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The conducting wall effect on single probe measurements

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Abstract . In this attempt, the conducting wall of the vessel is considered as a second probe along with a single probe, where both are completing an electrical circuit along with the plasma. In magnetically confined plasma, this concept leads to a considerable difference between the ion and electron density distribution Then the sheath potential will be affected by that difference.

Keywords Single probe, sheath potential, conducting wall effect.

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1. Introduction

The double probe technique has an important advantage where the total current to the system can never be greater than the saturation ion current, since any electron current to the total system must always be balanced by an equal ion current [1]. In this technique, the electrical circuit is closed and isolated from plasma vessel.

Single probe may be considered as a special case of the double probe. In this case, the wall of plasma vessel acts as a large reference electrode [1]. So the conducting wall is a part of an electrical circuit of the probe.

The electrical circuit of single probe (Figure 1) is composed of the body of the plasma, the tip of the probe and the wall of the vessel. For magnetic field-free plasma, both of the probe and the wall confront the same conditions of plasma; so they have same negative potential with respect to plasma and confined electrons electrostatically.

In case of magnetically confined plasma, there will be a certain density distribution within the plasma's body. So the probe and the wall confront different conditions; but both of them are negative (or less) with respect to plasma.

In this attempt, we are going to study the effect of the conducting wall that is completing the electrical circuit in case of single probe. Then the concept will be applied on a confined plasma by a quadrupole magnetic field system.

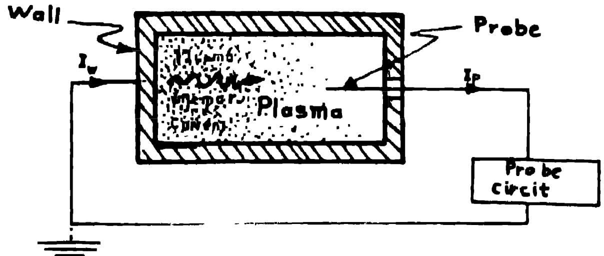

Figure 1. The electrical circuit of signal probe and wall

2. Wall effect theory

For a single probe circuit, when the wall acts as a reference body, the probe and the wall drain same amount of current density ($J_p = J_w$), where J_p and J_w are the drain current densities by the probe and the wall from the sheath region respectively. According to Kirchoff's law :

$$J_{ip} - J_{ep} = J_{iw} - J_{ew} , \tag{1}$$

where the subscripts i and e referred to ion and electron currents respectively. The net current of the system is zero. The concept of electrical circuit implies that there is an internal current inside plasma (to complete the loop). This current arises owing to the potential difference between the probe and the wall (Figure 2). In the case of field-free plasma (homogeneous density distribution), the plasma potential (ϕ_s) inside plasma body is approximately zero ($\phi_s = 0$). In

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this case, both of the floating probe and the wall will have a small negative potential (owing to the sheath) with respect to the plasma, and there is no internal current.

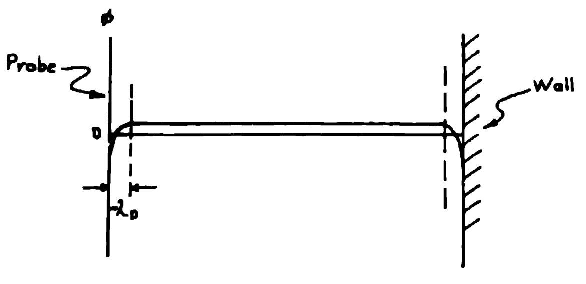

Figure 2. The potential distribution in space between the probe and the wall of magnetic field-free plasma.

In magnetically confined plasma, there will be certain types of distribution of plasma parameters such as density (n), space and floating potentials (ϕ_s, ϕ_f), electron temperature (T_e), ... *etc.*. In this case, let us consider three positions of the probe inside plasma, starting from hot to cold plasma near the wall (where the wall is relatively negative with respect to its neighboring plasma). Figure 3 shows the three different positions of the probe, where the probe and the wall act as two electrodes, and ϕ_w is the wall potential.

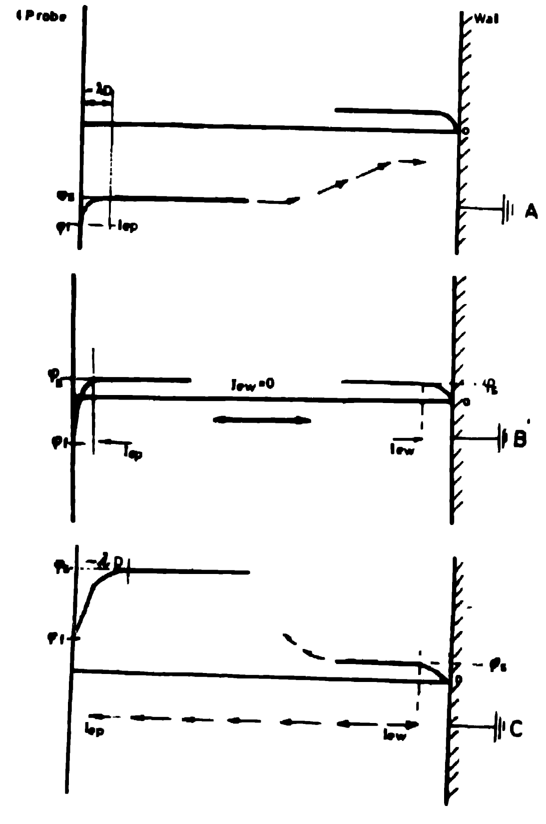

Figure 3. The potential distribution in space between the probe and the wall of many different space potential cases. (a) The probe placed in position of negative space potential, whereas the wall at approximately zero potential. (b) The probe and the wall have same potential. (c) The probe placed in position of positive space potential, whereas the wall at approximately zero potential.

Case 1. When $\phi_f < \phi_s << \phi_w$.

In this case, the probe is positioned in hot plasma region. The probe becomes attractive for the electrons in its vicinity. So owing to internal transportation, the apparent electron probe current (J_e) in retarding region is less than the probe current that appears in the theory of single probe. The apparent electron current of the probe is

$$J_e = J_{ep} - J_{ew}, \tag{2}$$

where J_{ep} is the internal electron current that is directed to the probe from plasma region. J_{ew} is the internal electron current that directed to the wall. J_{ep} is the random current given by

$$J_{ep} = (en_p/4)(8KT/\pi m_e)^{1/2} \tag{3}$$

where n_p is the density at the sheath edge of the probe. K, e, and m_e are Boltzmann's constant, charge and mass of electron respectively. J_{ew} is the current that follows from the vicinity of the wall, and it is

$$J_{ew} \simeq en_w(2\Delta\phi_w/m_e)^{1/2}, \tag{4}$$

where $\Delta\phi_w = |\phi_s - \phi_w| = \phi_s$, ($\phi_w = 0$, owing to the earthed wall), n_w is the density at the sheath edge of the wall. So the apparent current of eq. (2) becomes

$$J_e \simeq J_{ep}\left(1 - \frac{n_w}{n_p}\sqrt{\eta}\right), \tag{5}$$

where

$$\eta = 4\pi e|\phi_s|/KT_e . \tag{6}$$

Case 2. When $\phi_f < \phi_s \simeq$ ($\simeq 0$

In this case, both electrodes (probe and the wall) confined the electrons in their vicinities. So, there is no internal transportation ($J_{ew} = 0$), and then the apparent current is

$$J_e = J_{ep}. \tag{7}$$

This case is similar to that of field free plasma (Figure 2)

Case 3. When $\phi_w << \phi_f < \phi_s$:

This case is expected to be in cold plasma region. The probe is more attractive for electrons than the wall. So, owing to the internal transportation the apparent current is

$$J_e = J_{ep} + J_{ew}. \tag{8}$$

The apparent current is larger than that expected by the probe theory, or

$$I \simeq J_{ep}\left(1 + \frac{n_w}{n_p}\sqrt{\eta}\right). \tag{9}$$

Now, from eqs. (5), (7) and (9), we can get the general ratio of the probe current to the apparent current densities as

$$\frac{J_{ep}}{J} \simeq 1/\left(1 \pm \frac{n_w}{n_p}\sqrt{\eta}\right). \tag{10}$$

From eq. (3), we can say that J_{ep} is referred to n_p. The apparent current J_e is referred to the measured electron density n_{em}. So the ratio J_{ep}/J_e is equivalent to n_p/n_{em}. Eq. (10) can be rewritten as

$$\frac{n_p}{n_{er}} \simeq 1 \Big/ \left(1 \pm \frac{n_w}{n_p}\sqrt{\eta}\right). \tag{11}$$

2.1. The ratio n_w/n_p :

In order to find the ratio n_w/n_p, let us consider two flux of electrons in two opposite directions near the probe. The first one, the flux of electrons owing to the potential difference between the probe and the wall (Γ_ϕ)

$$\Gamma_\phi = n_w V_\phi , \tag{12}$$

where $V_\phi = (2e\Delta\phi_w / m_e)^{1/2}$. (13)

By this assumption, we regard that n_w builds up from the flux only. The second flux is a thermal electron flux (Γ_{th}) and is

$$\Gamma_{th} = n_p V_{th} , \tag{14}$$

where $V_{th} = (KT_e / 2\pi m_e)^{1/2}$. (15)

The relation between the two flux may be classified as

(i) $\Gamma_{th} = \Gamma_\phi$.

In this case, we get $\dfrac{n_w}{n_p} = \dfrac{1}{\sqrt{\eta}}$. (16a)

(ii) $\Gamma_{th} > \Gamma_\phi$.

Then, $\dfrac{n_w}{n_p} < \dfrac{1}{\sqrt{\eta}}$, (16b)

where the thermal flux is dominant.

(iii) $\Gamma_{th} >> \Gamma_\phi$.

Then, $\dfrac{n_w}{n_-} << \dfrac{1}{\sqrt{\eta}}$. (16c)

In this case, Γ_ϕ is approximately negligible.

(iv) $\Gamma_{th} < \Gamma_\phi$.

$$\frac{-}{n_p} > \frac{1}{\sqrt{\eta}}, \tag{16d}$$

where Γ_ϕ is dominant, and could lead to more extreme case to neglect Γ_{th}.

In classifying the confined plasma according to its temperature, one can say that

(a) In hot region where $|-\phi_s| < T_e$, the probe is more repulsive for electrons than the wall. So the relation (16b) is valid, and there is a large depletion of electron from the probe region to the wall (Figure 3a).

(b) In rather cold region, where $|+\phi_s| > T_e$, the probe is more attractive for electrons than the wall, so n_w will decrease, then the ratio (16c) is valid. There is no (relatively small) depletion of electrons to the wall (Figure 3b).

(c) In cold region where $|+\phi_s| >> T_e$, there will be a large depletion from the wall region to the probe, and the relation (16d) is valid (Figure 3c).

3. Looking for application

This theory is applied for a confined plasma, where there exists a density distribution. One of confining machines is linear quadrupole. In this attempt, we will consider the quadrupole of the University of Manchester Institute of Sciences and Technology (UMIST). This devise has been described by many workers [2–5].

In the UMIST quadrupole, single orbital motion limit (OML) probe technique has been used. Cherry [4] used it for $r_p/\lambda_D > 1$ in a small space range of shared flux. The same method has been adopted for $r_p/\lambda_D < 1$ and all quadrupole's regions were examined by Sanduk [5].

However, the theory and the techniques of single OML probe are well known and have been extensively studied by many researchers [6]. The single probe (specially thin probe that based on orbital motion limit theory) gives us a possibility to estimate both of ion and electron densities (n_i and n_e) in addition to electron temperature (T_e), and plasma potential (ϕ_s), from only one curve of $I - \phi$.

In plasma diagnostics theories by electrical probe, plasma density (n) can be estimated through the concept of quasineutrality ($n_i \cong n_e$), then $n_i = n$. Using OML probe, one can estimate both densities. Smith and Plumb [7] did not get equal densities ($n_i/n_e = 1 + 0.07\ m_i^{1/2}$). Geissler [8] also got a ratio of $n_i/n_e \cong 0.704$ which is far from unity.

In OML techniques, the density estimation normally depends on the limit of region of each species in the saturation current part.

In the presence of a strong magnetic field, the conditions of collection will no longer be satisfied, especially for electrons [9]. Because of this, and in case of using single probe, it is preferable to use the ion saturation part of the $I - \phi$ curve only. In this case, one should consider Lca and Allen [10] criteria of dealing with positive ion collection. Owing to this problem with OML electron collection, here we are going to use the retarding region to estimate the density of electron.

The data which we are going to deal with, are extracted from Ref. [5]. These data were obtained by using a *T*-shaped (made of molybdenum), cylinder of 5 × 10^{-5} m radius (Debye length of order 10^{-4} m) probe. The hydrogen plasma was confined by magnetic field of order 3 × 10^{-2} *T*. Figure 4 depicts n_i distribution in ψ/I space [5]. ψ/I is a sort of space coordinate in quadrupole geometry [4].

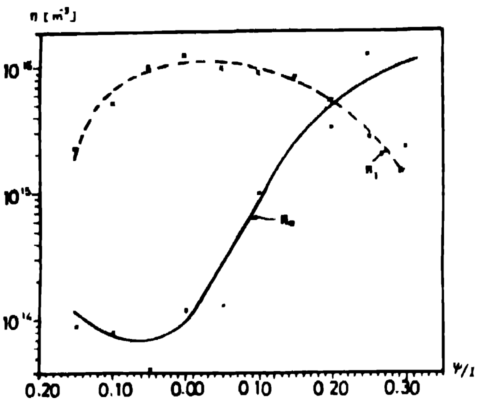

Figure 4. The distribution of experimental n_i and n_{em} in quadrupole space.

3.1. n_{em} estimation :

An estimation of T_e can be found through the assumption that the electrons have a Maxwellian velocity distribution. Electron current can be calculated from subtraction of the I_i OML from the probe current. Then, one can get for probe current :

$$\ln I_e = \ln I_{es} - (e\ \Delta\phi/KT_e), \tag{17}$$

where I_{es} is the electron current at ϕ_s. Eq. (17) is a linear form, and can be plotted after the calculation of I_e. From the slope e/KT_e, one can find T_e. By extrapolating the line back to $\phi_p = \phi_s$, I_{es} and then n_e can be estimated. Since this analysis is at the retarding region, the collecting electron current and density are called I_{er} and n_{er}. n_{er} is the measured electron density (n_{em}) that is mentioned in Section 2. Figure 4 shows the distribution of n_{em}.

3.2. Sheath potential ratio :

Assuming that the densities at the edge of the thick sheath are equal ($n_i \simeq n_e$), one can find the sheath potential ratio [$\alpha = \phi_s - \phi_f)/T$] for the single OML probe as [5]

$$\alpha = 1/2 \ln [\pi\ \tau\ \chi/4(\tau + \propto)], \tag{18}$$

where $\tau = T_e/T_i$ and $\chi = m_i/m_e$.

In the cold ion limit, $\tau >> 1$. For hydrogen (H_1^+), numerical solution of eq. (18) yields $\alpha = 3.07$, whereas for $\tau = 1$ we obtain $\alpha = 2.95$. For OML (in comparison with standard probe) $\propto$ depends on the mass and temperature ratio of ionized gas components, whereas the density ratio is equal to unity due to the assumption of neutrality at the edge of the sheath.

In a previous work [11], an explanation has been given to the reduction in α. It is referred to truncation of the electron velocity distribution as the probe drains electron from a closed flux-tube faster than they can be replaced. This explanation fits only the outer part of the quadrupole, and does not mention the single probe.

3.3. Calculation of the effect :

From the mentioned data [5], we can get η [eq. (6)]. Figure 5 shows the variation of $\sqrt{\eta}$ with ψ/I. A general form can be formulated for the above inequalities (16) as [12] :

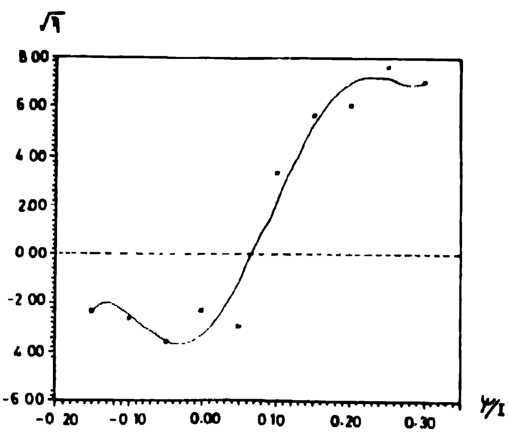

Figure 5. The distribution of $\sqrt{\eta}$ in quadrupole space

$$\frac{n_w}{n_p} = \frac{1}{R\sqrt{\eta}}, \tag{19}$$

where R is a dimensionless quantity and its values can be as $-\infty \geq R \geq +\infty$. According to eq. (19), one can rewrite eq (11) as

$$\frac{n_p}{n_{er}} \simeq 1/\left(1 \pm \frac{1}{R}\right). \tag{20}$$

From eq. (20), Figure 6 shows the variation of R with the theoretical ratio of n_p/n_{em}.

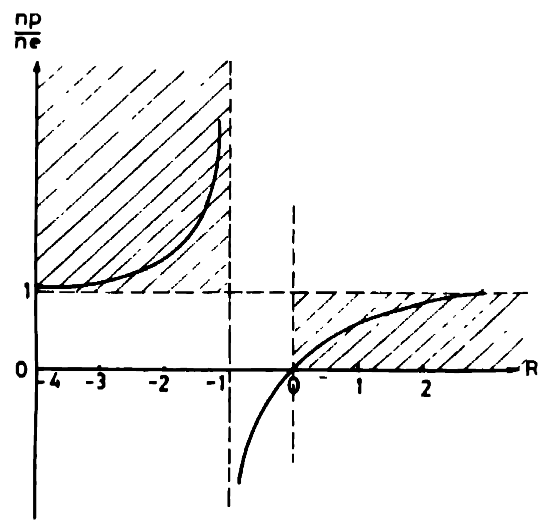

Figure 6. The behavior of the ratio n_p/n_{em} with R according to eq. (20).

Inside the thick sheath, the ions moves under the influence of the electrostatic potential ($e\phi > KT_i$). Therefore, the OML probe current is proportional to $(2e\phi/m_i)^{1/2}$. Accordingly, we can assume that $n_p \simeq n_i$. Then the ratio n_p/n_{er} can be assumed to be equal to n_i/n_{em}, where n_i and n_{em} are shown in Figure 4. With the aid of eq. (20), we can get the experimental estimation of R for the quadrupole. These results are shown in Figure 7.

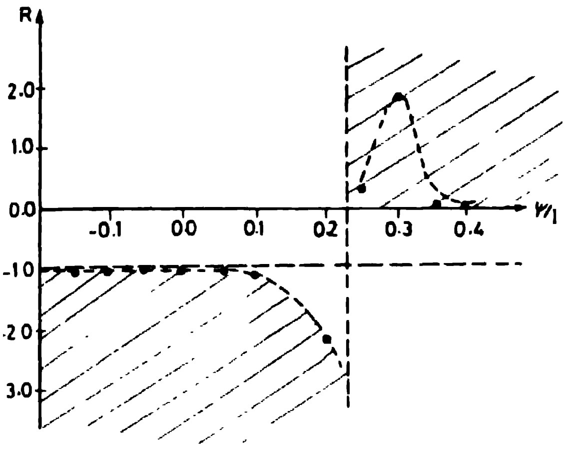

Figure 7. The distribution of experimental estimation of R in quadrupole space

The ratio n_w/n_p can be estimated from the experimental values of R and $\sqrt{\eta}$. These calculations are depicted in Figure 8. There is singularity of $1/\sqrt{\eta}$ at $\psi/I \sim 0.1$, because $\phi_s \simeq 0$ in this position.

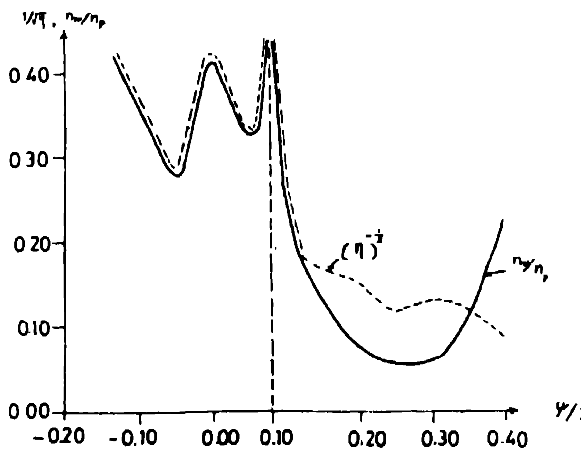

Figure 8. The distribution of the ratio n_w/n_p and $1/\sqrt{\eta}$ in quadrupole space

3.3.1 Sheath potential :

For a rough estimation of sheath potential (ϕ_{sh}) of the probe we can solve Poisson's equation. Inside the sheath, ion and electron densities are no longer equal. The sheath range is of the order of a few λ_D. Under the assumptions of one dimensional case and considering $\Delta n(n_i - n_{er})$ to be a constant, the solution of Poisson's equation (for that sheath) may take this simple form [12]

$$\phi_{sh} = -e/2\varepsilon_0(n_{is} - n_{er})\lambda_D^2 \,. \tag{21}$$

Figure 9 shows the theoretical and experimental plasma potential.

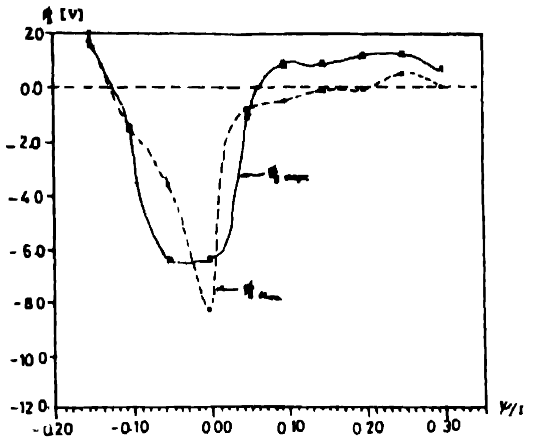

Figure 9. The distribution of the experimental and theoretical space potential in quadrupole space

4. Conclusion

(a) The conducting wall effect arises owing to the space potential difference in two different positions, the positions of the single probe and the wall.

(b) The behavior of the variation of ϕ_s with position (Figure 9) has approximately the same feature for both the theoretical and experimental estimation, which indicates that the density difference has an important role on that behavior.

(c) From Figure 7, the allowed values of R are $0 < R < 2$ and $-3 < R < -1$. The singularity (of R) is at position near $\psi/I \simeq 0.2$. It corresponds to the forbidden region $(-1 < R < 0)$ of Figure 6. The calculated space potential (from Poisson's equation) vanishes at this position (Figure 9). So there is an agreement between the two approaches in determining the position of $\phi_s \simeq 0$.

(d) In Figure 8, the singularity (of both n_w/n_p and $1/\sqrt{\eta}$) is at position $\psi/I \simeq 0.1$. That is owing to the experimental value of the potential (Figure 9), where it vanishes at this position. There is a shift in the determined position of $\phi_s \simeq 0$. The order of this shift is about 0.1. There is already an inaccuracy in position determination of order $\simeq 0.025$. In most of the double probe estimations, the position of vanishing of floating potential (ϕ_f) were found to be at $\psi/I \simeq 0.2$ [2–4].

(e) The typical plasma potential is approximately zero. We got this case at position $\psi/I \simeq 0.2$. At this position, $R \rightarrow \pm\infty$ and this leads to make $n_w \rightarrow 0$. In other words, there is no considerable density near the wall or there is no leakage.

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