CHAPTER I

1.1. GENERAL INTRODUCTION

Accurate measurement of plasma parameters such as electron density, collision frequency and electron temperature is essential for the proper understanding of the physical processes occuring in an ionised gas. Occasionally plasmas are subjected to magnetic field for confinement and other purposes. Hence the interaction processes between a magnetic field and plasma should be properly investigated. In this thesis measurements and calculations are described relating to positive column of electrical discharges confined in cylindrical discharge tubes when a magnetic field is present.

A number of diagnostic methods have been developed in recent years. In the present study the Langmuir probe method and spectroscopic method have been utilised to determine plasma properties. The diagnostics are complicated considerably in the presence of the magnetic field. In view of that some efforts have been made to incorporate the effect of magnetic field on the diagnostics.

In a magnetic field plasma parameters change. The changes in properties not only depend upon the value of the magnetic field, but also on the orientation of the field with the discharge tube axis. Experimentally, two types of orientations are suitable. One is when the magnetic field is parallel to the axis of the discharge tube. This magnetic field is called a longitudinal or an axial magnetic field. Secondly, the magnetic field may be perpendicular to the axis of discharge and is known as a transverse magnetic field. Studies have been made for plasma ~~p~~ properties when these two types of magnetic fields are sep~~e~~arately present.

A study of plasma properties in magnetic field not only reveals variations of the properties with magnetic field, but also enables us to verify the models that are applied to interpret the behaviour of plasmas. With these aims in mind we are carrying out investigations in our laboratory on the properties of magnetoplasma. The present work reports some results and their interpretation.

In the next subsection a review of relevant works has been presented. Thereafter, the scope of the present work has been explained. In Chapter II, details of the experimental set-ups have been described. In Chapter III through VIII, reports of investigations on properties of magnetoplasma have been described. Details of the references cited in the texts are given at the end of each chapter.

1.2. REVIEW OF THE PREVIOUS WORK

1.2.1. MEASUREMENT OF ELECTRON TEMPERATURE AND ELECTRON DENSITY IN LOW DENSITY MAGNETISED PLASMA BY PROBE METHOD.

The electric probe has long been used as a fundamental diagnostic tool for measuring local properties of plasma. The experimental arrangements generally are very simple. A small metallic electrode is placed in the plasma at the location of interest. External circuitry is provided to vary its electric potential. The current flowing to the probe is measured as a function of applied voltage. The current voltage diagram or the probe characteristic may provide important information about local properties of the plasma such as electron and ion number densities n_e and n_i , electron temperature T_e , the plasma potential V_s and electron distribution.

Probe theory is complicated because probes are boundaries to plasmas and near the boundaries the equations that govern the plasma behaviour change. A thin layer around the probe exists where electron and ion number densities differ, and the layer called ~~as~~ a sheath can sustain large electric fields. So the number of possibilities for a meaningful use of probes is subject to many restrictions, otherwise the results of probe measurements may be erroneously interpreted.

To every point in the plasma there is a corresponding potential Vs, with respect to a given reference point (for example a large electrode in contact with the plasma). This is known as space potential. If a probe (e.g. a small cylindrical conductor) is inserted at a point in plasma, due to unequal motions of electrons and ions, the probe quickly attains a potential negative with respect to Vs, this potential is known as floating potential V_f and a sheath is formed due to space charge effect. If the probe potential is raised to V_s by some external source, the probe is at the same voltage as the plasma and there is no sheath. Charged particles reach the probe with their thermal velocities and the electron current considerably exceeds the ion current. If the bias is now increased so that the probe is more positive than the plasma, the ions are increasingly repelled and the saturation electron current is drawn which is determined by effective area of the sheath. In the collisionless plasmas, the sheath thickness increases as the bias is made more positive and electron current never completely saturates.

If the probe is biased more negatively than V_s an increasing fraction of electrons is repelled and the probe current falls. The logarithmic slope of the characteristic in this region is equal to the local electron temperature. At V_f, the currents of electrons and ions drawn to the probe are equal and the net current is zero. With increasing negative bias no electrons can reach the probe and ion saturation current is drawn. From electron and ion saturation currents, plasma local density can be determined.

Since Langmuir's (1924—1926) pioneer work, the theory of probes in the absence of magnetic fields has been extensively developed. In the absence of magnetic fields the response of a probe depends on a number of parameters. These parameters determine the various domain at which electric probe can operate. In the collisionless limit $[\lambda >> r_p , \lambda >> \lambda_D]$ where λ is the mean free path of charged particles, r_p is the probe radius and λ_D is Debye shielding length given by $\lambda_D = 4.9 (T_e / n_e)^{1/2}$ in cm.) the theory is practically complete and extensive computed results are available [Bernstein & Rabinowitz (1959) Lam (1965), Laframboise (1966)] . The continuum case $(\lambda << \lambda_D << r_p)$ has been treated by Su and Lam (1963) and Cohen (1963) and some attempts have been made to cover the intermediate regime [Wasserstrom, Su and Probstein (1965) Chou, Talbot & Willis (1966), Bienkowski and Change (1968)] . A systemic account of probe theories is given by Chung, Tolbot and Touryan (1975).

It has been discussed by Chen et al (1968) that probe theory is particularly simple when $\xi_p = r_p / \lambda_D$ which is called as "Debye ratio" is large ($>>$ 10) and the sheath is thin so that the particle collection area is essentially the geometric area of the probe; or when ξ_p is small ($<<$ 1) and the sheath very thick so that probe current is governed by orbital motion theory of Langmuir. For a suitable choice of ξ_p in an experiment, it may be noted that λ_D is determined by the plasma source itself, whereas r_p is set only by the physical ? strength of the material of probe. Hence it might not be always possible to have the Debye ratio in the desired range. Fortunately for cylindrical probes, the computation of Laframboise (1966) shows that orbital motion theory is accurate for $\xi_p < 5$ and this is easy to satisfy. For a spherical probe orbital motion approximation is useful for $\xi_p << 1$ only.

Schott (1968) has enumerated conditions to be satisfied for an ideal probe operating in orbital motion approximation:

- The plasma to be homogeneous and quasi neutral in the absence of the probe.
- Electrons and ions to have Maxwellian velocity distributions with temperatures T_e and T_i respectively with $T_e >> T_i$. The mean free paths of electrons and ions λ_e and λ_i to be large compared to all other relevant characteristic lengths. Each charged particle hitting the probe is to be absorbed and not to react with the probe material.

- The sheath has a well defined boundary. Outside this boundary the space potential is constant.
- The sheath thickness is small compared to the lateral dimensions of the probe so that edge effects can be neglected.

Particularly in low pressure plasmas the condition of Maxwellian velocity distribution is often violated. An essential progress in probe theory was achieved by the work of Druyvesteyn (1930), who showed that actual velocity distribution can be derived from the form of characteristic. Another disadvantage for cylindrical probes is that the potential falls off slowly with radius so that r_s, the "absorption radius" defining the effective collection area can be much larger than λ_D. At low densities the length l of the probe must be much greater than r_s (and hence greater than r_p) in order to avoid end effects. The material for the probe should be resist~~e~~ant to sputtering, to heat and to chemical reaction. Furthermore, the work function of the material should be high in order to minimize secondary electron emission. For comparatively hot plasmas tungsten as probe material is a suitable choice. Nevertheless, the probe and its insulator support structure which is immersed in the plasma disturb the plasma and the measurements as well. Chung, Talbot and Touryan (1975) have reviewed the present state of knowledge about these disturbances.

Presence of magnetic field further complicates probe data interpretation. Experimentally it is known that the magnetic field substantially modifies the characteristics. The useful sharp knee at the space potential is blurred or disappeares completely. For more positive probe voltages (i.e. for electron collection) the current decreases substantially from its value at zero field. In a magnetic field the particles are constrained to move at different rates along and across the field lines. The problem thus becomes an anisotropic one. The charged particles can travel only a distance of the order of their Larmor radii $r_{Le,i}$ without making collision and when either r_{Le} or r_{Li} is of the order of r_p or less, collisions come into play even when the relevant mean free path λ is large compared to r_p. Thus the equations describing the problem in the neighbourhood of probe differ markedly from those valid far from the probe. The problem was tackled by several authors from different point of view and theories were interpreted in the light of experimental results. A systematic account has been provided by Chung, Talbot and Touryan (1975). The investigations of Chen et al (1968) who compared results obtained from probe measurements with those of other standard diagnostic techniques in magnetic field are of particular interest. After detailed experimental observations Chen et al recommended that if the requirements of spatial and temporal resolution permit, one should use a cylindrical probe with $r_p \ll r_L \ll l$ and ξ_p small.

For such a Langmuir probe, orbital motion limited current approximation can be used. Recently Bakshit et al (1977) investigated the transition region on probe characteristic which is used to determine T_e and V_s. In strong magnetic d fields, in which r_{Le} is much smaller than geometric dimension of probe, the magnetic field can affect the electron current drawn by the probe. So the standard methods for determining T_e and V_s may prove incorrect.

When the probe is large compared to mean free path, it collects so many electrons that the electrons in the surrounding space is absorbed more rapidly than they can be supplied by diffusion from the distant regions where they are produced. Therefore, electron collection by a positive probe is considerably reduced in presence of a magnetic field. The process of ion currents becomes relatively simple, because in most cases $r_{Li} >> r_{Le}$. So it appears that electron density of magnetoplasma can be determined from ion saturation current to a Langmuir probe using usual probe theories without considering magnetic field effect. But Chang and Chen (1977), observed that for a low density ($n_e \leqslant 10^{10}$ cm^{-3}) medium pressure plasma ($p \geqslant 0 \cdot 1$ torr) in a weak magnetic field ($B \leqslant$ 1 k gauss), an apparent increase of ion current comparable to the regular probe current caused by secondary electron emission from probe surface occurs. The influence of secondary electron emission becomes more complicated in a magnetic field. The plasma density obtained from electron saturation current by carefully applying the probe theories in a magnetic field agrees closely with electron density determined from microwave measurements, ~~by~~ but n_e obtained from ion saturation current using usual probe theories without magnetic field does not.

However, when magnetic field is small, effect of the field is significantly small to be neglected (Scott (1975)). It has been observed by Kagan and Perel (1969) that magnetic field has little effect on the probe characteristics for cylindrical probe ($r_p \ll \lambda_e$) which is perpendicular to the magnetic field, so long $r_p \ll r_{Le}$.

At this point we shall discuss about the investigations carried out for determining the effect of magnetic field on the positive column of plasma with probe method. Cummings and Tonks (1941) investigated ~~on~~ the positive column of low pressure mercury vapour arc by probe method when a longitudinal magnetic field was present. They concluded that normal radial electron density (n_e) distribution for a mercury plasma is not affected by the presence of longitudinal magnetic field. Subsequently Tonks (1941) obtained a theoretical interpretation. Later on Bickerton and von-Engel (1956) considered Cummings and Tonks' investigation inconclusive because of the difficulty of interpreting probe characteristics taken in presence of magnetic field. Cummings and Tonks observed a reduction of T_e with the increase of magnetic field. It may be noted here that value of magnetic field ($B \leqslant 70$ Oe) is small enough to neglect magnetic field effect on probe characteristics.

Bickerton and von-Engel (1956) studied the positive column of a helium discharge in longitudinal magnetic field by tungsten cylindrical and molybdenum disc wall probes. They measured T_e from the gradient of semi-log plot of electron current and electron densities were measured by relative changes in ion saturation current in various magnetic field strength. The authors observed that above 1 torr the maximum magnetic field ($B <$ 600 gauss) has only a x negligible effect on T_e . At the lowest pressure used (0.22 torr) the probe characteristics in a magnetic field indicates the presence of two groups of electrons, one having distinctly higher temperature than the other. Presence of two groupsof electrons in a low pressure plasma was also confirmed by Uehara et al (1975) by probe measurements. Bickerton and von-Engel further observed that when a longitudinal field is applied T_e is reduced. For low pressure discharge with low current (glow discharges) a change in the radial electron distribution takes place with magnetic fields and n_e at ~~axis~~ axis rises with the increase of field. It was concluded that in some cases of very low pressure in zero magnetic field, the Langmuir theory of free ion fall describes best the properties of plasma whereas in a magnetic field of sufficient strength Schottky's theory of ambipolar diffusion applies.

Sen and Jana (1977) while investigating the current voltage characteristic of glow discharges in an axial magnetic field ($B \lesssim$ 800 G) in air (p = 0.5 to 1 torr) have observed ~~a~~ that radial distribution of electrons can be represented by a Bessel function (Schottky's theory) in the presence of longitudinal magnetic field as well. Sen and Gupta (1969) from r.f. conductivity measurements in helium, neon and argon ($p = 0.7$ torr) in a longitudinal magnetic field ($B \leqslant 550$ G) have shown that Schottky's ambipolar diffusion theory is valid for these discharges in magnetic field and from the particle balance equation the authors found electron temperature to decrease with increasing field. Sen and Gupta also observed the Debye shielding distance decreases as the field increases.

Schott (1963) conducted probe measurement in a cylindrical diffusion chamber. An increase of electron temperature towards the wall at low values of magnetic field was observed. At high values of magnetic field, a radial decrease of T_e is found which is due to the transversal cooling down mechanism of electron gas by two particle collision.

While investigating on the enhancement of radiations from a helium plasma in longitudinal magnetic field Hegde and Ghosh (1979) made use of a Langmuir probe in the positive column. The authors observed that the electron temperature is reduced and axial electron density increases as the field ($B \leqslant 700$ Oe) increases. They did not discuss about the corrections of probe characteristics for the presence of the magnetic field.

For transverse magnetic field, Tonks (1939) has reported T.J. Killian's measurements on a low pressure (Outerwall temp. 38.6°C) mercury arc by probe method. Electron temperature and electron number density were determined from one wall to the other. An exponential variation of electron density with distance across the arc was observed. Apart from these probe measurements other measurements on the properties of plasma in the presence of transverse magnetic field have been made and investigations have been discussed in the next subsections.

1.2.2. MEASUREMENTS OF ELECTRON TEMPERATURE IN GLOW DISCHARGES IN TRANSVERSE MAGNETIC FIELD BY SPECTROSCOPIC METHOD:

The ideal experimental method would be one in which the probing mechanism does not disturb unduly the processes to be investigated. Consequently a spectroscopic method is preferred to other diagnostic methods. Spectroscopy of laboratory plasmas covers a wide area of work, varying from atomic structure to plasma physics. All the areas have been identified and discussed by Burgess (1972). It is the presence and interactions between ions, neutrals, electrons and photons that lead to atomic processes which both affect the plasma and provide information on plasma state.

For glow discharges in which electron temperature (1-5 eV) and electron density (10^8-10^9 cm^{-3}) are comparatively small, electron temperatures can be deduced from relative intensities of spectral lines. To determine T_e from relative intensity method, spectral lines are selected for which relevant atomic processes is understood and the excited state continuity equation considering all of the collisional and radiative processes that populate and depopulate the state concerned is written down. The process of solving the excited state continuity equations, thus obtained, is very complex. Simplifications may be made by weighting the relative contribution of seperate processes and establishing a certain type of equilibrium to prevail inside the discharge tube by considering dominating particle gain and loss terms.

Two types of equilibriums are of interest the local thermodynamic equilibrium model (LTE) and corona equilibrium model (CE).

When a plasma is in LTE, there exists a unique temperature which determines the velocity distribution function for species with the dominating reaction rate (usually the electrons). If such equilibrium exists, the analysis of the state of plasma is particularly simple since it is only such local plasma parameters as electron density, electron temperature and composition that determine the relevant populations. To obtain total LTE, the reverse of all fast processes must be maintained and exact balancing of total rates for complementary processes must be allowed to take place. Also, the relaxation times (reciprocal of the rates) for the important processes must be shorter than characteristic times of significant variations in local plasma conditions. Since most plasma of interest are optically thin to internal radiation (except perhaps for the resonance lines), collisional processes are usually more important in establishing LTE than radiative processes. Consequently collisional de-excitation rates must exceed radiative decay rates for true LTE. In LTE, energy of every particular kind is distributed over all particles present in the gas according to Boltzmann distribution law and in case of ionization, this equilibrium relation leads to Saha equation.

The number density of electrons necessary to obtain complete LTE has been calculated by Griem (1964). This electron density is given by

$$n_e \geqslant 9 \times 10^{17} (E_2 / \chi_H)^3 (kT_e / \chi_H)^{1/2} \ \mathrm{cm}^{-3} \qquad (1.1)$$

with E_2 the energy of the first excited level and χ_H the ionisation energy of hydrogen and k is the Boltzman constant. E_2, χ_H and kT_e all expressed in eV. To calculate this criterion, Griem considered that for lowest excited state (resonance level) the collisional excitation rate is ten times the radiative rate from that level. Later on this criterion was corrected by Hey (1976) by considering finer values of Gaunt factor appearing in collisional excitation rate co-efficient and incorporating the effect of metastable-metastable collisions.

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

$$n_e \geqslant 6 \times 10^{13} \chi_i^3 (kT_e)^{1/2} \quad cm.^{-3} \qquad (1.2)$$

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

$$n_e \geqslant C \; (kT_e)^{1/2} \chi_i^3 \quad cm.^{-3} \qquad (1.3)$$

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

For stationary and spatially homogeneous plasmas, LTE can be expected to hold if collisional processes with electrons from assumed Maxwellian distribution dominate in the rate equations. Since cross-sections increase rapidly with principal quantum number, whereas radiative decay rates decrease, this is often the case only for states with principal quantum numbers exceeding a certain value for which radiative decay and collisional excitation rates are comparable. Under the above circumstances it is consistent to related densities in states above the critical level with each other and to electron density in the same way as in a system in complete LTE. Richter (1968) has shown that the occupation number for states over this critical level are as in LTE with temperature T_e but the ground level is overpopulated by a factor. So the states over the critical level is considered to be in partial LTE. The electron density required for a level with quantum number p to be in partial LTE with higher levels is after Griem (1964) approximately

$$n_e \geqslant 7 \times 10^{18} \frac{z^7}{p^{8.5}} \left(kT_e / \chi_H \right)^{1/2} \quad cm^{-3} \qquad (1.4)$$

here (z) is the charged state of atom. Strictly speaking this estimate applies only for hydrogen ions. For other atoms, p is identified as effective quantum number of the level defined as

$$p_{eff} = z \left(\frac{R}{T_\infty - T_p} \right)^{1/2} \qquad (1.5)$$

where R = Rydberg constant, T_∞ is the ionisation limit, T_p is the term value of the level p and for neutral atoms z = 1. Drawin (1969) applied a semi-emperical formula of excitation rate co-efficient and made a correction to equation (1.4). Fujimoto (1973) treated LTE on the basis of a collisional radiative model for hydrogen ions and observed that LTE is identical with that ennunciated by H.R.Griem.

When electron densities are too low for establishment of LTE, it is still possible to obtain equilibrium whereby the collisional excitation and ionisation is balanced by radiative decay and recombination respectively. This type of equilibrium generally prevails in solar corona, so it is known as corona equilibrium (CE) model. In CE, the population of an excited level which can emit allowed spectral lines, is usually governed by collisional excitation from ground level and spontaneous radiative decay, but since decay is the faster process, the population is mainly in the ground level. CE can also be applied under restricted conditions to the line intensities of spectra from low density plasmas created in the laboratory. An approximate criterion for CE is to be valid for all excited levels is given by Wilson (1962) as,

$$n_e \lesssim 1.5 \times 10^{10} \chi_i^{-0.5} (kT_e)^4 \quad cm.^{-3} \qquad (1.6)$$

here again χ_i is the ionization potential of the atom in eV. 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

$$n_e \lesssim 10^{11} \chi_i^{1.5} (kT_e)^2 \quad cm.^{-3} \qquad (1.7)$$

McWhirter (1965) proposed another condition for CE and Fujimoto (1973) interpreted CE in terms of a collisional radiative model.

When an actual plasma can not satisfy the criteria already stated, complexity arises and all of the collisional and radiative rate processes are to be considered for a particular level. This is particularly important for plasma in transition region (from SC to partial LTE). Fujimoto (1979) has treated this transition region through quasi saturation phase (complete saturation phase means complete LTE) by ladder like excitation mechanism.

For spectroscopic diagnostics two assumptions are generally made and these assumptions make the problem easier to handle.

(i) The plasma is optically thin. The optical thin-ness or thickness of radiation generally treated in terms of optical depth. In case of an optically thin plasma, the absorption of radiation is negligible. So the radiation of each individual atom leaves the plasma and contribute to observed intensity. It is generally believed that for CE all the light sources, and for LTE all light sources above 10,000°K are quite transparent even in the central parts of the line (perhaps with exception of resonance line) (Lochte-Holtgreven,1968).

(ii) Additional simplifications can be achieved if it is assumed that electron energy distribution is Maxwellian.

Here we shall discuss in some detail about the energy or velocity distribution functions of electrons. For probe diagnostics the nature of electron energy distribution function is experimentally determined, whereas for spectroscopic methods a knowledge of electron energy distribution ~~is~~ function is necessary because the distribution function, generally designated by f, enters directly in the collision integrals. Also, the presence of a magnetic field can effectively influence f.

In an active plasma, the collisional effects of free electrons rapidly establish an equilibrium velocity distribution which is Maxwellian in character. An electric field present in the discharge or elastic collisions of electrons with other atoms, can destroy this equilibrium distribution. The significance of this function is that $f(\vec{r}, \vec{v}, t)\, d\vec{r}\, d\vec{v}$ 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. The distribution function in term satisfy an equation of continuity in position and velocity space i.e. Boltzmann transport equation. This equation equates the rate change of the number of electrons in $d\vec{r}\, d\vec{v}$ to net flow of electrons into this volume element. The flow in position space results from the velocity of electrons, while in velocity space it results from their acceleration due both to collision with gas atoms and the applied electric field. To simplify the integro differential equation an assumption is made that the distribution function is almost spherically symmetric in velocity space, hence, can be adequately represented by first two terms of an expansion in spherical harmonics involving the direction of electron velocity. In this way the Boltzmann equation is solved and generally the distribution function of unknown form is obtained numerically.

Occasionally for plasma with high ionisation, the solved distribution function differs in a minor way from a Maxwellian one and von-Engel (1965) wrote "generally, the energy distribution of electrons in a gas moving in an electric field is approximately Maxwellian". If distribution function becomes a non-Maxwellian one the concept of electron temperature is important only in the sense of average energy. When the degree of ionisation is small the socalled non-Maxwellian interactions of electrons with other particles result in elastic and inelastic collisions. These collisions induce energy exchanges between charged, excited and neutral particles and conversions between potential and kinetic energies occur, consequently for these energy transfers, f is affected.

For inelastic collisions, it is the electrons in the tail of the distribution that participate in the energy exchange. For a low temperature plasma, a small percentage of high energetic electrons in the tail is lost due to inelastic collisions and the tail is depleted. The nature of the function is not appreciably altered for bulk electrons which can not excite or ionise. This argument led von-Engel (1965) to consider energy distribution function to be Maxwellian (particularly for helium gas).

Elton (1970) has described at least four criteria to be satisfied if the free electrons in plasma to have a Maxwellian velocity distribution. These are:

$$t_{ee} << t_{ff} , t_{eh} , t_{part} , t_{inel} \qquad (1.8)$$

where t_{ee} is the energy relaxation time for colliding electrons. For a specific experiment, it must be much less than : (a) t_{ff} , the energy decay time for free free processes, (b) t_{eh} , the characteristic electron heating time, (c) t_{part} , the characteristic containment time for particles and lastly (d) t_{inel} , the relaxation time for electron impact including atomic processes such as excitation, ionisation etc. when the electron number density is comparatively high so that criteria (1.8) are fulfilled, the radiations from plasma also increase. Griem (1964) has expressed "most laboratory plasmas that emit enough light for spectroscopic observations are also sufficiently dense and long lived that the velocity distribution of electrons is very nearly Maxwellian at any instant of time and at any point in space".

Tonks and Allis (1937) investigated the effect of an external magnetic field on the electron velocity distribution function and Bernstein (1962) justified the use of a Maxwellian distribution for strong magnetic field in the approach via Boltzmann equation. It was experimentally observed by ~~xp~~ probe method that at least in longitudinal magnetic field electron energy distribution function is nearly Maxwellian (e.g. Bickerton and von-Engel (1956) for helium in 600 G field, Vorobjeva et al (1971) for pure mercury in 800 Oe field).

To report some measurements of properties of magnetoplasma by spectroscopic method: electron density in ring discharge (3.26 MHz) in argon ($p = 2.50$ torr) in longitudinal magnetic field ($B \leqslant 4.5$ kG) was measured by Ricketts (1970) by line intensity, and line to continuum intensity ratio method. The author selected lines of high lying levels assumed in LTE and observed marked decrease in T_e on the axis of discharge when axial magnetic field is applied. This temperature drop was explained in terms of possible heat transfer mechanism. An analysis of the profiles of certain HeI spectral lines emitted from a low pressure ($p = 0.5$ torr) after glow plasma submitted to a magnetic field of 10^5 G has been provided by Drawin and Ramette (1979). The authors observed that a strong magnetic field leads to profound modification of the line profiles and complicates the diognostics.

Now we shall discuss about the effect of a transverse magnetic field on the positive column of a low pressure discharge. As a cylindrical plasma column is subjected to a uniform transverse magnetic field it is pushed in the direction of Lorentz force. The electrons and ions are pushed in the same direction hence question of charge seperation does not arise, only the gyrofrequencies of electrons and ions will be vectorially in opposite directions (clockwise and anticlock-wise). So a deviation of density and potential distribution ~~fr~~ from cylindrical symmetry occurs. As a consequence ~~ther~~ there will be a potential difference between points of the wall on a diameter perpendicular to magnetic field and this potential difference is known as Hall voltage. Qualitative descriptions of plasma column subjected to transverse magnetic field have been given by Francis (1956).

By utilising Tonks and Allis's (1937) expressions for electron drift in transverse magnetic field Beckman (1948) showed that the field deflects the column towards the wall with the result that the total loss of electrons and ions is increased. This causes an increase in electron temperature and axial electric field strength. Beckman (1948) observed that the axial electric field E is changed to $E(\alpha + \beta^2/\alpha)^{1/2}$ in presence of a transverse magnetic field and electron density at a distance r from the axis and in field B is given by

$$n_B = n_0 \exp\left(-\frac{c r \cos\phi}{2 D_a}\right) J_0 (2\cdot 405 \cdot r/R) \qquad (1.9)$$

n_0 is the electron density at the axis, C is a constant depending on ion mobility, D_a is the ambipolar diffusion coefficient, J_0 is the Bessel function of zero order and of first kind and ϕ is the azimuthal co-ordinate. By measuring the voltage across a fixed distance by floating probe Beckman (1948) observed the electric field increases in a transverse magnetic field (B $\leqslant$ 1000 G) in gases like hydrogen, nitrogen, helium and neon.

Danders (1957) investigated on low pressure positive column in a homogeneous magnetic cross (transverse) field in Schottky manner and an equation of charge carrier density distribution was obtained. Current dependence on magnetic field was also examined experimentally.

Effect of a transverse magnetic field on low pressure glow discharges in different gases like, hydrogen, helium, neon etc. was also investigated by Sen et al (1971, 1972). The authors measured the discharge current and intensities of certain spectral lines in presence of field. Both the discharge current and spectral intensities were observed to increase first and after attaining a maximum at a certain magnetic field gradually decrease. In case of discharge current measurements, it was observed that the field (B max) at which the current becomes maximum is same for all gases and independent of pressure for the same initial discharge current, for spectral line intensity measurements, B max differ for different wavelength of lines of a same gas. From Beckmann's (1948) analysis quantiative interpretations of the phenomena were produced. For smaller values of reduced magnetic field (B/p) the authors modified Beckman's expression and have shown that the electric field and hence the electron temperature is changed by a transverse magnetic field as

$$E_B = E\left(1 + C_1 B^2/p^2\right)^{1/2} \qquad (1.10)$$

and

$$T_{eB} = T_e \left(1 + C_1 B^2/p^2 \right)^{1/2} \qquad (1.11)$$

where C_1 is a constant for a particular gas given by

$C_1 = \left\{ (e/m) \left(L/\vartheta_r \right) \right\}^2$ where e, m and L are charge mass and mean free path at a pressure of one torr of electrons and ϑ_r is the electronic random velocity. The analysis was extended through the low pressure mercury arcs by Sen and Das (1973). Experimentally, the authors observed that for increasing transverse magnetic field ($B \leqslant 300$ G) the arc current gradually decreases and voltage across the arc increases but the power consumed by the arc gradually increases and attaining a maximum value at a certain field decreases. Quantitative interpretation was given by considering enhanced charged particle loss and hence an increase in T_e and the decrease of axial electron number density. For low voltage cesium arc Bendarenko et al (1965) observed that as transverse magnetic field increases, the arc current decreases.

Recently Keneda (1977a, 1977b, 1978, 1979) in a series of papers studied the effect of transverse magnetic field ($B \leqslant 300$ G) on neon glow discharges ($p = 0.3$ - 10 torr). By measuring axial electric field strength by floating probes, Keneda observed that the axial field increases considerably with transverse magnetic field at lower pressures and the author modified Beckman's expression by taking account of electron loss at wall.

Ecker and Kanne (1964) treated theoretically the case of cylindrical plasma column in a transverse magnetic field. The authors investigated on the problem mainly for two cases: (i) in collision free limit where Langmuir's theory of free fall applies and (ii) in collision dominated region where Schottky's ambipolar diffusion theory applies. In the collision dominated case, they found magnetic field does not change the temperature. The shift of maximum density distribution in the direction of Lorentz force was given a linear perturbation treatment (hence, small values of magnetic field was considered). While formulating the basic equations which may describe the collision dominated positive column in a transverse magnetic field, Ecker and Kanne wrote "the electron temperature is ~~calc~~ calculated under the assumption that electron heat conduction is small in comparison to collision (elastic) losses. Then energy conservation law (for ~~th~~ electrons) balances the energy gain in the electric field with energy loss due to collisions with neutral particles and axial electric field is constant due to Maxwellian's equation". But to have this balance equation realised for a real plasma a certain criterion (Ecker and Zöler, 1964) is to be fulfilled. This criterion is $\lambda_e < 2R\nu^{1/2}$ where λ_e is the mean free path of electrons, R the discharge tube radius and γ is the fractional energy loss of electrons in an elastic collision. This condition is not satisfied in normal glow discharges and realised in practice only in cases of high current and comparatively high pressure arc discharges.

Blevin and Haydon (1958) have shown that a transverse magnetic field effectively increases the gas pressure from p to p_B so that

$$p_B = p\left(1 + C_1 B^2/p^2\right)^{1/2} \qquad (1.12)$$

C_1 has been already defined in equations (1.10) and (1.11). Assuming a Maxwellian velocity distribution of electrons and a constant average collision frequency, from the equivalent pressure concept, the variation of Townsend's first ionisation co-efficient in case of hydrogen is well understood in the high E/p region. But later on Haydon et al (1971) have argued that the velocity distribution for electrons in presence of transverse magnetic field may not be Maxwellian, so it is not appropriate to consider energy independent collision frequency when postulating equivalent pressure concept for electron behavior in hydrogen gas. From equivalent field concept of Allis (1956), Heylen and Bunting (1969) without assuming an 'a priori' constant collision frequency evolved an equivalent reduced electric field concept which reduces to more familiar equivalent pressure concept when electric field is kept constant. Using this concept and assuming Maxwellian velocity distribution for electrons, the transverse and perpendicular mobilities and their ratio tan θ for electrons in hydrogen in transverse magnetic field (swarm expt.) are well explained. The average electron collision frequency was observed to vary with electron energy. This conception was further verified from experimental datas obtained in case of other molecular gases like, oxygen, air and nitrogen.

Some measurements have been reported in case of r.f. discharges and cathode region of hollow cathode discharges in magnetic field. Also there are reports for Hall voltage measurements in plasmas. Since the works are outside the scope of present investigation, we shall not discuss them.

1.2.3. LOW PRESSURE DIFFUSE MERCURY ARC PLASMA IN A LONGITUDINAL MAGNETIC FIELD:

Measurements on a low pressure mercury arc plasma in a longitudinal magnetic field was made by Tonks (1939) and by Cummings and Tonks (1941). Tonks (1939) observed that a longitudinal magnetic field leaves the point to point electron number density unchanged and does not alter the relative potential in cross section of the discharge tube. Thereafter, Cummings and Tonks (1941) found by probe method that electron temperature slightly decreases and axial electron density slight increases as the axial magnetic field ($B \leqslant 70$ oe) increases. The authors stressed on the point that plasma may react differently on the uniformity of the axial magnetic field. So the magnetic field must be a uniform one without radial component. From a detailed theory they concluded that 'normal' distribution for electrons and ions in the cross section is not altered in the presence of a longitudinal magnetic field. Tonks (1941) has calculated approximately the dispersal effect along a plasma column in longitudinal magnetic field. The solution for radial electron and ion distribution is the sum of a series of zero order Bessel functions. The first term, which is the normal distribution, is constant along the length of the column, while successive terms decreases with distance along the column at rates which are complicated functions of B and electron temperature.

In contrast Davies (1953) observed a small increase in electron temperature in a longitudinal magnetic field ($B \lesssim 1580$ G) for a d.c. cesium plasma ($p = 0.03$ to 0.1 torr) by measurements of intensity distribution in recombinating spectrum. The observation of Davies can not be accounted for by existing theories, Bickerton and von-Engel (1956) have attributed this discrepancy between theory and experiment in the high current density ([illegible] 5A/cm^2) used in a capillary tube by Davies. For very high current ($i > 30$ A) arcs in argon ($p < 1$ torr) in a longitudinal magnetic field ($B = 2.3$ kG), Marhic and Kwan (1977) observed an axial variation of electron temperature and electron density.

vander-Sijde (1972) obtained variation of temperature and electron density profile for a hollow cathode argon arc in axial magnetic field ($B \leqslant 1250$ G) from radiation profiles and electron temperature was found to decrease with the increase of the field. Wienecke (1963) obtained an increase of pressure in the hot region of a cylindrical symmetric arc in an axial magnetic field. Wienecke concluded that the forces exerted by magnetic field on charged particles modify diffusion current and since an energy transport is connected with the diffusion, it is also changed in magnetic field. Davies (1953) observed that a Maxwellian distribution of electron speed prevailed in longitudinal magnetic field. Maxwellian velocity distribution for electrons was also observed by Vorobjeva et al (1971) in mercury vapour arc in a longitudinal magnetic field ($B \leqslant 800$ Oe) by probe method.

There is no clear cut definition of an arc. For a low pressure diffuse mercury arc Ecker and Zöler's (1964) criterion obtained from Ellenbaas-Heller heat balance equation, that energy gain of electrons in electric field is balanced by losses in elastic collisions, is not satisfied. On the contrary Ghosal, Nandi and Sen (1979) have shown that for such a discharge, the energy consumed by the discharge is lost mainly in ionizing collisions (also in excitation collisions) and the supplied energy is carried away by electrons and ions through ambipolar diffusion to the wall of the discharge tube (also by radiation). But from definitions given by Pfender (1978) for an arc (e.g. (i) relative high current density, (ii) low cathode fall, (iii) high luminosity of the column), we call these diffuse discharges in mercury, a low pressure mercury arc. K In these discharges, the volume ionisation is generally balanced by diffusion of charged particles. Ionisation in the volume is mainly by electron impacts of neutral and metastable atoms. Apart from diffusion, recombination of charged particles may play a role in the loss of charged particles. But in an active discharge, owing to the high value of electron temperature with respect to ion (or atom) temperature, recombination becomes comparatively less effective than diffusion. Two types of diffusion are known. One is the Langmuir free fall diffusion, effective in very low pressure region and the other is Schottky's ambipolar diffusion, operative in comparatively high pressure region. An ion fluid model described by Franklin (1976) covers these two domains through the transition region equally well. Electron temperature is calculated from a balance between particle loss and generation processes.

When a magnetic field is superimposed to a cylindrical plasma column, electron diffusion across and along the field becomes anisotropic and the radial diffusion is reduced. The plasma adjusts to this new situation by reducing its ionisation frequency which is determined by electron temperature. So a change in electron temperature is expected in a magnetic field. A reduction of electron temperature or axial E electric field in effect determines a reduced diffusion loss. The influence of longitudinal magnetic field on a cylindrical plasma column operating in Langmuir free fall domain has been treated by Self (1967). By ion fluid model which is equally responsive in high and low pressure regions, Franklin (1976) investigated on cylindrical plasmas subjected to axial magnetic field. Validity of ion fluid model was established by experimental evidences. According to Franklin the existance of longitudinal magnetic field can be regarded as an equivalent increase of pressure so far as radial motion is considered. Franklin (1976) further showed that due to decrease of radial diffusion of charged particles, ambipolar diffusion, if operative, will also be decreased in presence of a longitudinal magnetic field.

Some controversy arose regarding the ambipolarity assumption (in high pressure region) in the case of finite length cylinder with non-conducting walls placed in a longitudinal magnetic field. Disagreement between experimental data and ambipolar theory was observed (Geissler,1970). Later on Chekmarev et al (1977) have analysed the diffusive decay of a weakly ionised gas in a finite length cylinder with non-conducting walls in presence of axial uniform magnetic field and have found that ambipolarity of diffusion is also preserved in presence of the field. The way a magnetic field influences the ambipolar diffusion is best described by Franck et al (1972). In the absence of magnetic field the radial ambipolar field is positive, retarding plasma electrons and accelerating plasma ions. An increase of magnetic field causes a decrease in pure diffusion of electrons and ions. In classical theory pure diffusion of electrons and ions across magnetic field varies inversely with the square of the magnetic field in the absence of any instability,

$$D_{e\perp} = \frac{D_e}{1+b_e^2 B^2} \quad , \quad D_{i\perp} = \frac{D_i}{1+b_i^2 B^2} \qquad (1.13)$$

where b_e and b_i is electronic and ionic mobilities. Since at a given pressure electron mobility is larger than ion mobility by a factor 10^2 to 10^3, electron diffusion is diminished to a larger extent than ion diffusion. So as magnetic field increases, at a particular magnetic field B_r the radial electric field vanishes when $D_{e\perp} = D_{i\perp}$. For magnetic field higher than B_r, the ambipolar electric field will be negative accelerating electrons to the ~~wass~~ wall and retarding the ions. To realise experimentally B_r, where reversal of ambipolar field occurs, is hardly possible. Generally $B_r > B_{cr}$ where B_{cr} is the critical magnetic field where helical instabilities set in. Only for $0 < B < B_{cr}$ classical ambipolar diffusion takes place, whereas for $B > B_{cr}$ Kadomtsev instabilities set in.

In this context we shall discuss briefly about some of the anomalous behavior of column plasma in longitudinal magnetic field. Most of the anomalous behaviour have been studied in noble gases and in some molecular gases. For plasmas confined by a non-conducting discharge tubes, Hoh and Lehnert (1960) studied the effect of axial magnetic field in helium, hydrogen and krypton confined in long discharge tubes, so that diffusion to the ends can be neglected. The authors observed that upto a critical field B_{cr} the radial diffusion across the axial magnetic field decreases classically, but after B_{cr} the diffusion increases with B. Kadomtsev and Nedospasov (1960) interpreted the anomalous behaviour by discovering an instability in the form of helical wave which will be generaled by longitudinal electric field at high values of magnetic field. This instability known as current convective instability enlarges the effective ambipolar diffusion with increasing magnetic field by E x B drift which tends to drive the plasma electrons radially outward and to amplify diffusion. The value of B_{cr} is determined by the pressure. Later on Janzen et al (1970) observed in neon gas that the appearance of the instability depends upon the length of the discharge tube. For short discharge tubes ($L \lesssim 15$ cm.) there is no instability. For comparatively long discharge tubes Deutsch and Pfau (1976) observed an anomolous increase of column gradient in axial magnetic field ($B \ll B_{cr}$) in weak discharges in noble gases. The anolamous behaviour was explained by accounting the radial change in energy distribution of electrons in relation to longitúdinal magnetic field. Sato (1978) explained the same type of anomolous result as that of Deutsch and Pfau in terms of self excited ionisation waves (moving striations). Muira et al (1979) observed an abrupt decrease of axial electric field for a small interval of axial magnetic field in neon. After this fall the axial electric field rises again and decrease classically with the increase of field. The authors reported also the appearance of self excited ionisation waves along the abrupt fall of electric field.

Apart from these instabilities, another weak instability arises particularly in quiescent plasmas in axial magnetic field. This is known as drift dissipative instability (Timofeev, 1976). For current carrying discharges these instabilities are superposed by more strong current convective instabilities. Another type of anomolous diffusion known as Bohm diffusion which is proportional to reciprocal of magnetic field, is observed in highly ionised magnetoplasma confined in metal chambers. Behaviour of miscleeneous arc devices at normal pressure and exposed to magnetic field have been reviewed by Uhlenbusch (1976).

1.2.4. ENHANCEMENT OF SPECTRAL LINE INTENSITIES IN LONGITUDINAL MAGNETIC FIELD:

When a plasma column is subjected to a magnetic field there is a coupled change in the axial electron density and electron temperature. Since the spectral line intensities sometimes depend on these parameters, in a magnetic field there will be a change in spectral line intensities. In all types of magnetic fields (e.g. axial, transverse and rotational), enhancements of spectral line intensities have been observed.

Rokhlin (1939) studied the intensity distribution of spectral lines of mercury ($p = 10^{-3}$ torr, $i = 1.5 - 4$ A) and observed that for longitudinal magnetic field of limited extent having significant radial component, the intensities of mercury lines gradually increase and after attaining maxima gradually decrease. Takeyama and Takezaki (1968) observed emission enhancement of several He I and He II lines in a helium plasma ($p = 0.4 - 4$ torr) in axial magnetic field ($B \leqslant 6$ k Oe). The enhancement factor observed was independent of pressure. Ricketts (1970) observed increase of intensities of argon spectral lines for an argon ring discharge in axial magnetic fields.

Forrest and Franklin (1966) advanced a theory regarding behaviour of low pressure positive column arc discharges and calculated the radial light emission profile in axial magnetic field. The authors' theoretical model have been discussed in detail by Franklin (1976) and a contraction of radial column has been reported. ~~E~~ Recently Hegde and Ghosh (1979) measured enhancements of He (I) and He (II) radiation from a helium glow discharge ($p = 5 \times 10^{-3}$ torr) in axial magnetic field ($B \leqslant 700$ Oe). The radiation was observed to increase and after passing through a maximum slightly to decrease with the increase of the field. Hegde and Ghosh developed a collisional radiative model (CRM) for helium for a quantitative interpretation of the phenomena and for justifying the CRM advanced by them. But in CRM generally collisional radiative ionisation is balanced by collisional radiative recombination of charged particles. Whereas in active discharges, collisional ionization is balanced by ambipolar diffusion to the tube wall and recombination in the volume is negligibe. Subsequently Hegde and Ghosh (1979) found a very small collisional radiative recombination coefficient.

For ionic lines, Allen (1966) and Pinnington (1966) observed that the ionic lines are enhanced relatively by a forctor of 150 times than the atomic lines in the magnetic field. However, these investigators studied the radiation enhancement phenomenon from the interest of observing Zeeman splitting. Allen (1966) recognised the problem that the socalled magnetic enhancement is not that the ionic spectra is enormously brightened but that the arc spectrum is diminished (particularly for optically thick resonance lines). It should be noted here that the source used by these investigators are non-uniform ones, since radiation created at the central hot region is absorbed in the outer cooler region so that self reversal of the atomic (resonance) lines can occur.

The effects of transverse magnetic field on the radiation of a constricted discharge in helium, neon, nitrogen, hydrogen and mercury were observed by Kulkarni (1944). Sen, Das and Gupta (1972) observed that spectral intensity in glow discharges increases and after passing through a maximum decreases with the increase of transverse magnetic field. The authors gave quantitative explanation of the phenomenon considering coupled change of plasma parameters utilizing Beckman's (1948) analysis.

A group of investigators (Vukanovic' et al (1969), Pavlovic' et al (1979)) investigated the effect of homogeneous, inhomogeneous and rotating magnetic fields on the spectral intensities of free burning d.c. arcs. Their interest lies in finding a way for increasing line strength for finer spectrochemical analysis and from that point of view the authors recommended the application of an inhomogeneous and rotating magnetic field on the d.c. free burning arc because of large enhancement of spectral lines in those types of fields.

1.2.5. RECOMBINATION

For partially ionised gases, a particularly important reaction rate is that for electron ion recombination. In general two processes dominate in the loss side of charged particles' continuity equations - one is the ambipolar diffusion loss term and the other is a volume recombination loss term. By ambipolar diffusion, the charged particles created in the volume of the plasma by some mechanism diffuse away to the wall of the discharge vessel where they recombine and subsequently return to the plasma as neutral atoms in ground state. The charged particles may also recombine in the plasma volume through any of several possible mechanisms with oppositely charged particles and thereby create neutral particles in excited or ground states. In an afterglow plasma, when the electron temperature relaxes to a value corresponding to the ion temperature, loss due to ambipolar diffusion of charged particles, which is directly proportional to the ratio of electron temperature to ion temperature, reduces and thus in suitable conditions like a high gas pressure or a large discharge vessel, recombination reaction may dominate over that of ambipolar diffusion.

The macroscopic recombination coefficient α is defined by the relation (in the absence of ionization processes as in an afterglow)

$$\frac{dn_e}{dt} = -\alpha n_e n_i \qquad (1.14)$$

where n_e and n_i denote the number density of electrons and ions with which the electrons are recombining respectively.

If an electron is to recombine with an atomic or molecular ion, recombination energy which is the sum of internal energy of the ion and kinetic energy of electron is released. The ability of the system to dispose of this excess energy determines the probability that recombination will occur. Considering the principles of conservation of linear and angular momenta, in the review articles, McDaniel (1964) and Massey and Gilbody (1974) have analysed electron-ion recombination in terms of seperate reactions of the following types: radiative, dielectronic, three body collisional and dissociative recombinations.

If the energy released in recombination of an electron e and an ion A^+ is carried off by a photon ϕ, then it is a radiative recombination. This process may be represented by the reaction equation

$$e + A^+ \longrightarrow A + \phi \qquad (1.15)$$

Another way of handling the excess energy of recombination is to form a neutral atom in which two electrons are simultaneously excited. The energy of the resulting doubly excited atom lies above the series limit and is energetically unstable, but can be stabilised by the emission of a photon in a transition to a lower bound level. This process of dielectronic recombination may be represented by the reaction

$$e + A^{+} \longrightarrow A^{**} \longrightarrow A^{*} + \phi \tag{1.16}$$

A star (*) denotes an excited state.

If the recombination energy is carried off as increased kinetic energy by a third body involved in the collisions, then three body recombination occurs. Because electrons have such a small mass in comparison with other particles, the case in which the third body is an electron is distinguished, so that

$$e + A^{+} + e \longrightarrow A + e \tag{1.17}$$

and the case where the third body is some heavy particle X

$$e + A^{+} + X \longrightarrow A + X \tag{1.18}$$

The above process involving a neutral third body becomes important at sufficiently high neutral gas pressure, even though the neutral particles are no more effective than a positive ion in removing energy from an electron. At ordinary pressures this recombination reaction should be very slow.

In the event that the electron recombines with a molecular ion A_2^+, a particularly effective process is to have the recombination energy go into dissociating the molecule and into increasing the kinetic energy of the resulting products. This process of dissociative recombination is represented by reaction equation

$$e + A_2^+ \longrightarrow A_2^* \longrightarrow A^* + A + \text{kinetic energy} \quad (1.19)$$

In the course of dissociative recombination, the electron colliding with the molecular ion is captured to the autoionization level. Since the interaction between the atoms in the autoionization state is repulsive, they move apart. If the autoionization state does not have time to decay while the atoms move apart to certain distance, the result is a stable state of the dissociated particles.

In a system if chiefly ionised species are the molecular ions, large effective recombination is observed, then there seems to be little doubt that dissociative recombination, first suggested by Bates and Massey (1947), can occur rapidly enough to account for the observed decay rate.

The first theoretical calculations for dissociative recombination were made by Bates (1950). He analysed the problem as a two state process. First the excited unstable molecule is formed, whose constituents then move apart under the influence of their mutual repulsion thereby preventing autoionization. The expression for dissociative recombination coefficient α was derived from the Franck Condon principlesx in terms of the autoionization life time and the time for effective seperation to occur.

Thereafter, Warke (1966) derived the rate of dissociative electron capture by O_2^+ ions in a semiclassical formalism in which heavy ions are treated classically and the electrons quantum mechanically. For H_2^+ ions cross - section of dissociative recombination was calculated by Bauer and Wu (1956) and by Wilkins (1966) in a Born approximation. A theoretical model for estimating the value of dissociative recombination coefficient has been described by Watson (1975).

But accurate computation for any specific ion would be extremely difficult to perform, in as much as x an abinitio calculation requires detailed knowledge of the wave functions of all the molecular and atomic states of the reaction and their potential energy curves and autoionization probabilities as a function of inter-nuclear seperation of atoms. Smirnov (1977) pointed out other difficulties of this complicated process. The number of autoionization states is large (sometimes infinite) and recombinating molecular ion can be in excited vibrational states and this fact also influences the magnitude of α.

Actual values of α depend on the ionic species involved, but it is still possible to identify the order of magnitude of α for each of the recombinating processes described above. In Table (1.1) the characteristic values are shown. Values correspond to room temperature, and have been computed by Mitchner and Krugar (1973).

TABLE 1.1

Characteristic values of α .

	Process	α ($cm^3 sec^{-1}$) T = 300°K.
1.	Radiative	10^{-12}
2.	Three body (electron) $n_e = 10^{13}$ cm^{-3}	9×10^{-7}
3.	Three body (heavy particle)	
	helium (1 atoms. pressure)	7×10^{-9}
	argon (" ")	7×10^{-11}
	air (" ")	2×10^{-7}
	hydrogen(" ")	2×10^{-7}
4.	Dielectronic	10^{-12}
5.	Dissociative	10^{-7}

The description of recombination in terms of above mentioned independent reaction processes is traditional. In general however, these processes may be coupled. Bates, Kingston and McWhirter (1962) have demonstrated a coupling. The authors argued that loss mechanism in very tenous plasma (astrophysical) is generally referred as radiative recombination and three body electron collisional recombination may be applied to the loss mechanism in very dense plasma. These two mechanisms are really the two limiting cases of a more general loss mechanism which was called collisional radiative recombination by Bates et al. This general loss mechanism is not simply the sum of the two limiting types for it results from the combination of interacting collisional and radiative processes of ionisation, recombination excitation and de-excitation which can occur in a decaying plasma. Then a statistical ~~ta~~ treatment is applied and quantitative result for α_{CR} is obtained. Sometimes under suitable conditions the order of magnitude of α_{CR} becomes equal to 10^{-7} cm^3/sec. Thus when in a decaying plasma molecular ions can not be identified to be present, the recombination is of collisional radiative type. α_{CR} has been calculated for hydrogen, hydrogen ions, helium and for helium ions. For other elements, the computation becomes difficult to perform owing to large number of complicated excited states and for lack of knowledge for respective cross-section datas.

Most measurements of the electron ion recombination coefficient are made by measuring electron concentrations and other parameters in a plasma as a function of time after cutting off the exciting source. Under many conditions in these experiments, the electron temperature is the same as the gas temperature, but in some cases it is maintained higher through application of auxiliary heating of electrons, as through microwave pulse. The microwave method, first utilised by Biondi and Brown (1949) for measuring α in helium appears to be most reliable in current use. The experimental arrangements have been described by Biondi (1951). The general principle of microwave technique is this: High purity gas is admitted at a desired pressure in a cylindrical quartz bottle located inside a cylindrical microwave cavity. A pulse discharge of variable time duration is then produced by microwave energy fed from a magnetron. The chief effect of the electrons produced in the discharge is to change the resonant frequency of the cavity. If the spatial distribution of the electrons in the bottle is known, absolute values of average electron density can be obtained from measured frequency shift during an afterglow.

For a recombining plasma if $n_e = n_i$ and at $t = 0$, $n_e = n_e(0)$, the solution of eqn.(1.14) is

$$\frac{1}{n_e(t)} = \frac{1}{n_e(0)} + \alpha t \qquad (1.20)$$

so that the reciprocal of the number density is a linear function of time with slope α. Thus α can be determined from the loss rate of charge particles. When ambipolar diffusion is the main loss mechanism, decay rate of charged particles is an exponential one. Accurate values of α is difficult to determine because other loss processes like diffusion (in some cases attachment) are present, because electrons may continue to be produced after primary discharge is turned off. Gray and Kerr (1962) have published a theoretical analysis of after glow decay in which they considered both diffusion and recombination loss processes. Considering these loss processes a non-linear differential equation is obtained,

$$\frac{\partial n_e(\vec{r},t)}{\partial t} = -\alpha n_e^2(\vec{r},t) + D_a \nabla^2 n_e(\vec{r},t) \qquad (1.21)$$

here Da is the ambipolar diffusion coefficient. Gray and Kerr solved this equation numerically for widely different conditions, i.e. initial electron density distribution, cavity filling factor and ratio of recombination loss rate to diffusive loss rate β and for both spherical and infinite cylindrical geometries. Equation (1.21) has also been solved numerically by Oskam (1958) for infinite plane parallel geometry and by Frammhold, Biondi and Mehr (1968) for geometries having cylindrical symmetries.

The results obtained experimentally are analysed numerically by the above mentioned method. In few cases, the criteria for obtaining accurate values of α appeared to have been met. In many cases the criteria were definitely not fulfilled, wheseas in others no decision could be made. However, for a fair measurement of α, importance is given for the following conditions:

i) Measurements be made under condition in which β is large,

ii) attachment losses should be as small as possible,

iii) in order to maintain as simple an analysis of afterglow as possible, it is necessary that electron energy distribution maintains a stationary value,

iv) all the loss processes in general depend on T_e. In order to have simple conditions, it is necessary sometimes, that the electrons are in thermal equilibrium with gas molecules,

v) for the assumption $n_e = n_i$ to be made, it is necessary that ions present should be of a single type.

Furthermore, measured values of α are not very meaningful (in the sense of type of recombination) unless the identity of the recombining ions is definitely known. Positive identification is obtained by mass ~~ms~~ spectrometric probing or by spectroscopic observation of the plasma while recombination is occuring.

As we are interested in afterglows in mercury vapour, we shall review the measurements made in mercury afterglows. Mohler (1937) was first to determine α for mercury vapour. He used a probe to measure electron density after cut-off of an intense direct current discharge in mercury at 0.27 torr pressure. T_e in the afterglow was of the order of 2000°K and α was found to be 2.3×10^{-10} cm^3/sec. Mierdel (1943) however, has found that decay rate of electron density under very similar condition indicates an ambipolar diffusion type electron loss rather than recombination. Thereafter, Dandurand and Holt (1951) studied the electron removal processes in mercury afterglow by microwave technique and also be observing the visible and near ultraviolet light intensity and spectrum associated with the afterglow by a gated photomultiplier. They observed that the rate of electron density decay is determined at low pressure by ambipolar diffusion and at higher pressure by attachment. At the higher pressure region, some recombination is present and probably accounts for the line spectrum in afterglow (especially the bands at 3448 Å and 3480 Å). Value of α was found to be 5×10^{-9} cm^3/sec (corresponding T_e is around 2000°K) and the authors remarked ~~ak~~ that results was made complex by the presence of metastables in the plasma. Biondi (1953) investigated on the processes involving ions and metastable atoms in mercury afterglows. He argued that studies of electron production and removal in gases of large molecular weights were complicated by the fact that the electrons might not attain thermal equilibrium with the gas during afterglow measurements. As a result only qualitative remarks could be made concerning the processes occuring in mercury. This difficulty has been overcome by adding helium in mercury to reduce the electron energy decay time and measurements could be made of the behaviour of thermal electrons in a mercury helium mixture. Helium acts as a recoil gas and keeps Da small but leads to only a very small rate of complex or negative ion (by attachment) formation. In an afterglow in such a mixture, the ion population consists almost exclusively of ions of mercury and not of rare gas because its ionization potential is higher than that of mercury. Biondi applied the microwave techniques to determine the electron density decay rates. It was observed that atomic mercury ions are converted to molecular mercury ions by the reaction

$$Hg^+ + Hg + He \longrightarrow Hg_2^+ + He \qquad (1.22)$$

and the reaction occurs at a rate 140 ($P_{Hg} \cdot P_{He}$) sec-1. In comparatively high pressure region, these molecular ions recombine with electrons and the measured value of dissociative recombination coefficient of Hg_2^+ ions with electrons is 5.5 x 10^{-7} cm^3/sec. at 400°K. The author disagreed with Dandurand and Holt on the possibility of attachment. On the other hand he found that at the pressure over 1 torr, the electron density decay curve shows increasing evidence of recombination.

Baibulatov (1966) while investigating on the deionisation of a mercury plasma noted that when the ionising field is switched off, the production of new ion pairs practically ceases and charged particle concentration then decreases, approaching a finite but small value. For a mercury plasma of pressure 0.01 to 0.1 torr, deionisation takes place mainly through the diffusion of ion electron gas to the walls of the discharge vessel as well as through reduction of electron temperature as a result of inelastic electron scattering.

Thereafter, Nishikawa, Fuji-e and Suita (1971) investigated on the atomic collision processes occuring in a flowing afterglow excited by D.C. discharge by triple probe and optical measurements. They found that the decrease in intensity of mercury atomic lines is rapid near the discharge source followed by a slow rate some what distant from the source. The rapid decrease in line intensities near the source may be due to the electron attachment process thereby producing temporary negative ions by the reaction

$$Hg + e \longrightarrow Hg^-(^4P_{5/2}) \longrightarrow Hg(6^3P_0) + e \qquad (1.23)$$

From decrease in density of metastable atoms some what distant from the source, the diffusion coefficient and the rate at which metastable atoms are converted to metastable molecules are graphically obtained. Slow intensity decrease somewhat distant from the source is related to dissociative recombination. α was measured to be 3.7×10^{-7} cm^3 sec.$^{-1}$ which is 1.5 times smaller than that of M.A.Biondi. This discrepancy was attributed to relatively high electron temperature (0.12 eV) in comparison with the electron temperature in the afterglow reported by M.A.Biondi. The molecular ions are formed by the reaction

$$Hg^+ + 2Hg \rightarrow Hg_2^+ + Hg \qquad (1.24)$$

The short duration afterglow of an r.f. (28.5 MHz) discharge in mercury has been examined by Aubrecht et al (1960) at different temperatures (60°C - 215°C). The authors concluded that enhancement of intensity of mercury atomic lines in the afterglow of r.f. discharge are produced by ionizing collisions between metastable mercury atoms. The decay is produced predominantly by volume ion electron recombination. The decay of the atomic lines in the afterglow is not affected by r.f. power supplied to the discharge. At higher temperature ($\geq$ 468°K), molecular bands appear and intensities of atomic lines decrease and decay more rapidly.

Another afterglow study in mercury vapour was done by McCoubrey (1954). This was a spectroscopic observation for persistence time of 4850 Å 3350 Å bands during the afterglow. This experiment was not intended for a measurement of electron density decay rate, rather it was observed that 6^3P_0 atoms are converted to metastable diatomic Hg_2 ($^3O_u^-$) molecules by a three body collision involving two normal atoms and a value for diffusion coefficient of metastable atoms was obtained.

Generally dissociative recombination coefficient may depend on other parameters of a plasma afterglow. We shall discuss the interesting problem of temperature variation of α . In the investigations made by Frammhold Biondi and Mehr (1968) in neon and by Ogram et al (1980) in krypton, the microwave techniques were utilised to determine T_e dependance of α . In those experiments electrons do not relax to gas temperature during the afterglows, on the other-hand the temperature is controlled by steady microwave heating. As T_e is raised, ambipolar diffusion is also increased. However, it was observed that if every unstable molecule (in excited state) formed, dissociates before autoionization can take place, then the initial capture step is rate limiting and a dependance of as $T_e^{-0.5}$ is observed. If however, stabilisation of reaction by dissociation is rate limiting then a variation as $T_e^{-3/2}$ is predicted.

In some experiments for determination of recombination coefficient superimposed axial magnetic fields were used. But in all the analyses it is tacitly assumed that α does not depend on a magnetic field. Kuckes et al (1961) measured recombination in helium afterglow in a B-1 stellarator. In these experiments the degree of ionization was high from almost 100% to 2% as helium pressure was varied from 0.25 to 100 microns. It was observed in the experiment that (1) the loss rate is independent of the confining magnetic field between 2.9 to 3.5 kilogauss, (2) the intensity of light which is shown by spectral analysis to originate from the recombining helium atoms, is proportional to the electron loss rate, independent of pressure and magnetic field. The recombination was identified as three body one.

Knechtli and Wada (1961) measured recombination coefficient of a highly ionised (90% degree of ionisation) quiescent Cs plasma in steady state, without any current through the discharge and in a superimposed magnetic field of 1500 gauss. The experiments were not intended for investigating magnetic field dependence of α , but for establishing the suitability of this type of currentless quiescent discharge in plasma behaviour study and to identify the nature of recombination of Cs plasma. However, α measured in the experiments was substantially lower than the values reported in literature. The authors interpreted this in terms of low probability of formation of molecular ions leading to dissociative recombination, so that radiative or three body electronic recombination which have a slower rate than dissociative recombination might be the possible loss mechanism.

Thereafter, D'Angelo and Rynn (1961) investigated in the same type of Q-machine cold plasma device on Cs and K. In this machine which is similar to that of Knechtli and Wada, Cs and K Plasma is produced by surface ionisation on a hot tungsten plate of Cs and K atoms from an atomic beam oven. No current was used and Langmuir probes were used for diagnostics. It was concluded by the authors that when no current is passed through the plasma, a $1/B^2$ dependence of particle diffusion perpendicular to imposed magnetic field (B = 9 kilo gauss) is observed. Although the experiment was not designed for an accurate determination of α , it was assumed that α which was identified as threebody collisional radiative was constant with magnetic field.

Recently Fowler (1978) in a paper entitled "A possible dependence of recombination on magnetic field" has suggested that beam maintenance experiments of D'Angelo and Rynn in Cs and K and of Simon (1959) in molecular nitrogen gas which were designed to test ~~disapprove~~ Bohm diffusion may instead have revealed the exist~~a~~ence of unsuspected magnetic ~~f~~ effect upon recombination.

Fowler argued that it is the low angular momentum overlap between plane waves and orbital wave functions which makes electronic recombination such an improbable process, the rapid decrease that electron cyclotron radii undergo in a magnetic field might be expected to improve this situation drastically, especially for recombination into Rydberg states. The quantum number of the Bohr orbit which has the same angular momentum as a cyclotron orbit in a field of B tesla is 120 $B^{-1/3}$. Therefore, the phenomenon is in fact unknown in ordinary discharge afterglow experiments, because they are conducted at moderate pressure ($\sim$ 1 torr) rarely permit states to exist much above n = 20 (below which B must be greater than 200 tesla to observe an affect). But the beam experiments which were conducted between 10^{-6} and 10^{-3} torr would have permitted states as high as n = 200, and could easily have been influenced at 0.1 to 1.0 tesla fields employed. On the basis of D'Angelo and Rynn's data, Fowler suggested that behaviour of α for Cs and K would be

$$\alpha = 5\times10^{-18} + (3\times10^{-34}\,p + 4.8\times10^{-17})\,B \quad [m^3/s] \qquad (1.25)$$

with p in m^{-3} and B in tesla. The three terms are radiative recombination, threebody magnetic induced recombination and radiative magnetic induced recombination. Fowler concluded that purpose of his paper is merely to point out the possibility of a new avenue of research, and to suggest the desirability of some direct experiments of recombination coefficient in a magnetic field.

1.3. SCOPE OF THE PRESENT WORK

It is well known that properties of a plasma change in presence of magnetic field and the change in the properties is reflected in the change of values of plasma parameter. Characteristics of magnetoplasma have been reviewed by Francis (1956), von-Engel (1965), Chen (1974) and by Franklin (1976). In a magnetic field constant in space and time a charged particle possessing a radial velocity component moves in a helical path. The motion can be visualised as a combination of circular motion around a point, known as guiding centre and a linear motion of the guiding centre. A positive charge gyrates counter clockwise when viewed in the direction of magnetic field while an electron gyrates clockwise. Franklin (1976) has discussed the criteria for effective magnetisation of electrons and ions. In comparatively low values of magnetic field, the electrons are only effectively magnetised.

A description of plasma properties would include a detailed knowledge of the populations of all bound electronic states, a knowledge of the translational energies of electrons and various atomic species, and a determination of free electron densities. For understanding the behaviour of plasma in magnetic field, measurements of above parameters when a magnetic field is present is desirable.

For cylindrical plasmas in usual discharge tubes the positive column represents the true plasma region. In this region quasineutrality of charged particles is maintained. But in a magnetic field due to magnetisation of charged particles loss processes as well as the gain processes also change. These changes are manifest in corresponding changes in electron temperature and axial electron density. In the present investigation the following properties of a magnetoplasma have been investigated.

A. Electron temperature and electron density in low density magnetised plasma by probe method.

Following the quantitative analysis of Beckman, analytical expressions for the variation of electron temperature and electron density in a transverse magnetic field have been obtained by Sen and Gupta (1971). When the field is axial a detailed experimental analysis of these parameters has been provided by Bickerton and von-Engel (1956) and Aikawa (1976) has also studied the anisotropy of the electron distribution function by measuring the electron temperature in the direction of the magnetic field as well as in the perpendicular direction. As most of the effects of the magnetic field depend on the manner in which these parameters are affected by the field itself it is proposed to measure the electron temperature and electron density and their variation in both the transverse and axial magnetic fields.

It will also be of interest to see how the electron energy distribution is affected by the magnetic field. Further this study is expected to show how the orientation of the magnetic field with the discharge tube axis can influence the plasma properties.

B. Investigation of plasma parameters by spectroscopic method.

Since by probe measurements we obtain the local properties of plasma, for average properties other types of diagnostics are desirable. Investigations have therefore been carried out on measurement of electron temperature variation of a glow discharge in transverse magnetic field for hydrogen and helium gases by spectroscopic methods. As little work has been reported to include the effect of magnetic field on spectroscopic diagnostic it self, we have discussed the feasibility of the technique in detail and have obtained the variation of electron temperature in a transverse magnetic field and compared the results with theoretical analysis.

C. Mercury arc plasma in an axial magnetic field.

Due to availability of mercury in pure form and for immense practical utility low pressure mercury discharges in different conditions have been exhaustively studied. Actually certain types of mercury discharges (e.g. Hg - A discharges) are said to be best understood (Ingold, 1978). So a study of low pressure mercury arc discharge placed in an axial magnetic field has been undertaken to see the manner in which electron temperature and electron density are affected by the axial field. Properties of arc differs in some ways from those of glow discharges. In this study it is proposed to investigate the physical processes ~~at~~ actually occuring in an arc plasma. Hence in the present investigation air is the background gas which enables us to study how excitation ionization and deionization processes are influenced by the presence of air. For mercury arcs, associative ionization process is found to be a dominating ionization process. The effect of this process in positive column with and without magnetic field has been treated in detail and a relation ~~bet~~ between axial electron density and electron temperature has been obtained and compared with experimental results.

D. Influence of magnetic field on the enhancement of intensities of triplet series of mercury.

The radiation enhancement of intensities of sharp series triplet lines of mercury with longitudinal magnetic field has been studied with the object of understanding the processes of population and depopulation in different atomic states under the action of magnetic field. The theory of positive column was reviewed in the light of enhancement measurements. The influence of the field on metastable populations of mercury has been demonstrated.

E. Persistence times in afterglows in mercury arc maintained by r.f. field in presence and in absence of magnetic field.

The effect of an axial magnetic field on decay processes of a special type of mercury afterglow has been studied in this section. Since in mercury arc discharge, large number of molecular ions are found to be present, dissociative recombination of charged particles becomes a dominating loss process in the afterglows. So an investigation of particle loss processes in magnetic field may effectively determine the dependence of recombination on external magnetic fields. Apart from recombination other dominating loss mechanisms like diffusion and drift decrease in an axial magnetic field and recombination is considered to be independent of field. Recently Fowler (1978) has expressed his reservation on the constancy of recombination with magnetic field. So an investigation on loss processes in magnetic field is desirable for the proper knowledge of plasma loos mechanisms.

Under these headings it is proposed to study the interaction of the magnetic field with the plasma by measuring some of the plasma parameters and their variation ~~x~~ in the magnetic field. It is expected that this study will throw light on the physical processes ~~x~~ occuring in ~~the~~ a magnetoplasma.

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