Investigation of the Electron Energy Distribution Function in Capacitively Coupled (13.56 MHz) Radio Frequency Discharge in Dry Air

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ABSTRACT

In this study, the electron energy distribution function in capacitively coupled radio frequency dry air discharge in three different regions along discharge tube was measured. It was observed that all regions do have Fermi electron energy distribution function which increases in magnitude with increasing the applied power, and decreasing with increasing the internal pressure. This function magnitude reaches its highest value near the powered electrode, while it decreases towards the earthed one.

Keywords : Capacitively coupled radio frequency, Electron Energy Distribution Function (EEDF)

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INTRODUCTION

Radio frequency discharge

RF discharges were introduced in the 19th century when RF power generators with sufficient power became available. However, for a long time, these discharges did not have any practical applications, because RF power supplies and RF diagnostic equipments were not readily available. It was much easier and cheaper to produce direct current (DC) discharges than RF discharges. In RF discharges, electrodes can be placed outside the main discharge chamber in which the plasma contact with electrodes can be avoided. This is impossible to achieve with DC discharges since they can not operate in open electric circuits (Chirokov, 2005).

RF discharge can be classified in two types :
1)   Capacitivly- coupled RF discharge (CC discharge)
2)   Inductively- coupled RF discharge (IC discharge)

Capacitively- coupled RF discharge

Capacitively-coupled RF discharge consists of two parallel electrodes separated by a small gap into which the plasma gas is fed, and RF currents and voltages are introduced through capacitive sheaths built across the electrodes. Electrodes shape and dimension can be identical (symmetrical) or asymmetrical. The importance of design comes from the fact that the resultant sheath in the steady discharge conditions is affected. The power supply of the CCRF source is always coupled through an impedance matcher (called "Matching network") to the powered electrode (Singh, 2004).

In conventional CCRF, a discharge plasma is generated by driving one electrode with a single RF power source, typically at 13.56 MHz (Lee *et al*., 2004).

An RF generator is connected to the matching box and then to the output of the matching box which are connected to the parallel plate electrodes (Staack, 2008).

Inductively-coupled RF discharge

Inductively-coupled plasma (ICP) sources are used extensively for etching and deposition of thin films in microelectronics manufacturing. Such sources can produce a high-density uniform plasma in a low pressure gas without the need for external magnetic fields (Ramamurthi *et al*., 2003).

In an inductively-coupled discharge, the RF power is coupled through an antenna (inductor), instead of a circular electrode, which produces an electromagnetic field and acts like a powered electrode. The ICRF discharges are run at a relatively low pressure and are characterized by high density, low electron temperature (compared to CCRF), which is very thin and have low voltage sheaths (Singh, 2004).

Electron energy distribution function (EEDF)

The most important parameter of a plasma source is the electron energy distribution function (EEDF) which contains all the information about electron temperature, plasma density and plasma potential (Anderie *et al*., 2003). It should also be known that the shape of such a

function is highly sensitive to the type of discharge and its parameters even in experiments with the same gas or gas mixture.

The basic trick used for obtaining the EEDF is the exploitation of the Druyvisteyn formula:

$$F(E) = \frac{(8mV)^{1/2}}{Ae^{3/2}\,n}\frac{d^2I}{dV^2} \qquad\qquad\qquad ….(1)$$

Where m is the electron mass, e is the electron charge, A is the probe area, n is the electron density, I is the probe current and V is the probe voltage (Azooz, 2008). EEDF could easily be computed from the second derivative of the voltage-current which was employed in order to extract the EEDF from the voltage-current characteristic of a Langmuir probe, either by using analog devices or numerical methods. When numerical methods are involved, usually the EEDF is obtained after two steps, the first one gives the second derivative of the electronic current and the second one gives the EEDF (Anderie *et al.*, 2003).

As various properties of the plasma depend on different parts of the EEDF, such as diffusion coefficients which depend on the bulk of the EEDF and ionization or excitation rates that depend on the tail of the EEDF. The determination of the whole distribution is compelling for a comprehensive characterization of the plasma. The notation of the temperatures for the various parts of the EEDF is often a poor approximation for describing the whole EEDF (Fischer and Dose, 1999).

Langmuir probes

Langmuir probe measurements are powerful and experimentally simple way to characterize basic plasma parameters, which have been widely used as plasma diagnostic since they were introduced in the 1920s (Kim, 2004).

There are three types of electrical probes, such as single Langmuir probe, multiple Langmuir probes and Mach probes or Gundestrup probes (Sicard *et al.*, 2005).

The main advantages of Langmuir probes include their ability to cover a wide range of plasma parameters that can be measured, spatially and their temporally resolved result and simplicity of construction and relatively low price (Lazovic *et al.*, 2009).
In this research we have used a single Langmuir probe as a simplest powerful tool for radio frequency discharge measurements.

The discharge used in these measurements is a capacitive RF discharge working at 13.56 M Hz. The RF tunable choke is connected just outside the probe and is calculated to be resonant at the fundamental RF discharge frequency. A resonant RF choke with a variable capacitor is tuned at the fundamental RF frequency acting as an RF filter (Shaer *et al.*, 2007).

Instrument design and implementation

The probe that we used in this research is the single Langmuir probe which is made of copper with diameter 0.65mm, inserted inside the discharge tube, as shown in Fig. (1). To avoid changing this probe to antenna for these radio waves, we should install a high impedance between a discharge plasma and the probe by using a chock of capacity and coil. This RF

tunable choke is connected just outside the probe and is calculated to be resonant at the fundamental RF discharge frequency. A resonant RF choke with a variable capacitor is tuned at the fundamental RF frequency acting as an RF filter (Shaer *et al.*, 2007).

The measuring has been done for different radio frequency powers, under different discharge tube pressures, in three different positions inside the discharge tube.
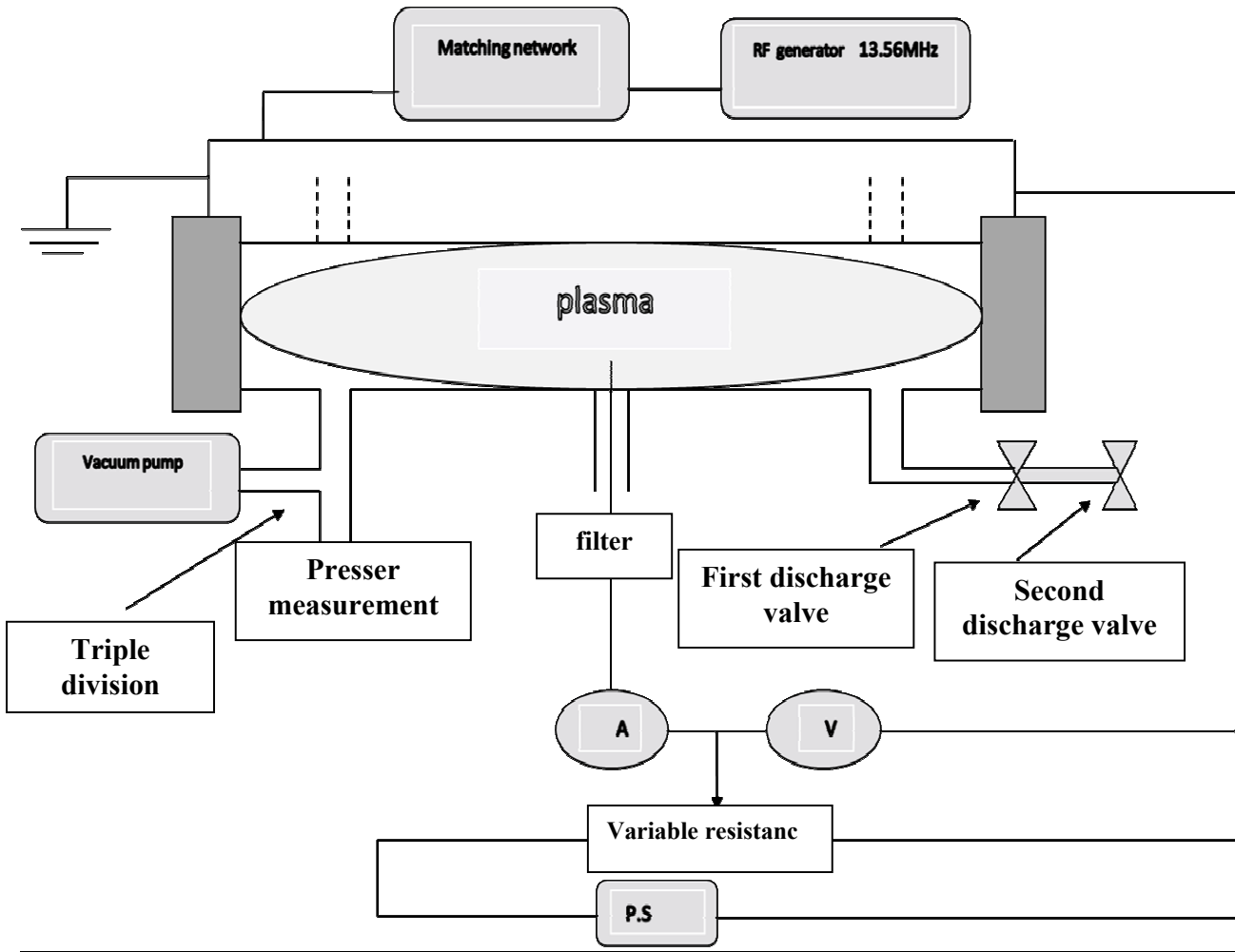

Fig. 1: The electrical circuit

RESULTS

We obtained the I-V characteristic for the single Langmuir probe under different operating circumstances (positions, applied power and pressure).

From the I-V characteristics of the single probe which was found in this research, we obtained the electron energy distribution function through calculating the second derivative of the ion current with respect to the probe potential, thus the plasma potential could be found.

Fig. (2) shows an experimental curve of single probe characteristic (dotty curve) and its fitting (solid curve). From these figures, we can see a good agreement with standard typical

curve of single probe characteristic near the power electrode, but the curves in the mid of discharge and near the earthed electrode had no agreement with these typical ones as shown in Fig. (3) and (4), (Shaer *et al*., 2007).
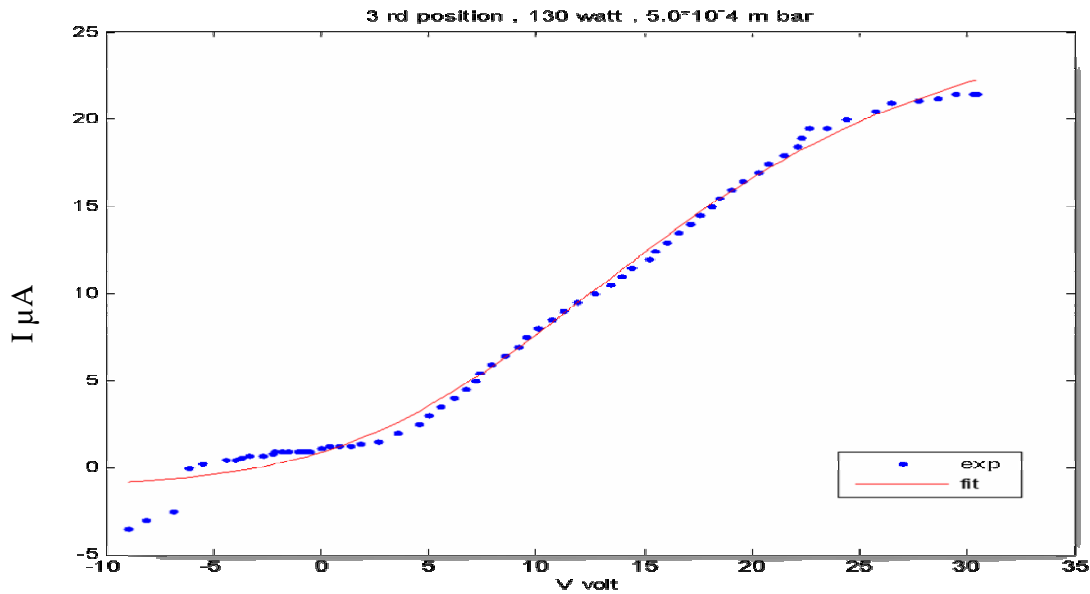

Fig. 2: I-V characteristic for single Langmuir probe in the position near the powered electrode (positive electrode) at power equal 130 watt and pressure 5.0×10^{-4} mbar.
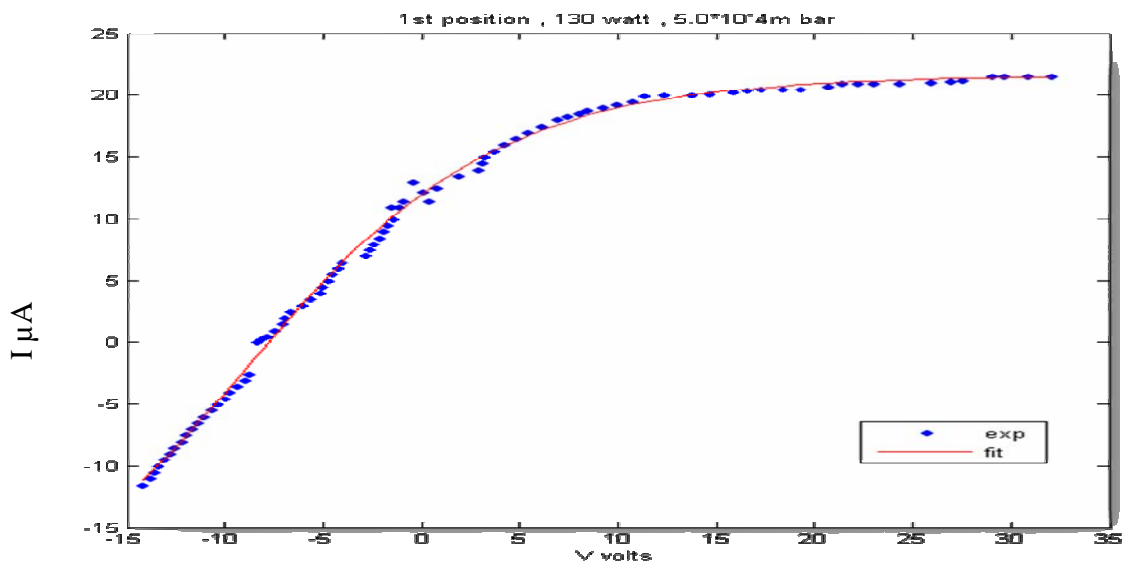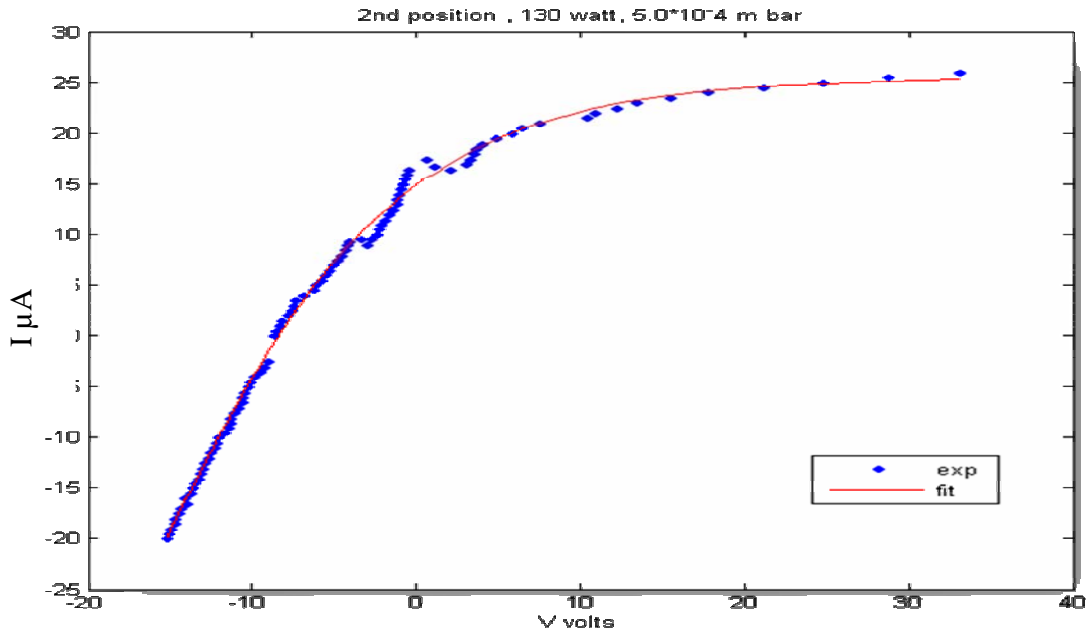

Fig. 3: I-V characteristic for single Langmuir probe in the position near the earthed electrode(negative electrode) at power equal 130 watt and pressure 5.0×10^{-4} mbar.

Fig. 4: I-V characteristic for single Langmuir probe in the mid of the discharge tube at power equal 130 watt and pressure $5.0×10^{-4}$ mbar

The I-V characteristic for a single Langmuir probe can be described by the expression :

$$I=exp[a_1 tanh((V+a_2)/a_3)]+a_4 \qquad \qquad ....(2)$$

As we know, the floating of single probe which is used in this work could not be a significant factor in calculating the plasma potential, so by taking the second derivative of equation (2), we obtain:

$$d^2I/dV^2=a_1[tanh^2((V+a_2)/a_3][2tanh((V+a_2)/a_3)- a_1$$
$$+(a_1/a_2)tanh^2((V+a_2)/a_3)]exp[a_1 tanh((V+a_2)/a_3)] \qquad ....(3)$$

Now to find the real plasma potential, equation (3) must be equal to zero (Azooz, 2008).

$$d^2I/dV^2=0 \qquad \qquad ....(4)$$

Figs. (5,6 and 7) show the value of plasma potential in the three regions (near the electrode powered, in the mid of the discharge tube and near the earthed electrode) which was obtained by using Matlab programming.
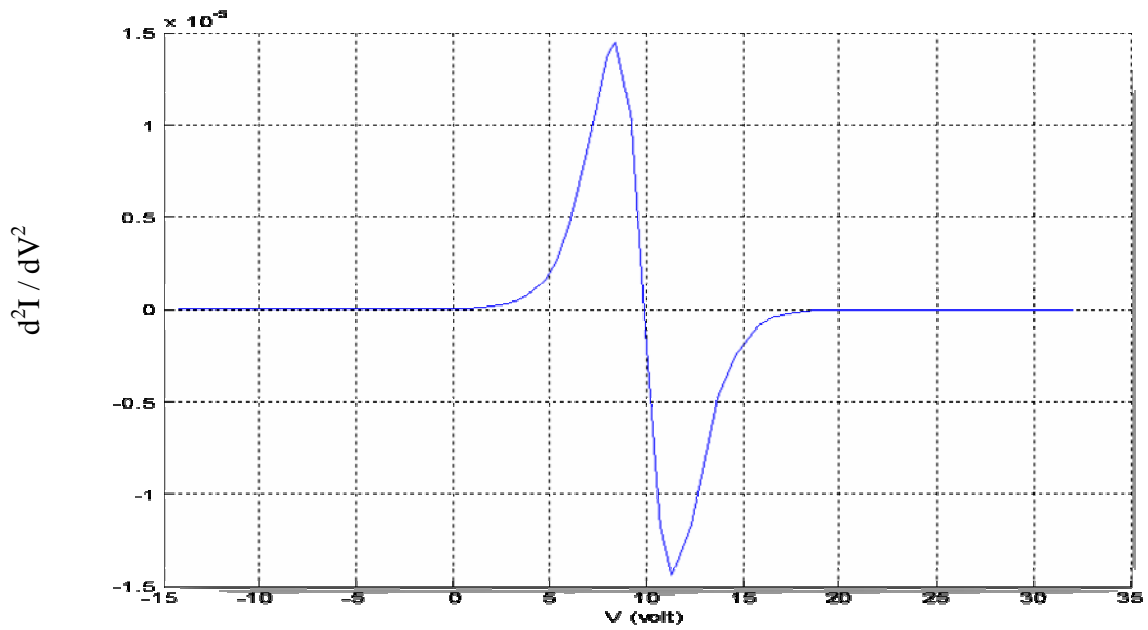
Fig. 5: The second derivative of the current with respect to the voltage near the earthed electrode
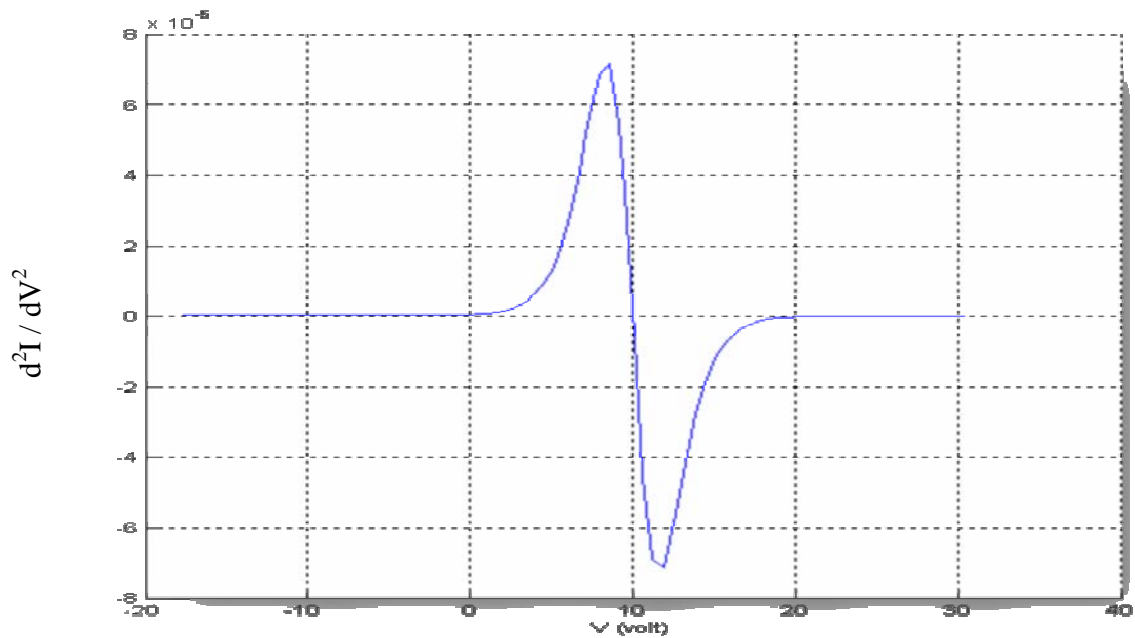

Fig. 6: The second derivative of the current with respect to the voltage in the mid of the discharge tube
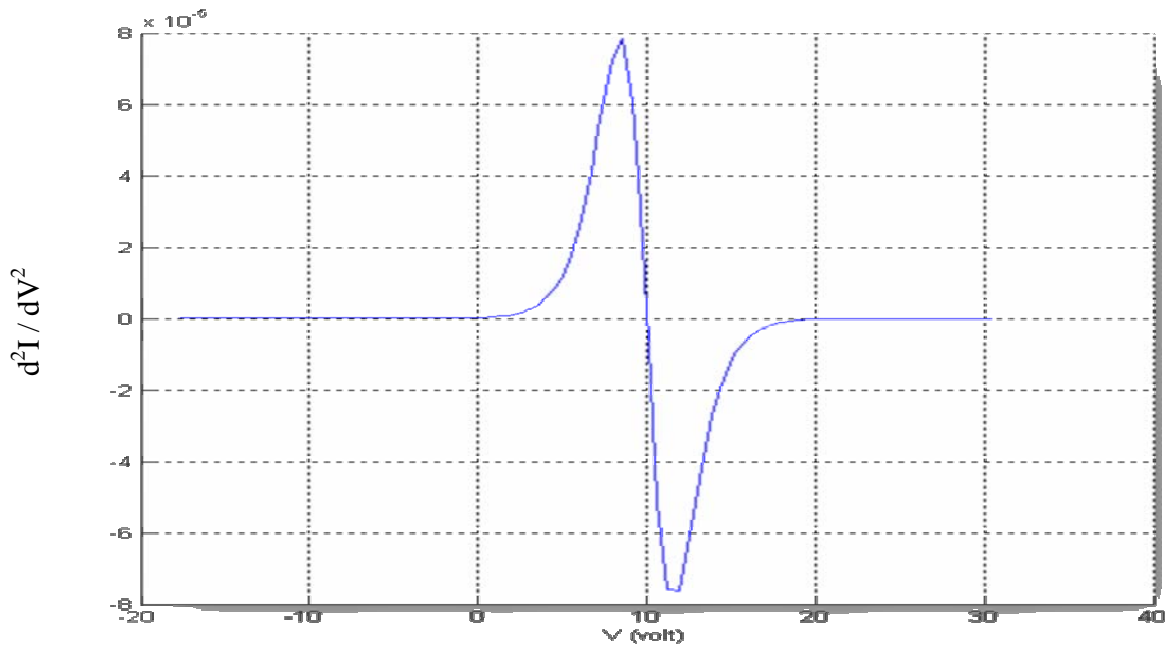
Fig. 7: The second derivative of the current with respect to the voltage near the powered electrode

Initially, the voltage at the negative electrode (earthed electrode) is sinusoidal with an average value equal to zero, while electrons oscillate at the frequency of the field. These oscillations are superimposed onto an arbitrary translation velocity, in which the displacement is in phase with the field while the velocity is out of phase by $\pi/2$. A sharp change in the direction of motion after oscillation stops the electron from achieving the full range of displacement that the applied force can produce. The electrons start a new oscillation after each collision with a new angle relative to the instantaneous direction of velocity. So, electrons are accelerated a way from cathode but the displacement is so small and could be negligible.

The potential at the cathode begins to go positive, so the effect of secondary ionization do actually appear, while electrons collide with the cathode, lowering its potential before the field direction is reversed then electrons are accelerated away increasing the potential value of this electrode. Soon and by this way, this electrode will be negative all the time of operating rf. Increasing the power of incident rf wave and internal pressure produce a higher plasma potential as shown in Fig. (8) and (9), (Aflori *et al.*, 2006).
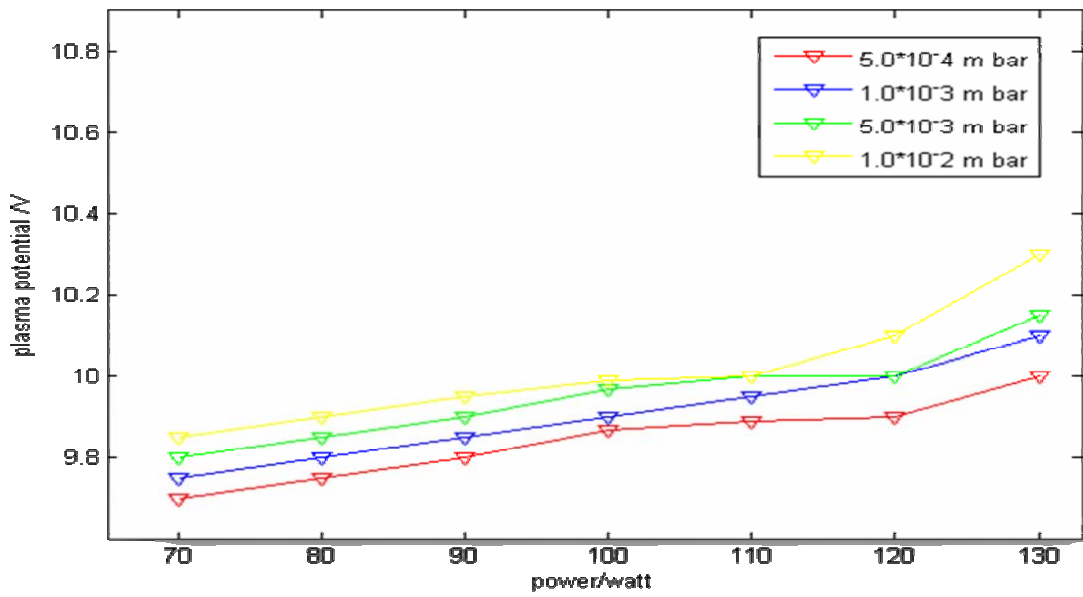
Fig. 8: The relation between plasma potential and the applied radio frequency power near the earthed electrode
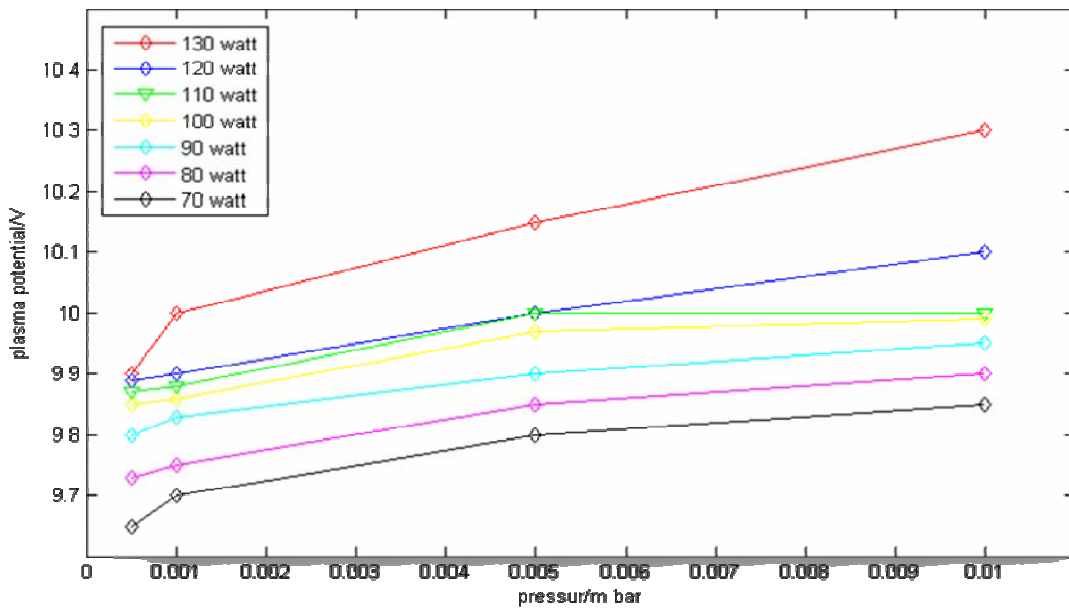

Fig. 9: The relation between plasma potential and the pressure near the earthed electrode

After we obtain the plasma potential for each curve of the I-V characteristic, we can measure the EEDF by using the second derivative for these curves in the conversion region of the current. Fig. (10) show the EEDF in the three positions inside the discharge tube, (near the powered electrode, in the middle of the tube and near the earthed one) at power of radio frequency 130watt and pressure 5.0×10^{-4} mbar.
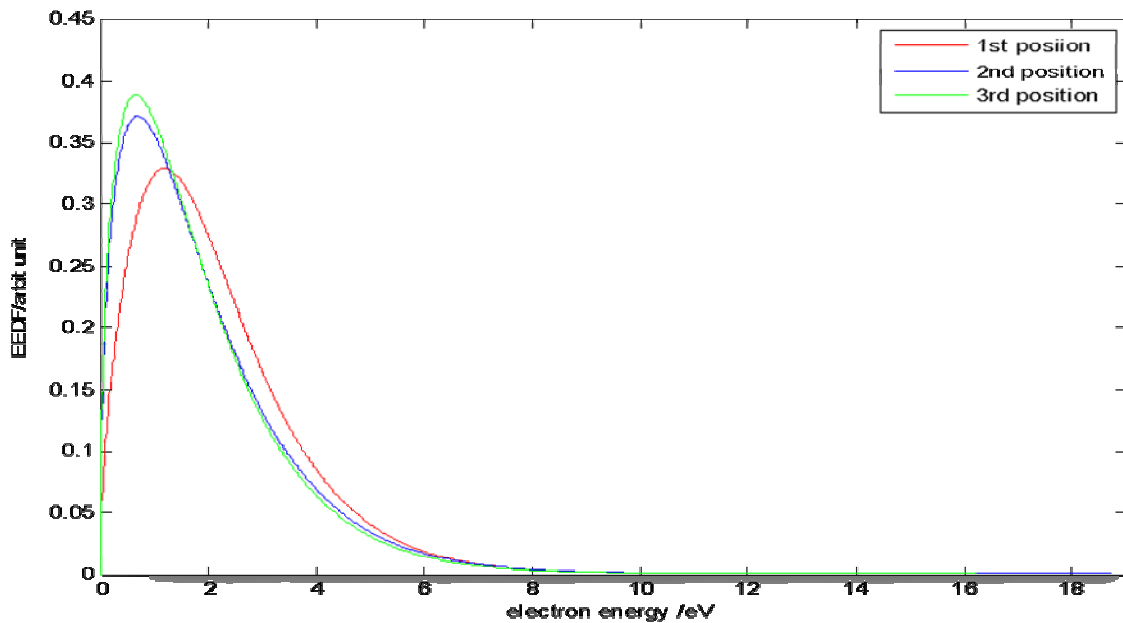

Fig. 10: The EEDF in the three position inside the discharge tube at power 130watt and pressure 5.0×10^{-4} mbar.

In comparison between these functions which were obtained in this study, one can conclude that these distribution functions do have a good agreement with Fermi distribution ones because most plasma electrons have spin equal to (1/2) as shown in Fig. (11) (Chen *et al.*, 2009) (Zakee, 2007) (Al-Jawaady, 2009).
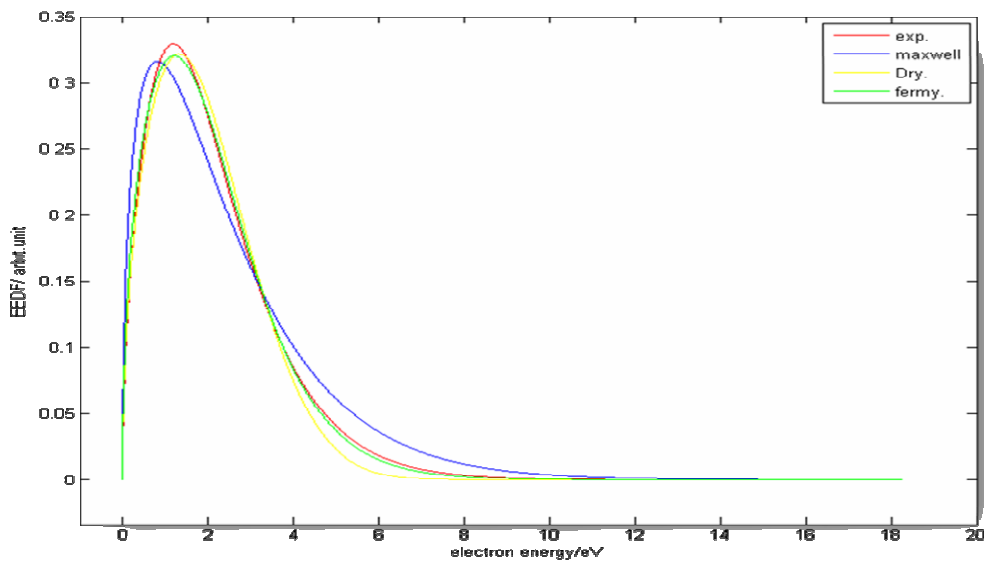
Fig. 11: **The EEDF compared with the normality functions (Fermi, Dryviston and Maxwell) near the earthed power at power 130 watt and pressure (5.0×10⁻⁴ m bar)**
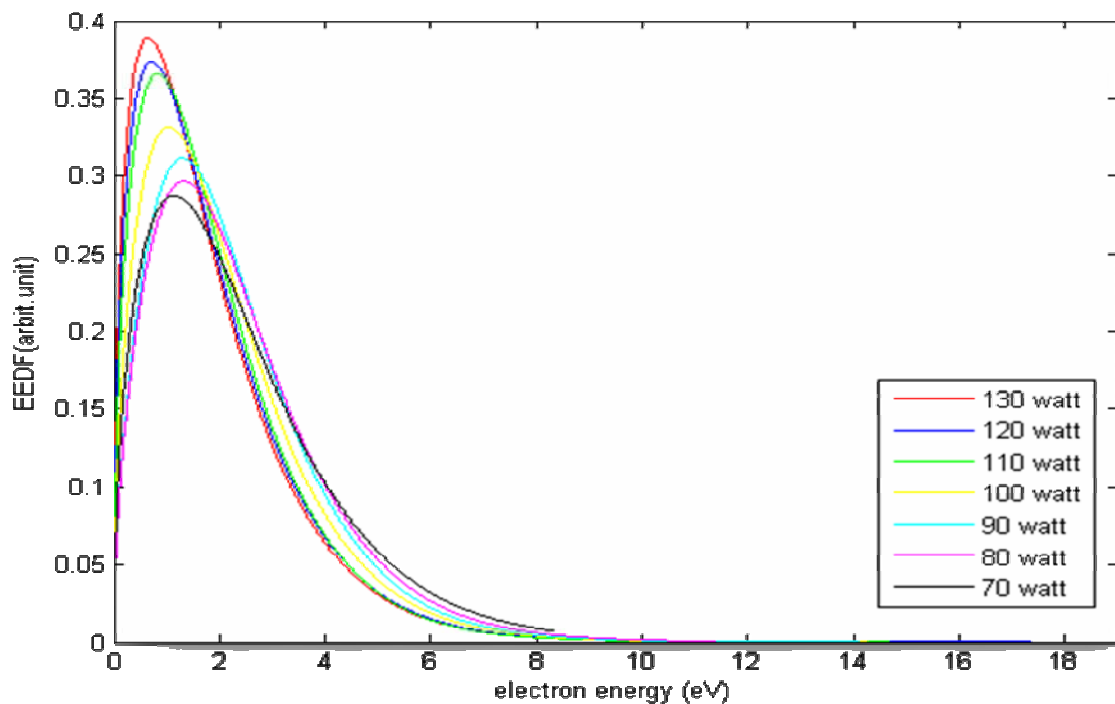

Fig. 12: The relation between EEDF near the positive electrode and different radio frequency powers

The change of electron energy distribution function with increased applied radio frequency power in pressure $(5.0 \times 10^{-4}$ m bar) near the positive electrode is shown in Fig. (12). From this figure we can conclude that the area under these curves increased by increasing the power of radio frequency wave which produced a discharge.

Fig. (13) show the dependence of electron energy distribution function magnitude on the internal pressure of discharge tube, such behavior may be attributed of plasma density changes with internal pressure.
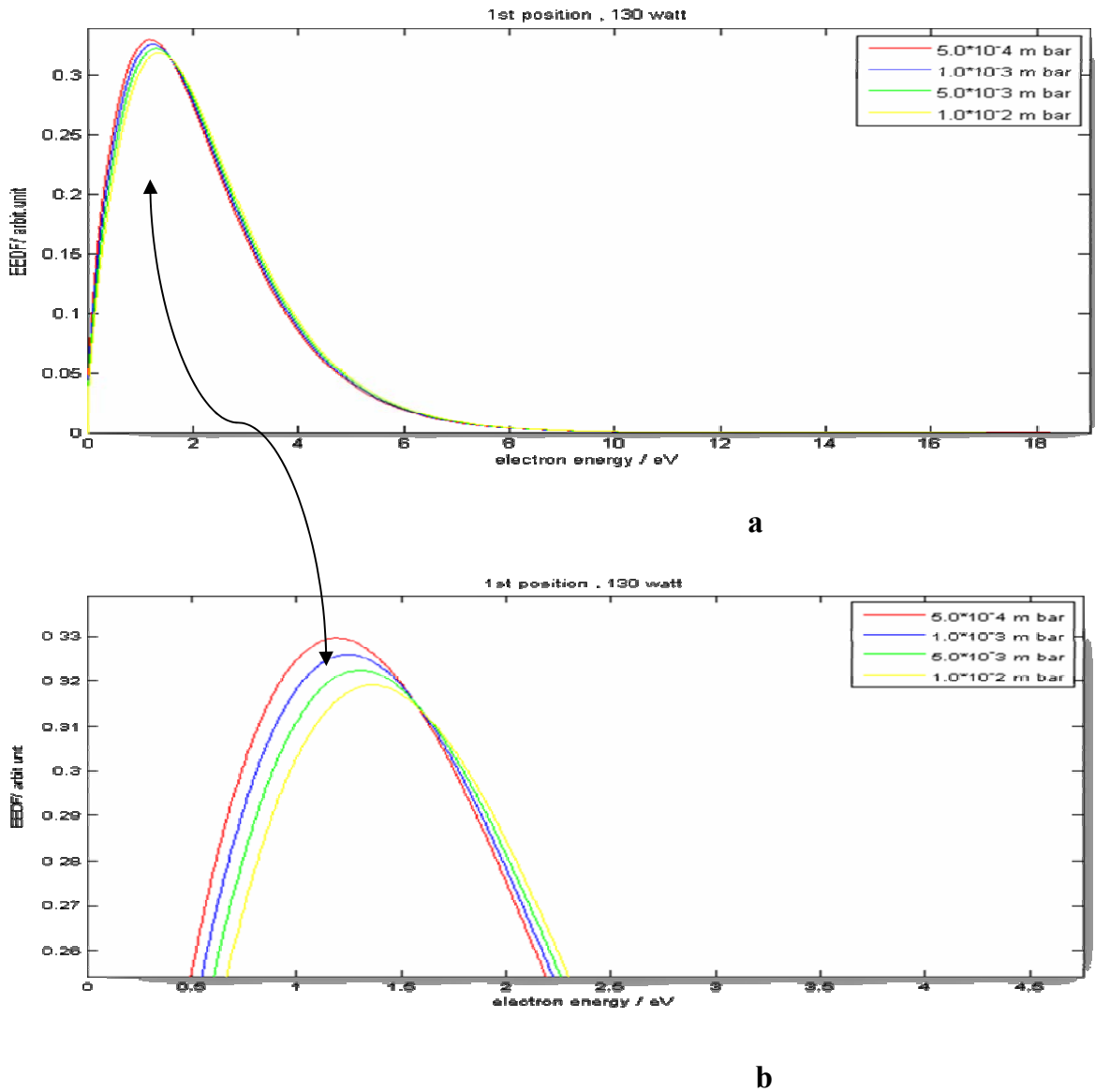
Fig. 13: The relation between EEDF with different pressure near the earthed electrode with power 130 watt (a), peaks section magnification (b)

CONCLUSION

We have investigated the EEDF in different regions along a capasitivly- coupled radio frequency discharge chamber. We have found the following features of the EEDF:

1- All functions in the regions of discharge gap did have a good agreement with Fermi distribution functions.

2- The area under these functions did increase with increasing radio frequency power which is namely influenced by plasma potential while this area decreases with the internal pressure increasing.

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