



ISSN: 0067-2904

The Effect of Axial Magnetic Field on The Breakdown Voltage of Air at Low Pressure

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Received: 20/12/2019

Accepted: 15/3/2020

Abstract

To add more details about the effect of the axial magnetic field on the plasma profile, the breakdown voltage of air was investigated at low pressure (9-15 Pa) in the presence of axial magnetic field (0.01-0.04T). The air was ignited by a DC voltage between two plain electrodes of aluminum separated by a distance (8.5cm). The measurements showed that the discharge voltage decreases to a minimum value, then returns to increase over the minimum with increasing the magnetic field strength, at all pressures in the range. It was also observed that a maximum decrease in the discharge voltage is obtained near the minimum of Paschen curve from the right side. The decrease in the discharge voltage was caused mainly by the effect of magnetic flux density on the diffusion of charged particles to the walls, especially on that of free electrons which were borne during the breakdown process.

Keywords: Breakdown voltage, Paschen curve, axial magnetic field, low pressure, air plasma.

تأثير المجال المغناطيسي المحوري على جهد انهيار الهواء عند الضغط المنخفض

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الخلاصة

لإضافة المزيد من التفاصيل حول تأثير المجال المغناطيسي في البلازما تم استقصاء فولتية الانهيار الكهربائي للهواء عند ضغوط واطئة (9-15Pa) وبوجود مجال مغناطيسي محوري (0.01-0.04T). لتوليد التفريغ الكهربائي في الهواء استخدمت فولتية مستمرة بين قطبين مستويين من الالمنيوم البعد بينهما (8.5cm). اظهرت القياسات بان زيادة كثافة الفيض المغناطيسي تؤدي الى نقصان فولتية الانهيار الكهربائي للهواء الى ادنى قيمة لها ثم تعود لتزداد فوق هذه القيمة مع زيادة كثافة الفيض المغناطيسي وعند جميع الضغوط ضمن المدى المذكور. لقد تبين ايضا بان اعظم نقصان فولتية الانهيار الكهربائي يحدث عند النهاية الصغرى لمنحن باشن من الجهة اليمنى وان النقصان في فولتية الانهيار الكهربائي ينتج اساسا بفعل تأثير المجال المغناطيسي في انتشار الجسيمات المشحونة نحو الجدران وخاصة الالكترونات الحرة التي تولد خلال عملية الانهيار الكهربائي.

Introduction

The magnetic field is widely used in the industrial applications of plasma, such as coating, etching the surfaces of materials, deposition of thin films in microelectronics, and isolating ions in chemical processes [1-3]. Due to the difficulty of presenting a full theory that explains the effect of magnetic field on the plasma profile, most researchers attempt to obtain facts about this subject from simulation

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and experimental studies. Hence, it is important to continuously add further data about how the magnetic field can be used to control plasma properties.

The following results were found in the literature that deals with the effect of magnetic field on the gases plasma. It was shown that the longitudinal magnetic field decreases the discharge voltage of subnormal glow discharge of air at low pressures, with an exponential formula being used to describe this fact [4]. The longitudinal magnetic field makes the electric breakdown of Argon and Nitrogen easier at low pressures [5]. Depending on the empirical equation, some authors explained the increase in plasma density and other plasma parameter by a longitudinal magnetic field [6]. The increase in the intensity of the emission spectrum lines of Hydrogen gas under the magnetic field is considered earlier [7]. It also noticed that the transverse magnetic field increases the discharge voltage and decreases the discharge current density [8]. Another study [9] displayed a mathematical model to show that the transverse magnetic field can be used to control the intensity of light of the negative glow region of the air glow discharge. It was also found, according to a simulation, that the transverse magnetic field can govern the erosion profile and the sputter rate of the cathode in a DC discharge magnetron [10]. The observation that the discharge current decreases with increasing the transverse magnetic field was analytically explained [11].

In the present study, it is shown that the discharge voltage decreases to a minimum value, then returns to increase over the minimum with increasing the magnetic field strength. A maximum decrease (12%) is obtained on the right side of Paschen curve, near the minimum, while the minimum of the curve has a minimum decrease as well as the low and high pressures in the range of 9-15Pa. It is also shown that the magnetic field can only reduce the radial diffusion coefficient of free electrons at these ranges of pressure and magnetic flux density.

Experimental setup

Figure-1 shows a photograph and schematic diagram of the experimental arrangement used in the present study. A DC current source was used to produce a uniform magnetic field in the range of 0.01-0.04T between two electromagnetic collies of iron cores, separated by a distance of 12.5 cm. The low pressure (9-15Pa) of air is produced and controlled by a vacuum system (a rotary vacuum pump (Welch8905A-3450RPM/1.8CFM) and a thermocouple vacuum gauge (Varian801)). A DC breakdown voltage is supplied smoothly from a DC power supply capable of supplying 750V with 50mA (homemade). The ballast resistor R (470Ω , 2W) is used in series in the circuit to limit the discharge current. A high impedance oscilloscope is used to obtain the breakdown voltage.

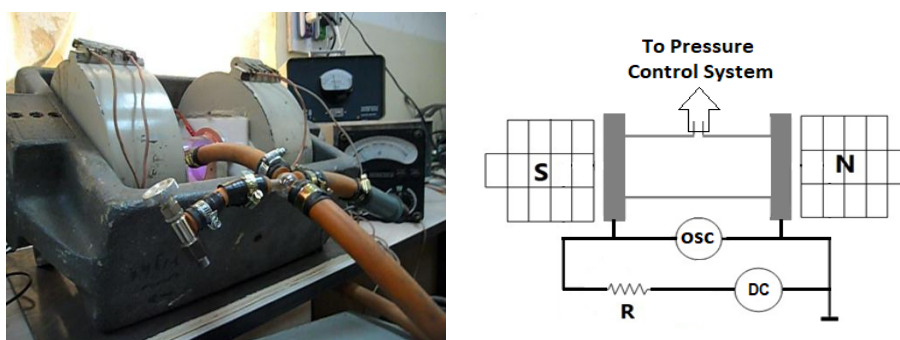


Figure 1-Photograph and schematic representation of the experimental setup

To breakdown the air, a Pyrex cylindrical tube with opened ends of length 8.5 cm and radius 3.75 cm is used with two flat disc electrodes of aluminum of the same radius fixed on the two ends of the tube. The tube and electrodes are cleaned and dried carefully before being used.

A flux meter is used to calibrate and measure the magnetic flux density between the poles, and the data are plotted in Figure-2. To avoid the distortion in the magnetic field near the poles, the discharge chamber is sited in the middle, 2 cm apart from the magnetic poles.

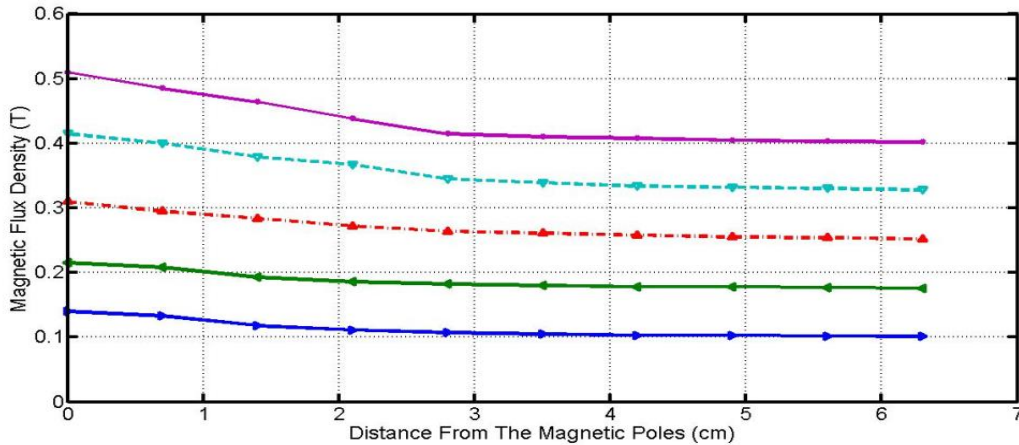


Figure 2-Magnetic flux density, 6.5 cm away from the north and south magnetic poles

Results and discussion

In the presence of the magnetic field, it is important to consider the ratio between the time of mean free path and that of one revolution of a helix motion in the breakdown process. The free time between collisions τ_i is well defined by [12]:

$$\tau_i = \lambda_i/v_i \tag{1}$$

where λ_i is the mean free path of an i charged particle (free electron or ion), which depends on the pressure and it is approximately the same for both charged particles [12], and v_i is the magnitude of the velocity of the same charged particle. In the presence of an electric field, the velocity is a vector sum of thermal and drift velocities.

The time of one revolution τ_{ci} of a helix motion of a charged particle around the magnetic field lines is represented by [13]:

$$\tau_{ci} = 2\pi/\omega_{ci} = 2\pi m_i/q_i B \tag{2}$$

where B , m_i , q_i and ω_{ci} are the magnetic field strength, the mass, the charge, and the angular frequency of the helix motion of the i charged particle. The charged particles that diffuse to the walls (perpendicular to the axial direction of the magnetic field) are traveled by their thermal velocities, so that between collisions, they experience a helix motion around the magnetic field lines.

The ratio between τ_i and τ_{ci} represents the number of revolutions N_{Ri} that an i charged particle dose during the free time between collisions, so we can write:

$$N_{Ri} = \frac{\tau_i}{\tau_{ci}} \tag{3}$$

In the range of pressure of 9-14.7Pa, magnetic field of 0.1- 0.4T, and at temperature of 293 K, the values of τ_i and τ_{ci} produce $N_{Re} > 1$ for free electrons and $N_{Ri} < 1$ for positive ions, as shown in Figure-3.

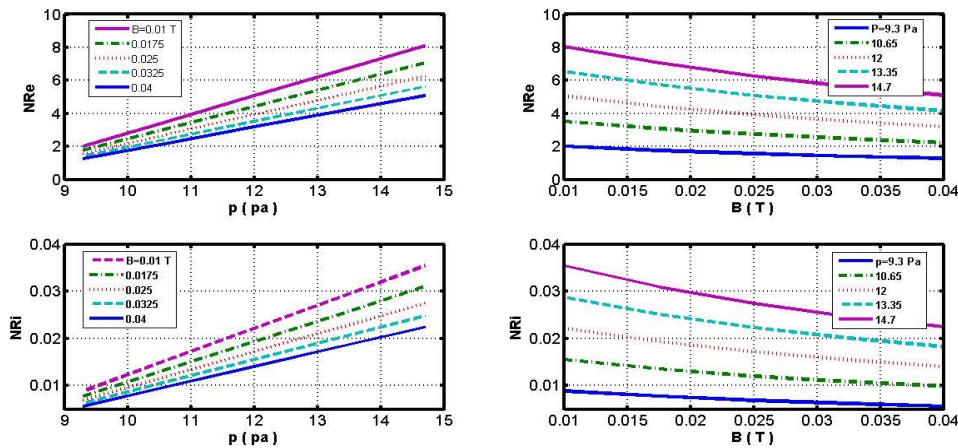


Figure 3-The values of N_{Re} and N_{Ri} at different values of air pressure (p) and axial magnetic field strength (B)

Because of the heavy mass of ions, they have no complete helix motion under these ranges of pressure and magnetic field. Thus, the magnetic field has a negligible effect on their diffusion to the walls. The condition $\omega_{ci}^2 \tau_i^2 \gg 1$, in which the magnetic field can reduce the diffusion of charged particles to the walls [13], can be stated in the form $N_{Ri} \gg \frac{1}{2\pi}$ by using equations (3) and (2) and can be satisfied only for free electrons, as shown in Figure-3. An important result that can be deduced from Figure-3 is that the magnetic field has a small influence on the number of revolutions of the helix motion for both charged particles at low pressures.

To show the effect of magnetic field on the diffusion coefficient of charged particles to the walls, which will change the breakdown voltage, we need also to calculate the radius of helix motion r_{ci} (Larmor radius) that is given by [13]:

$$r_{ci} = v_{\perp i} / \omega_{ci} = v_{\perp} m_i / q_i B \tag{4}$$

where $v_{\perp i}$ is the velocity of i charged particle that is perpendicular to the direction of the magnetic field (thermal velocity).

From the considered values of pressure, magnetic field, and gas temperature, the values of mean free path λ and r_{ci} are calculated from equations (1) and (4). The results show that $r_{ci} \gg \lambda$ for positive ions and $r_{ce} \ll \lambda$ for free electrons. This means that the magnetic field can only slow down the diffusion of electrons to the walls by restricting them in a helix motion between collisions. Hence, the free electrons can only be diffused to the walls by collisions and, after each collision, they diffuse by a step equal to r_{ce} [13].

The breakdown process of air produces a high number of charged particles (electrons and positive ions) in the bulk of the discharge tube [12,14]. Some of these charged particles will immediately migrate to the walls, according to Fick's law of diffusion [13]. The perpendicular (radial) diffusion coefficient of free electrons D_e can be given by [13]:

$$D_e \sim \frac{r_{ce}^2}{\tau_e} \tag{5}$$

Depending on equation (3), equation (5) can be written in another form:

$$D_e \sim \frac{r_{ce}^2}{N_{ce} \tau_{ce}} \tag{6}$$

From equation (6), the perpendicular diffusion coefficient of free electrons is calculated and plotted in Figure-4.

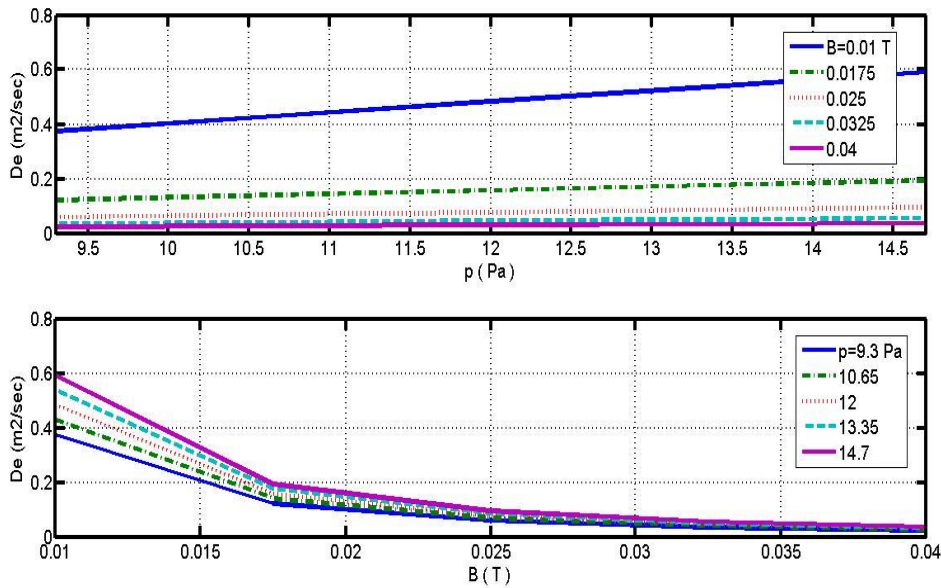


Figure 4-The values of (D_e) at different values of air pressure (p) and axial magnetic field strength (B)

Figure-4 shows that the diffusion of free electrons to the walls decreases with increasing the magnetic flux density at all pressures in the range (9-15Pa). It also shows that the pressure can increase the diffusion to the walls to a considerable value in the presence of the magnetic field by increasing the collision frequency.

The change in the radial diffusion coefficient of free electrons will produce a change in the breakdown voltage of air [13, 14]. However, there is no explicit function that can be used to show that change, hence it is obtained here from experimental measurements and plotted in Figure-5.

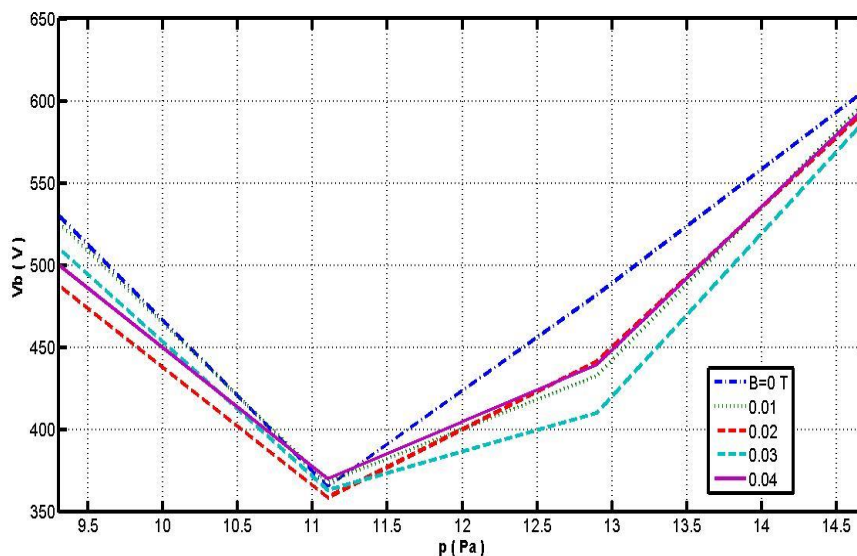


Figure 5-Changing air breakdown voltage (V_b) with air pressure (p) and axial magnetic field strength (B)

To show the change in the breakdown voltage more explicitly, the percentage of change $\Delta V_b = (V_{bB} - V_{b0})/V_{b0}$ is plotted in Figure-6 with fitting curves that were obtained by Matlab program, where V_{b0} is the breakdown voltage in the absence of the magnetic field and V_{bB} is the same voltage in the presence of the magnetic field.

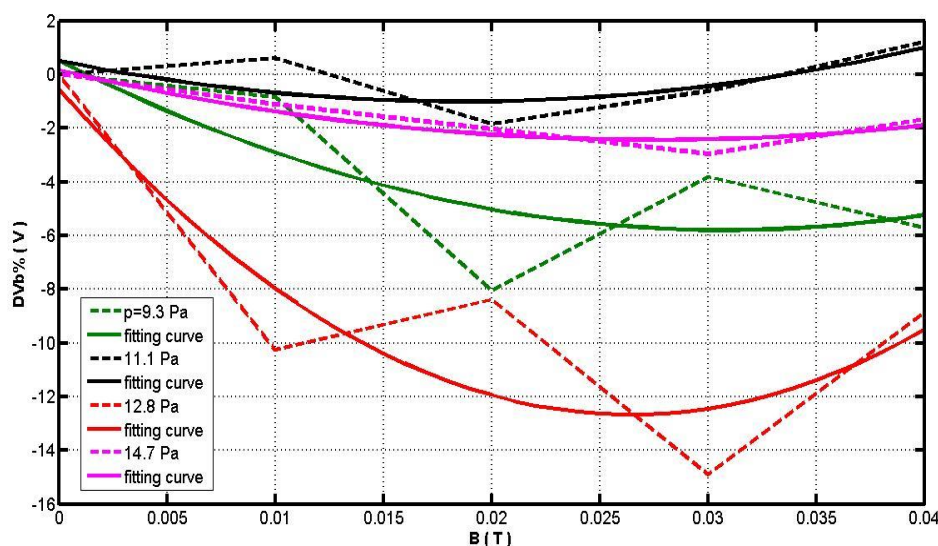


Figure 6-The percentage of changing the breakdown voltage of air at different values of the magnetic field strength with fitted curves

Figure-6 displays that, at all pressures in the range (9-15Pa), the discharge voltage decreases to a minimum value, then returns to increase over the minimum with increasing the magnetic field strength in the range. This behavior is expected because the radial diffusion coefficient that is given by

equation (6) is proportional to the magnetic field strength according to three factors, in two opposite ways; first, it is directly proportional to the square of the radius of a helix motion and, second, it is inversely proportional to the multiplication of the time of one period of revolutions and the number of revolution of the helix motion.

In the presence of the magnetic field, the breakdown voltage can be reduced to a high value (6-12%) on both sides of the Paschen curve, as shown in Figure-6. The maximum decrease (12%) is obtained on the right side of the curve because the high pressure produces a high number of free electrons during the breakdown process compared to the left side.

The discharge voltage decreases to a minimum value (about 2%) at high pressure in the range, far from Paschen curve minimum. This is achieved because the radial diffusion is essentially reduced at high pressure $D_e \propto 1/p$ [13, 14] so that the effect of the magnetic field on radial diffusion coefficient has no considerable value at high pressure, as shown in Figure-4.

In the absence of the magnetic field and at the pressure of Paschen curve minimum, the discharge voltage acquires the minimum value from electric field and pressure conditions [14], which are the governing factors in the breakdown process. But, due to the reduction of diffusion of electrons by the magnetic field, the discharge voltage can be changed to a small value in two ways; first, it decreases to about (1%) at moderate strength and, second, it increases to the same value at high strength in the range, as shown in Figure-6. The reduction is obtained due to the decrease in the radial diffusion coefficient of free electrons, while the increase is obtained due to the helical motion of charge particles during their drift to the poles, which represents an additional resistance added to the main resistance of the discharge, knowing that the velocity of most charged particles to the positive pole (drift velocity) has a radial component.

Conclusions

We observed that the magnetic field applied along the discharge axis promoted a reduction of the breakdown voltage of air to a high value (12%) near the minimum of Paschen curve, from the right side. The breakdown voltage of air at all pressures in the range (9-15 Pa) decreased to a minimum value, then returned to increase with increasing the magnetic field. The breakdown voltage is approximately not affected by the magnetic field at high pressures far from the minimum of Paschen curve and at the minimum itself. The breakdown is facilitated by the magnetic confinement of electrons which reduces the electron losses and effectively increases the collision frequency between electrons and the gas particles at a given reduced field, thus increasing the ionization efficiency.

Acknowledgement

We thank Mr. A. Obeid (College of arts / University of Mosul), for the manuscript language reviews.

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