Probing of Toroidal Electron Plasmas Confined on Helical Magnetic Surfaces

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With a skillful probing system, both large negative space potential ϕ_s and low electron current I_p of helical nonneutral plasmas have been measured. For the ϕ_s measurement, a differential circuit with a high-voltage probe is employed. In order to prevent the signal from delaying due to the large output impedance of the high-voltage probe, an operational amplifier is used to reduce the output impedance to ideally zero. For the I_p measurement, an instrumentation amplifier is employed to precisely cancel the common-mode noise. In addition, to alleviate the thermal noise due to the large feedback resistance in the circuit, a trick of T-network resistance is utilized instead of the single large resistance. Furthermore, to cancel the significant ground loop current, the reference potential of the circuit is grounded across a small resistance (100 Ω).

Keywords: helical nonneutral plasma, magnetic surface confinement, high-impedance emissive probe, large negative space potential, electrostatic probing system

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1. Introduction

Since 1923, the electrostatic (or Langmuir) probe has been intensively used for measuring probe current I_p and space potential ϕ_s [1]. The probe has played an important role for studies on basic plasma science [2] and even for plasmas confined in the peripheral layer of fusion plasmas [3]. Various types of the probe have been developed. Those are mainly categorized as to the number of the probe electrode. However, the method that determines plasma parameters from the current-voltage (*I*-*V*) characteristic is fundamentally the same for all types of the probe [4]. Also, electric circuits for the probes is basically the same, because the plasma parameters (such as ϕ_s) themselves never change, regardless of any types of the probe.

However, when the electrostatic probe is employed to toroidal nonneutral plasmas confined on magnetic surfaces [5], the conventional electric circuit can be no longer applied to measure the *I*-*V* characteristic of the plasma. This is because the characteristic is completely different from that of neutral plasmas. Figure 1 shows a schematic drawing that is compared the typical shape of the *I*-*V* characteristic of a conventional neutral plasma with that of a nonneutral (pure electron) plasma. Generally, the value of ϕ_s of neutral plasmas is at most in the range between ±100 V due to the quasi-neutral condition. On the other hand, in nonneutral plasmas, ϕ_s can reach −1 kV or even more negative, which actually depends on the initial energy of injected electrons and confinement properties of nonneutral plasmas [6]. Obviously, this value of ϕ_s is much

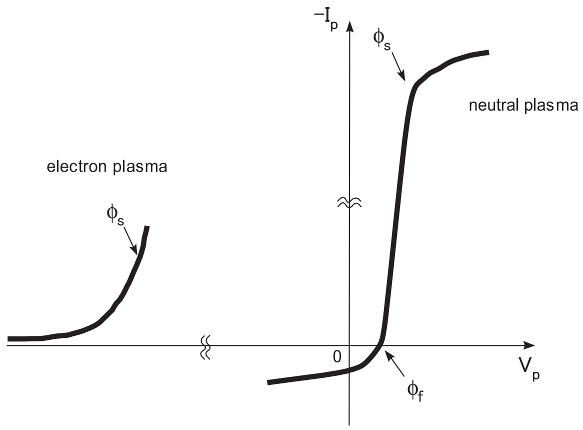

Fig. 1 A schematic drawing of the *I*-*V* characteristics obtained from a single probe. The drawing explains the difference in the characteristics between nonneutral plasmas and neutral plasmas.

(negative) larger than that of neutral plasmas, which calls for a skillful technique to measure such a large ϕ_s. The other thing which should be taken into account is that I_p collected in nonneutral plasmas is usually ∼ 1-700 μA [5], because of low n_e (∼10^{11-13} m^{-3}). This value of I_p is much less than the typical value ofI_p collected in peripheral layer of fusion plasmas having n_e ∼ 10^{19} m^{-3}. In fact, I_p of helical nonneutral plasmas have exhibited no electron saturation current [7]. This is due to the long electron Debye length λ_D of nonneutral plasmas, which is comparable to the plasma characteristic length. As a result, the *I*-

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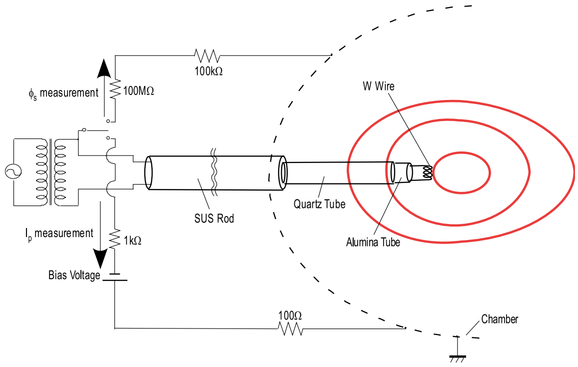

Fig. 2 A schematic drawing of the probing system.

V characteristic is governed by an orbital motion limited current [8]. In addition, since the nonneutral plasma possess strong **E**, the corresponding fast $\mathbf{E} \times \mathbf{B}$ flow is inherently generated in magnetic surfaces. This causes the I-V characteristic spread more, showing non-Maxwellian distribution as well as those observed in space plasmas [9]. Thus, the electric circuit has to be precisely measured such a small I_p.

The above unique properties require modifications for the probing system. In this paper, the modified probing system that is, for the first time, applied to helical nonneutral plasmas having low n_e with large negative ϕ_s is described. The detail of the system is explained in Sec. 2. In Sec. 3, typical results of both ϕ_s and I_p measured with the probing system are shown. Finally, a summary is given in Sec. 4.

2. Probing System

Regarding the production of nonneutral plasmas on the Compact Helical System (CHS) device, thermal electrons are injected from a typical diode-type electron gun [10] which is used a LaB_6 emitter as the cathode. Although the electron gun is usually placed outside the last closed flux surface (LCFS), the injected electrons propagate across magnetic surfaces and form helical nonneutral plasmas. The detail of this process is explained in Ref [11].

The probing system applied to CHS nonneutral experiments is shown in Fig. 2. The probe used here is one of emissive probes [12, 13], which is used for both the ϕ_s and I_p measurements with changing the resistance of the electric circuit. In other words, the probe acts as not only a floating emissive probe to determine ϕ_s but also a single probe to measure a local value of I_p of the helical nonneutral plasma when the probe bias voltage V_p is set to ϕ_s ($V_p = \phi_s$). The double or triple probes cannot be adopted to the helical nonneutral plasma; because the value of T_e is small, the plasma exhibits non-Maxwellian distribution due to flowing, and there is ideally no floating potential ϕ_f for the nonneutral plasma. Thus, those methods provide less accurate values, especially for T_e measurements. The structure of the single probe used here is as follows. The probe tip consists of a filament where a ϕ0.1 thoriated-tungsten (1%Th-W) wire is wound about 10 times. The size of the filament is 1×3 mm. The filament is connected to the resistance with a copper wire which is covered with an alumina tube of 620 mm in length. And moreover, these whole things are contained with a quartz tube of 610 mm in length in order to isolate both the filament and the copper wire against the grounded metal shaft (made of SUS304). The outer diameter of the quartz tube is ϕ7. As seen in Fig. 2, the reference potential of the probing system is grounded across a small resistance (100 Ω). The reason why the resistance is used is that the probing circuit suffered from substantial noise due to the ground loop on CHS. To alleviate the noise, the small resistance is installed in the probing circuit. As an inevitable result, there exists an additional voltage generated across the resistance. However, the corresponding voltage is about several volts, which is negligible small compared with ϕ_s of helical nonneutral plasmas; typically, the maximum value of ϕ_s is about -1 kV in the CHS nonneutral experiments. Thus, we have used this method to alleviate the ground loop on experiments.

2.1 Method of measuring I_p

One of most difficult points in the I_p measurement significantly emerges for the case where ϕ_s of a plasma is very large: $\phi_s \sim -1$ kV in the CHS nonneutral experiments [5, 7, 11]. This is because V_p must be larger than ϕ_s, otherwise the I-V characteristic cannot be measured. In this case, V_p easily exceeds much the absolute maximum rating (AMR) of the differential voltage of a single-ended operational amplifier (OP amp) if it is employed at the first section of the probing circuit. Thus, ϕ_s must be divided under the AMR of the OP amp employed. Since the AMR is usually several tens of volts, it is thus necessary to divide ϕ_s into $\sim \phi_s/1000$ for CHS nonneutral experiments. The other point which should be resolved is that the value of I_p is relatively small. In fact, in CHS nonneutral experiments, I_p is the order of $\sim$ 1-100 μA. This value of I_p is then transformed to an output voltage across a small shunt resistance; a 1 kΩ resistor is usually used in CHS nonneutral experiments. In order to meet these points, we have built the following circuit using a differential amplifier.

Figure 3 shows the schematic diagram of the first stage of the electric circuit for the I_p measurement. Notations used in Fig. 3 (for examples, e_1 and R) follow the common practice in electronics. Using the rules for working out the behavior of OP amp with external feedback, the input voltages at the inverting terminal (e_-) and the noninverting one (e_+) are given as

$$\left.\begin{aligned} e_- &= \left(\frac{e_1 - e_-}{R} + \frac{e_0 - e_-}{R}\right) R_1 \\ e_+ &= \frac{e_2}{R + R_1} \end{aligned}\right. , \qquad (1)$$

along with the output voltage e_0, that is

$$
\begin{aligned}
e_+ &= e_- = \frac{R_1/R}{1+R_1/R} \\
e_0 &= \frac{R_2/R_1 + 2R_2/R}{1+R_2/R} e_2 - e_1
\end{aligned} \quad . \tag{2}
$$

Thus, if we set $R_1 = R_2$ and $R_2/R = 1/1000$, values of e_-, e_+ and e_0 are thus approximated as

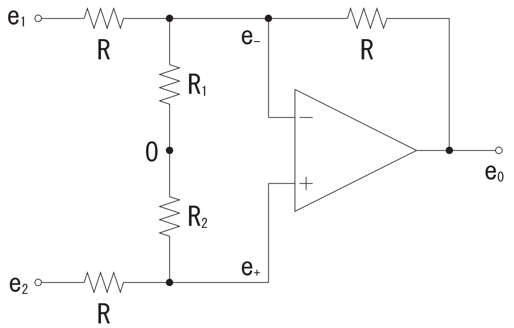

Fig. 3 A drawing of the differential amplifier applied to the circuit for the I_p measurement.

$$
\begin{aligned}
e_+ &= e_- \cong \frac{1}{1000} e_2 \\
e_0 &\cong e_2 - e_1
\end{aligned} \quad . \tag{3}
$$

For the I_p measurement, two different circuits are provided. One employs a differential circuit using a precision OP amp (MAX437) as shown in Fig. 4 (a). The other is also categorized as one of differential circuits but it uses an instrumentation amp (INA111) to alleviate electric noise due to the probing circuit, although the circuit diagram of it is not described in this contributed paper.

As indicated in Fig. 4 (a), the differential circuit utilizes three small resistors in the external feedback. Values of the resistors are less than 47 kΩ in this circuit. However, they (henceforth, called T-network) can equivalently produce a large value as the feedback resistor in the feedback network [14]. In this case, the T-network behaves like a single 100 MΩ resistor in the standard inverting amplifier circuit giving a voltage gain of about 170. Obviously, the most advantage using the T-network is to reduce the

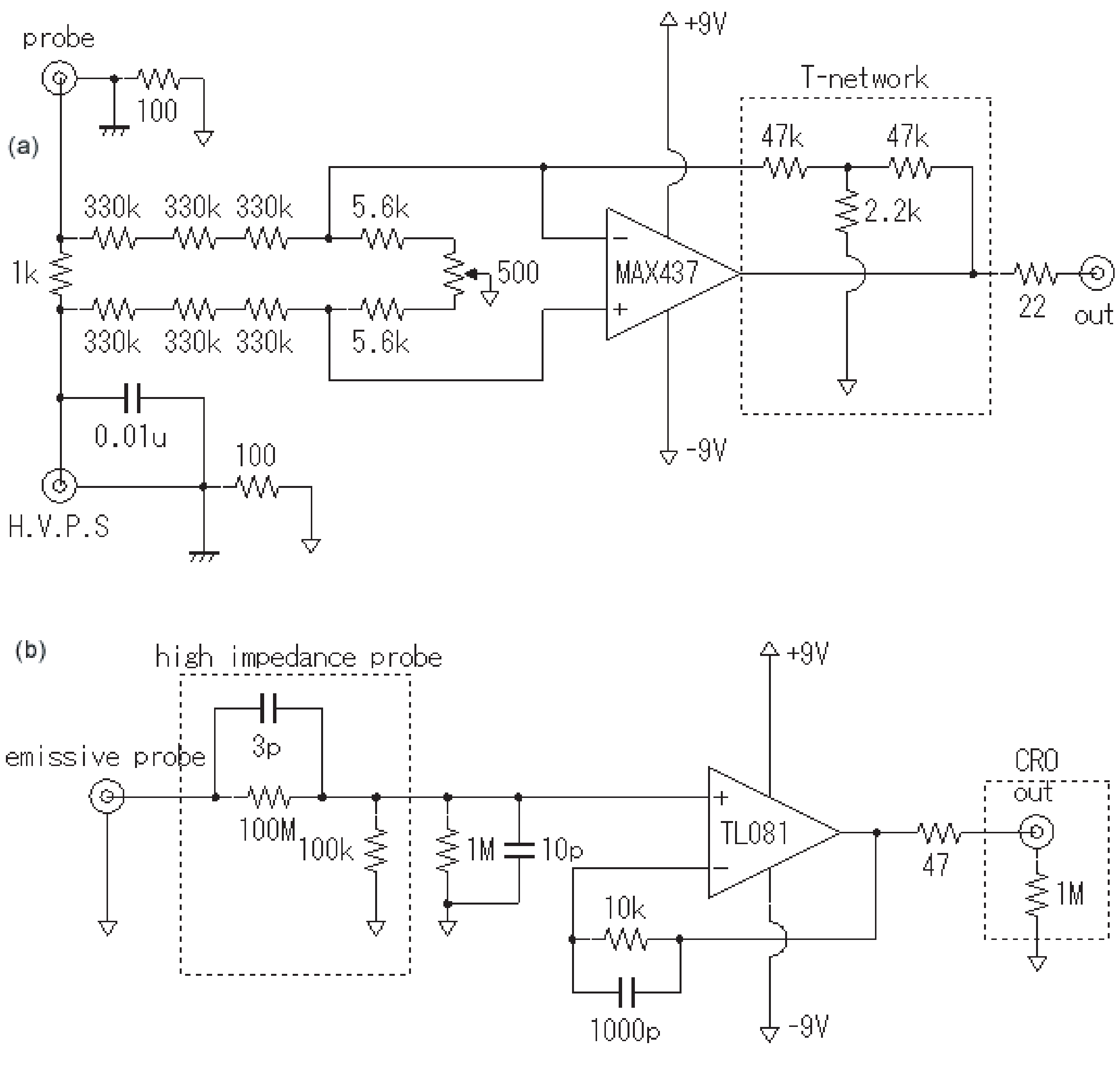

Fig. 4 The circuit diagrams of (a) for the I_p measurement and (b) for the ϕ_s measurement.

effects of thermal noise, which brings in better S/N ratio. Also, the T-network involves little stray capacitance because of small resistor values. Regarding the circuit using the instrumentation amp, on the other hand, the major advantage has been to achieve high common-mode rejection ratios, which enables e_0 (typically, the order of μV) to be precisely amplified. Details of this circuit will be reported elsewhere.

Using the circuit shown in Fig. 4 (a), I_p with its frequency up to ~40 kHz can be measured. In the circuit, a trimmer (500 Ω) is installed between the two input terminals in order to accurately adjust the value of the differential input resistance without using a single precise resistor.

2.2 Method of measuring ϕ_s

For the ϕ_s measurement, a high-impedance emissive method [15] has been applied. Since ϕ_s is negatively large, a high-voltage probe (Tektronix P6015 A) is used. Since the probe has a large resistance to measure large input voltage, thus it causes the probe signal to be transmitted with slow speed due to the large time constant (= RC). To avoid this problem, a noninverting amp is applied, which converts the large resistance to ideally 47 Ω, sufficiently small. The electric circuit of the impedance converter is shown in Fig. 4 (b). Using also the rules for noninverting amp, the gain of the circuit can be written as

$$\frac{V_{out}}{V_{in}} = 1 + \frac{R_2}{R_1}. \tag{4}$$

Therefore, if the R_1 is open, the gain becomes unity, working as a buffer.

3. Typical Results of $I_p(t)$ and $\phi_s(t)$ Using the Developed Circuits

Figure 5 shows typical results of the (a) $\phi_s(t)$ measurement and (b) $I_p(t)$ measurement where $V_p = \phi_s$. These data are measured at $r = 114$ cm in the 5O horizontal cross-section of CHS [16]. In this shot, the acceleration voltage V_{acc} of electrons is about −1 kV and the measured ϕ_s is about −700 V. Despite such large values of both V_{acc} and ϕ_s, data are clearly measured with the circuit system shown in Fig. 4 (b). The fluctuation seen in the measured $\phi_s(t)$ reflects a disruptive instability of helical nonneutral plasmas on CHS. The detail of this event is explained in a companion paper [6]. Meanwhile, regarding the measured $I_p(t)$, as shown in Fig. 5 (b), the data is measured with $V_p \sim -700$ V, which is large negative potential against the ground. And, the average value of the measured $I_p(t)$ is about 36 µA, which is hardly large in conventional probe measurements. Nevertheless, $I_p(t)$ is successfully measured with the probing circuit described in Fig. 4 (a).

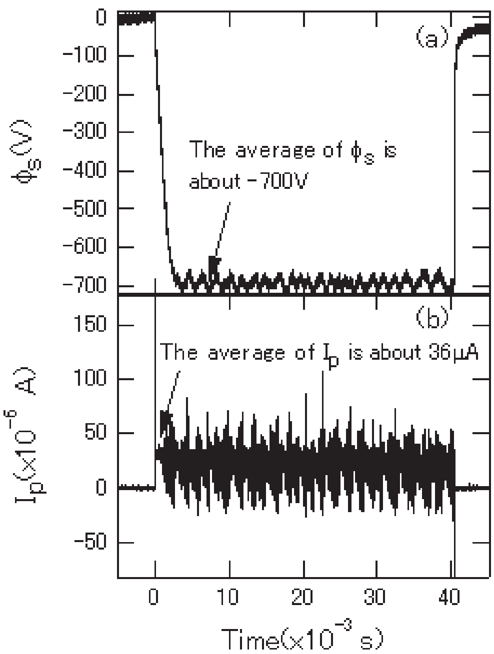

Fig. 5 Typical data of (a) $\phi_s(t)$ and (b) $I_p(t)$ measured with the developed circuits.

4. Summary

Nonneutral plasmas confined on magnetic surfaces have been studied on the CHS machine. The key parameters which determine properties of the plasmas are large negative space potential ϕ_s and small probe current I_p (consequently, small electron density n_e). In order to measure both ϕ_s and I_p with probing, we develop a new probing system using skillful circuit techniques. The measured data with the circuits demonstrate successful measurements of both ϕ_s and I_p in CHS nonneutral experiments.

[1] I. Langmuir, Gen. Elec. Rev. **27**, 449 (1924).
[2] O. Auciello and D.L. Flamm, *Plasma Diagnostics* (Academic Press, Inc., 1989) p.116.
[3] M. Takeuchi *et al.*, Plasma and Fusion Research: Rapid Communications **1**, 027 (2006).
[4] Sin-Li Chen and J.M. Goodings, J. Chem. Phys. **50**, 4335 (1969).
[5] H. Himura *et al.*, Phys. Plasmas **11**, 492 (2004).
[6] H. Himura *et al.*, in this conference proceedings. (2007).
[7] H. Himura *et al.*, Phys. Plasmas **8**, 4651 (2001).
[8] H.M. Mott-Smith and I. Langmuir, Phys. Rev. **28**, 727 (1926).
[9] Robert F. Pfaff *et al.*, *Measurement Techniques in Space Plasmas* (American Geophysical Union, Washington, DC) p.25.
[10] John H. Moore *et al.*, *Building Scientific Apparatus* (Addison-Wesley Publishing Company, 1983) p.302.
[11] H. Himura *et al.*, IEEE Transaction on Plasma Science **32**, 510 (2004).
[12] R.F. Kemp and J.M. Sellen Jr., Rev. Sci. Instrum. **37**, 455 (1966).
[13] J.J. Schuss and R.R. Parker, J. Appl. Phys. **45**, 4778 (1974).
[14] P. Horowitz and W. Hill, *The Art of Electronics* (Cambridge University Press, 1989) p.223.
[15] H. Himura *et al.*, Rev. Sci. Instrum. **74**, 4658 (2003).
[16] H. Himura *et al.*, Phys.Plasmas **14**, 022507 (2007).