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Measurement of Negative Ion Density by an Electric Probe with a New Analytic Formula

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1. INTRODUCTION

Theories on the collection of negative ions by an electric probe has been evolved from late 50s by Boyd and Thompson[1]. The current-voltage(I-V) curves of electric probe have been used in deduction of negative ion density by Doucet[2], Amemiya[3], Popov[4] and Shindo[5]. Laser photo-detachment(LPD) method was introduced and is comprehensively reviewed by Bacal[6]. For the probe analysis, they have used existing theories with Boltzmann negative ions providing the effective masses of positive ions and assuming the sheath potential and the temperatures of negative and positive ions. Even with this assumption, the following information is required: (i) Temperatures of positive and negative ions; (ii) Sheath potential with negative ions; (iii) Sheath area for positive ion collection; and (iv) Effective masses of background ions and mixture of background negative ions[5]. This paper proposes a new method with less assumptions and ambiguities than previous work, and results are compared to those by LPD method in MAP-II linear device[7].

2. EXPERIMENT

Figure 1 shows a schematic diagram of MAP-II. Typical arc discharge voltage and current are about 80 V and 45 A, respectively, with magnetic field of 200 Gauss. To change the density of negative ions, neutral pressure of hydrogen has been changed from 5 to 50 mtorr. The gas is injected into the target chamber and the pressure is measued using a Baraton pressure gauge. A planar electric probe with diameter 3.5 mm is installed at 80 mm from the center of the source chamber. Fifty I-V curves of electric probe are averaged for the analysis of negative ions to get the clear signal for the analysis in high pressure noisy plasmas. After obtaining the electron and ion saturation currents, electron temperatures of each I-V curve at typical pressures, we deduced the ratio of negative to positive ion densityby using a new analytic formula, which is to be addressed later, and compare it with that of LPD. Figure 2 shows the measured I-V curves for 8.3 - 39.0 mtorr. A frequency-doubled YAG laser($\lambda = 532$ nm) was used as a photon source. Negative ion density can be obtained from the ratio of the electron current by the photo detachment to the electron saturation current[8].

3. THEORY

For the strong negative bias voltage(V_B) applied to the probe as $V_B < -Max(|V_p|, |V_f|)$(or $eV_B < -Max(T_e, T_+, T_m)$,[2] negative ions do not affect the sheath formation, nor contribute to the (positive) ion saturation current, where $T_e,\ T_+,\ T_m$ are temperatures of electron, positive and negative ions. Then the positive ion saturation current at pressures $P_{1,2}$ are given by

$$I_{+s}(X_{1,2}) \propto A_{1,2}N_+(X_{1,2})n_{s1,2}v_{s1,2}\sqrt{T_{e1,2}/M_{1,2}} \tag{1}$$

where $A,\ N_+,\ n_s,\ v_s,\ M$ are sheath area for the collection of ions, positive ion density, normalized sheath density, normalized sheath velocity, and effective mass of positive ions, respectively. $X_{1,2}$ are gas mixtures of background and added negative ion gas at pressures $P_{1,2}$. From the quasi-neutrality, the following should be satisfied:

$$N_+(X_{1,2}) = N_e(X_{1,2}) + N_m(X_{1,2}) \tag{2}$$

where N_e and N_m are the densities of electrons and negative ions. As for the electron saturation current, although one cannot know the exact form with arbitrary magnetic field, we can put the following relation:

$$I_{es}(X_{1,2}) \propto A_pN_e(X_{1,2})\sqrt{T_{e1,2}/m_e} \tag{3}$$

where the negative ion current is neglected due to small ratio of ion mass to electron mass and A_p is the probe area for the collection of Boltzmann electrons. Using the non-dimensional parameters as $i_{1,3} \equiv I_{+s1,3}/I_{+s2}$, $\varepsilon_{1,3} \equiv I_{es1,3}/I_{es2}$, $\tau_{1,3} \equiv T_{e1,3}/T_{e2}$, $\mu_{1,3}$(ratio of reduced masses) $\equiv M_{1,3}/M_2$, $\Omega_{1,3}$(ratio of sheath factors) $\equiv A_{1,3}n_{s1,3}v_{s1,3}/A_2n_{s2}v_{s2}$, The above equations can be rearranged as

$$\alpha_2 = 1 - (\sqrt{\mu_{1,3}}/\Omega_{1,3})(i_{1,3}/\varepsilon_{1,3}) + \alpha_{1,3}\sqrt{\tau_{1,3}}/\varepsilon_{1,3}\ , \tag{4}$$

where $\alpha_1 \equiv N_{m1}/N_{+2}$,$\alpha_2 \equiv N_{m2}/N_{+2}$, and $\alpha_3 \equiv N_{m3}/N_{+2}$. Based upon existing experimental results[5, 7], as shown schematically in Fig. 3 we that small change of pressure is proportional to the small change of negative ion density:

$$\eta \equiv (P_3 - P_2)/(P_2 - P_1) = (N_{m3} - N_{m2})/(N_{m2} - N_{m1})\ . \tag{5}$$

Deviding $N_{m1,m2,m3}$ by N_2 and using Eqs. (4) and (5), $\alpha_{1,2,3}$ can be expressed as

$$\alpha_3 = (1+\eta)\alpha_2 - \eta\alpha_1\ , \tag{6}$$

$$\alpha_1 = [\alpha_2 + (\sqrt{\mu_1}/\Omega_1)(i_1/\varepsilon_1) - 1]\varepsilon_1/\sqrt{\tau_1}\ , \tag{7}$$

$$\alpha_2 = \left[1 - \frac{\sqrt{\mu_3}}{\Omega_3}\frac{i_3}{\varepsilon_3} + \eta\frac{\varepsilon_1}{\varepsilon_3}\sqrt{\frac{\tau_3}{\tau_1}}\left(1 - \frac{\sqrt{\mu_1}}{\Omega_1}\frac{i_1}{\varepsilon_3}\right)\right] \Big/ \left[1 - \frac{\sqrt{\tau_3}}{\varepsilon_3} + \eta\frac{\sqrt{\tau_3}}{\varepsilon_3}\left(1 - \frac{\varepsilon_1}{\sqrt{\tau_1}}\right)\right]. \tag{8}$$

4. ANALYSIS AND SUMMARY

For the ratio of negative to positive ion density, α_2 in Eq. 8), $\eta,\ i,\ \varepsilon,\ \tau$ can be provied from three I-V courves with three different pressures, yet $\mu_{1,3}$, $\Omega_{1,3}$ are to be given from other methods. For small ratio of negative ion density to the positive ion density($\alpha << 1$), one can put $\mu_{1,3}$ and $\Omega_{1,3}$ as unity. I-V curves by electric probe and data of LPD method have been obtained with large change of pressures(5-10 mtorr), but for the analysis we need values with small change of pressure(e.g., $\eta = 0.1$). So for small change of pressure, we used linear-fitting about plamsa parameters(T_e, I_{+s} and I_{es}). From Eqs. (6), (7) and (8), we can get $\alpha_{1,2,3}$. Once $\alpha_{1,2,3}$ are deduced, α_4 can be obtained using measured data($i_4, \varepsilon_4, \tau_4$) at P_4 by either Eq.(4)of Eq. (6). Figure 4 shows the measured the negative ion denstiy ratio(α) by electric probe and LPD. With small change of pressure($\eta = 0.1$), the ratios of negative ion density seem to be close to those($\alpha = 0.17 - 0.23$) by LPD: $\alpha_n = 0.15 - 0.24$ around $P_n = 8.3 - 18$ mtorr. As described in ref. [7], however, LPD method needs some modifications in the recombining plasmas. Since we applied the conventional LPD method in this series of experiment, we should examine the validity of the values because the dependence of α on the pressure indicates the recombining feature. In particular, whether the remarkable reduction in the electron saturation current can be attributed to the negative ion response or not is unclear for the moment. Also, the choice of η should be examined in more detail. These will be done in the future.

In summary, negative ion density is deduced by the measured values of electron and ion saturation currents and electron temperatures of three different pressures(P_1, P_2, P_3) by assuming the linear dependence of the ratio of negative ion density upon the pressure of process chamber or flow rate of added gases for the negative ion generation.

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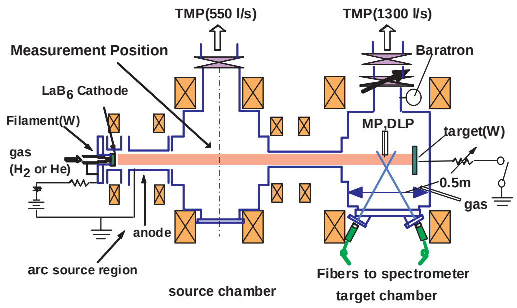

Figure 1: The schematic diagram for MAP-II

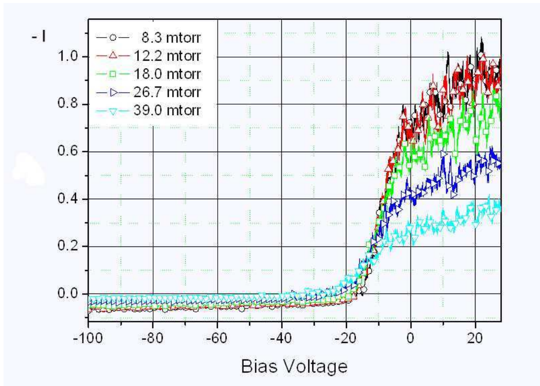

Figure 2: Measured I-V curves for 8.3 - 39.0 mtorr

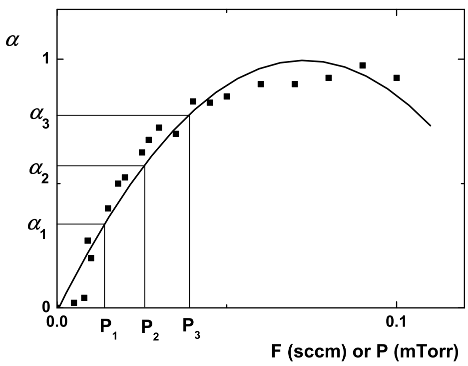

Figure 3: Typical dependence of on the neutral pressure. Monotonously varying region(regardless of increasing or decreasing) can be used to deduce negative ion density with linearity assumption. Solid squares are taken from ref. [5] for Ar-SF6 plasma.

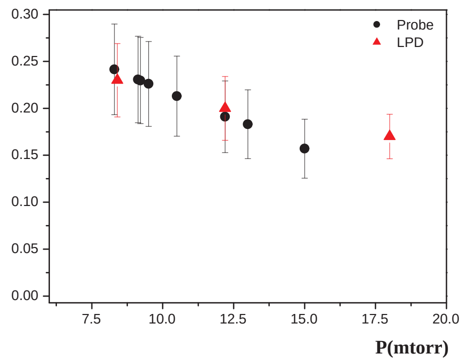

Figure 4: The measured negative ion density ratio by probe method(solid circles) and by LPD method(solid squares) in MAP-II hydrogen plasmas.