A floating potential method for measuring ion density

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A simple method for analyzing cylindrical Langmuir probe curves in a cold-ion plasma is described which yields the ion density in weakly collisional plasmas for which purely collisionless theories give erroneous results. The method is based on an extrapolation to the floating potential of the saturation ion current raised to the 4/3 power. This procedure is not supported by theory but apparently works because effects neglected in the theory tend to cancel. © 2002 American Institute of Physics. [DOI: 10.1063/1.1462630]

I. INTRODUCTION AND METHODOLOGY

Langmuir probe measurement of the plasma density \( n \) in the weakly collisional rf discharges used in semiconductor fabrication is difficult not only because of contamination of the probe tips but also because it has been found\(^4\) that collisionless theories of ion collection are subject to large errors giving rise to the observed shape of the \( V_{\text{f}} \). Since \( V_{\text{f}} \approx 5K_{\text{T}}e \), the sheath is well established at this potential, and the expected \( I_{\text{i}}(V_{\text{f}}) \) can be calculated without the uncertainties inherent in extrapolating to the space potential \( V_{\text{s}}(=0) \) due to the weak ion-accelerating fields there. The \( I_{\text{i}} \approx V_{\text{p}}^{3/4} \) is reminiscent of the Child–Langmuir (CL) law for plane electrodes. If one assumes that the sheath thickness is given by the CL law (neglecting the cylindrical curvature), the collection area expands as \( V_{\text{p}}^{3/4} \), giving rise to the observed shape of the \( I - V \) curve. The ion current at the sheath edge is given by the Bohm sheath criterion as

\[
I_{\text{i}} = \alpha_0 n A_{\text{s}} c_{\text{s}}, \quad c_{\text{s}} = (K_{\text{T}}/M)^{\frac{1}{2}},
\]

where \( A_{\text{s}} \) is the sheath area, and \( \alpha_0 \) is a constant equal to \( e^{-1/2} = 0.61 \) if \( T_{\text{i}} = 0 \) and \( \approx 0.5 \) if \( T_{\text{i}} \) is slightly elevated above room temperature.\(^2\) Hence, knowing \( V_{\text{f}} - V_{\text{i}} \) and \( I_{\text{i}}(V_{\text{f}}) \), one can compute \( n \) using the value of \( K_{\text{T}} \) from the electron part of the \( I - V \) curve. As we shall show in detail, the CL formula should not be applicable in these circumstances, but this procedure heuristically gives values of \( n \) in good agreement with independent measurements using microwave interferometry. (Note that \( I_{\text{i}} \) is a particle current; the electrical current is \( e I_{\text{i}} \), the ions being assumed singly charged.)

The procedure, then, is as follows. A sample \( I - V \) curve is shown in Fig. 1. First, the space potential \( V_{\text{s}} \) is found from the minimum in the \( dI/dV \) curve, shown in Fig. 2. In this case, a clear minimum can be found by drawing a smooth curve through the data points. In rf discharges plasma noise and inadequate rf compensation often make this curve hazy, sometimes with more than one minimum, as illustrated in Fig. 3 for a different \( I - V \) curve. The experimenter has then to choose \( V_{\text{s}} \) judiciously. Next, the ion part of the characteristic is raised to the 4/3 power and plotted against \( V_{\text{f}} \), as shown in Fig. 4. A straight line is fitted to the part of the curve that is not affected by electron current. Extrapolating to \( V_{\text{f}} \), where \( l = I_{\text{i}} - I_{\text{e}} = 0 \), gives an estimate of \( I_{\text{i}}(V_{\text{f}}) \). Note that the extrapolation to \( V_{\text{f}} \) is much shorter than to \( V_{\text{s}} \), so that the estimate of \( I_{\text{i}}(V_{\text{f}}) \) should be more accurate than \( I_{\text{i}}(V_{\text{s}}) \). The ion current is then calculated from the straight line fit to \( I_{\text{i}}^{4/3} \) and subtracted from the total current to give \( I_{\text{e}} \). This is plotted semilogarithmically in Fig. 5. Note that the ion correction to \( I_{\text{e}} \) has made the curve follow a Maxwellian over a much larger range of \( V(=V_{\text{p}}) \). Fitting a straight line to this curve yields the electron temperature \( K_{\text{T}} \) in eV

\[
\begin{align*}
I_{\text{e}} &= A_{\text{p}} n v_{\text{e}}, \exp(-\eta_{\text{e}}), \\
v_{\text{e}} &= (K_{\text{T}}/2\pi m)^{1/2}, \\
\eta_{\text{e}} &= - \frac{(V - V_{\text{f}})}{K_{\text{T}}},
\end{align*}
\]

where \( A_{\text{p}} \) being the probe area and \( n \) the plasma density in the body of the plasma. The reciprocal of the slope of the \( \ln I_{\text{e}} - V_{\text{p}} \) curve is then equal to \( K_{\text{T}} \). The value of \( I_{\text{e}} \) at \( V_{\text{p}} = V_{\text{s}} \) gives an estimate of \( n \), called \( N_{\text{e}} \), which is based on \( I_{\text{e}} \) alone. Since \( N_{\text{e}} \) depends exponentially on \( V_{\text{s}} \), it is subject to large errors arising from uncertainty in the determination of \( V_{\text{s}} \).

To find \( n \) from \( I_{\text{i}}(V_{\text{f}}) \), we assume a sheath thickness \( d \) given by the CL formula\(^3\)

\[
d = \frac{1}{3} \sqrt{2 \alpha_0 (2 \eta_{\text{f}})^{3/4} \lambda_{\text{D}}} = 1.018 \eta_{\text{f}}^{3/4} \lambda_{\text{D}},
\]

with \( \eta_{\text{f}} \) known once \( V_{\text{s}} \) and \( T_{\text{e}} \) have been determined. The sheath radius is the sum of \( d \) and the probe radius \( R_{\text{p}} \). Using Eq. (3) into Eq. (1) for a probe length \( L \) then gives

\[
n = N_{\text{i}}(\text{CL}) = I_{\text{i}}(V_{\text{f}})/2\pi R_{\text{p}}(d + L \alpha_0 c_{\text{s}}).
\]

Note, however, that \( d \) depends on \( \lambda_{\text{D}} \), which is proportional to \( n^{-1/2} \). Equations (3) and (4) thus constitute a quadratic equation for \( n^{1/2} \), whose solution gives the ion density as

\[
n = \left\{ \left[ -B + (B^2 + 4AC)^{1/2} \right]/2A \right\}^2,
\]

where

\[
A = \frac{1}{2} \left[ 1 - \frac{1}{2} \left( \frac{1}{n} \right)^{1/2} \right],
\]

\[
B = \frac{1}{2} \left[ 1 + \frac{1}{2} \left( \frac{1}{n} \right)^{1/2} \right],
\]

\[
C = \frac{1}{4} \left( \frac{1}{n} \right)^{1/2}.
\]

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where
\[ A = R_p, \quad B = \eta_f^{3/4}(e_0 KT_e/e^2)^{1/2}, \]
\[ C = \frac{1}{2}(V_f)/2\pi L_0 \alpha_0 c_s. \quad (6) \]

II. COMPARISON WITH THEORY

Although it will be shown that this method yields values of \( n \) in agreement with microwave measurements, it is not easy to justify theoretically. First, the CL formula used for \( d \) is for plane sheaths, not cylindrical ones. Second, the CL formula gives only a crude approximation to the sheath thickness because it neglects the Debye sheath, where the electron density cannot be neglected. Treatments which jump discontinuously from quasineutral plasma to pure ion sheaths are referred to as step models. Sometimes, a constant ion density is assumed which is called a matrix sheath. The Bohm formula requires ions to enter the sheath with the velocity \( c_s \), whereas the CL formula assumes zero velocity. Hutchinson\(^5\) has modified Eq. (3) to include an initial ion velocity \( c_s \). If we take \( V = 0 \) in the plasma rather than at the sheath edge as in Ref. 5, Hutchinson’s formula becomes
\[ d = 1.018(\frac{1}{2} \eta^{1/2} - 2^{1/2} \eta^{1/2} + 2^{1/2}) \lambda_D. \quad (7) \]

Use of this formula did not improve the results.

The exact solution for a combined Debye-CL sheath in plane geometry can be derived from Poisson’s equation
\[ \frac{d^2 V}{dx^2} = \frac{e}{\varepsilon_0}(n_e - n_i). \quad (8) \]

In a strictly one-dimensional (1D) problem, we must assume a sheath edge, since if the ion velocity \( v_i \) were zero at infinity, the density there would have to be infinite for the ion flux to be finite. For convenience we choose the sheath edge to be the plane where (a) \( eV = \frac{1}{2}KT_e \) relative to the plasma potential, so that the Bohm criterion is satisfied there, (b) \( v_i = c_s \), and (c) \( n = n_s = n_0 e^{-1/2} \). Shifting the origin of both \( x \) and \( V \) to this point, we now have, for Maxwellian electrons
\[ n_e = n_s e^{eV KT_e} = n_s e^{-\eta}, \]
\[ \eta = \frac{eV}{KT_e}. \quad (9) \]

For the ions, energy conservation requires
\[ \frac{1}{2}Mv_i^2 = \frac{1}{2}Mc_s^2 eV, \quad v_i = (c_s^2 - 2eV/M)^{1/2}. \quad (10) \]

Continuity of ion flux then gives
\[ n_i v_i = n_s c_s, \]
\[ n_i = n_s \frac{c_s}{v_i} = n_s (1 - \frac{2eV}{Mc_s^2})^{1/2} = n_s (1 + 2\eta)^{-1/2}. \quad (11) \]

Equation (8) then becomes
\[ \frac{d^2 V}{dx^2} = \frac{e}{\varepsilon_0} n_s [e^{-\eta} - (1 + 2\eta)^{-1/2}] = -\frac{KT_e}{e^2} \frac{d^2 \eta}{dx^2}. \quad (12) \]

Normalization to the Debye length \( \lambda_D \) at the sheath edge yields
\[ \eta'' = [(1 + 2\eta)^{-1/2} - e^{-\eta}], \quad (13) \]
where the (') indicates derivative with respect to $\xi = x/\lambda_D$, and $\lambda_D$. Following standard procedure, we multiply by an integration factor $\eta'$ and integrate from $\eta=0$ to $\eta$. Setting $\eta'=0$ at $\xi=0$, we obtain
\begin{equation}
\eta' = \sqrt{2[(1 + 2 \eta)^{1/2} + e^{-\eta} - 2]^{1/2}}.
\end{equation}

The next integration has to be done numerically, and the result is shown in Fig. 6 for two assumed values of $\eta'(0)$. The "sheath thickness" is indeterminate because it depends on the assumed boundary condition at $\xi=0$. If $\eta'=0$ there, then $\eta''$ or another derivative must be given a finite value in order for the curve to rise above zero. In practice, the boundary condition on $\eta'$ and $\eta''$ is determined by matching to the presheath. The two curves of Fig. 6 are plotted logarithmically in Fig. 7. Once $\eta$ becomes appreciable, the curve $\eta(\xi)$ has a definite shape, but its position relative to the sheath edge cannot be found without a presheath calculation. Also shown in Fig. 7 is the CL sheath thickness according to Eq. (3) and the floating potential $\eta_f = 4.68$ of a plane probe in argon. We see that it is possible to choose a boundary condition that makes the computed sheath thickness agree with $d_{CL}(V_f)$, but that the slopes of the curves are different there. The increase in $I_i$ with $V_p$ depends on the normalized probe radius
\begin{equation}
\xi_p = R_p/\lambda_D.
\end{equation}

Adding $\xi_p$ to the right-hand curve of Fig. 7 results in Fig. 8. Although the sheath radius at $V_f$ can agree with the CL prediction if the small gradients at the sheath edge happen to have the right value, the slopes do not agree at larger probe biases. Thus, it is difficult to see why the measured ion saturation current increases as $[V_p]^{3/4}$, as predicted by the inexact CL formula but not by the exact calculation.

Since the use of the CL formula is not justified because the sheath is not plane by cylindrical, we next solve the sheath equation for cylinders. In this case, the calculation can be carried out to infinity, and the arbitrary conditions at a sheath edge are not needed. However, in a simple treatment, collisions are ignored as well as the orbiting of ions around the probe due to their angular momentum. Poisson’s equation is now
\begin{equation}
\frac{1}{r} \frac{\partial}{\partial r} \left( r \frac{\partial V}{\partial r} \right) = \frac{\rho}{\varepsilon_0} + \frac{e}{\varepsilon_0} (n_e - n_i),
\end{equation}

where $n \rightarrow n_0$ and $V \rightarrow 0$ as $r \rightarrow \infty$. The ion velocity is
\begin{equation}
v_i = (-2eV/M)^{1/2} = (2\eta)^{1/2}c_s,
\end{equation}

and flux conservation gives
\begin{equation}
n_i = \frac{I_i}{2\pi r} = \frac{I_i}{2\pi r_c} (2\eta)^{-1/2},
\end{equation}

where $I_i$ is the inward ion flux per unit probe length. Normalizing to $\rho = \rho/\lambda_D$, we now have for Eq. (16)
This is the cylindrical equivalent of the Allen–Boyd–IBM mainframe. Recent computations by Chen and Arnush \(^6\) in terms of \(r\) iteration.

The coefficient of the ion term is a dimensionless ion current defined by

\[
J = \frac{I_i}{\pi n_0 \lambda D c_s}.
\]

In terms of \(J\), Poisson’s equation is simply

\[
\frac{\partial}{\partial \rho} \left( \rho \frac{\partial \eta}{\partial \rho} \right) = J \eta^{-1/2} - \rho e^{-\eta}. \tag{21}
\]

This is the cylindrical equivalent of the Allen–Boyd–Reynolds (ABR) equation for spherical probes.\(^7\) Solutions of Eq. (20) for various values of \(J\) were first done in 1964 on an IBM mainframe.\(^8\) Recent computations by Chen and Arnush\(^6\) on a personal computer are in agreement with the earlier results, which have been fitted with analytic functions\(^9\) for easy application. In the limit \(\rho \rightarrow \infty\), Eq. (21) has the asymptotic form \(\eta \sim J^2 / \rho^2\). Starting with this solution, one can integrate Eq. (21) inwards to obtain the potential profile \(\eta(\rho)\). Examples for two values of \(J\) are shown in Fig. 9. These are universal curves which apply to all probe radii \(R_p\), characterized by the important parameter \(\xi_p = R_p / \lambda_D\) [Eq. (15)].

The part of the curve for \(\rho < \xi_p\) is irrelevant, and the part for \(\rho > \xi_p\) is unchanged by the probe, since all incoming ions are absorbed by the probe, and therefore \(n_i\) and \(n_e\) are not affected by the presence of a probe. This is not true if the ions have angular momentum and can orbit the probe; in that case the more complicated theory of Bernstein and Rabinowitz (BR)\(^{10}\) must be used. For a given value of \(\xi_p\), such as the one shown in Fig. 9, the probe potential for given \(J\) is the value of \(\eta(\xi_p)\) on the curve for that \(J\). Thus, in our example, \(\eta \approx 20\) for \(J = 10\) and \(\approx 1200\) for \(J = 50\). An \(I_i - V_p\) characteristic for given \(\xi_p\) is generated by varying \(J\) and crossplotting. Note that \(\xi_p\) itself depends on the unknown value of \(n_0\), and the determination of \(n\) from \(J\) generally requires iteration. \(J\xi_p\), however, is independent of \(n_0\), and this quantity is often plotted instead of \(J\). In this cylindrical case, no artificial sheath edge is introduced, and hence there is no confusion between \(\lambda_D\) and \(\lambda_D^c\): \(\lambda_D\) is always evaluated using the density \(n_0\) at infinity.

For the present application, we need to find \(I_i(V_p)\). We start by fixing the value of \(J\). The floating condition is \(I_i = I_e\), where \(I_e\) per unit length is given by

\[
I_e = 2 \pi R_p n_0 v_e \exp(-\eta_f), \tag{22}
\]

and \(I_i\) is given by Eq. (20). Solving for \(\eta_f\), we find that \(n_0\) cancels, and we have

\[
\eta_f = \ln \left[ \frac{\xi_p}{J} \left( \frac{M}{4 \pi m} \right)^{1/2} \right]. \tag{23}
\]

However, \(\eta(\xi_p)\) must also satisfy the solution \(\eta(\rho)\) of Eq. (21) for the given value of \(J\) and \(\rho = \xi_p\). Figure 10 shows both \(\eta(\rho)\) and \(\eta_f(\xi_p)\) for \(J = 10\) on the same plot. The intersection gives \(\eta_f\) and \(\xi_p\) for that value of \(J\). By varying \(J\), one can generate the functions \(\eta_f(\xi_p)\) and \(J(\eta_f)\) for given \(\xi_p\), the dimensionless versions of \(V_f(R_p)\) and \(I_f(V_p)\) for given \(R_p\). Also shown in Fig. 10 is the position of the classical sheath edge, as usually defined at \(\eta = 1/2\). Contrary

The functions \(\eta(\xi)\) and \(\eta_f(\xi_p)\) for \(J = 10\) in argon. The “classical sheath edge” is the radius at \(\eta = 0.5\), where the ions have velocity \(c_s\). The “effective sheath radius” is that at which the assumed probe current would be collected if the Bohm criterion were satisfied there (which it is not).

FIG. 9. Potential profiles in a cylindrical sheath for two values of normalized probe current \(J\). The line \(\xi_p\) marks the probe radius.

\[
\frac{\partial}{\partial \rho} \left( \rho \frac{\partial \eta}{\partial \rho} \right) = \frac{I_i}{\pi n_0 c_s} (2 \eta)^{-1/2} - \rho e^{-\eta} = \frac{I_i}{2 \pi n_0 \lambda D c_s} (2 \eta)^{-1/2} - \rho e^{-\eta}. \tag{19}
\]

FIG. 10. The functions \(\eta(\xi)\) and \(\eta_f(\xi_p)\) for \(J = 10\) in argon. The “classical sheath edge” is the radius at \(\eta = 0.5\), where the ions have velocity \(c_s\). The “effective sheath radius” is that at which the assumed probe current would be collected if the Bohm criterion were satisfied there (which it is not).

FIG. 11. Computed values of \(\eta_f = -eV_f/K T_e, \alpha, \alpha / \alpha_0\) for a cylindrical probe in argon and purely radial ion orbits. The curve through the \(\alpha\) points is the analytic fit of Eq. (29).

FIG. 11. Computed values of \(\eta_f = -eV_f/K T_e, \alpha, \alpha / \alpha_0\) for a cylindrical probe in argon and purely radial ion orbits. The curve through the \(\alpha\) points is the analytic fit of Eq. (29).
to the plane case, however, the ion density there is not $n_0 \exp(-1/2)$ because $n_i \neq n_e$ at that point. The exact cylindrical solution does not require the arbitrary assumption that quasineutrality holds up to the sheath edge.

We can, however, define an effective collection radius (“sheath” radius) $R_s$, such that if the Bohm criterion were satisfied there, the correct ion current would flow to the probe. The cylindrical equivalent of Eq. (21) is

$$I_i = 2\pi R_s a_0 n_0 c_s.$$  

Eq. (24) takes its usual form with $\alpha$ replacing $\alpha_0$

$$I_i = 2\pi R_s a_0 R_p c_s.$$  

Thus, $\alpha$ can be considered a cylindrically modified value of the Bohm coefficient $\alpha_0$, and the ratio $\alpha/\alpha_0$ is a measure of

$$\alpha_0 (R_s/R_p) = \sqrt{2J/\xi_p}.$$  

If we now define

$$\alpha = \sqrt{2J/\xi_p} = \alpha_0 (R_s/R_p),$$  

Eq. (24) takes its usual form with $\alpha$ replacing $\alpha_0$

$$I_i = 2\pi R_p a_0 R_p c_s.$$  

FIG. 12. Probe densities computed with the CL formula (■), the ABR theory (▲), and electron saturation current (△), compared with microwave densities (---) at various pressures.

FIG. 13. Ion current at 1 mTorr, 450 W plotted as $I_i^p$ vs $V_p$ with $p=4/3$ (upper curve) and $p=2$ (lower curve). The straight-line fits are also shown.

FIG. 14. Dependence of calculated density on the exponent $p$ in $I_i^p - V_p$. Values of $n$ computed with the CL formula and the ABR theory are compared with that measured with microwaves (MW). The star marks the value $p=4/3$. 

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the expansion of the collection area beyond the probe area when the probe is at the floating potential. The position of $R_s$ is shown in Fig. 10; it is not at $\eta = 1/2$. Computed values of $\eta_I$, $\alpha$, and $a/\alpha_0$ as functions of $\xi_p$ are shown in Fig. 11. Note that $\eta_I$ approaches the plane-geometry value of 5.18 and $a/\alpha_0 \to 1$ as $\xi_p \to \infty$. From Eqs. (20) and (26) we can solve for $n_0$, obtaining

$$n_0 = N_I(A BR) = \frac{I_I(V_f)}{2\pi R_p c_e \alpha},$$

(28)

which can evaluated from the extrapolated $I_I(V_f)$ per unit length once $R_p$ and $K T_e$ are known. The value of $\alpha(\xi_p)$ can be found from the following analytic fit to the curve in Fig. 11:

$$\alpha = 0.607 + 2432/\exp(7.01 \xi_p^{0.96}).$$

(29)

Since $\xi_p$ depends on $n_0$, however, solution of Eq. (28) requires iteration.

III. COMPARISON WITH EXPERIMENT

The procedure for finding $V_s$ and $K T_e$ from the $I - V$ curve, as well as the density $N_e$, from the electron saturation current, was described following Eq. (2). The density $N_e(CL)$ can then be computed from Eq. (4) using $I_I(V_f)$. For comparison, the density according to ABR theory can be found from Eq. (28). All of these steps have been automated on an Excel® spreadsheet to give $V_s$, $K T_e$, $N_e$, $N_I(CL)$, and $N_I(A BR)$ from a 1000-point $I - V$ curve in $\approx 1$ s. Here we present data taken in a 2 MHz argon inductively coupled plasma with an rf-compensated Langmuir probe 0.015 cm in diam and 1 cm long at various pressures and rf powers. The probe densities are compared with those from microwave interferometry. Details of the experiment are described elsewhere.\footnote{The data in Fig. 12 span a range of $\xi_p$ from $\approx 1$ to 4.5. The floating-potential-CL method gives $n$ values agreeing with those from microwaves to within about 20%, while the ABR method gives consistently lower $n$. The electron densities $N_e$ behave sporadically, as one would expect from their sensitivity to the chosen value of $V_s$.}

In these analyses, $I_I$ was extrapolated to $V_f$ by fitting a straight line to the $I_I^p$ vs $V_p$ plot, where $p = 4/3$. A fit can also be made for other values of $p$. In particular, Langmuir’s orbital-motion-limited theory predicts $p = 2$, and solutions of the ABR equation show $p \geq 2$. Indeed, as shown in the example of Fig. 13, at low densities $I_I^2$ fits better to a straight line than does $I_I^{4/3}$, suggesting that some ion orbiting is taking place. Nonetheless, fitting with $p = 4/3$ gives more reasonable values of $n$. In this example, $p = 4/3$ yields $n_1 = 0.734$ while $p = 2$ gives $n_1 = 0.475$, compared with a microwave density of 0.872, where $n_1$ is in units of $10^{11}$ cm$^{-3}$. The sensitivity of $N_e(CL)$ and $N_I(A BR)$ to $p$ is shown in Fig. 14 for the 2 mTorr, 900W point of Fig. 12. We see that $p = 4/3$ gives yields better agreement between $N_e(CL)$ and the microwave measurement than does $p = 2$ or $1/2$. This is generally true of the cases we have examined, though $p = 4/3$ has no theoretical justification.

IV. DISCUSSION

The FP-CL method for cylindrical probes neglects three major effects: (1) Electron density and cylindrical curvature in the calculation of sheath thickness; (2) orbiting of ions around the probe; and (3) loss of ions moving in the $z$ direction, parallel to the probe axis. We have treated (1) with the ABR analysis, finding that it yields values of $n$ that are too low. The reason is probably that some ions have enough angular momentum to orbit the probe and miss it. Taking full account of this effect with the BR theory,\footnote{The effect of collisions was discussed by Stangeby and Allen\cite{ref12} in connection with the discrepancy between the BR and ABR theories for cylinders when $T_e \to 0$. They concluded that the ratio of the mean free path to the absorption radius determined which theory was applicable. This ratio is apparently of order unity in this paper, so that neither theory is valid.} however, yields $n$ values that are too high. We have previously suggested\footnote{The one-dimensional treatment fails to account for the finite length of the probe. When $\xi_p$ is small, incoming ions are crowded together and form a large positive space charge near the probe surface. As shown in Fig. 15, this space charge creates an electric field $E_z$, driving the ions out past} that a few collisions in the presheath can greatly decrease the amount of orbiting, and that the geometric mean between $n(ABR)$ and $n(BR)$ gives a good approximation in this case of partial orbiting. The FP-CL method apparently succeeds because of a fortuitous cancellation of effects (1) and (2).
Thus, the loss flux to both ends is given by

\[ I_{\text{loss}} = \frac{\sqrt{2} \pi (R_s^2 - R_p^2) \alpha n_0 c_s}{2 \pi R_p L \alpha n_0 c_s} \]

where \( \alpha \) now includes the probe length. With the help of Eq. (26), we can now write

\[ I_{\text{loss}} = \frac{1}{R_p} \frac{R_p^2}{\sqrt{2}} \frac{\alpha^2}{\alpha_0^2} - 1 \].

From Fig. 11, we see that for \( \xi_p = 1 \) (the worst case), \( (\alpha/\alpha_0)^2 \) is of order 20. For the probe dimensions used here, \( R_p/L = 0.0075 \). The endloss correction of Eq. (36) then amounts to \(
\approx 11\% \). However, it could be larger with thicker probes.

In conclusion, we have found a rapid method for analyzing probe characteristics which gives more accurate ion density measurements in rf plasmas than any existing probe theory. The method is entirely heuristic and is not supported by a detailed treatment of the sheath. It apparently works because of the self-cancellation of neglected effects.