Experimental investigation of Lissajous figure shapes in planar and surface dielectric barrier discharges

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Abstract. Dielectric Barrier Discharges (DBDs) operating in air at atmospheric pressure are widely employed as cold plasma sources for plasma processing and applications, in both volume and surface configurations. Surface dielectric barrier discharges, however, are mainly known for the manipulation of the boundary layer of an airflow surrounding a body, and thus for aeronautical applications. Lissajous figures, obtained by means of a high-voltage and a capacitive probes, are usually adopted for both these types of DBDs as a method for measuring the power consumption by the discharge. In this work, we propose to integrate this diagnostic tool with the measurement of current pulses, which are associated to microdischarges that usually develop in these plasmas because of the presence of the dielectric barrier. We have studied both planar and surface DBDs in presence of a continuous sinusoidal voltage feeding, and we have demonstrated that this method is promising in order to gain additional information about the discharge characteristics from the shape of the Lissajous figures.

1. Introduction
Dielectric Barrier Discharges (DBDs) operating in air at atmospheric pressure are widely employed as cold plasma sources for plasma processing and applications [1]. Their name is due to the presence of at least one insulating plate between the electrodes. In a planar and symmetrical configuration two metallic electrodes are covered with insulating layers and separated by a few millimeter gap. In an asymmetrical Surface Dielectric Barrier Discharge (SDBD), instead, plasma is created by ionizing a sheet of air nearby the surface of the dielectric barrier, because one electrode is glued to the dielectric surface whereas the other one is buried inside the insulating barrier itself. Both volume and surface dielectric barrier discharges are widely used in applications such as ozone generation, pollution control, plasma medicine and surface modification [1]. However, the growing interest for SDBDs is mainly ascribable to their promising applications in the flow control field [2, 3]. As a matter of fact, at the end of the nineties, the group directed by J.R. Roth from the University of Tennessee discovered that when these discharges are operated in quiescent air an airflow of several meters per second is observed above the dielectric sheet and near the plasma region [4]. This wind is usually called induced airflow because the main mechanism responsible for its generation is believed to be momentum transfer from the ions drifting in the electric field to the surrounding fluid by particle-particle collisions [5]. It is known that, when the electric field created by the voltage
difference imposed between the electrodes is sufficiently high, plasma is created and electrical charges are transported through the gap and accumulated on the insulating surfaces [6]. This charge accumulation generates an electric field that locally weakens the external one. When the total electric field falls below the threshold necessary for plasma ignition, the discharge extinguishes. If the voltage imposed to the fed electrode is increased, the discharge can be locally initiated again, and that is the reason why a sinusoidal high-voltage supply is adopted instead of a continuous one. Consequently, the presence of the insulating barrier usually leads to a regime where charges are mainly transported in sub-millimeter regions consisting of current filaments with temporal duration limited to a few tens of nanoseconds [7]. These plasma microdischarges are concentrated into two phase intervals of the sinusoidal voltage supply, when the modulus of the applied voltage difference is high enough and increases in time.

Evaluation of the area inside a Lissajous figure is a widely spread method for evaluating the power consumed in a both planar and surface DBDs fed with a sinusoidal high voltage difference. As a matter of fact, this figure is obtained by plotting the charge flowing into the circuit $Q$ as a function of the voltage difference $\Delta V$ between the electrodes [8]. The charge is measured by means of a capacitor in series with the discharge cell (the so-called capacitive probe). When the imposed electric field is too small for plasma generation, the $Q$ versus $\Delta V$ plot is a straight line, because the system behaves as a purely capacitive cell and the charge varies proportionally to the voltage, with the constant of proportionality given by the cell capacitance $C_{cell}^{off}$. Otherwise, if the voltage amplitude is high enough for discharge ignition, during the two phases of plasma activity the charge $Q$ does not vary as $C_{cell}^{off} \cdot \Delta V$ any more, and the Lissajous plot opens and forms a convex figure.

Lissajous figures for planar DBD configurations usually assume the shape of a parallelogram. The discharge cell can be thought as two capacitances in series: the first one ($C_{die}$) is given by the insulating barrier (or by the two barriers if both electrodes are covered), whereas the second one ($C_{gap}$) is due to the planar air gap. The value of the latter changes when plasma is created, so the Lissajous figure is delimited by four straight lines with a slope different or equal to $C_{cell}^{off}$, depending if they correspond or not to a phase of plasma activity [9]. Manley assumed that, during the discharge-on periods, the plasma between the electrodes fills the gap so that the voltage drop in the gap is equal to zero. In this case, the capacitance of the cell, and thus the slope of the the corresponding side of the Lissajous figure, reduces to the capacitance of the dielectric(s): $C_{cell}^{on} = C_{die}$ (see Figure 1 (a)) [10, 8].

![Figure 1](image.png)

**Figure 1.** Schematic of a Lissajous figure with the hypothesis that during the plasma activity the capacitance of the gap reduces to zero (a), or that it remains equal to the capacitance in absence of discharges (b).
The instantaneous charge $Q$ represents the total charge and thus captures the charge transported by current microdischarges too. A situation opposite to the one considered by Manley occurs when a DBD is operated just above the minimum voltage amplitude required for plasma ignition, and only few plasma microdischarges are created during a whole sinusoidal voltage cycle. In this case the capacitance of the gap essentially keeps the same, but the Lissajous figure becomes again a sort of parallelogram if the current microdischarges move and deposit charges: the instantaneous charge is given by $Q = C_{cell}^\text{off} \cdot \Delta V + Q_{\text{dep}}$, and even though the capacitance $C_{cell}^\text{off}$ is constant, $Q$ changes during the phases of plasma activity because the positive or negative deposited charge ($Q_{\text{dep}}$) changes each time a microdischarge crosses the gap. In this case, during the plasma activity, $Q$ varies in steps (Figure 1 (b)) [11], whereas during the off-phases, if the deposited charge does not change, the variation of $Q$ with $\Delta V$ follows a straight line $Q = C_{cell}^\text{off} + Q_{\text{dep}}$, with intercept $Q_{\text{dep}}$ given by the total charge left by microdischarges during the previous plasma activity. Without the assumption that the capacitance or the deposited charge keep constant, the variation of the total charge $Q$ during a voltage cycle thus depends on capacitance changes as well as on the accumulation of charges on the dielectric barriers.

For a SDBD, the situation is complicated by the fact that the discharge does not start and stop with a constant geometrical plasma shape, but the latter can change in the course of the discharge active phase [12], since the accumulation of charges onto the dielectric surface can influence the electric field configuration and thus the development of the following microdischarges [7]. Changes in the shape of the discharge region imply variations in the discharge capacitance, leading to the almond-shaped Lissajous figures often observed for surface discharges [12].

The aim of this paper is to combine the Lissajous figure plot with the detection, by means of a Rogowski coil, of current pulses associated to microdischarges, in order to distinguish the contributions of $C_{gap}$ and $Q_{\text{dep}}$ to the variations of the instantaneous total charge $Q$ during a voltage cycle. This method has been tested for a planar configuration and then applied to a SDBD. The two configurations and the electrical diagnostics adopted are described in the next two sections, which are followed by the presentation of the results obtained.

2. Experimental Setup

The planar configuration used in these experiments is symmetrical because two identical insulating barriers are used to cover the electrodes (Figure 2 (a)). The latter are stainless steel disks (diameter 35 mm and thickness 1.5 mm) that have been inserted into a drilled cylindrical scaffold in Macor (a glass ceramic material by Corning Inc., dielectric constant $\epsilon_r = 6.03$) with diameter equal to 40 mm and external height equal to 3.5 mm. Thus a dielectric barrier of 2 mm separates each electrode surface from the gas gap. The discharge gap was fixed at 0.8 mm. The total cell capacitance without plasma has been calculated using a 2D Laplacian electrostatic field solver (ESstat 7.0 by Field precision LLC). It is equal to $C_{cell}^\text{off} = 8.3$ pF, given by the series of $C_{gap} = 23.5$ pF and $C_{\text{die}} = 12.8$ pF (25.7 pF for each dielectric barrier). Calculations show that the electric field is uniform in the gap within 10% and decreases outwards. The voltage difference between the electrodes is imposed by grounding an electrode and by connecting the other one to the secondary coil of the transformer of a power generator (a V-20 Corona Station by Tigres Gmbh). The whole system, described elsewhere [13], constitutes a resonant circuit, so the sinusoidal voltage amplitude and period are not independent.

In the surface configuration, the electrodes are tin clad copper adhesive tapes (60 µm thick and 200 mm long) placed at the opposite sides of a flat dielectric panel (teflon, 2 mm thick), without overlapping in the chordwise y-direction (Figure 2 (b)). The insulated electrode is 10 mm wide, whereas the air exposed one is just 5 mm wide. An insulating polyisobutylene self-amalgamating tape is used for avoiding discharges at the lower electrode side, but also upstream of the exposed electrode ($y < 0$) and at the electrode ends. Different voltages (up to about 15 kV peak amplitude) has been tested, at the same frequency (16 kHz). In this case the the
3. Diagnostics

Three electric probes have been used for studying the discharge properties (Figure 2). Plasma current microdischarges have been experimentally studied with a sufficient high temporal resolution by means of home-made Rogowski coils. A capacitive probe was placed between the buried grounded electrode and the earth as a diagnostic for measuring power consumption and for visualizing the shapes of the Lissajous figures. A commercial HV probe (Tektronix P6015A, granted for a bandwidth of 75 MHz) was instead employed for evaluating the voltage at the exposed electrode. The outputs of all these probes were connected to different channels of a large bandwidth digital oscilloscope (Agilent MSO8104A with sampling rate equal to 2 GSa·s⁻¹) and their signals were acquired simultaneously.

3.1. Capacitive Probe

A capacitive probe consists in a capacitor inserted between the grounded electrode and the ground, in order to measure the charge flowing into the ground cable. The capacitance of the probe (C_{probe}) is known and must be sufficiently large so that the voltage difference ΔV between the DBD electrodes is almost equal to the voltage V applied to the powered electrode. In our experiments 100 nF and 46 nF were used for the symmetrical and asymmetrical configurations, respectively. This assures that the probe is not intrusive, and that the voltage drop across the capacitor (ΔV_{probe}) is small enough to be measured without necessarily using a high voltage probe. The capacitor-based charge method for power measurement was first introduced by Manley for discharges between parallel plates [10], whereas Pons et al. were the first ones to use it in the context of SDBDs for aeronautical applications [15]. The instantaneous charge Q is given by Q = C_{probe} · ΔV_{probe}, and the energy consumed by the dielectric barrier discharge in a voltage cycle is obtained by averaging the product Q · ΔV over a whole period T, which is

Figure 2. Experimental layout and diagnostics for the adopted planar (a) and surface (b) configurations. Arrows mean that the probe outputs are connected to the oscilloscope.
given by $N$ points separated by the time interval $\Delta t$:

$$
E = \frac{1}{N} \sum_{i=1}^{N} Q \cdot \Delta V.
$$

(1)

This can also be geometrically calculated as the area inside the Lissajous figure, as proposed by Manley [10]. As a matter of fact, as already said in the introduction, this is obtained by plotting the instantaneous charge as a function of the voltage drop in the discharge cell. Once $E$ is obtained, the dissipated power is given by $P = E/T$:

$$
T = \frac{1}{N^2 \Delta t} \sum_{i=1}^{N} Q \cdot \Delta V.
$$

(2)

3.2. Rogowski Coils

A current transducer like a Rogowski coil is suitable to measure electric current filaments [16]. In a DBD, the electric current flowing into the circuit can be viewed as the superimposition of a low-frequency sinusoidal capacitive current, which is almost independent of plasma presence in the gap, and a discharge current, which is associated with plasma microdischarges and appears as a series of fast current pulses. A Rogowski coil is a conducting wire that is wound in a spiral around a magnetic core and then returns to the original point. The coil is placed around the cable connecting the buried electrode to the ground: any variation in the current $I$ flowing into the cable generates an electromotive force at the output of the coil. By adding an integrating circuit, the output of the probe is proportional to $I$. We have built a few home-made Rogowski coils and calibrated them in the frequency range $10 \div 100$ MHz, as discussed in a dedicated paper [16]. Since we are mainly interested in the current signal associated with plasma microdischarges, we can separate this current component from the displacement one by means of a band pass filter based on the fast Fourier transforms, so that current events due to plasma microdischarges finally appear as pulses emerging from a noisy base line, as shown in Figure 3. At this point they are identified by setting a threshold sufficiently higher than noise spikes. Finally, a baseline is used to evaluate the intensity of peaks, as well as their beginning and end. We were able to study current pulses characteristics like number, amplitude, duration and charge transported [3]. In this work our aim was not to study the mean properties of these current pulses, but we recorded them in order to measure the charge transported inside the gap by plasma microdischarges. Since the instantaneous $Q$ signal obtained with the capacitive probe traces the total charge present inside the gap or on the dielectric surfaces at the considered moment, for each instant of plasma activity the charge transported by each microdischarge (recorded up to that moment) is added up in a variable that we call $Q_{\text{micro}}$, which is displayed in Figure 3. $Q_{\text{micro}}$ is equal to zero before the first current pulse of the considered half-cycle, then its value increases each time a plasma microdischarge is created:

$$
Q_{\text{micro}}(t_i) = Q_{\text{micro}}(t_{i-1}) + Q_{\text{pulse}}(t_i),
$$

(3)

where $Q_{\text{micro}}(t_i)$ denotes the value of $Q_{\text{micro}}$ at the time $t_i$ when the $i-$th current microdischarge is created, and $Q_{\text{pulse}}(t_i)$ is the charge transported by this microdischarge, i.e. the area subtended below the considered current pulse. In order to draw a comparison with the Lissajous figure, $Q_{\text{micro}}$ will be considered as a function of the instantaneous voltage difference between the electrodes (see Figure 3, in red).

4. Experimental Results

For the both dielectric barrier discharge configurations studied during this investigation, we have simultaneously acquired the signals corresponding to the three different electrical diagnostics.
Figure 3. Temporal signal of the discharge current. The phase of plasma activity begins at about 102.8 µs, when the first current pulse appears. The corresponding evolution of $Q_{\text{micro}}$ is plotted as a function of both time (black circles) and instantaneous voltage (red triangles).

These temporal series have been split into several parts corresponding to different voltage cycles, which have been analysed separately. For the representation of the Lissajous figures, a band pass filter was previously applied to both the $Q$ and $V$ signals, in order to cut noise at high frequencies, and to reduce the spikes visible in the capacitive probe signals that indicate the plasma activity. An high-pass filter was instead used for the current signals, in order to separate the microdischarge current peaks from the AC current signal, as discussed in the previous section.

4.1. Planar Configuration

Two Lissajous figures obtained for the planar configuration at two different voltage amplitudes (8.3 kV and 11.4 kV) are shown in black in Figure 4. Their shape nicely resembles a parallelogram composed of four straight lines with two different slopes. These $Q - V$ plots appear symmetric: as expected, there are no evident differences between the two voltage semi-cycles, because of the adopted planar setup with two dielectric barriers. For each semi-cycle, the amount of charge transported by current microdischarges ($Q_{\text{micro}}$) has been calculated as a function of the applied voltage. For the half of the Lissajous figure in which the voltage is rising towards its maximum (sides AC of Figure 4 (b)), the current transported by plasma microdischarges is positive and $Q_{\text{micro}}$ increases in correspondence of instantaneous voltages at which a current pulse is detected. As discussed in the introduction, we expect that $Q$ is related to the voltage drop between the electrodes as $Q = C_{\text{inst}} \cdot \Delta V + Q_{\text{inst}}$, where $C_{\text{inst}}$ and $Q_{\text{inst}}$ are the instantaneous capacitance of the system and instantaneous amount of charge accumulated inside it. If both these values are constant within a voltage interval, $Q$ varies linearly with $\Delta V$. It is evident that this happens during the two phases of plasma off (sides AB and CD), because no charges are transported by plasma filaments and the capacitance of the system keeps constant. This evidence that $Q_{\text{inst}}$ does not change means not only that these are phase of no plasma activity, but also that there is no rearrangement or recombination of the charges left on the insulating barriers. During the plasma active phases, instead, both $C_{\text{inst}}$ and $Q_{\text{inst}}$ can vary. In order to separate these two contributions affecting the shape of the Lissajous figure, we have supposed that $Q_{\text{inst}}$ is...
Figure 4. Examples of Lissajous figures (shown in black) obtained for two different voltage amplitudes (8.3 kV and 11.4 kV) in a planar configuration. The consumed power is equal to 13 W for the graph on the left and to 34 W for the one on the right. For red curves the charge $Q_{\text{micro}}$ transported by current microdischarges have been subtracted to the $Q$ signal of the Lissajous figure.

completely transported by plasma microdischarges, and we have thus measured $Q_{\text{inst}} = Q_{\text{micro}}$ with a current probe, and thus with a diagnostic tool independent from the Lissajous figure. At this point we have subtracted $Q_{\text{micro}}$ from the $Q$ signal of the Lissajous figure, and we have obtained a sort of new Lissajous micro, shown in red in Figure 4, which is no more a closed loop, because the two sides of no plasma activity remains unchanged, whereas BC and DA becomes BE and DF. These ones appear straight at all the considered voltage amplitudes, meaning that the cell capacitance can change at the beginning of the plasma-on or plasma-off phase (becoming equal to $C_{\text{on}}$ and $C_{\text{off}}$ respectively), because of a sudden change in the $C_{\text{gap}}$ value, but that then it keeps the same during each one of these temporal windows. The values of $C_{\text{on}}$ and $C_{\text{off}}$ obtained for the planar configuration are presented in Figure 5 as a function of the power, which has been calculated from the Lissajous figure as described in Section 3.

We have found that the capacitance $C_{\text{off}}$ is independent from the power level and equal to the $C_{\text{cell}}$ given by the series of the capacitances of two dielectrics and of the gap calculated in absence of discharges (Section 2). If variations in the $C_{\text{off}}$ values were observed this would mean that the gas phase remained perturbed after the stroke quenching or by electrode heating (at high power levels). In these experiments, however, $C_{\text{off}}$ seems to represent just the cold capacitance of the actuator. The capacitance $C_{\text{on}}$, instead, increases with the voltage amplitude, and for sufficiently high powers it becomes equal to the capacitance given by the series of the two insulating barrier: $C_{\text{on}} = C_{\text{die}}$. It is thus clear that the Manley assumption presented in the introduction is adequate only in these conditions. Moreover, it is evident from this discussion that, even though the plasma-off sides AB and CD are straight lines, their intercepts with the $Q$ axis represents the total charge left on the dielectric barriers during the previous plasma activity only if the capacitance $C_{\text{on}}$ remains equal to $C_{\text{off}}$ (Figure 1 (b)), otherwise these intercepts are influenced by capacitance variations too.
4.2. SDBD Configuration

The same method for the investigation of Lissajous figures has been adopted for the surface dielectric barrier configuration. In this case a band pass filter with a lower cut-off frequency was adopted (2 MHz instead of the 15 MHz used for the planar configuration), so that there are no oscillations associated to the plasma presence. This allows to appreciate if asymmetries are present between the two half-cycles of the Lissajous figure. Figures 6 (a) and (b) show two Lissajous figures (in black) obtained at two different voltage amplitudes (5.6 kV and 13.5 kV).

Figure 5. Capacitance in the presence ($C_{on}$) and absence ($C_{off}$) of plasma, calculated from the Lissajous figures obtained after the subtraction of $Q_{micro}$, as a function of the consumed power.

Figure 6. Examples of Lissajous figures (shown in black) obtained for two different voltage amplitudes (5.6 kV and 13.5 kV) in a surface configuration. The consumed power is equal to 3 W for the graph on the left and to 40 W for the one on the right. For red curves the charge $Q_{micro}$ transported by current microdischarges have been subtracted to the $Q$ signal of the Lissajous figure.
It is clear that in the first case a variation in the $Q$ signal happens abruptly at the beginning of the active phase of the positive semi-cycle (when the voltage is increasing towards its maximum, side AC), whereas the $Q$ variation is more gradual during the negative half-cycle (side CA). At the higher voltage amplitude, instead, the $Q - \Delta V$ plot appears more symmetric, even though the breakdown of the positive plasma phase is always more evident. This is due to the presence of a group of plasma microdischarges that are created at the discharge breakdown, probably by electrons that were previously accumulated on the surface of the insulating barrier, as discussed in reference [7]. The red curves correspond to the Lissajous figures obtained after subtracting $Q_{\text{micro}}$ from the original Lissajous plots. Again, it easily to notice that at high voltages the discharge semi-cycles behave quite similarly, whereas at low voltages the two semi-cycles appear considerably different. As a matter of fact, Figure 6 (a) shows that during the positive half-cycle plasma microdischarges transport a certain amount of charge $Q_{\text{micro}}$, and that after the subtraction of $Q_{\text{micro}}$ from the $Q - \Delta V$ plot, the new slope $C_{\text{on}}^+$ of the positive active phase looks quite similar to the slope $C_{\text{off}}$ of the plasma-off phase. On the contrary, during the negative half-period, almost no current microdischarges were detected, and this portion of the Lissajous figure is not affected by the subtraction of $Q_{\text{micro}}$. However, the slope of the curve changes, and this means that there is a capacitance change or a charge transfer happening in a way different from current plasma mirodischarges. These asymmetries between the two semi-cycles are probably due to the fact that during the positive half-cycle, electrons are moved from the insulating surface towards the exposed electrode, and can thus leave the discharge gap, whereas during the negative semi-cycles electrons are accumulated on the insulating surface. Eventually, it is worth to noticing that at high voltages, the transition from $C_{\text{off}}$ to $C_{\text{on}}$ is not abrupt but gradual (Figure 6 (b)). This is probably due to progressive changes in the geometrical shape of the discharge region, which leads to gradual changes in the cell capacitance $C_{\text{on}}$ and to the creation of an almond-like Lissajous figure.

The values of $C_{\text{on}}$ and $C_{\text{off}}$ obtained for the surface configuration are presented in Figure 7 as a function of the power. These preliminary results for SDBDs show that $C_{\text{on}}$ is higher

![Figure 7](image_url)

**Figure 7.** Capacitance in the presence ($C_{\text{on}}$) and absence ($C_{\text{off}}$) of plasma, calculated for both the positive and negative half-cycles from the Lissajous figures obtained after the subtraction of $Q_{\text{micro}}$, as a function of the consumed power.
for the negative half-cycle. This is probably due to the higher mobility of electrons, which are more easily accumulated on the insulating surface rather than ions. Both $C_{on}$ and $C_{off}$ tend to increase for the range of powers considered, and this could be associated to a spreading of the discharge region, meaning that the higher the voltage the more the plasma sheet extends to chordwise positions far from the exposed electrode. We will examine in more depth this point in future investigations. The temporal evolution of the spatial discharge region and of the number of microdischarges could be followed by recording the time emitted by the discharge using a photomultiplier tube or by acquiring short exposure time pictures with a fast camera. Eventual rearrangements of charges left on the insulating barrier by the forward and backward stroke could instead be detected by local measurements of the surface potential temporal evolution [17, 18].

5. Conclusions
In this work we have proposed to combine to electrical diagnostics, a capacitive probe and a Rogowski coil, in order to gain new insights about plasma properties from the shape of the discharge Lissajous figure. As a matter of fact, these figures are often considered only for measuring the power consumption associated to the dielectric barrier discharge. In order to gain information about the discharge characteristics some assumptions are required, because the charge variation with the voltage drop between the electrodes depends on variations of the cell capacitance and of the charge transported by plasma and accumulated on the insulating barriers. Here we have proposed an experimental method for separating these two contributions, which consists in the measurement of the charges transported by plasma microdischarges by means of an adequate processing of the Rogowski current probe signals. This allows to isolate the effect of any capacitance variations on the shape of the Lissajous figure. This method thus allows to obtain more accurate measurements of the cell capacitance during the discharge active phases, and to test the validity of some assumptions, such as the one proposed by Manley about the capacitance gas gap [10], in the considered operating conditions. Results concerning a planar DBD configurations have been presented, and preliminary results referring to a surface dielectric barrier discharge show that this method can be useful for extracting interesting information about the discharge development during the voltage cycle, such as the plasma spreading on the insulating barrier, and to answer some questions, such as if electrical charges are all transported in the form of current microdischarges or not.

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