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Experimental Studies on DC Axial Virtual Cathode Electric Discharge

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A new modification is carried out on the axial virtual cathode oscillator to improve the device performance. The device operates, according to the virtual cathode theory, to generate high power microwaves from the interaction between the energetic electron beam and virtual cathode field. The electrical parameters are measured to understand the behavior of the discharge by the use of the nitrogen gas. The breakdown potential V_b against Pd is investigated. A single electric probe is used to measure and estimate the plasma parameters. The virtual cathode position is defined from the axial distribution of electron density, electric field and plasma potential. The position of the virtual cathode has been estimated to be at about 2 cm from the mesh anode which can be confirmed from changing the electric field direction and from the maximum value of plasma density in that position. The exposed samples to microwave radiation ensure the effects of the microwave radiation on them.

Keywords: DC Discharge, Axial vircator, Virtual cathode, Microwave radiation, Electric probe, Itosan Nanoparticles/ 6 Mrcaptopurine / Cytotoxicity

Introduction

Vircator is one type of glow discharge (plasma device) which is modified to act as accelerator for electron beam leading to the current multiplication and is considered a source of high-power microwave. Vircators can operate within the frequency range of a few hundred megahertz to tens of gigahertz [1]. This device is redesigned to avoid some of the drawbacks such as the fixed anode-cathode space inability to work under pressure less than 10^{-2} Torr and difficulty in studying some of its applications. The development of this system will achieve a better understanding of its applications.

The principal mechanism of the virtual cathode oscillator is shown in Figure (1)

a) A uniform electron beam is ejected from the cathode and accelerated towards the diode gap where a DC high voltage is applied between the cathode and the anode.

b) The electron beam passes through the mesh anode and is injected into the area on the other side of the anode because the collision mean free path of the electrons is comparable or larger than the electrodes separation distance.

c) When the electron beam current becomes higher than the space charge limited current of the area behind the mesh, an electrostatic space charge potential is set up at a certain distance behind the mesh area (virtual cathode, vircator) [2].

d) Most of the incoming electrons can lose their kinetic energy at the virtual cathode and reflect back towards the injection position by Coulomb force or by the strong electric field around the virtual cathode.

e) The kinetic energy of the reflected electrons is modulated by the virtual cathode field and oscillates between the virtual and real cathodes.

f) At the same time, the position and amplitude of the virtual cathode field oscillate.

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g)The energetic oscillating electron beam interacts with the virtual cathode field when they oscillate with the same frequency and no phase shift to produce high power microwave [3].

The microwave field strength around the virtual cathode is an essential term for improving the efficiency of the microwave. This generally means that the virtual cathode area must be contained in a resonant cavity with volume and time larger than that of the interaction area. The cavity is useful to reduce the bandwidth, increase the efficiency and provide directional radiation [4, 5].

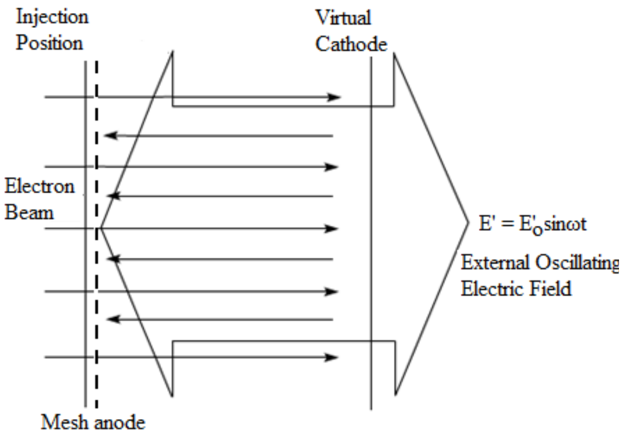

Figure (1) Simple model of axial vircator mechanism

Microwaves can be used in warfare as electromagnetic bombs [11]. Several experiments on polymer treatment with plasma showed that the polymer surface is modified in terms of surface energy, surface roughness and chemical composition, [12] so that it can be improved and become ready for various coatings.

Plasma is considered a source of electromagnetic spectrum with different frequencies and powers; each frequency has its own energy which enables it to be used in several applications such as polymer treatment. New designs and experimental studies have been carried out on vircator to improve the total current and to increase the microwave efficiency. [6-10]

Experimental Setup

An axial virtual cathode oscillator consists of an electron beam diode and a resonant cavity as most vircators is shown in Figure (2).

The diode is composed of two parallel circular electrodes. The two electrodes are brass mesh anodes connected to earth (zero potential) and a brass disc cathode connected to the negative potential of DC power supply which can provide a potential up to 3 KV and current up to 100 mA. The gap distance between the two electrodes is around 4 mm. The discharge vessel is evacuated to a basic pressure of $4x10^{-2}$ Torr.

The virtual cathode diode is enclosed in a discharge vessel. The vessel is made of Pyrex glass of 30 cm and 10 cm diameters. The cylinder is fixed with two aluminum flanges. The upper flange has a central hole for cathode connection and another one to introduce nitrogen gas inlet through a needle valve to keep a constant working gas pressure at $4x10^{-2}$ Torr or at any desired pressure. The lower flange has two ports, one for introducing the electric probe or introducing the sample and the other port is for the vacuum system. A single electric probe is used to determine the plasma parameters for nitrogen plasma, given gas pressure of $5x10^{-2}$ Torr and discharge current of 10 mA. The probe moves freely in the axial direction. The electron temperature is calculated from the slope of the logarithm of the electric probe current against the probe voltage. The electron density is calculated using the relation:

$$I_{es} = n_e A e \left(\frac{KT_e}{2\pi m_1}\right)^{\frac{1}{2}}$$

Where n_e is the electron density, A is the probe surface area, K is the Boltzmann constant, m_i is the ion mass, e the electron charge and T_e is the electron temperature.

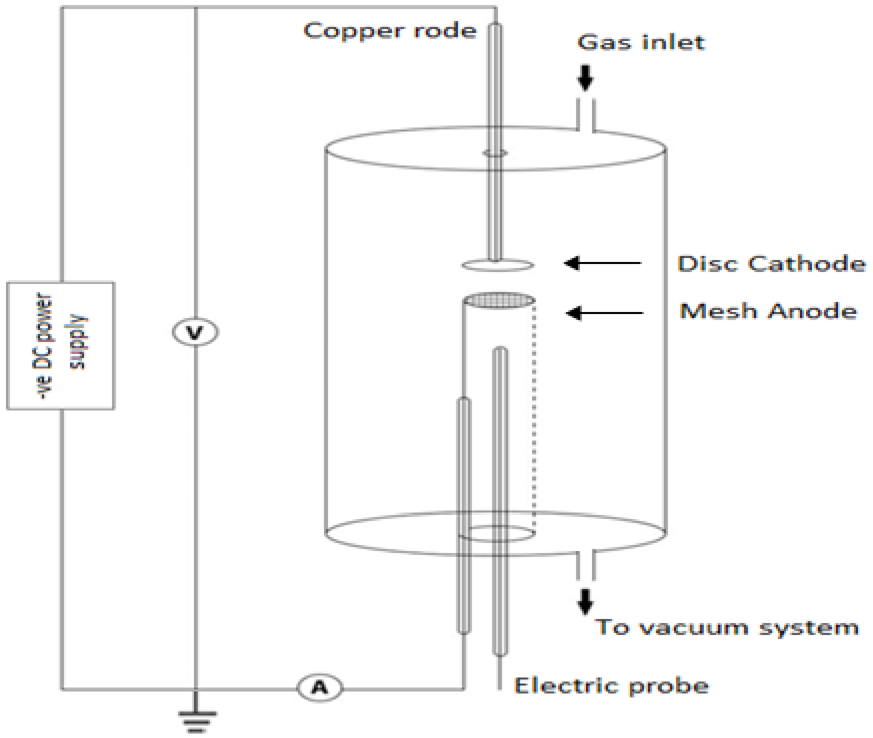

Figure (2) Schematic diagram of the system

Experimental Results

To understand the behavior of the discharge in the axial virtual cathode, the characteristic curve of a discharge is studied.

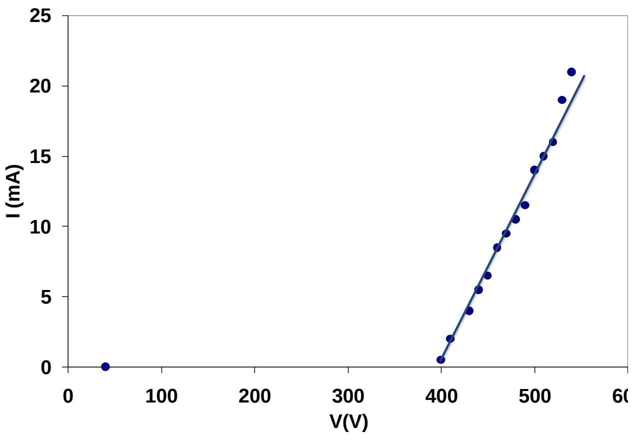

Figure (3) Voltage-current characteristic curve

Figure (3) shows the variation of discharge current as a function of discharge voltage. The discharge current starts at 400 V which is the breakdown voltage. At voltages greater than this value, the discharge current starts to increase sharply to reach its maximum value of 23 mA with consumed low energy. This is because the discharge becomes self-sustaining due to secondary electron emission. The region before breakdown voltage is the first and secondary Townsend region (dark region).

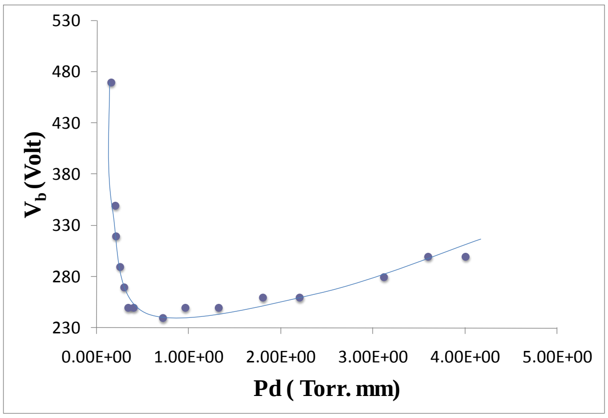

Figure (4) Paschen curve breakdown voltage V_b versus pd for Nitrogen gas

The Paschen's curve, presented in Figure (4), shows the relation between the breakdown voltage V_b and nitrogen gas pressure multiplied by the space between the mesh anode and disc cathode.

This relation has been presented by Von Engel as $V_b = C1(pd)/C2 + \ln(pd)$, where c_1 and c_2 are constants depending on the collision mean free path of the working gas [13]. It is clear from the curve that, the breakdown voltage decreases rapidly at the left hand side with the increase of the gas pressure till it reaches its minimum value at 240 V. In this region, the mean free path of ionization collisions between the electron and the atom is greater than the electrode separation distance, so the ionization process takes place behind the diode. Thus, the left-hand side of the curve is the best suitable condition for this experiment, where most of the neutral atoms are ionized outside the diode and the virtual cathode will be formed when the electron beam current at certain position exceeds the space charge limiting current at that position.

To study the plasma parameters such as the electron temperature, plasma density and potential that produced from the axial virtual cathode DC discharge, a single electric probe is used. [14,15]

The characteristic curve of the electric probe is shown in Figure (5) where the electric probe current is plotted against the applied voltage. From this curve, the electron temperature and density are estimated. Electron temperature is determined from the semi-log curve of the electron current I_e versus the probe voltage V_p.

Figure (6) presents the axial distribution of electron temperature. It is clear from the figure that there is more than one electron beam group; one is ejected from the real cathode, another is reflected from the virtual cathode and the third is formed due to beam-field interaction. It has been found that the electron temperature increase along the tube axis to reach its highest rate of 6 eV at a distance 4.5 cm from the mesh anode for first group and 10 eV at 5 cm for another electron beam.

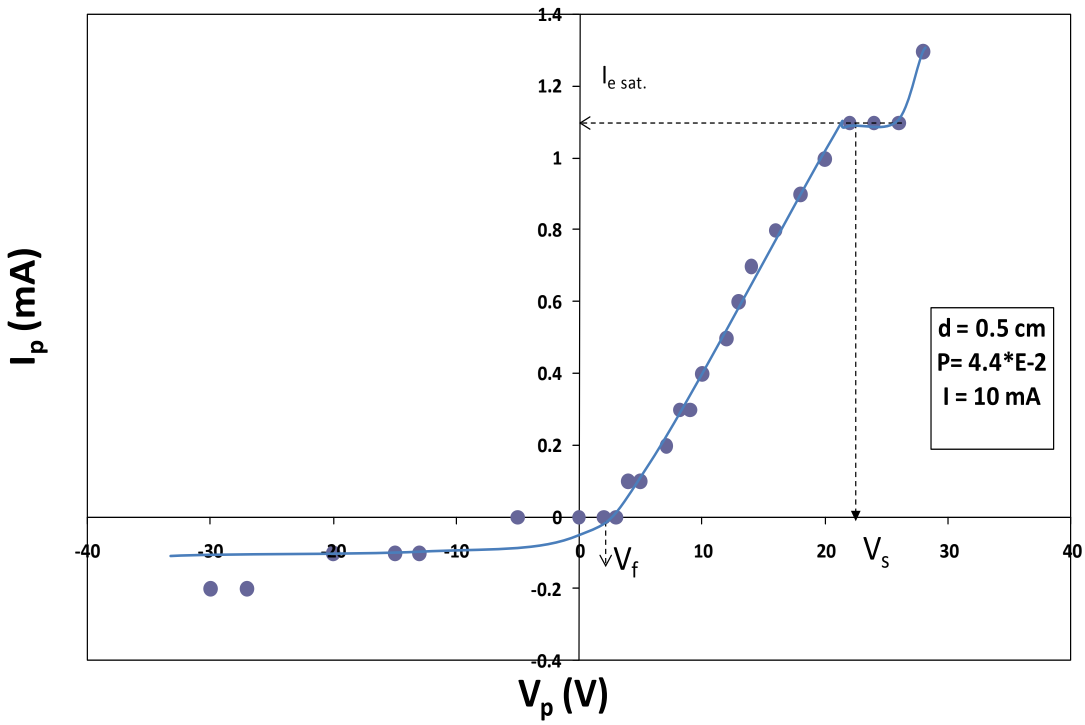

Figure (5) Characteristic curve of the electric probe

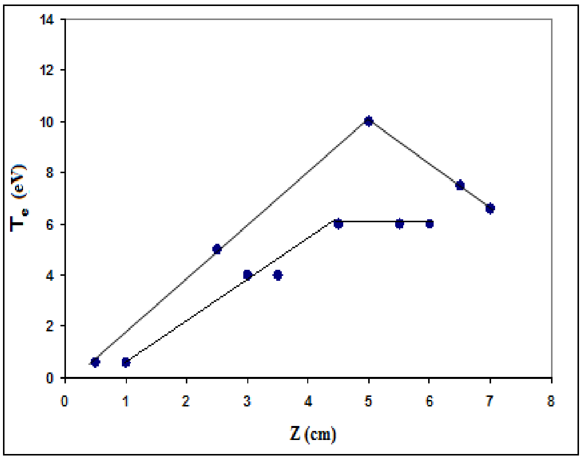

Figure (6) Axial distribution of the electron temperature

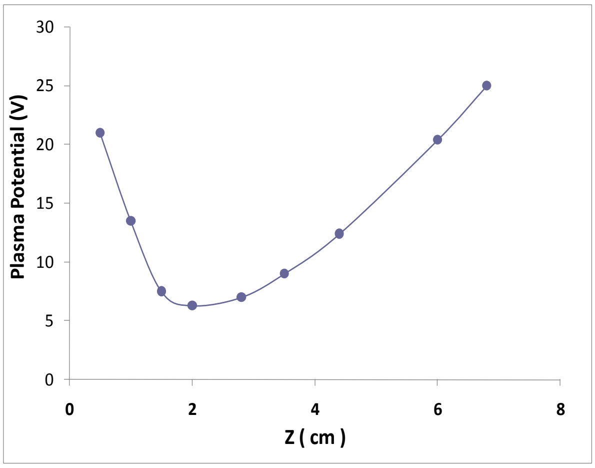

Figure (7) Axial distribution of the plasma potential

The axial distribution of plasma potential has been studied in Figure (7). The plasma potential is obtained from the maximum value of the first derivative of the probe's characteristic curve *I*p versus *V*p at different axial positions. It is noticed that the plasma potential decreases with increasing the axial direction to reach to its minimum value 5 V at Z = 2 cm because the negative charge is accumulated in the form of a dense cloud to act as a virtual cathode and the kinetic energy tends to zero. This region can be defined as the virtual cathode region. After the virtual cathode the potential strongly increases due to electromagnetic wave production.

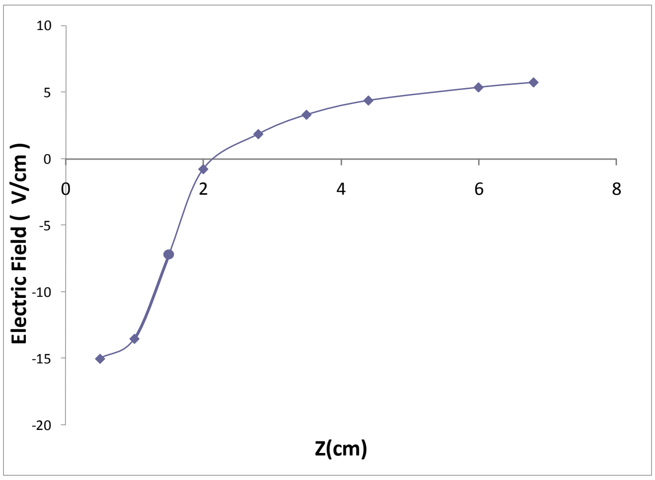

Figure (8) Axial distribution of the electric field

Figure (8) shows the axial distribution of the electric field, along the axes. The electric field is calculated from the axial plasma potential where $E = -grad\ \varphi$. It is found that the electric field changes its direction at a distance of 2cm from the mesh anode; this means that a new field affects the electron beam and changes its direction (virtual cathode field), or this may be due to the generation of a microwave field, having an opposite direction.

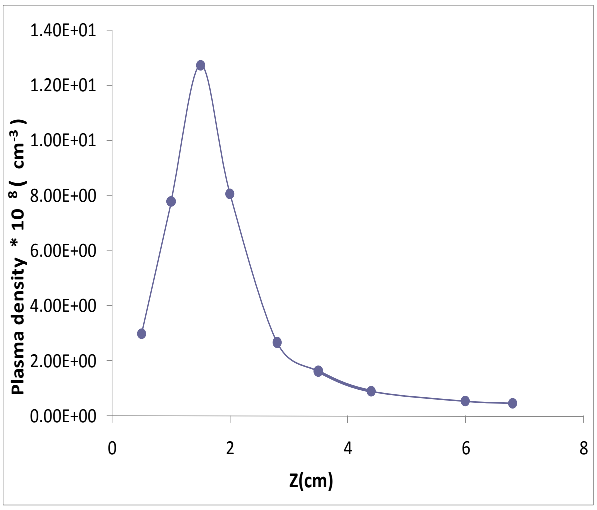

Figure (9) Axial distribution of the plasma density

Figure (9) illustrates the axial distribution of the plasma density for virtual cathode DC discharge plasma density obtained at different axial distance. It is clear that plasma density increases with the increase of the distance of the axial position from the mesh and reaches its maximum value of 13 x 10^8 cm^{-3} at z = 2 cm. This is may be due to the increase of ionization collisions with natural gas

outside the two electrodes which leads to the increase of the ionized
particles forming a dense plasma cloud with negative charge acting as a virtual cathode at 2cm distance from the mesh anode.
The position of the virtual cathode is estimated from the maximum density at a certain position and the minimum plasma potential at that point. The position of virtual cathode is estimated to be 2 cm from the mesh anode and is confirmed from the electric field when it changes its direction at that point as shown in Figure (8).

Effect of microwave radiation on different samples

The microwave radiation effect on different samples is studied. The experiment is carried out using a sheet of glass coated with transparent conductor (S_nO_2iF). The sample is exposed to microwave radiation for 5 minutes. The initial condition through treatment is the discharge current of 20 mA and the gas pressure of 5.6x10^{-2} Torr. Before treatment, the sample resistance was 34Ω while after treatment; the sample resistance becomes 5Ω then decreases to 3Ω after 10 minutes and never changes again, as shown in Figure (10).

This means that microwave radiation produces a transient voltage or shockwave leading to a decrease in the resistivity and increase in the conductivity of exposed sample, as well as having the same effect on any exposed electrical and electronic system. As a result, it leads to the damage of electrical conductors. This is the main concept behind the electromagnetic bomb, where the electromagnetic waves store their own energy and travel a million of miles through the space at the speed of light without losing this energy.

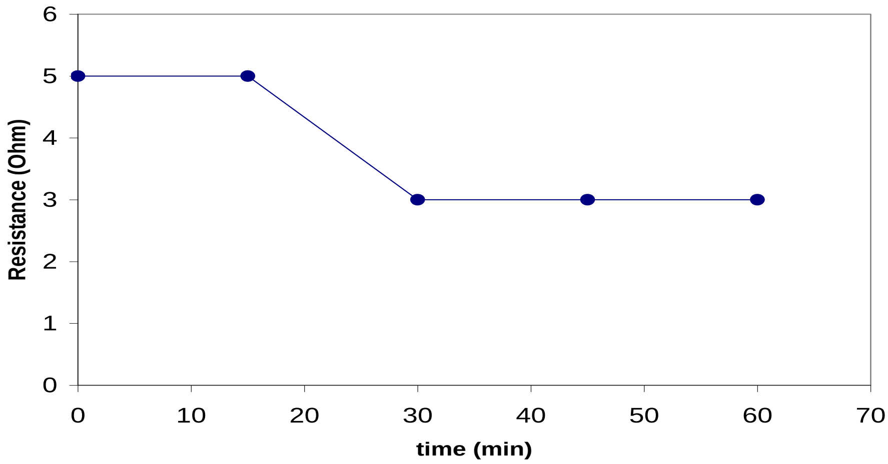

Figure (10) Resistance variation through time after treatment

In the second experiment polyester and of polystyrene are exposed to microwave radiation for 5 minutes at 5 cm distance from the mesh anode. The initial condition is a discharge current **equal to** 10mA and a gas pressure of 4 x10^{-2} Torr. After treatment, samples surface analysis is performed by Ftir Nicolet 1570 spectrometer. It is clear from Figs. (11 and 12) that the function group which is responsible for the chemical and physical properties of the matter, is changed after the treatment process. This means that the properties of polyester and polystyrene are changed after treatment, which gives a wide range of polymer applications.

Figure (13) shows a sheet of aluminum alloy exposed to microwave radiation for 15 minutes where the sample is placed at a distance of 5 cm from the mesh anode. The discharge current of 20 mA increases to 45 mA and nitrogen gas pressure is 6 x 10^{-2} Torr. Through the treatment, an increase in the gas density and gas conductivity, a change in the gas color are noticed. This operation can be explained in terms of sputtering of the aluminum surface, which introduces particulates that increase the density and flow more current so the discharge current jumps up. Having sputtered species in the discharge will induce a color change, not only in the nitrogen, but in nitrogen and aluminum particulates.

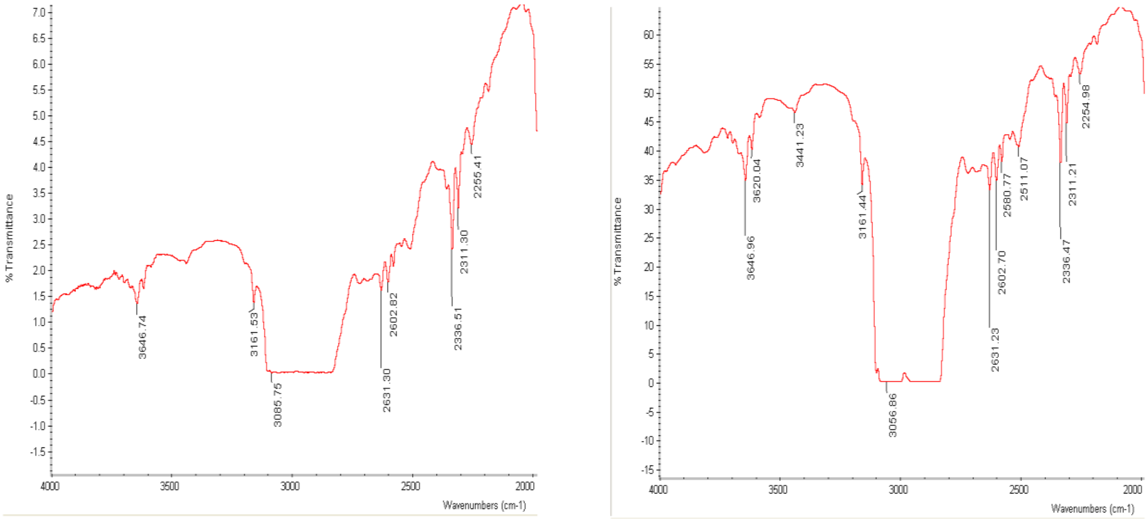

Figure (11) Polystyrene samples before and after treatment by microwave radiation

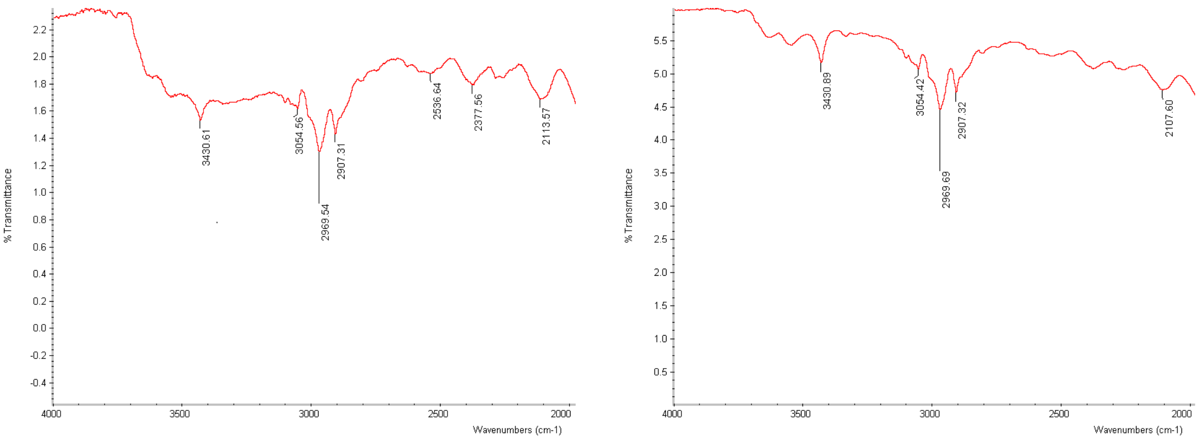

Figure (12) Polyester samples before and after treatment by microwave radiation

Figure (13) Aluminum sample exposed to microwave radiation

Conclusion

A new type of DC glow discharge operated by virtual cathode theory, using nitrogen gas, has been studied. The maximum electron temperature reaches its highest value of 10 eV at distance 5 cm from the mesh anode. From the axial plasma density distribution, the maximum value of plasma density is 13 x 10^8 cm^{-3} at z = 2 cm from the mesh anode; due to forming a dense cloud of negative charge acting as a virtual cathode around this point. The plasma potential decreases through the axis to reach its minimum value of nearly 15 volts at z = 2cm, and this region is defined as virtual cathode. The electric field of the electron beam changes its direction at 2 cm from the mesh anode. This means that a new field (virtual cathode field) affects the beam and changes its direction. The position of the virtual cathode has been estimated to be at 2 cm from the mesh anode, which can be confirmed from the electric field changing its direction and from the highest plasma density and minimum plasma potential at that position. The microwave radiation has important applications. It can produce a transient voltage or shockwave leading to a decrease the resistivity and increase the conductivity of exposed electrical conductors. The microwave radiation is used to modify the function group of polymer surface.

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References

1-E.A. Gurnevich, P.V. Molchanov, “The effect of the electron-beam parameter spread on microwave generation in a three-cavity axial vircator”, IEEE Transactions on Plasma Science, 2014
2- J. Benford, J.A. Swegle, and E. Schamiloglu, “High Power Microwaves”, Second Edition, Series in Plasma Physics, Taylor & Francis, 2007
3-G.A. Mesyats, “Pulsed Power”, New York: Kluwer Academic: Plenum Publishers, 2004.
4-Amitava Roy, Sandeep Kumar Singh, Rakhee Menon, D. Senthil Kumar, Saket Khandekar, Vijay Bhaskar Somu, Susant Chottray, P.C. Saroj, K. V. Nagesh, K. C. Mittal and D. P. Chakravarthy," Pulse Width Variation of an Axial Vircator", *IEEE Trans. Plasma Sci.*, vol. 38, no. 7, Jul 2010.
5-Debabrata Biswas and Rghwedra Kumar, "Efficiency Enhancement of the Axial Vircator", *IEEE Trans. Plasma Sci.*, vol. 35, no. 2, 2007.
6-W. Jiang, H. Kitano, L. Huang, K. Masugata and K. Yatsui, IEEE Trans. Plasma Sci. 24, 187 (1996).
7-W. Jiang, K. Woolverton, J. Dickens, and M. Kristiansen, IEEE Trans. Plasma Sci. 27, 1538 (1999).
8-W. Jiang, J. Dickens, and M. Kristiansen, IEEE Trans. Plasma Sci. 27, 1538 (1999).
9-W. Jiag and M. Kristiansen, Am. Inst. Phys. 8, 8 (2001).
10-Alexander E. Dubinov, Alexey G. Petrik, “Virpertron: A novel approach for a virtual cathode oscillator design”, Physics of Plasmas 24, 073102 (2017)
11-*Libor DRAŽAN, Roman VRÁNA*, “Axial Vircator for Electronic Warfare Applications”, Proceedings of Czech and Slovak Technical Universities, vol. 18, no. 4, Radioengineering, 2009
12-“Plasma Polymerization”, (http://www.plasmaetch.com/plasma-polymerization.php), 2015
13-A. von Engel, Electric Plasmas, their Nature and Uses, Taylor and Francies, London and New York 1983.
14- N. A. Krall and A.W. Triveliece, Priciples of Plasmas, Physics, McGraw-Hill, New York 1973.
15- S. Glaston and R.H. Lovberg, Controlled Thermonuclear Reaction, Van Nostrand, Princton 1960.