

# Electrical and mechanical characteristics of nanosecond pulsed sliding dielectric barrier discharges with different electrode gaps

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**Abstract.** This study proposes the characterization of a surface sliding discharge that extends over a length of 80 mm. The gas ionization is caused by series of high voltage pulses with nanosecond rising and decaying times while ion drift is forced by a negative DC component. Different plasma diagnostics such as electrical measurements, iCCD visualizations and strioscopy have been performed. They highlight that a threshold mean electric field between both air-exposed electrodes is required to fully establish a sliding discharge. Compared to a single nanosecond pulsed dielectric barrier discharge, the sliding discharge results in an energy consumption increase. Moreover, the pressure wave induced by the discharge is strongly impacted.

## 1. Introduction

Non-thermal surface plasma discharges can be used to control actively airflow over profiles. However, realistic applications at real aircraft or MAV scale require usually a large surface plasma in order to enhance the interaction region. Dielectric Barrier Discharges (AC-DBD) supplied by ac sine high voltage, are used for such applications at low Reynolds number and reduced scale [1, 2]. In this case, the flow control is based on the electrohydrodynamic force produced inside the discharge, resulting in an electrical wind-based wall jet. Recently, a new kind of plasma actuator has proven its effectiveness for airflow at high Reynolds number [3, 4]. In this case, the high voltage applied between both electrodes has a nanosecond pulsed waveform and the plasma extension is limited to a few millimeters. The flow control mechanism is no more caused by an induced body force but it seems result from fast heat deposition whose gas signature is a hemispherical region of high pressure propagating at sound speed. In view of overcoming the limited plasma extension, a new design based on three electrodes has been perfected to ignite a sliding discharge [5, 6]. Here the second air-exposed electrode that is supplied by a dc voltage allows us drifting electrical charges originating from the active electrode. In the present paper, an experimental study compares the electrical and mechanical characteristics of a single nanosecond surface dielectric barrier discharge (DBD) and a sliding discharge with electrode gap varying from 40 up to 80 mm. First, iCCD visualizations of both discharges are proposed. Secondly, the corresponding electrical measurements of discharge currents and energy consumptions are compared. Finally, shadowgraph characterizations of the induced pressure wave are performed



## 2. Experimental setup

The design used to produce a sliding discharge consists of three aluminum electrodes flush mounted on both sides of a 2-mm thick PMMA plate, as described in Figure 1. The single DBD design, composed of only two electrodes mounted on both sides of the dielectric plate (only electrodes (1) and (3) in Figure 1) is considered as the reference case (Gr). With this last design, a typical nanosecond discharge is generated by connecting electrode (1) to a pulsed high voltage power supply (FID). The high voltage waveform is shown in Figure 2 (1 kHz, 16 kV<sub>p</sub> peak voltage). The rising and decaying time are about 10 ns. To extend the plasma layer, a third electrode (2) is placed at 3 different positions from electrode (1) (gaps of 40, 60 and 80 mm). These designs are called G40, G60 and G80. The third electrode is supplied by a negative DC high voltage. Current measurements are performed on electrode (1) and (3) by means of Bergoz current transformers, allowing to compute the total input energy. Details of the electrical system can be found in [8]. Plasma imagery diagnostics are also carried out with the help of iCCD camera (PI-MAX-1024i) coupled with an UV lens (100F/2.8), showing the plasma morphology. Finally, experiments of shadowgraph visualizations of the induced pressure wave using the optical bench described in [7] are performed.

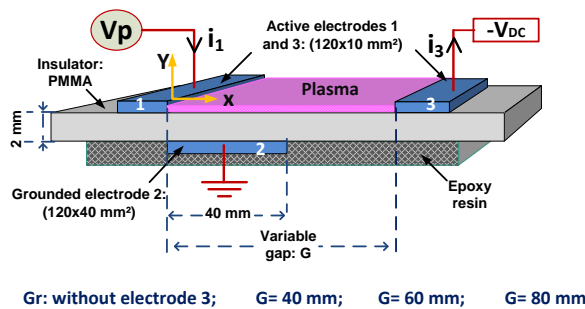


Figure 1: Schematic of the plasma actuator.

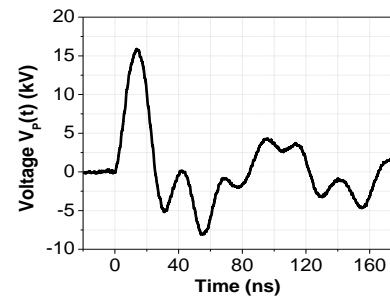


Figure 2 : Pulsed voltage versus time.

## 3. Results

### 3.1. iCCD visualisations of the discharges

Figure 3 shows top view iCCD images of the discharge for the four configurations. For all the cases, these images reveal that streamers propagate from electrode (1) over the actuator surface, as observed in [7, 9]. For the reference case (Gr), the pulsed voltage is fixed at 16 kV<sub>p</sub> (peak value). The plasma layer extends up to 16 mm from electrode (1) (Figure 3). When the third electrode is added and supplied by a negative DC voltage, the charged species slide over the dielectric surface. As demonstrated in [8], the presence of the third electrode, when it is not supplied, does not influence the pulsed discharge behaviour. For a gap between electrodes (1) and (3) equal to 40 mm (G40), a sliding discharge is obtained for V<sub>DC</sub> = -18 kV (V<sub>p</sub> = 16 kV<sub>p</sub>). By increasing |V<sub>DC</sub>| up to 34 kV<sub>DC</sub> and V<sub>p</sub> maintained at 16 kV, it is possible to extend more the plasma layer, over a length of 60 mm (G60 in Figure 3). For G80, a sliding discharge is initiated by increasing not only the DC voltage (-40 kV, corresponding to the DC power supply limitation) but also the pulsed voltage (V<sub>p</sub> = 20 kV<sub>p</sub>).

### 3.2. Electrical diagnostics

Figure 4-A and B illustrate the current measured at electrode (1) and (3) respectively, for all the cases. The currents i<sub>1</sub>(t) is composed of two peaks as observed in previous studies [7, 10]; that correspond to the ionization caused by the pulsed high voltage. When the sliding discharges are ignited, the positive peak value of i<sub>1</sub>(t) increases from 1.6 A/cm for the reference case (Gr) up to 2.4 A/cm for G40 and G60 (in both cases, V<sub>p</sub> = 16 kV<sub>p</sub>). For G80 (V<sub>p</sub> = 20 kV<sub>p</sub> and V<sub>DC</sub> = -40 kV), the current peak reaches 2.7 A/cm.

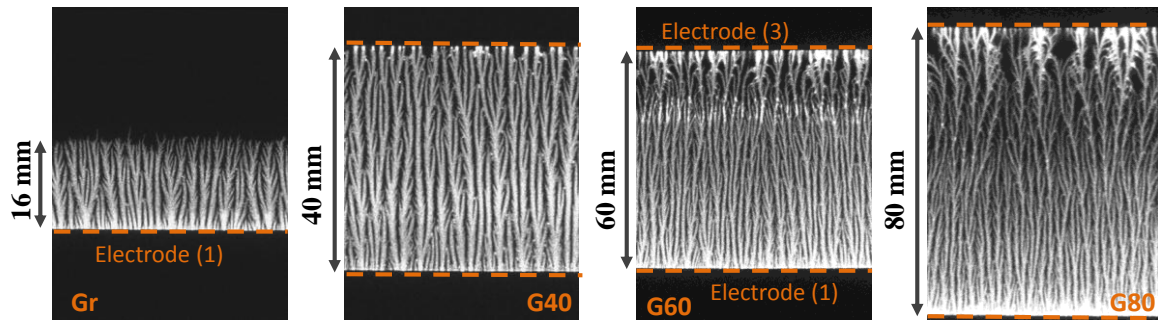


Figure 3 : ICCD images of the plasma layer for a single DBD (Gr) and the sliding DBD with gap equal to 40 mm (G40), 60 mm (G60) and 80 mm (G80).

Moreover, the establishment of the sliding discharge can be also highlighted by current  $i_3(t)$  (Figure 4-B), that reflects the amount of charges collected by electrode (3). For G40, G60 and G80 configurations, the  $i_3$  amplitudes are equal to 0.64, 0.38 and 0.15 A/cm, respectively. These variations in  $i_3$  amplitudes show the influence of the mean surface electric field between electrode (1) and (3), defined as  $V_{PD}/cm = (V_P - (-V_{DC}))/G$  where  $G$  is the gap between electrodes (1) and (3). Indeed, this value affects the propagation speed of the ionized species, as discussed in [8]. From current and voltage curves, the total energy consumed by the discharge is evaluated. As a reminder, it has been demonstrated previously that the input energy is strongly linked to the pressure wave intensity [3, 7]. The energy consumed by the discharge is computed as the addition of the pulsed and DC contributions. Figure 4-C presents the energy variation as a function of the mean electric field for  $V_P = 16$  and 20 kV, for G40, G60 and G80 configurations. On one hand, the total energy consumed by the three-electrode actuator is constant (0.24 mJ/cm for  $V_P = 16$  kV) and equal to the pulsed contribution when  $V_{PD}/cm < 6.5$  kV/cm because there is no sliding discharge as indicated by iCCD images (data not shown). On other hand, when  $V_{PD}/cm$  exceeds 6.5 kV/cm, the sliding discharge is established and total energy increase gradually (1.25 mJ/cm for G60). This result is consistent with AC sliding discharges results which are reported in [5] where the same threshold of 6.5 kV/cm has been observed.

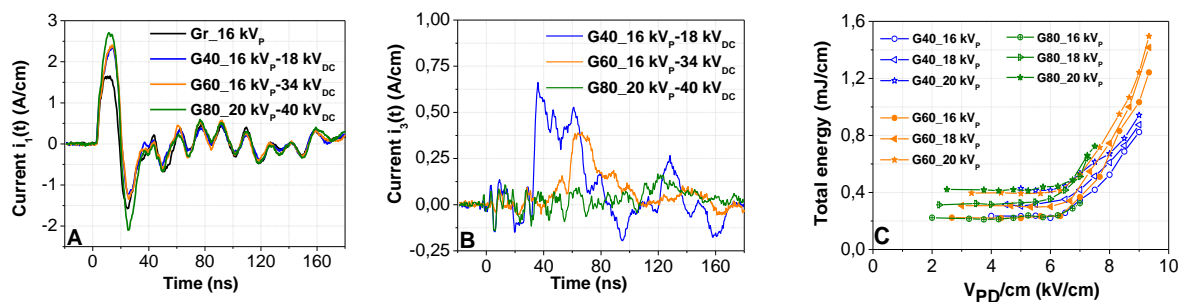


Figure 4 : Current waveforms measured at electrode (1) (A), at electrode (3) (B) and total energy consumption as a function of the mean surface electric field (C).

### 3.3. Optical characterization of the induced pressure wave

The last experiment is addressed to the pressure wave characterization through shadowgraph images. For all the configurations, Figure 5 shows side views of the air density gradient (pressure wave topology) at  $t = 30 \mu s$  after the discharge ignition. By investigating the position of the wave front versus time, a propagation of the wave at 351 m/s has been observed, as in [3, 7, 10]. For the reference case, the pressure gradient consists of a hemispherical wave and a planar one. The first one, originating from the edge of electrode (1), is attributed to the release of electrical energy transformed into a sudden localized heat source. The planar wave is suggested to be caused by the plasma extension over the dielectric surface. The present investigation confirms this hypothesis. Indeed, when

the sliding discharge is ignited, the planar wave extends from electrode (1) to electrode (3), as the surface discharge. Finally, one can remark the presence of a second hemispherical wave located at electrode (3) with the three sliding discharges, certainly due to a heat release induced by the current  $i_3$ . Concerning the pressure wave intensity, the shadowgraph images allow us to estimate it qualitatively through the grey level of the images. For instance, on the reference image (Gr in Figure 5) it can be observed that the rear half part of the spherical wave is less bright than the forward and front parts, indicating that the pressure gradient of the wave is maximum downstream electrode (1). For the sliding discharges, the intensity of the second spherical wave at electrode (3) is weaker than the one occurring at electrode (1). This can be explained by the lower amplitude of current  $i_3(t)$  compared to  $i_1(t)$ .

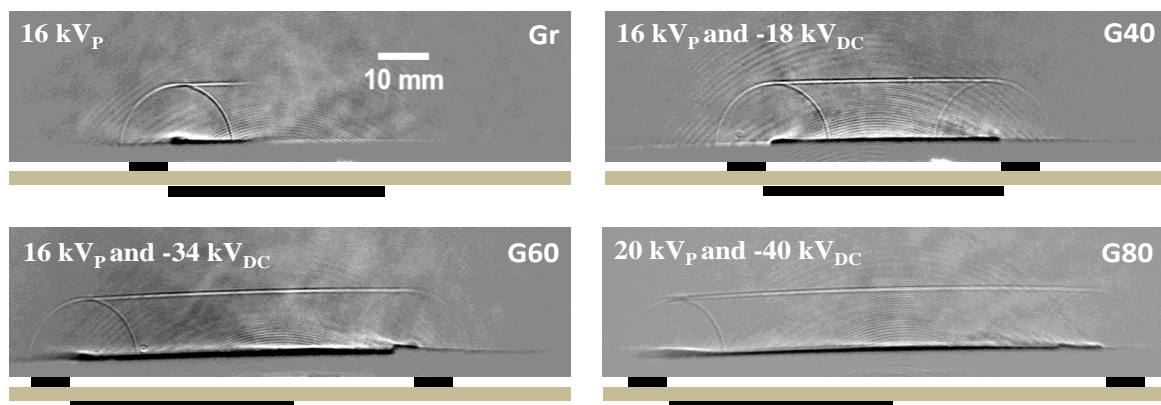


Figure 5 : shadowgraph images of the induced pressure wave for the studied configurations

#### 4. Conclusion

A single nanosecond dielectric barrier discharge based on two-electrode design and a sliding one that uses three electrodes are compared by electrical and optical diagnostics. The sliding discharge can be established over the dielectric surface, in the region located between both air-exposed electrodes, if the mean electric field is higher than a threshold value equal to 6.5 kV/cm. Moreover, the energy consumed by the sliding discharge is three or four times the one needed for a single DBD. The sliding discharge induces two spherical pressure waves which are linked by a planar one. Consequently, that should enhance the interaction region between the incoming flow and plasma.

#### 5. References

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