ISSN 1330–0008
CODEN FIZAE4

CHARACTERISTICS OF DC PSEUDO-ELECTRIC (VIRTUAL CATHODE) DISCHARGE IN HELIUM GAS

M. A. SAUDY[a], A. I. EATAH[a] and M. M. MASOUD[b]

[a]*Physics Department, Faculty of Science, Ain Shams University, Cairo, Egypt*

[b]*Atomic Energy Authority, Egypt*

Received 5 May 2004; revised manuscript received 14 March 2005
Accepted 2 May 2005   Online 6 February 2006

The plasma properties of a DC pseudo-discharge have been studied in helium as working gas. The discharge takes place between a disc cathode and a mesh anode, similar to a pulsed virtual-cathode oscillator. It has been found that breakdown characteristics essentially deviate from the expected regular Paschen curves. The current-voltage characteristics of the DC discharge show that it occurs in the region of abnormal glow. The breakdown voltage increases with the decrease of working gas pressure. When the electron beam density increases, the plasma covers the whole surface of the discharge cell outside the electrodes. The plasma has a negative potential with respect to the mesh and the location of the virtual cathode has been measured at around 1 cm from the mesh anode. The axial and radial distributions of electron temperature and ion density have been measured using a double electric probe. The electron temperature has been found to vary between 0.4 and 1 eV and the ion density from 2.8×10^{10} to 4.5×10^{10} cm^{-3}, outside the electrodes. The plasma electron temperature was nearly constant along the axial and radial directions. The plasma density has been found to decrease with axial distance due to electron beam energy loss, and also decreased in the radial position due to diffusion to the discharge walls.

PACS numbers: 51.50.+v, 52.80.Hc   UDC 537.525

Keywords: DC pseudo-discharge in helium, breakdown characteristics, abnormal glow, electron temperature, ion density

1. Introduction

The pseudo-discharge is a low-pressure gas discharge located at the left branch of the Paschen curve. In this region, the mean free path for ionizing collisions of electrons is comparable or larger than the electrode separation [1]. In the present investigation, the discharge geometry consisted of a cathode and a mesh anode similar to that of the virtual cathode oscillators [2,3] for high-power microwave production, or to cathodic arc [4], but with an applied DC voltage. The discharge mechanisms can be described as follows: the mesh anode accelerates electrons which are released from the cathode generating the electron beam. In the region between the electrodes, the electron collisions with neutral atoms essentially do not occur. Most of electrons pass through the mesh and collide with the neutral atoms at an average distance equal to the electron mean free path, forming a negative glow region, similar to a DC glow discharge. Electrons from the negative glow region will be reflected to the mesh anode to close the discharge circuit. Hence, the negative glow region works as a virtual cathode. The theory of steady state virtual cathode formation was first published by M. Kristiansen et al. [5] and H. S. Uhm et al. [6]. The electron beam current density and electric field were obtained from the solution of the Poisson equation. The ratio of the cathode electron beam current and injection current, to the forward current has been calculated by Uhm et al. [7]. It depends on the electrode spacing and the length of the drift tube.

In this work, the DC (VC) pseudo plasma discharge was studied using a mesh anode and disk cathode. The results were obtained by applying a 3 kV potential difference between the electrodes, in helium at gas pressures in the range from 10^{-2} to 10^{-1} mbar.

2. *Experimental set-up*

The schematic diagram of the experimental set-up is shown in Fig. 1. The discharge takes place between the cathode and mesh-anode with the applied potential difference V. Electrons are accelerated in the region I between the two electrodes. The distance between the two electrodes, d, is less than or equal to the mean free

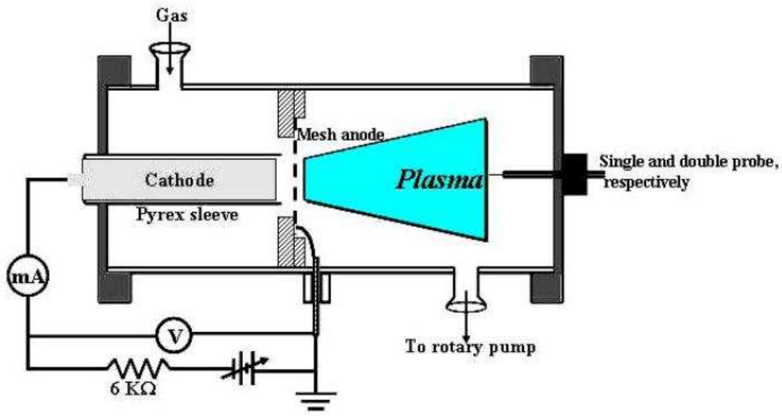

Fig. 1. Schematic diagram of the pseudo-discharge experiment.

path for electron-atom collisions (λ). Therefore, electrons are accelerated by V and propagate through the mesh to the expansion region II. There they collide with the gas atoms and form the plasma. The mesh will collect electrons from the plasma (back current). The discharge cell is a Pyrex cylinder with a 10 cm inner diameter and 25 cm long. The cathode is a copper rod of a 2 cm diameter and 10 cm long, and is placed in a Pyrex sleeve. The anode is a steel mesh with 30 holes per square inch and is placed at the distance of 4 mm from the cathode. The discharge volume was pumped to about 1.3 Pa (10^{-2} Torr, 1 Torr = 133.3 Pa) before its filling with the helium gas. Its pressure, P, was controlled by a needle valve. The discharge was sustained by using a DC power supply of 5 kV, using currents up to 30 mA. The cathode was connected to the negative potential terminal of the power supply, whereas the anode was at the ground potential. In the experiments, single and double electric probe techniques were used to determine the parameters of the glow discharge plasma region II. The plasma potential, electron temperature and ion density were measured by this technique.

3. *Experimental results and discussions*

Figure 2 shows the results obtained for the breakdown potential in helium gas as a function of the product Pd. For the left-hand branch of the curve, the breakdown potential (V_B) decreases rapidly with increasing Pd, which can be explained by the increase in the collision frequency, equivalent to an increase in the number of collisions between electrons and neutral atoms.

The minimum breakdown voltage was found to be 500 V at $Pd = 1.3$ m Pa (1 Torr cm). For the right-hand branch, the breakdown voltage increases slowly with

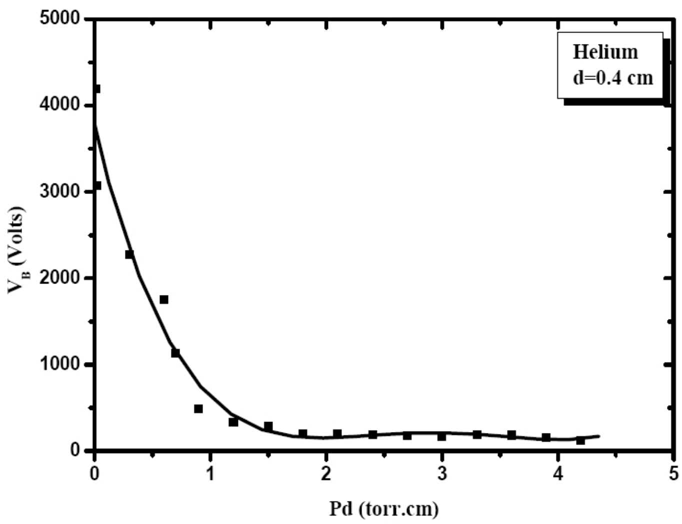

Fig. 2. Breakdown voltage V_B vs. Pd for helium discharge.

the increase of Pd, i.e. the ionization cross-section increases. Therefore, electrons need more energy to ionize the neutral atoms. The difference between this discharge and the normal DC glow discharges is that in the present discharge the neutral atoms are ionized outside the two electrodes.

Figure 3 shows the current–voltage characteristic curves of VC pseudo discharge with an electrode spacing of $d = 0.4$ cm, at helium gas pressures of 5.3, 8.0, 13.3 and 26.7 Pa (0.04, 0.06, 0.1 and 0.2 Torr). These $I-V$ curves show that the breakdown voltage increases when the gas pressure decreases. The glow covers the tube outside the two electrodes and an increase of the applied potential V leads to an increase in the electron beam current, and the glow becomes brighter. It is worth to point out that these curves differ from that of the DC glow discharge between two electrodes because in the glow discharge, the voltage drops after the start of breakdown to lower values and then grows with the increase of current. In the present work, when the discharge was started, an increase of voltage is required to increase the discharge current to sustain the discharge. Figure 4 shows an image of the plasma.

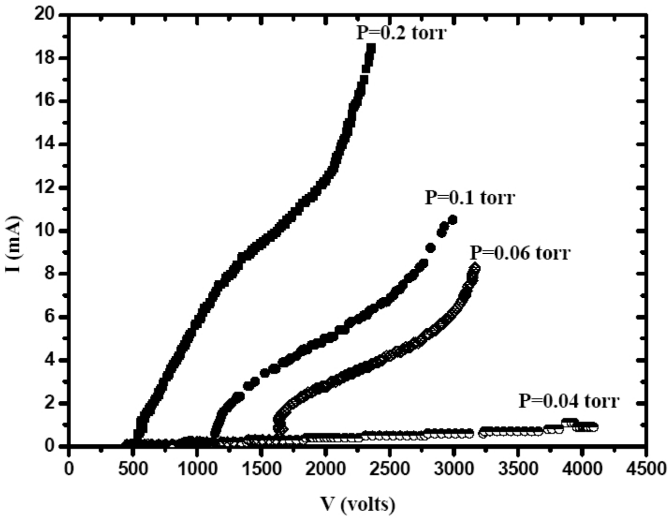

Fig. 3. Current–voltage characteristics of VC pseudo discharge.

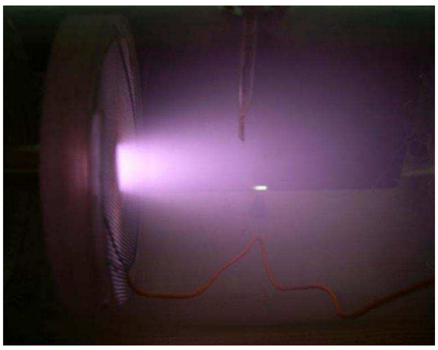

Fig. 4. Image of helium pseudo discharge.

Electrons gain energy by the potential difference between the electrodes. These electrons diffuse into the region II with an energy higher than the ionization energy and ionize neutral atoms [8]. A sheath is formed near the anode mesh surface, which acts as a virtual cathode.

The axial distribution of potential φ in the discharge tube, which is measured by a single electric probe (radius 0.3 mm) at two different pressures, is shown in Fig. 5. The plasma has a negative potential due to an excess of negative charge, which is accumulated in the virtual cathode region. The minimum potential was formed by the virtual negative cathode at a distance of around 1 cm from the mesh. The behavior is similar to the negative glow region in the hollow-cathode DC glow. The electric field distribution is calculated from the potential distribution using the relation $E = -\mathrm{d}\varphi/\mathrm{d}Z$, as shown in Fig. 6. The electric field profile shows clearly the space charge and the position of the virtual cathode.

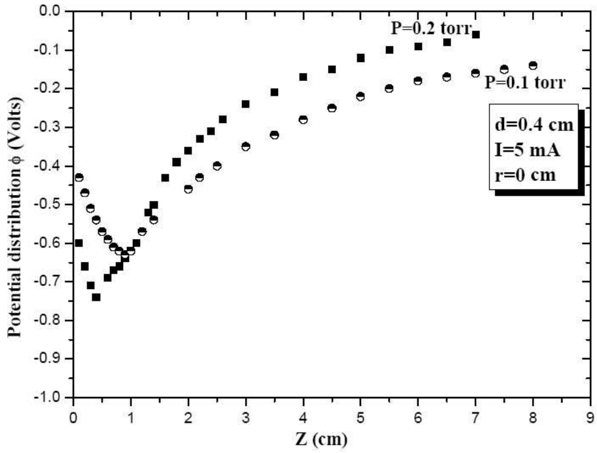

Fig. 5. Axial distribution of potential in the discharge tube.

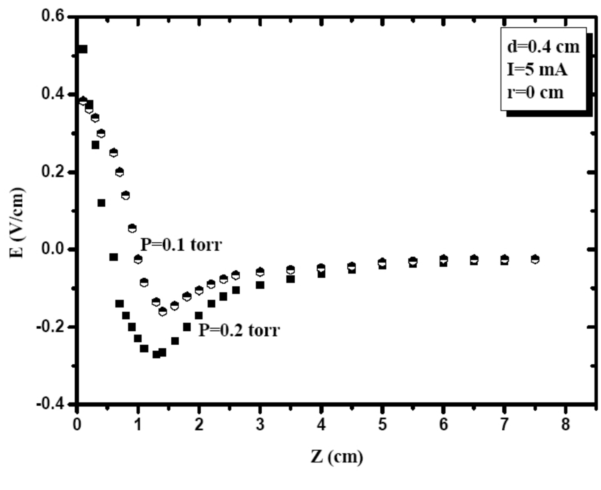

Fig. 6. Axial distribution of electric field in the discharge tube.

The axial distribution of electron temperature T_e is shown in Fig. 7. It is found that the electron temperature is nearly constant with axial distance for the pressures $P = 13.3$ and 26.7 Pa (0.1 and 0.2 Torr). The temperatures are 1.1 and 0.4 eV, respectively. The growth of T_e from low pressure compared to high pressure, is due to the high-power dissipation (increase of discharge potential while the current is constant). The electron energy was given by $E/P = V/(Pd)$. It is expected that the produced helium plasma has low temperature, too. This increase can be referred to the extended long life time of metastable helium atoms, which have a commutative ionization potential of 4.7 eV [9].

Figure 8 shows the ion density at helium pressure 13.3 and 26.7 Pa (0.1 and 0.2 Torr) in the region II as a function of the distance from the mesh Z. The ion density decreases from 4.2×10^{10} cm^{-3}, at $Z = 0.5$ cm, to 2.2×10^{10} cm^{-3} at $Z = 5$ cm for helium pressure 13.3 Pa (0.1 Torr). For the helium pressure 26.7 Pa (0.2 Torr), the ion density decreases from 3.8×10^{10} cm^{-3},

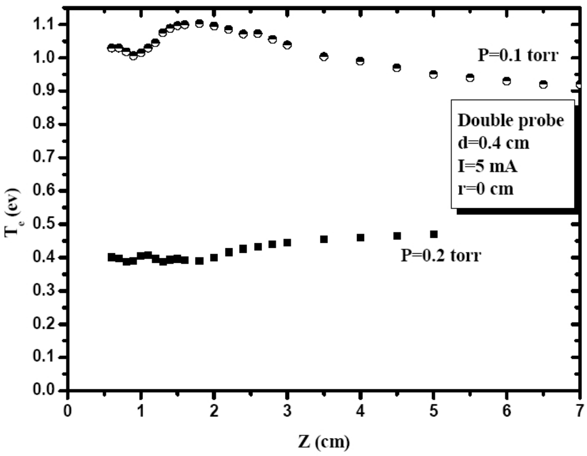

Fig. 7. Axial distribution of electron temperature.

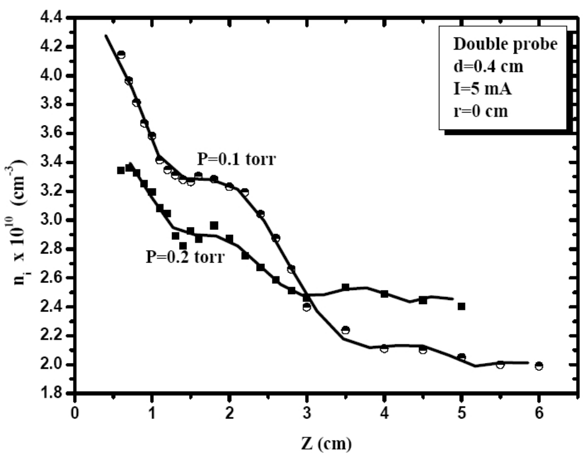

Fig. 8. Axial distribution of ion density.

at $Z = 0.5$ cm, to 2.5×10^{10} cm^{-3} at $Z = 5$ cm. This can be explained by the decrease of the electron beam energy, beside the diffusion to the chamber wall, and three-body recombination [10]. The ion density decays faster for low pressure than high pressure. This decay is related to the diffusion coefficient. As the temperature increases, the diffusion coefficient increases [9].

It has been found that the electron temperature did not change too much in the radial directions (see Fig. 9). It is assumed that any radial change of the electron beam energy is due the potential between the mesh anode and disk cathode. Figure 10 shows the radial ion density distribution, which has a maximum value of 4.5×10^{10} cm^{-3}, at the axis, $r = 0$. The measured decay of ion density with radius can be explained by the diffusion to the walls of the discharge chamber.

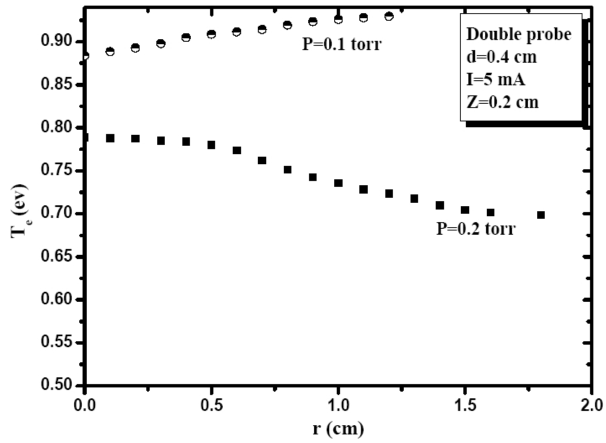

Fig. 9. Radial distribution of electron temperature.

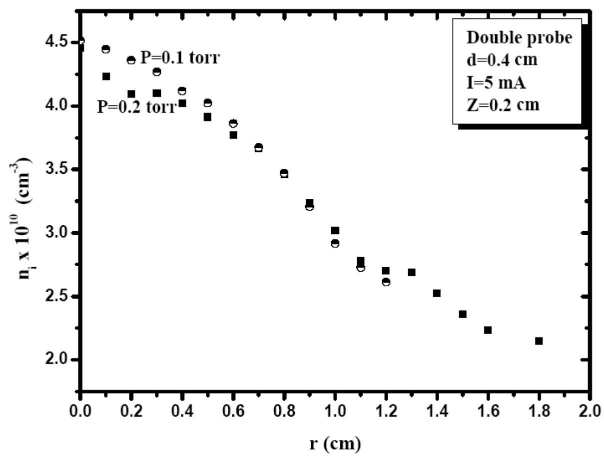

Fig. 10. Radial distribution of ion density.

4. Conclusion

In the present experiment, the characteristics of a VC pseudo discharge were investigated. The results of this experiment demonstrate that the breakdown voltage increases at lower helium gas pressure. The I – V curves show that the potential between the two electrodes increases monotonically with the increase of the discharge current. This behavior differs from that one of a DC glow discharge. With higher electron beam density, the plasma covers the entire expansion tube outside the two electrodes. The plasma had a negative potential and the virtual cathode had been detected at a position around 1 cm from the mesh. The electron temperature was of the order of 1 eV and nearly constant along the axial and radial directions. The ion density reaches a maximum value of 4.5×10^{10} cm^{-3} and decreases with axial distance due to the energy loss of the electron beam and decreases with radius due to diffusion to the discharge walls.

References

[1] J. Urban and K. Frank, *Proc. XXV ICPIG*, Japan **4** (2001) 203.

[2] C. D. Taylor and D. V. Giri, *A SUMMA book*, Taylor & Francis (1994) p. 7.

[3] W. Jiang, K. Masagata and K. Yatsui, Phys. Plasmas **2** (1994) 982.

[4] T. Zhang, B. Tang, Z. Zeng, Q. Chen and P. K. Chu, IEEE Trans. Plasma Sci. **27** (1999) 786.

[5] W. Jiang and M. Kristiansen, Phys. Plasmas **8** (2001) 3781.

[6] H. S. Uhm, E. H. Choi and M. C. Choi, Appl. Phys. Lett. **79** (2001) 913.

[7] H. S. Uhm, E. H. Choi and M. C. Choi, Appl. Phys. Lett. **81** (2002) 1532.

[8] K. H. Bai, J. I. Hong, S. J. You and H. Y.Chang, Phys. Plasmas **8** (2001) 4246.

[9] K. Kato, S. Lizuka and N. Sato, App. Phys. Lett. **65** (1994) 816.

[10] R. H. Huddlestone and S. L. Leonard, Academic Press INC (1965) 208.

ZNAČAJKE ISTOSMJERNOG PSEUDO-ELEKTRIČNOG (VIRTUALNO-KATODNOG) IZBOJA U HELIJU

Proučavali smo svojstva plazme u istosmjernom pseudo-izboju u heliju. Izboj je bio između kružne katode i mrežaste anode, slično pulsiranom oscilatoru s virtualnom katodom. Našli smo da značajke proboja znatno odstupaju od očekivanih prema običnim Paschenovim krivuljama. Krivulje struja – napon istosmjernog izboja ukazuju da se on dešava u području tinjavog izboja. Napon proboja se povećava smanjenjem tlaka helija. Nakon pojačanja gustoće elektronske struje uspostavi se plazma na cijeloj površini izbojne posude, izvan elektroda. U plazmi je negativan potencijal u odnosu na mrežastu anodu, i položaj virtualne katode se nalazi oko 1 cm iza te anode. Osnu i radijalnu raspodjelu temperature elektrona i ionsku gustoću mjerili smo pomoću dvostruke električne sonde. Našli smo elektronske temperature između 0.4 i 1 eV i ionsku gustoću od 2.8×10^{10} do 4.5×10^{10} cm^{-3} izvan elektroda. Temperatura elektrona u plazmi bila je gotovo stalna u osnom i radijalnom smjeru. Gustoća plazme se smanjivala u osnom smjeru zbog smanjenja energije elektronskog snopa, i također smanjivala u radijalnom smjeru zbog difuzije prema zidovima izbojne posude.