# USE OF ELECTROSTATIC PROBES IN PLASMA PHYSICS°

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## Summary

The principles of classical Langmuir probe theory are outlined to indicate the type of information theoretically obtainable by this technique. In the dense, hot plasmas and high magnetic fields encountered in modern plasma physics, difficulties arise both in instrumentation and in interpretation of the measurements. Because of these difficulties, perhaps the usefulness of probes lies primarily in the measurements of local fluctuating electric fields. The types of circuits required in probe work are described in general terms.

## Elementary Theory

The use of probes, or wire collectors of charged particles, to investigate the plasmas of gas discharges was developed by Langmuir as early as 1923. In its simplest form, a probe consists merely of a metal wire, usually tungsten, which is inserted in a plasma, somewhat as shown in Fig. 1. An insulator of glass, quartz, or ceramic is used to cover all but the tip of the wire so as to define accurately the collecting area of the tip. Since insulators tend to form a conducting surface film when exposedto a plasma, the end of the insulating tube is usually not in direct contact with the probe tip. A metal shaft may be used for electrostatic shielding and for forming part of a moving vacuum seal.

If a probe is inserted into a plasma and wired in a manner somewhat as shown in Fig. 3, its voltage can be varied relative to some fixed electrode, such as the anode or cathode of the discharge or its metal vacuum chamber wall. The current collected by the probe can be measured by a small resistor R and the current-voltage characteristic of the probe plotted; a schematic representation of this characteristic is shown in Fig. 2. The curve is conveniently divided into three main parts, labeled A, B, and C. The voltage labeled $V_s$ is the local space potential of the plasma; that labeled $V_f$ is the "floating potential", at which the probe draws no current.

In the early days of gas discharge physics, the plasmas investigated were relatively weak. The gas pressure was typically 1 micron or higher, and the plasma density around $10^{10}$ per cc. The fractional ionization was therefore less than $10^{-3}$. Under such conditions, the ions and electrons made many collisions with the neutral gas, and these collisions provided a damping mechanism which prevented fluctuations from occurring, as would happen in a fully ionized plasma. In such quiescent plasmas, the characteristic of Fig. 2 could be measured quite accurately and would yield a considerable amount of information.

If the probe is sufficiently small compared to the mean free path for collisions of the ions and electrons, it can be assumed that its insertion in the plasma does not change the characteristics of the plasma. If the probe is biased at the space potential $V_s$, there will be no electric fields generated by the probe, and particles will hit the probe at a rate given by their random velocities in the plasma. For electrons, the random current is

$$j_{er} = \tfrac{1}{4} n_o e \bar{v}_e = \tfrac{1}{2} n_o e \left(\frac{2kTe}{\pi m}\right)^{\frac{1}{2}} \tag{1}$$

where $n_o$ is the plasma density, $\bar{v}_e$ the average thermal velocity of the electrons, kTe the electron temperature, and m the electron mass. For ions, the corresponding quantity is

$$j_{ir} = \tfrac{1}{4} n_o e \bar{v}_i = \tfrac{1}{2} n_o e \left(\frac{2kTi}{\pi M}\right)^{\frac{1}{2}} \tag{2}$$

Since $m << M$ and in general $kT_e > kT_i$, $j_{er}$ is much larger than $j_{ir}$, and the latter can be neglected. Thus at $V_s$, the probe draws a large electron current, shown by $j_e$ in Fig. 2. This is known as the saturation electron current, given by $j_e = Aj_{er}$, A being the probe surface area.

As the probe is made more and more negative, more and more electrons are repelled, and part B of the probe characteristic is traced out. If the electrons are in thermal equilibrium, their velocity distribution will be given by an exponential law, and the density of electrons at a potential V will be given by

$$n_e(V) = n_o \exp\left[ e(V-V_s)/kT_e\right] \tag{3}$$

where $n_o$ is the density at the potential $V_s$. Thus,

°Received by the Program Committee on August 15, 1961, through IRE. To be presented as paper No. 4-2 at the Joint Nuclear Instrumentation Symposium, Raleigh, N. C.; September 7, 1961.

roughly speaking, the probe current at probe potential V will be decreased by this same factor:

$$j(V) = Aj_{er} \exp[e(V-V_s)/kT_e] \qquad (4)$$

The ion current will be negligible throughout most of portion B because the ratio $(kT_e/m)^{\frac{1}{2}} / (kT_i/M)^{\frac{1}{2}}$ is usually of the order of several hundred. From (4) it is seen that

$$\ln j(V) = e(V-V_s)/kT_e + \ln Aj_{er}$$

and

$$\frac{d \ln j(V)}{d V} = \frac{e}{kT_e} . \qquad (5)$$

Thus the electron temperature can be obtained by differentiating portion B of the curve when it is plotted on semi-logarithmic paper. If the electrons are not in thermal equilibrium, their actual velocity distribution $f(V_e)$ is theoretically proportional to $d^2j/dV^2$, and therefore it can be found by differentiating curve B twice, provided that it can be measured with sufficient accuracy. This double differentiation, as well as the operations of Eq. (5), is sometimes done electronically.

When the probe potential is sufficiently negative, the exponential factor in Eq. (4) can be so small that the electron current to the probe is equal to the ion current. The probe then would draw no net current and would be at the floating potential $V_f$ which it would have if it were connected to a very high impedance. The magnitude of $V_f$ can be estimated by assuming that the ion current density to the probe is the same as $j_{ir}$, the current density in the absence of electric fields. Equating $Aj_{ir}$, as given by Eq. 2, to $j(V)$, as given by Eq. 4, we have

$$\ln (j_{ir}/j_{er}) = e(V_f-V_s)/kT_e \qquad (6)$$

or

$$V_s-V_f = \frac{kT_e}{2e} \ln \left(\frac{kT_e}{kT_i} \frac{M}{m}\right) \qquad (7)$$

In practice, because of the influence of electric fields, it would be more accurate to set $kT_i=kT_e$ in Eq. 7; in any case, the temperature ratio occurs only in the logarithm. Thus $V_f$ depends essentially only on the electron temperature and the species of ions involved. The space potential $V_s$ is found by extrapolating parts B and C of the probe characteristic until they intersect.

Let us now consider portion C of the characteristic of Fig. 2. If the probe potential is made positive relative to space, ions will be repelled and electrons accelerated. The electron current will not increase much beyond $j_{er}$, however, because of space charge limitation. That is, because of the repulsion of the ions, there will be an excess of electrons near the probe, forming an electron "sheath". The negative charge in the sheath cancels the positive charge in the probe, so that electrons outside the sheath do not feel an accelerating field. The saturation electron current $j_e$ is then given by the random electron current incident on the sheath:

$$j_e = A' j_{er} \qquad (8)$$

where A' is the area of the sheath. Since the sheath thickness is approximately the Debye length $h = kT_e/4\pi ne^2$, which is usually much smaller than the probe, A' is usually almost equal to A. The gradual increase of $j_e$ with V is due primarily to the increase of the sheath thickness, and thus of A'. Eqs. 8 and 1 show that $j_e$ is a measure of $n_o (kT_e)^{\frac{1}{2}}$, and thus of the plasma density $n_o$ if $kT_e$ is known from the portion B of the characteristic. However, the current $j_e$ is often so large that one cannot extract it from the discharge without affecting it. The much smaller saturation ion current is therefore normally used.

We thus come finally to portion A of Fig. 2. At high negative potentials, essentially all the electrons are repelled, and the ions are accelerated to the probe. This time, a positive ion sheath is formed which shields out the negative charge of the probe. However, it turns out that this shielding is not perfect, and a potential of the order of $\frac{1}{2}kT_e$ leaks out into the plasma. Consequently, ions do not enter the sheath with a velocity $\bar{v}_i$, as might be expected, but with the much higher velocity $(kT_e/M)^{\frac{1}{2}}$. The ion current therefore depends not on $n_o(kT_i)^{\frac{1}{2}}$ but on $n_o(kT_e)^{\frac{1}{2}}$, and probes cannot measure $kT_i$ sensitively. A calculation of the saturation ion current $j_i$ must also take into account orbital effects; that is, ions accelerated toward the probe may miss it if they have too much angular momentum, much as a comet misses the sun. The orbital effects obviously depend on the shape of the probe. This rather tedious and tricky calculation has been carried out to various degrees of accuracy by a number of people. The result can be expressed approximately as follows:

$$j_i = K A n_o e \left(\frac{2kT_e}{M}\right)^{\frac{1}{2}} \qquad (9)$$

where K is a constant, of the order of unity, which depends on the probe geometry and also slightly on the ion temperature.

In principle, then, probes can measure the plasma density $n_o$, the electron temperature $kT_e$, the space potential $V_s$, and the deviation, if any, from thermal equilibrium of the electrons.

## Application to Intense Discharges

The plasmas encountered in modern plasma physics differ from those of the 1920's and 30's in several respects: 1) the degree of ionization is close to 100%; 2) the plasma densities and temperatures are higher, up to $n_o \sim 10^{16}$ per cc and $kT \sim 1000$ eV; 3) there is apt to be a strong magnetic field, of the order of tens of kilogauss; and 4) the discharges are often pulsed for short periods of time. As a consequence, the application of the principles of the last section has severe difficulties, which shall be considered in turn.

First, the exposure of a probe to intense fluxes of energetic particles causes heating of the probe. To prevent melting and vaporizing of the probe, refractory materials must be used for both the insulator and the conductor. Tungsten, molybdenum, and tantalum are commonly used for the probe tip, and aluminum or beryllium oxide for the insulator. The latter is more resistant to thermal shock because of its high heat conductivity. At high negative potentials a so-called "unipolar arc" can occur, in which the sheath edge acts an anode and the probe as a cathode for an arc, the circuit being completed through the body of the plasma. Platinum has been found to be less susceptible to these unipolar arcs than other metals.

Several methods have been used to overcome this structural problem. If the discharge is pulsed for a short time, of the order of a millisecond or less, it is sometimes possible to make a probe with enough heat capacity to absorb the energy delivered during a pulse; the probe then cools by radiation between pulses. Alternatively, it is sometimes possible to prevent melting by pulsing the probe voltage. Since the probe is not heated as intensely when at floating potential or more negative potentials than when collecting electrons, one can keep the probe biased negative except for short periods of time. A circuit such as that in Fig. 4 can be used to provide a saw-tooth sweep voltage of the order of 100 volts to the probe in several microseconds. Recessed probes have also been used, in which the collecting tip is withdrawn into the insulator. The probe then samples the plasma after it has been attenuated in traveling down the tube. The attenuation must then be calculated. The insulating tube itself, being at floating potential, does not suffer as much heating as a directly exposed probe would. If the discharge is so intense and of such long duration that none of these methods works, it would be necessary to move the probe mechanically through the plasma so that it does not stay in the discharge more than a few milliseconds.

A second difficulty is the interference of the probe with the discharge. In completely ionized plasmas the ions and electrons normally do not have any cold neutral particles to collide with. The insertion of a probe in a closed system, such as a torus, in which the particles pass by the probe again and again, can greatly increase the collision rate and hence cool the plasma. An even more serious effect is the vaporization of impurity atoms from the probe into the plasma. These impurity atoms, being of high atomic number, usually cannot be completely stripped of their electrons; the remaining electrons can then radiate energy by transitions from one energy level to another and thus quickly cool the electron gas.

Third, the existence of a strong magnetic field can greatly affect the probe current, and so far no complete theory of the behavior of a probe in a magnetic field exists. In even a weak magnetic field the electrons are forced to gyrate in circles smaller than the probe radius and thus are constrained to move along the magnetic lines of force. The insertion of a positive probe then quickly drains the electrons from those lines of force which intersect the probe, and the probe current depends on how fast electrons can diffuse back into this region. Thus in a magnetic field $j_e/j_i$ is much reduced, and the ratio depends on the diffusion coefficient, which is a measure of the rate at which electrons can cross magnetic lines of force. Since this is in general unknown, it is not easy to deduce the plasma density from $j_e$, although one can deduce the diffusion coefficient if $n_o$ is known. The measurement of $kT_e$ should not be greatly affected, but now the electron velocity distribution can be different in the parallel and perpendicular directions relative to the magnetic field, and the probe measurement would give information only about the parallel component. The use of $j_i$ to give $n_o(kT_e)^{\frac{1}{2}}$ would be possible if the field were sufficiently weak that the ion gyroradius $r_i$ were larger than the probe radius $\underline{a}$. In this case the motion of the ions would be essentially unaffected by the field; however, the sheath would be somewhat asymmetrical since it depends on the motions of the electrons, which are affected by the field. If the magnetic field were so strong that $r_i << a$, one could presumably relate the ion current to a diffusion coefficient. Unfortunately, in many cases of interest, $r_i \approx a$, and this intermediate case is extremely difficult to analyze theoretically. These considerations concern absolute measurements of density. Relative measurements in different parts of the discharge can still be made by use of $j_i$ if the other plasma parameters stayed relatively constant.

Fourth, fully ionized gases in magnetic fields have been found to be subject to oscillations in density and potential. These oscillations are of various types; those at high frequencies (1 kmc or above) are due to collective motion of electrons and would be averaged over by a Langmuir probe. Those at frequencies near the ion plasma frequency may cause a probe to give a spurious response, since the natural frequency of the sheath may be expected to be of this order of magnitude. In addition, low frequency oscillations (< 200 kc) of large amplitude can occur. If the probe is allowed to average over these large fluctuations in space potential, the probe characteristic may be distorted because it is a non-linear curve. In such a case a probe characteristic may be taken in a time short compared to a period of oscillation by mean of the circuit of Fig. 4. Often the plasma column becomes unstable and assumes an asymmetric shape. Probes are then most suitable for diagnosis because of their spatial resolution.

Fifth, bombardment by energetic particles may cause the probe to emit secondary electrons and thus show a spuriously large ion current. Thermionic emission may also occur if the probe becomes heated. Secondary emission so complicates the theory that it is usually neglected.

Finally, there is the fact that intense discharges are often pulsed for short times. This necessitates triggering circuits for timing the diagnostic equipment. Pick-up from transients and ground-loops must be eliminated; this is a nuisance rather than a difficulty. In one case the voltage transients were so severe that the probe had to be oil-filled for insulation. In pulsed plasmas which are changing in space potential, it is often convenient to use double probes, which use one probe as a collector and the other as a reference for the probe voltage. Since the system of two probes is floating and can draw no net current, this method also has the advantage that no current larger than the ion current can bombard the probes.

## Conclusion

For the reasons outlined in the previous section, it is difficult to obtain an accurate probe characteristic in an intense, magnetically confined plasma. Although the measurement of $kT_e$ and $n_o$ cannot be made very accurately on an absolute basis, the probe technique remains an important one because it is practically the only method of making local measurements. We have already seen that the spatial distribution of $n_o$ can be measured with probes; the absolute value of $n_o$ can be obtained by another technique, such as microwaves. Measurements of the plasma parameters by other diagnostic methods, such as spectroscopy or microwaves, must average over a large volume of plasma, or at least over a diameter. In contrast, probes can in principle resolve distances as small as the sheath thickness.

The most important application of probes may well turn out to be in the measurement of local fluctuating electric fields. We have seen that the floating potential of a probe differs from the space potential by a constant which depends only on the electron temperature. By using two floating probes close to each other and assuming that $kT_e$ does not differ in the two locations (usually a good assumption), one can measure the local electric field. This measurement would be valid as long as the frequencies of fluctuation are small compared with the response time of the sheath, and the characteristic length of the fluctuations is much larger than the sheath thickness. These requirements are often well satisfied, so that this measurement is subject to less uncertainty than the classical uses of probes. Moreover, since the probes are floating, and thus drawing very little electron current, there is a good chance they will not overheat. The types of circuits used are illustrated in Fig. 5. The potential difference $V_1-V_2$ between the two probes may be obtained either with a differential amplifier or with a transformer. This signal may then be observed on an oscilloscope, frequency-analyzed by a commercial spectrum analyzer, or squared to obtain the autocorrelation function of the potential. The squaring circuit yields $\overline{(V_1-V_2)^2}$, which is equal to $2\overline{V_1^2} - 2\overline{V_1V_2}$, since $\overline{V_1^2} = \overline{V_2^2}$; and the latter term gives the auto-correlation function. From an analysis of this or of the noise spectrum, which contains equivalent information, one can compute the diffusion rate of particles across a magnetic field. Needless to say, this is more easily done in a steady discharge than in a pulsed one. This type of analysis is extremely important, since it is presently believed that electrostatic oscillations may cause the rapid loss of magnetically confined plasmas.

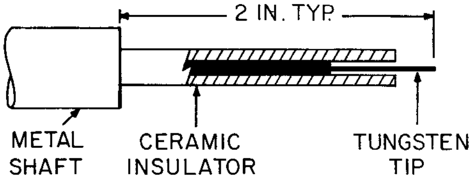


FIG. 1 SIMPLE PROBE

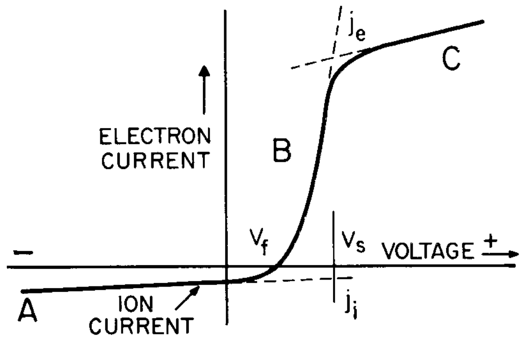


FIG. 2
SCHEMATIC OF PROBE CHARACTERISTIC

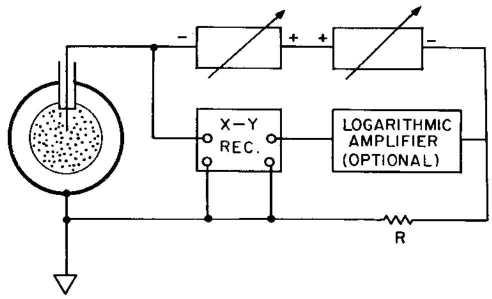


FIG. 3
CIRCUIT FOR OBTAINING DC PROBE CHARACTERISTICS

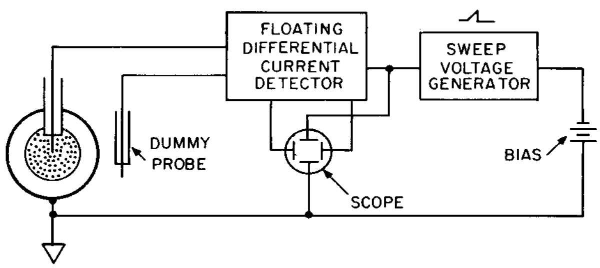


FIG. 4
CIRCUIT FOR OBTAINING FAST PROBE CHARACTERISTICS

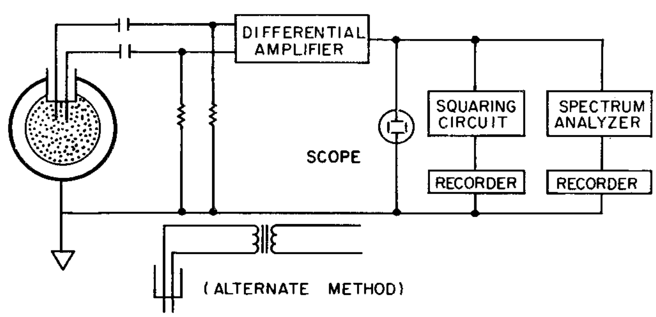


FIG. 5
CIRCUITS FOR STUDYING FLUCTUATIONS IN FLOATING POTENTIAL