Exitation of $N_2(C^3\Pi_u$,v=0–4) levels by streamer discharge in atmospheric pressure air: numerical study

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A numerical study on streamer induced excitation of $N_2(C^3\Pi_u$, v=0–4) vibronic levels in air is presented. It is shown that vibrational distribution of higher v=2–4 vibronic levels of $N_2(C^3\Pi_u)$ state is very sensitive to the electric field variations occurring due to the streamer head transit through given spatial coordinate and thus might be used as an complementary spectrometric tool for monitoring streamer head parameters in nitrogen/air streamer discharges when applied with sufficient spatio-temporal resolution.

1. Introduction

Electrical breakdown in air gaps is often developed by means of fast ionizing waves that take the form of thin filaments called streamers [1–7]. These ionizing waves occur as a consequence of the high electric field induced by the fast variations of the net charge density ahead of an electron avalanche with large amplification. The most important streamer characteristics are very high propagation velocity, a small streamer channel radius, and high density and mean energy of free electrons occurring in the streamer head. Thus the streamer head is a place where the reactivity of streamer plasma is produced and that is of considerable interest for various applications, such as pollution control, ozone formation, fast surface treatment, and plasma assisted combustion. Knowledge of vibrational distribution of $N_2(C^3\Pi_u)$ induced by the streamer head electrons is of particular interest due to its potentiality for streamer plasma diagnostics, namely for determination of the electric field in the nitrogen/air streamer discharge [1]. In this contribution we present numerical study of streamer induced excitation of $N_2(C^3\Pi_u$, v=0–4) vibronic levels based on a simplified one dimensional model that nevertheless mimics basic characteristics typically found in streamer discharges.

2. Model

The propagation of the positive streamer is simulated using drift-diffusion-reaction equations for charged species solved on the axis of the discharge within 1.5D model: the electric field is computed by means of disk method on the axis of the discharge by direct integration, assuming the discharge being a set of charged discs of a fixed radius, for details see [2–4]. The governing equations are:

$$\left.\begin{array}{l} \partial_t n_{\rm e} + \nabla\cdot(n_{\rm e}\,\mathbf{v}_{\rm e}) - \nabla\cdot(D_{\rm e}\,\nabla n_{\rm e}) = \\ \qquad n_{\rm e}\alpha|\mathbf{v}_{\rm e}| - n_{\rm e}\eta|\mathbf{v}_{\rm e}| + S_{\rm ph}, \\ \partial_t n_{\rm p} = n_{\rm e}\alpha|\mathbf{v}_{\rm e}| + S_{\rm ph}, \\ \partial_t n_{\rm n} = n_{\rm e}\eta|\mathbf{v}_{\rm e}|, \end{array}\right\} \quad (1)$$

where n_i is the density of charged species i (e: electrons, p: positive ions, n: negative ions), and $\mathbf{v}_i = \mu_i\mathbf{E}$ is the drift velocity and $\mathbf{E}$ is the electric field. We denote by D_i and μ_i the diffusion coefficient and the mobility of charged species i. Moreover α is the impact ionization coefficient, η stands for the electron attachment coefficient. All these coefficients depend on the local reduced electric field E/N, where $E = |\mathbf{E}|$ is the electric field magnitude, and N is the air neutral density, and are precalculated from cross section data as in [5]. Due to short timescales considered, the recombination of charges species is neglected. Moreover the electron detachment is neglected as well because its impact on the streamer propagation has only marginal influence thanks to the presence of the photoionization source term $S_{\rm ph}$. The photoionization source term is computed based on the integral model of Zheleznyak [7]. The charged species transport equations are solved using the modified Scharfetter-Gummel algorithm (ISG-0) proposed by [6] with $\epsilon = 0.04$. The computational domain of size of 1 cm is discretized on a fixed grid with a mesh size of 5 μm (2000 cells). A constant time step of 10^{-13} s is used during the simulation and the value was chosen to fulfill tight stability and accuracy requirements for resolution of coupled set of equations (1) at discharge conditions under consideration.

For the population of vibrational levels of $N_2(C^3\Pi_u,\ v$=0–4) electronic state we consider the equation:

$$\frac{\partial n_v}{\partial t} = -\frac{n_v}{\tau_v} + \nu_v n_e, \quad (2)$$

where n_v [cm^{-3}] is the population of state v, and ν_v is the frequency of creation of state v by electron impact, $\tau_v = [A_v + \alpha^v_{N_2} N_{N_2} + \alpha^v_{O_2} N_{O_2}]^{-1}$ is the effective lifetime of v-th vibrational level, α^v_X is quenching rate of given level due to collisions with molecule of type X of density N_X and A_v [s^{-1}] is the Einstein coefficient. Coefficients for $N_2(C^3\Pi_u,\ v$=0–4) states are given in Table 1. Rate coefficients as a function of E/N were taken from [1]. The set of equations (2) is solved simultaneously with the streamer equations (1), and thus, a full time-dependent distribution of $N_2(C^3\Pi_u,\ v$=0–4) is obtained. For simplicity, we have neglected vibrational relaxation of v=1–4 vibrational levels of the $N_2(C^3\Pi_u)$ state because under given conditions its influence on vibrational distribution on nanosecond timescale will be only marginal.

Table 1: Table of Einstein coefficients and quenching rates for $N_2(C^3\Pi_u,\ v$=0–4) .

	α_{O_2}[cm^3/s]	α_{N_2}[cm^3/s]	A_v[s^{-1}]
Ref:	[8]	[9]	[10]
0	3.0×10^{-10}	1.09×10^{-11}	26954178
1	3.1×10^{-10}	3.14×10^{-11}	26666667
2	3.7×10^{-10}	4.28×10^{-11}	26246719
3	4.3×10^{-10}	6.34×10^{-11}	25641026
4	$4.5 \times 10^{-10(\star)}$	9.86×10^{-11}	24752475

($\star$) estimated

3. Results

Positive streamer propagation in point-to-plane electrode configuration (gap of 1 cm, applied voltage of 15 kV) is simulated. Streamer radius is set to 0.5 mm in the 1.5D model and its propagation is initiated by placing a Gaussian plasma cloud in a high-field region at the tip of a pointed anode at position $x = 1$ cm. Anode tip radius of curvature is 324 μm. The Gaussian plasma cloud consists of electrons and positive ions with initial density of electrons and positive ions of 10^{14} cm^{-3} and the characteristic dimension of 5×10^{-2} cm. Initial density of $N_2(C^3\Pi_u,\ v$=0–4) is set to zero. The air number density considered is $N = 2.44 \times 10^{19}$ cm^{-3}.

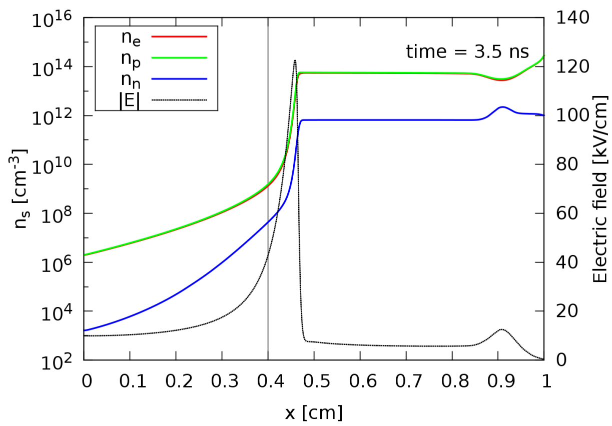

Figure 1: Density of charged species (n_e: electrons, n_p: positive ions, n_n: negative ions) and magnitude of the electric field $|E|$ for positive streamer at an instant of propagation (time of 3.5 ns) . Vertical line depicts x-coordinate (0.4 cm) where temporal dependencies of excited states are recorded.

The density of charged species and magnitude of the electric field $|E|$ in the gap at an instant of propagation of 3.5 ns is shown in Figure 1. Note that the streamer propagates to the left with approximate velocity of 1.4×10^6 m/s. During the simulation, at the position of $x = 0.4$ cm, the density of $N_2(C^3\Pi_u,\ v$=0–4) states, as well as the electric field, is recorded. Corresponding temporal dependence is shown in Figure 2. Note that the bump in the electric field after the time of 6 ns is caused due to the redistribution of the electric field in the computational domain after the impact of the streamer on the planar cathode, when all the gap is filled with charged species.

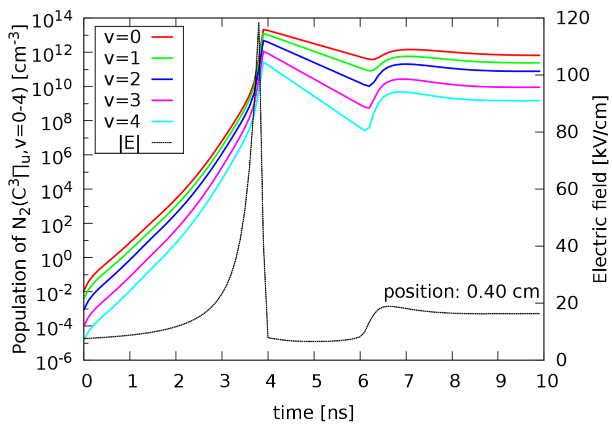

Figure 2: Temporal dependences of $N_2(C^3\Pi_u)$ state population for vibrational levels v=0–4 as recorded at reference position x=0.4 cm together with the magnitude of the electric field $|E|$ caused by passing of the positive streamer.

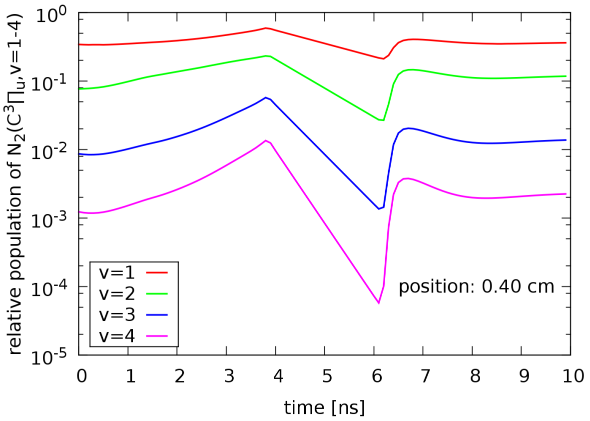

Figure 3: Temporal dependence of $N_2(C^3\Pi_u)$ for vibrational levels v=1–4 with respect to v=0 at reference position x=0.4 cm caused by passing of the positive streamer.

As can be also seen in Figure 2, the population of $N_2(C^3\Pi_u, v=0\text{–}4)$ strongly depends on the electric field of approaching streamer head and peaks slightly after the E/N maximum, in accordance with [11]. Relative population of $N_2(C^3\Pi_u, v=1\text{–}4)$ states with respect to the $N_2(C^3\Pi_u, v=0)$ level is shown in Figure 3. Vibrational distribution of $N_2(C^3\Pi_u, v=0\text{–}4)$ state derived for time instances 0, 2 and 4 ns from data presented in Figure 3 is shown in Figure 4.

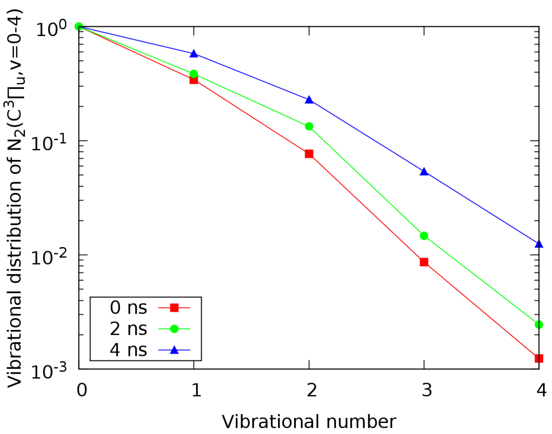

Figure 4: Vibrational distribution of $N_2(C^3\Pi_u, v=0\text{–}4)$ state derived from data presented in Figure 3 for time instances 0, 2 and 4 ns.

Figures 3 and 4 evidence enhanced sensitivity of the v=2–4 vibronic levels to electric field variation during streamer head transit through x=0.4 cm coordinate, followed by exponential decay which is controlled by the fast quenching of individual vibrational levels towards colder distribution conditioned by the residual field in the streamer channel. After the arrival of the bump, the $N_2(C^3\Pi_u)$ state vibrational distribution increases again.

4. Conclusions

In this work we have carried out numerical study on population of $N_2(C^3\Pi_u, v=0\text{–}4)$ excited by positive streamer developing in air at atmospheric pressure. Obtained results suggest that the vibrational distribution of $N_2(C^3\Pi_u, v=0\text{–}4)$ state is very sensitive to the electric field field variations occurring due to the streamer head transit and might be used as an complementary spectrometric tool for monitoring streamer head parameters when applied with sufficient spatio-temporal resolution.

5. Acknowledgements

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6. References

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