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Magnetic insulation in nitrogen subjected to crossed fields

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In the E/N range from 150 to 400 Td (1 Td = 10^{-17} Vcm^2), the combination of crossed *magnetic* fields resulting in avalanche growth inhibition in nitrogen are evaluated by means of a Monte Carlo simulation. The simulation technique employed analysis swarm development without any a priori assumptions on electron energy distribution functions and electron collisional frequencies. For the combined crossed fields evaluated, variation of number of free electrons, average positions of the swarm and pulsed Townsend energies with respect to sampling times are reported. The pulsed Townsend energies indicate considerable reduction in the mean energies when the electron avalanche at a given E/N is inhibited upon the application of a specific magnetic field value. Effectively reduced electric fields are calculated from the magnetic deflection angles obtained from the simulation. It is observed that the calculated effectively reduced fields with the related pulsed Townsend mean energies favor the effectively reduced field concept in the combined fields. © *2018 Author(s). All article content, except where otherwise noted, is licensed under a Creative Commons Attribution (CC BY) license (http://creativecommons.org/licenses/by/4.0/).*
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I. INTRODUCTION

In the field of electrical engineering and environmental engineering, investigations into electron swarm development in alternative gases to replace SF_6 are underway due to the global warming potential (GWP) index of this widely used electronegative gas which is about 24000 **for 100-year time horizon**.[1]

Nitrogen is a natural gas being the major component of the atmosphere and it has sufficient level of insulation strength suitable for insulation of high voltage devices.[2] The dielectric strength of N_2 can be increased to the same strength level of SF_6 by increasing the loading pressure in a gas insulated system however new enclosure design is required in order to overcome the mechanical stresses.

The concept of magnetic insulation in vacuum is well known and has found numerous number of areas in pulsed power and plasma technology where the applied magnetic field is perpendicular to the electric field.[3–5] **However, in high-pressure gas discharges, compared to vacuum**, crossed field discharge research and applications are moderate. When the magnetic field is applied perpendicular to the electric field, the change in swarm parameters are described through the equivalent increase of pressure or in terms of equivalent reduced electric field concept.[6,7] In the equivalent pressure concept energy distribution of electrons are considered to be Maxwellian with the collision frequency being constant. However, the equivalent reduced electric field concept has restriction only on the effective electron collision frequency.

Recently, Dincer et al have reported back diffusion and transmission of electrons in N_2 subjected to crossed fields employing Monte Carlo Simulation in crossed fields without any a priori assumptions with respect to electron-molecule collision frequencies and electron energy distributions.[8]

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In a previous paper, Govinda Raju and Dincer have also reported the changes in mean energies and ionization coefficients in N_2 at high E/N above 240 Td (1 Td = 10^{-17} Vcm^2).[9] Rate coefficients for electron impact excitations in N_2 subjected crossed fields have been reported in a recent paper by M. Vojnovic et al.[10]

Magnetic insulation concept has been extended to a dense gas by Houck et al.[11] In Ref. 11, it has been shown that the breakdown voltage at 760 torrs of SF_6 pressure with high current pulses up to 1 MA, can be increased about 20% with an applied magnetic field of about 20 T when compared with that of zero magnetic field breakdown voltage. The experimental results of Dincer and Gokmen[12] at pressures from 7 to 22 torrs with applied magnetic fields up to 1.2 T when scaled agree quite well with the measurements as shown in Fig. 5 of Ref. 11.

Magnetic insulation is well established technique in the field of plasma physics particularly in vacuum and space environment and in high power vacuum transmission lines. However, with gas filled gaps, the application of the technique is very limited.[11] Therefore, the concept of magnetic insulation is important in gas insulated systems and gas switches to maintain the desired insulation level with the application of crossed magnetic fields. The magnetic field produced by the short circuit current flowing through a coil can help to improve the insulation medium for a possible switch application as thermal conductivity can be decreased by the crossed magnetic field.

Gas insulated systems in practice operate at the right side of Paschen minimum. In the present paper, the simulations carried out correspond to the right side of the Paschen minimum where the application of the magnetic field reduces the mean energy of electrons and acts as reduced electric field is decreased. The goal of the present paper is to investigate the inhibition of electron avalanches in N_2 subjected to crossed field discharges.

II. SIMULATION TECHNIQUE AND THE MODEL

Simulation technique and the model has been defined previously by Dincer et al in order to investigate swarm development in crossed fields.[13] Uniform and time invariant electric and magnetic fields are applied along negative z and positive x directions respectively in Cartesian coordinates. The electron with velocity v is subjected to Lorentz force given as

$$\boldsymbol{F} = e\boldsymbol{E} + e(\boldsymbol{v} \times \boldsymbol{B}) = m\frac{d\boldsymbol{v}}{dt} \tag{1}$$

where, E is the electric field, B is the magnetic field an e and m are charge and mass of electron respectively.

The simulation is based on a free-flight time approach with fine time steps in such a way that the energy change during a time step is less than 3%. With the given directions of crossed fields, the acceleration along the magnetic field is zero and the related velocity components at the end of a time step Δt are

$$v_y{}^{(1)} = v_y{}^{(0)} + \left(\frac{e}{m}\right) v_z{}^{(0)} B_x(\Delta t) \tag{2}$$

$$v_z{}^{(1)} = v_z{}^{(0)} + \left(\frac{e}{m}\right)\left(E_z - v_y{}^{(0)} B_x\right)(\Delta t) \tag{3}$$

with corresponding displacements defined as

$$y^{(1)} = y^0 + v_y{}^{(0)}\Delta t + \frac{1}{2}\left(\frac{e}{m}\right) v_z{}^{(0)} B_x(\Delta t)^2 \tag{4}$$

$$z^{(1)} = z^0 + v_z{}^{(0)}\Delta t + \frac{1}{2}\left(\frac{e}{m}\right)\left(E_z - v_y{}^{(0)} B_x\right)(\Delta t)^2 \tag{5}$$

where, superscripts 0 and 1 denote the beginning and end of a time step respectively for the related components of velocity and displacements.

At the end of a time step, the state of the electrons with their positions and energies are calculated and updated. Dincer et al have reported previously the simulation of a collision process with the decision on the nature of collision.[14,15]

The threshold energies of inelastic collisions are subtracted from electron energies and if the inelastic collision is an ionization process the remaining energy is shared equally between the newly born and original free electrons. In the present investigation, only binary electron-molecule collisions are considered since the gas is weakly ionized and the gas number density N is 3.32 10^{16} cm^{-3}. The collision cross section set of Phelps and Pitchford for N_2 is employed for the simulation.[16,17]

Termination time of simulation depends on the relative magnitudes of E/N and B/N and the number of initial electrons. At time t = 0, initial electrons are released according to cosine distribution. All the electrons, including the new free electrons born as a result of ionization, are traced until the termination time or until they reach to cathode position due to back diffusion or are lost due to attachment collisions if the gas dielectric under investigation is electronegative. To simulate the pulsed Townsend experiment, the averaged quantity q representing the property of the electrons is calculated as.[18,19]

$$\langle q(t)\rangle = \frac{1}{n^{(t)}} \sum_{j=1}^{n^{(t)}} q_j \tag{6}$$

where, the number of electrons in the avalanche at time t is $n^{(t)}$ and q_j stands for the quantity to be sampled for the j th electron.

Pulsed Townsend electron mean energies, average positions of the swarm in z and y directions are calculated taking q as equal to ε, z and y respectively.

It is also possible to evaluate transverse drift velocity W_z and perpendicular drift velocity, W_y from the related average positions of the swarm with respect to time when the swarm is in equilibrium. The method used is capable of tracing all free electrons in the avalanche at fixed sampling times and the growth and decay of the electron avalanche can be observed simply by observing the number of free electrons during sampling times.

III. RESULTS AND DISCUSSION

In Figure 1 density normalized Townsends first ionization coefficients, in crossed fields evaluated in this paper are compared with the measurements of Ref. 24 at B/N = 1.5 10^{-18} Tcm^3. A recent Monte Carlo calculation of the same coefficient at B/N = 1.5 10^{-18} Tcm^3 is also displayed in this Fig. 1. We also report the ionization coefficient evaluated at B = 0 in Fig. 1 together with the results of various researchers for comparison.[10,20–23] It can be seen from these figures that our results of the evaluated

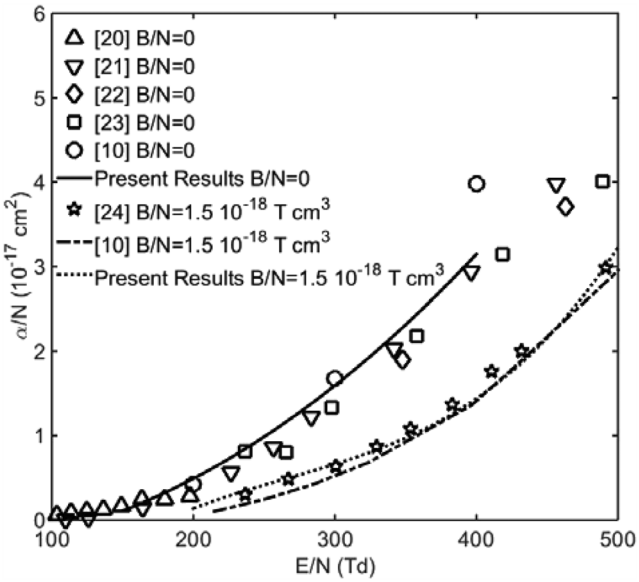


FIG. 1. Density normalized Townsend first ionization coefficient in Nitrogen.

ionization coefficients both in the absence and presence of magnetic field are in agreement with the available measurements of this coefficient.[10,20–24]

Furthermore, in the E/N interval of the present paper, with B = 0, electron drift velocity along the applied electric field evaluated is compared with the experimental and theoretical calculations as shown in Fig. 2.[10,25–27]

Figure 3 shows ionization growth at 150 Td in the presence and absence of magnetic fields normal to the electric field. In Fig. 3a, variation of number of electrons in the swarm with respect to time is investigated at 2.5 ns sampling times throughout the simulation until termination time of 80 ns. **The initial number of electrons are not the same for the both cases with magnetic field and without magnetic throughout the simulation. In order to reduce the Monte Carlo error, the number of initial electrons used depends on the relative magnitudes of E/N and B/N as reported by Dincer et al.[28] For example, in Fig. 3a, the initial number of electrons used is 5700 without the magnetic field and in the combined fields the initial number of electrons is 7000. The Monte Carlo error is kept less than 4% in the present paper**.

It can be seen from Fig 3a that, in both of the curves there is a reduction in the number of electrons initially until a certain time interval is reached. Since nitrogen is non-attaching, the loss in number of free electrons is due to back diffusion of electrons to a totally absorbing cathode.[13,14] The reduction in the free electron number is more pronounced with the crossed magnetic field of B/N = 5.42 10^{-19} Tcm^3 and after 25 ns the electron number stays constant throughout the simulation time indicating that ionization processes are not operative. However, variation in the electron number without the magnetic field indicates an increase in the number of electrons in the swarm after about 10 ns due to ionization collisions. It is also interesting to observe from Figure 3c that in the presence of the magnetic field there is a relaxation time of about 25 ns and after 25 ns the energy of the swarm is in equilibrium. This time interval corresponds with the time interval in which back diffusion of electrons is significantly dominant displaying the region of nonlocality. The relaxation time is reduced down to 10 ns when the crossed magnetic field is removed as can be observed from the B/N = 0 curve. Fig. 3b gives the average positions of the swarm along z and y directions with respect to sampling times. The inset in Fig. 3b is the average position along the applied field direction without the magnetic field. When the electron swarm is in equilibrium related drift velocities can be evaluated from the average positions with respect to time.[29]

The B/N value determined in Fig. 3 is the specific threshold value resulting in avalanche inhibition. For any B/N higher than the specific value, avalanche growth is not possible and

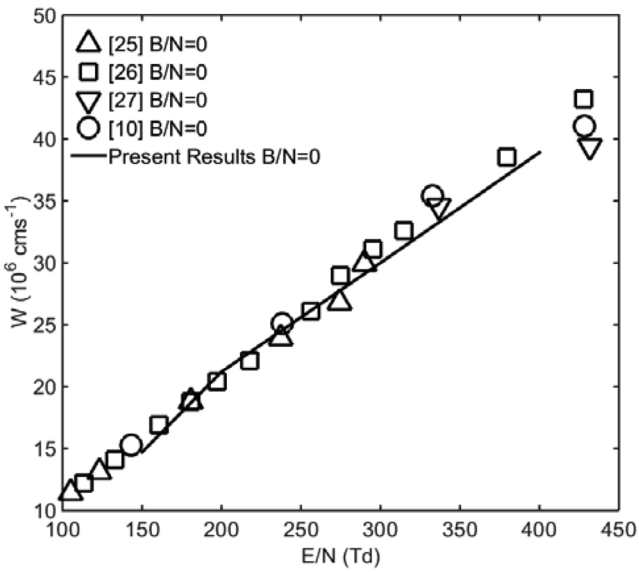


FIG. 2. Electron drift velocity in Nitrogen subjected to uniform electric field only.

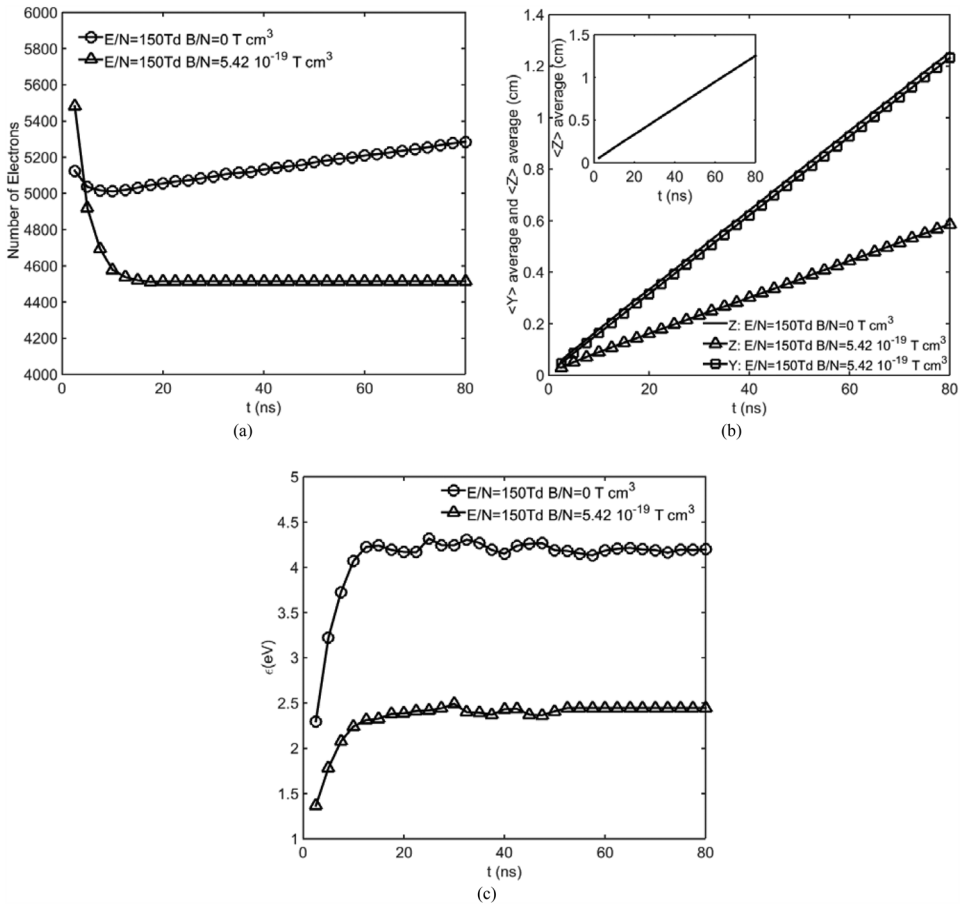


FIG. 3. Electron avalanche growth in crossed fields at 150 Td. a) Variation of number of free electrons in the swarms b) Average positions of the swarm with respect to sampling times c) Pulsed Townsend mean energies.

for any B/N lower than the specific value, ionization processes in the swarm will be operative resulting in avalanche growth.

Figure 4 gives the swarm development at E/N =150 Td for various B/N. In Fig. 4a the variation of number of free electrons is given together with the pulsed Townsend mean energies at B/N = 9.04 10^{-19} T cm^3. It can be observed from this figure that back diffusion of electrons is significant in the nonlocal region and the relaxation time is about 35 ns. The number of free electrons remains constant in the equilibrium region and avalanche growth is not possible. Furthermore the electron mean energy is reduced to about 1.5 eV compared with the value of 2.5 eV at the specific value of B/N = 5.42 10^{-19} Tcm^3.

Figure 4b displays the swarm development at B/N = 3.01 10^{-19} Tcm^3. It can be seen from Fig. 4b that the relaxation time is reduced and in the equilibrium region ionization processes are operative resulting in an increase in the number of free electrons. The electron mean energy is 3.3 eV which is higher compared with the value of 2.5 eV at B/N = 5.42 10^{-19} Tcm^3.

Figure 5 gives the avalanche growth in crossed fields at 200 Td. It can be seen from Fig. 5a that without the magnetic field, after 7.5 ns, the number of electrons in the avalanche increases with the simulation time due to ionization collisions. However, with the applied magnetic field of B/N = 1.05 10^{-18} Tcm^3, it is possible to suppress avalanche growth after about 20 ns when the swarm reaches equilibrium. The initial reduction of the number of electrons in the swarm is due to back diffusion of electrons in the non-equilibrium region and the time taken for the swarm to reach the equilibrium state is displayed in Fig. 4c where pulsed Townsend mean energies with respect to simulation time are displayed. Fig. 5b gives the average positions of the electron swarms in crossed fields with and without magnetic field.

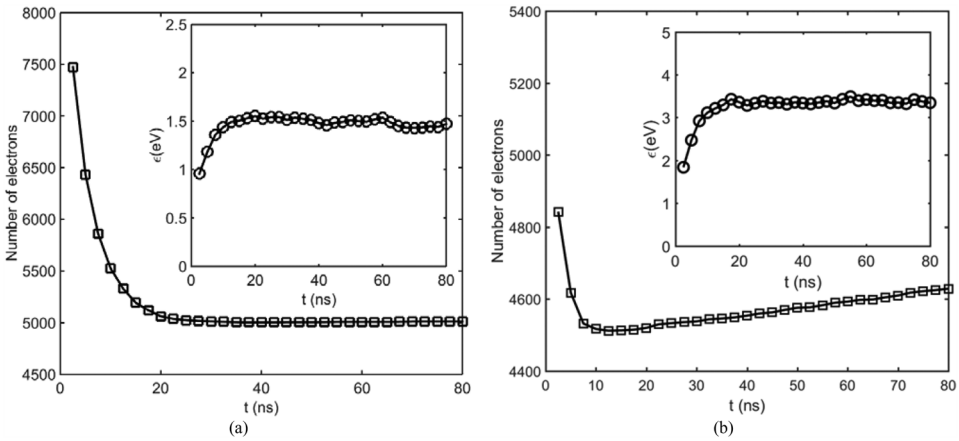


FIG. 4. Swarm development at E/N = 150 Td for various B/N. a) Variation of number of free electrons and pulsed Townsend energies at B/N = 9.04 10^{-19} Tcm^3 b) Variation of number of free electrons and pulsed Townsend energies at B/N = 3.01 10^{-19} Tcm^3.

In Figures 6 and 7 avalanche growth in crossed fields at 300 Td and 400 Td number density reduced fields are given respectively similar to Figures 3 and 5 together with average positions of the swarm and pulsed Townsend mean energies with respect to simulation time. In the absence

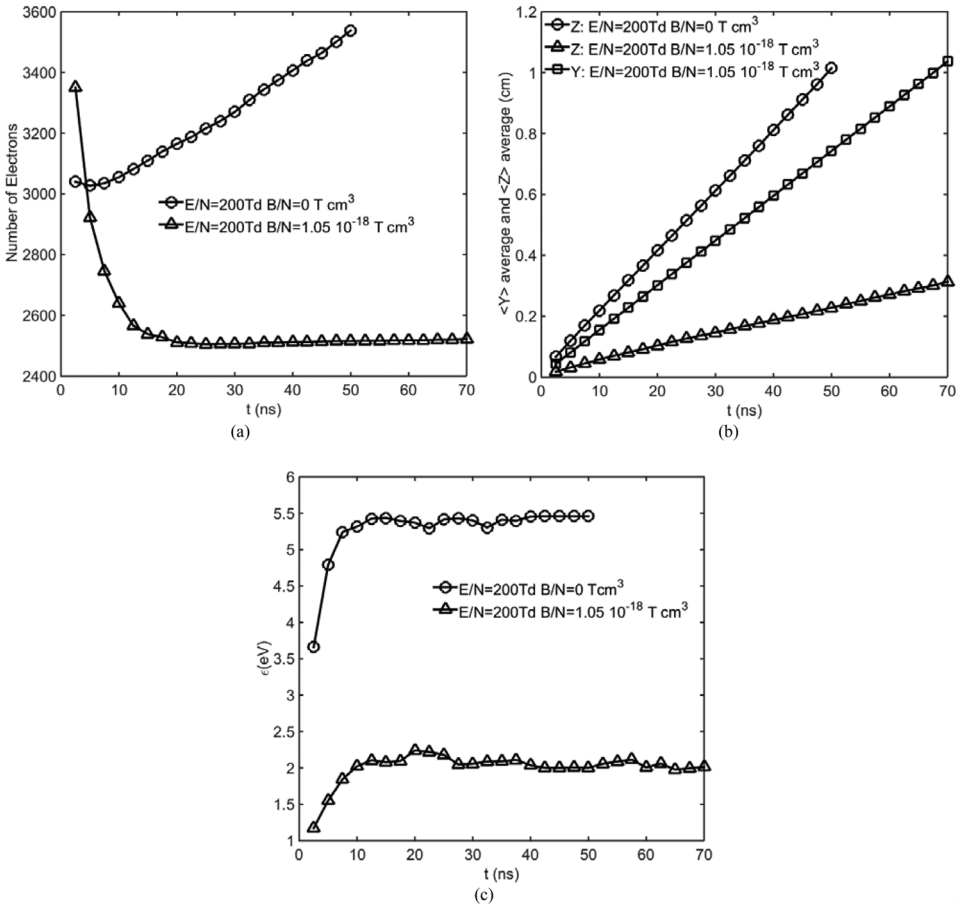


FIG. 5. Electron avalanche growth in crossed fields at 200Td. a) Variation of number of free electrons in the swarms b) Average positions of the swarm with respect to sampling times c) Pulsed Townsend mean energies.

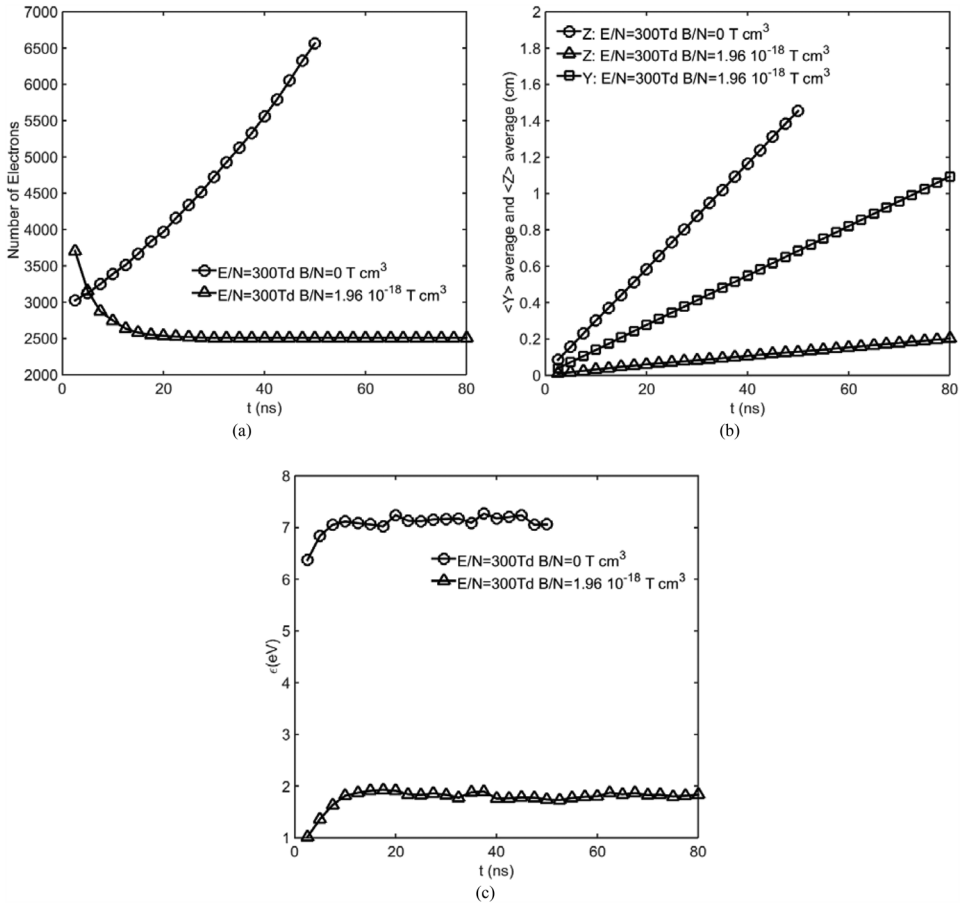


FIG. 6. Electron avalanche growth in crossed fields at 300Td. a) Variation of number of free electrons in the swarms b) Average positions of the swarm with respect to sampling times c) Pulsed Townsend mean energies.

of the magnetic field, avalanche growth is faster when the field magnitude is increased as can be seen from Figures 6a and 7a when the variation of number of free electrons are compared during the simulation. Application of the given specific crossed magnetic fields results in the avalanche inhibition as displayed in these figures. Furthermore, for the given specific crossed fields relaxation time decreases as E/N is increased.

Electron drift velocities W_z and W_y can be evaluated from the average positions along z and y directions respectively as shown in the figures in the presence of crossed fields and magnetic deflection angle θ can be defined as

$$\tan\theta = W_y/W_z \tag{7}$$

According to the equivalent reduced electric field concept the applied E/N is reduced to the equivalent reduced field $(E/N)_{EQ}$ given as

$$(E/N)_{EQ} = \frac{E}{N}\cos\theta \tag{8}$$

on the assumption that the magnetic field is removed and the applied E/N is reduced to $(E/N)_{EQ}$.

Table I gives the calculated magnetic deflection angles and corresponding equivalent reduced fields in the presence of crossed fields in which avalanche growth is inhibited together with the related pulsed Townsend mean energies. It is interesting to note that the calculated equivalent reduced fields from Eq. 8 and the corresponding pulsed Townsend mean energies evaluated in crossed fields from the simulation favor the equivalent reduced electric field concept since the mean of the $(E/N)_{EQ}$

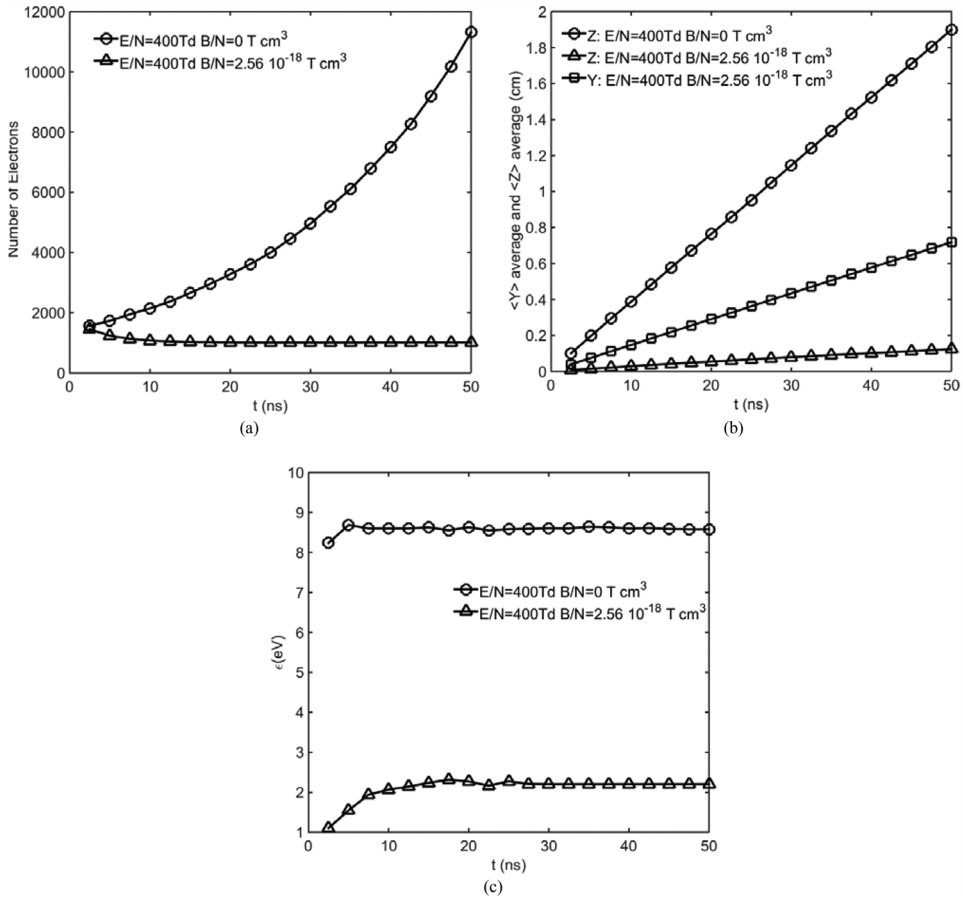


FIG. 7. Electron avalanche growth in crossed fields at 400Td. a) Variation of number of free electrons in the swarms b) Average positions of the swarm with respect to sampling times c) Pulsed Townsend mean energies.

calculated from the four entries is 55.39 Td with the corresponding mean value of the four entries of Pulsed Townsend mean energy which is 2.15 eV.

Figure 8 gives the electron energy distributions in N_2 at E/N = 150 Td without the magnetic field and also with the crossed magnetic field of B/N = 5.42 10^{-19} Tcm^3 resulting in avalanche inhibition. It can be observed from this figure that application of the crossed magnetic field results in depopulation of high energy electrons in the avalanche shifting the increased peak of the distribution to the lower energy range.

Figure 9 gives the electron energy distribution for the combined fields of E/N = 400 Td and B/N = 2.56 10^{-18} Tcm^3. It is interesting to observe that electron energy distribution has almost the similar shape when compared with electron energy distribution of the combined fields in Fig. 8 yielding the inhibition of the electron avalanche although the applied E/N is high.

TABLE I. Calculated magnetic deflection angles and corresponding equivalent reduced fields.

E/N (Td)	B/N (Tcm^3)	Angle (◦)	$(E/N)_{EQ}$ (Td)	Mean Energy (eV)
150	5.42 10^{-19}	68.07	56.02	2.4
200	1.05 10^{-18}	74.26	54.25	2.1
300	1.96 10^{-18}	79.47	54.74	1.9
400	2.56 10^{-18}	81.57	56.57	2.2

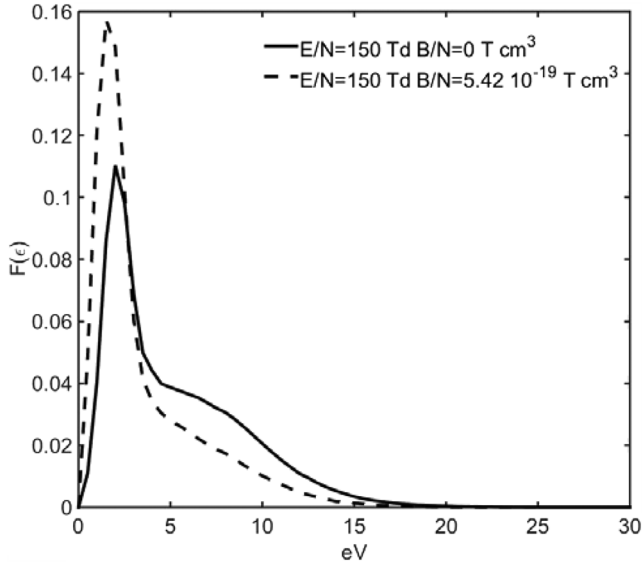


FIG. 8. Electron energy distributions in N_2 at E/N = 150 Td.

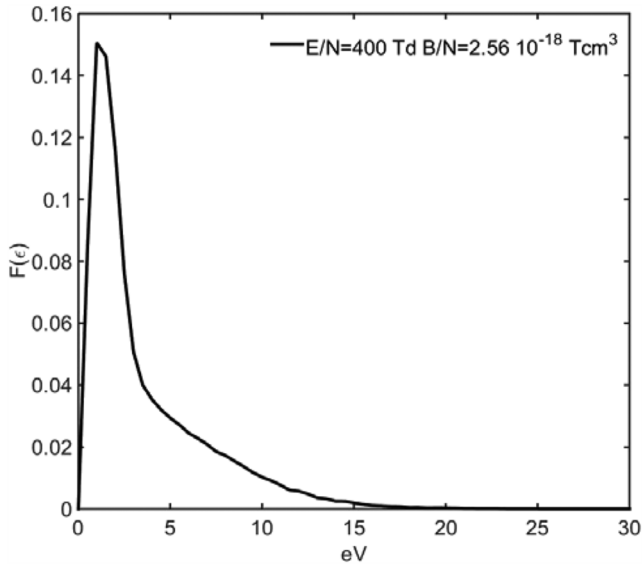


FIG. 9. Electron energy distribution in N_2 subjected to combined fields resulting in inhibition of avalanche formation.

IV. CONCLUSION

In crossed fields, at a given E/N, specific magnetic field magnitudes normal to the applied electric field are determined resulting in avalanche growth inhibition. The specific magnetic field values at given E/N values in crossed fields reduces pulsed Townsend mean energies in the swarms considerably when compared to those of developed avalanches at the corresponding E/N values without the magnetic field.

In the E/N range of the present investigation, for the combination of crossed fields resulting in inhibition of electron avalanche formation which are evaluated without any a priori assumptions with respect to electron energy distribution functions and collisional frequency of electrons, the equivalent reduced electric field concept is supported.

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