How Photo-ionization and Background Ionization Affect Streamers and Sprites

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ABSTRACT: Positive streamers require either photo-ionization or background ionization to propagate. We have investigated the effects of these competing mechanisms by comparing diameters, velocities and structure of positive streamers in numerical simulations and experiments. We draw conclusions on the importance of photo-ionization and background ionization for streamers in atmospheric air and other N_2:O_2 mixtures. Furthermore, we provide an explanation for the presence of feather-like structures in streamers in nitrogen.

1. INTRODUCTION

Streamers are fast moving ionization fronts that appear during the first stage of sparks and lightning. However, they can also occur independently in plasma reactors as well as in sprites above thunderstorms and as the streamer corona of a lightning leader Streamers can propagate both with and against the direction of the electric field (positive and negative streamers). The downwards propagating channels of sprites are generally positive streamers. Despite propagating against the electron drift direction, positive streamers emerge more easily and propagate faster than negative streamers [Briels et al., 2008, Luque et al., 2008]. Contrary to negative streamers, positive streamers need a source of electrons in front of the streamer head in order to propagate. This source can be either photo-ionization or background ionization. Background ionization in the form of negative ions can come from ionization generated by radioactive materials such as radon, from cosmic or solar radiation or from leftover ionization from a previous discharge in a situation with repetitive discharges. We have investigated the relative importance of these different sources of seed electrons on the propagation of positive streamers in standard temperature and pressure [Wormeester et al., 2010] and we will

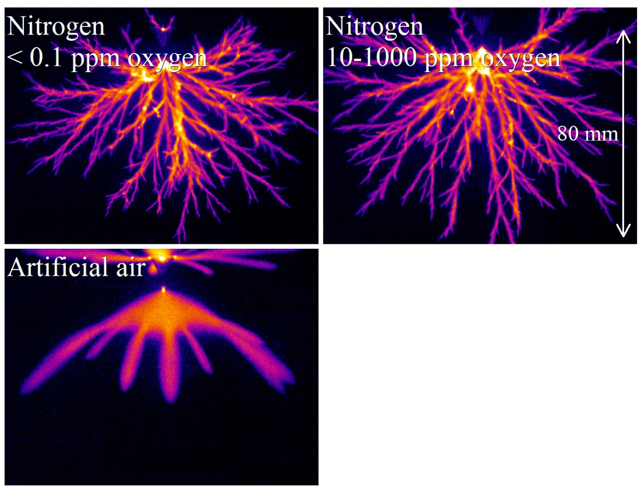

Figure 1. Experiments of streamers in a 16 cm needle-plane geometry. A positive voltage pulse of 25 kV is applied to the needle electrode. Pressure is 200 mbar, temperature is room temperature. Figure reproduced from

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extrapolate these results to other pressures and gas compositions at the conference. The effect of photo-ionization can be studied by altering the nitrogen-oxygen ratio, as the photo-ionization process involves an excited nitrogen molecule emitting a UV-photon which can ionize an oxygen molecule. The amount of ionizing photons scales with the nitrogen density, while the absorption length scales inversely with the oxygen density. Background ionization can be studied by altering the repetition frequency of repeated discharges or by adding radioactive admixtures.

2. EXPERIMENTAL RESULTS

Experiments were performed in a setup with a needle-plane geometry with a 16 cm gap between electrodes. The setup can be used for high purity gases (with impurities of 0.1 ppm or less, depending on the purity of the source gas) and pressures from 20 mbar to 1 bar. More details about the experimental setup and its results can be found in [Nijdam et al., 2010].

Figure 1 shows the results of experiments in various N_2:O_2 mixtures at 200 mbar. While the velocity and minimal diameter of the streamer seems to be very insensitive to the gas composition (values within one order of magnitude between different gases), the morphology of the streamers does change considerably. Streamers in high-purity nitrogen (less than 1 ppm of impurities) branch far more than streamers in air and the nitrogen streamers exhibit a feather-like structure, with small hairs connecting to the main streamer channels.

3. SIMULATION MODEL AND PARAMETERS

We have used the fluid code described by Luque et al. [2008] to simulate streamers. The code uses a fluid approximation for particle densities, where electrons drift and diffuse, while ions and neutrals are considered stationary. The electric field is coupled via Poisson's equation. Reactions included are impact ionization, attachment, detachment and recombination with rate coefficients taken from BOLSIG+ [Hagelaar and Pitchford, 2005] and Kossyi et al. [1992]. Photo-ionization is included using the commonly used model by Zheleznyak [1982] implemented in differential form by Luque et al. [2007]. Additional details of the model and its implementation can be found in [Wormeester et al., 2010].

The simulations were performed with a needle-plane geometry with a gap of 4 mm or 8 mm with a 12 or 24 kV potential between the charged needle and the grounded plate. The simulation volume was filled with artificial air (80:20 N_2:O_2) or pure N_2 with 1 ppm $O_{2,}$, both at standard temperature and pressure. In cases where background ionization was studied, a uniform level of O_2^- and positive ions was added. As an initial condition, a Gaussian seed of electrons and positive ions is added at the tip of the needle to initiate streamer formation.

4. SIMULATION RESULTS

We simulated streamers in air with either photo-ionization or varying levels of background ionization. The lowest level, 10^3 cm^{-3}, corresponds to the expected level of background ionization in buildings [Pancheshnyi, 2005], while the highest level, 10^7 cm^{-3} corresponds to the ionization remaining with repetitive discharges with a 1 Hz repetition frequency.

The results can be seen in figure 2. As soon as the background ionization level is

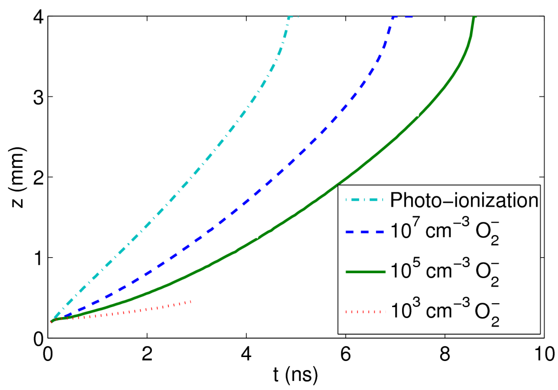

Figure 2. Streamer head as function of time for 4 streamers in air in a 4 mm gap. Simulations use either photo-ionization or background ionization. Background ionization

sufficiently high, streamers can propagate without photo-ionization. The level of 10^{3} cm^{-3}, corresponding to the expected level of ionization in “virgin” air, is not sufficient for positive streamers to propagate without the photo-ionization mechanism. Once a sufficient level of background ionization is present however, the time it takes for the streamer to cross the electrode gap doesn't depend strongly on the level of background ionization. Going from 10^{7} cm^{-3} down to 10^{5} cm^{-3} increases this time by only 20%.

In reality, both photo-ionization and background ionization will be present. We have therefore simulated streamers with both of these mechanisms present to determine which mechanism dominates streamer properties. In figure 3 it can be seen that photo-ionization dominates streamer propagation unless a very high level of background ionization, 10^{11} cm^{-3} or more, is present. This level corresponds to the residual ionization of repetitive discharges with a repetition frequency of 10 kHz. For all naturally occurring streamers in air at standard temperature and pressure, the influence of background ionization will be negligible.

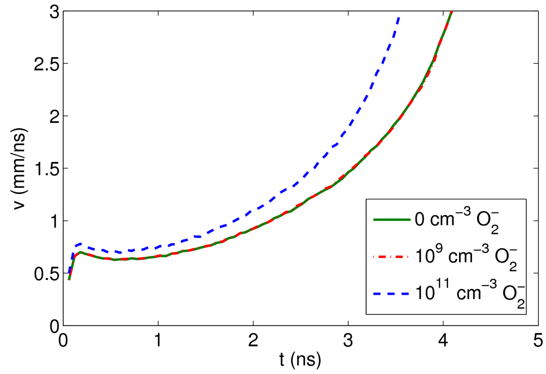

Figure 3. Velocities of streamers with photo-ionization and varying levels of background ionization in air. The

In nitrogen with a 1 ppm oxygen admixture, the role of photo-ionization is diminished as the characteristic absorption length of ionizing photons increases by over 5 orders of magnitude from 1.3 mm to 260 m. Nevertheless, photo-ionization alone is sufficient to generate propagating positive streamers with velocities and diameters that are remarkably similar to those in air. This was also seen in experiments as mentioned in section 2.

In near-pure nitrogen, the role of background ionization is more pronounced than in air, due to the lower amount of photo-ionization events. In figure 4 it can be seen that background ionization already has a noticeable effect on the propagation at levels of 10^{7} cm^{-3}. This level of background ionization corresponds to a repetition frequency of 1 Hz.

While streamers in nitrogen have velocities and diameters that are similar to streamers in air, the nitrogen streamers exhibit a feather-like structure with thin hairs connecting to the main streamer channel [Nijdam et al., 2010]. Such structures were not seen in air. We hypothesize that these hairs are avalanches started by individual electrons in the region where the electric field exceeds the breakdown field. In air, photo-ionization generates so many electrons that these avalanches overlap and are not distinctly visible. In high purity nitrogen, simulations show that the density of electrons outside the streamer is 3 orders of magnitude lower than in air, low enough for individual avalanches to be visible [Wormeester et al., 2011].

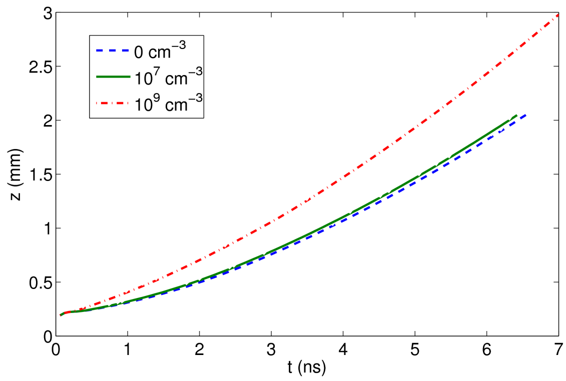

Figure 4. Position of streamer head of streamers in nitrogen with 1 ppm of oxygen with photo-ionization and varying levels of background ionization. The level of background

5. CONCLUSIONS

Despite needing a source of electrons in front of the streamer head, positive streamers appear to be remarkably insensitive to the amount and distribution of these electrons. Large changes in gas composition or background ionization level result in only small changes to the streamer velocity and minimal diameter, although streamer morphology does change with gas composition.

We have found that both photo-ionization and background ionization can provide sufficiently many free electrons for the propagation of positive streamers. Without photo-ionization, a minimum level of background ionization is required, 10^3 cm^{-3} was not sufficient to generate a streamer that crossed the electrode gap in air. In air, photo-ionization will dominate streamer propagation unless background ionization levels are very high, 10^{11} cm^{-3} or more.

In nitrogen with 1 ppm oxygen, photo-ionization still produced sufficiently many electrons for streamers to propagate, but due to the lower photo-ionization levels, the effects of background ionization were already visible at levels of 10^7 cm^{-3}, corresponding to a 1 Hz repetition frequency at standard temperature and pressure. Additionally, the lower level of free electrons outside the streamer can explain why feather-like structures were seen in experiments in nitrogen, but not in air.

The remarkable robustness of streamer properties under large changes of the gas composition or the source of the seed electrons encourages the investigation of the possibility of sprites and other discharge phenomena on other planets, such as Venus and Jupiter, where the photo-ionization mechanism as it is present in N_2:O_2 mixtures is absent [Dubrovin et al., 2010].

ACKNOWLEDGEMENTS

G.W. acknowledges support from STW-project 10118, part of the Netherlands' Organization for Scientific Re-search (NWO).

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