CHAPTER I:

1.1 The Plasma, its Parameters and Characteristics

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References
1.1 The Plasma, Its Parameters and Characteristics

Sir William Crookes, in 1879, considering the special properties of matter in the discharge tubes, advanced the idea that such gases should be considered as "Fourth state" of matter. Langmuir and Tonks in 1923 first introduced a special designation "Plasma". The term simply denotes the fully or partially ionized gases which are electrically quasi-neutral.

The plasma is the normal state of matter at temperature of the order of 10,000°K or more. It exhibits similarities with metals, semi conductors, strong electrolytes and ordinary gases.

In the framework of cosmology, the advent of plasma starts with the origin of the universe. In the same association plasma state is the predominant state of matter. Solids and liquids, as we have been accustomed to know them, represents "Uncommon state". These are to be found only as trace constituents of the universe, the sparsely occurring cold planets and meteoric matter.

About 98% of the matter of the universe exists in the plasma state, in widely differing situations. The atmospheric lightning discharge can produce plasma states (spark plasma) because of the tremendous electric field. The shock waves produced by electrical impulse or the movement of macroscopic objects travelling with supersonic velocities create a sheath of plasma around it due to
tremendous heating effect set up in the air by friction between rocket body and air.

Historically the existence of a highly extended plasma in the upper atmosphere was first suggested by Balfour Stewart\textsuperscript{3}, who in 1878 postulated its existence to explain the diurnal variations in the terrestrial magnetic field. It is known that the upper layers of the earth's atmosphere are continually being bombarded by radiations from the sun and the regions of outer space, and the particles present in this bombardment have been identified as chemical species having charges. In addition the role of electromagnetic radiations has been carefully examined and it has been fairly well established that solar radiations are responsible for the maintenance of the plasma state in the ionosphere at temperatures in the neighbourhood of \( 10^{7}\text{K} \), at altitudes of 70 km or higher, the density of electrons ranges from \( 10^4 \) to \( 10^7 \) per cubic centimeter. The mechanism responsible for the maintenance of this level of charge is photoionization. The earliest conclusive demonstration of the existence of the ionosphere was furnished by Breit and Turvè\textsuperscript{4}, who in 1926 showed experimentally that wave packets (electromagnetic pulses) could be reflected from ionosphere and received at the ground level.
The laboratory plasma may be produced with the application of d-c electric field or high frequency a-c field. But the high frequency alternating fields are preferable over the static electric fields for the production of gaseous discharges in the laboratory due to following important aspects.

In a static electric field an electron avalanche is removed from the gas on reaching the anode. If, however, the field is reversed before this occurs, the direction of motion of the electron cloud is reversed and the avalanche continues to build up due to the general electron drift velocity in each direction. Thus, under a high frequency electric field and wide electrode separation, electron concentration can grow provided the rate of generation of charge becomes greater than the rate of loss. For suitable conditions of frequency, gap dimension and gas pressure, there will be no continuous uni-directional drift of electrons to the anode. In such case the necessity for the secondary process which could replace the primary electrons lost to the electrodes, gets considerably reduced.

When electron concentration increases in this way electrical breakdown in the gas can occur and the discharge can be maintained with a value of electric field very much lower than that required in the case of static electric field.
Charged particles, photons and excited atoms striking the walls of the discharge tube produce secondary electrons. These secondary electrons do not contribute to the growth of the discharge unless they are emitted when the field is in a favourable direction.

High frequency discharge can be maintained in insulating vessels, and the motion of ions and electrons to the walls, set up static fields which largely control the equilibrium density of ionization in the space.

At very high frequencies, the breakdown mechanism becomes complex as a consequence of the amplitude of electron oscillations in the gap becoming comparable to the gap length, so that cumulative ionization can be produced in the gap by an electron travelling many times the gap length in the direction of the alternating field.

The factors which determine the breakdown field, and the subsequent current, ion density, etc., of the fully developed discharges are: (I) The gas pressure $p$, and hence the mean free path $\lambda e$, and electron collision frequency $\gamma$ (II) The frequency $f$, and wavelength $\lambda$, of the plasma exciting electric field (III) dimensions of the vessel in which discharge taking place.

At very low pressure $\lambda e > d, r$, hit the walls of the vessel more often than they hit gas molecules, and hence
secondary effects at the walls control the breakdown. For vessels of \( \frac{1}{4} \) cm x 25 cm, this occurs at pressures of about \( 10^{-2} \) torr. or less.

At high or medium pressures where, \( \lambda e < d, r \) that is when \( (\varphi > \frac{\lambda}{f}) \) the electrons make many collisions for each oscillation of the electric field and drift as a cloud in phase with the field. This motion can be described by a mobility, and the conditions can be divided into two sub-groups.

(I) If the frequency is sufficiently high, the amplitudes of oscillations may be less than the dimensions of the vessel. Then, charged particles are formed due to ionizing collisions in the gas, and are lost mainly by diffusion to the walls;

(II) At lower frequencies and larger amplitudes of oscillations the entire cloud of electrons is driven to the walls in each half cycle of the field. A secondary wall process is then essential to maintain a discharge.

For medium or high pressures, \( \lambda e < d, r \) at high frequency \( (\varphi < \frac{\lambda}{f}) \) the electrons make many oscillations of small amplitudes between collisions with gas molecules. Under these conditions a cloud of electrons would appear to be stationary, spreading outwards only by diffusion.

The oscillatory electric field may be produced in the discharge tube by internal or external electrodes, or by
induction from a conductor carrying an oscillatory current. In our laboratory we have produced plasma by an radiofrequency a-c field. Due to the r.f field, electrons oscillate and thus acquire energy from the field. These energised electrons by elastic or inelastic collisions with atoms and molecules loose their energy, generating new electrons and due to cumulative effect there is breakdown of the gas, the transition takes place from a state of low charge density to one of very high charge density. The electrons thus produced are lost also due to some charge removal mechanisms such as recombination, attachment, diffusion etc. Thus an active plasma is in a dynamic equilibrium with continuous production and destruction of positive, negative ions and electrons. The parameters, characterising plasma encountered under natural conditions or in laboratory equipments differ by many order of magnitude in different cases.

The "electron density" one of the plasma parameters, is defined as the number of electrons per unit volume. It varies from $N = 10^7$ cc. in clouds of interstellar gas to $N = 10^{15}$/cc. in the thermonuclear reactions.

The plasma contains electrons, positive and negative ions and if we assume that both type of ions carry single
charge then under the condition of quasi-neutrality the
electron density $N$ is given as $N = n_e + n_i$.

In the case when plasma contains only electrons and
positive ions then $N = n_e$.

The "degree of ionization", another parameter characteri­sing plasma, simply denotes the concentration of neutral
particles. That is, the degree of ionization $D_i = n_i/N_m$.
In the ionospheric D layer $N_m \approx 10^{15}$ and $D_i \approx 10^{-11}$
$10^{-12}$, in E layer $N_m \approx 10^{12}$ and $D_i \approx 10^{-7}$; and in the
F layer $N_m \approx 10^{11}$ and $D_i \approx 10^{-4}$. In solar corona for
practical purposes $N_m \approx 10^8$ and $D_i \approx \infty$; under other space
conditions, occasionally $N_m \ll N$ but frequently $N < N_m$.

The electron and ion temperatures characterise the state
of plasma, except some cases where the velocity distrib­ution of ions and molecules is in-significant. Moreover
we consider plasma as two temperatures plasma where
electrons and ions have maxwellian distribution of
velocities; but with different temperatures. Usually in
discharges, the plasma electron temperature, $T_e$, may be
of the order of $10^4 K$, while the positive ion temperature
$T_i$ is very close to gas temperature.

The electrons and ions have certain velocities so the
collisions of so many kinds are prevalent in the plasma.
In active plasma collisions can be of two kinds, either
elastic (momentum transfer collision) or inelastic (collision leading to ionization, attachment, recombination etc.). The collision frequency is a function of electron velocity, the gas temperatures and the charged particle density. In dense plasma electron-electron and electron-ion collisions are also possible which can be neglected safely in the case of laboratory plasma.

In the case of plasma oscillations\(^{(8)}\), the electrons and ions oscillate about their equilibrium positions. The frequencies of these oscillations are called the plasma electron and the plasma ion frequency, more commonly called the plasma frequency. These oscillations are electrostatic in nature\(^{(9)}\). The plasma electron frequency, is an important parameter when propagation of electromagnetic waves through plasma is studied. The plasma frequency \(\omega_p\) is given by the relation:

\[
\omega_p^2 = \frac{\omega_0^2}{m_e \epsilon_0}
\]

Similarly plasma-ion-frequency \(\omega_i\) is given by the relation

\[
\omega_i^2 = \frac{N_i e^2}{m_i \epsilon_0}
\]

When the electromagnetic waves propagate through plasma,
it behaves as dielectric for frequencies above the plasma frequency, the lossiness of which is determined by the collision frequency. At frequencies below plasma frequency the plasma behaves as conducting and the wave is either reflected back or attenuated. At frequencies of the order of plasma frequency the wave is either cut off or suffers a large attenuation.

A long range coulomb forces in a plasma act to maintain charge neutrality. Thus the plasma shields any local excess charge, so that up to a distance of a few Debye length its effect is no longer experienced. The shielding length is referred as Debye radius \((D)\) given by:

\[
D = \left( \frac{6\pi \sqrt{N/\epsilon^2}}{\epsilon^2} \right)^{1/2}
\]

The Debye radius is thus the measure of the thickness of the sheath formed at the boundary between plasma and conductor. The debye length may also be thought as the magnitude of charge separation in a plasma for which the resulting electro-static energy density equals the particle thermal energy density. Hence, considerable deviation from electrical charge neutrality can not be expected over distances larger than \(D\).

The appearance of non linearity in the presence of electromagnetic fields is an important characteristic
of plasma. The phenomena of non-linear interaction (cross-modulation etc.) are associated with this. The non-linearity is found due to the slowness in transferring energy acquired from the field to the heavy molecules by electrons in collisions. However, these non-linearities can be disregarded if the field intensity is below plasma field defined as:

$$E_p = 3kT_e \frac{m_e}{2e} \left[ B^2 + \omega^2 \right]^{\frac{1}{2}}$$

Where $E_p$ is plasma field, $\gamma = 2m_e/N$ fractional loss in each collision, $\omega$ angular frequency of the propagating signal, $K$ = Maxwell-Boltzmann constant $T_e = electron temperature$.

Wave interaction phenomena was first observed in 1933 by Talagan with low frequency radio waves which were propagating in the common region of the ionosphere. The interaction between microwaves propagating through a gas discharge was first reported by Goldstein et al. in 1953. They passed a high power microwave signal of frequency 8.6 G.C/S and another low power probing signal of frequency 9.4 G.C/S simultaneously through Helium,
Neon, Krypton, Argon and Hydrogen after glow at pressure range 2 to 20 mm Hg. It was found that in the Helium plasma the wanted wave showed an increase of attenuation due to the action of the disturbing signal. In Argon plasma attenuation was observed to be decreased at 450 mw disturbing power. In the presence of magnetic field the attenuation in all cases showed a significant increase. The change in Luminous intensity was also observed due to the application of disturbing signal.

Anderson and Goldstein (15) in 1955 reported a detailed experimental investigation of the microwave interaction in isothermal plasma. From the decay curve of the microwave attenuation they measured the time constant associated with the decay of electron temperature. It was observed that electron-ion collisions are important in the decay of the electron temperature even in the cases of weakly ionised plasmas. Dugal and Goldstein (16) in 1958 observed with microwave interaction techniques that coulomb collisions between electron and positive ions contribute significantly to the electron collision phenomena even at .001 percent ionization. They also found that relaxation times for electron-ion collisions vary inversely with the ion concentration.

Narsing Rao et al (17) in 1961 reported wave interaction studies in magneto plasma. It was found that
dissociation rates of plasma increases in the presence of disturbing signal, which was at cyclotron resonance frequency. Apart from enhanced collisional diffusion, this was attributed to some instabilities which can develop, when considerable selective heating of electron gas occurs. It was also found that at electron densities of the order of $10^{11}$ electrons/cc. the Neon plasma is completely dominated by coulomb interaction.

The results of microwave interaction phenomena described are confined to amplitude modulation of propagating signal. The modulation effects are observed in the propagation of microwave through periodically varying plasma i.e. through the plasma having periodic variation of electron density and collision frequency. These variations can be either spontaneous or can be excited through external agencies.

Kino and Allen$^{(18)}$ in 1961 performed an experiment on the effect of fluctuations on the electro magnetic wave propagation through plasma. The fluctuations were created by an audio oscillator of frequency $(1-5)Kc/s$ for connected in series with power supply exciting plasma. They observed that the resonant frequency of the cavity resonating in TM mode $TM_{11}$ fluctuates when the plasma tube was put inside the cavity, due to the fluctuations of the electron density in the plasma tube. The
fluctuations in the amplitude of the propagating wave are related directly with electron density fluctuations. This amplitude varies linearly with the modulation index of the discharge voltage.

The plasma having electron density fluctuations may cause phase and amplitude modulation of the propagating wave. The frequency spectrum of the signal propagating through such a plasma will show side bands at the frequency displaced at the rf excitation frequency and its harmonics\(^{(16)}\). In the case of small fluctuations the wave as a whole is affected. As in the case of temperature fluctuations there is no upper limit to the modulating frequency.

A collisionless Luxembourg effect\(^{(21)}\) may be found when a wave suffering Landau damping passes through a warm plasma. The changes in the plasma frequency influence the attenuation exponentially, leading to large amplitude modulation for small density variations. This collisionless damping too introduces side bands, although the spectrum may not be symmetrical. In the absence of any relaxation process there is no upper limit to the modulating frequency.

Iannuzzi\(^{(21)}\) in 1966 reported that plasma without the presence of any externally induced fluctuations can
modulate the propagating wave. Sarkar and Kamal\textsuperscript{(22)} studied the modulation effects on a microwave propagating through an a.c. excited plasma. They demonstrated that the microwave propagating through a.c. excited plasma gets modulated at the modulating frequency.

Polman\textsuperscript{(23)} in 1969 observed that the d.c properties of the positive column of a modulated gas discharge are strongly affected by the modulation, even at small modulation indices. Levitskii and Virko\textsuperscript{(24)} experimentally observed the cross modulation in mercury vapour plasma column at a pressure of 6\times10^{-3}\text{mm}.

John and Sarkar\textsuperscript{(25)} have done a theoretical analysis of the electromagnetic waves passing through a plasma having periodic variations in plasma parameters. They experimentally observed that a propagating signal is amplitude modulated when it passes through such a plasma. Experimental observations show almost complete resemblance with calculated value in the frequency range (300c/s to 1200c/s) termed as mid-frequency region. Below 300c/s experimental value of modulation indices were higher than the calculated. Neutral acoustic waves generation has been proposed as mechanism for higher modulation indices. Maximum modulation index was observed at frequency 100c/s. Authors also observed experimental values of
modulation indices to be higher than calculated beyond the frequency 1 K.c./s. The residual modulation persists even at frequencies of the order of 5 k c/s. Which has been attributed to the variation of electron density due to the modulation of the inelastic collision. The presence of neutral acoustic waves generation has been found later in 1971 by Anand and John (26).
**Review of Ionization and Detonation Times of Gases**

In recent years, the rate at which equilibrium ionization is reached behind shock waves in gases has been studied with considerable interest and from them one may estimate the relative importance of ionization and deionization processes involved. Batesock and Byron \(^{27}\) in 1951 measured the ionization rate of argon along with the time to reach the equilibrium ionization.

The measurements were based on the measurement of attenuation by probe technique. In the measurements they mentioned the dominant ionization process as electron-atom collision. They also gave an indication that the impurities present in the gas can apparently control about 10\% of the final ionization but no reasonable explanation has been found for the unusual effectiveness of impurities in ionizing argon. They observed good agreement between experimental and theoretical ionization rates.

Numer \(^{23}\) in 1956 has made similar measurements in the same \(^{29}\) in 1957 in his theoretical paper concluded that the electron-atom collision is a dominant process of ionization.

Experimental study of the rate of ionization behind shock waves in air have been done by ...ao-chilin, et al \(^{30}\), in 1962. They have measured electron density profile.
behind normal shock waves in air at initial pressures 0.02 ≤ p₁ ≤ 0.2 mm Hg and in the shock-mach-number range 14 ≤ M₉ ≤ 20, using microwave-reflection and magnetic-induction probes in a 24 inch diameter shock tube.

The rate of ionization by this process is limited by the energy transfer to electrons by elastic collisions with the atoms and ions in the gas and is relatively independent of the inelastic ionization cross section.

The measurement of ionization and deionization times of gases was untouched up to 1958 despite of the importance of this information in (a) The problems encountered in the field of communication with re-entering hypersonic vehicles at high altitude. (b) Better understanding of the physics of shock formation, combustion and other rapid chemical reactions. (c) Atmospheric and geophysical researches that is, in the meteoric ionization problems. (d) Aerodynamic problems.

Niblett and Blackman (31) in 1958 attempted this problem using hydro magnetic shock tube to obtain an approximate measurement of the time to reach the equilibrium ionization behind shock waves (adopting shock-reflection technique developed by Peas chek and Byron (27) in the Mach number range 11 to 17, moving into air at a pressure about
1 mm of mercury. The ionization time decreases with increasing mach number. The experimental results were represented as a graph of the ionization time $\tau_0$ vs mach number. Since the principal source of error in the measurement was the attenuation of the incident shock and the results thus indicated a lower limit for the ionization time of air. Secondly this method was based on the assumption that the intensity of the visible light emitted by the shock heated gas indirectly related to the local electron density.

Halvard Torgersen in 1951 developed a method for measuring the ionization times of gases subjected to pulses of ultra-high frequency radio waves using double probe method. A type Cv 64 magnetron was used as high frequency generator (3300 Mc/s) connected to cylindrical wave guide by coaxial line. The guide was nearly closed in one end and the other end was open. The diameter of the wave guide was slightly less than the critical cut off diameter for the operating frequency. Being below cut off the guide will not propagate U.H.F. energy, thus it will act as a load with nearly infinite impedance to the feeder line and high standing wave will set up. These standing waves along the feeder line will disappear when the gas ionises.

The probe picks up a high voltage at maxima and low
at minima. When there are no standing waves the probe pick up the same power giving rise corresponding shape of the pulses on the oscilloscope at different positions of the probe the standing wave ratio as a function of time, and the ionization speed may be determined. Further the ionization time as a function of gas pressure was measured at fixed probe position and constant input voltage to the magnetron. By this method no measurements have been done so far.

Manheimer et al. in 1959 put forward a method on the measurement of attenuation of microwaves which allows to measure ionization rate and ionization time of medium strength shock (mach number 8.2 to 11.4) heated gases by observing attenuation as a function of time as the shock heated tube passes through the waveguide, one can estimate the rate of ionization and the information about the rate of approach to thermodynamic equilibrium. Instead of shock waves, a discharge tube of the same diameter was passed through wave guide and d-c discharge in hydrogen was produced using a power supply of variable voltage (0-5000 V) which was able to give discharge current unto 7.5 mA. The ratio of microwave power without discharge and during discharge was measured by the crystal detector operated in the square law region and a sensitive
galvanometer. Thus attenuation constant was measured by
the relation

\[ \alpha (\text{db/cm}) = \frac{0.7}{2l} \ln \left( \frac{i_2}{i_1} \right) \]

They observed the ionization time of air to vary from
7 to 12/\text{sec.}

Lederman and dawson\(^{(34)}\) in 1967 applied microwave
technique to the measurement of ionization times of
air and argon when these are thermally ionized. The
technique used, utilizes an "end-wall" microwave resonant
cavity. It is essentially a microwave cavity operated in
the TE\(_{011}\) mode with an overdense plasma forming one wall of
a resonant cavity. Since the resonant frequency of such
a cavity is a function of the axial length of the cavity,
variable density plasma with its corresponding variable
conductivity is utilized to tune the cavity to different
resonant frequencies. It is shown that by applying two
frequencies to the cavity separated from each other by
a known frequency difference (\(\Delta f\)) which is small compared
to the resonant frequency of the closed cavity, a simple
method is arrived at to measure electron density, ionization
rate and ionization time.

They observed the ionization time of argon to be
longer than air and electron density increases linearly
with time. However, quantitative analysis for ionization time has not been due to some limitations of technique and gas purity. They simply interpreted ionization time of argon graphically around 40-50 $\mu$ sec. In the case of air due to short ionization an upper limits were found.

The study of decaying plasma has been done by so many workers in the field. But most of the scientists (35, 36, 37) have given much attention to the study of the recombination of the gases. The deionization of a mercury plasma has been demonstrated very well by Baibulatov (39).
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