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Asymmetric Double Langmuir Probe for Fast and Automatic Measurements of Plasma Temperature

Taner Uckan

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ASYMMETRIC DOUBLE LANGMUIR PROBE FOR FAST AND AUTOMATIC MEASUREMENTS OF PLASMA TEMPERATURE

Taner Uckan

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ABSTRACT

We present a fast technique for determining the plasma electron temperature T_e automatically from the small signal application of the asymmetric double Langmuir probe when it is operated in the region where $-1 < eV_a/T_e < 1$. The method described here is based on simple time and rms averages of the probe current that results from a sinusoidally varying applied voltage V_a.

I. INTRODUCTION

As discussed in Ref. 1, the asymmetric double Langmuir probe (ADLP) can be used to measure plasma electron temperature T_e and density n when it is operated in the region of small signal response. The area of one of the ADLP collectors is considerably larger than the other. In this probe application, the applied voltage is relatively low, $eV_a/T_e < 1$, since there is no need for direct measurement of the ion saturation current in order to unfold the plasma T_e and n. As a result, the requirements on the probe power supply are considerably eased.[1]

In this work, we present a fast technique for automatically determining the plasma T_e from the small signal application of the ADLP when it is operated in the region where $-1 < eV_a/T_e < 1$. The method is based on simple time and rms averages of the probe current that results from a sinusoidally varying applied voltage V_a. We then present an application of the method, followed by a brief discussion of its implementation.

II. PRINCIPLE OF THE METHOD

The basic parameters of the ADLP and its operation are not revisited here, since they are widely available in the literature.[1,2] Therefore, we start our discussions on the principle of this probe method by recalling[1] the current-voltage (I, V_a) characteristic of an ADLP in which the ratio of collector areas $A_1/A_2 \ll 1$:

$$I = I_+[1 - \exp(eV_a/T_e)] \quad , \tag{1}$$

where I_+ is the ion saturation current, given by

$$I_+ = 0.5enA_1[(T_e + T_i)/m_i]^{0.5} \quad . \tag{2}$$

Here A_1 and A_2 are the areas of the small and the large collectors, respectively; e is the electronic charge; and T_i and m_i are the ion temperature and ion mass, respectively. We should note that Eq. (1) differs significantly from the functional form of a single-ended Langmuir probe.[3] For example, this equation carries no information about the plasma space potential or about the electron saturation current. If we apply a sinusoidal voltage $V_a(t) = V \sin \omega t$, where V is the amplitude and $f = \omega/2\pi$

is the frequency of the signal, to the ADLP, then the corresponding probe current is

$$I(t) = I_+[1 - \exp(\alpha \sin \omega t)] \tag{3}$$

with $\alpha \equiv eV/T_e$. We now calculate the simple time and rms averages of this current:

$$I(\mathrm{dc}) \equiv (1/\tau) \int_0^\tau dt\ I(t) = I_+[1 - I_0(\alpha)] \quad , \tag{4}$$

$$I^2(\mathrm{rms}) \equiv (1/\tau) \int_0^\tau dt\ I^2(t) = I_+^2[1 - 2I_0(\alpha) + I_0(2\alpha)] \quad , \tag{5}$$

where $\tau = 1/f$ and I_0 is the zero-order modified Bessel function.

The ratio of these currents is

$$\begin{aligned} R &\equiv |I(\mathrm{rms})/I(\mathrm{dc})| \\ &= \{[1 - 2I_0(\alpha) + I_0(2\alpha)]/[1 - 2I_0(\alpha) + I_0^2(\alpha)]\}^{0.5} \quad . \end{aligned} \tag{6}$$

In Fig. 1, $R(\alpha)$ is displayed for $0 < \alpha \leq 1$. We observe, that if R is measured from the experiment of interest, the plasma T_e can readily be obtained from the figure. Then for $T_i \approx T_e$, the plasma density follows directly from Eqs. (2) and (4) with the value of $I(\mathrm{dc})$.

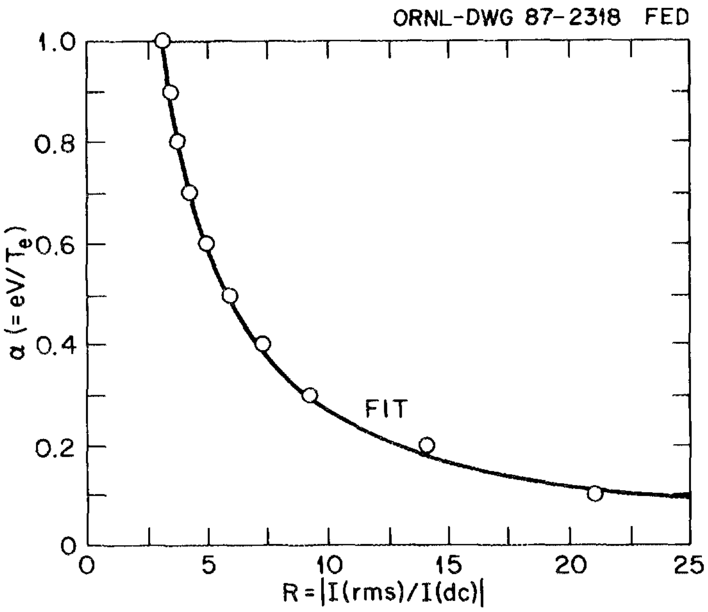

Fig. 1. Plots of $R \equiv |I(\mathrm{rms})/I(\mathrm{dc})|$, Eq. (6), and its fit $\alpha = 3.998R^{-1.1724}$ for $0 < \alpha\ (= eV/T_e) \leq 1$.

III. APPLICATION

As a demonstration of this technique, we carried out an experiment on a test plasma with the ADLP, as described in Ref. 1. The amplitude of the applied signal used was 5 V with a period of $\tau = 10$ ms. The measured asymmetry in the probe current was $|I(t = \tau/4)/I(t = 3\tau/4)| = 2$. In fact, this characteristic current asymmetry was used in determining the electron temperature of the test plasma in previous work[1] in which $T_e \approx 7.2$ eV was found, corresponding to $\alpha = eV/T_e = 0.69$. For these parameters, in Fig. 2(a), we show $V_a(t)$ and the resulting probe current $I(t)/I_+$, which is given by Eq. (3). We also display $I(t)$ measured from the experiment in Fig. 2(b). Comparison of the results shown in these figures indicates that the model of the probe current, Eq. (3), predicts the behavior of the ADLP very well.

The need for independent calculations of I(dc) and I(rms) can be met numerically simply by taking small time intervals $\Delta t = \tau/N$ in their integral functional forms, Eqs. (4) and (5), and then performing the resulting summations:

$$I(\mathrm{dc}) \approx (1/N) \sum_j I(t_j) \quad , \tag{7}$$

$$I^2(\mathrm{rms}) \approx (1/N) \sum_j I^2(t_j) \quad , \tag{8}$$

where $t_j = j\Delta t$ and $j = 1, \ldots, N$. Choosing $N = 20$ as an example, we obtain $I(\mathrm{dc})/I_+ = -0.1243$ and $I(\mathrm{rms})/I_+ = 0.543$. The absolute value of the current ratio is $R = 4.3685$. For this R value, using Fig. 1, we find $\alpha = 0.685$, which differs by about 0.8% from the value we started with. Knowing the amplitude of the applied voltage, we find that the plasma temperature is simply $T_e/e = V/\alpha$.

For convenience, the curve in Fig. 1 may be approximated by fitting a function to it. We find, for example, that

$$\alpha \approx 3.998 R^{-1.1724} \quad , \tag{9}$$

which is also displayed in Fig. 1, gives a good fit to Eq. (6). If we use the previous R value in Eq. (9), we find $a \approx 0.7$, with an error of about 1.5%.

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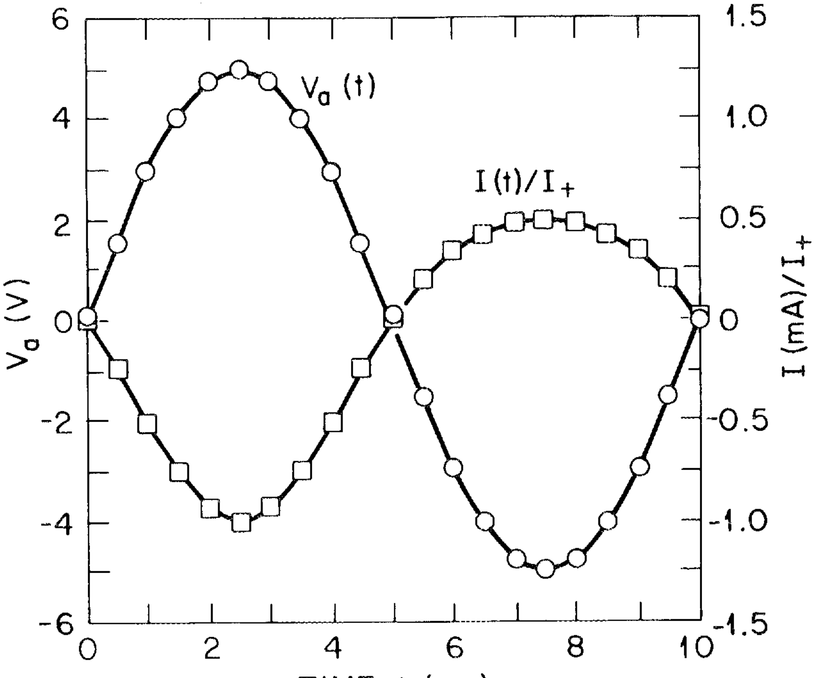
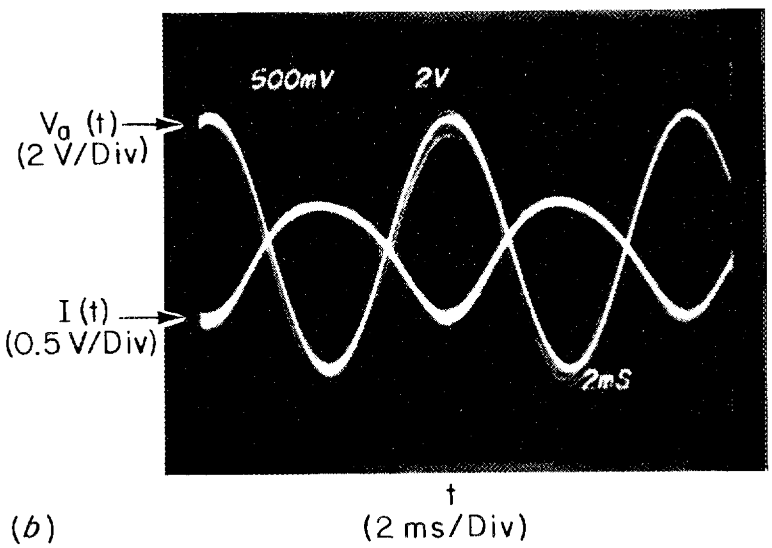


(*a*)



(*b*)

Fig. 2. (a) Typical current response of the ADLP, $I(t)/I_+$, resulting from an applied voltage $V_a(t) = V\sin(2\pi t/\tau)$, where, for this example, $V = 5$ V and $\tau = 10$ ms. (b) Probe current $I(t)$ voltage drop measured over a 400-Ω resistor during a test plasma experiment when this $V_a(t)$ is applied to the ADLP, as described in Ref. 1.

IV. DISCUSSION

Let us assume that the (I, V_a) characteristic of the ADLP can be obtained with the help of a fast computer data acquisition system. In this case, the routine time-averaging operations defined by Eqs. (4) and (5) can be performed very rapidly and efficiently. Thus, the ratio R that we need is found relatively quickly. Furthermore, including Eq. (9) in this process makes the temperature measurements very simple and relatively quicker than the usual probe applications.

The technique is applicable without computer-oriented calculations as long as I(dc) and I(rms) are obtained by some means. For example, this may be a set of commercially available analog devices[4] that do not require computer-asssisted computation but nevertheless provide the needed information directly and relatively quickly. We believe that the flexibility of this method makes its application a simple and efficient one. Our plan is to implement the technique with analog devices.

The frequency of the probe applied voltage should be determined so that the circuit and the probe stray capacities will have a minimal effect on and contribution to the measured current. We also note that, if analog devices are used, the ADLP operating frequency will be affected by their performance characteristics.

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[4]For example, information on analog signal-processing components is available in the *Data Acquisition Databook* (Analog Devices, Inc., Norwood, Mass., 1984).

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