Spatial and temporal evolution of microdischarges in Surface Dielectric Barrier Discharges for aeronautical applications plasmas

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Abstract. Surface Dielectric Barrier Discharges have been proposed long ago as a tool to improve aerodynamics and flow performances. Such electrical discharges could be employed to energize the gas phase and to induce flows. The discharge itself consists of a large number of repetitions of single electric current pulses, with short duration and limited spatial extension filling the region near electrodes. The connection between such macroscopic effect and the properties of the single microdischarge events has been investigated. In particular we have measured the direction and the velocity of propagation of the ionization wave during the different phases of the voltage cycle. Light collected from different parts of the gap arrives at a photomultiplier tube with a delay proportional to the velocity of the ionization wave. The measured propagation velocity was estimated as about 220 km/s in the so called backward discharge phase.

1. Introduction

Non equilibrium plasmas produced by Surface Dielectric Barrier Discharges (SDBD) have been proposed long ago as a tool to improve aerodynamics and flow performances [1-3]. Indeed a new sector of plasma application was started when it was realised that such electrical discharges could be employed to energize the gas phase and to induce flows [1]. Plasma aerodynamics soon developed into a lively field of applied plasma research. Although many aspects of the mechanisms through which plasmas could induce flows are not fully understood, some general features of the phenomenon has been clarified [1]. DBDs and so also SDBDs driven by high voltage oscillating signals applied to electrodes happen generally in short bursts of activity, concentrated in two separated portions of the wave period. They are composed of a pretty large number of individual events, carrying electrical currents in the air gap between the electrodes, a microdischarge [4], each triggered by the propagation of an ionization wave [5-6]. There are several tricky aspects, including the geometry of the electrodes and the charging of the dielectric material surface facing the discharge region. In particular the asymmetry in the two portions of the discharge is considered to be essential in the production of the so called ionic wind [7-9].

Here we presents results concerning the properties of microdischarges obtained by time resolved optical diagnostics using a photomultiplier tube (PMT) [6]. In particular we have measured the
direction and the velocity of propagation of the ionization wave during the different phases. Light collected from different parts of the gap arrives at the PMT with a delay proportional to the velocity of the ionization wave. In order to better separate the events we have introduced fixed delays using several optical fibers of different length.

2. Experimental Setup
The main characteristic of a DBD device is the insertion of a dielectric material separating the two electrodes. In this way the discharge path in the gas gap cannot connect directly the two electrode surfaces and charges accumulates on the dielectric surfaces, quenching the electric current flow. Steady operation is normally achieved by applying an oscillating voltage to reverse charge flow. In general this could be most easily accomplished by feeding one of the electrodes with a HV signal at kHz frequencies. At atmospheric pressure, in millimetre scale gap, the DBDs operate in the so called streamer regime characterized by narrow current filaments (radius below a hundred microns, length a few mm), with very short lifetimes (few tens of ns) [4].

In our experimental setup the electrodes for SDBD have been separated by a rectangular dielectric plate (220x200x5 mm). We used Plexiglas or Teflon, with a dielectric constant $\varepsilon_r$ respectively of 2.3 and 2.05. The lower electrode in aluminum (40x180x10 mm) was embed into a plexiglas scaffold (330x200x20 mm). The upper electrode was made of a tin clad copper adhesive foil (60 µm thick, 5 mm wide) glued onto the upper side of the dielectric plate. The two electrodes lie parallel with the edges just corresponding in order to avoid any overlap. A layout of the set-up is sketched in figure 1.

In such a setup discharges happen only in the air just above the upper side of the dielectric plate, usually around the upper electrode edge. Current filaments have one end on the exposed electrode and they extend more or less perpendicularly to the electrode edge towards the dielectric surface above the buried electrode. Current filaments then remain practically confined to a thin layer above the surface. This corresponds roughly to the region of the air gap where the electric field strength is maximum.

![Figure 1. Layout of the experimental setup with diagnostics.](image-url)
The directionality of the discharges, the asymmetry between currents starting or ending on the exposed electrode and the confinement on the surface are ideal features for any aerodynamical applications, since the whole electric activity of the plasma actuator could be concentrated in the boundary layer of the flow [2,7].

In order to drive the SDBD the buried electrode is connected through an HV cable to the secondary coil of a transformer, whose primary circuit is connected to a tunable power generator, providing the driving high voltage for the discharge. We used a V-20 Corona Station by Tigres Gmbh. Alternating voltage frequency is varied automatically between 18 and 50 kHz or it can be fixed depending on the operating choices. The upper electrode is grounded. A high voltage probe, P6015A by Tektronix, has been used to monitor the voltage on the upper electrode. The probe is granted for a bandwidth of 75 MHz, which is sufficient for assessing the effects on the circuitry voltage of the dynamics of streamers. In general an almost purely sinusoidal voltage was recorded, without any significant amplitude modulation, even during discharges at high power level. This ensures that the discharge phases happens only two times during the HV cycle, without the ripples and stasis sometimes reported in literature. In the setup we have also included a probe for the discharge current. A current transducer like a Rogowski coil is suitable to measure electric current filaments. As already discussed in a dedicated paper [8], we were able to study current pulses characteristics like number, amplitude, duration and charge transported [9]. A capacitance in series with the electrode setup have been used too in order to measure the effective power absorbed by the microdischarges as well as the total charge accumulated on the dielectric surface [9].

To sum up our findings, the signal results to be composed of two well separated burst of activity, one in each HV half-cycle. The two disjointed active phases are known as Forward Discharge (FD) and Backward Discharge (BD), referring to the electron motion from the exposed electrode to the dielectric surface or the other way. The two phases are composed of several current peaks, a few tens of ns in duration, corresponding to single microdischarges, filling a definite part of the HV cycle. Here we are primarily concerned with the light emitted from the discharge. We have already reported about the measured emission spectra of the discharges in a spectral band extending from 200 to 850 nm by means of a wide band, low resolution spectrometer (PS2000 by Ocean Optics) [9]. Spectra are typical of DBD, with the brightest feature being the 2nd positive system of nitrogen, emitted from the N2(1Πg) excited level of the molecule. Spectra shows also the presence of nitrogen molecular ion N2+, whose most intense emission line is at 391 nm [10]. In order to reconstruct the temporal evolution of the discharges we have used a PMT by Hamamatsu (H10721-210, having a 0.57 ns rise time) chosen for its fast temporal response and high sensitivity. Its ultra bialkali photocathode radiant sensitivity extends in the 230-700 nm range and peaks at 400 nm, closely matching the air DBD spectra [6]. Gain was maintained constant during experiments at 2x10^6 by regulating the potentiometer in the PMT supply circuit. The output of the PMT was registered by the low impedance input (50 Ω) of a large bandwidth digital oscilloscope (Agilent MSO8104A, 4 channels, time base 0.25 ns). As already discussed in similar experiments, the light emitted from each microdischarge appears in the PMT output as a few nanosecond pulse [6]. A typical signal is reported in figure 2. Here two events are displayed. Most events are single, when the PMT produces a typical triangular peak lasting 3±1 ns, which sets the best temporal resolution of our measurements. Sometimes, when emission lasts many nanoseconds, more partially superimposed peaks are recorded. They could be easily detected and separated. The overall duration never exceeds a ten nanoseconds. The light emitted from the microdischarge was collected by UV optical fibers FC-UV200-2 by Avantes.
Fiber material refraction index leads to a prediction of the signal propagation velocity $v \approx 2 \times 10^8$ m/s ($n=1.52$ at 400 nm), which means that each fiber, 2 m long, provides a delay of 10 ns. A four-furcated optics fiber FCB-UV200-2 by Avantes was used to merge signals arriving from up to four different viewlines. In order to increase the light collected, we imaged the discharge surface of the dielectric plane onto the fiber optics inlet by means of a commercial objective lens (1:2.8/F=50 mm by Durst). A CMOS camera MV-D1024 by Photon Focus was used to take pictures of the discharges. One of such pictures is shown in figure 3, where the resolution is 1 pixel = 11 µm. In these experiments the upper electrode was sectioned separating a pin 1 mm wide from the rest of the electrode. This ensures that microdischarges happen preferentially at the sharp ends of the pin and remain somewhat locked there. Although several microdischarges could be superimposed in the picture due to the quite long exposure time, the spatial extent of the events could be evaluated. A discharge pattern of a few millimetres can be anticipated from figure 3. The viewfield of the fibers was adjusted just to look this part of the electrode region. By back-illuminating the four-furcated fiber we have aligned the light spot of the four fiber endings to the pattern (at an height of about pixel 550 in figure 3). In these experiments the first channel pointed directly at the pin electrode lower edge (position (200,550) in pixels on figure 3), while the second channel pointed the dielectric surface downstream (position (410,550) on figure 3). The other two channels are even more downstream along the dielectric surface and cannot collect light in the present setup. We plan their use in subsequent experimental campaigns. We have precisely measured the distances between light spots, whose diameter was estimated 0.9 mm. Such distance, here 2.3 mm, could be used to evaluate the discharge propagation velocity. Then we could start collecting light with the PMT.

Figure 2. Two examples of the signal recorded from the PMT showing one or more sharp peaks.

The threshold, here 10 mV, used to count events was shown too.
3. Experimental results
As already discussed in the previous section, we have analyzed the delay between the PMT signals arriving from different spot along the discharge path. By subtracting the delay due to the variations in the optical fiber path length we have a measure of the absolute emitting time differences from different parts of the discharge. In order to achieve the maximal time resolution, multiple peaks like those reported in figure 2 were discarded. This greatly reduce the spread in the measured delays.

At first we selected signal coming from view-lines observing the same spot on the dielectric plate. The short duration of the discharges allows to check the theoretical delay caused by the optics fibers. A histogram of the relative frequencies of the difference between measured and theoretical delays show a nice sharp peak at about zero nanoseconds. This was reported for any two couple of channels and various delay fiber length, as could be grasped by the examples displayed in figure 4a. A Gaussian fit to the peaks was used as a value of the measured delay. As reported in figure 4b, a nice linearity was obtained by increasing the difference in the optical path between any of the two channels of the four-furcated fiber. A linear fit to the reported delays vs fiber length was used to measure the effective speed of light travelling along our fibers. This comes out to be $v = 1.93 \pm 0.01 \times 10^8$ m/s, corresponding to a refractive index of 1.56$\pm$0.01. This refers to the near UV region, since the DBD emission spectra are dominated by the nitrogen second positive system, which matches quite well the 300-500 nm peak sensitivity of the PMT [9,10]. By inverting the delay length of the two viewlines we could also confirm that no bias in the delay was introduced. Indeed the linear fit yields an intercept of 0.01$\pm$0.11 ns, consistent with no asymmetry at all.
Then we started viewing two different locations. As an example we show in figure 5 the delays measured between two twin PMT peaks collected in two points 2.7 mm away one from the other (see figure 1) as a function of the expected lag due to the difference in the optical path through the optical fibers. The first channel collects light from a viewline looking just at the edge of the exposed electrode, while the second viewed the region of the dielectric above the buried electrode. The power

- Fig. 4. (a) Relative frequency histogram of the differences between measured and theoretical delays for first and second channels (□, total length 8 m) and first and third (○, total length 12 m).
(b) Measured delay as a function of the delay fiber length, with a linear fit to data.

- Fig. 5. The measured delay peak as a function of the calculated delay imposed by the fiber length mismatch for backward discharge events at 94 W.
level was 94 W, corresponding to an HV amplitude of 8.9 kV and a frequency of 44.3 kHz. The first channel recorded about 450,000 events/s, with an average amplitude of 50 mV and a mean duration of 2.6 ns. The second channel count rate was smaller, about 80,000 events/s, with a similar mean amplitude and a slightly larger duration of 3.2 ns. When we recorded both channels simultaneously, we selected events belonging to the backward discharge. This corresponds to events where the voltage of the exposed electrode is positive and rising. In a typical dataset we collected about 300 events, whose relative delay is less than 500 ns. A delay histogram of count frequency was calculated as in figure 4 and the peak was fitted with a Gaussian peak. In general only one well defined peak was observed, containing about one third of the whole delay dataset. The results are presented in figure 5 showing the value of the delay peak.

![Figure 6](image-url)

**Figure 6.** Time lag between the two channels as a function of HV instantaneous value (a) or phase (b).

It is clear that a definite time lag is present between the two channels, independent from the preset delay. The nice linearity allows to estimate a time lag of 12.1 ± 0.6 ns. This corresponds to a propagation velocity of 223 ± 11 km/s directed from the edge to the dielectric surface. This direction is opposite to that of the drifting electrons (backward), somewhat parallel to that of the electric field.

Then we analysed also events belonging to the forward discharge. Unfortunately, while the count rate in the first channel was high enough, actually even larger than that of the backward events [6], the same does not hold for the second channel. Here only the 15% of the events happens in the forward stroke. We tried to reconstruct a delay histogram without finding any definite peak, at least for delays shorter than 500 ns. Due to the limited statistics we can neither estimate nor exclude a propagation, although it is confirmed that most of the FD events develops at or very near the edge of the exposed electrode and do not spread much on the dielectric surface. A better result could be achieved by collecting separately the two viewline channels and triggering only on FD events happening in the second, which however requires the use of two PMT. This will be performed in future developments. We also tried to measure the delay between the viewline looking the edge of the electrode and the
others further away on the dielectric surface, distant 5.4 and 8.1 mm from the edge (see figure 1). Again the small number of events, belonging to both BD and FD, from these faraway viewlines prevented us to collect a suitable dataset of delays.

Finally, using the segmented acquisition function of the scope, we accumulated statistics of events happening in a definite and limited range value of HV amplitude. A clear, albeit somewhat noisy, dependence can be appreciated from the data reported in figure 6. The time lag decreases steadily from the breakdown voltage, here at a phase of about 15°, up to the highest amplitude. The propagation velocity, always directed from the electrode edge towards the dielectric, increases from 130 to 250 km/s. These velocities are comparable for instance to those measured in the propagation of streamers in ambient air [11].

4. Conclusions

We have measured the direction and the velocity of propagation of the ionization wave during the development of a microdischarge in a surface dielectric barrier discharge. The measure was inferred from the time lag between two nearby events recorded with a phototube and collected from two different viewlines looking at two positions apart on the discharge region. We succeeded in measuring the velocity of propagation of the backward discharges which turned out to be about 200 km/s. Such velocity appears to increase as the applied external voltage is rising. The proposed method could be applied to study different groups of microdischarge events and different regions of the electrode as well as of the dielectric surface and results could be correlated with the findings of macroscopic diagnostics, in particular with the efficiency of aerodynamical effects or the predictions of numerical simulations of SDBD.

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