CHAPTER - I

INTRODUCTION

CHAPTER - I

INTRODUCTION

(A) REVIEW OF THE PREVIOUS WORKS I

1.1. PLASMA CONDUCTIVITY AND COIL PROBE DIAGNOSTICS

The knowledge of electrical conductivity of a plasma sometimes serves to enlighten the state of the plasma and hence to correlate other plasma parameters. In certain applications of plasma Physics (e.g., MHD generator) the knowledge of electrical conductivity is of direct importance in its own right. The electrical conductivity of highly ionized gases plays an important role in high temperature gas dynamics (specially for large dimension as in celestial gas dynamics) through the interaction of magnetic fields with the gas motion (magnetohydrodynamics). Measurement of electrical conductivity of a plasma can be made using variety of methods depending on the nature of the plasma (e.g. discharge plasma, shock induced plasma, plasma jets and other flow facility plasmas etc.). The plasma conductivity is mostly determined by conventional probes (electrodes). The inadequacy of the usual probe method becomes obvious in several circumstances. It was observed by Lin et al (1955) that in hot ionized gas the probe method is accompanied by difficulties arising from the existence of a cold boundary layer around the probe. In the case of cold plasma, the probe current gives little information on the conductivity. In that case an attempt for indirect measurement of conductivity may be made by measuring the electron density; but evaluation of conductivity becomes still difficult due to the fact that no exact method of measurement of collision frequency has yet been found.

The probe method is not applicable to a field-free plasma such as after-glow plasma, diffusion plasma and so on. Further, in the case of flowing plasma, the probe method should not be used because the inserted probe may appreciably disturb the dynamics of the flow. In some cases the plasma jet may even destroy the diagnostic probe. Hence coil probe technique has become very much popular to deal with conductivity problems in variety of circumstances. It has been observed that with ion densities in the range 10^{13}-10^{16} cm^{-3} it is one of the few techniques that can be used. The basic principle involved in most of the coil probe diagnostic technique lies in the fact that magnetic field associated with a solinoidal radio frequency electric field induces solenoidal current into the plasma under study, and the effect is reflected back into the probe coil wound around (and some times inserted in) the plasma. Hence this method is often termed as induction method or magnetic flux method by different authors.

1.1.1. In the coil probe method devised by Lin et al (1955) for the determination of electrical conductivity profiles of highly ionized argon produced by shock waves, however, no radio frequency source was employed. In their method the information was obtained from the search coil (probe) pick up of electromagnetic disturbances produced by the passage of shock waves through it. Possibly, the paper of Lin et al (1955) represents the first record of coil probe experiment for the determination of electrical conductivity of a plasma. While experimenting on the electrical conductivity of shock-produced argon plasma by conventional probe method they were encountered with the following difficulties.

It was shown by them that for small degrees of ionization the electrical conductivity of a plasma may be approximately given by

$$\sigma = Const \times \frac{T^{1/2}}{\rho^{1/2}} \cdot e^{-\mathcal{V}_1/2kT}$$

where ρ is the density of the gas, T is the absolute temperature, $\mathcal{V}_1$ is the first ionization potential of the gas, and k is the Boltzman constant. According to the results of their probe experiments it was found that the relation between σ and gas temperature showed somewhat exponential character; however, the indicated conductivity was as much as thousand times smaller than the theoretical value. They also observed that for some range of gas pressure the conductivity was found to be approximately proportional to the gas density instead of being inversely proportional to the square root as predicted by the theory. The discrepancy was attributed to the non-equilibrium effects. It was conjectured by them that the gas next to the probe and the shock tube walls was cooler than the gas away from these surfaces. It was thought that these cool boundary layers might greatly increase the apparent gas resistance. Instead of trying to explore these effects quantitatively,they rather concentrated on developing a new method.

To eliminate the inherent surface effects associated with probe measurements an experiment utilising the interaction between a magnetic field and the conducting gas behind the shock wave was designed. In their method an axially symmetric magnetic field was introduced into the glass section of the shock tube. A d.c. magnetic field was provided by a short solenoid, the axis of which was common to that of the shock tube. The probe coil (a small search coil) was placed slightly ahead of the field coil to pick up the electromagnetic disturbances produced by the passage of the shock wave through the magnetic field. The direct computation of electrical conductivity calls for the knowledge of the geometry of the arrangement and gas velocity and involves severe mathematical complications; however, it was much easier to experimentally obtain the response of the apparatus to moving metallic rod. This calibration was expected to serve to evaluate a geometric function which was difficult to calculate otherwise. The lack of exact simulation of the metal and the moving gas was easily taken into account in their analysis. According to them it was observed that conductivity distribution $\sigma(\xi)$ (They ignored the effect of radial non-uniformity and the term "distribution" meant axial distribution) could be obtained by solving an integral equation of the first kind with the metallic rod response function $V_e(S - \xi)$ as the karnel, where S is the position of the shock front with respect to the probe at a given time t, and ξ represents the axial co-ordinate of any point with respect to the shock front. It is now worthwhile to describe the constructional features of their probe coil which has got some ingenuity in avoiding the electrostatic effect associated with the shock phenomenon. During the early stages of the coil probe experiment, where a single 80-turn coil was used, electrostatic effects were noticed. During the experiment it was observed that even when the steady magnetic field was put off, large signals were found to pass through the search coil during each shock. This was, as termed by them, was due to electrostatic effects. Actually those pick-ups were due to the formation of finite capacitance between the search coil and the gas inside the shock tube. This is observed by many observers including the present author (Ghosal et al, 1976) and this is termed as stray capacitance effect. To get rid of this effect Lin et al devised a centre-tapped search coil arrangement. The search coil was a 50-turn 8 mm. long single-layered coil made of enamelled wire, the coil was actually made up of two 25-turn coils wound side by side and connected in series (Fig. 1.1). The junction point of the two coils was grounded, and the two ends of the combined coil were connected to the push-pull input of a Tektronix (512) oscilloscope. The value of the shunt input resistance (1000 Ω) was so chosen to give approximately critical damping of the search coil circuit. It may easily be understood from the figure that the capacitive pick-up from the two ends of the coil cancelled out by the push-pull arrangement, while the magnetic pick-up was unaffected. The experimental determination of the electrical conductivity was claimed to have agreed with the limit of accuracy of the theory and the discrepancy at lower temperatures was attributed to the non-equilibrium effects. Latter, Lamb and Lin (1957) took measurements in shock wave air plasma utilizing the same method and the results corroborated with the theoretical predictions.

1.1.2 A few years later K.B. Persson (Persson 1960, 1961) developed a new coil probe method for measuring the conductivity in a high electron density plasma. The theoretical aspect of their technique was endowed with simplicity and elegance which compensates for the technical regour of their measurement method. Here the coil probe was made to send solenoidal electric field into the plasma in order to collect information from inside. This may be termed as active probing in order to distinguish it from the passive probing arrangement of the experiment of Lin et al, where the probe was used as a pick-up device only, making the method unsuitable for stationary plasma. This active coil probe method was based on the interaction between the solenoidal electric field and a circular cylindrical plasma column and this formed a basis to design a pulse-operated bridge suitable for transient measurements of electrical conductivity in high electron density after glow plasma. A cylindrical plasma with rotational symmetry, long in comparison with its radius r_p, was confined within a tube made of non-conducting material. Another tube carried a solenoid which was long relative to its own radius but short in comparison to the length of the plasma column. The uniform pitches of the solenoid were such that the resonance frequency of the coil was much larger in comparison to the probing frequency. The stray capacitance effect was eliminated by applying a thin tin-oxide coating inside the second tubing. The thickness of the shield was so adjusted that the alternating field in one hand could penetrate into the plasma (thickness very small in comparison to the skin-depth at the relevant frequency) and on the other hand the axial electric field associated with the plain solenoid could automatically be short-circuited. The tin-oxide coating was applied in order to ensure that only the time varying magnetic field generated by the solenoid was allowed to penetrate into the plasma. The theory of their measurements was quite straight forward and simple. The magnetic flux generated by the solenoidal plasma currents was easily evaluated since the length of the ineteration zone was large in comparison with the diameter of the plasma. The plasma magnetic field induced a voltage ΔV in the solenoid and could be treated as a perturbation quantity. Quite justly the solenoid and the plasma were considered as a transformer with the solenoid as the primary and the plasma as a one-turn secondary winding with the resistances R_s and R_p and inductances L_s and L_p respectively, and with the mutual inductance M_{sp}, the perturbation voltage ΔV satisfies the differential equation,

$$\left(R_s + L_s \frac{\partial}{\partial t}\right)\left(R_p + L_p \frac{\partial}{\partial t}\right)\Delta V = -M_{sp}^2 \frac{\partial^2 V}{\partial t^2}$$

where V was the voltage impressed on the ~~ø~~ primary winding. The effect of L_p can completely be neglected if skin-depth is assumed to be large in comparison to the diameter of the plasma column and in that case the differential equation which involves the measurable quantity ΔV can be written as

$$\frac{\partial \Delta V}{\partial t} + \frac{R_s}{L_s}\Delta V = -\frac{M_{sp}^2}{R_p L_s}\cdot\frac{\partial^2 V}{\partial t^2}$$

where $\frac{M_{sp}}{R_p L_s}$ may be expressed in terms of the geometry of the arrangement and some plasma parameters, viz., ω_p (plasma frequency) and ν (electron-atom collision frequency) as :

$$M_{sp}^2 / R_p L_s = r_p^2 \langle \omega_p^2 \rangle / 8 r_s^2 c^2 \nu_m$$

where the average $\langle \omega_p^2 \rangle$ was defined as

$$\langle \omega_p^2 \rangle = \frac{8}{r_p^4}\int_0^{r_p} r\,dr \int_r^{r_p} \omega_p^2\, r\,dr$$

In his paper the last differential equation was solved both for sinusoidal and Gaussian-like pulse voltages. The steady state solution obtained for the first case with applied frequency ω was

$$\frac{\Delta V}{V} = \frac{r_p^2\,\omega^2}{8 r_s^2 c^2 \nu_m\left[j\omega + \frac{R_s}{L_s}\right]}\cdot\langle \omega_p^2 \rangle = \frac{\mu_0 r_p^4\,\omega^2}{8 r_s\, j\omega + R_s/L_s}\langle \sigma \rangle$$

where $\langle \sigma \rangle$ defined the suitable average conductivity. A measurement of the ratio $\Delta V/V$ yielded information about the average conductivity. The proportionality constant could not easily be evaluated exactly due to the presence of end effects (though could be done in principle). It was however easily determined experimentally by replacing the plasma with some electrolyte with known conductivity. It is to be noted at this point that this calibration technique utilising electrolytic solutions was used by various authors afterwards.

It was observed that for transient or decaying plasma the continuous sinusoidal probing was accompanied by difficulties. This demanded for low Q of the measurement circuit or higher probe frequency. Neither of the two alternatives could be used without sacrificing the available range for measurements. The difficulty was overcome by replacing the sinusoidal signal V in the last differential equation with a suitable pulse function. This was conveniently done by expanding V in terms of Gaussian function of the form $V_0 \exp[-(t/\tau)^2/2]$. It was shown that the unbalanced signal could be written as

$$\Delta V = -V_0 \frac{R_s}{R_p}\left(\frac{M_{sp}}{L_s}\right)^2 \sum_{i=2}^{\infty}\left(\frac{L_s}{\tau R_s}\right)^i \exp\left[-\frac{1}{2}\left(t/\tau\right)^2\right] \cdot H_i \cdot (t/\tau)$$

where $H_i\ (t/\tau)$ is the Hermite polynomial of the i^{th} degree. It was further shown that the maximum of the unbalanced pulse (when $(t/\tau)^2 = 3$)was most convenient for the measurements on the plasma and hence,

$$\left(\frac{\Delta V}{V_0}\right)_{max} \simeq \frac{9}{\tau}\ \frac{M_{sp}^2}{R_p R_s} \simeq -\frac{9\pi}{8} \cdot \frac{N^2 r_p^4}{R_s l_s \tau^2} \langle\sigma\rangle$$

It is now worthwhile to describe in brief the operation of the pulse-operated bridge designed by the author for measurements in transient plasmas (Fig. 1.2). Two single-layered solenoids were made as identical as possible. They were located symmetrically in separate compartments of a shielding box of brass. One of those solenoids was wound around the tube containing plasma. The solenoids were coupled together forming the bridge which was symmetric with respect to ground or the shielding box. The pulse applied to the bridge was supplied through toroidal ferrite core transformer which was designed to deliver very symmetric pulse with respect to the shield. The current pulse through the primary of the transformer was generated by high current thyratron sweep arrangement. The pulse delivered by the secondary, however, resembled Gaussian pulse (Pulse Width = 1 μ Sec.).

The discharge tube was inserted in one of the solenoids. The bridge constituting the symmetric transformer and the two solenoids and other resistive and reactive elements was balanced by several trimming arrangements. The basic principle on which the operation of the bridge was based was that, provided the bridge is well balanced before hand, it is driven off-balance if the plasma is introduced in one of the solenoids. The resulting resistively unbalanced signal, when observed and recorded, could yield informations of plasma conductivity. The automatic operation and recording arrangements and time adjustments by various triggering mechanisms were explained in his paper. The measurements were made for highly ionized after-glow plasma and the author obtained the temporal conductivity distribution. It was also indicated that linearity of the interaction (together with the electronic circuitry) was checked by the use of electrolytes. It is to be noted here that the use of electrolytic solution for calibration of the coil probe apparatus was also reported by Blackman (1959), a year before the work of Persson.

1.1.8. Blackman, in his paper entitled "Magnetohydrodynamic Flow Experiments of a steady state Nature" described a method in which the inductance of a coil surrounding a plasma is reduced by the shielding effect in the electrically conducting plasma. The reduced inductance increased the frequency of a circuit resonant at about 50 MC and the shift was detected by a radio receiver.

Savic and Boult (1962) intelligently utilized the above idea, that the inductance of a coil surrounding a conducting fluid changes, to devise a frequency modulation circuit for the measurement of gas conductivity and boundary layer thickness in a shock tube. They first theoretically calculated the change of inductance of a short coil due to the presence around its axis of a cylindrical, moving electrically conducting fluid and it was shown by them that the hydromagnetic influence could be kept small. The calibration and design of the frequency modulation circuit was based on those calculations. It was observed that conductivities of gases behind strong shocks in shock tubes could be measured with fair accuracy and adequate time resolution for the detection of local variations in flow structure. A different technique was adopted by Rosa (1961) in his well known MHD experiments in determining the conductivity of a flowing plasma. In his method the coil was embedded in the insulator wall of the MHD generator. The coil was resonated with a condenser at about 300 KHz and the damping of the circuit due to the exhaust of the gas through the insulating tube was measured to determine the gas conductivity. In this experiment also the calibration was effected by placing various salt solutions in the channel.

1.1.4. Olson and Lary (1961, 1962, 1963) suggested a different approach where the coil probe was immersed within the plasma instead of being wound around it. The first two papers (Olson and Lary, 1961, Lary and Olson, 1962) of their series discussed the theoretical aspects of the technique. Their third paper (Olson and Lary, 1962) was concerned mainly with the instrumental methods employed in the measurement of conductivity of the positive column of a hydrogen glow discharge and 4500°F rocket nozzle flow. Later on, immersive coil probe technique was reported by some authors (Moulin and Masse, 1964; Stubbe, 1968 and very recently Jayakumar et al, 1977). In spite of the obvious disadvantages of immersive probe methods Olson and Lary pleaded for some of its advantages. According to them the non-immersive method appeared to be rather insensitive to variations in plasma conductivity and were affected by the properties of the wall surrounding the plasma and by stray capacitive effects. The method described by them was little influenced by electrostatic effects and claimed to have recorded variations of plasma conductivity of as small as 1 mho/m or less. The basic principle involved for this technique was however the same as other methods i.e. this method depended upon the interaction of the conducting fluid with imposed r.f. magnetic field. In particular, r.f. impedance of a solenoid was affected by the presence of a conducting medium in the neighbourhood of the solenoid. In the case of a coil wound around a conductor, the r.f. magnetic field of the coil induces an azimuthal electric field which causes azimuthal current to flow through the conductor. This causes an increase in the apparent resistance of the coil. Similar results are expected to be obtained if the conductor surrounds the finite coil rather than being surrounded by it, as may be verified by applying the same argument to the external return flux. The technique involved the use of small movable probe containing the inductor (coil). Since the magnetic field diminishes rapidly with the distance from the coil, the conductivity in the immediate vicinity of the probe was sampled. The probe could be moved about in the plasma in order to resolve spatial variation of plasma conductivity.

The experimental apparatus designed to record the change in coil resistance as a function of conductivity and impressed frequency had some novelty of its own. The coil probe formed a part of the tank circuit of a Colpitts type oscillator. A vacuum tube supplied the power to sustain the oscillation of the tank circuit. At the on-set of the plasma, power dissipation due to the azimuthal currents induced by the coil in the conducting medium, resulted in a resistive loading of the tuned circuit which changed the grid current of the oscillator tube, the measurement of which was achieved through the use of a grid-dip meter. The grid current varied almost linearly with the power dissipated in the coil conductor circuit. As indicated earlier electrolytic solutions, whose conductivities were in the same range as plasmas were used to calibrate the conductivity probe. The calibration was further verified by the use of semiconductors for double check. First the measurements were made in the positive column of a glow discharge in hydrogen. An 8 mm. (outer dia) probe was immersed in a 25 mm. diameter plasma column. Special precaution was taken to eliminate the heating effect of the coil involving change of coil dimension and resistance, which would otherwise lead to erroneous results. To ensure this the coil temperature was held constant by a cooling flow of dry nitrogen. A thermo-couple was used to monitor the probe temperature. The performance of the coil probe (after suitable modifications) was also investigated for a MHD flow environment. A cool boron nitrite probe was inserted into a subsonic MHD flow with temperatures in the neighbourhood of 4500°F. The same calibration method was used in this experiment also.

1.1.5. Donskoi, Duaev and Prokof'ev (1963) of U.S.S.R. used the same induction technique of non-immersive type to measure electrical conductivity of heated gas streams. The streams were obtained as a result of burning of ethyl alcohol in oxygen containing 0.01% potassium. The pressure in the combustion chamber was maintained at 4 atm. The gas was supplied for 6-12 seconds, thus necessitating semi-transient measurements. The method was based on measurements of the parameters of tank circuit whose coil surrounded the heated gas. According to them when the respective positions of the coil and the plasma stream are kept constant, the parameters of the circuit (effective inductance, circuit resistance, Q factor etc.) depend upon the magnitude and distribution of electrical conductivity over the cross-section of the stream and also on the impressed frequency. Therefore, by measuring the parameters of the circuit for given dimensions of the coil and the stream at different frequencies, one can determine the magnitude and the distribution of electrical conductivity over the cross-section either by calculation or by calibration curves. In practice they have chosen the second method i.e. the non-absolute method as was done by previous authors. It was also assumed by them that distribution of gas streams was uniform. Accordingly they suggested that the observation of the change of one circuit parameter (viz. Q of the circuit) would only suffice to determine the conductivity provided the apparatus was well calibrated beforehand. In actual experiment the tank circuit was fed by a radio frequency oscillator and the output taken from the coil was amplified and fed to the oscilloscope facilitating semi-transient measurements. They thought that the change of output was due to the change of Q-factor only, but in practice the change of inductance and severe capacitive effects might have played an important role. However, since the method was based on previous calibration with electrolytes the results obtained may be expected to be not far from the true values. It is to be noted here that if the capacitive effects were prominent and the stream had a radial distribution, the results would have been far from the true azimuthal value of the electrical conductivity.

1.1.6. Another technique was described by Koritz and Keck (1964) for measuring the electrical conductivity of hypersonic wakes and any other conducting medium by measurement of Joule losses produced by the oscillatory magnetic field of a circular coil surrounding it. The technique was similar in principle to that developed by Lin, Resler and Kantrowitz (1955) to measure the conductivity behind shock waves in argon but the drawback of the passive probing arrangement was removed by substituting it by active probing method (i.e. by impressing radio frequency field to the coil). Consequently the method had the advantage that it may be employed in cases where the medium is stationary. Originally the apparatus was designed specifically to investigate the conductivity in the wake of hypersonic pellets; but later it was also used to measure the conductivity of electrolytic solutions, electrical discharges, flames, and plasmas produced in shock tubes. The results of their measurements for shock wave air plasma was corroborated by that of Lamb and Lin (1957).

The actual circuit consisted of a symmetrical r.f. bridge (The bridge developed by Persson (1961) may be recalled), two arms of which contained identical coils. When a conducting medium was inserted into one of the coils, the effective impedance of the coil changed and the bridge became unbalanced. They chose the probe frequency in such a way so that associated displacement current was negligible and the change of impedance of the coil was entirely resistive. Further for the complete penetration of the field the skin-depth was required to be much greater than the radius r_w of the plasma column. Mathematically the following two relations were satisfied

$$\sigma >> \omega\epsilon \quad \text{(for negligible displacement current)}$$

and

$$\sigma << 2\left(\mu\,\omega\, r_{\omega}^{2}\right)^{-1} \text{(for complete penetration of the field)}$$

where ϵ and μ are the dielectric constant and magnetic permeability of the medium and ω is the impressed frequency. Under the above conditions the change of the impedance of the coil was

$$\Delta R = P/I^2$$

where I is the rms current in the coil and P is the power dissipated in the medium. They studied the coil plasma (conductor) interaction first in a somewhat generalized way and later made relevant approximations. Since they intended to measure the conductivity of wakes behind the hypersonic pallets they considered both the radial (r) and axial (Z) non-uniformity of the conductivity. Thus assuming cylindrical symmetry P was given by

$$P = \int_{0}^{\infty}\int_{-\infty}^{+\infty} \sigma \, E_\phi^2(r, z) \cdot 2\pi r \, dr \, dz$$

where $E_\phi(r, z)$ is the induced solenoidal electric field at any point (r, Z) within the coil. This was calculated in a standard way to yield

$$E_\phi(r, z) = \frac{\mu N}{2\pi} \left(\frac{r_c}{r}\right)^{1/2} k^3 \, C(k^2) \, \frac{\partial I}{\partial t}$$

N, being the number of turns of the coil, $C(k^2)$ is the complete elliptic integral (Jahnke and Imde, 1945) which for small values of K may be approximated as

$$C(k^2) = \frac{1}{16}\pi \left(1 + \frac{3}{4}k^2 + \cdots + \cdots + \cdots\right)$$

where $k^2 = 4 r r_c / [(r_c + r)^2 + z^2]$, r_c being the radius of the coil.

Consequently ΔR may be written as

$$\Delta R = \frac{3}{4 r_c} \left[\frac{\pi \mu \omega N}{4}\right]^2 \int_{0}^{+\infty} \bar{\sigma}(r) \, r^3 \, dr$$

where $\bar{\sigma}$ (r) is some suitable axial average value of conductivity. To interpret the above equation in terms of their measurements they introduced a concept of effective radius $\bar{r}_\omega$

of the conducting column, in terms of which the above equation was written as

$$\Delta R = \frac{3}{r_c} \left(\pi \mu \omega N/16\right)^2 \bar{\sigma}(0)\, \bar{r}_\omega^{\,4}$$

where

$$\bar{r}_\omega = \left[\frac{1}{\bar{\sigma}(0)} \int_0^{+\infty} r^4 \, \frac{d\bar{\sigma}(r)}{dr} \, dr \right]^{1/2}$$

The equation for ΔR is equivalent to a model where

$$\sigma < \bar{r}_\omega = \text{Const.} \quad \text{and} \quad \sigma > \bar{r}_\omega = 0$$

It is interesting to note here that in contrast to others the formulae for ΔR given by them could be used for absolute determination (without calibration) of $\bar{\sigma}(0)$ provided $\bar{r}_\omega$ could be obtained by some other means. Unfortunately they derived the equation only to show that

$$\Delta R \propto \bar{\sigma}(0)$$

and obtained the conductivity results using calibration with electrolytes, the hazard of which was indicated previously (and later it will be discussed in some detail). The measurement of conductivity of stationary plasma was straightforward and simple but the wake measurements were difficult due to the unknown factor r_ω, but previously extensive studies on wake radii measurements were made by Taylor et al (1963) using optical technique, so it was possible to estimate the conductivity from the experimental results, calibration curves and the data of Taylor et al (1963). It was, however, assumed that the wake radius was equal to the plasma radius.

1.1.7. Tanaka and Hagi (1964, 1964); in a couple of papers (appeared in the same issue of Japanese Journal of Applied Physics) re-examined the tentatively adopted conductor approximation for plasma by various authors (viz. Tanaka and Usami, 1962; Gourdin, 1963; Khvashchtevski, 1962, and others mentioned above). Conductor approximation for plasma means that when an electrical a.c. is impressed upon it, the plasma is assumed to offer no resistance and a.c. conductivity essentially becomes d.c. conductivity. In their first paper, they critically analysed the interaction of alternating currents with plasma in general and showed that if the change of magnetic flux through a coil due to a presence of plasma inside it could be measured, the d.c. conductivity is possible to be obtained even in presence of displacement current, for a wide range of frequencies. Their analysis started from the well-known expression for a.c. conductivity ($\sigma_{a.c.}$) for partially ionized non-equilibrium cold plasma (Sengupta, 1961; Heald and Warton, 1965),

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

where m is the electron mass, e the electronic charge, n the electron number density, ν the electron-atom collision frequency and ω is the angular frequency of the applied radio frequency field. In the above equation the imaginary part appears due to inherent plasma reactance. Actually the phase lag which is apparent from the equation is due to the mass inertia. It may thus be seen that the conductor approximation is valid if $\omega << \nu$; in that case,

$$\sigma_{a.c.} = \sigma_0 = \frac{n e^2}{m \nu}$$

whereas for the another extreme case $\omega >> \nu$ the plasma impedance is purely reactive. They also studied the a.c. conductivity for intermediate frequencies where both resistive and reactive parts were dominating. Finally they solved the Maxwell equations in cylindrical form for uniform plasma. It was found that magnetic field* H(r) at any radial position r could be given by the equation

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

where

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

and R is the plasma radius. The reduction of magnetic flux ϕ due to the presence of plasma is evident from the above

---

*According to the authors H(r) is the magnetic field in the radial direction but actually field direction should be longitudinal.

equation for H(r). If ϕ_0 denotes the magnetic flux in the absence of the plasma, the reduction ratio could be written as

$$\alpha = \frac{\phi}{\phi_0} = \frac{2}{\beta R}\,\frac{J_1(\beta R)}{J_0(\beta R)}$$

The relation between σ_0 and reduction ratio ϕ/ϕ_0 was obtained numerically and plotted taking $\gamma = \nu/\omega$ as a parameter. This revealed an "interesting aspect " of the problem. It could be seen from the graphs that the d.c. conductivity obtained from the magnetic flux change is insensitive to the value of the parameter $\gamma = \nu/\omega$. Thus it was argued that provided the successful evaluation of the quantity ϕ/ϕ_0 is known, σ_0 could be determined reliably since no detailed knowledge of ν is required. In the second paper of Tanaka and Hagi, 1964, an example of magnetic flux measurement in the plasma and evaluation therefrom of the plasma conductivity was given. Basically the method was very similar to that of Blackman (1959). The plasma tube was inserted in a single turn coil of a LC oscillator. From the observed shift Δf of the resonance frequency at the onset of the plasma, magnetic flux penetrating the coil was evaluated and finally plasma conductivity was determined. It may be apparent now that all the active coil probe experiments mentioned in this section utilizes the change in either inductance or resistance of coil probe due to insertion of plasma, in one way or other. But theoretically each of them viewed the problem from different angles leading to some uniqueness of every experiment. Tanaka and Hagi viewed the inductance change effect in a different manner. According to them if plasma is conductive, the applied solenoidal r.f. field will induce eddy currents which will flow around the plasma dissipating energy in the region where they flow, by which magnetic flux is excluded from that region. The argument is similar to that given for the physical significance of skin effect. Thus the effective inductance of the network is reduced, resulting in a change in resonance frequency.

Measurements were carried out for two hot cathode type discharge tubes, one filled with 1 torr of argon and the other with 8 torr of neon. An ordinary Hartley type LC oscillator (frequency range 100-150 MHz), with a single turn coil, was employed. The radius of the coil (2.25 cm) was kept much larger than the radius of the discharge tube in order to minimize the stray capacity between the coil and the tube. The coil output and the output from a standard signal generator was fed to a mixer circuit (Fig. 1.3). The resonance frequency shift Δf due to the insertion of the plasma tube in L was then determined by observation of the beat between the oscillator signal and the standard signal. The observed frequency shifts Δf for different discharge currents were given in Figs. 1.4(a) and 1.4(b) from which it could be observed that in accordance with their theoretical prediction Δf was found to be positive and increasing with the discharge current I_p, as long as it was in the Ampere range. But it was also observed (not shown in the figures) that for extremely small values of I_p, Δf was found to be negative. Previously the same author (Tanaka and Usami, 1962) observed the negative change in 'f' more markedly in the case of a fluorescent lamp. According to them the observed negative change in 'f' is an open question. However the present author's comment on this observation will appear in the introduction of the next chapter. As may be seen below this effect was also discussed by Akimov and Konenko (1966) and Hausler (1967) quite at length.

To determine conductivity from the knowledge of Δf they obtained on the basis of a simple model of uniform plasma, the relation between the flux reduction factor and Δf as

$$\frac{\Delta f}{f} = K' \frac{S_1}{S_1 + S_2} \left(1 - \frac{\phi_1}{\phi_0}\right)$$

where $(S_1 + S_2)$ represents the cross-sectional area of the coil, S_1 being the central area occupied by plasma and S_2 the remainder, and ϕ_0 and ϕ_1 represent the magnetic flux penetrating S_1 before and after insertion of the plasma respectively and K^1 is a constant characteristic to the apparatus used. They did not at this stage utilize the usual calibrating technique using electrolytes and semiconductors to avoid the unknown factor K^1, instead determined it using a tricky method.

In order to determine K^1, aluminium foils in the shape of cylinder of various diameters were inserted in the coil. Since the skin depth was of the order 10^{-3} cm. for aluminium at the relevant frequency, the magnetic field was completely excluded out of the area S_1.

Hence $\phi_1 = 0$

and $$\frac{\Delta f}{f} = K' \frac{S_1}{S_1 + S_2}$$

Thus K^1 was found to be 0.2.

According to the present author, however, this method, was also a calibration method in another form, and since no guard was taken against the formation of capacitance between the coil and the aluminium foil, in all probability Δf values were obtained with severe uncertainties. Further, the criticism made by the authors against the calibration methods adopted earlier may be said to be applicable to their own method also. The major discrepancy observed between the conductivity results obtained by standard probe method and the coil probe method may be due to this; There should, however, remain intrinsic discrepancies between the results obtained by two different techniques. This may be understood (Chapter IV) if the effect of radial distribution of conductivity is taken into account.

1.1.8. It is now relevant to mention a very important work of Akimov and Konenko (1966) who investigated the validity of the two similar well-known coil probe methods for measuring plasma conductivities and also explored various other possibilities. Though they particularly discussed the work of Blackman (1959) and Donskoi et al (1962), their comments are also applicable to those who studied electrical conductivity by observing either change in resonance frequency 'f' or change in quality factor Q of the oscillator coil in which the plasma was inserted. In almost all these experiments in order to calibrate the apparatus, the plasma was replaced by electrolytes with known conductivity and made use of the calibration curves ($\Delta f = \Delta f(\sigma)$ or $\Delta Q = \Delta Q(\sigma)$) thus obtained. Akimov and Konenko, following their own observation questioned the reliability of this calibration method. The experimental apparatus, similar to that of Tanaka and Hagi (1964), consisted of a Colpitts oscillator used to excite the tank circuit, standard frequency (r.f.) generator and a mixer. The frequency shift was measured by the observation of beats. The measurements were made in electrolytes and in the positive column of an argon-mercury gas arc lamp. They obtained the quantity $\Delta f/f_0$ ('f_0' being the frequency of the oscillator before insertion of the test object) for electrolytes of different conductivities and also for plasma at different discharge currents enabling them to plot conductivity versus $\Delta f/f$ graphs

(Fig. 1.5) both for electrolytes and plasmas. The plasma conductivity was obtained by ordinary probe measurements. It may be observed from the figure that in contrast to the prediction of Tanaka and Hagi (1964) (but in conformation with experimental observations) the test object in the coil can decrease the oscillator frequency for some ranges of conductivities. According to the authors and also according to Hausler (1957), the reduction of frequency was due to the capacitive effect of the test object on the work coil. The presence of conducting body in the vicinity of a coil increases its stray capacity (see chapter III also) and consequently the oscillator frequency decreases. Another aspect may be observed from the graphs that the plasma and its simulating electrolytes do not have the same effect on the measurement circuit. The discrepancy between the plasma conductivity averaged over the cross-sections and the calibrating curves was attributed by them to the radial non-uniformity of the plasma in the arc. According to them, due to the skin effect, the method gives informations of the peripheral region of the plasma only where the conductivity is much smaller than the average value, but according to the present author even if the skin depth is much larger than the plasma radius the discrepancy is expected to remain, since probe method and coil method give information on moments of conductivity distribution of different orders (see chapter IV).

1.1.9. All the authors (mentioned above and also others viz. Hollister (1964), Murine and Bonomo (1964), etc.) using immersive or non-immersive coil probes determined in some way the average plasma conductivity because test plasma was radially inhomogeneous. Some of them, though aware of the fact that the test plasma was radially non-uniform, did not explore the type of average they were getting. The importance of the work of Ciampi and Talini (1967, 1969) lies in the fact that they studied the interaction of solenoidal electric field with a radially non-homogeneous plasma in a very generalised way and obtained the expression for meaningful averages of conductivity in relevance to the measurement techniques adopted by themselves or by earlier authors. The average was defined to be the conductivities equal to that of a fictitious homogeneous plasma imagined, the insertion of which into the coil would produce the same change of coil impedance parameters, that is observed for the true plasma. Since normally in the experiments both the change of inductance and resistance of the coil are measured, they obtained the expressions for two relevant average conductivities. For this they first expressed 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) and also in terms of the applied frequency ω, coil inductance λ etc. as,

$$Z = \left(8\pi^2 N^2 R/c\ell\right)\left(E_R/H_R\right) = i\omega\lambda s$$

where the parameter

$S = \left(2/i\mu K_0 R\right)\left(E_R/H_R\right)$, K_0 being the wave number, is generally a complex number depending on the medium characteristics and the probing frequency. The physical significance of the term S $(= \beta - i\alpha)$ is that it signifies the algebric reduction of the coil impedance due to the presence of the conducting fluid. This quantity may be experimentally determined, β represents the contribution of the medium to the coil inductance and α the resistive contribution due to the energy loss in the medium. To express the dependence of 'S' on the characteristics of a radially inhomogeneous medium, the Maxwell's equations were solved using cylindrical co-ordinates to obtain the equation

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

where the dimensionless quantity

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

is same as the quantity $(\beta\gamma)$ defined by Tanaka and Hagi (1964). It may easily be observed that for homogeneous plasma i.e., for $\sigma'(r)$ = Const., [$\sigma'(r)$ being the r.f. conductivity] the equation for 'S' reduces to

$$S = 2J_1(K)/K J_0(K)$$

which may now be compared to the expression obtained by Tanaka and Hagi (1964) (equation 4 of the first paper) and consequently 'S' represents in that case of the so called flux reduction ratio.

They solved the problem (i.e. the differential equation given above) numerically by taking the conductivity profile of the form

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

They analysed the dependance of S with conductivity σ_0 for different values of m and n i.e. for various conductivity profiles. In their analysis they however, made a low frequency approximation i.e. $\omega/\nu \ll 1$, so that the effect of displacement current could be neglected and therefore the r.f. conductivity $\sigma'(r/R)$ was replaced by the d.c. conductivity $\sigma(r/R)$. It was argued that if the conductivity profile is known beforehand, a measurement of α or β at any frequency gives the value of the on-axis conductivity σ_0 . It was also observed that for unknown profiles the α, β measurements could give informations about the plasma conductivity through data which are proportional to σ_0 . This observation was found to be valid for some range of σ_0 . It seems that the physical significance of this range of σ_0 in their derivation was a bit obscured. However, to the present author, the range of σ_0 is actually determined by the requirement of complete skin penetration of the r.f. field at the measuring frequency. Hence in the mentioned σ_0 range, the measurement of $\alpha(\sigma\ 1-\beta)$ for the unknown plasma and for a homogeneous medium of conductivity $\bar{\sigma} = k\sigma_0$ gives the same result at any frequency. Therefore, according to them with, reference to a resistive (or inductive) measurement the plasma "Simulates" a homogeneous medium and $\bar{\sigma}$ can be interpreted as a spatial average conductivity. Thus two averages σ_* and σ_{**} were obtained according to the resistive and inductive measurements respectively : $\sigma_* = \frac{4}{R_4}\int_0^R \sigma(r)\, r^3\, dr$

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

Experiment was performed for a flow facility plasma utilizing Q-factor measurements and employing calibration with electrolytes (H_2SO_4 solutions) to obtain the first average conductivity σ_* . Later they (Ciampi and Talini, 1969) extended the theory and measurements taking the effect ~~and~~ of collision frequency into account.

With due regard to the depth of the theoretical aspects of the problem treated by Ciampi and Talini, it is felt by the present author that the expression of the two meaningful averages and the relevant frequency and conductivity ranges could be obtained in a more simpler way, by considering the probe coil and the conducting medium to form a transformer (Ghosal et al, 1976, 1978), the primary and the single-turn secondary being the coil and the medium itself respectively. In this way the average σ_* was obtained yielding the same result (using equation (2) of reference Ghosal et al 1978) given by Ciampi and Talini. It is also observed, though not reported, that in the same way the expression for σ_{**}^2 could be obtained. Further, withholding the consideration of the sensitivity, accuracy and difficulty of the measurement technique, the frequency and conductivity range doublets could also be obtained by simple arguements by requiring that ω should be very small compared to the collision frequency so that the displacement current may be neglected (i.e. r.f. conductivity = d.c. conductivity) and σ should be sufficiently small so that the skin depth is very large compared to the plasma radius.

1.1.10. It is also felt in conjunction with the observations of Stokes (1968, 1969) that on the basis of average conductivity model no information concerning the nature of the conductivity profile could be obtained from the Q-factor measurements alone, and in fact a completely false picture of the character of the conducting region such as peak conductivity and the effective extent of the conducting region, can be obtained if the measurements are interpreted in terms of an average conductivity model. (See also Chapter V of the present thesis).

As for example, for profiles of the type treated by Ciampi and Talini, the difference between the azimuthal average and the on-axis 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 aforementioned factor may be extremely high. Further the choice of the profile demands that the plasma fills the available volume; this may be a valid assumption for an ordinary discharge plasma but the assumption will be fatal for other situations such as solid metal arcs, flow facility plasma, plasma jets, etc. In these cases the errors can be very much greater since the plasma conductivity may fall to zero some distance away from the confining wall. Temperature measurements on an argon plasma jet made by Moskvin and Chesnokova (1965)* indicate a peak conductivity of roughly 3000 mho/m, falling approximately to zero at a radius of about 3.3.mm. Stokes (1969) theoretically calculated the azimuthal average that should be obtained for the Moskvin-Chesnokova plasma stream to be exhausting along a 2 cm. diameter tube. This is given to be approximately 100 mho/m. Thus it is seen that the on-axis conductivity is 30 times larger than the apparent average. Given below are also the results obtained by the present author (Ghosal et al, 1978) for the azimuthal average $\overline{\sigma}_{\phi}$, volume average $\overline{\sigma}_{vol}$ and the on-axis conductivity σ_0 of a mercury arc plasma for direct comparison.

Table 1.1

Discharge current I (amps)	$\bar{\sigma}_\phi = \frac{4}{R^4}\int_0^R \sigma(r)\, r^3 dr$ (mhos/cm)	$\bar{\sigma}_{VOL} = \frac{2}{R^2}\int_0^R \sigma(r)\, r\, dr$ (mhos/cm)	σ_0 (mhos/cm)	$\sigma_0/\bar{\sigma}_\phi$	σ_0/σ_{VOL}
2.1	0.89	1.90	6.26	7.03	3.29
3.1	1.26	3.70	18.05	14.32	4.88
4.0	1.78	5.33	26.55	14.91	4.98
5.0	1.94	6.01	31.00	15.72	5.07

It may be observed from the above table that at 5 amps. discharge current the on-axis conductivity can be about 16 times the azimuthal average value.

However, the use of induction probing for measuring plasma conductivities, is by no means as fruitless as would appear from the above comments, instead the method can be fruitfully utilized to determine major characteristics of the plasma if the aforementioned measurement is supplemented with additional information using an approach of the present author (Ghosal et al, 1978, Chapter IV and Chapter V of the present thesis) or that of Goldenburg et al (1964).

1.1.11. In the preceding sections methods for determination of average azimuthal electrical conductivity have been discussed where the effect of plasma medium on either the coil resistance or the probe coil inductance was utilized for the purpose.

Mikoshiba and Smy (1969), on the other hand described a newer approach of measuring plasma conductivity by utilizing the dependence of the mutual inductance of two coils upon the conductivity of the medium lying between them. Out of the several advantages of the method highlighted by the authors in their paper, it seems to the present author that, "that it can be used over a continuous and wide range of frequencies with the result that a very wide range of conductivity can be measured (to 10^6 mhos/m)" is the most significant one. This improvement is the outcome of the inherent sensitivity of their apparatus which was not endowed with other electronic accessories. In the former type of single coil measurements the reflected impedance of the oscillator coil was small and sensitivity was usually achieved by using mixing techniques or "Q spoiling methods". With the two coil method described by these authors, one coil acts as a transmitter, the other as a receiver. The signal induced by the receiving coil is much less than that applied to the transmitting coil with the result that the relative reaction of the induced currents upon the receiver coil is much more pronounced and a very simple measurement of signal attenuation is sufficient for conductivity measurement.

The two coil technique was developed in order to measure the conductivity of a shock precursor plasma. The necessary theory was developed by considering a shock tube geometry with two radial conductivity distributions that might be expected in a precursor plasma, viz., uniform and annular conductivity profiles. Depicted in the diagram (Fig.1.6) are the coil configurations as used by them. The field coil consisted of one turn. Multiturn was avoided due to the appearance of undesirable resonance arising from winding capacitances. Field coil loading due to the presence of plasma in the immediate vicinity was minimized by connecting a suitably large resistor in series with the coil. The output was taken from a similar single turn search coil and was fed directly to oscilloscope probe (high input impedance). Stray capacitive effects were also observed by them, particularly at high frequencies. To solve this problem, a second search coil of similar construction to the first search coil was placed on the other side of the field coil with respect to the first one and both search coil signals were fed into a difference amplifier. Though it suffers from the weakness that the conductivity results are some sort of averages depending on the choice of the conductivity distribution model, the work may be said to be a significant advancement to other methods (discussed in earlier sections) in that it needs no calibration and also in that it provides a very wide range of measurable conductivity.

1.1.12. Basu and Maiti (1973) elaborately studied the non-immersive coil probe method for a hot-cathode low-pressure d.c discharge plasma where the electron atom collision frequency is comparable to the probe frequency. The situation corresponds to the case where the conductor approximation is no longer valid and the plasma is characterised by a complex conductivity $\sigma_r + i\sigma_i$. Tanaka and Hagi (1969), as discussed in article 1.1.7 was the first who focussed particular attention to the problem of coil probe conductivity measurements on plasma which shows impedance characteristics at working frequencies; but the problem of Tanaka and Hagi was how to obtain the "d-c conductivity" when the imaginary part of the conductivity is non-zero. However, the intention of Basu and Maity was different. They obtained both the real and imaginary part of the plasma conductivity by measuring the two parameters (instead of one, as done by Tanaka and Hagi) viz. resistive and inductive parts of the reflected impedance of the probe coil.

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

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

where v is the electron velocity, $f_0(v)$ is the equilibrium distribution function, ω is the angular frequency of the applied r - f field, $\nu(v)$ is the electron atom collision frequency of momentum transfer etc. The authors considered two situations where ν is independent of electron velocity and where ν is dependent on v. In the first case the above equation can readily be simplified to yield :

$$\sigma_r = i\,\sigma_i = \epsilon_0 \omega_p^2 / (\nu^2 + \omega^2)$$

For the second situation also ($\sigma_r + i\,\sigma_i$) satisfies the last equation if ν is replaced by some suitable effective momentum transfer collision frequency ν_{eff}. It was shown by them that both ν_{eff} & N (electron density) can be expressed in terms of two parameters α & β which are proportional to the real part and imaginary part of the coil impedance in presence and in absence of plasma respectively. They obtained the following relations :

$$\nu_{eff} = \omega\alpha / (1-\beta)$$

and $$N = \frac{8\,m}{e^2 \mu_e^2 a^2}\left(1-\beta+\frac{\alpha^2}{1-\beta}\right)$$ a being the radius of the plasma column.

Experimentally they measured the resistance and reactance of the coil with a Q-meter used in conjunction with a low power r-f oscillator. Measuring the Q of the coil and noting the capacitance required for tuning the circuit both in presence and in absence of plasma it was possible to obtain two important plasma parameters ν_{eff} and N

Though theoretically the two cases, where ν is independent of electron speed v and where $\nu = \nu(v)$, were considered quite at length, the present author notes that it was overstressed since the experimental observations cannot distinguish the above two situations and the observed collision frequencies are always the effective momentum transfer collision frequencies in some way or other. Besides, the expression of ν_{eff} and N were derived on the basis of uniform conductivity model which is far from being true in most cases. They were of course self-conceited by stating that these obtained parameters are the values averaged over the cross-section of the plasma, but proper understanding is only possible provided the nature of these averages are known theoretically. However, if the conductivity profile is known beforehand by some other means the above approach after little modification might yield more meaningful results.

(B) REVIEW OF THE PREVIOUS WORKS II

1.2 PLASMA WAVES : COLD AND WARM PLASMAS

It is generally known that a plasma has the character of a quasi-neutral elastic medium in which any perturbation which brings about a deviation from the equilibrium state gives rise to various types of oscillations and waves in the plasma revealing a great deal about the state and the nature of the plasma. Especially magnetic plasmas are enormously rich in wave phenomena. That there are various wave modes which can propagate through a plasma medium results from the fact that at least two distinct species viz. ions and electrons are present and there exists varieties of driving and restoring forces namely, electric and magnetic forces, pressure gradients, viscosity etc. in a plasma medium.

Theoretically, in principle, the existence of all the wave modes, the dispersion relations, non-linearities and other properties perhaps could be obtained but no such general theory is available due to severe complexity of the problem. However, the existence of different wave modes in the plasma and their dispersion relations may be obtained and best understood in several idealised conditions. One of the most popular idealization is commonly known as cold plasma approximations. By a cold plasma it is meant, one in which the ordered motions of the constituent particles are very large in comparison to thermal (random) motions of the particles and while the later may be neglected. Consequently one can describe a cold plasma by a fluid theory. The warm plasma waves on the other hand is the subject of plasma waves in regimes where thermal motions are important. For complete description, of warm plasma waves a more microscopic point of view is required than is allowed in a fluid model, nevertheless, surprisingly enough, a thorough view of plasma waves in warm plasma is obtainable through fluid models. A dimensional analysis of the warm plasma wave equations shows that the cold plasma approximation requires (Sanderson 1974).

$$\left(\frac{kT}{m}\right)^{1/2} << \omega/k \qquad \ldots (1.1)$$

where m and T are the mass and temperature of the particles k is the Boltzmann's constant and ω and k are the frequency and propagation constant of the wave. For studying the cold plasma waves the starting fluid equations are

(i) continuity equations

$$\frac{\partial n}{\partial t} + \nabla \cdot (n\vec{u}) = 0 \qquad \ldots (1.2)$$

(ii) momentum transfer equations

$$nm\left(\frac{\partial}{\partial t} + \vec{u}\cdot\nabla\right)\vec{u} = ne\left(\vec{E} + \frac{\vec{v}\times\vec{B}}{c}\right) \ldots (1.3)$$

which are supplemented by Maxwell's equations. The starting equations are obtained from the collisionless Boltzmann equation (Vlasov equation)

$$\frac{\partial f}{\partial t} + \vec{v}\cdot\frac{\partial f}{\partial \vec{r}} + \frac{e}{m}\left(\vec{E} + \frac{\vec{v}\times\vec{B}}{c}\right)\frac{\partial f}{\partial \vec{v}} = 0 \quad \ldots (1.4)$$

by taking zero and first order moments. As just mentioned, the plasma state is enormously rich in wave phenomena (even for cold plasma) and variety of classification schemes have already been devised (Stix 1962) to facilitate the cataloging of plasma waves. Since the normal modes of the plasma is strongly influenced by the plasma and field configurations a broad catagorization of plasma waves may always be made according to the state (field (B) free or field (B) embedded) of the plasma that supports the waves. Solution of equations (1.2) to (1.4) after linearization and using Maxwell's equations corresponds to electromechanical oscillations at the plasma frequency. Such oscillations are called by various names (Krall and Trivelpiece 1973) : Langmuir oscillations, plasma oscillations and space charge waves are the terms most commonly used. Since the calculation is based on cold-plasma approximation the properties of these oscillations do have some interesting features :

(a) Langmuir oscillations are dispersionless in a cold plasma.

(b) They do not propagate in a <u>stationary</u> cold plasma because, for a dispersionless wave, the group velocity $V_g = \partial\omega/\partial k$ is zero. Even though these oscillations do not propagate, they possess a phase velocity $V_p = \omega/k = \omega_p/k$.

(c) For a drifting cold plasma, however, it is seen that the Langmuir oscillations possess propagation characteristics.

(d) For a cold field-free plasma there is only one characteristic frequency $\omega_p = \omega_{pe}\sqrt{1 + m_e/m_i}$ where ω_{pe} is the so called electron plasma frequency $\left[\left(\frac{4\pi n_e e^2}{m_e}\right)^{1/2}\right]$ with no separate resonance at the ion-plasma frequency $\left[\omega_{pi} = \left(\frac{4\pi n_i e^2}{m_i}\right)^{1/2}\right]$

The cold plasma theory is valid provided the plasma is "cold" in the sense of approximation previously mentioned (equation 1.1); this approximation obviously breaks down where the phase velocity tends to zero. Consequently the wave modes having smaller phase velocities cannot be predicted according to this gross idealization. However, some finite temperature modification of the theory, but still within the confines of a fluid description, may be made in several circumstances (warm plasma). This may be done by supplementing the fluid equations by some equation of state, and precisely here lies the fundamental difference between cold and warm plasma theory. The insertion of the equation of state immediately releases the above mentioned oscillation modes into dispersive propagating modes and also predicts a new propagating wave mode called ion-acoustic mode. It must be noted however, that although the addition of equation of state is a step-forward towards realism, the fluid equations give an incomplete picture of warm plasma wave motion as for example it cannot predict Landau damping (Landau, 1945) which, physically, is the out-come of strong interaction of the thermal electrons with velocities of the order of the phase velocity of the space charge wave. Nevertheless, the plasma physicists are fortunate enough to observe that so far as the plasma waves are concerned, gross idealizations in any level of the theory have not divorced theory from experiments. Experimentalists always meet with situations where their plasma may be taken to be ideal in one form or other (so far as the wave propagation is concerned). Precisely for this reason the study of wave propagation leads to very important plasma diagnostic methods.

1.3. IONIC OSCILLATIONS

As mentioned earlier the warm plasma sustains, in contrast to cold plasma, propagating wave modes for Langmuir oscillations and also another new wave called ion-acoustic wave is predicted on the basis of warm plasma theory and also it is observed that there are ion plasma oscillations where the electrons provide a neutralizing background for these oscillations. These wave modes, first properly theorised by

Langmuir (Langmuir, 1926; Tonks & Langmuir, 1929), were observed by many authors (Penning, 1926; Pardue & Webb, 1928; Fox, 1930; Chow, 1931; Brown & Cowan, 1931; Appleton, 1923) including Tonks and Langmuir (1929). All these authors studied ionic oscillations only (not the propagating modes i.e. the ion-acoustic waves). As for example Appleton (1923) observed ionic oscillations from a striated discharge. Pardue and Webb (1928) took up their experiments on ion oscillations in an effort to correlate Whiddington's work (Whiddington, 1925) on moving striae and Appleton's work on ionic oscillations. The discharge tube was of the hot cathode type, 3 cm. in diameter and 26 cm. long. The oscillations were detected by capacitive and inductive (Series and parallel)pick-up. The frequencies observed by them were in the range from 15×10^4 to a few hundred cycles. These frequencies were found to be dependent on anode potential, pressure and filament current and the oscillations were believed to be ionic (because of the frequency range). The correlation of the ion oscillations and the striations observed by them was purely empirical and there results are now not worthwhile to mention. The outline of the theory of ionic oscillations as presented by them was due to personal contact with Langmuir. Langmuir's theory of ion waves first appeared in Proceedings of National Academy of Science (Langmuir, 1926). Later Tonks and Langmuir (1929) presented the theory of ion waves more elaborately, while presenting a work on "oscillations in Ionized Gases". In their paper simple theory (fluid theory was implicit) of electronic and ionic oscillations of ionized gas was developed. The electron oscillations, they assumed, are so rapid ($\simeq 10^9$ Hz.) that the heavier positive ions are unaffected. The natural frequency of the oscillation was given by $\nu_e = (ne^2/\pi m_i)^{1/2}$ and except for secondary factors (beam property of electrons) these were found not to transmit energy (i.e. non-propagating). The ionic oscillations were assumed to be so slow that the electron density had its equilibrium value at all times. For shorter wave-length, oscillations approach the natural frequency $\nu_i = \omega_i/2\pi = \nu_e(m_e/m_i)^{\frac{1}{2}}$ as upper limit. The oscillations of longer wave length were found to be similar to sound waves (presently known as ion acoustic waves) the phase velocity v_p approaching the value $(kT_e/m_i)^{\frac{1}{2}}$, where T_e is the electron temperature. The lower limit of wave length for these ion-sound waves were argued to be proportional to Debye Shielding distance λ_D (Debye and Hückel, 1923). The experiment was performed for hot cathode type mercury discharge plasma and the oscillations were detected with a zincite-tellurium detector. Experimentally three groups of oscillation frequencies were observed : (i) 300-1000 MHz, (ii) 50-60 MHz, (iii) 1.5 MHz and below. The first two groups were believed to be electronic oscillations for ultimate and beam electrons respectively and the third group of oscillations were attributed to positive ion oscillations. However, in their paper no explanation of the cause of these oscillations were given.

After the appearance of Tonk's and Langmuir's theory several authors (Fox, 1930; Chow, 1931; Brown & Cowan, 1931 etc.) reported their results of experiments on plasma oscillations in the light of Tonk's and Langmuir's theory. Chow (1931), in the course of an experiment to determine certain quantities (not related to oscillations), encountered the difficulty that the voltage across the tube was not constant. After an unsuccessful attempt to eleminate this fluctuations, he thought it was desirable to investigate the phenomenon in detail and naturally the interest was shifted to plasma oscillations. As mentioned earlier the phenomenon of travelling striations (studied by Aston and Kikuchi (1929) and Whiddington (1925) is accompanied by oscillations (Pardue and Webb, 1928; Fox, 1930 and others). In the paper of Chow a few more points were reported concerning travelling striations and oscillations in the positive column of an argon discharge. A set of wave lengths bearing simple relations with the length of the tube were calculated by means of Tonk's and Langmuir's theory of ion waves. Here mention must be made of the work of Brown and Cowan (1931) who first observed ionic oscillation in cold cathode discharge with the help of oscilloscopes and the results were found to check up satisfactorily with tests made by other methods by Emelěus(1927).

1.4 ION OSCILLATIONS AS TRAVELLING WAVES

All the experiments mentioned above, studied ionic oscillations through discharge plasma. In fact the existance of electrical oscillations occurring in electrical discharges in gases at low pressures has been known for many years. These oscillations may be grouped into two broad classes, of essentially different character. The frequency of the first group is found to be dependent on the constants of the external circuit used to maintain the discharge, such as capacity-resistance oscillations for the generation of which the discharge tube mainly acts as electronic valves for maintaining and controlling the fluctuations of potential in the external circuit. The second kind on the other hand are due to the properties of the ionized gas itself and credit must be given to the above mentioned experimenters who were able to sort out the first kind of oscillations from the true plasma oscillations (which were identified as ionic oscillations) and unknowingly opened a potential area of plasma diagnostic techniques (Sessler & Pearson, 1967) and also of other fields. Nevertheless, however, as regards the ion acoustic waves the main credit must go to Revans (1933), for his experiments in which he for the first time observed the oscillations manifested themselves as travelling waves. This was effected by a considerable improvement of the apparatus that was used by earlier workers. He made use of a movable probe to detect the travelling wave behavior of the ion oscillations. Revans studied the oscillations in one hand for a hot cathode mercury vapour discharge in a spherical enclosure and on the other hand for a similar discharge plasma in a long cylindrical tube. It was observed that when oscillations set in (this depended on filament current and anode potential) the electron temperature increased remarkably, and the frequencies present seemed to consist of a fundamental and a long series of harmonies. The fundamental was found to be independent for wide range of voltage and current variations and it was found to be in good agreement with that calculated on the basis of Sir J.J. Thomson's theory. It was shown by Sir J.J. Thomson that travelling waves with velocities lying between $(kT_i/m_i)^{\frac{1}{2}}$ and $[(kT_i + kT_e)/m_i]^{\frac{1}{2}}$ can be propagated through an ionized gas where the different terms are of usual significance. The electron oscillation mode was neglected. When the frequency is much less than the electron plasma frequency $\omega_e = (n_e^2/\pi m_e)^{\frac{1}{2}}$, the ion waves travel with a velocity $[k(T_i + T_e)/m_i]^{\frac{1}{2}}$. When $T_e \gg T_i$ the velocity reduces to $(kT_e/m_i)^{\frac{1}{2}}$. It is to be noted here that the same result was obtained earlier by Tonks and Langmuir (1929).

All the experimental observations led Revans to conclude that the glow was vibrating as a whole in a manner similar to the air in a Helmhottz-Resonator, the frequencies of the fundamental and the harmonies of which were determined by the container size and speed of the ion sound waves. Spontaneously excited electro-acoustic waves of the type predicted by Tonks and Langmuir (1929) were observed, in a range of gases, later after a long time following Revans by many authors (viz. Crawford and Lawson, 1960; Crawford, 1961; Geller and Lucerain, 1961; Crawford and Muhler, 1966; Frank et al, 1947). In a diagnostic experiment Emelĕus (1956) observed some low frequency fluctuations occurring in the parameters of a d.c. discharge and it was suggested that existence of spontaneously excited ion waves might be the source of it. To test this hypothesis Crawford (1961) studied d.c. mercury vapour discharges at very low pressure ($\simeq 10^{-6}$ Torr) in specially designed tubes. The dimensions of the tubes were chosen comparable to the electron-neutral collision mean-free-path so that the collisionless approximation could be said to be valid. Spectra of anode voltage fluctuations were observed to contain peaks varying slowly with current. Measurement of phase shifts was attempted which indicated the order of magnitude of the velocity of the travelling fluctuations. The results suggested that the ion-acoustic wave mechanism might be operating and that it was being enhanced by the presence of constriction. Of the two modes observed by Crawford (radially varying and azimuthally varying modes) the azimuthally varying mode was found to be excited very strongly and the phenomenon was put as an open question. To determine the compression ratio γ very accurately, he modified the Tonks-Langmuir formula for dispersion relation by including the axial and radial drift velocities of the ions and electrons.

A series of experimental works on spontaneously excited ion waves was done by Alexeff and his collaborators (Alexeff and Neidigh, 1961a-d, 1963, Alexeff et al 1962). In one of the earlier papers (Alexeff and Neidigh, 1961a) the existance of ionic sound waves in a magnetically supported plasma column was reported (in the same year other standing wave modes in a plasma column were seen to be reported by Consoli et al, 1961). Later Alexeff and Neidigh (1961b) analysed the data from the discharge experiments of Crawford, (1960) and were shown apparently to exhibit ionic sound waves. Additional work by Crawford (1961) mentioned earlier, with further correlations by Alexeff and Neidigh (1961c) confirms this analysis. An investigation of standing ion-sound waves in spherical discharge spaces was also made by them (Alexeff and Neidigh, 1961d). In this context the work of Gellen and Lucerain (1961), who observed standing ionic sound waves in a spherical plasmoid, may also be referred. In the following year the gas damping of spontaneously excited ion-sound wave modes was utilized to estimate the gas pressure in an arc type ion source of a magnetic isotope separator by Alexeff et al (1962). Precisely this work may be said to be the first experiment on plasma diagnostics utilizing the behavior of ion-acoustic waves in plasma. Later the authors (Alexeff and Neidigh, 1963) reported an extensive observations of ionic sound waves in plasmas and on the basis of those observations some parameters of the plasma were successfully determined. Self-excited oscillations were observed both in magnetically supported plasma columns and in spherical discharge tubes. The fundamental frequency and harmonics of each system agreed with those predicted by the ionic sound wave formula (developed by them) in terms of the electron temperature, the ion mass, and the dimensions of the system. A simple equation was used to predict when damping by the background neutral particles prevented a given mode of plasma oscillation from being observed. They also observed a very interesting resonance effect between the ionic sound and the ion cyclotron frequency in the magnetically supported plasma column. The electron temperature of a plasma was found by measuring the frequency of a standing ion-wave mode, and as was done previously (Alexeff et al, 1962) the neutral gas density was estimated by observing the gas damping of various standing ion-wave modes.

1.5 EXTERNALLY EXCITED ION-ACOUSTIC WAVES

Uptill now a brief review on the experimental observations of spontaneously excited ion acoustic waves in plasmas has been made. During the beginning of the seventh decade another series of experiments came in existence where the properties of ion-waves were studied by exciting these waves externally in plasmas (Vasil'eva et al, 1959; Hatta and Sato, 1961; Little 1961; Liperovski, 1961; Wong et al, 1962, 1964; Wong, 1965; Crawford and Self, 1963, etc.). The dispersion of these waves was studied much conveniently since the waves were generated by external sources. Hatta and Sato (1961) were able to excite ion-sound waves in a weakly ionized dark plasma, electrostatically by the use of a meshed grid. In order to get the waves in reduced background noise they chose the dark plasma of the so-called 'anode glow mode' (Malter et al, 1961) discharge with a hot cathode as the medium for the propagation of ion-waves. In order to excite the ionic wave in the dark plasma sinusoidal voltage of small amplitude was applied to the grid. The variable voltage affected the amount of ion supply from the anode glow space and modulated the ion density near the grid. Consequently, the ionic density wave seemed to be excited and propagated along the dark space. To detect the plasma density fluctuations due to the wave propagation they made use of a movable Langmuir probe. Because the medium was weakly ionized the ion-wave was found to be damped due to collisions between ions and neutral atoms. Theoretically a two fluid description was given including ion-neutral collisions. Experimental results obtained therein showed good agreement for measurements of phase velocity at higher frequencies. The dispersion relation, however, seemed to be apparently inadequate to explain the results for lower frequencies. This discrepancy was not explained by them. Later Sanderson (1974) also kept this discrepancy as an open question. (However, this may be explained in the following way : For their measurements Hatta and Sato did not possibly consider the possibility of forming standing waves. At higher frequencies the attenuation of the wave was high enough so that the wave reflected from the rear wall (or the electrode) of the tube interfered little with the propagating wave; but for lower frequencies the damping was not that strong and the reflected wave may be expected to strongly interfere with the wave generated by the excitor. Consequently the measured phase shifts being prone to errors, is expected to be smaller than its true value).

Little and his collaborators (Little, 1961; 1962; Little and Jones, 1965; Barret and Little, 1965), reported that ion waves could be excited with the use of an external coil which modulated the plasma density by varying the magnetic field. The plasma used in their experiments was a low pressure mercury arc. In his first paper (Little, 1961) both theoretical and experimental work on the problem of transmission of electro-acoustic waves in a bounded plasma was reported. This paper dealt with experiments in which a short exciter coil fed from an ultrasonic oscillator created waves in the positive column of the arc plasma. It was found necessary to maintain a steady axial magnetic field to reduce the particle loss to the walls, for that loss seemed to cause strong attenuation. Both radial and axial compression was found to exist for the mode of excitation reported therein. The waves were demonstrated by a photomultipler connected to a phase sensitive detector. The outputs of the phase sensitive detector were recorded on a chart recorder. The motion of the chart was synchronous with the motion of the photo-multiplier along the positive column. Transmission was observed from cut-off at 25 kHz. upto 50 kHz. corresponding to the wave lengths cut-off from 30 cm. to 3 cm. in the plasma. Damping, however, was not reported. In a later paper (viz. Little and Jones 1965) the wave attenuations were studied. The paper reported elaborately more precise measurements on the dispersion of these waves with and without an axial magnetic field. It was found that externally excited and self excited ion waves showed similar behaviors, namely a low frequency cut-off in transmission for the both at about 20 kHz. That no other observers had observed this low frequency cut-off, might be due to one important difference in parameters i.e. the choice of the pressure range (Little; 0.3 m. Torr; Others : 2 m. Torr.). It was also observed that when a small magnetic field was used the cut-off was more clearly evident than in zero magnetic field and the experimental results were in better agreement with a simple theoretical model over the lower part of the frequency range. Above 40 kHz, the slope of the dispersion curve fell sharply - this was the upper limit at which the external exciter coil was effective. Much light was also thrown on the subject of spontaneously excited waves, which previously was regarded as an obstacle. The principal drawback in these measurements was the presence of sizeable fluctuations in density.

Wong and others (Wong, 1965; Wong et al, 1962, 1964; Moteley and Wong, 1963), in their series of experiments were able to remove this difficulty by using quiescent plasma for their measurements. They obtained a very stable plasma in a device known as Q-machine, which was similar in construction to the alkali ion plasma source described by Rynn and D'Angelo (1960). In the Q-machine caesium and potassium atoms from an oven strike a hot tungsten plate and the alkali metal plasma is created by contact ionization. A second hot plate held the plasma axially, and the plasma was further radially confined by using longitudinal magnetic fields. Since the plasma was produced near one end of the column the recombination losses effected a drift of plasma away from the producing plate. Accordingly they obtained two different phase velocities for two directions (for waves moving upstream and downstream). The ionic sound waves were reported to be excited and detected electrostatically with grids placed perpendicular to the axis. The damping of the waves excited in the plasma of presumably equal electron and ion temperatures was found to be so strong that standing oscillations were not produced. Since wave frequency was much less than electron-electron collision frequency but greater than ion-ion collision frequency, they (Wong et al, 1964) followed the theoretical analysis of Jensen (1962) in treating the electrons as a fluid but the ions by a collisionless Boltzmann equation in the manner of Fried and Gould (1961). As usual they linearised the equations, made use of the Poission's equation for the self-consistent field and assumed Maxwellian distribution for ions and obtained the dispersion relation. The contribution of the different collisional processes was ignored but later estimated the different collisional processes (ion-electron, ion-atom, ion-ion etc.) term by term, by calculating the resistivity and viscosity effects. But these frictional processes failed to explain the experimental results for damping of the waves. It was therefore believed that for their experiment the collisionless damping prevailed. Qualitative evidence for collisionless damping (both temporal and spatial) for electron oscillations, were then available (Kofoid, 1961 and Gaulton et al 1962) but the experiment of Wong et al (1964) may be marked as the first quantitative measurement of Landau damping of ion-acoustic waves. Later Motley and Wong (1964) extended the previous experiment just discussed to denser plasmas ($n \lesssim 4 \times 10^{12} cm^{-3}$). The applied frequency used was below 60 Hz and the ion-ion collision frequency seemed to exceed the wave frequency and therefore fluid equations rather than collisionless equation better described the wave propagation. The experimental results showed transition from Landau damping to viscous damping of ion-acoustic waves and the results were in excellent agreement with the theory taking the viscous damping into account. In the same year Gould (1964) theoretically examined in detail the phenomenon of excitation of ion-acoustic waves by a pair of idealized grids in a collisionless plasma. It was shown that in a limited region, neither too close nor too far from the source, the disturbance closely approximates exponentially damped (spatially) ion-acoustic wave. This was in agreement with previous experimental results of Wong et al (1964). However, Gould's calculation points out an interesting fact that the electron contribution becomes dominant at positions far from the source as exhibited in a weaker damping of the wave and in that the phase of the wave becomes stationery with distance. Later Wong (1965) reported some observations which appeared to support this fact.

The works of Alexeff and his collaborators on spontaneously excited ion-waves was discussed in an earlier section. They also performed a series of experiments on externally excited waves in plasmas (Alexeff and Jones 1963, 1965; Jones and Alexeff, 1964, 1965). They used the so called time-of-flight technique (Alexeff and Jones 1963) in order to measure the velocity of ionic sound waves in a range of gases. In an elaborate paper (Alexeff and Jones 1965) they reported the experimental observation on ion-wave propagation and determined the compression co-efficient γ_e of plasma electrons. They made use of the quiescent plasma but not a Q-machine as was done by Wong et al (1964); instead the quiescent plasma was obtained by carefully adjusting voltage and current of the plasma source (Takayama et al, 1960). Ion waves were externally generated at the transmitting probe (not grid) by perturbing its voltage with a step function, pulse, or burst of sine waves. They were detected by observing the modulation of ion current to the receiving probe. The signal produced due to direct electrostatic coupling between the transmitting and receiving circuits, were easily separated from the weaker ion-wave signal by the time of flight technique. This technique allowed them to perform the velocity measurement before reflections from the walls could interfere, although under the experimental conditions discussed therein, no reflection was observed (Jones and Alexeff 1965b). The plasma parameters were such that collisionless theory was still valid. The plasma of Wong et al (1964) was also collisionless but suffered strong damping since $T_i \simeq T_e$. In other experiments viscous damping was prevalent, magnetic fields were present, boundary effects at the walls of the plasma probably occurred and streaming of electrons relative to ions affected the wave propagations. Plasma of Alexeff and Jones on the other hand, was collisionless with $T_o \gg T_i$ and the wall effects and streaming effects were negligible.

Sessler and Pearson (Sessler 1964; 1965a, 1965b, 1966, Sessler and Pearson, 1967) studied ion-waves for r.f. discharge plasmas. They removed the difficulty suffered by Wong (1965) in comparing the experimental results with Gould's (Gould, 1964) theory, by replacing the single grid arrangement made by Wong and others by a pair of closely spaced parallel grids as the exciter. Gould (1964), as a theoretical model, employed a pair of dipole grids with oppositely oscillating charges and infinitesimal spacing. Since the inclusion of the roots of the dispersion relation depended on boundary condition Wong looked forward in having another theoretical model that could describe more closely the actual single grid excitation. Instead of developing another excitation model, Sessler and

Pearson cho~~o~~se to replace the single grid of Wong et al by closely spaced double grid arrangements. Sessler (1965) reported measurements of the propagation constants of longitudinal ion waves in weakly ionized nitrogen gas at angular frequency greater than the ion-neutral collision frequency. In this case collisional damping should not be expected but the measurements showed an unexpected frequency dependence of both the phase velocity and attenuation. The hydrodynamic theory (viz. Denisse, J.F. and DelCroix, J.L., 1963) predicts propagation of undamped ion waves unless excitation frequency approaches ion-plasma frequency ω_i. As frequency approaches ω_i, the theory predicts a decrease of phase velocity. But experimentally, however, an increase of the phase velocity with frequency was observed and thus indicated that another strong dispersion mechanism was present. This could not be explained in terms of phase mixing (Fried and Gould, 1961) for the range of parameters they used. This effect was attributed by Sessler to the existence of complex compression ratio (γ_e) of electrons due to momentum transfer and thermal relaxation processes involved. The result of the experiment just discussed seems to contradict the later paper (Sessler and Pearson, 1967) which did not report the above mentioned unexpected dispersion mechanism (arising due to complex compression ratio) below ion plasma frequency. In that paper theoretical and experimental results were presented in detail on the propagation of longitudinal ion waves in a weakly ionized gas in a frequency range extending from considerably below to well above the ion plasma frequency. The theory described propagation in a uniform plasma on the basis of kinetic equations. Two theoretical approaches were discussed. In the case of weak damping the dispersion relation was derived and solved for complex propagation constant. When the damping is not weak, the spatial dependence of phase and amplitude of the disturbance excited by a pair of grids was calculated following Gould (1964)and Fried et al (1966); but this was evaluated for parameters appropriate to their experiment. The measurements were performed with grid excited ion-waves at frequencies between 0.1 and 10 MHz in hydrogen, nitrogen, argon and krypton r.f. discharges. At frequencies well below the ion-plasma frequency ω_i, the phase velocity was found to be frequency independent and was given by the Tonk's-Langmuir speed. At those frequencies the attenuation was found to be proportional to the neutral gas pressure and was therefore primarily caused by ion-neutral collisions. At frequencies approaching ω_i, the attenuation was higher than expected from collisions and the excess was attributed to ion-Landau-damping. For frequencies greater than ω_i, the results could not be explained by the theory if Maxwellian velocity distribution of the ion gas was assumed. This was explained by assuming the ionic velocity distribution to decrease more rapidly at high velocities than a Maxwellian distribution. One of the most strong points of the paper is that the reported data furnishes the first experimental evidence of ion-wave propagation at frequencies greater than ω_i.

1.6 SONIC PROBE DIAGNOSTICS

As has been implied in the above discussions, ion waves have many potential applications in plasma diagnostics. Contrary to probe measurements, experiments on such waves allow one to determine many parameters without disturbing the plasma. Phase velocity and attenuation at low frequencies, for example, yields electron temperature and ion-neutral collision cross-section respectively, while measurements at frequencies comparable to and above the ion-plasma frequency, give informations about the average ion temperature and the shape of the ionic velocity distribution. But in none of the above mentioned experiments the plasma diagnostics was of primary interest. However, a number of workers (Champion, 1962; Vatnagar 1964; Saxena and Gour 1969a,b; Gour and Saxena, 1970 and Saxena & Saxena, 1974) developed a new sonic probe plasma diagnostic techniques in which characteristics of ion-sound waves in plasma played the most important role. Related theories were also developed. These diagnostics studies involve transmission of sonic and ultrasonic waves (externally excited by transducers) through a plasma slab sandwitched by the unionized medium. Due to reflections at the plasma neutral gas interfaces the sonic wave gets attenuated and from the knowledge of this attenuation much informations on plasma parameters were obtained. This new diagnostic technique is somewhat similar to the micro-wave technique (Heald and Wharton 1965), but instead of microwaves, sonic signals are employed to explore the ionized medium. Propagation of sonic signals through plasma was possibly first studied by Champion (1962). He used an arrangement when an ultrasonic wave of variable frequency was launched by an ultrasonic transducer in one end of a r.f. excited plasma. The signal was received by a receiver at the other end. The theoretical analysis of this experiment was available after Surdin (1962) who studied the sonic propagation at frequencies both below and above ion-plasma frequency. The single fluid model was chossen but he did not consider the collision processes involved in deriving the dispersion relation, but later the attenuation was estimated separately by introducing suitable relaxation processes. The principal drawback of this analysis is that all the constituent particles of the plasma was assumed to be in thermal equilibrium ($T_e \simeq T_i = T$) which cannot be conceived at least in the case of ordinary discharge plasma. While the detailed report of the unpublished work of Champion is not available to the present author, the experiment of other authors in this line may be discussed. As mentioned earlier, the main principle underlying these experimental techniques is that the transmission of a plane acoustic wave from air into loss-less plasma and into air again is studied. Due to reflections, which occurs due to change of acoustic impedance (product of the gas density and the sonic speed) the wave encounters at the plasma-neutral gas interfaces, the transmitted waves are found to get attenuated. For a fully ionized plasma, clearly, the attenuation depends on the phase velocity of ordinary sonic wave and that of ion-acoustic wave; this means, the amount of attenuation contains informations on plasma parameters. Following this guideline Bhatnagar (1964) presented a method (theoretically) in detail, in determining electron and ion temperatures (T_e and T_i) of a plasma. The temperatures T_e and T_i were evaluated from measured values of reflection coefficients of the sonic wave at the plasma-neutral gas interfaces for two frequency regions, one a low frequency and the other a high frequency compared to the electron plasma frequency. The formula relating T_e and T_i with the reflection coefficients were derived from the single fluid model of a plasma with certain simplifying assumptions. Later the formula was modified in the case of plasma slabs. Saxena and Gour (1969) on the other hand obtained the ratio of the pressure amplitude of the incident wave (A_1) to that of the transmitted wave (A_3) for the propagation of sonics through plasma slab from somewhat simpler considerations (Kinsler and Fray). The formula was given by

$$\frac{A_2}{A_1} = \frac{4r}{(r + 1)^2}$$

where r is the ratio of the characteristic impedances of the plasma and air. To compute the characteristic impedances the knowledge of the sonic speed through these two mediums were necessary. Sonic speed in the plasma medium was taken to be equal to $[\gamma k(T_i + Z T_e)/m_i]^{\frac{1}{2}}$

where Z is the ionic charge. This is the speed of the ion waves (Venkatarangan, 1964) for a non-isothermal plasma medium. The above equation involving ratio (r) of the characteristic impedances of the medium was indicated to yield electron temperature. In their experiment sonics (1 - 40 kHz.) were transmitted through a partially ionized glow discharge plasma in a dead vacuum chamber. The sonics were produced by an audio-oscillator, feeding a small loudspeaker kept in the vacuum chamber at right angles to the discharge column. The transmitted signal was detected by a small microphone. The output was measuredby a galvanometer/V.T.V.M./C.R.O., after due amplification of the signal. The propagation of sonics through plasma resembled in many respects that of microwave propagation. A preliminary report of the estimated electron temperature was also given. Following the same experimental procedure and with minor modifications, an experimental study (Gour and Saxena, 1970) of the variation of attenuation of acoustic signal through a discharge plasma with the applied potential showed a minimum at the state of the plasma when $\omega = \omega_{pi}$ where ω_{pi} is the ion plasma frequency (ω_{pi} changes with applied potential through a change in electron or ion density n_{io}). Beyond this frequency the attenuation increased asymptotically indicating the transition of the plasma from the state of transparency to opacity. The variation of the percentage of attenuation with the acoustic frequency was found to be an oscillatory function and the amplitudes of this function showed a regular decrease with the increase in the applied voltage of the plasma. The experiment thus suggests a method for determining ion density of a plasma. Later, Saxena and Saxena (1974) made a comparative study of the sonic probe and the Jhonson-Malter (1950) double probe technique under the same experimental conditions by determining the electron temperature in a weakly ionized plasma produced in a dead "anechoic" vacuum chamber (Rivin, 1962). A fair agreement in the results obtained by these two methods was observed. It was also indicated that the sonic probe technique proved to be a very sensitive device for exploring weakly ionized plasma as compared to double probe. However, to the present author these series of works is very much prone to criticism for various reasons. Firstly, as will be discussed in a later chapter (Chapter VIII) and also (Ghosal & Sen, 1977), the above authors theoretically considered the case of fully ionized plasmas. But if the ionization is weak as in the case for ordinary laboratory plasma the theory should be modified by two major factors : (a) due to the presence of large neutral background the expression of the phase velocity of ion wave obtained earlier should be modified; and (b) since the elasticity of the ion fluid greatly differs from that of the neutral particle species, the wave in a weakly ionized plasma should not be described by waves having a single propagation constant. Secondly, a number of papers both theoretical and experimental (Ingard, 1966; Schultz and Ingard, 1969; Kaw, 1969; Ishida and Idehara, 1973; Sakuntala and Jain, 1978) are now available which proclaims the change of phase velocity of the pure acoustic mode through the neutral particles in a plasma due to energy transfer from the charge particles to the neutrals. When sonics are generated by transducers, this pure acoustic mode cannot be ignored in the case of partially ionized plasma. Ingard et al (Ingard, 1966; Schultz and Ingard, 1969 etc.) have derived the dispersion relation for this wave theoretically, taking the modification due to charged particles into account, and have shown that this wave may be driven unstable under certain conditions, if the electrons are maintained at a higher temperature than the neutrals. Experimental evidence to support this fact is also available (Fitaire and Mantei, 1972). However, Kaw (1969) pointed out that the increase of equilibrium temperature due to the energy transfer from electrons to neutrals, must not be neglected. The verification of Kaw's theory i.e. the effect of increased equilibrium temperature of the neutrals on the propagation of sonic waves through plasma is available after Ishida and Idehara (1973) and very recently due to Sakuntala and Jain (1978). The present author believes that this effect is also to be taken into account for the sonic probe diagnostic techniques mentioned earlier.

(C) SCOPE AND OBJECTIVE OF THE PRESENT WORK

1.7. Non-immersive diagnostic techniques in plasma may be classified as (i) R-F coil and capacitor probe methods (ii) Sonic probe methods, with or without electromagnetic pick up (iii) Spectroscopic methods (iv) Microwave probe methods etc. The present work concerns diagnostics using the first two methods, specifically R-F coil probes and sonic probe with electromagnetic pick up.

The r-f probe method is widely used for electrical conductivity measurements in plasma. From the review of the earlier works in electrical conductivity measurements it would be evident that in depth analysis in the following areas were lacking.

(i) The r-f coil probe average conductivity measurements to date essentially were by substitution method which consists of replacing the plasma by electrolytes of known conductivities. No attempts were made to correlate the coil impedance measurements with the theoretical results as would be obtained due to a conductive slug placed inside the work-coil with the eddy current, capacitive coupling and end effects considered. This correlation would have enabled direct measurement of conductivity without taking recourse to substitution.

(ii) Cognizance of possible radial distribution of azimuthal conductivity as contrasted to the assumption of a bulk or average conductivity (as encountered in say an electrolyte) was generally absent. The methods which solely determine some kind of average and bulk conductivity fails to provide an accurate prediction regarding on-axis conductivity and effective extension of the plasma.

(iii) In the few earlier works (in glow discharges) where such radial distribution has been introduced a priori, a Bessel function distribution is assumed whose validity for arc plasma is questionable.

In non-immersive sonic probe diagnostic area only one method has been reported (as reviewed before). The method consists of a loudspeaker as exciter and a microphone as a pick up device. As to be described in a subsequent chapter this method, which has been proposed for measuring electron temperature is not suitable for laboratory discharge plasma.

The present work attempts to eliminate the short-comings mentioned above and to extend the theoretical and experimental investigations in the field of non-immersive probe diagnostics in plasma.

1.8. The scope of the work may be described as follows:-

(i) Development of a theoretical bulk (azimuthal) conductivity model for r-f coil probe measurement has been achieved. The model takes into account eddy current and capacitive coupling. Using this model and the data from r-f coil probe the azimuthal conductivity may be measured for arc plasma. It has also been shown that for arc plasma the capacitive coupling plays only a minor role and may be ignored without any appreciable loss of accuracy. The method is absolute and no electrolytic substitution is necessary.

(ii) By combining the resulting bulk conductivity from ordinary probe method - which gives longitudinal average, and the r-f coil probe - which gives azimuthal average, it has been possible to determine two important parameters that define the radial conductivity (electron) distribution in arc plasma. Apart from the two parameters which are based on assumed functional for distribution, the methodology is capable of testing of any hypothesis regarding radial distribution of electrons. It has also been shown that the Bessel function distribution is definitely invalid for low pressure arc plasma. The theoretical basis for the above work has been worked out in details and it has further been shown that important physical parameters like bounds of peak conductivity, that of maximum extension of plasma and other such things can be predicted (independent of any hypothesis regarding radial distribution) from the results of two methodologies combined.

(iii) From experiments carried out from heat flow processes in an arc plasma it has been shown that the conventional heat flow mechanism viz. radiation, convection, ionic conduction, electronic conduction and conduction due to neutral particles cannot account for the heat flow. When the plasma constriction i.e. the high gradient of radial distribution observed in the earlier scope is taken into account, a new mechanism of heat flow - termed ambipolar diffusive heat flow, which has been theoretically identified in the present work is to be considered. It has also been shown that this mode is the major contributor in radial heat flow precesses. From the above analysis the important parameter - the electron-atom collision cross-section can be predicted. The results correlate well for the above parameter for electron energies above 1 ev. The present work also enables to furnish the electron-Hg atoms collision cross-section even for energies below 1 ev, for which no other method is available.

(iv) An acoustic probe diagnostic methodology has been developed which consists of an electrodynamic loudspeaker as the exciter of ion-acoustic waves and a toroidal coil (called Rogow-ring) as electromagnetic pick up. The ion-acoustic oscillation induces audio frequency voltage in this Rogow coil which can be conveniently measured and displayed in an oscilloscope in terms of amplitude and phase. Using this method, the phase-shift of the propagating wave has been measured by moving the Rogow ring along the plasma column. Substantial longitudinal (spatial) phase shift obtained indicates that a propagating rather than a standing wave phenomenon is taking place. From the measured phase velocities, the electron temperature has been determined. The electron temperature results correlate well with the available results. The necessary theory for the propagation of ion-acoustic waves has been developed considering a single fluid model approach taking the collision of the charged particles with the background neutral particles.

(v) The earlier method of ion-acoustic probe due to Sûxena et al which constitutestransverse emplacement of a sonic source and electro-acoustic detector has been theoretically examined in details in the case of very weakly ionized plasma. It has been shown that the method is not suitable for a laboratory discharge plasma, whereas the methodology developed by the present author is.

(D) TOPIC-WISE SUMMARY OF THE PRESENT INVESTIGATIONS.

<u>Azimuthal radiofrequency conductivity measurement in an arc plasma by studying the eddy current effect</u> :

Azimuthal radiofrequency conductivity of an arc plasma has been estimated by measuring the reflected resistance of a primary coil wound around a mercury arc tube. A linear relationship between the azimuthal conductivity and the discharge current has been obtained. The non-linearity and the existence of maxima observed by previous authors in the change in band-width versus axial conductivity curve have been explained theoretically by considering a generalized equivalent circuit. It has also been pointed out that the azimuthal conductivity measurement by this method is possible only when the conductivity of the plasma is fairly high.

Radial distribution function for the azimuthal conductivity of an arc plasma :

It is shown that the simultaneous measurement of the change in the band width of a coil wound around the positive column of an arc tube and the longitudinal field across the positive column can provide valuable information regarding the structural behaviour of the electrical conductivity or the electron density of the plasma column. A distribution function for the radial variation of the azimuthal conductivity of an arc plasma is proposed and the parameters of the distribution function have been obtained from the above measurements. The calculation of half-widths from the distribution function indicates that the plasma becomes more and more concentrated along the axis with the increase of the arc current. The change of this structural behaviour of the arc plasma is qualitatively explained.

Analysis of the Previous Coil-Probe Experiment :

The previous coil probe experiment is thoroughly analysed both from physical and mathematical point of view. It is shown that from the results of simultaneous measurements of azimuthal electrical conductivity (coil probe method) and longitudinal electrical conductivity (Langmuir probe method) of a plasma it is possible to obtain valuable informations on the major characteristics of the conducting medium such as maximum extension of the plasma, lower and upper boundaries of the peak conductivity and many other such things, and it is also shown that the obtainable informations are independent of the choice of the form of the distribution function. It is discussed ~~that~~ how the results of the aforementioned probe measurements can conveniently be extrapolated to obtain the major plasma characteristics with reduced uncertainties. Further the validity of the conductivity profile form, chosen in an arbitrary manner in the previous study is established.

Heat flow processes in the positive column of a low pressure mercury arc :

The problem of heat flow processes within a low pressure mercury arc with water-cooled walls has been investigated utilizing the first order perturbation technique to Boltzmann transport equation incorporating the term for the observed high gradient of radial distribution of azimuthal electrical conductivity of the arc. It is shown that the loss is due to heat conductivity of electrons, ions and neutral particles and also due to ambipolar diffusion by electrons. The experimental results enable us to calculate separately the contribution by the different processes and it is observed that the major part of the heat loss is due to diffusion and the loss due to conduction by electrons, ions and neutral particles is comparatively small. Further from the theory developed and the experimental results obtained, it has been possible to calculate the collision cross-section of electrons with the mercury atoms for electron energies less than 1eV.

A single fluid model approach to obtain the ion-acoustic wave dispersion and damping in a weakly ionized gas :

The macroscopic equations of motion for a weakly ionized gas where the collisions between the background neutral particles and the plasma particles cannot be ignored, have been considered. From these basic equations of motion the wave equation in "p" (the macroscopic pressure perturbation) and the corresponding dispersion relation has been obtained. The dispersion relation shows that the propagation constant has four roots of which two correspond to two distinct modes of propagation in the positive direction; the other two corresponding to two modes of propagation in the negative direction. Considering the frequency region much below the ion plasma frequency it has been observed that one of the roots which is a solution of the particular mode of the general equation corresponds to a sonic speed which closely simulates the Tonks-Langmuir speed for ion-acoustic wave and shows considerable dispersion and damping. The solution indicates however that both the dispersion and damping can be reduced either by increasing the percentage of ionization or by lowering the background pressure. It is further pointed out that by measuring the phase velocity and attenuation constant it is possible to calculate the electron temperature and the plasma neutral collision frequency. The usefulness of the analysis for a sonic probe to obtain the plasma parameters has been discussed.

<u>Attenuation of acoustic waves through reflections at the plasma neutral gas interfaces : Weakly ionized case</u> :

The problem of transmission of sonic waves through a weakly ionized plasma bounded in each side by a neutral gas medium has been treated by assuming the plasma to be a mixture of two intermingled fluids viz., neutral particle fluid and ion fluid in equilibrium. From a hydrodynamic analysis the wave equation for 'p', the macroscopic pressure perturbation has been obtained and it is shown that two independent wave motions, one due to the neutral particles and the other due to ions are propagated through the plasma with two different phase velocities. Assuming the usual boundary conditions at the interface, the amplitude of the transmitted wave has been calculated in case of weakly ionized plasma; the theory can be utilized for the determination of electron temperature from the measured value of attenuation if the percentage of ionization and collision cross-section can be obtained independently.

<u>Generation of ion-acoustic waves in a glow discharge plasma by sonic transducer : a new non-immersive sonic probe diagnostic method</u> :

Propagating ion-acoustic mode has been generated in a glow discharge plasma with the help of an electrodynamic loudspeaker placed within the discharge tube (but not in the actual discharge space). The wave is detected electromagnetically by a "Rogow" ring (multilayer toroid made of copper wire wound around an "O" type laminated iron core). Experimental observation of the dispersion is found to agree with the dispersion relation, theoretically obtained earlier (Chapter VII). From the measured phase velocity of the wave the electron temperature is obtained. The obtained electron temperature agrees fairly well with the earlier data of electron temperatures available for the same discharge conditions.

REFERENCES:

1. Adler, F.P. (1949). J. Appl. Phys., 20, 1125.
2. Akimov, A.V. and Konenko, O.R. (1966). Sov. Phys. Tech. Phys., 10, 1126.
3. Aleksandrov, A.F. and Yalsenko, I.M. (1965). High Temp. (U.S.A.), 3, 321.
4. Alexeff, I. and Jones, W.D. (1963). Proc. of the Sixth International Conference on Ionization Phenomena in Gases, Paris, editted by Hubert, P. (S.E.R.M.A., Paris 1964), Vol. 3, 121.
5. Alexeff, I. and Jones, W.D. (1965). Phys. Rev., 15, 286.
6. Alexeff, I. and Neidigh, R.V. (1961a). Bull. Am. Phys. Soc., 6, 309.
7. Alexeff, I. and Neidigh, R.V. (1961b). Oak Ridge National Laboratory Thermonuclear Project Semi-annual Report, ORNL-3104.
8. Alexeff, I. and Neidigh, R.V. (1961c). Phys. Rev. Letters, 7, 223.
9. Alexeff, I. and Neidigh, R.V. (1963). Phys. Rev. 129, 516.
10. Alexeff, I., Veach, A.M. and Yonts, O.C. (1962). Bull. Am. Phys. Soc., 7, 442.
11. Appleton, (1923). Phil. Mag., 45, 879.
12. Appleton, E.V. and Chapman, E.W. (1932). Proc. Phys. Soc. Lond., 44, 246.

13. Appleton, E.V. and Boohariwala, D.B. (1935). ibid., 47, 1374.

14. Aston and Kikuchi (1921). Roy. Soc. Proc. London, 99, 50.

15. Barret, P.J. and Little, P.F. (1965). Phys. Rev. Letters, 14, 356.

16. Basu, J. and Maiti, J.N. (1973). J. Appl. Phys., 44, 3976.

17. Basu, J. (1976). ibid., 47, 4234.

18. Bargland, S. et al (1963). J. Sci. Instrum. (G.B.), 40, 250.

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

20. Brown and Cowan(1931). Phys. Rev., 38, 376.

21. Caulton, M., Hershenov, B. and Pasche, F. (1962). J. Appl. Phys., 33, 800.

22. Champion, R.L. (1962). M.Sc. Thesis, Deptt. of Physics, North Carolina State College.

23. Childs, F.C. (1932). Phil. Mag., 13, 873.

24. Chow(1931). Phys. Rev., 37, 574.

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

26. Ciampi, M. and Talini, N. (1969). ibid., 40, 5394.

27. Cillers, W.A. et al (1963). Nucl. Fusion, 3, 78.

28. Colgate, S., Farguson, J. and Furth, H. (1958). Proc. Second U.N. Conf. on Peaceful uses of Atomic Energy (Geneva), 32, 129, 140.

29. Consoli, T., Le Gardeur, R. and Slama, L. (1961). Compt. Rend., 253, 1923.

30. Cooper, J. (1963). Plasma Phys. (J. Nucl. Energy C), 5, 285.

31. Crawford, F.W. (1960). Standford University Microwave Laboratory Report, ML-762.

32. Crawford, F.W. (1961). Phys. Rev. Letters, 6, 663.

33. Crawford, F.W. and Kuhler, R.J. (1965). Proc. of Seventh International Conference on Ionization Phenomena in Gases, Belgrade, 1965 (Beograd, 1966), Vol.II, 326.

34. Crawford and Lawson (1960). Standford University Rep., 753.

35. Crawford, F.W. and Self, S.A. (1963). Proc. of the Sixth International Conference on Ionization Phenomena in Gases, Paris, editted by Hubert, P.(S.E.R.M.A., Paris, 1964), Vol.III, 129.

36. Dawson, J. and Oberman, C. (1962). Phys. Fluids, 5,517.

37. Dawson, J. and Oberman, C. (1963). ibid, 6, 394.

38. Debye and Hückel (1923). Phys. Zeits., 24, 185, 305.

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

40. Emeleus, K.G. (1927). Proc. Cambridge Phil.Soc., 23, 531.

41. Emeleus,K.G. (1956). Nuovo Cimento, 3, 490.

42. Fitaire, M. and Mantei, T.D. (1972). Phys. Fluids,15,464.

43. Fox,(1930). Phys. Rev., 35, 1066.

44. Frank, Huxford and Wilson (1947). J. Opt. Soc. Am., 37, 718. See also Little's paper (Little 1961) for relevance.

45. Fried, B.D. and Gould, R.W. (1961). Phys. Fluids, 4, 139.

46. Fried, B.D., Kaufman, A.N. and Sachs, D.L. (1966). Phys. Fluids., 9, 292.

47. Frost, L.S. and Phelps, A.V. (1962). Phys. Rev., 127, 1621.

48. Frost, L.S. and Phelps, A.V. (1964). ibid., 136A, 1538.

49. Geller, R. and Lucerain, M. (1961). C.R. Acad. Sci., Paris, 253, 1542.

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

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

52. Ghosal, S.K. and Sen, S.N. (1977). Proc. Ind. Nat. Sci. Acad., 43, 96.

53. Gilardini, A. (1959). Nuovo Cimento Suppl. Sec.10, 13, No. 1-2.

54. Glasstone, S. and Lovberg, R.H. (1960). Controlled Thermonuclear Reactions, Van Nostrand, Princeton, N.Y. (USA).

55. Golovin, I.N. et al (1958). Proc. 2nd. U.N. Conf. on peaceful uses of Atomic Energy (Geneva), 32, 72.

56. Goldenberg, S.A. et al (1964). High Temp., 2, 616.

57. Gould, R.W. (1964). Phys. Rev., 136A, A991.

58. Gour, S.C. and Saxena, A.P. (1970). Ind. J. Pure and Appl. Phys., 9, 271.

59. Gourdin, M.G. (1963). Symposium on Magnetoplasmadynamic Electrical power generation, Session III, p. 36.

60. Green, H.S. and Leipnik, R.B. (1965). I.J.Engg. Sci.(G.B.), 3, 491.

61. Hatta, Y. and Sato, N. (1961). Proc. of the Fifth International Conference on Ionization Phenomena in Gases, Munich (North-Holland Publishing Co.,Amsterdam, 1962), Vol. I, 478.

62. Hausler, R.S. (1957). Zs. angew Phys., 9, 66.

63. Heald, M.A. and Wharton, C.B. (1965). Plasma diagnostics with microwaves, John Wiely & Sons, Inc., N.Y.

64. Hollister, D.D. (1964). AIAA J., 2, 1568.

65. Imam, A. and Khastagir, S.R. (1937). Phil. Mag., 23, 858.

66. Ingard, U. (1966). Phys. Rev., 145, 41.

67. Ionescu, V. and Mihul, C. (1935). J. Phys. Radium, 6, 35.

68. Ishida, Y. and Idehara, T. (1973). J. Phys. Soc. Japan, 35, 1747.

69. Jahnke, E. and Emde, F. (1945). Tables of Functions (Dover Publications, Inc., N.Y.), pp.73.

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

71. Jensen, V.O. (1962). Risö Report No.54, Riso Roskilde, Denmark.

72. Jhonson, E.O. and Malter, L. (1950). Phys. Rev., 80, 57.

73. Johnson (1967). Phys. Fluids, 10, 108.

74. Jones, W.D. and Alexeff, I. (1964). Bull. Am. Phys.Soc., 9, 469.

75. Jones, W.D. and Alexeff, I. (1965a). Bull. Am. Phys.Soc., 10, 200.

76. Jones, W.D. and Alexeff, I.(1965b). ibid., 10, 509.

77. Kaw, P. (1969). Phys. Rev., 188, 506.

78. Khozhablev, M.B. and Yarin, L.P. (1966). High Temp.(USA), 4, 576.

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

80. Kofoid, M.J. (1961). Conference on Plasma Physics and Controlled Thermonuclear Fusion Research, Saltzburg,1961, Paper CN-10/169.

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

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

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

84. Landau, L.D. (1945). J. Phys. (USSR), 10, 25.

85. Langmuir, I. (1926). Proc. Nat. Acad. Sci., 14, 627.

86. Lary, E.C. and Olson, R.A. (1962). Paper presented at the 3rd Symposium on Engineering Aspects of Magnetohydrodynamics, Rochester, N.Y.

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

88. Liperovski, V.A. (1961). Soviet Physics-JEPT, 12, 951.

89. Little, P.F. (1961). Proc. of the Fifth International Conference on Ionization Phenomena in Gases, Munich (North-Holland Publishing Co., Amsterdam,1962), Vol.II, 1440.

90. Little, P.F. (1962). Nature, 194, 1137.

91. Little, P.F. and Jones, H.G. (1965). Proc. Phys. Soc. London), 85, 979.

92. Lovberg, R.H. (1959). Ann. of Phys., 8, 3311.

93. Malter, L., Johnson,E.O., and Webster, W.M. (1951). R.C.A. Rev., 12, 415.

94. Margenau, H. (1946). Phys. Rev., 69, 508.

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

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

97. Moteley, R.W. and Wong, A.Y. (1963). Proc. of the Sixth International Conference on Ionization Phenomena in Gases, Paris, editted by Hubert, P. (S.E.R.M.A., Paris 1964), Vol. III, 129.

98. Moulin, T. and Masse, J. (1964). Symposium International Sur la production MHD d'Energie Electrique, Paris.

99. Murino, P. and Bonomo, R. (1964). XIX Congress Nazionale ATI, Seina, p.44.

100. Nagata, M. (1966). Elec. Engg. Japan (USA), 86, 40.

101. Oberman, C. and Shure, F. (1963). Phys. Fluids, 6, 834.

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

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

104. Olson, R.A. and Lary, E.C. (1963). AIAA J., 1, 2513.

105. Pardue, L.A. and Webb, J.S. (1928). Phys. Rev. 32, 946.

106. Penning (1926). Phys. Zeits., 27, 187.

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

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

109. Pollock, H., Goldman, L. and Westendrop, W. (1960). Bull. Am. Phys. Soc., 5, 337.

110. Pradhan, T. and Dasgupta, B. (1967). Phys. Rev., 160, 184.

111. Revans, R.W. (1933). Phys. Rev., 44, 798.

112. Rivin, A.N. (1962). Soviet Phys. Acoust., 7, 406.

113. Rynn, N. and D'Angelo, N. (1960). Rev. Sci. Instrum., 31, 1326.

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

115. Sakuntala, M. and Jain, V.K. (1978). J. Phys. D., Appl. Phys., 11.

116. Sanderson, J.J. (1974). "Plasma Physics". editted and compiled by Kee, B.E. Inst. of Physics London & Bristol, Conference Series No. 20, 55.

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

118. Saxena, A.P. and Gour, S.C. (1969a). Plasma Phys., 11, 611.

119. Saxena, A.P. and Gaur, S.C. (1969b). Int. J. Electron., 27, 13.

120. Saxena, A.P. and Saxena, R.K. (1974). Ind. J. Pure & Appl. Phys., 12, 198.

121. Schultz, M. and Ingard, U. (1969). Phys. Fluids, 12,1237.

122. Schweilzer, S. and Milchner, M. (1967). Phys. Fluids, 10, 799.

123. Sen, S.N. and Ghosh, A.K. (1966). Ind. J. Pure & Appl. Phys., 4, 70.

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

125. Sen, S.N. and Jana, D.C. (1978). Ind. J. Phys., 52B, 288.

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

127. Sessler, G.M. (1964). Phys. Fluids., 7, 90.

128. Sessler, G.M. (1965a). Phys. Letters, 16, 227.

129. Sessler, G.M. (1965b). Proceedings of Seventh International Conference on Ionization Phenomena in Gases, Belgrade, 1965 (Beograd, 1966), Vol.II, 326.

130. Sessler, G.M. (1966). Physics, Rev. Letters, 17, 243.

131. Sessler, G.M. and Pearson, G.A. (1967). Phys. Rev., 162, 108.

132. Stix, T.H. (1962). "The Theory of Plasma Waves". McGraw-Hill, N.Y.

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

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

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

136. Surdin, M. (1962). Phys. Fluids., 5, 1479.

137. Takayama, S.T., Ikegami, H. and Miajaki, S. (1960). Phys. Rev. Letters, 5, 238.

138. Tanaca, H. and Usami, S. (1962). Bull. Fac. Eng. Yokohama Nat. Univ., 11, 65.

139. Tanaca, H. and Hagi, M. (1964). J. Appl. Phys. Japan, 3, 335.

140. Tanaca, H. and Hagi, M. (1964). ibid., 3, 338.

141. Taylor, R.L. et al (1963). AIAA J., 1, 2186.

142. Thomson, J.J. and Thomson, G.P. (1928). Conduction of Electricity through Gases, Part II, p. 353.

143. Tonks, L. and Langmuir, I. (1929). Phys. Rev., 33, 195.

144. Uman, M.A. (1964). Introduction to Plasma Physics, McGraw Hill, Inc.

145. Vander Pol, B. (1919). Phil. Mag., 38, 352.

146. Vasil'eva, M.Y., Zaitsev, A.A. and Zndrgukhina, E.D. (1959). Izv. Acad. Nauk, S.S.S.R. Ser. Fiz., 23, 995.

147. Vatnagar, V.P. (1964). Ind. J. Pure & Appl. Phys., 2, 160.

148. Venkatrangan, P. (1964). Current Science, 33, 551.

149. Whiddington (1926). Engineering, 120, 20.

150. Wong, A.Y. (1965). Phys. Rev. Letters, 14, 252.

151. Wong, A.Y., D'Angelo, N. and Moteley, R.W. (1962). Phys. Rev. Letters, 9, 415.

152. Wong, A.Y., D'Angelo, N. and Moteley, R.W. (1964). Phys. Rev., 133A, A436.

153. Wu, C.S. (1965). Phys. Rev., 138, A51.

154. Wu, C.S. (1965). ibid., 140, A118.

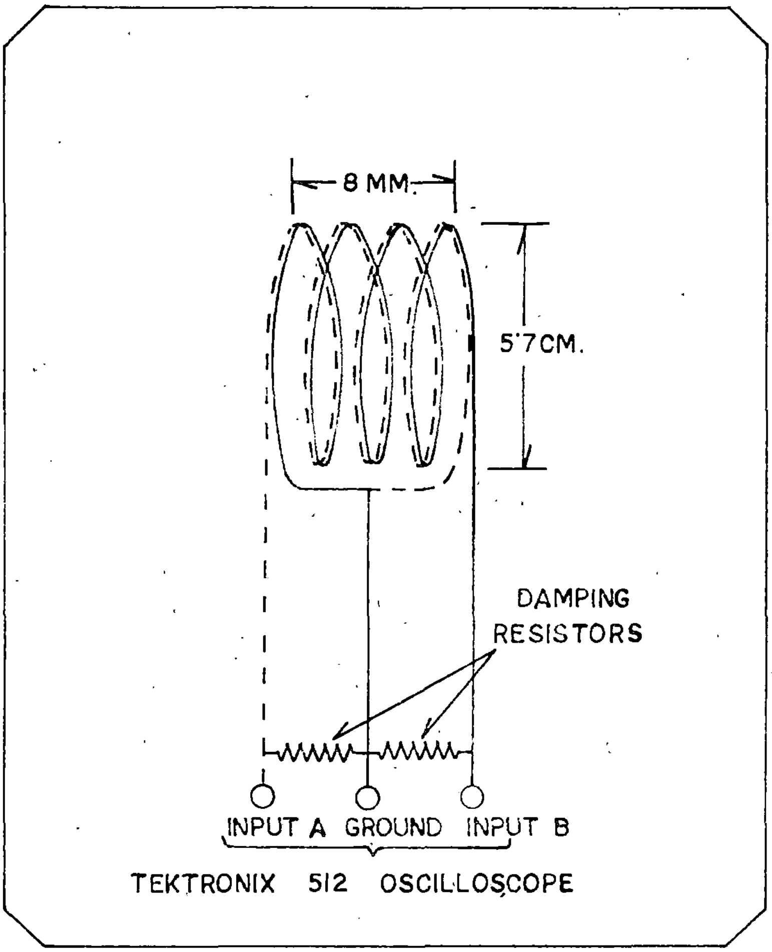


FIG. 1·1 . SCHEMATIC DIAGRAM OF THE SEARCH COIL USED IN THE APPARATUS.
THE CENTERTAPPED DESIGN IS INTENDED TO MINIMIZE ELECTROSTATIC PICKUP DUE TO THE SUDDEN APPEARANCE OF (SLIGHTLY) CHARGED GAS IN THE SHOCK TUBE.

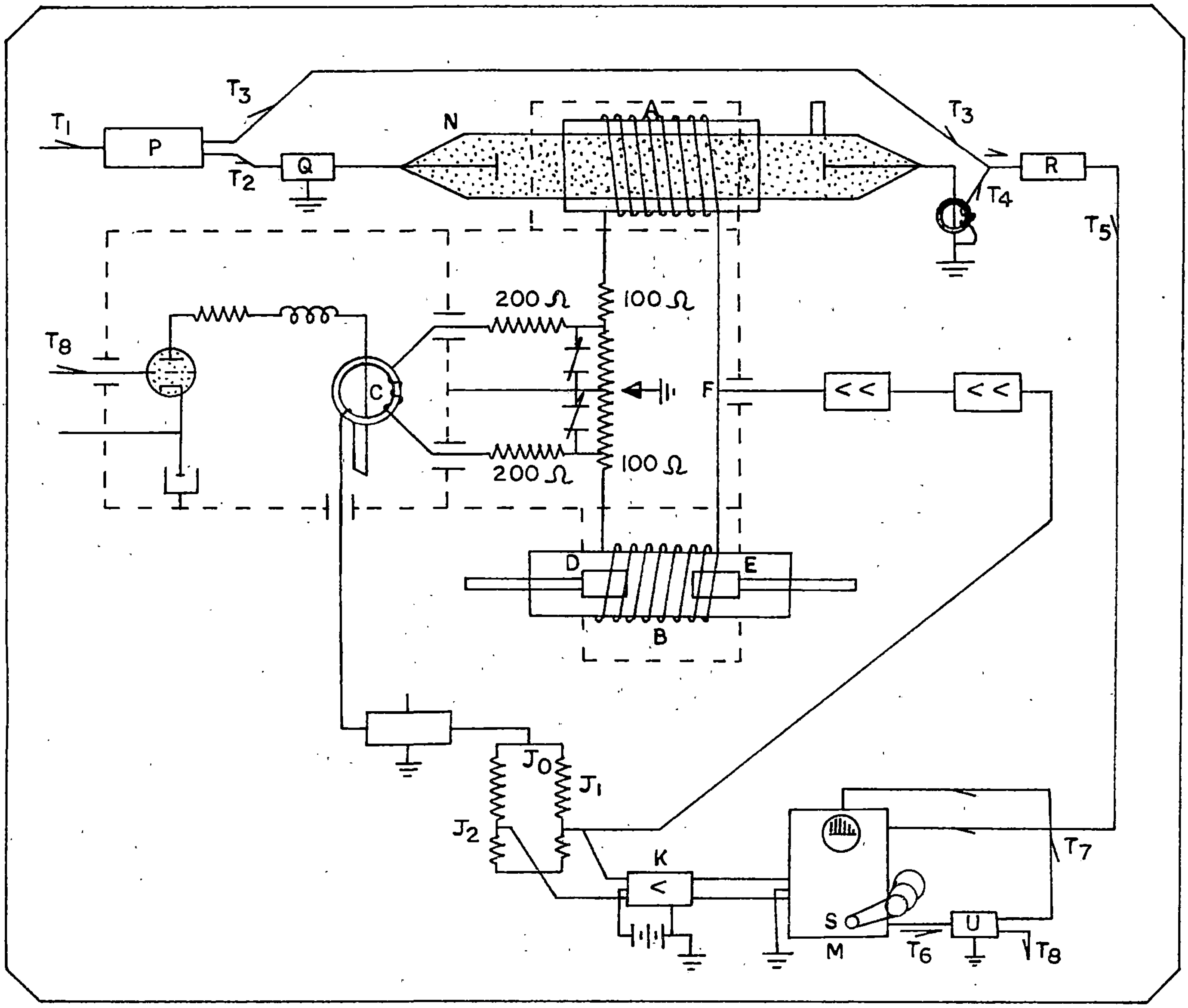


FIG. 1·2. SCHEMATIC DIAGRAM OF THE PULSE OPERATED BRIDGE WITH ITS AUXILIARY CIRCUITS FOR MEASUREMENTS ON TRANSIENT PLASMAS.

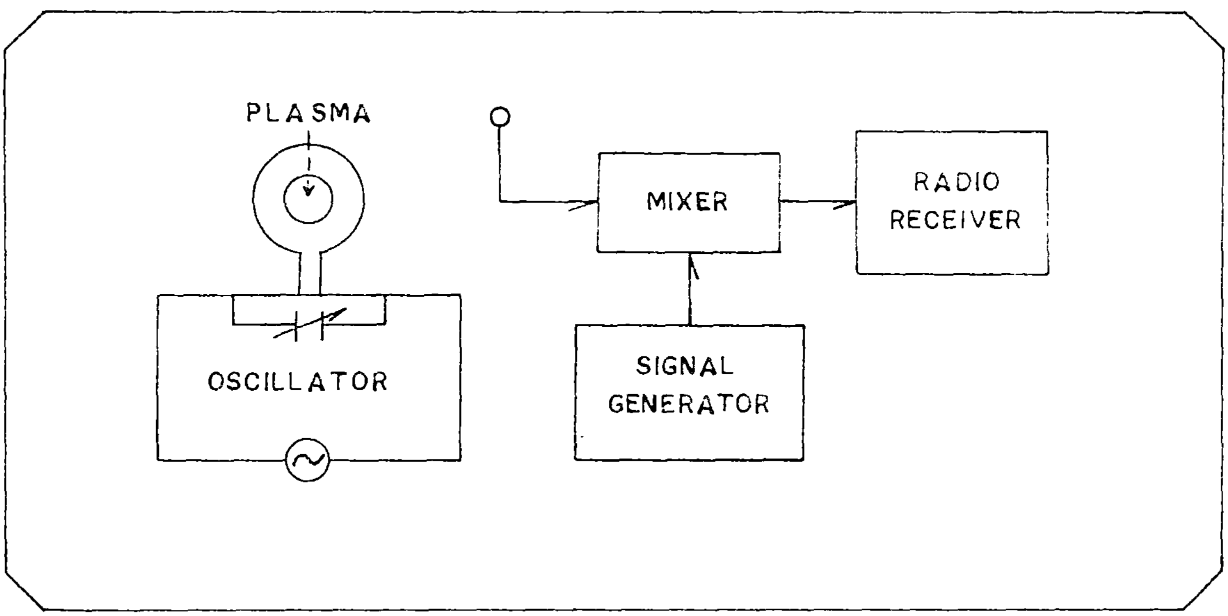
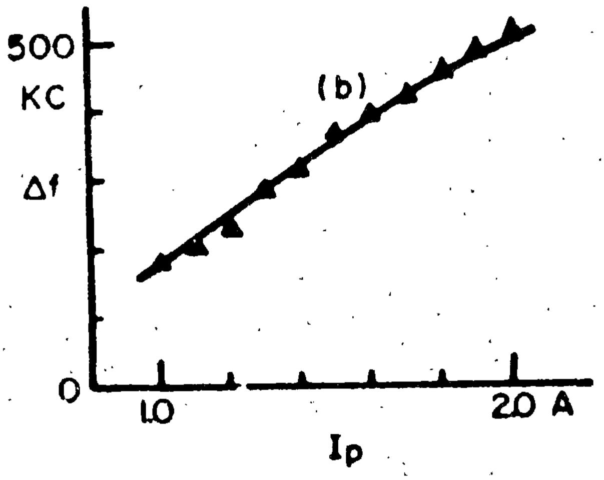
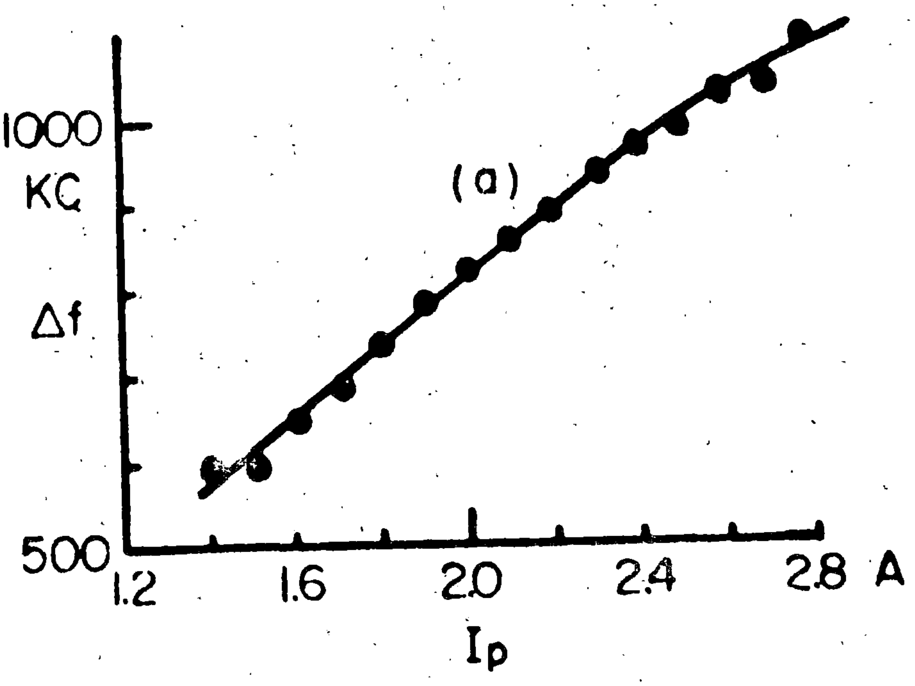


FIG. 1·3. SCHEMATIC DIAGRAM SHOWING THE METHOD.



(a)



(b)

Fig. 1.4. Frequency shift v.s. discharge current:
(a) Ar at 154 Mc
(b) Ne at 119 Mc

Reproduced from the paper of Tanaka and Hagi (1964)

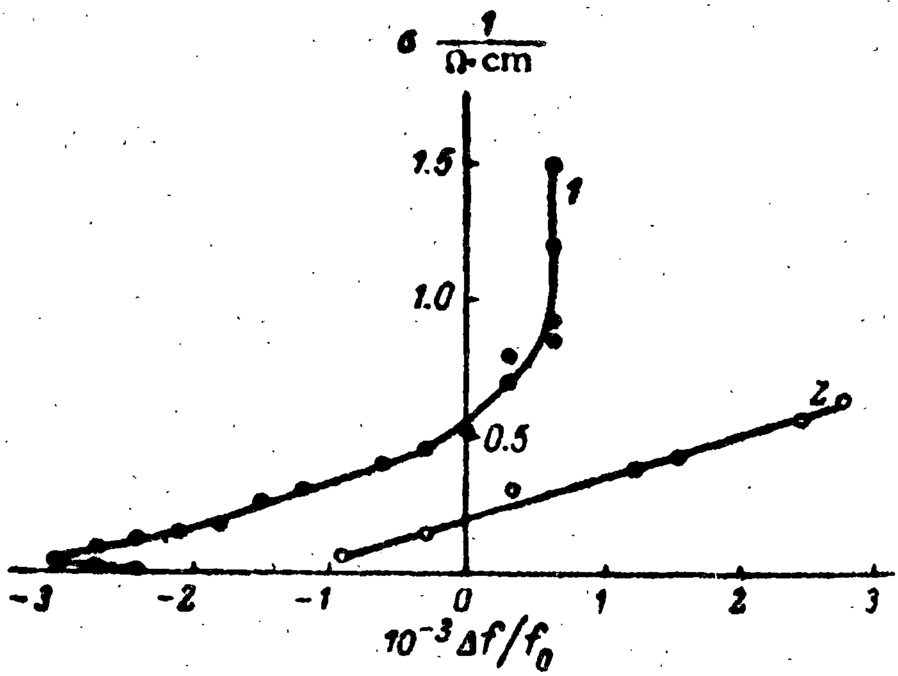


Fig. 1.5 The relative change in the frequency of the measuring oscillator and the corresponding conductivity of the plasma (1) and the electrolyte (2) at a frequency of 80 Mc. The capacitance of the oscillator circuit C_c = 10 $\mu\mu f$.

Reproduced from the paper of Akimov & Konenko (1966)

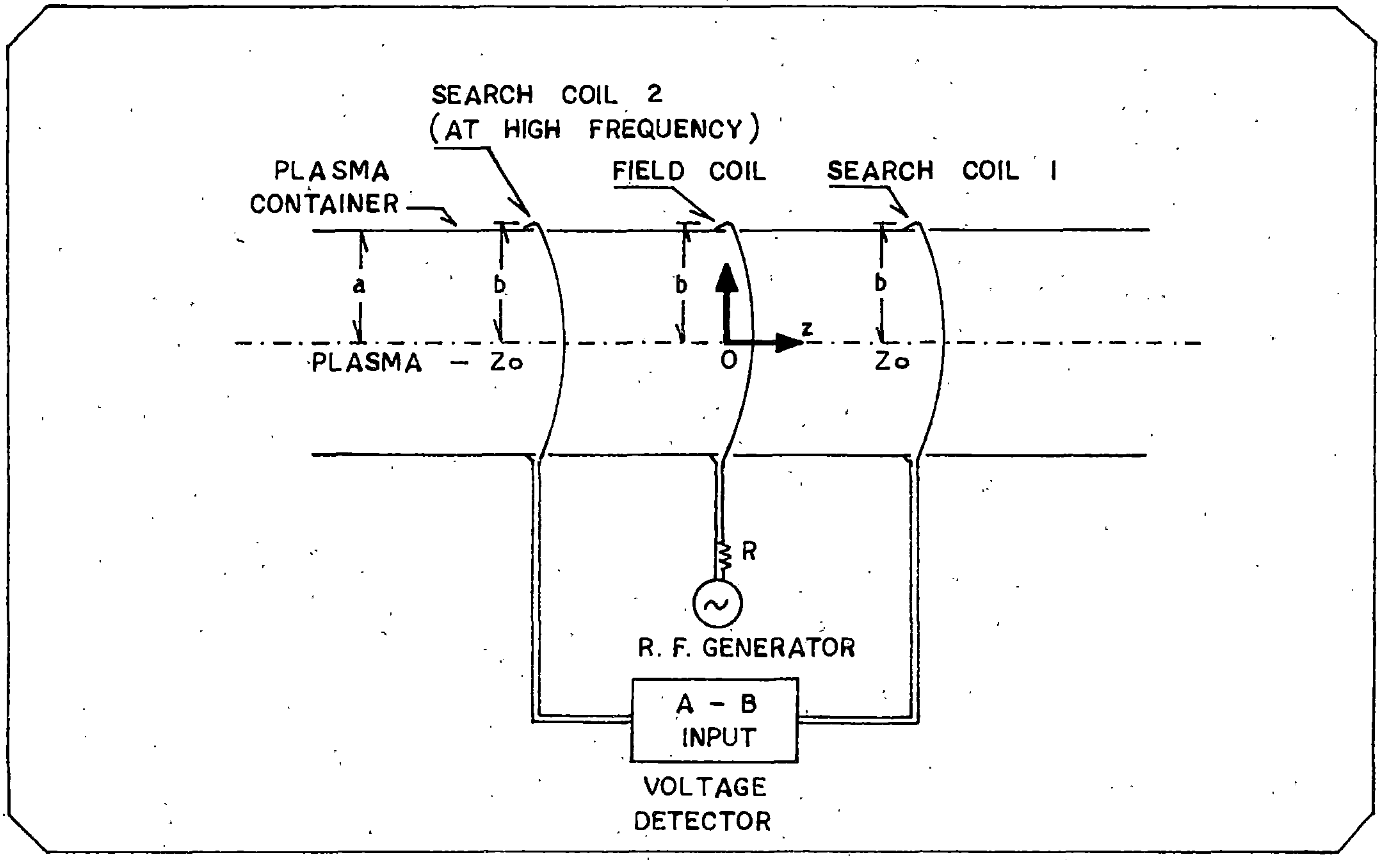


FIG. 1·6 . TWO COIL rf PROBE ASSEMBLY FOR CONDUCTIVITY MEASUREMENTS. SEARCH COIL I RECEIVES THE rf SIGNAL TRANSMITTED FROM THE FIELD COIL THROUGH PLASMA, FROM WHICH CONDUCTIVITY IS CALCULATED. SEARCH COIL 2 IS USED (AT HIGH FREQUENCIES) TO BALANCE OUT THE CAPACITIVE CURRENENTS IN THE SEARCH COILS.