Development of a trielectrode plasma curtain at atmospheric pressure

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The development of a nonequilibrium, low-power, trielectrode plasma curtain at atmospheric pressure is presented. The discharge is based on the combination of an ac dielectric barrier discharge with a dc corona discharge in a three electrode system, and can be sustained for large time periods and over interelectrode air gaps up to 20 mm and with an electrode length of \( \sim 10 \) cm in the transversal direction. The discharge is composed of a train of streamers, with a repetition frequency in the range 50–200 kHz, and carrying an average current in the range 0.1–0.4 mA. The geometry of the discharge makes it appropriate for gas decontamination. © 2008 American Institute of Physics. [DOI: 10.1063/1.2960996]

Presently, there is a well-known interest in the development of nonequilibrium, low-power, atmospheric plasma sources because it is kept out expensive vacuum equipment for several processing applications with these plasmas. In practice, these sources have been employed in microelectronics,1 surface modifications,2 light sources,3,4 surface sterilization,5 and gas decontamination,6 among others.

Devices based on dc corona discharges (CDs) with two active electrodes enable to establish ionized regions with considerable air gaps but they seem to be not very practical. Even though some factors may improve the discharge behavior (for instance, air flows in the discharge regions or ballast resistors in the circuits), problems related to ignition, spark transition, and nonuniform distribution of the discharge along the electrode side length are usually present. The ac dielectric barrier discharge (DBD) devices7 can overcome some of the quoted CD difficulties, but the ionization in these kinds of devices has been in general restricted to the vicinity of the electrodes resulting in ionized air gaps of a few millimeters length.

Based on the combination of a DBD with a CD in a three electrode system, we present here the development of a trielectrode plasma curtain (TPC) discharge that can be sustained for a long time, over interelectrode air gaps up to 20 mm and with an electrode length of \( \sim 10 \) cm in the transversal direction. The TPC is an extension of a previously published sliding discharge, in which a pure DBD is “stretched” along a dielectric surface by the action of a negative CD generated between one of the DBD electrodes and a remote third electrode.8

The schematic of the experimental setup is shown in Fig. 1. The electrode arrangement consisted in two flat aluminum foils (electrodes 1 and 2) with 50 \( \mu \)m thickness, 25 mm width, and 150 mm length in the \( z \) direction (see Fig. 1), air exposed and flush mounted on two polymethylmethacrylate dielectric surfaces with 4 mm width. There is a third not air-exposed electrode (electrode 3) with a 50 \( \mu \)m thickness, 5 mm width, and 150 mm side length in the \( z \) direction, located at the opposite side of the dielectric surface holding electrode 1. The specific positions of the electrodes relative to the dielectric plates are indicated in Fig. 1. The length \( d \) of the air gap was variable in the experiment. The electric circuit consisted of a positive variable dc and an ac power supply (continuous voltage \( V_{dc} \) in the range 0–20 kV and an alternating peak-to-peak voltage \( V_{ac} \) in the range 0–23 kV) connected in series to electrode 1. Occasionally, the positive dc source was replaced by a negative variable dc source and connected to electrode 2. The ac power supply consisted in a function generator coupled to an audio amplifier (of 700 W) that fed a high voltage transformer coil.9 For our circuit geometry, the optimum excitation ac frequency was 5.6 kHz. Electrodes 2 and 3 were each ground connected through 50 \( \Omega \) resistances that allowed measuring the TPC current \( I_{TPC} \) and the DBD current \( I_{DBD} \), respectively. The voltage applied to electrode 1, \( V(t) \), was measured with a HV probe.

FIG. 1. Schematic of the experimental setup.

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Note that the $I_d$ presented for $H_20849$ and $H_20850$ with 60 MHz of analogical bandwidth and 1 GSample/s of sampling rate.

In Fig. 2 typical waveforms of $V(t)$, $I_{TPC}$, and $I_{DBD}$ are presented for $d=15$ mm, $V_{dc}=20$ kV, and $V_{ac}=12$ kV (a) and 16 kV (b). Case (a) corresponds to a well-developed DBD between electrodes 1 and 3 but without TPC. For an enough high value of $V_{dc}$ [case (b)], the TPC is “turned on,” and a train of current pulses can be seen in the waveform of $I_{TPC}$. Note that the $I_{TPC}$ pulses appear only during the positive cycle of the DBD. The TPC discharge was identically developed when the positive dc source connected to electrode 1 varied in the range 50–200 kHz. The obtained values of $I_{TPC}$, and $I_{DBD}$ for $d=16$ kV, $V_{dc}=12$ kV (a) a $H_20850$. Current scale 10 mA/div, voltage scale 5 kV/div, and time scale 50 μs/div.

(1000 × /3.0 pF/100 MΩ). These electrical signals were registered by using a four-channel digitizing oscilloscope with 60 MHz of analogical bandwidth and 1 GSample/s of sampling rate.

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The light emitted from the discharge was detected by a converging lens and a quartz optical fiber coupled to either the entrance slit of a spectrometer or to a fast photomultiplier tube (pmt). The discharge optical emission of the spectral bands corresponding to the 0-0 transition of the second positive system of N$_2$ ($\lambda=337.1$ nm) and the first negative system of N$_2^+$ ($\lambda=391.4$ nm) was registered. Following the model of Shcherbakov and Sigmund, the relative amplitude of these two lines allowed to determine the ratio $E/N$ ($E$ is the electric field and $N$ is the gas numerical density), resulting in $E/N=5 \times 10^{15}$ V cm$^{-3}$. By using appropriate slits covering the converging lens in a direction parallel to the filaments, the pmt signal allowed to determine the transit time of the filament along the slit. This transit time was $100 \pm 20$ ns for a 2 cm length slit, resulting in a filament average velocity of $(2 \pm 0.4) \times 10^{7}$ cm/s. Following the discussion of Ref. 8, it was concluded that the filaments were cathode-directed streamers.

To derive some meaningful information on the discharge characteristics in terms of the $V_{dc}$ and $V_{ac}$ values, the following procedure was adopted. By setting the oscilloscope in the average acquisition mode an average waveform of the current signal over 128 samples was acquired. This statistical-averaged signal was time averaged over one period of the ac voltage to finally obtain average current values $I_{DBD}$ and $I_{TPC}$ for the DBD and TPC discharge. When operating the discharge over long time periods (several minutes) it was found that the average current values remained constant, thus supporting the adopted procedure. The uncertainty in the averaged current values was estimated as ±10 μA.

In Fig. 4 $I_{TPC}$ as a function of $V_{dc}$ for $V_{ac}=20$ kV and with $d$ as a parameter is presented. All the points represented in Fig. 4 correspond to a well-developed DBD with $I_{DBD}$ ~75 μA. For a given $d$, there is a threshold value of $V_{dc}$ (dependent on $d$) that “turns on” the TPC, with a fast increase in $I_{TPC}$ for larger $V_{dc}$ values up to the point where sparking is ultimately produced.

The other important feature that characterized the TPC behavior was the amount of current pulses generated during the discharge. This amount was represented by an averaged frequency ($f^m$) that was obtained directly from the trigger frequency of the oscilloscope. It was found that $f^m$ was well correlated with $I_{TPC}$, indicating that a current increase in a TPC is due to an increase in the streamer frequency rather than a change in the characteristics of an individual streamer. The obtained values of $f^m$ varied in the range 50–200 kHz.
To summarize, we have developed an atmospheric non-equilibrium discharge that remains stable over air gaps of about 20 mm length and with side lengths of $\sim 10$ cm. The discharge is composed of a train of streamers, with a repetition frequency in the range 50–200 kHz, and carrying an average current in the range 0.1–0.4 mA. The electrode geometry and the discharge characteristics make it appropriate for gas decontamination.

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