A future perspective on modeling streamer discharges: longer time scales and other gases

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Streamer discharges are the precursors of lightning leaders and sparks, they occur above thunderstorms as sprites, and they are used in diverse technological applications [1]. Because streamers develop strongly non-linearly at velocities of 10^5 to 10^7 m/s, numerical simulations have become a valuable tool to understand and predict their behavior. In recent years, quite some progress has been made in the modeling and understanding of streamers in air. Two examples that I was involved in are the comparison of single-streamer evolution between simulations and experiments [2] and the comparison of streamer branching between simulations and experiments [3].

Streamer simulations are usually performed with a fluid model, although more expensive particle simulations are sometimes also used. The cost of such 'microscopic' simulations is typically quite high, due to the thin charge layers that have to be resolved and due to the small time steps that have to be used to describe the electron dynamics. In many applications we want to consider multiple voltage pulses, combined with a complex chemistry. It is currently not feasible to perform 3D simulations of such phenomena. Similarly challenging is the study of the streamer-to-leader transition, which involves time scales on the order of microseconds or more, and typically also a complex discharge structure with many streamer branches.

Yet another challenge is that we are now often interested in streamers in gases other than air. In such gases, there are typically two main challenges: first, there can be a lack of input data, for example regarding electron-neutral cross sections, chemistry or photoionization parameters. Second, discharges in gases other than air often develop in a much more stochastic way than discharges in air, since photoionization in air is exceptionally strong. Such stochastic growth is intrinsically three-dimensional, and computationally even more expensive to describe than the relatively smooth discharge growth in air.

In this talk, I will give a future perspective on the modeling of streamers with these challenges in mind. I will discuss advances in numerical and computational methods, for example the use of large scale computations, GPUs (graphics processing units), or the development of alternative models such as the "kinetic Monte Carlo" method of Marskar [4]. Somewhat related is the topic of developing reduced models, in which we do not resolve the smallest temporal and spatial scales relevant for electrons. I will briefly discuss the present state of such models, and the remaining challenges before they can be used in practical applications. Yet another category of models are those based on data and machine learning, which I will also briefly mention. Finally, I will discuss what kind of input and experimental data could contribute to more accurate streamer discharge modeling.

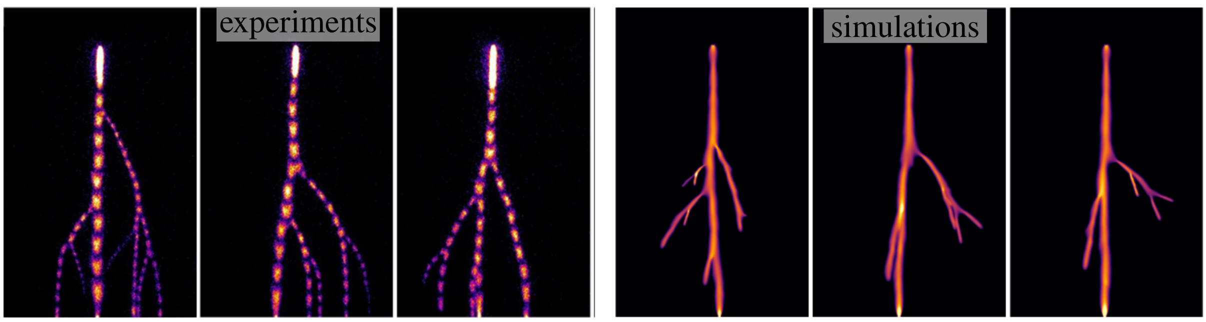

Fig. 1: Comparison of streamer branching between simulations and experiments, adapted from [3].

[1] Sander Nijdam, Jannis Teunissen, and Ute Ebert. The physics of streamer discharge phenomena. *Plasma Sources Science and Technology*, 29(10):103001, November 2020.

[2] Xiaoran Li, Siebe Dijcks, Sander Nijdam, Anbang Sun, Ute Ebert, and Jannis Teunissen. Comparing simulations and experiments of positive streamers in air: Steps toward model validation. *Plasma Sources Science and Technology*, 30(9):095002, September 2021.

[3] Zhen Wang, Siebe Dijcks, Yihao Guo, Martijn Van Der Leegte, Anbang Sun, Ute Ebert, Sander Nijdam, and Jannis Teunissen. Quantitative modeling of streamer discharge branching in air. *Plasma Sources Science and Technology*, 32(8):085007, August 2023.

[4] R Marskar and H K H Meyer. A kinetic Monte Carlo study of positive streamer interaction with complex dielectric surfaces. *Plasma Sources Science and Technology*, 32(8):085010, August 2023.