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

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(Received 5 December 2006 / Accepted 23 April 2007)

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 <∼ $5 \times 10^{17}\,\mathrm{m}^{-3}$, 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.

Keywords: triple Langmuir probe, load resistance, fluctuation measurement, floating potential, frequency response

DOI: 10.1585/pfr.2.S1091

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 diverter regions of high temperature plasmas or the low temperature and density plasmas produced at the low magnetic field (< 0.1 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_1(negative means a current flows into a plasma), $I_2, \ldots, I_5$, and the current flow in the circuit of V_p is I_p and the voltage of the tip against the space potential is $V_1, V_2, \ldots, V_5$. 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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$$\begin{aligned} -I_1 &= -I_{e0}\exp(\phi V_1) + I_i \\ I_2 &= -I_{e0}\exp(\phi V_2) + I_i \\ I_3 &= -I_{e0}\exp(\phi V_3) + I_i \\ I_4 &= -I_{e0}\exp(\phi V_4) + I_i \\ I_5 &= -I_{e0}\exp(\phi V_5) + I_i \end{aligned} \tag{1}$$

, where $\phi = e/kT_e$. The electron thermal diffusion current is expressed as I_{e0} where $I_{e0} = (1/4)n_e e \langle v_{the} \rangle S$, $\langle v_{the} \rangle$: 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} ¿¿ T_e), then $\exp(\phi V_{d2}) \sim 0$ and $\exp(\phi V_{d3}) \sim 0$ are satisfied. Then, the equation (2) reduces to a simpler one as,

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

From the current conservation, the relation of current 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 potentialV_s is derived as $V_s = V_f + \alpha T_e$(α is a constant depending on plasma species; $\alpha \sim 3.3$ for hydrogen plasma). The electron density n_e is derived as $n_e = \beta I_{is} T_e^{-1/2}/S$ $\beta$is constant depending on plasma species and ion temperature, I_{is} is an averaged ion saturation current, that is, $I_{is} = (I_{is1} + I_{is2})/2$, 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_{is}. 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: $I_1 + I_p = I_2 + I_3$ as,

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

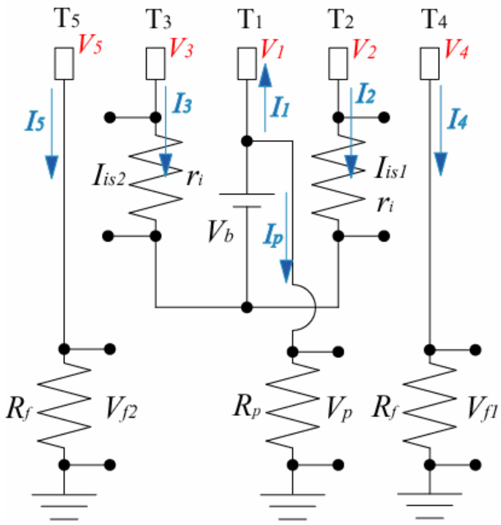

Fig. 1 The circuit of the typical triple Langmuir probe with five tips.

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

$$\frac{kT_e}{e} = -V_{d4} \Big/ \ln\left\{\frac{3(I_2 + I_3) - 2I_p}{(I_2 + I_3) - 2I_4}\right\}$$

Moreover, this equation is converted to eq. (7), using measured quantities V_{f1}, V_{f2}, V_p, I_{is1} and I_{is2} as,

$$T_{e\_cor} = \frac{V_p - \left(V_{f1} + V_{f2}\right)/2}{\ln\left\{\dfrac{3(I_{is1} + I_{is2}) - 2(V_p/R_p)}{(I_{is1} + I_{is2}) - 2\left\{(V_{f1} + V_{f2})/2/R_f\right\}}\right\}} \tag{7}$$

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_cor}. If the currents (I_p, I_4 or I_5) in the measurement circuits of V_f and V_p are negligibly small compared to I_{is} ($I_{is} >> I_p$, $I_{is} >> I_4$, $I_{is} >> I_5$), 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_{is} and $T_e^{-1/2}$. Typically, the effect to n_e is expected to be relatively small. The plasma space potential (V_s) is also affected through T_{e_cor}. It should be noted that the effect of the T_e-correction on V_s 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-evaluation experimentally and investigate applicability of the newly derived relation eq. (7), we tried to measure T_e, n_e and V_s using T-LP shown in Fig. 1 in reproducible low density plasmas of $n_e <\sim 5\times10^{17}$ 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_{is1} or I_{is2} 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_f or R_p 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_cor}, V_{s_cor}, n_{e_cor} (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_cor} 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_cor}, V_{s_cor}, n_{e_cor} (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,

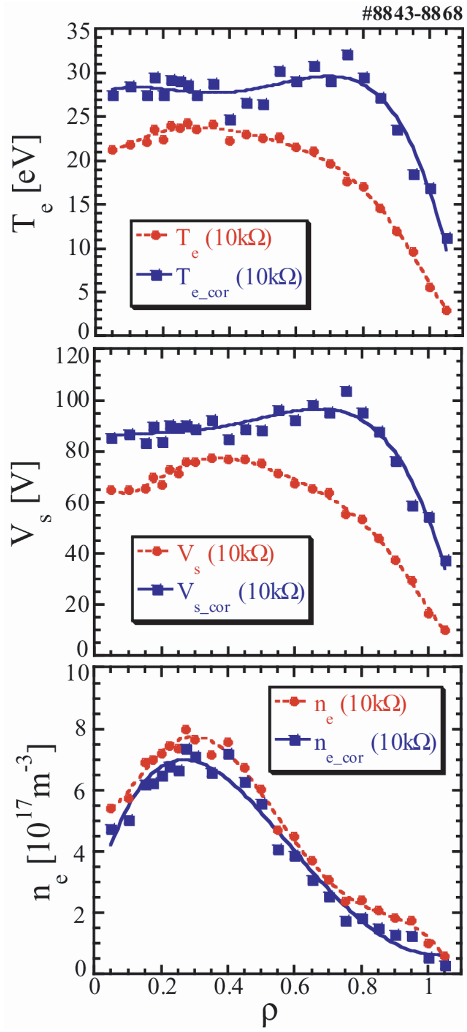

Fig. 2 The radial profiles of T_e, V_s, n_e (red cir-cle plot) and T_{e_cor}, V_{s_cor}, n_{e_cor} (blue square plot) measured by the resister of $R_f = R_p = 10$ kΩ.

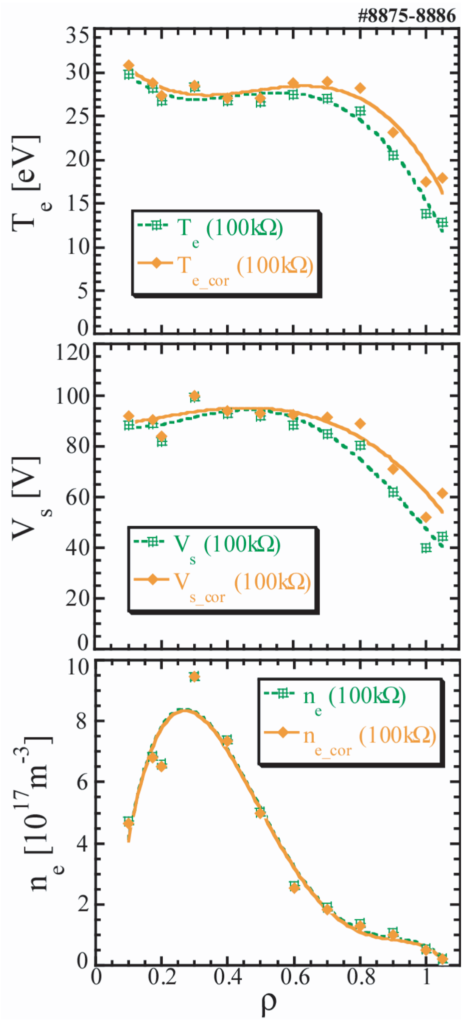

Fig. 3 The radial profiles of T_e, V_s, n_e (green square plot) and T_{e_cor}, V_{s_cor}, n_{e_cor} (or-ange lozenge plot) measured by the re-sistor of $R_f = R_p = 100\,\mathrm{k\Omega}$.

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 $R_f = 10\,\mathrm{k\Omega}$, 100 kΩ and 1 MΩ. The data was obtained from measurement applying probe tip to the voltage which amplitude is ±4 V and frequency is 10-250 kHz. The resistance of 1 MΩ is large enough to suppress the current flow. However, only the low frequency response ($f < 20\,\mathrm{kHz}$) is expected. For 100 kΩ, the frequency response up to 100 kHz is obtained, and for 10 kΩ, 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_s and their low frequency fluctuations up to 100 kHz, the resistance of 100 kΩ would be appropriate for above mentioned CHS plasmas. If we stress fluctuation measurement in relatively high density plasma, the relatively low resistance

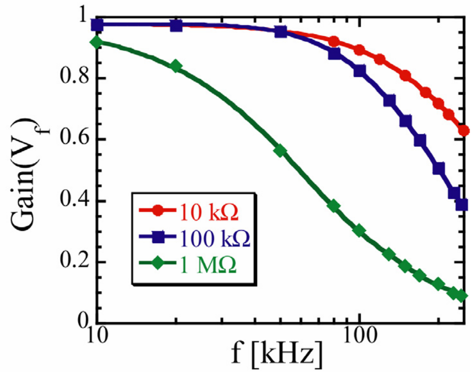

Fig. 4 The frequency responses of the V_f circuit for the resistance $R_f = 10\,\mathrm{k\Omega}$, 100 kΩ and 1 MΩ.

of 10 kΩ will be acceptable. In the experiments of H-mode plasmas produced at high toroidal field of ∼ 1 T in CHS, the resistors of 10 kΩ and 100 kΩ 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 $10^{18}\,\mathrm{m}^{-3}$ [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 $\sim 10^{17}\,\mathrm{m}^{-3}$. For this low density plasma in CHS, the resistor of 100 kΩ 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 kΩ is also acceptable for suppressing the current flow and having high frequency response.

Acknowledgement

This work is supported in part by a Grant-in-Aid for Scientific Research (A) from JSPS, No. 15206107.

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