REVIEW OF SCIENTIFIC INSTRUMENTS **87**, 033506 (2016)

Electrical probe characteristic recovery by measuring only one time-dependent parameter

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(Received 10 December 2015; accepted 27 February 2016; published online 16 March 2016)

Two straightforward methods for recovering the current-voltage characteristic of an electrical probe are proposed. Basically, they consist of replacing the usual power supply from the probe circuit with a capacitor which can be charged or discharged by the probe current drained from the plasma. The experiment requires the registration of only one time-dependent electrical parameter, either the probe current or the probe voltage. The corresponding time-dependence of the second parameter, the probe voltage, or the probe current, respectively, can be calculated using an integral or a differential relation and the current-voltage characteristic of the probe can be obtained. © *2016 AIP Publishing LLC.* [http://dx.doi.org/10.1063/1.4943669]

I. INTRODUCTION

The electrical probe is one of the most common tools used in plasma diagnostic,[1] covering a rather large range of electron temperature and density which might be measured. Moreover, probe techniques were improved to be also used for measuring or following the time evolution of plasma parameters in non-uniform and non-stationary or even transient plasmas.[2,3] The probes are also proposed to be used as diagnostics of rather high density and high temperature plasmas when the energy deposited to the probe surface might exceed the thermal limit of probe integrity. Consequently, the so-called reciprocating probe system was proposed and used, which limits the exposure time of the probe to high density and high temperature plasmas.[4]

In many cases, the time evolution of plasma parameters and their spatial distribution is of great interest. The first need was solved by the time-resolved technique for probe characteristics,[5] while the second one was solved using multi-probe systems.[6–8] In the latter case, the probes are placed in various plasma regions and simultaneous electrical signals of the probes are registered using special circuits and data acquisition systems (DASs).

In the classical manner, the current-voltage characteristic of a probe is obtained by varying the probe potential with respect to a reference electrode and, in the same time, by measuring two electrical signals: the probe potential and the probe current. Usually, this procedure requires a variable power supply and two measuring instruments or a data acquisition system with two channels. In the case of non-stationary or transient plasmas, it is very important to register the current-voltage characteristic of the probe faster than the evolution characteristic time of plasma parameters. In the case of periodic plasmas (RF or pulse), the sampling-hold boxcar technique is frequently used.[9] So, a programmable power supply with adjustable voltage sweeping rate may be needed. When several probes are used for plasma diagnostic, either the number of power supplies should increase or advanced electronic circuits must be used. In addition, the data acquisition system limits the number of probes through its limited number of acquisition channels. Thus, the number of available acquisition channels should be at least twice the number of probes.

To overcome some of the above mentioned issues, two rather simple methods for the recovery of the entire current-voltage characteristic are proposed. Basically, the methods assume the time registration of a single electrical signal, either the probe current $I = I(t)$ or the probe voltage $V = V(t)$, during charging and/or discharging of a capacitor connected series in the probe circuit. Subsequently, the probe voltage $V = V(t)$ or the probe current $I = I(t)$, respectively, is obtained by numerical calculations. Eliminating the time from the two temporal functions, the probe characteristic $I = I(V)$ is obtained. Regardless of the number of probes, the two methods operate with only one power supply. Moreover, the number of required acquisition channels is reduced to the number of probes.

II. THEORETICAL APPROACH

The proposed methods are based on the idea that the potential of a free probe inserted in the plasma will be always a floating one. Consequently, in the laboratory produced plasma, the probe connected via a capacitor to the grounded reference electrode of the system will charge or discharge the capacitor, depending on its initial charging state, to the floating potential of the probe.[10] Note that all potentials referred in this paper are measured with respect to the grounded reference electrode. Two procedures allow obtaining the current voltage characteristic of a probe using this kind of electrical circuit, namely, the *integral* and the *differential approach*, respectively.

A. Integral approach

The electrical circuit used to obtain the current-voltage characteristic of the probe by the *integral approach* is shown in Figure 1. Similar circuits were previously used for measuring

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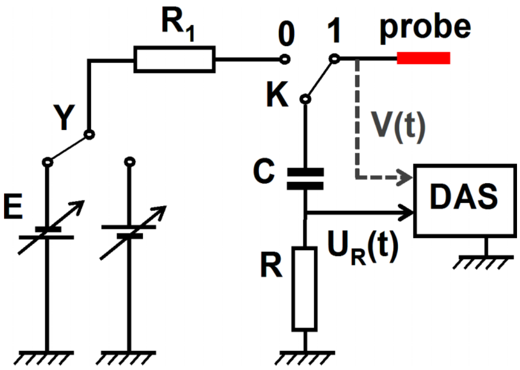

FIG. 1. Electrical circuit designed to record the current-voltage characteristic of a probe by the integral approach.

only the temporal evolution or the fluctuations of the ion saturation current in fusion related devices.[6–8] The main branch of the circuit has two elements: a capacitor C connected series with a measuring resistor R. This branch can be coupled to a power supply E or to the probe, via the switch K. The two power supplies, which can be selected via the switch Y, allow charging the capacitor either positively or negatively with respect to the grounded reference electrode.

When the switch K is in position 0, the capacitor C is charged to the potential V_0, fixed by the power supply ($V_0 = E$). The role of the resistor R_1 is to limit the intensity of the charging current. During this operation, the probe is floating and its floating potential V_f is determined by the plasma parameters, more precisely mainly by the electron temperature.[11] Once the switch K is moved in position 1, the probe is biased to the capacitor potential, V_0, and it starts to draw a current I from the plasma. The intensity of this current is obtained as $I = U_R/R$, where U_R is the potential drop measured on the resistor R. The presence of the current I will change, in time, the charging state of the capacitor as well as the potential drop on the capacitor and, consequently, the probe potential.

The *integral approach* consists of measuring, in time, the current intensity $I(t)$ flowing from the plasma through the circuit probe—capacitor—grounded reference electrode. Afterward, at each moment t, the corresponding probe potential $V(t)$ can be calculated using the integral relation,

$$V(t) = V_0 + RI(t) + \frac{1}{C}\int_0^t I(\tau)d\tau. \quad (1)$$

The initial moment $t = 0$ s is considered when the switch K is moved in position 1 and the probe is biased at the initial voltage V_0. Eliminating the time from the two temporal functions, $I = I(t)$ and $V = V(t)$, the current-voltage characteristic of the probe $I = I(V)$ can be obtained.

B. Differential approach

The electrical circuit required by the *differential approach* is shown in Figure 2. It is simpler than the circuit of the *integral approach*, its main branch having only one element, the capacitor C. The *differential approach* consists of measuring the time evolution of the probe potential $V(t)$, when the probe is connected through the capacitor C to the reference electrode. Thus, the probe potential is equal to the potential drop on the capacitor and the corresponding time evolution of the current intensity $I(t)$ flowing through the probe can be calculated using the differential relation,

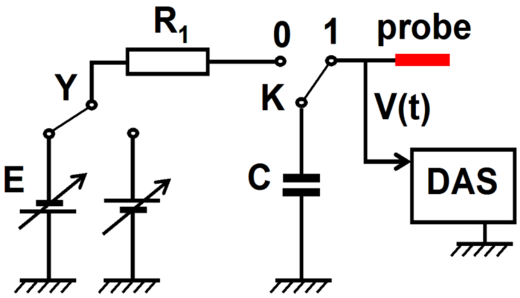

FIG. 2. Electrical circuit designed to record the current-voltage characteristic of a probe by the differential approach.

$$I(t) = C\frac{dV(t)}{dt}. \quad (2)$$

Relation (2) is valid at any moment t. Again, the current-voltage characteristic of the probe $I = I(V)$ can be obtained by eliminating the time from the two temporal functions, $I = I(t)$ and $V = V(t)$. Regardless of the applied method, *integral* or *differential*, the procedure of obtaining the entire current-voltage characteristic of the probe has two steps which are described in the following.

C. Ion branch of the probe characteristic

Let us consider as the first step of the procedure: the recovery of the ion branch of the probe characteristic. The capacitor has to be initially charged to a potential V_0, more negative than the floating potential of the probe ($V_0 < V_f$). When the capacitor is connected to the probe, the latter one will collect an ion dominated current from the plasma. This current will change the charging state of the capacitor. Thus, the potential drop on the capacitor will diminish (in absolute value) and the probe potential will become less negative with respect to the floating potential. The current collected by the probe will change accordingly. This process will continue till the current intensity goes to zero and the probe potential becomes the floating one. If the time evolution of the current intensity $I = I(t)$ is recorded (*integral approach*), the probe potential $V = V(t)$ can be calculated using relation (1). If the time evolution of the probe potential $V = V(t)$ is recorded (*differential approach*), the current intensity $I = I(t)$ can be calculated using relation (2). Thus, the so-called ion branch of the probe characteristic, $I_i = I_i(V)$, can be obtained. Please remind that this branch corresponds to probe potentials $V < V_f$.

D. Electron branch of the probe characteristic

The second step of the procedure is the recovery of the electron branch of the probe characteristic. This time the capacitor has to be initially charged positive with respect to the floating potential of the probe ($V_0 > V_f$). When the capacitor is connected to the probe, the latter one will collect an electron dominated current from the plasma. Similar to the first step, this current will change the charging state of the capacitor till the probe will become floating again and the current through the probe will become zero. Applying the *integral* or the *differential approach*, the so-called electron branch of the probe characteristic, $I_e = I_e(V)$, can be also obtained, for probe potentials $V > V_f$. In order to have the entire electron branch, including the so-called electron saturation current, the initial voltage V_0 has to be more positive than the local plasma potential V_p ($V_0 > V_p$).

E. Around the floating potential

Even if the measurements start with the capacitor-probe system biased positively or negatively with respect to the floating potential of the probe, V_f, the probe potential will always evolve towards V_f and the probe current will asymptotically tend to zero, reaching thus a quasi-steady state. This state is stable because each deviation of the probe potential from V_f (e.g., due to possible plasma fluctuations) will force the probe to collect a non-zero current which will bring new electrical charges from the plasma to the capacitor. The new collected charges will diminish the difference between the probe potential and V_f till the capacitor-probe system will regain the floating potential. It makes sense that the acquisition time for each branch of the probe characteristic will last till the current intensity in the circuit is of the order either of the precision of the data acquisition system or of the standard measuring error when the fluctuations of plasma parameters exceed the precision of the system.

III. EXPERIMENTAL VALIDATION

To validate the proposed methods, the experiments were performed in a steady state dc argon discharge plasma produced in a magnetic multipolar confinement system arranged in a cylindrical stainless steel chamber (40 cm in diameter and 60 cm in length) pumped down to 10^{-5} mbar by turbo pumping system.[12] Plasma parameters were specific for such experimental system.[13] The diagnostic was made using a cylindrical probe made of tungsten wire (0.2 mm in diameter and 10 mm in length) placed in the middle of the discharge chamber. The results reported for illustration were obtained for the following discharge conditions: discharge current of 60 mA, discharge voltage of 100 V, and argon pressure of 6×10^{-3} mbar.

The validation of either the *integral* or the *differential approach* requires the simultaneous registration of two temporal evolutions: the current intensity $I_m(t)$, via $U_{mR}(t)$, flowing through the probe and the probe potential $V_m(t)$. Thus, the parameter which has to be calculated from relation (1) or (2), depending on the applied approach, can be compared with the same parameter measured experimentally. That is why, even if the *integral approach* requires the registration of a single signal, $I_m(t)$, in Figure 1, is also illustrated the possibility of registering the probe potential $V_m(t)$. The dash line signifies that the registration of $V_m(t)$ is not mandatory. Note that all measured parameters will be marked with the subscript symbol m in order to be distinguished from the calculated ones.

A. Integral approach

The *integral approach* was applied, via the circuit presented in Figure 1, to register the entire current-voltage characteristic of the probe in two steps, as already described. The time evolutions of both current intensity $I_m(t)$ and probe potential $V_m(t)$ were acquired using a digital oscilloscope as DAS, with an input impedance of 1 MΩ. The probe potential $V_m(t)$ was registered only to validate the probe potential calculated by relation (1). Special care was paid to preserve plasma parameters during the two steps of the measurement. The probe current was measured on a resistor $R = 1$ kΩ and the probe bias was assured by a capacitor $C = 15$ μF. The large value of the resistor R assured a fair measurement of the ion current which was of the order of μA. The current charging the capacitor was limited by a resistor $R_1 = 10$ kΩ.

Typical experimental results for the time registration of the probe current $I_m(t) = U_{mR}(t)/R$ for both ion (curve i) and electron (curve e) branches of the characteristic are plotted in Figure 3(a). The ion current was multiplied by 20 for scaling purpose. The corresponding temporal evolution of the measured probe potential $V_m(t)$ is shown in Figure 3(b).

Before the moment $t = 0$ s, the switch K is in position 0 (Figure 1) and the probe is floating. Consequently, the current through the probe is zero and the potential measured on the probe is equal to the floating potential V_f. At $t = 0$ s, the switch

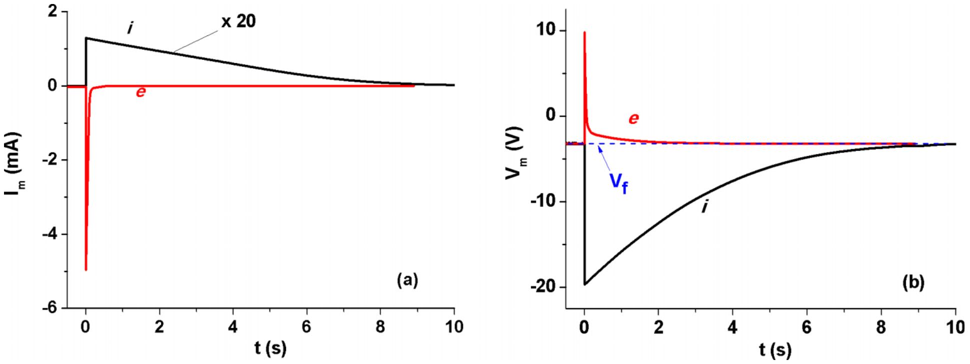

FIG. 3. Time evolution of (a) ion ($I_m(t) > 0$, curve i) and electron ($I_m(t) < 0$, curve e) current intensity of the probe characteristic; (b) the measured probe potential corresponding to the currents plotted in (a).

K is moved in position 1 and the probe is connected to the capacitor, which is charged at the initial potential V_0. After the transitory phase, even if the probe was biased positively (curve *e* in Figure 3(b)) or negatively (curve *i* in Figure 3(b)) with respect to V_f, the current flowing through the probe goes to zero and the probe potential is stabilized again at the floating potential. The extent of the transitory phase is different when the probe is measuring electron or ion current.

The time constant of the measuring circuit depends on the capacitor C as well as on the plasma impedance, corresponding to ion or electron branch of the probe characteristic, respectively. The resistor R has no influence on the time constant of the measuring circuit if it is much smaller than the plasma impedance. Let us detail the system plasma–probe from electrical point of view. When the probe is at floating potential, the system plasma–probe consists of an equivalent capacitor C_s connected series to an equivalent plasma impedance Z_p. The capacitor C_s is set up between the floating probe and undisturbed plasma, the so-called probe sheath region. Plasma impedance Z_p is an equivalent impedance of the entire circuit between undisturbed plasma region in front of the probe sheath and the grounded reference electrode. There are qualitative and quantitative differences between the two capacitors C and C_s. The main qualitative difference is that, through the passive capacitor C, only displacement currents might flow, while the reactive capacitance nature of the space charge in front of the floating probe is a result of a zero total conductive current. Once the probe potential is different from the floating one and the balance between electron and ion fluxes to the probe surface breaks, the capacitance of the sheath, C_s, turns into a dynamic impedance. Quantitatively, C_s is of the order of tens of pF for usual probes,[14] while the passive capacitor C might range from, let us say, tens of nF to hundreds of μF. The advantage of the proposed method is that any change of the plasma impedance is reflected in the current flowing through the probe and the knowledge of the plasma impedance itself is not required. The ion current collected by the probe is much smaller than the electron one, which corresponds to a larger impedance of the circuit and much longer time for the registration of the ion branch of the probe current than the electron one (Figure 3).

The time evolution of the probe potential corresponding to the time evolution of the two currents plotted in Figure 3(a) was calculated as

$$V(t) = V_{m0} + U_{mR}(t) + \frac{1}{CR}\int_0^t U_{mR}(\tau)d\tau. \tag{3}$$

Relation (3) is similar to relation (1), but this time $V(t)$ is calculated as a function of the directly measured parameter $U_{mR}(t)$. Combining the measured $I_m = I_m(t)$ and the calculated $V = V(t)$, the ion and the electron branches of the probe characteristic were obtained and separately plotted in Figures 4(a) and 4(b), respectively. The entire current voltage characteristic of the probe is plotted in Figure 4(c). To preserve the traditional representation of the current-voltage characteristic of a probe, the sign of the currents was reversed. Thus, the ion current is negative and the electron one is positive in Figure 4. In order to validate the approach, the calculated characteristics $I_m = I_m(V)$ (dash lines) were compared to the measured ones $I_m = I_m(V_m)$ (solid lines) in Figure 4.

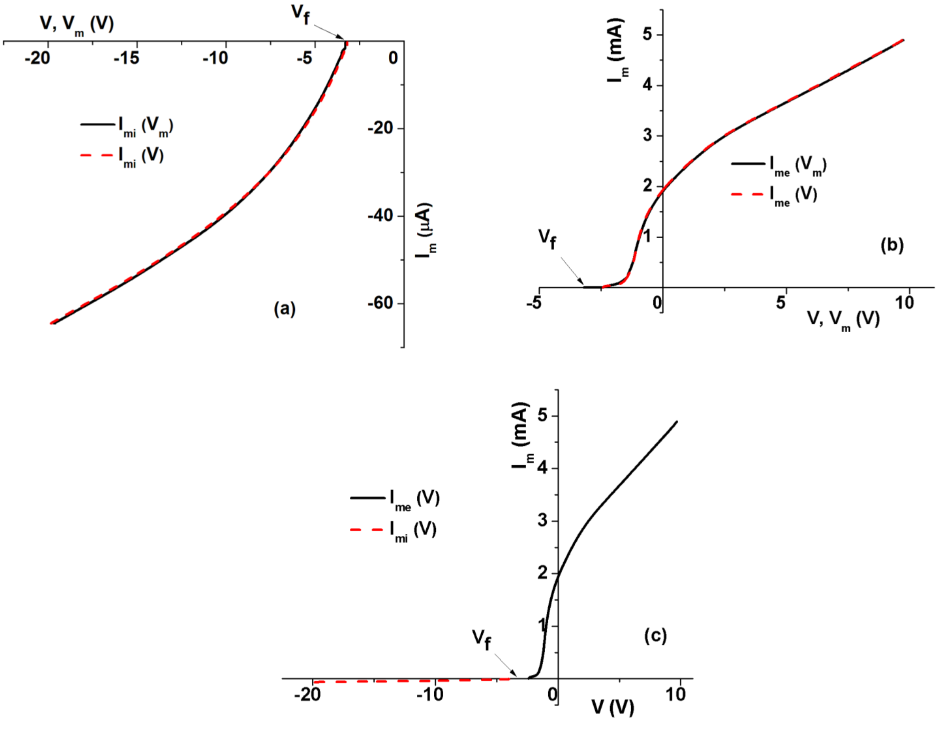

FIG. 4. The current-voltage characteristic of the probe: (a) ion branch; (b) electron branch; and (c) the entire characteristic. The measured probe current I_m is comparatively plotted against the measured V_m and the calculated V probe potentials, respectively.

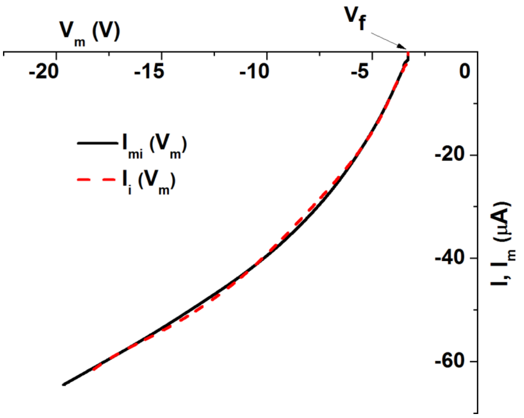

FIG. 5. The ion branch of the current-voltage characteristic of the probe. The measured I_m and the calculated I probe currents are comparatively plotted against the measured V_m.

The two recovered experimental branches, the ion one for $V < V_f$ (Figure 4(a)) and the electron one for $V > V_f$ (Figure 4(b)), have in common, within the measuring error of the potential across the resistor R, the floating potential of the probe V_f. Moreover, within the same error of measurement, the two recovered branches $I_{mi,e} = I_{mi,e}(V)$, based on the measured current and the calculated voltage of the probe (dash lines in Figures 4(a) and 4(b)), match very well with the corresponding branches $I_{mi,e} = I_{mi,e}(V_m)$ obtained by the standard method, when both current and voltage of the probe are measured (solid lines in Figures 4(a) and 4(b)).

B. Differential approach

The validation of the *differential approach* requires the comparison of two time evolutions: the current intensity $I(t)$ calculated with relation (2) and the measured current intensity $I_m(t)$. It is not possible to validate the *differential approach* with the electrical circuit shown in Figure 2, since it allows measuring only one parameter, $V_m(t)$, but it can be done with the electrical circuit shown in Figure 1. Relation (2) is valid only when the potential of the probe is equal to the potential drop on the capacitor (U_C). Otherwise, the relation has to be rewritten as

$$I(t) = C\frac{dU_C(t)}{dt}. \qquad (4)$$

For the electrical circuit shown in Figure 1, the potential drop on the capacitor can be calculated as

$$U_C(t) = V_m(t) - U_{mR}(t). \qquad (5)$$

Based on the measured parameters $V_m(t)$ and $U_{mR}(t)$, the current intensity $I(t)$ can be calculated using relations (4) and (5). Since we wanted that the validation method (using the electrical circuit in Figure 1) to be as close as possible to the experimental method (using the electrical circuit in Figure 2), we applied the *differential approach* only to obtain the ion branch of the probe current voltage characteristic. For this case, the relative difference between the potential drop on the capacitor U_C calculated with relation (5) and the measured probe potential V_m is $|(U_C - V_m)/V_m| = |U_{mR}/V_m| < 0.4\%$. Thus, $U_C \approx V_m$ and relation (2) can be directly applied to calculate the current intensity through the probe. The comparison of the two ion branches, the measured one $I_{mi} = I_{mi}(V_m)$ and the calculated one $I_i = I_i(V_m)$, is plotted in Figure 5.

The match of the two curves (measured and calculated) plotted in Figure 5 is less accurate than the corresponding curves in Figure 4(a). This aspect is better illustrated by plotting the relative difference between the calculated and the measured parameter: $(V - V_m)/V_m$ for the *integral approach* (Figure 6(a)) and $(I - I_m)/I_m$ for the *differential approach* (Figure 6(b)).

This difference is larger in the case of the *differential approach* (maximum 4%) with respect to the *integral approach* (maximum 2.5%). In both cases, the deviation of the calculated parameter from the measured one increases around the floating potential ($V_f = -3.2$ V). However, the very strong increase appearing in Figure 6(b) around the floating potential (not integrally shown) is caused by the fact that the difference $(I - I_m)$ becomes comparable or even larger with respect to the measured current I_m, the latter one tending to zero in that region.

C. Discussion

The test results validate the two methods and recommend them for different types of probe diagnostic. First of all, the methods are suitable for experiments with large number of probes.[15] In this case, the number of acquisition channels is equal to the number of probes. Second, the methods are very promising for magnetically confined fusion related devices

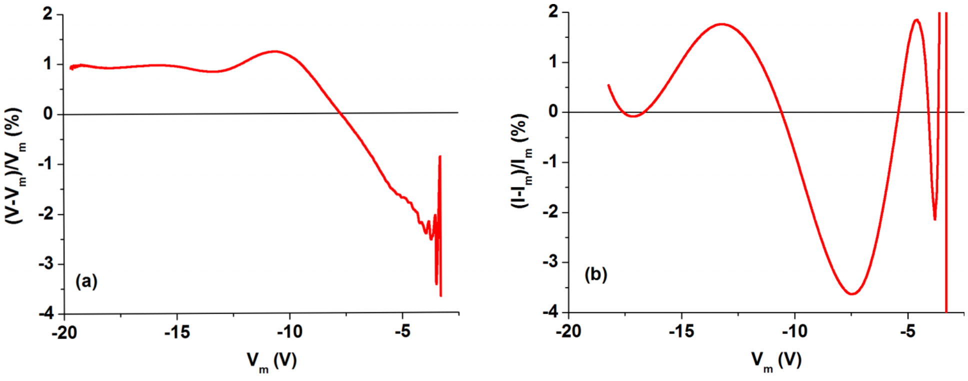

FIG. 6. The relative difference between the calculated and the measured parameters for the *integral* (a) and for the *differential approach* (b).

in which, often, only the ion branch of the characteristic is used for plasma diagnostic.[16] Therefore, the methods can be applied in a single step. Moreover, non-stationary or transitory plasmas can be investigated if their evolution characteristic time is larger than the time constant of the measuring circuit. The necessary time to charge and/or discharge the capacitor C depends on its capacitance but also on probe dimension and plasma parameters, which determine the probe current intensity. By decreasing the capacitance C and the probe size and/or increasing the plasma density and temperature, the acquisition time of the probe characteristic can be decreased.

The characteristic time for discharging the capacitor can be estimated by a simple relation,

$$\tau_d = \frac{C(V_0 - V_f)}{I_a}, \tag{6}$$

where I_a is the average current passing through the probe while the capacitor is discharged. In a first approximation, even if the current that discharges the capacitor does not vary linearly in time, I_a can be roughly estimated as $I_{max}/2$, where I_{max} is the maximum current passing through the probe. As an example, let us estimate τ_d for fusion experiments. Referring to the results discussed in Ref. 16, the ion saturation currents measured with probes are about 10 mA. Choosing a capacitor of 10 nF and charging the capacitor at about 50 V with respect to the floating potential, a discharging time of 0.1 ms is obtained. This time is much smaller than the typical discharge shot in fusion devices. It is obvious that this rough estimation given by relation (6) shows a linear dependence of τ_d on the initial charging voltage V_0 so that any increase of the voltage span leads to an increase of τ_d for the same capacitor used in the measuring circuit.

Choosing the capacitance value C is not straightforward in the case of using the present method for RF plasma diagnostic because the chokes mounted close to the probe tip, in order to increase the probe impedance to the RF signals,[17] coupled with stray capacitances of the measuring circuit and probe sheath impedance may ask for more elaborate procedure. But, in principle, the proposed methods can also be used for time-averaged RF plasma diagnostic with benefit of simple measuring circuit.

The situation might become more difficult in choosing the capacitance value C in the case of transient plasma diagnostic characterized by very short life-time, as the plasma plume produced by laser ablation. In general, the plasma plume produced by, e.g., nanosecond laser pulse exhibits two different structures which expand with different speeds and are characterized by two different life times.[18] In this case, the present method might be considered for the slow plasma plume having the characteristic time of the order of milliseconds, while the initial faster structure, which is shorter than microseconds, might be out of the realistic values of the measuring electrical circuit.

The *differential approach* uses a very simple relation, (2), to obtain the unmeasured parameter, while the calculations for the *integral approach* are more complex—see relation (1) or (3). However, the *differential approach* seems to be less accurate, at least for the current example. In this case, the temporal signals were integrated using the simple trapezoidal method. In order to perform the derivative, the temporal signal was fitted with a ninth order polynomial which was subsequently derived analytically. A reason for the poorer accuracy of the *differential approach* might be the commonly known fact that the derivative of a signal is noisier while the noise of the integrated signal is reduced with respect to the signal itself. This aspect might be overcome by a proper choice of the differentiation method. Thus, the processing of the acquired signal (smoothing, mathematical fitting, etc.) before derivation as well as the differentiation algorithm becomes very important for the accuracy of the *differential approach*.

For good results, it is very important to accurately know the values of the capacitor C and the resistor R, since both of them are key elements in relations (1) and (2). If the measuring circuit has important stray capacitance, an equivalent capacitance C has to be calculated. The system probe–plasma has to be replaced by a calibrating resistor, R_c. The equivalent C value will be deduced from the time constant, $\tau = (R + R_c)C$, of the new circuit. In our case, the catalogue value of C was 15 μF while the equivalent calculated value was 15.4 μF. Also, the catalogue value of R was 1 kΩ while the real measured value was 984 Ω. Any error on C or R will drift apart the calculated parameter from its real value.

IV. CONCLUSION

Two straightforward methods were described in this paper for the registration of the current-voltage characteristic of an electrical probe. They have the following advantages:

- The probe characteristic can be obtained by registering only one signal, either the current intensity flowing through the probe or the probe voltage. The second parameter can be calculated based on the temporal evolution of the first parameter. Thus, we dispose of single signal acquisition methods for obtaining the electrical probe characteristic.
- Each branch of the characteristic can be acquired with its own resolution, adapted to the current values, knowing that the electron and ion currents in the plasma can be very different, sometimes by orders of magnitude.
- The possibility of fast registration of the ion or electron part of the probe characteristic recommends the method for the diagnostic of pulsed or transitory plasmas. The acquisition time can be controlled by adjusting the circuit element C and the probe size.
- The method can be used for experiments with large number of probes because the number of acquisition channels is equal to the number of probes.
- The method is suitable for diagnostic of rather high density and high temperature plasmas of magnetically confined fusion related devices because often only the ion branch of the characteristic is used for plasma diagnostic.

A disadvantage of the methods is that two acquisition steps are necessary in order to obtain a complete current-voltage characteristic. Moreover, in fluctuating plasmas, the acquired signals exhibit larger fluctuations around the floating potential.

ACKNOWLEDGMENTS

The research was financially supported by the Romanian National Partnerships Program, under UEFISCDI Grant: PN-II-PT-PCCA-2011-3.2-1340, No. 174/2012.

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