Probing of Toroidal Electron Plasmas Confined on Helical Magnetic Surfaces

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With a skillful probing system, both large negative space potential \(\phi_s\) and low electron current \(I_p\) of helical nonneutral plasmas have been measured. For the \(\phi_s\) 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\(\Omega\)).

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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 \(\phi_s\) [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 \(\phi_s\)) 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 \(\phi_s\) of neutral plasmas is at most in the range between \(\pm 100\) V due to the quasi-neutral condition. On the other hand, in nonneutral plasmas, \(\phi_s\) 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 \(\phi_s\) is much

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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.
V characteristic is governed by an orbital motion limited current [8]. In addition, since the nonneutral plasma possess strong $E$, the corresponding fast $E \times B$ 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 has low $n_e$ with large negative $\phi_e$ is described. The detail of the system is explained in Sec. 2. In Sec. 3, typical results of both $\phi_e$ 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 LaB6 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 diagnostics, which is used for both 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 $\phi_e$ 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 $\phi_e$ 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 $\phi_e$ ($V_p = \phi_e$). 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 $\phi_f$ 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 $\phi$0.1 thoriated-tungsten (1%Th-W) wire is wound about 10 times. The size of the filament is $1 \times 3$ 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 $\phi$7. As seen in Fig. 2, the reference potential of the probing system is grounded across a small resistance (100 $\Omega$). 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 $\phi_e$ of helical nonneutral plasmas; typically, the maximum value of $\phi_e$ 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 $\phi_e$ of a plasma is very large: $\phi_e \sim -1$ kV in the CHS nonneutral experiments [5, 7, 11]. This is because $V_p$ must be larger than $\phi_e$, 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, $\phi_e$ 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 $\phi_e$ into $\sim \phi_e/1000$ 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 $\mu$A. This value of $I_p$ is then transformed to an output voltage across a small shunt resistance; a 1 k$\Omega$ 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 $R_x$) 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

\[
e_+ = \frac{e_1 - e_-}{R} + \frac{e_0 - e_-}{R_1} R_1,
\]

along with the output voltage $e_0$, that is
\[ e_+ = e_- = \frac{R_1/R}{1 + R_1/R} \]  
\[ e_0 = \frac{R_2/R_1 + 2R_2/R}{1 + R_2/R} \approx e_2 - e_1 \]  
\[ e_0 \approx e_2 - e_1 \]  
\[ e_+ = e_- \approx \frac{1}{1000} e_2 \]  
\[ e_0 \approx e_2 - e_1 \]  

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

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
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 \( \mu \text{V} \)) 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 \( \sim 40 \text{kHz} \) can be measured. In the circuit, a trimmer (500 \( \Omega \)) 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 \( \phi_s \)

For the \( \phi_s \) measurement, a high-impedance emissive method [15] has been applied. Since \( \phi_s \) 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 about 47 \( \Omega \), 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

\[
\frac{V_{\text{out}}}{V_{\text{in}}} = 1 + \frac{R_2}{R_1}
\]

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 \( r = 114 \text{cm} \) in the 5O horizontal cross-section of CHS [16]. In this shot, the acceleration voltage \( V_{\text{acc}} \) of electrons is about \(-1 \text{kV}\) and the measured \( \phi_s \) is about \(-700 \text{V}\). Despite such large values of both \( V_{\text{acc}} \) and \( \phi_s \), 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 \( V_p \sim -700 \text{V} \), which is large negative potential against the ground. And, the average value of the measured \( I_p(t) \) is about 36 \( \mu \text{A} \), which is hardly large in conventional probe measurements. Nevertheless, \( I_p(t) \) is successfully measured with the probing circuit described in Fig. 4 (a).

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 \( \phi_s \) and small probe current \( I_p \) (consequently, small electron density \( n_e \)). In order to measure both \( \phi_s \) 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 \( \phi_s \) and \( I_p \) in CHS nonneutral experiments.