Consistent method for registration of the electrical probe characteristic

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A rather simple but consistent method for registration of the electrical probe characteristic is presented. It consists of measuring the current probe intensity during charging and, respectively, discharging of a capacitor connected in the probe circuit in series with a resistor. Time dependence of the probe current allows calculating the probe potential at any moment so that the current – voltage characteristic of the probe can be obtained.

1. 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. Moreover, probe techniques were improved to be also used for measuring or following the time evolution of plasma parameters in 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 the high density and high temperature plasmas [4].

In many cases the time evolution of plasma parameters and their spatial distribution are of great interest. The first need was solved by time resolved technique for probe characteristics [5], while the second one was solved using multi-probe systems [6]. In this case probes are placed in various plasma regions and simultaneous probe characteristics are registered using special circuits and data acquisition systems [7].

In all of these cases the acquisition time of the probe characteristics is one of the main problems. In addition, for a multi-probe system, the data acquisition system limits the number of probes through its limited number of acquisition channels.

In the present contribution a rather simple method for recovering the entire current-voltage characteristic is presented. The method assumes only time registration of the probe current $I = I(t)$ during charging and/or discharging of a capacitor connected series in the probe circuit followed by the numerical calculation of the probe voltage $U = U(t)$. Using the two temporal dependences, the probe characteristic $I = I(U)$ is obtained.

2. Theoretical background

For the analytical model and the experimental validation test we propose a typical setup which considers the probe placed in a low-temperature non-magnetized plasma.

2.1. Ionic branch of the probe characteristic

A simple electrical circuit which allows measuring the ionic part of a probe characteristic was presented in a previous communication [8]. A rather large electrolytic capacitor C (~500 μF) is initially charged from a power supply to a voltage U_0 which is more negative than the floating potential of the probe ($U_0 < V_f$). It has to be mentioned that this circuit allowed only negative biasing of the probe with respect to ground. When the capacitor is connected in the probe circuit, it is discharged in time by the current collected by the probe.

The time dependence of the current $I(t)$ flowing through the probe circuit is measured as the potential drop $U_R(t)$ on the resistor R connected in series between the capacitor and the ground. This current corresponds to the ionic branch of the probe characteristic and it is flowing till the probe potential reaches the floating potential, when the probe current becomes zero. The time evolution of the probe bias $U(t)$ during this evolution of the probe current can be calculated according to relation:

$$U(t) = U_0 + RI(t) + (1/C)\int_0^t I(t)dt \qquad (1)$$

where both $U(t)$ and U_0 are negative quantities ($U(t)<0$ and $U_0<0$), while $I(t)$ is positive ($I(t) > 0$). Eliminating the time from the two temporal functions:

$$I = I(t) \text{ and } U = U(t) \qquad (2)$$

the ionic part of the current-voltage characteristic $I=I(U)$ of the probe is obtained. It corresponds to $U < V_f$.

2.2. Electronic branch of the probe characteristic

In the present contribution an electronic circuit similar to the one presented in [8] is used to obtain the entire current-voltage characteristic (Fig. 1). The power supply and the capacitor were replaced in order to allow charging the capacitor both positively and negatively with respect to ground. The measured quantity is again the potential drop U_R on the resistor R, which give us the current intensity in the probe circuit as $I = U_R/R$.

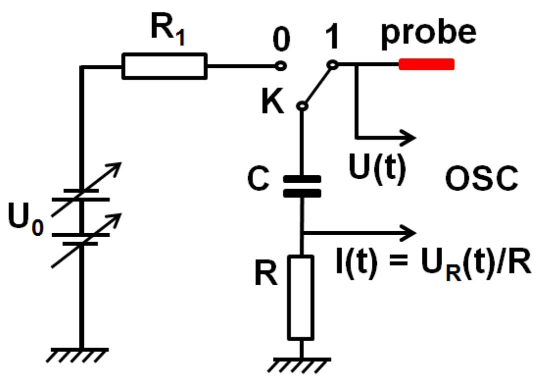

Fig.1. Probe circuit designed to record the entire probe characteristic.

In order to get the electronic part of the current-voltage characteristic, the capacitor has to be charged positively with respect to the local plasma potential V_p and, implicitly, with the floating potential ($V_f < V_p < U_0$) and then connected to the probe. The probe starts to collect electrons and the capacitor is discharged in time. The probe bias $U(t)$ is changing according to relation (1) till the probe reaches the floating potential. In this case the probe current $I(t)$ is negative ($I(t) < 0$).

As long as the probe bias $U(t)$ is positive with respect to the local plasma potential ($V_p < U(t)$), the probe current $I(t)$ corresponds to the electron saturation current I_{es}. When the probe potential becomes equal or negative with respect to the local plasma potential, $U(t) \leq V_p$, the probe current intensity decreases almost exponentially because the probe becomes more and more negative with respect to plasma potential and less and less thermal plasma electrons may reach its collecting surface. Moreover, in this case ions are also collected by the probe and the total current intensity of the probe $I(t)$ is an algebraic sum of two opposite currents, a negative electronic one $I_e(t)$ and ionic $I_i(t)$, respectively, which is positive

$$I(t) = I_e(t) + I_i(t). \qquad (3)$$

In time, the value of the probe current intensity decreases asymptotically to zero so that the probe bias becomes more negative, approaching also asymptotically to the floating potential of the probe. As in the ionic branch of the probe characteristic, from the two temporal functions given by relations (2), the electronic branch $I = I(U)$ of the probe characteristic is obtained. It corresponds to $U > V_f$.

3. Experimental set-up and results

The experiments were performed in a 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 [9]. Plasma parameters were specific for such experimental system [10]. 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 circuit presented in Fig. 1 was used to register the entire current-voltage characteristic of the probe in two steps: (i) the capacitor is charged at $U_0 < V_f$ and the ionic branch of the probe characteristic is obtained; (ii) the capacitor is charged at $U_0 > V_f$ and the electronic branch of the probe characteristic is obtained. For each step, the time evolution of both current intensity $I(t)$ and probe voltage $U(t)$ is acquired using an oscilloscope (OSC). The latter one was registered in order to validate the probe voltage 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.

Typical experimental result for the time registration of the probe current $I = I(t)$ for the ion branch of the characteristic is plotted in Fig. 2(a) (curve *i* – for scaling purpose the current values were multiplied by 20). At $t = 0$ s the capacitor, previously charged at the initial voltage U_0, is connected to the probe *via* the switch K (Fig. 1). The temporal evolution of the measured probe voltage $U = U(t)$ is shown in Fig. 2(b) (curve *i*).

Similar approach was used to get the time evolution of the probe current $I=I(t)$ for the electron branch of the probe characteristic (curve *e* in Fig. 2(a)) and for the measured probe voltage $U = U(t)$ (curve *e* in Fig. 2(b)).

Before the moment $t = 0$ s the switch K is in position 0 (Fig. 1) and the probe is floating. Consequently, the voltage measured on the probe is equal to the floating potential V_f. After the complete discharging of the capacitor, even if the probe was biased positive (curve *e* in Fig. 2(b)) or negative (curve *i* in Fig. 2(b)) with respect to V_f, the current flowing through the probe goes to zero and the probe voltage is stabilized again at the floating potential.

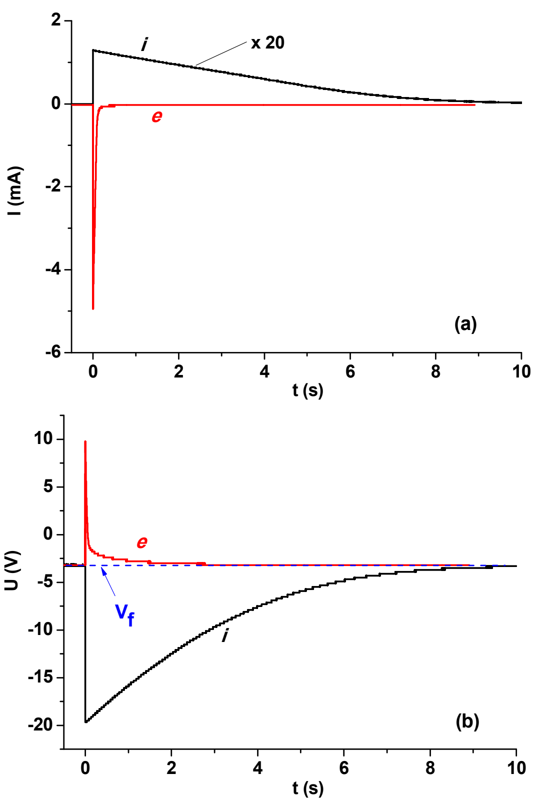

Fig.2. Time evolution of: (a) ionic $I(t) > 0$ (curve *i*) and electronic current intensity $I(t) < 0$ (curve *e*) of the probe characteristic; (b) the measured probe voltage corresponding to the currents plotted in figure (a).

Using the time evolution of the two currents plotted in Fig. 2(a) and the relation (1), the corresponding time evolution of the probe voltage was calculated. The time constant of the measuring circuit is given by both the capacitor C and plasma impedance corresponding to ionic and electronic branches of the probe characteristic, respectively. The plasma ionic current through the probe is much smaller than the electronic one, which corresponds to a larger impedance of the circuit and much longer time for the registration of the ionic branch of the probe current than the electronic one.

Combining the measured $I = I(t)$ and the calculated $U = U(t)$, respectively, the ionic and the electronic branches of the probe characteristic were obtained and plotted in Fig. 3. 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 Fig. 3.

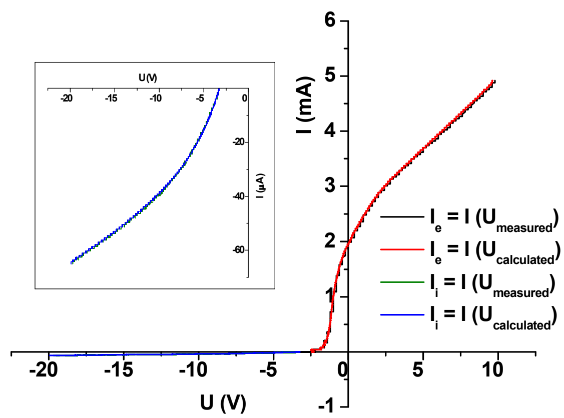

Fig.3. The current-voltage characteristic of the probe. The probe current is comparatively plotted against the measured and the calculated probe voltage, respectively. In the insert, the magnified ion branch of the characteristic is presented.

The two recovered experimental branches, the ionic one for $U < V_f$ (blue curve in Fig. 3) and the electronic one for $U > V_f$ (red curve in Fig. 3) 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 recovered $I = I(U)$ characteristic, based on the measured current and the calculated voltage of the probe, matches very well with the probe characteristic obtained by the standard method, when both current and voltage of the probe are measured (black curve for the electronic current and green curve for the ionic current in Fig. 3).

The test result included in this contribution validates and recommends the method also for the diagnostic of non-stationary or transitory plasmas for which the 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 plasma parameters which determine the probe current intensity. By decreasing the capacitance C

and/or increasing the plasma density and temperature, the acquisition time of the probe characteristic decreases for a fixed probe size.

4. Conclusion

The method for registration of the current-voltage characteristic of an electrical probe proposed in this contribution presents the following advantages:

- The probe characteristic can be obtained by registering only one signal, the current intensity flowing through the probe. The probe voltage can be calculated based on the temporal evolution of the probe current.
- Fast registration of ionic or electronic part of the probe characteristic recommends the method for the diagnosis of pulsed or transitory plasmas.
- The method can be used for multi-probe systems to simultaneously register the ionic or the electronic part of probes characteristics.

Acknowledgments

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