Interaction of current filaments in dielectric barrier discharges with relation to surface charge distributions

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Abstract. In a planar, laterally extended dielectric barrier discharge (DBD) system operated in glow mode, a filamentary discharge is observed. The filaments tend to move laterally and hence tend to cause collisions. Thereby, usually one collision partner becomes destroyed. In this paper, the collision process and especially the preceding time period is investigated. Beside the luminescence density of the filaments, the surface charge density accumulated between the single breakdowns of the DBD is observed via an optical measurement technique based on the linear electro-optical effect (pockels effect). A ring-like substructure of the surface charge distribution of a single filament is found, which correlates to the filament interaction behaviour. Furthermore, a preferred filament distance is found, suggesting the formation of a filamentary quasi-molecule.

Contents

1. Introduction
2. Experimental set-up
3. Calibration of the charge measurement
4. Interaction of filaments
5. Discussion
6. Conclusion
Acknowledgments
References
1. Introduction

Self-organized structures in dielectric barrier discharges (DBDs) have been of increasing interest in recent years. They usually occur in laterally extended systems, i.e. if the discharge gap is much shorter than the lateral extension. Both systems with one-dimensional (1D) and 2D lateral extension become investigated [5, 8, 10]. Self-organized structures appear in numerous gases and in a wide parameter range. They become investigated in low frequency devices as well as in radio frequency discharges [1, 4]. Besides the pattern formation itself, their temporal dynamic has been investigated in the past [6, 10, 11, 13]. A generic effect found in filamentary discharges is the collision of filaments that usually ends with the destruction of one of the collision partners. However, up to now, only in few cases the mechanism of filament motion could be explained [3, 11]. Also the interaction law of the particle-like discharge filaments is not understood.

In this work, the collision process of filaments is examined in detail. It gives insight into the phenomena taking place on the level of the surface charge distribution, which is one of the basic physical quantities of DBDs. The discovered internal structure of the filament profile is correlated to the filament trajectory preceding the collision. Furthermore, the surface charge measurement system that basically was introduced in [12] has been improved in temporal resolution and signal-to-noise ratio to such an extent that it is now possible to observe the changing surface charge distribution corresponding to a dynamic discharge pattern.

To begin with, in section 2 the experimental set-up comprising the optical surface charge measurement system is presented. Section 3 reports on the calibration of the surface charge measurement. In section 4, the surface charge structure of the filaments and their annihilation process is investigated and is discussed in section 5. Finally, the main results are concluded in section 6.

2. Experimental set-up

The discharge cell used in the experiment is sketched in figure 1. On the right-hand side the metal electrode is shown. It is polished so that it also acts as an optical mirror. It is covered with a BSO (Bi12SiO20) crystal with the thickness $d_{BSO} = 0.7$ mm that acts both as a dielectric barrier and the surface charge detector. An insulating spacer defines a discharge gap of thickness $d = 0.8$ mm. The counter electrode consists of a glass plate that is coated all around with indium tin oxide (ITO) and so is electrically conductive and transparent. Hence, the discharge can be observed along the current direction. The diameter of the discharge gap is $D = 40$ mm. Thus, the discharge cell has an extremely large aspect ratio that facilitates the formation of lateral self-organized structures in the discharge. The working gas in the discharge cell is helium at a pressure of $p = 100$ hPa. The discharge cell is driven by a sinusoidal voltage with the amplitude $\hat{U} = 100$–500 V and a frequency of $f = 100$ kHz.

To measure the surface charges accumulated on the dielectric barrier the linear electro-optic effect (pockels effect) of the BSO crystal is utilized. The crystal becomes birefringent in the electric field caused by the electric charges on its surface. The optical set-up to detect the surface charge density is shown in figure 2. The light from a red LED with a wavelength of $\lambda = 634$ nm is prepared to form a homogeneous, linear polarized beam. The beam is expanded by $f_1$ and $f_2$ to illuminate the whole discharge cell. The metal electrode acts as an optical mirror and reflects the incident light. Thus, the light beam passes the BSO crystal twice. The $\lambda/8$ retardation plate
**Figure 1.** Sketch of the discharge cell. A metal electrode is covered by a BSO crystal as dielectric barrier. An insulating spacer defines the discharge gap. The transparent counter electrode consists of a glass plate covered all around with ITO. The discharge is observed in current direction.

**Figure 2.** The light emitted by the LED is prepared to form a homogeneous liner polarized beam that becomes widened by $f_1$ and $f_2$ to illuminate the whole discharge cell. The reflected light passes an analyser and a bandpass filter rejecting all light not originating from the LED. Camera 1 records the resulting charge image. Camera 2 captures the emitted light from the discharge itself.

that also is passed twice causes the reflected light beam to be circular polarized. Additional retardation caused by the BSO crystal changes the polarization to be elliptical. The reflected light is coupled out with a beam splitter and passes an analyser which is perpendicular to the polarizer. The optical bandpass filter rejects the light spectrum outside the emission spectrum of the LED. Camera 1 captures the surface charge measurement signal. Camera 2, which is synchronized to camera 1, records via a mirror the light emitted by the discharge itself.

To calculate the surface charge on the BSO crystal from the image of camera 1, a reference image must be taken with no wall charges on the BSO surface before the actual measurement.
Figure 3. Timing of the LED light pulse. Both the sinusoidal driving voltage and the real current through the discharge are shown. The grey shaded areas depict the time slots when the LED is switched on.

The surface charge density $\sigma(x, y)$ then is given by

$$\sigma(x, y) = \left[ \frac{I(x, y)}{I_r(x, y)} - 1 \right] \frac{1}{2k} \varepsilon_0 \varepsilon_{BSO} a_{BSO}$$

with

$$k = \frac{2\pi}{\lambda} n_0^3 r_{41}.$$

$I_r(x, y)$ and $I(x, y)$ are the luminescence distributions of the reference image and the actual measurement image, respectively. $\lambda$ is the wavelength of the LED. The manufacturer of the BSO crystal specifies the permittivity $\varepsilon_{BSO}$ with 56, the refractive index $n_0$ with 2.54, and the electro-optic constant $r_{41}$ with 5 pm V$^{-1}$. However, it is known that the actual electro-optic effect can differ from the literature value significantly [7]. Therefore, a calibration measurement was performed that will be described later.

Beside the charges on the surface of the BSO crystal, the applied voltage to the electrodes affects the electric field within the crystal. So the actual charge measurement must take place when the applied driving voltage vanishes, i.e. in the zeros of the sinusoidal driving voltage. Moreover, the surface of the BSO crystal is covered alternately with positive and negative charge after each half-cycle of the driving voltage. As the exposure time of one camera frame lasts several hundred driver periods, care must be taken to avoid mixing up the surface charge distributions after the positive and the negative half-cycle. For these reasons, the LED is periodically switched on and off as shown in figure 3. Both the sinusoidal driving voltage and the real current through the discharge are shown. As there is exactly one current peak per half-cycle, the discharge operates in glow mode. The grey shaded areas depict the time intervals when the LED is switched on. In the example shown in figure 3, the LED is switched on after each negative half-cycle, i.e. the surface charge distribution caused by the negative breakdown is measured. By shifting the on-time of the LED by 180° the surface charge distribution of the positive half-cycle can be captured.

The frame rate of the cameras is 500 fps. The exposure time of camera 1 is 2 ms, hence every frame averages over 200 breakdowns in the discharge. The frame rate of camera 2 capturing the emitted light by the discharge is synchronized to camera 1, but the exposure time of camera 1 is only 200 µs, hence it averages over 20 cycles of the driving voltage.
camera resolutions are 600 × 800 pixels at 12 bit for camera 1 and 256 × 240 pixels at 8 bit for camera 2.

3. Calibration of the charge measurement

As mentioned earlier, the sensitivity of the BSO crystal has to be calibrated. Therefore, the discharge cell is filled with helium at atmospheric pressure to prevent a breakdown, and different sinusoidal driving voltages are applied. For the calibration measurement, the LED is switched on during the peak value of the driving voltage. Then, the charge on the capacity formed by the BSO crystal is determined optically. The charge integrated over the entire BSO crystal for different voltages is shown in figure 4 with points. The straight line depicts the linear fit of the measured values. The dashed line shows the expected capacity that results from the series connection of the crystal capacity and the gas gap capacity. The linear behaviour of the charge measurement system is validated very well, the actual proportionality coefficient given by the linear fit is $12.8 \pm 0.17 \text{ pC V}^{-1}$ and differs only slightly from the expected value of $13.7 \text{ pC V}^{-1}$.

In the following measurements, the surface charge density is corrected by the factor $13.7/12.8$.

The lateral homogeneity of the charge measurement has been checked, too. Therefore, the charge distribution was recorded once prior and once past a discharge experiment. The charge recording prior to a discharge is shown in figure 5(a). As expected, except from noise the charge density is zero. A profile across the discharge area from $x, y = 0 \text{ mm, 0 mm to } x, y = 40 \text{ mm, 40 mm}$ is shown in figure 6(a). The charge recording captured after a discharge has taken place is shown in figure 5(b). Besides some residual charges, no distinct structure in the charge distribution is expected. However, near the border, a cross-like disturbance of the surface charge distribution can be seen. The corresponding profile in figure 6(b) shows a significant deviation at the edge of the discharge area. It could be shown that the shape of the deviation evolving during a measurement is always the same and is the result of thermally induced mechanical stress,
Figure 5. Homogeneity of the charge distribution (a) before a measurement and (b) after a measurement. The emerging deformation is due to thermally induced mechanical stress of the crystal.

Figure 6. Profile of the homogeneity measurements in figure 5 from $x, y = 0 \text{ mm}, 0 \text{ mm}$ to $x, y = 40 \text{ mm}, 40 \text{ mm}$, both before the discharge (a, shifted upwards) and afterwards (b). Close to the border of the discharge area a significant distortion of the charge measurement occurs.

presumably caused by a rising tension in the BSO crystal mount. As the arising disturbance is, except from the edge of the cell, small compared to the observed patterns in the gas discharge it can be tolerated during the measurement.

4. Interaction of filaments

In figure 7, a typical self-organized pattern in the discharge is shown. The upper row shows the emitted light from the discharge as it can be seen with the bare eye. The two images were captured in the same recording with a time interval of 1.3 s between them. The edges of the discharge area are truncated by the camera. The corresponding surface charge distributions are
shown in the lower row of figure 7. The phase of the LED trigger was switched between the two recordings, so for the left pattern the discharge distribution after the negative half-cycle of the driving voltage was captured and for the right pattern after the positive half-cycle. As can be seen, the surface charge distribution in the zero of the driving voltage is basically an image of the preceding breakdown.

Most of the time, the pattern is stable and exhibits little dynamics, but from time to time filaments start to move and eventually collide with a neighbour, resulting in the annihilation of one of the collision partners. Remarkably, the annihilation takes place before the filaments visibly touch each other. At the height of $y = 30$ mm on the very right in the images is a filament that appears in the left column of figure 7 and has vanished in the right column which was captured later. These annihilation processes shall be investigated in this article.

To begin with, the surface charge distribution is examined in detail. For that purpose, the radial profile of a filament is computed. In figure 8, for both the luminescence density and the surface charge distribution radial profiles are shown. The profiles are averaged over all filaments shown in figures 7(a) and (b), respectively. The luminescence densities in figures 8(a) and (b) differ just in the time of their capture. Thus, they both look the same, i.e. they have a Gaussian shape with the same height and width. For later comparison, the width of the filament shall be defined as the width at a third of the height; this value usually is a good threshold to separate the filament from the background noise and corresponds well to the perceived width by the eye. The so defined width of the luminescence density is $w_{ld} = 2.1$ mm in both cases.

For the sake of clarity, the radial profile for the negative surface charge distribution seen in figure 8(a) is plotted with a reversed ordinate. The core of the surface charge distribution in

Figure 7. Self-organized patterns in the discharge (upper row) and corresponding surface charge distributions (lower row). The surface charge measurement was once triggered after the negative (left) and once after the positive (right) half-cycle of the driving voltage. The voltage amplitude is $\hat{U} = 285$ V.
Figure 8. Radial profiles of luminescence density and surface charge distribution of an average filament. The profiles are averaged over all filaments in figure 7(a) and (b), respectively.

The centre of the filament is significantly broader than the luminescence density but ends with a steeper edge. Remarkably, there is a small second maximum in the radial charge distribution, i.e. an additional ring of negative charge surrounds the filament core. This ring structure shall be used to define two characteristic widths, once the width $w_{\text{min}}$ defined by the charge minimum, and second the width $w_{\text{max}}$ defined by the charge maximum of the ring structure. The values resulting from the negative charge distribution are $w_{\text{min}} = 2.9$ mm and $w_{\text{max}} = 3.4$ mm.

The radial distribution of the positive surface charge distribution, shown in figure 8(b), has a shape roughly similar to the luminescence distribution. The most obvious deviation is a hump at the outer side of the filament. As a distinctive mark it shall define the width of the positive surface charge distribution, though the exact position is somewhat arbitrary. The position of the hump read from figure 8(b) yields to a width of the positive surface charge distribution of $w_{\text{pos}} = 2.6$ mm.

In the next step, the dynamic of a collision process of two filaments is regarded in detail. Figure 9 shows the evolution of the distance of two filaments during a collision process. In the beginning, the filaments have a distance of 4.4 mm from each other. During the first 400 ms of the observation, the filaments slowly approach to each other. Then, the filaments accelerate and at about 700 ms they rest at a distance of approximately 3 mm. About 100 ms later, the dynamic starts again, and when the filament distance falls below approximately 2.5 mm one of the collision partners is destroyed.

5. Discussion

To relate the pre-collisional dynamic to the filament shape, the characteristic filament widths from figure 8 are marked in figure 9. The first obvious finding that was already assumed from the pure visual observation is that the actual interaction distance is significantly larger than the width $w_{\text{id}}$ defined by the luminescence density. Instead, the width $w_{\text{pos}}$ defined in the positive charge distribution fits well to the collisional distance. To understand the relevance of the surface charge distribution, one has to remember the ignition mechanism of a single breakdown [10]. In the beginning of the ignition process, the surface charge distribution originating from the
preceding breakdown increases the electric field in the gas gap at the position of a filament; hence, the ignition starts at the same place that was covered by a filament in the previous breakdown. During the further evolution of the breakdown, the volume charges focus the current density into the filament centre and thus prevent the surrounding from ignition. If the surface charge regions of two filaments overlap to a certain extent, a common ignition takes place. The mentioned focusing effect of the volume charges restricts the growth of the ignited area, and so only one filament can evolve. Of course, this is a purely qualitative explanation that cannot explain the exact value of the annihilation distance; to gain quantitative predictions of the annihilation distance, corresponding numeric simulations will be necessary.

The width $w_{\text{min}}$ defined by the minimum of the negative surface charge distribution coincides with the rest position the filaments occupy before the annihilation process. To understand the relative stability of this distance the overlap of the radial charge distributions at that distance is shown in figure 10. The dashed and the dotted line both are a copy of the radial charge profile from figure 8(a), placed at the distance of $w_{\text{min}}$ from each other. The surface charge minima of the filaments coincide, and the charge ring, as it would appear for a single filament, lies within the charge core of the other filament and hence supports it. Of course, the actual surface charge distribution is not a simple superposition of two single filaments. Therefore, the real charge distribution profile for the intermediate rest position is shown for comparison as a solid line in figure 10. As can be seen, the ring structure is not developed any more at the point of junction of the filaments.

The distance $w_{\text{max}}$, defined by the maximum of the negative surface charge distribution, seems to be only vaguely connected to the trajectory of the filaments. The filament crosses this distance during the fast approaching process before the filaments reach their temporary rest position. A rather speculative assumption is that $w_{\text{max}}$ marks the turning point of the fast approaching process. That would suggest that the distance $w_{\text{max}}$ corresponds to an unstable distance of two filaments.
Figure 10. Charge profile in the intermediate rest position. The dashed and dotted curves both show the radial profile of the negative surface charge from figure 8(a) with a distance of $w_{\text{min}} = 2.9$ mm from each other. The solid line shows the actual surface charge profile averaged over 50 frames (100 ms).

6. Conclusion

In this paper, self-organized lateral structures in a glow-mode dielectric barrier discharge system are investigated. Besides the observation of the structures via their emitted light, an optical surface charge measurement system using the pockels effect is applied. This measurement technique that has been introduced in this experiment in [12] has been improved in temporal resolution and signal-to-noise ratio. Thus, it became possible to observe dynamic processes in the patterned discharge. In calibration measurements, the linearity and the sensitivity of the charge measurement could be verified.

For the first time it is possible to observe the dynamics of self-organized structures in a DBD along with the corresponding variation of the surface charge distribution. The dynamical process observed in this work is the filament collision with subsequent annihilation of one of the collision partners. While approaching, the filaments enter a distinct, obviously stable distance and rest there for several milliseconds. Regarding the filaments as solitary, particle-like structures the compound state in the rest position can be interpreted as a quasi-molecule, as it was suggested in earlier works [9, 13].

The surface charge pattern connected to a current filament is found to consist of different substructures. After the breakdown, the negative surface charge being formed on the anode comprises a strong core charge density surrounded by a weak charge ring. In contrast, the counter part on the cathode consist of a continuous positive surface charge distribution. In the radial profile of the surface charge distributions and the emitted luminescence distribution of a filament several distinctive filament radii (or diameters) can be defined. They can be related to distinctive distances of two filaments during the approaching process. Especially the distance of the above mentioned rest position and the annihilation distance can be identified.

These findings supplement the recent investigation of glow-like short-gap filaments that mainly focus on volume processes in the breakdown [2, 10, 14]. Furthermore, the experimental findings concerning the collisional process and their coincidence with the filament profile are important input for future theoretical investigations to clarify the interaction mechanisms.
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