CHAPTER I

REVIEW OF THE PREVIOUS WORK

BIBLIOGRAPHY

SCOPE OF THE WORK

CHAPTER - I

Review of the Previous work

A precise review on the phenomena related to the proposed work is, hereby, presented below with the object to work further and introduce new lines of investigation. Work is proposed to be carried out along the following lines.

A. Electron Collision loss factor in Collision dominated plasma

B. Theory on the radio frequency real and imaginary currents through a plasma

I. Measurement of radio frequency real current and imaginary current.

II. Radio frequency conductivity of a magnetised plasma.

C. Low frequency self excited oscillation in a plasma.

D. Cathode phenomena in an arc.

E. Diffusion and Hall voltage in a magnetised plasma.

F. Plasma Magnetisation Coefficient and Effective Arc Cross-Section.

A. Collision loss in a plasma

Energy loss in a plasma may be either due to elastic collisions or due to inelastic collisions. Inelastic collisions result in vibrational excitation, rotational excitation, recombination, capture, attachment, dissociation, ionization and collision of the second kind (Kleins and Rosseland). In case of inelastic collisions electrons lose their kinetic energy resulting in a decrease in the kinetic energy of plasma and hence potential energy of plasma increases.

This problem of determining the collision loss of electrons may be handled with the knowledge of electron energy distribution function and energy transfer cross-section. Defining drift velocity as the ratio of flow density of electrons to electron concentration, Von Engel (1965) obtained in the steady state,

$$\frac{V_d}{C} = \left(\frac{1}{2} K\right)^{1/2} \qquad (1.1)$$

where v_d and C are drift and random velocities and K is the collision loss factor. For Maxwellian electron energy distribution with small values of (E/P), Compton and Langmuir (1930) obtained an expression for collision loss factor for electrons as

$$K = 2.66 \frac{m_e M}{(m_e+M)^2} \times \left(1 - \frac{\frac{1}{2} MC^2}{\frac{1}{2} m_e C_e^2}\right) \qquad (1.2)$$

Thus for electron energy much higher than molecular energy,

$$K = \frac{8 m_e}{3M}$$

Thus in case of N_2, $K = \frac{8 \times 9 \times 10^{-28}}{3 \times 28 \times 1.67 \times 10^{-24}} = 5.1 \times 10^{-5}$

when the collision is purely elastic.

But K for N_2 as measured by Demitriades (1967) for slow electrons lies within 2.3×10^{-4} to 4.9×10^{-4}. Also in case of H_2, elastic collision loss factor is found to be

$$K = \frac{8 \times 9 \times 10^{-28}}{3 \times 2 \times 1.67 \times 10^{-24}} = 7.19 \times 10^{-4}$$

But K for H_2 as experimentally measured by Bekefi and Brown (1958) for slow electrons (0.039 eV to 1.6 eV) is found to be

$$K = (3.5 \pm .5) \times 10^{-3}$$

Thus even for slowest electrons, inelastic collision losses in molecular gases is quite appreciable. This is because the energy required for vibrational excitation does not exceed 0.5 eV for majority of cases of diatomic molecules.

Bashmin and Demitriev (1976) found for reduced electric field from 20 to 60 V/cm in plasma that 10% of the electron energy goes to excitation of rotational and translational degrees of freedom and 50% goes to excitation of vibrational degrees of freedom.

Since collision is elastic only when electron energy is extremely small, so the study of slow electrons has drawn the attention of many investigators [Bekefiand Brown (1958), Demitriades (1967), Brood (1925), Rusch (1925), Bruche (1927) Bamsaauer and Kollah (1929), Normand (1930), Gilardini (1972)].

Measurement was also performed for non-slow or fast electrons by Medies (1958), Bowe (1960), Afrosimov et al (1972), Janaca (1967), Biberman et al (1966).

Again characteristics of slow electrons (25 eV) are highly different from that of the fast electrons because of Ramsauer effect [Ramsauer (1921)]. In this range of energy, momentum transfer cross-section shows minima and maxima [Harnwell (1929)] and thus collision loss factor becomes highly dependent on electron energy. Though for higher energies there is a steady change in the collision loss factor. Morse (1935) obtained an expression for fraction of energy lost by an electron in one collision

$$\frac{\Delta \epsilon}{\epsilon} = \frac{2\Delta v}{v} = \frac{2m}{M}\left(1 - \cos\theta\right) \qquad (1.3)$$

And that lost per sec by an electron is,

$$dW = \frac{16\pi NQ}{M} m\epsilon^2 f \, d\epsilon \qquad (1.4)$$

for electrons lying within an energy ϵ to $\epsilon + d\epsilon$. Q is the momentum transfer cross-section, f is the energy distribution function for the electrons. Thus average collision loss factor requires the knowledge of momentum transfer cross section [Houston, (1928)]. Cross-section for energy transfer was measured by Normard (1930), Morse et al (1935) Crompton and Sutton (1952), Townsend and Baily (1921), Bowe (1960) and many others.

To raise the electron temperature much above the gas temperature ohmic heating was employed by Shingarkina (1972).

He measured the actual Hall parameter and thus the actual mean free time which is a function of electron temperature. The inelastic loss factor is evaluated for N_2 through comparison of results with computer calculation of electron energy balance.

With micro wave heating technique Gould (1954), Gilardini (1957), Bekefi and Brown (1958), Phelps et al (1957) performed their investigation.

Bekefi and Brown carried their measurement, for electron energy from 0.03 eV to 1.6 eV, and obtained an expression

$$T_e = T_g + \frac{2e^2 E^2}{3 m K \omega^2 k} \qquad (1.5)$$

Where E is the r.m.s. value of electric field at the centre of the cavity and is to be replaced by 0.758E for the average field inside the cavity. K is the collision loss factor and is obtained by comparison of results.

$$K = (3.5 \pm 0.5) \times 10^{-3} \text{ for hydrogen.}$$

Demetriads (1967) also obtained with micro wave heating technique, the collision loss factor of electrons for gas temperature 1700°K to 6100°K and electron temperature raised to 4127°K to 7540°K and is given by

$$K = \frac{2e^2}{3km\omega^2}\left(\frac{2Z}{A_r}\right)\left(\frac{dT_e}{dp}\right)^{-1} \qquad (1.6)$$

and they obtained K from 2.9×10^{-4} to 4.9×10^{-4} for N_2 plasma.

Adiabatic trap method was used by Pastukhov (1974) for the determination of collision loss factor. The expression is obtained on the basis of approximate solution of Fokker-Planck equation, which is found to yield good results.

Another method of precision analysis of the spectra of inelastic energy losses on atomic collision was adopted by Afrosimov et al (1972) which can be used for the determination of collision loss factor.

Bowe (1960) obtained expressions which can cover both elastic collision and inelastic collision for the determination of collision loss factor. They analysed the expression on the basis of the data obtained for H_e, N_e, Ar, Kr and X_e. They used

$$K = \lambda(\epsilon)\frac{2m}{M} \quad (1.7)$$

and

$$\lambda(\epsilon) = \alpha\,\epsilon^{-j} \quad (1.8)$$

Thus knowing α, j the collision loss factor can be calculated for various value of energy ϵ.

A theoretical work done by Dote and Shimoda (1980) describes individual loss factor for elastic collision, excitation, ionisation and for mean collision loss factor and they compared the relations on the basis of published data for H_e, N_e and Ar and was found to yield good results.

Sen and Jana (1978) measured the momentum transfer collision cross-section for slow electrons in magnetic field from radio-frequency conductivity measurements.

B. Measurement of Real and Imaginary Current through plasma

The passage of a.c discharge current through an ionized medium has been considered for a long time. For low frequency and high pressure, the current density set up by an ac electric field is given by Langavin (1905) mobility formula. The current remains in phase with the impressed electric field.

On the other hand, if rf voltage, not sufficient to cause breakdown for the gas be applied, the rf current flowing through the gas is given by Vandar Pol (1919)

$$j_{rf} = \frac{e^2 n E_o}{m} \left[\frac{\nu}{\nu^2 + \omega^2} - i \frac{\omega}{\nu^2 + \omega^2} \right] \tag{1.9}$$

where $E = E_o \exp.(iwt)$ is the applied rf field and ν is the collision frequency of electrons with neutral atoms, e and m are charge and mass of electrons and n is the electron density. Thus current is represented by formula involving characteristics of electrons and a part of the current is in phase quadrature with the ac field.

Assuming the energy distribution to be Maxwellian Margenau (1946) obtained for current density which has two components

$$i_{real} = \frac{4e^2 E\lambda n}{(2\pi mkT)^{1/2}} \cos \omega t \qquad (1.10)$$

$$i_{imaginary} = \frac{e^2 E n}{m\omega} \sin \omega t \qquad (1.11)$$

where, i_{real} is in phase with applied electric field.

Everhart and Brown (1949) measured the admittance in the micro wave region by measuring the discharge current for applied hf field of sufficient amplitude in helium which filled the cavity of a magnetron.

Sodha (1960) obtained an expression for the current density which has two components, one in phase and the other out of phase with the applied field. He has shown that for constant mean free path and energy loss factor and for low frequency, the distribution is Druyvesteyn. The conductivity obtained by Sodha (1960) was obviously a complex one.

The electrical conductivity of the conducting medium was determined by Koritz and Keck (1964) from measurement of Joule losses produced by alternating magnetic field in a coil surrounding the discharge tube. In addition, there are number of authors, who [Tanaka and Usami (1962), Gourdin (1963), Khvashchtevaski (1962)] made conductor approximation for plasma which means, when an ac is imposed upon a plasma, the plasma acts just like a resistance and ac conductivity essentially becomes a dc conductivity.

$$\sigma_{ac} = \frac{ne^2}{m\nu}\left[\frac{\nu^2}{\nu^2+\omega^2} - i\frac{\omega\nu}{\nu^2+\omega^2}\right] \tag{1.12}$$

A general theory regarding the variation of rf conductivity of ionized gases and its variation with pressure and magnetic field has been worked out by Gilardini (1959) who derived the expression for the conductivity of ionized gases,

$$\sigma_{rf} = \frac{e^2 n}{m} \cdot \frac{1}{\nu + i\omega} \tag{1.13}$$

and in presence of magnetic field he defined two conductivities, one for right-handed polarisation and other for the left-handed polarization,

$$\text{(rt. handed polarisation)} \quad \sigma_c = \frac{e^2 n}{m}\left[\frac{1}{\nu + i(\omega - \omega_b)}\right] \tag{1.14}$$

$$\text{(left handed polarization)} \quad \sigma_o = \frac{e^2 n}{m}\left[\frac{1}{\nu + i(\omega + \omega_b)}\right] \tag{1.15}$$

ω_b is the electron cyclotron frequency.

And conductivity in the direction of the magnetic field, H, is given by

$$\sigma_H = \frac{1}{2}(\sigma_c + \sigma_o) \tag{1.16}$$

The complex conductivity is, in general, related to plasma parameters by the following expression of Heald and Wharton (1965)

$$\sigma_r + i\sigma_i = -\frac{4\pi}{3}\epsilon_0 \omega_p^2 \int_0^\infty \frac{1}{\nu(v)+i\omega} \cdot \frac{d}{dv}\left[f_0(v)\right] v^3 dv \quad (1.17)$$

V is the electron velocity and $f_0(V)$ is the distribution function in the steady state, ν is the electron atom collision frequency and ω is the angular frequency of the applied rf. electric field.

Thus it is evident that a plasma, under the action of impressed r.f. electric field, carried real current, as well as imaginary current through it. Francis and Von Engel (1953) have pointed out that the capacitative current is much greater than the discharge current. The current flowing through the discharge can be estimated by loading the circuit with a resistance or a capacity which induce the same voltage drop as the discharge. In order to measure the current, it is necessary to discriminate one part of the gas discharge current from the capacitative current. A differential method is, therefore necessary to balance out the capacitative current flowing across the electrodes. Francis and Von Engel (1953) considered the total current and no mention, however, was made about the individual part of the discharge current. In order to reduce the capacitative current, they considered the electrode as small as possible. The capacitative current flowing across the electrodes was then balanced out by a bridge method. The bridge became unbalanced when the current was allowed to flow through the gas. The unbalanced component was proportional to the discharge current, and was then amplified, rectified and displayed on a CRO Screen. The calibration of the circuit was made by replacing the gas discharge by a known impedence and then observing the displacement of the trace on the CRO screen.

Penfold and Warder (Jr.) (1967) reviewed a number of methods commonly used for the measurement of rf plasma discharge current. A common method of current measurement is to minitor the voltage across a capacitor or an inductor element. A capacitor tends to suppress the harmonies, while the inductance emphasizes them. The voltage can be determined by the use of a high voltage probe with an oscilloscope read out. Penfold and Warder (Jr) (1967) measured the current by measuring the voltage drop across a specially constructed centre tapped inductor.

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

The real part of the r.f. conductivity of ionised gases such as air and nitrogen was measured by Sen and Ghosh (1966);

from the variation of r.f. conductivity with pressure it was possible to calculate the electron density, collision frequency and electron temperature. The work was extended to rare gases by Sen and Gupta (1969) and in addition to electron density, collision frequency and electron temperature, dielectric constant and Debye shielding distance were also measured and their variation with pressure was also investigated.

Ghosal, Nandi and Sen (1976) measured the azimuthal radio frequency conductivity of an arc plasma by measuring the reflected resistance of a primary coil would around a mercury arc tube. A linear relationship between the azimuthal conductivity and discharge current has been obtained. The nonlinearity and existance of maxima observed by the previous authors in the change of band width versus axial conductivity curve have been explained theoretically by considering a generalised equivalent circuit. It has been pointed out that the conductivity measurement by this method is only possible where the conductivity of the plasma is fairly high. Radio frequency conductivity of a magnetised plasma:

(A) Rf conductivity of an ionized gas without magnetic field:

Radio frequency conductivity as suggested by Vandarpol (1919) is given by

$$\sigma = \frac{e^2 n}{m}\left[\frac{\nu}{\nu^2+\omega^2} - i\,\frac{\omega}{\nu^2+\omega^2}\right] \qquad (1.18)$$

n is the electron concentration, ν is the electron atom collision frequency and ω is the frequency of the impressed field. The above equation shows that rf conductivity is complex and its real part tends towards maximum when ω approaches ν [Sen and Ghosh (1966)].

Conductivity of ionized air was measured by Child (1932) at 1 MC/S. Appleton and Chapman (1932) studied the rf conductivity of air plasma at 1000 MC/S. Appleton and Chapman found a maximum in the conductivity with pressure. Similar studies were made by Imam and Khastgir (1937) for pressure 10 to 120 cm at wave length 481 cm. Margenau (1946) considering velocity distribution and Boltzman transport equation obtained

$$\sigma_r = \frac{4}{3} \cdot \frac{n e^2 \lambda}{\sqrt{2\pi m k T_e}} \cos \omega t \qquad (1.19)$$

$$\sigma_i = \frac{n e^2 \lambda \omega}{3 k T_e} \sin \omega t \qquad (1.20)$$

Dawson and Oberman (1962, 1963) calculated hf conductivity of ionized gas and Berk (1964) showed how Dawson and Oberman model can be extended to yield kinetic description of the electrical process, which is uniformly valid for high and low frequency theories. Sen and Ghosh (1966) observed maxima, as observed by Appleton and Chapman. But they found the maximum conductivity to decrease with decrease of discharge current. The real part of the conductivity of the ionized air and nitrogen was measured for various values of pressure and discharge current. The frequency of the rf current in their measurement lies within 2 to 3 MC/S. Johnson (1967) calculated the electrical conductivity for a variety of assumed electron molecule collision frequencies. Nagata (1966) presented a simple technique for the measurement of plasma conductivity and discharge current was within 5 to 100 mA and various gas pressures were used. Experimental value of σ were in good agreement with the theoretical values of σ .

Ghosal, Nandi and Sen (1976 & 1978) measured azimuthal radio frequency conductivity and its change with radial distance for a mercury arc plasma.

(B) Magnetic field effects on the rf conductivity of an ionized gas:

Since the effect of magnetic field changes the electron and ion distribution in a plasma, the transport properties obviously undergo certain changes with change of magnetic field. Conductivity of ionized gases (air, N_2 and H_2) in a magnetic field was measured by Ionescu and Mihul (1932) above a pressure of 10^{-3} torr. With very intense magnetic field only electron vibration remains and maxima in conductivity with pressure undergoes changes with change in magnetic field.

An improved probe method for the measurement of electrical conductivity of low temperature plasma was derived by Khozhalev and Yasin (1966). Ciampi and Talini (1967) measured the average plasma conductivity by a rf probe for a cylindrical plasma which is assumed radially homogeneous. They obtained the average conductivity values from 75 to 100 mho/s with a Q factor measurement between 0.5 to 1.5 MHz. The probe used was calibrated with electrolyte (H_2SO_4) solution of standard conductivity.

From a study of the complex conductivity of Hg vapour at microwave frequencies Adler (1949) has shown plots of σ_r and σ_i with pressure or current when the other remains unaltered. Adler found that the theoretical and experimental value agree closely and σ varies linearly with discharge current. Aleksandrov and Yalsenko (1965) studied the complex conductivity of neon plasma by the Q-meter method. The frequency range used was 0.5 to 25 MC/S. A theory of rf conductivity of a magnetised plasma was proposed by Appleton and Booharivala (1935) who found that the real part of rf conductivity is given by

$$\sigma_{rH} = \frac{ne^2}{m} \times \frac{\nu(\omega^2+\omega_b^2+\nu^2)}{(\omega^2+\omega_b^2+\nu^2)^2-4\omega^2\omega_b^2} \qquad (1.21)$$

where $\omega_b = eH/m$ - - - - - - (1.22)

A general theory of rf conductivity as a function of magnetic field and pressure was obtained by Gilardini (1959). The complex conductivity is given by

$$\sigma = \frac{e^2 n}{m} \cdot \frac{1}{\nu + i\omega} \tag{1.13}$$

in absence of magnetic field and in presence of magnetic field he defined two conductivities, one due to right hand polarization and other due to left hand polarization

$$\sigma_{LH} = \frac{e^2 n}{m} \left[\frac{1}{\nu + i(\omega - \omega_b)} \right] \tag{1.14}$$

for left hand polarization and

$$\sigma_{RH} = \frac{e^2 n}{m} \left[\frac{1}{\nu + i(\omega + \omega_b)} \right] \tag{1.15}$$

for right hand polarisation.

And rf conductivity in the direction of the field is given by

$$\sigma_H = \frac{1}{2} \left(\sigma_{LH} + \sigma_{RH} \right) \tag{1.16}$$

Hence real part of the rf conductivity of a magnetised plasma is given by

$$\sigma_{rH} = \frac{e^2 n}{m} \left[\frac{1}{\nu^2 + (\omega - \omega_b)^2} + \frac{1}{\nu^2 + (\omega + \omega_b)^2} \right] \tag{1.17}$$

which on simplification reduces to the expression obtained by Appleton and Boohariwala. This relation was experimentally studied by Gupta and Mandal (1967) for air and carbon dioxide with magnetic field upto 680 Gauss. They found that maximum conductivity decreases and corresponding pressure at which conductivity attained the maximum value, gradually shifted towards higher pressure with the increase of magnetic field.

Sen and Gupta (1969) measured rf conductivity with and without magnetic field for Ne, He and Ar and found to follow the relation approximately

$$\frac{\sigma_{rH}}{\sigma_r} = \frac{P_{max}}{P_{H\,max}} \qquad (1.18)$$

Blackman (1959), Wu (1965), Oberman and Shure (1963), Nedospasov and Shipuk (1966), Schweitzir and Milchner (1967), Green et al (1965), Pradhan and Das Gupta (1967), Maiti and Basu (1968), Gupta, Mandal and Sen (1968) studied rf conductivity and its variation with pressure, current and magnetic field.

Ram, Chandra and Sarkar (1972) studied rf conductivity of a magnetized plasma both for transverse and longitudinal magnetic fields. They found large variation of σ_{rH} in case of longitudinal magnetic field while variation of σ_{rH} in case of transverse magnetic field was considerably small in their experiment.

Sen and Jana (1978) showed that

$$\frac{H}{P_{max}} = \text{Constant} \qquad (1.29)$$

corresponding to the maximum rf conductivity at a pressure P_{max}, when the plasma was treated with a transverse magnetic field H. They performed experiment at 2.45 MHz with Hydrogen and oxygen for transverse magnetic field 1150G to 1850G and obtained excellent agreement with theory and experiment.

C. Oscillation in a plasma, particularly in connection with low frequency oscillation:

The oscillation in a plasma is either longitudinal oscillation where no magnetic field component is associated with the wave generated, or "magnetohydrodynamic" or "hydromagnetic" waves in which case the frequency is low and velocity of propagation is many order less than that of light. This later category may be sub divided in two groups in which time varying magnetic field component is either parallel or perpendicular to the static magnetic field. Though in both cases time varying magnetic field component is small compared to the static magnetic field. Hydromagnetic waves are small amplitude plane waves.

The plasma oscillation was initially discovered by Penning (1926) and a detailed theory was put forward by Langmuir and Tonk (1929) according to which the natural frequency of electron plasma oscillation is given by

$$\nu_e = \left(\frac{n_e e^2}{\pi m_e}\right)^{1/2} = 8980\ n_e^{1/2} \qquad (1.30)$$

where n_e, e and m_e are concentration, charge and mass of the electron. And the ion plasma frequency is given by

$$\nu_p = \nu_e \left(\frac{m_e}{m_p} \right)^{1/2} \qquad (1.31)$$

m_p is the mass of the ions. The oscillation of larger wave lengths are similar to sound and its velocity of propagation approaches a value given by

$$V = \left(\frac{kT_e}{m_p} \right)^{1/2} \qquad (1.32)$$

The frequency 300 to 1000 MC/S agrees well with the predicted frequency of electron oscillation in a plasma. Another observed frequency of 50 to 60 MC/S may correspond to the beam electrons, while the frequency 1.5 MC/S and below may be attributed to + Ve ion oscillation. Penning (1926) observed the radio frequency oscillation in a low pressure Hg vapour under same condition as those lead to electron scattering [Langmuir (1926)]. The frequency of the corresponding plane wave associated with the electron plasma oscillation is given by

$$\nu^2 = \frac{n_e e^2}{\pi m_e} + \frac{c^2}{\lambda^2} \qquad (1.33)$$

where C is the velocity of the wave and λ is the wave length. The frequency of the ion plasma oscillation is given by

$$\nu_p = \left[\frac{n_e e^2}{\pi m_p + \frac{n_e e^2 m_p \lambda^2}{kT_e}} \right]^{1/2} \qquad (1.34)$$

The efficiency of power conversion to the oscillatory power may hardly attain a value more than one percent for a well-designed experimental set up. This was observed by Emeleus and his co-workers in their work (1949, 1951).

However, in this review of the previous works on oscillation in a plasma, we shall confine our discussion in general to the plasma oscillations and waves whose frequency is said to be low.

Wehner (1950) described a plasma oscillator where he succeeded in producing an uniform parallel beam of electrons which reflected to and fro several times between the grid and the repeller, and oscillation of 1-4000 MC/S could be picked up at the repeller, and the frequency could be regulated by the anode current or voltage and it was claimed by author that the frequency of oscillation was stable. This is probably the most successful plasma oscillator of practical importance.

Gabor (1951) gave a new mathematical formalism for oscillation in a plasma irrotational stream and showed that if the electrons are originated outside the magnetic field or if they issued from a cathode where there was no normal component of magnetic field, the curl of the total or Schwarzschild momentum would be zero every where.

Rohner (1955) described an experimental tube for studying the plasma oscillation and discussed them in terms of Tonk-Langmuir (1929) formula for ion oscillation.

Konyukov (1957) worked on low frequency oscillation inside a plasma formed of electronegative gases, where electrons, positive ions and negative ions were assumed to exist as different individual components of the plasma. Two bunches of low frequency oscillation were established whose frequency was found to depend on respective concentration in different ways.

Stix (1957) considered the natural mode of oscillation of a cylindrical plasma of finite density at zero pressure in presence of longitudinal magnetic field. They found the lower limit of frequency of the hydromagnetic wave to be close to the frequency of ion cyclotron frequency.

Bernstein and Kulsrud (1960) derived a dispersion relation for electrostatic oscillation in a magnetic field on the basis of Boltzman equation for arbitrary velocity distribution and for propagation in an arbitrary direction for five specified boundary conditions. The growth rate and frequencies of this oscillation are also determined and ion wave instabilities are discussed.

Fried and Gould (1961) explored the properties of ion plasma oscillation using Vlasov's equation for $T_e = T_i$ and it was found that there were discrete sequences of ion-plasma oscillation but all were strongly damped, i.e., $-I_m.\omega/R_e.\omega \geqq 0.5$ and hence were likely not to be observed. The ratio $-I_m.\omega/R_e.\omega$ can be made zero either by increasing T_e/T_i or by producing current through the plasma. In the later case $I_m.\omega$

can even be made positive. The current flow required is smaller the greater is the ratio T_e/T_i. This growing wave is seen to be an unstable oscillation.

D'Angelo and Motley (1963) observed low frequency oscillation in an inhomogeneous plasma. These oscillation seem to propagate across the magnetic field with the same velocity as the pressure gradient drift. And that his oscillation should follow from the macroscopic equation of collisionless plasma was noted by D'Angelo (1963). In addition to the experiment of D'Angelo and Motley (1963), the experiment of Lashinsky (1964) and Buchelnikova (1964) have established that the excitation of low frequency oscillation in a low pressure plasma depends in an important way on effects at the boundaries perpendicular to the magnetic field. The primary evidence for this is the fact that oscillation ordinarily develops when plasma is positively charged with respect to the end electrodes.

Chen (1964) studied the propagation of low frequency electrostatic oscillation through a low density fully ionised plasma in a strong magnetic field B. Two sets of waves were obtained by him. The wave either travels along B or transverse to B. They travel at the electron or ion diamagnetic drift velocities. Chen (1965) showed that when there is an electron sheath at the ends, the drift oscillation is short circuited and the instability leading to oscillation cannot develop. But an ion sheath in contrast particularly insulates the plasma from the connecting end plates and permits the growth of oscillation with wave lengths appreciably longer than the system.

In this connection one must mention that Langmuir and Mott-Smith (1924) divided the discharge space into "sheaths" and "plasmas". The sheath is a thin layer of charge surrounding the electrodes or probes or wall with strong gradient of electrostatic potential.

Vladiminov (1965) showed that the acceleration of ions in their escape to the ends may also lead to the excitation of low frequency oscillation which is said to be longitudinal ambipolar sound by the author.

Tanaka (1966, 1969), Kato et al (1967), Shut'ko (1968), Noon et al (1970), Tauth et al (1970), Duncan (1970),Krolikowsky (1969), Basannikov (1979), Agashi (1983), Penkratov (1971) and many others have investigated low frequency oscillations in plasmas under different conditions.

Rosa et al (1969) investigated low frequency uniform oscillation of the positive column of a low pressure arc. The oscillation is found not to be determined by the discharge circuit impedence and are not generated at either the cathode or the anode region. Both the electron density and electron temperature were found to be coherently oscillating. This phenomenon was interpreted as the ion-accoustic resonance mode of the plasma column oscillation.

Pasechnik and Popovich (1970) showed that the condition of oscillation and the frequency of oscillation is critically dependent on the potential difference between the plasma and the end of the electrodes. They studied the excitation of low frequency oscillation in a bounded plasma under controlled variation of conditions at the ends and obtained an expression for frequency

$$f = \frac{p}{\pi L}\sqrt{\frac{2e \cdot \Delta U}{M}} \qquad (1.35)$$

where p is the mode of longitudinal socillation, L is the length of the discharge, M is the mass of an ion, e is the charge of an ion and ΔU is the ambipolar diffusion potential between the end plates and plasma column. The intensity of oscillation increases rapidly as the potential U of the end plates with respect to the plasma is decreased below -10 volts. The frequency of oscillation is about 10 to 20 KHz. The oscillation does not occur below 10^{-2} torr. The oscillation is found to be practically independent of magnetic field, gas pressure and plasma density but is strongly dependent on U.

Gabovich et al (1973) studied the excitation of ion Langmuir oscillation by a fast ion beam and typical spectra by excited oscillation is shown in good agreement with the theoretical prediction. It was also found that the oscillation growth rate decreased with increasing magnetic field. Thus increase of magnetic field lead to the reduction of amplitude of oscillation and hence suppression of instabilities leading to oscillation. The oscillation propagated nearly right angle to the beam.

Zver.eva et al (1977) investigated the radial distribution of intensity of the spontaneous low frequency oscillation and noise in the frequency range of 10^4 to 2×10^5 Hz in a mercury vapour discharge under a pressure between 0.18 to 1.2 torr. The conformity of the axial and radial distribution of the intensity was shown. The velocity of ion-sound wave (1.7×10^5 cm/sec) and lower bound frequency (21 KHz) were calculated using the results of measurement of the radial distribution of intensity and phase. A comparison with theory was given and the resonance character of the radial modes of oscillation excited by the electron stream was pointed out.

In case of a discharge tube operating in its negative resistance region of its VI characteristics, the negative glow as pointed out by Sandulovicíu (1968) is a source of self excited oscillation. The frequency of oscillation may be represented with L,R,C where L is the discharge inductance, R is the resistance between anode and the wall of the negative glow region and C is the capacitance of this region including the wall with respect to the surroundings. The LRC of the circuit representing oscillation in a discharge tube differ with LRC in an ordinary circuit. Because in case of ordinary circuit LRC is independent of current flowing through the circuit but in case of discharge tube LRC and hence the frequency of oscillation is strongly dependent on discharge current [Sandulovicíu (1971)].

Mitra (1975) explained the increase in frequency of oscillation with decrease in discharge current on the basis of an inequality obtained by him by applying the observation of Sandulovicíu (1968, 1969, 1971).

D. Cathode phenomena in an arc

In spite of extensive research the cathode phenomena in an arc is poorly understood because of formidable complexities prevailing in this region. The most useful factor to know regarding the cathode of an arc is the mechanism underlying the emission of current from the cathode.

The expression for thermal current density first obtained by Richardson (1912) and latter modified by Dushman (1923, 1930) is represented as

$$j_C = AT_C^2 e^{-b/T_C} \tag{1.36}$$

where j_c is the current density, T_c is the surface temperature and A, b are constants.

But this equation, in general, cannot cope with the requirement of current density in an arc. This is particularly true for all low melting point cathode materials operating in the vapour mode. But in case of refractory materials like C, W, rare earth metals, the current density experimentally measured by Froom (1948, 1949), Somerville (1952), Von Engel (1965) was found to be in reasonable agreement with the value of current density calculated from Richardson-Dushman equation with cathode temperature not more than the boilding point of the cathode material.

Seeliger and Schmick (1927), Cobine and Gallegher (1948), Wroe (1958), Newman (1936), Ruthstein (1948), Arnold and Von Engel (1961), Holmes (1976) found that the transition of thermionic arc mode of the refractory metals to vapour mode takes place when pressure is brought down below a critical pressure at a constant current; they also observed that when current is raised above a critical current for a particular value of presssure similar transition is observed. Though no such transition was ever observed in case of low melting point vapour mode cathodes, for any pressure and current. The current density on the cathode of a vapour mode arc was found to be of the order of $10^6 A/cm^2$ and hence too high to be explained on the basis of thermionic emission. Richardson equation was modified by Schottky (1923) on the assumption of electrostatic image force on the cathode, thus

$$j_c = AT_c^2 \epsilon^{-b/T_c} \exp\left[\frac{e^{3/2} E^{1/2}}{k T_c \sqrt{4\pi\epsilon_r}}\right] \quad (1.37)$$

where j_c and T_c have the same significance as before, and e, E and ϵ_r are respectively electronic charge,electric field and permittivity of the emitting space.

Jones and Nicholas (1961) experimentally studied this relation for field ranging from 10^3V/cm to 10^6V/cm for two temperatures 197°K and 298°K and found the relation to hold good only for high field in terms of the nature of curve expected from the equation. And out of the three unknown constants, vide, emitting area, work function and field intensification factor, if any two correspond to any set of realistic values, the third one is definitely unrealistic. So such facts raise serious questions regarding the applicability of thermionic emission theory to the cathode of an arc. It is true, the energy released by the +Ve ions maintains the high temperature of the cathode. If these ions come from +Ve column, the ions must land on a large area of the cathode reducing current density on the cathode to a low value. So it is usually presumed that the +Ve ions are produced in the cathode fall region. In this case, high electron current density relative to the +Ve ion current density will be required to produce sufficient +Ve ions essential for maintaining the high temperature of the cathode [Cobine (1958)]. And due to high velocity of electrons, there will be only +Ve space charge in the cathode fall region. The fraction of +Ve ion current to the cathode may be obtained from the work of Shih and Pfender (1970). From the energy balance at the cathode fall space including heat lost by radiation, conduction and convection, they obtained

$$\frac{i_p}{i} = \frac{\phi_c}{V_c + V_i + \frac{kTe}{e}} \qquad (1.38)$$

where i_p and i are the ion current and total current density. ϕ_c, V_c, V_i, T_p, e and k are respectively the work function, cathode fall, ionisation potential, ion temperature, ionic charge and Boltzman constant.

This gives an ion current density at the cathode of an arc ranging from 15 to 50% of the total current density. Compton from heat balance at the cathode of an arc obtained.

$$\frac{i_p}{i_c} = \frac{\phi_c}{V_c + V_i - \phi_c} \qquad (1.39)$$

Von Engel and Steenbeck estimated for a carbon arc in air; taking $V_c = V_i = 15.8$ Volt and $\phi_c = 4.5$ eV and obtained $[i_p/(i_e+i_p)] = 1/7$. Thus ion current was 15% of the total current. Also Daalder (1978) found ion current fraction at the cathode of an arc to be within 10 to 20%.

In a refined model Lee and Greenwood (1963) and Lee et al. (1964) were able to calculate the fraction of ion current over the entire thickness of the cathode fall space and cathode transition space and found for a 200A carbon arc that this fraction varies from 15% at the cathode surface to zero at the column end.

This increase in the ion current density towards the cathode of an arc is consistant with the formation of net +Ve space charge forming the cathode sheath close to the cathode surface. The existence of +Ve space charge close to the cathode surface can produce an electric field [Malter (1936)] strong enough to produce enhanced current emission from the cathode. Due to high velocity of electrons than that of the ions, only +Ve space charge [Hsu and Pfender (1983)] may be considered in the cathode fall region and the space charge equation of Child (1911) gives

$$j_p = \frac{1}{9\pi}\sqrt{\frac{2e}{m_p}} \cdot \frac{V_c^{3/2}}{d_c^2} \qquad (1.40)$$

where j_p, e, m_p, V_c and d_c are respectively the ion current density, ionic charge, ionic mass, cathode fall voltage and span of the cathode fall space.

Von Engel and Steenbeck (1934) obtained the expression for field E_c at the cathode from the space charge equation and is given by,

$$E_c = \frac{4}{3}\left[\frac{9\pi j_p}{\sqrt{2e/m_p}}\right]^{2/3} \cdot d_c^{1/3} \qquad (1.41)$$

which give $E_c = \dfrac{4V_c}{3d_c}$ [Cobine (1958)] (1.42)

Now for low intensity arcs, V_c is of the order of ionization potential and d_c is of the order of a mean free path near the cathode. So the field at the cathode for a nitrogen arc between refractory electrode is of the order of 3.5×10^5 V/cm and may be of the order of 10^6 V/cm for Cu-arc where dense cathode vapour may reduce the mean free path resulting in increase in the field.

The high field at the cathode led many investigators to favour the theory of field emission and investigation was done by Compton (1923), Langmuir (1923), Dyke and Trolan (1953), Doucet (1960), Von Engel and Steenbeck (1934), Bauer (1961, 1966), Rakhovskii (1965), Guozdetskii (1970), Porotnikov et al (1976), Litvinov (1982).

Another expression for electric field E_c at the cathode is obtained by Mackeown (1929) in which the effect of both +Ve ion current density and electron current density at the cathode is concidered, where

$$E_C^2 = 7{\cdot}57 \times 10^5 V_C^{1/2} \left[j_p (1845 W_p)^{1/2} - j_e \right] \qquad (1.43)$$

where j_e, j_p and W_p are respectively the electronic current density, ionic current density and ionic mass.

Now taking V_c to be 10 volts for low intensity arcs, $J_e + j_p = 400$ amp/cm^2, the equation gives,

$$E_c > 5 \times 10^5 \text{ V/cm for } j_p = 0.05\, j_e$$

and $$E_c > 1.3 \times 10^6 \text{ V/cm for } j_p = 0.30\, j_e$$

Thus it appears that such fields may lead to field emission.

Fowler-Nordheim's (1928) theory of field emission, which was later modified by Murphy and Good (1956) was applied to the emission from an arc cathode,

$$I_C = 38{\cdot}5 \times 10^{12}\, S E_C^2 \frac{\epsilon_F^{1/2}}{(\epsilon_F + \phi)\phi^{1/2}} \cdot \frac{\pi k T/d}{\sin(\pi k T/d)} \cdot \exp\left[-\frac{6{\cdot}8 \times 10^7 \phi^{3/2}}{E_C} \right] \qquad (1.44)$$

I_c is the cathode current, S is the emitting area and E_c is the field at the cathode. The equation may be written as

$$j_c(T) = j_c(0) \frac{\pi kT/d}{\sin(\pi kT/d)} = j_c(0) K_T \qquad (1.45)$$

$$\text{so} \quad \frac{j_c(T_1)}{j_c(T_2)} = \frac{K_{T_1}}{K_{T_2}} = \frac{I_c(T_1)}{I_c(T_2)} \qquad (1.46)$$

Jones and Nicholas (1961) obtained experimental verification of this relation, though absolute value of emission current is of the order of 10^{-6} to 10^{-7} amp/cm^2 which is far lower than the actual current density on the cathode of any arc.

Since logarithmic of field current is experimentally a decreasing function of the reciprocal of the field strength, the field current increases extremely as the field strength is increased beyond the minimum field required to produce the first perceptible current [Eyring et al (1928)]. The presence of low work function impurity would greatly increase the current density in the local region of the cathode. Any point of increased emission will result in increase in the field strength at the cathode and hence further increase in current and hence a cumulative process will set in. And such impurities are believed to be necessary for the cold cathode tungsten arc observed by Newman (1932). In the experiment of Eyring et al (1928), Chamber (1934) and Beams (1933) measurable emission begins at fields of the order of 10^6V/cm for pure surfaces and 10^5V/cm for impure surfaces.

If current density from an arc cathode is plotted against pressure for constant discharge current as done by Seeliger and Schmick (1927), there is a sudden increase in current density with lowering of pressure at about 10 cm of Hg for a pure carbon arc in air. The transition is believed by the author to be due to change of thermionic mode to vapour mode of emission. Similar transition is also observed by Beckman and Somermeyer (1936) and Cobine et al (1939) under continuous arcing condition. The transition observed by Seeliger and Schmick and others for pure carbon and tungsten in air is a sudden transition of wondering arc spot to fixed arc spot, with the rise of pressure, showing also a sudden rise in arc burning voltage with the transition; while wondering cathode spot is an inevitable criteria of field type cold low boiling point cathodes only. Also during lowering of pressure at the point of transition from thermionic to vapour spot on the cathode, arc spots contract and start moving violently and arc burning voltage drops with the appearance of vapour mode and the whole process is reversed on reversing the mode of change of pressure, which indicates that the whole nature of change is reversible. The transition pressure is lowered for higher discharge current. Moreover it was found by Arnold and Von Engel (1961) that the transition pressure depends on electrode separation. The appearance of luminious intensity, violent motion of the spot, low arc burning voltage for carbon in air corresponds in every way to the spot on copper. Also it was noticed by Arnold and Von Engel (1961) that the wall of the arc container which remains clear during thermionic arc mode starts becoming black on transition to vapour mode, indicating absence and presence of carbon vapour in the thermionic mode and vapour mode respectively. The lower arc drop in the vapour mode suggests that smaller energy is consumed in the vapour mode spot than in the thermionic mode spot.

The excitation theory of arcs with evaporating low boiling point cathodes assumes the emission of electrons from the excited vapour atoms evaporated from the cathode of an arc [Von Engel and Robson (1957)].

Also the work of Kimblin (1971) is worth mentioning where he found, assuming single ionization, 55% of the vapour leaving the cathode fall space went through ionization.

Beilis (1988), Mentel (1977) and Blackburn (1978) also observed the effect of vapourization on the mechanism of emission in an arc.

From the theory of stepwise abletion Von Engel and Arnold (1960) found the excited vapour atoms to vapourise cathode material by transferring their energy to the individual atoms rather than heating the lattice as a whole. Thus in this condition simultaneous emission of electrons and vapour are possible without a high lattice temperature. Since the area of a spot is small, this is possible that the true heat influx to the lattice is small and hence lattice attains only a moderate temperature [Somerville (1952)] and most of the energy is spent against emission of vapour and electron. To maintain the temperature of the overall cathode, the kinetic energy is brought by the back scattered and fast neutral atoms resulting from the charge transfer and thus the temperature of the overall cathode is maintained.

Leycuras (1975), instead of considering emission of electrons from metal surface to vacuum, assumes the electrons to be emitted from metal surface to a dense vapour space which is usually formed around a vapour spot and finds that the work function is greatly lowered. Hence, as soon as, current density in the needles grown on the cathode surface [Alpert (1967), Jomaschke and Alper (1967)] and Mitterauer et al (1973)] exceeds a critical value, heat generated becomes sufficient to raise the temperature of the needles above the boiling point of the cathode material and dense vapour is formed around the needles. And thus due to reduction of work function in presence of vapour, there is a tremendous increase in current density, Leycuras also obtained the vapour density in case of Hg and other eight metals, the results show consistency with the experiment made by Kimblin (1973).

It has also been observed by Seeliger and Smick (1927) that carbon arc in argon and neon has highly mobile cathode spot over a wide range of pressure. Thus neon and argon apparently support vapour mode with carbon electrodes while the same in molecular gases like nitrogen and air supports both vapour mode and thermionic mode depending on the pressure, discharge current and cathode geometry and electrode separation.

It has also been observed by Von Engel and Arnold that during thermionic emission, the cathode appears dull red while it becomes black as soon as stationery spot is transformed to vapour spot.

In case of addition of impurity gas to a carbon arc operating in the vapour mode, either the arc extinguishes or is transformed to a thermionic arc. In case of addition of nitrogen as impurity, this conversion is due to quenching of excited carbon atom (C^*) by nitrogen moecule [Von Engel and Arnold (1961) and Holmes (1976)]. Holmes found that the transition from thermionic to vapour arc is initiated by excessive particle loss from the arc spot, whereas the reverse transition to the thermionic arc is caused by the nitrogen molecule quencing of excited carbon C^* atoms.

The way in which C^* is quenched by N_2 is described by Arnold and Von Engel (1961). The energy level diagram of N_2 shows that the first triplet state is about 6.2 eV [Hertzberg (1953)] above ground state giving rise to Vegard-Kaplan bands, while C^* has about 6.5 eV excitation (resonance) energy. Thus the triplet levels are very close for the C^* to loose its excitation energy to a N_2 molecule [Mitchell and Zemansky (1934)]. Hence quenching cross-section in this case is very high because of nearness of complete energy resonance. But C^* cannot be quenched by N_e atoms whose lowest resonance level is about 16.5 eV /Von Engel and Arnold (1962)_7.

Another fact obtained by Zhu and Von Engel (1981) is that the cathode fall of Cu in air is the same as that in argon, indicating that the Cu-vapour atmosphere around cathode spot is the dominant medium. Though thermionic mode cathode fall sharply depends on the working fluid in the arc container. The gas condition, however, has an important role towards the nature of cathode surface due to adsorbed gases which can exist as an impurity on the cathode surface resulting in decrease in work function as is done by the presence of oxygen /Suits et al (1938), Cobine (1938), Doan et al (1932)_7 as an adsorbed gas on the cathode surface.

Due to continuous arcing such adsorbed gases are gradually removed with increase in work function of the cathode surface. This explains why duration of field phase is gradually reduced when the arc operates at a current close to the critical transition current and transforms the arc to a thermionic arc after certain time of operation /Beckmen et al (1936) and Cobine et al (1939)_7. So at the on set of thermionic emission, cathode consumption will rise and hence there should be a rise in arc burning voltage. Owing to low current density obtained from Fowler-Nordheim theory and its particular failure to cold cathode emission, Rieder (1967) obtained an expression for field emission cathode current density from cold cathodes, which is valid for low cathode temperature and high field $> 10^7$V/cm

$$j_c = 1.54\ \frac{E_c^{\,2}}{e\phi_c}\ \exp\left[\frac{-6.83\times10^{9}(e\phi_c)^{3/2}}{E_c}\ f\left(\frac{3.79E_c^{1/2}}{e\phi_c}\times10^{-5}\right)\right] \qquad (1.47)$$

where j_C, E_C, ϕ_c etc have same significance as before.

From the relation of Mackeown (1929) and Rieder (1967), it follows that the field emission is possible only when $j_c > 10^7 V/cm^2$, even if unrealistically low work function is assumed.

A modification of field emission theory was suggested by Druyvesteyn (1936) on the basis of observation of Guntherschulze and Frick (1933), where they presumed the field to be produced in an extremely thin layer of high resistance material with +Ve ions on the outer surface. Such layers may be due to oxide coating. Ramberg (1932) found that the cathodes of Ca, C, W, Mg are thermionic in nature and that of Cu, Ag, Au and Hg are field emission type. But cathodes of Pt, Sn, Pb, Ni, Zn, Al, Fe, Cd lie truly in neither of the above groups and for metals with high boiling point in this group may combine the effect of thermionic and field emission and such emission is commonly known as TF-emission [Lee (1957), Lee (1958), Lee (1959), Ecker (1961), Bauer (1966) and Hantzsche (1982)].

Finally another work must be mentioned; Thomson and Loebs believe that the current of all arcs arises due to thermionic emission for which they presented the following arguments. If the current density at the cathode of an Cu arc is taken to be 3000 amp/cm^2 and 3.33% of this is carried by

+Ve ions, the +Ve ion current entering per square cm of cathode will be 100 amp/cm^2. If the cathode fall is of the order 20 volt, which is usually the order of cathode fall of an arc [Sen et al (1988)], the power consumed per sq. cm on the cathode surface will be 2000 jule or 480 cal/sec. If the specific heat of Cu is taken to be 0.10, 1 gm of Cu will undergo a rise of temperature of 4800°C in one sec. If the heat flow is low and such high temperature can exist on the cathode surface, the temperature of a layer of 500 atoms thickness (about 10^{-5} cm) and 1 sq. cm area should undergo a rise of temperature of 4000°C in only 7.5 x 10^{-5} sec. So even from a low boiling point metal surface, the necessary emission of electrons will be possible. And such a high rate of change of temperature can explain the experiment of Stolt (1924) where he moved an arc cathode at a high speed over a metal surface and found no trace leaving on the metal surface. Holmes (1976) presented a theoretical comparison between the thermionic and vapour mode arcs, which illustrates the essential similarity of the two arcs. Using carbon arc in nitrogen, the arc spot parameters are derived for both arc modes and are in good agreement with the theoretical predictions.

E. Diffusion phenomena in a magnetised plasma and Hall effect.

Owing to the highly mobile nature of electrons, and comparatively smaller velocity of ions there develops an electron concentration gradient in a direction transverse to the electric field which sets up a potential difference in a direction perpendicular to the applied electric field resulting in a change in ionic velocity in those directions. This results in the formation of space charge in the positive column of the plasma. Nature of the fluid, its pressure, thermal state and other factors like energy loss etc come into play for the final equilibrium to be established.

When in addition to electric field in a discharge plasma, there is a magnetic field in a direction either parallel or perpendicular to the electric field, there is again redistribution in the velocity space of plasma due to Lorentz force which acts on the random motion and drift motion of the charged particles and the plasma becomes anisotropic in many respects.

Townsend (1912) obtained a theoretical expression for diffusion co-efficient under the action of transverse magnetic field, given by

$$D_H = \frac{1}{1+\omega_B^2 \tau^2} \qquad (1.48)$$

where ω_B is the gyrofrequency and τ is the mean time of collision. In an attempt to formulate a quantitative theory of diffusion in presence of magnetic field, Tonk and Langmuir (1929) used theoretical results of Townsend (1912). These results were latter confirmed by Baily (1930) in experiments with electron swarm for photo electric currents and was found to hold for larger currents when allowance was made for space charge. Davis (1953) used a spectroscopic method to investigate the influence of magnetic field on electron temperature which was latter shown to be connected to diffusion voltage by the relation derived by Sen, Ghosh and Ghosh (1983)

$$\frac{kT_{eB}}{e} = \frac{V_{RB}}{\log\left[J_o(2{\cdot}405\, r/R)\exp.(-\alpha B)\right]} \qquad (1.49)$$

where V_{RB} is the diffusion voltage and T_{eB} is the electron temperature both in presence of transverse magnetic field applied to a cylindrical plasma column.

Davis (1953) observed small increase in the electron temperature which is in accordance with the observation of Sadhya and Sen (1980) where they verified the relation derived by Sen, Das and Gupta (1972)

$$T_{eB} = T_e\left(1 + C_1 \frac{B^2}{p^2}\right)^{1/2} \qquad (1.50)$$

Tonk (1941) found for uniform longitudinal magnetic field that the Boltzman equation is to be replaced by

$$n_e = n_o \exp.(-ev/kT\ell) \qquad (1.51)$$

where

$$\ell = \frac{\alpha D_e - \mu D_p}{\alpha D_e + \mu \frac{D_p T_e}{T_p}} \qquad (1.52)$$

μ is the ratio of radial drift velocity of electrons and ions, and he found that for longitudinal magnetic field,

$$D_e = D_{eB} \text{ and } D_p = D_{pB}$$

Diffusion process of a plasma column in a longitudinal magnetic field was studied by Hoh and Lehnert (1960) which confirmed the earlier results of Lehnert (1958). Experiment with He, Ne, Ar, Kr, N_2, H_2 are described. In the case of He good agreement was obtained between the collision diffusion theory and experiment upto a certain critical magnetic field. For stronger magnetic field potential drop across the column indicated a much higher diffusion rate across the magnetic field than expected by binary collision theory. He also observed that for tube length more than fifty times the radius of the column, the transition from normal to abnormal diffusion does not depend on the tube length and magnetic field length.

The positive column in a longitudinal magnetic field was studied by Bickerton and Von Engel (1956). They concluded that in a zero magnetic field the Langmuir theory of free fall of ions describes best the properties of discharge plasma whereas in a magnetic field of sufficient strength Schottky theory of ambipolar diffusion works well in the discharge plasma. They also concluded that when the gas becomes highly ionized, the partial pressure of electron gas may become so effective that longitudinal component of electric field and electron temperature should become independent of magnetic field. Their previous observation on low pressure positive column in Cesium at high current density was cited as an evidence behind their conclusion.

Bohm (1949) theoretically derived a new diffusion co-efficient in a magnetised plasma according to which the transverse diffusion co-efficient is given by

$$D_{\perp} = \frac{1}{3} \omega_r \gamma_b \alpha \tag{1.53}$$

where

$$\frac{4\alpha}{\pi} = \frac{(n - n_o)^2_{av}}{n_o^2} \tag{1.54}$$

is the mean square deviation of density fluctuation and γ_b is the Larmour radius of electrons and ω_r is the mean thermal velocity. Bohm (1949) also gave new expression for ambipolar diffusion co-efficient in a direction transverse to magnetic field according to which

$$D_{\perp} = 2D_{-\perp} \tag{1.55}$$

in place of

$$D_{\perp} = 2D_{+\perp} \tag{1.56}$$

and obtained large discripancy in the theory and experiment and suggested this to be owing to plasma oscillation.

Later Simon (1955) pointed out that due to highly anisotropic conductivity of a magnetised plasma, the ambipolar diffusion no longer exists, and ions and electrons diffuse across the magnetic field at their own intrinsic rate and space charge neutralization is maintained by slight adjustment of current in the direction of magnetic field. Their results were confirmed by Goswami (1957). Langmuir and Rosenbluth (1956) investigated like and unlike particle collision in a magnetised plasma where they found that the unlike particle collision diffusion predominated over that due to like particle collision. Kaufman (1958) extended the theory of diffusion to include the effect of transverse temperature gradient in a magnetised plasma and a closed set of equations is derived by an expansion in two small parameters "a" (radius of gyration) and $\nabla n/n$ (characteristic macroscopic distance). It is found that to the first order of $\alpha\,[= a/(\nabla n/n)]$, the ions and electrons diffuse at the same velocity but to the higher order in α, the diffusion velocity are different and charge separation may occur in a magnetised plasma. Thus Hall effect following the charge separation may arise. In their paper the relevant transport co-efficient like electrical resistivity, thermal conductivity and thermo-electric co-efficient are derived.

But Simon (1955) and Langmuir and Rosenbluth (1956) assumed no charge separation could occur as a result of ion-ion collision because of charge neutralization by electron flow along the magnetic lines of force. It was found that the ratio of flux from ion-ion collision to that due to ion-electron collision is of the order of

$$\left(\frac{m_i}{m_e}\right)^{1/2}\left(\frac{R_i}{D}\right)^2$$

where R_i is the ionic radius of gyration and D is the characteristic distance of the density variation.

But Spitzer (1956) and Chapman and Cowling (1953) and Kaufman (1958) found that a low density fully ionized plasma confined by a strong magnetic field diffused across the magnetic field primarily by ion-electron collision, the flux being proportional to the density gradient and Kaufman (1958) showed that the effect like particle collision on density gradient cannot be enough considerable because the ratio of flux due to like-like collision and like unlike collision is only

$$\left(\frac{R_e}{D}\right)^2$$

instead of that stated by Langmuir and Rosenbluth (1956). And the ratio $(R_e/D)^2$ is negligibly small.

Simon (1955) also showed that diffusion rate across a magnetic field did not obey Fick's low, i.e., the diffusion is proportional to H^{-2}, instead it was stated that the diffusion was proportional to the inverse fourth power of magnetic field strength and diffusion rate due to like particle collision was usually smaller than that due to unlike particle collision but may some time dominate.

Now there exists two theories to account for diffusion of a plasma across a magnetic field B. The first theory is essentially based on the Boltzman equation with collision terms and can be derived by Chapman-Enskog method. This theory is known as classical diffusion theory or $1/B^2$ diffusion theory and was extensively investigated and put to confirmation by D'Angelo and Rynn (1961), Simon (1958), Langmuir and Rosenbluth (1956), Demirkhanov (1961) and others. According to the theory,

transverse diffusions co-eff. $D_{\perp} = \frac{1}{3} \nu_c \gamma_b^2$

and parallel diffusion co-eff. $D_{\parallel} = \frac{1}{3} \nu_c \lambda^2 = D_{H=0}$

where λ is the m.f.p. and ν_c is the electron-ion collision frequency and γ_b is the Larmor radius of electrons at the mean thermal velocity ω, given by

$$\frac{1}{2} m\omega^2 = \frac{3}{2} kT_e \tag{1.57}$$

And another theory is the Bohm's 1/B diffusion theory which was later derived by Spitzer (1960) and also by Petschek (1960) by entirely different assumptions. This 1/B diffusion was experimentally confirmed by Hoh and Lehnert (1960), Bonnal et al (1961), Chenand Bingham (1961) and Yoshikawa and Rose (1962).

Takayana et al (1954) used probe technique to measure Hall voltage in a hot cathode discharge plasma. They obtained Hall voltage in argon upto 400 mV at a pressure of one torr for magnetic field varying upto 14 Gauss.

Sanduloviciu and Toma (1970) investigated Hall voltage in plasma and cautioned about superficial processes by the fast electrons in a dc glow discharge when working with Hall probes. They also studied the optimum working condition when working with Hall probes in a dc glow discharge.

Kunkel (1981) described a simple experimental arrangement for the measurement of Hall voltage in a low density plasma column. And they obtained an expression for Hall voltage,

$$V_H = \frac{X_2 - X_1}{2} E_H - \frac{kT_e}{e} \log \frac{\sin \frac{\pi X_2}{L}}{\sin \frac{\pi X_1}{L}} \qquad (1.58)$$

E_H is the Hall field. This expression shows if x_1 and x_2 are selected at equal distance from L/2, the last term in the expression for Hall voltage vanishes, giving

$$V_H = \frac{1}{2} (X_2 - X_1) E_H \qquad (1.59)$$

This shows that the Hall voltage between the opposite sides of such a positive column measures only half of that expected ideally in a conductor with the same carrier density. They supposed the reduction was caused by the ambipolar diffusion of the carrier whose density distribution is distorted in the presence of transverse magnetic field. They studied Hall voltage across a helium discharge column as a function of magnetic field, discharge current and gas pressure.

Sen and Ghosh (1985) deduced an expression for Hall field given by

$$E_y = \frac{iH}{n_o e\left[1+\gamma\log\left(1+C_1\frac{H^2}{p^2}\right)^{-\frac{1}{2}}\right]^{1/2}} \qquad (1.60)$$

$$\gamma = \frac{2T_e}{T_e + 2e\,V_i} \qquad (1.61)$$

They reported results of their measurements for a Hg-arc carrying a current of 3 amp and placed in a transverse magnetic field ranging from 64G to 526G and the results were in excellent agreement with that theoretically predicted.

Utilizing the expression given by Sen, Ghosh and Ghosh (1983), the open circuited diffusion voltage in an arc plasma (arc current varying from 2 to 5A and for three background pressures of .075, 0.1 and 0.13 torr) has been measured by Sen, Gantait and Acharyya (1989). Utilizing the radial distribution function of conductivity as introduced by Ghosal, Nandi and Sen (1978), an analytical expression for diffusion voltage has been calculated which can satisfactorily explain the observed results.

The diffusion voltage in a mercury arc plasma has been measured for arc currents from 2.5 to 5A in transverse and axial magnetic field from 380 to 1.1 KG by Sen et al (1990). Assuming the radial distribution of charged particles proposed by Ghosal et al (1978) and utilizing the method of Sen et al (1983) the ratio of electron temperature with and without a magnetic field has been evaluated. It becomes a maximum in an axial magnetic field and then decreases whereas it shows a minimum in a transverse field and then increases. An expression for the ratio of electron temperature with and without a field has been deduced that explains the results. Quantitative agreement between experiment and theory is quite satisfactory.

Sen, Acharyya and Gantait (1981) measured the diffusion current and the corresponding diffusion voltage in an arc plasma (arc current 2 to 5A and three pressures 0.075, 0.1, 0.13 torr) and utilizing the radial distribution function of conductivity as introduced by Ghosal et al (1983) the values of diffusion coefficient of mercury vapour have been evaluated. The diffusion coefficient of electrons in mercury vapour has been found to be of the order of 10^3 cm^2/sec which increases with the increase of arc current and decreases with the increase of pressure. A qualitative explanation of the observed results has been presented.

SCOPE AND OBJECT OF THE PRESENT WORK

Though a large amount of work has been carried out regarding the breakdown of gases and consequent production of plasma, measurement of plasma parameters, waves and oscillations in a plasma and other allied problems, still the nature of some of the physical processes occurring in a plasma during the period of its formation and maintenance have not been adequately investigated. The physical processes occurring in the initiation and maintenance of an arc plasma are still not properly understood. Further it is evident that the cathode phenomena in an arc discharge needs thorough investigation. The process of phase transition from glow to arc should be investigated in order to develop a theoretical basis for the occurrance of an arc plasma. Hence it is proposed to take up investigations in the following lines in the present work.

A. Energy loss mechanism in a collision dominated plasma

In case of collision dominated plasma, an electron suffers energy loss on account of its various interactions with other charged and uncharged particles. Such interactions are known as collision which, in turn, falls in two categories, vide, elastic collision and inelastic collision. A collision is said to be elastic when the total kinetic energy and momentum for the particles undergoing collision remains conserved but one of the particles with higher kinetic energy transfers a part of its kinetic energy to the other one during the collision.

Such a loss of kinetic energy, in case of plasma, frequently occurs with electrons whose kinetic energy is usually much higher than that of other constituent particles of the plasma. To account for the fraction of energy lost in one collision, a factor, known as average collision loss factor has been associated with the electron. An expression for such a factor (K) associated only with elastic collision has been given by Compton and Langmuir (1930), which was expected to be valid for low values of E/P. But experimental measurements for slow electrons undertaken by Bekfi and Brown (1958), Demitriades (1967), Brood (1925), Rusch (1925), Bruche (1927), Ramsauer and Kollah (1929), Normand (1930), Gilardini (1957, 1972), Bushmin and Demitriev (1976) show that even for very low values of E/P, the value of K was found to be much higher than the theoretically expected value of K for elastic collision. Thus even the slowest electrons do not suffer pure elastic collision. Moreover the value of K was found to depend on E/P and the characteristic of the working fluid and also on other factors like gas temperature, external magnetic field etc. An inelastic collision loss may arise due to either of the processes like vibrational excitation, recombination, attachment, dissociation, ionization and collision of the 2nd kind. For fast electrons, when inelastic collision has frequent occurrance, the collision loss factor has been measured by Shingarkina and Vasilev (1972), Bowe (1960), Medis (1958), Afrosinov et al (1972), Janca (1967), Biberman et al (1966).

All the above measurements were performed either for different range of E/P or for different range of electron energy.

But a general theory for the mechanism of collision loss of energy of the electrons was still to be developed. Such a theory is expected to relate the collision loss factor with reduced electric field, electron temperature and a constant which bears the characteristic of the working fluid. Also it was expected that the Joule heating in a discharge plasma is due to the collision loss of energy of the electrons which has almost the sole contribution to the discharge current. So, a relation between the discharge current and the collision loss factor which depends on the said parameters, was naturally expected. Collision loss factor is a function of the ratio of drift and random velocities (Von Engel 1965); and discharge current, collision loss factor and electron temperature - all depend on E/p, so such a theory was expected to have considerable impact on the understanding of the subject of discharge plasma. So it is proposed to undertake a detailed theoretical investigation regarding the energy loss in a collision dominated plasma and also provide experimental data to verify the theoretical results in case of low density discharge plasma with hydrogen, air and nitrogen as working fluid.

(B) Radio frequency conductivity of Ionised Gases

Vandarpol (1919) obtained an expression for rf current through a discharge plasma, which is found to be the composition of real and imaginary parts of the gas discharge current. Appleton and Chapman (1932), Margenau (1946), Adler (1949), Sen and Ghosh (1966), Gilardini (1959), Sen and Jana (1978) and many others showed that the rf conductivity through a gas discharge plasma is a complex quantity which points out that the current through a gas discharge plasma is a complex current.

Francis and Von Engel (1953) measured the real current by separating out the capacitative current by balancing a bridge. Penfield and Warder (Jr.) (1967) measured the r.f. real current by measuring the voltage drop across a specially constructed centre tapped inductor. Clark, Earl and New (1970) measured the gas discharge rf current by separating out the capacitative component of the current by a bridge method similar in principle to the method employed by Francis and Von Engel (1953).

Thus it is evident that to separate out the real and imaginary parts of the gas discharge rf current by the bridge balancing method is a difficult task. A lot of adjustment and screening is necessary throughout the measurement at different ranges of applied voltage. So it was felt that a convenient method might be developed in this respect. Thus we propose a resonance method following a theoretical support which will enable one to measure the real as well as the imaginary parts of the gas discharge rf current with the help of only two rf current meters connected in the circuit.

(C) Radio frequency conductivity in presence of transverse magnetic field

Radio frequency conductivity of a gas discharge plasma was found to be a complex quantity [Vandarpol (1919), Margenau (1946), Berk (1964), Sen and Ghosh (1966), Ciampi and Talini (1967), Adler (1949)], Adler (1949) has shown plots for σ_r and σ_i with pressure and current when the other parameters remain constant.

The rf conductivity in presence of transverse magnetic field was calculated by Gilardini (1959) which was found to be a complex conductivity. Later Sen and Ghosh (1966) modified this theory to explain the experimental results of the rf conductivity measurement in presence of transverse magnetic field. Gupta and Mandal (1967), Sen and Gupta (1969), Sen and Jana (1978) measured the rf conductivity of a gas discharge plasma in presence of transverse magnetic field. Ram, Chandra and Sarkar (1972) measured the rf conductivity in presence of both transverse as well as longitudinal magnetic field.

But almost all of the measurement is related to the measurement of real part of the rf conductivity of the gas discharge plasma. But it is pressumed that the imaginary part of the rf conductivity in presence of transverse magnetic field still requires some attention for the clear insight of the physical process occurring in a r.f. discharge through gas discharge plasma, so the theoretical analysis regarding the r.f. conductivity of ionised gas (its imaginary part) in a transverse magnetic field has thus been undertaken. It will be of interest to see how the r.f. conductivity varies with the variation of magnetic field.

D. Plasma Parameters diagnostic

Though there are a number of methods for the determination of plasma parameters such as single and double probe method, Radio frequency conductivity method, Microwave transmission and reflection method, spectroscopic method and Laser diagnostic technique, still a simple and alternative method has been proposed to be developed which can act as a supplementary method to the above. A microwave beam of variable frequency is proposed to be sent through a rectangular wave guide filled with plasma and with the help of a microwave interferometer the attenuation and phase change can be measured (α and β where α is the attenuation per unit length and β is the phase constant per unit length). The cut off frequency for the wave guide when filled with air and also when filled with plasma can be experimentally measured. A detailed mathematical analysis has been carried out where σ_r the conductivity (real part) and σ_i the conductivity (imaginary part), ϵ' the dielectric constant (real part) and ϵ'' the dielectric constant (imaginary part) can be related with the experimentally measured quantities, α , β , ω_c , ω_{cp} where ω_c and ω_{cp} are the cut off frequencies of the wave guide without and with the plasma respectively. From these relations it has been shown how the electron density and collision frequencies can be evaluated.

E. Effect of magnetic field on the cut off frequency of Microwaves in a plasma

The microwave reflection method is a well known plasma diagonistic method for determining the electron density in a plasma. It utilizes the same principle as is used in determining electron and ion density in the Ionosphere. But the essential criteria for the successful operation of a thermonuclear reactor is that magnetic field is used for the confinement of the plasma and in wave propagation in the ionosphere the effect of earth's magnetic field has to be taken into consideration. Hence it has been thought worthwhile to consider the effect of magnetic field on the value of cut off frequency when a micro-wave beam is propagated through the plasma column. A detailed mathematical analysis has been presented and variation of cut off frequency with magnetic field has been investigated. The calculations are useful when determining the electron and ion density in a magnetically confined plasma as in a thermo nuclear reactor.

F. Investigation of low density plasma in a magnetic field

In presence of transverse magnetic field, the diffusion inside a discharge plasma undergoes certain changes resulting in change in diffusion voltage. But due to Lorentz force there appears a Hall voltage too. Many investigators measured diffusion voltage in presence of transverse magnetic field. The work of Sen and Ghosh (1983), Tonk (1941), Bohm (1949), Simon (1955), Goswami (1957), Langmuir and Rosenbluth (1956), Kaufman (1958), and Spitzer (1956) may be mentioned. Many investigators have measured the diffusion voltage in a transverse magnetic field.

Some of the investigators like Sanduloviciu and Toma (1970), Kunkel (1981), Sen and Ghosh (1985) measured Hall voltage in case of a plasma.

But Hall voltage and diffusion voltage appear in the same plasma space so it is difficult to measure these two voltages separately. Thus it was felt necessary to have a detailed theoretical investigation to calculate the combination of the diffusion and that of Hall effect separately which will enable us to find a theoretical expression for the total voltage developed. So we have proposed a theory which gives an expression for the composition of two voltages, vide, diffusion voltage and Hall voltage. Experimental results for such a measurement as obtained here in case of a low density plasma shows excellent agreement for moderately transverse magnetic field. In the low field intensity region, there is, however, certain discrepancy. Separation of the two effects will enable one to find the relative importance of each effect in the different regions of the applied magnetic field.

G. Cathode Phenomena in an arc plasma

From the early part of the 20th century, the physical processes occurring on the surface and neighbourhood of cathode of an arc have drawn attention of many investigators because of its high current density, high current and low cathode fall unlike the cathode of a glow discharge.

The early attempt to explain the cathode phenomena was on the basis of thermionic emission and later field emission was also considered by many investigators and then in some cases it was thought that both thermionic and field emission have simultaneous role on the emission mechanism from the cathode of an arc. Thus cathode of Cu, Ag, Au etc. fall in one category where field emission plays the dominant role, while, C, W, rare earth metals fall in another category where thermionic emission is prominent. But the latter shows field emission below certain pressure in certain gases. Again Fe, Zn, Al etc are found to have combined effect of thermionic and field emission. Thus no general theory and origin of cathode phenomena of an arc has been proposed.

In this present investigation we undertake the problem to put forward a general theory which can cover all category of above said cathodes and thereby reducing the complexcities prevailing towards the understanding of the cathode phenomena of an arc.

In the present work we have proposed a general theory with adequate mathematical background and selected three different electrode materials in such a way, which were earlier observed to fall into three different categories, vide, thermionic emission category, field emission category and TF emission category, for consideration of testing the theory proposed by us. The experimental results with the said electrodes show excellent agreement with the present theory. As the occurrance and maintenance of a high current arc is not yet properly understood the proposed work may help in providing a generalised theory specially with regard to cathode processes in the arc.

H. Low frequency oscillation in an arc plasma

A plasma can support oscillations under different conditions all of which are longitudinal because the electric field and line of oscillation are parallel to the direction of propagation of oscillation. In one category of oscillation, there is no component of magnetic field associated with the oscillation while in some other cases small time varying magnetic field may be associated either along the direction or transverse to the direction of propagation of oscillation. These later oscillations are associated with the wave known as "magnetohydrodynamic" or hydromagnetic wave which propagates with velocities much lower than the velocity of light and the frequency, too, in this case, is many order less than in the case of electron plasma oscillation and may even be smaller than ion plasma oscillation.

But all of these processes usually transform power into the oscillation, which is no more than a little percentage of the total power associated with the discharge. But in the early time gas discharge tube with negative resistance characteristics were used for the generation of radio waves which had much higher percentage of total power conversion to the oscillation, as in the case of dynatron oscillator. In case of mercury arc which has a negative resistance characteristics and whose design is simple and inexpensive, a negative resistance oscillator may be designed which can handle and produce larger oscillatory power. A simple theory for such an oscillator was proposed by Cobine (1958). Thus we undertake this work with the aim of designing a high power oscillator whose design is simple and frequency will be easily adjusted with the help of L and C. Though in our Hg arc, $\frac{dv}{di}$ is negative for the portion of the v-i characteristics, we have utilised, the oscillation is never like dynatron oscillation whose frequency depends entirely on the tank circuit parameters. In the present case frequency and amplitude of oscillation detected is entirely controlled by the inner characteristics of arc. These low frequency oscillations depend on the properties of mercury arc tube. We have investigated the mechanism of generation of such oscillations and advanced an analytical theory showing their variation with pressure, arc current and magnetic field. The experimental results are in conformity with the theoretical derivation. The source of these low frequency oscillations has also been suggested.

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