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Experimental approaches for studying non-equilibrium atmospheric plasma jets

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This work reviews recent research efforts undertaken in the area non-equilibrium atmospheric plasma jets with special focus on experimental approaches. Physics of small non-equilibrium atmospheric plasma jets operating in kHz frequency range at powers around few Watts will be analyzed, including mechanism of breakdown, process of ionization front propagation, electrical coupling of the ionization front with the discharge electrodes, distributions of excited and ionized species, discharge current spreading, transient dynamics of various plasma parameters, etc. Experimental diagnostic approaches utilized in the field will be considered, including Rayleigh microwave scattering, Thomson laser scattering, electrostatic streamer scatterers, optical emission spectroscopy, fast photographing, etc. © 2015 AIP Publishing LLC. [http://dx.doi.org/10.1063/1.4933365]

I. INTRODUCTION

Serious attention towards studying miniature non-equilibrium atmospheric plasmas for treatment of biological systems has been initiated about two decades in connection with its efficiency for biological sterilization.\textsuperscript{1} In contrast with thermal plasmas, low power non-equilibrium atmospheric plasmas operate under the threshold of thermal damage to the tissue (eliminating tissue burn) and induce specific chemical responses on the cellular level and can offer mini-invasive surgery technique. Currently, non-equilibrium atmospheric plasmas found wide application in the areas of sterilization and disinfection,\textsuperscript{2–4} More exotic utilization includes cancer treatment, skin dentistry, drug delivery, dermatology, cosmetics, wound healing, cellular modifications, etc.\textsuperscript{1–7}

One particularly important configuration of the non-equilibrium atmospheric plasmas is jet. Non-equilibrium atmospheric plasma jets (NEAPJ) are typically formed in the millimeter range, while the length is about a few centimeters. Typically, NEAPJ are driven by the AC high voltage sources operating in the kHz frequency range and utilizing helium (He) as a working gas. We will consider and analyze physical processes involved in the discharge, including breakdown conditions, ionization front propagation dynamics, electrical coupling of the streamer tip with discharge electrodes, discharge current spreading, transient dynamics of plasma, and discharge parameters in NEAPJ, factors determining NEAPJ length, diameter, and propagation path, etc.

A. Types of NEAPJ

Typical NEAPJ source uses tubular discharge tube made of dielectric material and having few millimeters in diameter through which working gas (helium) is supplied. The discharge tube is usually equipped with pair of high-voltage electrodes. There are two most common configurations of the discharge electrodes as following. In one configuration, central electrode is mounted on the axis of discharge tube and the second electrode is mounted outside the discharge tube [type A in Fig. 1]. The central electrode can be insulated along its entire length or can have non-insulted tip directly contacting the plasma.\textsuperscript{11,33,34} Other configuration uses two
ring electrodes mounted outside the discharge tube [type B in Fig. 1].

There are two types of the high voltage waveforms utilized for initiation and supporting the NEAPJ, namely, sine-wave AC high voltage with typical frequencies of several tens kHz and rectangular high voltage pulses with typical pulse durations in \(\mu s\) and sub-\(\mu s\) range and repetition rate frequency in kHz range. Amplitude of high voltage varies in relatively wide range from 3 to 40 kV.

Typically, the discharge has two distinct spatial regions, namely, main discharge and plasma jet. The main discharge is sustained between the discharge electrodes and located entirely inside the discharge tube (see Fig. 1). NEAPJ are formed by the part of the discharge extending outside the discharge tube having shape of well-collimated plasma jet with typical length of approximately several centimeters and few millimeters in diameter.

**II. EXPERIMENTAL STUDIES OF NEAPJ**

**A. NEAPJ as a sequence of “bullet-like” streamer breakdowns**

Intensified charge-coupled device (ICCD) cameras are probably the first and the most common tool for NEAPJ diagnostics. First studies of NEAPJ conducted by fast ICCD cameras revealed non-continuous nature of the jets. Bright “bullet-like” ionization front extending from the discharge and moving along the helium flow was detected in these works (see Fig. 2). Velocities of ionization front propagation were found to be in the range from \(10^6\) to \(10^8\) cm/s depending on discharge parameters. The ionization front typically slows down along the propagation path as shown in Fig. 2.

Development of rapidly moving ionization front (or spark) at breakdown is associated with phenomenon of streamer. Classical definition of streamer is ionized channel rapidly growing between the breakdown electrodes supported by photoionization of gas in vicinity of the channel tip and following production of secondary avalanches. Streamer type of the breakdown is typical for relatively large gaps. For example, for air gaps created by two plane electrodes, Townsend breakdown mechanism of avalanches multiplication is employed than parameter \(p \cdot d < 200 \text{Torr} \cdot \text{cm}\), while streamer breakdown for \(p \cdot d > 5000 \text{Torr} \cdot \text{cm}\), where \(p\) the gas pressure, \(d\) the distance between the electrodes. Streamer breakdown is characterized by significantly faster development times compared to Townsend avalanche multiplication, since it develops on the time of single avalanche flight between the discharge electrodes, rather than Townsend breakdown which is associated with development of multiple avalanches.

**B. Air streamer fundamentals**

Let us now present a very brief qualitative description of streamer fundamentals using the example of cathode-directed air streamer between two plane electrodes. More
It has to be noted that low-frequency NEAPJ operating in He/Air mixture considered in this work differ to large extent from the classical case of air streamer between two plane electrodes. The similarities and differences of these two objects will be discussed below.

C. Electrical coupling between NEAPJ streamer head and discharge electrodes. Electrostatic streamer scatterers and plasma potential measurements

Presence of strong electrical coupling between the NEAPJ streamer tip and the discharge electrodes was demonstrated by Shashurin et al.\textsuperscript{20} The electric potential of the NEAPJ streamer tip was measured using external electrical potential created on the streamer’s propagation path. The idea of the method consists of stopping the streamer propagation by means of externally created electric potential produced by the metal ring surrounding the NEAPJ as illustrated in Fig. 4. An application of positive DC potential to the ring electrode \((U_r)\) of about 2.8 kV led to abrupt arresting the further streamer propagation beyond the plane of the ring as shown in Fig. 4. This effect is caused by the reduction of the local electric field around the streamer tip \((E_b)\). The notable reduction of the \(E_b\) is possible when the space potential at the streamer tip location \((\sim U_r)\) reaches values close to the streamer tip potential \((U_b)\). In the zero order approximation, the simplified criteria that the streamer potential is equal to the ring’s potential required to stop the streamer propagation exactly at the ring’s plane can be used. More details on the method can be found in Ref. \textsuperscript{20}.

Temporal evolution of the NEAPJ streamer tip potential is shown in Fig. 5 for three amplitudes of driving high voltages 2.6, 3.1, and 3.8 kV (type A configuration with bare central electrode was used).\textsuperscript{20} One can see that the central electrode potential in all cases was transferred along the main discharge column and the streamer channel to the streamer tip without significant voltage drops (less than 10–15\%). The value of the electric field in the streamer channel can be estimated to be about 100 V/cm and electric field in the tip vicinity \(E_b = 80–100 \text{ kV/cm}\).\textsuperscript{20}

Experiments conducted with type B discharge configuration with insulated discharge electrodes also support the idea of presence of strong electrical coupling between the streamer tip and the discharge electrodes.\textsuperscript{15,38} Indeed, these works demonstrated an instant interruption and inability of any further propagation of the streamer momentarily when HV pulse applied to the electrode was turned off. It has to be noted that these observations refute applicability of the model of completely isolated streamer tip proposed in early works for interpretation of NEAPJ physics.\textsuperscript{15}

\[ E \approx \frac{U_b - U_0}{2r_s}, \]  
where \(r_s\) is streamer channel radius.

FIG. 3. Illustration of cathode-directed streamer development between two plane electrodes.

details can be found elsewhere.\textsuperscript{17,18} If the electric field between the discharge electrodes \((E_0)\) is strong enough, the electrons may start producing avalanches by ionizing the surrounding gas atoms. The avalanches are amplified when the ionization coefficient \((\chi)\) exceeds the attachment coefficient \((\alpha)\). The avalanches start from the seed electrons, grow, and propagate towards the positive anode in accordance to the law \(n_e = e^{(\chi - \alpha)x}\), where \(x\) is the distance from the avalanche stat point (see Fig. 3(a)). Due to much higher mobility of electrons compared to ions, electrons are located in the leading part of growing avalanche, while uncompensated positive charge is located at the avalanche’s tail. This is schematically illustrated in Fig. 3(b). Avalanches reach maximal amplification just prior the anode and then electrons are absorbed by the anode surface, while positive ion tail is remaining in the gap and drifting back towards the cathode (see Fig. 3(c)). The ion tail produces its own electric field \((E_b)\). If avalanche prior to contact with the anode was strong enough, so that \(E_b \approx E_0\), the ion tail can produce field sufficient to trigger its own secondary electron avalanches (see Fig. 3(d)). Reaching \(E_b \approx E_0\) when secondary avalanches are initiated in vicinity of the ion tail indicates transformation of avalanche into a streamer. Ion tail serves now as a head of the streamer channel, propagating back towards the cathode as follows. The streamer head field photoionizes electrons around it and starts secondary avalanches which are pulled into the positive streamer head. Electrons from the fronts of the secondary avalanches are drawn into the streamer head and compensate it, while ion tails of the secondary avalanches form new streamer head slightly shifted towards the cathode (see Fig. 3(e)). This process continues multiple times and leads to formation of elongated streamer channel connected with anode and growing towards the cathode as illustrated in Fig. 3(f). Streamer breakdown develops in air when electric field reaches about 30 kV/cm for air gaps >3 cm. This corresponds to \(\chi - \alpha = 6.5 \text{ cm}^{-1}\) and number of electrons in avalanche of about \(10^5 - 10^6\).\textsuperscript{17} The electric field in the air streamer channel varies in relatively narrow range 4.5–5 kV/cm.\textsuperscript{18}

Typically, streamer channel has relatively high electrical conductivity providing good electrical contact between the streamer tip and the electrode on which it is growing.\textsuperscript{17} In approximation of ideally conducting streamer channel, the electric field in the streamer tip vicinity can be determined from the streamer tip potential \((U_b)\) and potential of this point of space \((U_0)\) in absence of the streamer (potential created by the sources other than the streamer) as follows:\textsuperscript{18,19}

\[ E \approx \frac{U_b - U_0}{2r_s}, \]  
where \(r_s\) is streamer channel radius.
D. NEAPJ streamer initiation requirements and propagation speed

Streamer initiation is associated with reaching the threshold value by the electric field sufficient for its reproduction at the next position along the propagation path.\textsuperscript{17} Due to the good electric coupling between the streamer tip and discharge electrode, the electric field can be simply estimated as $E_h \approx \frac{U}{S}$, according to Eq. (1) (in absence of additional potentials created by other sources). Therefore, initiation of streamer breakdown is governed by the magnitude of the discharge voltage.

In case low-frequency (~tens of kHz) AC high voltage is utilized for the NEAPJ production, the streamer development (typical times $<2–3 \mu s$) can be considered to be instant on the time scale of the discharge-driving voltage oscillations. Therefore, streamer breakdown is governed by the instant value of the discharge voltage and occurs exactly at the moment when minimal voltage required for the breakdown is reached. The streamer can be initiated at different phases of the time-dependent discharge-driving voltage depending on when the threshold electric field is reached (see Fig. 5). Experiments indicate that for type A discharge configuration with the bare discharge electrode, this threshold voltage value required was in the range $U_{\text{min}} = 2.5–3$ kV. The corresponding minimal electric field can be estimated from $E_h \approx \frac{U_{\text{min}}}{S}$ yielding electric field around the tip $E_h = 80–100$ kV/cm (using streamer channel radius $r_s = 0.15$ mm, see below).\textsuperscript{20}

Similar minimal breakdown voltages are also common for NEAPJ produced by the rectangle HV pulse, namely, $\geq 4$ kV.\textsuperscript{15,27} Numerical simulations conducted by Naidis predicted development of streamer down to 3 kV amplitude of exciting HV pulse.\textsuperscript{56} Utilization of HV pulses with amplitudes higher than the minimal voltage required for the breakdown is associated with so-called overvoltage conditions. Overvoltage (above the minimal voltage required for the streamer initiation) leads to development and propagation of the streamer under higher instant electrode voltage and, therefore, under higher electric fields in the streamer tip vicinity.

The propagation speed of the streamer ionization front is heavily dependent on the instant value of electric potential on the discharge electrode at the moment of streamer development. Indeed, experiments indicate that propagation velocity increased from $v_t = 2 \times 10^6$ cm/s for about 2.5–3 kV AC voltage (Refs. 11 and 20) to $(1–2) \times 10^7$ cm/s for 4–5.5 kV HV pulses (Refs. 15 and 27) and $(4–8) \times 10^7$ cm/s for 10–13 kV HV pulses (Ref. 29). Minimal measured $v_t$ of $2 \times 10^6$ cm/s is associated with the case of low-frequency (~tens of kHz) AC high voltage sources utilization for the NEAPJ creation, when streamer initiation occurs exactly at the moment when minimal voltage required for the breakdown is reached (no overvoltage).\textsuperscript{11,20} In contrast, utilization of HV pulses for the NEAPJ excitation readily creates overvoltage conditions, if HV amplitudes higher than minimal 2.5–3 kV required for the breakdown are used. Larger overvoltage causes higher electric field near the streamer tip $E_h$. This in turn accelerates development of elementary avalanches developing in front of the streamer tip, electron drift towards the tip, and finally accelerates the ionization front propagation. Numerical simulations providing good agreement with the experimental data were conducted by Naidis and shown in Fig. 6.\textsuperscript{56}

E. NEAPJ streamer length, shape, diameter and propagation path

One of the major factors governing streamer length is level of oxygen admixture in the helium flow. Attachment of electrons to oxygen molecules quenches development of avalanches and further propagation of the streamer.\textsuperscript{13} Obviously, helium flow ejected to the air from the discharge tube has increased air content along the propagation path due to interdiffusion of both gases. This leads to streamer stopping at some particular distance from the discharge tube when air content exceeds critical value and limits maximal NEAPJ length. Another factor limiting the streamer length is operating frequency of the device. Since typical streamer development times are about few $\mu$s, driving frequencies of discharge cannot be increased above the MHz frequencies since otherwise streamer will be unable to fully grow during the voltage cycle. Third factor limiting the streamer length is plasma decay in the streamer channel behind the ionization front which causes weakening of electrical contact between streamer head and electrode, and thus reduces the electric field around the streamer tip necessary for streamer propagation.

The dominant factor that governs the NEAPJ streamer length should be determined specifically in each experiment.
For type A NEAPJ with bare electrode in direct contact with plasma and 4 mm exit diameter of the discharge tube, streamer growth had interrupted at \( z = 4 \text{ cm} \) from the discharge tube when head potential was about 4 kV (even higher than at streamer initiation) and channel plasma density is high.\(^{\text{20}}\) This suggests that most likely, the dominant limiting mechanism is quenching of avalanches due to elevated air contain in the helium flow. Other recent work shows that absence of oxygen content in the He flow can remove the above limitation and significantly elongate the streamer length. The experiments conducted at 75 Torr nitrogen pressure yielded extremely long 28 cm length NEAPJ.\(^{\text{21}}\) Oppositely, admixture of the oxygen directly in He flow at levels of about fractions of percent is sufficient to significantly reduce NEAPJ length.\(^{\text{22,23}}\)

The NEAPJ propagation path coincides with the direction of the He flow. This is caused by higher presence of the ambient air and elevated attachment oxygen in direction perpendicular to the helium flow. This causes weaker avalanches developing perpendicular to the jet compared to that growing along the axis and sets preferential direction of the streamer propagation along the He flow.\(^{\text{24}}\) Direction of the streamer propagation can be controlled by creating more complicated paths of the He flow as shown in Ref. 10.

Additional way to perturb the streamer propagation path is to create external electrical potential. It was already shown above that streamer can be stopped by using the ring electrode with applied electric potential (see Fig. 4 and Ref. 20). Another interesting effect is attraction of streamer to positive electrode,\(^{\text{24,27}}\) which may look contradictory from the first glance since streamer tip carries positive space charge as well. The interpretation of this result is related to the fact that streamer propagation is associated with motion of electrons rather than heavy particles. Indeed, the electrons of the avalanches developing in front of the streamer tip are attracted simultaneously by the positive streamer tip and by the positive capacitor’s plate, and the resultant influence of both objects may cause streamer deflection towards the positive capacitor plate.\(^{\text{24}}\)

Let us now consider cross-sectional shape of NEAPJ. Spectroscopic studies of NEAPJ indicate that radiation is dominated by helium, nitrogen, oxygen, and hydroxyl radicals’ spectral lines.\(^{\text{31–33}}\) Cross-sectional distribution of spectral intensities of different species follows density distributions of the corresponding species. Indeed, helium radiation has maximum on the axis due to maximum of the He density along the axis, while radiation produced by the air-contained species is shifted from the axis since their density is minimal on the axis and increases in radial direction.\(^{\text{25}}\) For example, peak of nitrogen radiation is shifted off the axis about 0.7 mm at 20 mm away from the discharge tube exit (3 mm exit diameter of the discharge tube was used).\(^{\text{25}}\) Due to diffusion of air nitrogen into the helium, the off-centered shift decreased to about 0.3 mm at 40 mm away from the discharge tube.\(^{\text{25}}\) Relative magnitudes of powers radiated by helium to that by air-contained species may vary. Some cross-sectional photographs indicate donut cross-sectional shape of the NEAPJ, indicating dominant radiation from the air species,\(^{\text{25–27}}\) while others indicate presence of bright core in the center due to radiation from helium.\(^{\text{11,28}}\)

FIG. 5. Temporal evolution of streamer tip potential and discharge electrode potential for three amplitudes of driving high voltages 2.6, 3.1, and 3.8 kV. One can see that streamer tip potential is close to the potential of the central electrode and following its temporal behavior. Reproduced with permission from A. Shashurin et al., Plasma Sources Sci. Technol. 21, 04006 (2012). Copyright 2012 IOP Publishing.

F. Dynamics and temperature of heavy particles

It is important to understand that breakdown of the inter-electrode gap and following development of NEAPJ streamer are happening in virtually immovable gas. Indeed, typical gas speeds are about 10 m/s.\(^{\text{27,56}}\) So, for the entire
NEAPJ streamer produces extremely long-living metastable He states.\textsuperscript{17} One of the mechanisms of relaxation of these states is Penning ionization, when the energy of metastable level (e.g., 19.8 eV for He $2^3S$, lifetime $6 \times 10^7$ s) is sufficient to ionize ambient gas which ionization potential is lower (e.g., 14.5 eV for nitrogen). Penning ionization of the ambient gas can serve as an effective source of seed electrons required for initiation of avalanches in front of the streamer and this can potentially cause reduction of the number of electron generations created in front of the streamer tip compared to the air streamer.\textsuperscript{17}

Recent numerical simulations pay great attention to clarification of how various species excited in the NEAPJ interact with biological tissue.\textsuperscript{39–47} These works simulate rich plasma chemistry emerging in gas phase prior to delivery to the tissue, including tens of species and hundreds/thousands of various reaction and consider further effects they induce in the tissue, including of electrical charging, action of UV radiation, spreading, and penetration of the reactive species into the tissue.

G. Plasma density measurements

Application of conventional plasma density diagnostics for low frequency NEAPJ is problematic. Insertion of any type of probes into the plasma jet (typically few millimeters in diameter) is associated with strong perturbation of the plasma due to change of capacitive coupling of plasmas to ground leading to shorting the jet to the probe. Conventional microwave interferometry fails due to the small size of the plasma compared to the microwave wavelength, which leads to diffraction and negligible phase change; electrostatic probes introduce very strong perturbation and associated with difficulties at application in strongly-collisional atmospheric conditions.\textsuperscript{48}

Recently, plasma density and electron temperature in for RF microdischarges and DC microdischarges were measured using Thomson scattering on free plasma electrons (laser frequencies $\gg \omega_{pe}$, $\nu_{th}$).\textsuperscript{8,49,50} These measurements are characterized by outstanding spatial resolution down to 10–50 $\mu$m. However, the method has limited sensitivity when plasma ionization degree is low, namely, minimal detectable plasma ionization degree of about $10^{-6}$ was indicated ($\sim 10^{13}$ cm$^{-3}$ for atmospheric pressure discharges), due necessity to extract signal related to Thomson scattering on free plasma electrons from large amplitude background signal produced by Rayleigh scattering on molecules.\textsuperscript{8,49–51} In addition, laser
Thomson scattering method was only used with discharges associated with time-independent plasma density since long accumulation of signal (tens of milliseconds) is required in order to achieve detectable signal level.\(^8,49\)

### 1. Rayleigh microwave scattering

Plasma density in the low-frequency NEAPJ has been measured using elastic scattering of microwaves on plasmas.\(^11,52\) Microwave radiation (linearly polarized along the NEAPJ) is utilized to induce electron oscillations in plasma channel, and in the Rayleigh regime (when the channel is thin compared to the skin layer depth), the electric field amplitude of the scattered wave \(E_s\) is proportional to the total number of electrons in plasma volume \(E_s \propto n_e V\), where \(V\) the plasma volume, \(n_e\) the plasma density. Absolute value of plasma density can be determined from the measurement of the scattered radiation signal and plasma volume using calibration procedure and satisfying certain requirements for detection system as described in detail in Refs.\(^{11,53}\).

It has to be noted that Rayleigh Microwave Scattering (RMS) technique uses significantly lower microwave frequencies compared to that of molecules. This allows to significantly improve method sensitivity with respect to low plasma densities and obtain measurement in the single exposure in contrast with long accumulation of signal required for laser Thomson scattering which might be problematic for time-dependent \(n_e\) in NEAPJ.

Fig. 8 presents temporal evolution of the electrical and plasma parameters along with series of instantaneous ICCD camera images of the GWU low frequency NEAPJ device.\(^54\)

It was observed that the discharge consists of series of elementary breakdown events inside the discharge tube followed by the development of streamer propagating outside the tube in an open air shown in Fig. 8(b). Breakdown occurs once per period of the AC high voltage during a positive half-wave at the central electrode. The breakdown of the interelectrode gap is indicated by the peak of the discharge current \(I_d\) observed around \(t = 0\) in Fig. 8(c). \(I_d\) increases to about 6–8 mA at about 1 \(\mu\)s after the breakdown and then decays with the characteristic times of about 3–5 \(\mu\)s. This stage of the discharge is characterized by the presence of the discharge in the interelectrode gap only (main discharge), while no ionization wave outside the discharge tube is presented [see \(t < 3 \mu\)s in Fig. 8(c)]. The main discharge stage typically lasts about few \(\mu\)s after the breakdown and indicated by the green bar in Fig. 8(b).

The next stage of the discharge starts at about 3 \(\mu\)s after the breakdown when ionization front (streamer) comes out the discharge tube [see Fig. 8(b)]. The streamer propagates...
axially about 4 cm with speed of about $2 \times 10^6$ cm/s along the He flow ejected to an ambient air until it decays at $t \approx 5 \mu s$ as shown in series of instant photographs shown in Fig. 8(b). This stage of the discharge is marked by the red bar in Fig. 8(c). Measurements of plasma density ($n_e$) in the streamer channel conducted using RMS facility yield averaged value of $n_e$ along the streamer channel of about $10^{13}$ cm$^{-3}$. Numerical simulations provide same range of $n_e$ values. Note the plasma ionization degree in the jet is very low $\approx 5 \times 10^{-7}$ (gas density at 1 atm and 300 K is around $2 \times 10^{19}$ cm$^{-3}$). Electrical potential of the streamer tip measured during the streamer development is indicated by red dots in Fig. 8(c). It is seen that the streamer tip carries potential close to the potential of the central electrode as described above. The ionization front propagation quenches at $t \approx 5 \mu s$ and remaining streamer channel decays for the next 2–3 $\mu$s. The plasma decay is governed by dissociative recombination of He$_2$ ions with electrons ($\beta \approx 10^{-7}$ cm$^3$/s), yielding the decay time $\approx 1 \mu s$ for measured plasma density of $10^{13}$ cm$^{-3}$. The afterglow stage is indicated by the brown bar in Fig. 8(c).

The electrical current spreads in the discharge as follows. At the main discharge stage [green bar in Fig. 8(e)], the discharge current ($\approx 5–10$ mA) is circulated via the circuit: central electrode - main discharge - grounded ring electrode. When the streamer is developing, a portion of the circuit: central electrode - main discharge - grounded ring electrode away from it and usually breakdowns only part of the gap since it may exist only in vicinity of the He flow ejecting from the discharge tube.

Another difference is that NEAPJ streamer in He-air mixture has pre-determined straight path along the He flow in contrast with the random-walk of the air streamer, due to elevated attachment to oxygen perpendicular to the jet as indicated above. In addition, the electric fields in the air streamer channel differ significantly from that in NEAPJ helium streamer, namely, $\approx 5$ kV/cm in air compared to $\approx 100$ V/cm in NEAPJ streamer channel, respectively. This is consistent with the experiments conducted at different gaseous atmospheres summarized in Ref. 18, where the increase in the oxygen (or water vapor) content was demonstrated to lead to the growth of the electric field in the streamer channel.

Typical parameters of the low-frequency NEAPJ utilized at GWU excited by 25 kHz AC high voltage in He flow ejected for the discharge tube to an open air are presented in Table I.

| III. CONCLUSION |
| This paper reviews state-of-the art of the research conducted in the field of non-equilibrium atmospheric plasma jets operating in the kHz frequency range and using helium as working gas. These NEAPJ are associated with highly non-steady dynamics of the plasma parameters. Transient dynamics of plasma and discharge parameters was considered and physical processes involved in the discharge were analyzed. Good electric conductivity of the streamer channel and transfer of the electrodes potential to the streamer tip without significant potential drop is demonstrated. Presence of the air content in the helium flow governs streamer propagation along the straight path, its cross-sectional structure, and maximal streamer length. Excitation of the streamer with low frequency AC high voltage is associated with the streamer initiation at the moment when minimal breakdown conditions are reached. Plasma parameters of such streamer include average plasma density in the streamer channel of about $10^{13}$ cm$^{-3}$, ionization front propagation speed of  |
| Discharge voltage | 2.5–5 kV |
| He flow | 11–12 l/min |
| Discharge current | $<10$ mA |
| Plasma jet current | $<1$ mA |
| Main discharge stage duration | $\approx 3 \mu$s |
| Streamer stage duration | $\approx 2 \mu$s |
| Afterglow stage duration | $\approx 2–3 \mu$s |
| Streamer triggering voltage | 2.5–3 kV |
| Electric field in the streamer tip vicinity | 80–100 kV/cm |
| Field in the streamer channel | 100 V/cm |
| Streamer length | 4–5 cm |
| Streamer diameter | 0.3 mm |
| Speed of ionization front | $2 \times 10^{6}$ cm/s |
| Average plasma density in the streamer channel | $10^{13}$ cm$^{-3}$ |

H. Differences between NEAPJ streamer and air streamer

One important difference between the NEAPJ and air streamer is the seed media on which both streamers are growing. Classical air streamer starts from the avalanche developing at breakdown of the air gap. In contrast, NEAPJ streamer appears after breakdown and establishment of discharge in the interelectrode gap and grows directly on the plasma column of the main discharge. In addition, air streamer typically breakdowns the entire gap between the electrodes. NEAPJ streamer develops through the hole of the grounded electrode away from it and usually breakdowns
about $2 \times 10^6 \text{cm/s}$, and post streamer plasma decay governed by dissociative recombination He$_2$ ions with electrons of about 2–3 $\mu$s.

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54A. Shashurin, D. Scott, M. Keidar, and M. N. Shneider, “Physical processes in the low-frequency nonequilibrium atmospheric Plasma jets,” in 5th International Conference on Plasma Medicine, 18–23 May 2014, Nara, Japan.


