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Measurements of streamer head potential and conductivity of streamer column in cold nonequilibrium atmospheric plasmas

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Abstract
This work presents a simple method for the characterization of streamers developing in cold atmospheric plasma jets. The method is based upon stopping (‘scattering’) of streamers by means of an external dc potential in order to determine the potential of the streamer head. The experimental evidence presented in this work does not support the model of the electrically insulated streamer head. In fact, it shows that the electrode potential is transferred to the streamer head along the streamer column to which it is attached with no significant voltage drop. Based on the proposed method, we determine various streamer parameters such as head charge \((1–2 \times 10^8\) electrons\), electrical field in the head vicinity (about \(100\ kV\ cm^{-1}\)), average conductivity \((10^{-2}\ \Omega^{-1}\ cm^{-1})\) and plasma density of the streamer column \((2\times 10^{13}\ cm^{-3})\).

(Some figures may appear in colour only in the online journal)

1. Introduction

The study of cold atmospheric plasmas has attracted significant interest in recent years. The main reason for this extensive interest is the potential of cold nonequilibrium plasmas in the fields of bioengineering and medicine [1–4]. The areas of possible applications of cold plasmas include dentistry, drug delivery, dermatology, cosmetics, wound healing, cellular modifications, cancer treatment, etc.

Tremendous interest in cold plasmas has also triggered significant research efforts directed towards detailed understanding of the physics of the phenomena. The diagnostic tools that have been traditionally used for characterization of cold nonequilibrium atmospheric plasma jets include intensified charge-coupled device (ICCD) cameras, optical emission spectroscopy and measurements of the basic electric parameters of the discharge. Numerous works studied different aspects of cold atmospheric plasma jets including speed of ionization front propagation, variety of excited and ionized species and electrical characteristics of the discharge [5–8].

It was shown that the cold atmospheric plasma jet is formed by a streamer, whose leading front propagates at velocities of \(10^6–10^7\ cm s^{-1}\). A theoretical model considering the self-consistent propagation of a streamer head, fully insulated from the surroundings, was originally proposed in [9, 10]. Later theoretical studies on atmospheric pressure streamer dynamics were comprehensively carried out in [11], while recent progress achieved in nonequilibrium He plasma jets in air was reported in [12–15]. These theoretical considerations allow prediction of basic streamer characteristics including channel size, plasma and excited species densities, electrical fields, head charge, propagation speed of ionization front, etc. In our recent works we proposed a new method using Rayleigh microwave scattering for temporally resolved measurements of plasma density in atmospheric plasma jets and considered the lifetime of the afterglow plasma column remaining after the streamer passage and current spreading in the column [16, 17]. In addition, methods for measurements of the jet current and electric field in the streamer were proposed [18, 19].

Certainly, the lack of diagnostic methods available for studying cold atmospheric plasma jets limits the understanding...
of the phenomena. In this work, we propose a simple method for the measurement of potential of the streamer’s leading front, the streamer head \((U_h)\). Knowing \(U_h\) allows one to answer a number of important questions such as values of potential drop along the streamer column, charge of the streamer head and average conductivity of the plasma column.

2. Experimental details and methodology

The plasma gun (figure 1) is made of a Pyrex pipet through which the helium flow is supplied (the inner diameter of the thinner part of the pipet is about 4 mm, He flow rate is about 11.5 l min\(^{-1}\)). The gun is equipped with a pair of high HV electrodes—a central electrode (whose end was in direct contact with the plasma) and an outer ring electrode, as shown schematically in figure 1. The electrodes are connected to the secondary coil of a high-voltage resonant transformer, generating sinusoidal high-voltage waveforms with a frequency of about 25 kHz. Amplitudes of high voltage \((U_{HV} = 2.6, 3.1\) and 3.8\) are used in this work [4, 16, 17]. The discharge current \(I_d\) is measured by a shunt resistor 1 k\(\Omega\) placed in series in the discharge, as shown in figure 1. The plasma gun typically produces a 4–5 cm long plasma jet. The interaction of the streamer with the external electric potential is studied using a 10 mm diameter ring made of copper foil (thickness, 50 \(\mu m\)), having 1 mm height. The ring is installed coaxially with the jet and its potential is controlled by the dc high-voltage power supply, as shown in figure 1. Photographs of the jet are taken by an Andor iStar 334T fast-gated ICCD camera.

3. Experimental results and discussion

A series of instant photographs (exposure time = 10 ns) of the gun exhaust taken at different moments of time and the corresponding waveforms of the discharge voltage and current are presented in figure 2(a). It can be seen that the streamer develops at about 2.5–3 \(\mu s\) after the main interelectrode discharge (indicated by the peak of discharge current) and attains a length of about 4 cm in 2.5 \(\mu s\). The velocity of the ionization front propagation during the streamer growth varied in the range \((1.5–2) \times 10^6\) cm s\(^{-1}\). The photograph of the streamer taken with a longer exposure time of 5 \(\mu s\) (over the entire time of streamer existence) is presented in the rightmost photograph of figure 2(a). The radius of the streamer column \((R)\) was determined by measuring the size of the central highly luminous filament which can be clearly seen in the photograph. \(R\) was precisely measured using high-magnification imaging to be 0.15 \pm 0.05 mm. The object photographed in figure 2(a) is usually referred to as a cold atmospheric plasma jet [1, 6–9, 16, 17].

The interaction between the streamer with the dc potential created by the ring located at \(z = 3\) cm and the dependence of streamer length \(L\) versus ring potential \(U_r\) is shown in figure 2(b). One can see that the application of a higher positive potential to the ring electrode led to significant perturbation of the streamer propagation, namely to shortening the streamer. Based on this experimental evidence, we will use the term ‘streamer scattering on the external dc potential’ to denote this interaction in the following description.

Accumulation of 500 instant photographs of the streamer (100 ns exposure window each) taken at \(t = 4.5 \mu s\) after the main breakdown is presented in figure 3. It can be clearly seen that the plasma column coupling between the streamer head and the main interelectrode discharge remains behind the streamer head. Note that the image presented in figure 3 is intended to demonstrate the luminescence of the streamer column, and does not reflect the actual size of the streamer head, whose luminescence significantly exceeds the brightness range used in the image.

Let us consider the question of degree of electrical insulation provided by the streamer column shown in figure 3. First, we will evaluate whether the model of a fully non-conductive plasma column (where the streamer head is considered as a solitary charge fully insulated from the surroundings), developed earlier by Dawson and Winn and applied later for a streamer originated by a dielectric-barrier discharge (DBD) by Lu and Laroussi [9], can reasonably explain the experimental results shown in figure 2. To this end we will analyze the electrostatic problem of propagation of a fully insulated spherical streamer charge passing through the ring at potential \(U_r\) and find the critical values of the streamer head charge required in order to affect its propagation by the ring, kept at a potential of several kVs. Numerical simulations of this electrostatic problem show that the application of 2 kV potential to the ring can significantly perturb the electric field around the insulated streamer head \((\Delta E / E_0\) about 50\%), where \(E_0\) and \(E_1\) are the fields without and with the ring, respectively, and \(\Delta E = E_0 - E_1\) only if the streamer head charge is less than \(10^7\) electrons (see figure 4). These charges are significantly lower than those required for streamer existence [9, 20]. Indeed, the theoretical model of insulated DBD streamer indicates that head charges of \(> 3 \times 10^9\) electrons are required to ensure self-consistent propagation of the streamer [9]. Perturbation of the electric field around the streamer head...
Figure 2. (a) Series of instant photographs taken at different moments of time, indicating the propagation of ionization front. The corresponding temporal evolutions of the discharge current and voltage are also shown ($U_{HV} = 3.1$ kV). The photographs were taken with an exposure time of 10 ns, except for the right one where 5 µs exposure time was used (2–7 µs exposure window). Moment of time $t = 0$ is associated with the initiation of the interelectrode discharge. (b) Interaction (scattering) of the streamer on the dc potential created by the ring located at $z = 3$ cm and dependence of streamer length $L$ versus ring potential $U_r$ (exposure window $t = 2–7$ µs, $U_{HV} = 3.1$ kV).

having about $3 \times 10^9$ electrons by the ring kept at a potential of 2 kV is less than 0.1% (see figure 4). Certainly, such a small perturbation of the field around the streamer head cannot significantly affect the propagation of the streamer.

Let us now validate the model of a fully non-conductive plasma column based on the experimental data on the streamer column parameters obtained previously [16, 17]. These results indicate that plasma conductivity during the streamer existence is $\gg 10^{-4}$ Ω$^{-1}$ cm$^{-1}$ (being maximal at streamer initiation and decaying with characteristic times of electron attachment to the oxygen molecules of ambient air) [16, 17] and thus the Maxwell relaxation time $t_{rel} = \varepsilon_0/\sigma$ is less than 1 ns. The physical meaning of $t_{rel}$ is the time required for polarization of free charges in the conductor (or, in other words, conductor response time). This means that the charge in the streamer head can be treated as a charge insulated from the surroundings only for times $< 1$ ns. Since the characteristic times of the streamer growth are a few µs, one can consider that a charge exchange between the streamer head and the interelectrode discharge plasma is instantaneous, and thus the streamer column cannot be treated as a non-conductive medium.

Therefore, it may be concluded that the experimental data do not support the model of an insulated streamer head [9]. In contrast, the streamer head can instantly exchange the charge with the main interelectrode discharge through the streamer column, and thus it should be treated as one bearing certain electrical potential. The actual value of the streamer head potential is governed by the voltage divider which is formed by the streamer column (active resistor) and the streamer-ground capacitor as will be described below.
significant perturbation of field is created for the head charges

The shortening of the streamer shown in figure 2 can now be analyzed as follows. The ring in free space creates the distribution of electrical potential around itself which is characterized by a value of the order of \( U_r \) and occupies the spatial region of the ring’s diameter. The electric field around the streamer head when it approaches the ring is governed by the difference \( U_h - U_r \) [21]. Therefore, this electric field around the streamer head will be significantly reduced (and therefore can terminate the streamer propagation) if ring \( U_r \) is close to \( U_h \). The increase in \( U_r \) above \( U_h \) will lead to the streamer stopping at a certain distance prior to the ring; this distance will be larger for higher \( U_r \). This simple consideration qualitatively explains the shortening of the streamer path with an increase in the ring potential observed experimentally (see figure 2). In order to quantitatively characterize the perturbation of the electric field around the streamer head due to the presence of the ring we simulated this problem numerically. The dependence of the electric field perturbation at the streamer head \( \Delta E/E_0 \) introduced by the ring (the ring’s center coincides with the streamer head location) as a function of ring potential is shown in figure 5 (where \( E_0 \) and \( E_1 \) are the electrical fields on the streamer head without and with the ring, respectively, and \( \Delta E = E_0 - E_1 \)). It can be seen that a significant reduction in the electric field (about twofold) occurs when \( U_r \) is close to \( U_h \) (\( \Delta E/E_0 \) about 0.4–0.5); therefore, one can consider the condition \( U_r = U_h \) as sufficient to stop the propagation of the streamer. Based on this, we can propose a simple and natural method for measuring the electrical potential of the streamer head. The ring electrode is placed at the coordinate \( z^* \) and supplied with a dc potential (this leads to a shortening of the streamer path, as shown in figure 2). The ring potential \( U^*_r \), at which the streamer head path ends exactly at the ring plane, is recorded and \( U_h(z^*) = U^*_r \). For conditions of the experiment presented in figure 2(b) it is clearly seen that \( U_h = 2.8 \) kV. Note that the potentials of the streamer head required to support the streamer propagation obtained in this work are lower than those for a conventional air streamer (\( \geq 5 \) kV) since air is significantly pushed out from the streamer path by the He flow.

Figure 4. Perturbation of the electric field around the streamer head caused by the dc field ring scatterer (\( U_r = 2 \) kV) if the model of a solitary electric charge insulated from the surroundings is used. No significant perturbation of field is created for the head charges \( \geq 10^5 \) electrons.

Figure 5. Perturbation of the electric field around the streamer head bearing potential \( U_h \) created by the ring with potential \( U_r \). Significant perturbation of the field is created if \( U_r \approx U_h \).

Figure 6. (a) Dependence of the streamer head potential along its propagation path for \( U_{HV} = 2.6, 3.1 \) and 3.8 kV. Note that the experimental points refer to the different observation times corresponding to the streamer head propagation. (b) Dependence of the streamer head location versus time for \( U_{HV} = 2.6, 3.1 \) and 3.8 kV.

Now we will experimentally apply the methodology developed above and measure the streamer head potential. The dependences of \( U_h \) as a function of \( z \) for different applied high-voltage amplitudes \( U_{HV} \) are shown in figure 6(a). It can be seen that the dependence type changes from falling for \( U_{HV} = 2.6 \) kV to growing for \( U_{HV} = 3.8 \) kV. At first glance, such a change in the behavior of these curves with \( U_{HV} \) might be surprising. However, it can be readily interpreted if spatial dependence \( U_h(z) \) is translated into temporal dependence \( U_h(t) \). To this end the dependence of streamer head position as a function of time \( z(t) \) was recorded (see figure 6(b)).

Figures 7(a)–(c) present the temporal evolution of the streamer head potential \( U_h(t) \) for three amplitudes of driven high voltage \( U_{HV} = 2.6 \) kV, 3.1 kV and 3.8 kV, respectively, obtained by combining the data shown in figures 6(a) and (b). The temporal evolution of voltage applied to the discharge electrodes and the discharge current is also shown. It can be seen that in all cases \( U_h \) was close to the voltage applied to the electrodes (within 10–15%) and followed its temporal
evolution. This indicates that the potential of the central electrode is transferred to the streamer head without significant voltage drops. It should be noted that the voltage drop between the central electrode and the streamer head contains two parts, namely the drop in the near electrode sheath and along the plasma column. When the streamer appears, the drop in the near electrode sheath is expected to be relatively small—about several volts (of the order of a few \( kT_e/e \))—since the positive half-wave of the driven voltage is associated with the shift of the plasma column toward the central electrode, bringing it into contact with the electrode [22]. Therefore, the near electrode drop is negligible and the voltage drop between the central electrode and the streamer head is mainly governed by the drop along the plasma column. This characteristic of a small drop in voltage on the plasma column indicates that active resistance of the plasma column is significantly less than the capacitive resistance formed by the plasma column to the ground (can be estimated to be around several \( \text{M} \Omega \) for 4 cm plasma column) [16].

It should be noted that the determination of \( U_h \) can, in principle, be based on the streamer stopping at a certain distance from the ring, rather than exactly at the ring plane as considered above. However, the method used above (the streamer stopping exactly at the ring plane) is associated with fewer errors and greater simplicity, since the potential of the ring’s electric field at its center is mainly governed by the ring itself (due to the ring’s proximity), while the contribution of potential by other system elements bearing electrical potential (lead wires, electrodes) is negligible. If, in contrast, the approach of the streamer stopping at some distance along the z-axis from the ring > size of the ring is used, the contribution of other elements, e.g. wire leading the potential to the ring, becomes significant. Therefore, the last method will require very accurate consideration of the potential of other system elements, which might be quite complicated practically. In summary, figure 2(b) showing the dependence of the streamer stopping location on \( U_s \) is solely aimed to give a qualitative clarification of the effect, while all quantitative data are obtained based on the method of streamer stopping in the ring plane (which is associated with minimal errors due to the contribution of other system elements bearing electrical potential).

Now let us consider what parameters of the streamer can be determined based on the proposed method. The electrical charge of the streamer head can be estimated as a charge created by a hemisphere streamer head attached to the perfectly conducting streamer column as \( Q_h = 2\pi\varepsilon_0 RU_h \) [11, 21], where \( R \) is the streamer radius which was determined as described above. Note that this charge is about twice as low as that created by a sphere with the same potential and radius, which is caused by the contribution of the streamer column [11, 21]. The maximal value of the electric field can be estimated from \( E_m \approx U_h/2R \) [11, 21]. The average plasma density \( (n_e) \) in the streamer channel can be estimated using the expression \( I_e = en_eV_{th}S \), where \( I_e \) is the current flowing through the streamer channel, \( V_{th} \) is the electron drift velocity, \( S = \pi R^2 \) is the cross-section area of the streamer channel and \( e \) is the electron charge. The mean electric field in the streamer channel \( \Delta U/L \) is measured in this work to be about 50 V cm\(^{-1} \) (where \( \Delta U \) is the potential drop along the streamer and \( L \) is the streamer length), which corresponds to the reduced electric field of about \( 2 \times 10^{-18} \text{ V cm}^2 \) and finally yields electron drift velocity in the streamer channel \( \sim 2 \times 10^5 \text{ cm s}^{-1} \) [23, 24]. Based on measurements of \( I_e \) (about 0.5 mA) conducted by the Rogowski coil in [16], the plasma density can be estimated to be about \( 2 \times 10^{13} \text{ cm}^{-3} \), which coincides well with independent measurements previously conducted using the Rayleigh microwave scattering method [17]. The typical parameters of the streamers are summarized in table 1. Note that the relatively small radius of the streamer head 1.5 \( \times 10^{-2} \text{ cm} \) experimentally observed in this work causes relatively high values of maximal electric field of about 100 kV cm\(^{-1} \) at the streamer head (compared with, e.g., \( R_h \approx 3 \times 10^{-2} \text{ cm} \) and electric field of about 45 kV cm\(^{-1} \) in [13]).

![Figure 7](image-url)
Table 1. Typical parameters of the streamer on the growth stage (He flow = 11.5 L min\(^{-1}\), \(U_{HV} = 2.6\)–3.8 kV).

<table>
<thead>
<tr>
<th>Head charge, electrons</th>
<th>Speed of ionization front (cm s(^{-1}))</th>
<th>Streamer diameter (cm)</th>
<th>Characteristic electrical field in head vicinity (V cm(^{-1}))</th>
<th>Average conductivity of the streamer channel ((\Omega^{-1} \text{cm}^{-1}))</th>
<th>Average plasma density in the streamer channel (cm(^{-3}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>(1–2) \times 10^8</td>
<td>4–5</td>
<td>(1.5–2) \times 10^6</td>
<td>About 10^5</td>
<td>10^{-2}</td>
<td>2 \times 10^{13}</td>
</tr>
</tbody>
</table>

4. Conclusions

This work analyzes the interaction (scattering) of a streamer developed in a cold atmospheric plasma jet on an externally created dc field potential and proposes the method for measuring the streamer head potential. The obtained results do not support the model of a fully insulated streamer head. In contrast, the experimental data demonstrates that the conductivity of the plasma column, which the streamer head is attached to, is high enough, so that the potential of the discharge electrode is transferred to the head with no significant drops. The method proposed here allows us to determine a number of key streamer properties such as streamer head charge, electric field and conductivity/plasma density of the streamer column.

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