Langmuir probe differential measurement technique in inductively coupled RF plasmas

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Abstract. A differential measurement technique has been proposed in order to reduce noise level and stray capacitance leakage usually affecting Langmuir probe data. The technique employs two identically designed and biased Langmuir probes, connected to an instrumentation amplifier. Both probes are immersed in plasma of approximately the same space potential, one of them being plasma current collecting probe, and the second one being isolated from plasma and serving as a pick-up probe, detecting leakage currents from parasitic capacitive coupling and noise. Avoiding averaging of probe current data is the main advantage of the proposed differential technique. Experiments in the plasma expansion region of inductively driven RF source are shown to achieve lower electron temperature and higher electron density as measured by conventional single Langmuir probe. Obtaining more sharpness of the "knee" on the characteristic, thus lowering the uncertainty in plasma potential is another true merit of the differential Langmuir probe technique.

1. Introduction

In this paper we propose a Langmuir probe differential measurement technique used in inductively coupled RF plasma. Langmuir probe diagnostic methods are well established and well suited for collisionless plasma in low-pressure gas discharges. Inductive coupling of RF power by coil has been shown to be a very efficient manner of plasma production. The high densities obtained at low pressures (a few mTorr), together with the relatively low electron temperatures, are the main advantages of this discharge technology, making it suitable for variety of applications. A reliable estimation of plasma parameters is pretty important for the efficient development and design of inductively coupled (ICP) RF plasma source. ICP is however quite always superimposed with an electrostatic coupling, creating much trouble in probe diagnostics. Compensation with floating electrode and tuning chokes [1, 2] is already a must in RF Langmuir probe measurements. Although commonplace and routine, probe measurements in RF discharges are not only plagued by RF plasma potential oscillations, but also exposed to uncertainties, entailing error-prone interpretation of the probe characteristics: Overestimation of the electron temperature in the range 10% - 15% is commonplace error, mostly due to uncertainties in the least significant digits of probe current and voltage, arisen as a result from parasitic stray capacitance leakage and noise. Low frequency instabilities and temporal fluctuations of the plasma parameters in the discharge contribute to the uncertainty in probe characteristics. Large amplitude, low-frequency oscillations in local plasma density and potential could be overcome by using a fast-sweeping voltage supply to obtain the probe characteristic in a time short compared with the period of the oscillations [3]. This is more easily
said than done, again because of parasitic stray capacitors. A large sweep of the probe voltage \( \Delta V \) of approximately 100 V in 10 \( \mu \)s period \( \Delta t \) causes over 10 pF stray capacitance a leakage current \( \Delta I_c \) (\( \Delta I_c = C \Delta V/\Delta t \)) of 100 \( \mu \)A which can be far greater than the ion saturation current - unpleasant result especially if the current sensing resistor is misplaced so as to draw this leakage current. Same sweep in 1 \( \mu \)s over 10 pF would cause displacement current of 1 mA - inadmissible value, manifesting the necessity of precautions when measuring with large voltage sweeps in short times. Errors in plasma potential arise mainly due to instabilities and noise, forcing one to average measured probe voltage and current. Averaging entails arbitrariness of the "knee" location on the characteristic - the "knee" after averaging is not usually very sharp. The popular technique of averaging the measured current/voltage data contributes significantly to the uncertainty of measurement. Often the only measure against low frequency instabilities and power supply noise, the averaging yields an uncertainty in determining the plasma potential [4].

Lowering the uncertainty in the Langmuir probe voltage to current characteristics is the main intention of the present study, focusing on a differential measurement technique. Here the meaning of "differential" is twofold - on the one hand differential amplifiers are used to measure voltage over floating current sensing resistors, both placed on the "hot" side of two probes. On the other hand two identically designed and tuned Langmuir probes, but the first one active, and the second one isolated from the surrounding plasma, are used to obtain difference signal between both probe current signals. This difference is sensed (signals are subtracted) by an instrumentation amplifier. Differential Langmuir probe measurement technique is shown to provide for both cancellation of stray capacitance leakage and noise reduction, lowering thus uncertainties in measured probe current. Differential amplifiers are known also for high CMRR (Common Mode Rejection Ratio), which helps suppressing power supply- and mains- noise in measured probe characteristics. Avoiding averaging of probe current data is the main advantage of the proposed differential technique. Experiments in the expanded plasma region of inductively driven RF source are shown to achieve lower electron temperature and higher electron density as measured by conventional single Langmuir probe. Obtaining more sharpness of the "knee" on the characteristic, thus less arbitrariness in determining the plasma potential is another true merit of the differential Langmuir probe technique.

2. Design of a differential Langmuir probe arrangement with active probe and dummy

The proposed technique employs two identically designed and compensated Langmuir probes (figure 1), one of them being isolated from the surrounding plasma with ceramic cylinder over its tip. The probe tips are tungsten wires with a diameter of 0.5 mm. The nonisolated probe tip has a length of 5 mm. Both probes are immersed in plasma approximately 1 cm away from each other thus ensuring that they are at approximately the same conditions. Compensation is performed according to [1] for both probes - each probe has an individual floating ring electrode [5, 6], exposed to the plasma and coupled to the cylindrical Langmuir probe wire through a relatively large capacitor \( C_{cp} \). Tuned RF chokes at 27 MHz and 54 MHz are used in both probes, so as to achieve equal conditions (divider ratios, stray capacitances, etc) in both measurement circuits with the exception that the first probe tip is active (collects current from the surrounding plasma), and the second one is isolated from the plasma. Nevertheless, the second probe remains in contact with the plasma through its floating ring electrode.

In contrast to [1, 3, 7, 8] however, where the second probe is floating and the signal measured by this floating probe is voltage, here the second probe is biased in order to measure displacement currents caused by stray capacitance leakage and noise. Biasing this second (dummy) probe with the same ramp sweep voltage as applied to the active probe allows measurements of capacitive coupling and leakage currents, as well as of currents due to instabilities and noise in plasma. So far as the isolated dummy probe has its floating ring electrode exposed to the same space
Figure 1. Design of a differential Langmuir probe arrangement with active and dummy probe. Second isolated-tip probe is biased with ramp voltage.

potential as the active probe does, plasma oscillations are coupled in the same manner to both active and dummy probes, exiting equal unwanted currents. The differential probe measurement technique subtracts the unwanted current from the current collected by the active probe.

3. Equivalent circuit of the differential probe arrangement in plasma

The equivalent circuit of this probe arrangement (figure 2) is based on the circuit, proposed by [1]. Added to this is the equivalent circuit of the dummy. This second dummy probe is shown to have the same equivalent circuit elements with the exception of a sheath impedance - $R_{sh}$ and $C_{sh}$ are missing. With an isolated tip, the dummy is exposed to the plasma through its floating electrode, shown in the equivalent circuit through $R'_x$ and $C'_{cp}$, and coupled to the probe wire through $C'_{cp}$. Same tuning elements $L_1, C_1, R_1$ in the active probe, respectively $L'_1, C'_1, R'_1$ in the dummy at 27 MHz, and $L_2, C_2, R_2$ respectively $L'_2, C'_2, R'_2$ at 54 MHz, engage for equal leakage and noise currents in both probes.

Figure 2. Equivalent circuit of the differential Langmuir probe arrangement in plasma.

The equivalent circuit shows that fast sweep of large ramp voltages will cause over the equivalent stray capacitances equivalent parasitic displacement currents. Concerning plasma oscillations and noise coupling, as seen from the equivalent circuit, both probes feel the same space potential oscillations. Coupled through equal auxiliary impedances $Z_x$ and capacitors $C_{cp}$.
to each of the probe wires, these potential oscillations should cause equal noise currents in both
probe measurement circuits.
Thus, not only equal stray capacitance leakage currents are sensed by both measuring
resistors, but also equal noise currents (so far as leaked through the blocking chokes) can be
ruled out. In contrast to [1], here the two measurement resistors are placed between $V_{bias}$ source
and probe arrangement.

4. Measurement set-up
The differential Langmuir probe arrangement imposes the place of the corresponding current
sensing resistors on the "hot" side of the probes that is to say between active output of the
probe sweep voltage and plasma. Arranging both current sensing resistors $R_{meas}$ and $R'_{meas}$
(both 200 ohms) as near to each other as possible, is important in order to attain equivalence
of the stray capacitances and noise in both measurement circuits. Such "hot" position of the
resistors is favorable in concern to less stray capacitance leakage and noise than the grounded
one. However, differential amplifiers for high common mode voltage are needed, as sweep ramp
voltages as higher as 100 V appear at both sides of the resistors.

![Block diagram of the measurement set-up.](image)

Figure 3. Block diagram of the measurement set-up.

Figure 3 shows the block-diagram of the measurement setup designed for Langmuir probe
differential technique. Differential amplifiers INA117 are used to measure the voltage drop
over the current sensing resistors. INA117 is a precision unity-gain difference amplifier with
very high common-mode input voltage range. In many applications, where galvanic isolation
is not essential, the INA117 can replace isolation amplifiers. This can eliminate costly isolated
input-side power supplies and their associated ripple, noise and quiescent current. The INA117’s
0.001% nonlinearity and 200 kHz bandwidth [9] are superior to those of the conventional isolation
amplifiers.

The outputs of both INA117 differential amplifiers are subtracted by INA128 instrumentation
amplifier in order to rule out the leakage and noise currents from measured signals. The INA128
is low power instrumentation amplifier offering excellent accuracy [10]. Internal input protection
can withstand up to $\pm$ 40 V without damage. Current-feedback input circuitry provides wide
bandwidth even at high gain (200 kHz at $G = 100$). A single external resistor sets any gain
from 1 to 10,000. Here, unity gain is used to obtain the difference signal, proportional to the
true probe characteristic current $I_{dc}$. Digital oscilloscope Tektronix TDS360 measures and stores
probe voltage and current data.
5. Experimental results and discussions
The differential Langmuir probe arrangement was employed in the expanded region of an Ar plasma inductively driven source. The source is described in detail elsewhere [5]. Briefly it consists of a quartz tube where the HF power is inductively coupled to the plasma which then expands in a larger metallic chamber. The low gas pressure of 10 mTorr provided for collisionless regime. The applied power was 100 W. The measurements were performed at the axis of the metallic chamber 12 cm away from the end of the quartz tube.

Experiments at different sweep voltage frequencies established the performance of the differential Langmuir probe arrangement in respect to leakage-caused displacement of the probe characteristics, instabilities and noise. Comparisons with conventional single probe measurements held at the same time, using same measuring resistor and difference amplifier INA117 without any averaging applied, show the virtue of the differential measurement technique.

![Figure 4](image1.png)  
**Figure 4.** Comparison of the probe I-V traces obtained by the conventional method with the differential measurement.

![Figure 5](image2.png)  
**Figure 5.** Comparison of the probe I-V traces obtained with the differential measurement for different values of the scanning time.

Characteristics were measured using three different probe-scanning times, both with a single and a differential Langmuir probe arrangement. Scanning times of ~25 ms, ~1 ms and ~600 µs were used. Figure 4 compares a conventional single Langmuir probe characteristic with a characteristic measured by the differential probe arrangement at 600 µs scanning time. Both characteristics are measured without averaging. Not only the differentially taken characteristic is distinctly smoother, but also shifted right with well distinguished "knee", lowering uncertainty in estimation of plasma potential and electron temperature. Also the ion saturation current of the single probe characteristic appears to differ with approximately 10 µA from that of the differential one.

The probe characteristics measured with the differential method at different scanning times are presented in figure 5. Obviously, here the leakage currents are ruled out and do not have any impact on the characteristics with the scan frequency, as the case with the single probe. Moreover, without averaging, differentially measured characteristics are smoother than single probe ones for all three scan times. Here, the high CMRR of the instrumentation amplifier INA128 is to be appreciated as a main factor in suppressing low-frequency instabilities and noise in measured data.
Figure 6. Comparison of the electron temperature (a) and concentration (b) calculated from probe characteristics obtained by the two methods.

Figure 6 presents a comparison of the plasma parameters - electron temperature and concentration, extracted from measured data with single and differential Langmuir probe technique. Overestimation of the electron temperature with more than 10%, as well as underestimation of the electron density is observed for the single probe results, while the differentially measured characteristics give more reliable parameters, due to the absence of stray capacitance leakage and noise currents.

6. Conclusions
The present study employs a new differential Langmuir probe technique to measure more precisely probe characteristics, yielding higher fidelity in estimation of plasma parameters. Uncertainties due to parasitic stray capacitance-leakage, low-frequency instabilities and noise are minimized. Short scan times are shown not to displace the characteristics as with a single probe. Smooth and noiseless characteristics are measured in only one scan time without averaging, avoiding arbitrariness of "knee" location on the characteristic.

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References
[1] Sudit I D and Chen F F 1994 Plasma Sources Sci. Technol. 3 162–8
[2] Hopkins M B 1995 J. Res. Natl Inst. Stand. Technol. 100 415
[3] Chen F F Joint Nuclear Instrumentation symposium, Raleigh, N.C.; Sept. 7, 1961 pp 150–154
[4] Demidov V I, Ratynskaia S V and Rypdal K 2002 Rev. Sci. Instrum. 73 3409
[5] Dimitrova M, Djermanova N, Kiss’ovski Zh, Kolev St, Shivarova A and Tsankov Ts 2006 Plasma Process. Polym. 3 156–9
[6] Djermanova N, Ezekiev O, Kisovski Zh, Kolev St and Shivarova A 2004 Vacuum 76 389–92
[7] Godyak V A, Piejak R B and Alexandrovich B M 1992 Plasma Sources Sci. Technol. 1 36
[8] Sudit I D and Woods R C 1993 Rev. Sci.Instrum. 64 2440–5
[9] INA117: High Common-Mode Voltage Difference Amplifier (Rev. A) 2000
[10] Burr-Brown (TI) INA 128 ApNote