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

M. Takeuchi[1)], K. Toi, R. Ikeda[1)], C. Suzuki
and CHS Experimental Group

National Institute for Fusion Science, Toki 509-5292, Japan
[1)]Department of Energy Engineering and Science, Nagoya University, Nagoya 464-8603, Japan

E-mail address : m-takeuchi@nifs.ac.jp

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.

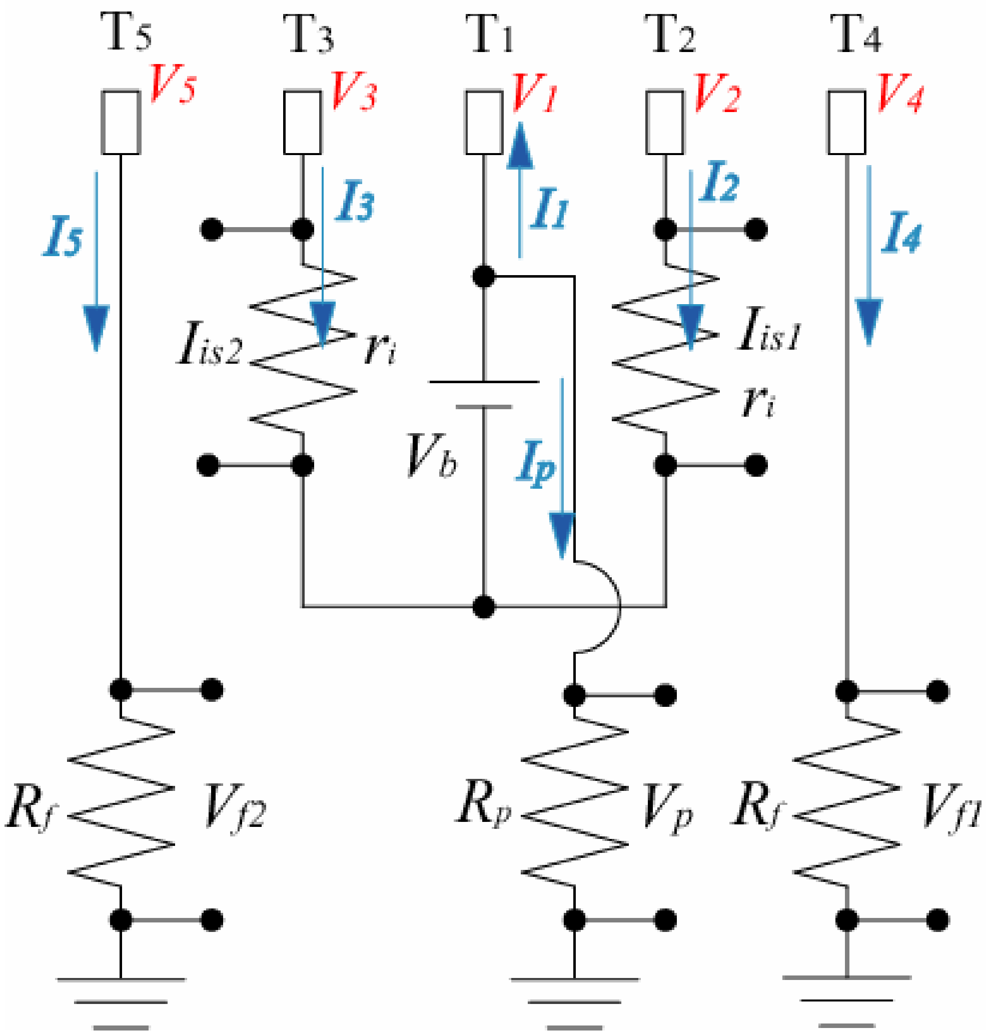
- In the edge and diverter regions of high temperature plasmas or the low temperature and density plasmas produced at the low magnetic field (< 0.1 T), I_{is} is a fairly low value.
In these situations, the current flow in the circuit of V_f and V_p is comparable to I_{is}, and cannot be neglected.

- For the purpose of the reduction of these circuit current, the high load resistor may be adopted. However, the frequency response of T-LP is significantly degraded.

- 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.

[1] S. L. Chen *et al.*, J. Appl. Phys. **36**, 2363 (1965)

The circuit of the typical triple Langmuir probe with five tips



$-I_1, I_2, \ldots, I_5$: current flow in each tip from a plasma

I_p : current flow in the circuit of V_p

$V_1, V_2, \ldots, V_5$: voltage of the tip against the ground

V_b : DC bias voltage

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.

The ion saturation current I_{is} is measured through low load resistance to avoid appreciable voltage drop of biasing voltage.

A typical T-LP method with five electrode tips (1)

The current flow into each tip T1 to T5 consists of electron and ion currents and is expressed as,

$$\begin{aligned} -I_1 &= -I_{e0}e^{\phi V_1} + I_i \\ I_2 &= -I_{e0}e^{\phi V_2} + I_i \\ I_3 &= -I_{e0}e^{\phi V_3} + I_i \\ I_4 &= -I_{e0}e^{\phi V_4} + I_i \\ I_5 &= -I_{e0}e^{\phi V_5} + I_i \end{aligned} \qquad (1)$$

$\phi = e / kT_e$

electron thermal diffusion current

$I_{e0} = (1/4) n_e e \langle v_{the} \rangle S$

$\langle v_{the} \rangle$: averaged electron thermal velocity

S: surface area of a tip

I_i : an ion current

When I_i is eliminated from the equations (1), the following relation is derived as,

$$\frac{I_1 + I_4}{3I_1 + I_2 + I_3 + I_4} = \frac{e^{\phi V_1} - e^{\phi V_4}}{3e^{\phi V_1} - e^{\phi V_2} - e^{\phi V_3} - e^{\phi V_4}}$$

or

$$\frac{I_1 + I_4}{3I_1 + I_2 + I_3 + I_4} = \frac{1 - e^{\phi V_{d4}}}{3 - e^{\phi V_{d2}} - e^{\phi V_{d3}} - e^{\phi V_{d4}}} \qquad (2)$$

$V_{d2} = V_2 - V_1$
$V_{d3} = V_3 - V_1$
$V_{d4} = V_4 - V_1$

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 $e^{\phi V_{d2}} \sim 0$ and $e^{\phi V_{d3}} \sim 0$ are satisfied. Then, the equation (2) reduces to a simpler one as,

$$\frac{I_1 + I_4}{3I_1 + I_2 + I_3 + I_4} = \frac{1 - e^{\phi V_{d4}}}{3 - e^{\phi V_{d4}}} \qquad (3)$$

A typical T-LP method with five electrode tips (2)

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,

$$e^{\phi V_{d4}} = \frac{1}{3} \qquad (4)$$

From eq. (4), electron temperature T_e is derived using measured quantities V_p, V_{f1}, V_{f2} as,

$$T_e = \frac{V_p - V_f}{\ln 3} \qquad (5)$$

$$V_f = (V_{f1} + V_{f2}) / 2$$

Plasma space potential V_s

$$V_s = V_f + \alpha T_e$$

α : a constant depending on plasma species;
α ~ 3.3 for hydrogen plasma

Electron density n_e

$$n_e = \beta I_{is} T_e^{-1/2} / S$$

β : constant depending on plasma species and ion temperature
I_{is} : an averaged ion saturation current, that is, $I_{is} = (I_{is1} + I_{is2}) / 2$
S : a collection area of ion saturation current

[2] H. Y. W. Tsui *et al.*, Rev. Sci. Instrum. **63**, 4608 (1992)

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,

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

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

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

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

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

Corrected electron temperature

$$\boxed{V_{s\_cor} = V_f + \alpha T_{e\_cor}}$$

Corrected space potential

$$\boxed{n_{e\_cor} = \beta I_{is} T_{e\_cor}^{-1/2} / S}$$

Corrected electron density

The effect of the T_e-correction on V_s would be relatively large, compared with that in n_e.

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).

Experimental condition of plasma

Experimental device : Compact Helical System
hydrogen plasma
low density plasmas of $n_e < \sim 5 \times 10^{17}$ m^{-3}
low temperature plasmas of $T_e < 30$ eV
very low toroidal field (< 0.1 T)
Heating : 2.45 GHz microwaves (~30 kW)

Simulation of transport phenomena in high temperature and density plasma

K. Toi *et al.*, 29th EPS on Plasma Physics and Controlled Fusion, Montreux, paper No. P4-061 (2002)
K. Toi *et al.*, J. Plasma Fusion Res. SERIES **6**, 516 (2004)

Langmuir probe and the circuit

five tips
radial resolution : 2 mm
poloidal resolution : 6 mm

Langmuir probe can be inserted from edge region to core region without a large disturbance and damage from plasma.

The value of the resistors R_p and R_f : 10 kΩ or 100 kΩ, r_i : 10 Ω.
Voltage divider : an input resistor R_f or R_p and output resistor of 100 Ω
The DC bias voltage V_b : 150 − 200 V.
The data acquisition :ADC having 0.5 or 1 MHz sample rate

Radial profiles of T_e, V_s, n_e derived w/o and with the correction using the resistors of $R_f = R_p = 10\ \mathrm{k\Omega}$

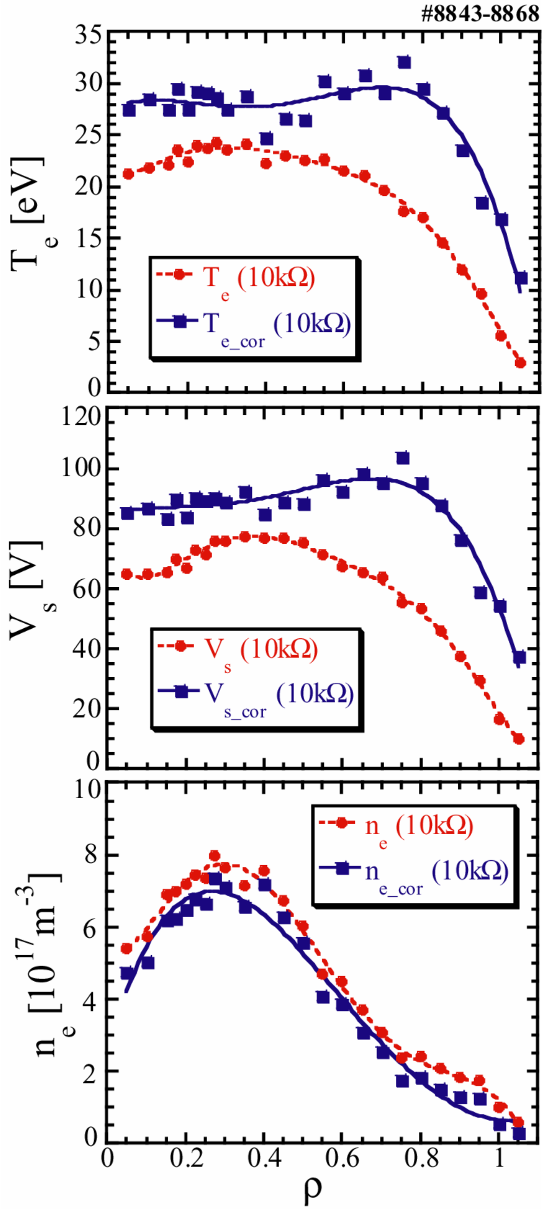
On the reproducible plasma discharges, the Langmuir probe radially was moved for the measurement of the radial profiles, shot by shot.

- 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.

- 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.



Radial profiles of T_e, V_s, n_e derived w/o and with the correction using the resistors of $R_f = R_p = 100$ kΩ

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.

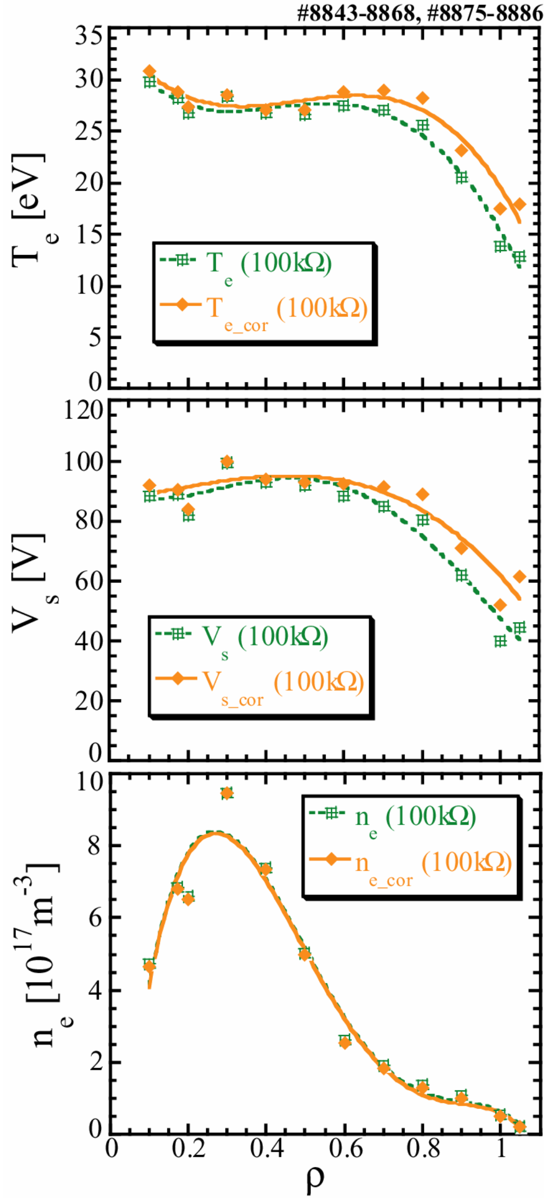
➢T_e and V_s do not have obvious differences with and without the finite current correction.

➢Accordingly, n_e also exhibit any obvious differences.

From these observations, it is concluded that

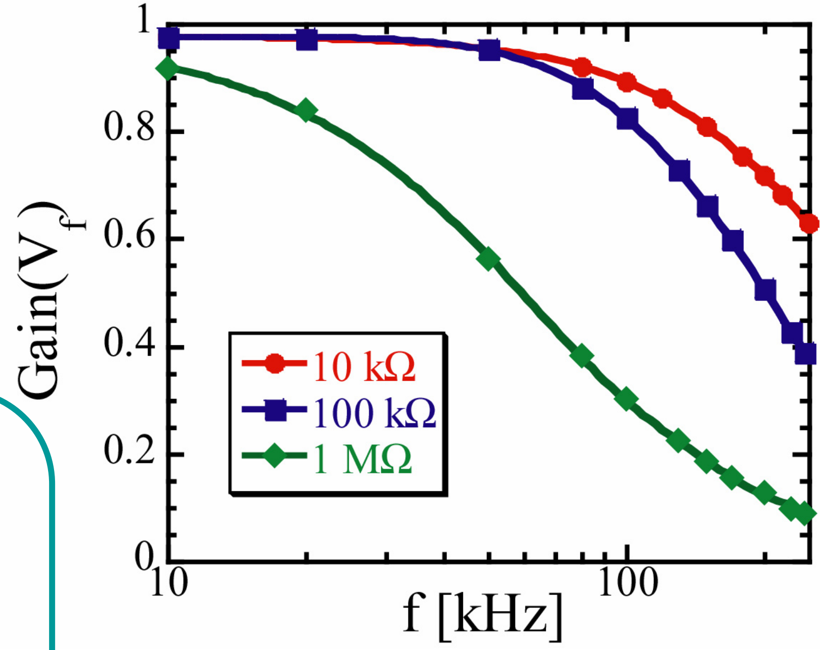
the resistance of 10 kΩ is not large enough to suppress the current flow in the circuits of V_p and V_f,

and the resistance of 100 kΩ is sufficiently large even for low density plasmas employed in these experiments.



The frequency responses of the V_f circuit for the resistance R_f = 10 kΩ, 100 kΩ and 1 MΩ.

Too large R_f and R_p degrades fast time response or high frequency response of electrical circuits for a T-LP.



For the experiments in CHS, we evaluated an appropriate value of R_f and R_p.

- 1 MΩ : large enough to suppress the current flow. However, only the low frequency response (f < 20 kHz) is expected.
- 100 kΩ : the frequency response up to 100 kHz is obtained,
- 10 kΩ : the response up to 150 kHz is obtained.

Accordingly, the resistance should be selected, depending on plasma parameters and experimental purposes.

Discussion and an example of measurement in the edge region of high temperature and density plasma

➢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,

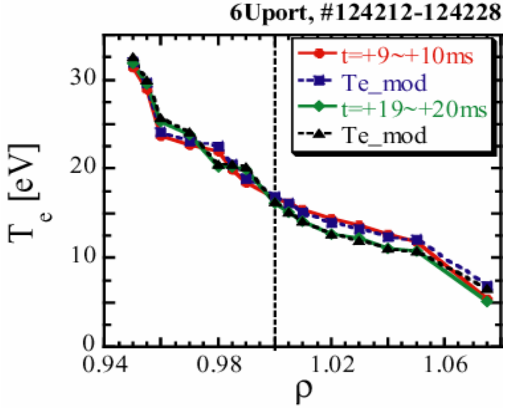
the relatively low resistance of 10 kΩ will be acceptable.

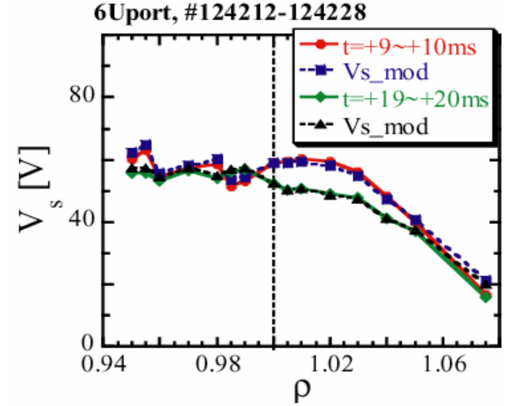
In the experiments of H-mode plasmas produced at high toroidal field of ~1 T in CHS

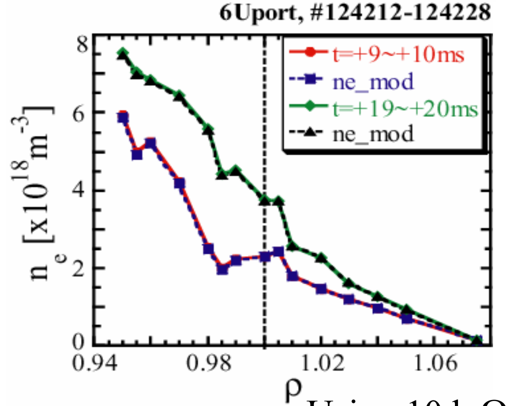
➢The resistors of 10 kΩ and 100 kΩ were adopted and the correction of T_e is less than 10% for both resistors even outside the last closed flux surface because the electron density is in the range more than 10^{18} m^{-3}[6].

➢Fluctuations up to 100 kHz were successfully obtained.

[6] M. Takeuchi *et al.*, Plasma Phys. Control. Fusion **48**, A277-A283 (2006)







Using 10 k Ω

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 $\sim 10^{17}$ 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.