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ELECTRIC PROBES AND NEW METHOD

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ABSTRACT

The unbiased floating double electric probe technique for measuring plasma parameters has been discussed theoretically for non-magnetised plasma. The single and double probes basic foundation are presented. The applications of the methods to determine the plasma parameters from experimental results are reported.

1. Introduction.

The attemp to determine characteristic properties of the plasma gas discharge by electric probes was one of the first ways in which physicists tried to study such discharges.

The earlist work simply involved measurement the potential by an insulated probe upon its insertion into the plasma. Langmuir et al. [1] proposed that, the probe potential should be externally varied and one could then determine a large number of properties of the plasma by analyzing the resulting behaviour of the current collected by the probe. This theory was developed and experimentally verified in series of articles [1-5].

The main disadvantages of the simple Langmuir probe is that, large electron current can be drawn from the plasma, also the probe has to be connected to some external potenial source, thereby seriously change the properties being measured. This can be overcome partially by using a double probe.

The double probe consists of a pair of ordinary Langmuir symmetric probes inserted into the plasma as close together as possible, consistant with their sheaths not overlapping. The over all assembly is allowed to float electrically, but a potential difference is placed between the two probes [6-9]. Since such assembly has the advantage of making the measurements independent of the acutal potential of the ambient plasma but still each probe individually disturb the plasma in his region.

The minimum disturbance of the electric probe can be achieved by using a double floating probe, where the probes are not subject to any external potential. The plasma space potential is used to determine the probe characteristics, by different load resistors on the probe output. This method is useful for the pulsed discharge, where the correction factor due perturbation can be neglected, and reduces the numbers of the experimental shots.

2. Single Probe :-

Consider an isolated plane probe immersed into the plasma, due to the high mobility of the electrons, they will reach the probe and its potenital becomes negative. This will forms a sheath of positive ions surrunds the probe, Figure (1). The space potnetial formed will prevent more electrons to reach the probe.

Since the main function of the probe depends on its current-voltage characteristics, so the basic circuit used is shown in Figure (2). There are different geometries of the probe, but here plane probe is considered, although cylinderical or spherical are experimentally prefered. When the probe potential is negative with respect to the plasma, the space charge sheath of the positive ion is formed to compansate the potential difference between the probe and plasma. The sheath layer appears as a dark region increases with the increase of the probe potential. For a probe with high negative potential, it collects positive ions current, depends on their concentration. With changing the probe potential from negative to positive value, with respect to the plasma, the voltage-current characteristic curve of the probe is obtained, Figure(3). The probe characteristic curve consists of different regions A-B-C-D-E, discussed as follow:

(A) When the probe is sufficiently negative with respect to the plasma, only the random positive ion current (I_i) is collected, and the space charge surrounds the probe will absorb the potential difference and screen the probe from the plasma.

(B-C) When the probe potential is made less negative, at a point B, electrons start to reach the probe beside the positive ions, and the probe current decreases with gradual increase of the probe potential. At a certain potential, C, the collected electron current is equals to the positive ion current and the current flows through the probe is zero.

(C-D) At that region the electron kinetic energy is sufficient to overcome the retarding force of the probe potential. Hence the electric probe current increases with the increase of the probe potential.

(D-E) At the point D the probe potential is at the plasma potential, i.e. the space charge disappear, and the probe will be in contact with the plasma and will collect both random thermal current of the electrons and positive ions. With the increase of the probe potential a saturation current is reached at the point E.

Further increase of the probe potential will accelerate the electrons which will increase the probe current due to collision and other processes.

Theoretical back ground for calculation of the electron temperature and density.

Assuming that the particles have a Maxwellian distribution, then the electron density (n_v) for electrons with velocity greater than v can be exprssed by the relation:

$$n_v = n_e \exp - \frac{m_e v^2}{2kT_e} \qquad \text{.... (1)}$$

where:

n_e is the plasma electron density,
m_e is the electron mass,
k is Boltzmann's constant and
T_e is the electron temperature.

The electron collected by the probe are those with a kinetic energy greater than the retarding electric force, i.e. $\frac{1}{2} m_e v^2 > eV$, where V is the probe potential. Hence the collected electron current density, J_{ec}, by the probe is:

$$J_{ec} = J_v = J_e \exp -(eV/kT_e) \qquad \ldots \qquad (2)$$

where :

J_e is the random electron current density at the sheath edge, directed towards the probe.

$$J_e = \frac{1}{4} e \bar{v} n_e \qquad \ldots \qquad (3)$$

where :

$\bar{v}$ is the average thermal (random) electron velocity within the plasma. For Maxwellian distribution.

$$\bar{v} = (8 kT_e / \pi m_e)^{\frac{1}{2}} \qquad \ldots \qquad (4)$$

$$\text{then } J_e = n_e e (kT_e / 2\pi m_e)^{\frac{1}{2}} \qquad \ldots \qquad (5)$$

The total collected current by the probe:-

$$I_c = I_{is} + I_{ec}$$

$$= I_{is} + I_{es} \exp -(eV/kT_e) \qquad \ldots \qquad (6)$$

where:

$$I_{ec} = J_{ec}A = J_e A \exp -(eV/kT_e) \qquad \ldots \qquad (7)$$

$I_{(i,e)s}$ is the saturation currents for i or e, and
A is the probe surface area.

Estimation of the electron temperature:-

From the characteristic curve of the probe, one can evalaute the electron temperature using equation (6). By substracting the ion current I_{is} and drawing the curve of logarithm i_e versus V give a straight line for the region B - E , Figure (4), the slope of that line is e/kT_e from which T_e can be estimated:

$$I_e = I_c - I_{si} = I_{es} \exp -(eV/kT_e) \qquad \ldots \qquad (8)$$

$$d(\ln I_e)/dV = -e/kT_e \qquad \ldots \qquad (9)$$

Estimation of the electron density:

The electron density can be estimated using equation (5) , where the electron temperature T_e has been determined previously, then :

$$I_{es} = J_e A = n_e A e (kT_e / 2\pi m_e)^{\frac{1}{2}} \qquad \ldots \qquad (10)$$

The saturation electron current is determined from Figure (4), the point D.

Ion temperature estimation:-

For most of the laboratory plasma, the electron density is equals to the ion density, i.e. $n_e = n_i$. The ion saturation current is the probe current at the point A Figure (3):

$$I_{is} = n_i A e (kT_i / 2\pi m_i)^{\frac{1}{2}} \qquad \ldots \qquad (11)$$

In this relation I_{is}, n_i, A and m_i are known, then T_i can be estimated.

Factors affecting the probe measurements:-

The probe theory depends on the collection of charged particles with certain energies by the probe, and the current density of that particles determine the plasma parameters. For particles with specified energies, the distribution function detetrmine their densities. The collection of these particles depends on the effective potential configuration affect them, where probe potential and space charge as well as other physical processes are considered. The probe circuit measures the current flows through it, hence the current density depends on the probe and sheath surface areas beside the trajectories of the moving charged particles.

The previous picture shows that the factors to be considered in the probe theory are :-

a) Particles distribution function.
b) Potential spacial configuration between the probe and the plasma (sheath edge).
c) Plasma shape and dimensions.
d) Probe shape and dimensions .
e) Paticles equation of motion due to electric field and other forces arise, taking into account the collisions.

These factors are discussed in details in several articles, and their basic equation is discribed (3,4 & 8).
The determination of plasma density, the collected current by a probe of area A and sheath thickness d_s, must be known.
For thick sheath less particles are collected by the probe.
For cylinderical probe , the probe current is exepressed by Langmuir [2] as :

$$I = ne\bar{v}A\ (1 - eV_p/kT)^{\frac{1}{2}}/2\,\pi^{\frac{1}{2}}$$

For thin sheath, most of the particles, cross the sheath directed towards the probe, are collected.

So equation (3) is applied , the factor $\frac{1}{4}$ in equation (3) is due to, $\frac{1}{2}$ of the plasma density is directed inside the sheath , and $\frac{1}{2}$ is the average of the direction cosine over a hemisphere.
The sheath thickness can be determined using the theoretical expression of the space charge current flows through the probe.

$$I = \frac{1}{9\pi}\ (2e/m)^{\frac{1}{2}}\ A\ V^{3/2}\ \ \alpha^2\ (1 + 2.66\ \sqrt{kT/eV})$$

where :

α = d for plane probe,
$\alpha = r_p^2\ (\gamma - 0.4\ \gamma^2 + 0.09167\ \ \gamma^3 - \ldots)^2$, for cylinderical probe.
$\gamma = \ln\ (r_p/r_s)$.

3. <u>Double electric probe :-</u>

It consists of two identical probes, normally cylindrical configuration, biased with respect to each other by an external source, but the entire system floats with the plasma potnetial. The double probe has the advantage that it can be used in plasma, with high space potential, and time dependant space potential. Also it draws no current from the plasma i.e. it disturb the plasma only at its location.

The probe construction and circuit are shown in Figure (5).

Since the two probes are floating, they tend to be negative with respect to the plasma, so it is assumed that they collect the full positive ion current. If the potential difference applied between them is V_d, then the space charge potential effect, gives the potential levels of the two probes as shown in Figure (6). Since no currents are drawn by the probe from the plasma, then the total electron currents must be equal to the ion currents.

$$i_{e1} + i_{e2} = i_{i1} + i_{i2} = 2i_s \quad .... \quad (12)$$

where i_{e1}, i_{e2} are the probes electron current, i_s is the saturation ion current $i_{i1} = i_{i2}$ and 1 & 2 represent probe 1 & 2 respectively.

The current passes through the probes circuit must be equals to half of the difference of the electron currents, from the facing area of the probes to each other,

$$i_{e2} - i_{e1} = 2i_d \quad ... \quad (13)$$

The potential relations of the two probes are :-

$$V_d + V_2 = V_1 + V_s \quad ... \quad (14)$$

or

$$V_d - V_s = V_1 - V_2 \quad ... \quad (15)$$

The collected current (i_p) of each particle (p) at each probe is similar to that in single probe,

$$i_p = i_{sp} \exp(-eV_b/kT_p) \quad ... \quad (16)$$

where i_{sp} is the saturation current of that particle,
V_b is the probe potential and
T_p is the temperature of that particle.

If the potential difference between the probes is increased, then the relatively positive probe collects more electrons, until at a certain potential it reaches a saturation.

The current equation of the electron is obtained by adding equation (12) and (13) as :

$$i_{e2} = i_d + i_s \quad ... \quad (17)$$

$$i_{e1} = i_s - i_d \quad ... \quad (18)$$

When the applied potential is reversed a similar are obtained, as shown in Figure (7).

Estimation of the electron temperature:-

From equation (6)

$$i_{e1}/i_{e2} = \exp\left\{-e(V_1-V_2)/kT_e\right\} \quad ... \quad (19)$$

From equations (15) and (18) :

$$i_{s1}-i_d/i_{s2}+i_d = \alpha = \exp\left\{-e(V_d-V_s)/kT_e\right\} \quad ... \quad (20)$$

where :

$$d(\ln\alpha/dV_d) = e/kT_e \quad ... \quad (21)$$

By drawing $\ln \alpha$ versus V_d will evaluate the electron temperature. In that case i_{s1} and i_{s2} represent the saturation current i_{i1} and i_{12} which can be obtained from the characteristic curve. This method in some cases has an error in the evaluation of T_e, where the electron temperatures are affected by the probes, i.e. T_{e1} for probe 1 and T_{e2} for the probe 2. The error in that case does not exceed $\frac{1}{2}(T_{e1} - T_{e2})$.

Estimation of the ion density:-

The maximum electron current to either probe is $2i_{is}$, which much less than the electron saturaton current i_{es} .

The ion density can be calculated from the relation

$$I = \frac{1}{2} n_o e A \, (kT_e / m_i)^{\frac{1}{2}} \qquad \ldots \quad (22)$$

4. <u>Double probe load resistor method:</u>

A new method has been introduced [10] for measuring the electron density and temperature in a plasma with a space potential enough to drive a current between two identical cylinderical probes. The main advantage of this method beside its simplicity, minimum experimental arrangements and measurements, and less disturbance, is that no correction factor is required.

For the two floating probes the plasma potential V_{p1}, V_{p2}, at the probe 1 and probe 2 respectively, is considered differs where $V_{p1} \neq V_{p2}$, and $V_{p2} - V_{p1} = \Delta V_p$ Suppose that each probe is subject to a variable potential, then the characteristic curves of both are similar to that of the single probe shown in Figure (3). The characteristic curves of the two probes are represented separately in Figure (8). A load resitor is connected between the probe leads, and the potential created on that resistor is used for the estimation of the plasma parameters. The probe circuit is shown in Figure(9).

At open circuit, $R = \infty$, the potential difference between the probe leads will be, AB, which is equal to the difference of the space potential between them, V_{ds}. Since the two probes are identical then the difference in the space potential, V_s, is :

$$\Delta V_s = V_{s2} - V_{s1} \qquad \ldots \quad (23)$$

where :

V_{s2} and V_{s1} are the plasma potential at the location of probes 1 and 2 respectively.
The difference in the floating potential between the two probes ΔV_f , taken as isolated probes, is:

$$\Delta V_f = V_{f2} - V_{f1} \qquad \ldots \quad (24)$$

It is noticed from the characteristic curve that ,

$$\Delta V_s = \Delta V_f = V_{ds} \qquad \ldots \quad (25)$$

When a load resistor, R is connected between the probe leads, it will exhibit a load line with a slope 1/R, and the current flows through it will be equals to the net current of each probe, I_c.

where : $$I_c = I_{i1} - I_{e1} = I_{e2} - I_{i2} \qquad \ldots \quad (26)$$

The voltage drop across the resistor R will be less than the potential difference between the two isolated probes where probe (1) potential decreased by ΔV_1 and the same for probe (2) ΔV_2. This can be written as:-

$$\Delta V_f = V + \Delta V_1 + \Delta V_2 \qquad \ldots \quad (27)$$

where $$V = I_c R \qquad \ldots \quad (28)$$

Define $$V_{sf_1} = V_{s1} - V_{f1} \qquad \ldots \quad (29)$$

and $V_{sf_2} = V_{s2} - V_{f2}$ ... (30)

For identical probes and plasma temperature and density does't change from one probe to the another one,

$\Delta V_s = V_{s2} - V_{s1} = \Delta V_f = V_{f2} - V_{f1}$

Hence $V_{sf_1} = V_{sf_2} = V_{sf}$

Where V_{sf} is the difference between the space and the flaoting potentials.
The collected electrons and ions currents, are near to floating position, could be written as follow:

$$I_{i_1} = e\, n_f A_{p_1} \exp(-e\Delta V_1/kT_e) \cdot \{2e(V_{sf}-\Delta V_1)/m_i\}^{1/2}$$

$$= e\, n_f A_{p_1} (2e\, V_{sf}/m_i)^{1/2} \exp(-e\Delta V_1/kT_e) \cdot \left(1-\frac{\Delta V_1}{V_{sf}}\right)^{1/2}$$

$$= I_{if_1} \cdot \exp(-e\Delta V_1/kT_e) \cdot (1-\Delta V_1/V_{sf})^{1/2} \quad \ldots \quad (31)$$

where:

$$I_{if_1} = e n_f\, A_{p_1}\, (2\, e\, V_{sf}/m_i)^{1/2} \quad \ldots \quad (32)$$

n_f = is the ambipolar ion density at floating potential and the electron current is :-

$$I_{e1} = I_{ef1} \exp(e\Delta V_1/kT_e) \quad \ldots \quad (33)$$

Similarly, the ions and electrons currents flows in probe 2 will be :-

$$I_{i2} = I_{if2} \cdot \exp(e\Delta V_2/kT_e) \cdot (1 + \Delta V_2/V_{sf})^{1/2} \quad (34)$$

and

$$I_{e2} = I_{ef2} \exp(-e\Delta V_2/kT_e) \quad \ldots \quad (35)$$

notice that the magnitude of ΔV only considered in the above equation and the signe represents an increase or decrease as shown in Figure (8). The current flows through the probe circuit I_c will be :

$$I_c = I_f \{ \exp(-e\Delta V_1/kT_e) \cdot (1 - \Delta V_1/V_{sf})^{1/2} - \exp(e\, \Delta V_1/kT_e) \} \quad \ldots \quad (36)$$

$$= I_f \{ \exp(e\, \Delta V_2/kT_e) \cdot (1 + \Delta V_2/V_{sf})^{1/2} - \exp(-e\, \Delta V_2/kT_e) \quad \ldots \quad (37)$$

where I_f is ambipolar current of ions or electrons.

Experimentaly the potential difference measurde between the two probes at open circuit R is equalto V_R

Hence V is obtained as :

$$V_{R=\infty} - V_R + = V \quad \ldots (38)$$

Where V_R is the measured potential betweem the two probes for load resistor R .

If ΔV_1 and ΔV_2 is large such that $\exp(-e\Delta V_1/kT_e) \ll 1$ and $\exp(-e\Delta V_2/kT_e) \ll 1$. ... (39)

Then equations (36) and (37) will be

$$I_c = - I_f \exp(e\, \Delta V_1/kT_e) \quad \ldots (40)$$

$$= - I_f \exp(e\, \Delta V_2/kT_e) \cdot (1 + \Delta V_2/V_{sf})^{1/2} \quad \ldots \quad (41)$$

Then :

$$\exp(e\,\Delta V_1/kT_e) = \exp(e\,\Delta V_2/kT_e).(1+\Delta V_2/V_{sf})^{\frac{1}{2}} \quad \ldots (42)$$

Since $\Delta V_2 \ll V_{sf}$ then equation (42) gives

$$e\,\Delta V_1/kT_e = e\,\Delta V_2/kT_e + \frac{1}{2}\,\Delta V_2/V_{sf}$$

$$= (e/kT_e + 1/2\,V_{sf})\,\Delta V_2 \quad \ldots (43)$$

Hence: $\Delta V_1 = C_1\,\Delta V_2$ ... (44)

Where $C_1 = 1 + kT_e/2e\,V_{sf}$ ... (45)

The drop in the probes space potential difference ΔV_f, due to the load resistor R will be

$$\Delta V = \Delta V_1 + \Delta V_2 = \Delta V_2(1+C_1) \quad \ldots (46)$$

Then equation (41) will take the form:

$$I_c = -I_f \exp(e/kT_e.\ \Delta V/1+C_1)$$

$$\ln I_c = \ln(-I_f) + \frac{1}{1+C_1}\,\frac{e}{kT_e}\,\Delta V \quad \ldots (47)$$

Experimental estimation of the plasma parameters:

First the potential difference between the two probes for open circuit is measured which represent ΔV_f. By using different high value load resistor 10 KΩ range) $\Delta V(\Delta V_f - V_{load})$ is obtained for each case. (cr. fig. 11)

Drawing ln I_c (V_{load}/R_{load}) versus ΔV the value of I_f could be obtained.

Substituting the value of I_f in equation (40), the electron temperature T_e could be calculated. The value of C_1 could be evaluated from the equation (47) with the knowledge of I_f, T_e, I_c & V. This could be done using the slope of the line, m, ln I versus ΔV where $m=(1/1+C_1).\ e/kT_e$. The evaluation of the value of V_{sf} could be done by the use of equation (45) and the value of C_1. The plasma density (n_p) value could be estimated using the obtained values, I_f, T_e & V_{sf} and, equations.

$$I_f = e n_f A_p (2eV_{sf}/m_1)^{\frac{1}{2}} \quad \ldots (48)$$

and

$$n_f = n_p \exp(-eV_{sf}/kT_e) \quad \ldots (49)$$

For very high load resistor

$$\Delta V_1 \ll V_{sf}$$

The solution of equation (36) and (37) gives

$$I_c = 2 I_f \ \text{Sinch}\ e\,\Delta V_1 / k\,T_e \quad \ldots(50)$$

Where $\Delta V_1 \simeq \Delta V_2 \simeq V/2$ and $\Delta V_1 / k\,T_e \ll 1$

Hence $$I_c = I_f \ e\,\Delta V / k\,T_e \quad \ldots(51)$$

With the previous knowledge of I_f and the use of equation (51) the accurracy of the theory can be observed

Experimental discussion on the probe measurments.

For high density plasmas, it has been found [11] that the electron temperature and density obtained by double probe agree with that obtained by laser scattering. (Fig 10)

The theoretical investigations for double probe [12], show that the plasma parameters, specially impurities and magnetic field, does not affect measurments near the floating potential

Results from θ-pinch discharge [10,13] shows an agreement between the load resistor method and previous results using spectroscopy and microwave for temperature as well as density. for both Compression phase (B = 0.2T) and after discharge plasma.

For low density plasma, glow discharge, fig (11,12,13) the load resistor technique results agrees with that obtained by single and double probe.

The approximations in the theoretical treatment have no noticable value on the results and are much less than the experimental error. The special cases of the plasma condition can be solved using the same procedure discussed previously. The measurments can be done using electronic circuit and data aquisition system, or point by point using Oscilloscope. Oscilloscope trace can reveal other processes in the plasma [14]

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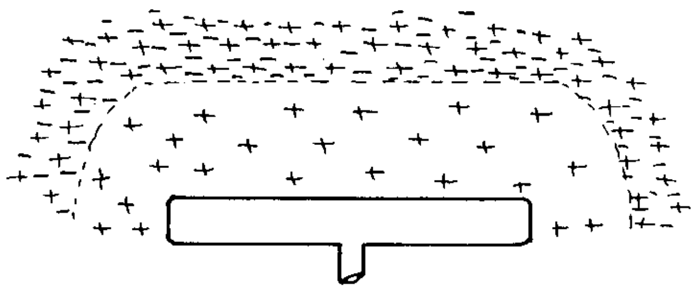

Fig. (1) Plasma and ion sheath in a plane probe.

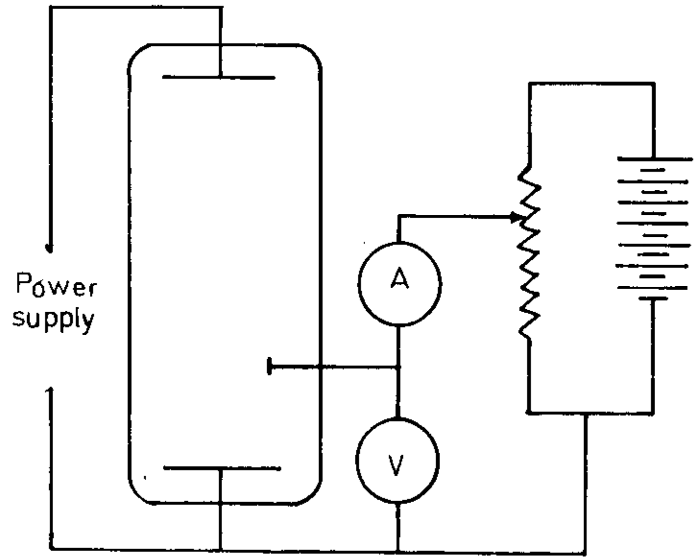

Figure (2) Single probe circuit

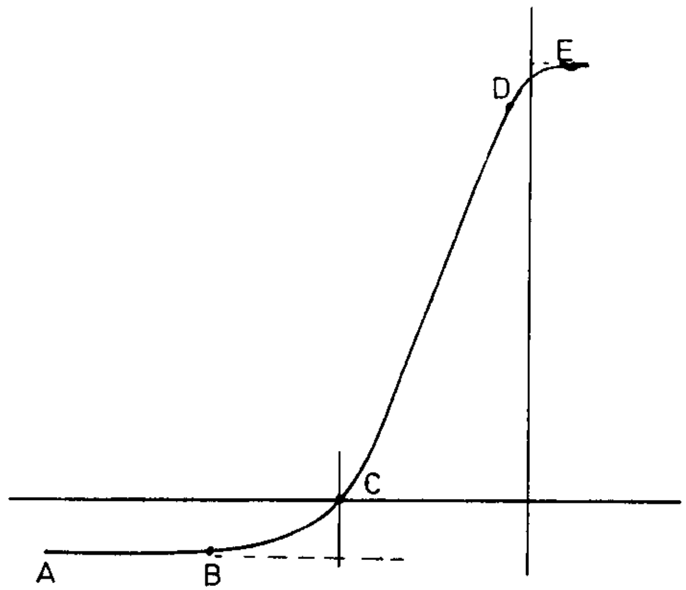

Figure (3) Voltage - Current characteristics for a single probe.

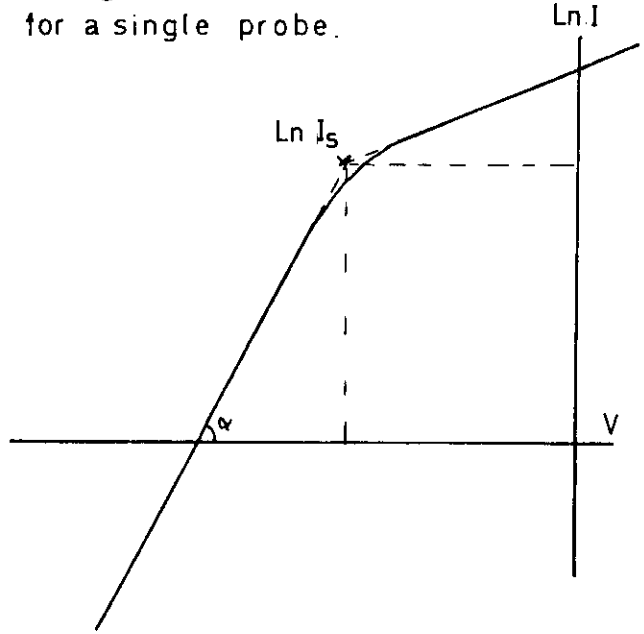

Figure (4) Logarithm of single probe current versus voltage

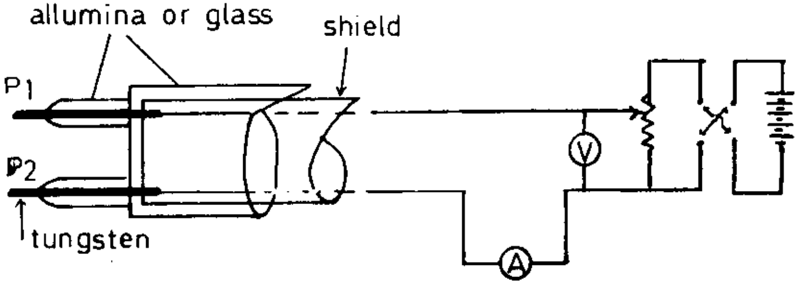

Figure (5) Double probe circuit

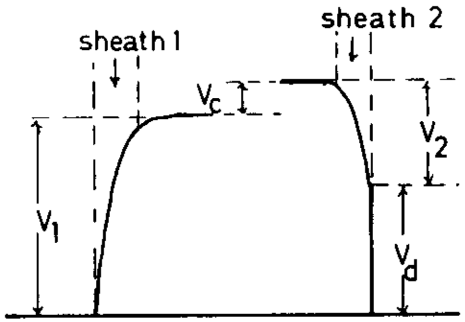

Figure (6) Potential levels in double electric probe.

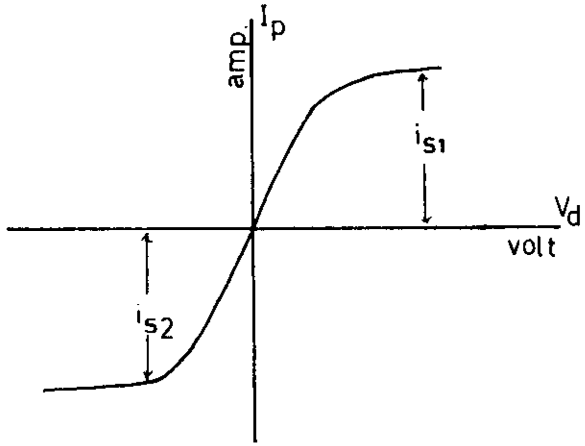

Figure (7) Voltage - Current characteristics of electric double probe.

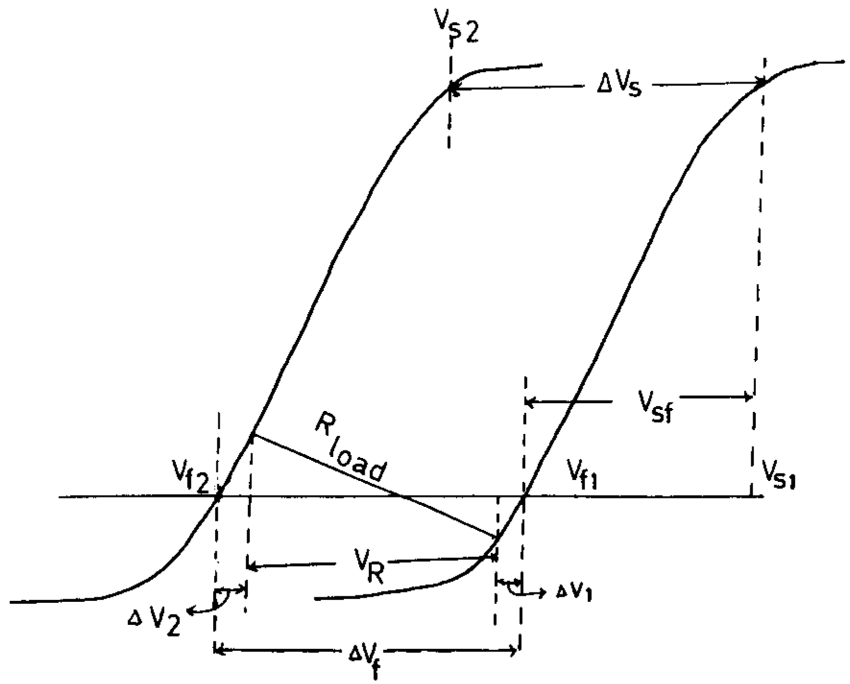

Figure (8) Load resistor double probe characteristics

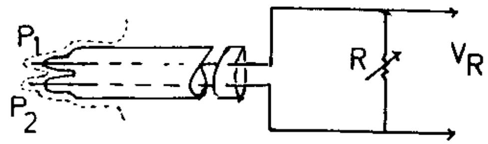

Figure (9) Load resistor double probe circuit

Plasma Physics, Vol. 16, pp. 969 to 975. Pergamon Press 1974. Printed in Northern Ireland

INTERACTIONS BETWEEN TWO COLLIDING LASER PRODUCED PLASMAS

 P. T. Rumsby, J. W. M. Paul and M. M. Masoud

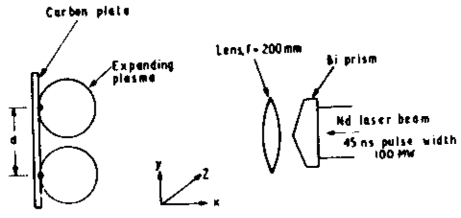

FIG. 1.—Experimental arrangement.

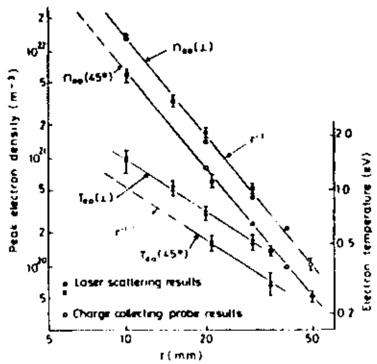

FIG. 10.—Single expanding plasma shell peak density and temperature for expansion along target normal (⊥) and expansion at 45° to target normal (45°).

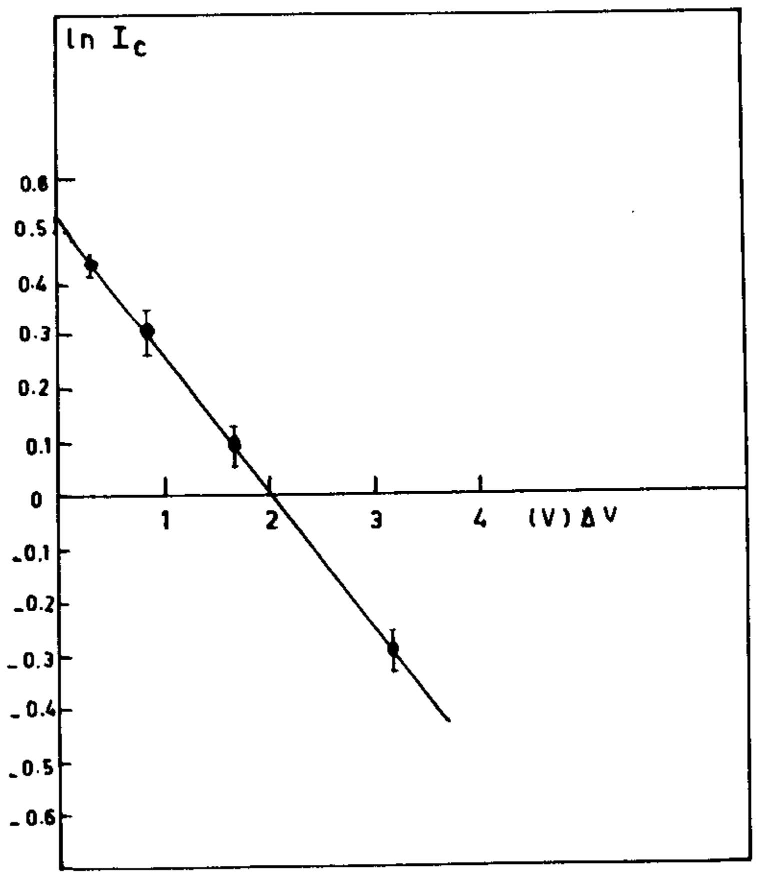

Fig.(11) Relation between potential and current.

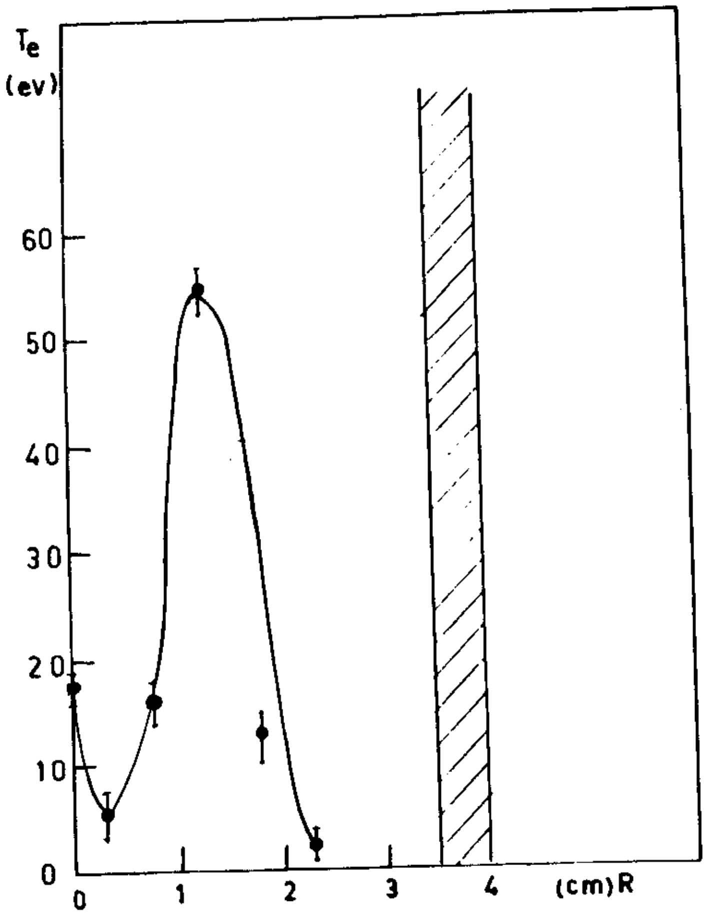

Fig. (12) Distribution of pre-ionization electron temperature along the radius.

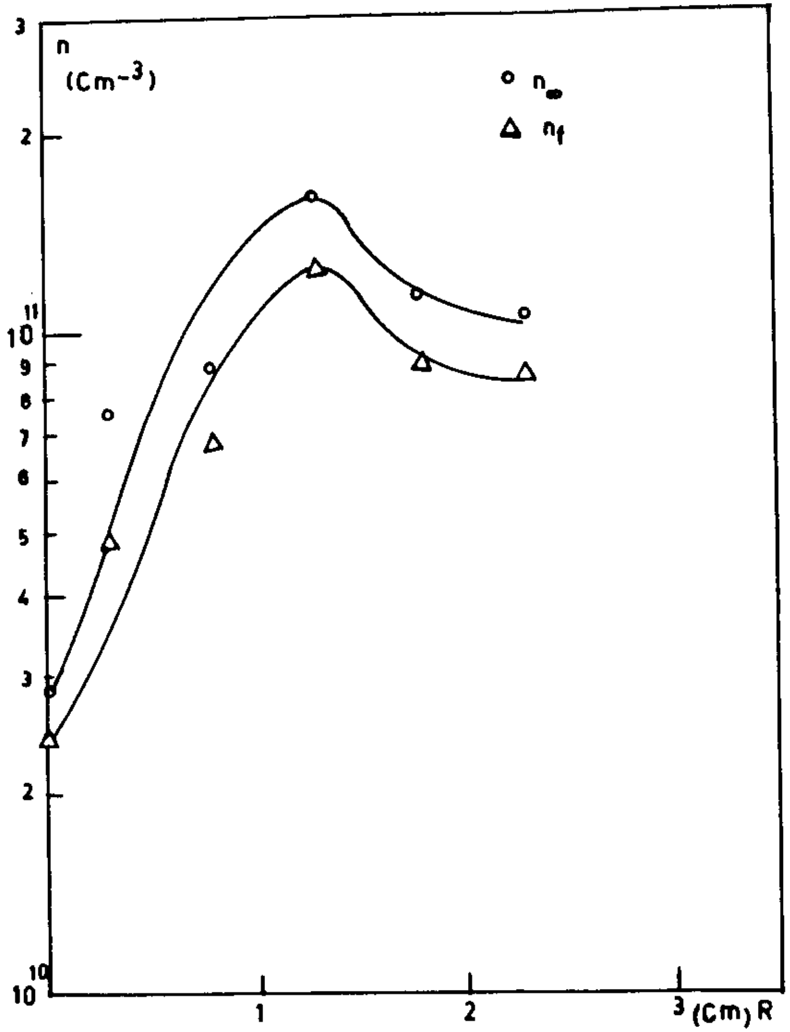

Fig. (13) Distribution of pre-ionization electron density along the radius.

Current Disruption Wave Generation

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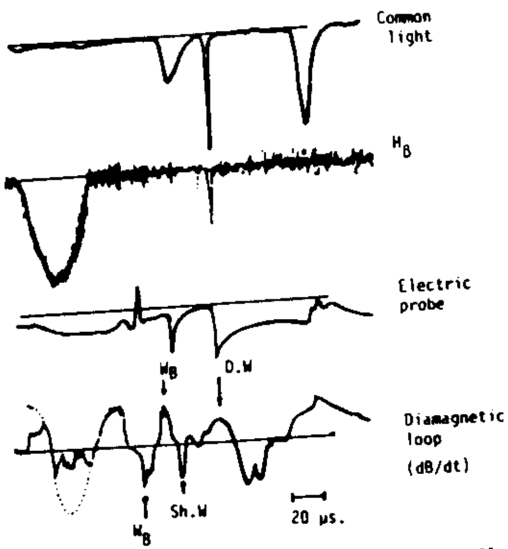

Fig. 4. Traces of the common light, spectral line H_β, electric probe and diamagnetic loop at $Z = 30$ cm.