CHAPTER I

REVIEW OF THE PREVIOUS WORK.

In this work it is proposed to study the physical processes occuring in a glow discharge and arc plasma and following lines of investigation have been undertaken:

1.1. Measurement of plasma parameters by probe technique

One of the standard methods for measurement of plasma parameters is the probe method and a variety of probes has been used to measure plasma properties. They all have the feature of being inserted into the plasma medium in order to sample plasma properties in a local region. Most probes perturb the plasma in some way, and care must be taken to ensure that plasma in the presence of the probe is the same as the plasma before the insertion of probe. The two simplest probes used in plasma measurements are (i) electrostatic (or Langmuir) and (ii) magnetic probes.

The electrostatic probe is used for the measurement of plasma properties because of its experimental simplicity and reliability. Generally a Langmuir probe is a thin insulated wire with a small exposed region at its end immersed in plasma to collect electrons or ions from the plasma, depending on the potential of the probe relative to the plasma potential. Usually some potential is applied to the probe from an external source relative to plasma potential and the resulting current flowing through the probe is recorded as a function of applied potential. Langmuir and Mott-Smith (1924) developed the theory of flow of current through such probes and the measurement of probe currents at different probe potentials can be used to obtain the values of the electron density, n_e , the ion density, n_i , the electron temperature T_e , the plasma potential V_p , the plasma floating potential V_f (i.e. the potential of the probe for zero net probe current), and the random electron and ion current densities J_{er} , J_{ir} .

If the potential of the probe is much larger than the local potential of the plasma, the probe attracts electrons and repels ions, forming a sheath region around the probes which is electron-rich, This sheath region is a few Debye lengths thick and occurs for the same reason that a given charged particle in a plasma is shielded; namely the range of the force field (potential) is limited by the tendency of the particles of opposite sign to cluster around a given charge. Thus the influence of a probe in a plasma is limited to a region about one Debye length from the probe. As the probes offer boundaries to the plasma and the properties of the plasma will change in the vicinity of the probe-boundaries, the whole probe theory becomes complicated.

In case of collisional plasma due to some secondary effects the sheath thickness increases with positive potential and electron current never saturates. The effect of ionisation on saturation probe current has been studied by Devyatou and Mal'kov(1984). They measured sink parameters for an infinite cylindrical probe and found that if the radius is small in comparison with the ionization length, then the sink parameter is determined by Bohm's expression (1949) in case of spherical probes. They considered the probe operation in presence of ionization and recombination processes in the bulk of the plasma.

According to Langmuir's probe theory the electron current through the probe is

$$I_e = I_{re} \exp. (- eV_p / KT_e) \ldots . \qquad (1.1)$$

where I_{re} denotes the random electron current and K is Boltzmann constant and T_e is the electron temperature.

$$I_{re} = \frac{1}{4} A_s n_e e \left(\frac{8 KTe}{m \pi}\right)^{1/2} \quad . . . (1.2)$$

A_s represents the effective electron collecting area of the probe and n_e is electron concentration of plasma. Assuming Maxwellian distribution of electrons, eqn. (1.1) gives the value of electron temperature T_e by the slope of the line in partial attraction regime in a semilogarithmic plot of I_e against V_p. I_{re} is the electron saturation current at space potential which can be calculated from the intersecting point of the two tangents in the characteristics ($I_e - V_p$). The procedure of drawing the tangents were:

(i) Considering the distribution to be a Maxwellian one, the tangent in the partial electron attraction regime was plotted through more points of highly negative probe potential and eqn. (1.1) is valid for electron current which is small in comparison with I_{re} (Schott, 1968).

(ii) Another tangent was plotted in electron saturation current region in such a way that it passes through maximum number of points. The saturation current region consists of two parts:

(a) Due to the growth of collective area, electron current I_e increases linearly with probe potential. (b) When probe potential is made more positive, break away from this linear increase is found. In this region, the probe becomes hot and the probe sheath expands so much that for a large voltage drop across the sheath, the electrons can further ionize in their way to probe. At the time of plotting the tangent the points just below breakaway point were utilised.

The effective probe area A_s has been considered to be equal to $2\pi r_p l$, since $l/r_p \gg 1$ where l represents the cylindrical probe length and r_p is probe radius. Thus eqn. (1.2) provides the measurement of electron density. Clements, et al (1971) measured the ionization density on a plasma jet. In their investigation the current to a negative probe in an argon plasma jet shows a strong dependance on probe bias and is of the order of magnitude less than the convection/diffusion saturation current.

The probe current decreases when the probe is biased negatively due to the repulsion of electrons. The logarithmic slope of the characteristic will correspond to the local electron temperature in this portion.

The ion and electron current cancel each other at V_f the floating potential. No electrons can reach the probe if more negative potential to the probe is applied and hence ion saturation current is drawn. The electron temperature and density can be determined by measuring electron and ion saturation current. Cherrington (1985) described the use of electrostatic or Langmuir probes for the measurement of electron density and temperature in low pressure reactive plasmas. The effect of cooling on probe has been investigated by Clements and Smy (1973). Their theoretical predictions indicate that while cooling effects can be substantial, accurate electron temperature measurements can be obtained if the probe is sufficiently small or is moved through the plasma at sufficient velocity.

Since the very inception of Langmuir's (1924 - 1926) work, the probe theory has been developed in many fields. The probe theory depends on a number of parameters which measure the various domain at which electrostatic probe can be utilised. Taking λ , mean free path of charged species, for collision with neutrals, r_p , the probe radius and λ_D , Debye shielding length ($\lambda_D = 4.9(T_e/n_e)^{1/2}$ in cm), the probe theory was found approximately valid in the collision limit given by[$\lambda \gg r_p$, $\lambda \gg \lambda_D$] . Bernstein and Rabinowtz (1959), Lam (1965) and Leframboise (1966), computed some results on the above considerations. Also Su and Lam (1963) and Cohen (1963) computed the continuum regime given by [$\lambda \ll \lambda_D \ll r_p$] , Wasserstrom, Su and Probstein (1965); Chou Talbot and Willis (1966); Bienkowski and Change (1968); Chung, Tolbot and Touryan (1975) carried out some calculations in the intermediate cases and a systematic analysis of probe theories has been provided. The probe theory becomes simple when the Debye ratio, $\xi_p = r_p/\lambda_D$ is much greater than 10 according to Chen, Etievant and Mosher (1968). They enunciated that in case of thin sheath the charge collecting area is effectively close to the geometric area of the probe or when $\xi_p \ll 1$. In case of thick sheath, the probe current is determined by orbital motion theory of Langmuir. For a suitable selection of ξ_p it is to be noted that λ_D is the characteristic of plasma source, whereas r_p is set only by the physical properties of probe. To estimate the approximate range of Debye ratio, Lamframboise (1966) computed that orbital motion theory is accurate for cylindrical probes for $\xi_p < 5$ which can easily be satisfied in experiments but orbital motion approximation is valid for $\xi_p \ll 1$ in case of spherical probes.

Some assumptions given by Schott (1968) in his orbital motion theory are as follows:

(a) In absence of probe, plasma should be homogeneous and quasi neutral.

(b) The distribution of electrons and ions should be Maxwellian with temperature T_e and T_i respectively and $T_e \gg T_i$. Electron and ion mean free path (λ_e and λ_i respectively) should be large compared to their Debye shielding distances. The charged species striking the probe structure should be absorbed and not react with the probe material as such.

(c) The sheath around the probe should have a well defined boundary.

(d) The edge effects can be neglected without losing accuracy if the sheath thickness is small compared to the lateral dimensions of the probe.

The condition of Maxwellian velocity distribution is often not maintained in case of low pressure plasma. One of the main assumptions of the conventional Langmuir probe theory is the demand for a Maxwellian distribution function of charged particles. Allen (1974) discussed the classical probe theory due to Langmuir (1924). Langmuir assumed that the potential difference between the probe and plasma was confined to a space charge sheath adjacent to the probe. Thus if the electrons have a Maxwellian distribution Boltzmann's relation gives $Z_e = Z_o$ exp. (eV/KTe). T_e = electron temperature V = negative potential. Electron temperature and electron and ion densities can be determined from this simple theory. Johanning (1984) calculated probe currents for non-Maxwellian electron energy distributions. The classical Langmuir formula for the orbital motion - limited current of cylindrical probes is simplified. The author has shown that the electron current is independent of electron energy distribution if the mean electron energy E is constant. However, Druyvesteyn (1930) showed that the actual velocity distribution might be derived from the form of probe characteristics. The selection of probe material will be such that it is resistent to heat, chemical activation and sputtering. To avoid the secondary electron emission due to particle bombardment, the work function of the probe material must be large. Chung, Talbot and Touryan (1975) reviewed the informations and findings about the perturbations of plasma due to probe.

Kumer et al (1979) made measurements of plasma density in argon discharge by Langmuir probe and microwave interferometer method. The measurement of plasma density in an argon plasma at 0.1 - 1.0 torr has been made using the ion-current data obtained from a cylindrical Langmuir probe and using a microwave phase shift interferometer.

Sanders and Pfender (1984) used the electric probe for the measurement of anode fall and anode heat transfer at atmospheric pressure of arcs in argon for different arc configurations and water-cooled anode surface close to the probe. With the help of an adjustable fine wire probe penetrating through a small hole in the centre of a flat anode they measured probe potential and electron temperature in the anode boundary layers. Pasternak and Offenberger (1975) used double ended tungsten wire probes mounted on a shaft of a small water cooled d.c. motor inside the arc chamber. Using conventional probe theory, spatially resolved probe current measurements provided electron temperature and cross-sectional density profiles of arc.

The probe technique has been extensively used in r.f. plasma. Boschi and Magistrelli (1963) have studied the effect of a sinusoidal signal of large amplitude on the characteristics of a Langmuir probe. They measured the average values of the current collected by the probe and also determined the value of electron temperature, plasma density and plasma potential. Ciampi and Talini (1967) determined the spatial average plasma conductivity by a radiofrequency probe. They used cylindrical plasma which is radially inhomogeneous. In their work the real and imaginary part of the probe impedance versus the probing frequency are found numerically for inhomogenous plasma. An application of this method is carried out in a flow facility plasma jet with Q factor measurements from 0.5 to 1.5 MHz and average conductivity values from 75 to 100 Mho/m are obtained. Lindberg (1985) has critically analysed the fundamental HF probe circuits ranging from 100 MHz to a few GHz.

Langmuir probe measurement was also used in HF discharges by Spatenka and Sicha (1985) to give experimental evidence of the presence of heavy atomic or molecular negative ions in the created polymer thin film layers.

Langmuir probe characteristics in a plasma containing electrons with drift velocities has been studied by Sawada and Miura (1980). They analysed the probe characteristics and discussed several problems and made some observations on Langmuir probe technique.

Measurement of the electron distribution function was done by some authors using probe techniques. The axial distribution of floating potential along the tube has been observed by Maciel and Allen (1985). In the ionospheric studies by Peterson et al (1981) it was observed that the distribution function may be found by using data taken by probes whose dimensions are small compared with the Larmor radius. Stenzel et al (1983) enunciated a technique for measuring the distribution function in a laboratory plasma. They used a microchannel plate whose smallest dimension was small compared to the Larmor radius. In this technique current had been collected by the probe at various geometric orientations and the data had been unfolded by a computer. A method was presented by Eremeev and Novikov (1982) for calculating the distributed parameters of a partially ionised gas in the vicinity of electric probes of spherical and cylindrical shapes, in the presence of collisions between the charged components and the neutral background.

An extensive investigation on the measurement of electron temperature and electron density in low temperature plasmas in air, hydrogen, and nitrogen with the help of cylindrical probe has been carried out by Sadhya, Jana and Sen (1979), in this laboratory. Recently Karamar (1987) measured electron density and temperature in the space of the electron beam with the help of Langmuir double probe. He also extended his measurements concerning the energy in an energetic electron beam in the vicinity of the focus of the beam.

For the practical use of Langmuir probe in deposition plasma Felts and Lopta (1987) measured the electron temperature and plasma density of different depositing plasmas as function of power, pressure and flow using double floating cylindrical type electrostatic probes and compared the results using Laframboise's theory. They also found that probes are a useful tool for characterizing sputtering and polymer forming plasmas.

Diffusion process in plasma:-

It is known that the number of electrons in the positive column plasma is controlled by the loss to the walls of the discharge tube. Since the current is constant along the positive column and is carried largely by the electrons, the loss of electrons to the walls must be balanced by corresponding gain from ionization within the column. The production of electrons throughout the interior of the column and their higher diffusion rate cause a radial distribution of the electron density which is highest at the tube axis and lowest at the walls. This electron density distribution produces a radial electric field that influences the radial movement of the electrons and ions. The electron diffusion rate is slowed down and the ion rate is enhanced by the presence of this electric field. If the mean scattering length of the charged particles is small compared to the tube radius, an ambipolar diffusion coefficient can be defined. This coefficient describes the rate at which ions and electrons diffuse while satisfying the quasi-neutrality condition $n_e \approx n_i$. The result is that the ions and electrons diffuse together at a rate which is twice that for the free diffusion of ions. The radial distribution of ions and electrons is given in terms of the ambipolar diffusion coefficient D_a as

$$n = n(0)\, J_o\left(r\sqrt{\nu_i/D_a} \right) \qquad \ldots(1.3)$$

where $n(0)$ is the electron density at $r = 0$ where r is the radius of cylindrical column and J_o is a Bessel function of zero order which for small values of $R\ (\nu_i/D_a)^{1/2}$ has a nearly parabolic dependence on r, i.e.

$$J_o(r) \approx 1 - (r/2)^2$$

where ν_i is the electron ionization frequency.

If the recombination rate at the walls is high, the electron density at that radius $r = R$ is essentially zero. So

$$J_o[R(\nu_i/D_a)^{1/2}] = 0$$

and it has the solution

$$R(\nu_i/D_a)^{1/2} = 2.40, \text{ or } \frac{1}{\nu_i} = \frac{R^2}{(2.40)^2 D_a} \qquad \ldots(1.4)$$

The term $1/\nu_i$ is the average time between ionizations. This time must equal the average time required for an electron to migrate to the wall, and this is what the right hand side of eqn.(1.4) represents.

Kosinar et al (1979) calculated the electric field, potential and charged particle concentration in a plasma sheath at an infinite electrically non-conducting plane. In the sheath, electrons were assumed to be distributed according to the Boltzmann law and the ions are accelerated in the sheath field and collide with the gas molecules.

Experimental measurements of the character of plasma diffusion was presented by Dremin and Stefanovskii (1979). It was noted that modulation of the curvature and torsion in such a system leads to the appearence of specific particle groups, analogous to the super-traped particles in the stellarators with helical windings. The method of determining plasma life times was discussed and results were used to calculate the diffusion coefficient of the plasma.

A new technique for temperature measurements in plasmas was described by Gouesbet and Valentin (1980). Its principle was to use the thermal diffusion of light particles added to the plasma as tracer.

Miyoshi and Ariyasu (1980) studied the energy distribution of electrons in hydrogen gas discharges. The energy distribution in the discharge was assumed as a balance between two processes. The first was an energy loss on collision between electron and molecule and the other was an energy gain from an electric field. The authors studied the relation between energy distribution and the discharge current, voltage and gas pressure etc. Experimental results were compared with those calculated by using the Boltzmann equation.

A method was proposed by Golubovskii (1981) in which the electron energy distribution function can be determined from probe current measurements at high pressure than are usually considered. The kinetic theory of electron current in a probe was developed for a diffusional regime, and it was shown that if the probe dimensions and the thickness of the discharges layer fulfil certain specific conditions, the distribution function is proportional to the first differential of the probe current with respect to probe potential.

In the ionospheric studies by Peterson et al (1981) it was observed that the distribution function may be found when dimensions are small compared to, or of the order of the Larmor radius of the particles being collected. Zasedka and Reztsov (1982) showed that spatial distribution of the electric field strength coincides with the spatial distribution of electron concentration and distribution of space charge density coincides with distribution of the electron concentration gradient.

A new technique has been developed by Kaya (1982) for the measurement of electron temperature. Its working principle may be stated as follows:

At two different potentials electron current is collected by the probe and measured, and the difference of the two potentials is proportional to the electron temperature. Sen, Ghosh and Ghosh (1983) measured electron temperature in glow discharge with the help of two probes (one at the axis and other at a short distance from the axis of the cylindrical tube in the same cross sectional plane). They measured diffusion voltage and determined electron temperature with previous knowledge of radial electron density profile.

Using probe measurements Maciel and Allen (1985) observed the axial distribution of floating potential along the tube.

An early problem of the transition from free to ambipolar diffusion of electrons has been re-examined by Dote (1985). Starting from the classical flow equations for electrons and positive ions and the continuity equations for charged particles, the authors have obtained a general characteristic equation of effective diffusion coefficient for electrons, where the results due to Allis have been corrected. The transition characteristics calculated from the above general equation have been extremely concrete and practical. Finally, this approach has been applied to glow discharge and an example of the characteristics has been presented as a function of plasma density for various values of electron temperature.

1.2. Measurement of diffusion coefficient of electrons in plasma.

Diffusion is a phenomenon in which charged or uncharged particles move from points of high concentration to those of low concentration. Considering the process of diffusion as due to collision of electrons with atoms it can be shown that the diffusion coefficient of electrons can be calculated to be

$$D_e = \frac{v_r \lambda_e}{3}$$

where v_r is their mean random velocity and λ_e the mean free path of the electrons. Terloud and Rietjens (1963) measured the diffusion coefficient of a highly ionized cesium vapour plasma by means of Langmuir probes and microwaves transmission. The results are compared with calculations in which the diffusion coefficient is assumed to be inversely proportional to the ion density. They observed that the decay of the electron temperature is more rapid than can be expected on the basis of elastic collision losses. When the density is decreased to an extent where collisions of ions with atoms becomes predominant, the diffusion coefficient becomes independent of n_i where n_i is the ionic concentration.

Crompton and Sutton (1952) experimentally determined the value of diffusion coefficient in case of nitrogen and hydrogen. They used two diffusion chambers with different dimensions, each was mounted in a pyrex glass envelope. One chamber was constructed of nichrome with a central disk of radius, b = 0.5 cm., height h = 1.0 cm. and annulus of outer radius c = 1.5 cm. whereas in the other the metal was silvered brass and a further division was made in the collecting electrode so that b = 0.5 cm. or 1 cm., h = 2.0 cm., c = 2.6 cm. A manometer using Apiezon oil of measured density was used to measure the pressure of the gases inside the chamber. The necessary voltages for the electrodes of the diffusion chamber were obtained from a stabilized d.c. power supply with a voltage divider across the output, which could be varied from 0 to 300 V. They found the value of diffusion coefficient $D = 1.34 \times 10^5 \mathrm{cm}^2 \mathrm{sec}^{-1}$ for hydrogen at

$$\frac{E\ (\text{electric field})}{P\ (\text{Pressure})} = 0.05\ \mathrm{V/cm}.$$

and drift velocity $v_d = 2.0 \times 10^5$ cm/sec.

For nitrogen the value of $D = 3.69 \times 10^5 \mathrm{cm}^2 \mathrm{sec}^{-1}$ for $E/P = 0.05$ and $V_d = 2.4 \times 10^5$ cm/sec. Crompton and Sutton (1952) calculated the value of D for different values of E/P and v_d for both the cases.

An experimental investigation of the electron temperature dependence of the ambipolar diffusion coefficient and electron ion recombination coefficient in the afterglow of plasma produced in neon has been made by Hess (1965). By means of a microwave cavity technique the electron density was measured as a function of time during the afterglow period of a d.c. discharge while at the same time the electron energy was increased by the power level of a microwave signal. It was found that the ambipolar diffusion coefficient D_a increases with increasing electron temperature T_e following the relation:

$$D_a \propto (1 + T_e/T_g),$$

while the recombination coefficient decreases with increasing electron temperature. Shimahara and Kiyama (1969) measured the diffusion coefficient of a plasma by the correlation of density fluctuation. An investigation was made by Kando et al (1972) in which anomalous diffusion coefficient changes in an axially decaying collisional plasma when the main mode of the instability is suppressed by the feedback technique.

Using microwave diagonostic technique in a afterglow discharge Mentzoni (1964) measured the rate of diffusion for the low current discharge. He obtained

$D_aP = 110 \pm 10\ cm^2 sec^{-1}$ and for high current discharge $216 \pm 20\ cm^2 sec^{-1}$ at pressure below 1 mm. Hg.

1.3. Measurement of electron atom collision frequency in an arc plasma by radio frequency coil probe in presence of a longitudinal magnetic field.

In plasmas continuous scattering of each particle to new directions and velocities by other particles due to many body interactions of different types occur. But these being very complicated processes it is difficult to make a quantitative analysis. However, to classify them and to find out which of them is relatively more effective, it is possible and useful also to find the statistical average of these effects.

In plasmas there are different types of collision between the particles viz.

1. Collisions among neutral particles,
2. Collisions among charged particles, and
3. Collisions between neutral and charged particles.

The collision frequency ν is the product of the number density of the colliding particles, the collision cross section and the mean value of the relative velocity. In our present investigation collisions between neutral and charged particles are taken into account to determine collision frequency in an arc plasma.

Though probe method is used for the measurement of electrical conductivity of a plasma it is not adequate due to formation of a cold boundary around its structure in case of hot plasma according to Lin et al (1955) and so unable to provide proper information on the conductivity. It is also noted that probe method is not suitable in flowing plasma, plasma jets and field free plasma. But the coil probe technique is in general a suitable means to measure conductivity.

The magnetic field linked with a solenoidal r.f. electric field induces solenoidal current into the plasma under investigation and the effect is reflected back into the probe coil; this is the fundamental principle of a r.f. coil probe diagonostic technique. Hence sometimes this method is termed an induction or magnetic flux method.

An experimental observation was made by Lin, Resler and Kantrowitz (1955) for the measurement of electrical conductivity of highly ionised argon from the search coil (probe)pick up of electromagnetic disturbances produced by the passage of shock waves through it. By solving an integral equation of the first kind with the response function $V_l(S-\xi)$ as the Karnel, where $S \longrightarrow$ the position of shock front with respect to the probe at a given time and $\xi \longrightarrow$ the axial coordinate of any point with respect to the shock front, the conductivity distribution $\sigma(\xi)$ (axial) could be determined. During each shock large signals were found to pass through the search coil, when a steady magnetic field was put off. According to them it was due to electrostatic effects. But it was pointed out by Ghosal, Nandi and Sen (1976) that this effect was due to stray capacitance effect. In fact those pick ups were due to the formation of finite capacitance between the search coil and the gas inside the shock tube. Lamb and Lin (1957) obtained identical results. Lin et al (1955)eliminated these effects by designing a centre tapped search coil arrangement.

An experiment was performed by Blackman (1959) to reduce the inductance of a coil wound around a plasma column by the shielding effect in the electrically conducting plasma. The frequency of a circuit has been changed by the reduced inductance. With the help of the above idea Savic and Boult (1962) devised a frequency modulation circuit to determine gas conductivity and boundary layer thickness in a shock tube.

Rosa (1961) made a different approach where the coil was embedded in the insulated wall of MHD generator and resonated into a condenser and the method yielded results on conductivity of the gas.

With the help of immersive method where the coil probe was kept inside the plasma, some authors viz. Moulin and Masse (1964), Stubbe (1968) and Jayakumar et al (1977) and Olson and Lary (1961, 1962, 1963) showed that the immersive method was more sensitive to variations in plasma conductivity than non-immersive method. On the contrary, Donskoi, Duaev and Prokif'ev (1963) adopted a non-immersive type method to estimate electrical conductivity of heated gas streams. The technique rested on the measurement of electrical circuit parameters, effective inductance, circuit resistance, Q-factor, mutual inductance etc. of tank circuit.

The results of electrical heat conductivity derived from the Boltzmann equation with Grad's method of orthogonalized moments retaining the coupling between diffusion and heat fluxes had been expressed by Suchy (1985). These are calculated for Coulomb interaction potentials screened with the Debye - Huckel length.

The electrical conductivity of the conducting medium however, was determined by Koritz and Keck(1964) from a measurement of Joule Losses produced by alternating magnetic field of a coil surrounding it. In this regard a number of authors viz. Tanaka and Vsami (1962), Gourdin (1963) Khvashchtevaski (1962) made a conductor approximation for plasma which means that when an alternating electrical voltage is impressed upon it, the plasma is considered to offer no resistance and a.c. conductivity essentially becomes the d.c. conductivity. They argued that if the change in magnetic flux linked with a coil, when plasma is in its core, be measured, it may be possible to estimate d.c. conductivity for a range of frequencies. They put an expression for a.c. conductivity

$$\sigma_{a.c} = \frac{ne^2}{m\nu}\left(\frac{\nu^2}{\nu^2+\omega^2} - j\ \frac{\omega\nu}{\nu^2+\omega^2}\right)$$

where m and e are the electronic mass and charge, n the electron density, ν the electron atom collision frequency and ω is the angular frequency of the r.f. field imposed. The imaginary term corresponds to inherent plasma reactance developed due to mass inertia.

Tanaka and Hagi (1964), however, projected the effect of inductance change in a different way. If the plasma is conductive, the imposed radio frequency field may induce eddy currents and will dissipate energy in the region where they flow. As a result the magnetic flux will be screened off from the region. Hence it will cause a reduction in the effective inductance of the net work and will result in a shift in resonance frequency. Though all the active coil probe experiments discussed so far utilise the shift in either inductance or resistance of the coil probe due to plasma in one way or other, experimental results have been explained theoretically from different approaches leading to some exclusiveness of each problem.

Akimov and Konenko (1966) scrutinised the validity of the two similar coil probe techniques for determining plasma conductivities and discussed various possibilities. They gave stress on the works of Blackman (1959) and Donskoi et al (1963); their observations are also useful to the study of electrical conductivity from a shift in resonance frequency or quality factor Q of the coil within which plasma is kept. In contrast to the prediction of Tanaca and

Hagi (1964), the test object in the coil may change the oscillator frequency for some ranges of conductivities. Hausler (1957) and lateron Ghosal, Nandi and Sen (1976) showed that the shift in frequency is due to the capacitative effect of the test object on the coil. A conductor in the vicinity of a coil increases its stray capacity as a result of which the oscillator frequency decreases. Actually plasma conductivity averaged over the cross sections differ from calibrating curves, due to radial nonuniformity of the plasma. However, Ghosal, Nandi and Sen (1978) asserted that even if the skin depth is much larger than the plasma tube radius, the disagreement is expected to exist since coil probe technique gives information on moments of conductivity distribution of different order.

With the help of either immersive or non-immersive probes many workers as well as Hollister (1964), Murino and Bonoma (1964) determined the average (bulk) conductivity, because in every case the test plasma was radially nonuniform. Ciampi and Talini (1967, 1969), investigated the interaction of solenoidal electric field in conjunction with radially nonuniform plasma in a very generalised way. They put forward an equation for a radial profile of conductivity as

$$\sigma(r) = \sigma_0 [1 - m(\frac{r}{R})^n] \quad ...(1.5)$$

In the analysis however, the authors only considered a low frequency approximation whose displacement current has been ignored and hence for the radio frequency, conductivity becomes the d.c. conductivity. With a prior knowledge of conductivity profile, a measurement of m & n from equation (1.5) at any frequency provides the value of axial conductivity σ_0. This observation was however valid for limited range of frequencies. In this range the above measurement for the unknown plasma and for a homogeneous medium of conductivity $\bar{\sigma} = h\sigma_0$ gives the same result. Hence with connection to resistive or inductive measurement plasma simulates a homogenous medium and according to authors $\bar{\sigma}$ can be interpreted as a spatial average conductivity. Thus two averages σ^* and σ^{**} were obtained according to the resistive and inductive measurements respectively as given below:

$$\sigma^{*} = \frac{4}{R^4}\int_0^R \sigma(r)\, r^3\, dr$$

$$\sigma^{**} = \frac{3}{4}\left[\frac{4}{R^4}\int_0^R \sigma(r)\, r^3 dr\right]^2 + \frac{3}{4}\,\frac{6}{R^6}\int_0^R r^5 dr\left[\frac{4}{r^4}\int_0^r \sigma(r)\, r^3 dr\right]^2$$

With the help of measured Q factor and a calibration curve to find the first average conductivity σ^* Ciampi and Talini (1967) carried on an experiment in a flow facility plasma. Later on they (1969) elaborated their theory and measurement to incorporate the collision frequency. Ghosal, Nandi and Sen (1976, 1978) also pointed out that the expression of the two meaningful averages (σ^* and σ^{**}) and the relevant frequency and conductivity ranges could be obtained in a simpler way. The authors performed an experiment where they utilised a probe coil technique and concluded that the conducting medium forms a transformer where the primary and the single turn secondary are the coil and the conducting medium (plasma).

Ghosal, Nandi and Sen (1976) pointed out that, the loss of r.f. power of the resonant circuit due to the presence of plasma column within a coil was affected by two factors (i) eddy current loss and (ii) capacitative by pass. With the help of a composite equivalent circuit the authors concluded that the reflected resistance in the primary due to the eddy current flowing through the plasma is significant in the arc region and obtained an expression for effective resistance R' as

$$R' = R_0 + \frac{\omega^2 M^2}{R_1}$$

where R_0 is the radio frequency resistance of coil, ω the angular frequency, M, the mutual inductance and R_1 is the mutual plasma resistance. Taking the plasma to be of uniform conductivity, the authors obtained an expression for the azimuthal conductivity

$$\sigma_s = \frac{\pi(\alpha - 1)}{\ell \omega^2 M^2} R_0$$

where α a dimensionless quantity denoting the ratio of the radio frequency current in absence and in presence of the discharge and 'ℓ' is the equivalent length of the coil inductance formed between the coil and the plasma. In their next paper, however, they pointed out that an arc cannot be considered as a uniform medium from the point of view of conductivity and charge density. They started with a generalised radial conductivity distribution and determined experimentally a quantity which is a function of the assumed conductivity and determined experimentally a quantity which is a function of the assumed conductivity distribution. With a consideration of an annular cylinder defined by the radii r and $r + dr$ and length ℓ where ℓ is the length of the coil, the reflected impedance for this annular cylindrical plasma under the above condition has been shown to be $\omega^2 M^2(r)/R(r)$, where $R(r)$ is the azimuthal resistance of the annular cylinder and $M(r)$ is the mutual inductance between the coil and the annular cylinder of the plasma and ω is the angular frequency of the applied radio frequency field. They provided an expression for the reflected impedance as

$$\frac{\ell \omega^2 M^2(r)\sigma(r)\,dr}{2\pi r}$$

where $\sigma(r)$ denotes the azimuthal conductivity of the plasma at a distance r from the axis. Hence the total effective impedance becomes

$$R' = R_o + \frac{\omega^2 \ell}{2\pi}\int_0^R \frac{M^2(r)\sigma(r)}{r}\,dr \qquad \ldots(1.6)$$

where R is the tube radius. Here $M(r)$ can be simplified as $M(r) = Kr^2$ where K is a constant which depends on the number of terms of the primary coil. Accordingly eqn. (1.6) can be reduced to

$$\alpha - 1 = \frac{\omega^2 K^2 \ell}{2\pi R_o} \int_0^R r^3 \sigma(r)\, dr \qquad \ldots(1.7)$$

And further

$$\int_0^R \sigma(r) r\, dr = I / 2\pi E \qquad \ldots(1.8)$$

where I is the arc current and E is the axial voltage drop per unit length. Using eqn. (1.7) and (1.8)

$$\frac{\int_0^R r^3 \sigma(r)\, dr}{\int_0^R r\sigma(r)\, dr} = \frac{\alpha - 1}{f^2 K^2 \ell} \; \frac{E}{I} R_o \qquad \ldots(1.9)$$

where f is the frequency of the radio frequency current.

Ghosal et al (1978) assumed $\sigma(r)$ to be of the approximate form

$$\sigma(r) = \sigma_o \left[1 - \left(\frac{r}{R}\right)^2\right]^n \qquad \ldots(1.10)$$

where n is a constant. From eqn. (1.9) and (1.10)

$$n = \frac{R^2}{a} - 2$$

where $a = \frac{\alpha - 1}{f^2 K^2 \ell} \frac{E}{I} R_o$ ...(1.11)

And from eqn. (1.8) and (1.10) the expression for axial conductivity is

$$\sigma_o = \frac{I/E}{2\pi} \frac{2(n+1)}{R^2} \qquad \text{...(1.12)}$$

Ghosal, Nandi and Sen (1978) also obtained the identical result as given by Ciampi and Talini. Gantait (1988) performed experiment to observe variation of σ_o with arc tube radius, and obtained that σ_o decreases exponentially with the increase of R. An emperical relation of σ_o with R has been given

$$\sigma_{o(R)} = \sigma_{o\langle R \to o\rangle} \exp(-\beta R).$$

where β is a constant and $\sigma_{o\langle R \to o\rangle}$ the axial conductivity at $R \longrightarrow 0$.

It is to be noted that on the basis of average conductivity model [Stokes (1965, 1969)] the nature of conductivity profile could not be obtained from the Q factor measurement alone. The profiles of the type treated by Ciampi and Talini (1967), the difference between the azimuthal average and the axial conductivity can be as much as a factor of 5 and if the profile constants m and n are varied indefinitely the aforesaid factor may be extremely larger. The selection of the profile demands that the plasma fills the available volume and it may be approximate for an ordinary discharge plasma but may not be true for other situations such as flow facility plasma, plasma jets, metal arc etc. where the errors may become higher as the plasma conductivity may vanish at some distance away from the (tube) wall.

Moskvin and Chegnokova (1965) measured temperature on an argon plasma; they found a peak conductivity of roughly 3000 mho/m, falling approximately to zero at a radius 33 mm. Stokes (1969) theoretically calculated the azimuthal average that should be measured for the Moskvin-Chesnokova plasma stream assumed to be exhausting along a 2 cm. diameter tube. This is given to be approximately 100 mho/m, It is observed that the axial conductivity is 30 times higher than the apparent average.

Uramoto (1970) described a method for determining the electron-neutral collision frequency in a low density plasma. In the experiment the author used a radio frequency signal of constant frequency and voltage applied between plane probes while the density is varied to determine an antiresonance point. The above method is sensitive to external circuit impedance and avoids the perturbing effect of the strong r.f. field at resonance. Ghosal, Nandi and Sen (1978) estimated the azimuthal average $\overline{\sigma}_{\phi}$, volume average $\overline{\sigma}_{vol}$ and the axial conductivity σ_0 of mercury arc discharge and found that axial conductivity can be ten times the aximuthal average value.

Effective collision frequencies in a weakly ionized turbullent plasma had been measured by Spence and Roth (1986) using resonant absorption of an extraordinary wave, propagating across a plasma column. They measured the attenuation and phase shift of a transmitted wave in a swept frequency measurement using an HP8510 network analyser.

Expressions were obtained by Pleshanov (1968) for longitudinal and transverse conductivity and an anisotropy angle for anon-quasi neutral plasma. It was shown that the transverse conductivity of such plasma is finite in super high magnetic field and consequently the specific power output may be unlimited, in contrast with the case of quasineutral plasma which has a finite output.

Pytte (1969) developed a method for the calculation of the conductivity tensor, including collisional contribution associated with a wave in a plasma in a magnetic field. The author calculated electron current contribution in terms of Landau collision. Nicol et al (1971) determined the collision frequency and collision model in flame plasmas by means of magnetic field dependent microwave absorption and dispersion. They used acetylene-oxygen and acetylene-air flames burning through an x-band wave guid resonator parallel to the microwave electric field vector and perpendicular to an external magnetic field to study electron cyclotron resonance. The authors found that the absorption and dispersion are slowly decreasing functions with the magnetic field strength. It was also observed that the collision frequency amounts to 210 $\pm$ 4 GHz for the acetylene-oxygen flames and 249 $\pm$ 4 GHz for the acetylene-air flames.

Seashottz (1971) performed an experiment on "effect of collisions on Thomson scattering in a magnetic field with unequal electron and ion temperatures and electron drift". The author observed that collision frequency decreases when magnetic field influence is reduced.

1.4. Plasma parameters from diffusion voltage measurements both in transverse and longitudinal magnetic field.

The effect of a magnetic field on the breakdown condition of a gas was calculated by Wehrli (1922) and obtained that λ , the mean free path of the electron assumed constant for all the electrons changes to λ' as in presence of magnetic field the electrons describe a cycloidal path.

$$\lambda' = \lambda\left[1 - \frac{eH^2\lambda}{8Em}\right] \qquad \ldots(1.13)$$

where e is the charge and m is the mass of the electron, H is the magnetic field in gauss and E is the voltage per unit length of the tube. The author concluded that the effect of magnetic field is equivalent to an increase of pressure P_e to P_{eH} where

$$P_{eH} = \frac{P_e}{[1 - eH^2\lambda/8Em]} \qquad \ldots(1.14)$$

where P_e is the effective gas pressure. By taking electron energy and drift velocity into consideration, Blevin and Haydon (1958) derived a new expression for equivalent pressure and showed that a transverse magnetic field effectively increases the gas pressure from P_e to P_{eH} so that

$$P_{eH} = P_e \left(1 + C_1 H^2 / P^2 \right) \qquad \ldots(1.15)$$

where $C_1 = \left(\frac{eL}{mv_r}\right)^2$ involving random velocity distribution of electrons is assumed constant within certain limit of H/P. From the concept of equivalent pressure, the variation of Townsend's first ionization coefficient in a transverse magnetic field can be explained in high (E/P) region in which the distribution of electrons is assumed to be Maxwellian with a constant average collision frequency. Haydon et al (1971) critically analysed the velocity distribution for electrons in presence of magnetic field and found it not to be Maxwellian, so that in case of application of the concept of equivalent pressure for electron behaviour in gases like hydrogen as studied by the authors, the collision frequency is required to be taken as energy dependent. Heylen and Bunting (1969) formulated an equivalent reduced electric field concept in a constant electric field. In transverse magnetic field, the transverse and perpendicular mobilities and their ratio for electrons have been explained assuming Maxwellian velocity distribution.

The average electron collision frequency was observed to vary with electron energy. In case of molecular gases such as oxygen, air and nitrogen the results were experimentally verified.

The mobility of electrons in the direction of the electric field in presence of a magnetic field is reduced and Townsend and Gill (1937) obtained

$$\mu_H = \frac{\mu}{1+\omega_H^2 \tau^2} \qquad \ldots(1.16)$$

where $\omega_H = \frac{eH}{mc}$ and τ represents the time between two successive collisions. In presence of magnetic field Blevin and Haydon (1958) deduced an expression for mobility by considering the bulk properties of electron avalanche and is given by

$$\mu_H = \frac{\mu}{1+C_1 H^2/P^2} \qquad \ldots(1.17)$$

The eqn. (1.17) was verified experimentally by Sen and Gupta (1964) by computing the values of electron mobility in air discharge in presence of magnetic field and over a wide range of pressure.

The effect of magnetic field on electron mobility in a d.c. arc plasma was studied by Hasem(1984) and he showed that the decrease of electron mobility in the magnetic field may be due to hindering of the upward motion of excited particles (ions, excited atoms, and molecules) in the magnetised plasma.

Ecker and Kanne (1964) studied theoretically the effect of a transverse magnetic field on a cylindrical plasma column. In the formulation of the basic equation to describe the collision dominated positive column in a transverse magnetic field, Ecker and Kanne calculated the expression for electron temperature under the assumption that electron heat conduction is small in comparison to collision (elastic) losses and the energy conservation law (for electrons) balances the energy gained in the electric field with energy loss due to collisions with neutral particles. For this balance equation in a real plasma Ecker and Zöler (1964) put a criterion as

$$\lambda_e < 2R\gamma^{1/2} \qquad \ldots(1.18)$$

where λ is the mean free path (electrons) R is the discharge tube radius and γ is the fractional loss of electrons in an elastic collision. This condition is not achieved in normal discharge and appeared in practice only in case of high current and relatively high pressure discharge (arc). The authors investigated the problem mainly for two cases: firstly collision free limit where Langmuir theory of free fall is valid and secondly in collision dominated region where Schottky's ambipolar diffusion theory applies. They found that magnetic field does not change the temperature in the collision dominated discharges and gave a linear perturbation treatment taking small values of magnetic field.

Marchetti et al (1984) used a self consistent mode coupling theory to calculate the coefficient of self diffusion in a three dimensional classical one component plasma subjected to an external magnetic field. They found a Bohm like behaviour for asymptotically large fields for diffusion in the plane perpendicular to the magnetic field.

(B) Diffusion in longitudinal magnetic field:

If a magnetic field acts parallel to the axis of the positive column, the effective diffusion coefficient Da is reduced to

$$D_b = D_a / \left(1 + \frac{\omega_{ce}^2}{\nu_c^2} \right)$$

Here $\omega_{ce} = \frac{Be}{m}$ and ν_c is the electron collision frequency. Thus it is evident that as the magnetic field is increased, the rate of electron diffusion is decreased. In a longitudinal magnetic field, the ions being more massive will be less constrained then electrons from radial diffusion. However, the electric field created by radial distribution of the electrons still tends to restrain the ions. Thus the ions as well should diffuse at approximately the same rate as those of electrons.

The 'normal' distribution both for electrons and ions is not altered when it is subjected to a longitudinal magnetic field. Tonks (1941) approximated the dispersal effect along a plasma column in longitudinal magnetic field. Radial electron and ion distribution's solution is the sum of a series of zero order Bessel functions. The 'normal' distribution along the length of the positive column remains unchanged in the first term, while successive terms decrease with distance along the column at rates which are complicated functions of T_e , the electron temperature and the magnetic field strength, H. Davies(1953) also found that the electron velocity distribution in longitudinal magnetic field is Maxwellian. An investigation was carried by Vorobjeva et al (1971) in mercury vapour arc subjected to an axial field ($H \leq$ 800 Oe) and found that Maxwellian distribution holds good for electron velocity. The energy gained by electrons in electric field balanced by losses in elastic collision is not fulfilled in case of low pressure diffused mercury arc, according to Ecker and Zöler (1964) as observed from Ellenbaas - Heller heat balance equation. On the otherhand, Ghosal, Nandi and Sen (1979) showed that for such a discharge, the energy consumed by the discharge is lost primarily in ionising collisions and a major part of ionising particles is lost through ambipolar diffusion to the wall of the discharge tube. There is some inadequacy in defining an arc. But for some criteria of arc such as (a) relative high current density, (b) low cathode fall, (c) high luminosity of the column defined by Pfender (1978) dominate the discharges in a low pressure mercury arc. Generally, in these discharges, the volume ionization is balanced by diffusion of charged particles. Inspite of diffusion, recombination of charged particles plays a vital role in their loss mechanism. Recombination becomes more significant than diffusion in an active discharge for the high value of electron temperature with respect to ion temperature. Hoyaux (1968) enunciated that normal ambipolar diffusion prevails for the column which is sufficiently long with respect to its radius at low magnetic fields. But above a certain magnetic field, plasma turbulence progressively sets in and leads to an abnormal loss of particles and an increase in voltage drop. There are two known types of diffusion: (1) In low pressure region Langmuir free fall diffusion is effective and (2) in high pressure region Schottky's ambipolar diffusion is dominant. Franklin (1976) described an ion fluid model relating the two domains in the transition region. A balance between particle loss and generation processes predicts the determination of electron temperature.

Franck et al (1972) carried on an experiment to determine electron temperature T_e in longitudinal magnetic field. He found that when a longitudinal magnetic field is superimposed on a low pressure plasma, reversal of the radial ambipolar electric field takes place at a definite magnetic field B_r. He found the value of electron temperature from the value of B_r. Marhic and Kwan (1977) found that both electron temperature and electron density change. From radiation profiles vander Sijde (1972) found change of temperature and density profile for a hollow cathode argon arc in axial magnetic field ($H \leq 1250$ G). In a longitudinal magnetic field Wienecke (1963) found an increase of pressure in the hot region of a cylindrical symmetric arc. The author observed that the forces exerted by the field on charged particles modify diffusion current and hence field.

The electron diffusion across and along the field becomes anisotropic and reduction of radial diffusion results due to application of magnetic field on a cylindrical plasma column. The plasma adjusts to this new situation by decreasing its ionization frequency which is determined by electron temperature and hence the change of electron temperature occurs. So a reduction of diffusion loss results due to decrease in electron temperature or axial electric field. Considering Langmuir free fall model Self (1967) estimated the influence of longitudinal magnetic field on a cylindrical plasma column. Also, taking the ion fluid model Franklin (1976) investigated the properties of cylindrical plasma subjected to an axial magnetic field, and his investigation is applicable both in high and low pressure regions. He showed that ambipolar diffusion will be reduced by the application of a longitudinal magnetic field due to the reduction in radial diffusion of charged particles.

Geissler (1970) observed the disagreement between experimental data and ambipolar theory in case of a finite length of cylindrical column with non-conducting walls and placed in an axial magnetic field in high pressure region. The diffusive decay of a weakly ionised gas in a finite length cylinder having non-conducting walls was analysed by

Chekmarev et al (1977) in presence of longitudinal magnetic field and observed that ambipolarity of diffusion exists in magnetic field too. Previously, Franck et al (1972) pointed out how the magnetic field influences the ambipolar diffusion.

Electronic and ionic diffusion reduce when a magnetic field is increased. The variation of electron and ion diffusion across a magnetic field can be shown classically as

$$D_{e,i1} = \frac{D_{e,i}}{1 + b_{e,i} H^2} \quad \ldots(1.19)$$

where $b_{e,i}$ is the square of the mobility of respective species. The electron diffusion is reduced more than ion diffusion, as the electron mobility is large than ion mobility by a term 10^2 to 10^3 at a given pressure. Due to increase of magnetic field the radial component of electric field vanishes for $D_{e1} = D_{i1}$ at a particular magnetic field H_r. While studying the problem of plasma instability, the anomalous behaviour of plasma column in longitudinal magnetic field has been studied mostly in noble gases. Hoh and Lehnert (1960) studied the influence of longitudinal magnetic field in hydrogen, helium and krypton, confined in non -

conducting and long discharge tubes, so that the diffusion can be neglected at the ends. They found that the radial diffusion across the axial magnetic field decreases classically upto H_{cr} and above H_{cr} the diffusion increases with magnetic field. An interpretation of anomalous behaviour of diffusion has been given by Kadomtsev and Nedospasov (1960) by considering an instability in the form of helical wave which will be created by axial electric field for high values of magnetic field. This instability enhances the effective ambipolar diffusion with increasing magnetic field by $E \times H$ drift which pushes the electrons to outward radial direction and amplify the diffusion. H_{cr} is calculated from the measurement of pressure. Janzen et al (1970) observed in neon gas that the instability depends on the length of the discharge tube. No instability is observed in short length ($L \leq 15$ cm.) discharge tube. In case of long discharge tubes Deutsch and Pfau (1976) observed an anomalous increase of diffusion in noble gases in weak discharges and in presence of axial magnetic field ($H \ll H_{cr}$). Sato (1978) interpreted the same results as that of Deutsch and Pfau in terms of self excited ionization waves.

In axial magnetic field there is another weak instability in quiescent plasmas. This instability is known as drift dissipative instability according to Timofeev (1976). These instabilities are regarded as high current convective instabilities for active discharges.

The problem of longitudinal diffusion of electrons in a plasma in an external magnetic field was solved by Sestak and Forejt (1986) in case of electron ion plasma and that of a plasma of identical particles by Bychkov et al (1980) who analysed the relation between the energy dependence of the elastic scattering cross section of the electron and the kinetic coefficients of electrons moving in a gas in a constant electric field. They computed the relation which depends upon the electron velocity distribution function. The representation obtained is used to establish the energy dependence of the elastic scattering cross section of the electron and to calculate diffusion coefficient in presence of longitudinal magnetic field.

In this laboratory Sen and Jana (1977) investigated the current voltage characteristics of glow discharge in presence of axial magnetic field. They observed that the discharge current increases with the increase of magnetic field for the range of pressure

0.685 torr to 0.925 torr. The results showed that the radial distribution of electron follows zero order Bessel function and is valid in magnetic field also. Considering the physical processes involved in a mercury arc discharge taking air as buffer gas Sadhya and Sen (1980) described a model in which air behaves as a quenching gas. They obtained the distribution function of both types of ions (atomic and molecular) and developed an expression for T_e / T_{eH}, where T_e is electron temperature without longitudinal magnetic field and T_{eH} is electron temperature with longitudinal magnetic field. The experimental results were in quantitative agreement with theoretical deduction within the range of (H/P) values studied.

Cohen and Sultorp (1984) calculated the longitudinal self diffusion coefficient for a magnetised plasma considering the kinetic theory in the weak coupling approximation.

1.5. Radio frequency breakdown of gases in presence and in absence of magnetic field.

Ionisation and subsequent breakdown of a gas subjected to uniform a.c. field differ in many important aspects from ionisation and subsequent breakdown by uniform d.c. field. The charged particles in the bulk of the gas are accelerated when a high frequency or microwave electric field is imposed across a gas. It is well known that electrons are always present in a given volume of a gas due to cosmic radiation; and through these electrons the transfer of energy from the applied electric field of any kind to the volume of the gas results. The electrons are accelerated much faster than ions because of their lighter mass and as a result, the energy transferred from the imposed electric field to the electrons is so much larger that we can neglect the motion and subsequent effects on the heavier particles. In an ac field, the direction of the force on the electron alters and the electrons will oscillate within the bulk of the gas provided the vessel-walls are sufficiently far apart. It is the prime feature that characterises high frequency or microwave discharges from low frequency or d.c. discharges.

Actually at high frequencies and in the absence of any gas atoms, the electrons would oscillate out of phase with field and no energy would be transferred. But in presence of gas atoms electrons accelerated by electric field collide frequently with the gas atoms and hence change the phase condition. It results a net transfer of energy from the field to the electrons and electrons lose energy by collisions with the gas atoms. However, in a favourable situation an electron may gain sufficient energy to exceed the excitation energy level of the atom and lose most of its energy. It results in subsequent radiation when it returns to its ground state. It is noteworthy that the electrons lose energy not only by elastic collisions but also by inelastic collisions. The resulting energy distribution of electrons may produce sufficient number of electrons having energy comparable to ionization energy of the gas atoms so that they may ionise the atoms. When this occurs we have multiplication of electrons and the process may be a cumulative one. It is also very important to note that the electrons at the same time may undergo loss due to diffusion to the walls, recombination with the positive ions, or by attachment to neutral atoms or molecules. A balance equation of these productions and loss rates determines the electron density of the steady state discharge and it in turn characterises the electrical properties of the same. If the electric field is sufficiently large, the electron density attains very large value with a luminous glow in the bulk of the gas and hence causes breakdown of the gas.

The general characteristics of the breakdown curves have been investigated by several workers. Gutton and Gutton (1928) determined the potentials between external electrodes required to start the discharge in hydrogen at low pressures with oscillations of wavelengths between 3 to 5620 meters whereas Krichner (1930) utilised internal electrodes for breakdown purposes. Townsend and Gill (1938) considered only the motion of free electrons in the gas under the influence of an alternating electric field ignoring wall and electrode processes and space charge effects. Thomson (1930) carried an extensive work on the electrodeless ring discharge and latter (1937) derived an elementary theory regarding each electron as oscillating about a mean position in the gas.

In order to ionise the gas electron must at some point in its trajectory attain enough energy for ionization and it must strike a molecule before it returns this energy again to the field. If $E_o \cos\omega t$

be the magnitude of the imposed field, the energy acquired 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 (V_i is the ionization potential of the gas atoms or molecules). 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. Only those electrons which start with zero initial velocity and in zero phase of the applied field can participate in the motion.

Several authors found double minimum in the striking potential as a function of pressure. Gutton and Gutton (1928) characterised the double minimum as due to resonance phenomenon in the gas. Gill and Donaldson (1931) reported that when the field is directed along the tube only one minimum appears, but when it is across the tube, another minimum, at high pressure appears. According to them 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. On the contrary when pressure decreases, the electrons acquire more energy from the field out of their long free paths and hence the striking field slowly become smaller. However, the amplitude of electron oscillation becomes larger and larger and ultimately the amplitude becomes approximately equal to the distance between the walls. As a result, the loss of electrons increases sharply and a much greater field is necessary to initiate the desired discharge. Similar work had been reported in this context by Thomson (1937), Zouckerman (1940), Githens (1940), Chenot (1948) and Pim (1948, 1949).

Hale (1948) reported his measurements in argon and xenon over the range of 5 Mc/s. to 50 Mc/sec. and pressures varying from 20 to 50 micron. He pointed out that the breakdown field for high frequency field is determined by those electrons in the gas which succeed in acquiring ionizing energy in one mean free path. The value of the electronic mean free path is deduced from kinetic theory which entails some doubts. Actually an effective mean free path is needed in this case because the electronic mean free path changes with the energy of the electron and as the energy of the electron varies between zero and ionizing energy. Also the assumption that the probability of ionization becomes a maximum when the electron gains the ionizing energy is not supported by experimental results by Smith (1930). According to Smith (1930) the efficiency of ionization increases quite rapidly with increasing electron energies slightly above the ionizing energy.

From a different approach Gill and von-Engel (1948) carried on experiments where they measured the starting potential of a h.f. discharge as a function of frequency (wavelength) of the imposed field in gases at very low pressure, of the order of 10^{-3}mm. Hg. From these results Gill and von-Engel, put forward a theory of the initiation of the discharge. It is noted that the starting field is independent of the gas and the pressure, but depends upon wavelength of the applied field and the dimension and material of the vessel, although the fully developed discharge shows the spectrum of the gas.

Townsend and Williams (1958) studied the breakdown condition in air and hydrogen for values of p.d. = 15 mm cm of Hg and frequency 5 MHz to 70 MHz. They found double minima, the first minimum was not very sensitive to breakdown voltage and gas pressure as in lower frequency of the applied field.

Cooper (1947) carried on investigation in ultra-high frequency breakdown of air in coaxial lines and waveguides for separation between 0.1 cm and 0.3 cm and over the pressure range of 20 cm to 760 cm. It was found that the breakdown field to be 70% of the d.c. field at two wavelength namely 10.7 cm and 3.1 cm. Posin (1948) carried on similar experiment for 3.0 cm as Herlin and Brown (1948).

Brown and McDonald (1949) provided the theoretical interpretation and experimental investigation of breakdown of gases in cylindrical cavities and between coaxial cylinders at the wavelength of 9.6 cm. The theoretical interpretation is based on the criterion that at the point of breakdown ionization rate is equal to the rate of loss due to diffusion. Other electron removal processes namely attachment and recombination are considered to be negligible for the type of discharge. By analogy with the first Townsend coefficient for d c ionization where the electron loss is governed by mobility, the high frequency ionization coefficient is controlled by diffusion.

Holstein (1946) pointed out 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 rms value of h f field. He interpreted the breakdown criterion having a general character introducing direct current analogy. He then obtained a relation between the breakdown field E , the gap length d and the gas pressure p as

$$(Pd)^2 = \frac{\pi^2 KT_e}{e(E/P)(\alpha/P)}$$

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

Margenau and Hartman (1948) analysed the methods for determining the electron energy distribution theoretically.

Kihara (1952) introduced a molecular model for collision processes between gas molecules and charged particles and obtained an absolute expression for mobility coefficient, diffusion coefficient and electron temperature in terms of some molecular constants and some measurable parameters.

Taillet and Brunet (1965) 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 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.

In high frequency discharge, besides two general types of electron loss mechanisms (mobility and diffusion), there may be another type of loss mechanism due to formation of negative ion in some gases. Negative ions appear in gases under two conditions:

(i) They may be generated in the bulk of the gas through attachment of free electrons to atoms and molecules (largely and through dissociation of molecules in a polar phase of electron impact).

(ii) They may appear 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 which in turn enhances the rate of carrier loss by recombination.

In a series of works Loeb (1921, 1923, 1924) worked out the possible theories of formation of negative ion from electron and neutral molecules.

The breakdown of gases by h f electric fields in conjunction with a steady constant magnetic field has also been investigated by Townsend and Gill(1938) who calculated the effect of magnetic field on the h f breakdown of a gas in a magnetic field.

In discharge vessels, where the electric and magnetic field 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 the breakdown field decreases. If the electric and magnetic fields are perpendicular to each other, not only diffusion is decreased, but for certain value of magnetic field and applied frequency resonance will occur (when $\omega = \omega_b$, the electron cyclotron frequency). Actually it indicates that the magnetic field reverses the direction of electrons, without loss of energy, as the imposed electric field reverses. Although the magnetic field supplies no energy to the electron, it nevertheless changes its direction so that the electron may acquire energy from the electric field provided that the motion is not frequently interrupted by collisions with gas molecules.

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 in presence of transverse magnetic field. They performed the above experiment at 30 MHz and 48 MHz and over the range of pressure from few micron to 240 microns. A decrease of starting field was found 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 become minimum when the magnetic field was employed. Brown(1940) carried on some extension of the similar work to the case of hydrogen and reported similar results therein.

Lax, Allis and Brown (1950) performed experiments and explained theoretically the breakdown voltage of a gas excited by a microwave field in presence of transverse magnetic field. They used helium gas containing a small admixture of Hg vapour and obtained breakdown curves for different values of pressure. The breakdown voltage becomes minimum for a magnetic field which is independent of the pressure of the gas.

Ferritti and Veronesi (1955) determined breakdown voltage in air using cylindrical electrodes at 10 MHz and 30 MHz.frequencies varying magnetic field from zero to 800 gauss. The pressure of the gas was maintained at 0.1 mm, 0.5 mm and 10 mm Hg. and in all sets of observation breakdown voltage decreased in presence of magnetic field.

Deb and Goswami (1964) investigated the electrical breakdown in a high frequency electrodeless discharge at low pressure subjected to a steady magnetic field and pointed out 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.

Bengall and Haydon (1965) investigated the pre-breakdown ionization in nitrogen gas to show that the influence of a transverse magnetic field is equivalent to an increase in the gas pressure from p to $p_{eH} = p\,(1 + \omega_B^2/\nu_C\ )^{1/2}$ where ω_B is the electron cyclotron frequency and ν_C is electron molecule collision frequency.

In a coaxial resonator in the presence of longitudinal magnetic field Ivanov and Gavrilova (1972) carried on investigation of high frequency single electrode discharge. They pointed out that under certain conditions the losses due to high frequency single electrode discharge become large and are governed mainly by the secondary emission coefficient of the electrode material and by the ratio of frequencies ω and $\omega_b (= eH/m)$. Grollean (1974) studied high frequency resonance discharge 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.

Though a fairly large amount of work in resonance magnetic field was reported, little work has been done so far in which non-resonant magnetic field is employed. Sen and Ghosh (1963) investigated the breakdown in air and nitrogen in crossed non-resonant magnetic field using the radio frequency field of frequency 8.1 MHz and 7.15 MHz respectively over 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 values lie within 100 gauss. It was noticed that each curve, for a steady crossed magnetic field, has got a minimum breakdown voltage at certain pressure which shifts to higher pressure as the magnetic field is increased. An increase of breakdown voltage was also observed on the imposition of perpendicular magnetic field. Sen and Gupta obtained the breakdown characteristics in non-resonant magnetic field varying from 0 to 120 gauss in helium, neon and argon and obtained the same results as Sen and Ghosh (1963), the frequency of the applied h f field was 4 to 12 MHz. With the help of theory by Kihara (1952) for breakdown of gases by radiofrequency 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.

Sen and Bhattacharyya (1969) calculated the values of α/P at different E/P values from the r.f. breakdown measurements in case of air, oxygen and carbondioxide within the pressure range 1 to 6 mm of Hg and in transverse magnetic field from 0 to 1800 gauss.

It was noticed 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 phenomenon of air in presence of axial magnetic field over the pressure range 5 to 115 mtorr.

Ram and Sarkar (1971) investigated the r f (16 MHz) breakdown characteristics of argon in presence of low (0 to 180 gauss) longitudinal and high (100 to 1500 gauss) non-resonant transverse magnetic field. But in transverse magnetic field the breakdown voltage was found to increase upto a certain magnetic field and decreased with increase of magnetic field above 40 mm Hg.

Sen and Jana (1977) established the validity of diffusion theory in radio ffequency breakdown in molecular gases in axial magnetic field.

Radiofrequency breakdown characteristics at 55 MHz frequency of air have been studied in the presence of a parallel low intensity magnetic field over the pressure range of 5 to 15 mtorr by Kumar et al (1971). The breakdown potential has been found to decrease with increase in magnetic field. This decrease is much prominent at the lowest pressure. It has also been found that the variation of breakdown potential with pressure shows broad minimum in low magnetic field. This change becomes almost linear beyond 80G. Thus an appreciable reduction in diffusion loss of electrons under the above mentioned condition has been observed experimentally.

Bhattacharyya and Das (1974) studied the breakdown potential in air over the pressure range of 50 to 300 micron under the simultaneous action of an r f (5.7 MHz) and a variable transverse d c field (0-30 V/cm). The breakdown potential is always higher than that in the absence of d c field for all values of pressure and the pressure at which the breakdown voltage becomes minimum always shifts to higher pressures with the increase in the d c field. It is assumed that electrons are lost not only by diffusion but also due to mobility due to application of d c field. Bhattacharyya and Das (1977) investigated the variation of breakdown potential of dry air, oxygen and hydrogen using r f electric field (6.2 MHz) over the range of gas pressure 0.5 to 8.0 torr also in presence of uniform (350 G, 500 G) transverse magnetic field. The theory of breakdown using high frequency electric field has been modified for crossed r f electric and steady magnetic fields to explain the results.

Bhattacharyya and Das (1982) investigated the variaton of radio frequency (8.9 MHz) electric field breakdown of gases like air, hydrogen and oxygen for gas pressures of 0.25, 0.5 and 0.3 torr respectively, in the presence of transverse magnetic field varying from 0 to 3000 gauss. For each gas a minimum value of the breakdown field is found at a certain value of the magnetic field, both values being different for each of the three gases. In this investigation they obtained a second breakdown field of much lower magnitude in a strong magnetic field when the electron cyclotron frequency is much higher than the electron - neutral collision frequency, both being much higher than the frequency of the applied field. By considering the average motion of the electrons in a very strong magnetic field, transverse to an electric field of small magnitude, linear relations are obtained between the second breakdown field and the corresponding magnetic field.

Recently Whang and Noh (1986) reported that breakdown of N_2 gas by 13.56 MHz electric field is very different from that under steady fields. The second order differential equation derived from the Boltzmann equation is used for the electron distribution function. The ionization rate and diffusion coefficient are calculated using kinetic theory. They conclude that the breakdown condition is that the number of electrons provided by ionization equates the number diffusing to the walls of the discharge vessel. They calculated the breakdown electric field using computer and compared the results with experimental values.

1.6. Spectroscopic investigation of the intensities of spectral lines in a plasma.

Spectroscopy is a very wide subject in itself, having well developed applications to nearly all categories of plasma research. The various methods of spectral diagnostics are based on established relationships between plasma parameters and radiation characteristics such as intensity, absorption coefficient and spectral line broadening. The spectral study of the radiations given off by a plasma can be a ready source of information about its state. However the spectroscopic technique is a more accurate diagonostic technique than dc probe method, r f probe method and microwave technique.

Plasma parameters viz. electron temperature and electron density of glow discharge can be determined from the relative intensities of radiation. Frequently relative measurements are not only technically simpler, but they are also the only possible means from the theoretical point of view.

In the absence of equilibrium, the population density of the first excited states is lower because of the emitted radiation; the concentration of free electrons and ions is lower than at equilibrium, for example, as a result of diffusion losses;

near the ionization limits of atoms and ions equilibrium assemblies of levels are formed (Saha's relationship is fulfilled beginning with the S-level of the atom and the t^+ level of the ion). Experimentally the following measurements are possible :

(a) relative intensity of two or more lines;

(b) relative intensity of atom and ion lines or lines from ions of different charge;

(c) relative intensity of the continuum at two wavelengths;

(d) relative intensity of lines and continuum.

Formulae for determining the plasma temperature by these methods are

(a) $$\frac{I_p}{I_s} = \frac{A_p g_p \lambda_s}{A_s g_s \lambda_p} \exp\left(-\frac{E_p - E_s}{KT}\right) ;$$

(b) $$\frac{I_p}{I_s^+} = \frac{A_p g_p \lambda_{s^+} Z_+ n_o}{A_{s^+} g_{s^+} \lambda_p Z_o n_+} \exp\left(-\frac{E_p - E_s^+}{KT}\right);$$

(c) $$\frac{I_{K1}}{I_{K2}} = \frac{\xi_1}{\xi_2} \exp\left[\frac{hC(\lambda_2 - \lambda_1)}{\lambda_1 \lambda_2 KT}\right] ;$$

(d) $$\frac{I_p}{I_{K2}} = 2{,}15 \cdot 10^{10} \frac{A_p g_p}{\lambda_p \xi_2} \cdot \frac{n_o}{n_e n_+} T^{1/2} \exp\left(-\frac{E_p}{KT}\right)$$

The accuracy of the temperature determination is the higher the greater the energy difference

$$\Delta T/T = (KT/\Delta E)[\Delta(I_1/I_2)/(I_1/I_2)]$$

Theoretically, the accuracy of the measurements is a minimum for method (a), a maximum for method (b).

For practical realization some modification are to be considered.

1) With method (a) it is sometimes possible to select lines, that are similar in wavelengths, intensity profile and this increases the accuracy of the measurement.

2) Method (b) is applicable only in the limited temperature range where one can match atom and ion lines of comparable intensity.

3) With method (c) it is necessary to compare sections of the continuum which differ strongly in wavelength and intensity and this creates some difficulties, furthermore, the values of the factor ξ are rarely known with high precision;

4) Method (d) is convenient only in that it allows to select a line and the adjoining continuum for measurements. However, in many instances the intensity of the continuum is small, or the accuracy with which its absolute value is known, is insufficient.

The local thermodynamic equilibrium model(LTE) and corona equilibrium model (CE) are the main two models of equilibrium plasma. In LTE model, a unique temperature exists in plasma which determines the velocity distribution function for electrons. The analysis of the state of the plasma is particularly simple in this equilibrium since it is only such local plasma parameters as electron density, electron temperature and composition that determine the relevant populations. Collisional processes are usually more important in establishing LTE than radiative processes, since most plasma of interest are optically thin to internal radiation (except perhaps for the resonance lines). Consequently collisional de-excitation rates must exceed radiative decay rates for true LTE. According to Boltzmann distribution law energy of every particular kind is distributed over all particles in the gas and Saha equation is the result in case of ionization in this equilibrium. In equilibrium plasma it is possible to apply methods (a), (c) and (d). Method (b) requires the use of some model for an equilibrium population distribution, for example the model of coronal equilibrium, which is valid at low n_e.

By using $n_e \geqslant 10^{14} E_2{}^3 (KT)^{1/2}$ [for the equilibrium population of the first (and higher) excited states (excitation energy E_2) with respect to the ground state] , it is possible to determine the minimum energy (equatum number) of the level beginning with which methods (a) and (d) are applicable. A decrease in the range of population equilibrium decreases the value of ΔE , that can be utilized in measurements. If the continuum intensity is not very large (precisely in this case it is frequently necessary to deal with non-equilibrium conditions, since intensity $I_e \sim n_e{}^2$ and nonequilibrium increases with lower n_e), large values of ΔE can be obtained with method (d). In fact Park (1968) described the spectral line intensities to determine the electron temperature in a nonequilibrium nitrogen plasma. In this work the relative populations of excited states of atomic nitrogen in a collision-dominated nonequilibrium plasma for given ratios of nonequilibrium ground state number density and given electron temperatures consisting of atoms, single charged ions and electrons are calculated by the method of Bates, Kingston and Mcwhirter (1962).

From the resulting populations, the spectral intensities of two prominent visible lines are calculated assuming the plasma to be optically thin for these lines. It is shown that with the exception of a decaying plasma at temperatures greater than $8000^{o}K$, the calculated nonequilibrium intensities disagree with the equilibrium spectral line intensities that would be conventionally employed to determine the temperature of a plasma in equilibrium. Gruzdev et al (1974) investigated an He plasma with high ionization at atmospheric pressure for the investigation of equilibrium establishment. They showed that for a laboratory plasma with ionization $\chi > 0{\cdot}1$ at atmospheric pressure and T_e $3000^{o} - 4000^{o}K$ ionization equilibrium is not achieved due to the unbalanced radiative decay of the resonance state of He 1 resulting an its overpopulation and under population of He III.

To investigate the temperature dependence of spectral lines intensity emitted by thermal plasma, Bielski (1966) presented the temperature dependence of atom, ion and electron concentrations and provided a graphical method of determining the temperature T_m at which the intensity of a spectral line reaches a maximum value under condition when the sum of atom and ion concentrations is constant (independent of temperature). This method can be applied to the lines emitted by atoms and ions of any multiplicity of ionization. Another investigation has been made by Pacheva et al (1970) to measure electron temperature in a hollow cathode discharge tube by the method of relative line intensities. An analytical method developed by Gratreau (1973) which provides a simultaneous determination of both electron temperature T_e and density n_e of a dense plasma by using time - resolved relative spectroscopic measurements of lines from He-like and H-like ions.

Griem (1964) calculated the number density of electrons to obtain complete LTE. The expression of electron density is given by

$$n_e \geqslant 9 \times 10^{17} (E_2/\chi_H)^3 (KT_e/\chi_H)^{1/2} \text{cm}^{-3} \quad \dots (1.20)$$

with E_2 the energy of the first excited and χ_H the ionization energy of hydrogen and K is the Boltzmann constant. Griem considered that the collisional excitation rate is ten times the radiative rate from that level for lowest excited state. Hey (1976) modified this criterion by considering finer values of Gaunt factor appearing in collisional excitation rate coefficient and incorporating the effect of metastable-metastable collisions.

Wilson (1962) provided an equation for LTE to be valid as

$$n_e \geqslant 6 \times 10^{13} \chi_i^{3} (KT_e)^{1/2} cm^{-3} \quad \cdots (1.21)$$

χ_i is the excitation energy of atom in eV. From these criteria, Elton (1970) has given a single criterion for electron density necessary to maintain complete LTE in the discharge tube as

$$n_e \geqslant C (KT_e)^{1/2} \chi_i^{3} cm^{-3} \quad \cdots \quad (1.22)$$

where C is a constant equal approximately to 1.4×10^{13}, assuming complete trapping of resonance lines and 1.4×10^{14} assuming no trapping whatsoever.

LTE can be expected to hold for stationary and spatially homogeneous plasmas, if collisional processes with electrons obeying Maxwellian distribution dominate in the rate equations. The principal quantum numbers of states for which radiative decay and collisional excitation rates are comparable often exceed a critical value but radiative decay rates decrease with principal quantum number. In these circumstances it is logical to relate density states above the critical level with each other and in the same way to electron density in a complete LTE system. Richter (1968) showed that the ground level is over-populated by a factor, though the occupation number for states over this critical level are as in LTE with temperature, T_e. Due to this reason the critical level is in partial LTE. With quantum number p for a level, the electron density in partial LTE approximated by Griem (1964) is

$$n_e \geqslant 7\times10^{18} \frac{Z^7}{p^{8.5}} \left(KT\grave{e}/\chi_H\right)^{1/2} \text{cm}^{-3} \quad \ldots (1.23)$$

here Z is the charged state of atom. This estimation is valid only for hydrogen ions. For other atoms, p is identified as effective quantum number of the level defined as

$$P_{eff} = Z\left(\frac{R}{T_\infty - T_p}\right)^{1/2} \quad \ldots (1.24)$$

where R is Rydberg constant, T_∞ is the ionization limit, T_p is the temperature value of the level p and for neutral atoms Z = 1. Introducing semi-emperical formula of excitation rate coefficient, Drawin (1969) corrected eqn. (1.24). Fujimoto (1973) considered LTE on the basis of a collisional radiative model for hydrogen ions which is identical with that enunciated by Griem.

LTE does not prevail in low electron concentration. It is possible to obtain equilibrium here whereby the collisional excitation and ionisation is balanced by radiative decay and recombination respectively. Solar corona is an example of this kind of equilibrium (CE), so is known as corona equilibrium (CE) model. In CE, the allowed spectral lines emitted from the population of an excited level is governed by collisional excitation from ground level as it is the faster process than the spontaneous radiative decay. For all excited levels CE to be valid is given by Wilson (1962) as,

$$n_e \leqq 1.5 \times 10^{10} \chi_i^{-0.5} (KT_e)^4 \ cm^{-3} \quad \cdots (1.25)$$

Wilson also described a semi-corona (SC) domain when CE is valid except for levels close to ionisation limit.

The criterion for SC domain in case of ions without metastable levels is

$$n_e \leqq 10^{11} \chi_i^{1.5} (KT_e)^2 \ cm^{-3} \quad \ldots(1.26)$$

Another condition for CE has been proposed by Mcwhirter (1965) and Fujimoto (1973) interpreted CE in terms of a collisional radiative model. It is necessary to mention that when all the above criteria do not apply for an actual plasma, all of the collisional and radiative rate processes are to be considered for a particularlevel. In transition region (fromSC to partial LTE) this is important. Fujimoto (1979) adopted this transition region through quasi saturation phase by ladder like (stepwise) excitation mechanism.

The following two assumptions are made to handle spectroscopic problem easily.

(A) Optically thin plasma is taken because the radiation generally treated in terms of optical path and the absorption of radiation is negligible. Both for CE and LTE light sources above $10{,}000^{o}K$ are transparent in the central parts of the line [except for resonance line (Lochte-Holtgreven, 1968)] .

(B) The electrons are assumed to obey Maxwellian distribution for simplification. In spectroscopic methods a knowledge of electron energy distribution function 'f' is involved directly in the collision integrals. An equilibrium of Maxwellian type velocity distribution is established by the collisional effects of free electrons in an active plasma.

But due to the presence of electric field in the discharge or elastic collisions of electrons, this equilibrium may be destroyed. The distribution function $f(\vec{r},\vec{v},t)d\vec{r}d\vec{v}$ denotes the number of electrons at position $\vec{r}$ in $d\vec{r}$, with velocity $\vec{v}$ in the range $d\vec{v}$ at time t. This function satisfies Boltzman transport equation in which the rate change of the number of electrons in $d\vec{r}$ $d\vec{v}$ is equal to the net flow of electrons into this volume element. From the velocity of electrons, the flow in position space occurs. On the otherhand acceleration due both to collision with gas atoms and the applied electric field can be derived from the velocity space. For that reason the distribution function is taken almost spherically symmetric in velocity space to avoid mathematical complexity.

Thus the Boltzman equation is solved and the distribution function of unknown form is obtained numerically by taking first two terms of an expansion in spherical harmonics. In case of high ionization plasma, the solved distribution function differs a little from a Maxwellian one. But von-Engel (1965) assumed that the energy distribution of electrons in a gas moving in an electric field is approximately Maxwellian in nature. In case of small degree of ionization the socalled non-Maxwellian interactions of electrons with other particles result in elastic and inelastic collisions. Thus energy exchanges between charged, excited and neutral particles takes place due to these collisions and conversions between potential and kinetic energies occur. These energy transformations effect the distribution function, 'f'.

For inelastic collisions, it is the electrons in the tail of the distribution that participate in energy exchange. In case of low temperature plasma, some high energetic electrons in the tail is lost due to inelastic collisions. The functional nature is not altered for non-ionised bulk electrons. This phenomenon led von-Engel (1965) to consider energy distribution to be Maxwellian (mainly for helium gas).

In case of free electrons obeying Maxwellian velocity distribution, Elton (1970) framed up four criteria as follows:

$$t_{ee} \ll t_{ff}, t_{eh}, t_{part}, t_{inel} \qquad \ldots(1.27)$$

For a specific experiment, the energy relaxation time for colliding electrons, T_{ee} must be less than:

(1) t_{ff}, the energy decay time for free processes,

(2) t_{eh}, the characteristic electron heating time,

(3) t_{part} , the characteristic time for particles, and lastly,

(4) t_{inel} , the relaxation time for electron impact including atomic processes such as excitation, ionization etc. The radiation of plasma is increased, when the number density is high so that criteria (1.27) are fulfilled. Griem(1964) described that the laboratory plasmas that emit enough light for spectroscopic observations are sufficiently dense and long lived so that electrons velocity distribution at any instant of time and at any point in space is Maxwellian.

In the investigation of plasma diagonostics Evans (1974) enunciated that plasma parameters can be deduced from radiation generated within it and emitted, or from the changes undergone by radiation introduced into the plasma but derived from an independent source. He found that the distribution of electrons amongst the possible levels in a population of excited atoms or ions immersed in plasma is determined by collisions with other particles and by radiation processes. The local thermodynamic equilibrium (LTE) model and the steady state corona model are used to predict the electron distribution.

The use of an optical spectrographic system in the study of a CF_3H plasma process has been investigated by Frieser et al (1980).

Golovistskii et al (1987) determined the plasma discharge parameters of gas mixtures containing helium in narrow tubes by spectroscopic technique. They come to the conclusion that a significant advantage of spectroscopic methods for plasma diagonostics over probing technique is the fact that all spectroscopic measurements are done in a non-contact fashion and are done without disturbing the plasma at all. The proposed spectroscopic method is suitable for quite a wide group of plasmas in which the only condition is that the plasma be optically thin for the helium lines whose lower levels are metastable. If the concentration of metastable helium atoms is somehow measured by self absorption for example, then this method becomes universal. A significant achievement of this method is also the fact that it can be applied for plasma diagonostics to any gas discharge devices, which lack any adaptations for plasma diagonostics.

1.7. Dependence of spectral intensities on arc plasma

To interpret results obtained from some typical plasma light sources as examined by common spectroscopic instruments, some knowledge about atomic parameters such as oscillator strength, line width and continuum emission coefficient are needed. The classicial treatment of light absorption by harmonic and anharmonic electron oscillatòrs had led to definition of a dimensionless constant, absorption oscillator strength, f_{lu} expressing the absorptive power for each characteristic frequency as a fraction of the total absorptive power of the electron. The expression for f_{lu} has been given by Kuhn (1964) as

$$f_{lu} = A_{ul}\,(g_u/g_l)/\,3\gamma$$

where $\gamma = 8\pi^2 e^2/\,3mc\lambda^2$

where A_{ul} denotes transition probability and g_u and g_l levels are statistical weights of upper and lower levels. The statistical weights are related to the inner quantum number of a level

$$g_L = 2J_L + 1$$

and to the quantum number of a term

$$g_M = (2L+1)(2S+1)$$

Another factor, self absorption, plays a vital role in determining the intensities of spectral lines. Cowan and Dieke (1948) explained that the self absorption within a gas layer of uniform excitation temperature has the effect of levelling out all intensity differences. This often causes serious difficulties in determining the ratios of strength of spectral lines in multiplets and hyperfine multiplates.

Self absorption is by no means restricted to absorption lines i.e. lines connected with the ground level. Also lines whose lower state is metastable often show marked self absorption or even self reversal. In quantitative studies of spectral line profiles it is essential to take self absorption into consideration.

Measurements have been made by Fowler and Duffendack (1949) regarding the intensity of radiation from the low voltage arc in helium as a function of gas pressure, tube current and tube potential. The experimental results indicate that the radiation is the result of a primary electron process and this process has been generally assumed to be direct.

From the experiment of Fowler and Duffendack (1949) it is evident that the line intensities depend on arc current linearly. In previous experiment Duffendack and Koppius (1939) investigated the variation of intensity with abundance in gas mixtures. Over the range in densities investigated, the curves were found to be of the saturation type. This saturation was interpreted as the complete utilization of available primary electrons in inelastic impacts direct excitation being regarded as the source of the radiation. A new spectroscopic method of high pressure arc diagnostics has been described by Teh-Sen. Jen (1968). In this investigation general properties of the resonant line spectral profile emitted by high pressure arcs are investigated. The shape of the strongly broadened and greatly reversed profile is studied using the computed DIines profiles from sodium d.c. arcs and the relationship to the key plasma parameters has been established. It is found that the relative intensities at the lateral peaks of the resonant profile are proportional to the corresponding intensities in the Planck spectrum for an effective central temperature T_e. This T_e is uniquely related to the actual central temperature with only slight dependence upon the shape of the temperature profile.

Ovechkin et al (1969) calculated the mean optical density indicated by Bartels' model using graphs of relative intensities as a function of distance. The slope of all curves is similar and points to a proportionality between the line width and the square root of the distance from centre. The mean optical density of plasma decreases with the reduction of Cu atom concentration when the self attenuation mainly takes place in the source central zone.

Emission in the near ultraviolet from transient arcs between gold electrodes carrying arc currents in the range 0.8 - 1.75 A was studied by Boddy et al (1969). Analysis of the intensities of the Au I lines was carried out in terms of a model involving two distinct zones. There is intense emission from the second positive system of nitrogen. Temperature of the order of 6000°K is obtained from the analysis of the rotational fine structure of the (0,0) band. In another investigation, the radial temperature distributions are measured spectroscopically for the current range of 5 - 570 Amp. in steps of between 5 and 50 amp. by Schade (1970) in case of cylindrical nitrogen arc (1 atom, 5 mm Ø). At the highest current of 570 Amp. the temperature attains a maximum 26000°K corresponding to a degree of ionization of 11.5%.

Auzinya et al (1979) described a spectroscopic method for measuring the temperature in an argon and air arc at atmospheric pressure. Accuracy of methods for measuring temperature in an argon-air arc depends on concentration of argon. On the basis of obtained results, the method of measuring the temperature in an argon - air arc is determined.

Drouet et al (1986) measured the arc - current distribution at the anode in vacuum at low pressure. In this investigation the arc was triggered by a laser pulse between a 3 mm outer diameter copper cathod and a 90 mm outer diameter brass anode formed from nine concentric rings, connected to the power supply through individual current transformers to allow simultaneous monitoring of the current in each ring. Measurements are reported for arc currents of 58, 137 and 204 Amp. electrode separation of 10, 15, 25, 35 and 45 mm and gas pressures from 10^{-6} to 10 torr during current pulse between 0.025 and 1 ms.

Rocca et al (1981) discussed the effect of an axial magnetic field on the spontaneous emission from an argon hollow cathode discharge and variation of spectral intensity with discharge current. In their investigation the longitudinal magnetic field is shown to decrease the effective density of beam electrons in the negative glow.

In our laboratory Sen et al (1987) investigated experimentally the variation of intensity of mercury lines with discharge current varying from 2.5 Amp. to 5 Amp. under transverse magnetic field varying from zero to 1.6 KG. The increase was found to be linear. The increased intensity shows a minimum around 200 - 250 G, but for smaller values of arc current, the effect of magnetic field is more prominent.

1.8. Investigation of glow discharge plasma subjected to the discharge of a bank of condensers.

Analysis of wire explosion phenomenon by electrical and optical method has been utilised by many authors. Nevodichanski et al (1968) considered the axial light emission of plasma created during an electrical explosion of thin metallic cylinders. It is shown that depending on the pressure, the intensity curve of the light emission from plasma shows a series of local peaks which are either due to the cumulative effect of converging shock waves or due to the pinch effect. Skowronek et al (1970) discussed the influence of plasma frequency on the light emitted by an exploding ionized gaseous filament. In their experiment a very dense and easily reproducible plasma was generated by the explosion of a thin pre-ionised gaseous column. The optical thickness of the discharge was measured by means of laser and the absorption coefficient was found to be higher than 18 cm^{-1}. The spectral brightness of the discharge is measured from wave lengths 0.2 μ to 4.8 μ. The instantaneous spectral distribution shows an abrupt drop in the near infrared at 1 μ. This is interpreted as being due to the plasma frequency with a corresponding electron density of $(1 \pm 0.2) \times 10^{21}$ cm^{-3}.

Pinch effect of metal plasma obtained by exploding wire has been studied by Aycoberry et al (1962). Through a thin metallic wire a 1 μF , 100 KV capacitor was discharged with ringing frequency of 200 Kc/s. Pinch effect during the first micro seconds had been observed by exploded wire, and current and voltage were recorded by oscilloscope.

In the study of exploding wire phenomenon an electrolytic capacitor of large capacitance 400 to 500 μF charged upto several hundreds of volts was used as the source of energy by Iguchi and Kawamada (1967).

In 1962 Vitoviskii and co-workers reported that the soft X-ray was generated from wires exploded in vacuum. Handlestenerhag and co-workers (1971) observed that from exploding tungsten wires in vacuum X-rays were emitted. They showed that X-rays were emitted near the melting point of the wire. Vitkovitsky and co-workers (1962) explained that the emission of X-rays was due to the result of decelerated electrons initially emanated from the early onset of ionization. Qualitative explanation for the emission of hard X-rays was made by Stenerhag and co-workers (1971) by using a model based on thermoionic electron emission from the wire.

The duration times and the initiation mechanism of the restrikes of thin tungsten wires exploded in air was investigated by Vlastos (1968). He concluded that the restrikes of tungsten wires are always generated at the exterior wire explaining the dwell times of wire at high voltages. Vlastos's experimental arrangement consisted of a capacitor 9.6 μ F, an inductance 26 nH and a resistance 13 m Ω. Coaxially symmetric exploding wire gap; a height of 150 mm, an outer diameter of 530 mm; an inner diameter of 500 mm and four symmetrically placed circular quartz windows with diameters of 70 mm. By utilising a specially constructed manipulator the wire could be mounted in the gap under vacuum. The gap was evacuated by a rotary vacuum pump with a displacement at speed of 9 m^3/h a oil diffusion pump with a capacity of 150 liter/sec. The final vacuum was found to be about 5 x 10^{-5} torr. The condenser bank charging voltage was measured by an ammeter connected in series with a resistance of 300 m Ω $\pm$ 2%. The current was measured by a Rogowsky coil and a passive RC integrator. A probe with a rise time of about 2 n sec. was used for the current derivative. The rotating mirror streak camera of maximum resolution of 2.6 mm/μ sec. was synchronized with the voltage and current recordings. The Kerrcell shutter cameras had constant exposure time of 30 and 50 n sec. respectively. By means of simultaneous oscillographic recordings of the current and the signals from the monitors of the cameras, the exposure times were determined. The importance of Vlastos's observation was that due to mechanical or electrical properties of thin tungsten wires it produces a slow condenser banks at low voltages.

In case of glow discharge the enhancement of spectral line by shock waves was observed by Miyashiro (1984). In his investigation fast electric discharge is generated across a shock wave. The lower pressure around the cathode in front of the shock wave enables electrons to strongly diffuse radially and therefore the glow is maintained with little constriction even at high average pressure. Experimentally it is seen that the glow diameter, discharge fluorescence and current are enhanced by the shock wave.

Enhanced radiative temperature has been observed by Skarsgard et al (1969) at the plasma frequency in nearly Maxwellian helium afterglow plasmas. These measurements confirm the predicted bremsstrahlung emission from plasma oscillations generated by suprathermal electrons.

Enhancement of electrical conductivity in a gas was enunciated by August (1967). He performed an analytical and experimental investigation to investigate the plasma characteristics induced in air by alpha particle emissions for radioisotope material. Primary ionization caused by collisions produce sufficiently energetic electrons to cause secondary ionizations. Associated with these induced levels of electron energy are reduced probabilities that the freed electrons will be lost through attachment and dissociative recombination processes, thereby attaining an appreciable level of electrical conductivity in the gas. He estimated an average electron density through an ionized air layer adjacent to an alpha particle emitting surface having 2 millicurrents per inch^2 to be 10^9 - 10^{10} e/cm^3 and its graded distribution normal to the surface was also estimated.

The local dependence of the rise time of the emissive line intensities of Ne in a cylindrical hollow cathode has been measured by Yamashita et al (1980) as a step towards studying the mechanism of emission. The temporal change of the intensities at the central axis portion shows a clear initial peak enhancement and then a decrease to the stationary state.

The rise time of the intensity at the central axis portion is always a few microseconds faster than the edge portion.

Decker et al (1981) used fast 200 KV capacitor bank as a current source for a dense plasma focus. They described a fast high voltage, high impedance capacitor band designed as a current source for a dense plasma focus with a voltage of 200 KV, initial current rise 2×10^3 A/S, current rise time $\leq$ 500 ns and impedance 35 MΩ. The bank consists of 50 parallel storage modules which are connected by parallel plate transmission lines.

Scope and Object of the Present Work:-

In the present investigation both immersive and non-immersive diagonostic techniques have been adopted. We utilize (a) spectroscopic method, (b) r f coil and capacitor probe in conjunction with longitudinal magnetic field under the scheme of non-immersive diagonostic technique, and (c) single probe and (d) probes of different constructional geometry and different modes of insertion under immersive scheme.

Though a large amount of work has been carried out regarding breakdown of gases and consequent production of plasma, measurement of plasma parameters, waves and oscillations in a plasma and other allied problems, still the nature of some of the physical processes occuring in a plasma during the period of its formation and maintenance have not been adequately investigated. The physical processes occuring in the initiation and maintenance of an arc plasma are still not properly understood. Further the phase of transition from glow to arc should be investigated in order to develop a theoretical basis for the occurance of arc plasma. In this compilation some of the associated problems have been investigated.

(i) Measurement of plasma parameters in an arc by probe method

(ii) Measurement of plasma parameters in an arc plasma by diffusion voltage measurement.

In order to develop a generalized theory for the occurance of arc plasma and to investigate the transition of glow discharge to arc plasma experimental and analytical investigation has been undertaken by Sen and some of his research fellows (1973, 1976, 1978, 1979, 1980, 1985, 1986, 1987), during last few years. Actually to develop the theory for the occurance of arc plasma, a large collection of data regarding plasma parameters and their variation in a perturbing field is necessary. It is therefore, worthwhile to study whether the Langmuir single probe technique can be utilised for measurement of arc plasma parameters. This will also show the validity of Langmuir probe theory in the arc plasma region. Besides there is an important mechanism by which charged particles are lost in a plasma, and the process is known as ambipolar diffusion. Hence besides the experiment for Langmuir probe an experiment has been set up to measure the resultant diffusion voltage in an arc. The process of diffusion is basically connected with the radial distribution function of charged particles and an expression for the radial distribution function of conductivity in an arc plasma has been provided by Ghosal, Nandi and Sen (1978). The object is to analyse the experimental results by utilizing the new distribution function. This experiment can also show the validity of distribution function as proposed by Ghosal, Nandi and Sen (1978). This experiment may be extended in presence of different buffer gases, at different pressures and with different tube radii.

(iii) Measurement of electron atom collision frequency in an arc plasma by radio-frequency coil probe in conjunction with a longitudinal magnetic field:-

There are some standard methods for calculating the electron atom collision frequency in glow discharges but the corresponding results in case of an arc plasma have been little reported so far. The electron atom collision frequency is an important parameter and its variation with pressure and arc current will provide information regarding the collisional processes in an arc plasma. In carrying out this investigation it has been argued that an external magnetic field can be used as a probe.

Here the theory developed by Ghosal, Nandi and Sen (1976, 1978) regarding the radial distribution of conductivity of an arc plasma has been modified due to its tensorial behaviour when the arc is placed in a longitudinal magnetic field. A working formula has been developed to measure the electron atom collision frequency where the magnetic field has been used as a probe.

The present study is to explore the tensorial behaviour of plasma conductivity in an arc plasma in presence of magnetic field and hence from the measured impedance parameters both in presence and in absence of magnetic field the electron atom collision frequency can be determined. The relevant theory has been developed taking the effect of radial distribution of conductivity into account.

(iv) Evaluation of electron temperature in transverse and axial magnetic field in an arc plasma by measurement of diffusion voltage:

In this laboratory Sen, Ghosh and Ghosh (1983) developed a method to evaluate the electron temperature in air glow discharge (pressure 1 torr) from the measurement of diffusion voltage taking the radial profile of charge distribution as Besselian. They also measured the variation of electron temperature in a magnetic field by placing the discharge tube in a transverse magnetic field (0 to 100 G). In case of the arc plasma this technique has been utilized considering radial distribution of charged species as provided by Ghosal, Nandi and Sen (1978). Analytical expressions have been deduced to calculate the ratio T_{eH}/T_e where T_{eH} and T_e are electron temperature with and without magnetic field from measured values of diffusion voltages in presence of an external magnetic field. Further it has been observed by Sen and Gantait (1988) that the voltage current characteristics undergo a similar change for both the alignments of magnetic field but the transverse magnetic field has a more dominant effect on the properties of arc plasma than that of an axial magnetic field. Hence in the present investigation, it is the aim to evaluate the electron temperature in an arc plasma by measuring the diffusion voltage and study its variation in both transverse and axial magnetic fields and provide a theoretical analysis of the observed results.

(v) Breakdown of argon under radiofrequency excitation in transverse magnetic fields.

The object in this section of the work is to study the physical processes involved when a gas breakdown under the simultaneous presence of a radiofrequency and a transverse magnetic field.

The breakdown characteristics of argon gas under radiofrequency excitation over a frequency range and for small H/P (ratio of magnetic field to gas pressure) values have been calculated on a theoretical model suggested by Hale (1948). Taking the concept of equivalent pressure into account in presence of magnetic field, breakdown voltage has been calculated as a function of frequency for different gas pressure and magnetic fields. On the basis of this model, it is also possible to calculate the minimum breakdown field (volts cm^{-1}) in presence of magnetic field without much mathematical complexity. The theory developed both from the 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.

(vi) Intensity enhancement of spectral lines with increasing of arc current in arc plasma:-

It has been shown by Sen and Gantait (1987) that the intensity of spectral lines increases linearly with the increase of current in a mercury arc but the rate of increase is different for different wavelengths. The phenomena has been explained by the principle of self absorption of the spectral lines as has been done in the case of glow discharge, by Sen and Sadhya (1985), who deduced a detailed mathematical analysis to explain the results. In order to extend the results in case of other metallic arcs and to investigate whether it is the case in general, the present investigation has been undertaken.

An analytical expression for the ratio of intensity of the spectral lines with increasing arc current has been deduced assuming self absorption which predicts results in close agreement with those observed experimentally. In this experiment it is proposed to show how self absorption plays a dominant role in determining the intensities of spectral lines in case of optically thick plasmas and particularly its effect on intensity variation when the arc current is changed. This work can however be extended in case of vacuum arcs where pressure can be monitored systematically.

(vii) Investigation of glow discharge plasma subjected to the discharge of a bank of condensers:-

Discharge of a series of bank of condensers charged to high voltages has been utilised to create a transient high density plasma in a rarefied gas. The phenomena has been ascribed to the process of thermal ionization. Little work has been reported when a bank of condenser discharges take place through a steady state discharge. The object is to study how the physical processes are affected and how the plasma parameters change when the glow plasma receives a transient burst of energy. A spectroscopic method has been adopted for measurement of the intensity of spectral lines in a glow discharge when a bank of condensers discharges through it. A quantitative measurement of electron density and temperature is made in air and hydrogen glow raised to highly conducting condition by discharge of the bank of condensers. It is also noteworthy to state that this work can be performed in different gases with a broader interest of transient plasma heated to a very high value of electron temperature.

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