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# Longitudinal Magnetic Field Effect on the Electrical Breakdown in Low Pressure Gases

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The electrical breakdown has been investigated for low-pressure argon and nitrogen discharges under the influence of an external longitudinal magnetic field. Plane-parallel aluminum electrodes (5 cm diameter) separated by a variable distance d (4.0 cm $<$ d $<$ 11.0 cm) were sustained with a dc voltage (0 $<$ V $<$ 1 kV). A Helmholtz coil was used to produce an uniform magnetic field(B) parallel to the discharge axis. Paschen curves were obtained and the secondary electron emission coefficient ($\gamma$), the first Townsend ionization coefficient ($\alpha$) and the ionization efficiency($\eta$), were plotted with respect to the variation of the reduced field (E/P). To observe the effect of the magnetic field these curves were plotted for fixed values of B=0 and B=350 Gauss. As consequence of the longitudinal magnetic field, the free paths of the electrons in the Townsend discharge are lengthened and their lateral diffusion is reduced, thus reducing electron losses to the walls. The data presented in this paper give a quantitative description of the B-field effect on the Townsend's coefficients and overall it is concluded that the DC electrical breakdown of the gases is facilitated if a longitudinal magnetic field is applied along the discharge axis.

## 1 Introduction

The electrical breakdown of gases has been, since long time, the subject of many studies [1-4]. The interest in studying the magnetic field effect on the characteristics of electrical breakdown and on the properties of a Townsend discharge is motivated by a necessity of gaining a better understanding of the complex mechanisms of gas discharge phenomena and also because the B-field may contribute favorably for dealing with practical problems associated with the use of this kind of discharge for plasma processing technologies [5,6]. In this work, breakdown potentials in Ar and $N_2$ under the presence of an external longitudinal magnetic field were measured in the Townsend discharge regime. In this regime the electrons in the tail of the energy distribution function have enough energy to ionize the gas atoms. The secondary electrons thus produced can also obtain a sufficient amount of energy from the electric field to ionize atoms and produce new electrons. This gives rise to an avalanche-like growth of the degree of ionization. For this to occur, the loss of electrons should be rather small. The electron losses occur by recombination with ions as a result of diffusion toward the walls and also, as in the case of electronegative gases, as a consequence of the formation of negative ions.

We have developed an experimental device to observe the effect on the gas breakdown, of a magnetic field parallel to the electric field. We expected the lateral diffusion of electrons to be hindered by the magnetic field consequently reducing losses and enhancing the ionization efficiency in the Townsend regime. In fact, as the experimental results show, this phenomenon was confirmed by the reduction of the breakdown voltage when a magnetic field was applied .

## 2 Theory of the electrical breakdown

If, in drifting in the field direction, an electron ionizes $\alpha$ atoms in the time it takes to travel 1 cm, the growth $dn_e$ in the number of electrons traversing a segment of length $dx$ is given by [2]

$$dn_e = \alpha n_e dx \; . \tag{1}$$

Therefore, the electron density increases in an avalanche-like manner

$$n_e(x) = n_e(o) \exp[\alpha x] \tag{2}$$

where $n_e(0)$ is the initial density of electrons and the coefficient $\alpha$ is called the first Townsend ionization coefficient. In the theory of breakdown, the coefficient $\alpha$ is the most important characteristic determining the dielectric strength of a gas. The coefficient $\alpha$ is related to the ionization rate $\nu_i$, which is equal to the number of ionization events caused by an electron in a unit time:

$$\nu_i = n \int_{\varepsilon_i}^{\infty} f(\varepsilon) q_i(\varepsilon) \sqrt{2e/m} \sqrt{\varepsilon} d\varepsilon \; . \tag{3}$$

Here $\varepsilon_i$ is the ionization energy of the atom, $f(\varepsilon)$ is the electron energy distribution, and $q_i(\varepsilon)$ is the cross section for ionization of an atom from the ground state, in collision with an electron of energy $\varepsilon$. Since $\alpha$ is equal to the number of ionization events per unit path length, obviously

$$\alpha = \nu_i / v_d; \tag{4}$$

where $v_d$ is the electrons drift velocity.

The first Townsend's coefficient, which depends on the gas type and gas pressure, as well as on the electric field $E$ in the inter-electrode space, can be expressed following Townsend theory as:

$$\frac{\alpha}{P} = A \exp[-\frac{BP}{E}]; \tag{5}$$

where A and B are constants for a particular gas and P is the pressure. It is more convenient to use the ionization coefficient $\eta$ (or ionization efficiency) defined as the number of ionization events caused by an electron in passing through a potential difference of one volt:

$$\eta = \alpha / \mathrm{E} = \nu_i / v_d \quad E. \tag{6}$$

This quantity depends only on the reduced electric field $E/P$. The experimental data are usually presented either in the form $\eta\ (E/P)$ or as $\alpha/P\ (E/P)$.

The number of secondary electrons detached from the cathode by impact of the various particles produced in the gas(positive ions, photons, excited atoms,...) is known as the effective secondary electron emission coefficient, or second Townsend coefficient $\gamma$. Additionally to $\alpha$ it is an important parameter in the Townsend regime and it depends on the electrode material and on the nature of the filling gas used. The secondary ionization coefficient is related to that of Townsend's first ionization coefficient $\alpha$, and by using eq. 6 this dependence can be expressed in terms of the ionization coefficient $\eta$ [2]:

$$\gamma = \frac{1}{e^{\eta V_B} - 1}. \tag{7}$$

Thus, $\gamma$ depends on the cathode material and gas type, as well as on the ratio $E/P$ [7]. Experimentally, the breakdown voltage ($V_B$) at a certain value of E/P is determined from Paschen curves, by determining $V_B$ at the corresponding value of *Pd*.

# 3 Experimental setup

A schematic diagram of the electric circuit for measurement of breakdown voltage is illustrated in Fig. 1. The vacuum glass chamber of 130 mm internal diameter and 300 mm length, was preliminarily evacuated to pressure below $10^{-4}$Torr. The electrodes were made of aluminum and the operating pressure was varied in the range (0.05 – 0.4) Torr. A low intensity B-field (0 – 350) Gauss, in the direction of the electric field, could be produced by the Helmholtz coil, however the breakdown voltage measurements were made only at zero B-field and at 350 Gauss.

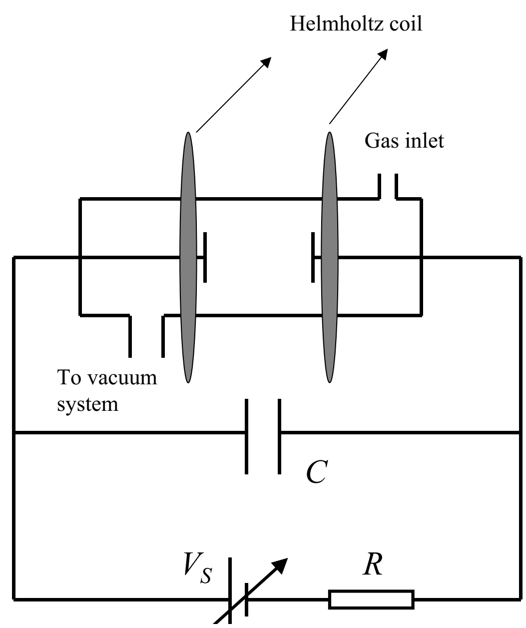


Figure 1. Schematic diagram of the circuit for measurement of breakdown voltage. R=300 kΩ, C=10.6 $\mu$F.

# 4 Results and discussion

## 4.1 Measurements of the gas breakdown potential – Paschen curves

The gas breakdown voltage $V_B$ was determined as a function of the product *Pd*. The measurements were made for argon discharge in the pressure range of 0.08 Torr to 0.40 Torr with the inter-electrode distance varying between 2.0 cm and 8.0 cm. For nitrogen discharge the pressure was varied between 0.05 Torr and 0.08 Torr and the inter-electrode distance between 4.0 cm and 11 cm. In these operational ranges, the application of an induction magnetic field with intensity of the order of 350 Gauss is effective in confining of the electrons and is negligible in the case of ions. At this B-field value and by considering a typical value of electron temperature about 3 eV we estimate the electron gyroradius (Larmor radius) to be about 0.14 mm which is much smaller than the discharge column radius of 25 mm. In this way, a magnetic field of 350 G promotes an efficient plasma confinement once the electrons keep frozen to the B-field lines. For breakdown to occur there must be sufficient number of collisions between electrons and the gas particles to enable the required amount of ionization in the inter-electrode space. If pressure is too low then the inter-electrode distance must be correspondingly increased; alternatively, if the inter-electrode distance is small then the pressure must be correspondingly increased. At higher inter-electrodes distances, the magnetic field acts more efficiently for lower pressures, because the collisionality decreases by decreasing the pressure thus enhancing the effectiviness of the magnetic confinement. It was also observed that the breakdown voltage values are almost invariable for values of the gas pressures above 0.1 Torr and for induction magnetic field values below 350 Gauss.

The consequences of the action of the magnetic field are that the electron free paths across the residual gas are lengthened and also that the lateral diffusion of the electrons can be reduced. These combined effects imply that the losses of electrons are reduced and they can now make more collisions with the gas molecules than they could do in the absence of the magnetic field. In effect, the breakdown voltage is reduced, as shown in Figs. 2 and 3 for argon and nitrogen, respectively. On the left side of the minimum Paschen curves, $V_B$ decreases fast when increasing *Pd* which can be attributed to the increase in the collision frequency between electrons and neutral atoms or molecules. However, on the right side of the minimum, the breakdown voltage increases gradually when increasing *Pd*, which can be attributed to the decrease in the ionization cross-section, making the electrons to require more energy in order to achieve the breakdown of the discharge gap [8].

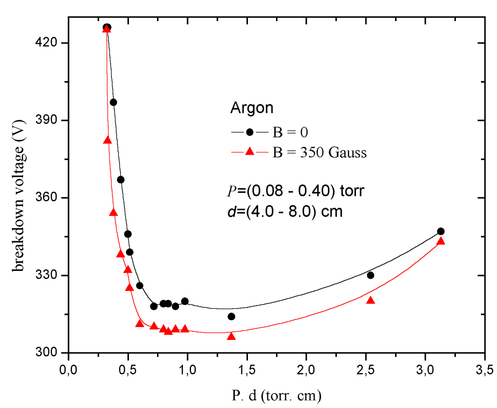


Figure 2. Breakdown voltage ($V_B$) for Ar as a function of *Pd* (Paschen curves) for two values of magnetic field.

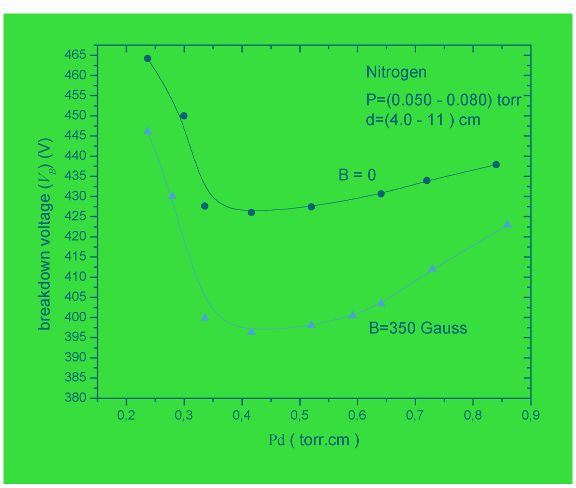


Figure 3. Breakdown voltage ($V_B$) for nitrogen as a function of *Pd* (Paschen curves) for two values of magnetic field.

Overall, the results show that the effect of the magnetic field on the Paschen curves is to reduce the breakdown voltage, especially on the region of Pashen's minimum. This effect is more pronounced for nitrogen than for argon. This can be attributed to the higher efficiency of the secondary ionization processes in $N_2$discharge as compared to Ar discharge at the conditions of the pressure and reduced field investigated. At lower values of *Pd* , on the left side of the minimum, the effect of the B-field is reduced because in this region the breakdown is governed primarily by the electrode material properties rather than by ionization process in the bulk of the gas.

## 4.2 Ionization efficiency

Figures 4 and 5 show the variation of the ionization efficiency with E/P for argon and nitrogen.

We observe from these figures that $\eta$(E/P), at small $E/P$, increases sharply, but then reaches a maximum and falls off on further increase of $E/P$. The point of maximum is obtained by differentiating $\eta$ (eq. 6) with respect to $E/P$ and setting the derivative equal to zero. This maximum of $\eta$ has a value of $\eta_{\max}$ = A $B^{-1}e^{-1}$ which is proportional to the inverse of the ionization potential of the gas (Vi = B/A). The effect of the magnetic field corresponds to a lowering of the ionization potential of the gas. For the nitrogen discharge only the descending branch of the curve was obtained, as shown in fig. 5 but the qualitative effect of the B-field on the ionization efficiency in nitrogen is similar to that in argon

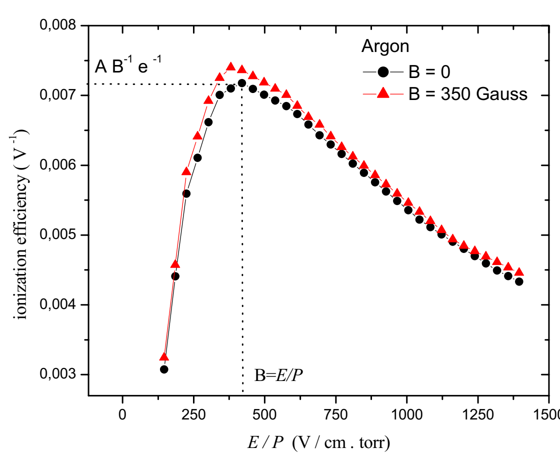


Figure 4. Ionization efficiency ($\eta$) as a function of E/P for argon using the data of Fig. 2.

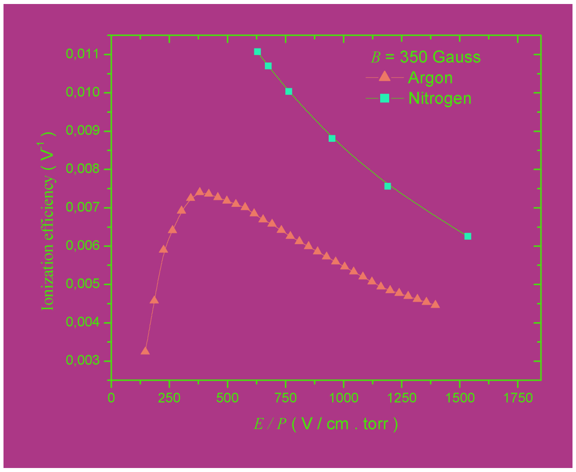


Figure 5. Ionization efficiency ($\eta$) as a function of $E/P$ for argon and nitrogen ($B$ = 350 Gauss).

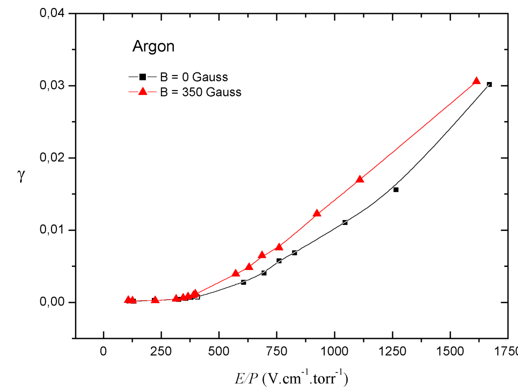


Figure 6. Variation of the secondary ionization coefficient with E/P for Ar gas.

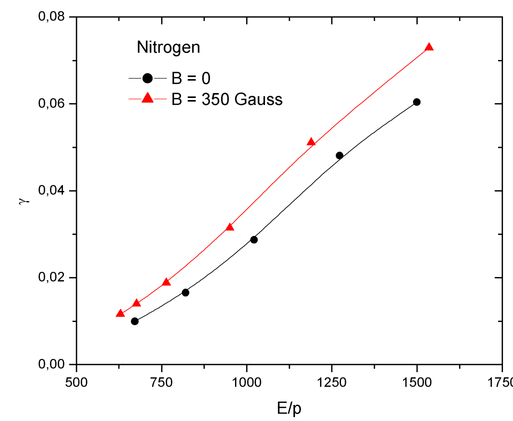


Figure 7. Variation of the secondary ionization coefficient with E/P for $N_2$ gas.

### 4.3 Secondary emission coefficient

The variation of the effective secondary electron emission coefficient $\gamma$ with the reduced field E/P is shown in Figs. 6 and 7 for Ar and $N_2$, respectively. It is usually observed that the curve of $\gamma$(E/P) has a minimum [7] but in the experimental range of reduced field investigated only the ascending branches of the curves are obtained. We observe that $\gamma$ rises faster for nitrogen than for argon and that it increases with the magnetic field, an effect that, especially for argon, becomes less effective as the reduced field is decreased. The secondary emission of electrons can be due to any combination of effects of impacts of positive ions, photons, excited atoms on the aluminum electrode and depends also on the state of the cathode surface. For weak reduced fields, the mean electron energy is low and excitation within the gas becomes more important than ionization. Secondary electrons are then ejected from the cathode mainly by photon impact (photoelectric effect), a mechanism less sensitive to the magnetic field. On the other hand, at high values of E/P the secondary electron emission is governed by impact of ions on the cathode and, at even higher values, by the impact of neutral rapid species [7, 10]. These mechanisms are dependent on the dynamics of the charged particles, and the emission of secondary electrons is enhanced by the confinement effect promoted by the application of a magnetic field. The magnetic field effect associated with the increase of $\gamma$, at a given value of E/P, is equivalent to a decrease in the work function of the cathode material, because, in the presence of a B-field, a lower voltage would be required to maintain the discharge as would be for the case of field-free discharge but with a cathode of lower work function. The efficiency of electron emission by the incidence of the ions onto the cathode increases when using a smaller ion mass, i. e. $\gamma(N_2) > \gamma$(Ar) at a given $E/P$ value [9] a behavior that is demonstrated by comparing the curves in Figs. 6 and 7.

## 5 Conclusions

The breakdown voltages in low pressure gases have been measured for argon and nitrogen discharges using plane-parallel aluminum electrodes. We have investigated the influence of a longitudinal magnetic field on the Paschen curves and on the Townsend parameters. We observed that the magnetic field applied along the discharge axis promoted a reduction of the breakdown voltage. 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. This effect is equivalent to a change of the operating gas by another of lower ionization potential. The presence of the magnetic field enhances the secondary ionization coefficient at a given $E/P$ value. This effect is equivalent to a decrease of the work function of the cathode material. It was also observed that the breakdown voltage and the Townsend parameters are almost invariable for values of the gas pressures above 0.1 Torr and for induction magnetic field values below 350 Gauss.

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