Measurement of Electron Density and Temperature and Their Fluctuations Using Modified Triple Langmuir Probe Grounded through Finite Resistance

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In the triple Langmuir probe (T-LP) method, the electron temperature ($T_e$) and density ($n_e$) can be simultaneously derived from potential measurements of electrode of T-LP and the ion saturation current ($I_{is}$) where no current flows in the electrodes for potential measurements. In the case of aiming at measuring high-frequency fluctuations, however, the smaller load resistance of electrode is required for high frequency response. Then the finite current can flow in the measurement circuits of the floating potential ($V_f$) and the plus-biased potential ($V_p$). When the current becomes comparable to $I_{is}$, the $T_e$ derived from measured $V_f$ and $V_p$ without the current considerably deviates from an actual value. This would be significant for fairly low density plasma of the $n_e < 5 \times 10^{17} \text{m}^{-3}$, and the correction of the finite current is necessary. A new relationship between $T_e$ and potential signals ($V_f$ and $V_p$) where the finite current in the electrodes for $V_f$ and $V_p$ measurements is taken into account was derived, and experimentally confirmed the validity in the experiments of the Compact Helical System.

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1. Introduction

The triple Langmuir probe (T-LP) method [1] enables us to obtain the electron temperature ($T_e$), electron density ($n_e$), space potential ($V_s$) and their fluctuations with high time and spatial resolutions. These plasma parameters can be derived from the simultaneous measurements of the potential signals ($V_f$ and $V_p$) and ion saturation current ($I_{is}$), where $V_f$ and $V_p$ stand for the floating potential and the plus-biased potential respectively. No current flows in the electrodes are assumed as a simple case. In the edge and divertor regions of high temperature plasmas or the low temperature and density plasmas produced at the low magnetic field ($< 0.1 \text{T}$), $I_{is}$ is a fairly low value. In these situations, the current flow in the circuit of $V_f$ and $V_p$ is comparable to $I_{is}$, and cannot be neglected. For the purpose of the reduction of these circuit current, the high load resistor may be adopted. If such high load resistance is used, the frequency response of T-LP is significantly degraded. As a result, it is difficult to measure the fluctuations in the range of the several 10 kHz.

In this paper, the effect of the finite current in the potential measurements of $V_f$ and $V_p$ on $T_e$ evaluation is discussed and a new relation to derive $T_e$ with the correction is derived. An appropriate circuit resistor for the potential measurements is accessed so that $T_e$ can be derived without large correction and having high frequency response of the probe circuit for fluctuation measurements.

2. Typical Triple Langmuir Probe Method

We discuss a typical T-LP method with five electrode tips, as shown in Fig. 1. This method with five tips is aimed at reducing the phase delay error introduced by finite probe tip separations in standard triple probe method [2]. The five electrode tips consist of a tip ($T_1$) for measurement of $V_p$ and two tips ($T_2$ and $T_3$) for $I_{is1}$ and $I_{is2}$, and other two tips ($T_4$ and $T_5$) for $V_{f1}$ and $V_{f2}$. It is postulated that the current flow in each tip from a plasma is expressed as $I_t$ (negative means a current flows into a plasma), $I_2$, ..., $I_5$, and the current flow in the circuit of $V_p$ is $I_p$ and the voltage of the tip against the space potential is $V_{T1}$, $V_{T2}$, ..., $V_{T5}$. The potential signals $V_{f1}$, $V_{f2}$ and $V_p$ are measured through relatively high load resistance such as $R_f$ and $R_p$, to meet the requirement of no-current flow. On the other hand, the ion saturation current $I_{is}$ is measured through low load resistance to avoid appreciable voltage drop of biasing voltage. Note that a signal of $V_{f1}$, $V_{f2}$ or $V_p$ is transferred to an isolation amplifier through a voltage divider.

The current flow into each tip $T_1$ to $T_5$ consists of electron and ion currents and is expressed as,

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where \( \phi = e/kT_e \). The electron thermal diffusion current is expressed as \( I_0 \) where \( I_0 = (1/4)n_e e<v_{th e}>^2 \): averaged electron thermal velocity, \( S \): surface area of a tip. The \( I_i \) stands for an ion current. When \( I_i \) is eliminated from the equations (1), the following relation is derived as,

\[
\frac{I_1 + I_4}{3I_1 + I_2 + I_3 + I_4} = \frac{1 - \exp(\phi V_{d4})}{3 - \exp(\phi V_{d2}) - \exp(\phi V_{d3}) - \exp(\phi V_{d4})} \tag{2}
\]

where \( V_{d2} = V_2-V_1 \), \( V_{d3} = V_3-V_1 \), \( V_{d4} = V_4-V_1 \). If the bias voltage between the \( T_1 \) and \( T_2(T_3) \) is higher than \( T_e \) by several times \( V_{d2} >> T_e \), \( V_{d3} \), \( V_{d4} \), \( \exp(\phi V_{d2}) \sim 0 \) and \( \exp(\phi V_{d3}) \sim 0 \) are satisfied. Then, the equation (2) reduces to a simpler one as,

\[
\frac{I_1 + I_4}{3I_1 + I_2 + I_3 + I_4} = \frac{1 - \exp(\phi V_{d4})}{3 - \exp(\phi V_{d3})} \tag{3}
\]

From the current conservation, the relation is \( I_1 + I_p = I_2 + I_3 \).

If \( I_p \) and \( I_4 \) are negligibly small compared to \( I_1, I_2, I_3 \), then \( I_p \) and \( I_4 \) can be set to be 0. In eq. (3), Therefore, \( I_1 \) is eliminated using this current relation as,

\[
\exp(\phi V_{d4}) = 1/3 \tag{4}
\]

From eq. (4), \( T_e \) is derived using measured quantities \( V_p \), \( V_f1 \), \( V_f2 \) as,

\[
T_e = (V_p - V_f)/\ln 3 \tag{5}
\]

Here, the floating potential \( V_f \) is averaged over two signals obtained by two independent tips, that is, \( V_f = (V_f1 + V_f2)/2 \). The plasma space potential \( V_p \) is derived as \( V_p = V_f + \alpha T_e \),(\alpha \) is a constant depending on plasma species; \( \alpha \sim 3.3 \) for hydrogen plasma). The electron density \( n_e \) is derived as \( n_e = \beta I_0 T_e^{-1/2}/S \), \( \beta \) is a constant depending on plasma species and ion temperature, \( I_0 \) is an averaged ion saturation current, that is, \( I_0 = (I_{i1} + I_{i2})/2 \), \( S \) is a collection area of ion saturation current).

### 3. Correction of Finite Circuit Current to Electron Temperature Evaluation

We consider the case that the current flow in the circuit of \( V_f \) and \( V_p \) is comparable to \( I_i \). When \( I_p \) and \( I_4 \) is not negligible small compared to \( I_1, I_2, \) and \( I_3 \), the eq. (3) is rewritten by elimination of \( I_1 \) using the current conservation relation: \( I_1 + I_p = I_2 + I_3 + I_4 \) as,

\[
\exp(\phi V_{d4}) = \frac{I_2 + I_3 - 2I_4}{3(I_2 + I_3) - 2I_p} \tag{6}
\]

From eq. (6), \( T_e \) is derived as,

\[
\frac{kT_e}{e} = -V_{d4}\ln\left(\frac{3(I_2 + I_3) - 2I_p}{(I_2 + I_3) - 2I_p}\right) \tag{7}
\]

Moreover, this equation is converted to eq. (7), using measured quantities \( V_f1, V_f2, V_p, I_{i1} \) and \( I_{i2} \) as,

\[
T_{e-corr} = \frac{V_p - (V_f1 + V_f2)/2}{\ln\left(\frac{3(I_{i1} + I_{i2}) - 2(V_p/R_p)}{(I_{i1} + I_{i2}) - 2(V_f1 + V_f2)/2/R_f}\right)} \tag{7}
\]

As seen from the comparison of eq. (5) and eq. (7), the correction of the finite current in the \( V_f \) or \( V_p \) measurement circuit is included into the denominator of eq. (7). We call \( T_e \) derived using eq. (7) the corrected electron temperature \( T_{e-corr} \). If the currents \( I_p, I_4 \) or \( I_3 \) in the measurement circuits of \( V_f \) and \( V_p \) are negligibly small compared to \( I_i \) \( (I_i >> I_p, I_4 >> I_3) \), then the eq. (7) becomes equivalent to eq. (5) which is the usual relation to derive \( T_e \) from the data of a triple Langmuir probe with 5 tips.

Thus, \( T_e \) measurement is directly affected by the finite circuit current as mentioned above. On the other hand, the electron density is indirectly affected by the correction of \( T_e \), because \( n_e \) is proportional to the product of \( I_i \) and \( T_e^{1/2} \). Typically, the effect to \( n_e \) is expected to be relatively small. The plasma space potential \( V_p \) is also affected through \( T_{e-corr} \). It should be noted that the effect of the \( T_e \)-correction on \( V_p \) would be relatively large, compared with that in \( n_e \).
4. Experimental Test of the Finite Circuit Current Effect on Parameter Measurements by a Triple Langmuir Probe

In order to evaluate the magnitude of the correction in $T_e$, $n_e$ and $V_s$ using T-LP shown in Fig. 1 in reproducible low density plasmas of $n_e < 5 \times 10^{17}$ m$^{-3}$ and $T_e < 30$ eV produced at very low toroidal field (< 0.1 T) in the Compact Helical System [3]. These low temperature and density plasmas were produced with 2.45 GHz microwaves for a simulation of transport phenomena in high temperature and density plasma [4, 5]. In this plasma, the Langmuir probe can be inserted from edge region to core region without a large disturbance and damage from plasma.

We used the Langmuir probe with the five tips that the radial resolution is 2 mm and the poloidal resolution is 6 mm. The tip made of tungsten is a cylinder which length is 2 mm and the diameter is 0.5 mm. The electrical circuit of the Langmuir probe is constituted as Fig. 1. The value of the resistors is as follows. $R_p$ and $R_f$ are 10 kΩ or 100 kΩ, and $r_i$ is 10 Ω. The DC bias voltage $V_b$ is 150-200 V, so that $V_b$ is larger than predicted $T_e$ by several times and $I_{i1}$ or $I_{i2}$ corresponds to the measurement of the ion saturation current. The $V_f1$, $V_f2$ and $V_p$ were monitored through a voltage divider which has an input resistor $R_p$ or $R_f$ and output resistor of 100 Ω. The data were acquired by an analog digital converter having 0.5 or 1 MHz sample rate.

The hydrogen plasma was produced by 2.45 GHz microwave, of which the power is ∼30 kW. On the reproducible plasma discharges, the Langmuir probe radially was moved for the measurement of the radial profiles, shot by shot. First, we acquired data using the circuits with the resistors of $R_f = R_p = 10$ kΩ. Figure 2 shows the radial profiles of $T_e$, $V_s$, $n_e$ (red circle plot) derived without the correction and $T_{e, corr}$, $V_{s, corr}$, $n_{e, corr}$ (blue square plot) with the correction, where the data are averaged over the time for 145-155 ms. The electron temperature obtained by the corrected relation eq. (7) $T_{e, corr}$ is larger by about 20-30 % in core region with relatively high $n_e$ and by about 1.5 to 2.5 times in the low density plasma edge. The plasma potential $V_s$ is also increased by the $T_e$ correction. An important point is that the radial profile of $V_s$ was appreciably modified and the profile of the radial electric field was also modified appreciably. On the other hand, $n_e$ slightly decreased. It should be noted that $n_e$ profile was calibrated by the line integrated electron density measured by 2 mm microwave interferometer because the estimation of collection area of T-LP in this plasma condition is complex.

Next, we obtained T-LP data, changing the resistors of $R_p$ and $R_f$ from 10 kΩ to 100 kΩ at the same plasma conditions to those in Fig. 2. The radial profiles of the $T_e$, $V_s$, $n_e$ (green square outline plot) and $T_{e, corr}$, $V_{s, corr}$, $n_{e, corr}$ (orange lozenge plot) averaged over the time for 145-155 ms are compared in figure 3. In this high resistor case, $T_e$ and $V_s$ do not have obvious differences with and without the finite current correction. Accordingly, $n_e$ also exhibit any obvious differences. The plasmas for this measurement with $R_f = R_p = 100$ kΩ have somewhat different density profile which is more peaked compared that obtained in the experiment shown in Fig. 2. This difference is thought to be due to the reproducibility of plasma discharge. From these observations, it is concluded that the resistance of 10 kΩ is not large enough to suppress the current flow in the circuits of $V_p$ and $V_f$, and the resistance of 100 kΩ is sufficiently large even for low density plasmas employed in these experiments.

On the other hand, too large $R_f$ and $R_p$ degrades fast time response or high frequency response of electrical circuits for a triple Langmuir probe. For such situation, T-LP would not be applicable for measurements of electrostatic plasma fluctuations of which frequency range usually extends at least 100 kHz. For the experiments in CHS,
we evaluated an appropriate value of $R_f$ and $R_p$. Figure 4 shows the frequency responses of the $V_f$ circuit for three cases of $R_f = 10 \Omega$, 100 k$\Omega$ and 1 M$\Omega$. The data was obtained from measurement applying probe tip to the voltage which amplitude is $\pm 4$ V and frequency is 10-250 kHz. The resistance of 1 M$\Omega$ is large enough to suppress the current flow. However, only the low frequency response ($f < 20$ kHz) is expected. For 100 k$\Omega$, the frequency response up to 100 kHz is obtained, and for 10 k$\Omega$, the response up to 150 kHz is obtained. Accordingly, the resistance should be selected, depending on plasma parameters and experimental purposes. For instance, if we stress measurements of equilibrium parameters of $T_e$, $n_e$ and $V_f$ and their low frequency fluctuations up to 100 kHz, the resistance of 100 k$\Omega$ would be appropriate for above mentioned CHS plasmas. If we stress fluctuation measurement in relatively high density plasma, the relatively low resistance of 10 k$\Omega$ will be acceptable. In the experiments of H-mode plasmas produced at high toroidal field of $\sim 1$ T in CHS, the resistors of 10 k$\Omega$ and 100 k$\Omega$ were adopted and the correction of $T_e$ is less than 10% for both resistors even outside the last closed flux surface because the electron density is in the range more than $10^{18} \text{m}^{-3}$ [6]. Fluctuations up to 100 kHz were successfully obtained.

5. Summary

We have accessed the effect of finite current which flows an electrical circuit for $V_f$ or $V_p$ measurement in a triple Langmuir probe, and derived the new equation to evaluate $T_e$ using signals obtained by T-LP. This correction was experimentally investigated in low temperature plasmas produced at very low toroidal field ($< 0.1$ T) where electron density is in the fairly low density range of $\sim 10^{17} \text{m}^{-3}$. For this low density plasma in CHS, the resistor of 100 k$\Omega$ in the measurement circuit of $V_f$ or $V_p$ was appropriate for suppressing the circuit current and ensuring sufficiently high frequency response up to 100 kHz for fluctuation measurements. In the edge region of relatively high density plasmas produced at higher toroidal field, the resistor of 10 k$\Omega$ is also acceptable for suppressing the current flow and having high frequency response.

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