CHAPTER VI

ELECTROSTATIC PROBES: A CRITICAL REVIEW
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ABSTRACT

Electrostatic probe method for the measurement of electron temperature in a plasma in the presence and absence of magnetic field has been reviewed. Its limitations for applicability and reliability on measurement of electron temperature have been pointed out.
Electrostatic probe is an important plasma diagnostic tool. It is a small metallic electrode, usually a wire inserted into plasma region. The probe is attached to a power supply capable of biasing it at various voltages, positive and negative with respect to the plasma. The current collected by the probe then provides information about the condition of the plasma. Langmuir's theory of probe is applicable only under Maxwellian velocity distribution of electrons. The velocity distribution of electrons, specially in a low pressure plasma is generally not only far from being Maxwellian but is not even isotropic. Langmuir's theory of probes and experimental technique since then have been refined by various workers. Druyvestein has shown that the actual electron velocity distribution can be derived from the form of the characteristics. After the work of Langmuir the first major contribution to experimental technique of electrostatic probe was the floating double probe technique of Johnson & Malter. This was followed by the floating triple probe method of Okuda & Yamamoto and also of Chen and Sekuguchi, the variable area probe technique of Fetz & Oechsner and the fixed bias floating double probe technique of Szuszewicz. These methods permit the investigation even of those plasmas in which a reference potential in the form of an electrode is absent, or where space potential is not defined (e.g. electrodeless h.f. discharge, after glows and the upper atmosphere). Attempts have been made to extend the
range of applicability of the electrostatic probes. In this connection plasma at high gas pressure and plasma under magnetic fields are important.

In spite of all these efforts it is still broadly true that little confidence can be attached to most electron temperature and density data obtained by using probes, except those obtained at relatively high electron temperature, these measurements are unreliable due to invariable probe surface contamination, presence of hysteresis, etc.

This chapter attempts to present an up to date introduction to literature on electrostatic probes. In the section (6.2) we have taken simple theory of probe in the absence of magnetic field. The section (6.3) deals with the theory of probe in the presence of strong and weak magnetic fields. Experimental method of determining electron temperature from single and double probes are given in the section (6.4). Section (6.5) deals the effect of magnetic field on the probe characteristics and on $T_e$ determination. The last section (6.6) is devoted to the discussion on the reliability of measured electron temperature and possible errors in probe measurements.

6.2 FUNDAMENTAL THEORY OF PROBES

Let the probe has the form of a wire of small diameter and whose potential is made negative with respect to the plasma. The wire then repels the electrons and becomes surrounded by a sheath of positive ions. In this
sheath the net positive space charge equals the negative charge on the wire so that the field of the wire does not extend appreciably beyond this sheath. The current collected by the wire is almost accounted for by the rate at which ions arrived at this sheath edge. Langmuir gave the theory of current collection by the probes, which is outlined below.

**Langmuir's Theory**

Langmuir made the following simplifying assumptions:\(^1\)

(i) The space charge sheath is separated from the plasma by a sharp boundary.

(ii) The gas density is low so that collision effect inside the sheath can be neglected.

(iii) The electrodes are perfect absorbers of electron and do not give out secondary electrons.

All of these assumptions are, however, not exactly true under real conditions.

Considering above assumptions and assuming that potential \( \mathcal{Q} \) of the plasma sheath with respect to probe is, positive when it attracts the ions and negative when it repells them. Let \( f(u,v) \) be the normalized distribution functions for the velocities of ions collected by the probe. Here \( u \) and \( v \) are radial and tangential velocities respectively. This function depends only on the components \( u \) and \( v \), because of cylindrical symmetry of the situation. The current collected per unit length of the probe is given by

\[
\mathcal{I} = 2 \pi a_1 n \int \int u f(u_1, v_1) \, du_1 \, dv_1 \quad \ldots (6.1)
\]
here \( n_i \) is ion density and \( e \) is the electronic charge. Subscript 1 denotes the velocities at the sheath edge of radius \( a_1 \). The values of \( u_1 \) and \( v_1 \) can be obtained by setting equations of conservation of energy and angular momentum of ion at the probe surface of radius \( a_0 \) and sheath edge of the radius \( a_1 \).

The value of \( u_1^* = -\frac{2e\phi}{M} \) if \( \phi < 0 \)

\[ = 0 \quad \text{if} \quad \phi > 0 \]

\( v_1 \) can not take all values but in fact bracketed by limits,

\[ v_1^* = \pm \left[ \frac{a_0^2}{a_1^2 - a_0^2} \left( u_1^2 + \frac{2e\phi}{M} \right) \right]^{\frac{1}{2}} \]  

The following two types of distribution functions are of interest to study the probe performance.

**Case I - Constant velocity but random directions**

The distribution function for this case can be readily estimated from the observation that the distribution of state points in velocity space, all fall randomly on the surface of a sphere of radius \( V \). This quantity \( V \) is the magnitude of the velocity. Now it is seen from the probability theory that the distribution function is a plane right angle to the polar axis of the sphere is

\[ f(u, v) = \frac{1}{2\pi V^2} \left( 1 - \frac{u^2 + v^2}{V^2} \right)^{\frac{1}{2}}, \quad \text{for} \quad (u^2 + v^2) < V^2 \]

\[ = 0, \quad \text{for} \quad (u^2 + v^2) > V^2. \]
Substituting this functional relation in (6.1) yields the current collected by the probe per unit length. It is thus found that

\[ i = 0 \quad \text{when } \phi < \phi_0 \]

\[ = 2 \kappa a_0 \left( \frac{n_i e v}{4} \right) (1 + \phi/\phi_0), \text{when } \phi_0 < \phi < 0 \]

\[ = 4a_1 \left( \frac{n_i e v}{4} \right) \left\{ \sin^{-1} \frac{a_0}{(a_1^2 - a_0^2)^{1/2}} \left[ \left( \frac{\phi}{\phi_0} \right)^{1/2} \right. \right. \]

\[ + \frac{a_0}{a_1} \left( 1 + \phi/\phi_0 \right) \sin^{-1} \left[ \frac{\phi_0 - \left[ \frac{a_0^2/(a_1^2 - a_0^2)}{\phi + \phi_0} \right]^{1/2}}{\phi_0} \right] \]

\[ \text{when } 0 < \phi < \left( \frac{a_1^2}{a_0^2} - 1 \right) \phi_0 \]

\[ = 2 \kappa a_1 \left( \frac{n_i e v}{4} \right), \text{when } \phi > \left( \frac{a_1^2}{a_0^2} - 1 \right) \phi_0 \quad \ldots(6.3) \]

In the above expression the potential \( \phi_0 \) is defined by

\[ v = \left[ \frac{2 e \phi_0}{M} \right]^{1/2} \quad \ldots(6.4) \]

It is clear from the result of (6.3) that the probe current is independent of the sheath radius whenever the retarding voltage (i.e. \( \phi < 0 \)) is impressed on the electrode. Furthermore the current depends linearly on the applied voltage. On the other hand when the probe potential accelerates the ions (i.e. \( \phi > 0 \)) the current for the small values of potential increases with the square root of the potential and eventually saturates to a constant value which depends on the density of the ions and the sheath radius. The case of the distribution function considered here applies to the situation of a low
density glow discharge. The positive ions are usually cold and in the vicinity of the probe where collisions are rare the ions under the accelerating field confirm to a distribution function of the form mentioned above.

Case II - Maxwellian distribution of velocities

In low density glow discharge as a result of collisions with neutral atoms the electrons are thermalized, their temperature however, exceeds that of the neutral by several orders of magnitude. The argument of this section is thus of interest when the probe potential is positive with respect to the plasma. It is obvious that discussion pertaining the structure of the sheath applies to the electrons as well. When the probe potential is made negative it is clear that some of the more energetic electrons overcome the retarding potential and reach the electrode but electronic current is expected to decrease rapidly as the potential is made more negative.

When the distribution function is of the form

\[ f(u,v) = \frac{m}{2 \sqrt{k T_e}} \exp \left[ - \frac{m}{2k T_e} (u^2 + v^2) \right] \quad \ldots (6.5) \]

where \( m \) is the mass of the electron and \( T_e \) is the electron temperature. Substitution of (6.5) in the expression (6.1) for the current to the electrode leads to

\[ i = 2 \sqrt{\frac{m}{k T_e}} Z \left\{ \frac{a_1}{a_0} \left( 1 - \operatorname{erf} \left[ \frac{a_0^2 \eta}{a_1^2 - a_0^2} \right] \right) + \operatorname{erf} \left[ \frac{a_1^2 \eta}{a_1^2 - a_0^2} \right] \right\} \]

for \( \eta > 0 \) \ldots (6.6)

\[ = 2 \sqrt{\frac{m}{k T_e}} I_e \eta \text{ for } \eta < 0 \] \ldots (6.7)
In the above expression \( \eta = e \phi / k T_e \),

\[ I = \eta e^{(k T_e/2 \lambda m)^{1/2}} \]

and the error function (erf) defined by

\[ \text{erf}(x) = \frac{2}{\sqrt{\pi}} \int_{x}^{\infty} e^{-y^2} dy. \] ..(6.8)

The values of current thus indicate that for an accelerating potential \( (\eta > 0) \) it is a quadratic function for small \( \eta \), it reaches an asymptotic value for large \( \eta \) and depends on both the sheath radius and the radius of the wire. For accelerating potential \( (\eta < 0) \) the logarithm of the current is linear function of the potential. Furthermore, the current for this case is independent of sheath radius.

**Refinements in Langmuir's Theory**

The Langmuir's theory outlined above is subjected to various limitations because the assumptions on which this theory is based are not exactly valid. Medicus have refined and simplified the Langmuir's theory considering the same assumptions. He obtained the relation for current collection by spherical and cylindrical probes, for retarding as well as accelerating field, considering thick or thin sheath. Further Drauvestien\(^8\) have shown that the actual electron velocity and energy distribution can be derived from the characteristics. He has shown that the second derivative of the probe current with respect to probe potential is proportional to the particle velocity and energy distribution in the case of a retarding field.
Attempts have been made to apply Langmuir's theory for high density and moderate density plasmas, in which the sheath is no longer uniform and do not have well defined boundaries also. It has been shown by various workers that a presheath is formed in front of positive ion sheath, as a consequence, Langmuir's assumptions are no longer valid. In this connection work of Bohm, Kagan, and Parel is important. Bohm gave a first crude approximation of ion current \( I_i \) for spherical probe. His formula reads

\[
I_i = 0.4 n_0 e \left[ \frac{2kT_e}{M} \right]^{\frac{3}{2}} S
\]

where \( n_0 \) is charge carrier density, \( M \) is the ionic mass and \( S \) is the sheath area, above formula shows that it is independent of ion energy. Bohm's formula is applicable to cases, where the probe potential \( V_p \) exceeds \( \frac{2kT_e}{e} \) (i.e. the presheath fully developed) and the ratio of space charge sheath radius to probe radius is not far from unity, otherwise increase in probe current due to growth of space charge is to be taken into account. Wenzl, Shultz and Brown using an approach different from that of Bohm found expression similar to above. The ion current formula for cylindrical probes of the latter authors includes also dependence of probe potential.

The most rigorous treatment for above condition is given by Bernstein and Rabinowitz, in which monoenergetic ions and Maxwellian electrons are considered. In contrast to Langmuir's theory the space charge sheath is not postulated but appears as a consequence of the mathematical procedure.
An important feature of the above in contrast to Bohm\textsuperscript{15} is that, the ion current also depends weakly on ionic energy. We observe that there is an agreement between the above and the work of Kagan and Parei\textsuperscript{20} for a part of parametric ranges. These papers of Kagan and Parei\textsuperscript{20} forms a connecting link between Bohm's\textsuperscript{15} and Rabinowitz's work\textsuperscript{23}. A complete extended analysis of Shultz and Brown\textsuperscript{22} is given by Lam\textsuperscript{24} who has derived an approximate ion current formula for cylindrical and spherical probes, in order to facilitate the evaluation of plasma parameters from measured characteristics, which cover the following parametric ranges.

\[ \frac{E^+}{kT_e} \text{ arbitrary and finite; } \frac{(rp/h^2)}{RP} \gg 1 \]

where \( E^+ \) ionic energy \( rp \) is the probe radius and \( h \) is Debye shielding length.

Proceeding from Rabinowitz\textsuperscript{23} and Lam\textsuperscript{24} and Chen\textsuperscript{25} has shown that within a wide range of parameters the square of ion current \( I_i^2 \) is proportional to the probe potential \( V_p \).

For sphere and low \( V_p \) his formula reads

\[
\frac{dI}{d V_p} \text{ (ZI_i)}^2 = 2.6 \times 10^{-20} \frac{Z}{M} \left[ n_o R_p (Z T_e) \right]^\frac{1}{3}
\]

where \( Z \) and \( M \) are charge and atomic weight of ion. The slopes are measured in \( A^2/V \) and \( kT_e \) in eV.

Chen\textsuperscript{26} and Schott\textsuperscript{27} have reviewed the probe behaviour in detail. Above only a brief consideration is presented. It is for the experimental physicist to find out which of the probe formula offered in the literature for the low pressure case actually does apply to his specific experimental conditions.
6.3 THEORY OF PROBES IN PRESENCE OF MAGNETIC FIELD

So far very little has been published on probe theoretical studies when an external magnetic field is present (which is essential for plasma stability) Spivak and Reichruder, Bickerton and Angle and Nobota considered an infinite plane probe along the magnetic field to avoid the two dimensional problem. They had to assume an arbitrary sheath edge where the density is different from the unperturbed plasma density. An arbitrary distribution function is assumed and it is integrated to obtain the flux at the probe surface. Because of the uncertainty in the actual shape of the sheath in this geometry and also the finite size of the probe which draw $\omega_0 T$ (gyro collision frequency ratio) time larger current density along the magnetic field, it seems practically impossible to measure the plasma parameters in the conventional manner.

Another approach was made by Bitroti who considered the collection of charge particles along magnetic field and averaged the various magnitudes over the probe cross-section to reduce the problem one dimensional. Anomalous diffusion process was introduced and the integro-differential was solved numerically. The electron saturation current calculated by him is the same as that without the magnetic field, because the term arising due to his considerations are far less than unity for most of the laboratory plasma. Therefore electron saturation current is virtually independent of $V_p$ and $B$, which is in clear contradiction to experimental results. Bohm developed a satisfactory analysis of the
problem. He obtained for the collected current a value lower than the experimental results, but the order of the magnitude of the current value is confirmed by Santamartín\textsuperscript{32} in his thesis. He also observed the depletion of the plasma near the probe and insensibility of the results to the shape of probe along the magnetic field.

The theory developed by Bohm\textsuperscript{15} also has some defects. These are (i) the assumption regarding the probe potential in which ions are repelled but electrons are not affected is only true for $\tau << 1$ but not for the general case, (ii) the diffusion equation assumed is valid up to a distance of the mean free path along the field and up to the electron Larmor radius across the field. But the density of the surface within the mean free path and Larmor radius is assumed to be constant, (iii) results are taken to be independent of the probe potential.

Chen\textsuperscript{26} has given the theory for ion saturation current for probe dimensions greater than Debye length. He has given expression for the plasma parameters in terms of common elliptic function for the ellipsoid of revolution inclined at an arbitrary angle to the magnetic field.

Recently Verma \& Shama\textsuperscript{33} have given a theory in which care has been taken to choose arbitrary probe potential irrespective of the range. This theory is applicable for weak, mild and strong magnetic fields under symmetrical conditions. Theories have been developed for spherical as well as for cylindrical probes,
We, thus find that all the above theories on probes in the presence of a magnetic field, take into account only isolated parts of the probe characteristics, i.e. for a particular range of probe voltage.

6.4 USE OF ELECTROSTATIC PROBES

1. Single Langmuir Probe

Plasma parameters can be evaluated by plotting probe characteristics (probe voltage v/s probe current) obtained by biasing Langmuir probe with reference to one electrode using variable voltage source. The obtained probe characteristics can be explained as follows:

(i) When the probe is biased sufficiently negative with respect to the plasma, the probe will collect only ions. We then get a constant current region AB (Fig. (6.1)) called the saturation ion current, which is determined by the rate at which ions reach the probe.

(ii) When probe potential becomes less and less negative, and eventually positive, electrons are able to reach the probe in addition to ions and the magnitude of current changes from B to C, although positive ion current still predominates in this region. At the point C equal numbers of positive ions and electrons are collected by the probe and no current flows, the probe potential at C is referred as the floating potential.

(iii) When the probe potential is made more positive beyond C, the number of electrons collected exceeds the number of ions and the current direction is reversed. The current
now increases rapidly with increasing applied potential, and
gets a electron saturation region at DB where the probe potential
is positive enough, which is defined by the maximum rate of
reaching of electrons at the region CD the probe is surrounded
by an electron sheath, because of their number. Only those
electrons which have sufficient energy to overcome the
repulsion of the electron sheath, will then be able to
penetrate it and reach the probe. Let V be the potential
difference across the sheath i.e. between bulk of plasma and
probe surface. Then assuming Boltzmann distribution law, the
probability that an electron will have this amount of energy
is \( \exp(-eV/kT) \). Consequently, if \( n_e \) is the electron density
in bulk of plasma and \( n_p \) the density at the probe surface, then
\[
   n_p = n_e \exp(-eV/kT_e) \quad (6.11)
\]
where \( T_e \) is the electron temperature in the plasma. The
electron current \( I_e \) at any point will be given by
\[
   I_e = I_{es} \exp(-eV/kT_e) \quad (6.12)
\]
where \( I_{es} \) is the electron saturation current.
As we can see that at D (Fig. (6.1)), the value of the probe/vue is \( V_d \), the value of \( V \) is zero. Hence if the \( V_{p} \) is the
probe voltage at any point between C and D,
\[
   V = V_d - V_p \quad (6.13)
\]
Thus for the determination of \( T_e \), we often write equation (6.12)
as
\[
   \log I_e = \log I_{es} - \frac{eV_d}{kT_e} + \frac{eV_p}{kT_e} \quad (6.14)
\]
The first two terms of R. H.S. are constant. Thus

$$\log I_e = \text{constant} + \frac{e V_p}{kT_e}.$$  \hspace{1cm} (6.15)

The plot of experimental value of \(\log I_e\) and \(V_p\) will give a straight line with slope \(e/kT_e\). Hence electron temperature can be evaluated.

2. **Double Probes**

The double probe consists of two Langmuir probes. In the double probe technique, no current is drawn from the plasma. The observed current \(i_d\) is supplied by the battery, and the plasma essentially provides the conducting medium containing ions and electrons. An idealized plot of the measured current as a function of the potential difference is shown in Fig. (6.2).

The obtained probe characteristics can be explained as follows:

(i) Suppose the voltage applied from the battery is such as to make probe \(P_2\) highly negative with respect to probe \(P_1\). Probe \(P_2\) will then collect positive ions at the maximum rate, so that the observed current is equal to \(I_{is_2}\), the saturation ion current to probe \(P_2\). Probe \(P_1\) will then collect an equivalent number of electrons but no ions. However, since the ions move more slowly, than do the electrons, it is the maximum ion current, rather than the maximum possible electron current, which determines the maximum value of the current flowing through the plasma between the probes.

(ii) As the potential of probe \(P_2\) is made less negative, the current remains constant along \(AB\), but in the vicinity of \(B\) the potentials are such that some electrons, in addition to
ions are collected at probe $P_2$. The absolute value of the net plasma current $i_d$ thus decreases from B to C.

(iii) At C the external voltage between the probes is zero, both the probes then have the same potential with respect to plasma and no current flows.

(iv) As the direction of the voltage is changed, so the probe $P_1$ now becomes negative with respect to $P_2$, the situation is exactly reversed and the curve CDE is obtained for the current $i_d$, which now flows in the opposite direction, as a function of the voltage $V_d$ applied between the probes, the DE gives $I_{is_1}$, the saturation ion current to probe $P_1$ and this will be identical to $I_{is_2}$ if the probes are identical. The saturation ion current to both probes can be given by

$$I_{is_{1,2}} = \frac{1}{2} n_{0_{1,2}} e^{-v_{e_{1,2}}}.$$

The electron current $i_e$ to a given probe can be determined from the fact that absolute value of total current $i_d$, i.e. regardless of direction, must be equal to the difference between the absolute values of the ion and electron currents to the probe. Thus for probe $P_2$, for example,

$$\pm i_d = I_{is_2} - I_{e_2} \quad \text{thus} \quad I_{e_2} = I_{is_2} \pm i_d \quad (6.17)$$

Since there is no net removal of electrons or ions from the plasma, it follows that the total positive ion current to the probe must always equal to the total electron current, thus

$$I_{is_1} + I_{is_2} = \sum I_{is} = I_{e_1} + I_{e_2} \quad \text{...(6.18)}$$

Now applying Maxwell-Boltzmann distribution law as before we get
$I_{e1} = I_{is1} \exp (-eV_1/kT_e)$  \hspace{1cm} (6.19)

$I_{e2} = I_{is2} \exp (-eV_2/kT_e)$

where $V_1$ and $V_2$ are the potentials across the sheath surrounding the probe $P_1$ and $P_2$. Allowing for any unknown potential $V_0$ in the plasma, due to contact phenomena or other causes, it is seen that the applied potential difference $V_d$, which is measured is related to other potentials by,

$$V_d = V_1 + V_0 - V_2 \hspace{1cm} (6.20)$$

**Evaluation of Electron Temperature**

a. Logarithmic Plot Method:

By combining above two equations (6.19) for $I_{e1}$ and $I_{e2}$ we get using equation (6.18),

$$\log \frac{I_{e1}}{I_{e2}} = \log \left[ \frac{\Sigma I_s}{I_{e2}} - 1 \right] = \log \frac{I_{is1}}{I_{is2}} + \frac{eV_c}{kT_e} - \frac{eV_d}{kT_e} \hspace{1cm} (6.21)$$

First two terms in the righthand side are constant. Thus

$$\log \left[ \frac{\Sigma I_s}{I_{e2}} - 1 \right] = \text{constant} - \frac{eV_d}{kT_e} \hspace{1cm} (6.22)$$

Hence a plot of $\log \left[ \frac{\Sigma I_s}{I_{e2}} - 1 \right]$ versus $V_d$ will give a straight line with slope $e/kT_e$. Thus the value of electron temperature can be evaluated by evaluating the value of $I_{is1,2}$ by locating the break point of $i-v$ characteristics. It is seen that this method does not depend on probe area, orientation, sheath area etc. In contrast to the single probe method deviations of the semi-log plot from linearity do not always indicate the presence of non-Maxwellian electron energy distributions. This deviation
may also be due to a difference in electron temperature in the vicinity of the two probes.

b. Equivalent Resistance Method:

The above method is based on a tedious calculation and graph plot. To avoid this computation, an easier method to evaluate electron temperature called "equivalent resistance method" may be employed.

We have seen that, from the last method (equation 6.21)

\[
\frac{I_{e1}}{I_{e2}} = K \cdot \exp \left( \frac{eV_d}{kT_e} \right)
\]

where \(K\) is given by

\[
K = \left[ \frac{I_{e1}}{I_{e2}} \right] = \frac{n_{e1} v_{e1} A_1}{n_{e2} v_{e2} A_2} \exp \left( -\frac{eV_c}{kT_e} \right).
\] .. (6.24)

Differentiating (6.23) with respect to \(V_d\)

\[
\left( I_{e2} \frac{dI_{e1}}{dV_d} - I_{e1} \frac{dI_{e2}}{dV_d} \right) / I_{e2}^2 = K \cdot \exp \left( \frac{eV_d}{kT_e} \right)
\] .. (6.25)

and using equations (6.17) and (6.24) we have

\[
\left[ (I_d \frac{d\Sigma I_{is}}{dV_d} - \Sigma I_{is} \frac{dI_d}{dV_d} + I_{is1} \frac{dI_{is1}}{dV_d} - I_{is2} \frac{dI_{is2}}{dV_d}) / I_{e1}^2 \right]_{V_d=0} = \frac{e}{kT_e}
\] .. (6.26)

where \(\Sigma I_{is}\) denotes sum of ion currents flowing to the probe system at a given \(V_d\). The ion currents do not change strongly with \(V_d\) near \(V_d = 0\) compared to the electron current currents near this point. Terms which are multiplied by derivatives of the ion current may, therefore, be neglected. Thus we arrive at a
simple expression for $T_e$.

$$T_e = - \frac{\sigma}{k} \left[ \frac{I_{e_1} I_{e_2}}{I_{es}} \cdot \frac{dV_d}{dI_d} \right]_{V_d=0} \quad \ldots \ldots (6.27)$$

The quantity $\left| \frac{dV_d/dI_d}{V_d=0} \right|$ which is called "equivalent resistance", represents the slope of double probe characteristics at the point, where it intersects the current axis. $I_{es}$ can be determined by locating point of intersection of tangent line on saturation portion with current axis. This method permits an easy determination of $T_e$.

According to above mentioned methods of Johnson and Malter, electron temperature $T_e$ can be determined by selecting two arbitrary points on the linear part of double probe characteristics after locating its break points corresponding to the saturation ion current. Burrows has shown that the value of $T_e$ calculated in this manner will not be accurate if the positive ion current variation rate with $V_d$ to the two probes are different. A more accurate method for determining $T_e$ according to him is to take these two points on either sided of the point of inflection in double probe characteristics, this point of inflection usually lies half-way across the break point (on voltage scale) on the characteristics for the case where two probes have equal areas. A well defined saturation for probe characteristics is not obtained in many cases. Chiplonkar and Desai have observed that the break point in double probe characteristics can more easily be located if one plots $\log I_d - V_d$ curves in addition to the usual $I_d - V_d$ curves.
### TABLE - 6.1.

<table>
<thead>
<tr>
<th>Pressure</th>
<th>Discharge current mA</th>
<th>r cm/s</th>
<th>Johnson &amp; Malter Method</th>
<th>Log id-Vd method</th>
<th>Burrow's method</th>
</tr>
</thead>
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<tr>
<td>4.0</td>
<td>1.0</td>
<td>14,500</td>
<td>26,400</td>
<td>29,000</td>
<td></td>
</tr>
<tr>
<td>6.0</td>
<td>0.2</td>
<td>12,900</td>
<td>29,500</td>
<td>25,800</td>
<td></td>
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<tr>
<td>1 torr (Air)</td>
<td>4.0</td>
<td>0.5</td>
<td>14,800</td>
<td>28,200</td>
<td>28,000</td>
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<td>0.0</td>
<td>10,600</td>
<td>24,200</td>
<td>24,200</td>
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</tr>
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<td>15,100</td>
<td>15,100</td>
<td></td>
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</tbody>
</table>
An idea about relative magnitude of $T_e$ calculated for identical conditions by the three procedures can be seen from the following table (6.1).

6.5 EFFECT OF MAGNETIC FIELD ON PROBE CHARACTERISTICS

An application of magnetic field modifies the probe curve and the saturation electron current decreases below its value for zero magnetic field.\(^{36}\) In the absence of magnetic field, the ratio of electron to ion saturation currents to a probe is normally of the order of the electron to ion thermal velocities, i.e. of the order of $10^2$, while it has been observed theoretically and experimentally that in the presence of magnetic field electron to ion saturation ratio is of the order of $10^{-20}$. Recently it has been observed that the contrary to what has been assumed in the past, that a small magnetic field can have considerable effect on the ion current collection, even the ion gyro-radius is much larger than the probe size.\(^{37}\) In the presence of a magnetic field, characteristics of single probe and double probe are also altered by the probe size, shape and orientation with respect to the field direction. Sato\(^{37}\) observed experimentally that current collection in a double probe is asymmetric when one probe is placed parallel to the field and other is perpendicular to the field. Because the current in perpendicular probe(i) is much more effected by the field than current to the parallel probe. The ratio of these two currents gradually increases with increasing magnetic field. Sugawara & Hatta\(^{38}\) experimentally and theoretically observed various double probe configurations
in the presence of magnetic field, and concluded that two probes placed facing each other and collecting perpendicular current is a suitable and reliable arrangement for the observations in a magnetic field.

Another noticeable effect is the disappearance of the usual sharp knee at the space potential. Instead of this electron saturation appears at an apparent space potential.\textsuperscript{37}

In addition to the above, the work of Dote\textsuperscript{39} is also of importance. He observed that for single probe the value of magnetic field beyond which, the electron current begin to decrease, depends slightly on pressure, while the ratio between electron to ion saturation current is nearly independent of pressure.

6.6 \textbf{ERRORS AND LIMITATIONS IN PROBE MEASUREMENTS}

Use of electrostatic probes for measurements of plasma parameters are subjected to various criticism. Many workers have indicated numerous possible sources of errors in the evaluation of plasma parameters. It is, therefore, essential to summarize the most important deficiencies.

1. \textbf{General:}

Theory of probes has been developed on certain assumptions, viz., Maxwellian distribution of energy and velocity, presence of isotropy and homogeneity and quasi-neutrality in plasma column. Plasma is assumed to be collisionless. But in practical case of laboratory plasma there is a serious deviation from the above assumptions.
This deviation plays prominent role for high gas pressure, dense plasma and in the presence of magnetic field which causes anisotropy in the plasma.

2. **Probe Size**:

Difficult situation arises when a probe of finite length and shape is immersed in a plasma, resulting in some apparent as well as some inherent disturbances in probe measurements, which we shall discuss below.

It is assumed that the presence of probe does not alter the potential or charge distribution in space or in the plasma, and that the energy distribution of electrons reaching the probe is the same as that in the undisturbed plasma. This implies that the probe must be small relative to significant changes in potential over the occupied space. A large plane probe will disturb the field even in the absence of space charges.

Recently Szuczechewicz [40] has studied the effect of area of the probe on plasma measurements and shown that accurate results may be found by using very small probe. For the case of single probe he has shown that a ratio of reference electrode area to probe area of $10^4$ will guarantee no distortion of probe characteristics. Waymouth [41] has also shown that not only the area but also the size of the probe and reference electrode may influence the ambient plasma parameters. Hence both the relative and the absolute size of a probe are important for the reliability of a probe measurement.

Generally, simple small cylindrical or spherical probe are used. It also limits the use of probes at higher
pressure where field gradient is steep i.e. near corona points.

The probe should also not draw enough current to disturb the plasma, the presence of space charge sheath prevents this serious drain upto some extent. This can also be achieved by using small probes.

The correction resulting from the use of such small probes puts further limitations on the measurements. The use of small probes requires that correction factor should be applied (for geometrical correction and other for effecting area) in order to interpret the current densities corresponding to the current readings. The correction factors as given are highly idealized, and are not accurate.

3. Sheath:

In principle, it is assumed that when a probe is immersed in a plasma a transition region called "sheath" appears, extending for a considerable distance around the probe, independent of the potential of the probe, and which gives the effective area of the probe. It is also assumed that the sheath surface is little disturbed by the probe and by the electrical forces of the probe field. But in practice the above assumptions are not valid. Only for small negative probe potentials, the above assumptions are correct, where most of the electrons penetrate fairly close to the probe and the sheath thickness 'd' is small.

In general, for strongly negative probes, the following factors are active to make the results inaccurate.
The majority of the electrons entering the sheath are repelled by the probe. Thus, the central zone of the sheath has increased electron densities due to incoming and repelled electrons, while the densities are diminished near the probe surface and positive ion densities are high by convergence. Thus, the charge distribution in the sheath surface is not exactly that of undisturbed plasma.

Under such conditions at high pressure, the electrons will collide with molecules after entering the sheath. They will then lose energy by elastic and inelastic, exciting and ionizing impacts. Consequently, in a thick sheath, the energy distribution reaching the probe may not be that existing in the undisturbed plasma. This effect is the one that limits the use of the probes in evaluating energy distribution in plasma at lower $E/p$ and higher pressure.

The new ions and electrons created in the sheath by electron impact will change the carrier densities relative to the undisturbed probes, as well as the energy distribution.

In theory it is assumed that all carriers striking the sheath surface will reach the probe and register as current and only such carriers which represent the original plasma outside the sheath will reach the probe and yield probe current. But in practice this condition is not fulfilled due to scattering, collision and reflection of the electrons by molecules present in the sheath and by the probe surface itself. The failure is greater, the more negative the probe and thicker the sheath. Probe current is also disturbed by the current of electrons and
ions which were not present initially and are produced in the sheath by the impact of electrons, metastable atoms, and high energy photons. Further, probe current is also affected by secondary emission from probe by the action of photons, ions and metastable atoms. With strongly negative probes, the secondary electrons can also multiply in the sheath. The electronic carriers, when emitted, give a positive charge and falsify the value of current, this limits the use of probe for measurements in arc plasma.

4. Measurements:

For obtaining true value of $T_e$ we require true and precise measurement of current and voltage. The value of probe potential $V_p$ as measured by an instrument may not represent the true potential difference between electrode and probe in the case of single probe and between both probes in the case of double probe. The reasons are described here.

(i) Unless the probe surface and reference electrodes are of the same metal and have undergone similar history as regards exposure to gases, bombardment by ions and heating, it is certain that they have intrinsic contact-potential difference. This adds to or subtracts from potential applied.

(ii) A part of the voltage $V_p$ applied to the probe is dropped across the sheath. Since this voltage drop across the sheath is unknown to the experimenter, the actual voltage applied to the probe is an uncertain quantity. Thus if the plasma space potential $V_s$ at the sheath with respect to the reference electrode, is changed during measurement interval, the curve obtained by plotting the probe current against the
externally applied voltage can not give accurate information about $T_e$. The variation of $V_8$ may occur by the presence of fluctuations and drift within the bulk of the plasma and more intrinsically, is caused by drawing probe current through the plasma without infinite conductivity. The errors caused by the variation of $V_8$ have been measured by several workers.\textsuperscript{45,46}

5. Plasma Resistance

The equivalent plasma resistance $R$ between probes or between probe and reference electrode plays a significant role on the determination of $T_e$. The equivalent resistance in the measuring circuit of the probe depends on both the plasma conductivity and the configuration of the probe itself. Its role is of much importance in the presence of magnetic field where anisotropy in conductivity exists. Matsumara and Li-chen\textsuperscript{47} have considered the effect of equivalent plasma resistance experimentally and theoretically. Maximum possible errors in determining $T_e$ by usual graphical methods due to plasma resistance $R$ are calculated and discussed for various types of configuration of the probe. The following conclusions have been arrived.

(i) In the actual measurement when $R \neq 0$, the gradient of the semilog plot of electron current curve decreases with increasing electron current. $T_e$ obtained by the usual graphical method will be larger than its true value since $T_e$ is inversely proportion to the gradient.

(ii) The maximum theoretical errors in determining $T_e$ by neglecting $R$ are all within a factor of 2 for plane,
cylindrical and spherical probes. If \( R \) is known, the errors can be eliminated.

6. **Probe Surface Contamination**

It is observed by many workers,\(^{48-51}\) that contamination of the probe surface, may strongly distort the probe characteristics and influence the quality of the data deduced. They have attributed this distortion to the change of work function of the probe surface due to contamination. The usual criterion for the presence of surface contamination effect is the observation of the phenomenon of "hysteresis" in probe characteristics.\(^{48}\) Probe curve takes different paths with increasing and decreasing the probe voltage. This phenomenon is more obvious in the electron retarding region of the probe characteristic than in the electron accelerating region. This can result in larger differences in the probe current at a particular external probe-reference electrode potential difference for voltage sweeps of opposite sense.

Hirao and Oyama\(^{52}\) have explained the effect of contamination of the probe surface with the help of a "equivalent circuit model" of probe surface. They have assumed it to be made up of several layers as shown in Fig.\((6.3)\). Thus it may be considered as consisting of large capacitors and resistors.

In the presence of hysteresis the electron temperature measured are at best a high estimate of the true electron temperature. Although it has not been possible to describe the
degree of error in quantitative term, it is usually true to say that the higher the degree of hysteresis, the higher will be the error in the estimated temperature. The degree of hysteresis is loosely defined here as the relative displacement of the current-voltage characteristics along the voltage axis in volts. A given amount of hysteresis has much more serious effect for low $T_e$.

The degree of hysteresis has two interesting aspects. Firstly, it depends on the density of the plasma, called the "density dependence," where the probe curve is seriously distorted as the density of the ambient plasma decreases. The second is the "frequency dependence." The hysteresis curve changes its shape with the change of the frequency of the applied probe potential. In the case of low sweep frequency, the hysteresis is much but it decreases as the sweep rate is increased, and finally vanishes for some very high frequency. In this case the probe-characteristic of a contaminated probe is similar to a clean probe and thus we may expect a current measurement of $T_e$.

The above suggestion concerning the sweep rate, however, ignores the possibility that hysteresis may be a manifestation of the existence of surface patches of significantly different work function on the probe or reference electrode, possessing different adsorption and desorption characteristics for surface-active, neutral or charged species. Such a patchy work function condition on the probe surface would mean that for a given probe to reference electrode potential difference, parts of probe surface may be biased in
the electron accelerating region while other parts may be biased in the electron retarding region of the probe characteristics. This will clearly reduce the range of linearity of a semi-log plot and, indeed, as is often observed in Maxwellian plasma, can result in the absence of an adequate range of linearity from which to deduce an electron temperature. The net result is invariably an erroneously high estimate of $T_e$ and it is apparent that such errors will not be eliminated by varying the probe voltage sweep rate. This effect has been clearly demonstrated in the experiments of Bunting and Heikkila\textsuperscript{56} in a low temperature in which gold-plated stainless steel probes were discharge cleaned until sufficient gold was removed to produce a visible patchy surface. With such a probe surface, although no visible hysteresis was apparent, a high estimate was obtained for the $T_e$ from distorted characteristics. Similar results have been obtained by Thomas and Battle\textsuperscript{57} in a high temperature plasma.

The most important of the above discussion is that the absence of observable hysteresis is, in itself, no guarantee that probe data will provide a true value of $T_e$. It is true in all cases that an erroneously high temperature is associated with a small range of linearity of the probe semi-log plot compared to that in an ideal case.
6.7 CONCLUSION

It may be concluded that, though probe forms an important method of estimating electron temperature in a plasma, it suffers from a number of shortcomings as reviewed above. Most of the errors are due to the fact that a probe perturbs the plasma. Therefore, it is broadly true to say that not much confidence can be attached to most electron temperature and density data obtained by using probes except those obtained at a relatively high electron temperature. Thus a non-perturbing method, such as microwave or laser or spectroscopic methods of diagnostics are preferred. The present studies on sonic probe diagnostic is a step in this direction.
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