October 14 - 17 2019

TEPA

11 years of TGE research on Aragats

Numerical modeling of stepping process in negative lightning leaders

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Relevance of The Study

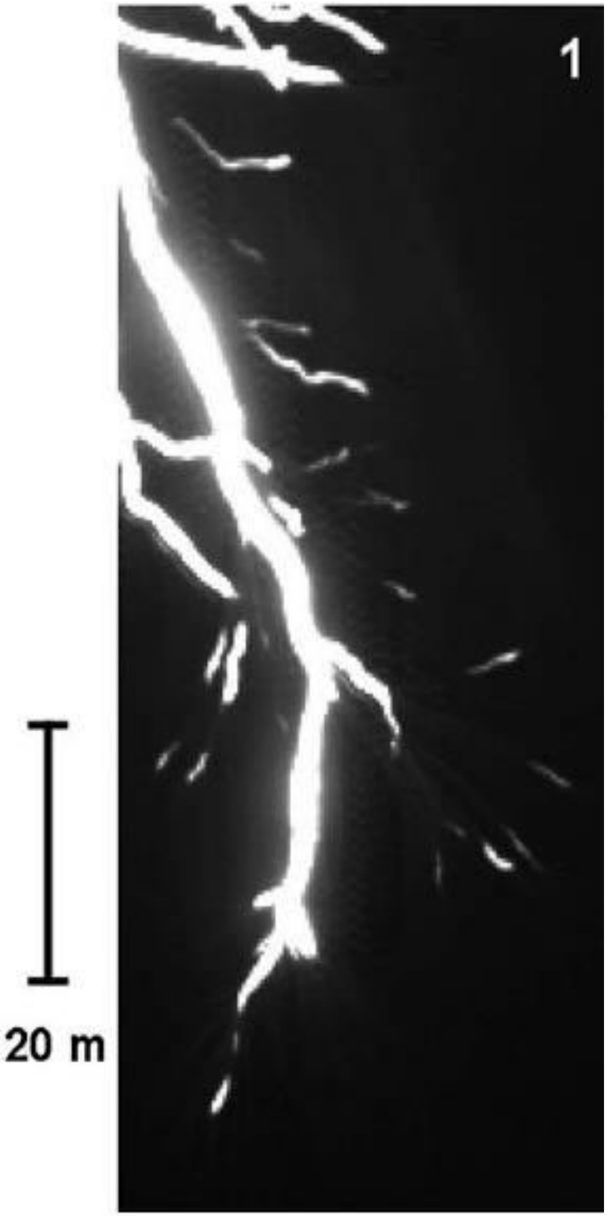
The top ten questions in lightning research by Dwyer and Uman [2014]:

2. <u>What physical mechanisms govern the propagation of the different types of lightning leaders</u> (<u>negative stepped</u>, first positive, negative dart, negative dart-stepped, negative dart-chaotic) between cloud and ground and the leaders inside the cloud?

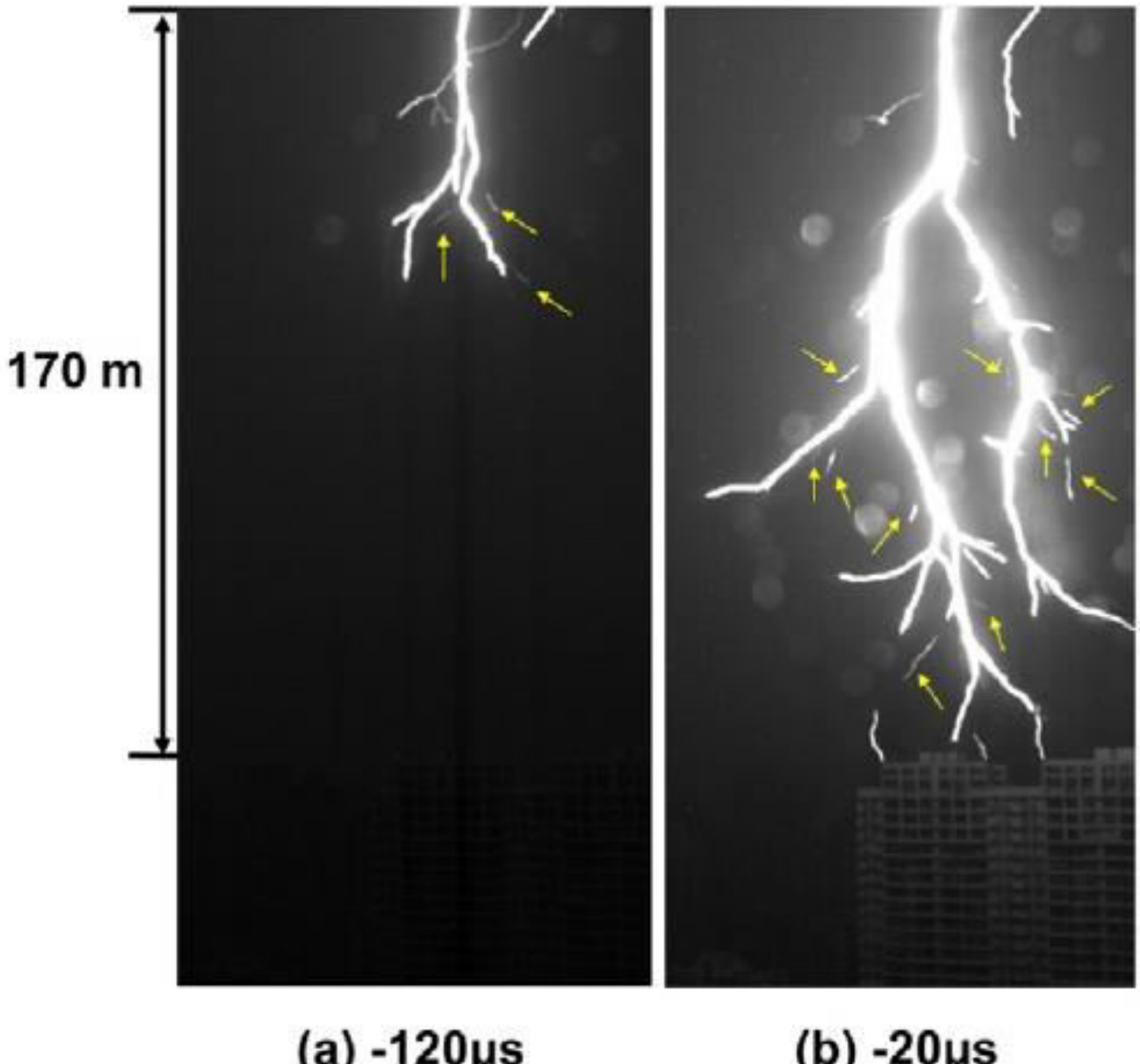
...

5. <u>By what physical mechanism do lightning leaders emit pulses of X-rays?</u> Do the X-rays play a role in lightning propagation? By what mechanism do thunderclouds generate relatively-steady internal X-rays? Do X-rays and other high energy radiation affect cloud electrification and play a role in lightning initiation?

Motivation



Petersen et al. [2013]



Qi et al. [2016]

Goals of The Study

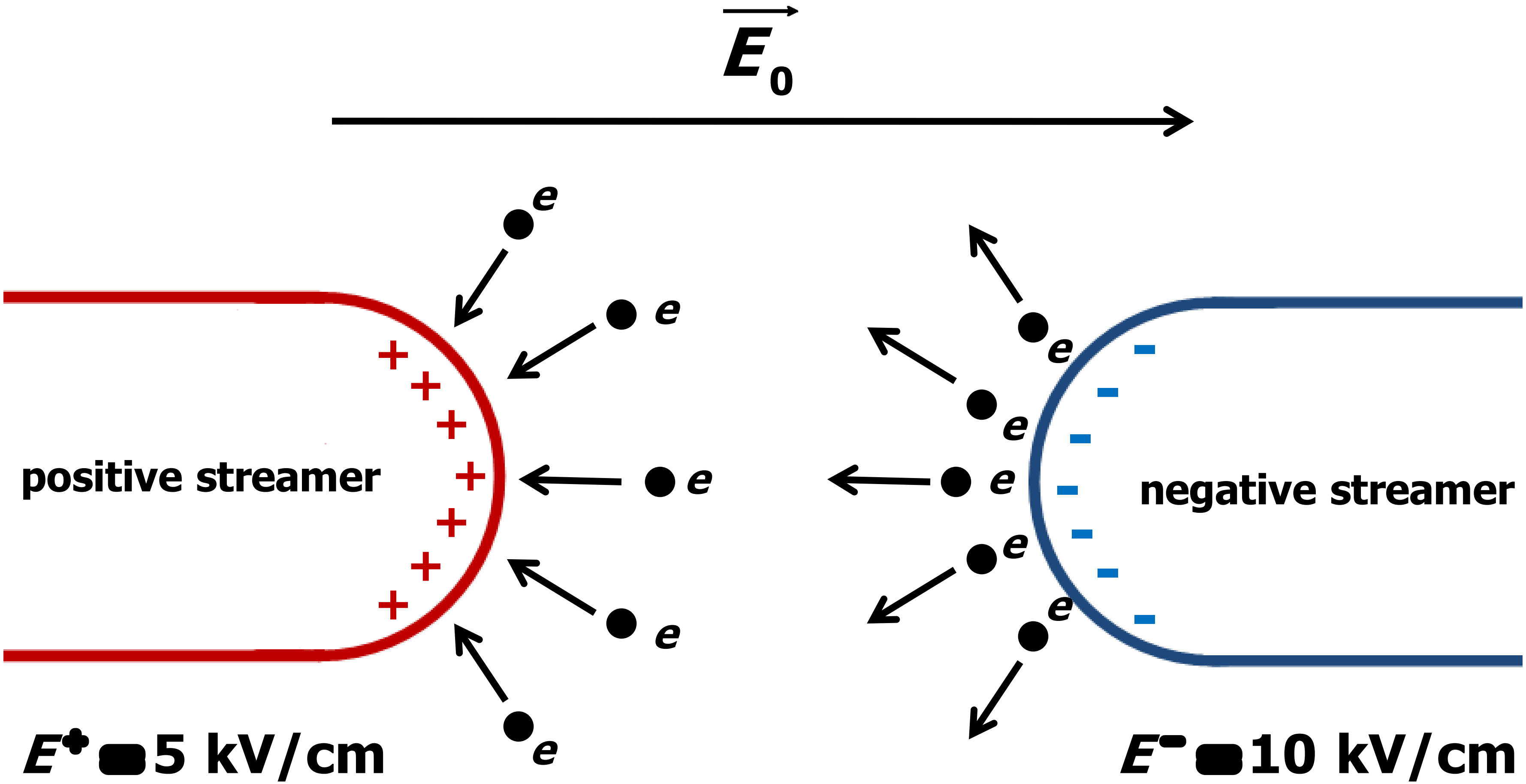
1. **On the basis of [*Iudin et al.*, 2017]* to develop a numerical model of the negative stepped lightning leader taking into account the asymmetry between the positive and negative streamers development of and having sufficient space-time resolution to describe the processes occurring in the negative leader streamer zone;**

2. **To describe the entire sequence of processes composing the negative leader stepwise development, including the emergence of space stems and space leaders developing from them;**

3. **After achieving the maximum qualitative and quantitative correspondence between model and real discharges, to draw conclusions about the processes responsible for the negative leader stepwise development.**

***Iudin, D. I., V. A. Rakov, E. A. Mareev, F. D. Iudin, A. A. Syssoev, and S. S. Davydenko (2017), Advanced numerical model of lightning development: Application to studying the role of LPCR in determining lightning type, *J. Geophys. Res. Atmos.*, 122, doi:10.1002/2016JD026261.**

Polarity Asymmetry



$$E^{-} = 2E^{+}$$

Problem Formulation

External field

E_0 [redacted] 3⊙10^4 V/m

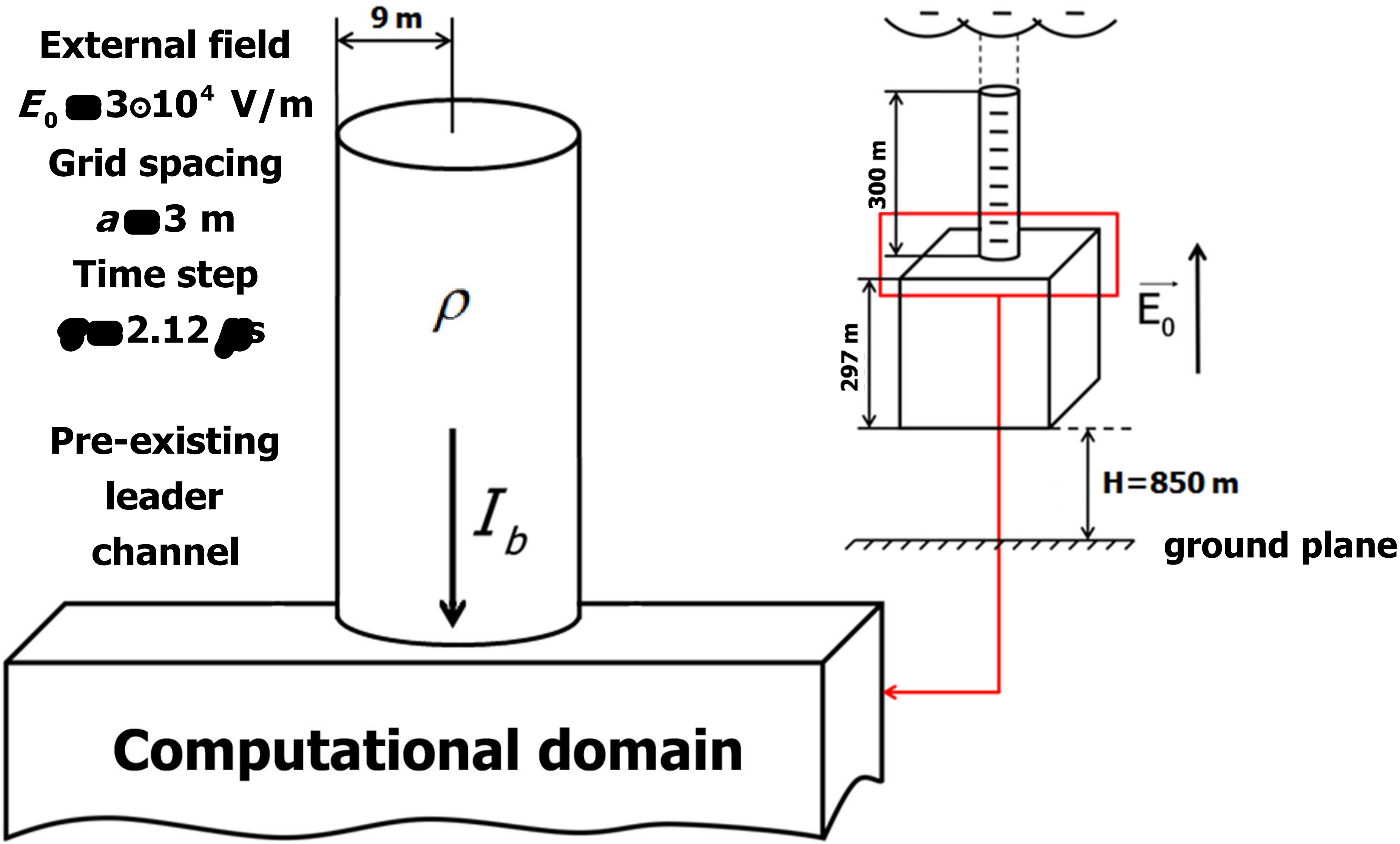
Grid spacing

a [redacted] 3 m

Time step

[redacted] 2.12 [redacted] s

Pre-existing leader channel



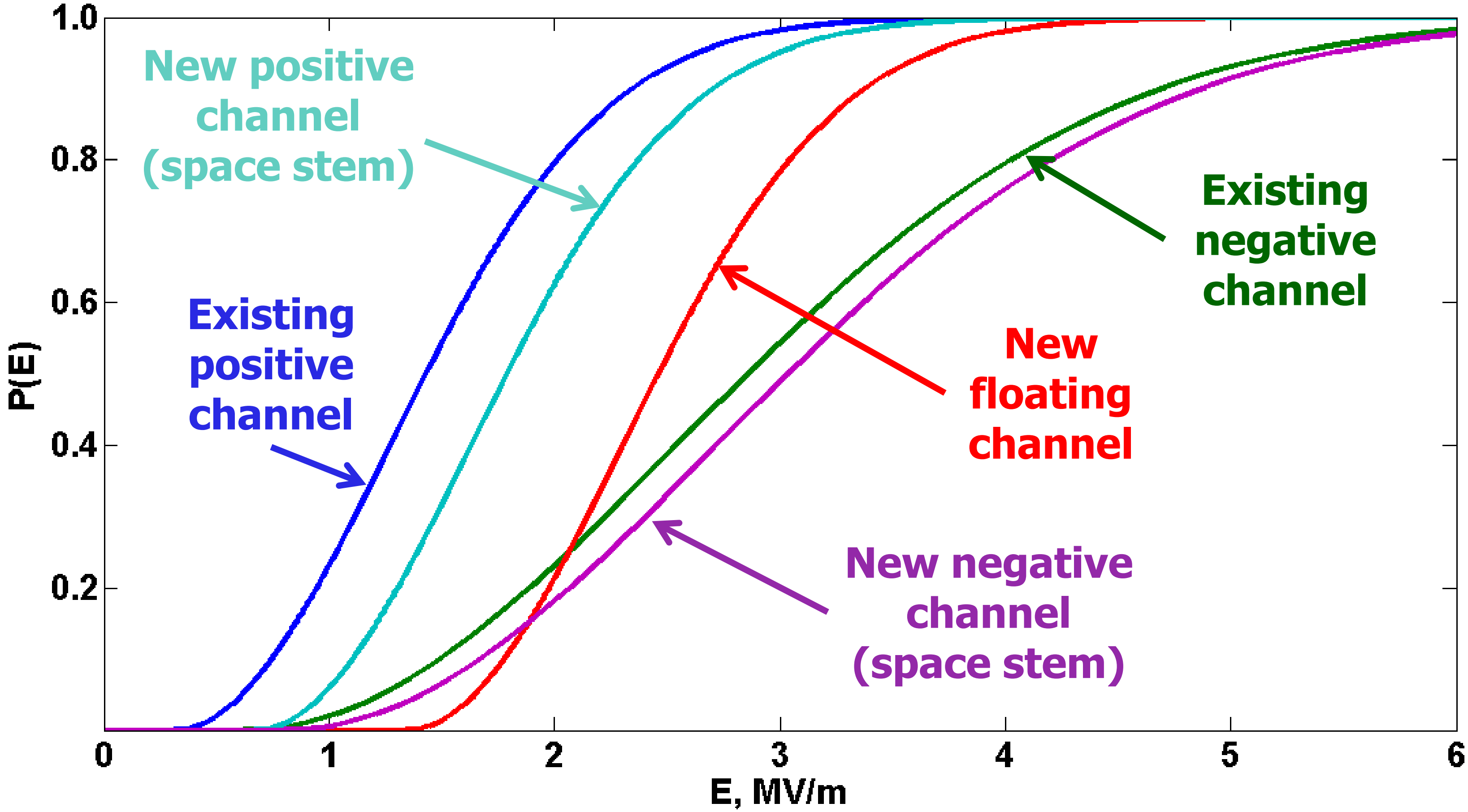
Probabilistic Approach

$$P\left(E_{\vec{r},\vec{r}'}\right)=\begin{cases}1-\exp\left[-\left|\dfrac{E_{\vec{r},\vec{r}'}-E_{th}}{E_{ith}}\right|^{2}\right] & E_{\vec{r},\vec{r}'}\geq E_{th} \\ 0, & E_{\vec{r},\vec{r}'}<E_{th}\end{cases},$$

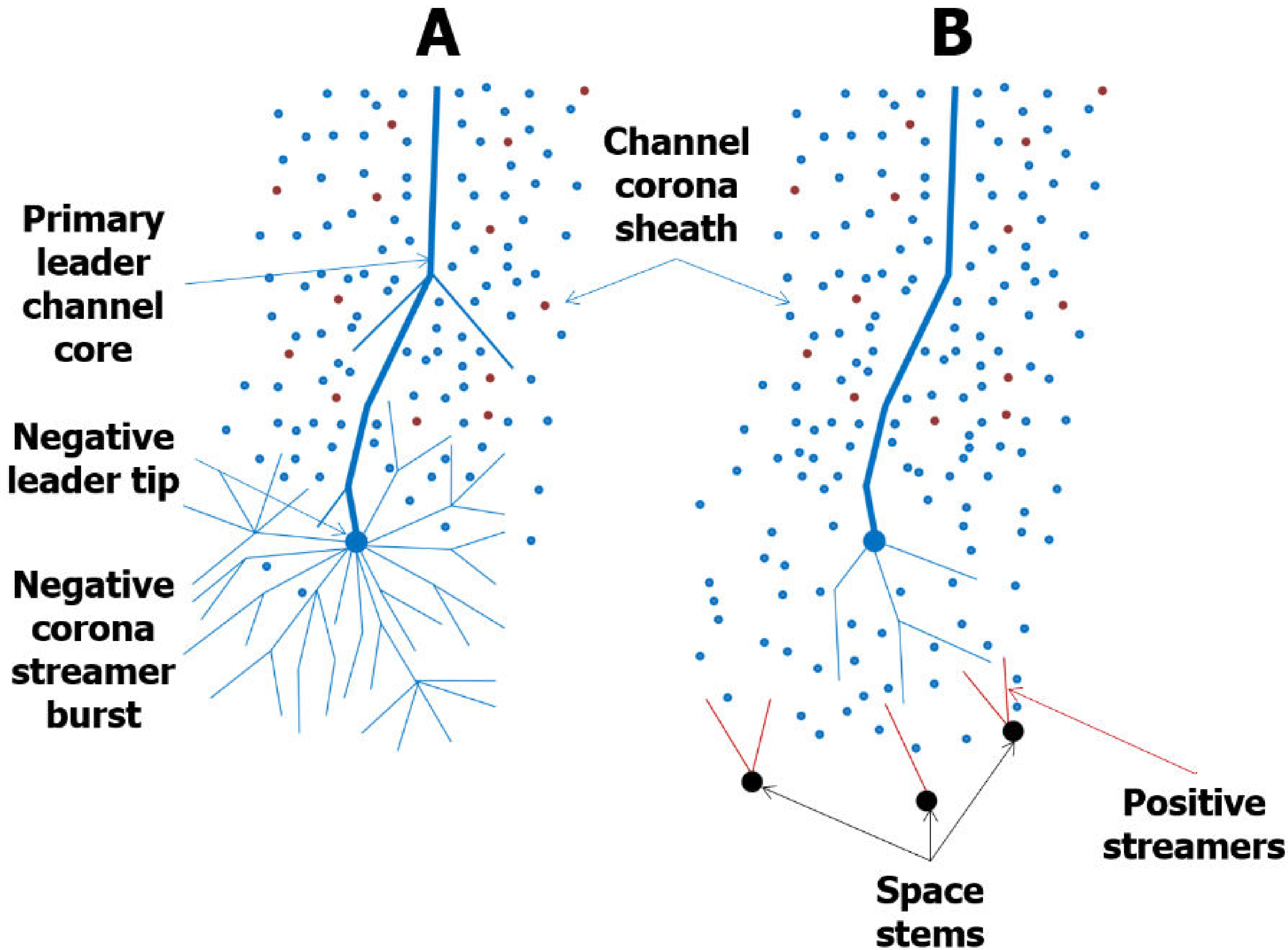
$$E_{ith}^{+}=1.34\ \mathrm{MV/m}$$

$$E_{pth}^{+}=0.31\ \mathrm{MV/m}$$

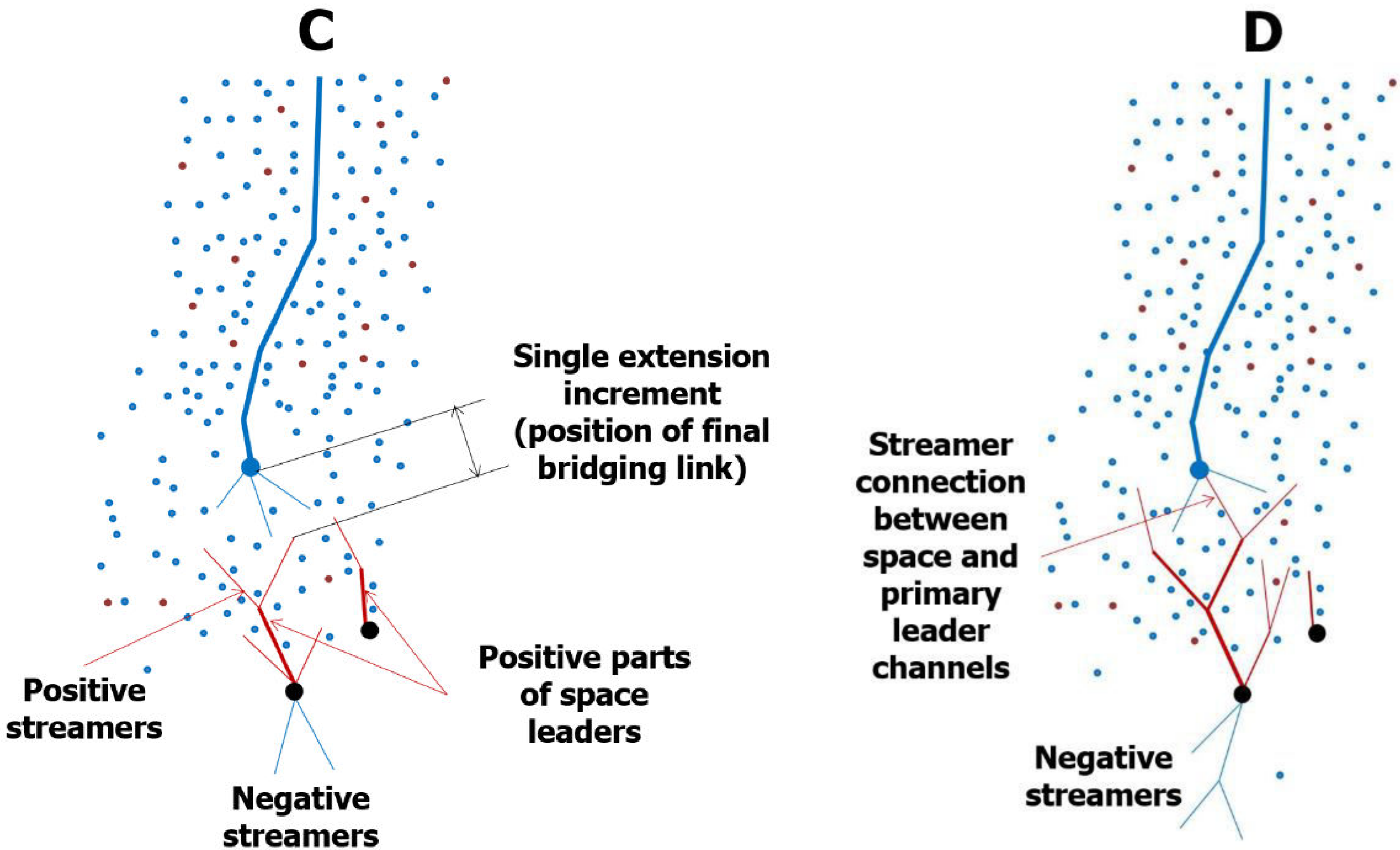
$$E_{pth}^{-}=0.62\ \mathrm{MV/m}$$



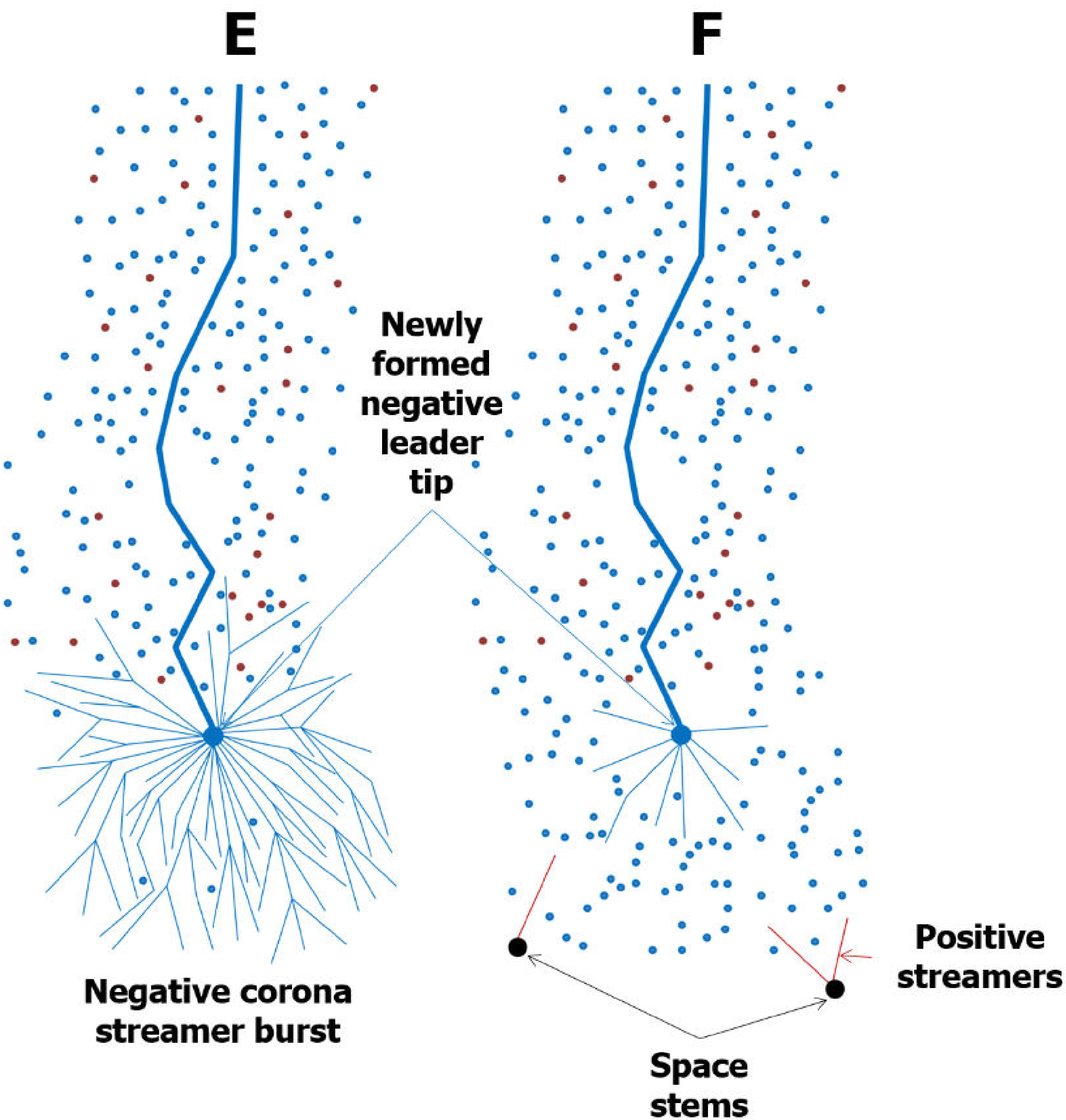
Step-Formation Process



Step-Formation Process

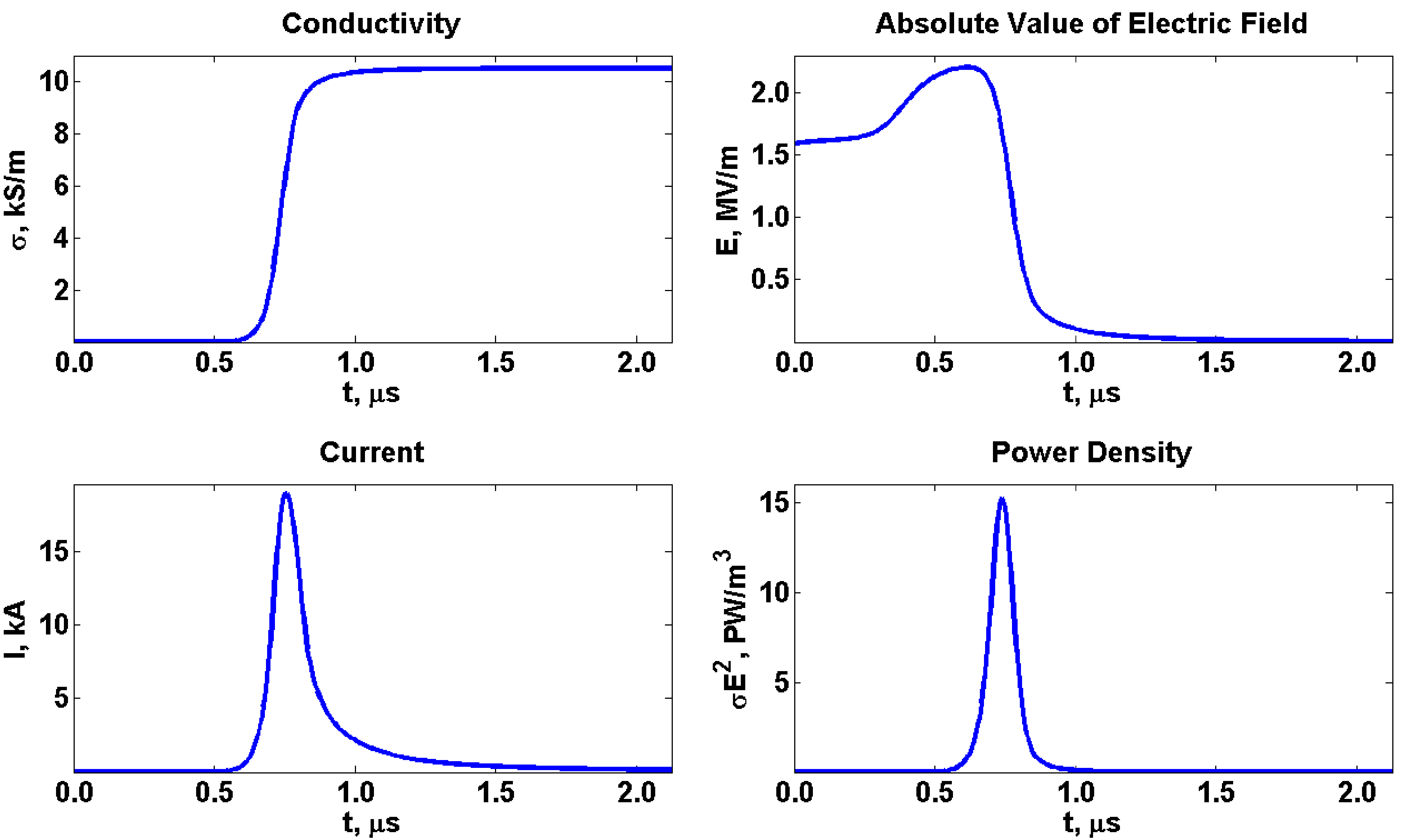


Step-Formation Process

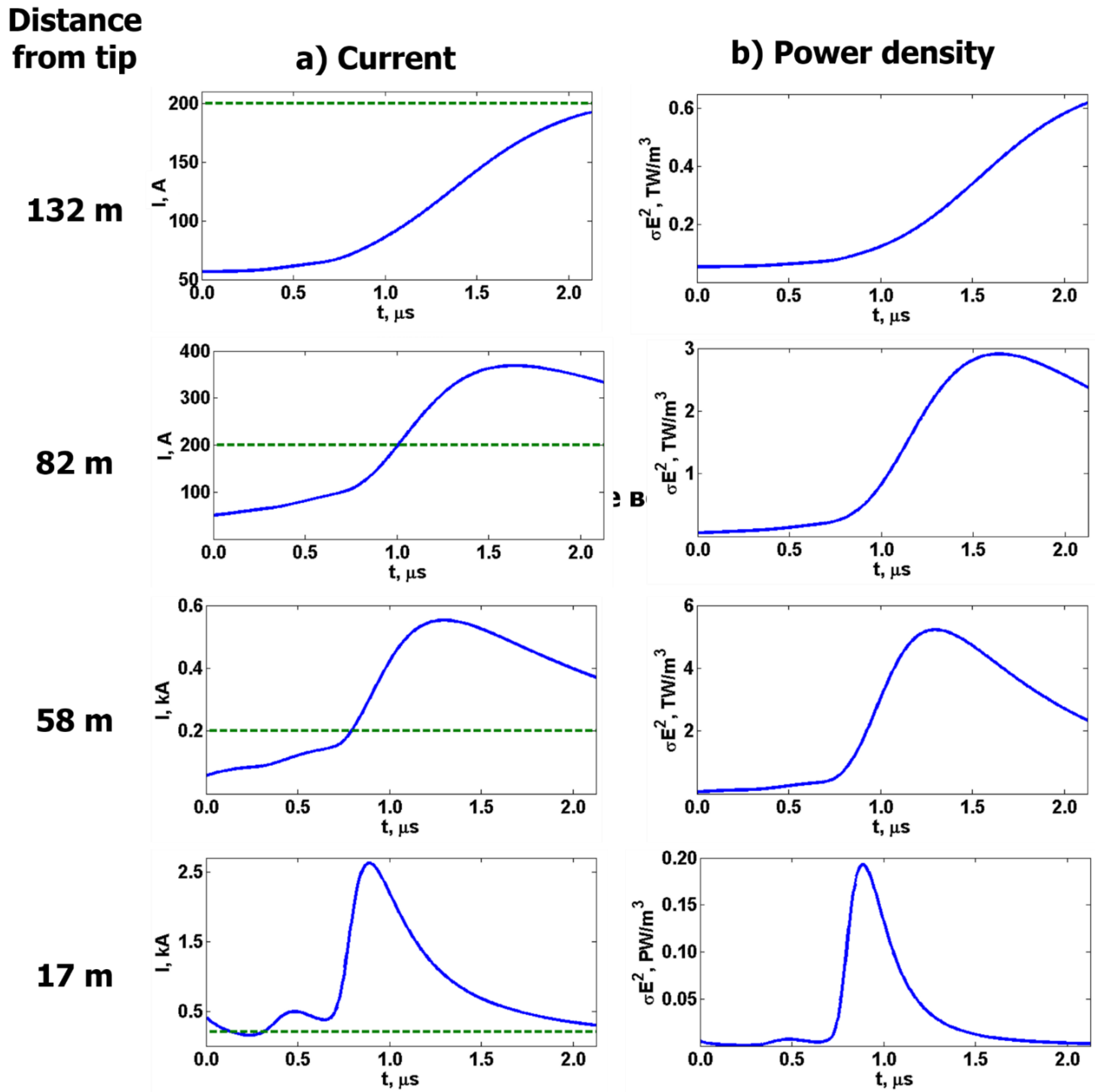


Model Results: Steps Parameters

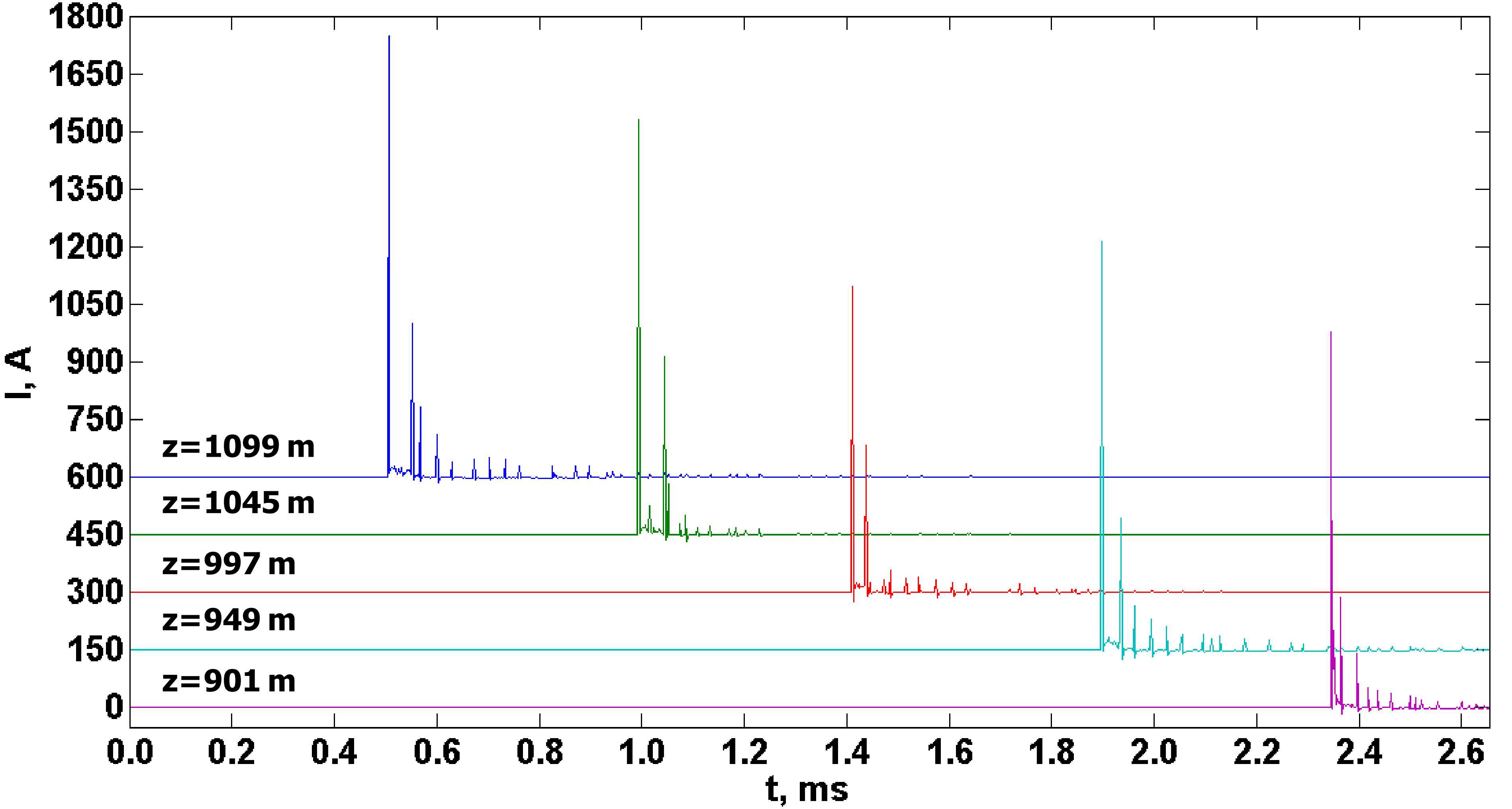
Streamer-to-leader transition in final bridging link connecting the main negative leader with the space one



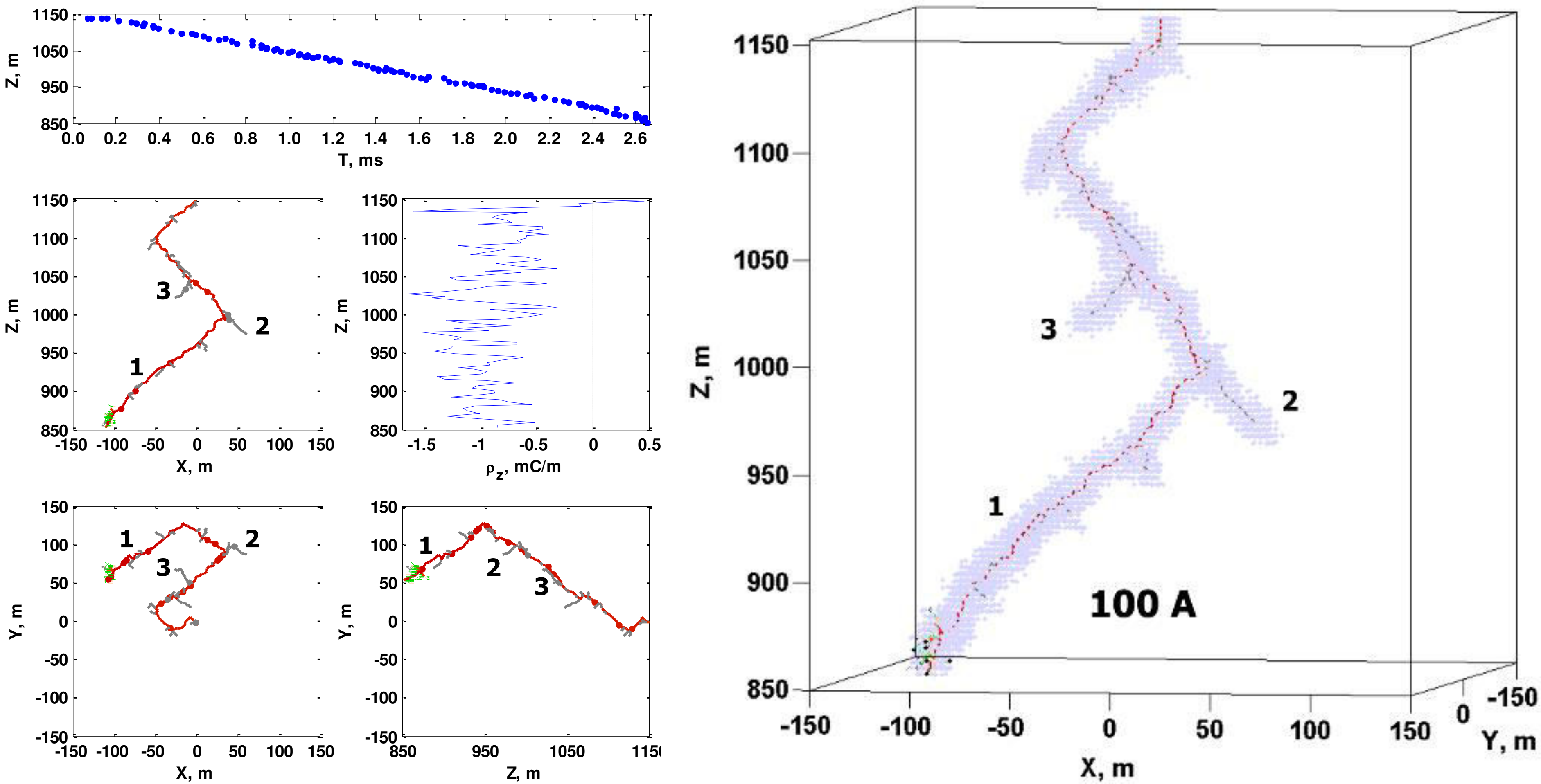
Model Results: Step-Associated Wave Dissipation



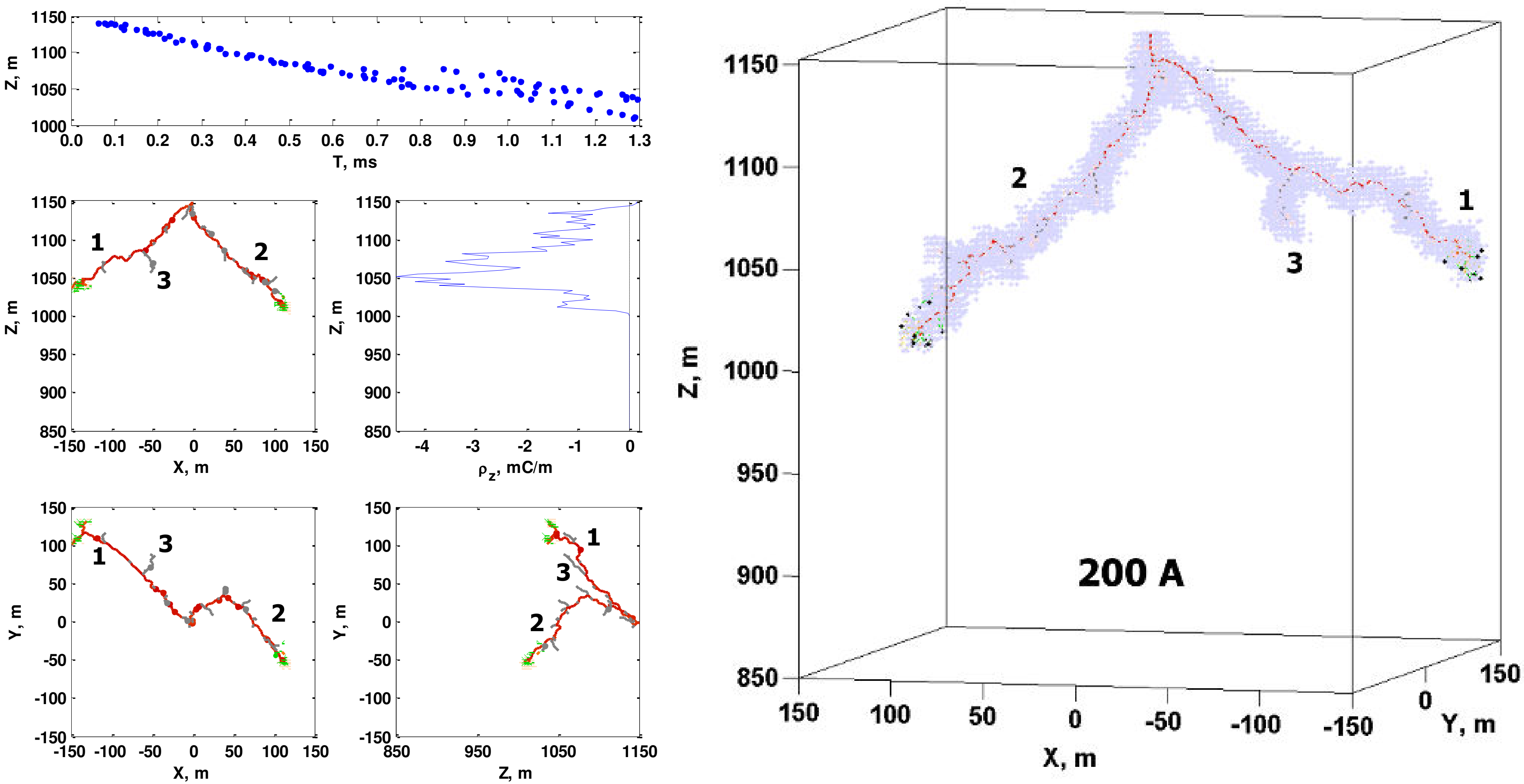
Model Results: Current Oscillograms in Channel Sections



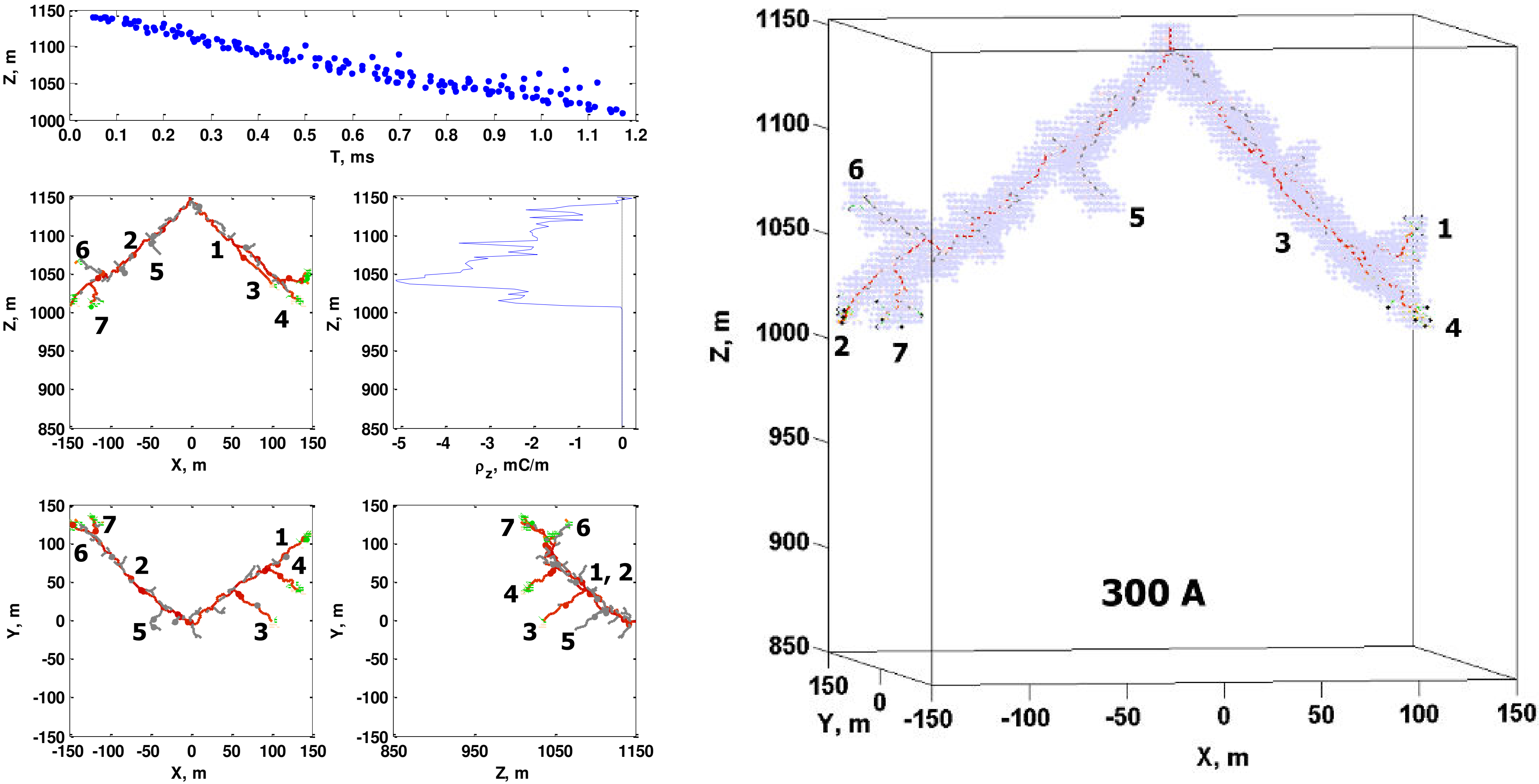
Model Results (100 A)



Model Results (200 A)



Model Results (300 A)



Model Leaders General Parameters

Branch number	3D propagation speed, 10^5 m/s	Interstep intervals, μs	3D step length, m	Charge transferred, mC	Line charge density, μC/m
100 A					
1	2.14	29.1	9.0	1.99	369
2	1.88	44.0	8.8	1.92	524
3	2.27	46.2	8.9	1.83	504
200 A					
1	2.23	36.3	9.1	2.04	379
2	2.33	26.4	8.8	1.92	408
3	2.15	43.8	9.2	1.99	563
300 A					
1	2.72	24.2	9.2	1.88	325
2	2.70	21.6	9.1	2.05	406
3	1.81	51.8	8.8	2.01	398
4	2.11	45.7	8.9	2.01	346
5	2.20	43.2	8.6	2.11	493
6	2.62	41.2	9.1	1.88	524
7	2.75	32.7	9.1	1.94	442
Mean	2.30	37.4	9.0	1.97	437
Experimental data	2.00	5.0-50.0	≈10.0	1.00-4.00	500-1000

Summary

1. A numerical model of the negative lightning stepped leader was developed, which
- for the first time takes into account the asymmetry of development fields of positive and negative streamers;
- takes into account the evolution of discharge channels electrical parameters;
- has a sufficiently high spatio-temporal resolution, which allows one to adequately describe the entire sequence of the negative leader step-formation process, its branching, and formation of the leader channel sheath.

2. The nature of the step-formation process is caused by the difference between characteristic fields of positive and negative streamers development;

3. It is shown that the cause of space stems appearance is the field amplification arising due to the negative charge inhomogeneously distributed in front of the newly formed negative leader tip during the negative corona streamer burst, which completes the step-formation process.

4. The model leader parameters (propagation speed, step length, interstep intervals, charge transferred by the step, leader channel sheath line charge density) are in good agreement with experimental data and modern knowledge about the physics of lightning.

Acknowledgment

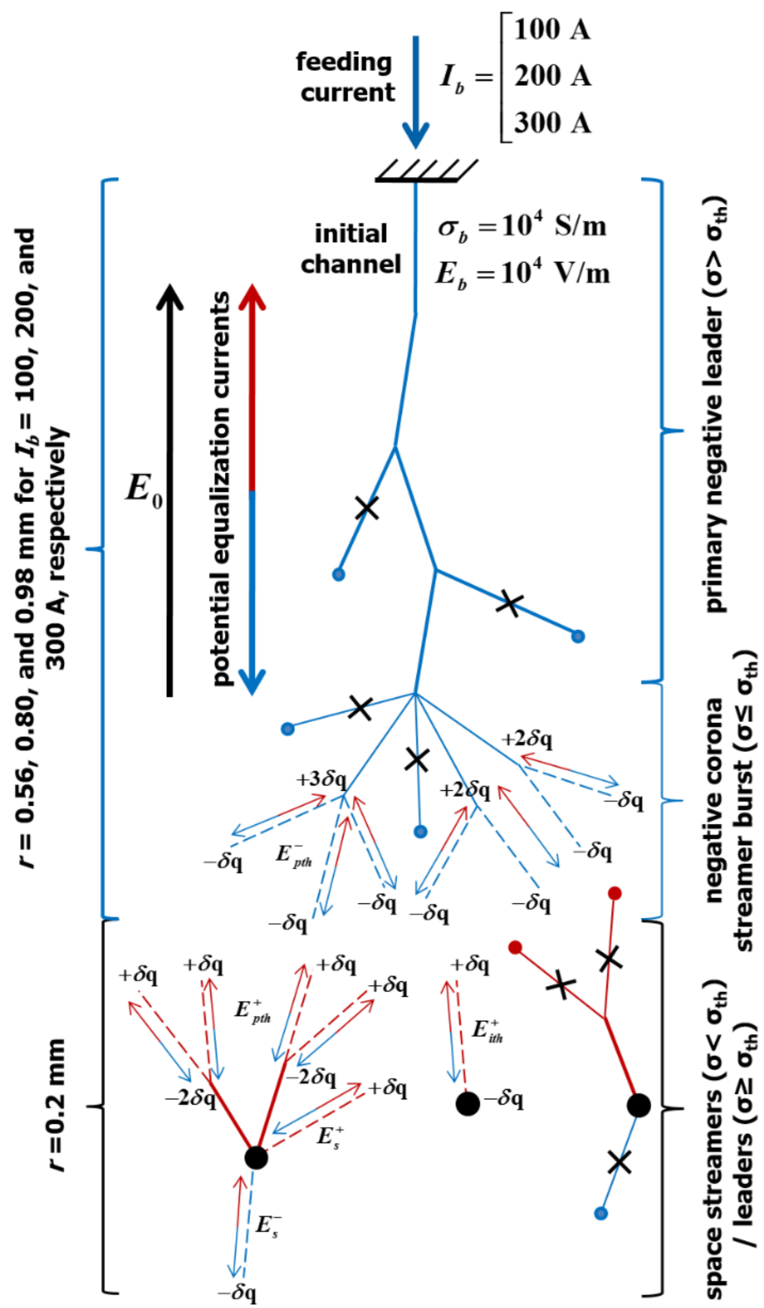
The speaker sincerely thanks his scientific manager Dmitry Igorevich Iudin for providing the ideological basis of the work and comprehensive support during its realization and Vladimir Aleksandrovich Rakov for deep involvement in the theme of this study, numerous valuable comments and moral support.

Iudin D. I., Doctor of Philosophy, Doctor of Biological Sciences, Leading Researcher of IAP RAS

Rakov V. A., Doctor of Philosophy, professor of the University of Florida, USA

Thank you for attention!

General Leader Development Algorithm



A new link appearance accompanied with dipole-type charge separation:

$$\delta q = \alpha E,$$

$$\alpha = 5.03 \cdot 10^{-12}\ \text{C} \cdot \text{m/V}.$$

Conductivity of each link evolves in accordance with equation:

$$\sigma(t+1) = \left(1 + \eta E^2 - \beta\right)\sigma(t),$$

$$\sigma(t=0) = \sigma_0 = 10^{-5}\ \text{S/m}.$$

Streamer channel turns into a leader one when its conductivity exceeds the value of

$$\sigma_{th} = 1\ \text{S/m}.$$

Each link contributes charge transfer via potential equalization currents

$$I = \sigma \pi r^2 E.$$

Each link either becomes a part of the primary negative leader (via the step-formation process) or decays with probability depending on its conductivity

$$P_d = 1 - cth(\sigma/\sigma_m),$$

$$\sigma_m = 10^4\ \text{S/m}.$$

Symbols:

- positive link
- negative link
- decayed link
- space stem
- negative space charge
- positive space charge

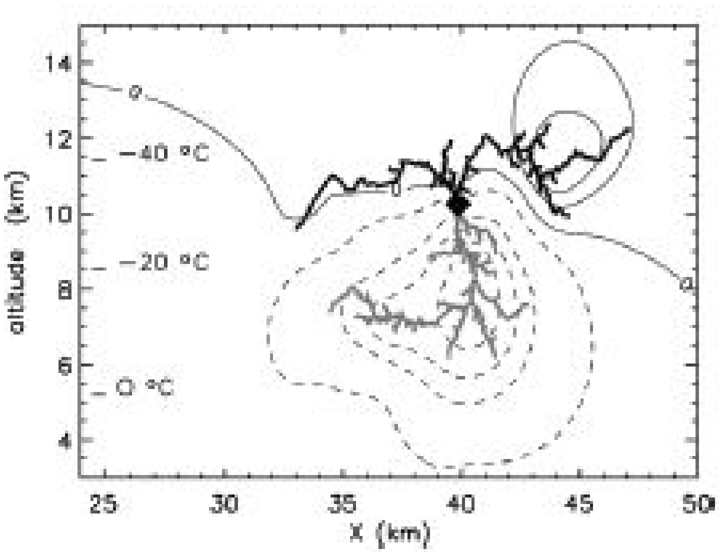
$\sigma_0 = 10^{-5}$ S/m, $+\delta q$, $-\delta q$ - newly-formed link, E

Characteristics of natural negative lightning stepped leaders observed using photoelectric systems and framing cameras

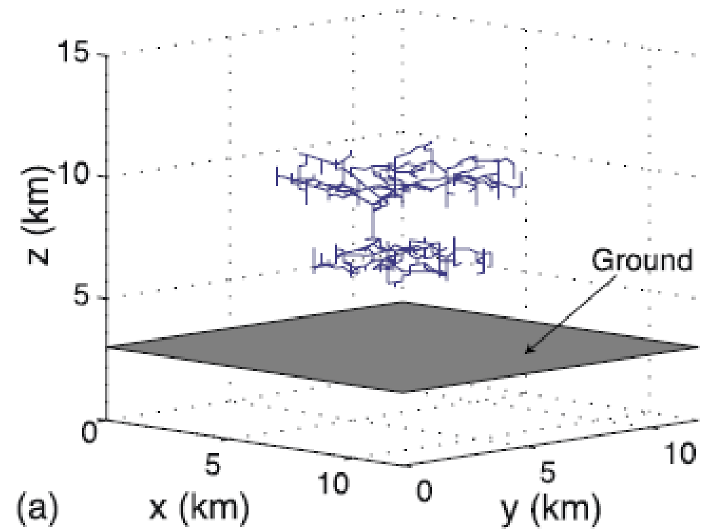
Study	Interstep interval, μs	2D step length, m	2D[a] leader speed, 10^5 m/s
Chen et al.[b] [1999] (Australia)	5.0-50.0	7.9-20	4.9-11.0
Chen et al.[b] [1999] (China)	18.0-21.0	8.5	4.9-5.8
Lu et al. [2008]	0.2-15.7	-	15.0
Hill et al. [2011]	12.2-40	4.8-7.1	2.7-6.2
Petersen and Beasley [2013]	-	-	5.6
Tran et al. [2014]	-	14, 15	6.5-9
Qi et al. [2016]	13.9-23.9	-	4.1-14.6
Jiang et al. [2017]	6.9[c]	1.3-8.6	-

[a] Except for *Petersen and Beasley* [2013], who measured 1D leader speed.
[b] Studies based on the use of ALPS photoelectric system, as opposed to framing cameras used in all other studies summarized in this table.
[c] Found as the observation period of 667 μs divided by the total number (96) of individual step-wise channel extensions.

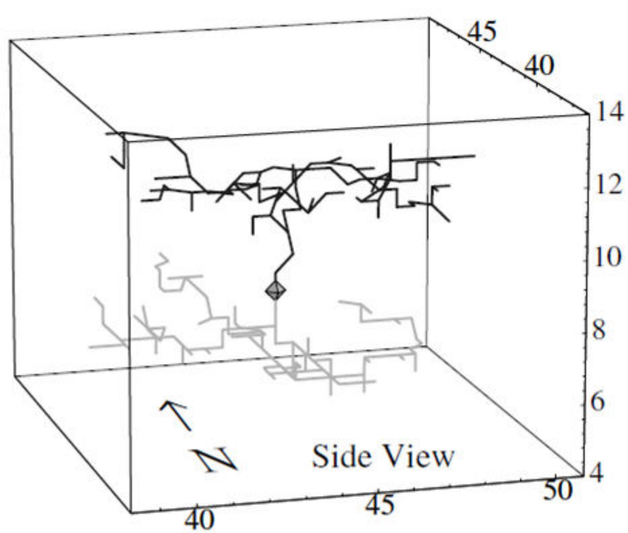
Examples of other lightning parametrization models



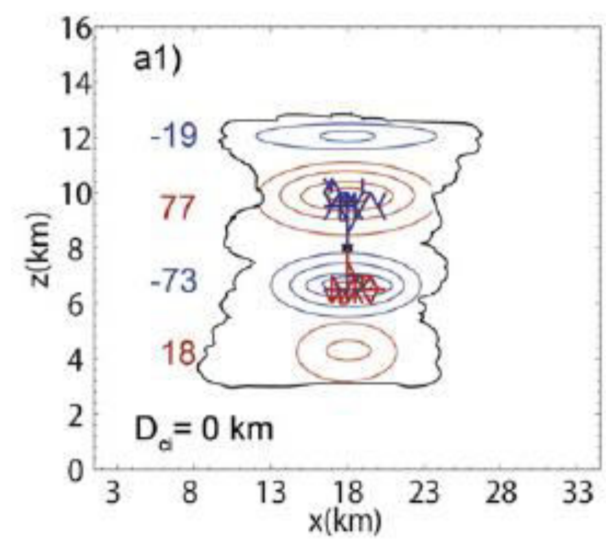
Tan et al. [2006]



Riousset et al. [2006]

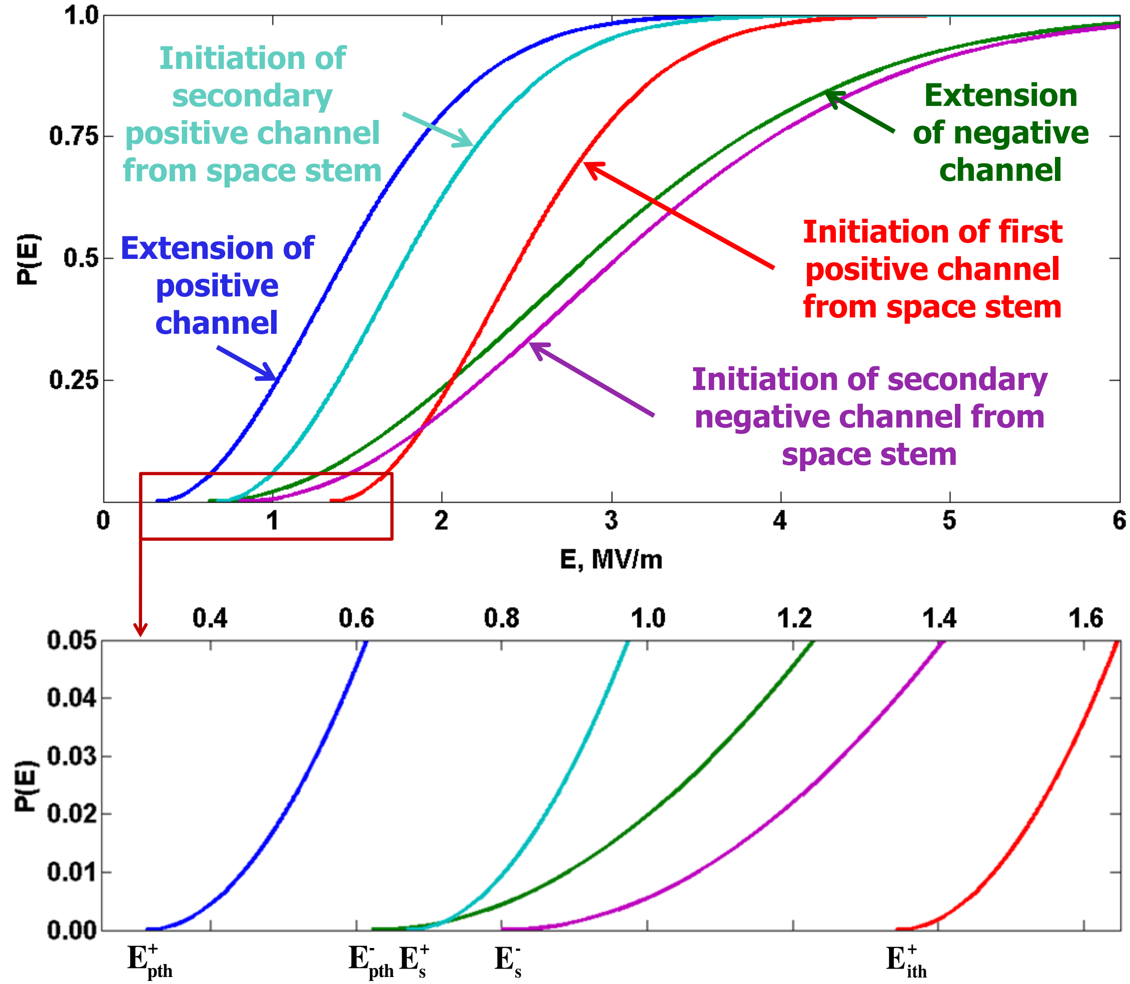


Mansell et al. [2002]



Wang et al. [2016]

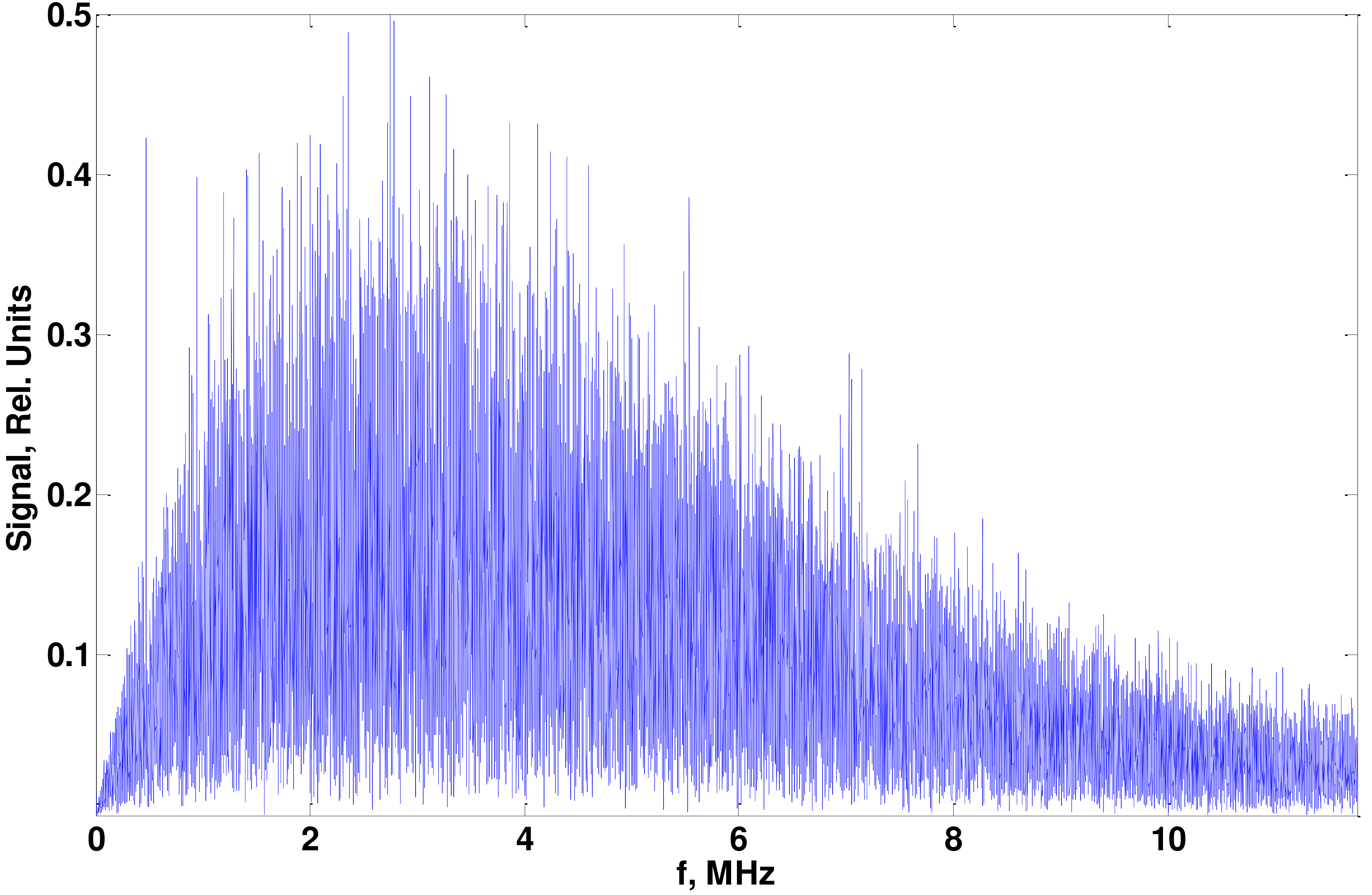
Probabilistic Approach



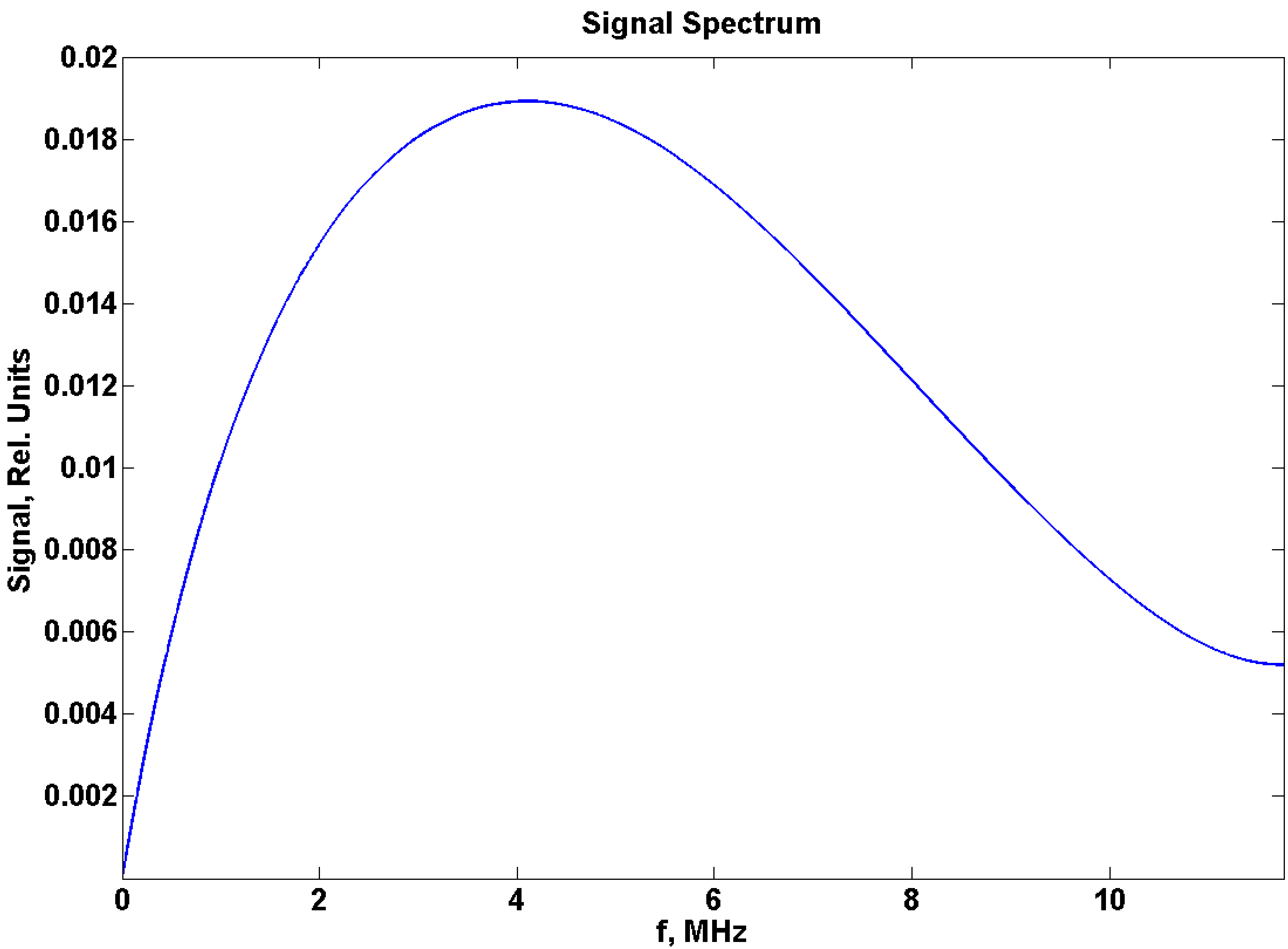
Threshold fields

E^+_{pth}, MV/m	E^-_{pth}, MV/m	E^+_s, MV/m	E^-_s, MV/m	E^+_{ith}, MV/m	E^-_{ith}, MV/m
0.31 (1.43)	0.62 (2.86)	0.67 (1.79)	0.81 (3.04)	1.34 (2.46)	2.68 (4.92)

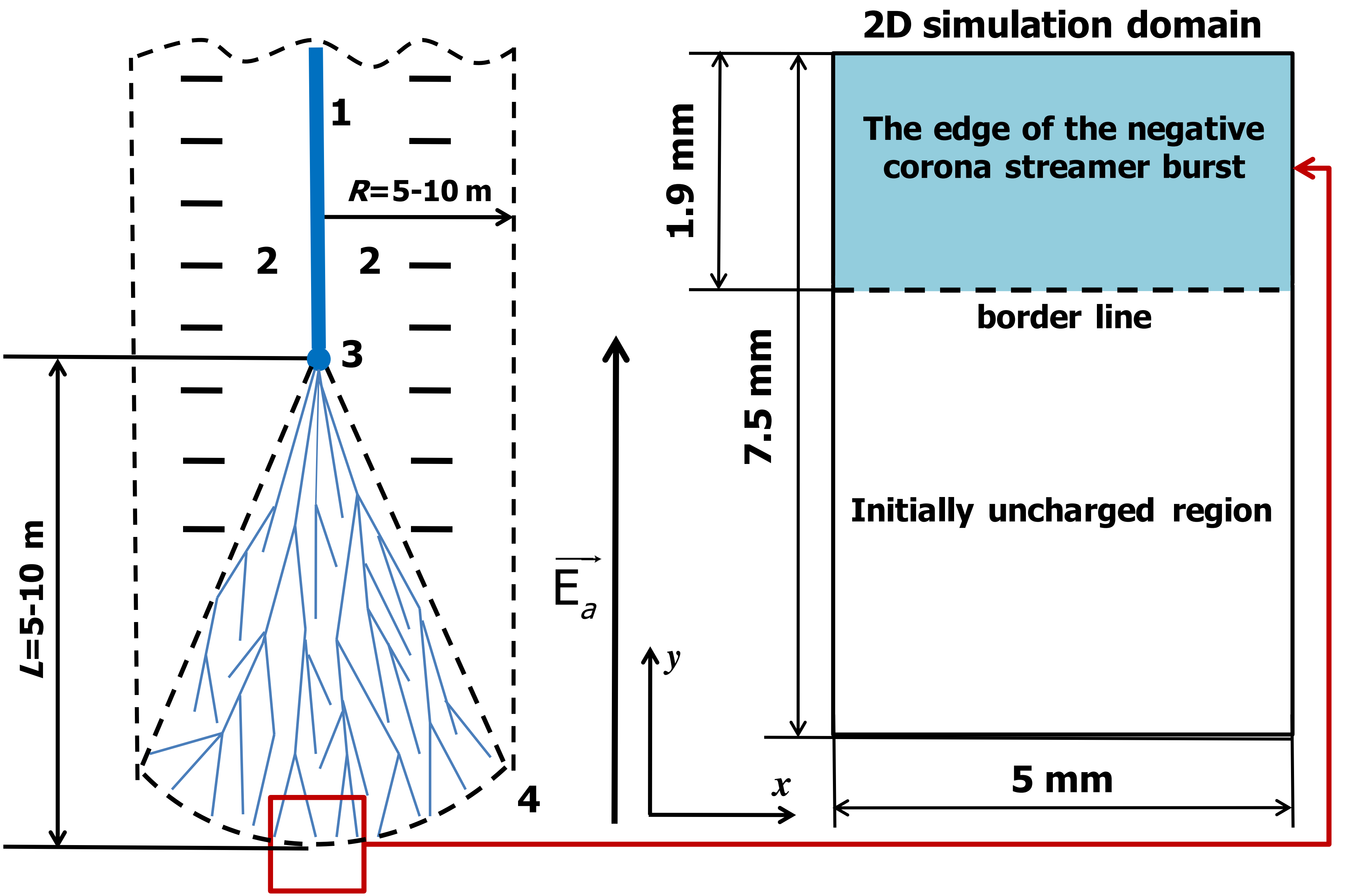
Model Results: Step-Associated Spectrum



Model Results: Step-Associated Spectrum

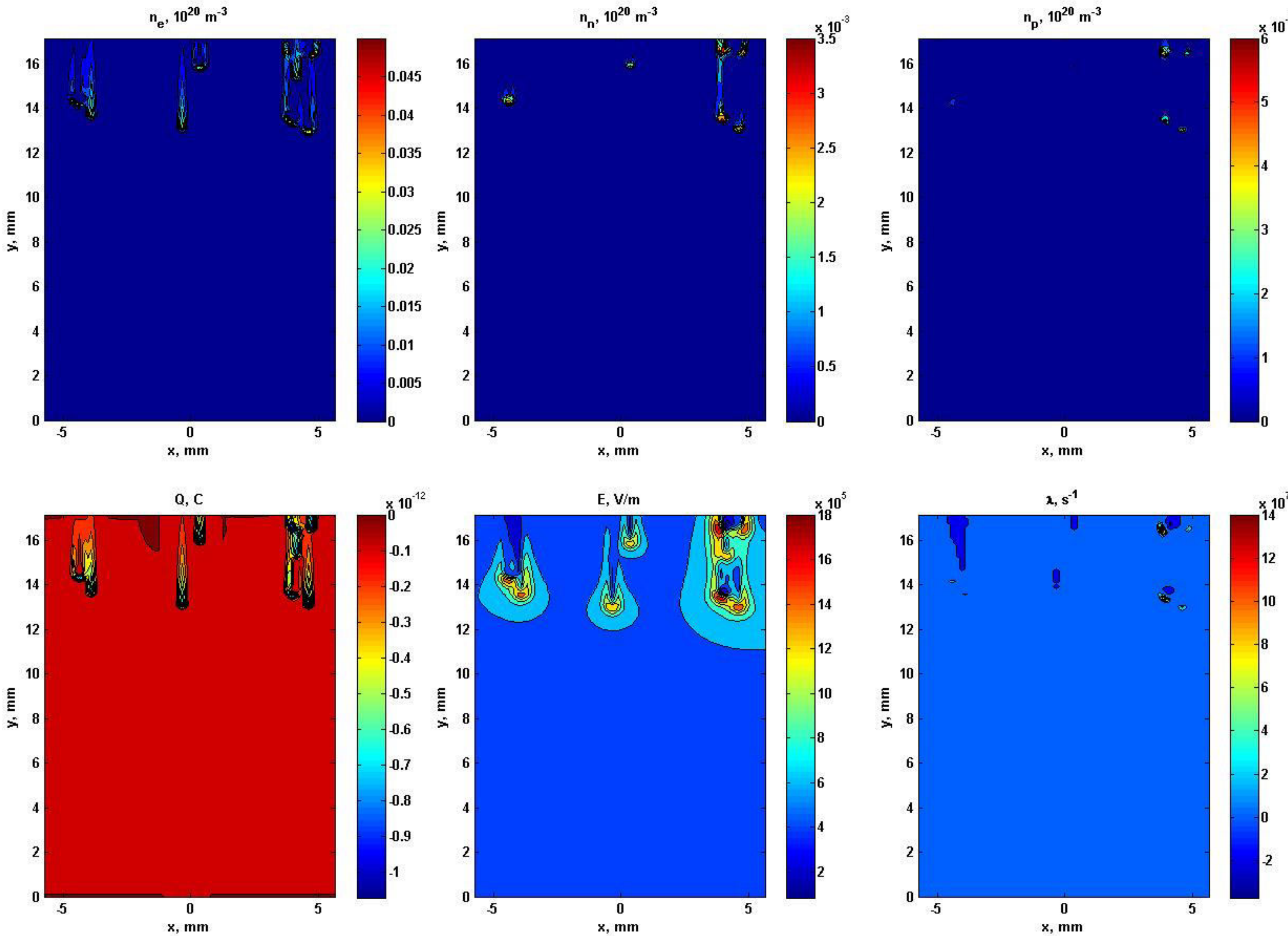


Problem formulation

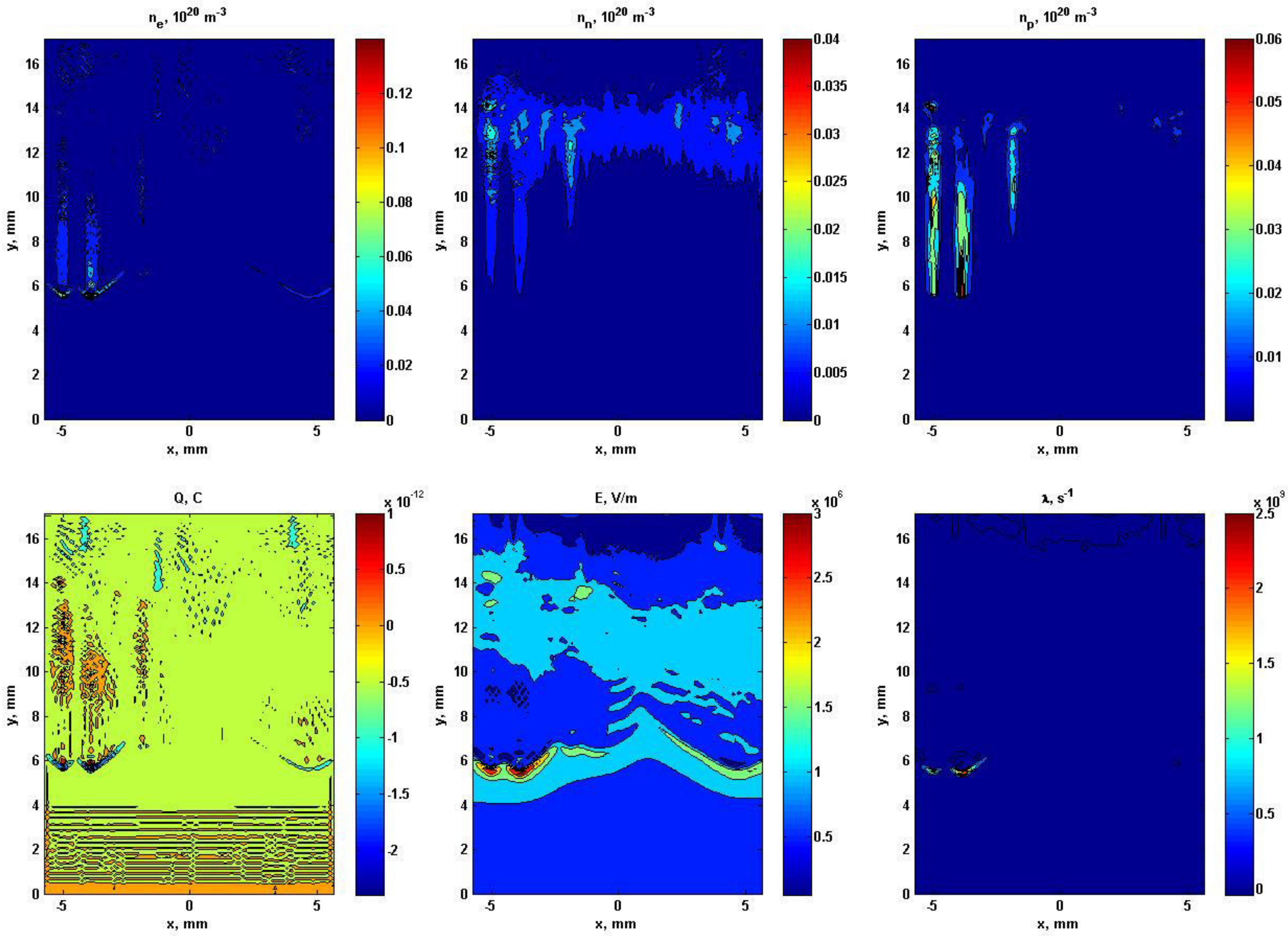


1 – negative leader channel; 2 – leader channel sheath; 3 – negative leader tip; 4 – negative corona streamer burst

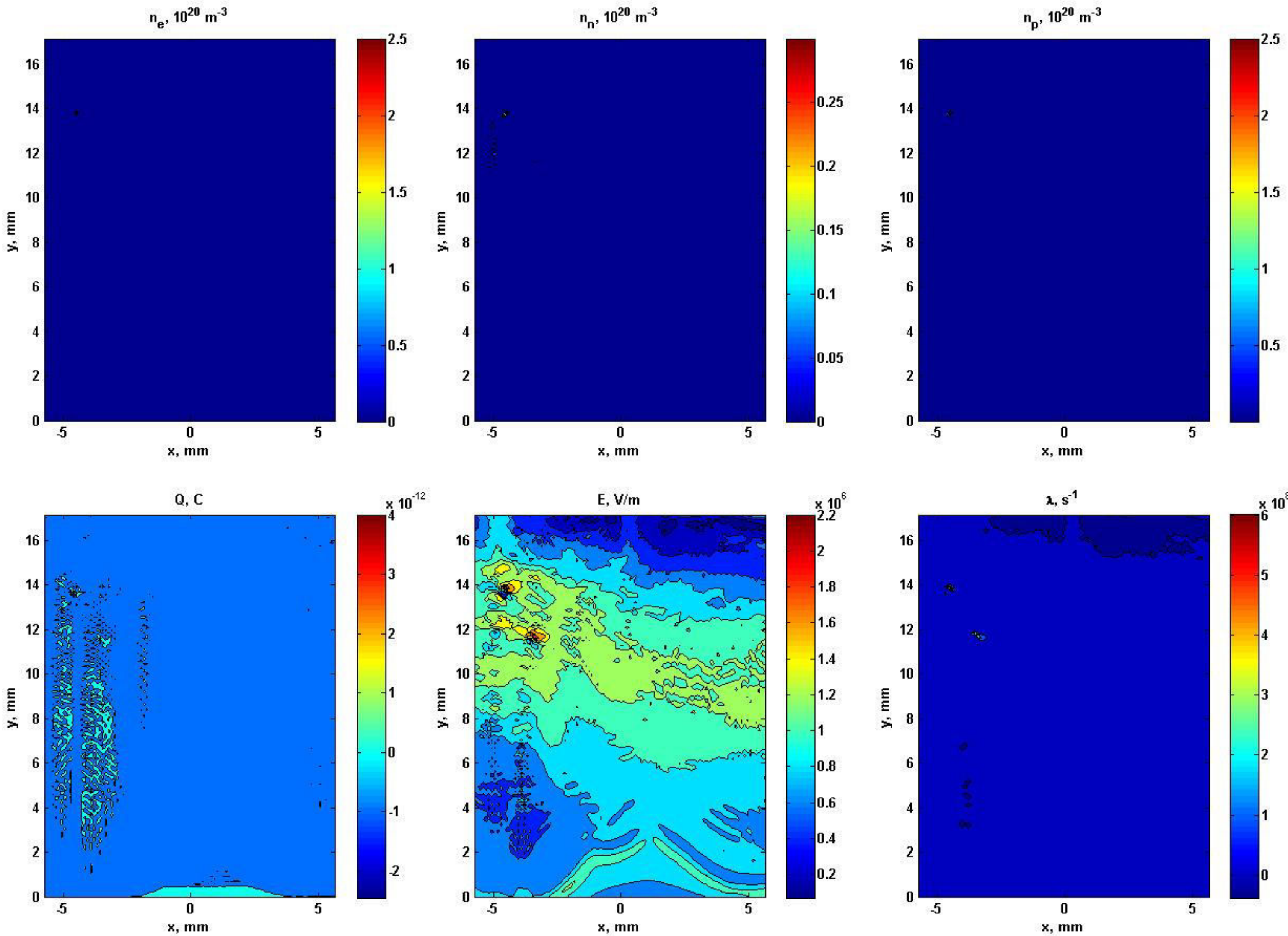
Результаты Моделирования
Начальный этап



Результаты Моделирования
Промежуточный этап



Результаты Моделирования
Финальный этап



Dynamics of Ions in Thunderclouds & Lightning Initiation

D.I. Iudin, V.A. Rakov, A.A. Syssoev, and A.A. Bulatov

Content

- **Basic Equations: Species evolution and Depository multiplication**
- **Ion Production Centers: Critical rate of appearance and Positive feedback**
- **Illustrative example: Streamer interaction and Lightning seed formation**

Balance equation for electrons

$$\frac{\partial n_e}{\partial t} = (\nu_i - \nu_a) n_e \qquad \nu_a \approx 10^8 \text{ s}^{-1}$$

ionization frequency **attachment frequency**

$$\nu_i(E_b) = \nu_a(E_b)$$

$$E_b(z)[\mathrm{MV/m}] = 3.2 \cdot \exp\left(-\frac{z[\mathrm{km}]}{8.4}\right)$$

under normal conditions at sea level

Basic equations

detachment process

$$\frac{\partial n_e}{\partial t} = (\nu_i - \nu_a)n_e + \boxed{\nu_d n_n}$$

$$\frac{\partial n_n}{\partial t} = \nu_a n_e - \boxed{\nu_d n_n} - \boxed{\nu_h n_n}$$

$$\frac{\partial n_p}{\partial t} = \nu_i n_e - \boxed{\nu_h n_p}$$

ion losses to hydrometeors

charge transfer processes: from light unstable ions to stable heavy ions

Quasi-stationary approximation

$$\nu_a \gg \nu_d \gg \nu_h$$

$$\begin{pmatrix} n_e(t) \\ n_n(t) \\ n_p(t) \end{pmatrix} \approx \begin{pmatrix} \frac{\nu_d}{\nu_a} \\ 1 \\ 1 \end{pmatrix} \cdot \exp(\lambda^+ \cdot t)$$

$$\lambda^+ \approx \frac{\nu_i \nu_d}{\nu_a} - \nu_h = \mathfrak{J}_i - \nu_h$$

Electrons are an intermediate product of plasma-chemical reactions

$$\nu_a n_e \approx \nu_d n_n$$

Balance equation for negative ions

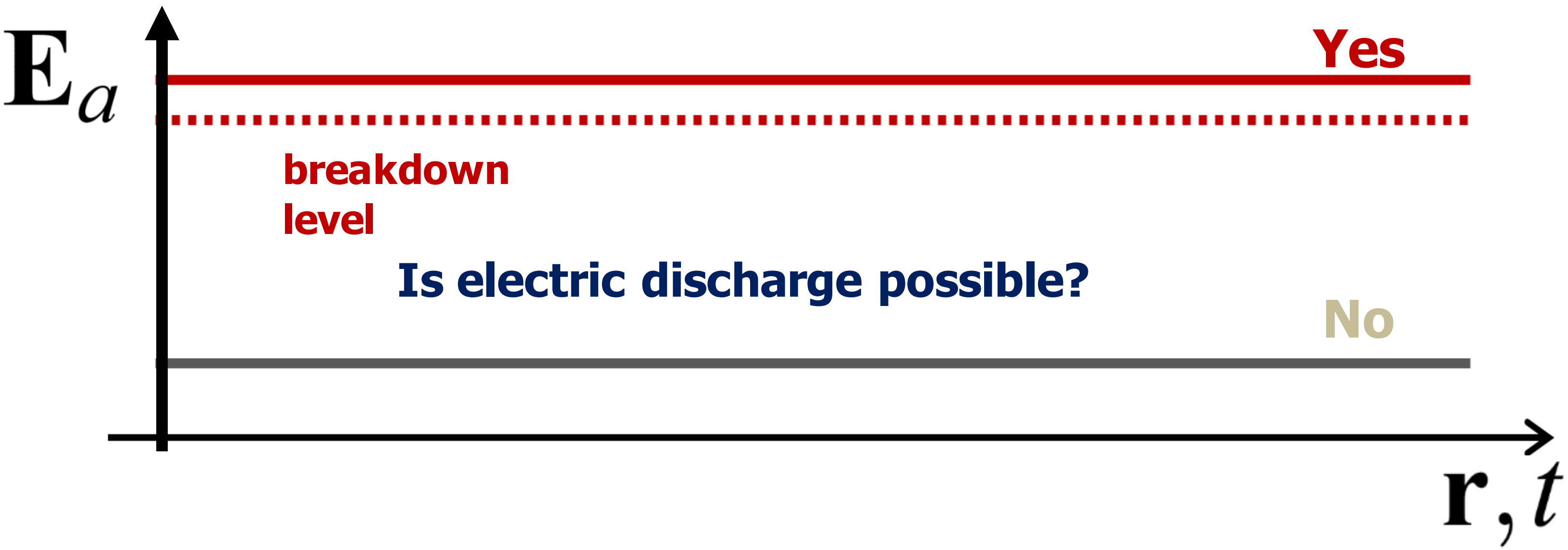
Effective ionization frequency

$$\lambda^{+} \approx \frac{\nu_i \nu_d}{\nu_a} - \nu_h = \mathfrak{I}_i - \nu_h \qquad \mathfrak{I}_i = \frac{\nu_i \nu_d}{\nu_a}$$

$$\frac{\partial n_n}{\partial t} = (\mathfrak{I}_i - \nu_h) n_n$$

$$\mathfrak{I}_i(E_c) \simeq \frac{\nu_i(E_c)\nu_d(E_c)}{\nu_a(E_c)} \simeq \nu_h(E_c) \longrightarrow E_c \lesssim E_b$$

Uniform electric field



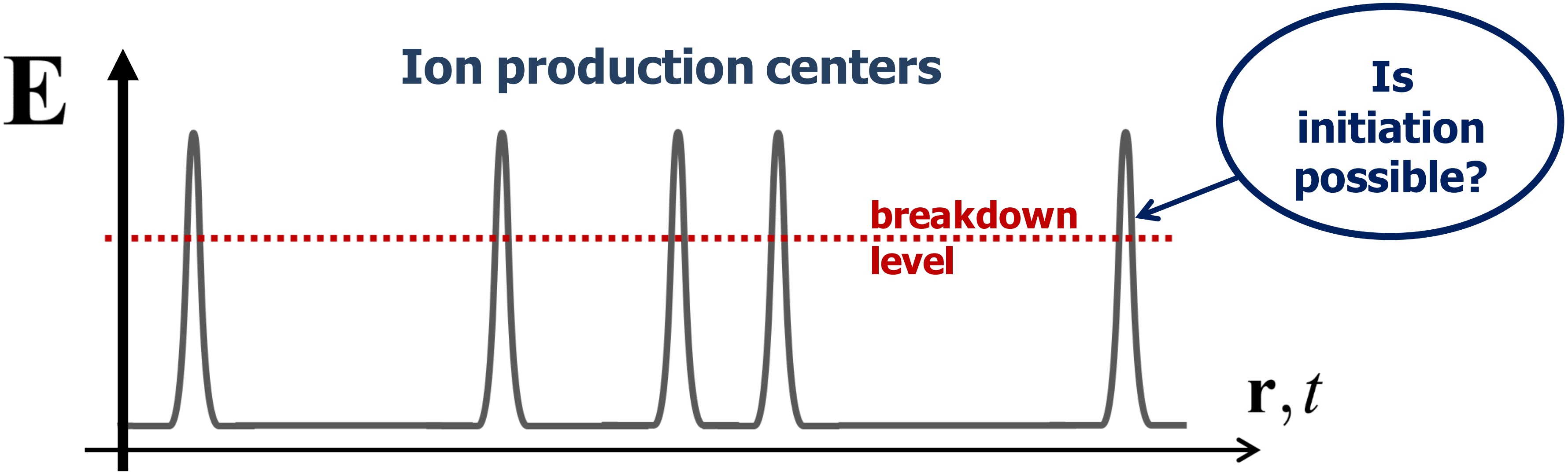
Frequency of ion losses to hydrometeors $\nu_h \simeq 1\ \mathrm{s}^{-1}$

For electric fields measured inside thunderclouds $\mathfrak{I}_i \ll \nu_h$

Thundercloud electric field

$$\frac{\partial n_n}{\partial t} = (\mathfrak{J}_i(\mathbf{r},t) - \nu_h)n_n \qquad \langle \mathfrak{J}_i(\mathbf{r},t)\rangle \ll \nu_h$$

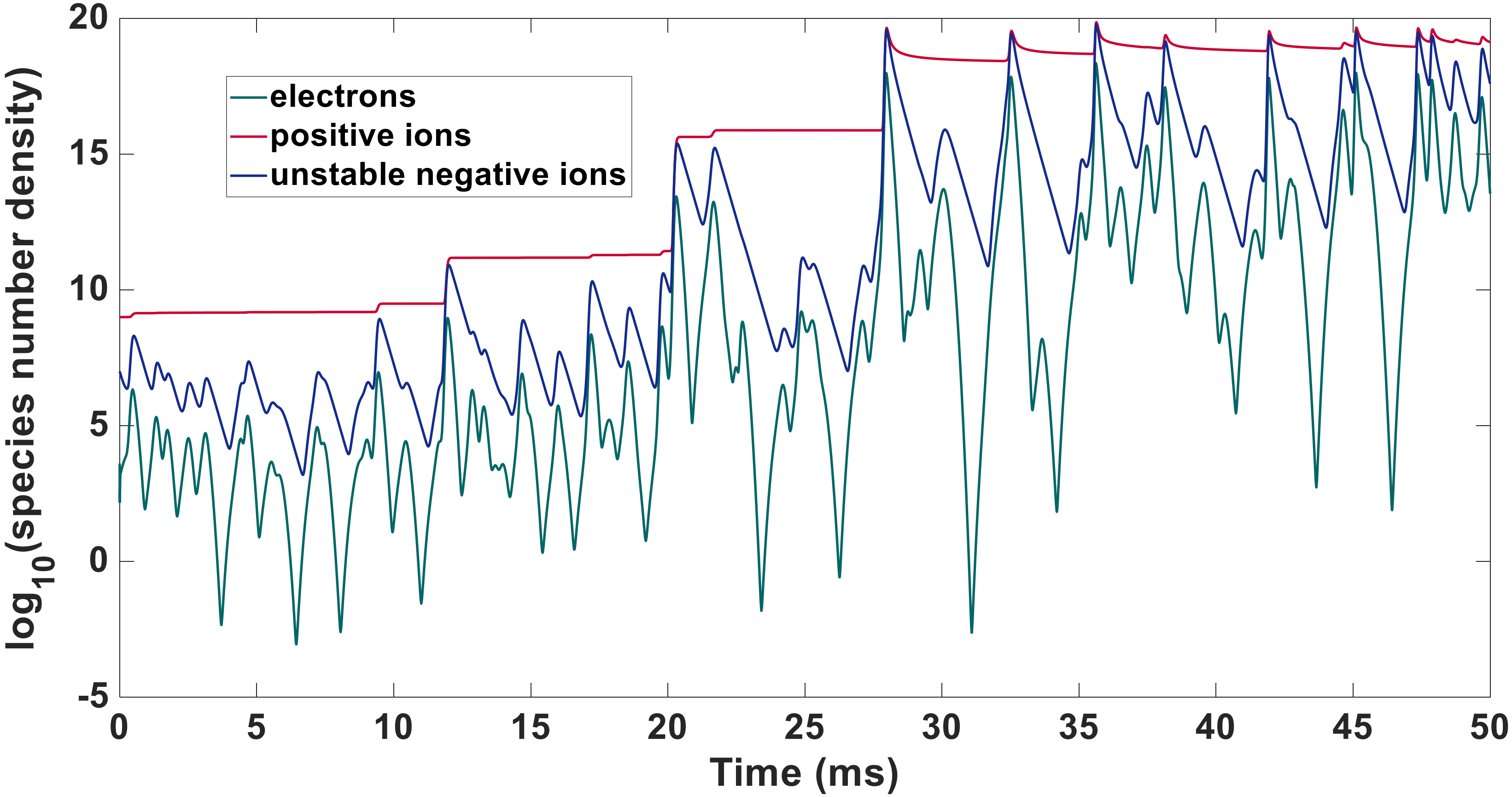
$$\mathfrak{J}_i(\mathbf{r},t) = \mathfrak{J}_i(\mathbf{E}(\mathbf{r},t)) \geq \nu_h \qquad \mathbf{E}(\mathbf{r},t) \geq E_c$$



$\mathfrak{M}$ ← **average number of ion production centers per unit time per unit volume**

$\cong 0.1\, m^{-3} s^{-1}$

Ion Concentration Increase



In residual ion spot, the electron detachment provides seed electrons just before the field amplitude reaches the breakdown value, intensifying electron and positive ion production when a new center is activated.

Positive feedback

$\uparrow \mathfrak{M} \longrightarrow \uparrow$ **Ion concentration** $\longrightarrow$

$\longrightarrow \uparrow \langle \mathbf{E}^2 \rangle^{1/2} \longrightarrow \uparrow \mathfrak{M}$

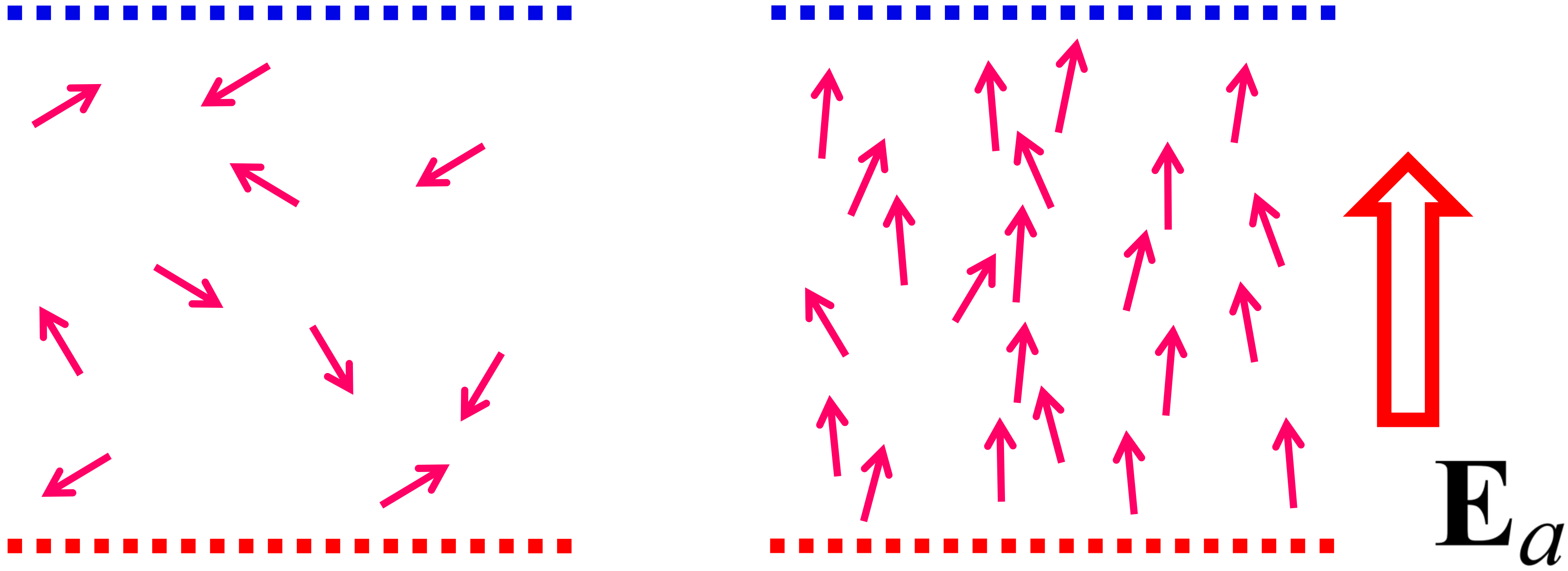
$$\langle \mathbf{E}^2 \rangle^{1/2} \gtrsim E_s^+$$

Townsend avalanches $\longrightarrow$ **Streamer discharges**

$10^{-2} - 10^{-1}$ m **$10^{-1} - 1$ m**

Volumetric discharge activity

$$\langle \mathbf{E} \rangle = 0 \qquad\qquad \langle \mathbf{E} \rangle = \mathbf{E}_a$$



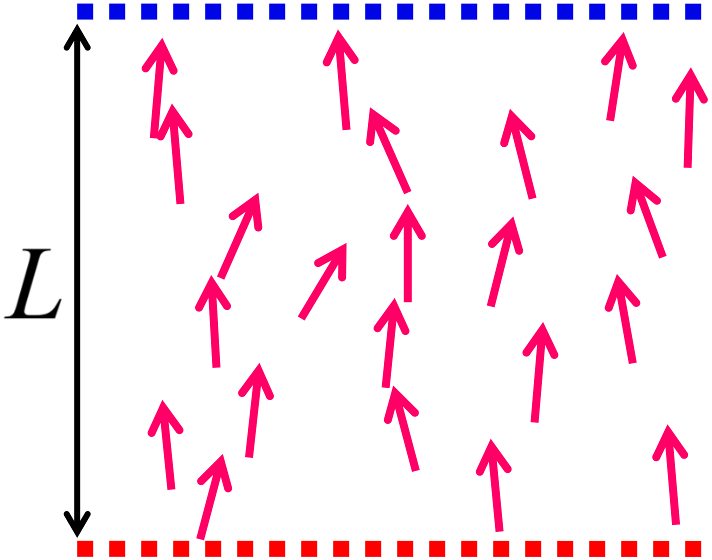
$$\left\langle \mathbf{E}^2 \right\rangle^{1/2} \gtrsim E_s^+$$

Just the presence of streamers does not guarantee that a leader will form

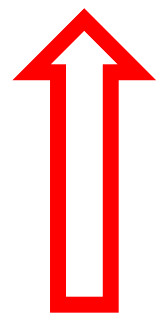
Volumetric discharge activity

$$\langle \mathbf{E} \rangle = \mathbf{E}_a$$

$$LE_a < U_c$$

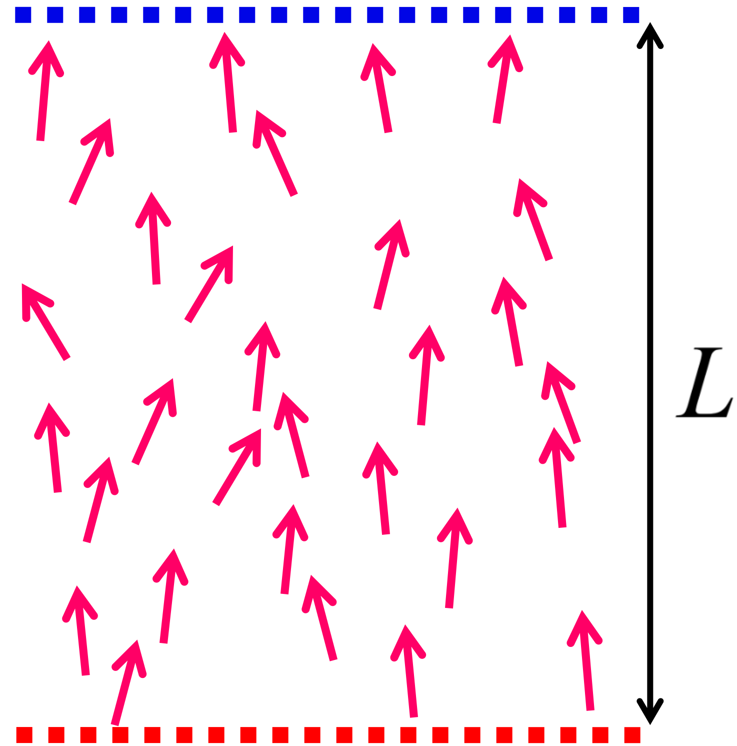


precursors



$$\mathbf{E}_a$$

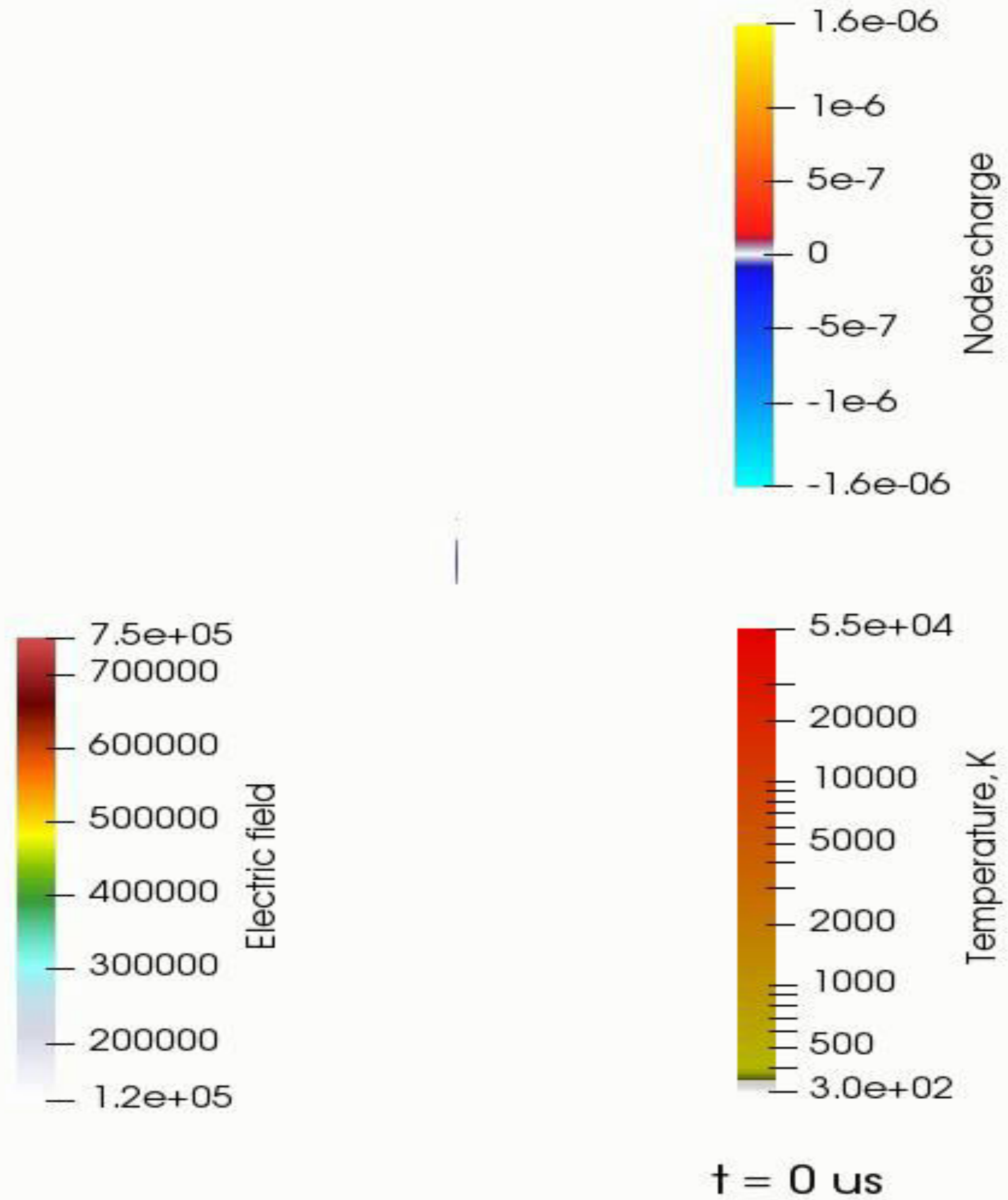
$$LE_a \gtrsim U_c$$



lightning

$$U_c \simeq 3\ \mathrm{MV}$$

Lightning seed formation



Conclusion

- The process of energy relaxation in thundercloud starts with avalanches and then proceeds to larger spatial scales.
- We postulate the existence of ion production centers accompanying hydrometeors collisions or near collisions.
- The rate of occurrence of ion production centers should exceed the critical level, which has been observed in thunderclouds.