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Deduction of the absolute negative ion density by using planar and cylindrical electric probes simultaneously

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Analytic formulas are derived for the deduction of the absolute density of negative ions by using the measured electron temperatures and saturation currents of positive ions and negative charges from current-voltage curves taken by planar and cylindrical probes at two different pressures without assuming the sheath potential, sheath velocity, temperatures of positive and negative ions, and effective masses of positive ions. Ratios of ion and electron saturation currents and electron temperatures of two probes and sheath areas of a long thin cylindrical probe at two different pressures are incorporated into two equations with two unknowns for the negative ion density. The procedure to deduce the absolute negative ion density is given. © 2006 American Institute of Physics. [DOI: 10.1063/1.2360509]

For the etching processes, maximum etching rate strongly depends upon the negative ion density.1 Not only does one need negative ion sources for more effective neutral beam injection heating for the high power fusion devices such as ITER,2 but there are also negative hydrogen ions (H−) contributing to recombination, although hydrogen molecular ions (H2+) may contribute more.3 Various negative ionic processes are important in controlling the electron density in the lower ionosphere.4 Boyd and Thompson5 developed theories on the collection of negative ions by a spherical probe, assuming that positive ions are cold for the sheath potential and warm negative ions are governed by the Boltzmann relation, which is the same as electrons for the ratio of densities of negative ions to the unperturbed plasmas. Amemiya6 expanded this with warm positive ions for the density of negative ions by comparing the ratios of ion and electron collection; and ion acoustic wave analysis.10

Shindo et al.10 introduced a practical method to deduce the density of negative ions by comparing the ratios of ion and electron saturation currents providing the effective mass of mixed gases, temperatures of negative and positive ions, and sheath potential. Laser photodetachment method was introduced and is comprehensively reviewed by Bacal,11 yet in many cases an electric probe should be used as a collector of electrons detached by the lasers with energy of around 0.1 J. The I-V curves of electric probe have been used in deduction of negative ion density by Douce12 for the large magnitude of biased voltage comparing to thermal energies of charged particles, by Amemiya13,14 using the second derivatives, by Shindo10 using the ratios of saturation currents of electrons and ions, and by Popov15 using three trial functions. Chabert et al.16 introduced a two-probe method to deduce the ratio of negative ion density to electron density. They used one large planar probe for the measurement of ion saturation current, and one small cylindrical probe for electron saturation current and electron temperature, in order to avoid the perturbation due to a planar probe for the electron saturation current. All of them are using existing theory with Boltzmann negative ions and provision of effective masses of positive ions, temperatures of negative and positive ions, and sheath potential. Lichtenberg et al.17 validate the Boltzmann relation of the negative ions by assuming the surface losses are much larger than the volume recombinations without attenuation, yet it makes the negative ion flux negative in magnitude. Even with this assumption, one needs the following information for deducing negative ion density from existing theories and methods: (i) temperatures of positive and negative ions; (ii) sheath potential with negative ions; (iii) sheath area for positive ion collection; and (iv) effective (or reduced) mass of positive ions of background gas and of negative ion gas, which are to be measured either by quadrupole mass analyzer or ion acoustic wave analysis.10

For the strong negative bias voltage applied to the probe as eVp ≲ max(e[Vp]−, e[Vf]−, Tp, T−),13 with arbitrary plasma potential, Vp, and floating potential, Vf, negative ions are almost repelled (see Fig. 1), where Tp, Ts, and T− are temperatures of electron, positive, and negative ions, respectively. Then the positive ion saturation current at pressures P1 and P2 are given by

$$I_{s+}(X_{1,2}) \sim A_{1,2} N_s(X_{1,2}) n_s(X_{1,2}) v_s(X_{1,2}) \sqrt{\frac{T_p(X_{1,2})}{M(X_{1,2})}}, \tag{1}$$

where $A_{1,2}$ are sheath areas for the collection of ions, $N_s$ is the density of the positive ions, $T_p$ is the electron temperature in eV, $X_{1,2}$ are gas mixtures of background (noble gas) and added negative ion gas (depending upon flow rate) at the pressure $P_{1,2}$ (or flow rate of $F_{1,2}$), and $M(X_{1,2})$ are the effective (or reduced) masses of positive ions at $P_{1,2}$, $n_s$ and $v_s$ are the normalized sheath density and sheath velocity which

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can be given as the following with Boltzmann negative ions and electrons:

\[ n_+ = (1 - \alpha) \exp(-\eta_1) + \alpha \exp(-\eta_2), \]

\[ v_+ = \sqrt{2 \eta_1 + \gamma \tau_1}, \]

where \( \alpha = N_+/N_0 \) is the ratio of negative ions to the positive ions with a gas mixture \( X \), \( \eta_1 \) is the sheath potential normalized by the electron temperature \( -eV_0(X)/T_e \), \( \tau_+ \) and \( \tau_1 \) are the temperatures of positive and negative ions normalized by the electron temperature. Here \( \gamma \) is a constant given as 2 by Shindo\textsuperscript{10} and as 1/3 by Amemita.\textsuperscript{6} It can be 1 if one puts the total energy of positive ions at the sheath \( T_s/2 \) (one-dimensional), or 3 if total energy is 3\( T_s/2 \) (three-dimensional), assuming that positive ion temperature is constant along the perturbation region, although it varies with position, drift velocity, and magnetic field.\textsuperscript{18,19}

From the quasineutrality, the following should be satisfied:

\[ N_+(X_{1,2}) = N_+(X_{1,2}) + N_-(X_{1,2}), \]

where \( N_+ \) and \( N_- \) are the densities of electrons and negative ions. Saturation current \( i_{es} \) of negative charges (negative ions and electrons) is approximated as the electron saturation current, because currents contributed by the negative ions \( I_{-s} \) is very small comparing the electron saturation current \( I_{es} \): \( I_{es}/I_{es} = (N_+/N_0 \sqrt{T_e/T_s}) m_e/m_+ \ll 1 \) [e.g., for oxygen atom ion, with \( T_e/T_s = 0.1 \), \( I_{es}/I_{-s} < (N_+/N_0)(1/500) \), i.e., unless electron density is less than 0.2\% of the negative ions, electron saturation current is dominant in the saturation current of negative charges]. Although one cannot know the exact form of the electron saturation current with arbitrary magnetic field, it has the form as

\[ I_{es} = I_{es}(X_{1,2}) = N_+(X_{1,2}) A_p \sqrt{T_e(X_{1,2})} m_e, \]

where \( A_p \) is the probe area. The combination of Eqs. (1) and (3) leads to the simpler form as

\[ i_2 = \frac{N_2}{N_1} \frac{\sqrt{\tau_2}}{\mu_2} \frac{e_2}{\sqrt{\tau_2}}, \]

where the nondimensional parameters are defined as

\[ \frac{I_{es}(X_{2})}{I_{es}(X_{1})} \frac{\sqrt{\tau_2}}{\mu_2}, \]

and \( N_{1,2} = N_{+}(X_{1,2}), N_{e,1,2} = N_{e}(X_{1,2}) \). Equation (2) becomes

\[ \frac{\sqrt{\mu_2}}{\Omega_2} i_2 = e_2(1 - \alpha_1) + \alpha_2 \sqrt{\tau_2}, \]

then the ratio of the negative ion density to positive ion is obtained as

\[ \alpha_1 = 1 - \frac{\sqrt{\mu_2}}{\Omega_2} \frac{i_2}{e_2} - \alpha_2 \frac{\sqrt{\tau_2}}{e_2}, \]

where \( \alpha_1 = N_{-}/N_0 \) (ratio of negative ion density to positive ion density at \( P_1 \)), and \( \alpha_2 = N_{e-2}/N_0 \) (ratio of negative ion density at \( P_2 \) to positive ion density at \( P_1 \)) as shown in Fig. 2. Hence \( i_2, e_2, \tau_2 \) can be measured from \( I-V \) curves, but \( \mu_2 \) (ratio of reduced masses), \( \Omega_2 \) (ratio of sheath factors), and \( \alpha_2 \) should be provided in order to get \( \alpha_1 \).

Since the saturation currents collected by a cylindrical probe is different from those by a planar probe due to the sheath factor (due to change of the collection area) for the ion saturation current and due to geometrical factor for electron saturation current,\textsuperscript{20} if a very thin cylindrical probe (i.e., \( \lambda_D \ll \lambda \alpha, x_s \ll 1 \)) is used, one can get two different sets of equations for \( \alpha_1 \) and \( \alpha_2 \), where \( \lambda_D \) and \( x_s \) are the Debye length and sheath thickness, respectively. Then one can solve the equations for \( \alpha_1 \) and \( \alpha_2 \). If we treat Eq. (6) as one by a planar probe, then that by a cylindrical probe can be given as

\[ \alpha_1 = 1 - \frac{\sqrt{\mu_2}}{\Omega_2} \frac{i_2}{e_x} - \alpha_2 \frac{\sqrt{\tau_2}}{e_x}, \]

where the probe bias voltage \( (V_p) \) should be larger than the plasma potential \( (V_p) \) to see the clearer difference of electron saturation current compared to that by a planar probe. Here ratios of electron temperature \( (\tau) \) and effective masses \( (\mu) \)
should remain the same for the same plasma with different probes, but the ratios of saturation currents \(i_{2c}/e_{2c}\) and sheath factors \(\Omega_{2c}\) of the cylindrical probe is different from those of a planar probe \((i_{2c}, e_{2c}, \Omega_{2c})\). Especially, the ratio \(e_{2c}\) of electron saturation currents for a thin cylindrical probe is different from that of a planar probe \((e_{2})\) due to the limited current by orbital motions, when the sheath is thick compared to the probe radius.\(^{20,21}\) Then from Eqs. (6) and (7), \(\alpha_{1,2}\) are calculated as

\[
\alpha_1 = 1 - \frac{\sqrt{\mu_2}}{\mu_2 - e_{2c}} \frac{i_2}{\Omega_2 - i_{2c}},
\]

\[
\alpha_2 = \frac{\sqrt{\mu_2/2 \tau_e}}{1 - e_{2c}/\epsilon_2} \frac{i_2}{\Omega_2 - i_{2c}} - \frac{i_2 \sqrt{\mu_2}}{\Omega_2 \tau_e}.
\]

Here \(i_{2c}, e_{2c}\) can be measured from two \(I-V\) curves taken by planar and cylindrical probes at two different pressures. Yet the ratios of the sheath factors \(\Omega_{2c}\) and ratio of the effective (reduced) masses \(\mu_2\) are required for the deduction of \(\alpha_{1,2}\). First, the effective mass of positive ions can be expressed as \(M_e = (N_0/M_0 + N_0/M_0)/(N_0/M_0)\), where \(N_0\) is the positive ion density of added gas for generation of negative ions, \(N_{b1}\) is the positive ion density of background gas, and \(M_0, M_0\) are masses of added and background gases. For example, in the Ar+O\(_2\) mixture, \(N_0\) and \(M_0\) are density and mass of O\(_2\) or O\(_2\), and \(N_0\) and \(M_0\) are those of Ar\(_2\), while \(N_0\) is the density of O\(_2\) or O\(_2\). Then the following are obtained with \(\delta = N_0/N_0\) and \(\mu_2 = (M_e + \delta (M_e - M_0))/(M_e + \delta \alpha_1 (M_e - M_0))\), \(N_{b1}/N_{b1} = (N_0/N_0) - \delta \alpha_1\), and \(N_{b1}/N_{b1} = \delta \alpha_2, N_{b1} = N_{b0,1} = N_{b0,2}, N_{b1,2} = \delta N_{b1,2} = 0 < \delta < 1\) are used.\(^{10}\) This can be approximated as the following: (i) \(\mu_2 \approx 1\) most cases except for \(M_0/M_0 < \alpha < 1\); (ii) \(\mu_2 = (\alpha_1/\alpha_1) (M_e/M_0)\) for \(M_0/M_0 < \alpha < 1\), which can be obtained as a function of \(\alpha_1\) from the following equation:

\[
\mu_2 - a(\alpha_1) \sqrt{\mu_2} + b(\alpha_1) = 0,
\]

where \(a(\alpha_1) = k_i /a_1 \Omega_2 \tau_e, k = M_e/M_0, \) and \(b(\alpha_1) = (1 - \alpha_1) k_i/\alpha_1 \Omega_2 \tau_e).\) In this case, \(\mu_2\) should be obtained by the iterative method after getting \(\alpha_1\) with initial values of \(\mu_2\) as unity. This indicates that the ratio of effective masses approximately becomes unity for most cases, unless the mass of added gas for negative ions is very large.

Second, the ratio of sheath factor \((\Omega_2 = S_2/S_1 = A_2 n_{2c} v_{2c} / A_1 n_{1c} v_{1c})\) becomes:

\[
\Omega_2 = \frac{A_2 \sqrt{\mu_2}}{A_1 \sqrt{\mu_1}} + 2 \frac{\eta_{12}}{2} \left(1 - \alpha_2 e^{-\eta_{12}/2} \leq \alpha_2 e^{-\eta_{12}/2}\right),
\]

if we follow the expression of most previous works\(^{5,6,9,10}\) with Boltzmann negative ions. But for the case of Shinoda,\(^{10}\) we follow:

\[
\Omega_1 = S_1 / S_0 = A_1 n_{1c} v_{1c} / A_0 n_{2c} v_{2c} = n_{1c} v_{1c} / n_{0c} v_{0c}
\]

\[
= 0.61 \left(t_{a1} + \left[\eta_{11} / t_{a1} + \eta_{11}\right] \left(1 - \alpha_1\right) \exp[\eta_{11}] + \alpha_1 \exp[-\eta_{11}]\right),
\]

where \(A_1 = A_0 = A_p\) is assumed, and \(S_1\) is the sheath factor at \(P_1\) with negative ions and \(S_0\) is the one at \(P_0\) without negative ions (i.e., only with background plasma), so that the absolute values of temperatures of positive \(t_{a1}\) and negative \(t_{11}\), and sheath potential \(\eta_{11}\) should be given. The sheath factor can be approximated assuming a small change of each variable due to a small change of pressure from \(P_1\) to \(P_2\): \(\eta_{22} = \eta_{11} + \beta, t_{22} = t_{11} + \beta\). Then (i) \(\Omega_{1} \approx \Omega_2 \approx \Omega_2 = 1\) for \(\alpha_1, \alpha_2 \ll 1\) with the thick sheath \(x < a_p, A_1 \approx 1\); (ii) \(\Omega_{2} \approx \Omega_{2} = 1\) for \(\alpha_1, \alpha_2 \approx 1\) with the thick sheath \(x < a_p,\) (iii) \(\Omega_{2} \approx (A_2 / A_1) (\alpha_1 / \alpha_1)\) for \(\alpha_1, \alpha_2 \approx 1\) with the thick sheath, where \(\eta_{22}/t_{22} = \eta_{11}/t_{11}\) is assumed. For the cases of (ii) and (iii), the ratio of the sheath areas is given as \(A_2 / A_1 = (x_2 / x_1)^{3/4} = (\lambda_1 / \Lambda_1)^{3/4}\), where \(x_{2,1}\) and \(\lambda_{2,1}\) are the sheath thicknesses and Debye lengths at pressures \(P_2\) and \(P_1\), and \(n = 2, 1, 0\) for the spherical, cylindrical, and planar probes, respectively. If we calculate the sheath factor \((\Omega)\) in terms of measured electron temperature \(T_e\) and saturation current \(I_{s2}\) for the cylindrical probe, it becomes as the following using Eq. (3):

\[
\Omega_{2} = \frac{S_2}{S_1} = \frac{\lambda_2}{\lambda_1} = \frac{T_2}{T_1} \frac{I_{s2}}{I_{s1}} \left(\frac{T_2}{T_1}\right)^{3/4} = \frac{\tau_2}{\tau_1}^{3/4} = \sqrt{\frac{\tau_2}{\tau_1}}
\]

From these analyses, \(\alpha_{1,2}\) can be calculated for all the values of ratio of negative ion density to the positive ion density \(0 < \alpha < 1\) using Eqs. (8) and (9) with measured values of \(i, e, \tau\), while \(\mu\) and \(\Omega\) should be given as the following: (i) \(\mu_2 = 1\) most cases except for \(M_0/M_0 \ll \alpha < 1\); (ii) \(\mu_2 = (\alpha_1/\alpha_1) (M_e/M_0)\) for \(M_0/M_0 \ll \alpha < 1\), which is a function of \(\alpha_1\) and can be calculated by Eq. (10); (iii) \(\Omega_{2} \approx \Omega_{2} \approx \Omega_{2} \approx 1\) for the planar probe; (iv) \(\Omega_{2} = (A_2 / A_1) = (3/4) / \epsilon_2\) for \(\alpha < 1\) (cylindrical probe); (v) \(\Omega_{2} = (A_2 / A_1) (\alpha_1 / \alpha_1)\) for \(\alpha \ll 1\) (cylindrical probe), which should be calculated by an iterative method.

After getting the ratio of negative ion density to the positive ion density \((\alpha)\), one can get the absolute density of negative ions by the following procedure: With \(\alpha_1 = N_{-1} / N_1\), and \(N_{-1} = N_{-1} = N_{-1} = \alpha_1\), the absolute density of the negative ions can be expressed as the electron density as

\[
N_{-1} = \frac{\alpha_1}{(1 - \alpha_1)} e^{-1} e_a = \frac{4}{(1 - \alpha_1)} e_a (B T / \eta_{m0})^{1/2},
\]

where the saturation current of the negative charges at \(P_1\) for \(B=0\) is given by \(I_{s1} = I_{s1} + I_{s2} = I_{s1} = e a_p N_{-1} (B T / \eta_{m0})^{1/2}/4\) due to \(m_c \ll M_0\). For \(B \neq 0,\) neither \(N_{-1}\) nor \(N_1\) can be deduced easily. However, if \(I_{s1} = N_{-1} = I_{s1} (V_p - V)\) is assumed for a planar probe, unperturbed electron density can roughly be obtained as \(N_0 = 4 I_{s1} / e a_p \exp[e (V_p - V) / P_{TS}] \times (B T / \eta_{m0})^{1/2}\) from \(I_{s1} = I_{s1} = I_{s1} (V_p - V) + I_{s2} (V_p - V) = I_{s1} (V_p - V)\).
for the measurement of electron saturation current. We can get the whole spectrum of variation of negative ions with pressure if we extend this method for the two different adjacent conditions, i.e. \( P_1, P_2 \), \( P_3, P_4 \), etc. Our method is valid for both positive and negative slope of \( \alpha(P) \), and the sign of the slope will be determined by the sign of the change of ion saturation currents.

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