Topic number: 6

Propagation mechanisms of positive streamers in air and other N_2:O_2 mixtures: photo-ionization versus background ionization

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Streamers are thin channels of ionized gas that are of significant importance in processes of atmospheric electricity (for example lightning and sprites) as well as in industrial applications such as lighting and cleaning of toxic gases. We distinguish between positive and negative streamers. Negative streamers propagate in the direction of the electron drift, while positive streamers move against the drift direction and therefore require a source of electrons ahead of the streamer head.

In most literature, this electron source is assumed to be photo-ionization: excited nitrogen molecules emitting a UV photon which ionizes an oxygen molecule elsewhere in the gas. Since the characteristic absorbtion length of these ionizing photons scales inversely with the oxygen density of the gas, one would expect the characteristics of streamers to change with changing oxygen density. However, experiments carried out in a vacuum vessel with a needle-plane electrode configuration have shown that streamers in different gases are remarkably similar even though the oxygen concentration is changed by a factor of 10^5 [1].

In the experimental setup, the distance between the needle and plane electrodes is 16 cm. A high speed ICCD camera is used to capture streamer images. Using short exposures, the velocity of the streamer is determined by the ratio of the streamer length and the exposure time. Figure 1 shows that the propagation velocity of positive streamers depends on the applied voltage, but changes very little with gas composition. The experiments in pure nitrogen still might include a small oxygen admixture, specified to be below 1 ppm, due to limitations of the supplied gas.

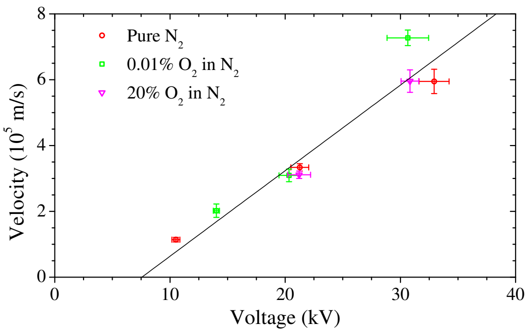

Fig. 1: Streamer velocities measured at 200 mbar for three different gasses. The horizontal error bars indicate the spread in the applied voltages, the vertical error bars indicate the sample standard deviation for 4–6 measurements. The velocities are measured roughly in the middle of the gap, except for the cases where the discharge does not reach this far (at lower voltages), in these cases, the velocity is determined at a position close to the end of the streamer channels.

As an alternative to photo-ionization as electron source, a homogenous background ionization of O_2^- and O_2^+ was suggested in [2] and has here been investigated in simulations. When a sufficiently high electric field is present, such as the field in front of the streamer head, electrons can detach from the oxygen ions. Estimates on the level of this background ionization range from 10^3 cm^{-3} (ambient air in buildings) to 10^7 cm^{-3} (residual ionization from repeated discharges with a 1 Hz frequency) to higher levels for discharges with higher repetition frequencies.

Numerical simulations were performed with a code using an adaptive grid refinement scheme [3, 4]. The model consists of a fluid description for the densities with drift, diffusion and reaction terms. Included reactions are impact ionization, attachment, detachment and recombination. Photo-ionization is included in some simulations using the Zhelezniak model [5] approximated by a set of Helmholtz equations [6]. The electrode configuration is needle-plane. Simulations are done at 300 K and 1 bar, using a voltage of 12 kV (4 mm gap) or 24 kV (8 mm gap).

The simulations show that both mechanisms produce propagating streamers. In N_2 with a 1 ppm admixture of O_2, there is very little difference in streamer velocity between both mechanisms, as can be seen in figure 2. In addition, streamer width and maximum electric field are similar as well. Observed velocities are in agreement with experimental data, as can be seen from a comparison of figure 1 and figure 2. Note that the streamer velocity does not depend on gas pressure: a scaling law that can be derived from a dimensional analysis of the model equations as well as from experiments [7].

Additional simulations using different photo-ionization models show that the streamer properties remain very similar. Even when the number of photo-ionization events in the simulation is artificially reduced by a factor of 10, the streamer velocity is only 20% lower. Additionally, simulations with different levels of background ionization in air show similar results: lowering the level of O_2^- from 10^7 cm^{-3} to 10^5 cm^{-3} results in a 20% lower propagation speed.

Both simulations and experiments show that positive streamers are remarkably insensitive to their electron source: both the mechanism as well as the number of source electrons have only a minor effect on propagation velocities.

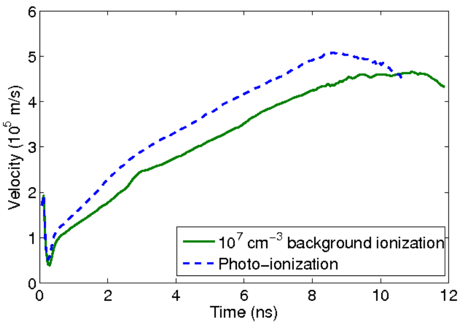

Fig. 2: Velocities of positive streamers in N_2 with a 1 ppm O_2 admixture. Simulations were done in air at 300 K and 1 bar with a 24 kV voltage over an 8 mm needle-plane gap.

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