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Particle and fluid models for streamers: comparison and spatial coupling

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Streamers are growing filaments of weakly ionized non-stationary plasma produced by a sharp ionization front that propagates into non-ionized matter within a self-enhanced electric field. They generically occur in the initial electric breakdown of long gaps. Streamers are used in industrial applications such as lighting, gas and water purification or combustion control, and they occur in natural processes as well such as lightning or transient luminous events in the upper atmosphere.

To understand ionization fronts and the growth of streamer channels, both fluid and particle models have been developed. Particle models follow the free flight of each single electron and treat their collisions with the neutral background gas molecules stochastically. They deal with the streamer dynamics at microscopic level and contain all the relevant physics. 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 super-particles carrying the charge and the mass of many physical particles, but super-particles in turn create unphysical fluctuations and stochastic heating [1].

Fluid models, on the other hand, approximate the electrons and ions as continuous densities. They are computationally efficient in regions with large particle densities like the interior of a streamer finger. However, the fluid model contains less physics than the particle model, and the density approximation also has other drawbacks in describing the streamer dynamics at the ionization front. For example, the statistics of few single particles in the front can create fluctuations of velocity and ionization rate and might trigger inherent instabilities. If the field is high, these effects are particularly severe, and the electrons are about to run away. The fluid model does not appropriately describe these interesting dynamics, in contrast to the particle model.

We have compared the properties of streamer ionization fronts of particle models and of conventional fluid models for negative planar fronts in nitrogen [2]; the transport coefficients for the fluid model were generated from swarm experiments in the particle model to maintain the maximal consistency between the two models.

The comparison shows that the ionization density behind the particle front is higher in the particle model while front velocities are similar. We have related this density discrepancy to the fact that the electron energies and, consecutively, the ionization rates in the leading edge of the front are considerably higher in the particle than in the fluid model. We found that this effect is due to the strong density gradients in the front, and not due to field gradients. So for high fields and consecutively strong density gradients at the streamer tip, there is a clear need for particle simulations, and particles, rather than super-particles, should be used to get physically realistic density fluctuations when modeling, e.g., the branching process of a streamer.

Therefore, a hybrid computation scheme has been developed that couples a fluid and a particle model in different regions of the ionization front [3, 4]. The basic idea is demonstrated in Fig. 1, namely to follow the single electron dynamics in the high field region of the streamer where the electron density gradient is steep, and to present the interior region with large numbers of slower electrons through a fluid model with appropriate transport coefficients. The optimal position of the model interface and the appropriate construction and length of the buffer region have been found [3], and an additional improvement of the fluid model by a gradient expansion will be discussed in [4].

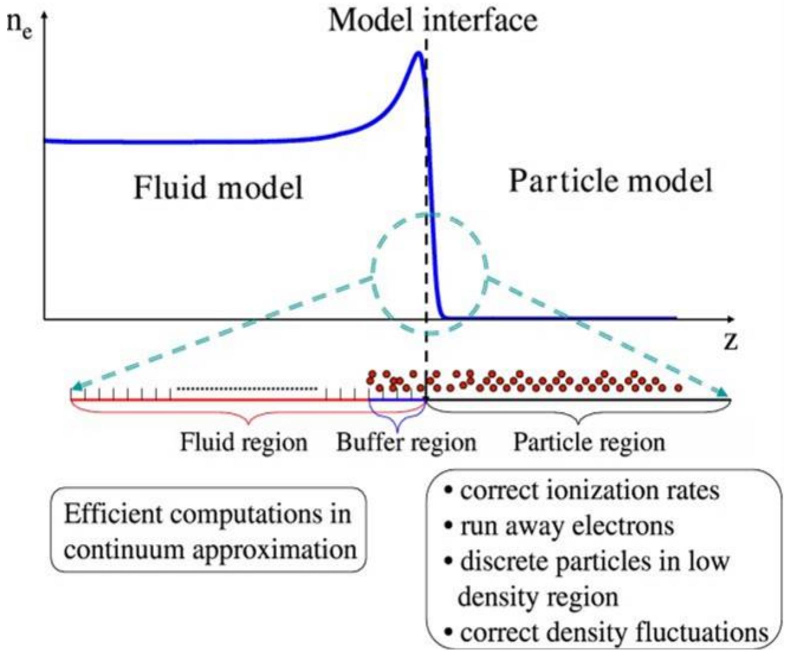

Fig. 1 The streamer ionization front, that here is indicated by the electron density $n_e(z)$, and its presentation by particle or fluid model in different spatial regions.

The coupling of particle and fluid model largely reduces computation times and computational memory requirement while maintaining the whole single electron physics in the relevant region of the ionization front. Moreover, since electrons with high energies are generated in the region that is represented by the particle model, run-away electrons (with subsequent X-ray production) and stochastic ionization avalanches can be modeled in a full streamer simulation, once the coupling is implemented in 3D.

Reference

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