Dynamics of a pulsed negative nanosecond discharge on water surface and comparison with the positive discharge

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Keywords: nanosecond discharge, plasma in contact with water, time-resolved imaging, ionization wave

Abstract
The fundamental physics underlying non-thermal plasmas produced by pulsed discharges at atmospheric pressure is of great interest, especially considering the technological and environmental applications of these plasmas. Discharge dynamics is highly dependent on experimental conditions, such as the propagation medium and the voltage polarity. Herein, we investigate pulsed nanosecond discharges produced by a negatively polarized voltage in a medium of air in-contact with water.

Electrical and optical characterization of the discharges is achieved using the appropriate probes and ultrafast imaging, respectively. The time-integrated images are acquired under varying conditions of applied voltage, and the discharge emission is shown to be a homogeneous disk at voltages between $-4$ and $-15$ kV. When the voltage is increased (absolute value) beyond $-15$ kV, the homogeneous emission is superimposed with filaments. The temporal evolution of the discharge emission (1 ns integration time) shows that it remains homogeneous and has a ring-like ionization front. At higher voltages and during the falling period, the discharge reignites as filaments that significantly elongate and decrease in intensity until extinguishment. A comparison of discharge emissions obtained at positive and negative polarities indicates that the features of both may be controlled by manipulating the space charge formation dynamics.

1. Introduction

Streamers are one of the most studied discharge modes in plasma physics. Loeb, Raether, and Meek were the first researchers to investigate the physical processes implicated in streamer development [1–4]. Their works were published in the early 1950s, and they indicate that streamers develop via two main processes: photoinitiation and space charge formation [5–7]. Since then, technological advancements in the fields of fast pulsed power supplies and fast detection techniques (e.g. ultrafast and cameras with high sensitivity), have facilitated the characterization of streamer dynamics and properties under various experimental conditions [8].

Streamer discharges are generally compared to small-scale lightning [9–11], and they are considered a transient phase between electron avalanche and spark [12, 13]. Therefore, they have been extensively investigated on a fundamental level, using both, experimental [14–19] and theoretical [20–25] techniques. The influence of various parameters (pressure, gas composition, temperature, electrode geometry, field homogeneity, etc) on the propagation dynamics and physical properties of streamers has also been reported [8]. In addition to the fundamental investigations, researchers are highly interested in the technological applications of streamers, particularly considering their favorable properties of low temperature [26], high density of charged species and radicals [27], and intense electric field [28]. So far, streamer discharges have been applied in the fields of medicine [29], liquid treatment [30], ozone generation [31], and material processing [32–34].

At first, streamers were mainly investigated in gaseous medium. However, since the early 2000s, many studies have focused on analyzing the propagation and dynamics of these discharges in liquids [35–37], particularly water [38–41]. Although the discharge ignition mechanisms in gases and liquids are different, the
propagation dynamics in these two media are rather comparable, as it is based on space charge formation and photoionization. However, it should be noted that despite their similarity, the importance of streamer propagation mechanisms (e.g. speed, density, pressure, etc) in different media are relatively different [42–44]. Lately, researchers have studied a hybrid configuration of streamer propagation that occurs at the gas-liquid interface. In general, there are two kind of gas-liquid interfaces: dynamic and stationary. The former is encountered when plasmas are generated inside bubbles that are freely moving in liquid [45–48]. Meanwhile, the latter represents the standard case of a steady state liquid exposed to a plasma environment [30, 49–51]. Note that plasmas can be coupled to a liquid directly (the liquid is considered to be an electrode, anode or cathode, in the system) or indirectly (the plasma is produced independently of the liquid, but interacts with it, like in a plasma jet). In this study, we analyze directly coupled plasmas that are generated at the stationary interface of air-water.

To characterize the interactions of streamers or plasmas with water, researchers typically rely on the analysis of plasma properties and dynamics at water surface. Depending on the discharge conditions (continuous or pulsed DC, AC, gas composition, etc), various emission structures at the water surface have been observed, including dots, rings, discs, and filaments [49, 52–55]. The fundamental analysis of these emission patterns is of great importance due to their effect on the local production and transport of reactive species [56–59]. Although the mechanisms involved in the structuration process are still not well understood, it has been proposed that oxygen species [52], injected power [54, 55], water polarity [30, 49], and other water properties (composition, acidity, conductivity…) [60] play a crucial role in this process.

Previously, we had studied the temporal evolution of a positive polarity discharge at the water surface [61]. Using 1 ns time resolved imaging, we had shown that initially, the discharge takes the shape of a disk (~1 mm diameter); however, after a few nanoseconds, the disk evolves into a ring, which later decomposes into dots that propagate regularly at water surface. Herein, we use the same experimental setup to investigate the dynamics of a discharge generated by negatively-polarized high voltage pulses at the surface of water. Images of the discharge are recorded at various integration times (1 ns, 10 ns, and 1.5 μs), then they are correlated to the electrical measurements. The results obtained in this study are compared to those published previously [61], and a fundamental mechanism of discharge dynamics at the nanosecond time-scale is proposed.

2. Experimental setup

Figure 1 schematically shows the experimental setup used in this study. Using a negatively-polarized pulsed power supply (NSP 120–20-N-500-TG-H, Eagle Harbor Technologies), electrical discharges were generated in air in contact with water. The pulse width and magnitude are adjustable from 50 to 500 ns and from 1 to 20 kV, respectively. The experiments were run in single mode at 500 ns pulse width; when other pulse widths are investigated, it is explicitly indicated. A tungsten rod (diameter of 2 mm from Goodfellow) with a mechanically polished tip (~10 μm curvature radius) was used as cathode, and it was mounted on a micrometer positioning system. The air-gap distance between the cathode and the water surface was adjusted to ~10 μm for all experiments conducted herein. At this distance, discharges may be produced at the water surface, with minimal influence on the plasma column above. On the other hand, the ground, a stainless-steel plate with diameter thickness of 15 mm and 6.5 mm, respectively, was placed at the bottom of a cylindrical quartz cell filled with deionized water (conductivity ~5 μS cm⁻¹).
The voltage and current of the generated discharges were measured using a high-voltage probe (P6015A from Tektronix) and a current monitor (6585 from Pearson), respectively. An oscilloscope (MSO54, 2 GHz, 6.25 GS/s from Tektronix) was used to acquire the electrical characteristics.

Dynamics of plasma emission at the water surface was monitored using an ICCD camera (PIMAX-4: 1024 EMB from Princeton Instruments). The camera was mounted at 45° angle with the vertical, and it recorded images of a 10 mm × 10 mm area on the surface. The ICCD integration time was set to 1 ns, 10 ns, or 1.5 μs, depending on the investigated phenomenon. The synchronization between the ICCD and the voltage pulse was ensured using a delay generator (Quantum Composers Plus 9518 Pulse Generator).

The electric field distribution at the water surface and around the cathode was analyzed by 2D simulation using the Comsol Multiphysics software. The simulation aims to resolve Laplace’s equation to determine the spatial distribution of the electric field. In the simulation, we considered the following parameters: water with dielectric permittivity of 80, metal cathode on which a voltage is applied, air with dielectric permittivity of 1, and a gap of 10 μm.

Figure 2(a) depicts the electric field distribution simulated at voltage of −15 kV. The figure shows a high electric field close to the cathode tip. The radial variation profiles of the electric fields generated at voltage values of −5, −10, −15, and −20 kV (Figure 2(b)) show that at near the cathode pin, the field intensity is around $10^8$–$10^{10}$ V m$^{-1}$. At the water surface and 2 mm away from the cathode pin, the field intensity decreases by four orders of magnitude.

3. Results

The voltage, current, and camera trigger waveforms of a typical discharge generated at applied voltage of $V_a = −8$ kV and pulse width of 500 ns are shown in figure 3. $V_{av}$, pre-set voltage, is slightly different from the voltage measured at the cathode. The difference between $V_a$ and the measured voltage is due to the accuracy of the pulser’s knob, there is not any physical meaning of this difference. In the following, $V_a$ was used to ensure reliability of the results. The electrical characteristics of a failed discharge (i.e. discharge OFF) are similar to those acquired for a successful discharge (i.e. discharge ON). There is no drop in the voltage waveform, but it shows only insignificant variations (figure 3 at 125–200 ns) for a successful discharge. As for the current waveforms, the displacement component (induced by temporal variations in voltage) is clearly visible. The discharge represented in figure 3 has a current peak of $∼2.5$ A; however, the value varies between $−2$ and $−25$ A, depending on $V_a$ that was varied from $−4$ to $−20$ kV.

The discharges investigated here are known to be highly stochastic, i.e. a discharge does not occur at each pulse. In addition, there is no guarantee that a discharge occurs at the same moment as another discharge, even under the same conditions. Instead, discharges may exhibit temporal delay (positive or negative), also known as jitter. Usually, the delay is very short (less than few nanoseconds). Nevertheless, it must be taken into consideration, especially when the integration time of ICCD images is in the order of 1 ns. Herein, temporal jitter was accounted for by recording the ICCD trigger signal along with the voltage and current waveforms of each discharge (figure 3), then measuring a reference time between the delay generator signal (at 0.5 V) and the...
current (at a fixed level for a given $V_a$). Using this method, the acquired ICCD images may be temporally ordered. The shortest time at which photons are first detected is denoted $t_0$ ($t_0$ is less than 1 ns).

3.1. 1.5 $\mu$s-integrated discharge emission
Morphologies of plasma emission were acquired at various $V_a$ in the range of $-5$ to $-20$ kV; the pulse width was fixed at 500 ns. The images were recorded at an integration time of 1.5 $\mu$s, longer than the pulse width, to ensure that all the emitted radiations are considered. As shown in figure 4(a), the discharge emission generated at $V_a = -5$ kV is localized at the water surface below the cathode pin and has a disk-like shape (diameter of $\sim 1.5$ mm). As the amplitude of $V_a$ is progressively increased to $-15$ kV, the plasma emission dimension increases, but the homogeneous disk-like structure is retained. Further increasing $V_a$ to $-20$ kV leads to further expansion in the disk diameter, as well as to the apparition of filamentary-like plasmas (streamers) on the contour of the disk. Figure 4(b) shows that within the tested range of $V_a$ ($-4$ to $-20$ kV), the diameter of the disk-like feature increases almost linearly from $\sim 1.5$ to $\sim 13.5$ mm, with a slope change at $V_a = -15$ kV, the voltage at which the filaments start to appear. It seems that the development of the streamers helps to further expand the ionization front of the homogeneous disk-like emission, probably due to the relatively high electric field at the streamer heads.

3.2. Discharge dynamics at 10 ns time scale
The temporal development of the discharge was studied by acquiring images at an integration time of 10 ns. Figures 5(a) and (b) show the current-voltage characteristics and the temporal evolution of the discharge
emission generated, at $V_a = -10$ kV and 500 ns of pulse width, respectively. The voltage waveforms of a failed discharge and an occurred one are very similar. As for the current waveforms, they show differences in the time period of 40–100 ns. The peak current of a successful discharge is around $-2.5$ A. The discharge emission initially has the structure of a $\sim 3$ mm-diameter localised disk with a hot spot center directly beneath the cathode (pin at 10 ns). As time goes on, the diameter of the disk increases, but its intensity decreases. By adjusting the camera delay, we scanned all the pulse (up to 1000 ns) and a reignition was not observed.

The ICCD images (10 ns-integrated) and current-voltage characteristics, recorded at $V_a = -15$ kV and 500 ns pulse width, are shown in figures 6(a) and (b), respectively. Between 50 and 200 ns, the voltage values of an occurred discharge are slightly less than those of a failed discharge. During this period, the discharge current flows through the plasma and peaks at around $-3$ A. Initially, the discharge emission (figure 6(b)) has a disk-like structure and is localized just beneath the cathode pin, as in the case of $V_a = -10$ kV. With time, the disk expands, but its intensity decreases. As for the ionization front (clear at t $\sim$50 ns), it takes the shape of a ring (see the zoom at 50 ns) up to approximately 150 ns. No emission is observed during the period of 150–830 ns; however, after 850 ns, the discharge reignites with a filamentary-like emission (see the zooms at 1030, 1060, and 1080 ns). As time goes on, the length of the filaments increases, but the global intensity of the emission decreases until it is extinguished at $\sim$1090 ns. Interestingly, a small difference is detected between the voltage waveforms of failed and occurred discharges during the period of $\sim$850–1100 ns, when plasma re-ignition occurs. During this period, a positive current $<0.5$ A is also measured.

When the applied voltage is further increased (in absolute value) to $-20$ kV (at 500 ns pulse width), new phenomena are highlighted. First, the voltage waveforms of failed and occurred discharges show variations throughout the entire pulse period (figure 7(a)). During the voltage rising period, the current peaks at around $-24$ A, then it peaks again at $-15$ A in the voltage plateau. For the specific discharge case represented in figure 7(a), the second peak occurs at $\sim$240 ns; however, for other discharges, the peak statistically moves within the plateau. A third current peak of $\sim$5 A is detected during the falling period of voltage. As for the discharge emission, it initially takes shape of a homogeneous disk whose diameter increases with time (figure 7(b)), and at t $\sim$30 ns, the ionization front is ring-like. The global emission continues to expand during the plateau period (40–200 ns); however, with time, it becomes less homogeneous, and 'fan blade' shapes start to show (see zoom at 120 ns). Between 200 and 500 ns, the discharge emission expands further, but the number and breadth of fan blades decreases. Towards the end of this period, only one or two long filaments with a diffuse head are observed (see images at 400, 460, and 480 ns). During the voltage falling period, the discharge reignites as filaments (see image at 600 ns) that significantly elongate with time before being extinguished at t $> 850$ ns.

Overall, the 10 ns-resolved images, particularly those recorded at high voltage, reveal that plasma dynamics may be divided into three stages: stage 1 - voltage rising edge, stage 2 - voltage plateau, and stage 3 - voltage falling edge. Knowing that the duration of the plateau significantly affects the characteristics of the plasma emission after discharge ignition in stage 1, we investigated this effect by acquiring images of the discharge at various pulse widths in the range of 100–500 ns ($V_a = -20$ kV, ICCD integration time $= 1.5 \mu$s). As shown in figure 8, the emission is perfectly homogenous and disk-like at 100 ns pulse width. For pulse widths between 110 and 150 ns, the disk shape of the emission is maintained; however, the diameter of this shape increases, and some fan blade
Figure 6. (a) Electrical characteristics of a typical discharge generated at \( V_a = -15 \) kV and pulse width of 500 ns. (b) 10 ns-integrated ICCD images showing the temporal evolution of the discharge emission.

Figure 7. (a) Electrical characteristics of a typical discharge generated at \( V_a = -20 \) kV. (b) 10 ns-integrated ICCD images showing the temporal evolution of the discharge emission.
structures start to appear. When the pulse width is increased between 200 and 300 ns, the emission shape begins to change, and filaments originating from the cathode pin can be detected, along with the fan blade structures. Longer pulse widths (400 and 500 ns) lead to longer and more intense filaments. Based on the recorded images, there are two types of filaments: (i) intense and long and (ii) mild and short. At 500 ns pulse width, both types can be observed, with the first type being the parent filaments, and the second type being the children filaments (see zoomed image).

3.3. Discharge dynamics at 1 ns time scale

To investigate the ignition phase of the discharge, the ICCD integration time was shortened to 1 ns, and a series of images were recorded under various conditions of applied voltage and at fixed pulse width of 500 ns. Figure 9(a) depicts the 1 ns-integrated ICCD images acquired at $V_a = -8$ kV during the first 28 ns. During the first several nanoseconds, the emission is clearly localized at the tip of the cathode, where the electric field is the highest. However, after 10 ns, plasma emission at the water surface takes the shape of a disk that expands with time. At $t > 20$ ns, the expanding disk transforms into a ring whose ionization front propagates continuously, albeit at reduced intensity, as time goes on. The expansion data (expansion radius versus time) obtained from the ICCD images can be fitted by a linear function (figure 9(b)), and the average speed of expansion is estimated to be $\sim 20 \text{ km s}^{-1}$.

At $V_a = -14$ and $-20$ kV, the emission structure and plasma dynamics are similar to those observed at $V_a = -8$ kV, as shown in the 1 ns-integrated ICCD images presented in figures 10(a) and 11(a). However, the emission disks produced at higher voltages (absolute value) are larger and more intense. The expansion data shown in figures 10(b) and 11(b) can also be linearly fitted, and the average expansion velocities at $V_a = -14$ and $-20$ kV are $\sim 37$ and $\sim 59 \text{ km s}^{-1}$, respectively.
4. Discussion and comparison with positive discharges

The temporal evolution of plasmas on the surface of water is rarely studied, and the reports available in the literature on this subject are few \[56, 62\]. Diamond \textit{et al} \[49\] and Liu \textit{et al} \[55\] have investigated the dynamics of plasma emissions created by AC-generated air discharges on water surfaces. Their results show that the emissions are filamentary during the positive half-period, and disk-like during the negative half period. Diamond \textit{et al} \[49\] have also observed that when the distance between the pin and the water surface is increased, the emission takes the shape of a ring with a disk at its center. Images recorded at 1 $\mu$s resolution show that during the negative half period, the emission is initially disk-like, then it evolves into a ring with a disk at its center, and to two concentric rings at the end of the half period. In a study on plasma streamer propagation on the surface of water, Kanazawa \textit{et al} \[62\] have shown that plasma emission produced by a pulsed positive voltage is filamentary (10 ns resolution). The filaments originate from the anode pin and propagate radially on the water surface. Very recently, we have investigated the propagation of streamers on the surface of deionized water, under pulsed positive voltage conditions \[61\]. The results obtained at 1.5 $\mu$s integration time demonstrate that the emission is filamentary (results similar to those obtained by Kanazawa \textit{et al} \[62\]). However, at 1 ns resolution, organized structures described as plasma dots are clearly shown to propagate on the surface of water, with a velocity of a few hundred kilometers per second. In figure 12, we compare the plasma emission structures of discharges produced by positive and negative high voltages (at 20 kV and various pulse widths), using the same experimental setup. At 1.5 $\mu$s-integrated images (figure 12(a)), variations between the emissions generated at different polarities are clearly shown. At 100 and 200 ns pulse widths, organized filaments appear in positive polarity, whereas a homogeneous disk appears in negative polarity. When the pulse width is increased beyond 300 ns, relatively unorganized and intense filaments start to show under both polarity conditions, and they are superimposed with the organized filaments in positive polarity, or the homogeneous disk in negative polarity. The 1 ns resolved images shown in figure 12(b) (at 20 kV and pulse width of 500 ns) demonstrate that emissions generated by positive polarity voltages take the shape of dots propagating at the speed of 100–300 km s$^{-1}$. Meanwhile, the emissions produced under negative polarity conditions are rather disk-like, and they have an ionization front that propagates at 20–60 km s$^{-1}$. The comparison between emissions generated at different

![Figure 10](image1.png)

\textbf{Figure 10.} (a) 1 ns-integrated ICCD images showing the temporal evolution of the discharge emission during the first 28 ns ($V_a = -14$ kV, 500 ns pulse width). (b) Evolution of the discharge radius as a function of time.

![Figure 11](image2.png)

\textbf{Figure 11.} (a) 1 ns-integrated ICCD images showing the temporal evolution of the discharge emission during the first 28 ns ($V_a = -20$ kV, 500 ns pulse width). (b) Evolution of the discharge radius as a function of time.
voltage polarities is of great interest as it provides an understanding of the effect of voltage polarity on emission morphology and dynamics.

In addition to the experimental studies, streamer propagation has also been investigated using theoretical simulations [21–25, 63]. Based on the available reports, positive streamers propagate faster than the negative ones due to space charge formation and the enhancement of the electric field at the head of streamers produced under positive polarity voltage conditions. Meanwhile, the propagation of negative streamers is supported by electron drift, a phenomenon that basically ‘dilutes’ electrons and suppresses field enhancement, leading to slower propagation of streamers.

In addition to plasma emission structure, voltage polarity affects the propagation velocity of the discharge. In fact, the velocity measured under positive polarity conditions is about 10 times faster than that detected under negative polarity (typically, ~300 versus ~30 km s⁻¹). Based on the 2D simulation of the electric field distribution (figure 2), the estimated electric field at the water surface zone located 2 to 3 mm away from the electrode tip is about 10⁸ V m⁻¹. This value of the electric field can be used to calculate the mobility of the plasma (μ₂) according to the following equation: μ₂ = v / E, where v is the propagation velocity and E is the magnitude of the electric field. The calculated values indicate that plasma dots produced using positive polarity voltages are 10 times more mobile than the ionization front observed under negative polarity, with μ₂⁺ and μ₂⁻ being ~3 × 10⁻⁴ and ~3 × 10⁻⁵ m² V⁻¹ s⁻¹, respectively. Comparatively, electron and ion mobilities in typical atmospheric pressure plasmas are ~μₑ = 6 – 7 × 10⁻² [64] and ~μ₁ = 2 × 10⁻⁴ m² V⁻¹ s⁻¹ [27, 65, 66], respectively. Interestingly, the mobility of positive ions in atmospheric pressure plasmas is quite similar to that of plasma dots produced under positive polarity conditions (μ₂⁺ ≈ μ₁). Further investigations are needed to provide a more comprehensive understanding of plasma dynamics on water surface at different polarities.

So far, it has been established that streamer dynamics is strongly related to the effect of local separation between positive ions and electrons in inducing the formation of space charge [67–70]. This effect is well accepted, and it describes the propagation dynamics of individual streamers. To explain the 2D propagation of plasma dots observed under positive polarity, space charge formation was also investigated herein. The qualitative descriptions illustrated in figure 13 show that as soon as a positive voltage pulse is applied, an intense electric field is generated at the anode tip, as well as at the water surface area near the anode. This electric field accelerates the transport of free electrons in air and at the water surface towards the anode pin. The strong acceleration of electrons near the pin (due to the high electric field) leads to the ionization/excitation of the medium (air–water interface) and results in plasma emission (figure 13(a)). At first, the plasma emission takes the shape of a disk, as expected. However, with time, the electrons, whose mobility is much higher than that of ions, leave the ionization medium and flow in the circuit through the anode, leaving behind the positive ions.

Figure 12. Comparison of the discharge emissions generated by positive and negative voltages: (a) 1.5 μs-integrated images at V_a = ±20 kV and different pulse widths and (b) temporal evolution of 1 ns-integrated ICCD images recorded at V_a = ±20 kV and at pulse width of 500 ns.
Although knowing the nature of ions that are produced during this step is crucial for quantitative analysis, they cannot be easily identified using conventional optical emission spectroscopy (not shown here). Therefore, advanced diagnostics and/or model are highly needed. Nevertheless, previous simulation studies, such as [71, 72], have shown that positive ions such as H$^+$, N$_2^+$, and OH$^+$ may be formed during discharges with water. At this stage, one can accept that these ions exist in the discharge and produce an additional electric field that has the same effect as the applied field, albeit at a distance a little bit further from the anode tip (figure 13(b)). As the ring-like distribution of positive ions radially expands, repulsive interactions between the ions can take place, leading to structure instabilities. Consequently, the ring breaks into small fragments that are island-like. This phenomenon is described in figure 13(b) as the initial stage of dot formation. A few nanoseconds later, each island becomes an individual plasma that produces its own space charge, which facilitates the propagation of the discharge on the water surface, away from the anode. Ultimately, the interactions between neighboring islands lead to the formation of the final individual dots (figure 13(c)).

Under negative polarity conditions, the applied electric field is initially directed towards the cathode pin, as shown in figure 14. The discharge is thus initiated by the acceleration of electrons away from the cathode pin. The positive ions that are left behind produce a space charge that competes with the applied one (figure 14(a)), which minimizes the probability of ionization front instabilities, unlike the case of positive discharges.

Figure 13. Scheme of discharge development at the water surface under positive polarity conditions: (a) discharge ignition, (b) ring distortion under space charge influence, and (c) formation and propagation of bullets.

Figure 14. Scheme of discharge development at the water surface under negative polarity conditions: (a) discharge ignition, (b), (c) discharge development under space charge influence.
Compared to the applied field, the electric field felt by the electrons at the ionization front is relatively smaller, resulting in slower electron transport. Consequently, the ionization front maintains its ring-like shape and keeps on radially propagating outward (figures 14(b), (c)). Moreover, a relatively homogeneous emission is always detected between the cathode and the ionization front, due to the presence of space charges (produced by ions that can be assumed fixed during a short time-scale) behind the latter, which keeps the medium optically active (excitation, de-excitation, ionization, etc).

The previous discussion of temporal discharge dynamics (positive and negative discharges) at the surface of water is a generalization of the 1D streamers reported in several papers. Herein, we produce 2D surface streamers using a symmetrical electric field distribution. For such streamers, in addition to consider the space charge effect produced at the head of each one, it is also crucial to consider the interactions between them. The propagation medium (water) may also play a role (e.g. molecule polarization, evaporation, etc) in the propagation mechanism. The perspective of this work is to investigate the plasma dynamics by considering the simulations of positive and negative 1D streamers, available in literature [23, 24, 73], as a starting point.

5. Conclusion

This study investigates the dynamics and electrical characteristics of pulsed nanosecond discharges generated in air at the surface of water, using a negatively polarized high voltage source. The images collected at 1.5 μs integration and various conditions of applied voltage show a homogenous disk-like emission between −4 and −15 kV. Beyond −15 kV, superimposed filaments appear on the homogenous emission. The diameter of the emission disk increases linearly with increasing applied volatge, but the slope changes at −15 kV, the voltage where filaments started to appear. At 1 ns resolution, the recorded images show a homogeneous discharge emission with a ring-like ionization front. When the applied voltage is high, fan blade structures are observed in the period of voltage plateau of the high-voltage. During the voltage falling period, the discharge reignites as emission disk increases linearly with increasing applied volatge, but the slope changes at −15 kV, the voltage where filaments started to appear. At 1 ns resolution, the recorded images show a homogeneous discharge emission with a ring-like ionization front. When the applied voltage is high, fan blade structures are observed in the period of voltage plateau of the high-voltage. During the voltage falling period, the discharge reignites as filament structures that significantly elongate with time while their intensity keeps on decreasing until extinguishment. A comparison of discharge emissions produced under positive and negative polarity conditions indicates that the dynamics is largely governed by space charge formation. The findings reported herein will be used in a simulation study that aims to identify and quantify the physical phenomena governing streamer propagation at the water surface under positive and negative polarity conditions.

Acknowledgments

The research reported in this publication was financially supported by the Natural Sciences and Engineering Research Council of Canada (NSERC), under award number RGPIN-2018-04869. The authors thank the Fonds de Recherche du Québec—Nature et Technologie (FRQ-NT) and the Canada Foundation for Innovation (CFI) for funding the research infrastructure.

Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

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