Published in final edited form as:

Plasma Sources Sci Technol. 2012 June ; 21(3): . doi:10.1088/0963-0252/21/3/034006.

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

A. Shashurin¹, M. N. Shneider², and M. Keidar¹

¹Department of Mechanical and Aerospace Engineering, School of Engineering and Applied Science, The George Washington University, Washington, DC 20052, USA

²Department of Mechanical and Aerospace Engineering, Princeton University, Princeton, NJ 08544, USA

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 streamer by means of 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. On the contrary, it is shown 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), average conductivity ($10^{-2} \Omega^{-1} \text{cm}^{-1}$) and plasma density of the streamer column ($2 \times 10^{13} \text{cm}^{-3}$).

INTRODUCTION

The study of cold atmospheric plasmas has been significantly grown in recent years. The main reason for this extensive interest is cold nonequilibrium plasmas potential in the fields of bioengineering and medicine.^{1,2,3,4} The areas of possible application of cold plasmas include dentistry, drug delivery, dermatology, cosmetics, wound healing, cellular modifications, cancer treatment etc.

Tremendous interest to the cold plasmas has also triggered significant research effort directed towards detailed understanding of physics of the phenomena. The diagnostic tools that have been traditionally utilized for characterization of cold nonequilibrium atmospheric plasma jets include intensified charge-coupled device (ICCD) cameras, optical emission spectroscopy and electrical measurements of the discharge properties. Numerous works studied different aspects of the cold atmospheric plasma jets including speed of ionization front propagation, variety of excited and ionized species and electrical characteristics of the discharge.^{5,6,7,8} It was shown that the cold atmospheric plasma jet is formed by the streamer, which leading front propagates at velocities of 10^6-10^7cm/s . The theoretical model considering the self-consistent propagation of the fully insulated from the surroundings streamer head was originally proposed in Ref. [9,10]. Later theoretical efforts on the atmospheric pressure streamer dynamics were comprehensively considered in Ref. [11],

while recent progress achieved for the nonequilibrium He plasma jets in air was reported in Refs [12,13,14,15]. 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 utilizing Rayleigh microwave scattering for temporally resolved measurements of plasma density in atmospheric plasma jet, considered lifetime of 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 the cold atmospheric plasma jets limits understanding of the phenomena. In this work we propose a simple method for measurements of potential of the streamer's leading front, the streamer head (U_h). Knowing of U_h allows answering number of the important questions such as values of potential drop along the streamer column, charge of the streamer head and average conductivity of the plasma column.

EXPERIMENTAL DETAILS AND METHODOLOGY

Plasma gun (Fig. 1) is made of a Pyrex pipet through which the helium flow is supplied (the inner diameter of the thinner part of the pipet was about 4 mm, He flow rate was about 11.5 L/min). The gun is equipped with pair of high HV electrodes - central electrode (which end was in a direct contact with plasma) and outer ring electrode as shown schematically in Fig. 1 (a). Electrodes are connected to a secondary coil of high-voltage resonant transformer generating sinusoidal high voltage waveform with frequency 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 shunt resistor $1\text{ k}\Omega$ placed in series in discharge as shown in Fig. 1. The plasma gun typically produces the 4–5 cm length plasma jet. The interaction of the streamer with the external electric potential is studied using the 10 mm diameter ring made of copper foil (thickness - 50 μm) and 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 Fig. 1. The photographing of the jet is accomplished by Andor iStar 334T fast gated intensified CCD camera.

EXPERIMENTAL RESULTS AND DISCUSSIONS

The series of instant photographs (exposure time=10 ns) of the gun exhaust taken at different moments of time and the corresponding waveforms of discharge voltage and current are presented in Fig. 2a. It can be seen that streamer develops at about 2.5–3 μs after the main interelectrode discharge (indicated by the peak of discharge current) and reach the length of about 4 cm for 2.5 μs . Velocity of the ionization front propagation during the streamer growth varied in the range $1.5\text{--}2 \times 10^6$ cm/s. The photograph of the streamer taken with longer exposure time of 5 μs (over the entire time of streamer existence) is presented on the right photograph of Fig. 2a. The radius of the streamer column (R) was determined by measuring the size of the central highly luminous filament which can be clearly seen on the photograph. R was precisely measured using high magnification imaging to be 0.15 ± 0.05

mm. The object photographed on Fig. 2a is usually referred to the term of cold atmospheric plasma jet.^{1,6,7,8,9,16,17}

Interaction of the streamer with the DC potential created by the ring located at $z=3$ cm and dependence of streamer length L vs. ring potential U_r are shown in Fig. 2b. One can see that application of higher positive potential to the ring electrode led to significant perturbation of the streamer propagation, namely to shortening of the streamer. Basing on this experimental evidence, we will utilize 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 $t=4.5$ μ s after main breakdown is presented in Fig. 3. It can be clearly seen that plasma column coupling between the streamer head and main interelectrode discharge remains behind the streamer head. Note, the image presented in Fig. 3 is intended to demonstrate luminescence of the streamer column, and does not reflect the actual size of the streamer head which luminescence is greatly exceeds the brightness range utilized in the image.

Let us consider the question of degree of electrical insulation provided by the streamer column shown in Fig. 3. First, we will evaluate if the model of fully non-conductive plasma column (where streamer head is considered as solitary charge fully insulated from the surroundings) developed earlier by Dawson and Winn and applied later for the streamer originated by dielectric-barrier discharge (DBD) by Lu and Laroussi⁹ can reasonably explain the experimental results shown Fig. 2. To this end we will analyze the electrostatic problem of propagation of 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 potential of several kVs. Numerical simulations of this electrostatic problem show that application of 2 kV potential to the ring can significantly perturb the electric field around the insulated streamer head (E/E_0 about 50 %, where E_0 and E_I are the fields without and with the ring respectively and $E=E_0-E_I$) only if streamer head charge is less than 10^7 electrons (see Fig. 4). These charges are significantly lower than that required for the streamer existence.^{9,20} Indeed, the theoretical model of insulated DBD streamer indicates that head charges of $>3 \cdot 10^9$ electrons are required to ensure self-consistent propagation of the streamer.⁹ Perturbation of the electric field around the streamer head having about $3 \cdot 10^9$ electrons by the ring kept potential of 2 kV is less than 0.1 % (see Fig. 4). Certainly, such small perturbation of the field around the streamer head can not significantly affect propagation of the streamer.

Let us now validate the model of 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 $10^{-4} \Omega^{-1} \text{ cm}^{-1}$ (being maximal at streamer initiation and decaying with characteristic times of electron attachment to the oxygen molecules of the ambient air)^{16,17} and thus Maxwell relaxation time $t_{rel}=\epsilon_0/\sigma$ is less than 1 ns. The physical meaning of t_{rel} is the time required for polarization of free charges in conductor (or, in other words, conductor response time). This means that charge in the streamer head can be treated as one insulated from the surroundings only for times <1

ns. Since characteristic times of the streamer growth are few μs , one can consider that charge exchange between the streamer head and interelectrode discharge plasma is instantaneous, and thus the streamer column can not be treated as a non-conductive media.

Therefore, it may be concluded that the experimental data does not support the model of insulated streamer head.⁹ On the contrary, 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 formed by streamer column (active resistor) and streamer-ground capacitor as it will be described below.

Shortening of the streamer shown Fig. 2 can be now analyzed as follows. Ring in free space creates the distribution of electrical potential around itself which is characterized by the value of the order of U_r and occupies the spatial region of about ring's diameter. The electric field around the streamer head when it is approaching the ring is governed by 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 of U_r above the U_h will lead to stopping the streamer at a certain distance prior to the ring and this distance will be larger for the higher U_r . This simple consideration explains qualitatively shortening of the streamer path at increase of the ring potential observed experimentally (see Fig. 2). In order to quantitatively characterize the perturbation of the electric field around the streamer head due to presence of the ring we simulated this problem numerically. The dependence of electric field perturbation at the streamer head E/E_0 introduced by the ring (ring center coincides with streamer head location) as function of ring potential is shown in Fig. 5 (where E_0 and E_I are the electrical fields on the streamer head without and with the ring respectively and $E = E_0 - E_I$). It can be seen that significant reduction of the electric field (about twofold) occurs when U_r is close to U_h (E/E_0 about 0.4–0.5) and therefore, one can consider the condition $U_r = U_h$ as sufficient to stop propagation of the streamer. Based on this, we can propose simple and natural method for measuring the electrical potential of the streamer head. The ring electrode is placed at certain coordinate z^* and supplied with DC potential (this leads to shortening of streamer path as shown in Fig. 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 Fig. 2(b) it is clearly seen that $U_h = 2.8$ kV. Note, the potentials of the streamer head required to support the streamer propagation obtained in this work are lower than that for the conventional air streamer (~ 5 kV) since air is significantly pressed out from the streamer path by the He flow.

Now we will experimentally apply the methodology developed above and measure the streamer head potential. The dependences of U_h as function of z for different applied high voltage amplitudes U_{HV} are shown in Fig. 6(a). It can be seen that dependence type is changing from being falling for $U_{HV} = 2.6$ kV to growing for $U_{HV} = 3.8$ kV. From the first glance, such change of behavior of these curves with U_{HV} might be looking 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 function of time $z(t)$ was recorded [see Fig. 6(b)].

Fig. 7(a–c) presents the temporal evolution of streamer head potential $U_h(t)$ for three amplitudes of driven high voltage $U_{HV}=2.6, 3.1$ and 3.8 kV respectively obtained by combining the data shown in Fig. 6 (a) and (b). The temporal evolution of voltage applied to the discharge electrodes and discharge current are 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 potential of the central electrode is transferred to the streamer head with no significant voltage drops. It should be noted, that the voltage drop between the central electrode and the streamer head contains of two parts namely drop in a near electrode sheath and along the plasma column. When the streamer presents, drop in the near electrode sheath is expected to be relatively small – about several Volts (of the order of few kT_e/e), since the positive half-wave of the driven voltage is associated with shift of plasma column towards the central electrode and bringing it in contact with the electrode.²² Therefore, the near electrode drop is negligible and voltage drop between the central electrode and the streamer head is mainly governed by the drop along the plasma column. Smallness of voltage drop on the plasma column indicates that active resistance of the plasma column is significantly less than capacitive resistance formed by plasma column to the ground (can be estimated to be around several $M\Omega$ for 4 cm plasma column).¹⁶

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

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 charge created by hemisphere streamer head attached to the perfectly conducting streamer column as $Q_h \approx 2\pi\epsilon_0 R U_h$,^{11,21} where R -streamer radius which was determined as described above. Note, this charge is about twice lower than that created by a sphere with same potential and radius, which is caused by contribution of streamer column.^{11,21} The maximal value of

electric field can be estimated from: $E_m \approx \frac{U_h}{2R}$.^{11,21} An average plasma density (n_e) in the streamer channel can be estimated using the expression $I_s = en_e V_{dr} S$, where I_s - current flowing through the streamer channel, V_{dr} - electron drift velocity, $S = \pi R^2$ - cross-section area of the streamer channel and e - electron charge. The mean electric field in the streamer channel U/L is measured in this work to be about 50 V/cm (where U -potential drop

along the streamer and L - streamer length), which corresponds to the reduced electric field about $2 \times 10^{-18} \text{ Vcm}^2$ and finally yields electron drift velocity in the streamer channel - $2 \times 10^5 \text{ cm/s}$.^{23,24} Based on measurements of I_s (about 0.5 mA) conducted by Rogowski coil in Ref. [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 Rayleigh microwave scattering method.¹⁷ The typical parameters of the streamers are summarized in Table 1. Note, 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 at the streamer head (compared to e.g. $R_h \sim 3 \times 10^{-2} \text{ cm}$ and electric field of about 45 kV/cm in Ref. [13]).

CONCLUSIONS

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

Acknowledgments

This research was supported in part by GWU Institute of Biomedical Engineering (GWIN), Princeton Plasma Physics Laboratory University Support program (sponsored by DOE) and by NIH National Center for Research Resources (NCRR). We thank Drs. Y. Raitses and A. Starikovskiy for valuable discussions.

References

1. Keidar M, Walk R, Shashurin A, Srinivasan P, Sandler A, Dasgupta S, Ravi R, Guerrero-Preston R, Trink B. British Journal of Cancer. 2011
2. Fridman, A. Plasma Chemistry. Cambridge University Press; 2008.
3. Fridman G, Friedman G, Gutsol A, Shekhter AB, Vasilets VN, Fridman A. Plasma Processes Polym. 2008; 5:503.
4. Shashurin A, Keidar M, Bronnikov S, Jurjus RA, Stepp MA. Appl Phys Lett. 2008; 92:181501.
5. Lu X, Jiang Z, Xiong Q, Tang Z, Pan Y. Appl Phys Lett. 2008; 92:151504.
6. Mericam-Bourdet N, Laroussi M, Begum A, Karakas E. J Phys D: Appl Phys. 2009; 42:055207.
7. Sands BL, Ganguly BN, Tachibana K. Appl Phys Lett. 2008; 92:151503.
8. Ye R, Zheng W. Appl Phys Lett. 2008; 93:071502.
9. Dawson GA, Winn WP. Z Phys. 1965; 183:159.
10. Lu X, Laroussi M. J Appl Phys. 2006; 100:063302.
11. Bazelyan, EM.; Raizer Yu, P. Spark Discharge. Boca Raton, FL: CRC; 1997.
12. Naidis GV. J Phys D: Appl Phys. 2011; 44:215203.
13. Naidis GV. Appl Phys Lett. 2011; 98:141501.
14. Breden D, Miki K, Raja LL. Appl Phys Lett. 2011; 99:111501.
15. Jansky J, Bourdon A. Appl Phys Lett. 2011; 99:161504.
16. Shashurin A, Shneider MN, Dogariu A, Miles RB, Keidar M. Appl Phys Lett. 2009; 94:231504.

17. Shashurin A, Shneider MN, Dogariu A, Miles RB, Keidar M. Appl Phys Lett. 2010; 96:171502.
18. Begum A, Laroussi M, Pervez MR. International Journal of Engineering & Technology. 2011; 11:209.
19. Sretenovic GB, Krstic IB, Kovacevic VV, Obradovic BM, Kuraica MM. Appl Phys Lett. 2011; 99:161502.
20. Raizer, YP. Gas discharge physics. Springer-Verlag; Berlin: 1991.
21. Raizer YP, Milikh GM, Shneider MN, Novakovski SV. J Phys D: Appl Phys. 1998; 31:3255.
22. Raizer, YP.; Shneider, MN.; Yatsenko, NA. Radio-Frequency Capacitive Discharges. CRC Press; Boca Raton, Florida: 1995.
23. Dutton J. J Phys Chem Ref Data. 1975; 4:577.
24. Grigoriev, IS.; Melikhov, EZ. Handbook of Physical Quantities. Boca Raton, FL: CRC Press; 1997.

Fig. 1. Schematics of the experimental set up showing plasma gun, its electrical circuit, and metal ring with applied DC potential utilized to stop the streamer.

Fig. 2.

(a) Series of instant photographs taken at different moments of time and 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 exposure time of 10 ns, except for the right one where 5 μs exposure time was used (2 to 7 μs exposure window). Moment of time $t=0$ is associated with initiation of 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 vs. ring potential U_r (exposure window $t=2-7$ μs, $U_{HV}=3.1$ kV).

Fig. 3.

Accumulation of 500 instant images of the streamer taken at $t=4.5\ \mu\text{s}$ after main breakdown (exposure time = 100 ns, $U_{HV}=3.1\ \text{kV}$) indicating presence of the afterglow plasma column behind the streamer head which electrically couples the streamer head and main interelectrode discharge. Note, this image is intended to demonstrate luminescence of the streamer column, and it does not reflect the actual size of the streamer head which luminescence is greatly exceeds the brightness range utilized here.

Fig. 4.

Perturbation of the electric field around the streamer head caused by DC field ring scatterer ($U_r = 2\text{kV}$) if the model of solitary electric charge insulated from the surroundings is used. No significant perturbation of field is created for the head charges $> 10^7$ electrons.

Fig. 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 $U_r \approx U_h$.

Fig. 6.

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

Fig. 7.

Temporal evolution of discharge current (I_d), discharge voltage (U_d) and streamer head potential (U_h) for $U_{HV}=2.6, 3.1$ and 3.8 kV. Potential of streamer head is close to potential of central electrode and following its temporal behavior in all cases. This indicates that voltage drops potential of central electrode is transferred to the streamer head without significant drops.

Table 1

Typical parameters of the streamer on the growth stage (He flow=11.5 L/min, U_{HV} =2.6–3.8 kV)

Head charge, electrons	Streamer length, cm	Speed of ionization front, cm/s	Streamer diameter, cm	Characteristic electrical field in head vicinity, V/cm	Average conductivity of the streamer channel, $\Omega^{-1}\text{cm}^{-1}$	Average plasma density in the streamer channel, cm^{-3}
$1\text{--}2\times 10^8$	4–5	$1.5\text{--}2\times 10^6$	3×10^{-2}	about 10^5	10^{-2}	2×10^{13}