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Negative Streamer Propagation in Nitrogen

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Abstract

For the development of negative streamer, a one dimension simulation is presented when a negative electric field is applied at atmospheric pressure to a 4 mm gap in nitrogen. At applied electric fields of 55, 60, 65 and 70 kV/cm, streamer parameters were studied at various time intervals. The aim of this paper is to determine the minimum electric field that must be applied for stable propagation of negative streamer discharge in nitrogen gas. As functions of position and time, the calculations provide detailed electron and ion density predictions, electric fields and density of space charges. The time interval was with a nanosecond resolution. Using 8000 element mesh to resolve the characteristics of the streamer, spatial resolution over the separation of electrodes 4 mm was obtained. The results were obtained by solving the equation of continuity for electrons and ions and the Poisson equation solution.

Keywords: gas discharge, negative streamer, nitrogen, stable streamer.

انتشار الستريمر السالب في النتروجين

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الخلاصة

نظرا لتطبيقات بلازما تفريغ الستريمر في المجالات الطبية والصناعية فقد تم دراسة خصائص البلازما الناتجة من هذا النوع من التفريغات الكهربائية. يمكن انتاج هذا النوع من البلازمافي درجة حرارة الغرفة وعند الضغط الجوي الاعتيادي حيث لا تحتاج الى نظام تفريغ ولكنها تحتاج الى فولطية عالية. ويكون نمط هذا التفريغ خيطيا.في هذا العمل تم دراسة تفريغ الستريمر السالب ببعد واحد لفجوة بين الانود والكاثود مقدارها 4 ملم وتمتسليط مجالات كهربائية بقيم مختلفة على الفجوة (55, 60 , 65 و 70 كيلو فولط/سم) وكانت هذه الفجوة مملوءة بغاز النتروجين.تم استخدام نموذج (موديل) الموائع لعمل محاكاة حاسوبية باستخدام برنامج كومسول لتشخيص خصائص البلازما التي ينتجها تفريغ الستريمرالسالب .ومن النتائج التي حصلنا عليها تم الحصول على تشخيص جيد من خلال دراسة خصائص انهيار الغاز التي تتمثل في حساب كثافة الالكترونات, توزيع المجال الكهربائي, كثافة شحنة الفضاء و معدل طاقة الالكترونات عند ازمان مختلفة وهدف الدراسة هو حساب مقدار اقل مجال كهربائي لازم لنشوء تفريغ ستريمر مستقر.

1. introduction

Streamers can be developed in nature within the streamer corona of the typical lightning leaders in different regions of thunderclouds in sprites, jets and other transient luminous events. Streamers have various applications in gas, water treatment, ozone generation, particle

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charging and flow control[1]. Streamer discharges are important building blocks of any ionizable matter for sparks and lightning; they are thin plasma channels generated from a conductive electrode exposed to high voltage that unexpectedly penetrate non-conducting media. By raising the electric field at the electrode tip to a degree that simplifies an electron impact ionization reaction, they propagate through the defined medium[2]. when a streamer is formed, charged particles are created at the front in a high field region, required to maintain in the channel high plasma conductivity. The electric field at the tip of streamer, in turn, is regulated via the space charge produced. This property enables the production of streamers in weak electric fields that are much less than the gas ionization threshold. There is, however, the so-called stability field, the minimum background electrical field strength, necessary to allow stable streamer propagation [3]. Vitcllo et al. in 1994[4] considered how the dynamical characteristics of negative streamers are determined by their multidimensional structure. Results from two-dimensional simulations were presented at atmospheric pressure for N_2 and plane-parallel electrodes. In 2007, Li et al. [5] investigated negative streamer ionization fronts in nitrogen under normal conditions in both a particle model and a fluid model in local field approximation. Several distinct phases of streamer evolution were clearly discernible. They demonstrated the transition between these phases, showing how the self-consistent radial and axial structure varies with time. Recently the generation of energetic electrons by the streamer with a negatively charged head using a self-consistent two-dimensional Particle-in-Cell Monte Carlo collision model was studied by Levko and Raja[6]. A small number of energetic electrons have been found to greatly accelerate the propagation of the streamer and even change the propagation direction of the streamer.

In this paper, calculations are provided for a situation where the streamer crosses the gap. The effects of the spatial distributions of electrons and ions are obtained. The calculations are carried out by solving the continuity equation coupled with Poisson's equation in order to determine electron and ion densities

2. Modeling Theory

Fluid model was used in this simulation. The fluid model is based on the self-consistent solution of electron and ion continuity and momentum transport equations combined with the Poisson equation for solving the potential between the electrodes[7].The model is one dimensional employing a method of finite elements using COMSOL 5.3a software.

In general, it is possible to derive fluid models from Boltzmann equation. Via continuity equations, the motion of charged particles can be approximated [5]:

$$\frac{\partial n_e}{\partial t} + \nabla . j_e = S \tag{1}$$

$$j_e = -\mu E n_e - D \nabla n_e \tag{2}$$

The mean electron velocity is u=<v>, n_e is the electron density, $j_e = u n_e$ represents the electron flux density, S is the electron source (due to electron impact ionization also photons can generate free electrons through photoionization in the gas). μ reflects mobility because of collisions and impact ionization, and D is the matrix for diffusion.

The term for the source of electrons can be written as:

$$S = |n_e \mu(\mathrm{E})\mathrm{E}| \alpha\,(\mathrm{E}) \tag{3}$$

Where α (E) is the ionization reaction coefficient.

For a gas that is not attached, ignoring ion mobility, the continuity equation for the density of positive ions n_p has to be used:

$$S = \frac{\partial n_p}{\partial t} \tag{4}$$

Continuity equations together with the electric field Poisson equation:

$$\nabla . E = \frac{e(n_p - n_e)}{\varepsilon_0} \tag{5}$$

Fluid model is built on local equilibrium assumption that transport and reaction coefficients are the only functions of local parameters, in the continuity equations. This assumption is referred to as the approximation of the local field if this parameter was the local electrical field, which was used in this simulation [5]. Initial values of electron density follow the equation $n_{e0} = n_{e0max}$*exp (-((x-x_0)/sigma) ^2) +n_{e0min}.

Also, plasma factors (plasma frequency, Debye length and number of particles in Debye sphere) can be calculated.

a. Plasma frequency:

Plasma frequency is a plasma parameter. The frequency of plasma oscillations (electron-electron collisions) is much higher than the frequency of electron-atom collisions [8].

$$\omega_p = \sqrt{\frac{n_e e^2}{\varepsilon_0 m_e}} \tag{6}$$

Where ω_p is the plasma frequency [9].

b. Debye length

The basic parameter of ideal quasineutral plasma is the Debye length. It is the distance over which external electric fields are shielded by a collection of charged particles of the plasma. A plasma can be described as a weakly ionized gas, in which the length of Debye is small compared to its size L, i.e. L >>λ_D[8]. In plasma, the length of Debye is given by:

$$\lambda_D = \sqrt{\frac{\varepsilon_0 K T_e}{n_e e^2}} \tag{7}$$

Where: λ_D is the length of Debye, ε_0 is free-space permittivity, k is Boltzmann constant, e is the charge of an electron, T_e is the electron temperature, and n_e is the electron density.

C. number of particles in Debye sphere

The plasma parameter, N_D, describing the number of charge carriers inside a sphere (called the Debye sphere whose radius is the length of the Debye screen) surrounding a given charged particle, is sufficiently large to shield the particle's electrostatic effect outside the sphere. Ideal plasma has many particles per Debye sphere, i.e.

$$N_D = \frac{4}{3} n_e \pi \lambda_D^3 \gg 1 \tag{8}$$

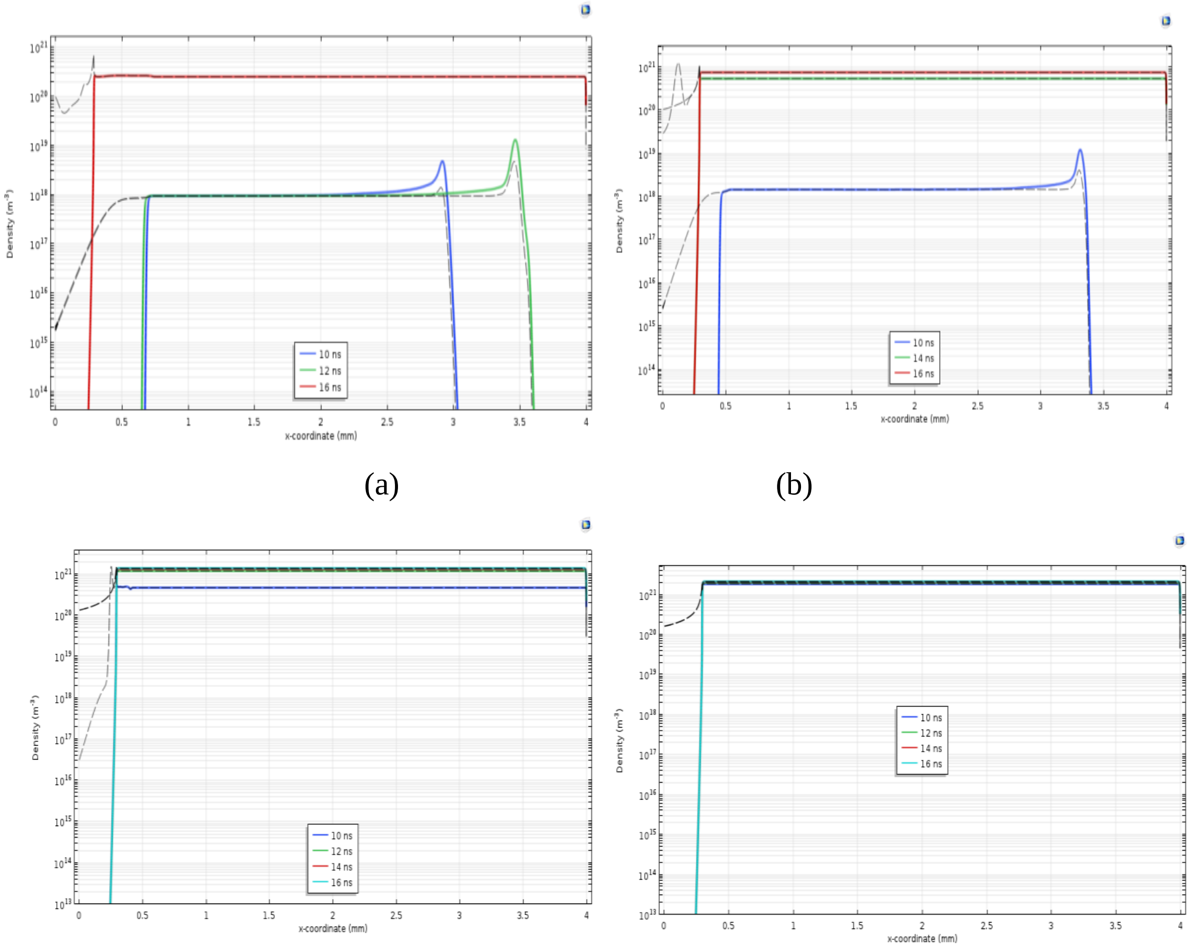
which is a requirement for the collective behavior in plasma [9].

3. Results and discussion:

Results for the negative streamers development in nitrogen gas under atmospheric pressure in one dimension are provided. The gap spacing was 4 mm, with electric fields of 55, 60, 65 and 70 kV/cm applied at the beginning of the calculation instantaneously (these electric field values chosen because streamer discharge needs high applied voltage to propagate). The calculation was started by ≈ 5 x 10^{16} seed electrons (initial electrons) (representing gas ionization due to radioactivity or cosmic rays) released from the cathode by 0.02 mm at t=0.

3.1 number density of ions and electrons

Distributions of electrons and ions at different times and different applied electrical fields during discharge development are shown in Figure 1. For example, in Figure 1.a, the electron density in the body of streamer at 10 ns, at 12 ns ≈ 10^{18} /m^3 and at 16 ns ≈ 3x10^{20} /m^3. Consider the profile at time period 16 ns. The velocity of the streamer was very high; in 10 ns, the streamer traveled around 2.25 mm, with a mean velocity of 2.25 x 10^5 m/s. The electron density near the streamer head was around 5x10^{18}/m^3, but fell down along the channel to 10^{18}/m^3, due to recombination with positive ions, and electron drift to the anode. With time, the density was increased by ionization. The maximum was at the head of the streamer. The density stayed relatively constant in the body of the streamer. The streamer traveled 2.75 mm at t= 12 ns, with an average velocity of 2.29 x 10^5 m/s, so the velocity of streamer propagation has increased by 4000 m/s. Thus the density and velocity increased with time. In Figure 1.b and Figure 1.c the density and velocity remained constant at 12 ns and above. In Figure 1.d at E= 70 kV/cm the streamer was stable that the density and velocity of streamer remained constant as time was increasing. It can be noted that the initiation time of the streamer decreased with the increase of the applied electric field. Also, as time increased the initiation of the streamer became closer to the electrode.



(a) (b)

(c) (d)

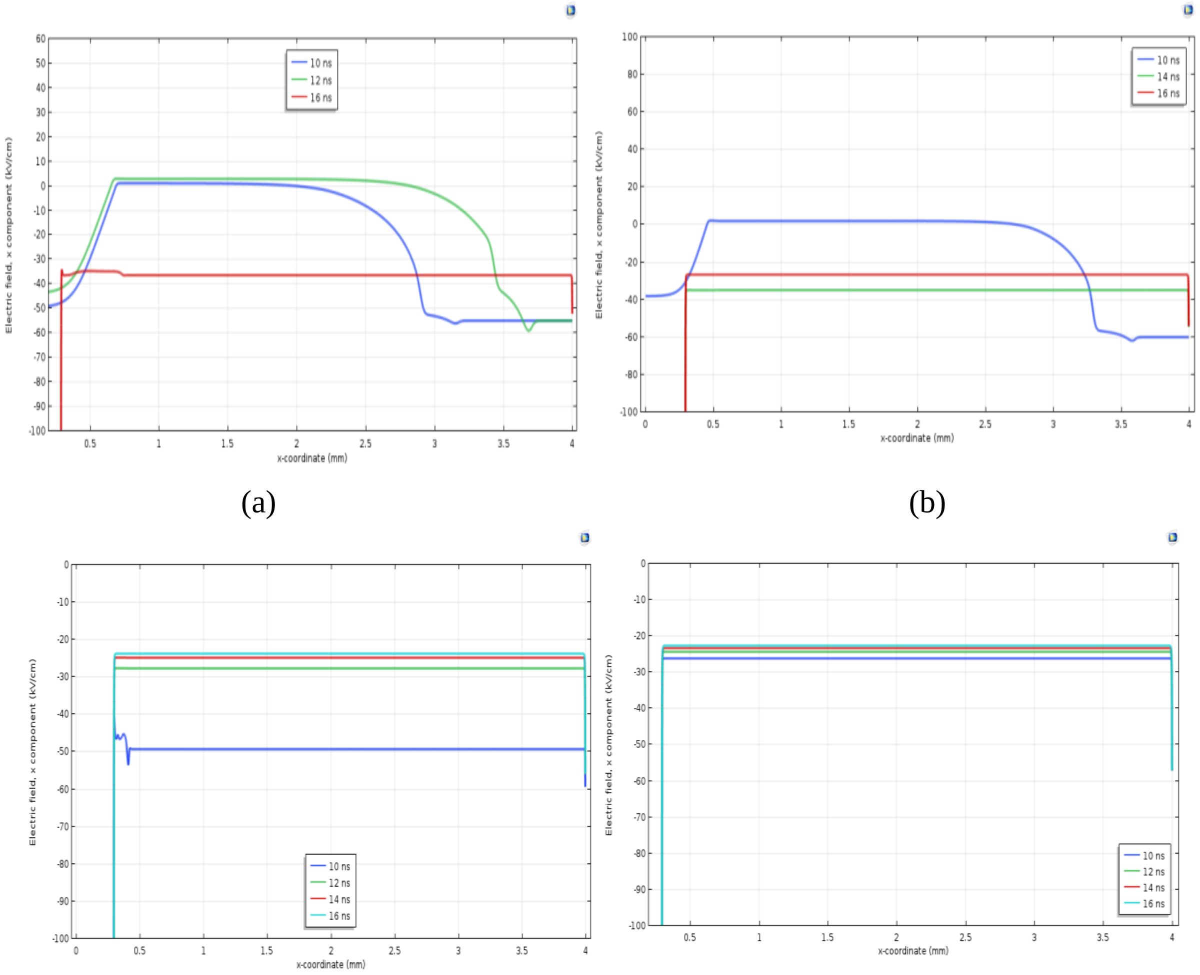
Figure 1-Density distributions of electrons and ions computed at different times(in nanoseconds) and at different applied electric fields: (a) 55,(b) 60, (c) 65 and (d) 70 kV/cm.

3.2 Electric field in the streamer and space charge density

In order to evaluate streamer propagation, the electric field along the gap was determined from the gradient of the potential distribution (Equation 5) for different times during discharge development. Taking into consideration the details of Figures 2 and 3, profiles for the time period between 10 ns and 16 ns. The charge density and the electric field at the streamer head increased by space charge effects, causing a "spike" in the electrical field to travel as an ionizing wave through the gap. An electric field was at its minimum value in the streamer column. Note that the electric field was left relatively constant in the body of the streamer. Due to ionization, a growth in the number density of electrons occured in the high electric field region (streamer head) (Figure 1). The electric field increased with the applied electric field and time. It was noted that when the electrons move away from the head of the streamer, the field decreased, and continued decreasing until reaching a minimum value when plasma channel forms (streamer body). As the streamer ended, electric field reached a maximum value. During a streamer discharge, due to the net discharge charge's shielding effect, the electric field in the streamer's body falls.

3.3 mean electron energy

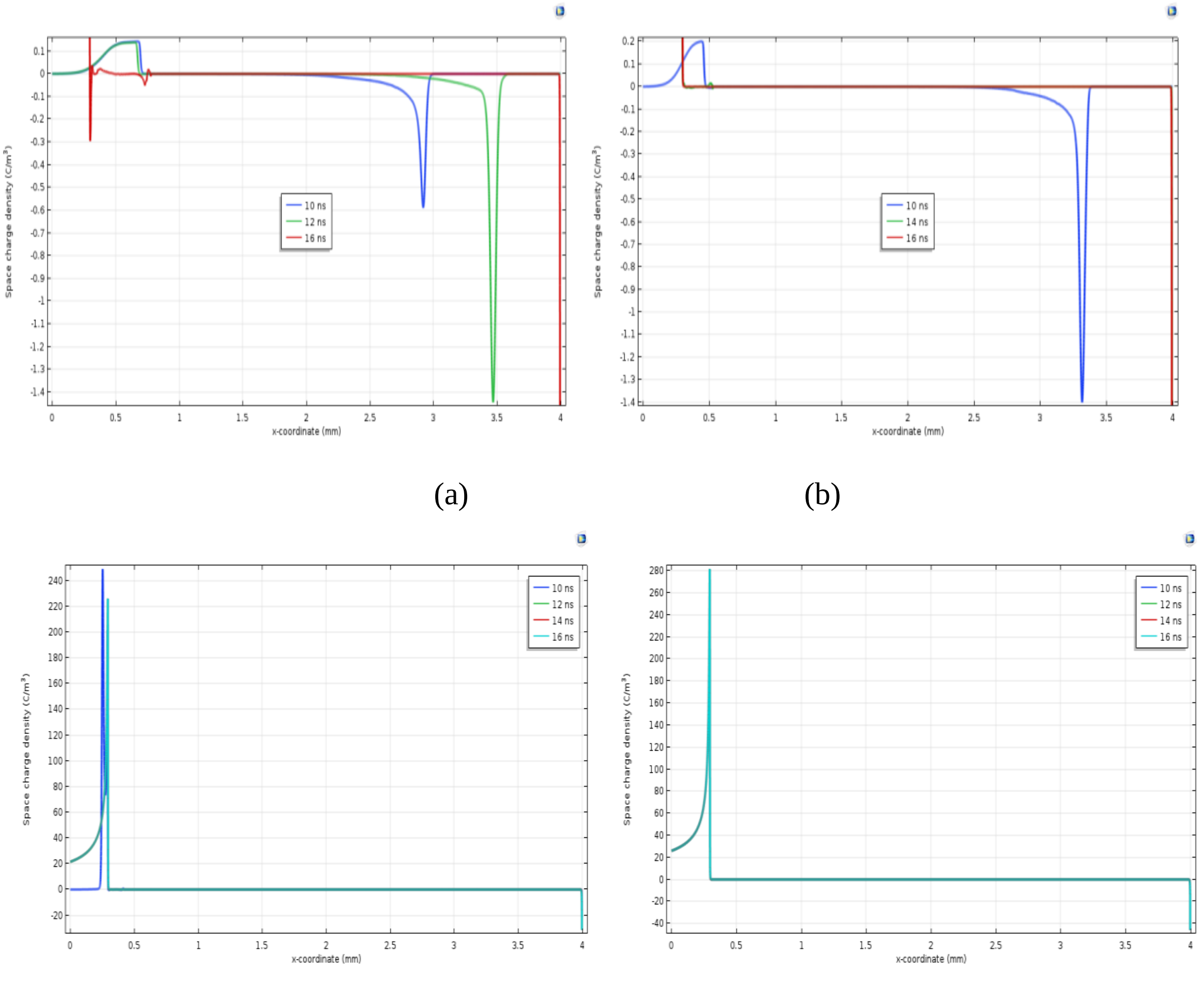
Electron energy (equivalent to the electron temperature) is one of the most important parameters that characterize plasma. Figure 4 shows the mean electron energy (in electron volt) along the gap through different instants of time and at different applied electric fields. From the figure, it was noticed that in the streamer channel the mean electron energy is almost constant except at the streamer head. The mean electron energy increased with the applied electric field.



(a) (b)

(c) (d)

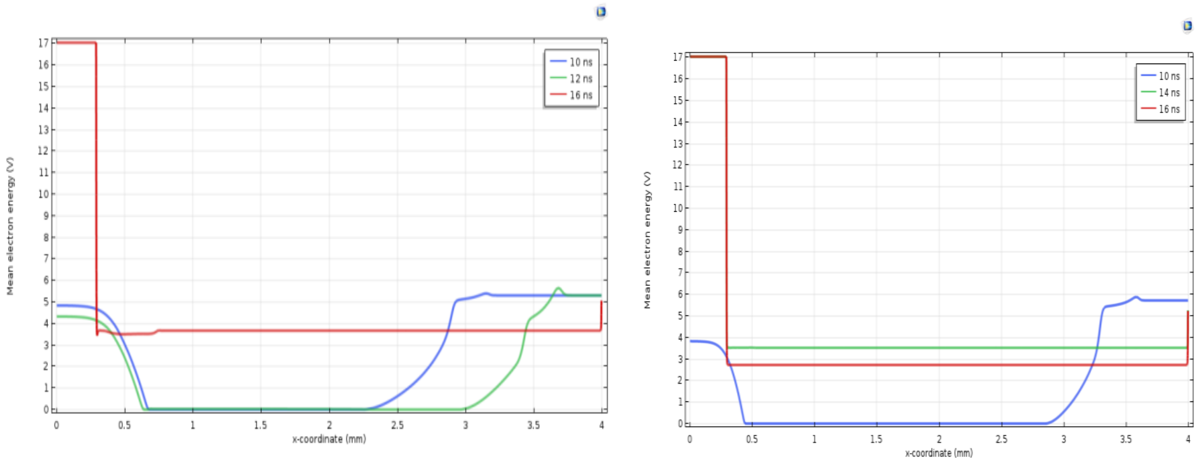
Figure 2-Distributions of the electric field along the discharge axis, indicated at times in nanoseconds at different applied electric fields: (a) 55, (b) 60, (c) 65 and (d) 70 kV/cm



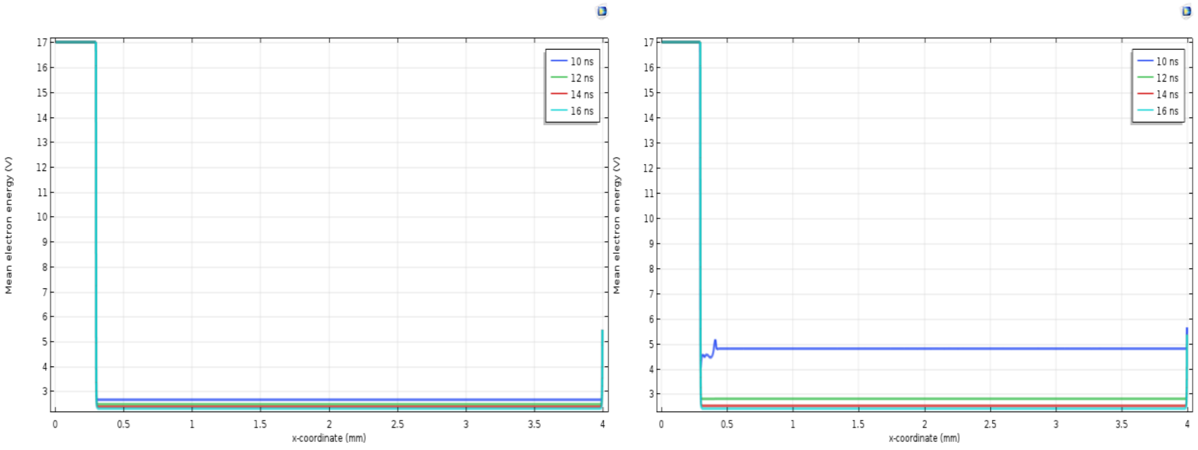
(a) (b)

(c) (d)

Figure 3- Space charge density distributions, at times indicated in nanoseconds, along the axis of the discharge and at different applied electric fields: (a) 55, (b) 60, (c) 65 and (d) 70 kV/cm.



(a) (b)



(c) (d)

Figure 4-Distributions of the mean electron energy along the discharge axis, at times indicated in nanoseconds, and at different applied electric fields: (a) 55, (b) 60, (c) 65 and (d) 70 kV/cm.

Table 1- Streamer velocity

applied electric field (kV/cm)	Time (ns)	Velocity (x 10^5m/s)
55	10	2.25
	12	2.29
	16	2.34
60	10	2.9
	14	2.67
	16	2.67
65	10	3.75
	12	3.12
	14	2.67
	16	2.34
70	10	3.75
	12	3.12
	14	2.67
	16	2.34

3.5 Plasma properties

Plasma was characterized by three factors: plasma frequency ω_p, Debye length λ_D and number of particles in Debye sphere N_D. These parameters were calculated from Equations 6, 7, and 8. The obtained results are shown in Table 2. From results, it is noted that the plasma conditions were satisfied.

Table 2- Plasma properties

applied electric field (kV/cm)	Time (ns)	Density (/m^3)	Plasma frequency (Hz)	Debye length (m)	Number of particles in Debye sphere (/m^3)
55	10	10^{18}	$5.4x10^{10}$	$9.09 x10^{-7}$	3
	12	10^{18}	$5.4x10^{10}$	$14.86x10^{-7}$	14
	16	$25 x 10^{19}$	$8.9x10^{11}$	$117.47 x10^{-7}$	1693937
60	10	$1.45 x 10^{18}$	$6.3 x10^{11}$	$6.17 x10^{-7}$	2
	14	$5.5 x 10^{20}$	$13.03 x10^{11}$	$5.92 x10^{-7}$	477
	16	$7.5 x 10^{20}$	$15.4x10^{11}$	$5.07 x10^{-7}$	409
65	10	$4.7 x 10^{20}$	$11.8 x 10^{11}$	$7.5 x 10^{-7}$	829
	12	$12 x 10^{20}$	$19.4 x 10^{11}$	$3.58 x 10^{-7}$	230
	14	$13.4 x 10^{20}$	$20 x 10^{11}$	$3.27 x 10^{-7}$	196

	16	14×10^{20}	20×10^{11}	3.07×10^{-7}	169
70	10	20×10^{20}	25.09×10^{11}	2.71×10^{-7}	168
	12	20×10^{20}	25.09×10^{11}	2.62×10^{-7}	151
	14	20×10^{20}	25.09×10^{11}	2.57×10^{-7}	143
	16	20×10^{20}	25.09×10^{11}	2.53×10^{-7}	135

4. Conclusions:

From these calculations, it was concluded that:

1. The space charge density remained constant as the streamer propagated.
2. More significantly, the electric field in the head of the streamer varied (Figures 2 a and b), since it depends on the charge of the streamer's head.
3. When the electrons moved away from the head of the streamer, the field decreased, and continued decreasing until reaching a minimum value when plasma channel formed (streamer body). As the streamer ended, electric field reached a maximum value. During a streamer discharge, due to the net discharge charge's shielding effect, the electrical field in the streamer body falls.
4. the minimum applied electric field required for stable propagation of negative streamer discharge in nitrogen was 70 kv/cm.
5. The mean electron energy in the streamer channel was almost constant except at the streamer head and it increased with the applied electric field.
6. When the value of the applied electric field reached stability field, the streamer velocity was constant.

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