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Radio emission from fast streamers

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Outline

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Streamer mechanism (postitive streamer)

[Loeb and Meek, 1941]

Photons produced in the head of the streamer travel ahead, produce ion-electron pairs, and the electrons serve as avalanche seed in high electric field at streamer head.

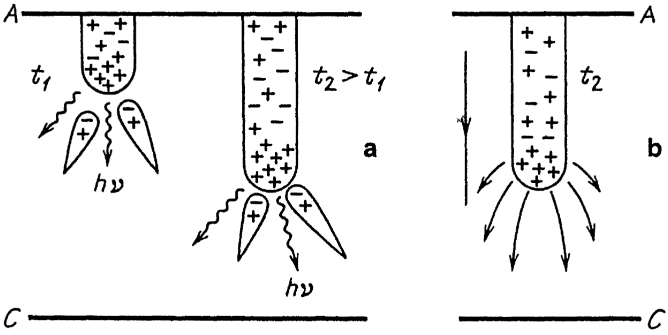

Figure: Positive streamer [figure from Raizer, 1991, p. 335]

Parametric model

We look for a solution for a moving ionization front in the shape of the **streamer**, i.e., a cylinder (channel) with a hemispherical cap (head). We can identify relationships between parameters describing this solution:

Parameter relationships

1. Relationship between E fields, from electrostatic distribution of surface charge.
2. Continuity of total (conductivity + displacement) current through the streamer front.
3. Propagation stability criterion, connecting ionization with the maximum field.
4. Velocity-radius relation, from electron density balance during photoionization/impact ionization.

We get a family of valid solutions, spanning a range of streamer radii a. The most unstable solution is chosed as the correct one (i.e., at maximum velocity V).

For details, see `https://arxiv.org/abs/2003.09450` (relationships are summarized on the next slide). Application to streamers at sea-level air gave reasonable ($\sim$ several 10%) agreement with experiment [Allen and Mikropoulos, 1999] and hydrodynamic modeling [Bagheri et al., 2018], and reasonable streamer threshold fields.

Reduced system of algebraic equations for (a, V, E_s, E_f, n_s)

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Parameters: streamer radius a, streamer velocity V, channel field E_s, front field E_f, channel electron density n_s.

1. Relation between E fields from electrostatic distribution of surface charge [analytical fit from method-of-moment calculations] (E_s , E_f):

$$E(\xi) \approx \left[2 + 0.56(2L/a)^{0.92}\right] \frac{E_e - E_s}{1 + \xi/\ell} + E_e, \qquad E_f = E(0), \qquad \ell/a \approx 0.3 \div 0.5$$

2. Continuity of total current through the streamer front [e.g., Babaeva and Naidis, 1997] (E_s, n_s, V):

$$J_c = \varepsilon_0 \left.\frac{\partial E}{\partial t}\right|_{\xi=0} \qquad \Longrightarrow \qquad e n_s v(E_s) = \frac{\varepsilon_0 V (E_f - E_e)}{\ell}$$

   v – drift velocity.

3. Propagation stability criterion from the flat ionization front theory [Lagarkov and Rutkevich, 1994] (n_s, E_f):

$$n_s = \frac{\varepsilon_0}{e} \int_0^{E_f} \frac{\nu_t(E')}{v(E')} \, dE'$$

   ν_t – total ionization rate. This is approximately equivalent to $\tau_M \sim \tau_{\text{ion}}$.

4. Velocity-radius relation, from the photoionization/impact ionization balance [Pancheshnyi et al., 2001] (V, E_f, a):

$$\int_0^{\infty} S_{\text{ph}}(\xi) \exp\left[\int_0^{\xi} \frac{\nu_t(E)\, d\xi'}{V \pm v(E)}\right] d\xi = 1$$

   S_{ph} is the photoionization source from a front of radius $\sim a$ (for unit n_s).

Modification of the parametric model for fast streamers

Lab conditions involve ∼1–10 cm long streamers with typical velocities $\sim 10^6$ m/s. We apply the same method to long (∼1–10 m) streamers, also in uniform external fields. As the velocity grows with length, these streamers now may approach speeds $10^7 - 10^8$ m/s, i.e., become the so-called **fast streamers** [Rison et al., 2016].

If the speed of a streamer approaches c, we have to take into account the finite time it takes for photons to travel forward before they create photoionization. This is done by correcting the **4th relation** (i.e, the velocity-radius relation, from electron density balance during photoionization/impact ionization):

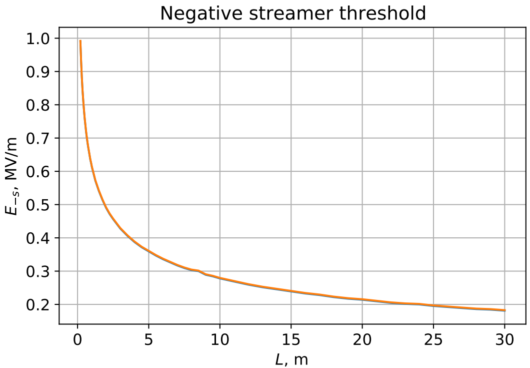
$$S_{\text{ph}}(\xi) \qquad \Longrightarrow \qquad \alpha S_{\text{ph}}(\alpha\xi), \qquad \alpha = \frac{1}{1 - V/c}$$

(details to be published).

Outline

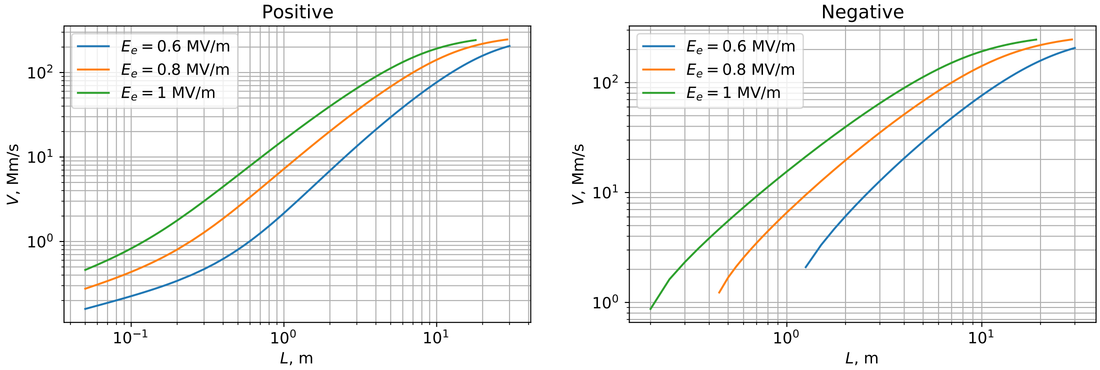
Negative streamer threshold

In the case of the **negative** streamer polarity, solution does not exist for small fields. The threshold depends on the length of the streamer L. This is different from positive streamers, whose threshold is determined by electron attachment and recombination in the channel (a process that we neglect here). In the lab streamers (∼10 cm), the threshold is $E_{-t} \approx 0.75$–1.25 MV/m [Raizer, 1991, p. 362].



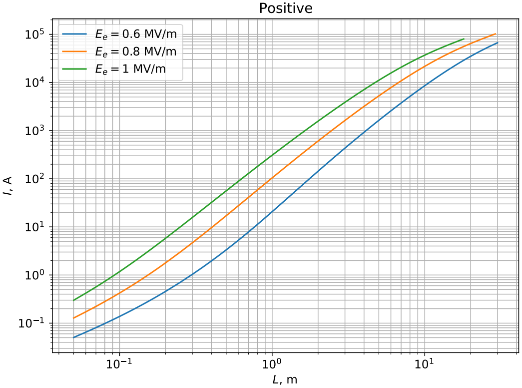
Velocities

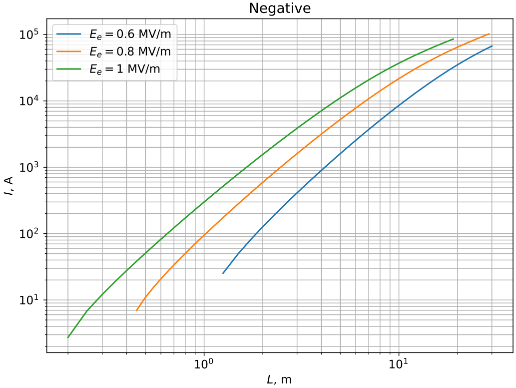
The velocity indeed approaches c.



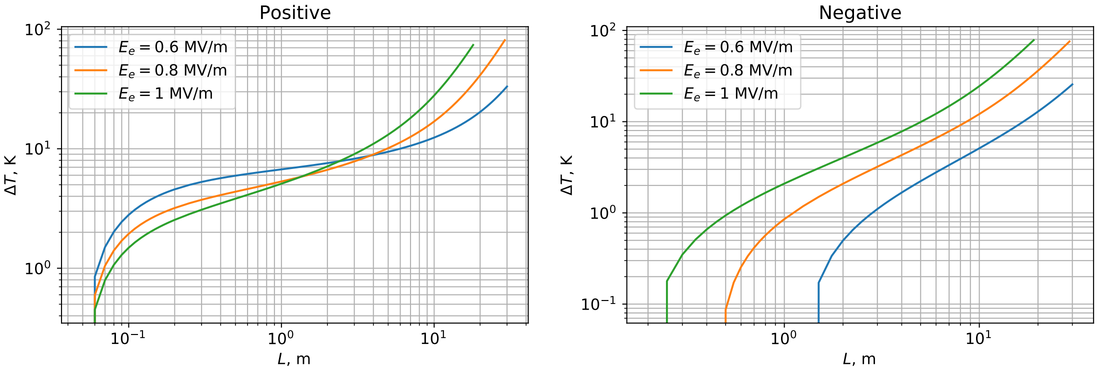
Currents

Laboratory streamer currents are $I \sim 0.1$ A [Raizer, 1991].





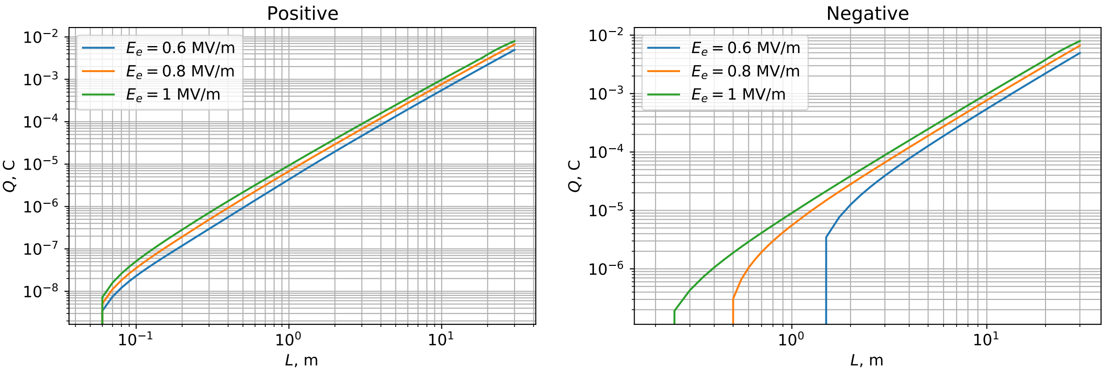
Heating



Despite the high currents, the heating is not significant.

Charge

The charge of the streamer is equal and opposite to the charge left behind.



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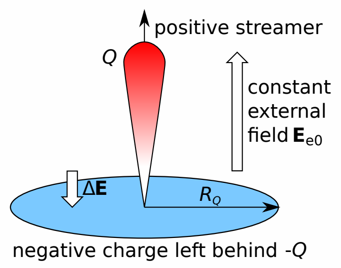
Simple model of changing external field



- Q – total charge of the streamer, and (with the opposite sign) the charge left behind;
- We assume the streamer collects charge from a disk of radius R_Q;
- We take $R_Q = 10$ m in our calculations
- Field reduction by the left-behind negative charge, assumed uniform (as a rough approximation):

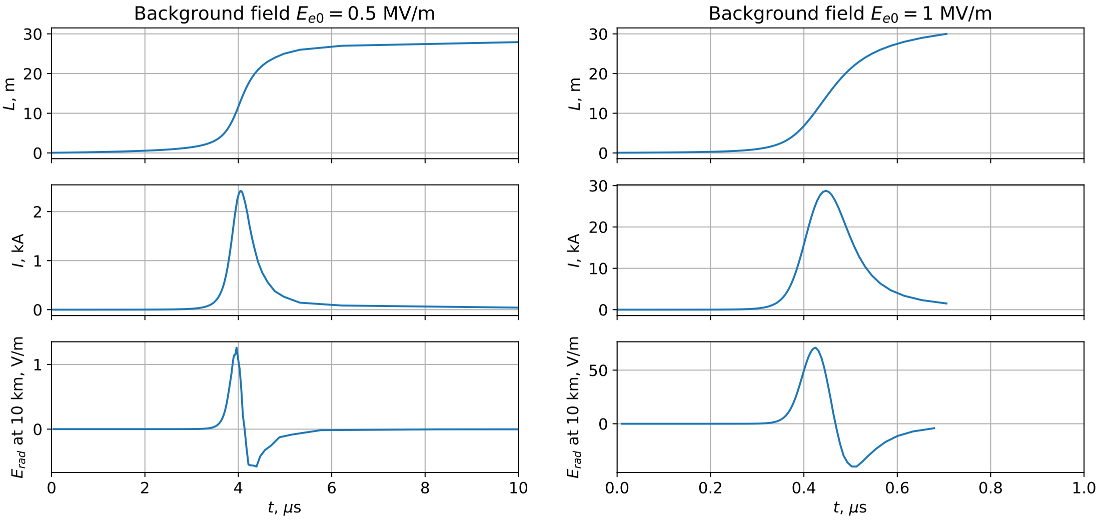
$$\Delta \mathbf{E} = -\hat{z} \frac{Q}{2\epsilon_0 \pi R_Q^2}$$

- The corrected uniform external field $\mathbf{E}_e(t) = \mathbf{E}_{e0} + \Delta\mathbf{E}(t)$.
- Radiated field (far-field, point-source, nonrelativistic approximation):

$$E_{\text{rad}} = \frac{\mu_0}{4\pi D} \frac{dM}{dt} \sin\theta$$

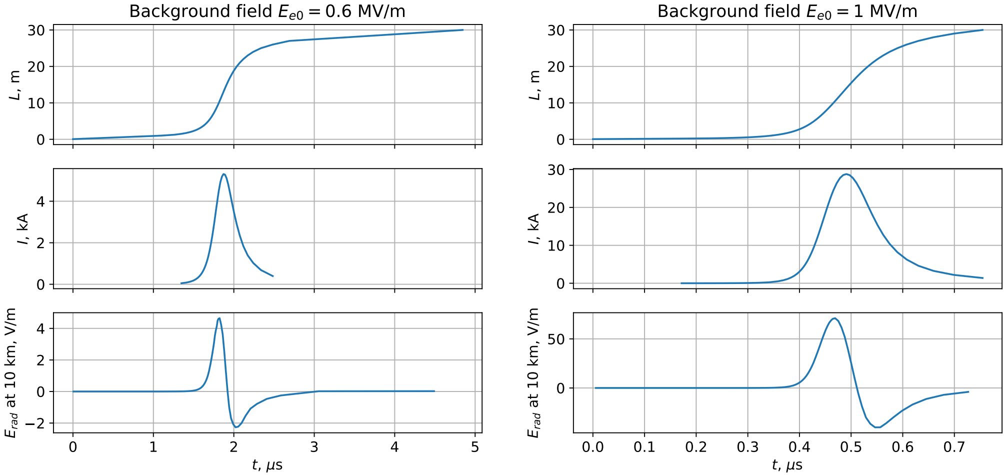
where D is the observation distance, $M = IL$ is the current moment, θ is the angle with the vertical.

Results: positive fast streamer



Results: Negative fast streamer

Note: A negative streamer cannot start at $L = 0$ because of high threshold.



Outline

Summary

- Streamers in uniform fields may accelerate close to the speed of light.
- We calculated parameters of such streamers using the method of `https://arxiv.org/abs/2003.09450`.
- We calculated radiation assuming that the streamer is stopped because of the field of the charge that it leaves behind.
- The radiation field (amplitude and time scale) varies in wide range, depending on the background field in which the streamer propagates.

Acknowledgements

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Outline

Slides for extended presentation

- Streamer mechanism (negative streamer)
- More results for constant E_e

Streamer mechanism (negative streamer)

The avalanches started by photoelectrons are directed outward, but the streamer moves so fast that it catches up with them.

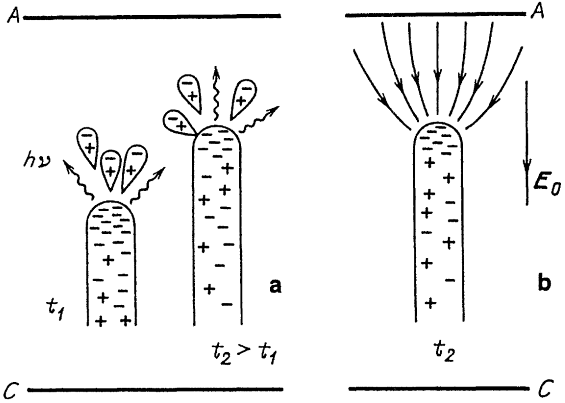
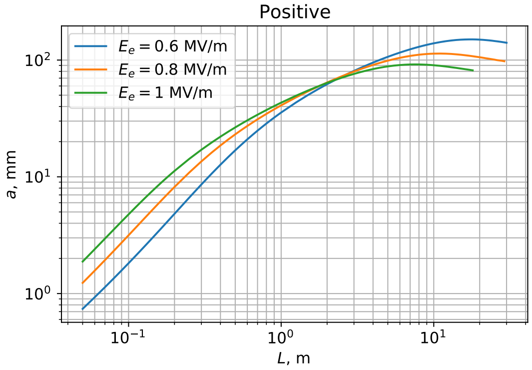
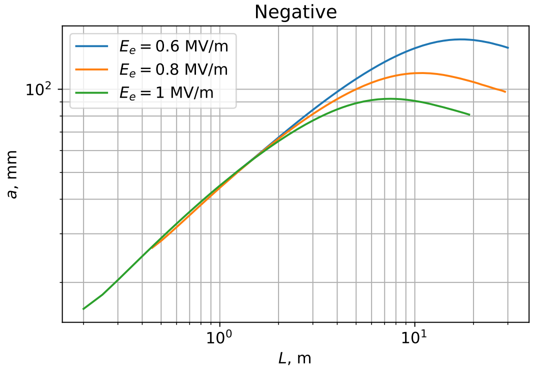


Figure: Negative streamer [figure from Raizer, 1991, p. 338]

Radii


Positive
$E_e = 0.6$ MV/m
$E_e = 0.8$ MV/m
$E_e = 1$ MV/m
10^2
10^1
10^0
a, mm
10^{-1}
10^0
10^1
L, m


Negative
$E_e = 0.6$ MV/m
$E_e = 0.8$ MV/m
$E_e = 1$ MV/m
10^2
a, mm
10^0
10^1
L, m

Channel electron density

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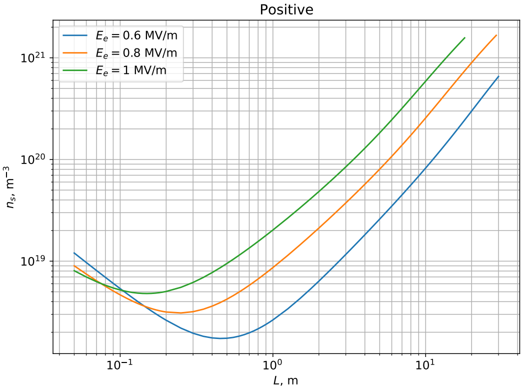

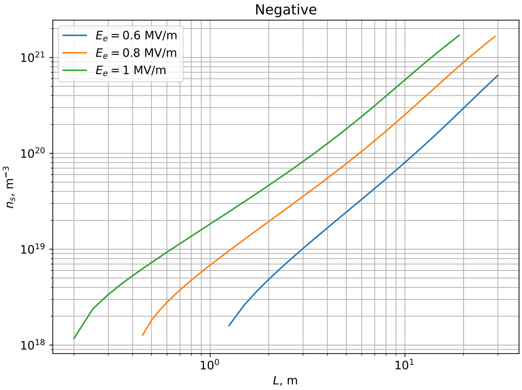

Channel conductivity