Dynamic model of streamer coupling for the homogeneity of glowlike dielectric barrier discharges at near-atmospheric pressure

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A streamer coupling theory is developed to describe the formation of homogenous emission and the high propagation speed of emission patterns in near-atmospheric pressure discharges. By considering the effects of both electron diffusion and electronic drift in the streamer head, the minimum required preionization level $n_{\min}$ for the formation of streamer coupling is found to be dependent on electric field strength, gas pressure, and electron temperature. The final stage of discharge is a microdischarge, when the preionization level n_0 is smaller than $n_{\min}$. However, when n_0 is larger than $n_{\min}$, streamers can couple to each other and form a glowlike discharge, and the homogeneity and propagation speed of the emission pattern in the streamer coupling head increases with the preionization level. The streamer coupling model can also be possibly used to explain many phenomenon in near-atmospheric pressure discharges, such as the bulletlike luminous discharge when atmospheric pressure plasma jets eject into ambient air.

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I. INTRODUCTION

Homogeneous or glowlike emission in near-atmospheric pressure discharges has been studied for decades, and there have been many observations of homogeneous discharges in the configuration of dielectric barrier discharges (DBDs) in different gases [1–4]. Most of these works have focused on experimental conditions for their formation and methods of improving discharge homogeneity. High preionization level is verified to be necessary for homogeneous discharges [4–6]. However, the formation mechanism, different from that of glowlike discharges at low pressure and streamer discharges at high pressure, has not been fully clarified [6,7].

We here focus on the glowlike discharge mechanism at near-atmospheric gas pressure and propose a dynamic model, called the streamer coupling discharge model. The streamer coupling model was primarily advocated by Palmer to predict a volume-stabilized glowlike discharge in atmospheric pressure CO_2 TEA laser discharge [8]. In Palmer's theory, the interaction of simultaneous developing streamers leads to the formation of one large discharge channel, and the dominating force in each streamer head is the diffusion of electrons [9,10]. However, experimental results show that, in near-atmospheric pressure discharges, the dominating force responsible for the electron cloud expansion in a streamer head is the electrostatic repulsion of high-density charged particles, instead of the diffusion driven by the electron density gradient [11]. A crucial role in the steamer dynamics is played by the streamer head, where the displacement of electrons with respect to positive ions produces a high induced electric field, and the field in turn governs the electron drift motion [12]. Another defect in Palmer's model is no explicit relationship between the formation of a homogeneous discharge and important physical properties of the discharges, such as electric field and gas pressure.

In this work, by considering the electron diffusion, the electrostatic repulsion in streamer head, and the electron drift driven by the electric field, an improved streamer coupling model is proposed to describe the dynamics of discharge patterns at near-atmospheric pressure. We obtain the minimum required preionization level for a streamer coupling discharge, apply the model to atmospheric pressure helium plasma, and compare the predicted results with experimental measurements.

II. STREAMER COUPLING MODEL

A. The dynamics of one streamer

We use the "fluid approximation" for each streamer. For the sake of simplicity, we here investigate only the primary anode-directed streamer, which moves toward the anode and in the same direction of electron drift. The streamer dynamics is mainly governed by the following equations:

$$\frac{\partial n_e}{\partial t} = -\vec{\nabla} \cdot (n_e \vec{v}_e) + S_e, \quad (1)$$

$$\vec{\nabla} \cdot \vec{E} = -\frac{e}{\varepsilon_0}(n_i - n_e), \quad (2)$$

where

$$\vec{v}_e = -\mu_e \vec{E} - \frac{D_e}{n_e}\vec{\nabla} n_e \quad (3)$$

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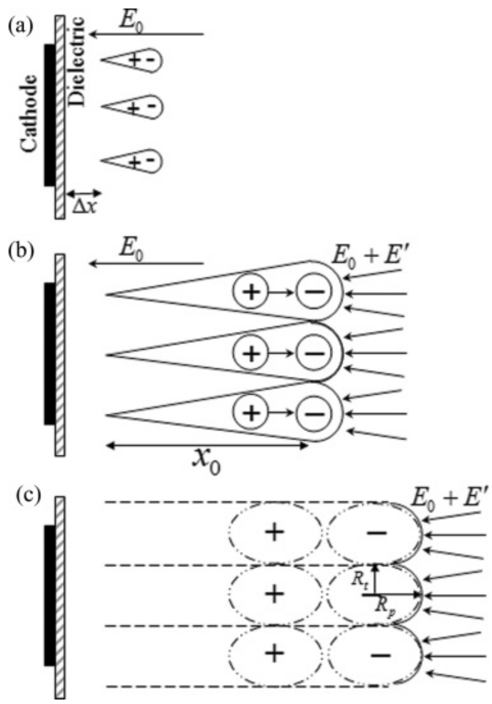

FIG. 1. Simultaneous avalanche-streamer transition. (a) Avalanches start to develop when electric field arises to a certain value E_0. (b) Primary avalanches turn into streamers when they satisfy the criterion of streamer formation at the length of x_0. (c) Adjacent streamers just overlap with each other to form streamer coupling.

is the electron velocity, $\vec{E}$ is the electric field, t is the time, and S, μ, and D are the particle source and the mobility and the diffusion coefficient, respectively. The subscripts e and i refer to electrons and positive ions, respectively; e in Eq. (2) is the absolute value of electron charge. Here we have used the assumption that there is only one kind of positive ions.

In near-atmospheric pressure discharges consisting of two flat electrodes, electrons simultaneous leave the dielectric surface coated on the instantaneous cathode [5,6], when the electrode polarity connected to the rectangular wave power source turns from positive to negative half cycle at time $t=-\Delta t$. Here Δt is the rise time of the external electric field from 0 to the value $E=E_0$, at which the primary avalanche starts at $x=\Delta x$. After the time $t=0$, the external electric field $E=E_0$ is applied as a uniform background electric field and fixed constant [see Fig. 1(a)]. At the place $x=x_0$ with $t=t_0$, these simultaneous primary avalanches turn into simultaneous streamers. The streamer head radii in the propagation and the transverse directions are assumed to be R_p and R_t, respectively [see Figs. 1(b) and 1(c)]. Thus the basic dynamics of the development of avalanches and streamers is in the external electric field E_0. The detailed analysis and assumptions responsible for these equations are given as follows.

(1) Resulting from drift and diffusion of charged particles in the local electric field $\vec{E}$, avalanche propagation is mainly determined by the motion of electrons. The ions can be treated as immovable particles, since their mobility μ_i and diffusion coefficient D_i can actually be neglected, comparing with those of electrons [11,13,14].

(2) The source term S_e is assumed to be directly proportional to the exponential of the first Townsend ionization rate α in the process of primary avalanche, as $S_e \propto e^{\alpha x}$, where x is the length of the avalanche [11]. In the other process of streamer propagation, the source term S_e could be treated as $S_e \propto E e^{-|E_0/E|}$, where E_0 and E are external and total electric fields, respectively [15]. In the present work, we mainly focus on the former case.

(3) We concentrate on the streamer dynamics under a strong external electric field $\vec{E}_0$, as the requirement of discharges at near-atmospheric pressure. According to the criterion of streamer formation, a streamer is born of an avalanche if the electric field E' induced from the space charge in the streamer head reaches the order of external field E_0 [11]. The correspondingly approximate equality is

$$E' = 2\frac{e}{4\pi\varepsilon_0 R_0^2}e^{\alpha x_0} = E_0, \tag{4}$$

where R_0 is the characteristic radius of space charge in the streamer head at the transforming moment. The streamer head region of intense ionization, moving together with a strong field, transforms the gas into plasma. A plasma channel is left behind due to the production of new plasma region.

For the avalanche-streamer transition, if the expansive force on the streamer head edge is dominated by electrostatic repulsion or electron diffusion, according to Eq. (3), the speed of electrons can be approximately expressed as

$$\upsilon_e \approx \max\left[\mu_e|\vec{E}_0+\vec{E}'|,\left|-\mu_e\vec{E}_0-\frac{D_e}{n_e}\vec{\nabla}n_e\right|\right]. \tag{5}$$

In near-atmospheric pressure discharges, the expansion of an avalanche head is mainly due to the repulsive force rather than the diffusion one. The difference of the two forces in magnitude can be one or two orders in many cases, such as in atmospheric pressure discharges [11].

Due to the cancellation of the induced repulsive field between the simultaneously developed adjacent streamer heads in the transverse direction, the dominating terms of Eq. (5) for the directions of propagation and transverse are repulsion and diffusion, respectively. Thus the radii in these two directions are different, and

$$R_p \geqslant R_t. \tag{6}$$

According to Eqs. (4) and (6), the spherical closed surface of radius R_p cover the total space charge head, whose charge is proportional to the enclosed electric charge $e\exp(\alpha x_0)$. Using Gauss's theorem, the electric flux through the spherical closed surface is proportional to the enclosed electric charge $e\exp(\alpha x_0)$, as expressed by

$$4\pi R_p^2 E_p' = Q_0/\varepsilon_0 \approx e\exp(\alpha x_0)/\varepsilon_0,$$

where Q_0 is the space charge in streamer head. We can obtain the induced electric field from the negative space charge at the front of the streamer head,

$$E_p' \approx \frac{e}{4\pi\varepsilon_0 R_p^2}e^{\alpha x_0} = \frac{1}{2}E_0. \tag{7}$$

The space charge in a streamer head has axial symmetry, although it does not have spherical symmetry. The electron dynamics at streamer head front is mainly determined by the local electric field, which is governed by Gauss's theorem in the propagation direction, as shown in Eq. (7). Thus the development of an avalanche and a streamer approximately obeys

$$\frac{dR_p}{dt} = \mu_e E'(t) \approx \frac{e\mu_e}{4\pi\varepsilon_0 R_p^2} e^{\alpha x}.$$

We can use the approximation $\alpha(E) = \alpha(E_0)$ during the development of an avalanche to simplify the calculation when the external electric field is only slightly distorted [11]. Using $x = \mu_e E_0 t$, R_p can be obtained from the last equation as

$$R_p(x) = \left(\frac{3e}{4\pi\varepsilon_0 E_0}\right) e^{\alpha x/3},$$

for $x < x_0$. Using this expression at $x \to x_0$ and Eq. (7), when a streamer is born of an avalanche:

$$\frac{1}{2}\mu_e E_0 = \mu_e E'_p = \left.\frac{\mu_e E_0 d R_p}{dt}\right|_{x=x_0} \approx \frac{\mu_e \alpha(E_0) R_p}{3}.$$

Therefore we obtain the streamer head radius in the propagation direction:

$$R_p \approx \frac{3}{2\alpha(E_0)}. \tag{8}$$

Now we focus on the dynamics in the transverse direction, and only the case of two adjacent avalanches or streamers connected and near-connected is discussed. Assuming that the distance between the adjacent simultaneous streamers is d (only $d/2 \lesssim R_t$ is discussed here), the distance from the middle of the two heads to the tip of one streamer is δ, which satisfies

$$\delta \leqslant \tfrac{1}{2}d - R_t \ll \tfrac{1}{2}d$$

when $d/2$ is slightly larger than R_t. Thus we can estimate the electric field strength E'_t at the tip of transverse direction as

$$\begin{aligned} E'_t &\approx \left|\frac{Q_1}{4\pi\varepsilon_0 R_t^2} - \frac{Q_2}{4\pi\varepsilon_0 (d - R_t)^2}\right| \\ &< \frac{Q_1}{4\pi\varepsilon_0 R_t^2}\left|\frac{1}{R_t^2} - \frac{1}{(d-R_t)^2}\right| R_t^2 \\ &\approx \frac{Q_1}{4\pi\varepsilon_0 R_t^2}\frac{4\delta}{d/2} \ll \frac{Q_1}{4\pi\varepsilon_0 R_t^2}, \end{aligned} \tag{9}$$

where Q_1 and Q_2 are the two streamer head's effective charges, both of which are smaller than the total space charge $e\exp(\alpha x_0)$ in one streamer head due to $R_t < R_p$. Since the electric field E'_t is much smaller than $Q_1/(4\pi\varepsilon_0 R_t^2)$, which is in the same scale of E'_p, we need to consider the effect of diffusion, which is almost not affected by the adjacent avalanches or streamers before they are overlapped, according to Eqs. (3), (5), and (9). Thus we here assume that the expansive force at streamer head edge is dominated by electron diffusion in the transverse direction.

The radius R_t grows with time t before the avalanche-streamer transition, and $t \approx x/(\mu_e E_0)$. According to Eqs. (7) and (8), we obtain the avalanche developing time t_0:

$$t_0 \approx \frac{1}{\mu_e E_0 \alpha(E_0)} \ln \frac{9\pi\varepsilon_0 E_0}{2e\alpha^2(E_0)},$$

where $E \approx E_0$ is used from $x = 0$ to $x = x_0$ in the avalanche development. Inserting this value into the characteristic diffusion law, we obtain the corresponding transverse radius R_t increased by diffusion:

$$R_t \approx \left[\frac{4D_e}{\mu_e E_0 \alpha(E_0)} \ln \frac{9\pi\varepsilon_0 E_0}{2e\alpha^2(E_0)}\right]^{1/2}. \tag{10}$$

The integral of E should be considered for a more accurate calculation. However, considering the uncertainty due to lack of clear plasma edge, the above approximation is enough for our estimation.

B. The dynamics of collective streamers

Using seed electron density n_0, we can define two dimensionless streamer densities for the transverse and the propagation directions, respectively:

$$\xi_t \equiv \frac{4\pi}{3} R_t^3 n_0$$

and

$$\xi_p \equiv \frac{4\pi}{3} R_p^3 n_0.$$

Here ξ_t and ξ_p can be treated as two criteria for determining the formation of streamer coupling and describing the dynamics of streamer coupling, respectively. The details are discussed as follows.

First, we focus on the homogeneity in the transverse direction. As shown in Fig. 1(c), these simultaneous streamers will overlap if the transverse radius R_t is larger than the half-distance between adjacent streamer head centers. For better discussion and comparison with experimental results below, the density of simultaneous primary electrons is expressed as the volume density n_0, which is known as the preionization level. We can make the rough estimation that the streamers can couple to each other only if the half-distance between the heads of adjacent streamers is smaller than R_t. This requires a preionization level n_0 high enough to reduce the distance between streamer heads, i.e.,

$$n_0 \geqslant \frac{3}{4\pi {R_t}^3}. \tag{11}$$

The equal sign case of Eq. (11) is shown in Fig. 1(c). The overlapping streamers hereafter are called streamer coupling, whose propagation is like one single streamer, except that it has a much larger space charge head. The corresponding criterion for streamer coupling formation can be reexpressed as

$$\xi_t \geqslant 1, \tag{12}$$

and thus we obtain the expression for the primary electron density,

$$n_0 \gtrsim n_{\min} \equiv \frac{3}{4\pi}\left[\frac{4k_B T_e}{eE_0\alpha(E_0)} \ln \frac{9\pi\varepsilon_0 E_0}{2e\alpha^2(E_0)}\right]^{-3/2}, \tag{13}$$

where the Einstein relation of $D_e/\mu_e = k_B T_e/e$ is used, k_B is the Boltzmann constant, T_e is the electron temperature, and $n_{\min}$ is defined as the minimum required preionization level. Since $\alpha = \alpha(E_0,\mathrm{P})$, $n_{\min}$ is a function of the external electric field E_0, the gas pressure P, and the electron temperature T_e.

The streamer coupling in the propagation direction can be described by the dimensionless density ξ_p. The dynamics of charged particles are determined by the electric field, and the motion of streamer coupling is mainly determined by the electric field strength at the front of the streamer head E_M. In the case of $\xi_p > 1$, we approximately treat the number ξ_p of total streamer heads in the space $\frac{4\pi}{3}R_p^3$ as the multiple of electric field from one single streamer. Using Eq. (8), ξ_p can be expressed as

$$\xi_p \approx \frac{9\pi}{2\alpha^3(E_0)} n_0.$$

Considering Eq. (7), the total electric field can be estimated as

$$E_M \approx (1 + \xi_p/2)E_0.$$

In the case of $\xi_p \leqslant 1$, the streamer coupling effect can be ignored, since there is not more than one streamer head in the space $\frac{4\pi}{3}R_p^3$. Therefore E_M can be estimated as

$$E_M \approx \begin{cases} \left(1 + \frac{9\pi}{4\alpha^3} n_0\right) E_0 & \text{if} \quad \xi_p > 1, \\ 1.5E_0 & \text{if} \quad \xi_p \leqslant 1. \end{cases} \tag{14}$$

The strength of electric field E_M results from the total effect of streamer heads when $\xi_p > 1$ and is small when $\xi_p \leqslant 1$.

Besides the minimum requirement of preionization level [see Eq. (13)], the uniformity of preionization is also important for the generation of homogenous discharges. A nonuniform distribution of high surface charge density on the dielectric may cause a radially inhomogenous discharge, since the induced electric field could be strongly inhomogeneous. When the rise time of external electric field is short enough, a sufficiently large perturbation of the surface charge can stimulate the formation of a filamentary discharge [16]. In this case, Eqs. (12) and (14) are not valid. The details of this instability are not discussed here.

C. The minimum required seed electron density in an atmospheric pressure helium plasma

Applying the above theoretical results to an atmospheric pressure helium plasma, we find that the minimum required seed electron density is relatively low for a discharge with a high electron temperature and a low external electric field (see Fig. 2). Choosing data $\alpha \approx 5.3 \times 10^3 \mathrm{m}^{-1}$ from the estimated experimental value [17], and a typical experimental condition of $T_e = 2\mathrm{eV}, E_0 = 4\mathrm{kV/cm}$, we can obtain

$$n_{\min}^{\mathrm{He}} \sim 1.1 \times 10^5 \mathrm{cm}^{-3}. \tag{15}$$

The above result is dependent on experimental conditions. The experimental minimum required density for an atmospheric pressure helium homogeneous discharge is on the order $10^5\mathrm{cm}^{-3}$ [10], which is in favor of our predicted result of a typical experimental condition.

Based on the above calculation, the predicted result for the streamer head radius in the propagation direction is $R_p^{\mathrm{He}} \sim 0.03\,\mathrm{cm}$ and in the transverse direction is $R_t^{\mathrm{He}} \sim 0.01\,\mathrm{cm}$. The two values suggest that the distribution of space charge in the streamer head is like a "goose egg", as shown in Fig. 1(c). These results support the above estimation that the electrostatic force is larger than the diffusion force in the propagation direction.

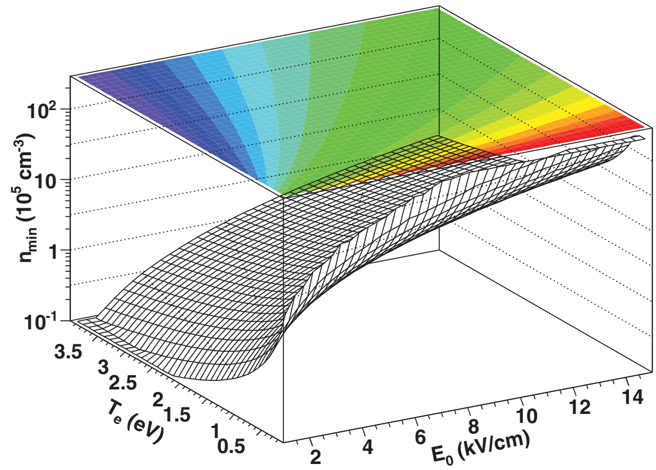

FIG. 2. (Color online) Distribution of minimum required seed electron density $n_{\min}$ for atmospheric pressure helium plasma with electron temperature T_e and electric field E_0.

Figure 3 shows the transverse one-dimension distribution of the total field strength E in the propagation direction at the front of the streamer heads for the same discharge condition as Eq. (15). Only the cases of two adjacent streamers coupled and near-coupled are drawn. The electric field strength at the streamer head tip is estimated from Eq. (14) in the range of $\xi_p > 1$, and the electric field at small obliquity away from the tip direction is roughly estimated by projecting E_M to

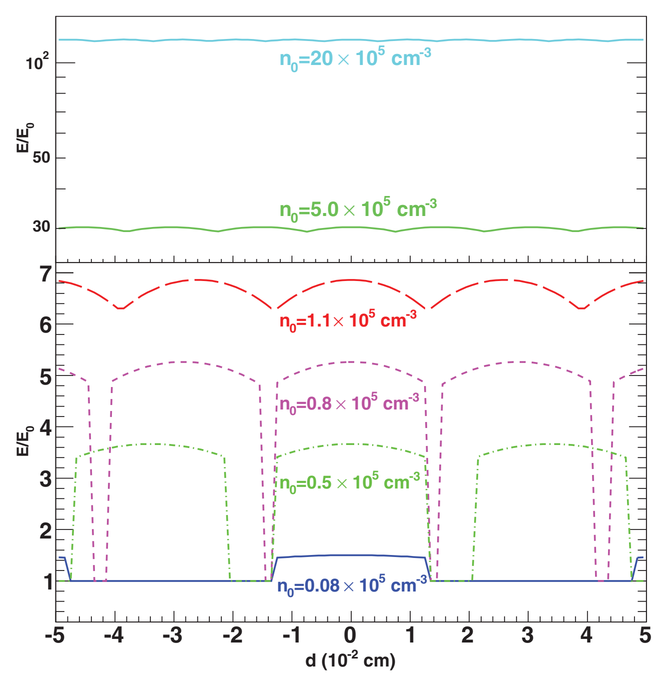

FIG. 3. (Color online) Distribution of the total electric field E projected in the streamer direction at the front of streamers for different primary seed electron densities. We choose an electron temperature of 2 eV and a helium plasma at atmospheric pressure. The lines for $n_0 = 5.0 \times 10^5\mathrm{cm}^{-3}$ and $20 \times 10^5\mathrm{cm}^{-3}$ are plotted for an exponential y axis, and the other lines for a uniform y axis.

the corresponding obliquities. The electric field in the space between streamers is only the external electric field E_0 when the streamer heads are not connected.

Streamers do not couple with each other when the primary seed electron density n_0 is lower than the minimum required preionization level $n_{\min}$, such as $n_0 = 0.08$, 0.5, and $0.8 \times 10^5 \text{cm}^{-3}$. The corresponding experimental observation is the presence of microdischarges, and the plasma is filamentary. End-on views of these discharges show that there are many bright spots, each of which has an almost cylindrical plasma channel [18]. The electric field is continuous for the streamer coupling when $n_0 \geqslant n_{\min}$, and its relative smoothness increases with n_0, such as $n_0 = n_{\min}, 5n_{\min}$, and $20n_{\min}$. This indicates that the distributions of ionization and radiative processes are almost homogeneous for the case of streamer coupling, and the emission homogeneity is improved by increasing the preionization level n_0. This prediction is qualitatively consistent with the experimental results [6,10], which suggests that a homogeneous discharge can be obtained only with a high preionization level.

D. The propagation of streamer head in an atmospheric pressure helium plasma

Since the streamer coupling head is the most intensive ionization region, the propagation of the streamer coupling head represents the motion of the discharge pattern in an actual experiment. The development of the streamer coupling is led by the drift of electrons at the front of the streamer coupling head, since streamers propagate along the direction of the strongest electric field [11]. Therefore we can obtain the propagation speed of the streamer coupling head:

$$\upsilon \approx \begin{cases} \mu_e E_0\left(1+\frac{9\pi}{4\alpha^3}n_0\right)E_0 & \text{if} \quad \xi_t \geqslant 1, \\ \mu_e E_0\left(1+\frac{9\pi}{4\alpha^3}n_0\right)E_0 & \text{if} \quad \xi_t < 1 \text{ and } \xi_p > 1 \\ 1.5\mu_e E_0 & \text{if} \quad \xi_p \leqslant 1. \end{cases} \quad (16)$$

Figure 4 shows the propagation speed of the discharge pattern in the above three ranges, using the data of electron mobility $\mu_e = 1.1 \times 10^3 \text{cm}^2\text{V}^{-1}\text{s}^{-1}$ in an atmospheric pressure helium plasma [7]. Different discharge regions are separated by two vertical dashed lines according to preionization levels. The left vertical dashed line divides the left region of single streamers, ignoring the collective effect from the right region of streamer coupling, where the interaction of the electric field from other streamers needs to be considered. The right vertical dashed line divides the streamer coupling region into two subregions. The right region is corresponding to streamers overlapping with each other and inducing a glowlike discharge, as denoted in Fig. 4. In the middle region, although the discharge is not physically contacted, the streamers are weakly coupled but do not result in a glowlike discharge.

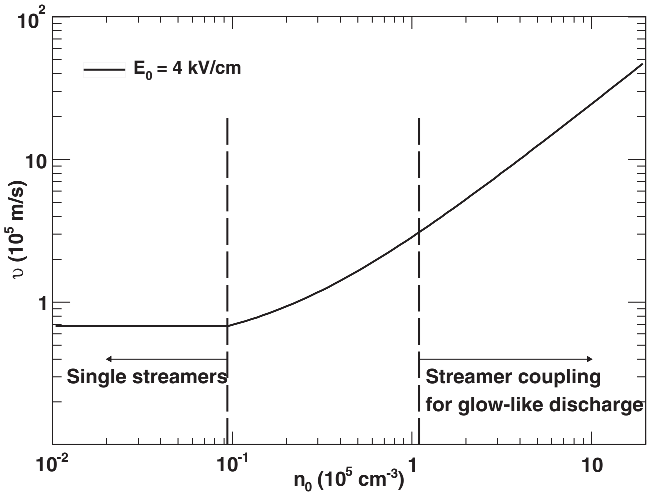

FIG. 4. Distribution of the propagation speed of the emission pattern with primary electron density at $T_e = 2$ eV and $E_0 = 4$kV/cm for atmospheric pressure helium plasma. The left and right regions separated by vertical dashed lines denote discharges of single streamers and streamer coupling, respectively.

III. DISCUSSION

There are few experimental results from the direct investigation of streamer radius and homogeneity in glowlike discharges to confirm this streamer coupling model directly. However, the importance of initial electrons spontaneously leaving the cathode for forming a homogenous discharge in atmospheric pressure DBDs has been widely studied [5,16]. The increase of the discharge homogeneity with a high level of preionization is verified by simulations and experiments [5,6]. In particular, the requirement of a minimum preionization level in the streamer coupling model is consistent with the "memory effect" of charged particles from last discharge, contributing to preionization level [6]. In the first several half cycles without the "memory effect," there is no homogenous discharge, but instead a filamentary discharge. These results are in agreement with the streamer coupling model.

The propagation of "single streamers" has been reported to be much different in head field and speed [7,11–15,19]. The radius of a "single positive streamer" has been revealed to grow with time, and the speed is about one order of magnitude higher than that of a negative streamer [7,11,12]. These observations contradict classical single streamer theory, which predicts that both single streamers have the same scale of speed, and that the values of speed and radius are constant for the same discharge conditions [7,11]. These phenomena of a "single positive streamer" could possibly be explained by our streamer coupling model, which suggests that it is not a classic single positive streamer, but an overlapped one consisting of many single streamers, since there may be many induced secondary avalanches around the positive streamer head. These avalanches can couple with each other when their negative heads are driven by the induced electric field from positive streamer head and coupled secondary avalanche heads simultaneously. Thus the total charges and the radius of the positive streamer head will increase with the propagation of the positive streamer, and its velocity also increases due to the enhancement of the induced electric field. This process proves that the streamer is very difficult to be sustained as a "single streamer".

In the following subsections, we will interpret the puzzling phenomena of "plasma bullets" at atmospheric pressure and present a possible experiment to verify our dynamic streamer model.

A. The phenomena of "plasma bullets" at atmospheric pressure

In recent experiments, an atmospheric pressure plasma jet (APPJ), originating from a dielectric barrier discharge and spraying into ambient air, is found to be traveling in a bulletlike plasma volume with a high propagation speed of the order of $10^4 \sim 10^6$ m/s and a ring-shaped cross-sectional emission pattern, named a "plasma bullet" [20–24]. The model of a self-sustained photoionization streamer [24], first developed by Dawson and Winn [19], was invoked to explain the nature of a plasma bullet as a "single streamer" and its plasma channel as absolute insulation [15,19]. In a "single streamer" model, the brightest place is located at the streamer tip, the center of streamer front, where the total electric field is the most intense. Although the model suffices to account for the scale of propagation speed, it is inadequate to explain the ring-shaped emission pattern of axial-symmetrical homogeneity in its cross section and the change of propagation speed with external electric field [21–23]. Furthermore, it can also not explain the propagation of negative "plasma bullets" [25], which are not prolonged mainly by photoionization [7]. Thus, an APPJ is neither a "single streamer" discharge nor like a traditional Townsend or glow discharge, which are homogeneous in the radial directions and reach their brightest emission in the vicinity of the anode or cathode [4–6].

Now using the above streamer coupling model, we try to explain the ring-shaped emission pattern by two factors, the axially symmetric distributions of gas mixing ratios and the initial electrons, which determine chemical and physical processes, respectively. The main ionization process in plasma jets of helium gas flow is Penning ionization between helium metastable states and nitrogen molecules [23,26], and the ionization rate α reaches its maximum value when the content ratio of nitrogen in the helium plasma is about at the level of 10^{-4}, which distributes as a ring shape in the cross-sectional direction when an APPJ ejects into ambient air [27,28]. The residual charges of the last half cycle are trapped near the inner surface of dielectric [29] or in the bulk space inside the tube [30] and work as the seed charges when the power electrode changes its polarity. These seed charged particles of the axially symmetric distribution can initiate a ring-shaped coupling streamer head in the case of high enough density, since the streamers have precedence to develop at the highest α place of the ring-shaped distribution in the cross-sectional direction over other places along the APPJ, and this development suppresses discharges at other places through the induced electric field. Thus it is very easy to form a ring-shaped streamer coupling head when an APPJ flows out of tube nozzle, as explained by Fig. 3, and this head indicates a ring-shaped emission in cross-sectional direction.

According to the streamer coupling model, the propagation speed of the discharge pattern depends on the streamer coupling density ξ_p, which is determined by the preionization level n_0 and the external electric field E_0; see Eq. (16) and Figs. 3 and 4. The scale and the variation trend of the propagation speed in Fig. 4 is consistent with the experimental results of a "plasma bullet" [20–22,24]. The explanation would be developed quantitatively in future researches.

B. A possible experiment

Although the streamer coupling model is consistent with the above mentioned experimental results, it must be noted that, as this model is a new attempt and as no other experiments verify the model quantitatively, it is impossible to give definitive comparisons with experimental results. An identifying experiment needs to be done to verify the predictions quantitatively.

For an atmospheric pressure helium discharge of DBD, by using a transversely excited atmospheric pressure CO_2 laser system [31], we can control the preionization level n_0 in the setup of capacitively coupled plasma to verify Figs. 3 and 4. Figure 3 suggests that the contrast between streamer emissions and the background emission increases with n_0 when $n_0 < n_{\min}$, and that the homogeneity and intensity of the emission pattern increases with n_0 when $n_0 > n_{\min}$. Figure 4 suggests the propagation speed of discharge pattern under a certain electric field and preionization level, and that it increases with n_0. We can verify our model with such experiments.

IV. CONCLUSIONS

We have analytically derived the minimum required preionization level and the propagation speed of the emission pattern for anode-directed streamer coupling, and we have determined the streamer coupling requirement to generate a homogeneous emission pattern in near-atmospheric pressure discharges. These depend on the external electric field strength, the gas pressure, and the electron temperature. In our model, streamer head expansion in the transverse direction is suppressed by the space charge in adjacent streamer heads, and the total space charge in one streamer head can be described by the radius in the propagation direction. Based on these predictions, we have discussed the emission homogeneity and its propagation speed in an atmospheric pressure helium plasma as an example. Our predictions are consistent with experimental results.

Although there is no definitive experiment to verify this dynamic model, the model of streamer coupling is very useful for understanding the dynamical processes in the development of a near-atmospheric pressure plasma. It is also interesting for investigating the overlap of streamers in the emission pattern of a homogeneous discharge. More detailed comparisons between theoretical and experimental results are still to be expected.

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