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Letter

Time-resolved electric field measurements during and after the initialization of a kHz plasma jet—from streamers to guided streamers

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Abstract

This work presents the investigation of a 30 kHz operated atmospheric pressure plasma jet impinging a dielectric BSO-crystal, allowing time-resolved electric field measurements based on the Pockels effect. Observations indicate that from the time the voltage is applied, the plasma first develops through unstable branching before a stable periodic behavior is established. This initialization of the plasma jet suggests the importance of the build-up of leftover ionization, which creates a preferred pathway for the streamer-like discharges. After initialization the time and spatially resolved electric field of guided ionization waves induced in the crystal is obtained, showing a highly periodic charging and discharging at the surface of the crystal. When the ionization wave arrives at the crystal charge is deposited and constant electric fields are generated for approximately 14 μ s. Then a (back) discharge will remove the deposited charge at the surface, related to the moment when the applied voltage changes polarity and it agrees with imaging reported on in other literature.

Keywords: plasma jet, electric field, time resolved, guided streamers, ionization waves, initialization, pockels effect

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

In the last decade, atmospheric pressure plasma jets applied for medical purposes [1] have been investigated and characterized to a great extent, including but not limited to the production of species, gas flow dynamics, heavy particle and electron temperature and biological effects for different applications using different numerical and experimental methods [2]. Plasma jets are generated at different frequency ranges. When using a pulsed DC or kHz-AC system the jet consists of highly periodic streamer-like discharges, referred to as guided ionization waves. In literature also the terms plasma bullets or

guided streamers are used and the discharges are first observed by Teschke *et al* [3].

Where regular streamers create their own trajectory and as such are not reproducible, guided ionization waves are highly repetitive and once created follow the same path. Literature suggests that this is because of a memory effect due to leftover ionization and metastables that guide consecutive streamers in the same direction, making them reproducible [4–6].

This work includes the investigation of the electric field induced in a dielectric target by helium-in-air ionization

waves using the 30 kHz-plasma jet, described more comprehensively in [7]. A small stainless steel pipe with inner diameter of 0.8 mm is used as powered electrode through which 700 sccm helium flows. This is placed within a larger dielectric pyrex capillary, with inner diameter of 2.4 mm. Around the capillary is a copper wire attached to the ground, at 5 mm from the tip of the powered stainless steel pipe and 12 mm from the end of the capillary. The jet is positioned at an impact angle of 45 degrees with respect to the crystal. As such the jet will not block the light passing through the crystal needed to measure the Pockels effect. The distance towards the target is 7 mm. Recently this plasma jet has been investigated regarding the influence of geometry [8] and a parametric study for the impingement of the jet on a dielectric target [9]. Before every measurement the helium flows for 10 min to flush the system to remove air and any possible water vapor in the capillary.

The discharge is generated between the tip of the AC—powered electrode inside the capillary and the ground attached around it. When enough charge has accumulated beneath the ground, the streamer propagates towards the end of the capillary. From there the ionization wave is created propagating away from the jet towards the target. Exactly one ionization wave is created each AC—period, during the positive half period. This is confirmed by both electrical measurements at the ground and fast optical imaging [8, 9].

In this research the guided ionization wave is investigated by targeting it to an electro-optic BSO crystal. According to the Pockels effect the electric field induces a change of refractive index of the material [10], which can be determined by looking at the polarization of light passing through it. As such this allows for investigation of the jet in contact with a (dielectric) surface. Since these ionization waves are easily influenced by external effects, methods for electric field measurements are limited. Using Stark polarization spectroscopy, the electric field for helium-in-air guided ionization waves is determined by Sretenovic *et al* between 10–30 kV cm⁻¹ [11], similar to values obtained with numerical work [12–14].

The Pockels effect has been used for electric field measurements of streamers [15] and since the dielectric BSO material will influence the discharge less than other metallic probes or antennas, it is used in recent investigation for guided ionization waves to measure electric field [7, 16] induced by surface charge [17].

By using the Sénarmont setup [18], see figure 1, the electric field in the BSO crystal is determined by measuring the change in refraction index of the crystal. Depending on the polarization of incident light, a phase difference is induced for the transmitted light related to the change in refraction index. The optical system is at 50% transmittance when the angle of the analyzer $\beta = \pi/2$. This allows linearization of the transmission function. Due to optical activity in the crystal a natural rotation of 10 degrees is present and needs to be added [19]. The change in refraction index in the crystal can be determined by comparing different intensities captured with the iCCD camera. Intensity I_0 is measured when there is no discharge and subtracted from the intensity I when the ionization waves are present and targeting the crystal. This intensity difference is normalized, using the maximum and

Figure 1. The ideal setup used for electric field measurements with the plasma jet impinging the electro optic crystal. The transmission depends on the delay Γ and the angle β of the analyzer.

minimum intensity possible for this optical system. $I_{\max}$ and $I_{\min}$ are obtained without an applied electric field present, respectively when $\beta = 55^\circ$ and $\beta = 145^\circ$. The axial component of the applied electric field (tangential to the propagating light) throughout the crystal is then calculated using

$$E = \frac{\lambda}{\pi d n_0^3 r} \frac{I - I_0}{I_{\max} - I_{\min}}, \quad (1)$$

with the diode's wavelength $\lambda = 633$ nm, the crystal's thickness $d = 0.5$ mm, index of refraction $n_0 = 2.54$ and pockels coefficient $r = 4.8$ pm V⁻¹ [7].

The initialization of the plasma jet is captured using single shot exposures of 33 μ s, i.e. the applied AC period. The results are shown in figure 2. By *initialization* it is meant the period of time needed for a stable jet plume to form. Before igniting the plasma jet, I_0 , $I_{\max}$ and $I_{\min}$ are obtained and 20 exposures of each are taken and averaged. Then, while taking single shot exposures the applied voltage is increased manually to 2 kV, which is our reference setting and above breakdown value. To ensure that the maximum number of measurements is taken during the initialization stage, the camera is triggered on an internal clock. It was not possible to match this to an external event related to a specific time within the AC cycle. As such the exposure time of 33 μ s is necessary to ensure the capture of the induced effect to the crystal by a single ionization wave.

Figure 2 shows the measured electric field in the BSO crystal related to this initialization. After breakdown clear electric field patterns are observed. As stated, the jet impinges the crystal at 45 degrees. The capillary is positioned left of the images pointing to the right. As such at the impact point helium/air mixing is flowing along the surface to the right.

In the images in figure 2 two effects can be seen: firstly the streamer patterns will be discussed and additionally the appearance of the larger background structure. Initially streamer patterns are observed at the crystal with arbitrary shape and direction. Approximately 0.5–1 s later they disappear and a seemingly steady state is reached. The time it takes to reach the steady state is relatively long. This suggests it is (partially) due to the presence of the dielectric target, which has a low charge mobility. The literature suggests the memory effect as possible cause for the observed transition. The role of pre-ionization is discussed for the transition from filamentary to glow mode plana-to-plane DBD's [4, 20]. Hofmann *et al* showed either guided or branching streamers are observed depending on the applied voltage or frequency [5], with which

Figure 2. The measured electric field (kV cm^{-1}) in the crystal at 7 mm from the plasma jet. Single shot exposures of $33 \mu\text{s}$ are taken ($4 \times 4 \text{ mm}$) and the voltage is increased manually to 2 kV at $t = 0 \text{ s}$. Visible is the electric field profile consisting of a big background structure and an addition small effect of a surface discharge. To obtain the true field of the discharge, the shown measurements have to be corrected for the background structure. (a) $t = 0 \text{ s}$, (b) $t = 0.18 \text{ s}$, (c) $t = 0.36 \text{ s}$, (d) $t = 0.54 \text{ s}$, (e) $t = 0.72 \text{ s}$, (f) $t = 0.90 \text{ s}$, (g) $t = 1.08 \text{ s}$, (h) $t = 1.26 \text{ s}$, (i) $t = 1.44 \text{ s}$, (j) $t = 1.62 \text{ s}$, (k) $t = 1.80 \text{ s}$, (l) $t = 1.98 \text{ s}$.

the amount of left-over ionization and metastables is probably altered. Numerical work shows streamers overlap when the pre-ionization density is higher than 10^5 cm^{-3} [6].

Other effects could be of importance as well. Firstly residual species, e.g. water vapor, on the target's surface could influence the discharge in an early stage. For this reason dry gas flow is applied to the crystal for ten minutes prior to measurements. Secondly the He/air mixing could be slightly modified because of a limited gas heating [21]. However since the very weak jet source used in this work limits strongly the gas heating, the memory effect is more likely to be the reason for the observed transition from branching to guided surface discharges. Though a great number of cycles is needed for this transition it is expected that the transition is much faster for volume discharges.

After a transition occurs to a repetitive discharge (after 0.72 s—figure 2(e)), an averaging of measurements can be made to suppress noise, see figure 3(a). The electric field generated by surface charges of 1.5–2 mm in length is measured, together with a background signal that has emerged simultaneously with the initialization of the plasma jet.

Figure 3. Figure (a) shows the average electric field (kV cm^{-1}) measured throughout one AC—period of $33 \mu\text{s}$ after initialization obtained using figure 2. Without the induced field of deposited charge by the impinging ionization wave, the background structure is observed, see figure (b). As such the values need to be corrected to obtain the true field induced by the surface charge.

This *quadrupole/bow-tie* shaped background signal does not change throughout any experiments and is not reported in literature that uses the Pockels effect for surface discharge measurements [17, 22, 23]. Those reports have used a pulsed light source instead of a continuously operated diode as is used

Figure 4. Voltage–current characteristics and the electric field (kV cm^{-1}) throughout one AC—period, without the background signal by subtracting the image from $\tau = 34 \mu\text{s}$. Fifty exposures of $1 \mu\text{s}$ are taken at varying delays triggered on the current peak, when a voltage is applied of 1.5 kV and the target distance is 5 mm . A highly periodic charging and discharging at the surface of the crystal is observed inducing the electric field changes. The voltage changes polarity at $\tau_d = 13.8 \mu\text{s}$, which initiates the (back) discharge removing the deposited charge by recombination. (a) Voltage–current characteristics, (b) $\tau_d = 2 \mu\text{s}$, (c) $\tau_d = 3 \mu\text{s}$, (d) $\tau_d = 5 \dots 11 \mu\text{s}$, (e) $\tau_d = 12 \mu\text{s}$, (f) $\tau_d = 13 \mu\text{s}$, (g) $\tau_d = 14 \mu\text{s}$, (h) $\tau_d = 15 \mu\text{s}$, (i) $\tau_d = 16 \mu\text{s}$, (j) $\tau_d = 17 \mu\text{s}$, (k) $\tau_d = 18 \mu\text{s}$, (l) $\tau_d = 19 \mu\text{s}$, (m) $\tau_d = 20 \mu\text{s}$, (n) $\tau_d = 21 \mu\text{s}$, (o) $\tau_d = 22 \dots 33 \mu\text{s}$.

in this research. This suggests the background signal could be induced by a photo current generated by the radiant power of light, interacting with the field generated by the plasma jet.

As such the background field shown in figure 3(b) could be falsely presented as electric field if another effect causes the polarization of incident light to change. The background field

is not induced directly by the voltage applied to the jet, since it is not observed when voltage is applied without gas flow. Figure 3(b) shows the background signal when the induced effect of the deposited charge by the ionization waves is not present.

Contrary to the spot induced by surface charge, the background signal does not change throughout one AC—period. By taking exposures of 1 μs instead of 33 μs changes in the spot caused by the plasma jet are examined throughout one AC—period. Though a quasi steady state was observed before, now the effect of the transient behaviour of the guided ionization waves becomes visible, see figure 4. Multiple exposures are averaged for each delay, which is varied from 1 to 34 μs . Again the jet impinges the crystal at 45 degrees and it is positioned on the left hand side in the images shown, pointing to the right. At the impact point helium/air mixing flows to the right as indicated.

The iCCD—camera is triggered on the current peak, figure 4(a), resulted from the accumulation of charge beneath the ground. As the exposure time is 1 μs , the first image at $\tau_d = 2 \mu\text{s}$ includes the moment of impact of the guided ionization wave, observed in figure 4(a) at $\tau = 2.95 \mu\text{s}$. The applied voltage changes polarity at $\tau_d = 13.8 \mu\text{s}$. Electric field values shown in figure 4 are obtained by subtraction with the electric field measured at a delay of 34 μs , to omit the stationary background signal and only get the changes throughout one period. The stationary background signal is visualized in figure 3(b). An applied voltage of 1.5 kV is used and the distance to the target is 5 mm. Electric field values are shown as negative, meaning opposite to the propagation direction of the incident light. The surface charge deposited by the ionization waves is positive. This is concluded after comparing with the electric field when voltage is applied to the crystal directly.

One period of a highly periodic charging and discharging at the surface of the crystal is observed in figure 4. The moment when the guided ionization wave reaches the crystal, charge is deposited and constant electric fields are generated for approximately 14 μs . Additional electric field is measured from charge deposited by an extended discharge behind the spot where the guided ionization wave reaches the crystal. The disappearance of charge at the surface, and as such the measured electric field, is initiated when the voltage changes polarity. A (back) discharge removes the deposited charge most likely through recombination, which takes approximately 5 μs and relates well with a weak afterglow reported by Guaitella *et al* [9]. In their parametric study also the shape of the discharge at the crystal is of interest. In general, the discharge forms either a single spot at the surface where the jet impinges the target or an extending discharge is present behind the spot propagating along the surface, as is measured in this study.

Similar time-resolved imaging based on the Pockels effect is done by Wild *et al* [17], for surface charge measurements. They observed positive charging at the crystal during the positive half period and negative charging during the negative half period. However with the jet configuration used in this research, ionization waves are only generated during the positive half period. For many applications it is important to know if this would cause a long-lived accumulation of

charge at the surface, since there is no production of negative surface charge to counteract this. However figure 4 shows that this is not the case. At the moment the voltage polarity changes, a (back) discharge originating from the surface of the crystal is initiated and charge is removed. This indicates that a conductive channel has to be present between the powered electrode and the crystal, for the change of polarity to have this effect.

Maximum electric field values measured are between 3–5 kV cm^{-1} , which is lower than measured by Sretenović [11] and several numerical models [12–14]. However those models and experiments obtain values within the plasma plume without a target, while this research measures electric fields in a target due to deposited charge by a guided ionization wave. Since an average is obtained throughout the thickness of the crystal and the spot size is of similar size, the electric field inside the crystal is expected to decrease. As such the electric field value at the surface of the crystal will be higher, as indicated by the work done by Mu *et al* [24] and Norberg *et al* [25]. This however has to be investigated further.

Concluding, time resolved investigation is done of the transient behaviour of branching and guided ionization waves at a surface. By using a Pockels diagnostic, electric fields are measured in an electro-optic crystal targeted by an 30 kHz operated atmospheric pressure plasma jet. During the initialization of the jet, a clear transition is observed from branching to guided streamer at the crystal's surface. Most likely this is due to the build-up of species created in previous discharges. After this transition a quasi steady state is observed, causing the typical reproducibility of guided ionization waves. During the applied AC—period a highly periodic charging and discharging at the surface of the crystal is observed, related with fast optical imaging [9] and current—voltage waveforms. The charging is caused by the impact of the guided ionization wave and the discharging by the change of polarity of the applied voltage. This distinctively characterizes this jet-configuration, since with other jet-configurations additional negative ionization waves can be produced, thus removing the deposited positive surface charge in a different manner.

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