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A NEW LOW FREQUENCY RF PROBE TECHNIQUE FOR ELECTRON DENSITY DETERMINATION IN THE TEMPORAL AFTERGLOW PLASMA

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The use of classical electric probes for studying plasma parameters of the high voltage pulsed discharges, encounters enormous difficulties. Besides the difficulty of a proper galvanic insulation of the probe required during the high voltage pulse, the probe can exert great influence over the plasma potential by the current that it draws from the plasma. In this paper, we proposed a new method for the determination of the electrical conductivity of the plasma in the afterglow of the high voltage pulsed discharges, using a low frequency RF plane probe. The application of a small low frequency signal to the plane probe could successfully eliminate all the disadvantages mentioned above.

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1. Introduction

Due to their exhibited advantages over continuous and RF glows, the pulsed discharges gain more attention in a wide variety of applications, like film deposition, plasma chemistry, semiconductor processing, etc. For this reason, fast time-resolved experimental methods need to be developed in order to control the main parameters of the high voltage pulsed plasmas.

It is well known that electric probes have the fundamental advantage over many other diagnostic techniques for studying plasma parameters, but the use of these probes in the high voltage pulsed plasmas encounters enormous difficulties. One of them is the necessity of a good galvanic insulation of the probe during the high voltage pulse. Also, the plasma potential may change rapidly, inducing spurious currents in the probe. Other problem could arise in the afterglow when the probe can exert great influence over the plasma potential by the current that it draws from the plasma.

In this paper, we proposed a new method for the determination of the electrical conductivity of the afterglow of the high voltage pulsed discharges, using a low frequency RF plane probe. The application of a small low frequency signal to the plane probe could successfully eliminate all the disadvantages mentioned above.

2. Experimental set-up

The experimental set-up is presented in Fig. 1.

The afterglow was produced under various discharge conditions; namely, the peak voltage across the tube of 4-20 kV, the peak current of 50-150 A, the half-width duration of the current pulse of 30-100 ns, the repetition rate of 30 Hz, and the neon pressure in the range 1-15 torr. High voltage pulses of short duration were obtained by discharging a storage capacitor through a rotary spark gap with a commutation time below 10 ns [1]. The discharge tube, made of glass, contains a cylindrical hollow cathode made of molybdenum (10 mm diameter and 30 mm length) and an anode consisting of two rings (10 mm diameter) made of stainless steel and placed symmetrically at the two ends of

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the cathode. The probe tip is the cross section of a tungsten wire with a diameter of 0.8 mm and its support is completely insulated from the plasma and from the cathode. The capacitance, ***C***, of the probe-cathode system in vacuum has a few pF, Fig. 2.

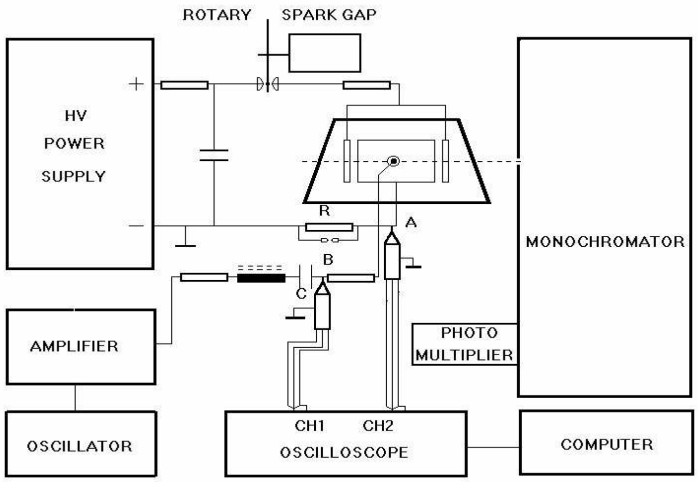
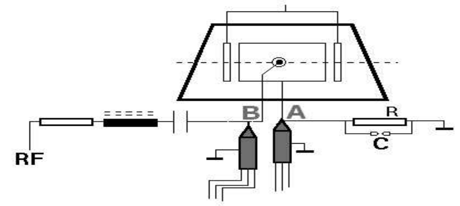


Fig. 1. Experimental setup.

A double-triode sinusoidal oscillator produces the RF signals, which are then amplified by a three-grid amplifier tube. This home made RF generator has the frequency adjustable in the range 90÷250 kHz and the amplitude in the range 0÷25 V. Since the RF signal is used for the high voltage pulsed discharge afterglow plasma diagnostics, high voltage pulses could reach the oscillator during the experiments. That is why we built a robust oscillator with electron tubes. Moreover, the RF source has been additional protected by a shock coil introduced in the probe circuit. We choose the period range of the RF signal to be much grater than the high voltage pulse width, so that the shock coil do not attenuate the RF signal. The signal was rectified by a diode 1N4448.

We chose the signal frequency in the range 90÷250 kHz so that it is much smaller than the electron-atom collision frequency in our temporal afterglow plasma and also much smaller than the proper plasma frequency. In these conditions according to basic results in reference [2], the presence of the ionized gas into the probe– cathode gap, acts like an extra resistance ***r*** mounted in parallel to the capacitor ***C*** of the gap, as it can be seen in Fig. 2.

The RF probe circuit has been conceived in order to measure the plasma resistance between the probe and the reference electrode (the cathode) at different moments in the temporal afterglow by measuring the time evolution of the current and the voltage of the probe during the afterglow.



Equivalent RF circuit

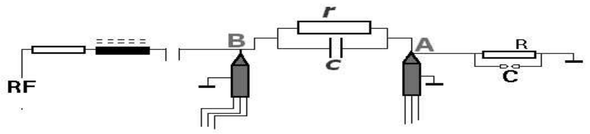


Fig. 2. The equivalent RF circuit.

During the afterglow, when there is no current between anode and cathode, we could record the current of the probe circuit by measuring the voltage across the variable resistor **R** connected between the tube cathode and the ground (point A in the Fig. 1). In order to avoid the high voltage pulse broadening we mounted a small spark-gap **C** in parallel to the variable resistor **R**. In this way the resistor doesn't influence the time constant of the pulsed discharge circuit and it becomes active only during the afterglow. The RF voltage across the the probe– cathode gap is the difference between signals measured in point B and in point A.

The voltage and current measurements have been measured simultaneous with TEKTRONIX probes and recorded on a TEKTRONIX 2432A oscilloscope connected to an IBM computer through an IEEE-488 AT-GPIB interface

3. Results and discussion

The insertion of the probe (the capacitor ***c***) in a series RLC RF circuit, being initially at resonance, introduces a difference of phase between the voltages measured in points A and B, depending on the applied frequency and on the variable resistance **R**. The presence of the afterglow plasma in the discharge tube (which means that the capacity ***c*** is shunted by the time variable resistance ***r*** of the plasma) modifies the difference of phase during the afterglow. In Fig. 3a and 3b are presented the positive alternation of the RF signals measured in point A and B representing the current and the voltage probe signals in the afterglow of the high voltage discharge in neon at 5.5 torr. In the experimental conditions: the applied RF signal frequency 150kHz, the resistance R of the external circuit 3 kΩ the two RF probe signals are in phase at 29 μs in the afterglow, Fig. 3c.

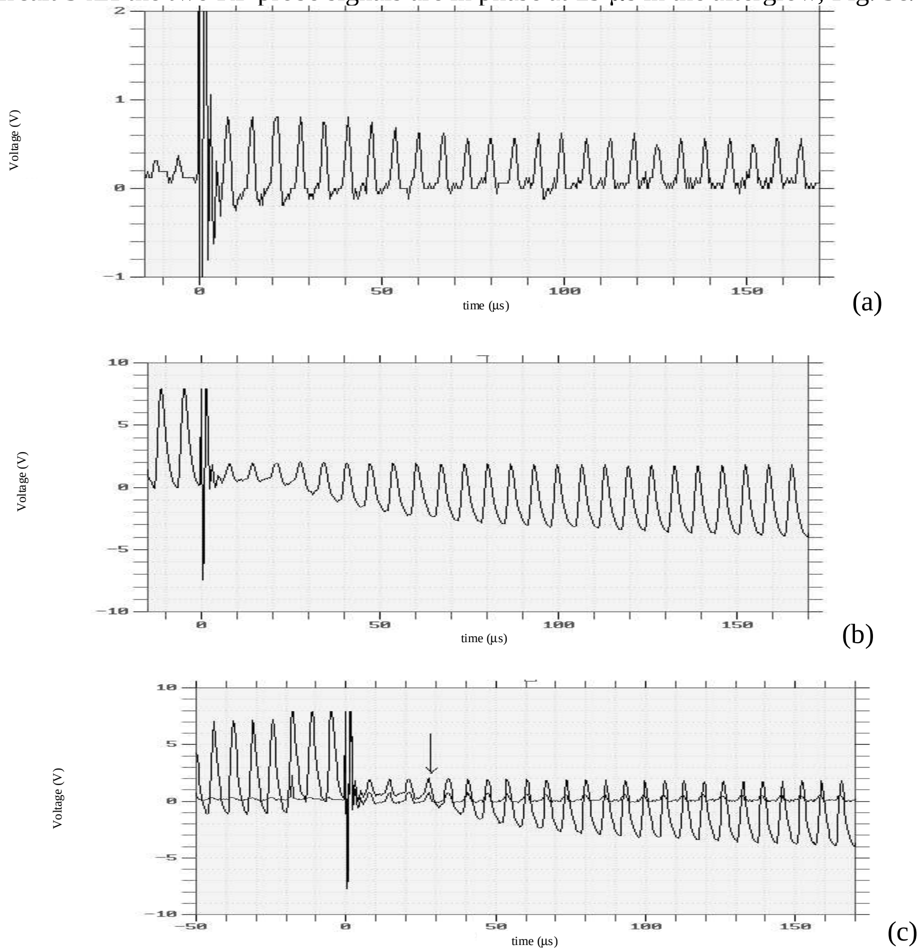


Fig. 3. The temporal evolution of the probe current (a), the probe voltage (b) and the current and voltage RF probe signals, the current and voltage RF probe signals (c).

Choosing the spark gap capacity **C** to be equal to the probe-cathode capacity ***C***, simple calculations, roughly lead to the following formula for the phase difference when plasma is present in the discharge tube:

$$tg\ \varphi \cong \frac{\omega CR\ (R - r)}{R + r + \omega^2 C^2 R\,(R^2 + r^2)} \tag{1}$$

As it can be seen from the formula, when the phase difference between current and voltage is zero, the resistance ***r*** (that depends on plasma resistivity) is equal to R. Thus, varying the circuit resistance R from 9 to 500 kΩ we could determine the resistance ***r*** at different moments during the afterglow.

Taking into account the surface of the plane probe and the distance probe - cathode, we could plot the afterglow plasma conductivity at different moments during the afterglow, Fig. 4.

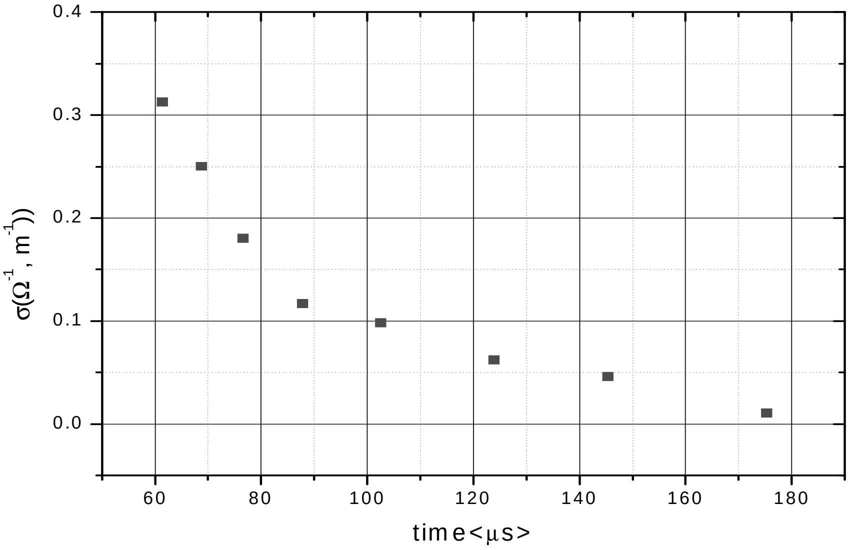


Fig. 4. Temporal evolution of conductivity in the afterglow of a hollow cathode pulsed discharge.

It is well known that the ionized gas conductivity is

$$\sigma = \frac{ne^2}{\nu_c m} \tag{2}$$

where n = is the charge density (in our case electron density); m = is the charge mass (electron mass); e = electron charge; ν_c = collision frequency charge particle - neutral atom in the plasma $\nu_c = \frac{\bar{v}}{\lambda} = \sigma N \sqrt{\frac{3kT}{m}}$ with T = electron temperature, σ = kinetic cross section, N = the density of the neutral atoms. When the positive alternation of the RF signal is applied, the electrons assure the conductivity of the plasma, in our experimental conditions. Taking into account that in the afterglow temporal range 20 – 100 μs, the electron temperature is constant and equal to 0.4 eV [4] and the collision frequency electron - atom is about 2×10^9 Hz, it is now possible to determine the electron density. The Fig. 7 (a) presents the temporal evolution of the electron density during the afterglow of a high voltage pulsed discharge in neon at 5 Torr pressure.

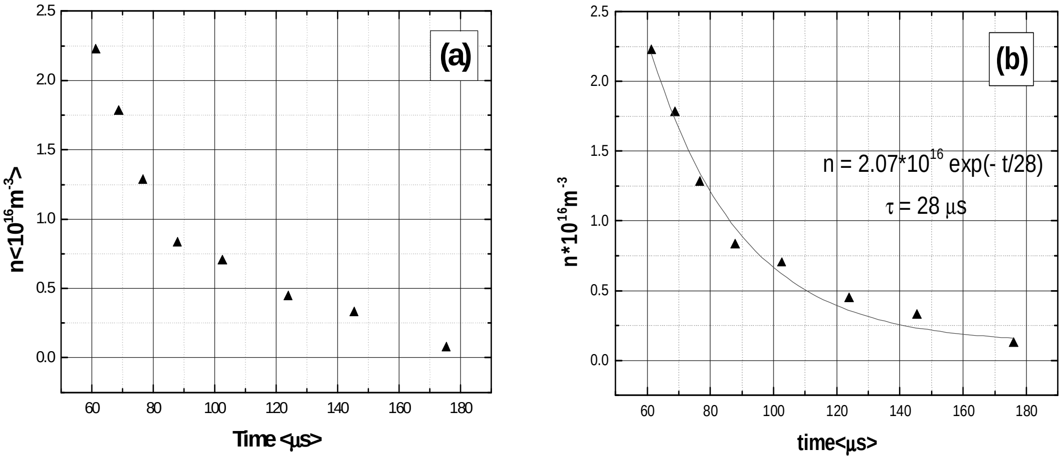


Fig. 7. The temporal evolution of the electron density during the afterglow (a), the fitting curve with the diffusion time of electrons (b).

Assuming that in our experimental conditions the afterglow plasma is dominated by the diffusion with a constant coefficient $\mathbf{D_a}$, the electron concentration has an exponential decay $exp(-t/\tau)$ with a diffusion time $\tau = \frac{\Lambda^2}{D_a}$, where Λ is the diffusion length. The fitting curve of the electron density data obtained in the temporal range 80 –180 µs in the afterglow of a high voltage pulsed discharge is presented in Fig. 7b .

The obtained diffusion time ≈ 28 µs is in good agreement with the value 27.6 µs obtained from theoretical calculus:

$$\frac{1}{\tau_e} = \frac{kT_{gas}}{\Lambda^2 p_{Ne}\sigma}\sqrt{\frac{\pi k T_{gas}}{8 m_{N^+e}}}\left(1+\frac{T_e}{T_{gas}}\right) \qquad (3)$$

where $p_{Ne} = 5\ Torr$, $T_{gas} = 2100\ K$ [3], $\Lambda = 4.3\ mm$, $T_e = 3430$ K [4], $\sigma = 10^{-15}$ cm^2.

4. Conclusions

The new low frequency RF probe technique proposed in this paper is a convenient method for the temporal afterglow plasma diagnostics. Measuring the plasma conductivity in different electrical circuit configurations, this method allows the determination of the electron and ion density at various moments in the afterglow. In this paper, we determined the temporal evolution of the electron density in the neon afterglow plasma, the experimental diffusion time being in good agreement with the theoretical value.

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