Avalanche-to-Streamer Transition in Particle Simulations

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Abstract—The avalanche-to-streamer transition is studied and illustrated in a particle model. The results are similar to those of fluid models. However, when superparticles are introduced, numerical artifacts become visible. This underscores the need of models that are hybrid in space.

Index Terms—Particle simulation, streamers.

STREAMERS are growing filaments of weakly ionized nonstationary plasma produced by a sharp ionization front that propagates into nonionized matter. Streamers are used in industrial applications such as lighting [1], ozone generation, and gas and water purification, and they occur in natural processes such as lightning and transient luminous events in the upper atmosphere [2]. Streamers can emerge from ionization avalanches in free space when the self-induced field becomes comparable to the applied field; this was recently reinvestigated in the framework of a fluid model in [3]. Reference [4] discussed that fluid models cannot be applied to avalanches in noble gas in a very low field; and in [5], striations were found in this case. In nitrogen and in intermediate fields, particle and fluid models give essentially the same results for planar ionization fronts, whereas there are growing deviations again at larger fields as discussed in [6].

Here, we show how a streamer emerges in a particle model from few seed electrons and a consecutive avalanche. The system is pure nitrogen at standard temperature and pressure in a constant high field of 100 kV/cm (equivalent to 42 Td). We assume that the electrodes are far away or do not exist as in many natural discharges. Qualitatively similar results in a fluid model are shown in [3, Fig. 1].

The particle model includes the complete electron velocity and energy distribution, as well as the discrete nature of particles. However, the required computation resources grow with the number of particles and eventually exceed the limits of any computer. This difficulty can be counteracted by using superparticles carrying the charge and the mass of many physical particles, but superparticles in turn create unphysical fluctuations and stochastic heating, as we will demonstrate hereafter.

The simulation starts from 100 pairs of electrons and ions at one point and follows the initial particles and their offspring up to 0.36-ns time. In Fig. 1, the simulated streamer is shown at two different times: $t = 0.18$ ns with real particles (first row), $t = 0.36$ ns with real particles (second row), and once again $t = 0.36$ ns, now in a superparticle simulation (third row).

At time $t = 0.18$ ns (first row), we have approximately 10^5 electrons, and the maximal field enhancement is ~1%. Therefore, the discharge is still in the avalanche phase. For the second row, de computation is continued with real particles, whereas for the third row, superparticles are introduced as follows. If a specified number of particles, in our case 10^5, is reached, a particle remapping is applied to reduce the number of computational particles; in this step, half of them are thrown away at random, and the weight of the remaining computational particles is doubled. At $t = 0.36$ ns, the total number of electrons is roughly 1.5×10^7 within the real particle simulation. The space-charge layer has clearly formed. The maximal field enhancement is ~50%. At $t = 0.36$ ns within the superparticle simulation, the total number of superparticles is about 7×10^4, each representing 256 real electrons. No charge layer has formed, but the charge density is noisy with a maximum inside the discharge. Clearly, superparticles here are not appropriate to deal computationally with large electron numbers. In [7], we describe how to circumvent the unwieldy runtimes of real particle models by using a hybrid model which couples particle and fluid models in different spatial regions.

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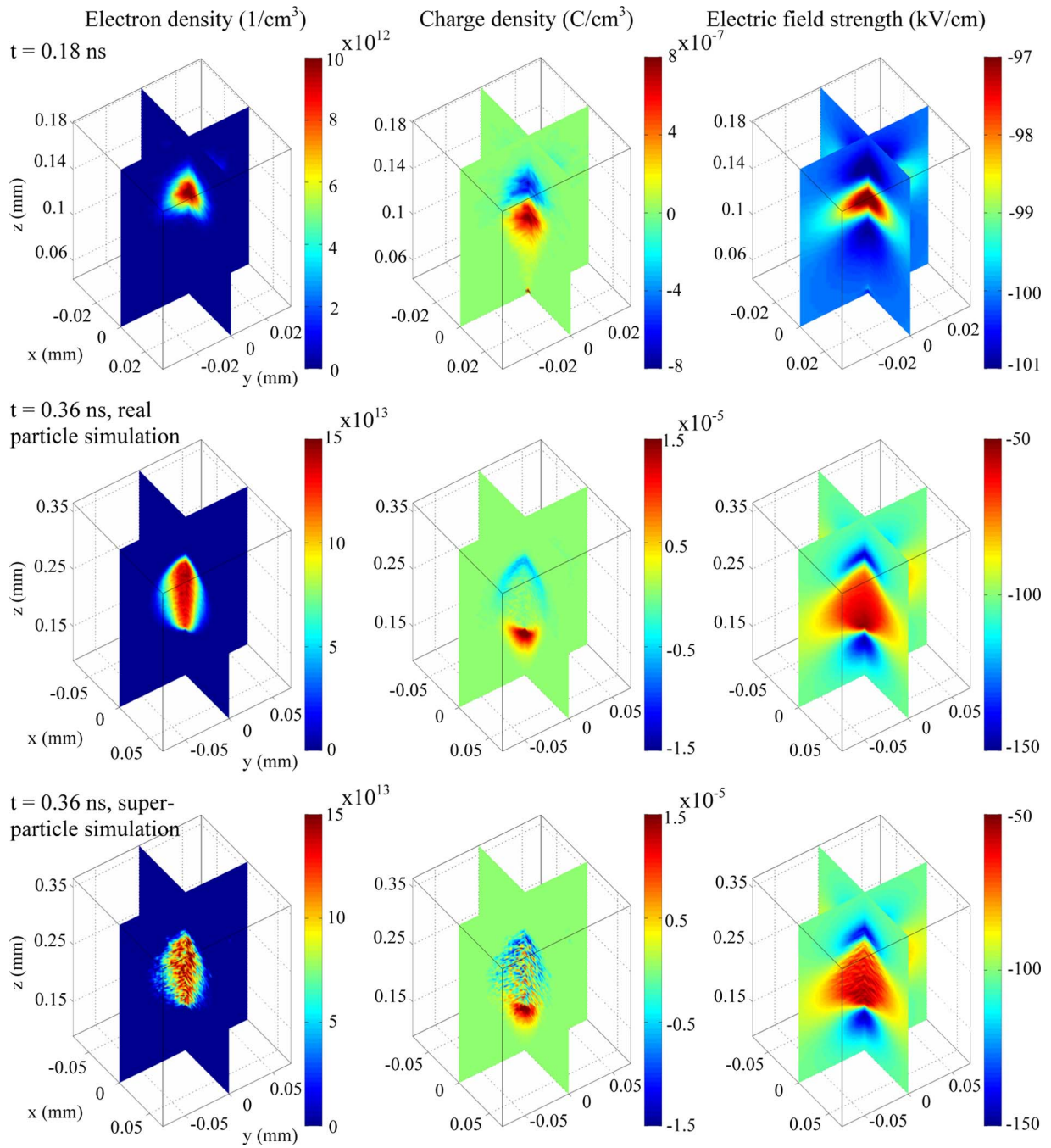
Fig. 1. Avalanche to streamer transition in nitrogen at standard temperature and pressure. A constant background electric field of 100 kV/cm points downwards. First row: avalanche of real particles at $t = 0.18$ ns, second row: streamer formed by real particles at $t = 0.36$ ns, third row: the same system at the same time $t = 0.36$ ns, but using super-particles with the mass of 256 real particles. The columns show from left to right: electron density, charge density, and electric field strength. Particle densities and fields are represented on two orthogonal planes that intersect with the 3-D structure.