Effect of fast electrons on streamer propagation simulated with a beam-bulk model for the production of TGFs

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We present results of beam-bulk model on self-consistent streamer dynamics and electron acceleration. The model combines a Monte Carlo Collision code that simulates the high-energy electrons (>100 eV) and a fluid code that simulates the bulk of the low-energy electrons and ions. In comparison to the results obtained with a classical fluid model for a negative streamers, the beam-bulk model predicts a decrease of the magnitude of the peak electric field and an increase of the streamer velocity due to high-energy electrons that move ahead of the streamer where they ionize the neutral gas. Due to the feedback of runaway electrons on the streamer propagation, production of runaway electrons by the streamers needs to be simulated including their self-consistent effects. That applies also to runaway models for justifying TGFs from streamer regions of lightning leaders.

1. Introduction

For last 25 years the atmospheric electricity has came to increased attention because of the discovery of electromagnetic and radiative processes occurring in the atmosphere above thunderstorms. Transient Luminous Events (TLEs) were firstly observed in 1989 [1]. Later, Terrestrial Gamma-ray Flashes (TGFs), the sub-ms bursts of photons from thunderstorms with energies reaching above 20 MeV, where discovered above thunderstorms in 1991 by the Compton Gamma-ray Observatory [2]. It is generally accepted that TGFs are bremsstrahlung from high-energy electrons accelerated in thunderstorm electric fields (e.g. [3]), but the mechanism responsible for the acceleration, and its relation with TLEs or lightning, is still debated. The theoretical models of TGFs build on the relativistic runaway electron avalanche (RREA) [4] which requires seed electrons with energies in the runaway regime. The question arises whether cold electrons could be accelerated into the runaway regime in the fields of streamers that feed a leader. In this contribution, we use a hybrid approach that couples fluid and particle models in order to study electron acceleration in streamers and the effect of energetic electrons on propagation of streamers.

2. Model

Negative streamers are simulated using a 1.5D model in a point-to-plane geometry. (e.g. [5, 6]). A beam-bulk approach proposed by Belenguer and Boeuf [7] is employed: electrons are divided in the energy space into two groups: a) the low energy electrons described by drift-diffusion equations [8] and b) the high energy electrons described by particles. The high-energy electrons are followed using the PIC-MCC code [9, 10] which is extended in energy with the relativistic binary-encounter-Bethe (RBEB) electron impact ionization model of Celestin and Pasko [11]. The interface in electron energy between the drift-diffusion and the PIC-MCC models is $100\,\mathrm{eV}$. This value corresponds to the energy of an electron having approximately the velocity of the streamer. For electrons with energies below $100\,\mathrm{eV}$ the electron mobility, ionization rate, attachment rate and diffusion coefficient for the drift-diffusion model have been tabulated from pre-computed swarm calculations using the PIC-MCC code in constant electric fields. Thus consistency between the two models is secured. Computer particles that lose energy to below $100\,\mathrm{eV}$ leave the PIC-MCC model and are injected into the fluid model by recalculating their density onto the grid mesh. The electrons injected into the particle model are calculated from a table of distribution functions precomputed in a constant electric field. Thus knowledge of the electric field and the electron density on the mesh allows to determine the probability that electrons reach energies above $100\,\mathrm{eV}$. The coupling of electrons across the energy interface is repeated at every time step.

3. Results

We consider a negative streamer propagation in point-to-plane electrode geometry for a point of radius $3.5\,\mu\mathrm{m}$, a gap of $1\,\mathrm{cm}$, and an applied voltage of $-25\,\mathrm{kV}$. The streamer radius is fixed to $0.5\,\mathrm{mm}$ at ground pressure. Simulations are performed without

pre-ionization or photoionization in order to emphasize the role of high-energy electrons with the time step of 10^{-4} ns and the mesh size of $5\,\mu$m. The discharges are initiated with a neutral gaussian plasma cloud composed of electrons and ions at rest with a density $10^{16}\,\mathrm{cm}^{-3}$ at maximum and standard deviation 0.5 mm placed in the vicinity of the pointed electrode. The results presented are for different altitudes: 0 km, 10 km and 20 km scaled to sea-level density.

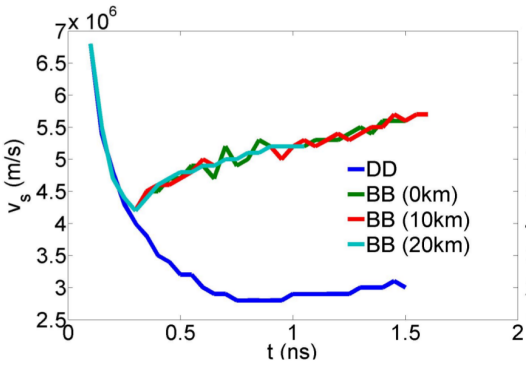

Figure 1: Streamer speed as a function of time simulated with the pure drift-diffusion (DD) model and the beam-bulk (BB) model. The beam-bulk model is shown at 3 different altitudes, scaled to 0 km altitude.

The streamer propagation velocities in the two models are shown as functions of time in figure 1. Once the streamers have developed, the velocity given by the beam-bulk model is almost twice as large compared to the velocity from the pure drift-diffusion model.

The peak electric field in the streamer head, $E_{\max}$, is shown in figure 2. When the streamers are formed, $E_{\max}$ reaches $\sim 7E_{\mathrm{k}}$ in the beam-bulk model and keeps almost constant value whereas the field in the pure drift-diffusion model reaches values above $9E_{\mathrm{k}}$ at the end of the simulation, where E_{k} is the conventional breakdown field.

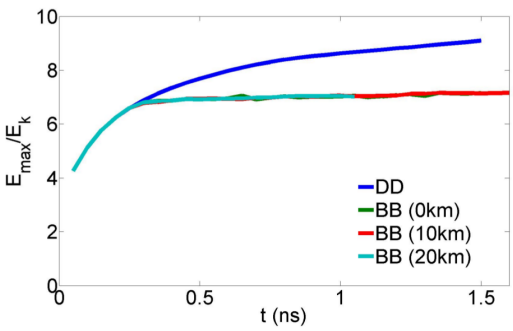

Figure 2: Maximum tip electric field, as a function of time simulated with the pure drift-diffusion (DD) model and the beam-bulk (BB) model. The beam-bulk model is shown at 3 different altitudes, scaled to 0 km altitude.

4. Conclusions

The results suggest that the effect of high energy electrons on streamer propagation is important on the velocity, peak electric field and thus, through diminished peak electric field, on eventual branching and on the production rate of runaway electrons. The runaway source mechanism is an important ingredient for better understanding of TGF observations expected from future space missions like TARANIS and ASIM in 2015/16.

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