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Asymmetric Double Langmuir Probe: Small Signal Application

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FOR THE UNITED STATES
DEPARTMENT OF ENERGY

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5285 Port Royal Road, Springfield, Virginia 22161
NTIS price codes—Printed Copy: A02 Microfiche A01

ORNL/TM-10391
Dist. Category UC-20 a,d,f

Fusion Energy Division

ASYMMETRIC DOUBLE LANGMUIR PROBE: SMALL SIGNAL APPLICATION

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Date published: November 1987

Prepared by the
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Oak Ridge, Tennessee 37831
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ACKNOWLEDGMENTS

The author gratefully acknowledges valuable discussions with N. A. Uckan and the help of T. Rayburn during the fabrication of the probe. The continuous support and encouragement of P. K. Mioduszewski are also appreciated.

ABSTRACT

We discuss the asymmetric double Langmuir probe (ADLP) and demonstrate the possibility of using it to measure plasma 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. This probe can be operated at a relatively low applied voltage, $eV_a/T_e < 1$, and still provides sufficient information to determine the plasma T_e and n. There is no need for a direct measurement of the ion saturation current, which can be on the order of a few amperes in large fusion devices. This reduces the requirements on the probe power supply.

I. INTRODUCTION

Knowledge of the plasma edge properties in fusion devices is important for understanding of the overall confinement and the plasma-wall interactions.[1] The basic edge plasma parameters are the density, n, and the temperature of the electrons, T_e, and the ions, T_i. Typical measured edge plasma parameters in existing tokamak fusion devices such as the Tokamak Fusion Test Reactor (TFTR)[2] and the Joint European Torus (JET)[3] are $T_e \simeq 100$ eV and $n \simeq (1\text{–}5) \times 10^{18}$ m^{-3}.

Langmuir probes are a widely accepted diagnostic for measuring T_e and n. The most common probe type is the floating double Langmuir probe, which has two collectors with equal areas and draws no current from the plasma. As we discuss later, this type of probe needs an applied voltage of $V_a < -2T_e/e = -200$ V in order to measure the ion saturation current, which is needed for estimating the plasma temperature and density and is typically 5 A/cm^2.

Temperatures and densities in the edge plasmas of future large tokamak devices will be higher because of large amounts of plasma auxiliary heating power. For example, in the case of the Tore Supra tokamak,[4] the estimated edge parameters are $T_e \simeq 200\text{–}300$ eV and $n \simeq (1\text{–}10) \times 10^{18}$ m^{-3}. Consequently, typical Langmuir probes with a probe collector area $A = 1$ cm^2 would require power supplies that could provide high voltage ($V_a > 200$ V) and high power ($P_a > 1$ kW) in order to carry out the measurements.

In this work, we present a means of reducing this probe power supply requirement by using the asymmetric double Langmuir probe (ADLP), in which the area of one collector is considerably larger than the other. This probe can be operated at a relatively low applied voltage, $eV_a/T_e < 1$, and still provides sufficient information to determine the temperature and the density from the measurements. With the use of this ADLP, the need for direct measurement of the ion saturation current, which can be on the order of a few amperes in large fusion devices, is avoided. As a result, the requirements on the probe power supply are considerably eased.

In Sec. II, we briefly review the basic parameters of the ADLP and its operation. The small signal application of this probe is discussed in Sec. III. The ADLP has been used in its small signal region on a test plasma, and the results are presented in Sec. IV. Finally, in Sec. V, the probe applications are briefly discussed.

II. ASYMMETRIC DOUBLE LANGMUIR PROBE

Let us consider two collectors with different areas, $A_1 \ll A_2$, that are inserted into the plasma as shown in Fig. 1. The applied voltage difference between the collectors, $V_a = V_2 - V_1$, allows an external current flow I. Here V_1 and V_2 are the collector voltages relative to the plasma space potential. The components of this current in terms of ion current I_+ and electron current I_e for collectors 1 and 2 are given by

$$I_{c1} = I_{e1} + I_{+1} \ , \tag{1}$$

$$I_{c2} = I_{e2} + I_{+2} \ . \tag{2}$$

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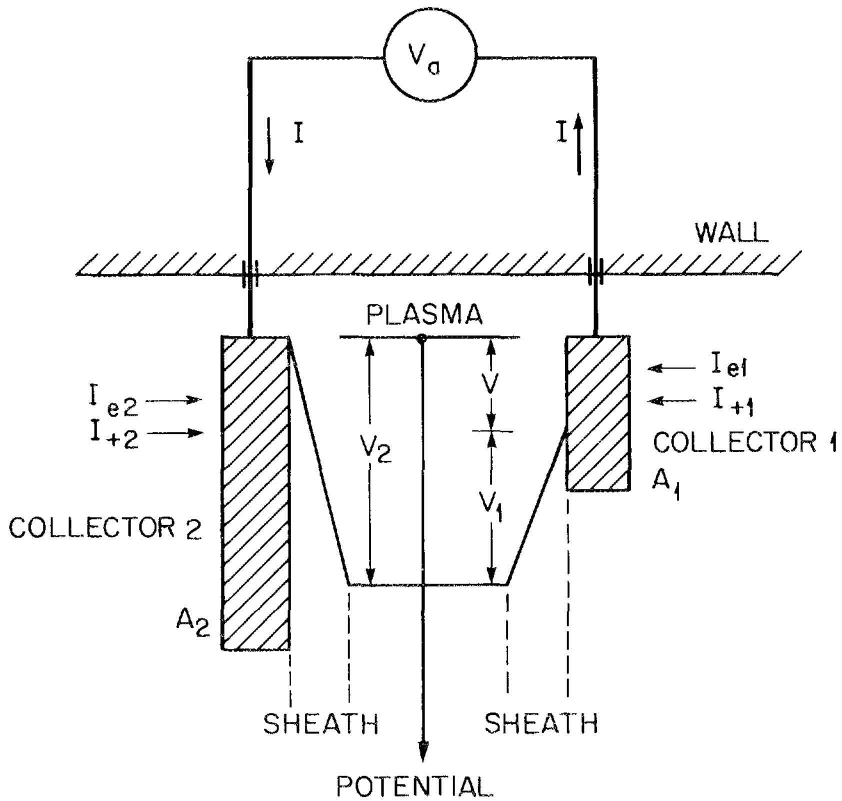

Fig. 1. Typical asymmetric double Langmuir probe (ADLP) with collector areas of $A_1 \ll A_2$. Here V_1 and V_2 are the potentials between the sheaths and collectors 1 and 2, respectively. The applied voltage $V_a = V_2 - V_1$ across the collectors allows an external current flow I.

Because of the floating probe system, we also have

$$I_{c2} = -I_{c1} = -I \ . \tag{3}$$

We combine Eqs. (1)–(3) and express the probe external current as

$$I = I_{+1}[(I_{e2}/I_{e1}) - (I_{+2}/I_{+1})]/[1 + (I_{e2}/I_{e1})] \ . \tag{4}$$

Here the explicit forms of the electron and the ion saturation currents are given by[5]

$$I_{e1} = -en_1 c_e A_1 \exp(-eV_1/T_e) \ , \tag{5}$$

$$I_{e2} = -en_2 c_e A_2 \exp(-eV_2/T_e) \ , \tag{6}$$

$$I_{+1} = 0.5enc_s A_1 \ , \tag{7}$$

$$I_{+2} = 0.5enc_s A_2 \ , \tag{8}$$

where e is the electronic charge, n_1 and n_2 are the densities in the vicinity of collectors 1 and 2, and c_e and c_s are the electron average thermal speed and the ion sound speed, respectively.

Using Eqs. (5)–(8) in Eq. (4), we find the (I, V_a) characteristic of the ADLP,

$$I = I_{+1}[(n_2/n_1)\exp(-eV_a/T_e) - 1]/[A_1/A_2 + (n_2/n_1)\exp(-eV_a/T_e)], \tag{9}$$

which reduces to

$$I = I_{+1}[1 - (n_1/n_2)\exp(eV_a/T_e)] \tag{10}$$

for $A_1/A_2 \simeq 0$. Here the ion saturation current of collector 1 is

$$I_{+1} = 0.5enA_1[(T_e + T_i)/m_i]^{0.5} \ , \tag{11}$$

where m_i is the ion mass.

The ADLP can be used conventionally to estimate the unperturbed plasma density n and the temperature T_e in the usual fashion by measuring the probe current I as a function of probe applied voltage V_a and assuming $n_1/n_2 = 1$ in Eq. (10). However, the need to measure the ion saturation current I_{+1} at $V_a \ll -T_e/e$ can be avoided if we use the (I, V_a) characteristic of the probe, as we discuss next, in the region where $-1 < eV_a/T_e < 1$. We identify this region as a small signal application of the ADLP.

III. SMALL SIGNAL APPLICATION

Let us study Eq. (10) for small values of the probe applied voltage, $V_a < T_e/e$. We first define the ADLP currents to be $I_1 \equiv I(V_a = V_{a1})$ and $I_2 \equiv I(V_a = V_{a2})$, where $V_{a2} = -V_{a1} = -V_a$, as illustrated in Fig. 2. We then take the ratio of these currents, after using Eq. (10), and write

$$\begin{aligned} R(\alpha) &\equiv I_2(-\alpha)/I_1(\alpha) \\ &= [1-(n_1/n_2)\exp(-\alpha)]/[1-(n_1/n_2)\exp(\alpha)] \ , \end{aligned} \tag{12}$$

with $\alpha \equiv eV_a/T_e > 0$. In the limit $n_1/n_2 = 1$, Eq. (12) further yields

$$R = -\exp(-\alpha) \ , \tag{13}$$

or, alternatively, the electron temperature becomes

$$T_e = eV_a/\ln|1/R| \ . \tag{14}$$

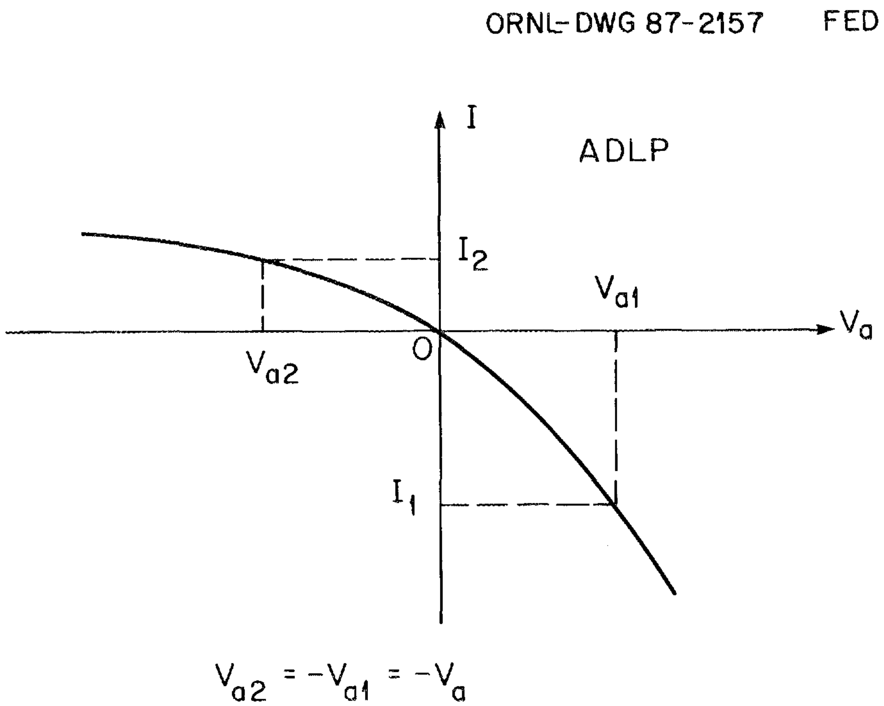

Fig. 2. Typical (I, V_a) characteristic of the ADLP. Also shown are $I_1 = I(V_{a1})$ and $I_2 = I(V_{a2})$ with $V_{a2} = -V_{a1}$.

For a small signal application, such as $eV_a/T_e = 0.5$, we have a probe current ratio $R = -0.6$. Therefore, this characteristic of the ADLP can be used to unfold the plasma parameters as follows. After measuring the current ratio R as a response to the small amplitude probe applied voltage, which can be a sinusoidal waveform, we estimate T_e and n from Eqs. (14) and (10), respectively.

We note here that, for an ADLP with a finite area ratio, it is easily shown from Eqs. (9) and (10), with $n_1/n_2 = 1$, that the electron temperature is given by

$$T_e = eV_a/\ln|[1 + (A_1/A_2)R]/[R + (A_1/A_2)]| ,$$

and this reduces to Eq. (14) when $A_1/A_2 = 0$.

IV. APPLICATION TO THE PMITF

We now apply the diagnostic method described in Sec. III to the Plasma-Materials Interactions Test Facility[6] (PMITF) to measure the plasma parameters. The PMITF is a single-cell mirror device that produces steady-state test plasmas with electron cyclotron resonance heating using a 2.45-GHz microwave source. A schematic of the ADLP head used in the experiment and its orientation with respect to the magnetic field are shown in Fig. 3. The probe collector areas are $A_1 \simeq 0.2\ \mathrm{cm}^2$ and $A_2/A_1 \simeq 127$. This probe system can also be employed as a single Langmuir probe (SLP) to cross-check the results obtained in the ADLP configuration. We first carry out the SLP measurements and get the usual (I, V_a) probe characteristics, as shown in Fig. 4. We then estimate the electron temperature to be $T_e \simeq 7.2$ eV from the (I_{e1}, V_a) plot displayed in Fig. 5. The plasma density is obtained in the usual fashion from the ion saturation current, Eq. (11), by taking $T_i = 0$, and we find $n \simeq 4 \times 10^{16}\ \mathrm{m}^{-3}$. We then switch to the ADLP configuration and again obtain the (I, V_a) probe characteristic. The result is displayed in Fig. 6. We observe that when $V_a = 0$ the probe current also becomes zero, $I = 0$. This indicates that the local densities around the collectors are the same, $n_1/n_2 = 1$, since Eq. (10) predicts that

$$I(V_a = 0) = I_{+1}(1 - n_1/n_2) . \tag{15}$$

Therefore, Eq. (14) is applicable to this test experiment. When the ADLP applied voltage V_a is varied from +5 V to −5 V, we measure the corresponding currents to be $I_1 = -1.6$ mA and $I_2 = 0.8$ mA, which yields $R = -0.5$. Hence, from Eq. (14), we then readily find $eV_a/T_e = 0.69$ or $T_e \simeq 7.2$ eV. Using these values in Eq. (10),

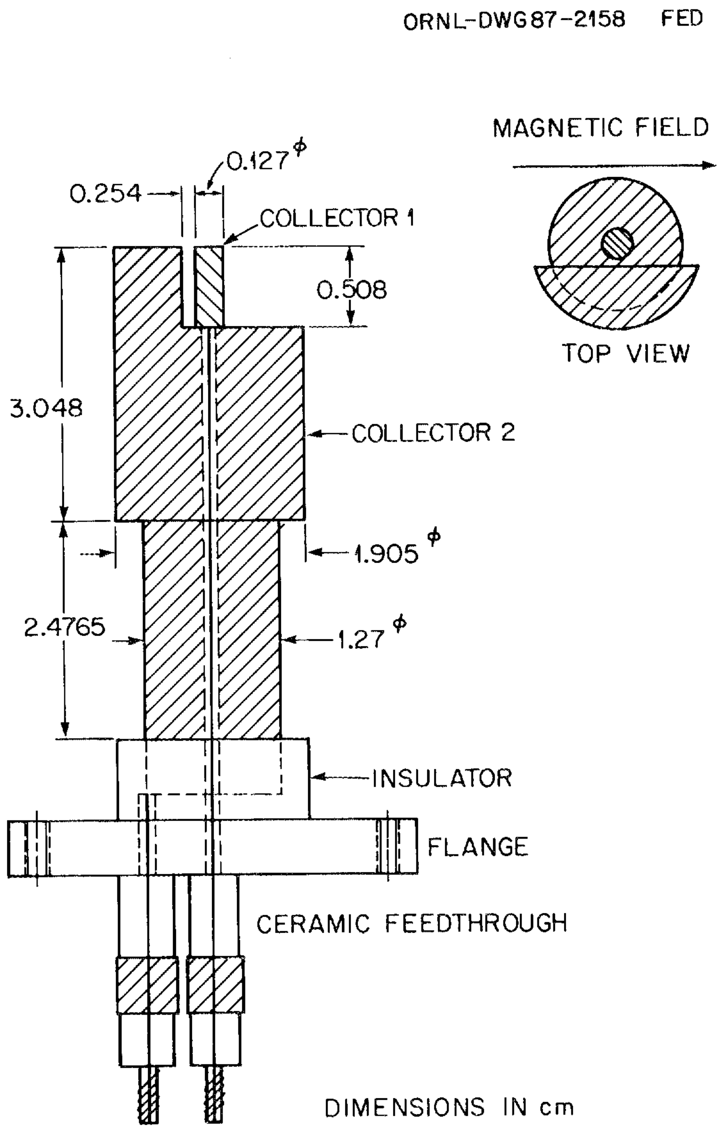

Fig. 3. Schematic of the ADLP used in the plasma test experiment and its orientation with respect to the magnetic field. Here the areas of the collectors are $A_1 \simeq 0.2$ cm^2 and $A_2/A_1 \simeq 127$. The probe system is made of graphite and can also be employed as a single Langmuir probe (SLP).

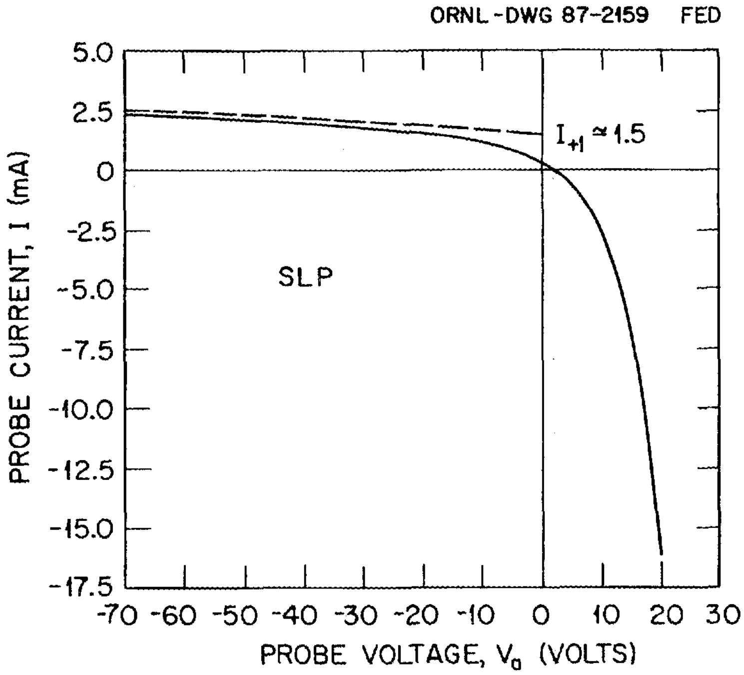

Fig. 4. (I, V_a) characteristic of the SLP result, obtained from the plasma test experiment. The measured ion saturation current is $I_{+1} \simeq 1.5$ mA.

we get an ion saturation current of $I_{+1} \simeq 1.6$ mA, which is about the same value we have measured with the SLP, as shown in Fig. 4. Again, the plasma density is obtained from Eq. (11).

This test clearly indicates that the ADLP can be used in plasma measurements without the full (I, V_a) characteristic but with the small signal response. Since there is no need for direct measurement of the ion saturation current, we have reduced the demand on the output voltage from the probe power supply. For example, in this experiment, if we compare the required power outputs for the SLP and the ADLP power supplies, we see that, for the same probe current,

$$P_a(\mathrm{ADLP})/P_a(\mathrm{SLP}) = 5\ \mathrm{V}/60\ \mathrm{V} = 8 \times 10^{-2} .$$

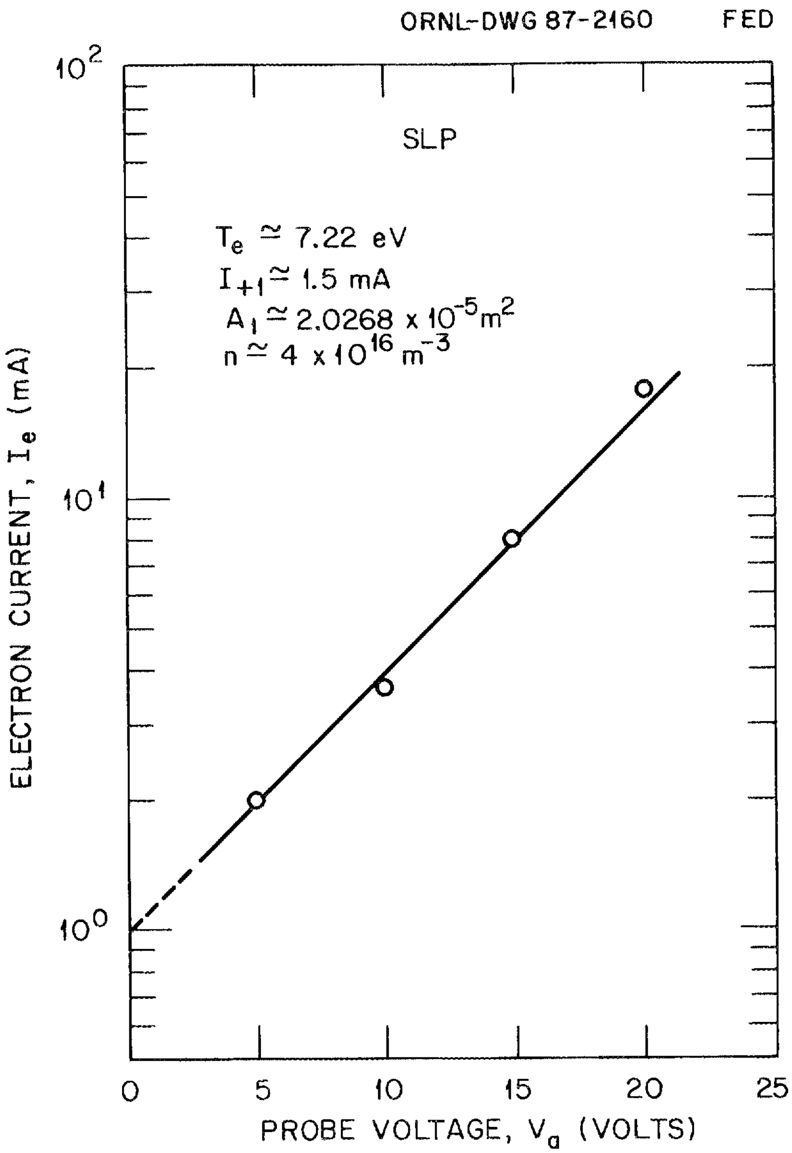

Fig. 5. Plot of (I_{e1}, V_a) obtained from Fig. 4. The estimated electron temperature is $T_e \simeq 7.2$ eV, and the plasma density is $n \simeq 4 \times 10^{16}$ m^{-3}.

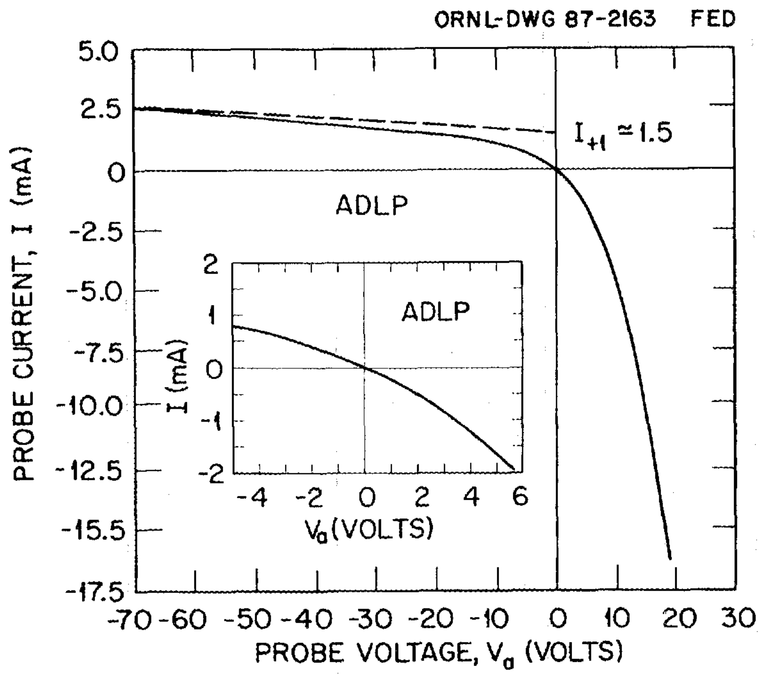

Fig. 6. (I, V_a) characteristic of the ADLP obtained from the plasma test experiment. $I_{+1} \simeq$ 1.5 mA, as in Fig. 4.

V. DISCUSSION

In this work we have discussed the ADLP and demonstrated the possibility of employing it as a diagnostic tool for measuring plasma parameters when it is operated in the region of small signal response. In this probe application, it is not necessary to measure the ion saturation current directly. This substantially reduces the probe applied voltage, thus easing the requirements on the power supply. This reduction should greatly simplify the operation of Langmuir probes in large tokamak devices, where expected typical edge plasma parameters are $T_e > 100$ eV and $n > 10^{18}$ m^{-3}.

We note that during operation of the ADLP it is possible to observe a nonzero probe current I even though $V_a = 0$. According to Eq. (15), this indicates $n_1 \neq n_2$ at the vicinity of the collectors. In such cases, the three unknowns, T_e, n, and n_1/n_2, can still be determined with the help of a simple iterative scheme from the three measured values of the probe currents, I_1, I_2, and $I(V_a = 0)$. We believe that this can be avoided by properly designing the probe collectors so that the large-area collector samples the same plasma as the small-area collector. A practical criterion for the collector area ratio of the ADLP, $A_2/A_1 \gg (n_1/n_2)\exp(\alpha)$, can be obtained from Eq. (9) with $\alpha = eV_a/T_e < 1$.

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