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Effect of Supersonic Ion Beams on the Triple Probe Measurement

H.-J. Woo[1], **K.-S. Chung**[*1], **Y.-S. Choi**[1], **M.-J. Lee**[1], **D. Zimmerman**[2], and **R. McWilliams**[2]

[1] Electric Probe Applications Lab. (ePAL), Hanyang University, Seoul 133-791, Korea
[2] Dept. of Physics and Astronomy, University of California, Irvine, CA 92697, U.S.A.

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Although theory of the triple probe for Maxwellian plasma is well known, analysis with ion beams has not been established. Since plasma parameters, especially electron temperature, are distorted severely in the presence of supersonic ion beams, a new model for deducing electron temperature is introduced by solving the governing equations of the triple probe including the beam currents to three probe tips through simple assumptions.

1 Introduction

Since the triple probe (TP) does not require any voltage sweep differently from the single and double probes, it can measure the plasma parameters such as floating potential (V_f), electron temperature (T_e) and density (n_e) with the intrinsic response time of probe itself, and it has, therefore, the good resolutions against space and time variation. [1, 2] In addition, TP does not require the complicate procedure of data analysis to obtain plasma parameters from the measured signals. For these two reasons, the triple probe is known as one of the powerful diagnostic tools for not only stationary but also rapidly varying time-dependent plasmas.

The electron temperature and density compensation in the TP measurement were already performed in shock tube plasma with supersonic flows. However, it has not been applied yet for the case of supersonic ion beam. In the case of supersonic flow, there is no significant effects of the Mach and Reynold numbers on TP measurements. [3] In the transient and turbulent plasma such as tokamak [4–6], and reverse field pinch [7, 8], TP is often used for the measurement of the electron temperature and density fluctuations. The multi-pin configuration working as TP is suggested to be compensated, since three probes of a TP do not often pick up plasma signal at the same plasma potential, that is, to avoid the local gradients of plasma parameters. [4–6] However, these are all the electron temperature and density taken by assuming the Maxwellian ion and electron distributions.

In this work, we introduce a simple theory and method for deducing the electron temperature and density with the presence of supersonic ion beams. The experimental set up and probe assembly are introduced in section 2 with supersonic ion beams. The modification procedure to estimate the electron temperature is presented in section 3. Conclusions are given in section 4.

2 Experimental Set-Up

Figure 1 shows the schematic diagram of the test facility at University of California, Irvine. Generally, the plasma is generated from the lower hybrid radio frequency (RF) current applied to the conducting electrode in the shape of ring or coil (ring shape in this experiment) with the magnetic field of up to 2 kG and $f = 1 - 1000$ MHz with 1-100 watt RF power inputs. The supersonic ion beams are produced by the RF ion beam source from Veeco/RF-Ion Beam Tech. The RF ion beam source has a typical parameters as a beam diameter of 3 cm, beam energy range of 50 eV - 1200 eV, beam current density of up to 5 mA/cm^2 with 80 - 200 watt of RF power input. In this

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[*] Corresponding author: e-mail: kschung@hanyang.ac.kr, Phone: +82 2 2220 0465, Fax: +82 2 2299 1908

experiment, Ar plasma was produced with 1 mTorr of pressure, 185 G of magnetic field intensity, 103.4 MHz of RF frequency and 30 watt RF power input, and the supersonic Ar ion beams were produced with controlling the energies ranging from 70 to 370 eV.

For the measurements of plasma parameters such as n_e, T_e, T_i and ion velocity distribution function, the versatile electric probe and laser induced fluorescence (LIF) system [9] were used. The versatile electric probe is composed of triple probe (TP) and mach probe (MP) as is shown in Fig. 2. The TP is composed of three molybdenum tips with dimensions of 1 mm dia. × 3 mm length and the MP is composed of two molybdenum tips with 1 mm dia. × 8 mm length. The background ion temperature is measured as 0.05 eV by using LIF.

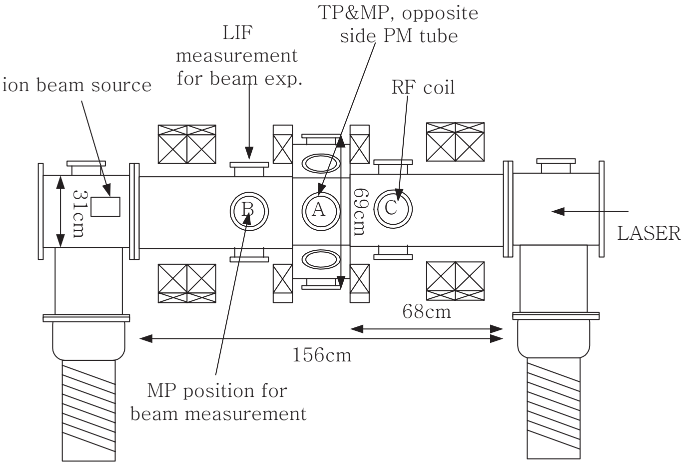


Fig. 1 Schematic diagram of the test facility and diagnostic systems

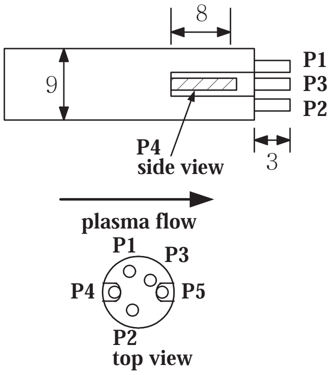


Fig. 2 Versatile electric probe tips: P1, P2 and P3 are for the triple probe, P4 and P5 are for the mach probe, respectively.

The supersonic ion beams are measured with the negatively biased probe is shown in Fig. 3. The maximum beam density is about 4.5×10^8 cm^{-3}, which is smaller than the background plasma density by 10 times.

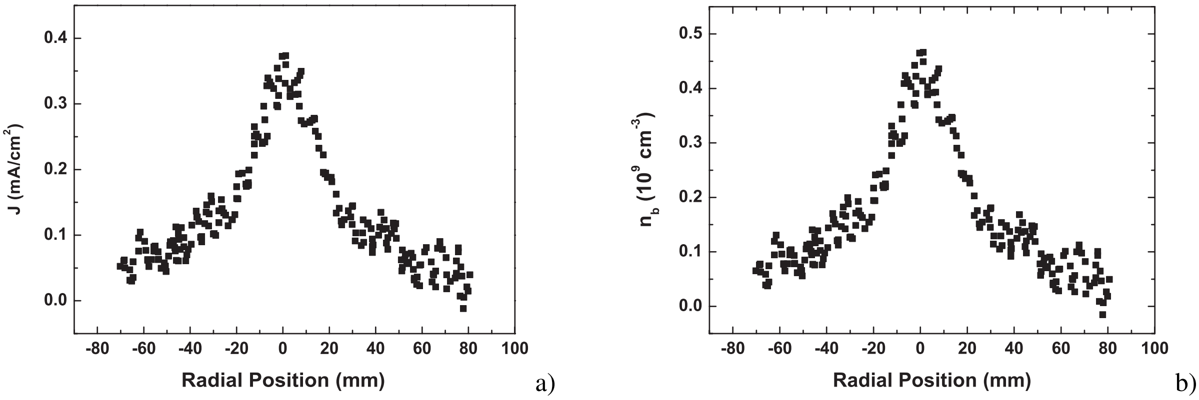


Fig. 3 The reference supersonic ion beam density: a) current density, J (mA/cm^2) and b) number density, n_b ($\times 10^9$ cm^{-3}) at 80 watt RF power input with $f = 18.75$ MHz and 3×10^{-4} Torr.

3 Data and Results

Figure 4 shows the conventional triple probe circuit for direct display system. When the presence of supersonic ion beams in the plasma, the collected currents of each probe tip are modified as follows with the beam current:

$$-I_1 = -J_e exp(-eV_1/kT_e)S + J_i(V_1)S + J_b(V_1)S_x, \tag{1}$$

$$I_2 = -J_e exp(-eV_2/kT_e)S + J_i(V_2)S + J_b(V_2)S_x, \tag{2}$$

$$I_3 = -J_e exp(-eV_3/kT_e)S + J_i(V_3)S + J_b(V_3)S_x, \tag{3}$$

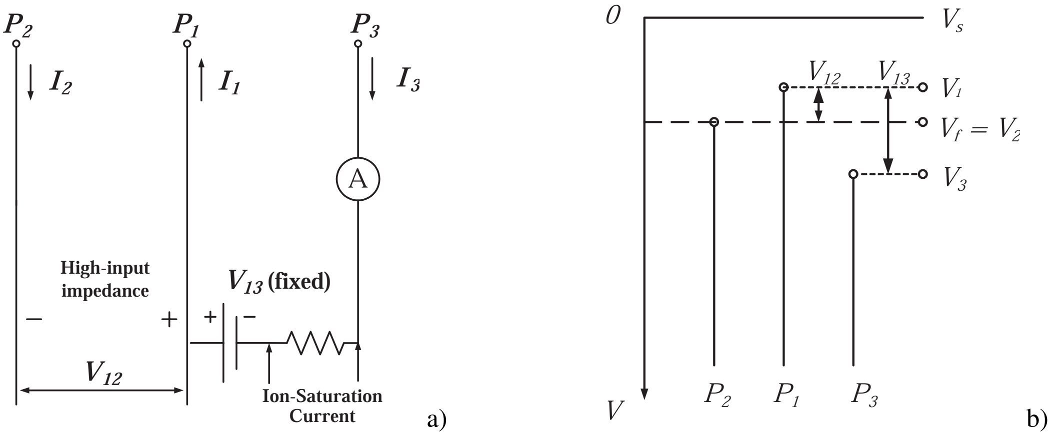


Fig. 4 The equivalent circuit of triple probe with direct display system and its potentials: a) Equivalent circuit and b) Potentials of each probe tip.

where S, S_x, k, T_e, $V_{1,2,3}$, J_e, J_i, and J_b are the probe collection area, cross-section of probe when the supersonic ion beam impinges, Boltzmann constant, electron temperature, potentials applied to three probe tips with respect to the plasma potential, electron and ion saturation current densities, and ion beam current density, respectively. Here

$$J_e = n_e e\sqrt{kT_e/2\pi m_e}, J_i(V) = n_i e\sqrt{kT_e/m_i}g(V), J_b(V) = n_b e\sqrt{2E_0/m_i}f(V), \tag{4}$$

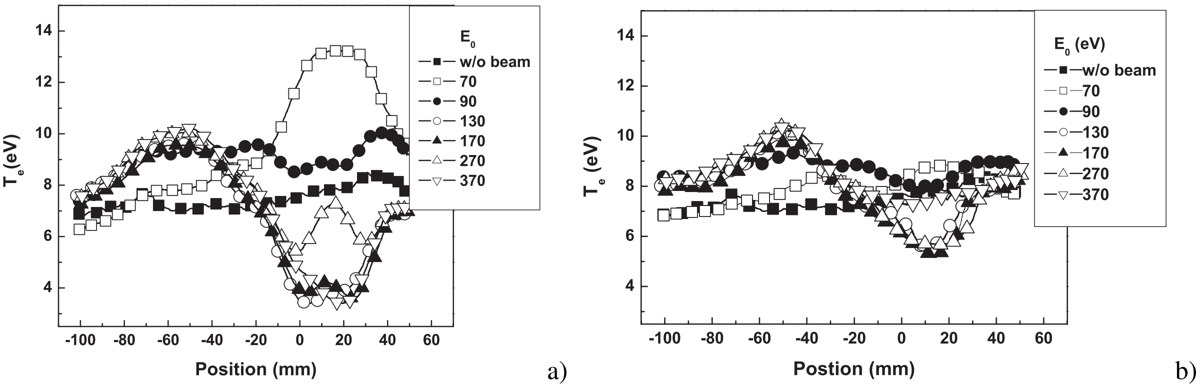
where E_0, $g(V)$ and $f(V)$ are the beam energy, distribution function of ion current and distribution function of beam current with respect to the biased potentials, respectively. If the beam currents collected from each probe tip are not the same, the triple probe relation on electron temperature can be obtained by letting $I_2 = 0, I = I_1 = I_3$. Then the operation (Eq. (2) - Eq. (1))/(Eq. (3) - Eq. (1)) will give:

$$\frac{I + (J_b(V_1) - J_b(V_2))S_x}{2I + (J_b(V_1) - J_b(V_3))S_x} = \frac{1 - exp(-eV_{12}/kT_e)}{1 - exp(-eV_{13}/kT_e)}, \tag{5}$$

where $V_{12} = V_2 - V_1$, $V_{13} = V_3 - V_1$, $I = I_1 = I_3$ and $J_b(V_1) \approx J_b(V_2) \approx J_b(V_3)$ as assumed in the conventional TP theory. Since the potential difference between tip 1 and tip 3, V_{13}, is typically much larger than electron temperature, T_e, then, RHS of Eq. (5) can be reduced to $1 - exp(eV_{12}/kT_e)$. Since no beam current is considered in the conventional TP theory, the electron temperature is deduced as $T_e = -V_{12}/0.693$. The electron temperature calculated from the conventional TP theory are shown in Fig. 5 a). In this figure, one can see the rapid variation of the electron temperature in the beam region. However, this variation is not appropriated and contrary to the common sense due to not only the low ion-electron collision rate but also the iso-thermal property of electron. The ion-electron collision frequency (ν_{ie}) is $0.258\ Hz$ at the experimental condition, so one does not expect strong interaction between ion beams and background electrons. In the plasma density calculation, we presume that plasma density has only ion beam changed by the ion beam distributions, which is 10% of background plasma ions, since ion temperature of the beam is cold.

To compensate the supersonic ion beam effect on the TP, Eq. (5) should be corrected from the simple assumptions. The beam currents collected by the probe tip 1 and tip 2 are expected almost the same, that is, $J_b(V_1) \approx J_b(V_2)$, because there is no big difference between probe voltage as $0.693T_e$ and generally $T_e \leq 10eV$ in the low temperature plasmas. While the beam currents collected by the probe tip 1 and tip 3 are expected a bit different due to the applied voltage difference, $V_{13} = 200V$. From these facts, Eq. (5) can be written as

$$\frac{I}{2I + (J_b(V_1) - J_b(V_3))S_x} = 1 - exp(-eV_{12}/kT_e), \tag{6}$$



a) b)

Fig. 5 Electron Temperatures: a) from the conventional TP theory and b) from a new theory with compensation of supersonic ion beams.

and the difference of the beam currents collected by probe tip 1 and tip 3 are easily taken by subtracting the plasma current measured without the beam. The corrected electron temperature with the compensation of beam current is shown in Fig. 5 b). The electron temperatures at the region far from the ion beam have almost the same values before and after the compensation, while the variations of electron temperature in region of beam passage after compensation of ion beam effect is smaller than the case of conventional TP theory. This analysis is more suitable for the experimental conditions of small ν_{ie} and isothermal property of electron, although the tendency with different energies of ion beams is to be investigated later.

4 Conclusion

Plasma parameters such as electron temperature and density are measured with triple probe in the lower hybrid frequency RF plasma sources with and without supersonic ion beams. Abnormal behavior of electron temperature is corrected by introducing a new and simple theory of TP for improvement of current analysis. For compensation of the effect of ion beams on triple probe measurement, especially on the electron temperature, a new theory is developed with simple assumptions of $J_b(V_1) \approx J_b(V_2)$ and $J_b(V_1) \neq J_b(V_3)$. The compensated electron temperature is more reliable for this experimental conditions. However, one needs the detailed experiment for ion and electron energy distribution from I-V characteristics of single probe or gridded energy analyzer. Also, the present simple theory should be refined for the case of $J_b(V_1) \neq J_b(V_2)$.

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