CONTROLLING INCEPTION AND BREAKDOWN CHARACTERISTICS IN PULSED DIELECTRIC BARRIER DISCHARGES WITH VARIABLE PULSE WIDTH - INFLUENCE OF THE PRE-PHASE

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ABSTRACT

The pre-phase before the breakdown of pulsed dielectric barrier discharges (DBDs) is investigated. For this purpose fast optical and electrical measurements were performed on symmetrical DBDs with 1 mm gap in a gas mixture of 0.1 vol% O_2 in N_2 at atmospheric pressure. A temporally limited diffuse emission previous to the breakdown of the subsequent discharge was observed near the anode. This isolated emission is correlated with a space charge which leads to a shift of the inception point of the cathode directed ionization front (positive streamer). The appearance of this emission in the pre-phase has significant consequences on the discharge properties such as the spatio-temporal structure of the discharge emission and on the duration and amplitude of the electrical discharge current. The experimental results are compared with one-dimensional fluid simulations and indicate that the pre-ionisation and generation of electrons in the volume can be the main reasons.

1. INTRODUCTION

There is an increasing interest in dielectric barrier discharges (DBDs) at atmospheric pressure for technological applications. Due to their ability to generate non-thermal plasmas with low gas temperature and high electron energy, they can efficiently produce active species which are needed e.g. for air purification or ozone generation [1].
One question of interest is the role of memory processes for the inception and development of the discharge. The behaviour of a DBD in general is supposed to be strongly influenced by the processes in the so-called pre-breakdown phase [2]. In a pulsed driven DBD the duration of this pre-phase is limited by the rise time of the HV pulse (in our case $\approx 50\,\mathrm{ns}$). The pulsed operation offers the duty cycle (pulse width) as an additional electrical operation parameter besides the voltage amplitude and the pulse repetition frequency [3, 4]. In this context pulse width does not mean the duration of the discharge itself but the delay to the previous one. Therefore two different delays are possible, one given by the repetition frequency and one by the pulse width.
In this study we analyse the influence of the pulse width on the pre-phase and its consequences for the following breakdown of pulsed driven DBDs at atmospheric pressure.

2. EXPERIMENTAL SETUP

A symmetric double-sided dielectric barrier discharge arrangement is used for the investigation as shown in figure 1. It consists of a Plexiglas gas cell including half-sphere alumina (Al_2O_3, $\varepsilon \approx 9$) covered stainless steel electrodes.

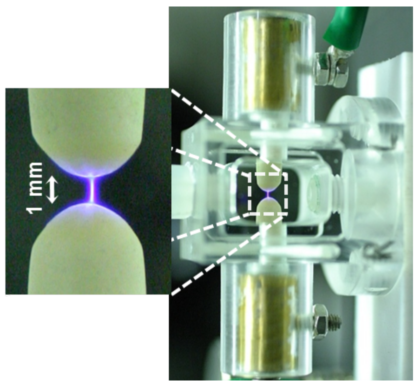

Fig. 1: *Photograph of the discharge cell with a spatially fixed filament (in this case around 1000 subsequent DBDs) between the alumina covered electrodes in detail.*

The discharge gap between the electrodes is 1 mm while the dielectric barrier thickness is about 0.5 mm. The gas mixture of 0.1 vol% O_2 in N_2 is flowing through the cell with a total flow of 100 sccm at atmospheric pressure.

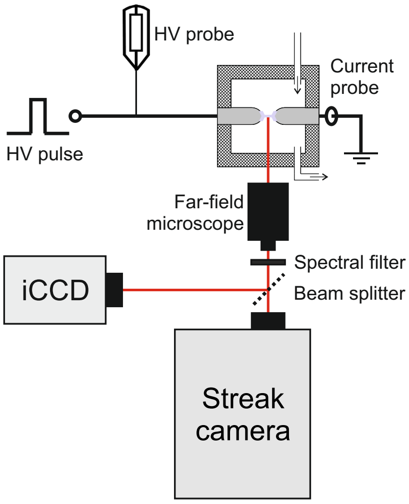

Fig. 2: *Scheme of the set-up including the diagnostics.*

The DBD is driven by positive unipolar square wave pulses with 10 kV amplitude at a repetition frequency of 10 kHz (i.e. 100 µs period, see figure 3 (a)). The pulse width is varied from 50 µs (symmetrical pulse) to 1 µs. The steepness of the rising and falling slopes of the high voltage pulses is about 250 V/ns specified by the pulse generator (DEI, PVX-4110). The DBDs are observed simultaneously by a fast iCCD camera and a streak camera system connected to a far-field microscope (Questar, QM100), see figure 2. With the iCCD camera (Andor, iStar, $\Delta t \geq 2$ ns, $\Delta x \approx 2$ µm) it is possible to record high resolution pictures of single as well as accumulated DBDs and their propagation on the electrode surfaces. The streak camera system (Hamamatsu, C5680) delivers the spatio-temporal discharge development along the discharge axis during rising and falling slopes of the high voltage pulse with high temporal ($\Delta t \geq 50$ ps) and spatial resolution ($\Delta x \approx 2$ µm). The cameras are sensitive in the visible and UV spectral range. For the spectral resolution of the second positive system of N_2 (0-0 transition) an interference filter (Melles-Griot, CWL 337.1 nm, 3 nm bandwidth) is inserted in the optical path.
Electrical measurements are performed with fast voltage (Tektronix, P6015A) and current probes (Tektronix, CT-1) and recorded with a digital phosphor oscilloscope (Tektronix, DPO 7254C).

3. RESULTS AND DISCUSSION

As shown exemplarily in figure 3 (a) for 10 µs pulse width the pulsed operation leads to a single DBD (also referred to as microdischarge) at the rising and one at the falling slope, respectively. For a symmetrical pulse, i.e. 50 µs pulse width, the DBDs on both slopes show the same behaviour [3]. For pulse widths shorter than 50 µs, i.e. an asymmetrical pulse, there are different times between subsequent discharges in the slopes (e.g. 10 µs and 90 µs, see figure 3 (a)). Reducing the pulse width has significant consequences on the electrical current waveforms of the DBDs in the falling slope like a lower amplitude (e.g. for 10 µs) or the complete blurring of the current pulse (e.g. for 1 µs pulse width), see figure 3 (b). This is discussed in more detail in [3, 4].

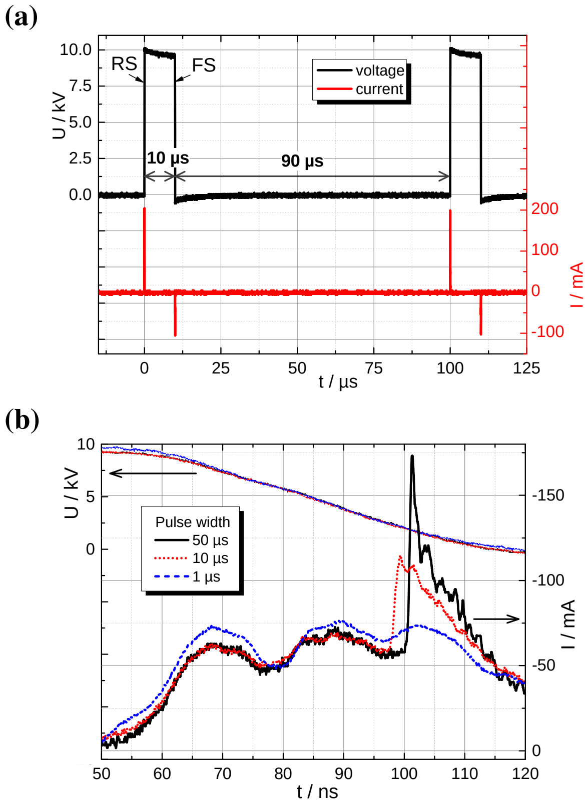

Fig. 3: ***(a)*** *Voltage and current waveforms exemplarily for a HV pulse with 10 µs pulse width (10 µs between rising and falling slope (indicated as RS and FS, respectively) and 90 µs between FS and RS).*
(b) *Voltage and measured total current (without displacement current subtraction) in detail at the falling slope for different pulse widths.*

In figure 4 the two-dimensional (2D) structure and spatio-temporal development of the emission of the 0-0 transition of the second positive system (SPS) of N_2 by means of spectrally resolved iCCD and streak camera images are shown exemplarily for both slopes of the 10 µs pulse. The 2D structure is featured by a constricted channel in the volume which is broadening towards the anode and branches on the surface of the electrodes. There is a zone of lower emission in front of the cathode which is more extended for the DBD in the rising slope.

The streak camera images reveal the spatio-temporal development along the axis of the DBD channel. The position of the dielectric surfaces is indicated by white solid lines in figure 4. An accelerated propagation towards the cathode (positive streamer) followed by a transient glow in the gap can be observed. The propagation velocity is higher for the DBD in the rising slope but the discharge duration is shorter than for the DBD in the falling slope. There is a different breakdown regime with the simultaneous presence of cathode and anode directed propagation in the falling slope for a pulse width of 1 µs [4]. Contrary to this the DBD characteristics in the rising slope for 10 and 1 µs pulses are almost the same as for the 50 µs pulse.

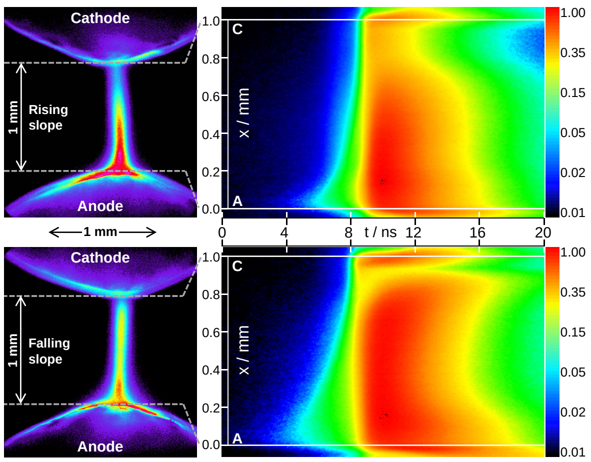

Fig. 4: *Spectral resolved 2D structure (iCCD, 150 ns gate width, 1000 accumulations, linear intensity scale, left column) and spatio-temporal development (streak, 100000 accumulations, logarithmical intensity scale, right column) of the DBD at rising and falling slope of a pulse with 10 µs width. Emission of the second positive system of N_2, 0-0 transition at 337 nm. The images of the falling slope are flipped vertically for better comparability.*

Consequently, it can be stated that a time in the range of $\lesssim 10$ µs between two discharges followed by a longer pause leads to significant changes of the discharge characteristics. Different conditions in the gap (e.g. the pre-ionisation) just before the breakdown are the reason for this behaviour. The emission of the SPS of N_2 could be used as a measure for the presence of (high energetic) electrons because the N_2(C) state–which is responsible for the SPS emission–is mostly excited by electron impact at atmospheric pressure [5].

The DBD development including the pre-phase of the falling slope of the 10 µs pulse was recorded in a 50 ns time window which is shown in figure 5. Approximately 25 ns before the global intensity maximum there is a localised diffuse emission in front of the anode which lasts ≈ 10 ns and spreads ≈ 200 µm in the gap. This emission in the pre-phase is correlated to an increased space charge which leads to a shift of the inception point of the cathode directed propagation, compare figure 4. Such a localised emission was observed neither in the falling slope of the 50 µs pulse nor in the rising slopes of the 50, 10 and 1 µs pulses.

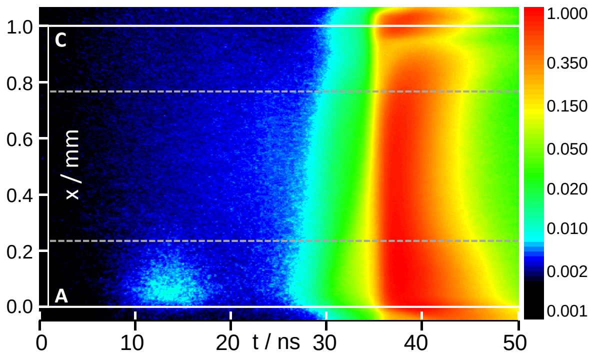

Fig. 5: *Spatio-temporal DBD development in the falling slope of a 10 µs pulse featuring a localised diffuse emission maxima in front of the anode during the pre-phase (lasting ≈10 ns from $t = 10 \dots 20$ ns). Emission of the second positive system of N_2, 0-0 transition at 337 nm. The dashed gray lines indicate the areas for the averaged curves in figure 6 (0 to 0.25 mm and 0.75 to 1.00 mm).*

To analyse the pre-phase in more detail the SPS emission in front of the anode and the cathode was taken from the streak camera measurements for all three considered pulse widths and averaged over 250 µm, see figure 6. For the symmetrical pulse there is no significant difference between the emissions in front of both electrodes. In the case of the 1 µs pulse the inception point of the discharge in front of the cathode instead of the anode is cleary visible, see [4]. The emission in front of the cathode starts approximately at the same moment as the localised emission in the pre-phase near the anode of the 10 µs pulse. Therefore one can conclude that the high pre-ionisation in this area due to the space charge density generated by the positive ions created in the previous discharge is already sufficient to start the propagation towards the cathode as well as the anode.

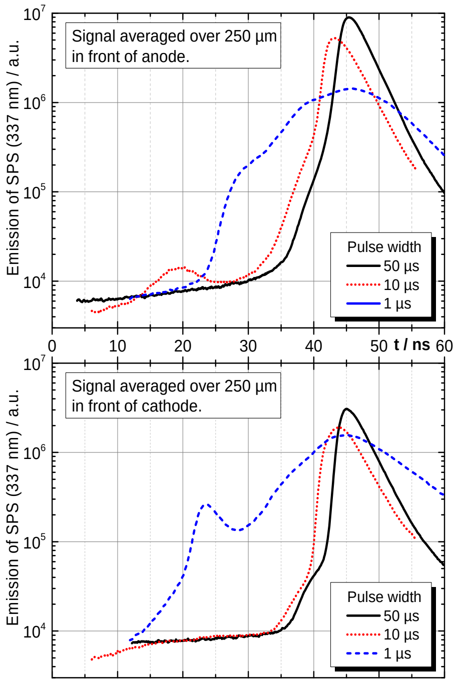

Fig. 6: *Comparism of the pre-phase emission development in front of anode and cathode in the falling slope for 50, 10 and 1* µs *pulse width. Emission of the second positive system of* N_2*, 0-0 transition at 337* nm *was taken out of the streak camera measurements (areas for averaging indicated in figure 5).*

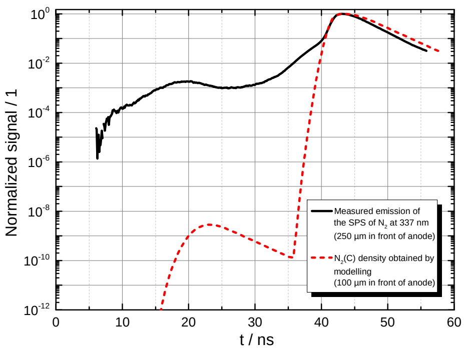

Fig. 7: *Comparism of the measured emission of the SPS of* N_2 *in the pre-phase and the* $N_2(C)$ *densities obtained by modelling in front of the anode for the falling slope of a pulse with 10* µs *width.*

The experimental results were compared with a time-dependent, spatially one-dimensional fluid model which takes the balance equations for the densities of all relevant species, the mean electron energy, the Poisson equation as well as an equation for the surface charge density on the dielectrics into account [6]. Besides the geometry of the DBD arrangement and the gas composition only the measured voltage signal was used as input data. The comparison of the calculated and the measured electrical current shows qualitative agreement. The decrease of the current at the falling slope compared to the rising slope for asymmetric pulses with pulse widths in the range of $\lesssim$10 µs can be explained by the presence of charge carriers in the gap before the reignition of the discharge.

In figure 7 the measured SPS emission is compared with the calculated density of $N_2(C)$. The modelled density as well as the measured SPS emission feature a localised maximum $\approx$20 ns before the global maximum. However, there is a difference of some orders of magnitude in the relative intensity between the maximum in the pre-phase and the global maximum. This has to be improved in future work.

4. SUMMARY

The influence of the pulse width on the pre-phase of pulsed single DBDs in 0.1 vol% O_2 in N_2 was investigated by means of electrical and optical diagnostics as well as one-dimensional fluid modelling. For asymmetrical pulses with $\lesssim$10 µs width in the pre-phase of the DBD in the falling slope a diffuse emission (SPS of N_2) in front of the anode was observed which leads to changes in the spatio-temporal DBD development in the falling slope. These findings are qualitatively confirmed by the simulation. For 1 µs pulse width there is no diffuse emission in the but a start of a cathode and anode directed propagation near the cathode at same the time as the diffuse emission occurs in the falling slope of the 10 µs pulse, i.e. the pre-phase directly proceeds into the breakdown due to the higher pre-ionisation generated by the previous discharge.

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