Investigation of an atmospheric pressure helium jet in front of a dielectric or grounded surface with current, emission and surface charge measurements

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A capillary plasma jet in helium is investigated by means of phase resolved optical imaging and electrical measurements. In addition the Pockels-effect is used to investigate the space and phase resolved distribution of surface charges. Furthermore, the influence of the distance between the jet and the surface is investigated. The phase resolved optical imaging reveals the discharge dynamics with a dielectric barrier discharge inside the capillary as well as plasma bullets exiting the capillary. Finally, the contribution will correlate these results by means of the current signal with the phase resolved distribution of surface charges. It is concluded, that the charge exchange between the jet and the surface occurs within the conducting channel and resembles the inverse current pulse. With increasing distance, the number of inverse current pulses is reduced and the count of charge exchange processes is reduced as well.

1. Introduction

In plasma medicine, plasma devices are applied to treat biological surfaces either for investigation or treatment purposes [1]. Investigation on plasma jets are mainly focused on the operation in open atmosphere [2]. But when a surface is placed in front of the jet, the electrical field is disturbed. Furthermore the surface can be of different types like conducting or isolating and hence influence the jet through deposited surface charges and gas flow disturbances.
For investigation of the gas flow conditions, schlieren photography is generally applied [3] as well as fluid modelling [4] and tracer particle fluorescence [5]. The influence on the gas flow with a surface in front of the jet is investigated in [6].
With this contribution, we want to discuss the influence on the electric properties when placing a dielectric or conducting surface in front of an atmospheric pressure helium jet. Therefore electrical signals as well as phase resolved imaging are applied for the grounded electrode in front. In case of the dielectric surface, the Pockels effect is applied to acquire phase resolved absolute surface charge densities in correlation with the electrical signal.

2. Experimental setup

The plasma jet is composed of two ring electrodes wrapped around a quartz capillary (inner diameter

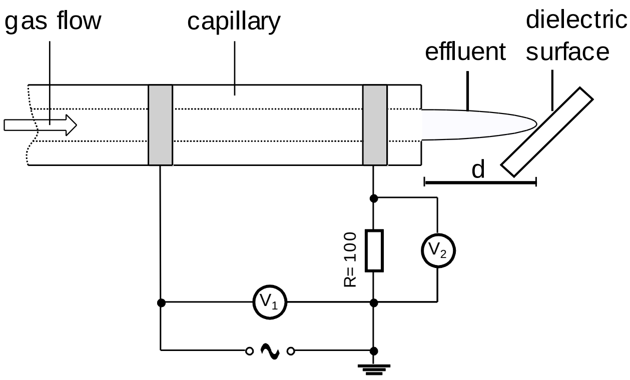

Figure 1: Experimental setup of the plasma jet with the dielectric surface in front.

1.5 mm, outer diameter 3 mm, see figure 1).
A sinusoidal voltage is applied on the first electrode (left one in figure 1). For the generation of the high voltage, a sinusoidal signal generated by a waveform generator (f=13 or 18 kHz, Tektronix AFG 3102) is given to a power amplifier (ENI 1040L) in series with a high-voltage transformator. The second electrode is grounded. The opposing surface has a distance d to the jet nozzle and is either a copper plate for the PROI measurements or a dielectric BSO ($Bi_{12}SiO_{20}$, as shown in figure 1) surface for the surface charge measurements. A high-voltage probe (P6015A Tektronix) is connected to the first ring electrode for voltage measurements. The current is measured with voltage probes (P2220 Tektronix) over 100 Ω resistors. The PROI measurements are performed with an ICCD camera (4Picos-DIG, Stanford Computer Optics Inc., 50 ns steps, 10 ms

acquisition). A gas flow of 3 slm helium is passed through the inside of the capillary.

For the surface charge measurement, an opto-electric BSO crystal is used as opposing dielectric. If charge is deposited on the surface of the BSO crystal, its electric field induces an optical birefringence in the crystal bulk (Pockels effect). In that case, the BSO acts as a retardation plate. The absolute charge density accumulated on the surface is deduced by measuring the polarization shift of a light beam that passes through the crystal. The setup for the light beam preparation and evaluation is presented in [7]. Further detail on this technique is discussed in [8-10].

3. Results and discussion

The electrical signals for the jet with both surfaces are shown in figure 2. In the case of a grounded counter electrode two characteristic current signals are observed during each voltage period at the ring electrode. The first, fast current pulse lasts for 1 µs with current amplitude of up to 3 mA. Shortly after the fast current pulse, an inverse current pulse with duration of 5 µs and amplitude of 1 mA and opposite polarity is measured. Additionally, the inverse current pulse correlates with a current pulse at the plate electrode with duration of 18 µs. This current characteristic is symmetric for both cycles of the applied sinusoidal voltage with peak to peak amplitude of 4 kV.

Comparing this characteristic with the measured characteristic of the dielectric counter electrode (figure 2b)) shows some similarities as well as differences. Although the applied voltage (8 kV_{pp}) is twice the value for the case of a grounded electrode, the setup could not be ignited in a symmetric mode with other tested values. The presented value is chosen for its stability over the investigated range of distance variation. Beside the missing symmetry in the current shape, the two characteristic current pulses are observed in each period. In addition, a second set of pulses is observed in the negative voltage cycle indicating an additional discharge during the negative voltage cycle. A closer look indicates that the discharge in the positive cycle is actually ignited shortly before the voltage turns positive. This can be explained by our previous observation of a negatively biased surface due to the two charge exchange events during one negative voltage cycle [7].

A distance variation for the grounded electrode in front of the jet showed, that the time between the first fast current pulse and the inverse current pulse increases for an increased distance. For an even higher increase of distance, the inverse current peak vanishes and only the fast current pulse remains. This is observed for the dielectric surface as well.

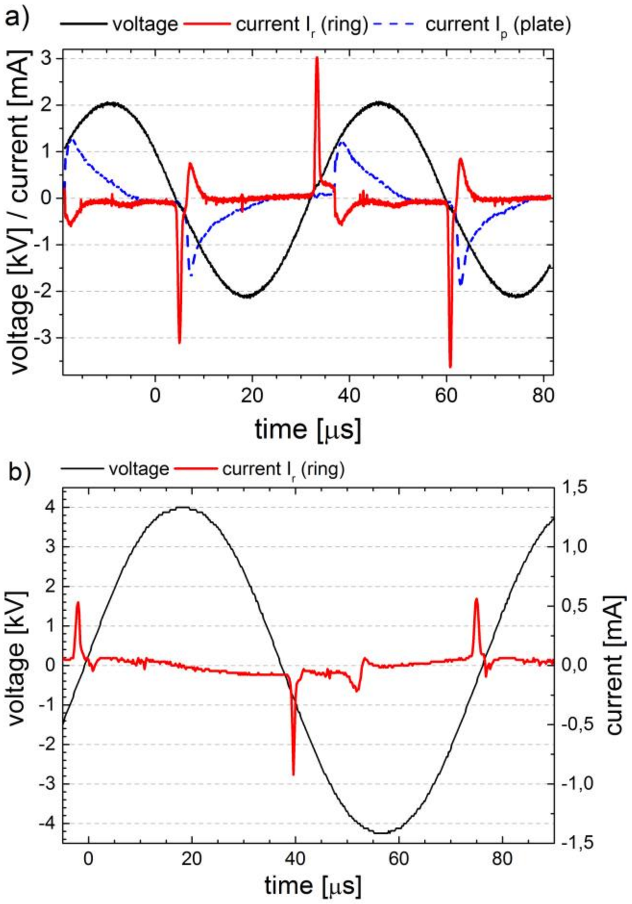

Figure 2: Voltage and current signals for the plasma jet in front of a a) grounded (d=5 mm) or b) dielectric (d=2 mm) electrode.

The disappearance of the inverse current peak requires first the correlation of the plasma dynamics with the current signals. The plasma dynamic is investigated by means of phase resolved optical imaging similar to [11]. From the measurement, four important events are observed in figure 3. First is the discharge inside the capillary between the two ring electrodes. This discharge is a typical dielectric barrier discharge (DBD) and deposits charges on the inner wall of the dielectric capillary (depicted by the blue region at the capillary edge in figure 3). Afterwards a weak emission near the capillary edge is observed (t=34 µs, x=13 mm) that results in the bullet propagation (second event) outside the capillary with a velocity up to $8 \cdot 10^3$ m/s. Just before the visible contact of the bullet with the external grounded electrode, the return stroke is observed (third event, see also [11] for the discussion on the return stroke). When the return stroke reaches the capillary edge, the plasma channel is observed within the gap.

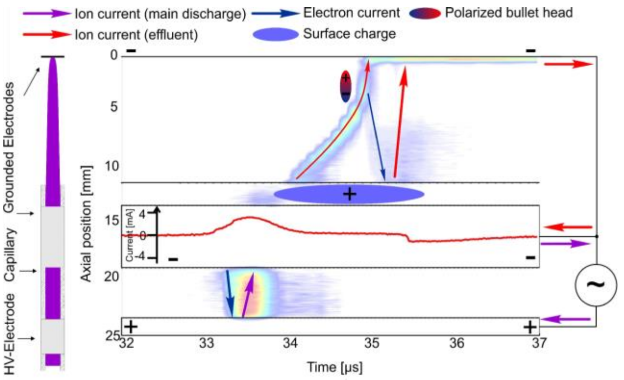

Figure 3: Phase resolved optical imaging (PROI) of the discharge dynamics for the positive voltage cycle (d=12 mm). The current is depicted on the grounded ring electrode for phase correlation. The arrows indicate possible charge movements along the discharge dynamics.

Now considering the relation of the discharge events with the discharge current depicted in phase in figure 3 as well, it is obvious that the DBD correlates with the fast current signal and the plasma channel causes the inverse current peak. To understand the polarity of the inverse current peak, the relevant charge transport events within the plasma dynamic are marked in figure 3. Within the DBD the ions move from the powered electrode towards the grounded electrode and are partially deposited on it. In the increasing external electrical field and by the enhancement through deposited charges on the capillary, ions drift outside of the capillary and accelerate towards the external grounded electrode and the bullet mechanism (or guided streamer [12]) is created, but the bullet does not carry enough charges to create a significant current pulse. But the electrons in the bullet tail excite the channel and thus the charges on the surface of the capillary are removed and transported to the grounded electrode. Therefore the current at the ring electrode is of inverse polarity, for charges are removed spontaneously and they recombine at the external electrode. It is important to note, that the timeframe of the bullet impact is merely 200 ns, while the current describes a timeframe of several μs.

Finally, the deposition of charge on the dielectric surface is investigated by using the Pockels method. The BSO crystal is placed at four different positions and the results are correlated with the respective current. The spatial distribution of the charges was recently presented in [7]. In figure 4 the temporal average is shown for the investigated distances. As already mentioned before, the average charge value is negatively biased due to a ring of negative charges around the positive charges in the centre of the surface. The ring is a result of the higher mobility of the electrons compared to the ions. Therefore the average value in the beginning of figure 4 seems to be a neutral surface (0 nC cm^{-2}) but instead the centre reaches peak values between 1 nC cm^{-2} (at d=6 mm) and 3 nC cm^{-2} (at d=2 mm). Only for d=8 mm no charge deposition could be observed for the selected settings. The curve for d=2 mm (red squares) shows two charge exchange processes during the negative cycle of the voltage while it has one in the positive cycle. This correlates in time and number with the inverse current peaks. Also the timeframe of the charge exchange agrees with the inverse current peaks in the order of some μs. When the distance is increased, the current shows a reduced number of inverse current peaks and simultaneously the number of charge exchange events is reduced.

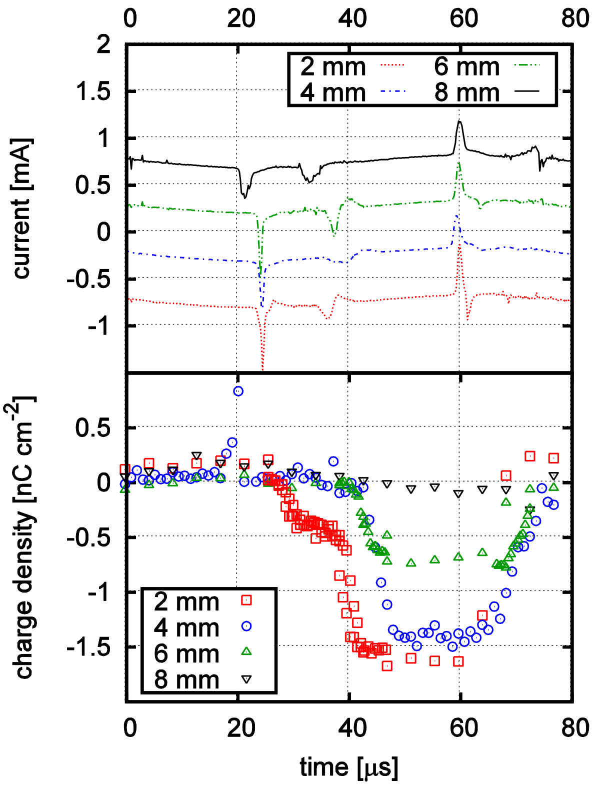

Figure 4: Current signal and mean charge density on a dielectric surface in front of the jet.

For d=4 mm a spontaneous increase of the average charge density is observed. When changing the distance, the discharge still sometimes becomes instable and we believe this peak to be a result from a spontaneous additional discharge. Another measurement with a reduced temporal resolution (about half) didn't show this increase and it does not correlate with any other phase resolved measurement. Therefore this is regarded as an artefact for this set of measurements.

4. Conclusion

The contribution compares the current and voltage characteristics of a plasma jet in front of a dielectric as well as a conducting surface by phase resolved measurement of the current, optical imaging and surface charge density. When the conducting electrode is placed, the current and voltage characteristic is symmetric with two current features in each cycle of the voltage. A fast current pulse indicates a DBD discharge between the two ring electrodes and a subsequent inverse current pulse. The removal of surface charges from the inner wall of the capillary results in the inverse current pulse. The two characteristic current features are observed for the setting with the dielectric surface as well, but the current is not symmetric anymore for a second set of current pulses appears during the negative voltage period. Furthermore it is discussed, that an increase of electrode distance results in a reduction of number of inverse current peaks as well as surface charge value and charge exchange events. The current pulse alone can therefore clearly act as an indicator for the charge exchange on the surface.

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