Feather-like structures in positive streamers

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In experiments of positive streamers, feather-like structures were observed in N_2 mixtures with an impurity level below 1 ppm, e.g. when the N_2 contains 1 ppm O_2 or less. These feathers did not appear in streamers in air. Based on numerical simulations, we provide a possible explanation for the difference in feather-formation in these mixtures.

1. Introduction

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 disinfection. 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 recent experiments by Nijdam *et al* [1], small hairs were observed connecting to the main streamer channels, giving the entire channel a somewhat feather-like appearance. These feathers were visible in “pure” nitrogen with at most 1 ppm contamination of oxygen, as can be seen in figure 1, and in pure argon. In air, no such feathers were observed.

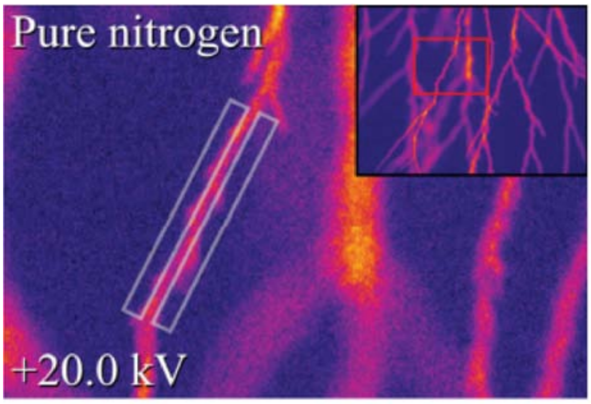

Fig. 1. Zoom to segments of positive streamers in nitrogen at 200 mbar. Hairs are inside the rectangular boxes. The picture is from [1].

2. Hypothesis on the origin of feathers

We hypothesize that the feathers are separate electron avalanches moving towards the streamer. Free electrons in front of the streamer head drift towards the streamer due to the enhanced electric field generated by the space charge layer in the streamer head. Once the electrons enter the region where the electric field is above the breakdown value, where the impact ionization rate exceeds the attachment rate, more free electrons are created than there are lost. This results in an avalanche that drifts towards the streamer head. This can be seen schematically in figure 2. If the avalanche is created directly in front of the streamer head, it will be overtaken by the propagating streamer and will therefore not be visible in experiments. Avalanches seen in experiments start away from the path of streamer propagation.

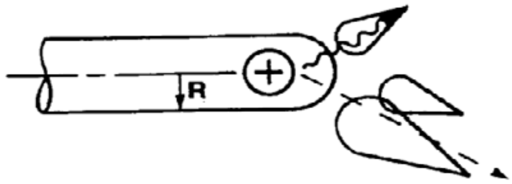

Fig. 2. Schematic representation of a positive streamer propagating from left to right as found in [2] and many other papers and textbooks.

If at the critical electric field, where the impact ionization and attachment rates are equal, the electron denisty is low, one expects that these avalanches do not overlap and can be seen as distinct structures. On the other hand, if the electron density is already high enough so that the average distance between free electrons is much smaller than the dimensions of the streamer, one expects so many avalanches that they will overlap and can no longer be seen as separate entitites, but only as a whole, being part of the propagating streamer.

The source of electrons in front and to the sides of the streamer head is assumed to be photo-ionization. An excited nitrogen molecule falls back to the ground level emitting a photon with the right energy to ionize an oxygen molecule. The characteristic ionization length of these photons scales inversely with the oxygen density and as a consequence, the density of free electrons in the region away from the streamer head are expected to be orders of magnitude higher in air than in nitrogen with only a very small oxygen admixture. Therefore we expect avalanches to overlap more easily in air, while in nitrogen with a 1 ppm oxygen admixture, the avalanches are more likely to be distinct.

3. Numerical simulations and results

Numerical simulations were performed with a code using an adaptive grid refinement scheme [3]. 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 as described in [4]. The electrode configuration is needle-plane. Simulations are done at 300 K and 1 bar, using a voltage of 24 kV with an 8 mm gap between the tip of the needle and the planar electrode. Since we use a fluid approximation, our code can not be used to model individual avalanches. For this, a particle code or a hybrid code such as [5] is needed. However, we can still use results from the fluid code to draw conclusions on whether the presence of hairs and the corresponding feather structure can be expected or not.

The left panel of figure 3 shows the electron density and the boundary of the region where the electric field exceeds the critical field and avalanches can occur; the simulation is in air. With the rate coefficients from BOLSIG+ [6] for impact ionization and attachment, as they were used in the simulation, this critical field is 32 kV/cm. It is immediately obvious that at the outer boundary, the electron density is already 10^5 mm^{-3}. This will generate so many avalanches that they will overlap and are no longer distinct.

Running the same simulation on a mixture of N_2 with 1 ppm O_2 gives completely different results. As can be seen in the right panel of figure 3, the electron density away from the streamer head is around 10^2 mm^{-3}. Additionally, the density of the attaching oxygen has been reduced by 5 orders of magnitude, so the critical field is lower than in air, which in turn means that avalanches can be formed at a greater distance from the streamer head. At these levels of electrons, the number of avalanches in this nitrogen mixture will be low enough in number to be visually distinct, resulting in observable hairs in experiments.

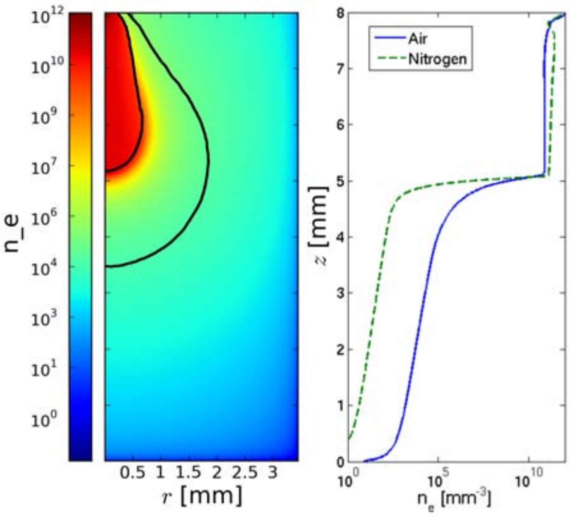

Fig. 3. left: Electron density in mm^{-3} of a positive streamer in air. Black line indicates where the electric field exceeds the breakdown value. Right: Electron densities on the axis of positive streamers in air (solid line) and N_2 with a 1 ppm O_2 admixture (dashed line).

We can estimate the number of hairs per mm of streamer length by counting the number of free electrons in the region where the field is above the breakdown field. As a first estimate, we obtain 400 electrons per mm in 2 boxes parallel to the streamer channel as depicted in figure 1.

In experiments in nitrogen at 200 mbar, 1.5 hairs per mm of streamer length were observed. Applying similarity laws for streamers [7], this corresponds to 7.5 hairs per mm at 1 bar. However, our simulations have a much higher background electric field and therefore electron densities will be much higher than in experiments. In addition, the precise level of O_2 contamination in the experiment is unknown. The 1 ppm level that we used in our simulations is an upper bound for the experimental value. Lower O_2 concentrations result in less free electrons and a lower hair density. Finally, not every free electron will end up forming a distinct avalanche. Indeed, electrons that are closer to the streamer may already be part of an ongoing avalanche, while we count them as source of their own avalanche.

Since our numerical code assumes cylindrical symmetry, a streamer can only be followed up to the point where it branches. This limits the length of streamers in nitrogen that we can simulate and therefore we can't directly match the parameters used in experiments.

4. Conclusion

We have proposed that the feather-like structures in positive streamers are due to individual avalanches created by photo-ionization. They are visible only in nitrogen mixtures with a very small admixture of oxygen, and not in air, since in air the avalanches are too dense and largely overlap. The numerical simulations with a fluid model, while not suited for simulation of individual hairs, have provided reasonable estimates of the avalanche density to support our hypothesis. Our estimate is an upper limit for the number of hairs. This number is lower in experiments because the local electric fields in the experiments are lower and the oxygen content is below 1 ppm, while 1 ppm was used in the simulations.

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