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Citation: Physics of Plasmas (1994-present) 22, 033511 (2015); doi: 10.1063/1.4914930
View online: http://dx.doi.org/10.1063/1.4914930
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Bent paths of a positive streamer and a cathode-directed spark leader in diffuse discharges preionized by runaway electrons

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(Received 19 December 2014; accepted 2 March 2015; published online 16 March 2015)

Diffuse discharges preionized by runaway electrons can produce large-area homogeneous discharges at elevated pressures, which is an intriguing phenomenon in the physics of pulsed discharges. In this paper, runaway-electron-preionized diffuse discharge (REP DD) was obtained in a wide pressure range (0.05–0.25 MPa), and under certain conditions a positive streamer and a cathode-directed spark leader could be observed to propagate at some angles to the applied (background) electric field lines. For a 16-mm gap at an air pressure of 0.08–0.1 MPa, the percentage of pulses in which such propagation is observed is about 5%–50% of their total number, and in the other pulses such bent paths could not be observed because there is even no streamer or cathode-directed spark leader in diffuse discharges. In our opinion, such propagation of the positive streamer and the cathode-directed spark leader at some angle to the background electric field lines owes to different increase rates of the electron density in different regions of the discharge volume under REP DD conditions. Therefore, during the formation of a REP DD, the increase of the electron density is inhomogeneous and non-simultaneous, resulting in an electron density gradient at the ionization wave front. © 2015 AIP Publishing LLC

[http://dx.doi.org/10.1063/1.4914930]

I. INTRODUCTION

Great attentions have been paid on the study of the streamer breakdown of the dense gases1–6 because of the complexity of the formation processes of streamers in atmospheric7–9 and laboratory discharges.10–16 Most recently, it was reported that a positive streamer could propagate at a near-right angle to background electric field lines along the trace of enhanced preionization created by a KrF excimer laser.17 In the study cited, the pulses produced by the laser had a wavelength of 248 nm and a pulse energy of ~1 mJ with a pulse duration of ~20 ns and the maximum repetition frequency of 10 Hz. The (unfocused) laser beam was shaped by four shutters to a quasi-rectangular beam. This beam propagated through a vacuum chamber filled with different nitrogen–oxygen mixtures with a tip electrode positioned 103 mm from the cathode plane. The laser beam was aligned to the symmetry plane, which included the electrode tip. The ionization density was about 8 × 10^8 cm^-3 in pure nitrogen at 0.1 MPa for the laser operated at full power, and it was too low to modify the electric field. Numerical simulation that presented in Ebert’s work confirmed their experimental observation.17

Preionization can also be provided by runaway electrons (RAEs). These electrons gain energy from the electric field in the gap. When the energy gained is larger than the lost in elastic and inelastic collisions, the electrons go into continuous acceleration or runaway mode. The RAEs are more likely to be generated in a discharge gap when a high-voltage-nanosecond-pulse is applied to an electrode with a small radius of curvature.18 Moreover, X-ray radiation would appear due to both collisions between RAEs and gas molecules, and bremsstrahlung between the dense plasma front and the metal foil.18 Generally, RAEs and X-rays are produced at the breakdown stage in the form of an ionization wave.18–23 The ionization wave propagates from the electrode with small curvature radius to the plane electrode. In the ionization wave and behind it, there is a region with high electron density, and ahead of its front, there is a region in which the electron density is comparatively low. The gas in the gap is preionized by RAEs and X-rays, resulting in the appearance of a runaway-electron-preionized diffuse discharge (REP DD).24 However, the REP DD would be transformed to a spark by increasing the gas pressure, voltage amplitude, and/or pulse duration, and by shortening the inter-electrode gap.25–28 In a REP DD in atmospheric pressure nitrogen, the electron density could reach 10^{14} cm^{-3}.29 Therefore, a positive streamer and cathode-directed spark leader may be produced in the preionized gap. In our opinion, the difference between laser preionization and RAE preionization7 is that the former could exist in the entire discharge gap at a time, while the latter is inhomogeneous and non-simultaneous in different regions of the discharge volume.

We suppose that in a REP DD, a positive streamer could also propagate nearly perpendicular to the background electric field. Therefore, the objective of our study is to...
investigate the formation of a positive streamer and cathode-directed spark leader in a REP DD to confirm the existence of their bent paths in this type of discharge.

II. TERMINOLOGY

Generally, diffuse discharges could be formed due to RAEs and X-rays without any additional ionization.21,22,24–27 We term this type of discharge a REP DD. In order to accurately describe the streamer-to-spark transition in such discharges in an inhomogeneous electric field, it is necessary to define some terminologies. In general, the plasma densities are mainly affected by the mode and conditions of a discharge, thus they are different at different breakdown stages. For a positive streamer in air and nitrogen at atmospheric pressure, the electron density could reach \(10^{14} \text{ cm}^{-3}\). The same electron density is also obtained in a REP DD under experimental conditions similar to those used in the study presented in this paper. Higher electron density could be achieved under certain conditions. For example, in nanosecond discharges in \(\text{H}_2\) at pressures of 0.1–0.3 MPa, the plasma density reached \(2 \times 10^{15}\) and \(1.6 \times 10^{16} \text{ cm}^{-3}\) in the vicinity of the cathode and in the center of the interelectrode gap, respectively.

The radiation due to the second positive system of the nitrogen molecule dominates over others in a streamer and REP DD. The radiation spectrum of a spark channel with a high electron density \((\sim 10^{17} \text{ cm}^{-3})\) and more differs from those of the streamer and REP DD. For a spark leader in nitrogen, when it partially bridges the gap, the electron density is \(10^{15}–10^{16} \text{ cm}^{-3}\) and its radiation spectrum is similar to that of the spark channel. Furthermore, wideband radiation and radiation of atoms and ions for nitrogen also appear under that situation. Thus, as to the nanosecond-pulse discharges in an inhomogeneous electric field, before a spark channel appears, a streamer or a spark leader has been formed.

As to breakdowns in a large discharge gap, there are many bright thin channels starting from the head of the leader and extinguishing at some distance from it. These bright thin channels were termed a streamer corona in Bazelyan and Raizer’s work, but we think they are actually a spark leader corona. In general, a streamer arises from an electron avalanche as it reaches a certain critical size. The streamer bridges the gap; then, a spark leader appears; and finally, the spark leader transforms into a spark channel. Therefore, the breakdown in a large discharge gap is mainly depended on the propagation of a spark leader. That is the reason for which we term those bright thin channels spark leaders, and their plasma parameters are similar to those of the spark channel.

III. EXPERIMENTAL SETUP AND MEASUREMENTS

The schematic of the experimental setup #1 is shown in Fig. 1. This setup was consisted of a RADAN-220 pulser and a discharge chamber, and it had been already used in the studies on the properties of the REP DD. The discharge chamber was filled with air or sulfur hexafluoride \((\text{SF}_6)\) with 2.5% of nitrogen. The gas pressure ranged from 0.02 MPa to 0.25 MPa. The voltage pulse produced by the RADAN-220 pulser was applied to a tubular electrode with a small curvature radius through a short transmission line. This potential electrode was made by rolling a stainless steel foil of thickness 100 \(\mu\text{m}\) into a tube of diameter 6 mm. The grounded plane electrode was at a distance of 13 or 16 mm from the lower surface of the potential electrode. The voltage pulses were measured by a capacitive divider located at the end of the transmission line. The voltage pulse duration at a matched load was \(\sim 2\) ns, and the pulse rise time in the transmission line was \(\sim 0.5\) ns. The current through the gap was measured by a shunt composed of thin-film chip resistors. The current of a supershort avalanche electron beam (SAEB) was measured by a collector located downstream of the anode made of a metal grid with a transparency of 14%, diaphragm with a 1-cm-diameter hole, and a 50–\(\mu\text{m}\)-thickness AlMg foil. The SAEB current was the current of the RAEs downstream of the anode (thin metal foil). This current was measured simultaneously with the discharge current and voltage in the gap. Images of the discharge were taken by a Sony-A100 digital camera. Electrical signals from the capacitive voltage divider, shunt, and collector were recorded by a Tektronix DPO70604 digital oscilloscope (6 GHz, 25 GS/s). The detectors were connected to the oscilloscope via RadioLab 5D-FB PEEG coaxial pulse cables with standard N-type connectors and Barth Electronics 142-NM attenuators with a bandwidth of up to 30 GHz. The integral emission spectra were recorded by an EPP-2000C spectrometer (Stellar Net Inc.). The pulse polarity was an important parameter that could influence the characteristics of the gas discharge by changing the electric field direction near the potential electrode. Experiments were performed in single pulse mode at both positive and negative polarities of the RADAN-220 pulser. For the negative polarity, negative pulses were applied to the electrode with small curvature radius (cathode). For the positive polarity, positive pulses were applied to the electrode with small curvature radius (anode).

The schematic of the experimental setup #2 is shown in Figure 2. The setup was consisted of a home-made
MPC-100L nanosecond pulser and discharge electrodes placed in atmospheric air. The output voltage had an amplitude of 0–120 kV, a rise time of \( \approx 70 \) ns, and a full width at half maximum of 130 ns. Experiments on this setup were only performed in single shot mode. The discharge was ignited in the gap between a tubular and a plane electrode. The tubular electrode was an 12-mm-diameter tube made of a 1-mm-thickness copper sheet. The plane electrode was a copper plate with a thickness of 5 mm and a diameter of 80 mm. All experiments were performed in open air. For the positive polarity, the tubular electrode was grounded and the plane electrode was connected to the output of MPC-100L. For the negative polarity, the tubular electrode was connected to the output of MPC-100 and the plane electrode was grounded. Therefore, the tubular electrode could be the cathode when it was connected to the output of MPC-100 or the anode when it was grounded. Figure 2 shows the case of the negative polarity. The voltage was measured by a homemade water resistive divider connected to the output of MPC-100L, and the division factor was \( \approx 6700 \). The current was measured by a Pearson current probe (model 4100) with a rise time of 10 ns and current-voltage ratio of 1 A/1 V. The signals were transmitted to a Tektronix DPO 2024 digital oscilloscope (1 GS/s, 200 MHz). The images were taken by a Canon EOS500D digital camera with a Tamron Lens (Model A001), which was in parallel to the discharge area and was approximately 1 m away from it.

IV. RESULTS AND DISCUSSION

A. Experiments on setup #1

In the experiments, the REP DD was formed as nanosecond voltage pulses were applied to the electrode with small curvature radius. Typical waveforms of the voltage, current through the gap, and SAEB currents at negative and positive polarities are presented in Figures 3 and 4. It could be observed from Figure 3 that the SAEB current downstream of the AlMg foil arose only when negative polarity of the voltage was applied to the electrode of with small curvature radius. Moreover, the formation of a SAEB was observed in different gases and in a wide pressure range,\(^{18,19,25}\) and it was also detected downstream of a gas diode anode made of thin metal foil. In the REP DD formed in atmospheric pressure nitrogen on the RADAN-220 pulser, the electron density reached \( 10^{14} \) cm\(^{-3} \).\(^{29}\)

Shown from Figure 4, typical waveforms of the voltage pulses and the current through the gap were obtained, but the SAEB current was failed to be measured. It was because the RAEs were difficult to be detected when the potential...
electrode was positive. When the positive polarity of the voltage was applied to the electrode with small curvature radius, the generation of RAEs took place in the region of electric field amplification and their motion toward the tubular anode was accompanied by X-ray radiation. Because of the measurement of the SAEB was conducted downstream the plate electrode (cathode), the detection of RAEs was failed, however, the detection of the X-rays radiation in the case of the positive polarity proved evidence of the existence of RAEs. Furthermore, because the RAEs were generated near the ionization wave front and moved to the anode, they failed to gain high energy and slowed down in the gas outside of the ionization wave front when the electric field was low. Therefore, the generation efficiency of the characteristic radiation was higher than that of bremsstrahlung, making the X-ray radiation usually difficult to be measured. Nevertheless, detection of X-rays was made possible by decreasing the interelectrode gap and by using a tungsten anode to enhance the electric field.21

Images of the REP DD in air and in SF6, with ~2.5% of nitrogen are shown in Figures 5 and 6, respectively. Note that not all the REP DD was formed with streamers or spark leaders. It could be observed that the REP DD with no streamer and spark leader was formed in 50%–95% of the total number of the pulses in a 16-mm air gap when the pressures ranged from 0.08 MPa to 0.1 MPa, and there are only bright spots at the tubular electrode (Figure 5(a)). The REP DD with streamers, spark leaders, and spark channels was formed only in 5%–50% of pulses. Images of the REP DD with streamers, spark leaders, and spark channels are presented in Figures 5(c)–5(f), Figures 6(b)–6(d), and Figures 7(a) and 7(b).

In order to record images in a single pulse, nitrogen was added into SF6 to increase the discharge glow intensity. Such addition was particularly important to record images of a streamer at a relatively low radiation intensity. By increasing the discharge glow intensity, it was more easily to observe the position and form of streamers and spark leaders changing from pulse to pulse. As the pressure increased, the REP DD behaved as separated diffuse jets with diameters of ~1–2 mm (Figures 6(a), 6(b), and 6(d)), which arose from the bright spots at the tubular electrode. These bright spots at the cathode with anode spark leaders, normally not reaching the anode, could be clearly seen in Figure 6(b).

When the voltage pulses with positive polarity were applied to the electrode with small curvature radius, separate diffuse jets were also observed (Figure 6(a)) and so were streamers with spark leaders (Figures 6(b)–6(d)). This evidenced the generation of RAEs and X-rays and the formation of a REP DD in the positive polarity case (Figures 6(b)–6(d)). However, the energy of RAEs and X-rays in the case of positive polarity was much lower than that in the case of negative polarity, making the SAEB current much more difficult to be measured for the positive polarity. It should be pointed out that the range of experimental conditions in which a REP DD arose for positive polarity was narrow as well as bright spots at the plane electrode and spark leaders appeared much earlier than those for negative polarity.
The interelectrode gap and gas pressure could also affect the paths of the positive streamer and the spark leader in their formation.\textsuperscript{25–28} It was shown that the path of a spark leader could bent at a right angle as it moved from track to track.\textsuperscript{28} and the electron density in the spark leader reached $\sim 10^{16}$ cm$^{-3}$.\textsuperscript{29} In our experiments, it could be seen from images of a cathode-directed spark leader (Figure 7(b)) that the distance between tracks was about 1 mm, which was more noticeable than that reported in paper.\textsuperscript{29}

Note that the formation and propagating path of streamers and spark leaders changed from pulse to pulse. In the case of negative polarity, at least 50\% of the pulses resulted in a REP DD without bright spots at the plane electrode (Figures 5(a) and 6(a)). In some other cases, positive streamers and cathode-directed spark leaders developed. On the basis of several hundreds images of different discharge formation captured under the same condition, it was possible to elucidate the features of the positive streamer formation and the cathode-directed spark leader formation. The sequence of different stages in the discharge formation was investigated by using an HSFC-PRO four-channel CCD camera when tens of kilovolts were applied.\textsuperscript{26}

Images of the discharge at different paths of a positive streamer under the same conditions are presented in Figure 5. It is seen from Figure 5(b) that early in the process, a bright spot arose at the plane electrode (anode). Then, a
positive streamer propagated from the bright spot toward the cathode (Figure 5(c)). The visible length of the streamer was \( \sim 6 \text{ mm} \) (about one-third of the gap). Finally, the streamer bridges the gap (Figures 5(d)–5(f)). The formation of a diffuse discharge due to overlapped heads of electron avalanches was also described in Ref. 37, from which we consider the diffuse channel in Figures 5(d)–5(f) is a streamer because the heads of electron avalanches from which the diffuse discharge was formed were overlapped. Furthermore, the streamer in Figures 5(c)–5(f) was positive because it propagated from the anode. It was observed that the positive streamer sometimes took a direction different from that of the background electric field lines, as shown in Figures 5(e) and 5(f). In brief, the positive streamer propagates at an angle, including a nearly right angle, to the background electric field (Figure 5(f)).

In an inhomogeneous electric field, the formation of an ionization wave propagated from electrode with small radius of curvature could lead to the breakdown of the discharge gap. The electron densities ahead and behind the ionization wave front were significantly different. The increase rate of the electron density was different in different regions of the discharge volume. Under these conditions, a positive streamer and cathode-directed spark leader might propagate at an angle to the background electric field. In our experiments, such phenomenon was normally observed once the first ionization wave crossed the gap and a diffuse discharge was formed (Figures 5–7). The electron density in the positive streamer was higher than that in the diffuse discharge, and the streamer behaved as a bright jet against the diffuse discharge glow. Therefore, as the positive streamer and cathode-directed spark leader were formed, the electron density increased nonsimultaneously with different rates in different regions of the discharge volume, resulting in an electron density gradient at the ionization wave front. As a result, the direction of the electrical field component differ from that of the background electric field, making the positive streamer and the cathode-directed spark leader in the REP DD bend their paths during the propagation. Just as Nijdam pointed out in her experimental results obtained under different conditions, “streamers prefer and follow elevated levels of electron density but cannot propagate through areas with very high electron density.”

The polarity of applied pulses plays an important role in bending the paths of streamers and spark leaders in REP DD. In our experiments, the formation of a positive streamer (Figure 6(c)) and cathode-directed spark leader (Figure 6(d)) propagating at some angle to the background electric field was observed in the case of positive polarity. The positive streamer propagating from the anode appeared in air at a pressure of 0.05 MPa and similar propagation appeared in Figures 5(e) and 5(f) under different pressures and interelectrode gaps. The propagation direction of the positive streamer greatly changed when the distance between its front and the plane electrode was about 6 mm. A cathode-directed spark leader propagated at some angle to the background electric field in SF\(_6\) with \( \sim 2.5\% \) of nitrogen at a pressure of 0.25 MPa. At the upper right corner of Figure 6(d), it could be observed that the cathode-directed spark leader even propagated in the direction to the side wall of the discharge chamber. However, in the case of negative polarity, no such bent path of the streamer channel and the spark leader was observed.

To sum up, it can be stated that the existence of bent paths of the streamers and spark leaders are possible in a REP DD in the positive polarity case. The positive streamer and cathode-directed spark leader propagate at some angle to the background electric field. However, to what degree the inhomogeneity would be adequate for such propagation at a large angle to the background electric field is still unclear, and further quantitative estimation is necessary. In the future, we expect to create a theoretical model and continue studying this interesting phenomenon in the REP DD.

B. Experiments on setup #2

Figure 8 shows typical waveforms of the voltage and current of the REP DD in a 20-mm interelectrode gap for both negative and positive polarities. In both cases, the current was \( \sim 120 \text{ A} \) and its polarity was as the same as that of the applied voltage. The current pulse width was shorter than the voltage pulse width, indicating that no spark occurred in the discharge.

Figure 9 presents images of the discharge in different gaps for both negative and positive polarities. Each image showed the discharge glow for a single shot pulse. In order to enhance the contrast, all the images are processed under the same condition by using image processing software. Diffuse discharges were observed in all images. Furthermore, diffuse channels between two electrodes and bright spots at the electrodes could also be observed in all images. Note that a weakly glowing diffuse jet appeared in Figures 9(d)–9(f) as well as a short diffuse jet from diffuse channels between two
electrodes was observed in Figures 9(a)–9(c). Their formation is closely related to the bent path of the steamer in the diffuse discharge.

V. CONCLUSION

Typical discharge images of the REP DD taken in our experiments reveal that a positive streamer and cathode-directed spark leader propagate at an angle to the background electric field lines. It could be explained by the nonsimultaneous and inhomogeneous increase in electron density during the formation of the REP DD. The increase rates of the electron density are different in different regions of the discharge volume preionized by RAEs and X-rays. Thus, an electron density gradient arises in the discharge plasma, resulting in an electrical field component whose direction differs from that of the background electric field and bent paths of the positive streamer and cathode-directed spark leader. However, such phenomenon is observed only in part of the pulses (about 5%–50% of the total number of pulses in a 16-mm air gap at a pressure of 0.08–0.1 MPa). A theoretical model of this phenomenon for further studies on the REP DD is expected in the future.

ACKNOWLEDGMENTS

This work on setup #1 was supported by the Russian Foundation for Basic Research under Contract No. 14-29-00052. The work on setup #2 was supported by the National Natural Science Foundation of China under Contract Nos. 51222701, 51207154, and 51477164 and the National Basic Research Program of China under Contract No. 2014CB239505-3.


FIG. 9. Discharge images for negative (a)–(c) and positive (d)–(f) polarity. The gap is 20 mm (a) and (d); 25 mm (b) and (e); and 40 mm (c) and (f). Air, 0.1 MPa. MPC-100L pulser.

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