at different gas pressures, the present work has been undertaken.

In crossed electric (r.f.) and magnetic field configuration, the motion of charged particles, viz. electrons, is composed of cyclotron motion superposed over an elliptical motion. Diffusion rate in perpendicular directions of magnetic field is reduced. The rate of ionization is also effected in presence of magnetic field as pointed out by Grey Morgan (1965) while obtaining the effect of magnetic field on Townsend's first ionization coefficient. So the breakdown potential is expected to be a function of magnetic field. Considering the equivalent pressure concept of Blevin and Haydon (1958) in presence of magnetic field, the variation of breakdown potential with magnetic field is expected to be of identical in nature with the variation of breakdown potential with gas pressure.

For high value of magnetic field, it is possible that in an active discharge under certain favourable condition the loss of electrons by diffusion may not be compensated by the rate of production of electrons by collision. So the discharge will not be sustained under such conditions unless gain of energy is increased by increasing the strength of the applied electric field. Again when the magnetic field strength is very high, a much smaller electric field intensity may also create sufficient number of electrons to initiate the discharge. Strong magnetic field may keep almost all the electrons confined within the cavity without creating appreciable density gradient of particles as their numbers will be very small due to poor production by ionization in weak electric field. So the diffusion loss may be almost negligible. This discharge may be maintained by increasing the electric field until charged particle concentration becomes so large that appreciable density gradient of charged particles occurs when diffusion loss of electrons will outpace production by collisions and the discharge will go off. Grey Morgan (1965) has shown theoretically that for a very low pressure discharge, the discharge should go off when the cyclotron diameter of an average electron equals the dimension of the vessel.

So the main object of the present part of work will be to investigate in detail, the effects of the strong magnetic field on different mechanisms responsible for the gas breakdown and to verify from the experimental results the physical processes in exciting and extinguishing the discharge. The extent of quantitative agreement between experimental results and theories developed both from basic equation of motion of electrons in presence of crossed electric and magnetic field, and also by using the equivalent pressure concept in presence of magnetic field will help in understanding the processes involved in the discharge and also the range of validity of equivalent pressure concept of high values of H/p, the ratio of magnetic field to gas pressure.

3. Direct Current Glow Discharge in Longitudinal Magnetic Field.

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 masses, only the electrons are appreciably affected by the magnetic field. The spiralling parallel to the axis of the tube between collisions reduces the radial diffusion of the 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.

Detailed calculations regarding the motion of electrons in presence of both the electric and magnetic field have been carried out by Allis and Allen (1937), Tonks and Allis (1937) and Huxley (1937). A detailed experimental measurements of electron temperature, radial electron density and the axial field by the probe method in case of glow discharge in helium in presence of longitudinal magnetic field has been carried out by Bickerton and von Engel (1956). The experimental results, in general, are in agreement with the theoretical prediction of lowering of electron temperature and axial electric field and increase of radial concentration of electrons.

Toader (1969) studied the behaviour of the positive column of a d.c. glow discharge in neon and helium and observed that the axial electric field decrease with the increase of magnetic field and the effect becomes prominant with the lowering of gas pressure.

In the cathode region most of the electrons move with relatively high speed normal to the cathode surface. A longitudinal magnetic field, therefore, has little effect upon the properties of the dark space except to inhibit the radial motion of those electrons which are scattered by hitting gas molecules. The theory of the anode fall proposed by von Engel shows that a longitudinal magnetic field will have little effect on anode fall. Also it has been shown by Penning, Moubis and Jurriaanse (1946) that there is a light variation in cathode and anode fall of the order of 2.5 volts for change of discharge current of 10 mA. so that for change of discharge current less than 1 mA., both cathode and anode fall may be taken as practically constant.

The discharge current is a function of electron concentration and the axial electric field and corresponding electron energy. When a glow discharge column is placed in a longitudinal magnetic field, increase of electron concentration will tend to increase the discharge current and decrease of axial electric field and electron energy will tend to decrease the discharge current. It is expected that these two opposing effects will compete with each other and at certain value of the magnetic field the optimum value of the discharge current will flow. Thus the object of this study is to see whether the above physical process be followed by measuring the variation of discharge current in presence of longitudinal magnetic field and to ascertain the mechanisms responsible for the flow of d.c. glow discharge current in presence of longitudinal magnetic field. The theory will be developed by taking into consideration of the variations, in presence of longitudinal magnetic field, of the different parameters controlling the total d.c. glow discharge current and compared with the experimental results.

4. Electric Current in Discharge Column Excited by Radio Frequency Electric Field.

In absence of any bulk motion of the material medium, the current in the material medium is composed of the following parts (i) True current (ii) Polarisation current (iii) Vacuum displacement current. When a cavity filled with gas is placed between two electrodes connected to a source of alternating electric field, in absence of any free charge carrier, the polarisation and displacement current ~~ga~~ together ~~with~~ will account for the total current. If the electric field is of sufficient strength to create a self sustained discharge column in the cavity, then a current will also flow due to motion of true charges. So the current noted in an ammeter connected in series with the electrodes, when the discharge is 'on', is the sum of current flowing due to real motion of the charge and the capacitative current composed of polarization and displacement current. From this current if the current, that is recorded when there is no discharge i.e. no free charge, is substracted then we get the current that flows due to actual motion of charged particles of the discharge column and it is termed as discharge current.

The current flowing through an ionized medium by the application of small alternating electric field had been considered in many problems of interaction of microwaves with plasma and in the analysis of ionospheric problems. For low frequencies of applied field and high gas pressure the alternating current is practically in phase with the applied field as shown by Langevin (1905). But for very high frequencies of the applied field and low gas pressure, the current is in quadrature with the applied field. The intermediate between the two extremes had been considered by Margenau (1946). Assuming Maxwell's distribution, the current density obtained by Margenau yielded two components: one in phase with the applied alternating field and the other in quadrature with it. Sodha (1960) obtained ~~alternatingxfieldxand~~ the expression for the plasma conductivity and found it to be a complex quantity.

Brown (1949) measured the complex admittance by measuring the discharge current applying a microwave electric field of sufficient amplitude in the cavity of a magnetron field with helium.

Francis and von Engel (1953) have pointed out that the capacitative current is much greater in magnitude than the discharge current. They provided an experimental technique to measure the total discharge current balancing out, by a bridge method, the current flowing across the external electrodes without discharge when high frequency field is applied. Penfold and Warder Jr. (1967) reviewed a number of methods commonly used for the measurement of discharge current.

To measure the real part of the plasma conductivity, it is necessary to collect the real charges that are accumulated at the end walls and hence use of internal electrodes is necessary. But the two metal electrodes immersed into a plasma excited by high frequency field may produce capacitative current much higher than when the medium was neutral gas. So simple balancing out of capacitative current in this situation by using identical cavity without discharge will give much higher value of discharge current and consequently the error in measurements.

Moreover, if the gas pressure be high and frequency of the applied field be such that the ratio of electron neutral collision frequency to applied field frequency is very high then the discharge current will be practically in phase with the applied field. A thorough investigation may be made about the nature of this discharge current to find the true current voltage relation for high frequency gas discharge and also to verify the existing theories on the variation of real part of the plasma conductivity with different external parameters like applied electric field, gas pressure etc. So the main objective of this part of the work is to design and fabricate proper fast electronic circuitry to measure the real part of the discharge current after eliminating the capacitative current when the discharge is 'on'. The current voltage curves at different gas pressures expected to yield the informations regarding the variation of real part of plasma conductivity with plasma parameters. The measurement may be extended at finding the change of capacitative current in active plasma medium formed between the electrodes enclosed in the cavity.

5. Measurements in Field-Free Plasma Using Electrical Probes.

The electrical probes has long been used as a fundamental diagnostic technique for measuring the local properties of a plasma. A large number of authors studied, both theoretically and experimentally different aspects of measurements. The first classical theory on probe measurement was due to Langmuir (1923) who assumed that the potential difference between the probe and the plasma was confined to a space charge 'sheath' adjacent to the probe and the plasma outside the sheath is unperturbed by the presence of probe. Assuming Maxwellian distribution of the electrons and totally absorbing probe, an expression for the probe current is obtained for electrons and saturated ion current which ~~yild~~ yielded the values of electron temperature and electron density.

Wasserstrom, Su and Probstein (1965) considered the ion-neutral collisions on ion current collection by spherical and cylindrical probes which was later followed by Chou, Talbot and Willis (1966), Self and Shih (1968) and Bienkowski and Chang (1968). The effect of electron neutral collisions, on electron saturation current to cylindrical and spherical probes in a stationary plasma has been examined by Peterson (1971) using the Talbot-

Chou (1969) approach. In the electron retarding region of the probe characteristic, which is generally used to infer the electron temperature, the effect of electron-neutral collisions on the probe current is not well understood.

The presence of a magnetic field further complicates probe data interpretation. The complications introduced are two-fold. First, particles are constrained by the magnetic field to move at different rates along and across the field lines so that particles motions become anisotropic. Secondly, charged particles can travel only a distance of the order of their Larmor radii even when the relevant mean free path is large compared to Larmor radii. The simplest and most stright forward case arises when Larmor radii of electrons and ions are both larger than the probe radius and the Debye length when current voltage characteristic of the probe follows collisional zero magnetic field solutions. & Bickerton (1954) have shown that the inverse gradient of semi-log plot of electrons current in presence of magnetic field is proportional to electron temperature as in zero magnetic field for high negative probe potential. The identical results have been obtained by Sugawara (1966) in a weakly ionized neon discharge under moderate magnetic field and similar conclusion was made theoretically by Sanmartin (1970).

A swarm of electrons in an electric field may have mean energy (or temperature) far in excess of the thermal value associated with the gas molecules even in a weak field. There is, in many case, some doubt whether the use of Maxwellian velocity distribution is permissible and even to represent a good approximation. In some problems of ionisphere and in many problems of plasma physics, a plasma is required which is quiscent, stationary, homogeneous, free of electric field and currents and in which the free electrons and ions have Maxwellian distribution of energy. But the conventional methods of producing plasmas are not free of electric fields and currents which complicate the analysis.

Phelps, Fundingsland and Brown (1951) used field free plasma, obtained from a afterglow to determine the ratio of real and imaginary components of plasma conductivity. The bush-cathode method of producing a stationary field-free plasma used by Persson (1962) has anisotropies in the electron velocity distribution.

Ekbote, Schott and Whitfield (1970) have investigated theoretically and experimentally the source of plasma which is quiscent, homogeneous, stationary, free of electric field and currents. The plasma was produced by a discharge in a region between two concentric cylinders. Quiscent diffusion plasma, free of electric field and currents, was formed having densities between 10^{8} to 10^{11} cm.$^{-3}$ and electron temperature between 0.3 to 0.5 eV. A spherical source of plasma free of electric field and current was designed by de Hoog and Schott (1970). Brodskii and Voronehev (1970) produced a current-free ceasium plasma by the irradiation of mixtures of ceasium and mercury vapours by the resonant line of mercury.

When the electrons are allowed to diffuse out by making holes at the electrodes from a plasma columns, maintained by an external electric field, to an identical gas column but without any electric field, the charged particles will rapidly loose their initial energy by collisions with the neutrals and will be lost by processes like recombination and other loss mechanisms. Hence both the density and temperature of the electrons, at the identical gas atmosphere, will be far less in field free condition than when exciting external field is present.

In a cylindrical cavity with axial exciting electric field, if a longitudinal magnetic field is applied simultaneously to plasma columns with and without exciting field, both the electron density and temperature are expected to be effected in the presence of the magnetic field. For the plasma column maintained by an exciting electric field, presence of longitudinal magnetic field will make diffusion loss to decrease and so density of electrons increases. But as the effective mean free path decreases, the energy gained by the electrons from the external field decreases and hence electron temperature decreases. But for the plasma column without any source for supplying energy, the presence of magnetic field will confine more fast going away electrons inside the cavity due to cyclotron rotation and so the electron temperature will increase with increase of electric field. Due to this confinement of large number of electrons, the total collisions suffered by electrons in a finite time will increase with increasing magnetic field and hence larger number of electrons will be lost by recombination and other processes reducing the number density of electrons.

Probe measurements may be extended to study these two types of plasmas simultaneously under similar other parametric conditions and both in presence and in absence of magnetic field. The experimental results on electron temperature and density may be compared to ascertain the mechanisms operating in the plasmas and whether the above mentioned physical processes are valid. With this object the present part of the work is aimed at measuring the electron temperature and density and their variations in presence of magnetic field for discharge column produced in identical columns and same gas conditions, but one with exciting field present and other without any external source of energy. A comparison of results of the present investigation may be made with the results of previous workers to test the validity of extending the theory of probe measurements in obtaining the plasma parameters for a wide variety external parametric conditions and particularly in field free plasma.

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