Effect of Applied Electric Field and Pressure on the Electron Avalanche Growth

L. ZEGHICHI (1), L. MOKHNACHE (2), and M. DJEBABRA (3)

(1) Department of Physics, Ouargla University, P.O Box.511, OUARGLA 30 000, ALGERIA
zeghichi.leyla@univ-ouargla.dz
(2) L. Mokhnache, Batna University, Batna, ALGERIA
lmokhnache@yahoo.fr
(3) Institute of Health and Safety, Batna University, Batna, ALGERIA
mebarek_djebabra@yahoo.fr

Abstract: - The purpose of this paper is to mimic, using the Monte Carlo Simulation, the electron avalanche growth by tracking individual paths of charged particles; the effect of space charge is included by solving the Poisson equation. An electronic avalanche is produced, when an electric field, sufficiently intense, is applied to a gas. At some stage of formation of free electrons and ions; the electronic avalanche becomes a conductor channel, and then self sustainment of the discharge. The simulation is carried out in O2 gas for two different pressures, under the effect of uniform electrical fields. The streamer breakdown criterion for the different applied uniform fields is examined.

Key-Words: - Electrical discharge, Electrical Breakdown, Collision probability, Poisson's equation, Monte Carlo Simulation.

1 Introduction

The term "discharge" was applied to any flow of electric current through gas, and to any process of ionization of the gas under the effect of an applied electric field. The modern field of gas discharge physics is thus occupied with processes connected with electric currents in gases and with generating and maintaining the ability of a gas to conduct electricity [1].

Gases are important in the field of high voltage engineering. They are used mainly for the insulation and prevention of electrical breakdown in high voltage circuits and transmission lines [2].

At higher fields, charged particles may gain sufficient energy between collisions to cause ionization on impact with neutral molecules. Ionization by electron impact under strong electric field is the most important process leading to breakdown of gases. When the electron multiplication is large the difference in mobility of electrons and positive ions introduces a space charge field which distorts the applied field.

The type of discharge is determined by the various physical conditions of gases, namely, pressure, temperature, electrode field configuration, nature of electrode surfaces, and the availability of initial conducting particles are known to govern the ionization processes [3-7]. The breakdown voltage of a given gap depends on the gas parameters such as the ionization coefficient (α), the attachment coefficient (η), the recombination coefficient (β), and the Townsend second ionization coefficient (γ), which in turn are functions of the electric field and of such factors [8].

The Monte Carlo Simulation (MCS) is used to describe the different phenomena leading to electronic avalanche and the discharge process such as: the elastic and inelastic (ionization, attachment, and excitation) processes.

The MCS consists on tracking the electrons' trajectories; it is based on the mean free path or the mean free flight time. The physical parameters of the molecules that compose the studied gas: Collision cross section, Collision probability, Collision energy (elastic, attachment, excitation and ionization), are used to model the gas discharge. By using sampling laws, we obtain the parameters of electronic avalanches' development and growth: mean energy values, ionization and attachment coefficients.

This paper is to describe the Monte Carlo model, for electron dynamics
In this paper we use the simulation results to verify the breakdown criterion and to find the solution of Poisson equation for the space charge field which is the main parameter producing the discharge. The effect of the applied electric field is investigated

2 Simulation Method

The MCS has come to be known as the only approach capable of providing useful imitating tool for the electron's motion in gas discharge physics.

MCS is a stochastic method; it applies to problems with absolutely no probabilistic content in addition to those with intrinsic probabilistic structure. This method is based on a set of stochastic algorithms providing the approximation of numerical quantities by performing statistical sampling experiments on a computer. Pseudorandom numbers are used to describe the development of the real system in question.

Monte Carlo experiment generates randomly a group of trial electrons. The application of the constant step MCS version for the study of electron's motion, under the effect of the electric field, requires the evaluation process, after experiencing energy loss and gain, of the different parameters taking into account the different processes of atomic collisions (elastic or inelastic).

A. Collisions' Treatment

We have adopted a free flight time approach; the electron mean free flight time between two successive collisions is determined by the electron collision total cross section Q (ε) as:

$$Tm = \frac{1}{N.Q(\varepsilon).v(\varepsilon)} \quad \textbf{(1)}$$

where: v (ε) is the drift velocity of electrons and N the gas number density.

The free flight time is divided into a number of smaller elements according to:

$$dt = \frac{Tm0}{K} \quad \textbf{(2)}$$

where: K is a sufficiently large integer.

The collision probability P_1, that follows the Poisson's distribution, is given by:

$$P_1 = 1 - \exp\left(\frac{dt}{Tm}\right) \quad \textbf{(3)}$$

The interval [0, P1] is divided into segments of lengths that correspond to the probabilities of different types of collision after increasing scheduling of these probabilities.

The remaining portion of the interval [0, 1] is for the case where no collision is possible.

The electron energy is described as follows:

For the elastic collision the energy is given by:

$$\varepsilon_1 = \left(1\text{-}\,2\frac{M}{m}\cos(\delta)\right)\varepsilon_0 \quad \textbf{(4)}$$

where: δ is the scattering angle of the electron after the collision, m and M are, respectively, the masse of electron and an O_2 molecule and ε_0 is the electron's energy before collision.
For the processes (attachment, excitation and ionization), the onset energy "*los*" of the process is subtracted from the electron energy:
For an attachment of the electron, all its energy is to be lost, and therefore it is lost in the swarm.

$$\varepsilon_1 = 0 \quad \textbf{(5)}$$

For an exciting process of a molecule to a higher stat (different rotations, vibrations and electronic excited stats), the energy of the electron is reduced with the energy needed to excite the molecule and the resulting energy is given by:

$$\varepsilon_1(m) = \varepsilon_0(m) - los \quad \textbf{(6)}$$

And for an ionizing process, the remaining energy is shared between the, primary and ejected, electrons with the ratios R and (R –1) as:

$$\begin{aligned} \varepsilon_{primary} &= R(\varepsilon_0 - los) \\ \varepsilon_{ejected} &= (R-1)\times(\varepsilon_0 - los) \end{aligned} \quad \textbf{(7)}$$

where: R is a uniform random number between zero and unity.

B. Implementation

At time t = 0, the initial electrons are emitted from the cathode according to a cosine distribution. The energy gain of the electrons in a small time interval dt is governed by the equation of motion. The occurrence of collision between an electron and a gas molecule and its kind are determined by comparison of the collision probability $P1$ with computer generated random numbers R.

C. Algorithm

1. Execution of a loop of 10^3 to repeat N times the maximum time tmax
2. Generation of the initial electrons and calculation of the time step.
3. Time: t = t + dt.
4. Simulation of the velocity of each electron and determination of the energy gain.
5. Determination of the collision type and the electron parameters after collision "velocity, position and energy"
6. Next electron.
7. Verification of the stopping criteria.
8. If the maximum number of histories (10^3) is attained go to (9.) else go to (2.).
9. Statistical treatment of the ionization and the attachment coefficient and the mean energy values.

3 Sampling Laws

By means of the MCS, coupled with the motion equations, the electron trajectories and electrons collisions with the gas molecules are simulated. During the successive collisions for each electron, some information (position, number of electrons positive and negative ions velocity and energy) is stored in order to estimate, using the sampling laws, the discharge parameters.

The effect space charge is also included by solving the Poisson's equation

A. Electron Swarm Parameters

The statistical treatment is carried out to obtain the physical parameters such as the attachment and the ionization coefficients.

For with the purpose of we exploit the key quantity $\bar{z}$ which is given by the sampling formula below:

$$\bar{z} = \frac{1}{N}\sum_{i=1}^{N} z(i) \quad \textbf{(8)}$$

The ionization coefficient α

$$\alpha = \frac{\ln\left[\left(N_{pion}/n_0\right)+1\right]}{\bar{z}} \quad \textbf{(9)}$$

The attachment coefficient η

$$\begin{cases} \eta = \dfrac{N_{nion}}{n_0}\dfrac{1}{\bar{z}}\left(\text{if } \alpha = 0\right) \\ \eta = \dfrac{N_{nion}}{N_{pion}}\alpha \end{cases} \quad \textbf{(10)}$$

where: n_0 is the initial electrons number, N_{pion} and N_{nion} are, respectively, the number of positive ions et the number of negative ions (counters).

The mean energy of electrons $\bar{\varepsilon}$ is known as

$$\bar{\varepsilon} = \frac{1}{N}\sum_{i=1}^{N} \varepsilon(i) \quad \textbf{(11)}$$

B. Space Charge Field

The total number of electrons in the gap increases over many orders of magnitude. To limit the number of simulation particles, a statistical subroutine is introduced, when the total number of simulation particles exceeds the maximum number $N_{\max}$ permitted, to choose a new group of larger particles to represent the old larger group of smaller particles.

To obtain the space charge field distribution, we use the distributions of the new electrons, positive and negative ions, which are produced by ionization and attachment processes, to resolve the Poisson equation [7]:

The space charge field at the la k^{th} cell is:

$$E_k = E_{k-1} + \frac{1}{2}(\Delta E_{k-1} + \Delta E_k) \quad \textbf{(12)}$$

ΔE_k : the variation of the electric field in an elementary cell of the studied domain, it depends on the number of charged particles in this cell.

$$\Delta E_k = \frac{1}{\varepsilon_0}(-q_{ek} + q_{pk} - q_{nk}) \quad \textbf{(13)}$$

q_{ek} , q_{pk} , q_{nk} : charges at cell s' centers

The electric field at the first cell is:

$$E_1 = E_c + \frac{1}{2}\Delta E_1 \quad \textbf{(14)}$$

Where E_c is the electric field at the cathod.

4 Results and Discussion

As we assumed above the electrical discharge in gases depends on the gas Type (pressure: nature)The geometry . Electrical voltage In this purpose paper we describe the development of an electrical discharge in O2 by MCS in plane-plane geometry. The calculations are performed at gas pressures of 1 and 100 (torr). The cross section set of the O2 molecule used is that referred in [9].

At t = 0, a number of electrons are released from the cathode with small energy 0.1 (eV).

The figures (Fig. 1, Fig. 2, Fig. 3) show, respectively, the variation with time of the ionization coefficient (α), the attachment coefficient (η) and the mean kinetic energy; for Oxygen gas at a pressure of 1 (torr), a temperature of 293 (K)20(° C) with a gap length of 2 (cm) and an applied electric field of 10 (kV/m).

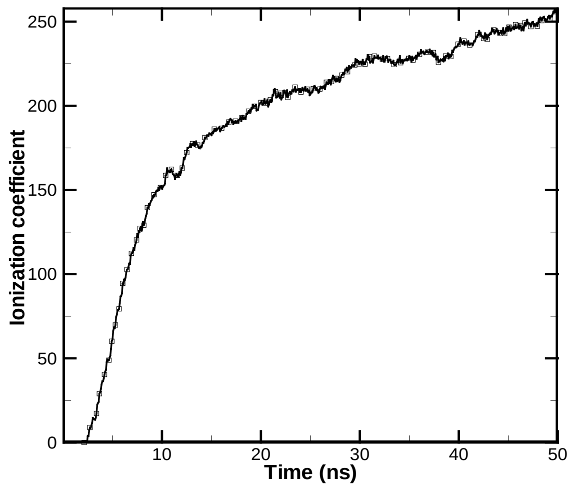

Fig. 1 Temporal variation of the ionization Coefficient at P=1torr and E0=10 kV/m.

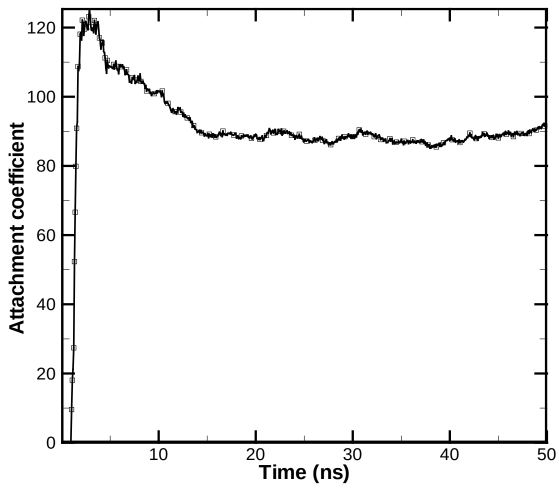

Fig. 2 Temporal variation of the attachment coefficient at P=1torr and E0=10 kV/m.

At low pressure 1 (torr), the ionization coefficient increases with time, however, the attachment coefficient decreases but the Townsend breakdown criterion is not verified. At time t= 50 (ns), the number of the total space charge is about 16307 (10065 electrons).

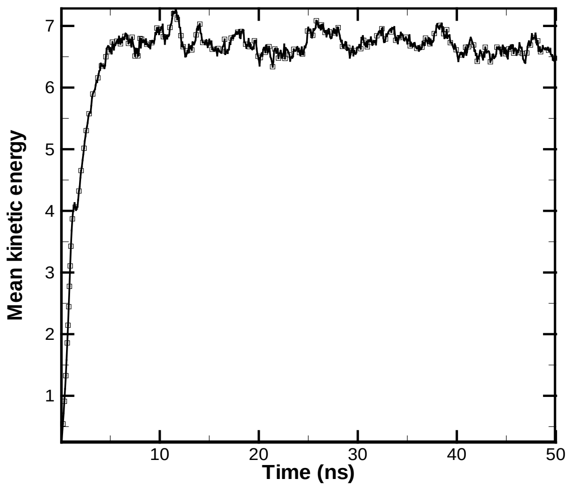

Fig. 3 Temporal variation of the mean kinetic energy at P=1torr and E0=10 kV/m.

Figure (3) shows that the electrons have a short free path (in 2cm interval) and as the energy gain depends on the distance traveled, the mean kinetic energy of the electrons does not vary significantly.

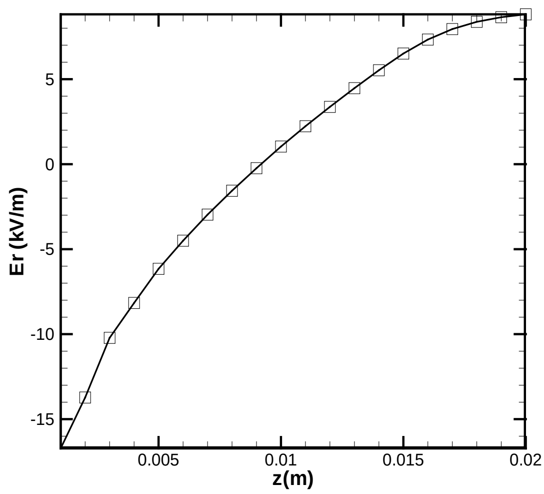

Fig. 4 Spatial charge field distribution at P=1 torr and E0=10 kV/m.

The figure (Fig. 4) shows the spatial repartition of the space charge field at pressure of 1 (torr) under an applied electric field of 10 (kV/m) where we deduce that the space charge field is intense near the cathode but it is not sufficient to sustain the discharge. This result is in good agreement with the value given E. Kuffel [4].

The figures (Fig. 5 and Fig. 6) show, respectively, the variation with time of the ionization coefficient (α) and the attachment coefficient (η); for Oxygen gas at a pressure of 100 (torr), a temperature of 293 K (20° C) with a gap length of 2 (cm) and under an applied electric field E0=1000 (kV/m).

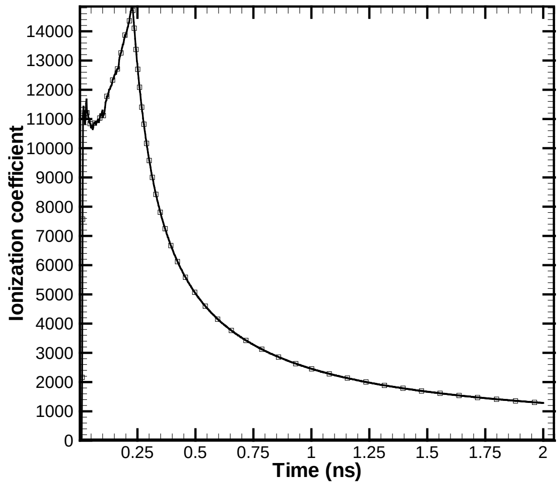

Fig. 5 Temporal variation of the ionization coefficient at P=100 (torr) and E_0=1000 (kV/m).

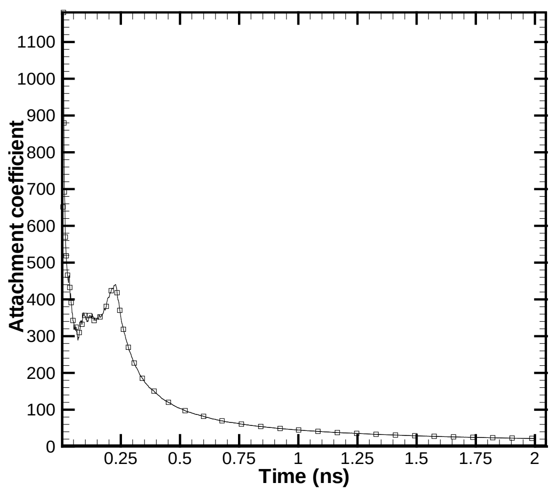

Fig.6 Temporal variation of the attachment coefficient at P=100 torr and E0=1000 kV/m.

The figures (Fig. 7 and Fig. 8) show, the distribution of the electric field Er due to space charge, at times t = 2ns and t = 2.22ns respectively. For Oxygen gas at a pressure of 100 (torr) and a temperature of 293 K (20° C) with a gap length of 2 (cm):

At time t= 2 ns (Fig. 7), the total number of space charge is about 784434 and thus the streamer formation criterion is not verified.

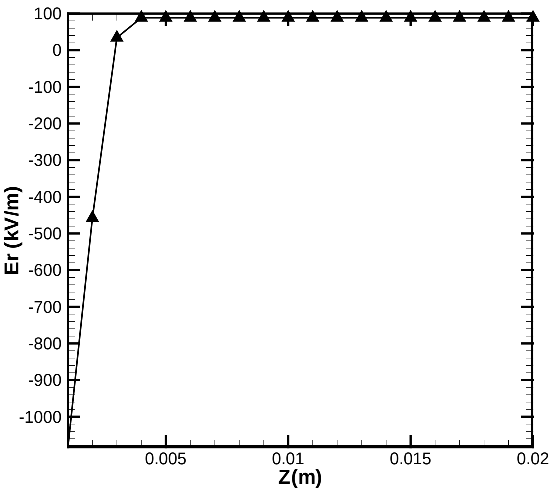

Fig. 9 Spatial distribution of the space charge field at P=100 (torr) and E0=7000 (kV/m).

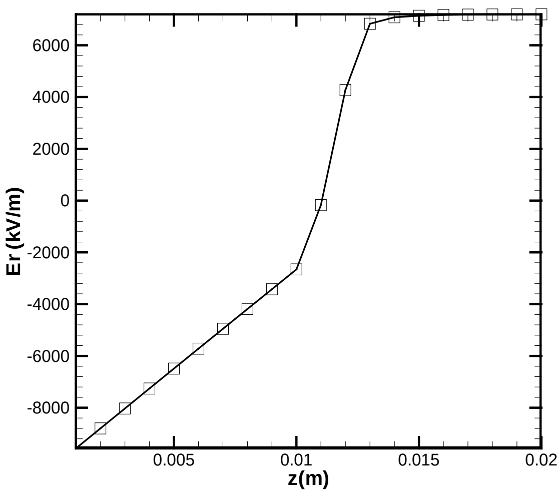

Fig. 10 Space charge field distribution at t=2.22ns and P=100 torr underE_0=7000 kV/m

At time t=2.22 ns (Fig. 8), under an applied electric field E0= 7000 (kV/m), the total number of space charge is of 9846099 and it is able to produce sufficiently strong electric field which allow secondary electrons due to photo-ionization to develop into the avalanche head. The space charge field is of the same order magnitude as the applied electric field and streamer breakdown criterion $\overline{\alpha}d$ =18.03 is verified; so we can say, in this case, that the streamer breakdown is established, this result is in good agreement with [7].

5 Conclusion

In conclusion of this paper, when the voltage is sufficiently high the ionization increases and the gas becomes conductor and the current passing through is increased where the onset of the electric breakdown. By means of the Monte Carlo simulation's results, in uniform electric fields, the macroscopic parameters (electrons mean energy, ionization and attachment coefficients) of an electrical discharge well as the space charge field distribution, are obtained as functions of time. When the voltage is sufficiently high, the ionization coefficient increases and the gas become conductor, and therefore the appearance of the electrical breakdown. The effect of pressure and applied voltages of the discharge development and the electric breakdown appearance are is also studied.

In this context, we tested the electrical breakdown criteria for different values of applied electric field (pressure and applied voltages) (Townsend for the low pressures and Streamer for the high pressures)

References:

[1] Y. R. Raizer, "Gas Discharge Physics", Berlin: Springer-Verlag, 1991.

[2] M. M. Pejovic, G. S. Ristic and J. P. Karamarkovic "Electrical breakdown in low pressure gases", J. Phys. D: Appl. Phys. 35 , pp. R91–R103, 2002.

[3] J. M. Meek, J. D. Craggs, Electrical Breakdown of Gases, Oxford : Clarendon Press, 1953.

[4] E. Kuffel, W. S. Zaengl and J. Kuffel: High Voltage Engineering Fundamentals, 2nd ed Butterworth-Heinemann, 2000, 534 p.

[5] M. S. Naidu, High Voltage Engineering, 2nd ed. New York: Quebecor/Book Press, 1995.

[6] G. R. Govinda Raju and J. Liu. "Simulation of Electrical Discharges in Gases–Nonuniform Electric Fields", IEEE Transactions on Dielectrics and Electrical Insulation, vol 2 (5), pp. 1016-1041, 1995.

[7] G. G. Raju, Dielectrics in Electric Fields, Marcel Dekker, New York: CRC Press, 2003.

[8] G. R. Govinda Raju and J. Liu. "Simulation of Electrical Discharges in Gases– Uniform Electric Fields". IEEE Transactions on Dielectrics and Electrical Insulation, vol 2 (5), pp. 1004-1015, 1995.

[9] A. V. Phelps, Atomic & Molecular Physics. JILA NIST-CU website. [Online] 2005. Available:
[10] ftp://jila.colorado.edu/collision_data/electronneutral/ELECTRON.TXT