# Observable Electrical and Electromagnetic Effects of Developing Streamer Systems

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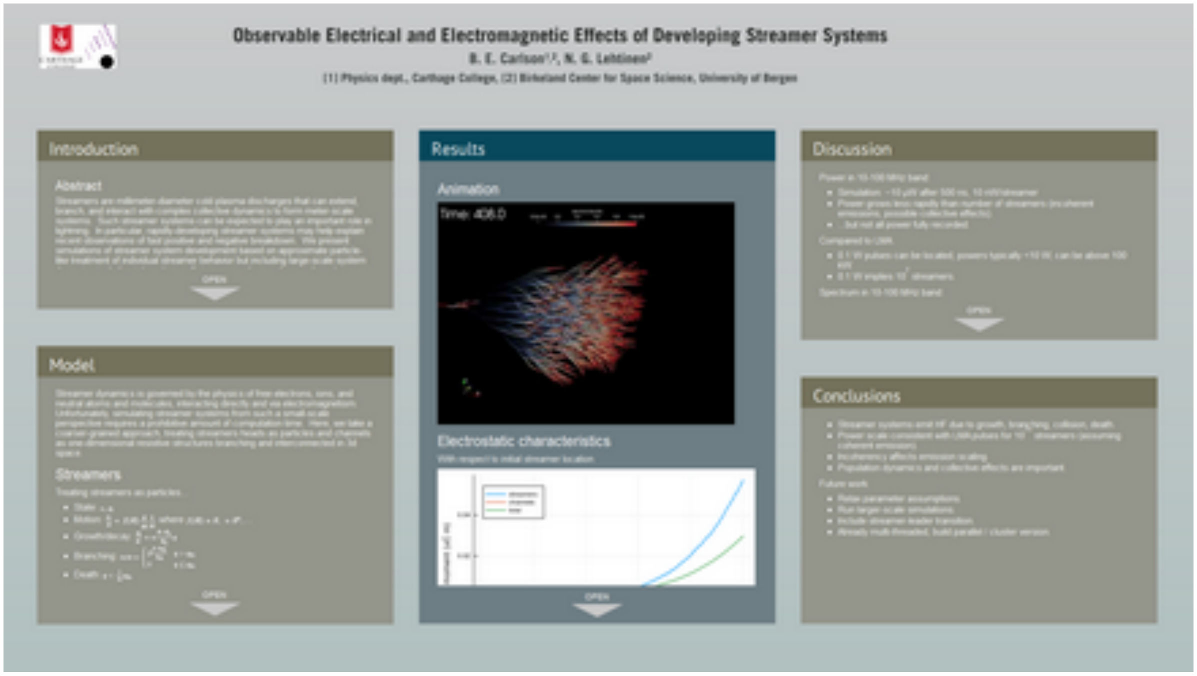
**Abstract**

Streamers are millimeter-diameter cold plasma discharges that can extend, branch, and interact with complex collective dynamics to form meter-scale systems. Such streamer systems can be expected to play an important role in lightning. Small-scale streamer systems may grow to provide sufficient ionization and intensification of field to support initiation of hot plasma channel development. Streamer systems developing ahead of the lightning channel may guide channel extension and help explain the observed step-wise extension process. Rapidly-developing streamer systems may also help explain recent observations of fast positive and negative breakdown. We present simulations of streamer system development based on approximate particle-like treatment of individual streamer behavior but including large-scale system dynamics including interaction, collision/connection, and secondary streamer initiation. Here we focus on the observable effects of such streamer system development, including electrostatic field change and electromagnetic wave emissions with frequencies up to 500 MHz. Preliminary results suggest high-frequency (HF) emissions due to streamer acceleration and interaction in isolated streamer systems are comparable in scale to observations of HF emission from lightning and develop before detectable static field change occurs, but these results depend on simulation parameters.

# Observable Electrical and Electromagnetic Effects of Developing Streamer Systems





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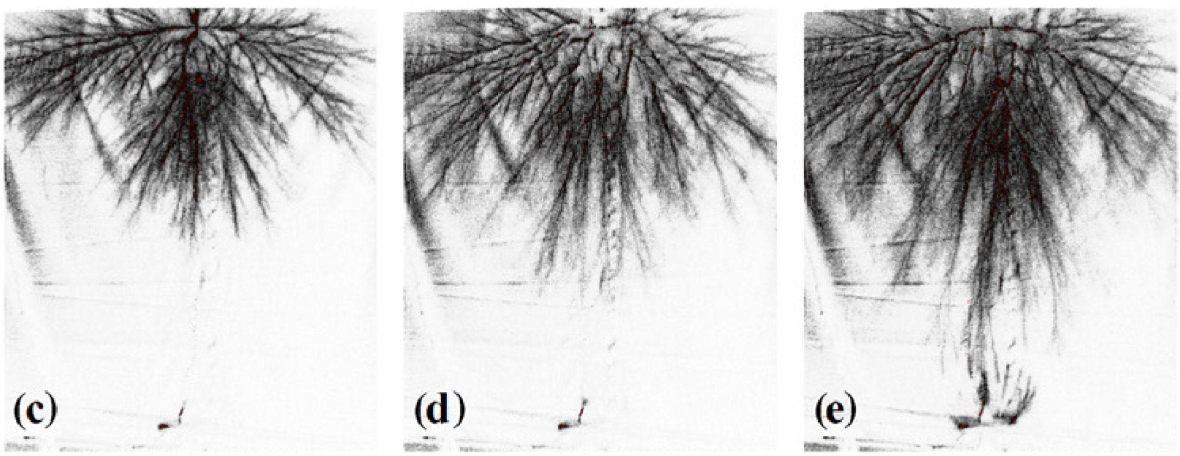
# INTRODUCTION

## Abstract

Streamers are millimeter-diameter cold plasma discharges that can extend, branch, and interact with complex collective dynamics to form meter-scale systems. Such streamer systems can be expected to play an important role in lightning. In particular, rapidly-developing streamer systems may help explain recent observations of fast positive and negative breakdown. We present simulations of streamer system development based on approximate particle-like treatment of individual streamer behavior but including large-scale system dynamics including interaction, collision, connection, and secondary streamer initiation, and predict the resulting electrostatic field change and electromagnetic wave emissions for comparison with observation.

## Streamer corona

Streamers are millimeter-diameter filamentary cold plasma discharges composed of a "head" with relatively high charge and conductivity followed by a "tail" with gradually decaying conductivity. Streamers can form whenever the ambient electric field and potential are sufficiently high, and once formed can grow and extend into less-intense field regions. If the streamer grows intense enough, it can branch, leading to multiple streamers. At meter scale in the lab:




From figure 2, Kochkin et al, 2012

The dynamics of such systems can be quite complicated. On the scale of lightning, sytems of tens of millions of interacting streamers seem to give rise to quite intricate structures:

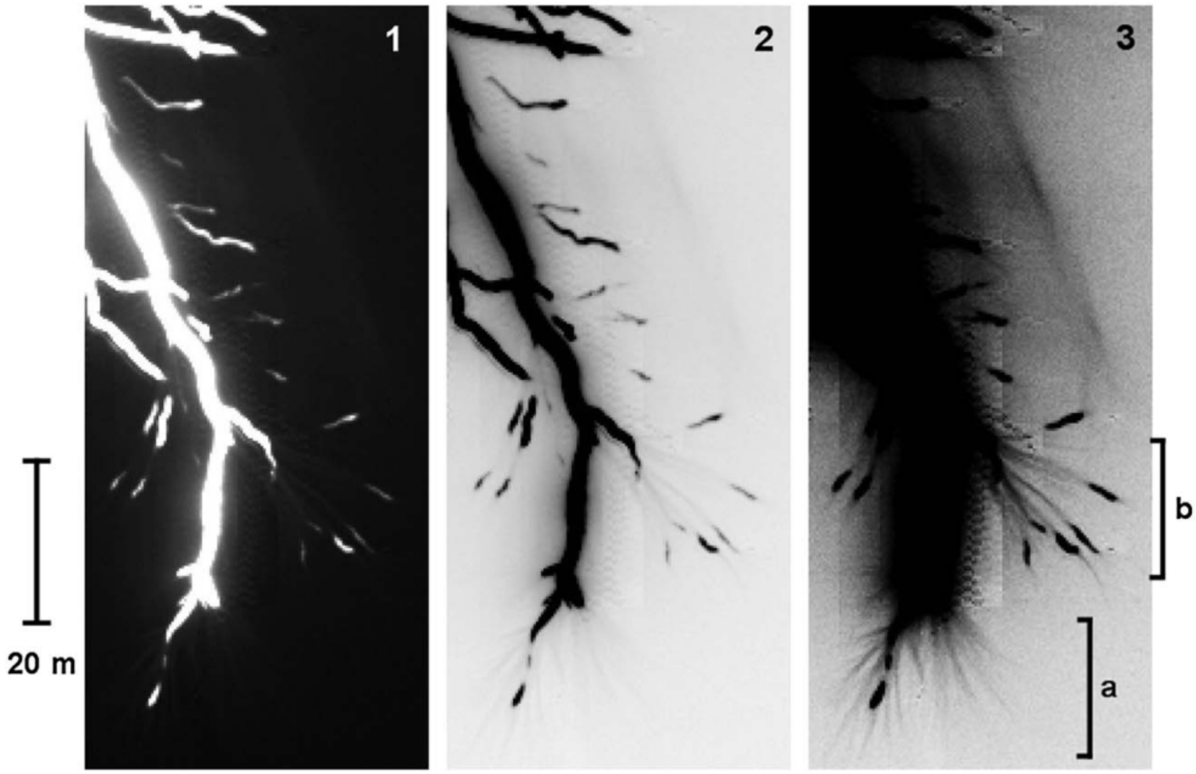



Fig. 5 from Petersen and Beasley, JGR Atm., 2013

The meter-scale filamentary structures visible in these photos are likely due to systems of interacting streamers driven outward by the intense charge deposited at the core of the lightning channel.

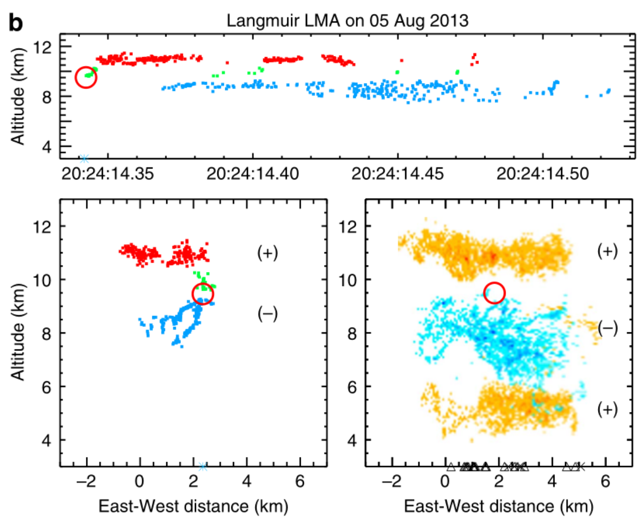
## Electromagnetic effects

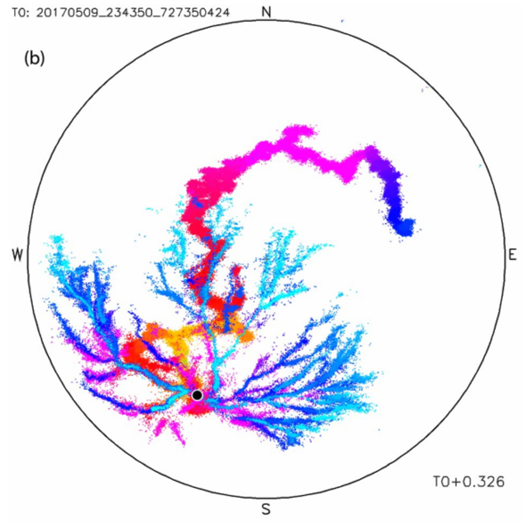
Streamer systems carry charge outward from the lightning channel, allowing it to transfer much more charge overall than if the charge remained confined to the channel.

Streamers development takes place on nanosecond to microsecond timescales, and thus is likely responsible for much of the HF and VHF radio emissions produced by lightning.

Streamer interaction and collision can take place on timescales as short as a few picoseconds and is predicted to produce significant VHF and UHF radio emission (Shi et al., 2019).

Understanding the dynamics of streamer corona is thus essential for interpretation of radio observation of lightning, for example by lightning mapping arrays (LMAs) and interferometers, which detect HF emission to map lightning without detailed knowledge of the physical context of its production.  Example LMA and interferometer data:




From fig. 2, Rison et al., 2016. From fig. 2, Shao et al., 2018.

This work focuses on building a model of interacting streamer systems that can predict electromagnetic emissions for comparison to observation.

# MODEL

Streamer dynamics is governed by the physics of free electrons, ions, and neutral atoms and molecules, interacting directly and via electromagnetism. Unfortunately, simulating streamer systems from such a small-scale perspective requires a prohibitive amount of computation time. Here, we take a coarser-grained approach, treating streamers heads as particles and channels as one-dimensional resistive structures branching and interconnected in 3d space.

## Streamers

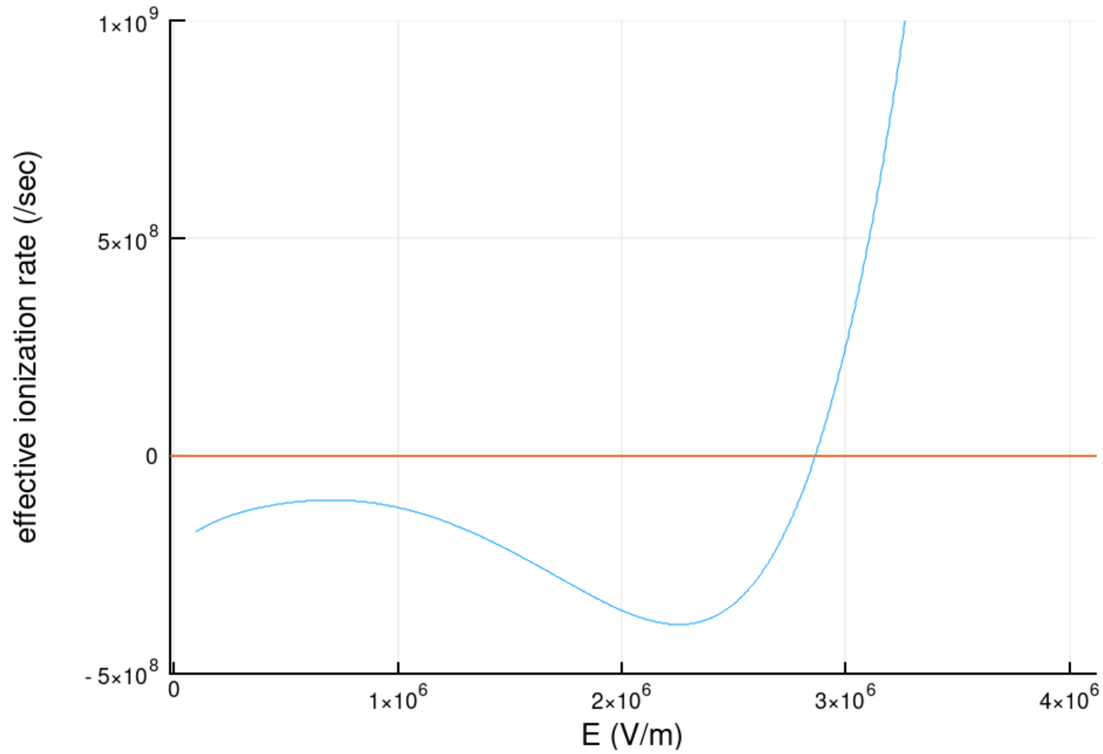
Treating streamers as particles...

- State: $\vec{r}_i, q_i$
- Motion: $\frac{d\vec{r}}{dt} = f(|E|)\frac{\vec{E}}{|\vec{E}|}\frac{q}{|q|}$ where $f(|E|) \propto E, \ \propto E^3, \ldots$
- Growth/decay: $\frac{dq}{dt} = \alpha\frac{E-E_0}{E_0}q$
- Branching: $\mathtt{rate} = \begin{cases} \beta\frac{q-q_{\mathrm{th}}}{q_{\mathrm{th}}} & q > q_{\mathrm{th}} \\ 0 & q \leq q_{\mathrm{th}} \end{cases}$
- Death: $q < \frac{1}{10}q_{\mathrm{th}}$
- Collision: connect and snap location to nearest junction, kill streamer if low charge and junction has opposite charge.
- Launch: new streamer from junction if $E > 2E_0$
- Parameters have different values for positive and negative streamers, set by reference to experiment and/or simple estimation (e.g. $q_{\mathrm{th}}$ for + is set such that streamer's lateral E-field is 1 MV/m, twice the stability field.)

## Channels

Treating channels as narrow branched structures built from short segments...

- Charge recorded at junctions.
- Charge distributed over attached segments as triangular function (i.e. line charge density is linearly interpolated between junctions).
- Segment current: $I = \Delta V/R$
- Resistance: $R = LR_{\mathrm{l}}(n)$ where resistance per length$R_{\mathrm{l}}(n) = \frac{R_{\mathrm{l\,min}}}{\left(1-\frac{R_{\mathrm{l\,min}}}{R_{\mathrm{l\,max}}}\right)n+\frac{R_{\mathrm{l\,min}}}{R_{\mathrm{l\,max}}}}$
- "Electron density" $n$ evolves by $\frac{dn}{dt} = n(\nu_i(E) - \nu_a(E))$
- Ionization: $\nu_i(E) = \mu E\alpha_i e^{-E_i/E}$
- Attachment: $\nu_a(E) = \mu E(\alpha_{a2}(E) + \alpha_{a3}(E))$, $\alpha_{a2}(E) = \alpha_{a0}e^{-E_{a0}/E}$, $\alpha_{a3}(E)$ power law approximation...




- Track the developing segment behind streamer head, convert to non-moving segment when length reaches a certain minimum. (I.e. not adding segments every time-step.)

## Time evolution

- Calculate fields and potentials (Fast Multipole Method)
- Calculate time derivatives (first order ODE system)
- Evolve via Bogacki-Shampine 2/3 with adaptive timestepping (BS3 in DifferentialEquations.jl).
- Record results.

## Electromagnetic emissions

EM waves produced by

- Acceleration and growth of streamer head charge: $E_{\text{rad}} = \frac{1}{4\pi\epsilon_0}\frac{1}{Rc}\frac{\vec{n}\times(\vec{n}-\vec{\beta})\times(q\dot{\vec{\beta}}+\dot{q}\vec{\beta})}{\left(1-\vec{n}\cdot\vec{\beta}\right)^3}$ where $\beta = v/c$
- Rate of change of current carried by streamer channels: $E_{\text{rad}} = \frac{1}{4\pi\epsilon_0}\frac{-L}{Rc^2}\frac{dI}{dt}$
- Sum over all streamer heads, channel segments.
- Derivatives calculated through ODE solution interpolating polynomial ($\dot{q}$, $\vec{\beta}$, $\dot{\vec{\beta}}$) or by hand over time-step ($I$)

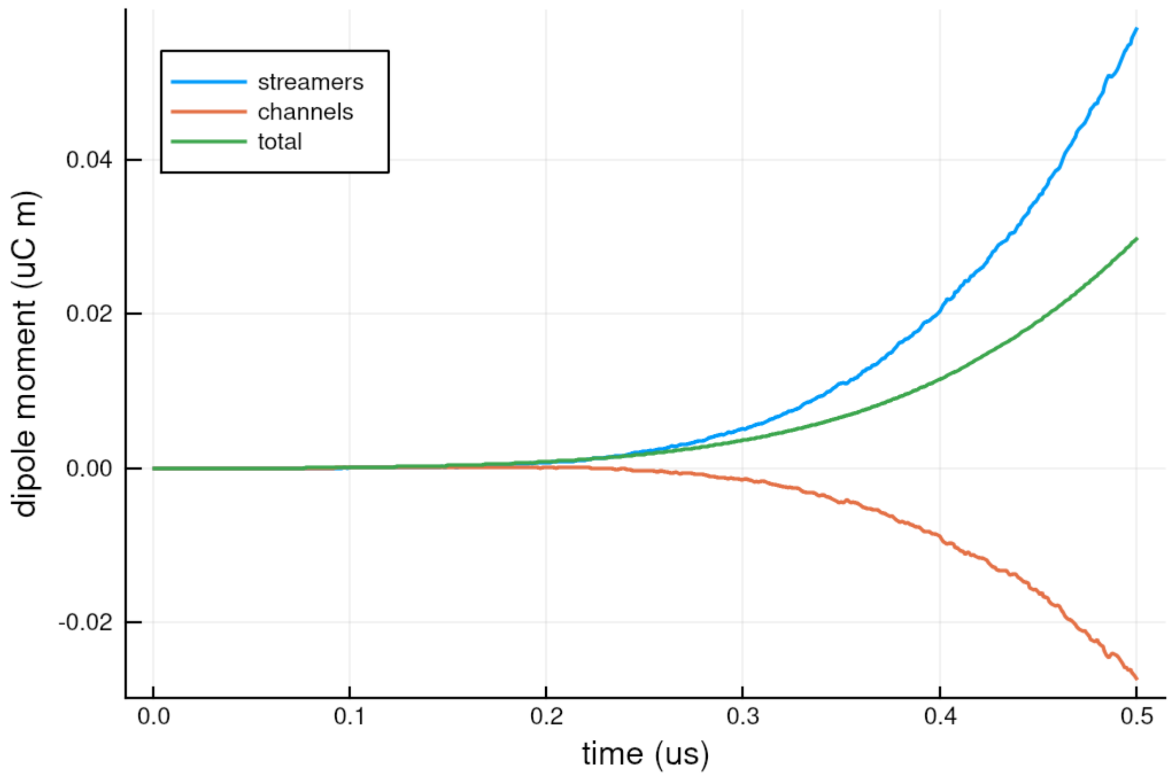
# RESULTS

## Animation

[VIDEO] https://www.youtube.com/embed/ZL1G_Gd9qRw?feature=oembed&fs=1&modestbranding=1&rel=0&showinfo=0

## Electrostatic characteristics

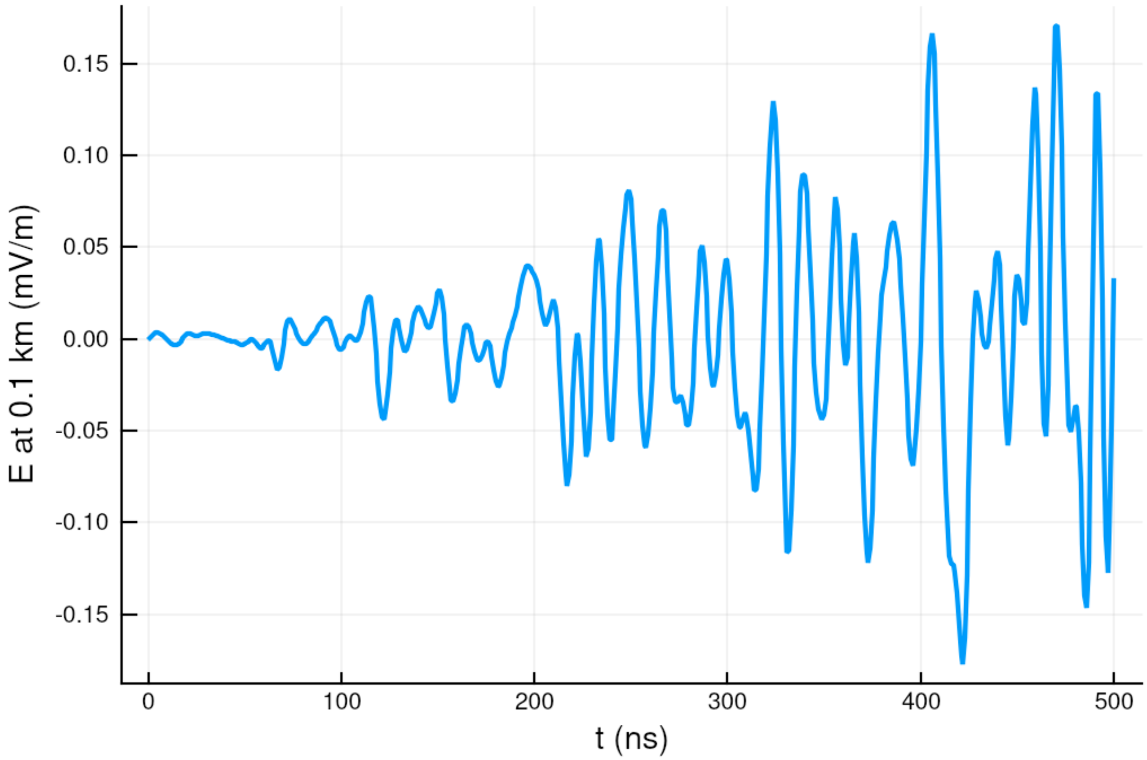
With respect to initial streamer location

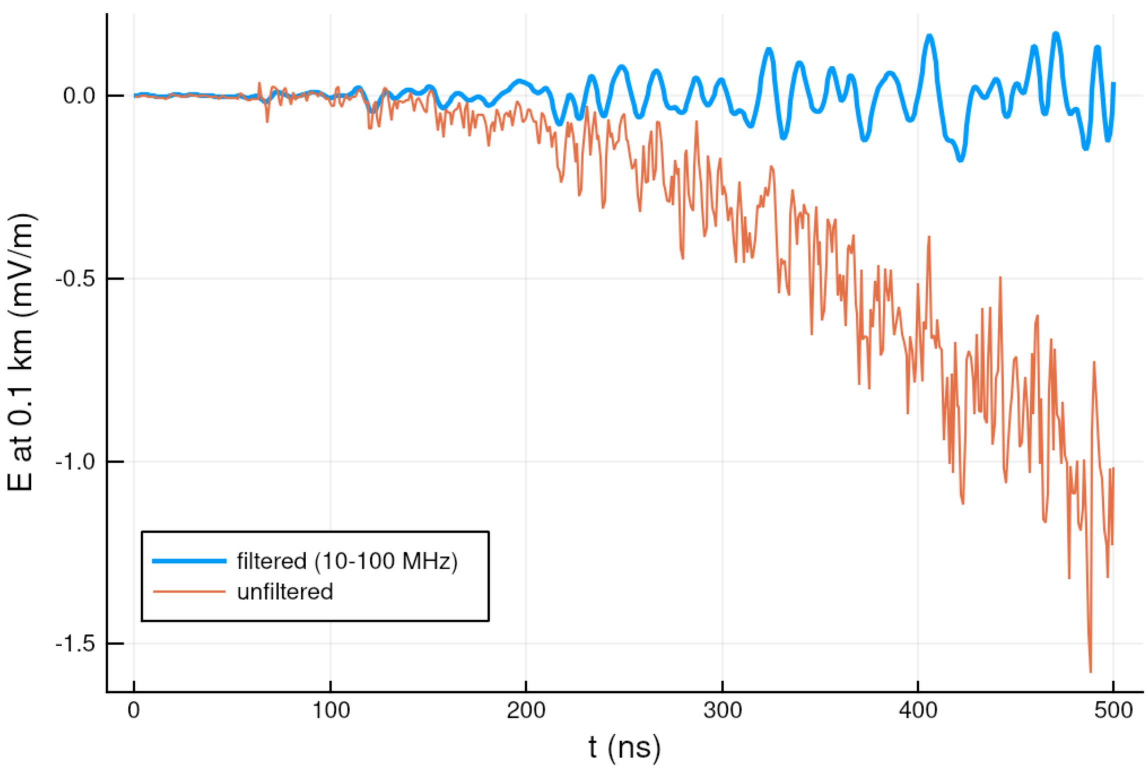


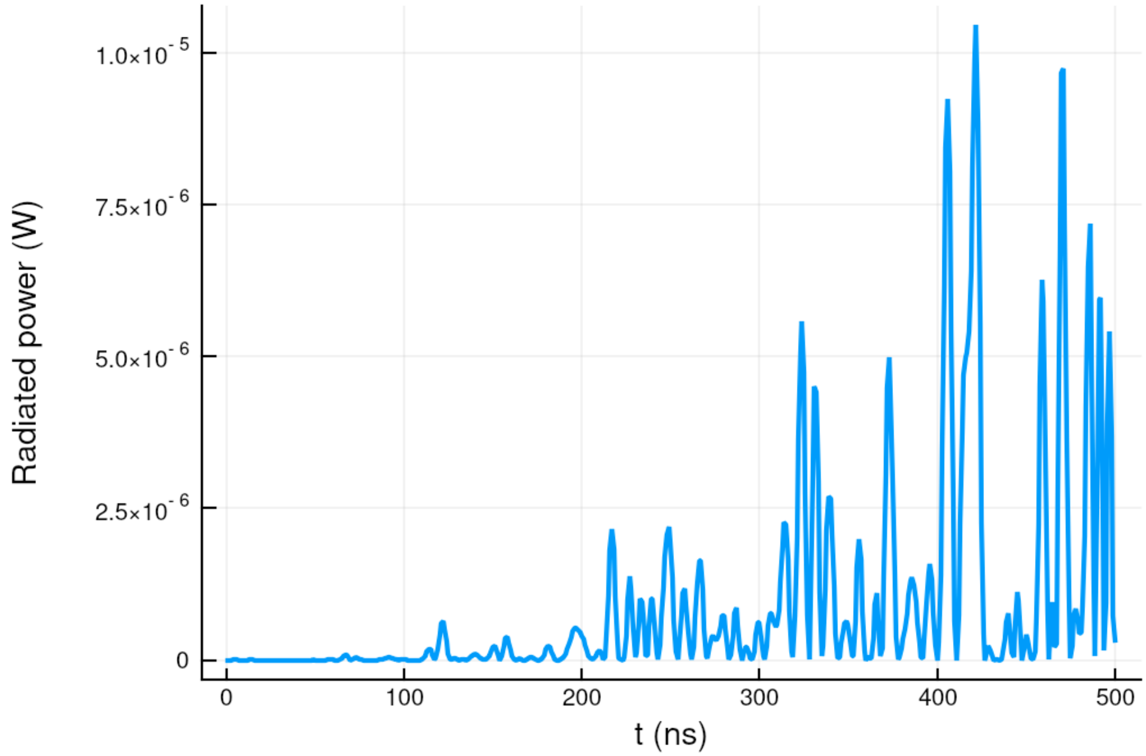

Would not produce observable field at ground level, though growing rapidly. (Naive / silly power-law extrapolation suggests 1 Cm at ~100 µs, would produce 10 mV/m static field at 10 km distance).

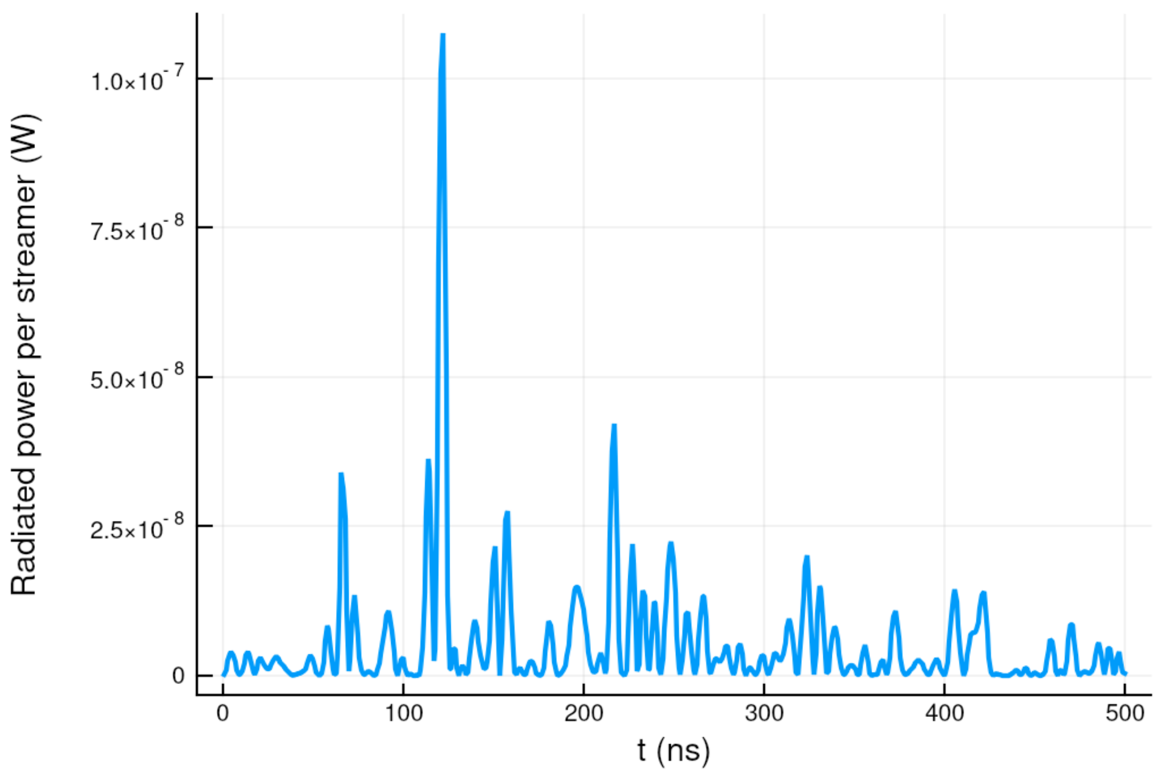
## Electromagnetic radiation

Filtered to 10-100 MHz

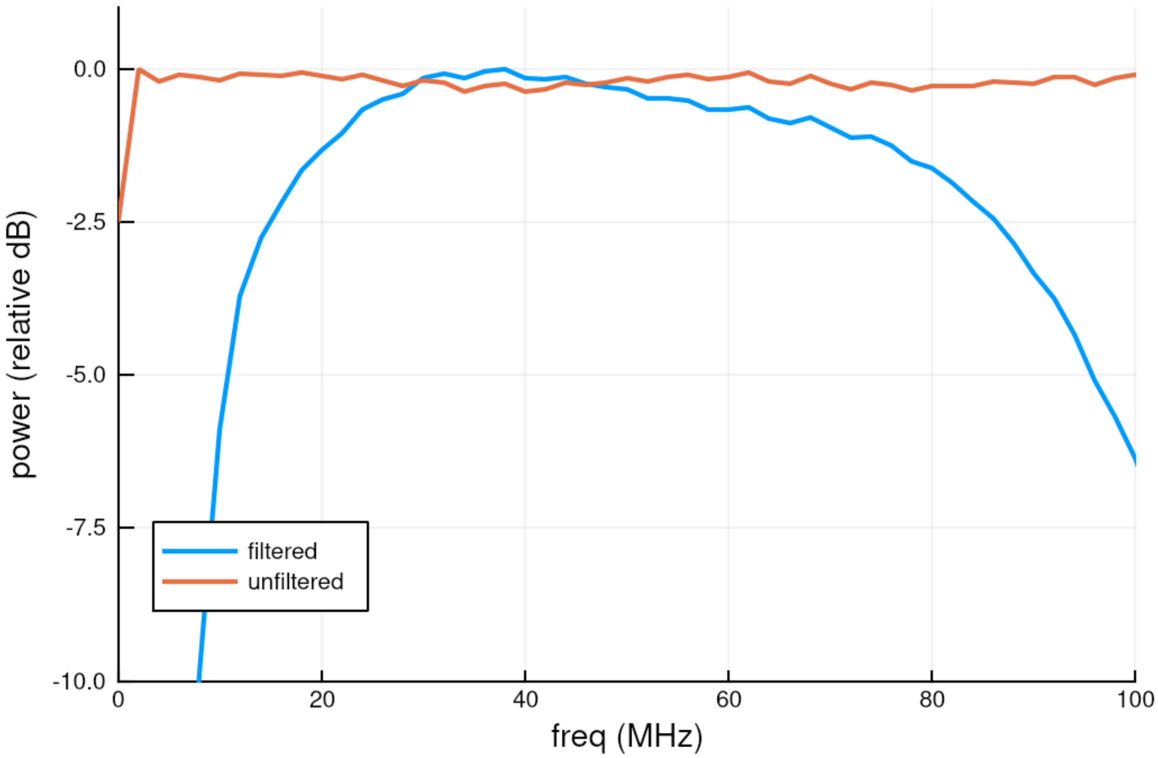

0.15
0.10
0.05
0.00
-0.05
-0.10
-0.15
E at 0.1 km (mV/m)
0
100
200
300
400
500
t (ns)


0.0
-0.5
-1.0
-1.5
E at 0.1 km (mV/m)
filtered (10-100 MHz)
unfiltered
0
100
200
300
400
500
t (ns)




Power spectrum


0.0
-2.5
-5.0
-7.5
-10.0
0
20
40
60
80
100
power (relative dB)
freq (MHz)
filtered
unfiltered

# DISCUSSION

Power in 10-100 MHz band:

- Simulation: ~10 μW after 500 ns, 10 nW/streamer
- Power grows less rapidly than number of streamers (incoherent emissions, possible collective effects).
- ...but not all power fully recorded.

Compared to LMA:

- 0.1 W pulses can be located, powers typically <10 W, can be above 100 kW.
- 0.1 W implies $10^7$ streamers.

Spectrum in 10-100 MHz band:

- Flat, consistent with Shi et al. (2019).
- Likely dependence on simulation parameters, filtering necessary.

Caveats / questions:

- Velocity dependence?
- Streamer growth and branching conditions?

# CONCLUSIONS

- Streamer systems emit HF due to growth, branching, collision, death.
- Power scale consistent with LMA pulses for $10^{7+}$ streamers (assuming coherent emission).
- Incoherency affects emission scaling.
- Population dynamics and collective effects are important.

Future work:

- Relax parameter assumptions.
- Run larger-scale simulations.
- Include streamer-leader transition.
- Already multi-threaded, build parallel / cluster version.

Sorry but time is up!

# ABSTRACT

Streamers are millimeter-diameter cold plasma discharges that can extend, branch, and interact with complex collective dynamics to form meter-scale systems. Such streamer systems can be expected to play an important role in lightning. Small-scale streamer systems may grow to provide sufficient ionization and intensification of field to support initiation of hot plasma channel development. Streamer systems developing ahead of the lightning channel may guide channel extension and help explain the observed step-wise extension process. Rapidly-developing streamer systems may also help explain recent observations of fast positive and negative breakdown. We present simulations of streamer system development based on approximate particle-like treatment of individual streamer behavior but including large-scale system dynamics including interaction, collision/connection, and secondary streamer initiation. Here we focus on the observable effects of such streamer system development, including electrostatic field change and electromagnetic wave emissions with frequencies up to 500 MHz. Preliminary results suggest high-frequency (HF) emissions due to streamer acceleration and interaction in isolated streamer systems are comparable in scale to observations of HF emission from lightning and develop before detectable static field change occurs, but these results depend on simulation parameters.

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## SWITCH TEMPLATE