Three Dimensional Modeling of Streamer Interaction

Feng Shi[1], Ningyu Liu[1] & Hamid Rassoul[2]
[1]Space Science Center, University of New Hampshire, Durham, NH, USA
[2]Department of Physics and Space Sciences, Florida Institute of Technology, Melbourne, FL, USA
Contact: Feng.Shi@unh.edu

University of New Hampshire

Introduction

- Streamers play important roles in the initiation and propagation of lightning, as well as in sprites [Rakov and Uman, 2003].
- The interaction of streamers have not yet been fully studied and understood.
- We have recently developed a 3-D streamer model, and report the simulation results of the interactions of two streamers developing in a $1.5E_k$ field, which may be found during the corona flash stage of the negative leader stepping [Bazelyan and Raizer, 2000].

Model

- Takes into account:
  - electron impact ionization
  - two-body and three-body electron attachments
  - electron-positive ion and negative-positive ion recombinations
  - drift and diffusion of electrons
  - photoionization

$$\partial n_e/\partial t + \nabla \bullet (n_e \mathbf{v}_e - D_e \nabla n_e) = (\nu_i - \nu_{a2} - \nu_{a3}) n_e - \beta_{ep} n_e n_p + S_{ph}$$

$$\partial n_p/\partial t = \nu_i n_e - \beta_{ep} n_e n_p + S_{ph}$$

$$\partial n_n/\partial t = (\nu_{a2} + \nu_{a3}) n_e - \beta_{pn} n_p n_e$$

$$\nabla^2 \varphi = -(n_p - n_e - n_n)/\varepsilon_0$$

- Streamers are initiated from two identical plasma columns:
  - peak densities 10^{20} m^{-3}
  - lengths 0.6 mm, radii 0.1 mm
  - Gaussian characteristic scales 0.2 mm
  - distance 0.3 mm between each other

Results

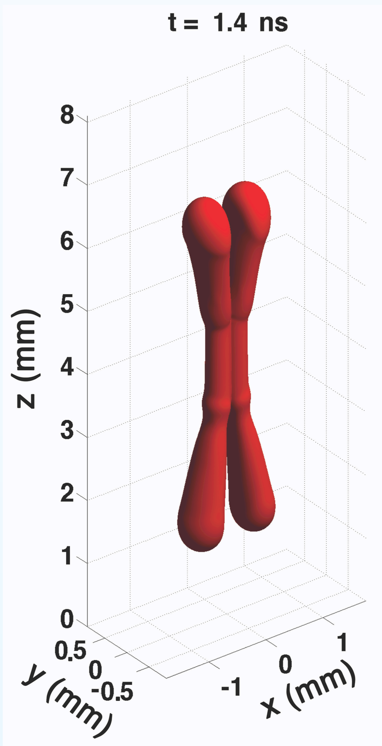

Figure 1: Surface plot of equal electron number density of 10^{19} m^{-3} for the discharge at ground pressure at t = 1.4 ns in a uniform field of 1.5 E_k pointing downward. Streamers with the same polarity strongly repel each other, so that they no longer propagate in the direction of the ambient field.

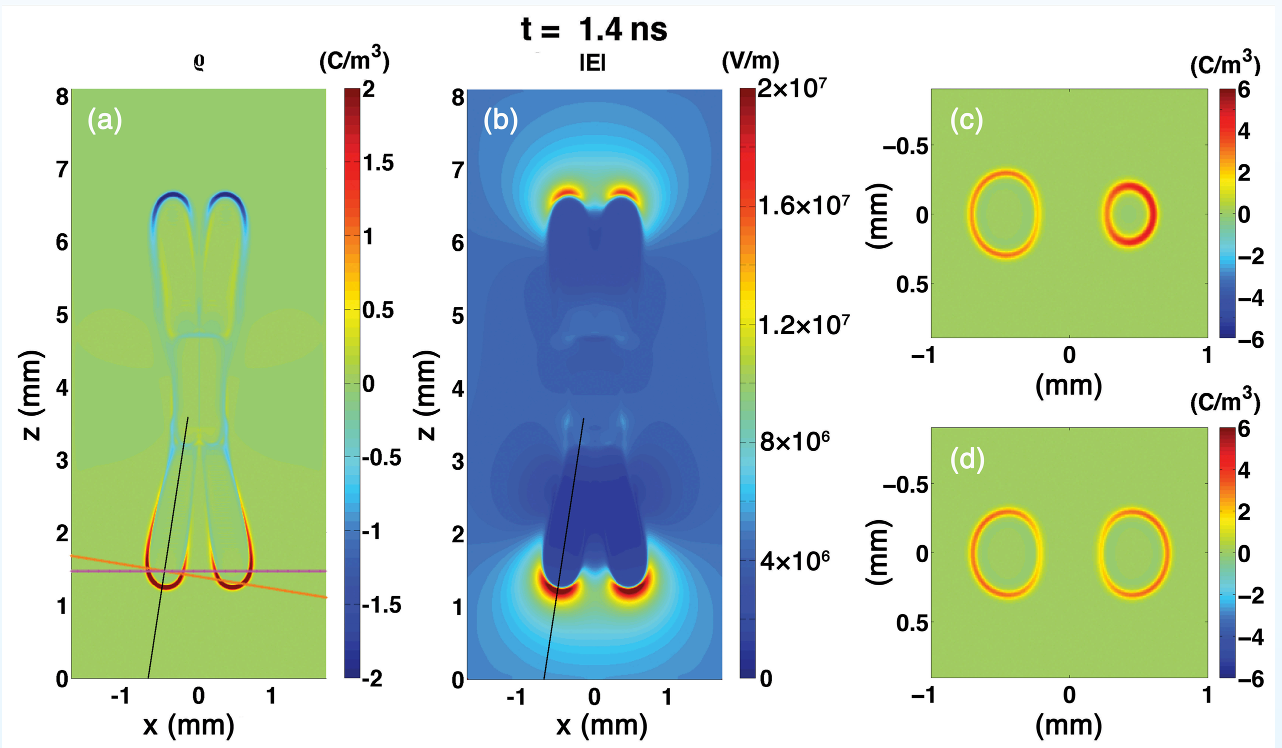

Figure 2: Cross sectional views at t = 1.4 ns of:
(a) space charge density on *x*-*z* plane (*y* = 0),
(b) magnitude of electric field on *x*-*z* plane (*y* = 0),
(c) space charge density on the plane perpendicular to *x*-*z* and denoted by orange line in (a),
(d) space charge density on the horizontal plane and denoted by purple line in (a).
No symmetry of the channels can be found due to electrostatic repulsion between streamers of the same polarity. Black line shows the propagation direction of the left positive streamer channel.

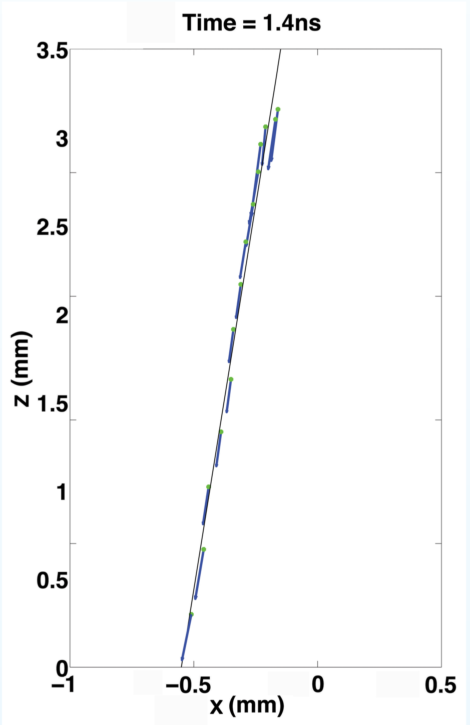

Figure 5: The direction of the peak field from t = 0.1 ns to t = 1.4 ns for the left positive streamer, showing that it remains in the same direction after the streamer is fully formed. The green dots and the blue arrows represent the peak field locations and directions at each moment of time, respectively. Note that the magnitude of the peak field has been rescaled so that the arrow direction can be clearly seen. The black line shows the predicted propagation path of the left positive streamer channel, as shown in Figure 2.

For interacting positive streamers, given the fact that the negative streamers are far away from positive streamers and thus can be neglected, the peak electric field at each streamer head can be expressed as:

$$\mathbf{E}_{\max} \sim \mathbf{E}_L + \mathbf{E}_\rho + \mathbf{E}_{\rho'} \qquad (1)$$

Here, $\mathbf{E}_{\max}, \mathbf{E}_L, \mathbf{E}_\rho, \mathbf{E}_{\rho'}$ are the peak field, ambient field, electric field of its own space charge and electric field of space charge by the other positive streamer, respectively.
According to our simulation results and [Kulikovsky, 1997],

$$E_\rho \sim \rho_{\max} r_\rho / 3\varepsilon_0 \propto \rho_{\max} d_s \sim const.$$

where $\rho_{\max}, r_\rho, d_s$ are peak space charge density, width of space charge layer, and width of streamer channel, respectively.
Considering that the interacting streamers are relatively far away from each other when they are fully formed, the space charge around the other streamer head can be approximately regarded as a point charge, and also assume that the space charge is uniformly distributed in the space charge layer [Kulikovsky, 1997]:

$$Q \sim \rho_{\max}\left(\frac{4}{3}\pi r_\rho^3\right) \propto \rho_{\max}\left(\frac{4}{3}\pi d_s^3\right)$$

Then the space charge field can be expressed as:

$$E_{\rho'} \sim \frac{Q}{4\pi d^2} \propto \frac{\rho_{\max}\left(\frac{4}{3}\pi d_s^3\right)}{4\pi\varepsilon_0 (2l_s \sin\theta)^2} \propto \frac{(\rho_{\max} d_s)}{\sin^2\theta}\frac{d_s^2}{l_s^2} \sim const.$$

where θ, l_s are the angle with respect to ambient field and streamer channel length, respectively. In the last step, we take use of the results that d_s, l_s have the same growth rate.
Therefore, from Equation (1), we have

$$\mathbf{E}_{\max} \sim const.$$

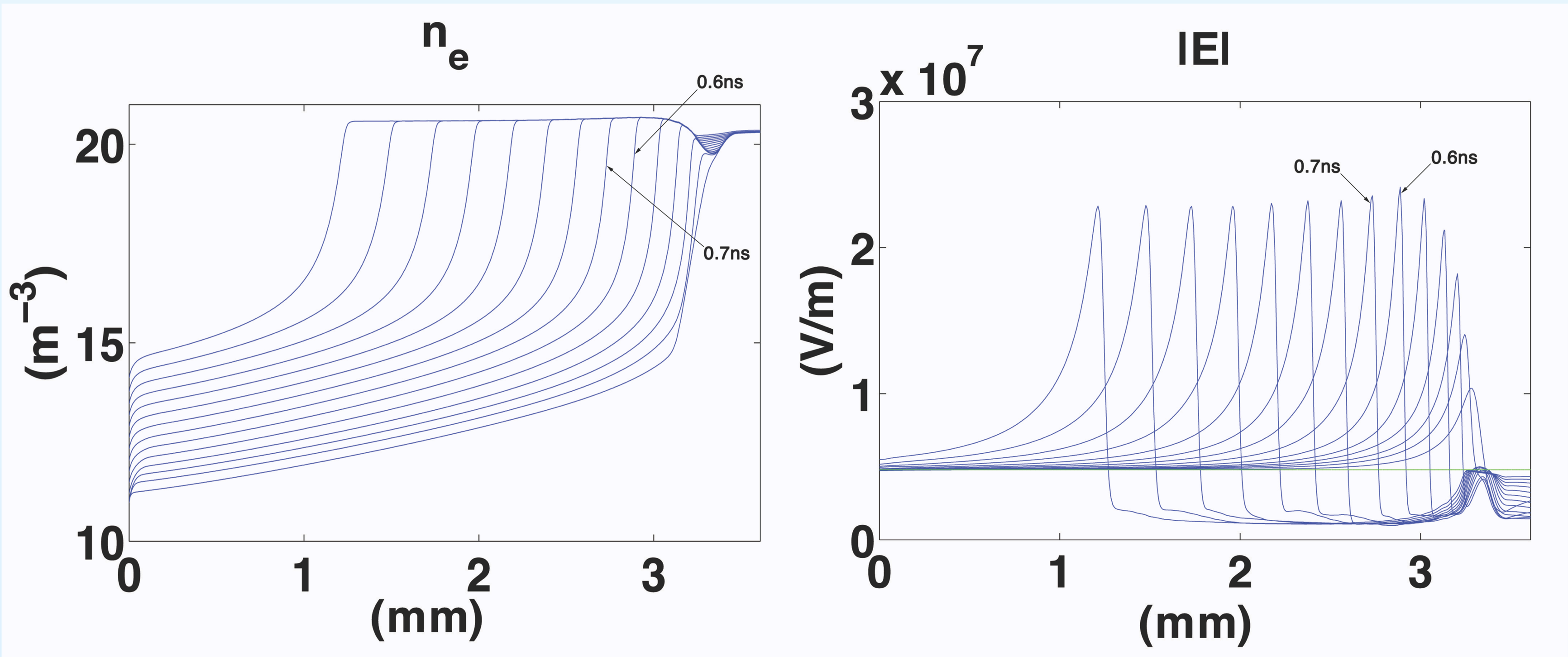

Figure 3: Evolution of electron density and electric field profiles for the left positive streamer along the black line in Figure 2 from t = 0.1 ns to t = 1.4 ns with a constant time interval Δt = 0.1 ns. The channel density and peak field are almost constant for the positive streamer after ~0.7 ns. The green line on the electric field profiles shows the magnitude of the ambient field.

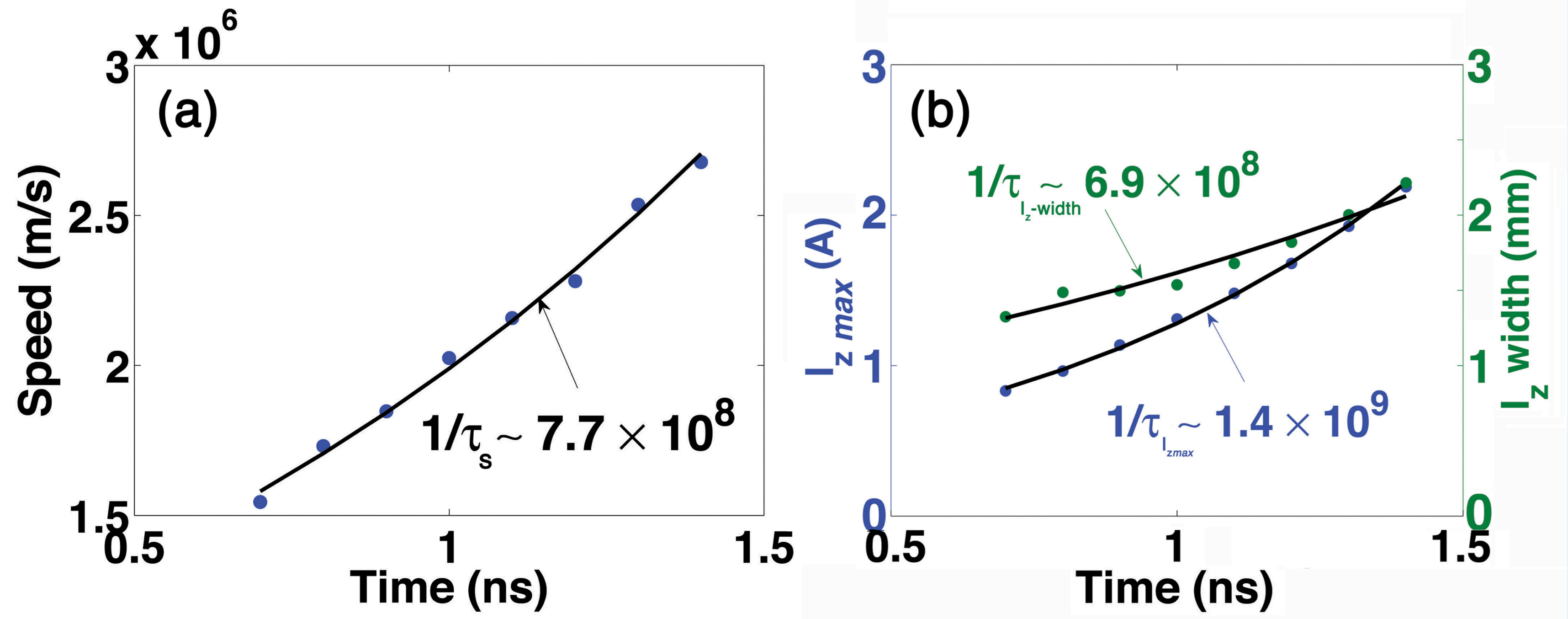

Figure 4: (a) The growth rate of speed, and (b) the growth rates of the vertical current peak and the width of the current profile.
The dots represent data from simulations, and the lines are exponential fitting curves.
The combined growth rate for the maximum and width of the vertical current distribution is ~$3/\tau_s$ similar to isolated streamers [Shi et al., 2016].

Conclusion

- The direction of the head peak field determines the propagation direction of streamers.
- No symmetry of the channel can be found, and the interacting streamers no longer propagate along the direction of the ambient field.
- Two interacting streamers propagate with a fix angle to the ambient field, i.e. the streamers will not merge.
- Main characteristics for each of the two interacting streamers, such as the growth rates of speed and vertical current, are similar to isolated streamers initiated under the same conditions.

Acknowledgements

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