I N T R O D U C T I O N

REVIEW OF THE PREVIOUS WORK

(A) Optical Properties of Arc Plasma:-

(a) Intensities of arc plasma spectral lines in longitudinal magnetic field:

A spectroscopic method is generally preferred to other diagnostic methods because it does not perturb essentially the processes under investigation. It also covers substantially a wide range of investigations. Burgess (1972) categorised all the areas and pointed out that interactions between neutrals, electrons, ions and photons lead to atomic processes and provide very useful information on the plasma state. In this diagnostic technique spectral lines are so selected whose relevant atomic processes are understood and for which the excited state continuity equation taking all of the collisional and radiative processes that populate and depopulate the states can be obtained. The complexity thus obtained in solving the excited state continuity equations can be overcome with the help of two simplifications, one weighting the relative contribution of separate processes and another establishing a certain type of equilibrium to prevail inside the discharge tube by considering dominating particle gain and loss terms. However, the analysis of spectroscopic diagnostic is generally made convenient by adopting the following considerations:

i) The plasma is optically thin. In an optically thin plasma, the absorption of radiation is negligible. Therefore, it is expected that the radiation of each individual atom leaves the plasma and contributes to the observed intensities.

ii) The electron energy distribution is Maxwellian. As in the case of glow discharge in which electron temperature (T_e) can be deduced from relative intensities of spectral lines, it is possible in case of arc plasma too.

Now we shall briefly state how the spectral line intensities are related with n_e and T_e; when a plasma exists in LTE there prevails a uniquelly specified temperature for species (usually the electrons) with the dominating reaction rate that determines the velocity distribution function and the relevant analysis of the plasma state becomes easier because the local plasma parameters as electron density, electron temperature and composition define the relevant populations. For availing a total LTE, the reverse of all fast processes will be maintained as well as exact balancing of total rates for complementary processes will be introduced to take place. It is asserted that the relaxation times (reciprocal of the rates) for the processes concerned should be effectively negligible in comparison with the characteristic times of significant variations in local plasma conditions. It is admitted that collisional processes play a dominant role in maintaining LTE than radiative processes as most of plasma under usual interest are optically thin to internal radiation however, with an exception in the resonance lines. As a result it is obvious that in true LTE, collisional deexcitation rates should exceed radiative decay rate. It is worthwhile to note that the energy distribution of every particular type over all kinds of species present in the gas obeys Boltzmann distribution law in LTE and thereby this relation leads to Saha equation for ionization. In this connection Griem (1964) was able to calculate the electron density given by

$$n_e \gg 9 \times 10^{17} (E_2/\chi_H)(KT_e/\chi_H)^{1/2} \quad cm^{-3} \tag{1.1}$$

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

Wilson (1962) advanced an equation for determining electron density n_e in LTE as

$$n_e \gg 6 \times 10^3 \chi_i (KT_e)^{1/2} \quad cm^{-3} \tag{1.2}$$

where χ_i is the ionisation energy of atom. Elton (1970) deduced n_e out of these criteria as

$$n_e \gg c\,(KT_e)^{1/2}\,\chi_i \qquad cm^{-3} \tag{1.3}$$

where c , the constant approximates 1.4×10^{13}.

When collisional processes with electrons which are essentially assumed to have Maxwellian distribution in velocity space dominate in the rate equations, LTE for both stationary and spatially homogeneous plasma is believed to exist. The principal quantum numbers of states for which radiative decay and collisional excitation rates are comparable often exceed a critical value because cross sections increase rapidly but radiative decay rates decrease with principal quantum number. So it is reasonable to relate densities in states above the critical level with each other and likewise to electron densities as in a system in complete LTE, Richter (1968) pointed out that though the occupation number for states over this critical level are as in LTE with temperature, the ground level is over populated by a factor. Consequently the states over the critical level is assumed to exist in partial LTE. In this system the electron density with quantum number p is approximated by Griem (1964) as

$$n_e \gg 7 \times 10^{18}\,\frac{Z^7}{p^{8.5}}\,(KT_e/\chi_H) \qquad cm^{-3} \tag{1.4}$$

here Z is the atomic charge. His approximation is however, only valid for hydrogen ions. Considering the other types of atoms p is identified as effective quantum number of the level and defined as

$$p_{eff} = Z\left(\frac{R}{T_{\alpha} - T_p}\right) \tag{1.5}$$

where R = Rydberg constant, T_{α} = the ionisation limit and T_p = the term value corresponding to level p.

Drawin (1969) corrected equation (1.4) applying semi-empirical formula for excitation rate coefficient and Fujimoto (1973) observed that LTE on the basis of a collisional radiative model for hydrogen ions is identical with that established by Griem (1964).

However, in low electron concentration LTE does not prevail. In this case where the collisional excitation and ionisation are balanced by radiative decay and recombination respectively, it is possible to achieve an equilibrium. This kind of equilibrium exists in solar corona and for that it is designated as corona equilibrium (CE) model. In CE, the population is mainly in the ground state since the population of an excited level that can emit spectral lines is mainly governed by collisional excitation and spontaneous radiative decay but the later is much faster and hence ignored. Wilson (1962) gave an approximate criterion for determination of electron density for all excited levels as

$$n_e \leqslant 1.5 \times 10^{10} \chi_i^{-0.5} (KT_e) \quad cm^{-3} \tag{1.6}$$

Wilson (1962) proposed a semicorona (SC) domain with a restriction for levels close to ionisation limit.

In the case of ions without metastable levels the electron density for SC domain is proposed as

$$n_e \leqslant 10^{11} \chi_i^{1.5} (KT_e)^{2} \quad cm^{-3} \qquad (1.7)$$

McWhirter (1965) also gave another criterion for CE but Fujimoto (1973) advanced a model known as collisional radiative model to interpret CE. It is also worthwhile to mention that when all the above criteria do not satisfy an actual plasma, all of the collisional as well as radiative rate processes will be taken for a level concerned. It is also inevitable in dealing with a transition region from SC to partial LTE. In this reference Fujimoto (1979) made an effort in treating the transition through quasi saturation phase by ladder like (stepwise) excitation mechanism.

In addition, for a spectroscopic method a knowledge of electron energy distribution function denoted by f is necessitated as it enters directly in the collision integrals. And this function is also influenced by the presence of applied magnetic field. A Maxwellian type equilibrium velocity distribution is readily and rapidly established by the collisional effects of free electrons in an active plasma. However, an electric field present in the discharge condition or elastic collisions of electrons with other atoms may destroy the equilibrium. The distribution function satisfies an equation of continuity in position and velocity type. It is recognised as Boltzmann transport equation where the rate change of the electron density is equal to the net flow of electrons in an arbitrary volume element. The flow in the position space derives from the electron velocity whereas in the velocity space it results from its acceleration out of the collision with gas atoms and the electron field applied externally. To avoid much mathematical complexity the distribution function is taken almost spherically symmetric in velocity space.

Thus the Boltzmann equation taking first two terms of an expansion in spherical harmonics is solved and in practice the distribution function is found numerically. When the degree of ionisation is high enough it is also occasionally found that solved distribution differs a little from being Maxwellian. However, von-Engel (1965) approximated that the energy distribution of electrons in a gas moving in an electric field is more or less Maxwellian in general. For plasma with low ionisation the socalled non-Maxwellian interaction of electrons with other particles result in elastic and inelastic collisions. Consequently energy exchanges take place between charged, excited and neutral particles. These energy transformations effect 'f' the distribution function, since the potential and kinetic energies undergo neutral conversion. Thus the argument that inelastic collision for only the electrons in the tail of the distribution function participate in the energy transfer and for a low temperature plasma a small part of electrons in the tail participate in energy exchange led von-Engel (1965) to assume energy distribution function to be Maxwellian for helium gas in particular.

Elton (1970) framed up four criteria for free electrons in plasma to be Maxwellian as

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

where for a specific experiment t_{ee}, the energy relaxation time for colliding electrons, must be less than : (i) t_{ff} the energy decay time for free free processes, (ii) t_{eh} the characteristic electron heating time, (iii) t_{part} the characteristic containment time for particles and finally t_{inel}, the relaxation time for electron impact including atomic processes such as excitation, ionisation etc. When the electron density is too high to fulfil the criteria (1.8), the radiations from plasma also increase. Griem (1964) enunciated that the most laboratory plasmas that emit enough light for spectroscopic investigations are sufficiently dense and long lived. The velocity distribution of electrons is closely Maxwellian at any instant of time and at any point in space.

Now we are in a position to discuss how the spectral line intensities related with electron temperature and its density and subjected to an external longitudinal magnetic field are affected. It was experimentally observed by probe method that at least in longitudinal magnetic field electron energy distribution 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).

When longitudinal magnetic field is applied to a plasma column it changes the axial electron density and electron temperature. As we have discussed earlier intensities depend on these parameters and in presence of a magnetic field there is a change in intensities. In all modes of insertion of field viz. longitudinal, transverse and rotational, enhancement of intensities have been observed with quantitative and qualitative difference, however.

For a very limited extent of longitudinal magnetic field Rokhlin (1939) studied the intensity distribution of spectral lines of mercury ($P = 10^{-3}$ torr, $i = 1.5 - 4$ A) and observed that the line intensities of mercury plasma gradually increase and after attaining maxima gradually decrease. Takeyama and Takezaki (1968) carried on an experiment on emission enhancement of several HeI and HeII lines in a helium plasma ($P = 0.4 - 4$ torr) in longitudinal magnetic field ($H \leqslant 6$ KOe) and predicted that the enhancement factor is independent of pressure at least for the range of pressure investigated. Ricketts (1970) observed an increase of intensities of argon spectral lines for an argon ring discharge in longitudinal magnetic fields.

Forrest and Franklin (1966) put forward a theory regarding the behaviour of low pressure plasma column of arc discharge in longitudinal magnetic field and estimated the light emission profile out of its radial component. Franklin (1976) gave a theoretical model and reported a contraction of radial column. Hegde and Ghosh (1979) observed that spectral line intensities of HeI and HeII of a helium glow discharge ($P \doteq 5 \times 10^{-3}$ torr) in longitudinal magnetic field ($H \leqslant 700$ Oe) increase and after attaining maxima slightly decrease with the increasing magnetic field. In this context Hegde and Ghosh originated the collisional radiative model (CRM) for helium for a quantitative understanding of the phenomena. In this model it was shown that collisional radiative ionisation is generally balanced by collisional radiative recombination of charged particles. In active discharges however, collisional ionisation is balanced by ambipolar diffusion to the discharge tube wall and recombination in the bulk is taken as negligible. Subsequently Hedge and Ghosh (1979) calculated that the collisional radiative recombination coefficient is very small.

Allen (1966) and Pinnington (1966) independently carried on an investigation on enhancement phenomenon for ionic lines out of interest for observing Zeeman splitting.

They found that the ionic line intensities are enhanced relatively by a factor of 150 times than the atomic lines in the magnetic field. It should, however, be noted that these investigators used non-uniform sources wherein radiation created at the central hot region is observed in the outer cooler region and therefore, self reversal of the atomic resonance lines may occur.

Rocca, Fetzer and Collins (1981) studied the effect of an axial magnetic field upto 800 G in an argon HCD (hollow cathode discharges) by making measurements of the spontaneous emission intensity from a variety of neutral and ionised levels selecting high purity graphite as cathode for its low sputtering yield. They measured line intensities of selected spectral lines for Ar I and Ar II at 2.5, 2, 1.5 and 1 torr. The intensity of the sponteneous emission in the Ar II was observed as a function of the magnetic field with the current density as parameter (upto 80 mA/cm^2). They observed that ion transition displayed a significant decrease of the spontaneous emission intensity with increasing magnetic field. But for variation of the emission intensity of Ar I the neutral argon transition is not much sensitive to the magnetic field strength. They concluded that an axial magnetic field in an argon hollow cathode discharge decreases the population of Ar II levels, but the population of Ar I excited levels which are nearly saturated at low current densities is insignificantly altered.

In a spectroscopic study of plasma parameters of a high current vacuum arc in an axial magnetic field it was observed by Schellekens (1983) that the interaction of the particles in the arc is collisional and the pressure built up in the arc may be influenced significantly by ion-neutral friction.

In this laboratory Sen and Sadhya (1986) studied the enhancement of spectral intensities of mercury triplet lines in longitudinal magnetic field. In their observation the triplet radiations coming out from the axial part of positive column of the low pressure mercury arc discharge are found to be increased in presence of the axial magnetic field (0 - 2000 G). For a fixed arc current they plotted a curve between I_H / I, where I_H and I are intensities of radiation with and without magnetic field versus magnetic field and found that it increases, with the increase of magnetic field thereafter passing through a broad maxima, decreases very slowly. They however observed that (I_H / I_{max}) values are not the same for three lines investigated. It is noteworthy that when a positive column is subjected to a magnetic field there occurs a coupled variation of axial density $n_e(0)$ and electron temperature T_e where T_e is considered to be uniform over the cross sectional plane of the arc tube. Generally $n_e(0)$ increases whereas, T_e decreases in longitudinal magnetic field. Spectral intensity enhancement is dependent on $n_e(0)$ and T_e. Sen and Sadhya (1986) categorically pointed out that since all the three lines originate from a single upper energy level, their dependence on $n_e(0)$ as well as T_e should be the same and it should result in the same rate of radiation enhancement for the three lines. As discussed earlier, their finding showed quite a different situation. To interpret the results they considered a third parameter, self-absorption (when the plasma is not optically thin) which was different for different lines and hence of much importance in the process of enhancement of intensity. They also provided another support from an observation by Les and Niewodniczauski (1961) where the intensity ratios of the visible triplets of mercury atoms differed widely depending on the condition of the source. It was explained by the phenomena of reabsorption of the lines. Sen and Sadhya (1986) quantitatively estimated and enunciated that as self absorption affected the intensity of spectral lines and was strongly coupled to the population of lower levels, the enhancement factor in the presence of magnetic field should depend on population densities of lower levels of the lines.

It is well known that when there is an appreciable self-absorption the spectral intensity I_{ul} of a line with upper energy level u and lower one l is given (Sen and Sadhya (1986)) as

$$I_{ul} = \text{Const.}\, A_{ul} \int_{-R}^{R} n_u(r) \left[\int d(\nu) \exp\left\{ -\beta(\nu)\sigma \int_{r}^{R} n_l(r)\, dr \right\} \right] dr \qquad (1.9)$$

where $n_{ul}(r)$ are the local number densities of the upper radiating level and lower level as a function of position (radial profile), A_{ul} is the transition probability of the spectral line and $\alpha(\nu)$ is the normalised spectral emission profile $\int \alpha(\nu) d\nu = 1$. The fraction of the emitted line intensity which arrives at the detector after traversing the medium from position r is given as

$$\exp\left\{ - \sigma \beta(\nu) \int_{r}^{R} n_{l}(r)\, dr \right\} \tag{1.10}$$

where σ is the absorption cross-section per atom at the line centre, irrespective of r and $\beta(\nu)$ is the line profile of absorption normalised to unity at the line centre $\beta(\nu_0) = 1$ and $r = 0$ at the centre of the discharge. If there is no absorption

$$I_{ul} = \text{const.}\, A_{ul} \int_{-R}^{R} n_{ul}(r) \left[\int_{-\infty}^{+\infty} \alpha_{\nu}\, d_{\nu} \right] dr \tag{1.11}$$

as $\int_{-\infty}^{+\infty} \alpha(\nu)\, d\nu$ the normalised emission profile is unity

$$I_{ul}^{0} = \text{const.}\, A_{ul} \int_{-R}^{R} n_{u}(r)\, dr \tag{1.12}$$

After Vriens et al (1978) and Uvarov and Fabrikant (1965), Sen and Sadhya (1986) considered that the excited mercury atom distribution function across the cross-section of the arc tube being nearly parabolic and put forward a simplied expression as

$$I_{ul}^{0} = \text{const.}\, A_{ul}\, \tfrac{4}{3}\, n_{u}(0) R \tag{1.13}$$

where $n_u(0)$ is the axial number densities of radiating atoms. Taking the role of self-absorption into account they defined the spectral intensity as

$$I_{ul} = \text{const.}\ (1 - A_s)n_u(0)A_{ul} \tag{1.14}$$

where A_s is the self-absorption quantity (number) of a spectral line. Taking the effect of magnetic field they gave an expression as

$$\frac{(I_{ul})_H}{I_{ul}} = \frac{(1-A_s)_H\,[n_u(0)]_H}{(1-A_s)\,[n_u(0)]} \tag{1.15}$$

and estimated self absorption assuming distribution of the radiating and absorbing atoms in the same manner as

$$(1-A_s) = \frac{\left\{\int_{-R}^{R} n_u(r)\left[\int_{-\infty}^{+\infty}\alpha(\nu)\exp\left(-\beta(\nu)\sigma\int_{r}^{R} n_l(r)\,dr\right)\right]\right\}dr}{\frac{4}{3}Rn_u(0)} \tag{1.16}$$

Sen and Sadhya considered that the emission and absorption profiles are identical and gaussian in nature. It is relevant here to note that it is the outcome of Doppler broadeing of spectral line intensities where all other broadening of spectral line intensities are ignored in comparison. With a solution for a gaussian profile of emission and absorption by Mosberg and Wilkie (1978)

$$\int_{-\infty}^{+\infty}\alpha(\nu)\,\beta^{n}(\nu)\,d\nu = \frac{1}{n+1}$$

they expressed a quantitative formulation

$$\left(1-A_s\right) = 1 - \frac{3}{4}\sum_{n=1}^{n=\infty} \frac{(-)^{n+1}\,\sigma^n\, n_\ell(0)\, R^n}{(n+1)!}\left[\int_{-2/3}^{2/3}\left[\frac{2}{3}-\left(y-\frac{y^3}{3}\right)\right]d\left(y-\frac{y^3}{3}\right)\right]^n \tag{1.17}$$

where $y = r/R$. Values of $n_\ell(0)$'s are calculated utilising Forrest and Franklin's (1969) equations by Sadhya and Sen (1980). In that paper they utilised the values of the collision integral $\langle Q_{ij} v\rangle$ given by Johnson et al (1973) to calculate the values of $n_0(0)$, $n_1(0)$ and $n_2(0)$ the population densities of 6^3P_{012} levels at the axis of their arc tube.

Again σ the cross-section of absorption at the line centre (when only Doppler broadening is considered) is given as

$$\sigma = \pi r_0 c f_{\ell u} \lambda_{u\ell}\left(\frac{M}{2\pi K T_g}\right)^{1/2} \tag{1.18}$$

where r_0 is the classical electron radius, c is the light velocity, $f_{\ell u}$ and $\lambda_{u\ell}$ are the absorption oscillator strength and the wavelength of transition respectively, M the mass of the mercury atom, T_g the inner wall temperature and K is the Boltzmann constant. They calculated the values of σ with help of eqn.(1.18) taking the f values from Gruzdev (1967). These results and the values of $K_0 = \sigma n_\ell(0)$ where K_0 is the absorption co-efficient of radiation at the line centre are being reproduced in table 1.1

Table 1.1

λ (Å)	5461	4358	4047
f Gruzdev(1967)	0.14	0.11	0.10
σ (cm^2)	6.5×10^{-12}	4.077×10^{-12}	3.44×10^{-12}
K_0 (cm^{-1})	0.0735	0.0938	0.1348

They obtained finally an expression

$$\frac{(I_{u\ell})_H}{I_{u\ell}} = \left[1 - f_{\ell u} \lambda_{u\ell} \rho \left\{ \left[n_\ell(0)_H - n_\ell(0) \right] \frac{[n_u(0)]_H}{n_u(0)} \right\} \right] \tag{1.19}$$

where $$\rho = \frac{1}{3} \pi r_0 c \left[\frac{M}{2\pi K T_g} \right]^{1/2} R \tag{1.20}$$

and R is the tube radius.

As the electron temperature decreases and electron density along the axis increases when mercury are is inserted in a longitudinal magnetic field, eqn. (1.19), therefore, indicates that the intensities of spectral lines will change in the magnetic field but will be diminished by self absorption for $\left[n_\ell(0) \right]_H$ increases with H. The effects will however, be different for the spectral lines because f, and $\left[n_\ell(0) \right]_H$ are different for them. They considered the discharge in sufficiently high magnetic field (H = 1500 G) where all the changes are saturated $\left[\left[n_\ell(0)_H \right] \gg n_\ell(0) \right]$

Since relative population of the excited levels always obey a Boltzmann distribution with T_e as temperature (Ritcher, 1968) and eqn. (1.19) was modified as

$$\frac{(I_{ul})_{max}}{I_{ul}} \left[1 - f_{lu} \lambda_{ul} \left\{ n_o(0) \exp \frac{-(E_l - E_0)}{KT_H} \right\} \right] \frac{[n_u(0)]_H}{n_u(0)} \tag{1.21}$$

where E's are energies of the respective levels. They verified eqn. (1.21) from experimental data and on the assumption that the spectral line intensities are governed by the self absorption factor which was different for the three lines in a magnetic field.

(b) Intensities of arc plasma lines in transverse magnetic field.

The effects of transverse magnetic field on the radiation of constricted discharge in hydrogen, helium, nitrogen, neon and mercury were investigated by Kulkarni (1944). Kallas and Chaika (1969) investigated the intensities of emission lines from d.c. discharges in neon and neon helium mixtures subjected to a constant magnetic field upto 30 gauss and found a slow increase in the line intensity with increase of magnetic field. They attributed this change to atomic alignment. While carrying on a study of the hallow cathode discharge in a magnetic field Pacheva and Zhechev (1971) observed the effect of the magnetic field on the spectral line intensity on the helium discharge with an aluminium cathode.

Sen, Das and Gupta (1972) observed that spectral line intensities in glow discharge increase and after passing through a maximum decrease with the increase in transverse magnetic field. The authors provided a quantitative explanation of the phenomenon assuming a coupled change of plasma parameters utilising Beckmann's (1948) analysis.

Ose and Rothhardt (1973) investigated the effect of a local transverse magnetic field on correlation properties of variable light emission from low current discharge in argon at low pressure. They utilised an analogous method whereby the spatial correlation functions were obtained directly by averaging the signals from the photomultiplier tube circuit. They found that with increasing field strength, the self-excited travelling striations are suppressed at first, but then stochastic disturbances are observed showing a very small correlation length in the direction of the tube diameter with a periodically decaying correlation in the axial direction.

Ikee and Takeyama (1975) measured spectral line intensities emitted from helium discharge in a magnetic field for $2^1S - n^1P$, $2^1P - n^1S$, 2^1P-n^1D, 2^3S-n^3P, 2^3P-n^3S and 2^3P-n^3D series upto a principal quantum number $n = 10$ and obtained the population densities of the excited states. They calculated the electron temperature and electron density with the help of Saha - Boltzmann equation since the states are in thermal equilibrium for $n \geqslant 5$. Pasternak and Offenberger (1975) carried out a spectroscopic investigation in a high density d.c. argon arc plasma and measured the plasma parameters. From Doppler boardening and Zeeman line splitting the ion temperature was very accurately measured.

An experimental study of radial distribution of spectral line intensity emitted from a cylindrical discharge tube was studied by Takezaki (1977). He showed that the magnetic field enhances the intensities of all spectral lines except λ 5852 Å. He showed that as the magnetic field was increased from 0.K gauss to 1.8 K.gauss, the population densities of $3P^1D_2$, $3P^3D_2$ and $3P^3D_3$ are increased. He moreover, studied the total line intensities and radial distribution of gas temperature as a function of the field strength and pressure.

(c) Recombination phenomena in afterglow plasma

An electron ion recombination is a very important reaction for a partially ionised gas. In general two mechanisms dominate in the loss-side of charged particles continuity equations -

i) the ambipolar diffusion loss and (ii) a volume recombination loss. The charged particles in the volume of the plasma container diffuse by ambipolar diffusion away to the discharge tube wall where they recombine and consequently turn into ground states of neutral atoms in the plasma. The charged particles in the bulk of the plasma may too recombine through any of several possible mechanisms with the oppositely charged particles where they create neutral particles either in excited or in ground states. In an afterglow plasma, the loss due to ambipolar diffusion of charged particles which is directly proportional to the ratio of electron temperature to ion temperature decreases if the electron temperature enervates to a value corresponding to the ion temperature. Therefore, recombination reaction of ambipolar diffusion type dominates over in the condition like a high gas pressure or a large discharge container.

In the afterglow plasma where ionisation processes are absent the macroscopic recombination co-efficient α is defined as

$$\frac{dn_e}{dt} = -\alpha n_e n_i \tag{1.22}$$

where n_e and n_i are the concentrations of electrons and ions (with which the electrons are recombining) respectively. When an electron recombines with an atomic or molecular ion, recombination energy defined as the sum of internal energy of the ion and kinetic energy of electron is liberated. The ability of the system to dispose this excess liberated energy determines the probability of occurance and dominance of recombination phenomena.

McDaniel (1964), Massey and Gilbody (1974) analysed electron - ion recombination with the help of separate reactions namely radiative, dielectronic, three body collisional and dissociative recombinations on the basis of principles for conservation in linear and angular momenta.

In a radiative recombination a photon Ψ carries off the energy liberated out of recombination of electron e and an ion I^+. This mechanism can be defined by a reaction equation as

$$e + I^+ \longrightarrow I + \Psi \qquad (1.23)$$

In a dielectronic recombination the excess liberated energy is used to excite the neutral atom in which two electrons are simultaneously excited; and the energy of the resulting doubly excited atom lies above the series limit which is energetically unstable. However, it will be stabilised by the emission of a photon in a transition to a relatively lower stable state as

$$e + I^{+} \longrightarrow I^{++} \longrightarrow I^{+} + \Psi \qquad (1.24)$$

In three body recombination phenomena a third body participated in collision and carries off the recombination energy in the form of its increased kinetic energy. The case in which the third body is an electron is distinguished because it has small mass compared with other particles and the reaction is

$$e + I^{+} + e \longrightarrow I + e \qquad (1.25)$$

And the case where the third body is some heavy particle is defined as

$$e + I^{+} + X \longrightarrow I + X \qquad (1.26)$$

The above process involving neutrals as third body becomes significant at sufficiently high gas pressure though the energy is taken away from an electron much more effectively by ions than by the neutrals. At ordinary gas pressures however, this type of reaction becomes much slower.

For an effective process where the electrons recombine with a molecular ion I_2^{+}, recombination energy is used for dissociating the molecule and for increasing the kinetic energy of resulting products. The dissociative recombination process is represented by the reaction equation as

$$e + I_2^{+} \longrightarrow I_2^{*} + I + E_{ke} \qquad (1.27)$$

where E_{ke} is the kinetic energy of the products. During the course of this process the electron under collision with molecular ion is captured to the autoionisation state. In this state the interacting force of atoms causes them to move apart as the force is repulsive. If the autoionisation level does not have the time to decay while the atoms move apart to certain distance, the consequence is a stable state of the dissociative particles.

Bates and Massey (1947) suggested for a system where the molecular ions are chiefly ionised particles that the observed recombination accounts for rapid dissociative recombination. Bates (1950) put forward a theoretical deduction for the dissociative recombination and analysed the problem as a two states process; that the excited unstable molecule is formed first whose constituents then move apart under the action of their mutual repulsive interaction thereby preventing autoionisation. The mathematical derivation for dissociative recombination coefficient α was made with the help of the Frank Condon principle in terms of the autoionisation life time.

In a semiclassical formalism Warke (1966) deduced the rate of dissociative electron capture by the oxygen molecular ion. Bauer and Wu (1956) estimated the cross section of dissociative recombination for hydrogen molecular ions whereas Wilkins (1966) calculated the same in a Born approximation. For calculating the value of dissociative recombination coefficient Watson (1975) put forward a theoretical model. The precise computation for any particular ion is extremely intricate and difficult to do, in as much as an abinitio calculation needs detailed knowledge of the wave functions of all the molecular as well as atomic levels of the given reaction and also their potential energy curves with the knowledge of ionisation probabilities as being a function of inter-nuclear separation of atoms. Smirnov (1977) unfolded other hindrances of this complicated process uniquely. The number of autoionisation levels is large, sometimes it becomes infinite and recombining molecular ion may belong to excited vibrational levels and this fact affects the value of α too. The magnitude of α actually rests on the ionic particles which participated in the recombination process, even though it is possible to categorise the order of magnitude of α for each of the related process. Mitchner and Krugar (1973) computed the magnitude of all the types of recombination reactions at room temperature.

The independent reaction process in recombination are not physically realisable. In general these mechanisms are coupled. Bates, Kingston and McWhirter (1962) demonstrated a coupling picture for the description of the recombination mechanism. The authors analysed that the loss mechanism in very tenuous plasma is generally referred as radiative recombination whereas three body electron collisional recombination may be related to the loss mechanism in very dense plasma. The two mechanisms are actually the two limiting cases for a more general loss mechanism categorised as a collisional radiative recombination by Bates, Kingston and McWhiter (1962). Since the loss comes out from the combination of interacting collisional and radiative processes of ionisation, recombination, excitation and de-excitation in a decaying plasma, the sum of the two limiting cases is not the total loss. In a statistical treatment a quantitative result for α_{CR} is obtained where α_{CR} is the recombination coefficient for collisional and radiative process. It is also worthwhile to note that in a decaying plasma molecular ions can not be identified to be present but the recombination may be of collisional radiative type. The magnitude of α was calculated for both atom and ion species viz. hydrogen and helium. For other species the exact computation becomes much complicated for large number of complicated excited levels and for a deficiency of knowledge for their respective cross sections.

With the knowledge of electron concentrations and other relevant parameters in a plasma as a function of time after withdrawing the energising source the electron ion recombination coefficient is found in most measurements. In many conditions of these experiments so far, the electron temperature is taken as same as the gas temperature, but in some other events it is kept higher through application of auxiliary heating of electrons, as with the help of microwave pulse.

Biondi and Brown (1949) made use of the microwave method for determining the value of α for helium. The detailed experimental apparatus was also described by Biondi (1951). In this technique, a high purity gas is introduced at the desired pressure in a cylindrical quartz bottle placed within a cylindrical microwave cavity. With the help of a microwave pulse from a magnetron a pulsed discharge is generated which in turn changes the resonant frequency of the cavity. It is then obvious that with the help of spatial distribution of the electrons absolute value for average electron concentration may be calculated from measured frequency shift during an afterglow.

In an afterglow plasma with the conditions that $n_e = n_i$ and at $t = 0$, $n_e = n_o(0)$, the solution of the equation turns out as

$$\frac{1}{n_e(t)} = \frac{1}{n_e(0)} + \alpha t \tag{1.28}$$

where the reciprocal of the number concentration is some linear function of time with slope α. Therefore, the value of α can easily be calculated from the loss rate of the charge species. In a loss mechanism where ambipolar diffusion dominates, decay rate of charged species is some exponential function. It is also duly noted that the accurate value of α is really difficult to measure as other loss mechanisms like diffusion and attachment (not always) are present and as there is a fair possibility of electron production after primary discharge in withdrawn.

Gray and Kerr (1962) provided a non-linear differential equation for a loss mechanism in afterglow plasma considering both diffusion and recombination processes so that

$$\frac{\partial n_e(r,t)}{\partial t} = -\alpha n_e^2(\vec{r},t) + D_a \nabla^2 n_e(\vec{r},t) \qquad (1.29)$$

where D_a is the ambipolar diffusion coefficient. Gray and Kerr (1962) obtained the numerical analysis for different conditions viz. initial electron concentration distribution, cavity filling factor and ratio of recombination loss rate to diffusive loss rate β and for both spherical and infinite cylindrical (without boundary effects) geometries. The equation (1.29) was also solved by Oskam (1958) for infinite plane parallel geometry as well as by Frammhold, Biondi and Mehr (1968) for geometries of cylindrical symmetry.

Though a number of experiments in measuring the value of α was made, in relatively few cases the criteria appeared to have been fulfilled properly. For a fair determination of α , the focus should be on the conditions listed below:

i) The losses due to attachment of species should be comparably small.

ii) The diffusive loss rate β should be large in the prevailing condition.

iii) Electron energy distribution should be an effectively stationary one otherwise analysis becomes much complicated.

iv) Single type ions should be present to satisfy the assumption that n_e equals to n_i.

v) Electrons should be in thermal equilibrium with gas molecules.

vi) All the loss mechanisms should depend on electron temperature explicitly.

If the identity of the ions under recombination is not known properly, only the value of α does not give any meaningful picture of its type. The direct identification may be obtained by mass spectrometric probing or by spectroscopic observation of afterglow plasma.

Mohler (1937) determined the value of α for mercury vapour. The electron density was measured after withdrawing an intense direct current discharge in mercury at 0.27 torr pressure. α was measured to be 2.3×10^{-10} cm^3/sec. with T_e in the afterglow plasma of the order of 2000^oK. Mierdel (1943) observed that the decay rate of electron concentration under similar conditions indicates an ambipolar diffusion type electron loss rather than recombination. Dandurand and Holt (1951) investigated the electron removal mechanisms in afterglow plasma of mercury by microwave technique and observed the visible and adjacent ultraviolet light intensity and spectrum by gated photomultipler arrangement. They however, substantiated that the rate of electron concentration decay is measured at higher pressure by attachment whereas at lower pressure by ambipolar diffusion. In the high pressure discharge, some recombination is present and probably accounts for the line spectrum in afterglow. Corresponding to T_e around 2000^oK, the value of α was calculated to be 5×10^{-9} cm^3/sec. In our investigation the result however has been remarked to be complex for the presence of metastable atoms in a mercury afterglow. He pointed out that electron production and its removal in gases of large molecular weights are complicated because electron might not attain thermal equilibrium with the gas during afterglow measurements. This hindrance was removed 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 mixture. Helium behaves like a recoil gas and keeps D_a , the diffusion coefficient very small but leads to only a small rate of negative ion formation out of attachment. In such a mixture for an afterglow, the charged particle population consists exclusively of ions because ionisation potential for helium (rare gas) is higher than that of mercury. With the help of a reaction

$$Hg^+ + Hg + He \longrightarrow Hg_2^+ + He \qquad (1.30)$$

it is shown that atomic mercury ions are converted into respective molecular ions and the reaction takes place at a rate 140 (p_{Hg} , p_{He}) sec^{-1}. In relatively high pressure discharge, these molecular ions recombine with electrons and the value of dissociative recombination coefficient of Hg_2^+ ions with electrons at 400°K is 5.5×10^{-7} cm^3/sec. He also observed in the discharge at pressure 1.0 torr that the electron density decay curve shows increasing evidence of recombination processes.

Baibulatov (1966) carried on an investigation on the deionisation mechanism of a mercury plasma and noted that when the energising field is withdrawn, the production of new ion pair effectively stops and charged particle density then decreases upto a finite but small value. For a mercury plasma at pressures from 0.01 to 0.1 torr, deionisation occurs both through the diffusion mechanism of ion electron gas towards the walls of the discharge tube and through the reduction of the electron temperature out of inevitably inelastic electron scatterings.

Nishikawa, Fujie and Suita (1971) carried on an investigation on the atomic collision processes in a flowing afterglow maintained by d.c. discharge with the help of triple probe and optical measurements. They noticed that the reduction in mercury line intensities is much faster close to the discharge source whereas it becomes slower at distances somewhat apart from the source. This rapid reduction in intensities close to the source may be ascribed to the electron attachment process thereby producing temporary negative ions by reaction

$$Hg + e \longrightarrow Hg^{-}\ ({}^{4}P_{5/2}) \longrightarrow Hg\ (6^{3}P_{0}^{\prime}) + e \qquad (1.31)$$

From the reduction in metastable atom concentration somewhat apart from the source, the diffusion coefficient and the rate at which metastable atoms are changed into metastable molecules are found with help of drawing graphs. The magnitude of α was found to be 3.7×10^{-7} cm^{3}/sec^{-1}, 1.5 times smaller than that of Biondi (1953). This disagreement was ascribed for comparatively high electron temperature (0.12 eV) with respect to that in the afterglow reported by Biondi. The reaction for the formation of molecular ions is given by

$$Hg^{+} + 2Hg \longrightarrow Hg_2^{+} + Hg$$

Aubrecht, Whitcomb, Anderson and Pickett (1966) investigated on a short duration afterglow of an r.f. discharge in mercury at different gas temperature from $333^{o}K$ to $488^{o}K$ and inferred that the intensity enhancement of mercury atomic lines in the afterglow of r.f. discharge are formed by ionisation collisions between metastable mercury atoms. The decay is produced predominantly by ion electron recombination in the volume. It was observed that at higher temperature ($\gg$ $468^{o}K$) molecular bands appear and atomic line intensity decreases more rapidly. Mc Courbray (1954) investigated on an afterglow plasma in mercury vapour the persistence time of λ 4850 Å and λ 3350 Å bands spectroscopically. They found that 6^3P_o atoms are converted into metastable diatomic Hg_2 molecules through three body collision involving two normal atoms. They obtained the value for diffusion coefficient of metastable atoms but did not measure the electron density decay rate.

The two groups of workers Frammhold, Biondi and Mehr (1968) and Orgram, Chang, Hobson (1980) measured T_e as a function of α by microwave technique in neon and krypton respectively. In the experiment electrons do not relax to gas temperature during the afterglows, on the contrary the temperature is maintained by microwave heating steadily. Since T_e is increased, ambipolar diffusion is also raised.

It was however, noticed that if each molecule in excited state dissociates before autoionisation can occur then the initial capture step is rate limiting and a variation of as $T_e^{-0.5}$ is found. If however, stabilisation of reaction by dissociation mechanism is rate limiting then a dependence as $T_e^{-1.5}$ is predicted.

It has been assumed so far that a magnetic field does not influence the value of α. Kuckes et al (1961) investigated recombination process in helium afterglow in a B-I stellarator. It was observed that the loss is independent of magnetic field between 2.9 to 3.5 kilogauss and the intensity of light arising from the recombining helium atoms is proportional to the electron loss rate which is independent of pressure and magnetic field.

Knechtli and Wada (1961) measured recombination coefficient for a highly ionised quiescent plasma of cesium in conjunction with a superimposed steady magnetic field of 1500 gauss. They designed the experiment not to study the magnetic field effect on α, but to realise its suitability in the study of plasma parameters and identify the type of its recombination mechanism. They however showed the value of α to be substantially lower than its literature value. They explained this disagreement on the assumption that the probability of forming molecular ions leading to dissociative recombination is very slow and radiative or three body recombination which has a slower rate than dissociative recombination may possibly be the loss mechanism.

D' Angelo and Rynn (1961) carried some investigation on quiescent plasma of both cesium and potassium in a Q - machine where 'Cs' and 'K' plasma are generated through surface ionisation by impinging Cs and K atom from an atomic beam oven on a hot tungsten plate. They observed in currentless plasma that the particle diffusion depends on perpendicularly applied magnetic field (H = 9.0 kilogauss) as on $\frac{1}{H^2}$ and pointed out that the three body collisional radiative coefficient remains constant irrespective of magnetic field.

Fowler (1978) searched for a possible dependence of recombination on magnetic field and suggested that the experiments of D' Angelo and Rynn in Cs- and K-quiescent plasma in molecular nitrogen gas which were designed to disapprove Bohm diffusion may instead have shown the effect of magnetic effect on recombination. Fowler (1978) argued that the low angular momentum overlap between plane waves and orbital wave functions makes electronic recombination such an improbable mechanism; and the rapid decrease that electron cyclotron radii under go in a magnetic field might be expected to improve this situation severely, particularly for recombination process in the Rydberg states. In fact the phenomenon is hidden in ordinary discharge afterglow experiments at the moderate pressure ($\sim$ 1 torr) which rarely permit states to exist much above n (quantum number) = 20, below which H must be greater than 200 tesla to to observe a change. The beam plasma experiments conducted at pressure from 10^{-6} to 10^{-3} torr would have permitted the states for which $n \sim 200$, and have easily been affected at 0.1 to 1.0 tesla fields applied. On analysing the data of the experiment by D' Angelo and Rynn's, Fowler gave an expression of α in conjunction of magnetic field for Cs and K quiescent plasma as

$$\alpha = 5 \times 10^{-18} + (3 \times 10^{-34}\, p + 4.8 \times 10^{-17})\, H \tag{1.33}$$

with p, the pressure in m^{-3} and H, the magnetic induction in tesla.

Kurkin and Shashkov (1983) investigated the roles of recombination ionisation in the development of instability in a discharge after the pump source is withdrawn. The recombination ionisation would lead to a non-self-sustaining current produced by bulk ionisation in the discharge gap shortly after the pump source is switched off. The authors observed only a decaying current which was associated with plasma decay in the weak field over times 1 - 10 ms above which there is no appreciable ionisation under their experimental conditions. However, they did not detect the instability developed.

(B) Electrical Properties of Arc Plasma

(a) Arc Plasma in Axial Magnetic Field:

Some investigation on a low pressure mercury arc subjected to a variable axial magnetic field had been performed by Tonks (1939) and by Cummings and Tonks (1941). Tonks (1939) pointed out that an axial magnetic field leaves the point to point electron concentration unaltered and does not change the relative potential across the cross section of the discharge tube. Thereafter, Cummings and Tonks (1941) measured by probe technique that electron concentration slightly increases whereas its temperature decreases with the increasing longitudinal field ($H \lesssim 70$ Oe). They emphasised that plasma may react differently due to non-uniformity of the axial magnetic field. So the magnetic field should be uniform without any radial component. It was inferred from a detailed theory put forward that "normal" distribution both for electrons and ions in the cross section is not altered when it is subjected to a longitudinal magnetic field. Tonks (1941) 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 remains unchanged along the length of the positive column, while successive terms decrease with distance along the column at rates which are complicated functions of T_e, the electron temperature and H, the magnetic field strength.

On the contrary Davis (1953) found a small increase in electron temperature in an axial magnetic field H ($H \lessapprox 1580$ G) for a d.c. cesium plasma (p = 0.03 to 0.1 torr) in his measurements regarding the intensity distribution in recombination spectrum. However, the observation made by Davis could not be accounted for by the existing theories. Bickerton and von-Engel (1956) have attributed this anomaly between theory and experiment in the high current density ($5A/cm^2$) used by Davis. For very high current ($i > 30A$) arcs in argon ($p < 1$ torr) in an axial magnetic field (H=2.3K.Gauss) Marhic and Kwan (1977) found that both electron temperature and electron density change. vander Sijde (1972) found change of temperature and density profile for a hollow cathode argon arc in axial magnetic field ($H \leq 1250$ G) from radiation profiles. He found that the electron temperature decreases with the increase of the field. Wienecke (1963) found an increase of pressure in the hot region of a cylindrical symmetric arc in a longitudinal magnetic field. The author inferred that the forces exerted by the field on charged particles modify diffusion current and since an energy transport is related with diffusion, it is also influenced by the field. Davis (1953) found that the electron velocity distribution in longitudinal magnetic field is Maxwellian. Vorobjeva et al (1971) carried on an investigation in mercury vapour arc subjected to an axial field ($H \leq 800$ Oe) and remarked that Maxwellian distribution for electron velocity prevails in the field.

There is some inadequacy for defining an arc. For a low pressure diffuse mercury arc Ecker and Zoler's (1964) criterion obtained from Ellenbaas - Heller heat balance equation, requires that the energy gained by electrons in electric field is balanced by losses in elastic collisions is not fulfilled. In contrast Ghosal, Nandi and Sen (1979) showed that for such a discharge, the energy consumed by the discharge is lost primarily in ionising collisions (also in excitation collisions) and the major part is lost through ambipolar diffusion to the wall of the discharge tube (also by radiation). But from criteria laid 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 the discharges in mercury a low pressure mercury arc. In these discharges, the volume ionisation is generally balanced by diffusion of charged particles. Ionisation in the bulk is primarily by electron collision of neutral and metastable atoms. Apart from diffusion, recombination of charged species plays also a role in their loss mechanism. However in an active discharge for the high value of electron temperature with respect to ion (or atom) temperature recombination becomes comparatively significant than diffusion. Out of the two known types of diffusion, one is the Langmuir free fall diffusion which is effective in very low pressure region and the other is Schottky's ambipolar diffusion which is dominant 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 determined considering a balance between particle loss and generation processes.

When a cylindrical plasma column is subjected to a magnetic field, electron diffusion across and along the field becomes anisotropic and the radial diffusion is reduced. The plasma adjusts to this new situation by decreasing its ionisation frequency determined by electron temperature. So obviously there is change in electron temperature in the magnetic field. Consequently a reduction in either of electron temperature or axial electric field determines a reduced diffusion loss. Self (1967) estimated the influence of longitudinal magnetic field on a cylindrical plasma column operating in Langmuir free fall domain. Franklin (1976) investigated the properties of cylindrical plasma subjected to an axial magnetic field by ion fluid model which is equally responsible in high and low pressure regions. Franklin categorised that the implication of longitudinal magnetic field can be regarded as an equivalent increase of pressure so far as radial motion is concerned. He however, showed that for reduction in radial diffusion of charged particles, ambipolar diffusion if it is dominant, will also be diminished by the application of a longitudinal magnetic field.

In case of finite length cylinder with non-conducting walls placed in axial magnetic field ambipolarity assumption particularly in high pressure region evokes some controversy. Geissler (1970) observed the disagreement between experimental data and ambipolar theory. Afterwards Chekmarev et al (1977) 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 found that ambipolarity of diffusion exists in magnetic field too. However, Franck et al (1972) pointed out the way a magnetic field influences the ambipolar diffusion.

An increase of magnetic field reduces diffusion of electrons and ions. In classical theory diffusion of electrons and ions across magnetic field varies inversely with the square of the magnetic field (in absence of any instability); defined as

$$D_{e,i\perp} = \frac{D_{e,i}}{1 + b_{e,i} H^2} \qquad (1.34)$$

where $b_{e,i}$ is the square of the respective species mobility. Since at a given pressure electron mobility is larger than ion mobility by a term 10^2 to 10^3, the electron diffusion is reduced to a larger extent than ion diffusion. So as magnetic field increases, at a particular magnetic field H_r the radial component of electric field vanishes for $D_{e\perp} = D_{i\perp}$. In case of magnetic field higher than H_r, the ambipolar electric field will be negative accelerating electrons to the wall and retarding the ions. To conceptualise experimentally H_r where reversal of ambipolar field occurs is hardly possible. In general $H_r > H_{cr}$ where H_{cr} is the critical value of magnetic field and where helical instabilities set in. Only for $0 < H < H_{cr}$ classical ambipolar diffusion occurs, whereas for $H > H_{cr}$ Kadomtsu instabilities set in.

In this regard some works on the anomalous behaviour of plasma column in longitudinal magnetic field have been studied mostly in noble gases and to some extent in molecular gases. For plasmas confined by non-conducting discharge vessels, Hoh and Lehnert (1960) studied the influence of longitudinal magnetic field in hydrogen, helium and krypton confined in long discharge tubes, so that diffusion to the ends can be neglected. The authors observed that the radial diffusion across the axial magnetic field decreases classically upto a critical field H_{cr}, but after H_{cr} the diffusion increases with the magnetic field. Kadomtsev and Nedospasov (1960) interpreted the anomalous behaviour by discovering an instability in the form of helical wave which will be created by axial electric field for high values of magnetic field. This instability is designated as current convective instability and it enhances the effective ambipolar diffusion with increasing magnetic field by ExH drift which tends to push the plasma electrons to outward radial direction and to amplify diffusion. The value of H_{cr} is calculated from the knowledge of pressure.

Later on, Janzen et al (1970) found in neon gas that the appearance of the instability depends on the length of the discharge tube. For short discharge tube length ($L \leqslant 15$ cm) there is no appreciable instability. Deutsch and Pfau(1976) found an anomalous increase of column gradient in axial magnetic field ($H \ll H_{cr}$) in weak discharges of noble gases in comparatively long discharge tubes.

The anomalous character was counter-balanced by the radial change in energy distribution of electrons in relation to longitudinal magnetic field. Sato (1978) interpreted the same type of anomalous result as that of Deutsch and Pfau in terms of self excited ionisation waves. In an experiment Muira et al (1979) observed an abrupt fall in axial electric field for a small interval of axial magnetic field in neon. After this fall the axial electric field rises again and decreases classically with the increase of field.

Besides these instabilities, another weak instability arises mainly in quiescent plasmas in axial magnetic field. According to Timofeev (1975) this is known as drift dissipative instability. For active discharges these instabilities are superposed by more high current convective instabilities. Another type of anomolous diffusion known as Bohm diffusion is inversely proportional to magnetic field and is observed in strongly ionised magnetoplasma contained in metal chamber.

In this laboratory current voltage characteristics of glow discharge in longitudinal magnetic field was investigated by Sen and Jana (1977) and it was observed that the discharge current increased with the increase of axial magnetic field for the range of pressure (viz. 0.685 to 0.925 torr Assuming the radial distribution of particles as Bessalian they explained the results quantitatively. The results also showed that Bessalian distribution was valid in magnetic field as well.

A few years latter Sadhya and Sen (1980) studied the variation of current and voltage across a mercury arc plasma as well as variation of the electron temperature in longitudinal magnetic field. It is important to note that most of the results reported for mercury arc plasma are with argon as background gas; Sadhya and Sen (1980) used in their investigation air as the background gas which enables them to study how the excitation, ionization and de-ionization processes are influenced by the presence of air. It is well known that in the case of molecular gases the ionisation is mainly due to electron impact of the ground state atom whereas in the case of a mercury arc, ionisation is mainly through inelastic electron impact with excited states like 6^3P_2 and with ground states, and the phenomena of associative ionization may be present. Considering the physical processes involved in a mercury arc discharge where the buffer gas was air and the pressure was low, they unfolded a model in which air plays the role of quenching gas and observed that in that type of discharge both atomic and molecular ions of mercury arc present. Considering the existence of both types of ion they obtained the distribution function and developed an expression for T_e/T_{eH} and found that within their range of (H/P) values (H, magnetic field and P, the pressure) the experimental results were in quantitative agreement with the theoretical deduction.

Recently Bessenrodt-Weberpals et al (1986) carried on an investigation in a steady state low pressure hollow cathode arc (H CA) which is stabilised by a longitudinal magnetic field. They also measured densities, temperature, velocities and fluctuations of electrons, ions and neutral particles by various local methods such as Thomson and Rayleigh scattering and laser induced fluorescence (LIF). They supported their experimental data by a theoretical treatment of plasma using a two-fluid model which provides a good description of the dynamics of HCAS.

(b) <u>Voltage current characteristics of low current arcs in air with metal electrodes:</u>

If two electrically conducting electrodes of any kind are brought into contact and then separated in a closed circuit with a d.c. source, a self sustained arc discharge takes place. Unlike the glow discharges, the arc cathode has a fall of potential of the order of 10V and a very high current density; thermal effects are necessary for its initiation and sustenance and the radiation emitted from the region near the cathode has the spectrum of the vapour of the cathode material. For a given value of the electode distance, the arc voltage decreases as the arc current rises and for a given current the voltage rises with increase in electrode separation. The positive column has become uniform and its axial electric field is constant. The total arc voltage drop V_{arc} across the two electrodes can be expressed as

$$V_{arc} = V_c + V_p + V_a \qquad (1.35)$$

where V_c = cathode fall

V_p = total fall of voltage at the positive column

V_a = anode fall.

In a series of papers, Bez and Hocker (1954-56) analysed the results for the anode region fall. Conservation of charge carriers in the anode region requires production of positive ions. Based on this requirement and on the existence of a net space charge in the sheath they developed the theories for anode fall. In their analysis it was considered that the voltage drop in the anode region was identical with the anode fall and that the region over which it acts is of the order of an electronic mean free path. But their proposed model did not take into account the fact that macroscopic flow effects could drastically alter the requirements for ion production. This model did not also include axial diffusion and energy losses from the arc plasma to the anode structure.

Ecker (1961) proposed a different approach and was able to predict the shape of the arc in the anode region by solving the conservation equations together with Maxwell's equations simultaneously. Since his treatment was primarily for low current arc , flow effects in the arc were neglected. The anode region of high intensity arcs is, however, frequently governed by self-induced flows (Chou and Pfender (1973)), Pfender and Schafer (1975), Pfender (1978), Chen and Pfender (1981) . Busz, Penckert and Finkelnburg (1956), Schoeck and Eckert (1982), Bose and Pfender (1969) independently measured the anode fall in high intensity arcs with direct and indirect techniques.

Bito and Szigeti (1968) carried on calorimetric measurements for anode fall. They determined current dependence and the pressure dependence of anode fall in case of argon.

de Socio and Boffa (1970) invented a new technique for measurement of anode fall in arc generators and their measurements were in good agreement with the theoretical model for low and intermediate values of arc currents.

In order to evaluate the anode fall they utilised a water-cooled probe at the axis of a plasma jet at some distance from the anode. The probe was either kept at floating potential or was electrically connected with the anode through resistors and batteries in series. By varying the external resistance different values of the electric current characteristics were obtained, thus permitting the estimation of the anode fall.

Schoal and Zahn (1969) carried on some experimental investigation of the processes which govern the anode region in the Faraday-darkspace and in the positive column.

Recently Sanders and Pfender (1984) also measured anode fall and anode heat transfer in high intensity arcs maintained at atmospheric pressure.

Namitokov and Krasovitskii (1973) gave a theory for evaluation of the physical mechanism occuring in the formation of the cathode sheath in an arc. They estimated the cathode drop from the discharge parameters using self-consistent field approximation.

Bito (1969) measured the time dependence of cathode fall and the potential gradient of the positive column in a mercury discharge. Lateron, Boylett and Mclean (1971) also measured cathode fall by moving electrode methods and fast oscillography. They obtained a value of 8V + 6% for the cathode fall in a mercury arc at 10A. The cathode fall space had been evaluated to be less than 5×10^{-4} mm.

Agarwala and Halmes (1983) carried on investigation on arcing voltage of metal vapour vacuum arc and showed the voltage current characteristics of all seven metals (Cu, Al, Sn, Mg, Zn, Cd & Bi) and found positive slopes over the entire range of currents used. And the characteristics are linear. Similar investigation had also been performed earlier by Sherman, Webster, Jenkins and Holmes (1978) and Mitchell (1970). They could deduce an empirical relation for the linear region.

(c) Arc Plasma in Transverse Magnetic Field:

The effect of an external magnetic field on the velocity distribution function of electrons in a plasma was investigated by Tonks and Allis (1937). In an approach via Boltzmann equation Bernstein (1962) justified the distribution function as being Maxwellian.

When a transverse magnetic field is applied to a cylindrical plasma column it pushes the plasma in the direction of Lorentz force. It therefore, leads to a deviation in density and potential distribution for cylindrical symmetry and thereby a potential difference between pointes of the wall on a diameter perpendicular to magnetic field is observed and known as Hall voltage. Francis (1956) gave a qualitative description of a plasma column subjected to a transverse magnetic field .

Tonks and Allis (1937) deduced an expression for electron drift in transverse magnetic field and latter Beckmann (1948) showed that the transverse magnetic field deflects the plasma column towards the wall and results in an increased total loss of electrons and ions followed by an increase in electron temperature and axial electric field strength. Further Beckmann (1948) showed that owing to the transverse magnetic field the axial field E is modified to

$$E\left(\alpha + \beta^2/\alpha\right)^{1/2}$$

Where .

$$\alpha = 1 - h^2 + h^4 \exp h^2 \int_h^\infty \frac{\exp(-h)}{h} \, dh \qquad (1.36)$$

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

$$h = \frac{eH\lambda}{m\omega} \tag{1.37}$$

and H is the magnetic field, λ is the electronic mean free path, ω is the most probable electronic speed; and the electron density at a distance r from the axis is given by

$$n_H = n_0 \exp\left(-\frac{cr\cos\phi}{2D_a}\right) J_0\left(2.405\,\frac{r}{R}\right) \tag{1.38}$$

where n_o is the electron density at the axis, R is the discharge tube radius, c is a constant depending on ion mobility, D_a is the ambipolar diffusion coefficient, J_o is the Bessel function of zero order and of first kind and ϕ is the azimuthal co-ordinate. In some gases like hydrogen, nitrogen, helium and neon, Beckmann (1948) investigated the change in electric field by measuring the voltage drop across a fixed distance with the help of floating probe and found that the electric field increases in a transverse magnetic field (H $\leqslant$ 1000 G). Danders (1957) carried on an experiment in a low pressure positive column in a homogeneous transverse magnetic field and obtained an equation of charge carrier density distribution and found that discharge current depends on magnetic field strength.

Sen et al (1971, 1972) investigated the effect of transverse magnetic field on low pressure discharges in different gases like hydrogen, helium and mercury vapour in their spectral line intensity measurement in the field. Besides the increase in intensities of certain spectral lines they observed that the discharge current increases and after attaining a maximum at a certain magnetic field strength gradually decreases. The field (H_{max}) at which the current becomes maximum is the same for all gases and independent of pressure for the same initial discharge current. Considering small values of (H/P) they modified Beckmann's expression for electric field (1.40) and hence electron temperature was deduced as (1.41)

$$E_H = E \left(1 + C_1 \frac{H^2}{P^2} \right)^{1/2} \qquad (1.40)$$

and

$$T_{eH} = T_e \left(1 + C_1 \frac{H^2}{P^2} \right)^{1/2} \qquad (1.41)$$

where C_1 is a constant for a particular gas given by

$C_1 = \left\{ (e/m) \ (L/V_r) \right\}^2$ where e, m and L are charge, mass and mean free path at a pressure 1.0 torr of electrons in the plasma and V_r is the random velocity of electron. The analysis has also been extended to low pressure mercury arcs by Sen and Das (1973). In the respective experiment, the authors observed that the arc current gradually decreases and voltage drop across the arc increases but the power consumed by the arc gradually increases and attaining a maximum value at a certain field decreases for increasing magnetic field (H $\leqslant$ 300 G). The authors gave a quantitative analysis of the observed results by considering enhanced charged particle loss and an increase in T_e, the electron temperature. Bendarenko et al (1965) investigated that the arc current in low voltage cesium arc decreases for increasing transverse magnetic field.

The effect of transverse magnetic field (H $\leqslant$ 300 G) was also thoroughly investigated by Kaneda (1977a, 1977b, 1978, 1979) on neon discharges at a gas pressure of 0.3 - 10.0 torr and discharge current of 40 mA. Kaneda observed that the axial electric field of the positive column increases considerably with transverse magnetic field in lower gas pressure and compared the results with a theory which takes electron loss at the wall into account.

Ecker and Kanne (1964) explained the effect of a transverse magnetic field on a cylindrical plasma column theoretically. 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 Zoler (1964) put a criterion as

$$\lambda_e < 2R\gamma^{1/2} \tag{1.42}$$

where λ_e 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 cases of high current and relatively high pressure discharges (arc). The authors carried on investigation on the problem mainly for two cases: firstly collision free limit where Langmuir's 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.

Wehrli (1922) calculated the effect of a magnetic field on the breakdown condition of a gas and assumed that λ the mean free path of the electron is constant for all the electrons and in presence of magnetic field the electrons describe a cycloidal path and consequently λ changes to λ' where

$$\lambda' = \lambda \left[1 - \frac{eH^2\lambda}{8Em}\right] \tag{1.43}$$

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

given by

$$P_{eH} = \frac{P_e}{\left[1 - eH^2\lambda/8Em\right]} \tag{1.44}$$

Blevin and Haydon (1958) arrived at a new expression for equivalent pressure by taking into account the electron mass energy and drift velocity and showed that a transverse magnetic field effectively increases the gas pressure from P_e to P_{eH} such that

$$P_{eH} = P_e \left(1 + C_1 \frac{H^2}{P^2} \right) \tag{1.45}$$

where C_1 has its usual significance. Taking a Maxwellian velocity distribution of electrons and a constant average collision frequency, from the concept of equivalent pressure, the variation of Townsend's first ionisation coefficient in a transverse magnetic field is well realised in the high (E/P) regime. In presence of magnetic field the velocity distribution for electrons was criticized by Haydon et al (1971) for not being Maxwellian. Therefore, in formulating the concept of equivalent pressure for electron behaviour in hydrogen gas the collision frequency should be taken as energy dependent. Without taking 'a priori' constant collision frequency Heylen and Bunting (1969) developed an equivalent reduced electric field concept in a constant electric field. With the help of this concept and taking electrons to be in Maxwellian velocity distribution, the transverse and perpendicular mobilities and their ratio $\tan\theta$ for electrons in transverse magnetic field for hydrogen have been explained. The average electron collision frequency was observed to vary with electron energy. This concept was further experimentally, verified in molecular gases like oxygen, air and nitrogen.

Townsend and Gill (1937) showed that the mobility of electrons in the direction of the field in presence of a magnetic field is reduced and deduced

$$\mu_H = \frac{\mu}{1 + \omega_H^2 \tau^2} \qquad (1.46)$$

where τ is the time between two successive collisions and $\omega_H = \frac{eH}{mc}$. Belvin and Haydon (1958) assuming the bulk properties of electron avalanches deduced an expression for mobality in presence of the magnetic field as

$$\mu_H = \frac{\mu}{1 + C_1^2 \frac{H^2}{P^2}} \qquad (1.47)$$

Sen and Gupta (1964) computed the values of electron mobality in air discharge in presence of magnetic field (0 to 300 Gauss) and over a wide range of pressure. The authors verified the equation (1.47) experimentally.

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

(d) Determination of Plasma Parameters in Arc Plasma by Probe Method

Since the early development of diagnostic tools for measuring local properties of a plasma, the electrostatic probe has become popular for its experimental simplicity and reliability. A small metal probe (viz. tungsten) is inserted into the plasma at the location of interest. An external circuit has been provided to apply some potential to the probe. The current flowing through the probe and anode is recorded as a function of applied potential, The current voltage characteristics of a probe may provide some important information about local properties of plasma such as electron and ion concentrations (n_e & n_i), electron temperature T_e, plasma potential and floating potential; since the probes offer boundaries to the plasma and the properties of the plasma will change near the boundaries, the whole probe theory becomes more complicated. In fact, a thin layer called sheath exists around the probe. This sheath can maintain large electric field due to unequal number densities of electron and ions in it.

If a probe is immersed at a point in plasma, the probe attains a potential which is negative with respect to plasma potential. In other words, when the probe is made less negative a few of the highly energised electrons are collected which partially cancel the ions thus reducing ion current.

The potential at which electron current just cancels ion current is known as floating potential V_f . If the probe potential is increased to V_p by an external source, the charged particles then reach the probe with their thermal velocities and as a result the electron current considerably exceeds that of ions. If the potential is still increased so that the probe is more positive than the plasma potential, the ions are increasingly repelled and the saturation electron current is drawn which is measured by the effective area of the sheath around the probe. However, in the collisional plasmas, the sheath thickness increases with positive potential due to some secondary effects and electron current never completely saturates.

Recently Devyatov and Mal'kov (1984) studied the effects of ionisation on saturation probe current. They determined sink parameters for an infinite cylindrical probe and showed for the spherical probe that if the radius is small in comparison with the ionisation length then the sink parameter is determined by Bohm's expression (1949). They also considered the probe operation in presence of ionisation and recombination in the bulk of the plasma.

The probe theory as developed by Langmuir gives electron current as

$$I_e = I_{re} \exp\left(- eVp/KT_e\right) \qquad (1.48)$$

where I_{re} is the random electron current, and K is the well known Boltzmann constant

$$I_{re} = \frac{1}{4} A_s \; n_e \, e \left(\frac{8KT_e}{m\pi} \right)^{1/2} \qquad (1.49)$$

A_s is the effective collection area of the probe for electron and n_e is the undisturbed electron concentration. From the above equation (1.48), electron temperature T_e corresponding to the assumed Maxwellian distribution is determined by calculating the slope of the line in partial attraction regime in a semilogarithmic plot of I_e against V_P. Here I_{re} corresponds to the electron current to the probe at plasma potential (space potential) which is calculated from the intersecting point of the two tangents in the characteristics. The tangents were drawn in the following formalism:-

a) The tangent in the partial electron attraction regime was plotted through more points of highly negative probe potential since in this regime the distribution is expected to be Maxwellian and equation (1.48) is applicable for electron current which is small in comparison with I_{re} Schott (1968)

b) Another tangent in electron saturation current region was plotted in such a way that it posses through maximum number of points. The electron saturation current region may be divided into two parts: One corresponds to a linear increase of I_e with probe potential due to the growth of collective area (as sheath expands). When probe potential is made more positive, a breakaway from this linear increase is found. In this region however, the probe becomes very hot and the sheath expands so much that for a large voltage drop across the sheath, the electrons can further ionise in their way to probe. While plotting the tangent the points just below the breakaway point were utilised.

Since the ratio ℓ/r_p (where ℓ is cylindrical probe length and r_p is probe radius) is very much greater than unity, the effective area A_F has been considered to be equal to $2\pi r_p \ell$. Thus from eqn. (1.49), electron density can be measured.

In operation if the probe is biased negatively than V_p, an increasing fraction of electrons is repelled, and as a result probe current decreases. The logarithmic slope of the characteristic in the portion will correspond to the local electron temperature. At V_f, the ion and electron current mutually cancel each other. If more negative potential to the probe is applied, no electrons can reach the probe and hence ion saturation current is drawn. From the two measurements of electron and ion saturation current, their temperature (kinetic energy) and density can be evaluated.

Since the very onset of Langmuir's (1924 - 1926) work, the probe theory has been developed to a large extent. The probe theory depends on a number of parameters. These parameters measure the various domain at which electrostatic probe can be utilised. In the collisons limit $\left[\lambda \gg r_p,\ \lambda \gg \lambda_D\right]$ where λ is the mean free path of charged species, r_p is the probe radius and λ_D is the Debye shielding length ($\lambda_D = 4.9\ (T_e/n_e)^{1/2}$ in cm), the probe theory is more or less established. On this basis some important extensive computed results are available from works by Bernstein and Rabinowitz (1959), Lam (1965) and Laframboise (1966). The continuum regime $\lambda \ll \lambda_D \ll r_p$ has been computed by Su and Lam (1963) and Cohen (1963). Some calculations have been carried out in the intermediate case by Wasserstrom, Su and Probstein (1965), Chou Talbot and Willis (1966), Bienkowski and Change (1968), Chung, Tolbot and Touryan (1975) and a systemic analysis of probe theories has been provided. Chen, Etievant and Mosher (1968) pointed out that the probe theory becomes simple when $\xi_p = r_p/\lambda_D$ which is called as "Debye ratio" is much greater than 10 and the sheath is thin so that the charge collecting area is effectly close to the 'geometric area of the probe, or when ξ_p is much smaller than 1 and the sheath is very thick so that probe current is determined by orbital motion theory of Langmuir. For a suitable selection of ξ_p for the experiment concerned it is worthwhile to mention that λ_D is characteristic of plasma source, whereas r_p is set only by the physical properties of probe. It should also be noted here that it might not always be possible to have the Debye ratio in the expected range of values as given above.

For cylindrical probes Lamframboise (1966) computed that orbital motion theory is accurate for $\xi_p < 5$ which can easily be satisfied in experiment but for a spherical probe orbital motion approximation is valid for $\xi_p \ll 1$ only.

Schott (1968) in his orbital motion approximation pointed out some assumptions as follows:

i) In absence of probe plasma should be homogeneous and quasi neutral.

ii) Electrons and ions should belong to Maxwellian velocity distribution with T_e and T_i with the restriction $T_e \gg T_i$ Electron and ion mean free path (λ_e and λ_i) 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.

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

iv) The sheath thickness is small compared to the lateral dimensions of the probe so that edge effects can be ignored without losing accuracy.

In low pressure plasma the condition of Maxwellian velocity distribution is often not maintained. A substantial progress of probe theory was made by Druyvesteyn (1930) who showed that actual velocity distribution might be derived from the form of probe characteristic . There is another short coming for cylindrical probe in that potential falls off slowly with absorption radius r_a (defined from the effective collective area of probe) and it can be much higher than λ_D. However, in lower densities measurement, the probe length ℓ must be much larger than r_a and hence than r_p in order to minimise and effects. The probe material is so chosen that it is resistent to heat, chemical activation of any kind and sputtering. It is also worthwhile to note that the work function of the probe material must be large so that secondary electron emission due to particle impact is very very small. It is needless to mention that the probe structure with its insulator support inserted in the plasma perturbs the plasma to a certain extent and hence measurements as well. In this regard Chung, Talbot and Touryan (1975) reviewed the present state of information and findings about the perturbations.

Utilising Langmuir probes situated in the plasma of a low current (120 - 360 mA) vacuum arc on copper electrodes Kutzner and Glinkowski (1982) measured electron temperature and floating potentials by ring shaped probes. They put forward an analysis assuming a shifted Maxwellian ion velocity distribution and evaluated characteristic parameters from the derived floating potential equation.

On the 'measurement of anode falls and anode heat transfer in atmospheric pressure high intensity arcs' by Sanders and Pfender (1984) the electric probe measurements have also been performed at and close to a plane water-cooled anode surface in argon arc for different arc configurations.

With the help of an adjustable fine wire probe penetrating through a small hole in the centre of a flat anode they carried on potential and electron temperature measurements in the anode boundary layers.

Pasternak and Offenberger (1974) carried on probe measurements with the help of double ended tungsten wire probes mounted on a shaft of a small water-cooled d.c. motor in side the arc chamber. Spatially resolved probe current measurements entitled them to determine electron temperature and density profiles of the arc cross section using conventional probe theory.

Sen, Ghosh and Ghose (1983) measured electron temperature in glow discharge with the help of two probes (one at axis and other at the surface of the tube in same cross sectional plane). They measured diffusion voltage and evaluated electron tempeature with prior knowledge of radial electron density profile.

Using probe measurements Maciel and Allen (1985) observed the axial distribution of floating potential along the tube. Langmuir probe measurement was also used in HF discharges by Spatenka and Sicha (1985) to give experimental evidence of the presence of the heavy atomic or molecular negative ions in the created polymer thin film layers.

In this laboratory Sadhya, Jana and Sen (1979) carried on 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.

Direct measurement of the electron distribution function has been a complicated task in most plasmas. In the ionospheric studies by Peterson et al (1981) the distribution function may be found by unfolding data taken by probes whose dimensions are small compared to, or of the order of, the Larmor radius of the particles being collected. Stenzel et al (1983) developed a technique for measuring the distribution function in a laboratory plasma. In thier technique they used a microchannel plate whose smallest dimension was very small compared to, or of the order of, the Larmor radius of the particles being collected. In this process current had been collected by the probe at a variety of geometric orientations, and the data had been unfolded by a computer.

Recently Karamar (1987) carried on 'probe measurement in the high voltage glow discharge' and measured electron density and temperature in the space of the electron beam using Langmuir double probe. He also carried out further measurements concerning the energy in an energetic electron beam in the vicinity of the focus.

(e) Plasma Conductivity measurement by coil probe technique

Measurement of electrical conductivity of a plasma can be performed using a number of methods depending on the nature of the plasma (viz. discharge plasma, shock induced plasma, plasma jets etc). Generally plasma conductivity is measured by conventional probes. It was pointed out by Lin et al (1955) that in hot plasma the probe becomes surrounded by a cold boundary layer around its structure. In the case of cold plasma also the probe measurement does not provide adequate information on the conductivity. An attempt has also been made for indirect measurement of conductivity by determining electron density and collision frequency. The probe method is not also valid for a field free plasma such as afterglow plasma, diffusion plasma etc. It is also noted that this method is not suitable in flowing plasma because the immersed probe structure may considerably perturb the dynamics of the flow. In some cases the plasma jet may even destroy the probe. Hence coil probe technique has become very popular in use to handle conductivity problems in numerous cases.

The fundamental principle of a r.f. coil probe diagnostic technique lies in the fact that 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. Hence many authors called this method as induction or magnetic flux method.

Lin, Resler and Kantrowitz (1955) devised a coil probe method to measure electrical conductivity profiles of highly ionised argon produced by shock waves and they did not use radio frequency source. In this experiment observation was made from the search coil (probe) pick up of electromagnetic disturbances produced by passage of shock waves through it. To avoid the inherent surface effects associated with probe measurements they designed an experiment capitalising the interaction between a magnetic field and the conducting gas behind the shock wave. They observed that conductivity distribution $\sigma(\xi)$ could be determined by solving an integral equation of the first kind with the response function $V_e(S-\xi)$ as the kernel where S is the position of the shock front with respect to the probe at a given time, and ξ represents the axial coordinate of any point with respect to the shock front. However, they did not consider the effect of radial non-uniformity and meant 'distribution' as axial distribution. A point is noted that even when a steady magnetic field was put off, large signals were found to pass through the search coil during each shock. According to them it was due to electrostatic effects. But Ghosal, Nandi and Sen (1976) in this laboratory pointed out that it was due to stray capacitance effect. Actually those pick-ups were due to the formation of finite capacitance between the search coil and the gas inside the shock tube. To eliminate these effects however, Lin et al (1955) designed a centre tapped search coil arrangement. Later on, Lamb and Lin (1957) made observation in shock wave air plasma with the help of the same method and confirmed the results with theoretical analysis.

Persson (1960, 1961) innovated a new coil probe method for measuring the conductivity in a high electron density plasma. He designed the coil probe to send solenoidal electrical field into the plasma in order to collect information from plasma core. This active coil probe measurement rested on the interaction between the solenoidal electric field and a plasma column. The authors carried on the measurements for highly ionised afterglow plasma and obtained the temporal conductivity distribution.

Blackman (1959) ennunciated a procedure in which the inductance of a coil wound around a plasma column is reduced by the shielding effect in the electrically conducting plasma. The reduced inductance changed the frequency of a circuit and this shift in frequency had been detected by a radio receiver.

In this regard Savic and Boult (1962) devised a frequency modulation circuit to determine gas conductivity and boundary layer thickness in a shock tube with the help of the above idea.

Rosa (1961) gave a different method in measuring the conductivity of a flowing plasma. In his experiment the coil was embeded (supported) in the insulator wall of the MHD generator and resonated into a condenser. He determined gas conductivity by measuring damping of the circuit due to the exhaust of the gas through the insulating tube.

Olson and Lary (1961, 1962, 1963) put a different approach where coil probe was kept inside plasma in lieu of being wound surrounding the plasma. In this context some work on immersive coil probe technique was reported by some authors, Moulin and Masse (1964), Stubbe (1968) and Jayakumar et al (1977). In spite of its some disadvantages Olson and Lary pleaded that immersive method was more sensitive to variations in plasma conductivity than the non-immersive method. This method was however the same as other methods and it depended on the interaction between conducting fluid and imposed r.f. magnetic field. It is worthwhile to note here that r.f. impedance of a solenoid is affected by the presence of a conducting medium in the neighbourhood of the solenoid. In the case of a coil wound around the plasma conductor, the r.f. magnetic field of the coil induces an azimuthal electric field which causes azimuthal current to flow through the conductor. It is expected that similar results also come out if the conductor surrounds the finite coil rather than being wound by it.

Donskoi, Duaev and Prokof's (1963) adopted the same non-immersive type technique to measure electrical conductivity of heated gas streams. The method was based on measurements of the electrical circuit parameter (effective inductance, circuit resistance, Q factor, mutual inductance etc) of tank circuit. They determined the magnitude and the distribution of electrical conductivity over the cross section by calibration curves.

Koritz and Keck (1964) described a method for measuring the electrical conductivity of hypersonic wakes and any other conducting medium measuring Joule losses produced by oscillatory (alternating) magnetic field of a coil surrounding it. The method had the advantage that it may be utilised when the medium is stationary.

In this regard a number of authors (viz. Tanaka and Usami (1962), Gourdin (1963), Khuashchtevaski (1962)) made conductor approximation for plasma which means that when an electrical a.c. is impressed upon it, the plasma is considered to offer no resistance and a.c. conductivity essentially becomes d.c. conductivity. They showed that if the change in magnetic flux through a coil due to plasma as its core could be measured, it is possible to measure d.c. conductivity for a range of frequencies. They developed their mathematical analysis with an expression for a.c. conductivity ($\sigma_{a.c.}$) for a partially ionised non-equilibrium cold plasma (Sengupta (1961)), Heald and Wharton (1965) as

$$\sigma_{a.c.} = \frac{ne^2}{m\nu}\left[\frac{\nu^2}{\nu^2+\omega^2} - j\,\frac{\omega\nu}{\nu^2+\omega^2}\right] \qquad (1.5)$$

where m & 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 radio frequency field. The imaginary part corresponds to inherent plasma reactance developed due to mass inertia.

For the conductor approximation to hold it is seen that $\omega \ll \nu$ and then it follows

$$\sigma_{a.c.} = \sigma_0 = \frac{ne^2}{m\nu} \tag{1.51}$$

whereas for other extreme case where $\omega \gg \nu$, the plasma impedance becomes solely reactive. They also studied the a.c. conductivity for intermediate range of frequencies where both reactive and resistive parts were dominating. They however, put forward an equation for a cylindrical uniform plasma as

$$H(r) = \frac{H(R)}{J_0(\beta R)} J_0(\beta r) \tag{1.52}$$

where

$$\beta^2 = -\frac{\omega^2}{c^2} \frac{n_e^2}{m\nu} \frac{4\pi\nu}{\nu^2 + \omega^2} \left(1 + j\frac{\nu}{\omega}\right) \tag{1.53}$$

and R is the plasma radius. The reduction in magnetic flux for the presence of plasma is revealed from the above relation for H(r). If Φ_0 and Φ denote the magnetic flux without and with plasma, the reduction ratio would be written as

$$\alpha = \frac{\Phi}{\Phi_0} = \frac{2}{\beta R} \frac{J_1(\beta R)}{J_0(\beta R)} \tag{1.54}$$

A plot between σ_0 and α taking $\gamma = \frac{\nu}{\omega}$ as a parameter showed that the d.c. conductivity obtained from the magnetic flux change in insensitive to the parameter $\gamma = \frac{\nu}{\omega}$. Thus with the accurately measured value of Φ/Φ_0, σ_0 could be evaluated properly since no detailed knowledge of ν is necessary. Actually they observed the shift of the resonance frequency at the onset of the plasma, evaluated magnetic flux of the coil and finally determined plasma conductivity.

Tanaka and Hagi, however, viewed the inductance change effect in a different manner. If the plasma is conductive, the applied r.f. field will induce eddy currents which will flow around plasma and consequently will dissipate energy in the region where they will flow, by which magnetic flux is screened off from the region. Thus the effective inductance of the net work is reduced, resulting in a shift in resonance frequency.

It is noteworthy that though all the active coil probe experiments discussed so far utilises the shift in either inductance or resistance of coil probe due to plasma in one way or other, theoretically each of them tackled the problem from different angles leading to some uniqueness of each experiment as such.

Akimov and Konenko (1966) studied the validity of the two similar well-known coil probe methods for measuring plasma conductivities and discussed various possibilities. Though they discussed the work of Blackman (1959) and Donskoi et al (1962), in particular, their remarks are also useful to those who investigated electrical conductivity measuring a shift in resonance frequency f or quality factor Q of coil inside which plasma is inserted. It may be found that in contrast to the prediction of Tanaka and Hagi (1964), the test object in the coil can change the oscillator frequency for some ranges of conductivities. According to Ghosal, Nandi and Sen (1976) and Hausler (1957), the reduction of frequency was due to the capacitive effect of the test object on the coil. The presence of a conducting body in the vicinity of a coil increases its stray capacity and consequently the oscillator frequency decreases. The disagreement in value of plasma conductivity averaged over the cross sections with that from calibrating curves was attributed by them to the radial nonuniformity of the plasma in the arc. According to them, due to the skin effect, this measurement gives information of the peripherial region of the plasma only where the conductivity is much smaller than the average value. But Ghosal, Nandi and Sen (1978) pointed out that even if the skin depth is much larger than the plasma radius, the disagreement is expected to remain since coil probe technique gives information on moments of conductivity distribution of different orders.

Utilising either immersive or non-immersive coil probes the above mentioned workers as well as Hollister (1964), Mürino and Bonomo (1964) measured the average plasma conductivity because the test plasma was radially nonuniform. Giampi and Talini (1967, 1969) studied the interaction of solenoidal electric field with a radially nonuniform plasma in a very generalised way. They deduced the impedance of a solenoid of length l in terms of the electric field E_R magnetic field H_R and coil parameters (length l and radius R, number of turns n etc.) as well as in terms of the applied frequency ω, coil inductance Ψ etc. as

$$Z = \left(8\pi^2 N^2 R/c\ell\right)\left(E_R/H_R\right) = i\omega\Psi S \tag{1.55}$$

where $S = \left(2/i\mu K_0 R\right)\left(E_R/H_R\right)$

K_0 being the wave number is generally a complex quantity depending on the medium characteristics and the probing frequency. The term S can be written in a form $(\beta - i\alpha)$ and signifies an algebric substraction of the coil impedance due to the presence of conductive medium. However, this term can be experimentally measured. Actually β represents the contribution of the medium to the inductance of the coil and α the resistive contribution due to energy loss in the medium. The dependence of S on the characteristics of a radially nonuniform medium was expressed solving Maxwell's equations in cylindrical coordinates system as

$$\frac{d^2E}{dr^2} + \frac{1}{r}\frac{dE}{dr} + \left(\frac{K^2}{R^2} - \frac{1}{r^2}\right) = 0 \tag{1.56}$$

where

$$K^2(r) = \left(K_0^2 R^2/\mu\right)\left(\epsilon + 4\pi\sigma'(r)/i\omega\right)$$

For uniform medium, the equation for S reduces to

$$S = 2\, J_1(K)/K\, J_o(K) \qquad (1.57)$$

They solved the differential equation (1.56) where they assumed the radial profile of the conductivity as

$$\sigma(r) = \sigma_o \left[1 - m \left(\frac{r}{R}\right)^n \right] \qquad (1.58)$$

In their analysis they put a low frequency approximation i.e. $\omega/\nu \ll 1$, such that displacement current term could be ignored and hence the r.f. conductivity $\sigma'(r/R)$ was replaced by the d.c. conductivity $\sigma(r/R)$ With a prior knowledge of conductivity profile, a measurement of α or β at any frequency provides the value of axial conductivity σ_o . It was also investigated that for unknown profiles the measurement of α and β could provide information about the plasma conductivity through some quantity which are proportional to σ_o . This observation was however, valid for some range of frequencies. In this range the measurement of α and β for the unknown plasma and for a homogeneous medium of conductivity $\bar{\sigma} = h\,\sigma_o$ gives the same result. Hence, with reference to induction or resistive measurement plasma simulates a homogenous medium and according to them $\bar{\sigma}$ can be interpreted as a spatial average conductivity. Thus two averages σ^* and σ^{**} were obtained according to the resistive and inductive measurements respectively.

$$\sigma^* = \frac{4}{R^4} \int_0^R \sigma(r)\, r^3\, dr \qquad (1.59)$$

$$\sigma^{**} = \frac{3}{4}\left[\frac{4}{R^4}\int_0^R \sigma(r)\, r^3 dr\right]^2 + \frac{3}{4}\,\frac{6}{R^6}\int_0^R r^5 dr\left[\frac{4}{r^4}\int_0^r \sigma(r)\, r^3 dr\right]^2 \tag{1.60}$$

Ciampi and Talini also performed the experiment in a flow facility plasma utilising Q - factor measurements and employing calibration curve to find the first average conductivity σ^*. Later on, they (1969) extended their theory and measurement to incorporate the effect of collision frequency. In this regard Ghosal, Nandi and Sen (1976, 1978) pointed out that the expression of the two meaningful averages and the relevant frequency and conductivity ranges could be achieved in a more simpler way. They performed the experiment by utilising the probe coil and considering the conducting medium to form a transformer where the primary and the single-turn secondary were the coil and the medium itself respectively. As they mentioned, 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, eddy current loss and capacitative by pass. They adopted a compositive equivalent circuit and deduced an expression for the effective resistive impedance of the coil as (ref. fig. 1.1)

$$R' = R_0 + \frac{R_2 c^2}{(C_0+c)^2 + \omega^2 R_2^2 c^2 C_0^2} + \frac{\omega^2 M^2}{R_1^2 + \omega^2 L_1^2} R_1 \tag{1.61}$$

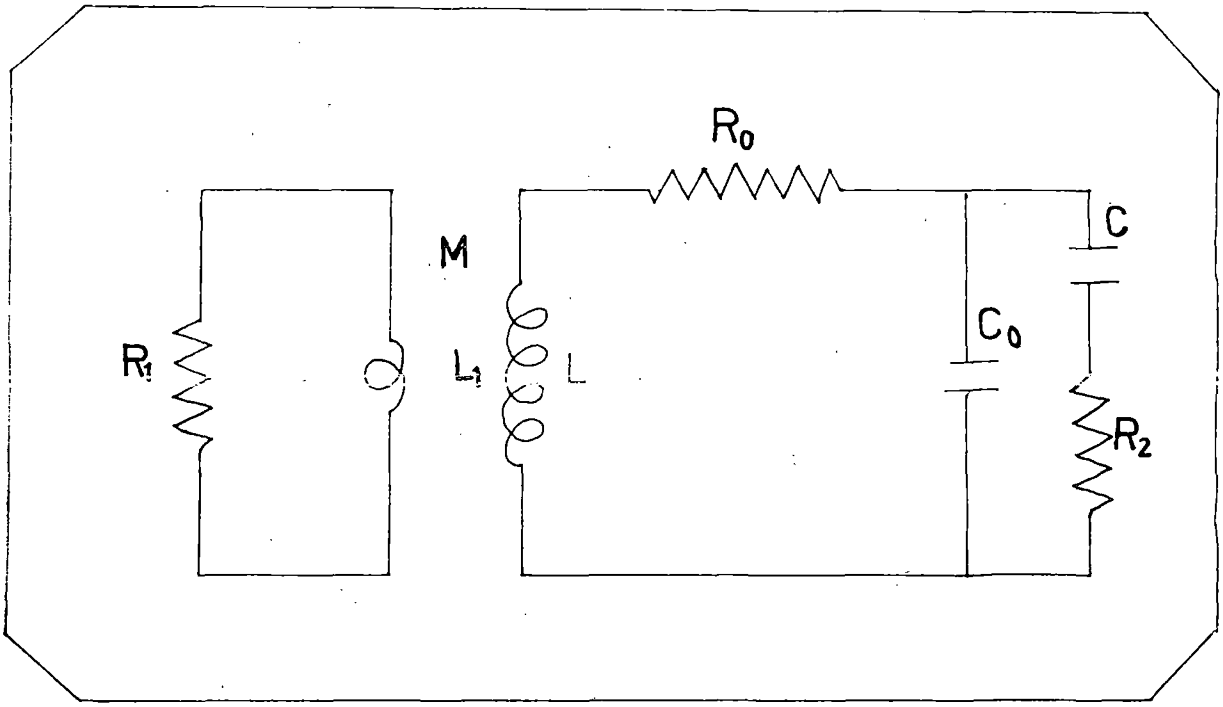

FIG. 1·1. THE EQUIVALENT CIRCUIT

where R_0 = coil resistance (ohm), C_0 = value of the tuning capacitor (farad); C = stray capacitance (farad) formed between the core and the plasma column; R_2 = axial plasma resistance (ohm); R_1 = azimuthal plasma resistance (ohm); ω = angular frequency (radian); L_1 = eddy secondary inductance (Henry); L = coil inductance (Henry), between L and L_1. The last term in eqn. (1.61) is the reflected resistance in the primary due to the eddy current flowing through the plasma.

For some higher values of conductivity (designated by the glow-arc transition region in fig. (1.2) the second and third terms of eqn. (1.61) are predominant and $(R^1 - R_0)$ becomes minimum. However, in the arc region the reflected resistance term only is significant and the bandwith rises linearly until R_1^2 and $\omega^2 L_1^2$ are comparable. In their experiment $\omega^2 L_1^2 \ll R_1^2$ and the eqn. (1.61) can be simplifield as

$$R' = R_0 + \frac{\omega^2 M^2}{R_1} \tag{1.62}$$

Assuming the plasma to be of uniform conductivity Ghosal, Nandi and Sen (1976) put forward an expression for the azimuthal conductivity as

$$\sigma_s = \frac{\pi(\alpha - 1)}{l\omega^2 M^2} R_0 \tag{1.63}$$

where α is the ratio of the radiofrequency current in absence and in presence of the discharge, ω is the

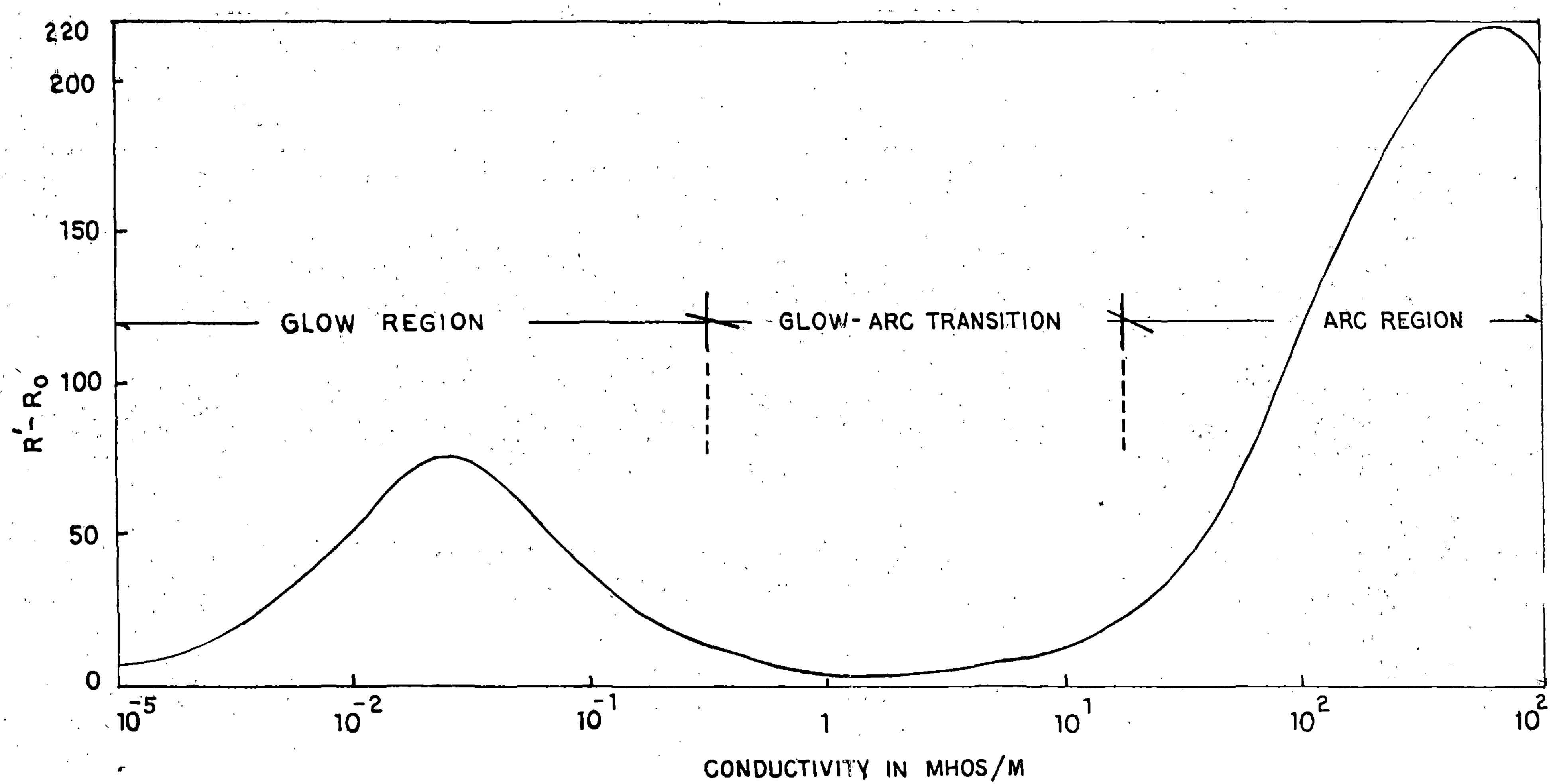

Fig. 1·2. THEORETICAL NATURE OF VARIATION OF $(R'-R_0)$ WITH $(\log 1/R_1)$. [THEORETICAL CALCULATIONS EQN.1·61].
$C = 10$ PF , $C_0 = 45$ PF $M = 0{\cdot}359\ \mu H$, $L = 18\ \mu H$, $\omega = 2\pi \times 5{\cdot}1$ MHz $R_0 = 10\ \Omega$, $L_1 = 7{\cdot}2 \times 10^{-3}\ \mu H$.
REPRODUCED FROM THE PAPER OF GHOSAL, NANDI AND SEN (1976) .

angular frequency of the radiofrequency current, l is the length of the coil, M is the average mutual inductance formed between the coil and the plasma and R_0 is the radiofrequency resistance of the coil. In their next paper (1978) they pointed out that an arc cannot be regarded as a medium of uniform charge density or conductivity. In their investigation they started with some generalised radial conductivity distribution and measured experimentally a quantity which is a function of the assumed conductivity distribution.

With an assumption 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 by $\omega^2 M^2(r)/R(r)$ 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 also provided an expression for the reflected impedance of the annular cylinder of the plasma as

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

where σ_r is the azimuthal conductivity of the plasma at a distance r from the axis. Since the total impedance is the sum of the contributions of all the elementary annular cylinders imagined within the plasma column, the total effective impedance becomes

$$R' = R_0 + \frac{\omega^2 l}{2\pi} \int_0^R \frac{M^2(r)\,\sigma(r)}{r}\, dr \tag{1.64}$$

where R_o is the radiofrequency resistance, R is the tube radius of the arc tube. Here M(r) can be written as M(r) = Kr^2 where K is a constant which depends on the number of turns of the primary coil. Accordingly the above eqn.(1.64) can be simplified as

$$\alpha - 1 = \frac{\omega^2 K^2 l}{2\pi R_0} \int_0^R r^3\, \sigma(r)\, dr \tag{1.65}$$

Further

$$\int_0^R \sigma(r)\, r\, dr = \frac{I}{2\pi E} \tag{1.66}$$

where I is the arc current and E is the axial voltage drop per unit length. From eqn. (1.65) and (1.66) it follows that

$$\frac{\int_0^R r^3 \sigma(r)\, dr}{\int_0^R r\, \sigma(r)\, dr} = \frac{\alpha - 1}{f^2 K^2 l} \; \frac{E}{I} \; R_0 \tag{1.67}$$

where f is the frequency of the radiofrequency current.

They assumed $\sigma(r)$ to be of the approximate form

$$\sigma(r) = \sigma_0 \left[1 - \left(\frac{r}{R}\right)^2 \right]^n \tag{1.68}$$

where n is constant. From eqn. (1.67) and (1.68) it has been shown that

$$n = \frac{R^2}{a} - 2 \tag{1.69}$$

where $a = \dfrac{\alpha - 1}{f^2 K^2 l} \dfrac{E}{I} R_0$

And from eqn. (1.66) and (1.68) the expression for axial conductivity has been written as

$$\sigma_0 = \frac{I/E \; 2(n+1)}{2\pi R^2} \tag{1.70}$$

Ghosal, Nandi and Sen also obtained the same result as given by Ciampi and Talini. It is noteworthy 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. As for example, for profiles of the type treated by Ciampi and Talini, 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 allowed to be varied indefinitely the aforesaid factor may be extremely large . Further the choice of the profile demands that the plasma fills the available volume; this may be valid for an ordinary discharge plasma but detrimental for other situations such as flow facility plasma, plasma jets, metal arcs etc. In these cases the errors may be very much larger since the plasms conductivity may vanish at some distance away from the confining wall. Moskvin and Chesnokova (1965) carried on a temperature measurement on an argon plasma jet where 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 approximately 100 mho/m. Thus it is found that the axial conductivity is 30 times larger than the apparent average. Ghosal, Nandi and Sen (1978) estimated the azimuthal average $\bar{\sigma}_{\phi}$, volume average $\bar{\sigma}_{vol}$ and the axial conductivity σ_0 of a mercury arc and showed that axial conductivity can be 16 times the azimuthal average value. However, the short coming of the measurement has been supplemented with additional information using an approach by Ghosal, Nandi and Sen (1978) and Goldenburg et al. (1964).

Mikoshina and Smy (1969) on the other hand unfolded a newer approach of measuring plasma conductivity capitalishing the dependence of the mutual inductance of two coils, upon the conductivity of the medium lying between them. Out of many advantages of the method it is significant that it can be used over a continuous and relatively wide range of frequencies with which a very wide range of conductivity can be measured (upto 10^6 mhos/m). In fact, this is the outcome of the inherent sensitivity of their experimental apparatus which was not furnished with other electronic accessories. In the former type of single coil measurements the reflected impedance of the oscillator coil was very small and sensitivity was generally obtained by utilising mixing techniques or 'Q' spoiling methods. But in the above two coil method by Mikoshiba and Smy (1969) one coil acts as a transmitter whereas the other as a receiver. The signal induced by the receiving coil is much less than that applied to the transmitting coil since the relative reaction of the induced currents on the receiving coil is much more strong and a straight forward measurement of signal attenuation is enough to measure conductivity of interest.

Basu and Maiti (1973) investigated hot cathode low-pressure d.c. discharge plasma where the electron atom collision frequency is comparable to the probe frequency. It is obvious in this case that the conductor approximation is no longer applicable and the plasma is characterised by a complex conductivity $\sigma_r + i\,\sigma_i$. As discussed earlier Tanaka and Hagi (1969) focussed their attention to the problem of coil probe conductivity measurements on plasma which revealed impedance characteristics at working frequencies; but their intention was to achieve the d.c. conductivity when the imaginary part of the conductivity is a non-zero quantity. However, Basu and Maiti (1973) measured both the real and imaginary part of the plasma conductivity by measuring the resistive and inductive parts of the reflected impedance of the coil probe.

After Heald and Wharton (1965) the complex conductivity of plasma can be related by a expression as

$$\sigma(r) + i\,\sigma(i) = -\frac{4\pi}{3}\,\epsilon_0\,\omega_p^2 \int_0^\infty \frac{1}{\nu(v) + i\omega}\,\frac{df_0(v)}{dv}\,v^3\,dv \tag{1.71}$$

where v is the electron velocity, $f_0(v)$ is the equilibrium distribution function, ω is the angular frequency of the applied radiofrequency field $\nu(v)$ is the electron atom collision frequency of momentum transfer.

Scope and Object of the Present Work:-

In the proposed scheme of work entitled "Investigation on the Electrical and Optical Properties of Arc Plasma", both immersive and non-immersive diagnostic techniques have been adopted. In this laboratory under the scheme of non-immersive diagnostic techniques in plasma the researchers have so far used the following methods:

i) Spectroscopic methods, with and without magnetic fields either axial or transverse

ii) R.F. coil and capacitor probe methods.

iii) Sonic probe methods, with and without electromagnetic pick up..

iv) Radiofrequency probe (where it acts as a secondary source)

v) Microwave probe

And under the immersive diagnostic techniques the following methods have been adopted:-

vi) Single probe

vii) Double probe

viii) Moving probe

ix) Probes of different constructional geometry and different mode of insertion.

The present work concerns diagnostics using the methods stated in i, ii, iv, vi, and ix.

Though a vast amount of literature has grown around both the theoretical as well as experimental work carried out on the elucidiation of the arc plasma properties, the basic physical mechanism regarding the occurance of arc plasma and the transition from glow discharge to arc region, the nature of physical processes in arc plasma (viz. the conduction of heat and electricity, high frequency generation, propagation of different waves etc.) and a generalised theory regarding manifold spectroscopic observations has not yet been firmly established. As discussed in the review article, the diagnostic techniques are not free from shortcomings in one way or the other (either due to strong perturbing effect or insensibility) in the measurement of plasma parameters. However with a view to provide more basic data for an arc plasma the present measurements have been made by a variety of diagnostic techniques, mode of observation and source of plasmas.

It has been established from theoretical analysis and also supported by experimental data that properties of a plasma of any kind change in presence of a magnetic field and the change in the properties is reflected in the change in values of plasma parameters. To a great extent characteristics of magnetoplasma have been reviewed by many authors (Francis (1956), von-Engel (1965), Chen (1974) and Franklin (1976)).

In order to develop a generalised theory of the processes occuring in an arc plasma it is essential to have a detailed knowledge regarding the population of all bound electronic states, the transitional energies of electron and various atomic species, free electron densities, radial electron density distribution, average axial conductivity, diffusion of plasma particles and various loss mechanisms. It is also desirable to study the behaviour of plasma in a magnetic field. With this context the present work attempts to investigate the properties of arc plasma in presence and in absence of magnetic field and to extend the theoretical and experimental investigations in the field with both immersive and non-immersive probe diagnostics. It is proposed to take up the investigation along the following lines:

(i) Dependence of the intensity of mercury triplet lines on discharge current and transverse magnetic field in an arc plasma

The spectral enhancement in the intensities of sharp series of triplet lines of mercury ($7^3S_1 - 6^3P_{012}$) corresponding to λ 4047 Å, 4358 Å & 5461 Å with arc current as well as with transverse magnetic field with a view to understand the process of population and depopulation in different atomic states, and the role of self-absorption has been undertaken. In the earlier investigation by Sen and Sadhya (1986) regarding the variation of intensity of the mercury triplet lines in presence of longitudinal magnetic field it was observed that the effect of magnetic field was different as regards the variation of intensity and occurance of maxima in these lines. These variations were explained by considering the reabsorption of the emission lines. It is evident that the intensity of the spectral lines will be dependent on change of pressure, discharge current as well as on the alignment of magnetic field. In this section it is proposed, therefore to study the effect of arc current, the alignment of magnetic field and the possible role of selfabsorption on the intensities of sharp series of triplet mercury lines.

(ii) Persistence of afterglow maintained by a radiofrequency field in a mercury arc.

The afterglow process in a decaying plasma and the measurement of coefficient of recombination has been studied in detail. The study provides information regarding the various processes of electron loss dissociative and radiative recombination and their relative importance in a decaying plasma.

However, afterglow in low pressure mercury arc vapour which remains visible for many seconds (T)(which is defined as the persistence time) can be generated by imposing a radiofrequency field to the decaying discharge. It is proposed to measure the time of persistence for different arc currents and also for different times of excitation of the arc. As it is also known that diffusion is one of the main causes for the loss of charged particles and as diffusion loss is dependent upon the applied magnetic field it is proposed to investigate the effect of a magnetic field on such a decaying plasma. Hopefully a systematic study of how the time of persistence varies with experimental parameters would permit of the evaluation of the various loss mechanisms. This is unfortunately hindered by an apparently unavoidable dependence of the magnitude of r.f. field on the intensity (probably mainly the electron content) of the decaying plasma itself. It is proposed that the continuance of afterglow may be due to additional ionization produced by the radiofrequency field and so in the present case the process of ionization and recombination can be studied in greater detail.

(iii) Voltage, current and power relation in an arc plasma in a variable axial magnetic field.

Current and voltage characteristics of glow discharge in longitudinal magnetic field has been studied by Sen and Jana (1977). Considering the radial distribution of particles as Bessalian it has been possible to explain the results quantitatively. The results also show that the Bessalian distribution holds in presence of magnetic field also. Electron temperature and its variation in an axial magnetic field has been investigated by Sadhya and Sen (1980) by a spectroscopic method. A distribution function for the radial electron density has been deduced by them. The results obtained by Sen and Das (1973) indicate that the theoretical (Beckman, 1948, Sen and Das, 1971) deduction regarding the variation of electron density and electron temperature in a transverse magnetic field in case of glow discharge is valid in case of arc plasma also. The object of this experiment is to investigate whether the same model is valid in case of arc plasma when subjected to an axial magnetic field, and to find out whether the properties as well as the plasma parameters in an arc plasma are dependent upon the alignment of the magnetic field with respect to direction of flow of arc current. Hence it is proposed to investigate in the present study the variation of voltage, current, and power relation in a mercury arc plasma in an axial magnetic field and to provide a theoretical analysis of the observed experimental results.

(iv) Voltage current characteristics of low current arcs in air with metal electrodes.

A considerable amount of information has been collected on measured arc characteristics with numerous attempts to establish empirical relations of the form

$V_a = f(I)$ where V_a is the potential drop across the arc and $f(I)$ is a function of the arc current. An analysis of these empirical relations so far can not however provide the values of the parameters of the arc plasma such as anode and cathode fall, contact potential and other allied properties. The object of this work is to study the voltage current characteristics in arc plasma produced under atmospheric pressure and to determine the above parameters of the plasma after a systematic analysis of the results.

(v) Conductivity and power relation in an arc plasma in transverse magnetic field

The effect of a variable transverse magnetic field on the voltage current characteristics and power relation in an arc plasma (arc current upto 2 amp) has been earlier investigated by Sen and Das (1973) and a detailed mathematical deduction has been provided to explain the observed results. The object of the work is to extend the investigation to higher arc currents than that investigated by them and to study the interaction of strong magnetic field with arc parameters.

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

In this laboratory for the last few years Sen and some of his research fellows have taken up the systematic investigation of the properties of arc plasma in order to develop a generalised theory as to the occurance of arc plasma and bringing out the salient changes when the transition of glow discharge to arc plasma takes place. In fact, a large collection of data regarding plasma parameters and their variation in a perturbing field is necessary to develop the theory for the occurance of arc plasma. Therefore, it is worthwhile to study whether the Langmuir single probe method can be utilised for measurement of arc plasma parameters. This will also give the validity of

Langmuir probe theory for the glow discharge to the arc plasma region. There is also another important mechanism by which charged particles are lost from a plasma. One of the basic factors is the loss by the ambipolar diffusion process. Hence it is proposed to set up an experiment to measure the resultant diffusion voltage in an arc. It is well known that the process of diffusion is basically connected with the radial distribution function of charged particles and an expression for the radial distribution function of the electrons in an arc plasma has been provided by Ghosal, Nandi and Sen (1978) (and by the present author for wider range of arc currents and different tube radii). This experiment can also indicate the validity of distribution function as proposed by Ghosal, Nandi and Sen. This experiment may however be extended in presence of different buffer gases at different pressures and with different tube radii.

(vii) Dependence of radial distribution function for the azimuthal conductivity of an arc plasma on tube radius

By combining the results of bulk conductivity measurements from ordinary probe technique —— which provides axial average, and the r.f. coil probe —— which provides azimuthal (radial) average, Ghosal, Nandi and Sen (1978) have been able to obtain information that gives knowledge regarding the structural behaviour of the electrical conductivity or the electron concentration of a radial arc profile. They have also pointed out that the Bessalian distribution function does not hold in low pressure arc plasma. The object of the present work is to find the dependence of the proposed distribution function on tube radius. This work may be carried out at different pressures and also by applying transverse and axial magnetic field to the plasma to see how these two factors affect the distribution function proposed by Ghosal, Nandi and Sen (1978).

BIBLIOGRAPHY

1. Agarwal, M.S. and Holmes, P. (1984), J.Phys. D (GB), 17, 757.
2. Aikawa, E. (1976), J.Phys. Sec. Japan, 40, 1741.
3. Akimov, A.V. and Konenko, O.R. (1966), Sov. Phys. Tech. Phys., 10, 1126.
4. Allen, L. (1966), Proc. Phys. Sec., 87 pt. 2, 585.
5. Allis, W.P. (1956), in Hand-b. Phys., 21 (Rd.S.Flugge Springer-Verlag, Barlin).
6. Aubrecht, J.A., Whitcomb, B.M., Anderson, R.A. and Pickett, R.C. (1968), J. Opt. Soc. An., 58, 196.
7. Baibulatov, P. Kh. (1966), Sov. Phys. Uspakhi, 9, 451
8. Basu, J. and Maiti, J.N. (1973), J.Appl.Phys., 44, 3975.
9. Bates, D.R. (1950), Phys. Rev., 78, 492.
10. Bates, D.R., Kingston, A.E. and McWhirter, R.W.P. (1962), Proc. Roy. Soc., A267, 297 and ibid A270, 155.
11. Bates, D.R., and Massey, H.S.W. (1947), Proc. Roy.Soc., A192, 1
12. Bauer, E. and Wu, T. (1956), Can. J.Phys., 34, 1436.
13. Beckman, L. (1948), Proc. Phys. Soc., 61, 515.
14. Belvin, H.A. and Haydon, S.C. (1958), Aust. J.Phys., 11, 18.
15. Bendarenko, I.I., Gus'kov, Yu, K. and Lebedev, M.A. (1965), Sov. Phys. Tech. Phys., 10, 633.
16. Bernstein, I.B. and Rabinowitz (1959), Phys.Fluids, 2, 112.
17. Bernstein, M.J. (1962), Phys. Rev., 127, 335, 342.

18. Bessenrodt-Weberpal, M. et al (1986), IEEE Trans. Plasma Sci. (USA), PS-14, 492.

19. Bez, W. and Höcker, Z. (1954), Naturforsch, 9A, 72.

20. Bez, W. and Höcker, Z. (1955), Naturforsch, 10A, 706.

21. Bez, W. and Höcker, Z. (1956), Naturforsch, 11A, 118.

22. Bez, W. and Höcker, Z. (1956), Naturforsch, 11A, 192.

23. Bickerton, R.J. and von-Engel, A. (1956), Proc. Phys. Soc., 76, 468.

24. Bienkowski, G.K. and Chane, K.W. (1968), Phys. Fluids, 11, 784.

25. Biondi, M.A. (1951), Rev.Sci., Instr., 22, 500.

26. Biondi, M.A. (1953), Phys. Rev., 90, 730.

27. Biondi, M.A. and Brown, S.C. (1949), Phys. Rev., 75, 1700.

28. Bito, J. (1969), 9th. International Conference on Phenomena in Ionised Gases, Bucharest, Rumania, 151.

29. Bito, J. and Szigeti, Gy (1968) Hiki (Hungary), 7, 5.

30. Blackman, V.H. (1959), AIOSR TN-59-681.

31. Blevin, H.A. and Haydon, S.C. (1958), Aust. J. Phys., 11, 18.

32. Bohm, D. et al (1949), The Characteristics of Electrical Discharges in Magnetic field, McGraw Hill Book Co. Inc., New York.

33. Boiko, V.A. et al (1983), Opt. & Spectrosc. (USA), 54, 442.

34. Bose, T.K. and Pfender, E. (1969), AIAAJ, 8, 1643.

35. Boylett, F.D.A. and Maclian, I.G. (1971), J. Phys. D. (G.B) 4, 677.

36. Burgess, D.D. (1972), Space Sci. Rev. 13, 493.

37. Busz-Peuckert, G. and Finkelnburg, W (1956), Z.Phys., 144, 244.

38. Chekmarev, I.B., Simkina, T.Yu, and Yuferev, V.S. (1977), Plasma Phys., 19, 15.

39. Chen, D.M. and Pfender, E. (1981), IEEE Trans.Plasma Sci., PS-9, 265.

40. Chen, F.F. (1974), Introduction to Plasma Physics (Plenum Press, N.Y.).

41. Chen, F.F., Etievant, C. and Mosher, D. (1968), Phys. Fluids, 11, 811.

42. Chou, T.S. and Pfender, E. (1973), Wärme-und Stoffübertragung, 6, 69.

43. Chou, T.S., Talbot, L. and Willis, D.R. (1966), Phys. Fluids, 9, 2150.

44. Chung, P.M., Talbot, L. and Touryan, K.T. (1975), Electric Probes in Stationary and Flowing Plasmas: Theory and Application (Springer-Verlag, Berlin).

45. Ciampi, M. and Talini, N. (1967), J. Appl.Phys., 38, 3771.

46. Ciampi, M. and Talini, N. (1969), Ibid, 40, 5394.

47. Cohen, I.M. (1963), Phys. Fluids, 6, 1492.

48. Cummings, C.S. and Tonks, L. (1941), Phys.Rev., 59, 514.

49. Danders, M. (1957), Z.Agrew.Phys., 9, 223.

50. Dandurand, P. and Holt, R. (1951), Phys. Rev., 82, 868

51. D'Angelo, N. and Rynn, N.(1961), Phys.Fluids, 4 1301.

52. Davies, L.W. (1953), Proc. Phys.Soc., B66, 33.

53. de Socio, L.M. and Boffa, C.V. (1970), Programme of the 56th.National Congress of Italian Physical Society, p55.

54. Deutsch, H. and Pfau, S. (1976), Beitr. Plasma Phys., 16, 23.

55. Devyatov, A.M. and Malkov, M.A. (1984), Moscow Univ. Phys. Bull. (USA), 39, 80.

56. Donskoi, et al (1963), Sov. Phys. Tech. Phys., 7, 805

57. Drawin, H.W. (1969), Z. Phys., 228, 99.

58. Drawin, H.W. and Ramette, J. (1979), Z.Naturf., 34a, 1051.

59. Druyvesteyn, M.J. (1930), Z.Phys., 64, 790.

60. Ecker, G. (1961), Exakten Naturwiss, 33, 1.

61. Ecker, G. and Kanne, H. (1964), Phys. Fluids, 7,1834.

62. Ecker, G. and Zoler, O. (1964), Phys. Fluids, 7,1996.

63. Elton, R.C. (1970) in Methods of Experimental Physics, Vol. 9A (Eds: H R.Griem and R.H.Lovberg, Academic Press, N.Y.).

64. Forrest, J.R. and Franklin, R.N. (1966), Brit. J.Appl. Phys. 17, 1569.

65. Forrest, J.R. and Franklin, R.N. (1969), J.Phys., B2, 471.

66. Fowler, R.G. (1978), Phys. Lett. 65A, 239.

67. Frammhold, L. Biondi, M.A. and Mehr, F.J. (1968), Phys. Rev., 165, 44.

68. Francis, G. (1956), in Hand b. Phys. Vol. 22 (Ed. Flugge, Springer-Verlag, Berlin).

69. Franck, G., Held, R. and Pfeil, H.D. (1972), Z. Naturf., 27a, 1439.

70. Franklin, R.N. (1976), Plasma Phenomena in gas discharges (Oxford University Press).

71. Fujimoto, T. (1973), J.Phys. Soc.Japan, 34,216, 1429.

72. Fujimoto, T. (1979), J. Phys.Soc.Japan, 47, 265,273.

73. Geissler, K.H., (1970), Phys. Fluids, 13, 935.

74. Ghosal, S.K., Nandi, G.P. and Sen, S.N. (1976), Int. J. Electron., 41, 509.

75. Ghosal, S.K., Nandi, G.P. and Sen, S.N. (1978), Int. J. Electron, 44, 409.

76. Goldenburg, S.A. et al (1964), High. Temp., 2, 616.

77. Gourdin, M.C. (1963), Symposium on Magnetoplasmadynamic Electrical power generation, session III, p.35

78. Gray, E.P. and Kerr, D.E. (1962), Ann.Phys. (N.Y), 17, 276.

79. Griem, H.R. (1964), Plasma Spectroscopy (McGraw Hill Book Co., N.Y.).

80. Gruzdev, P.F. (1967), Opt. Spectrosc., 22, 89.

81. Hashem, M.S.M. et al (1984), J.Quant.Spectrosc. & Radiate Transfer (G.B.), 31, 91.

82. Hausler, R.S. (1957), Zs, Angew Phys., 9, 66.

83. Haydon, S.C. McIntosh, A.I., and Simpson, A.A. (1971), J.Phys. D., 4, 1257.

84. Hayes, M.A. et al (1984), Rev.Sci. Instrum (USA), 55, 928.

85. Heald, M.A. and Wharton, C.B. (1965), Plasma diagonostics with microwaves, John Wiley and Sons, Inc., New York.

86. Hegde, M.S. and Ghosh, P.K. (1979), Physica, 97C,275.

87. Hey, J.D. (1976), J.Q.S.R.T., 16, 69.

88. Heylen, A.E.D. and Bunting, K.A. (1969) Int.J. Electron., 27, 1.

89. Hoh, F.C. and Lehnert, B. (1960), Phys. Fluids,3, 600

90. Hollister, D.D. (1964), AIAAJ, 2, 1568.

91. Ikee, R. and Takeyama, H. (1975), J.Quant.Spectrosc. Transfer (G.B.), 15, 701.

92. Ingold, J.H. (1978), In Gaseous Electronics, Vol.1 (Eds. M.N.Hirsh and H.J. Oskam, Academic Press,N.Y.).

93. Janzen, G., Mosher, F. and Rauchle, E. (1970), Z. Naturf., 25a, 992.

94. Jayakumar, R., Chakravarty, D.P. and Rohatgi, V.K. (1977), Rev.Sci.Instrum., 48, 1706.

95. Johnson, P.C., Cooke, M.J. and Allen, J.E. (1978), J.Phys. D., 11, 1877.

96. Kadomstsev, B-B. and Nedospasov, A.V. (1960), J.Nucl. Energy, Part C1, 230.

97. Kallas, H. and Chaika, M. (1969), 9th.International Conference on Phenomena in Ionised Gases, Bucharest,597.

98. Kaneda, T. (1977a), Jap. J. Appl.Phys., 16, 1887,2293

99. Kaneda, T. (1977b), Phys. Lett., 63A, 288.

100. Kaneda, T. (1978), J. Phys. D., 11, 279.

101. Kaneda, T. (1979), J. Phys. D., 12, 61.

102. Karmar, J. (1987), Acta, Phys.Slovaca, (Czechoslovakia), 37, 11.

103. Khvashchtevski, S. (1962), Nukleonika, 7, 369.

104. Koritz, H.E. and Keck, J.C. (1964), Rev.Sci.Instrum., 35, 201.

105. Korol'kov, A.N. Stepanov, V.A. (1983), J. Appl. Spectrosc. (USA), 38, 513.

106. Knechtli, R.C. and Wada, J.Y. (1961), Phys. Rev. Lett. 6, 215, also in Proc.Inst.Radio Engrs. 49 (1961), 1926, Phys. Rev.Lett., 10 (1963) 513.

107. Krall, N.A. and Trivelpiece, A.W. (1973), Principles of Plasma Physics, McGraw Hill Book Co.

108. Kuckes, A.F., Motley, R.W., Hinnov, E. and Hirschberg, J.G. (1961), Phys. Rev.Lett., 6, 337.

109. Kulkarni, S.B. (1944), Curr.Sci., 13, 254.

110. Kurkin, S.M., Shashkov, V.M. (1983), Sov. Phys.Tech. Phys. (USA), 28, 604.

111. Kutzner, J. and Glinkowski, M. (1982), IEEE Trans. Plasma Sci. (USA), PS-11, 233.

112. Laframboise, J.G. (1966), Univ. of Toronto, Institute of Aerospace Studies Report, 100.

113. Lamb, L. and Lin, S.C. (1957), J. Appl. Phys. 28, 754.

114. Lam, S.H. (1965), Phys. Fluids, 8, 73, 1002.

115. Langmuir, I. (1924-1926) in Collected Works of Irving Langmuir, Vols. 3, 4, & 5, (Ed.C.G.Suits, Pergamon Press, N.Y., 1961).

116. Les, Z. and Niewodniczauski, H. (1961), Acta.Phys. Polon, 20, 701.

117. Lin, S.C. et al (1955), J. Appl.Phys. 26, 95.

118. Lochte-Holtgreven, W. (1968) in Plasma diagonostics (North Holland Publishing Co., Amsterdam).

119. Maciel, H.S. and Allen, J.E. (1985), G.D. 85 Proceedings of the Eight International Conference on Gas Discharges and their Applications, 344.

120. Marhic, M.E. and Kwan, L.I. (1977), J. Appl.Phys. 48, 3713.

121. Massey, H.S.W. and Gilbody, H.B. (1974), Electronic and Ionic Impact Phenomena, Vol. 4, (Oxford Univ.Press).

122. McCoubrey, A.O. (1954), Phys. Rev. 93, 1249.

123. McDaniel, E.W. (1964), Collision Phenomena in Ionized Gases (John Wiley, N.Y.).

124. McWhirter, R.W.P. (1965) in Plasma Diagonostic, Techniques (Eds. R.H.Huddlestone & S.L.Leonard, Academic Press, N.Y.).

125. Mierdel, G. (1943), Z.Phys. 121, 574.

126. Mikoshiba, S. and Smy, P.R. (1969), Rev.Sci.Instrum, 40, 1187.

127. Mitchell, G.R. (1970), Proc. IEE, 117, 2315.

128. Mitchner, M. and Krugar, Jr.. C. H. (1973), Partially Ionised Gases (John Wiley, N.Y.).

129. Mohler, F.L. (1937), J. Research Nat.Bur.Standards 19, 559.

130. Mosberg, E.R. Jr. and Wilkie, M.D. (1978), J.Quant. Spectrosc. Rad. Transfer, 19, 69.

131. Moskvin, Yu. V. and Chesnokova, N.N. (1965), High Temp., 3, 335.

132. Murino, P. and Bonomo, R. (1964), XIX Congresso Nazionals ATI, Seina, P.44.

133. Muira, K., Imazu, S. and Takamatsu, T. (1979), Japan, J. Appl.Phys., 18, 1203.

134. Moulin, T. and Masse, J. (1964), Symposium International Surla Production MHD d'Energie Electrique, Paris.

135. Namitokov, K.K. and Krasovitskii, V.B. (1973), Sov. Phys. Tech. Phys. (USA), 18, 682.

136. Nishikawa, M., Fuji-e, Y. and Suita, T. (1971), J. Phys. Soc. Japan, 31, 910.

137. Ogram, G.L., Chang, J.and Hobson, R.M. (1980), Phys. Rev., 21A, 982.

138. Olson, R.A. and Lary, E.C. (1961), USA Res.Lab.Rept. M-1282-1.

139. Olson, R.A., and Lary, E.C. (1962), Rev.Sci.Instrum. 33, 1350.

140. Olson, R.A., and Lary, E.C. (1963), AIAAJ, 1, 2513.

141. Ose, E. and Rothhardt (1973), Beitr.Plasma Phys. (Germany), 13, 213.

142. Oskam, H.J. (1958), Philips Res. Rep., 13, 335.

143. Pacheva, Y.H. and Zhechev, D.Z. (1971) C.R.Acad. Bulg. Sci. (Bulgaria), 24, 1617.

144. Pasternak, A.W. and Offenberger, A.A. (1975), J. Appl. Phys. 46, 1135.

145. Pavelescu, G. et al (1984), Beitr, Plasma Physics (Germany), 24, 237.

146. Pavlovic, B.V., Mihailidi, T.A. and Geogrijevic, I. (1979), Teh. Fiz. (J.Engrg. Phys.), 20, 41 and references therein.

147. Persson, K.B. (1960), Gen. Elec. Res.Lab.Rept.No. 60-RL-2545C.

148. Persson, K.B. (1961), J. Appl.Phys., 32, 2631.

149. Peterson, W.K. et al (1981), J. Geophys. Res., 86, 761.

150. Pfender, E. (1978) in Gaseous Electronics, Vol.I (Academic Press, N.Y.).

151. Pfender, E. and Schafer, J., (1975), Heat Transfer, C97, 45.

152. Pinnington, E.H. (1966), Proc.Phys.Soc. 87, Pt.2, 586

153. Richter, J. (1968) in Plasma diagnostics (ed), L. Holtgraven (Amsterdam: North Holland).

154. Ricketts, B.W. (1970), J.Phys. D., 3, 1678.

155. Rocca, J.J., Fetzer, G.J. and Collins, G.J.(1981), Phys. Lett. A, (Netherlands), 84A, 118.

156. Rokhlin, G.N. (1939), Fiz. Zh. 1, 347.

157. Rosa, J.R. (1961), Phys. Fluids, 4, 182.

158. Sadhya, S.K., Jana, D.C. and Sen, S.N. (1979), Proc. Nat.Acad. Sci., 45, 309.

159. Sadhya, S.K. and Sen, S.N. (1980), Int.J.Electron., 49, 235.

160. Sanders, N.A. and Pfender, E. (1984), J.Appl.Phys., (USA), 55, 714.

161. Sato, M. (1978), J. Phys. D., 11, L 101.

162. Savic, P. and Boult, G.T. (1962), J.Sci.Inst. 39, 258.

163. Schellekens, H. (1983), J. Appl.Phys. 54, 144.

164. Schoal, G. and Zahn, R. (1969), 9th.International Conference, Phenomena in Ionised Gases, Bucharest, Rumania, 148.

165. Schoeck, P. and Eckert, E.R.G. (1982), Proceedings of the 5th.International Concerence in Ionization Phenomena in Gases (North Holland, Amsterdam), Vol.II, 1812.

166. Schott, L. (1963), CR VI Conf.Int.Phen. d'Ionisation dan les gaz. (Paris, S.E.R.M.A.), 2, 171.

167. Schott, L. (1968), in Plasma Diagnostics (Ed.W. Lochte-Hottgreven, North Holland Publishing Co., Amsterdam).

168. Self, S.A. (1967), Phys.Fluids, 10, 1569.

169. Sen, S.N. and Das, R.P. (1973), Int.J.Electron., 34, 527.

170. Sen, S.N., Das, R.P. and Gupta, R.N., (1972), J.Phys. D., 5, 1260.

171. Sen, S.N., Ghosh, S.K. and Ghosh, B. (1983), Ind. Jour. Pure & Appl. Phys., 21, 613.

172. Sen, S.N. and Gupta, R.N. (1964), Ind. J. Phys., 38, 383.

173. Sen, S.N. and Gupta, R.N. (1969), Ind. Jour. Pure & Appl. Phys., 7, 462.

174. Sen, S.N. and Gupta, R.N. (1971), J. Phys. D., 4, 510.

175. Sen, S.N. and Jana, D.C. (1977), J.Phys.Soc. Jap., 43, 1729.

176. Sen, S.N. and Sadhya, S.K. (1986), Pramâna, 26, 205.

177. Sengupta, D.L. (1961), Proc. IRE, 49, 1872.

178. Sicha, M. et al (1983), Czech. J.Phys. Sect.B., B33, 1226.

179. Simon, A. (1959), An Introduction to Thermonuclear Research (Pergamon, N.Y.).

180. Smirnov, B.M. (1977), Introduction to Plasma Physics (Mir Publishers, Moscow).

181. Spatenka, P. and Sicha, M. (1985), Czech. J.Phys. Sect.B. (Czechoslovakia) B35, 1189.

182. Stott, P.E. (1975) In Courses on Plasma Diagnostics and Data Acquising System (Eds. A.Eubank and E. Sindoni, Editrice, Compositori, Bologna).

183. Stenzel, R.L. et al, Rev.Sci.Instrum., 54, 1302.

184. Stokes, A.D. (1965), Proc.Inst. Elec.Engrs., 112, 1583.

185. Stokes, A.D. (1969), J.Appl.Phys., 40, 1973.

186. Stubbe, E.J. (1968), Proc. IEEE, 56, 1483.

187. Sue, C.H. and Lam, S.H. (1963), Phys.Fluids, 6, 1479

188. Takeyama, H. and Takezaki, Y. (1968), J.Q.S.R.T., 8, 1023, 1863.

189. Takezaki, Y. (1977), J.Sci.Hirosima Univ.A.(Japan), 41, 35.

190. Tanaka, H. and Hagi, M. (1964), J. Appl.Phys. Japan, 3, 335.

191. Tanaka, H. and Hagi, M. (1964), Ibid., 3, 338.

192. Tanaka, H. and Usami, S. (1962), Bull.Fac.Eng. Yokahama Nat.Univ., 11, 65.

193. Timofeev, B. (1976), Sov. Phys. Usp., 19, 149.

194. Toma, M., Sanduloniciu, M. (1983), International Conference on Phenomena in Ionised Gases, Duseldorf, Germany.

195. Tonks, L. (1939), Phys. Rev., 56, 360.

196. Tonks, L. (1941), Phys. Rev., 59, 522.

197. Tonks, L. and Allis, W.P. (1937), Phys. Rev., 52, 710.

198. Townsend, J.J. and Gile, E.W.B. (1937), Phil.Mag., 26, 290.

199. Uhlenbusch, J. (1976), Physica, 82C, 61.

200. Uvarov, F.A. and Fabrikant, V.A. (1965), Opt. Spectsoc. 18, 323.

201. vander-Sijde, B. (1972), J.Q.S.R.T., 12, 1497, 1517.

202. von-Engel, A. (1965), Ionised Gases, 2nd.Edn. Oxford University Press).

203. Vorobjeva, N.A., Zaharova, V.M. and Kagan, Yu, M. (1971), 9th. Int.Conf. on Pheno.Ionised Gases, p. 260.

204. Vriens, L., Keijser, R.A.J. and Lighthart, F.A.S. (1978), J.Appl.Phys., 49, 3807.

205. Vukanovic, V., Georgijevic, V., Vukanovic, D. and Todorovic, M. (1969), Spectroechim Acra 24B,555.

206. Warke, C.S. (1966), Phys. Rev., 144, 120.

207. Wasserstrom, E., Su, C.H. and Frobstein, R.F. (1965) Phys. Fluids, 8, 56.

208. Watson, W.D. (1975), in Atomic and Molecular Physics and Interstellor Matter (Les Houches Session 26, North Holland and Publishing Co., Amsterdam).

209. Wehrli, M. (1922), Ann. d. Phys. 4, 69.

210. Wienecke, R. (1963), Z.Naturf., 18a, 1151.

211. Wilkins, R.L. (1966), J. Chem. Phys. 44, 1884.

212. Wilson, R. (1962), J.Q.S.R.T., 2, 477.