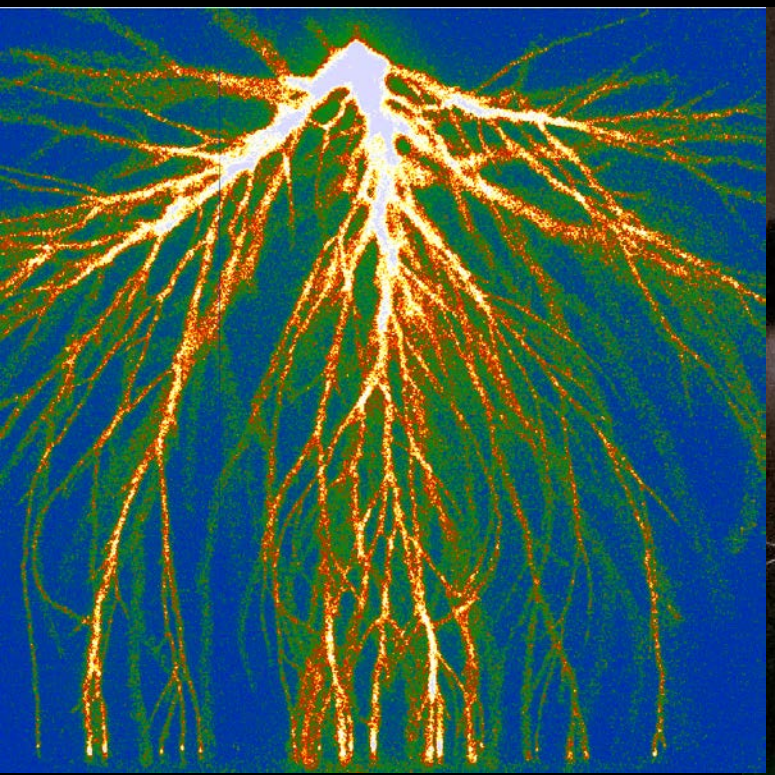
Pulsed positive discharges in air: Streamers and beyond

Ute Ebert,

Centrum Wiskunde & Informatica in Amsterdam
and
Technische Universiteit Eindhoven

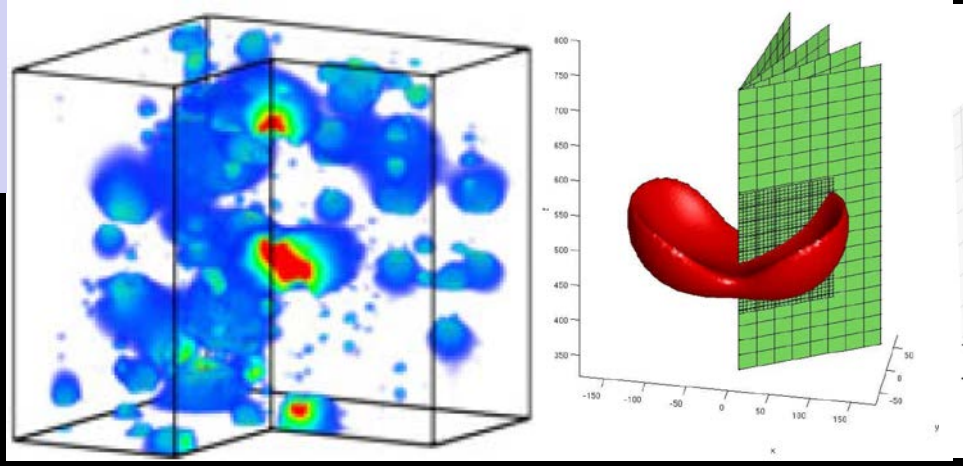


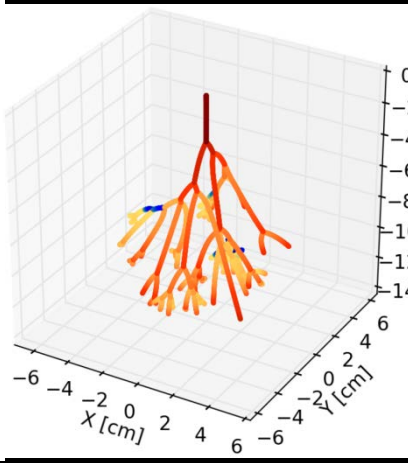
I have removed two unpublished slides.

Ask me for the complete file personally,

or follow updates on my publication site www.cwi.nl/~ebert

Scientific computing:
Hundsdorfer,
Camporeale et al





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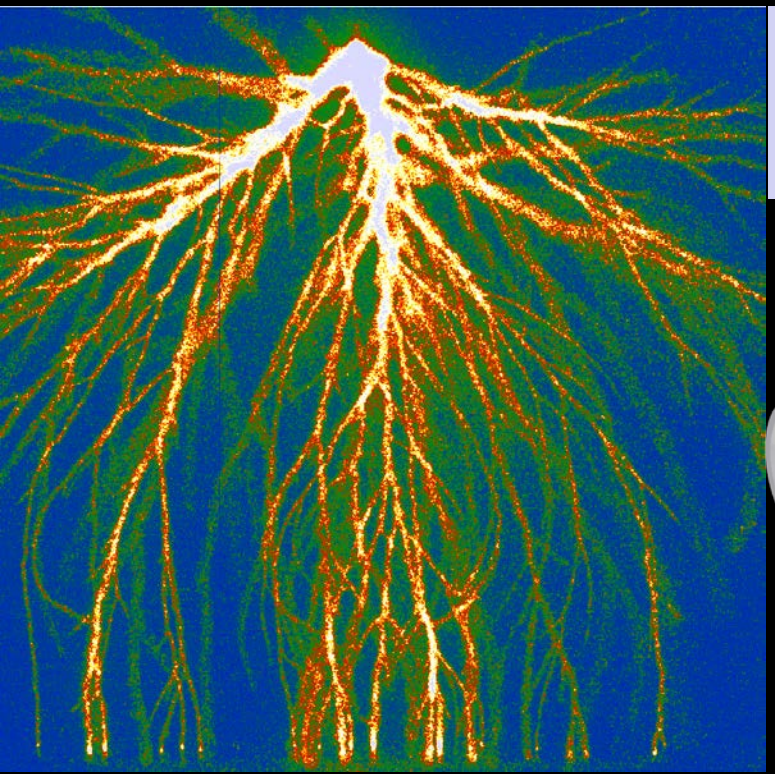
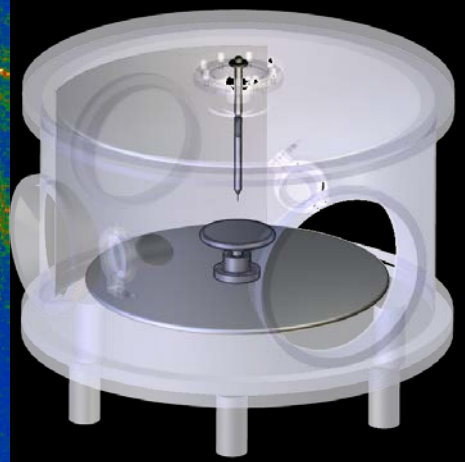


Plasma physics:
Nijdam, van
Veldhuizen et al



Electrical engineering:
Pemen, van Heesch, van Deursen

Plasma medicine

(“Plasma bullets”)

Lightning protection

Electric switching

Air purification

Disinfection

Plasma assisted

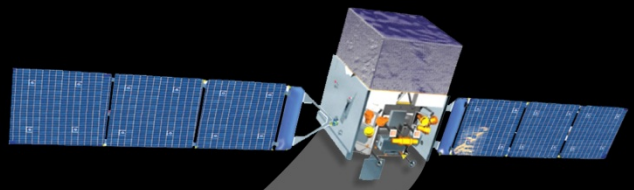
- **ignition**
- **combustion**
- **aviation**

X-ray pulses from approaching negative lightning leaders

Terrestrial Gamma-Ray Flashes into space

Fermi GBM positron event

Dec. 14, 2009, 11:53 UT

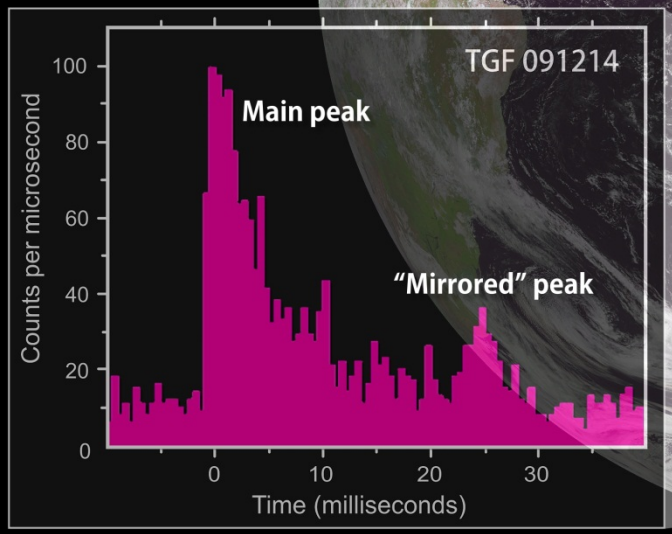


Fermi above Egypt

Mirror point

Magnetic field line

TGF 091214



[Briggs et al., JGR 2011; NASA]

Streamer to leader transition
with lightning surge generator, at 1 MV

by Kochkin, Nguyen & van Deursen at TU Eindhoven

+1 MV lightning surge on upper electrode in STP air

1 m gap

Each shot is a different discharge.

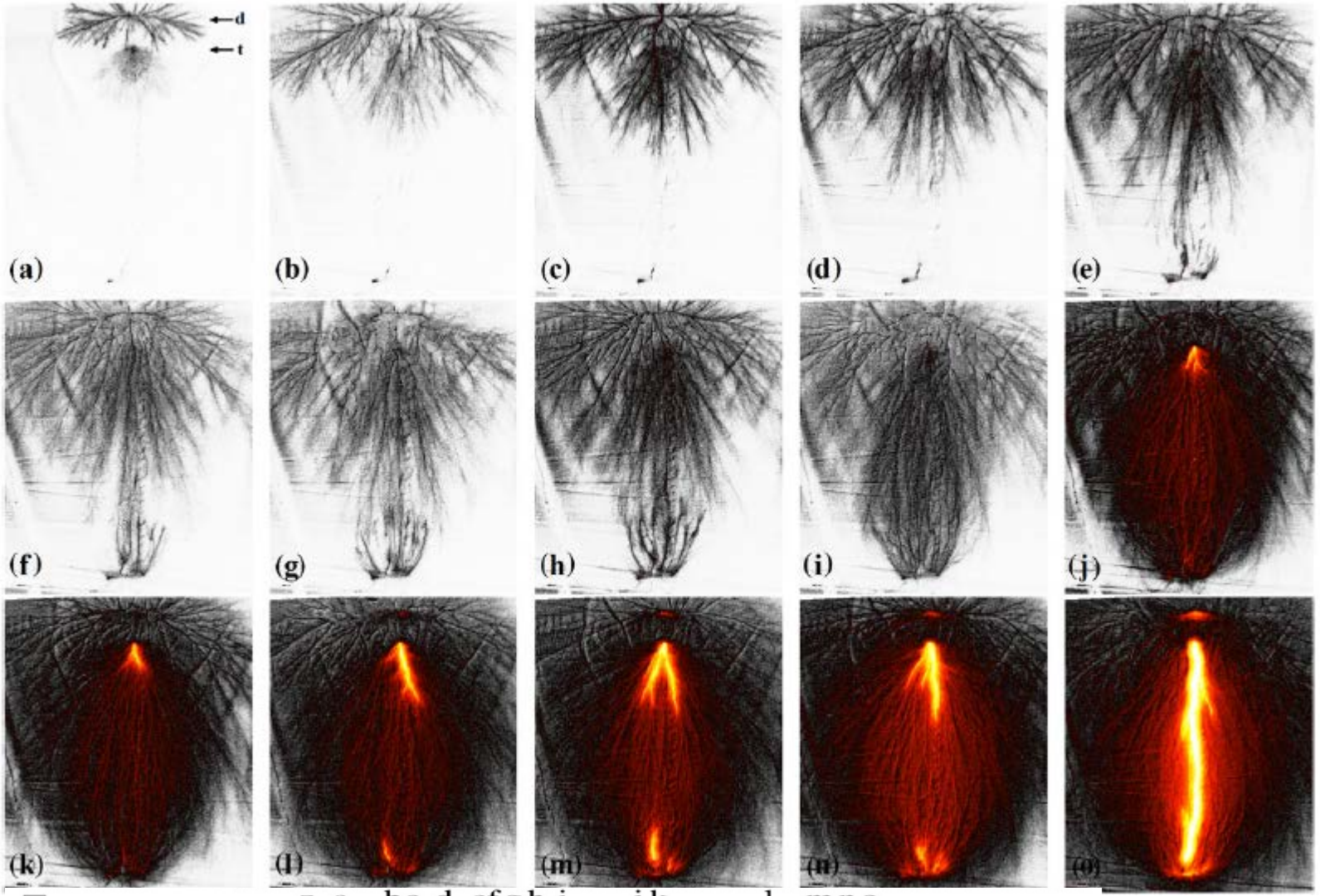
Exposure time increases per shot.

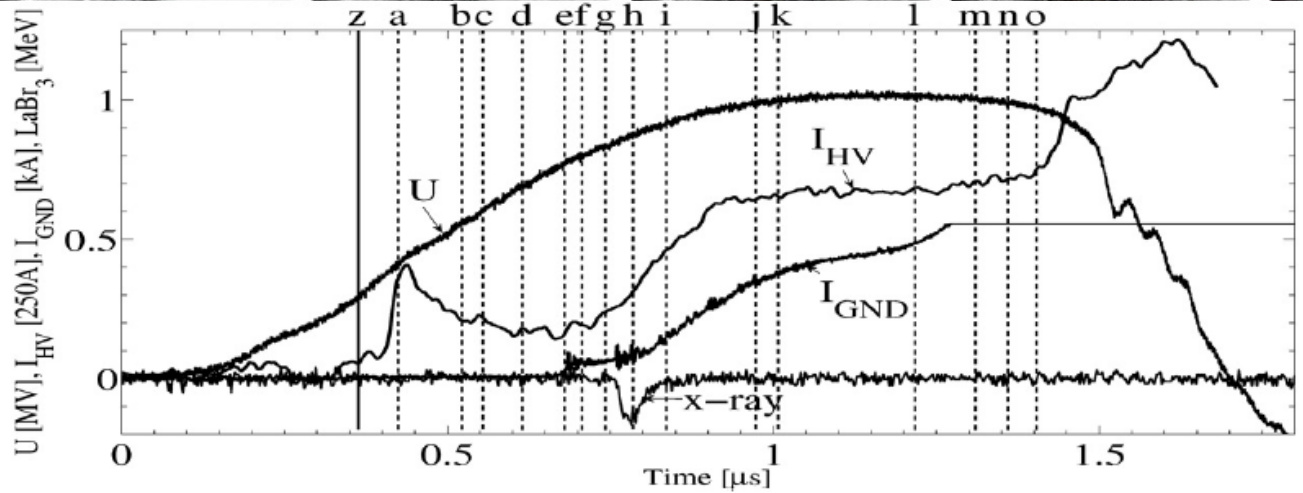
[Kochkin, Nguyen, van Deursen, Ebert, J Phys D 2012]

Positive streamers,

negative counter-streamers,

transition to leader





Hard X-rays (>200 keV) from positive “sparks”

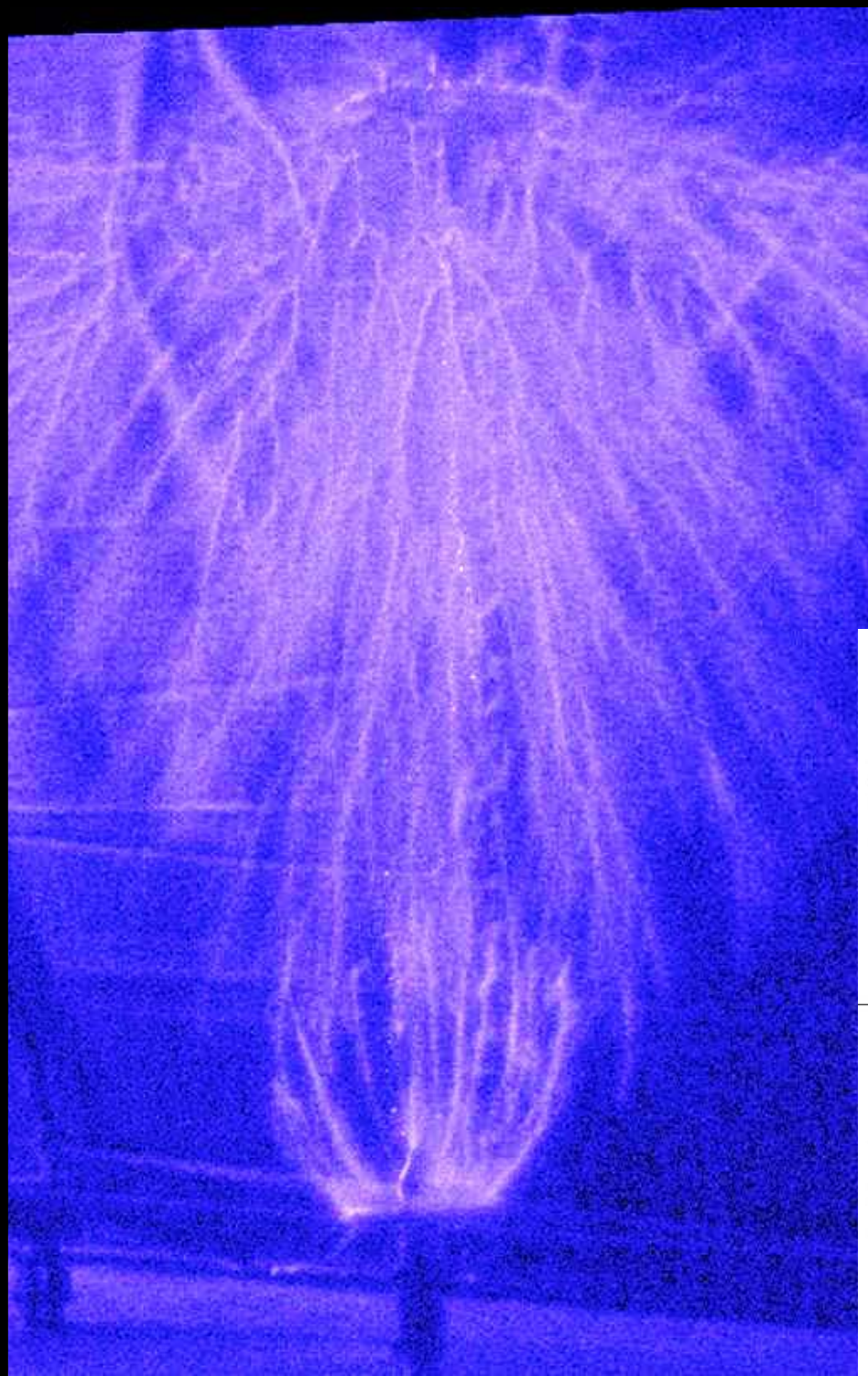
1 MV over 1 m

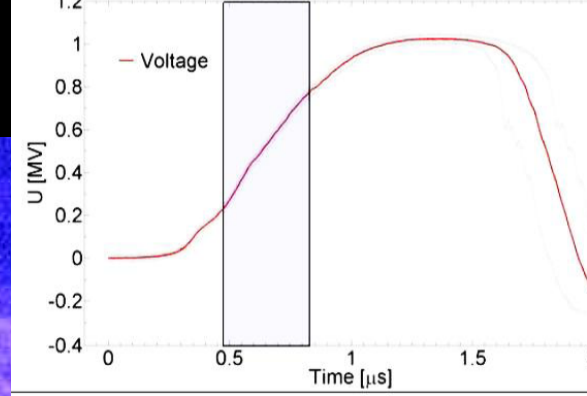
X-ray source:

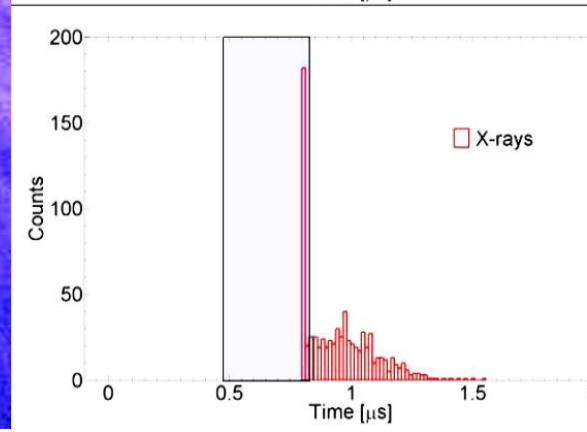
Negative streamers!

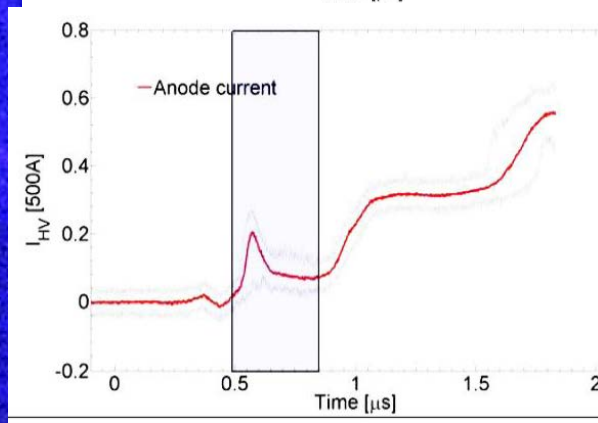
Typical energies: ~200 keV

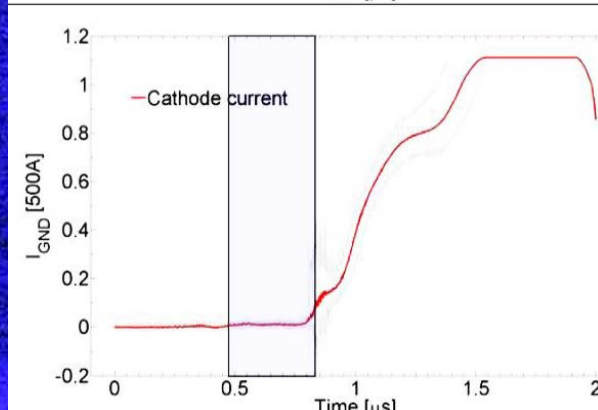
[Kochkin, Nguyen, van Deursen, Ebert, J Phys D 2012]



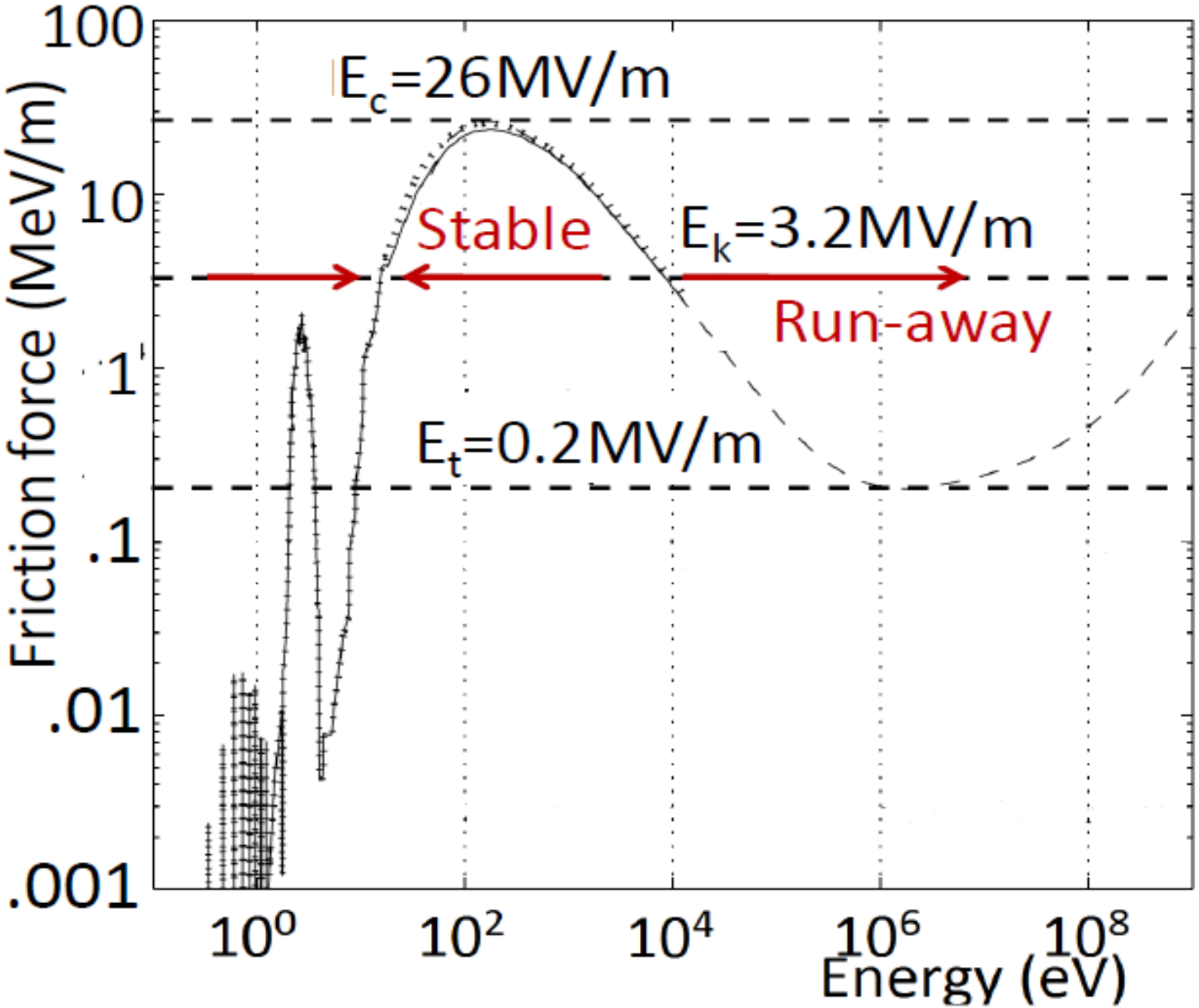






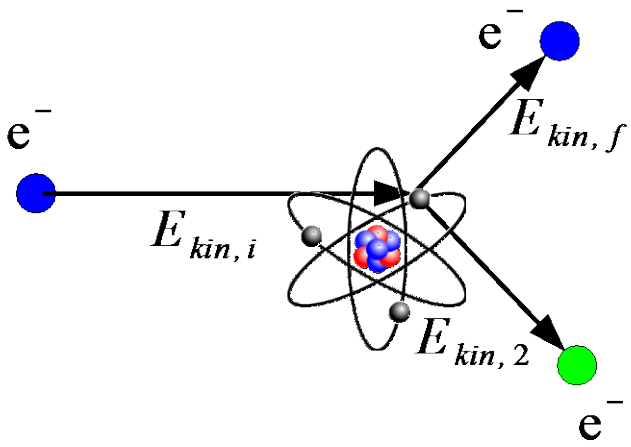


X-rays and γ-rays due to electron run-away and Bremsstrahlung



Generation of electrons and photons

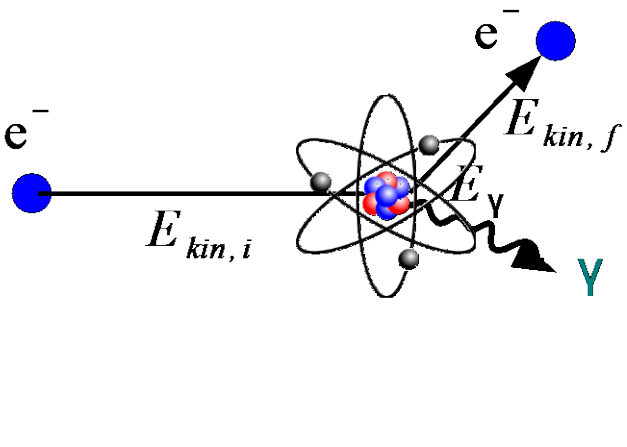
Impact ionization



e⁻ + M

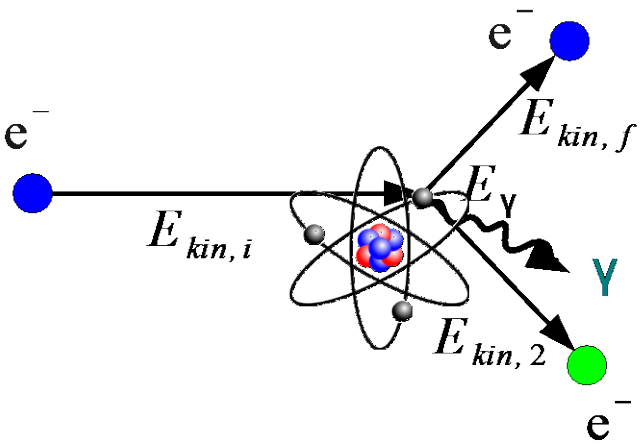
→ 2 e⁻ + M⁺

e-n-Bremsstrahlung



→ e⁻ + M + γ

e-e-Bremsstrahlung

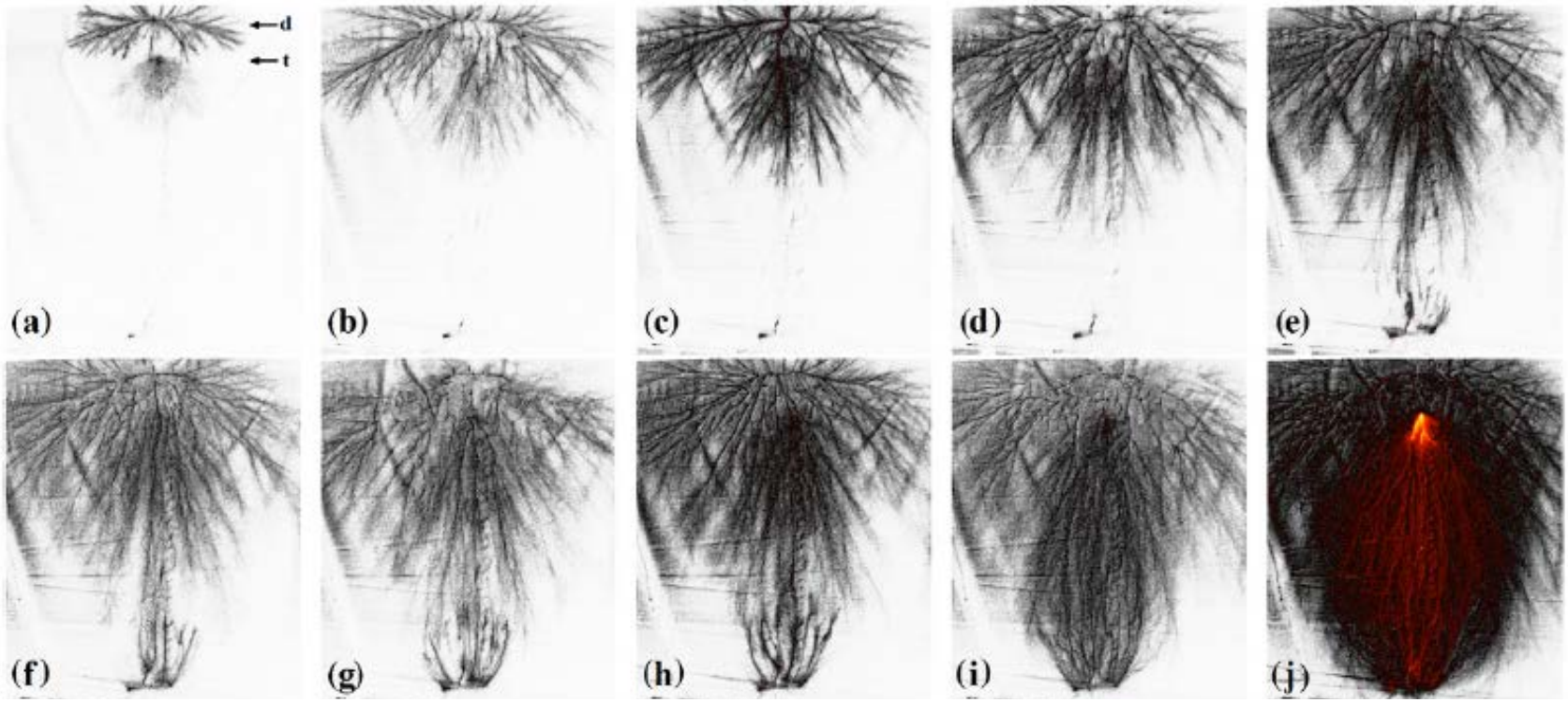


→ 2 e⁻ + M⁺ + γ

[Koehn, Ebert, Mangiarotti, J. Phys. D 2014]

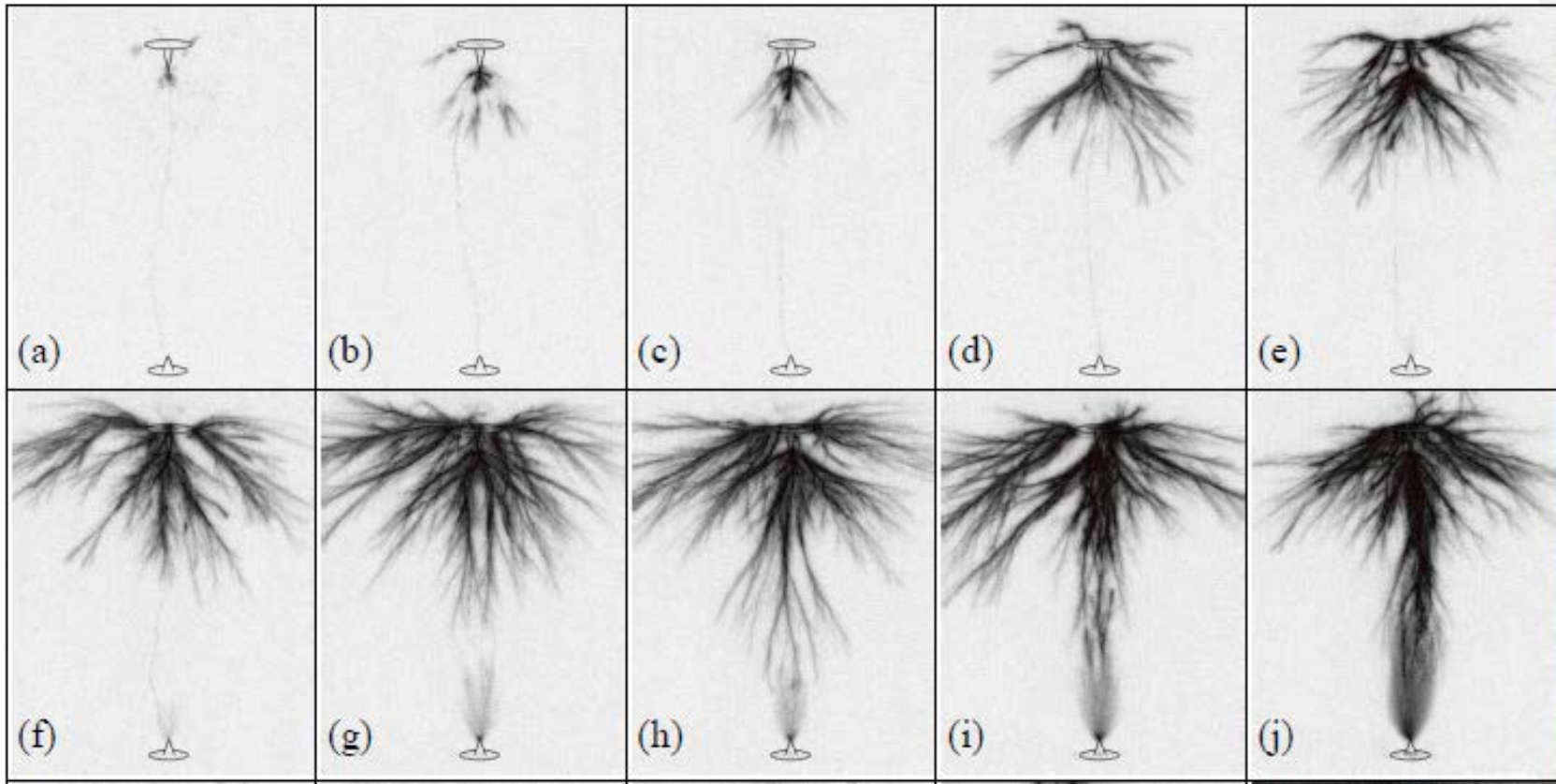
Positive streamers

[Kochkin et al, J Phys D 2012]



Negative streamers

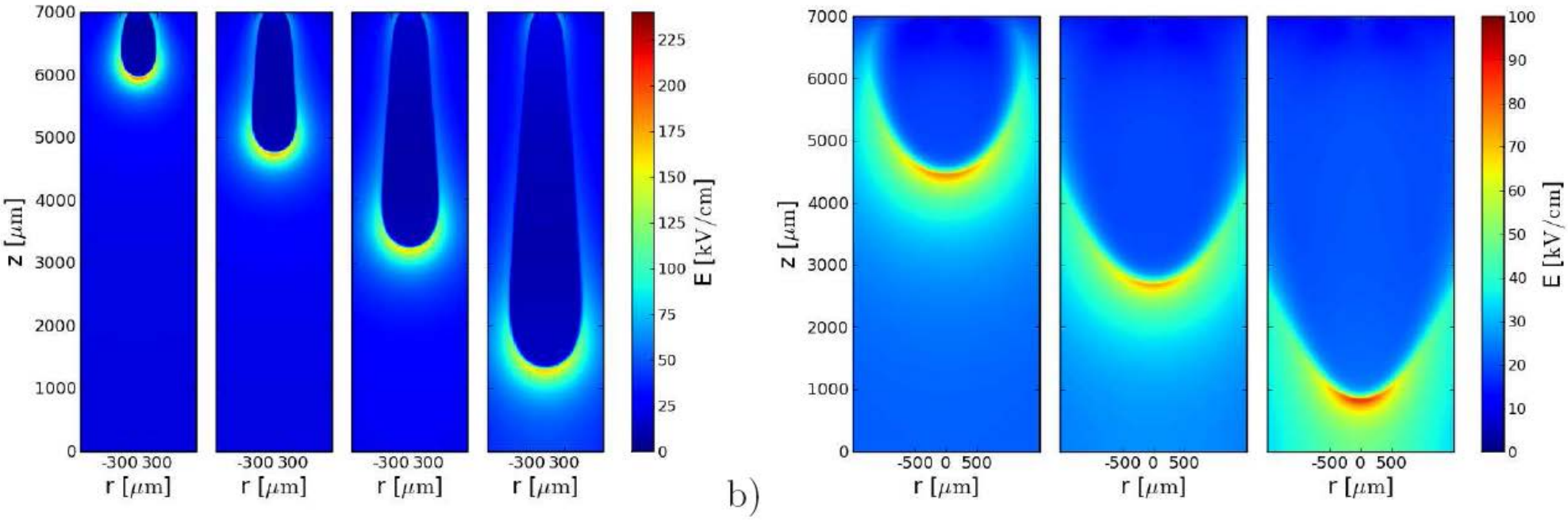
[Kochkin et al, J Phys D 2014]



Needle-plane electrodes, air, 1 bar, 300 K

(with photo-ionization)

Electric field of positive and negative streamer

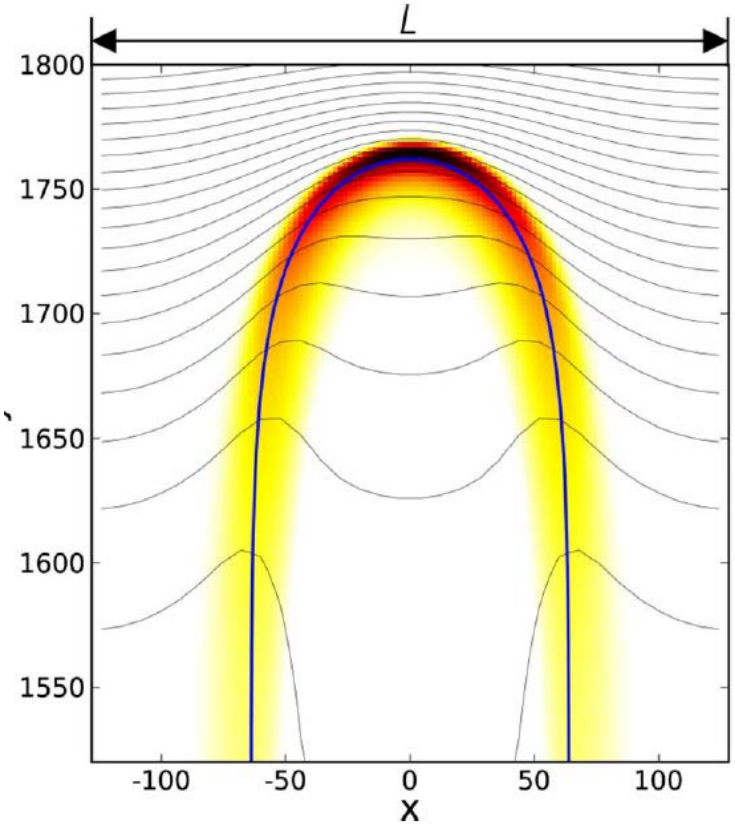


Positive streamer stays narrow
→ field more enhanced
→ faster

[Luque, Ratushnaya, Ebert, J Phys D 2008]

Towards a multi-streamer theory

Electrodynamic characterization of streamer head by E_{max} and R



$n_{interior} \approx n(E_{max})$ [Li, JAP 2007 and earlier]

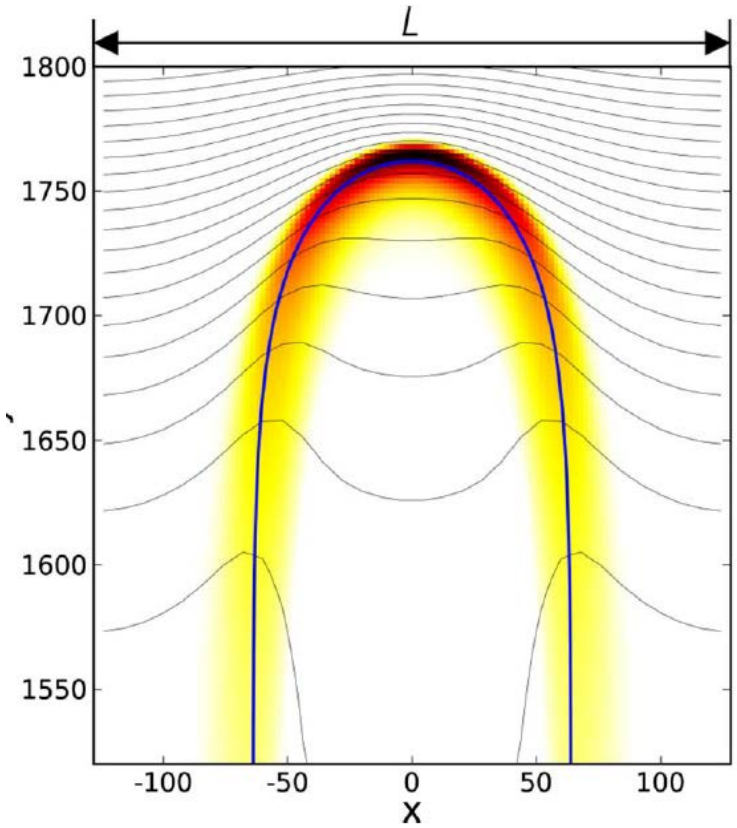
$v = v(R, E_{max})$ [Naidis, Phys Rev E 2009]

$j_{interior} = 2v\ \varepsilon_0\ E_{max}/R$ [Ratushnaya *et al*.]

Towards a multi-streamer theory

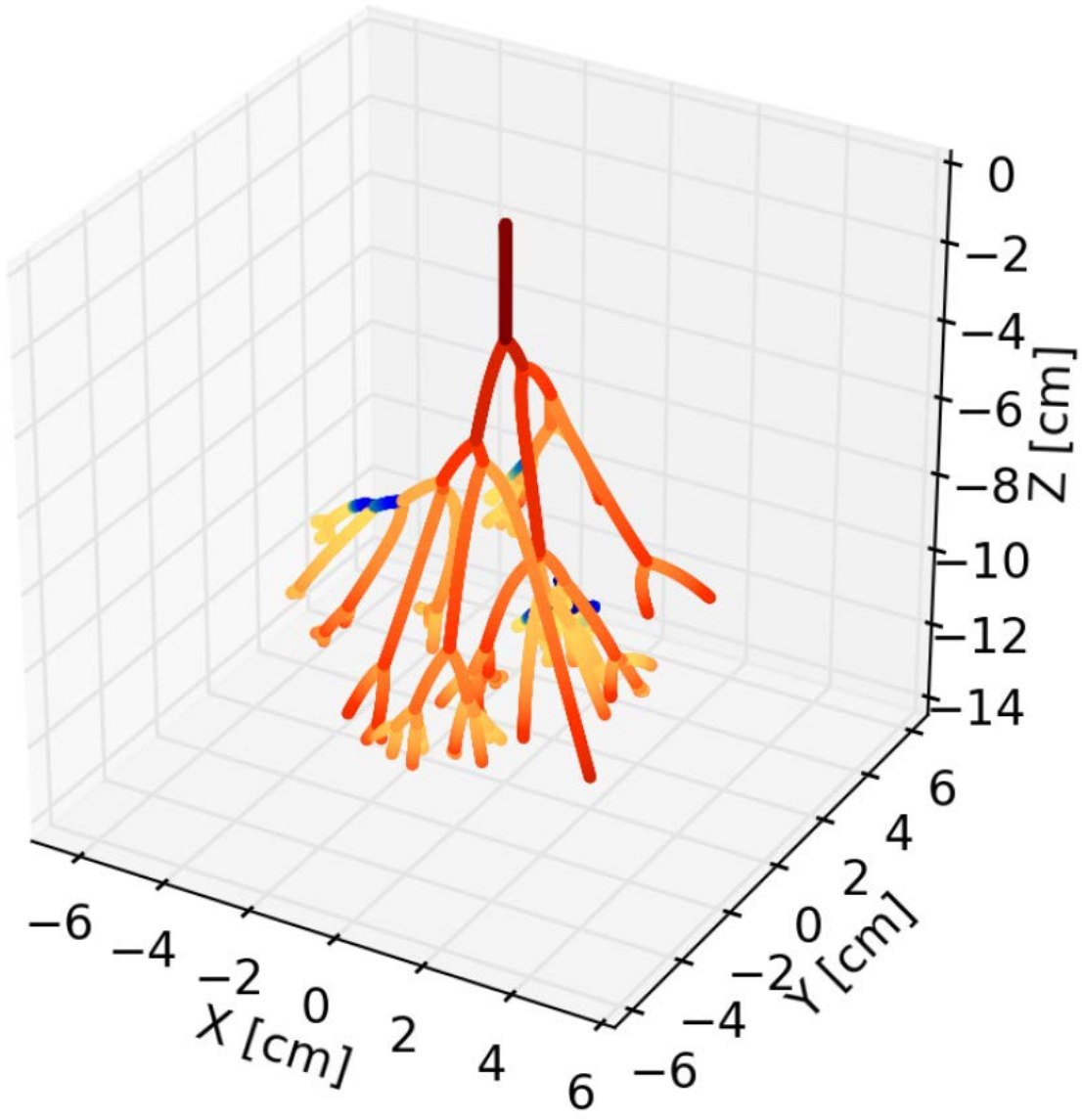
Electrodynamic characterization of streamer head by E_{max} and R

Use charge conservation!



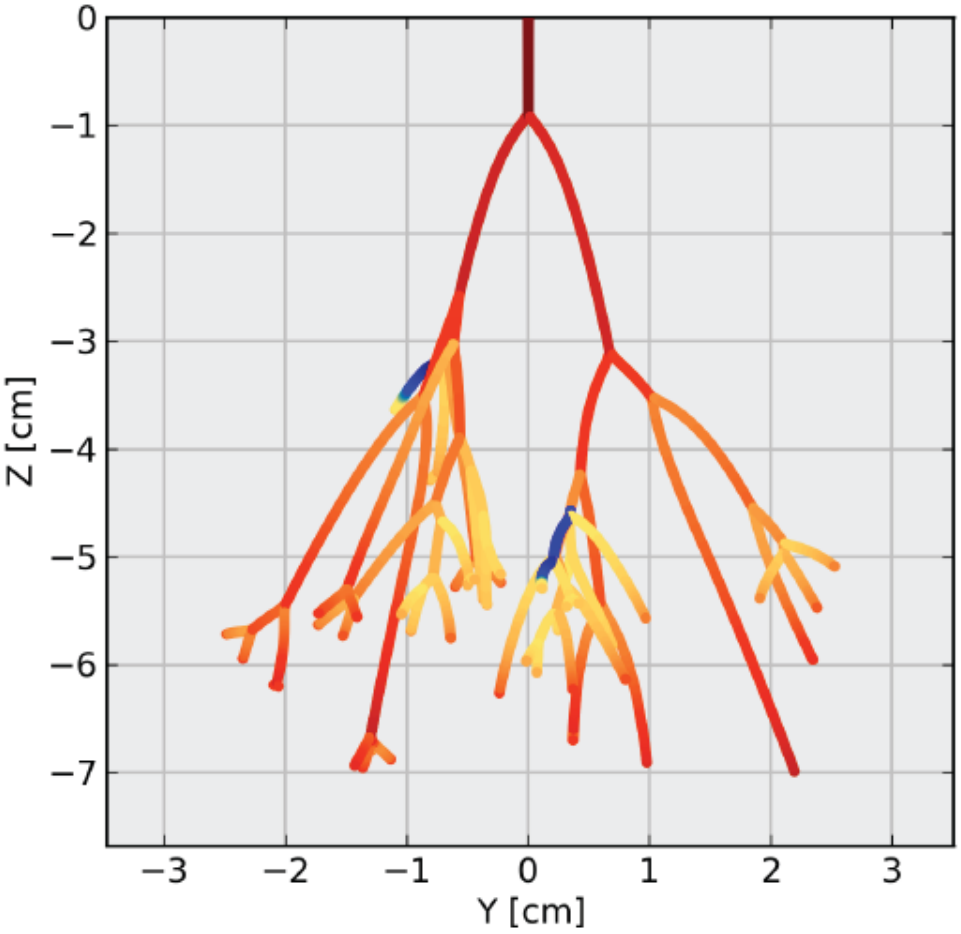
Then the channel interaction and the discharge tree

[Luque, Ebert, New J Phys 2014]



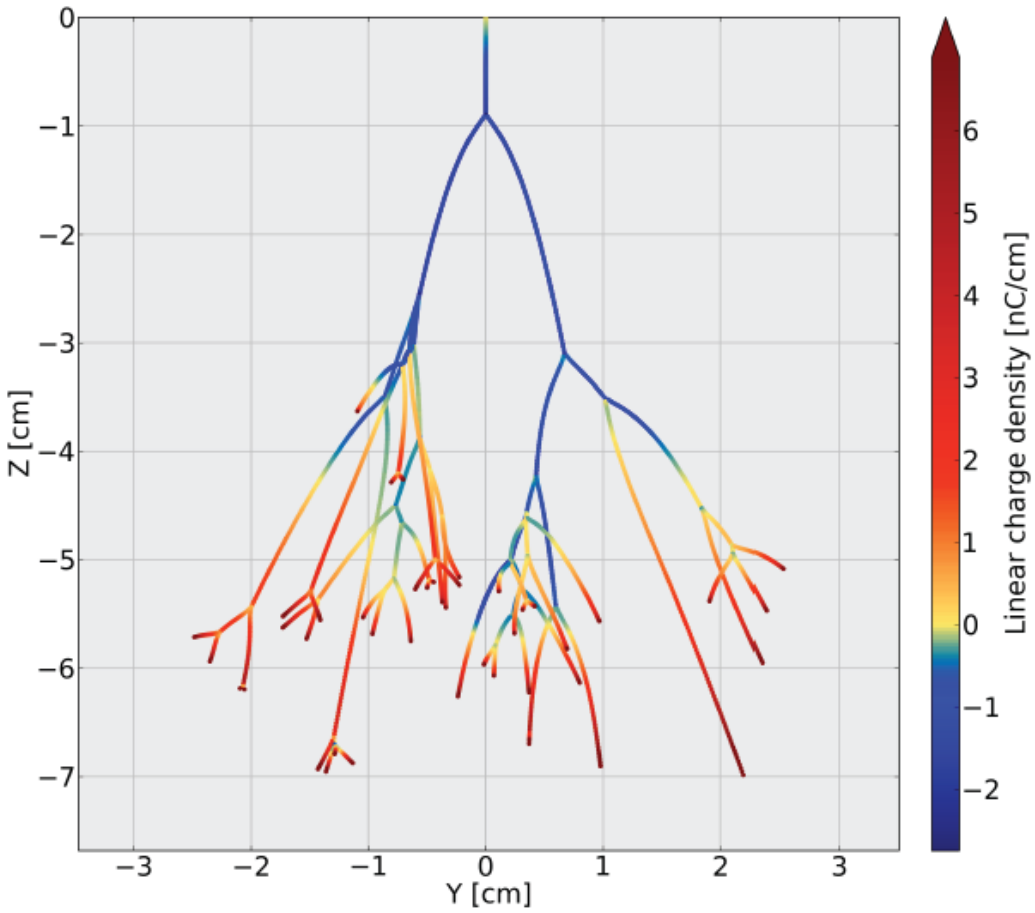
Electric field

with field inversion



Positive and

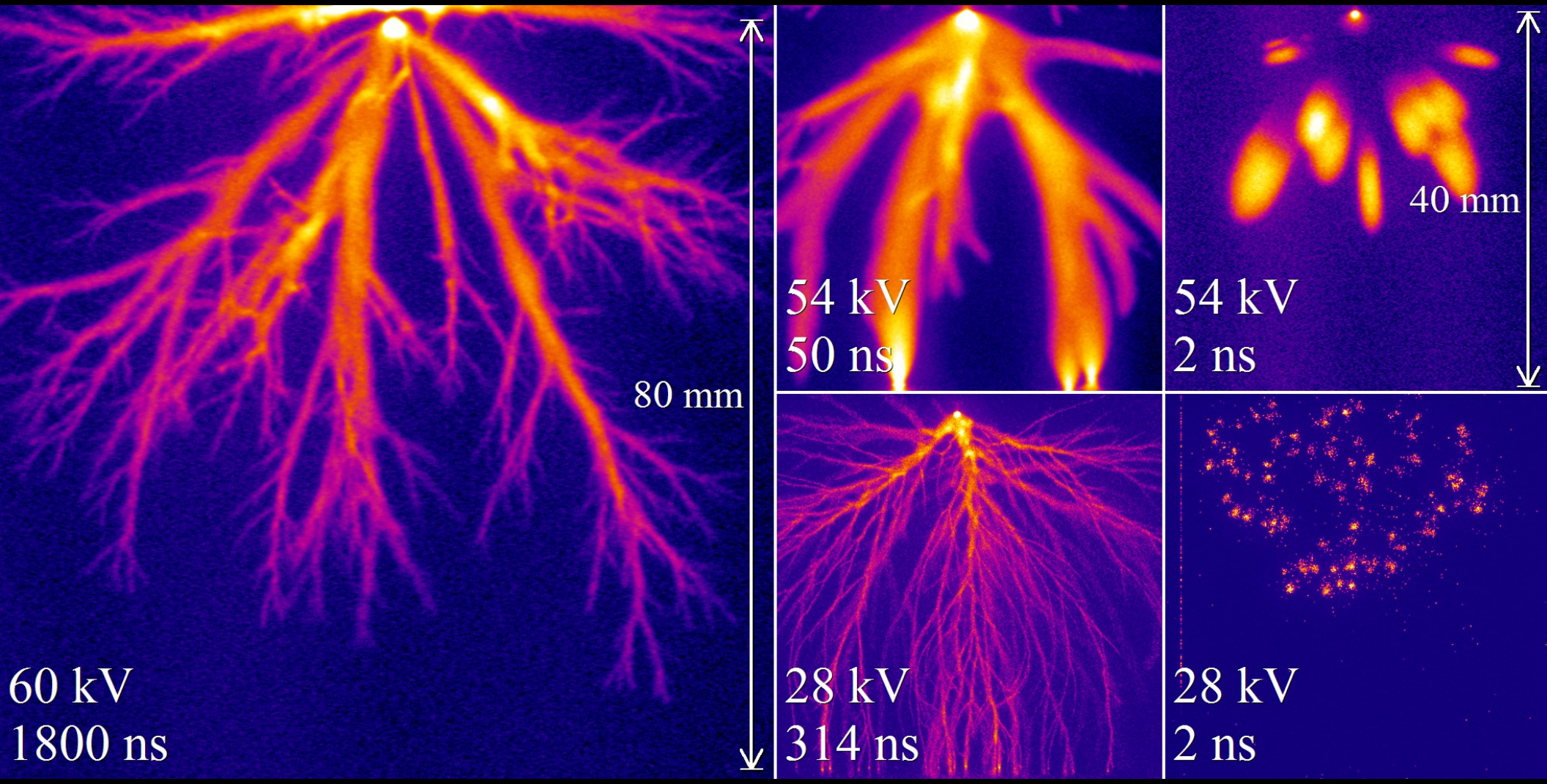
negative line charge



[Luque, Ebert, New J Phys 2014]

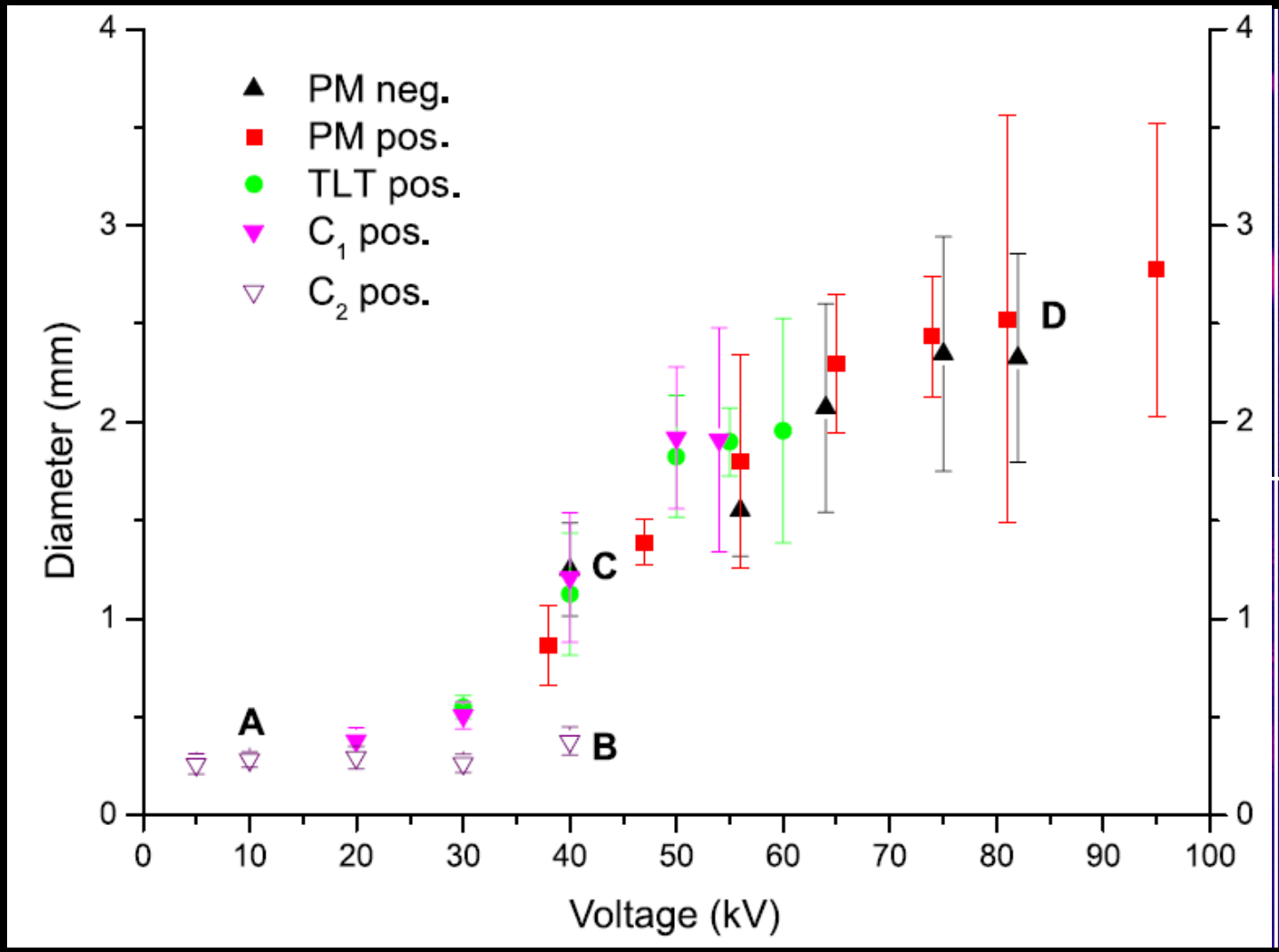
Include varying diameters, longer time scales: Chemistry, heating and transition to leader ...

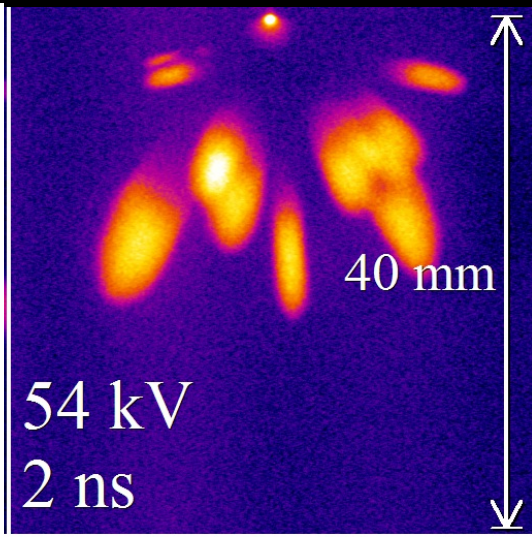
Streamer diameters and velocities in STP air

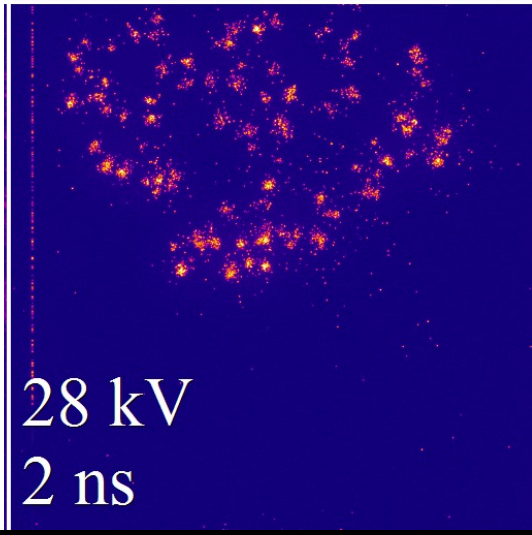


[Briels et al, J Phys D 2008]

Streamer diameters and velocities in STP air







[Briels et al, J Phys D 2008]

Thick streamers very efficiently convert electrical power into chemical radicals for biofuel processing, disinfection, sterilization .... *[van Heesch et al, J Phys D 2008]*

Why do streamer diameters differ?

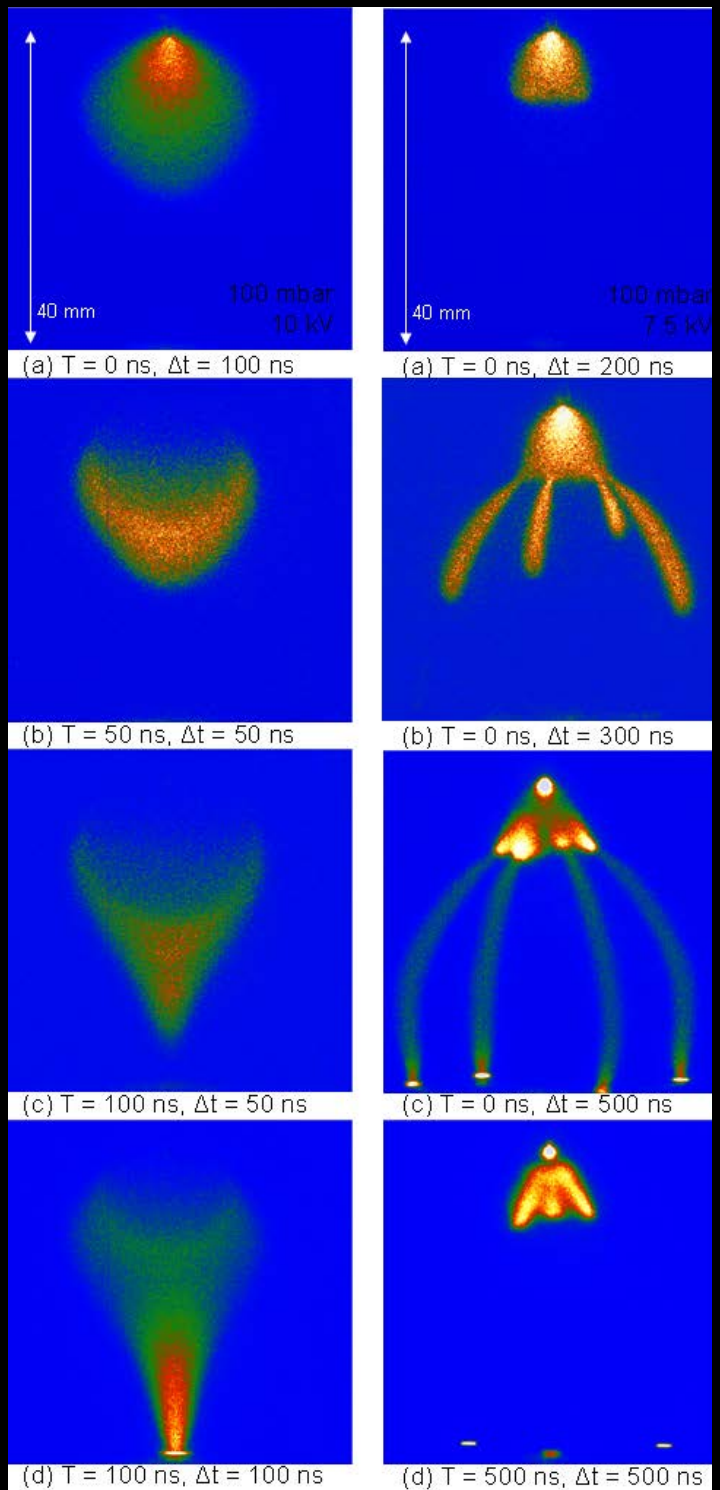
Look at dynamics:

Inception cloud,

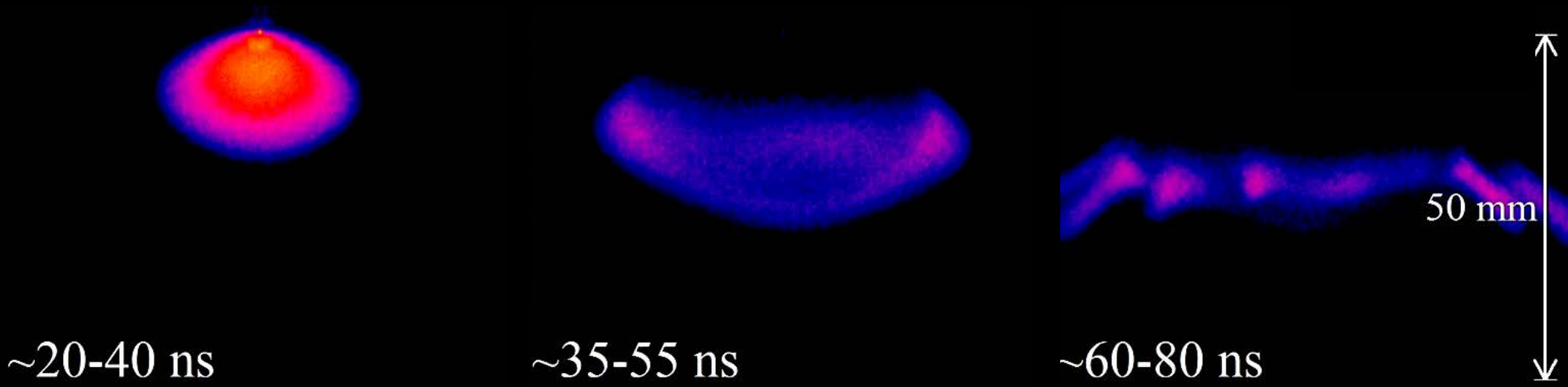
destabilization,

streamer emergence.

[Briels et al., IEEE TPS 2008]



Air, 200 mbar, +35 kV



~20-40 ns ~35-55 ns ~60-80 ns

Assuming spherical equipotential cloud:

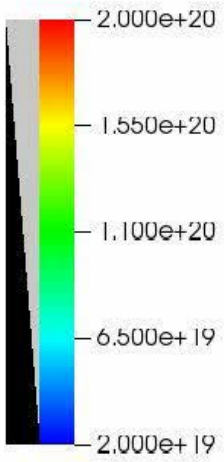
$R_{max} = U/E_c$

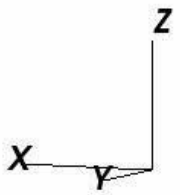
Good approximation!

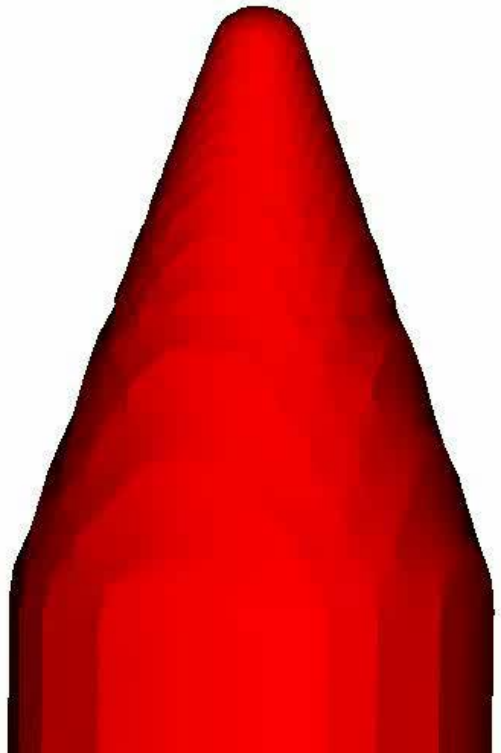
[Nijdam et al, IEEE TPS 2011]

S. Nijdam, published in [Ebert et al., Nonlinearity 2011]

8 kV

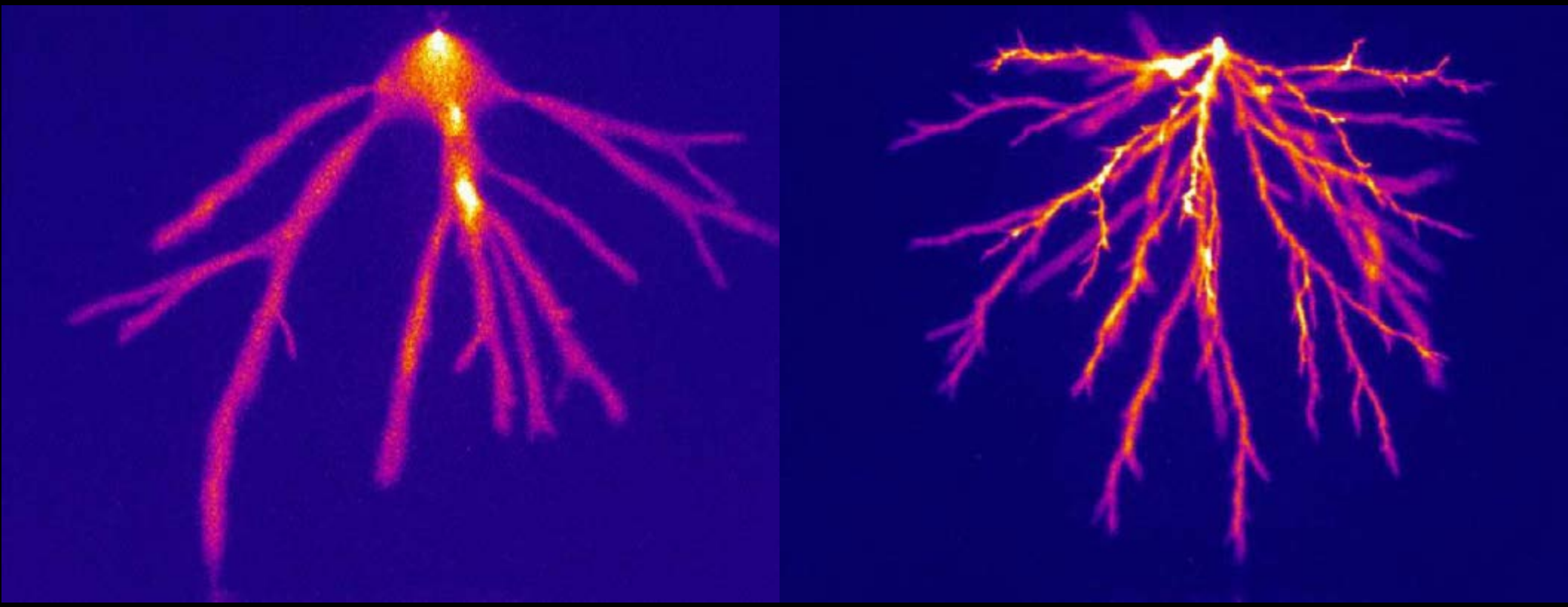






Positive streamers in

air nitrogen

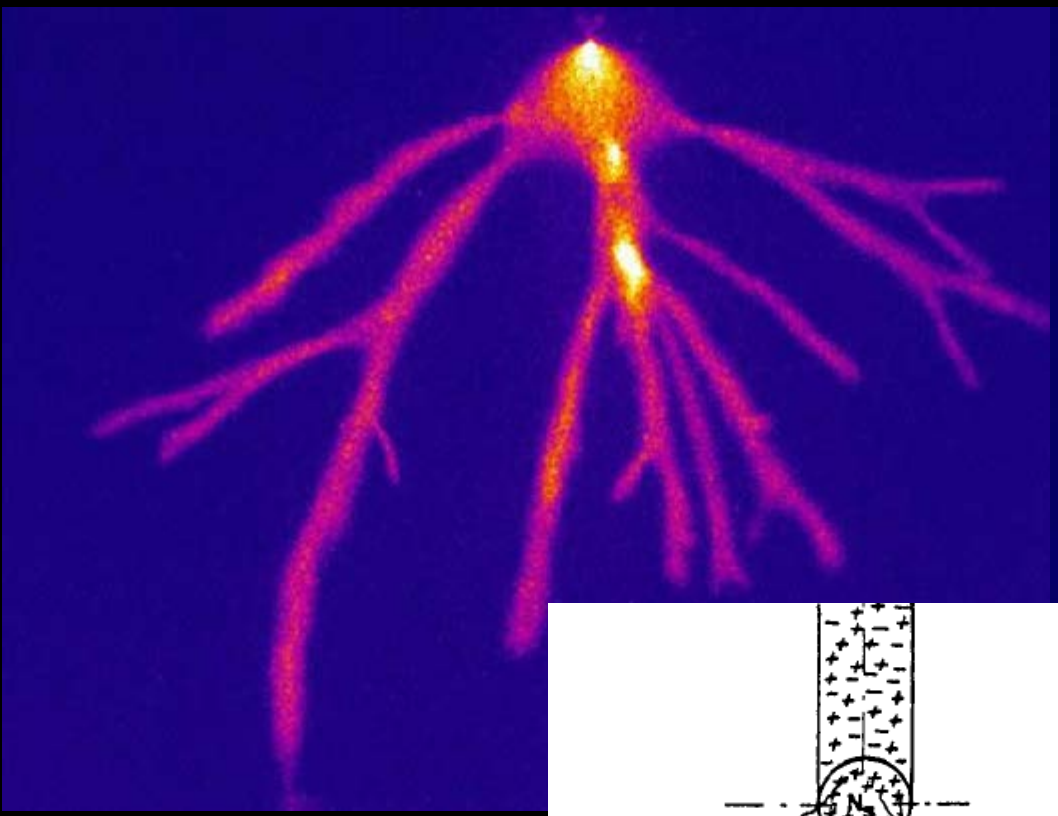


4 cm gap, 400 mbar, 16 kV voltage pulse

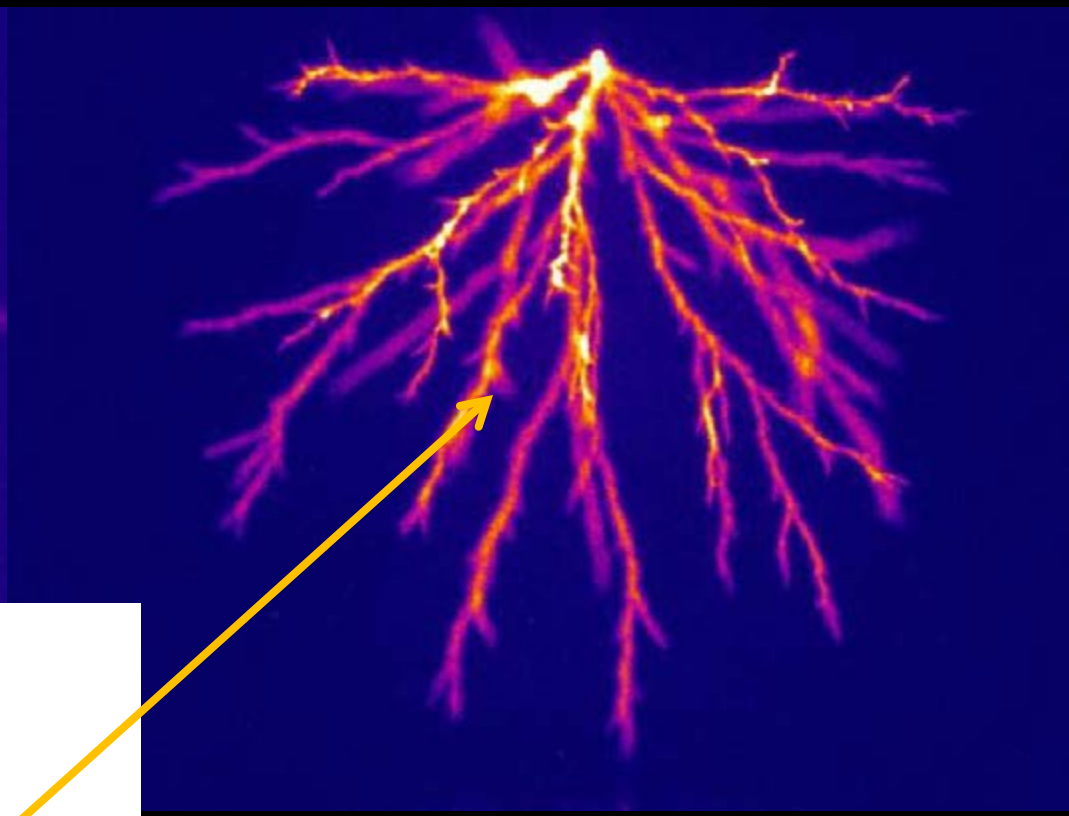
[Briels et al, J Phys D 2008]

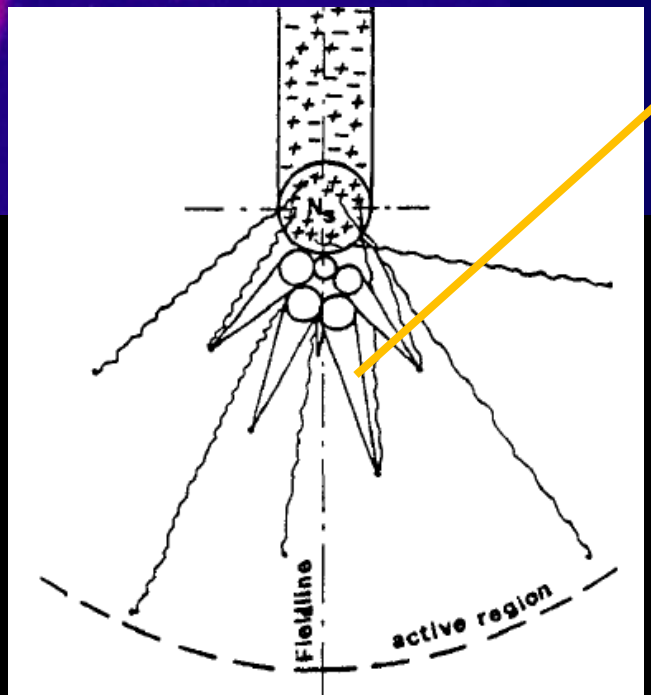
Positive streamers in

air



nitrogen



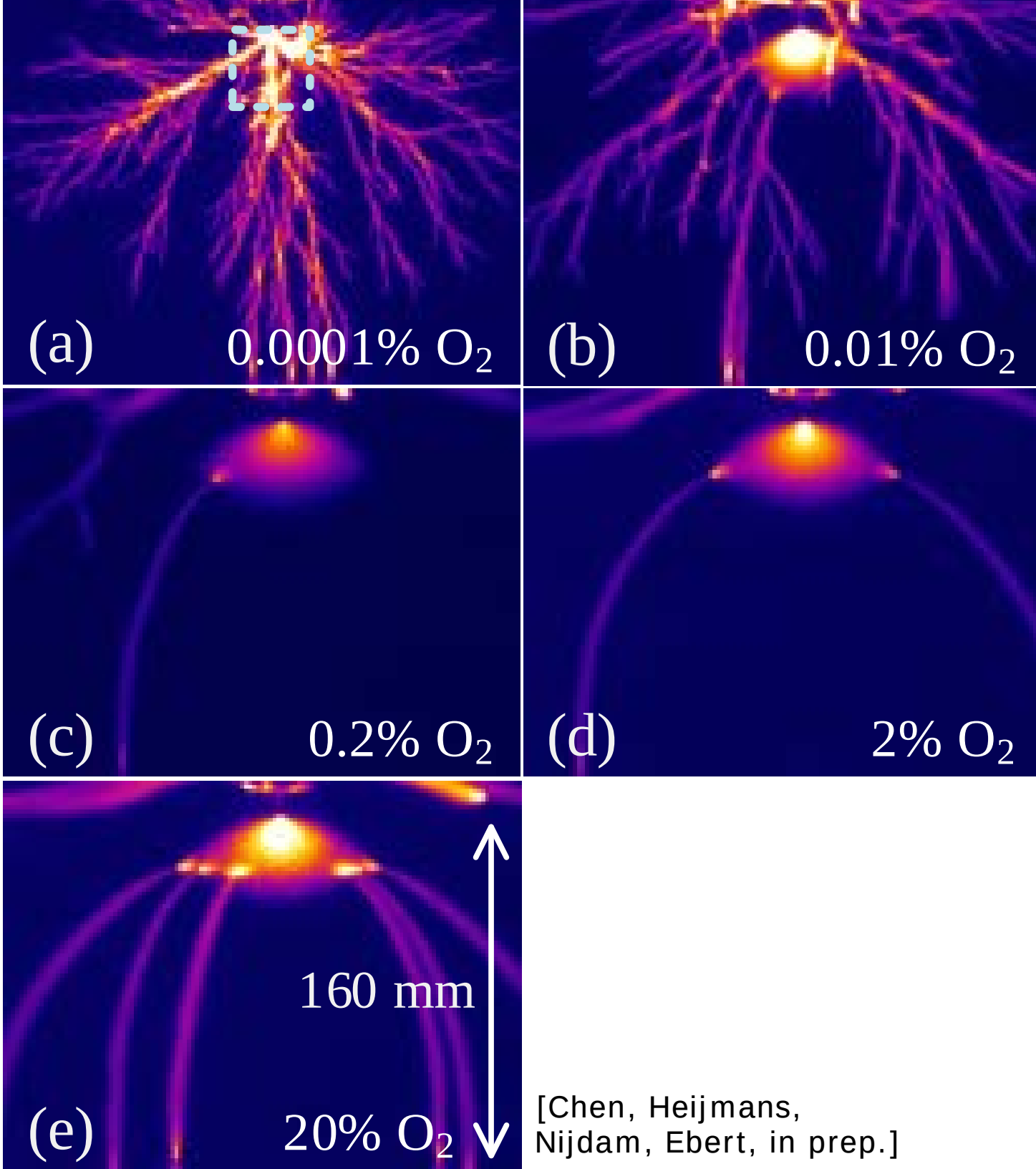


Single avalanches visible in nitrogen

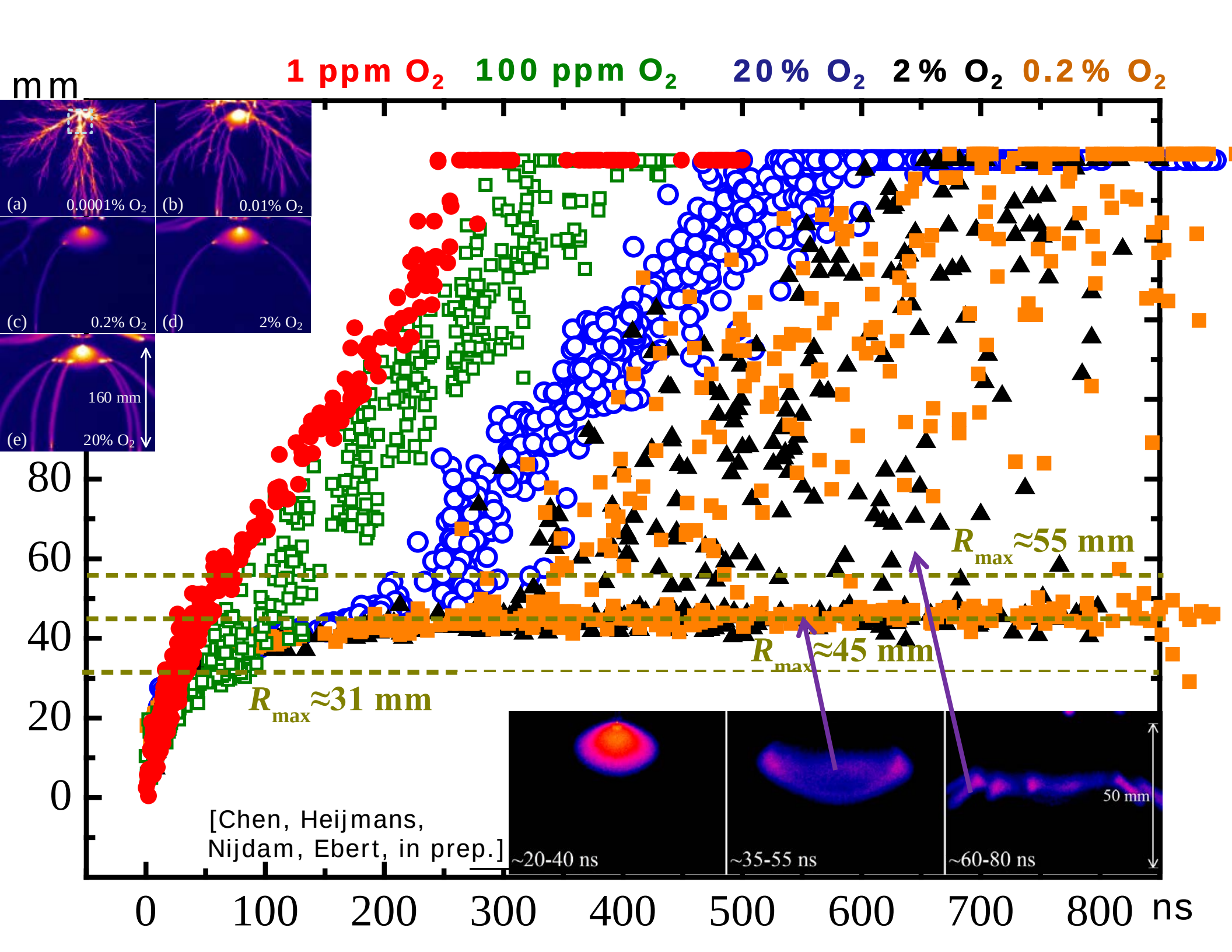
[Wormeester et al, JJAP 2011]

N_2:O_2 mixtures

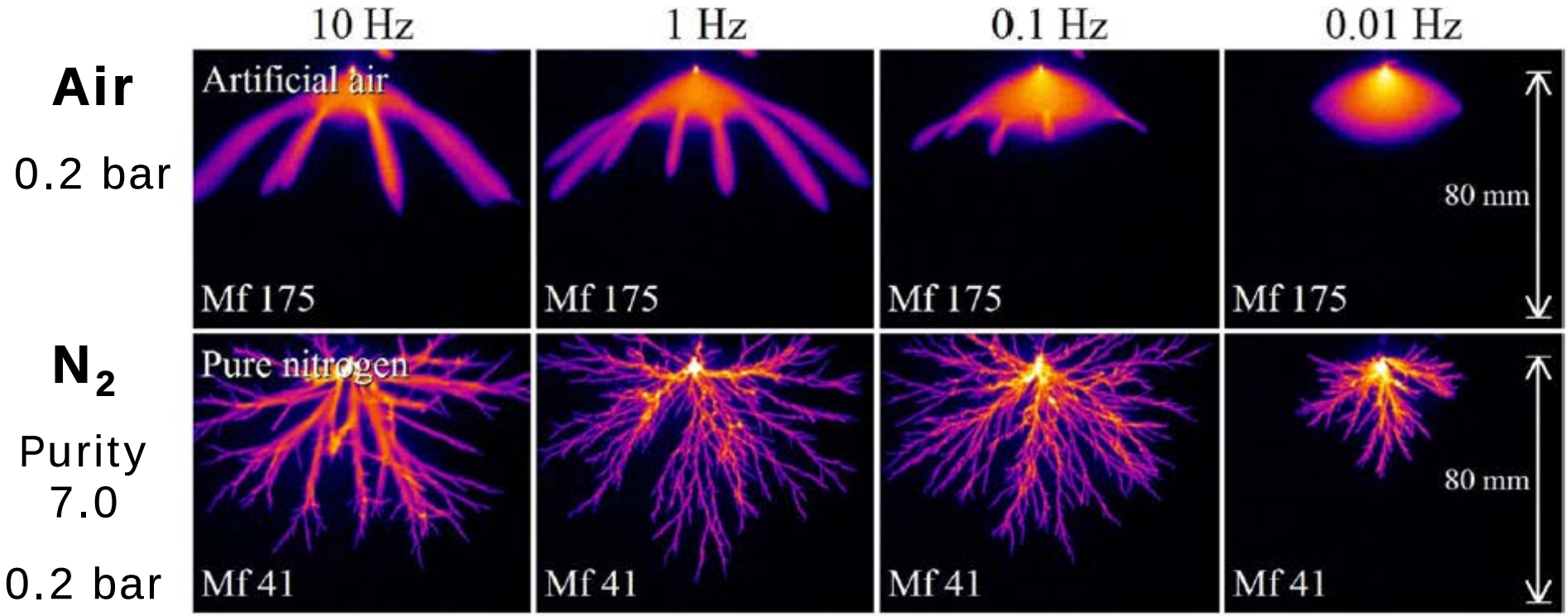
100 mbar,
20 kV pulses
within 20 ns,
1 Hz



[Chen, Heijmans,
Nijdam, Ebert, in prep.]


mm
1 ppm O2
100 ppm O2
20% O2
2% O2
0.2% O2
(a) 0.0001% O2
(b) 0.01% O2
(c) 0.2% O2
(d) 2% O2
(e) 20% O2
160 mm
80
60
40
20
0
Rmax≈55 mm
Rmax≈45 mm
Rmax≈31 mm
[Chen, Heijmans,
Nijdam, Ebert, in prep.]
~20-40 ns
~35-55 ns
~60-80 ns
50 mm
0
100
200
300
400
500
600
700
800
ns

Repetitive voltage pulses of +25 kV and 130 ns duration

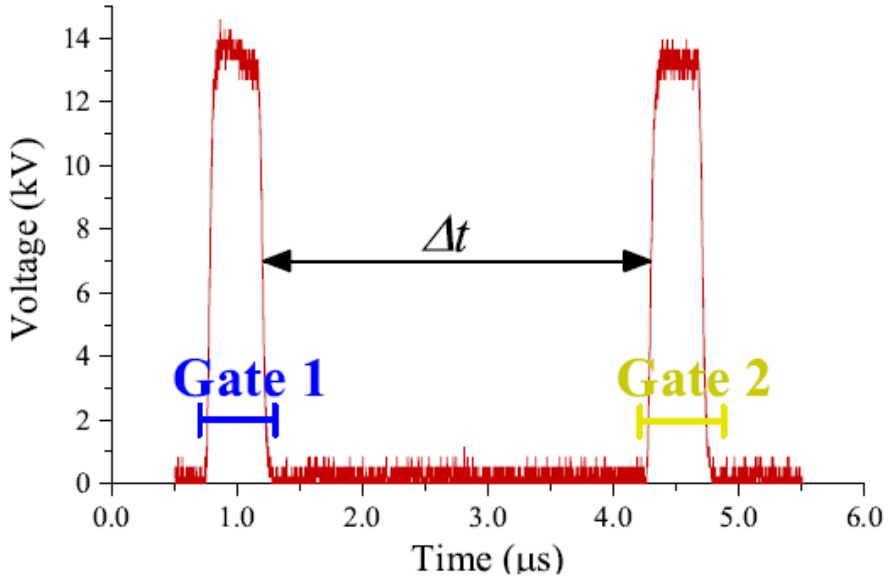


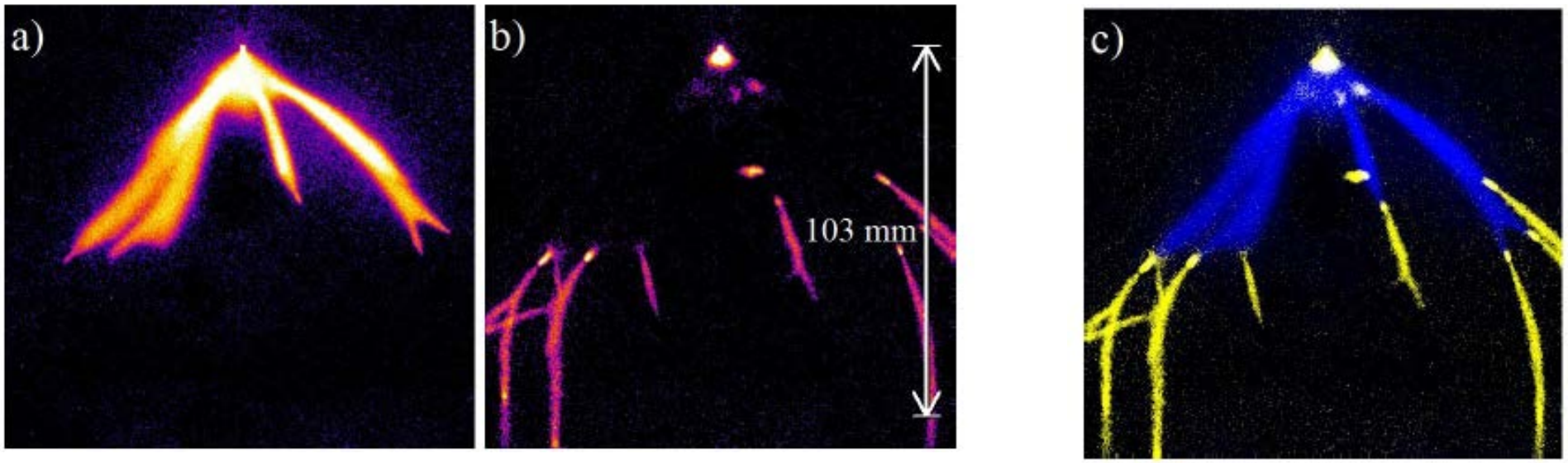
[Nijdam et al, J Phys D 2011]

Due to electron attachment, photo-ionization ...

Streamer re-ignition

in different N_2:O_2 mixtures

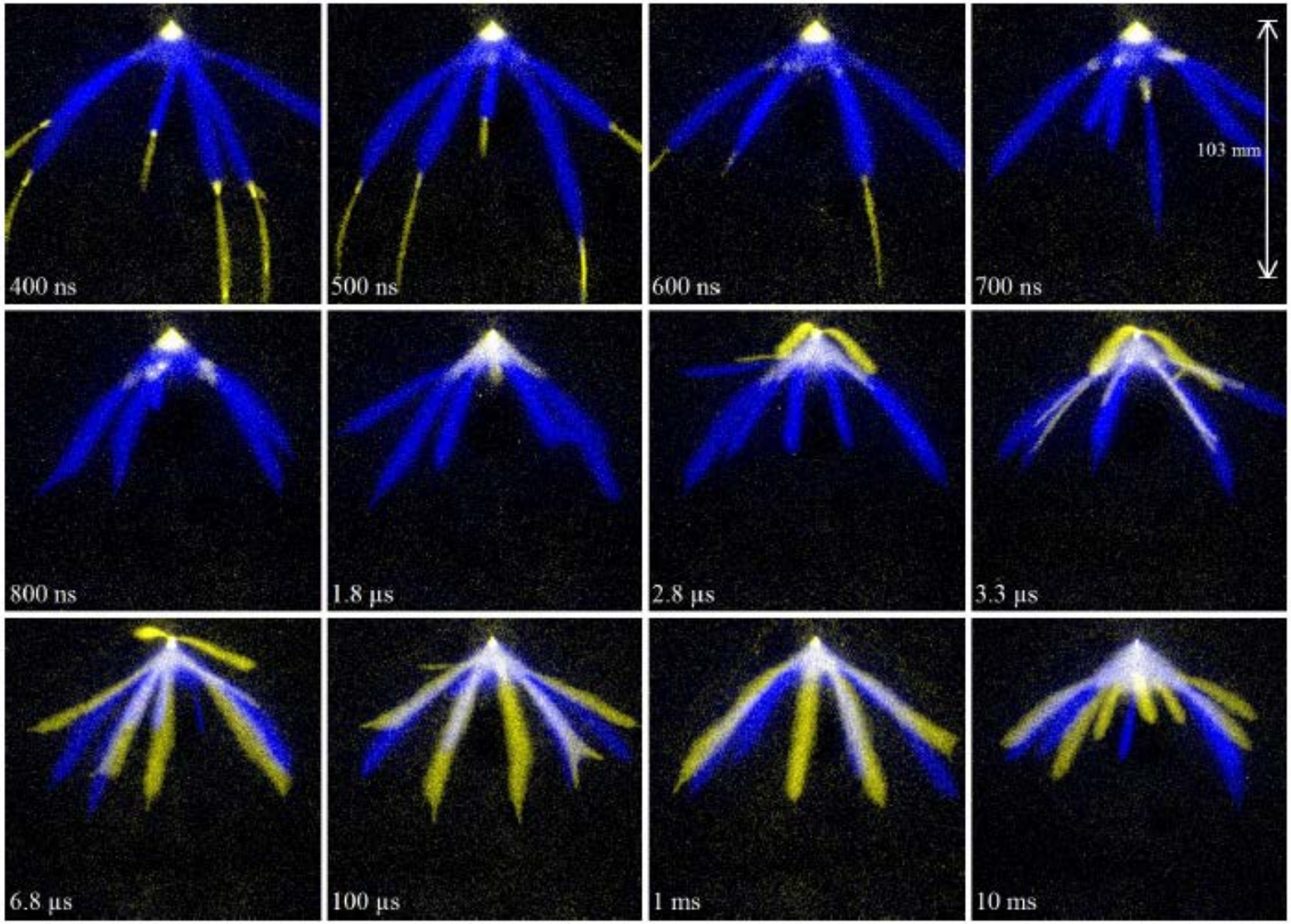




[Nijdam, Takahashi, Markosyan, Ebert, PSST 2014]

Streamer re-ignition,

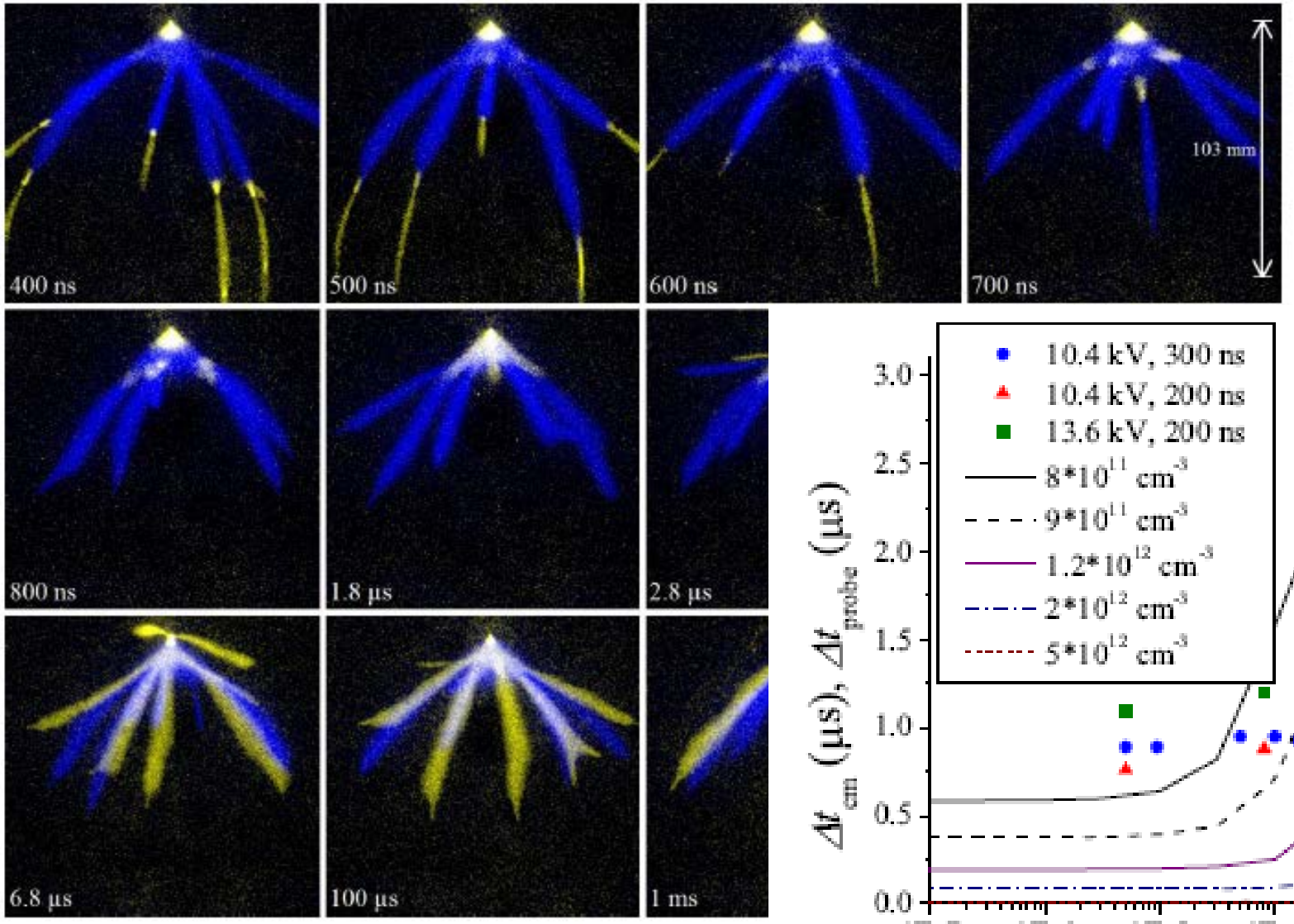
here in artificial air at 133 mbar



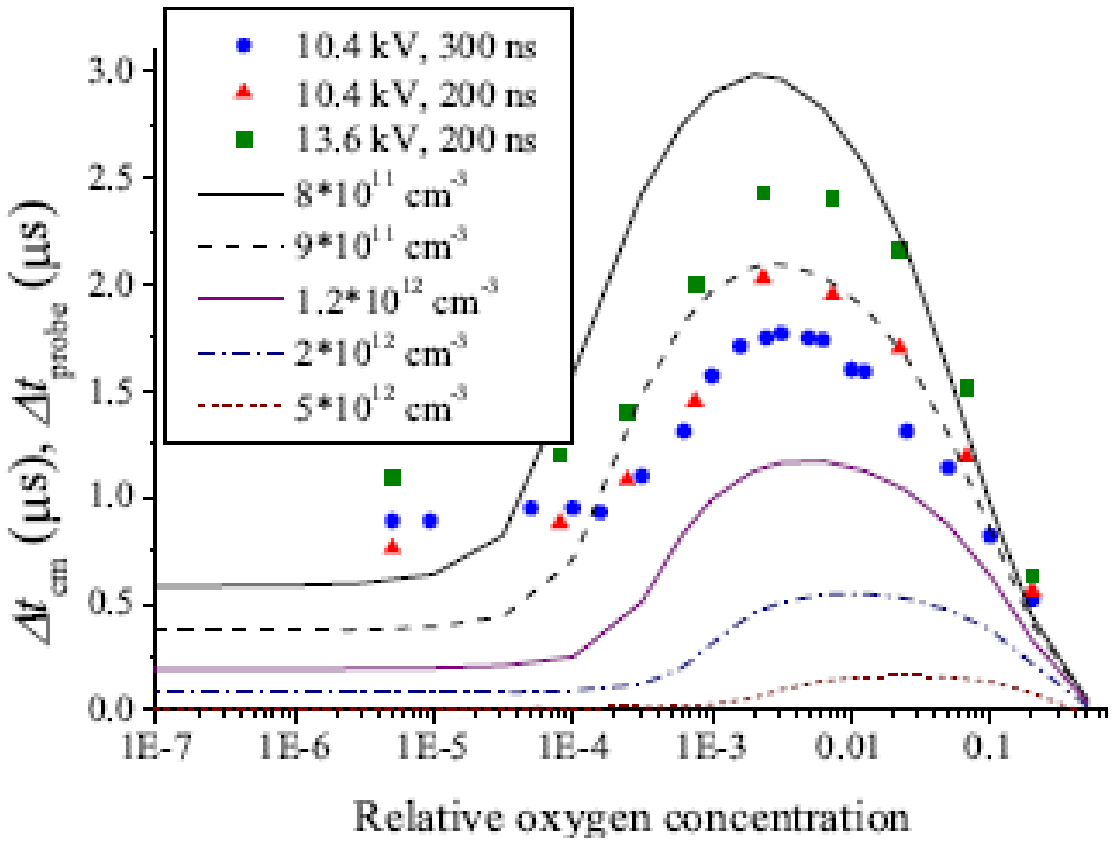
[Nijdam, Takahashi, Markosyan, Ebert, PSST 2014]

Streamer re-ignition

in different N_2:O_2 mixtures



Quantitatively explained, without fitting!



[Nijdam, Takahashi, Markosyan, Ebert, PSST 2014]

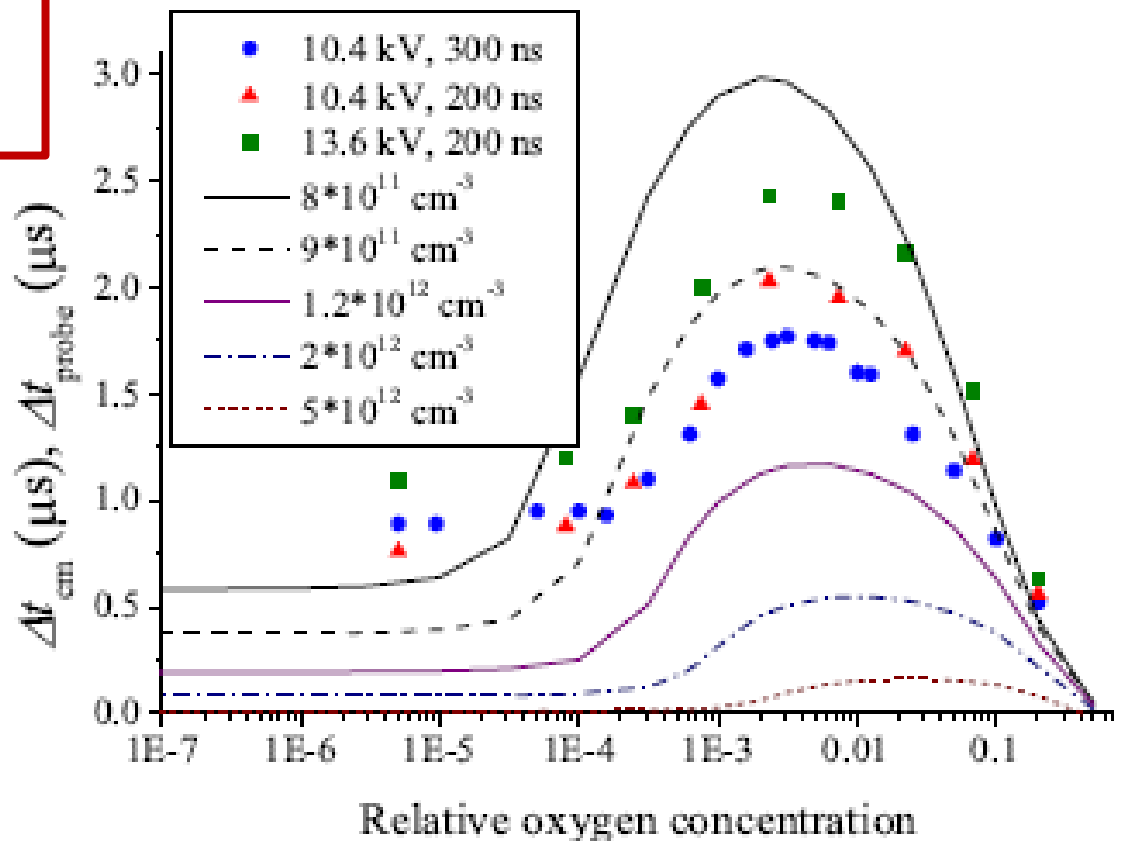
Streamer re-ignition

in different N_2:O_2 mixtures

~500 reactions:
which ones are important?

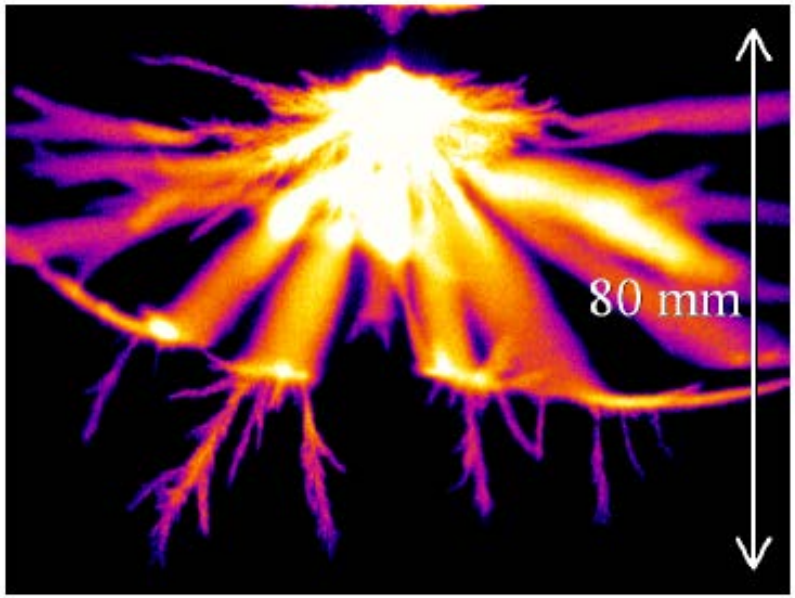
-> Pathway analysis
[PumpKin-tool, Markosyan et al., Comp. Phys. Comm. 2014],
www.cwimd.nl

Quantitatively explained, without fitting!

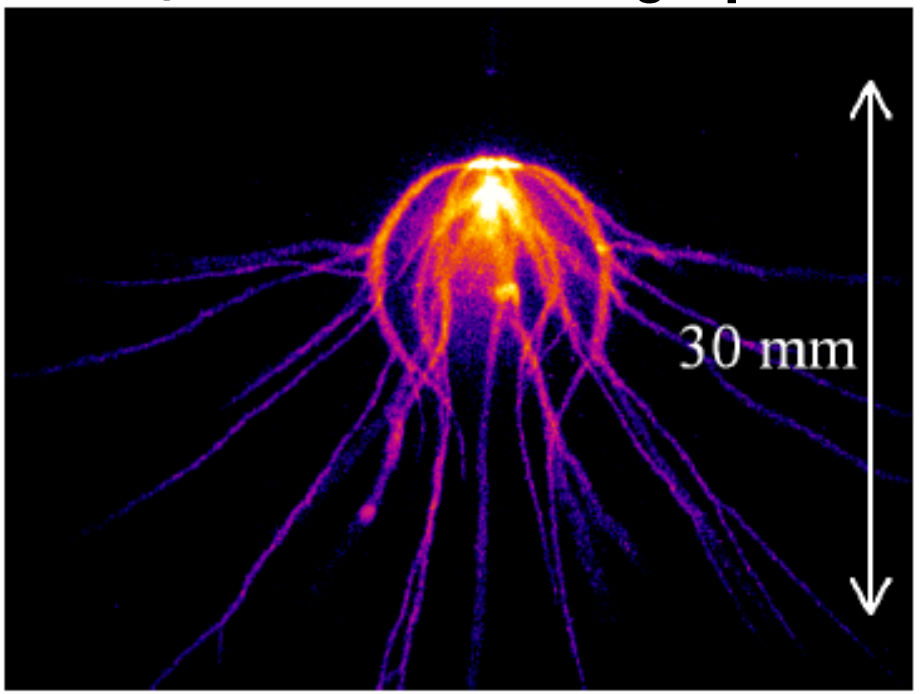


[Nijdam, Takahashi, Markosyan, Ebert, PSST 2014]

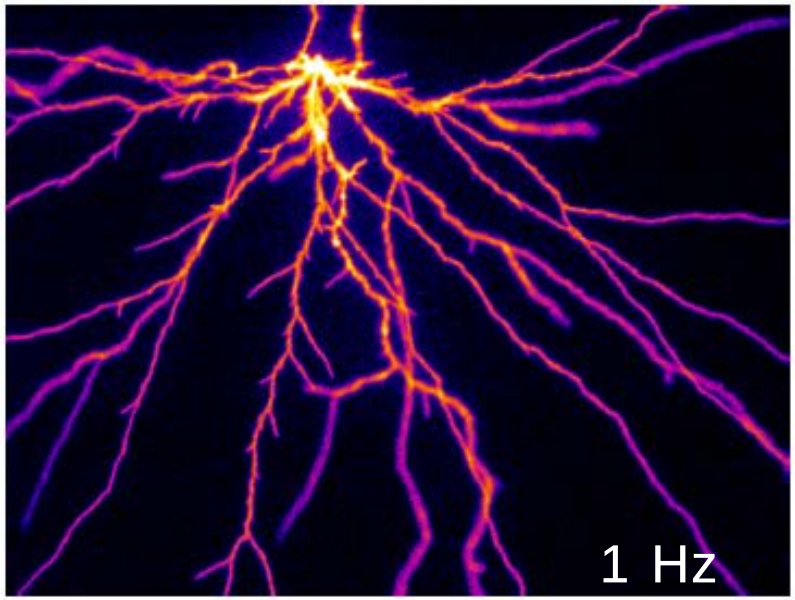
High purity nitrogen, rep. frequency 1 Hz or more

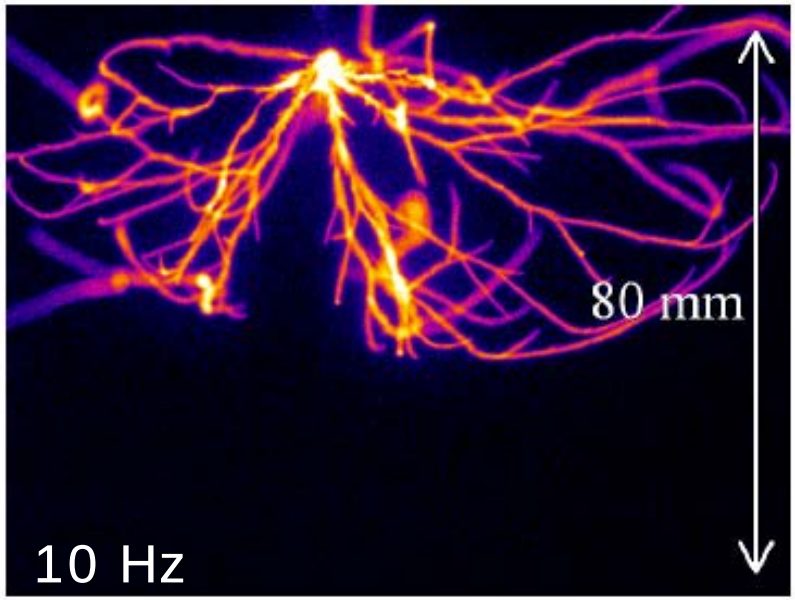


Air, reflected voltage pulse



[Nijdam et al, IEEE TPS 2011]





[Heijmans et al, in prep.]

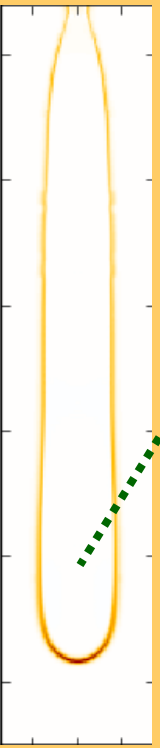
Collision cross-sections for different gases

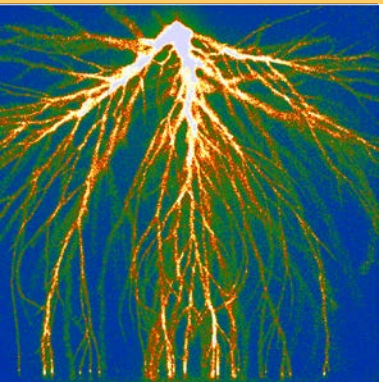
Stochastic electron motion
(Monte Carlo or Boltzmann)

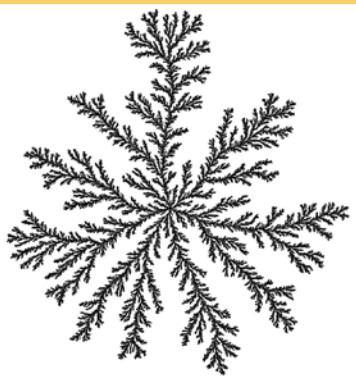
Transport and reaction coefficients for
density model – or new density model

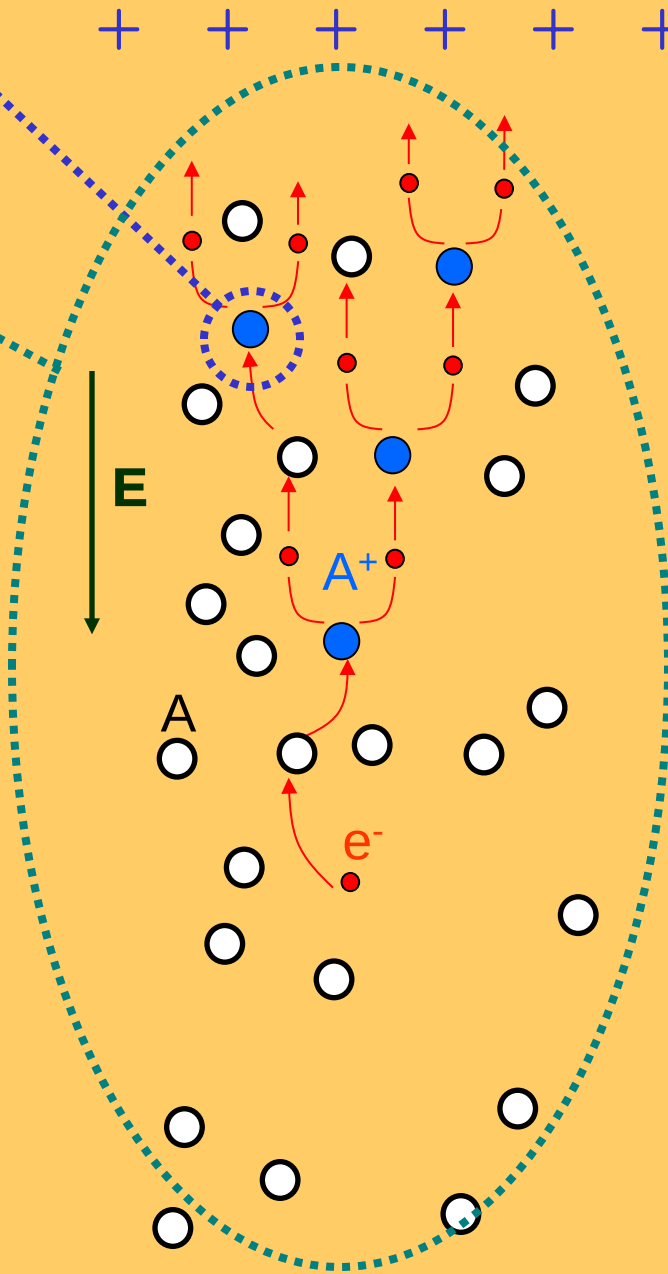
Density or spatially hybrid model

Further model reduction
to moving boundaries and
to discharge trees as a whole



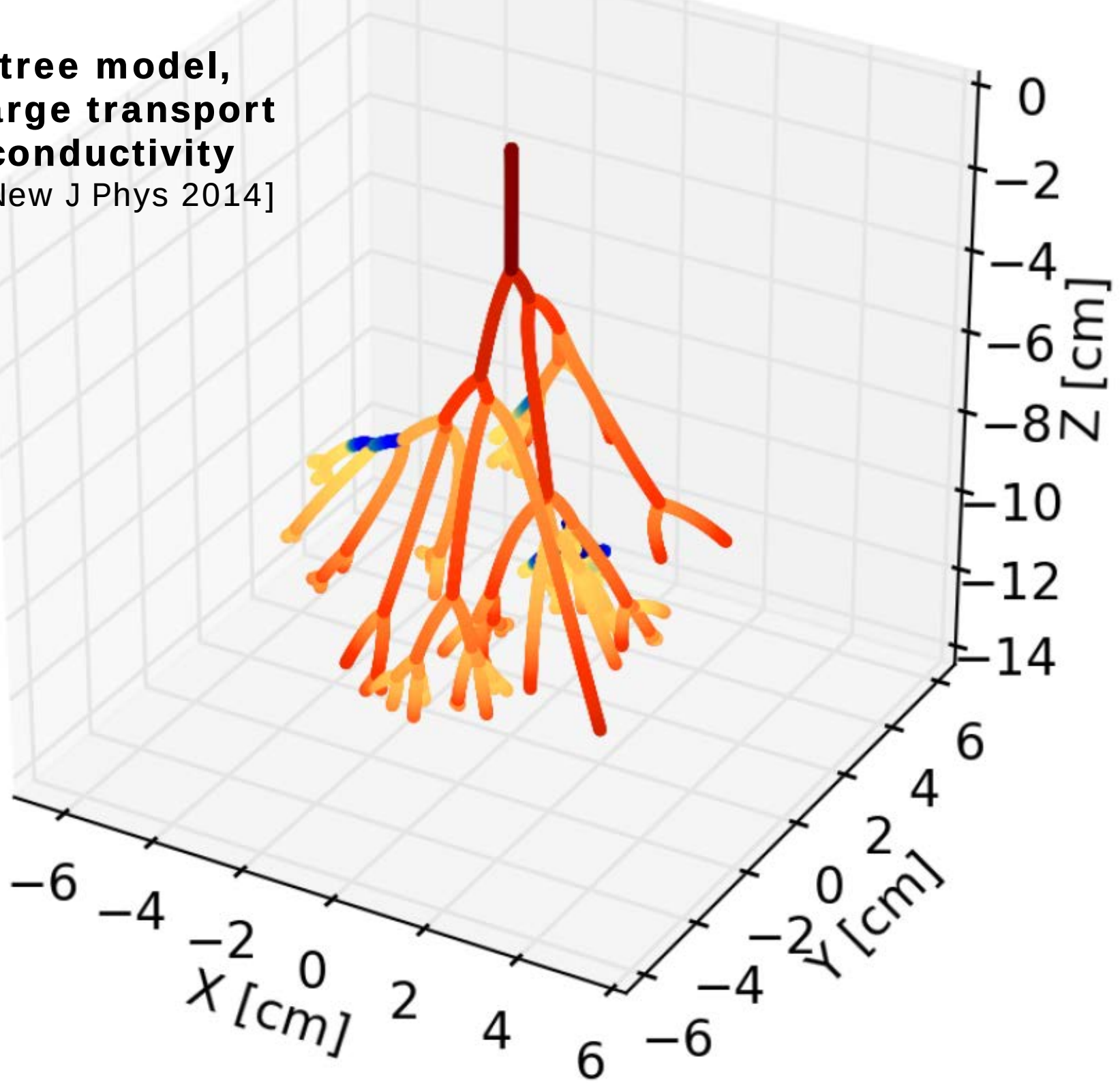






Discharge tree model, based on charge transport and finite conductivity

[Luque, Ebert, New J Phys 2014]



A streamer: field focussing

Complete system:

Zoom:

n_e, equi-φ

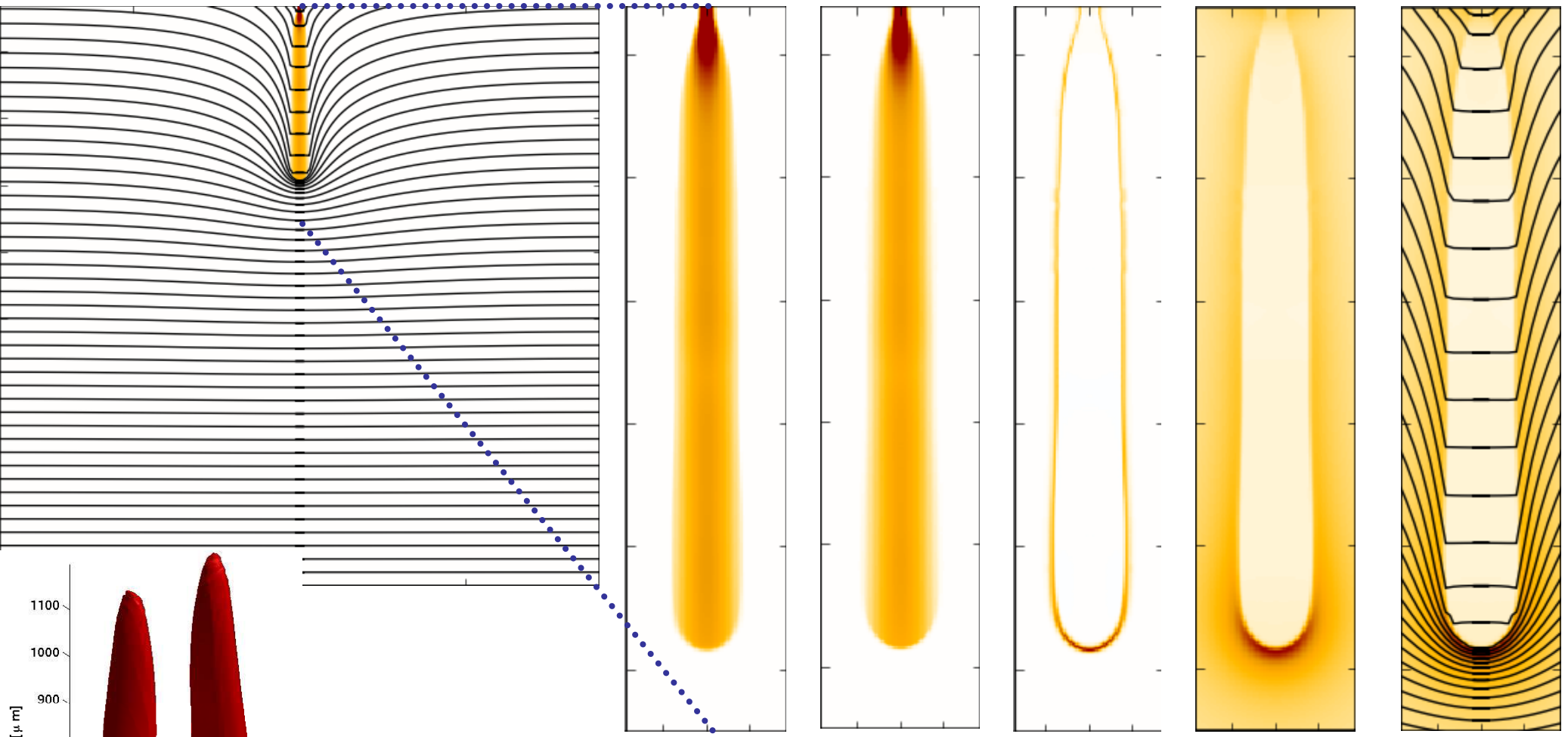
n_e

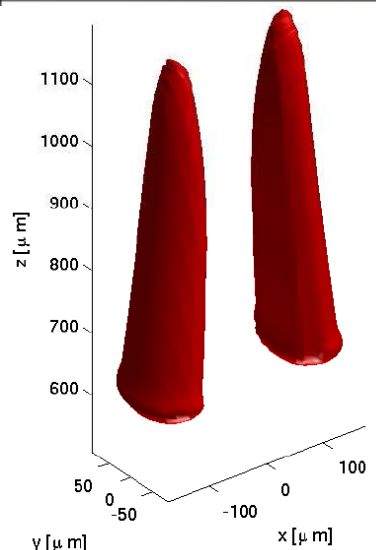
n_+

n_+-n_e

|**E**|

+ equi-φ





[Ebert et al., Nonlinearity 2011]

[Luque et al., Phys Rev Lett 08]

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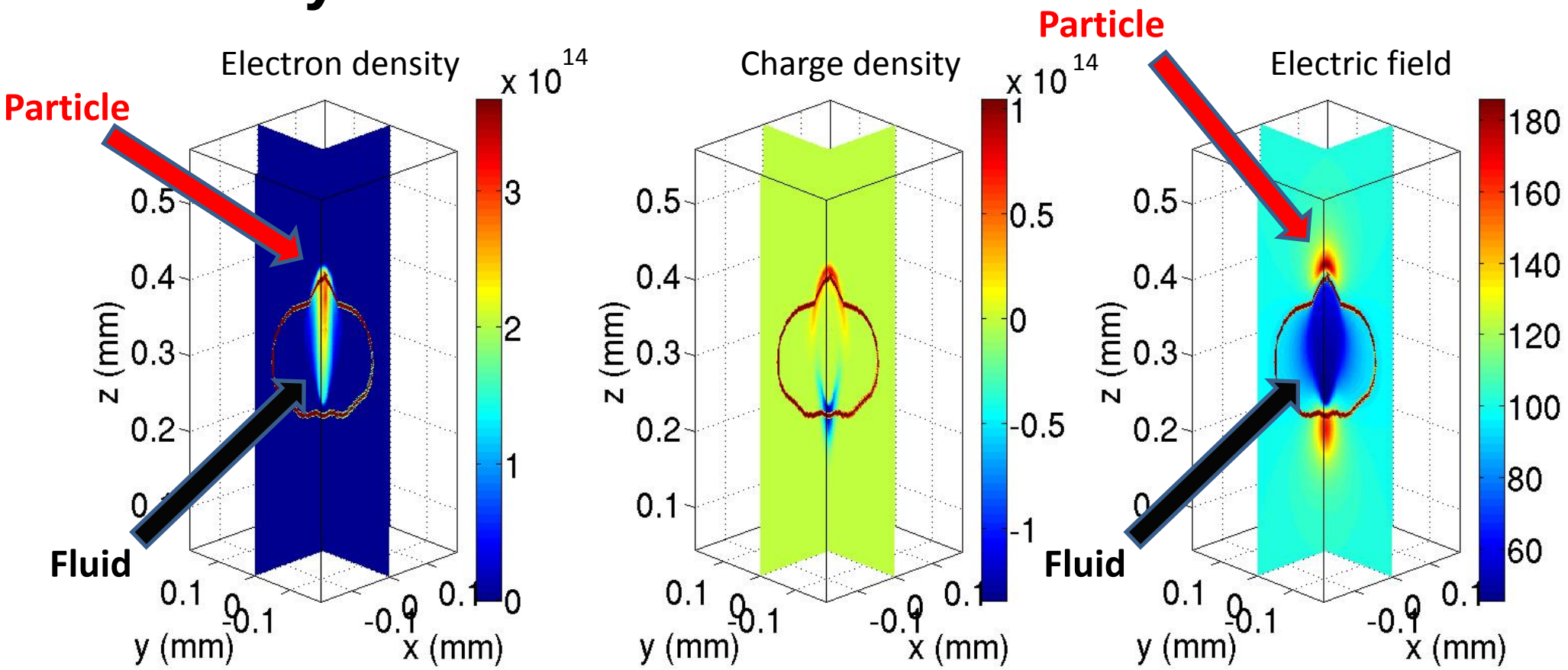
3D hybrid model



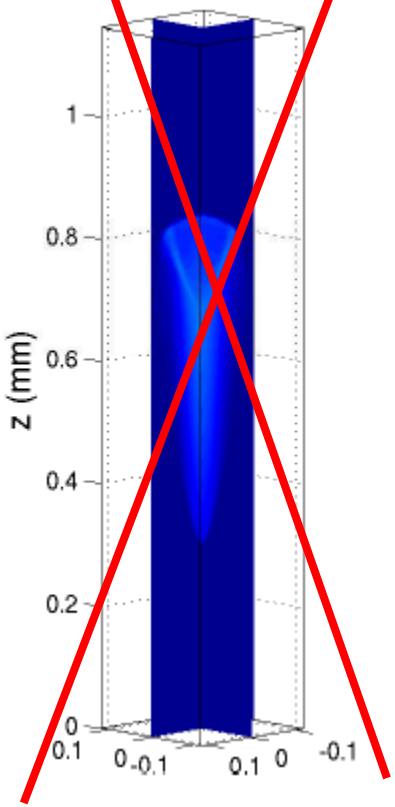
yields electron run-away and X-rays.

[Li et al., JAP 2007, JPD 2008, …, J Comput Phys 2012]

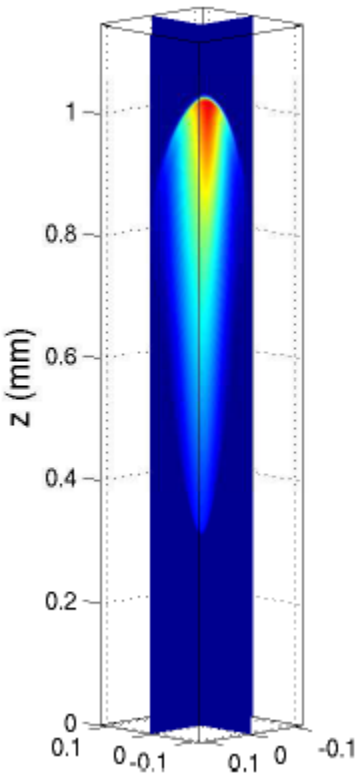
3D: Negative streamer in STP N_2

in overvolted gap (E_{back} = -100 kV/cm)

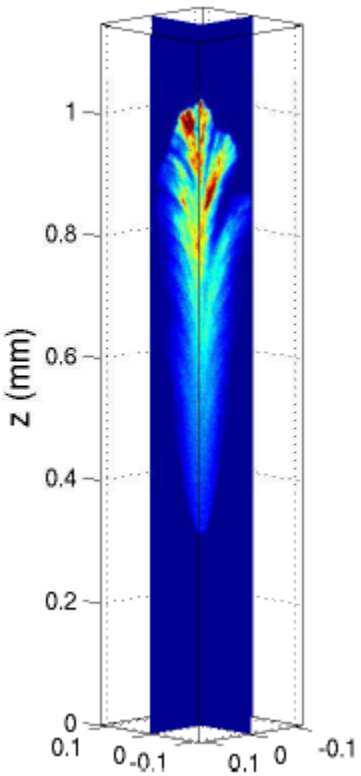
Classical fluid



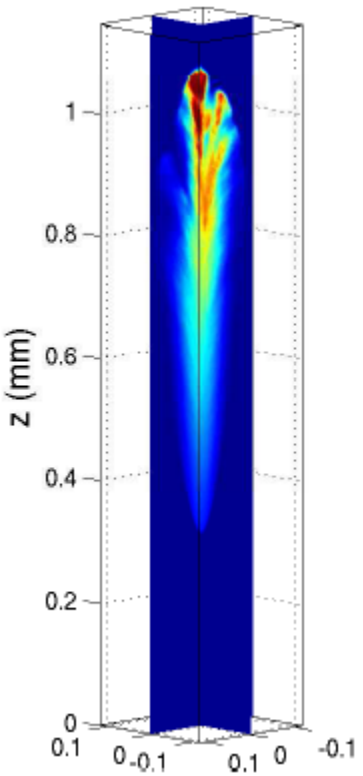
Extended fluid

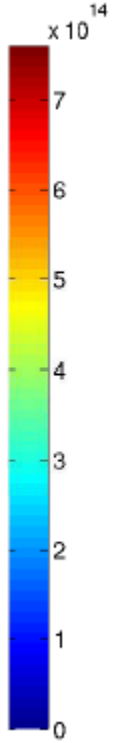


Super-particle



Hybrid



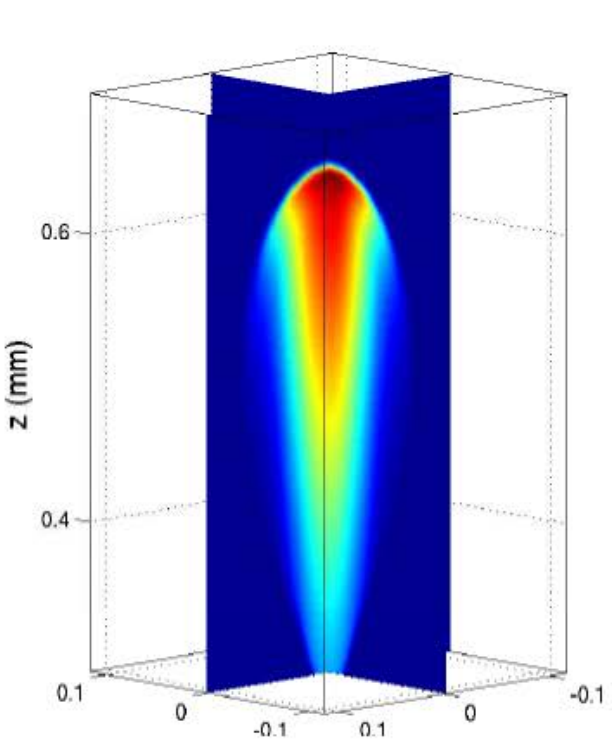


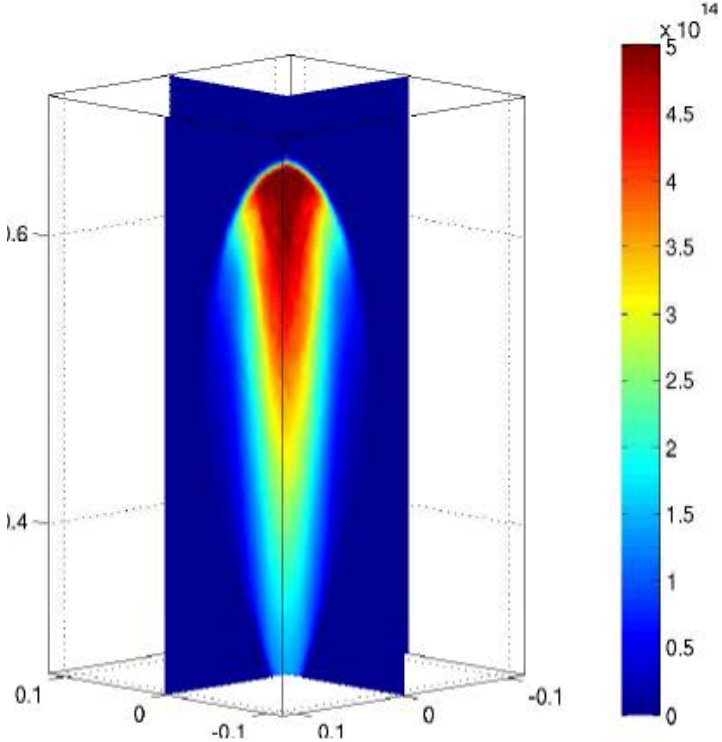
Based on gradient expansion
[Li et al., J Comput Phys, 2010]

... systematic new model:
[Markosyan, Dujko et al.,
J Phys D 2013]

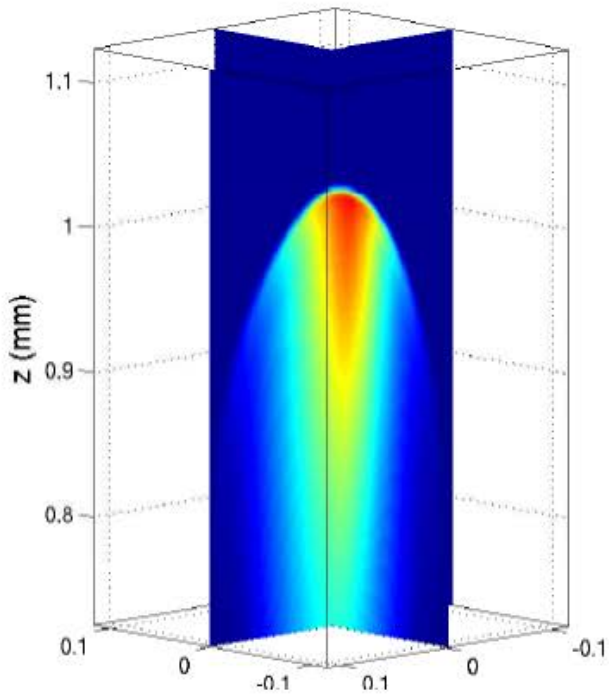
Extended density model

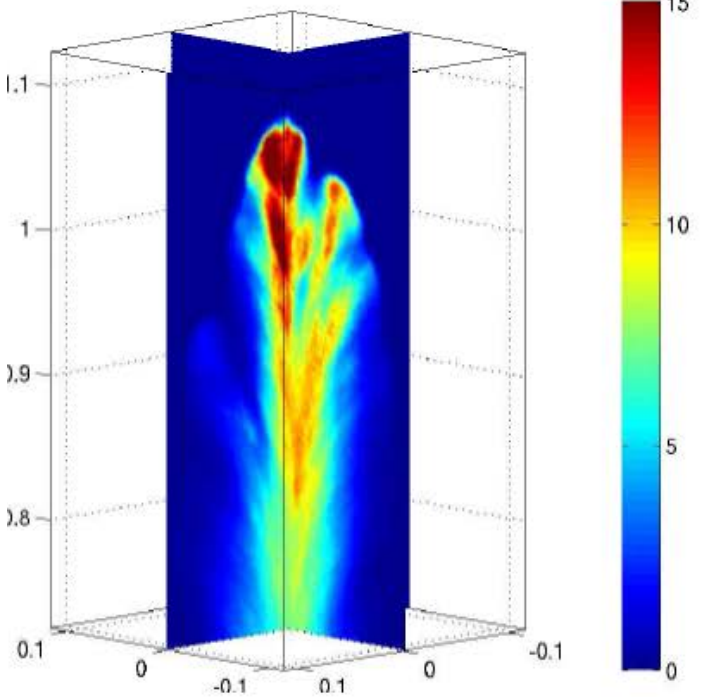
Hybrid model





Extended density model approximates propagation well,



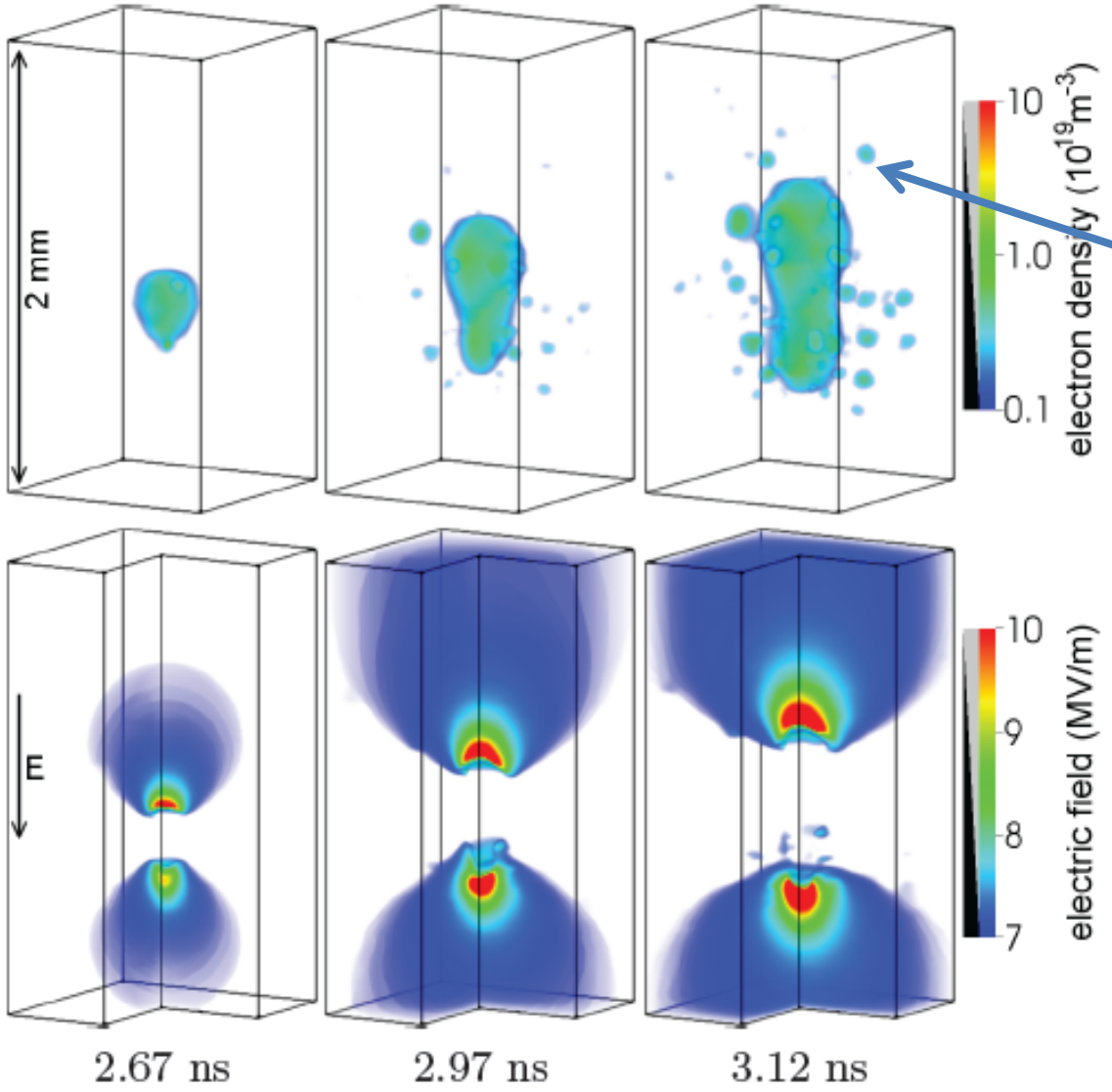


but branching occurs too late.

[Li et al., PSST 2012]

BUT

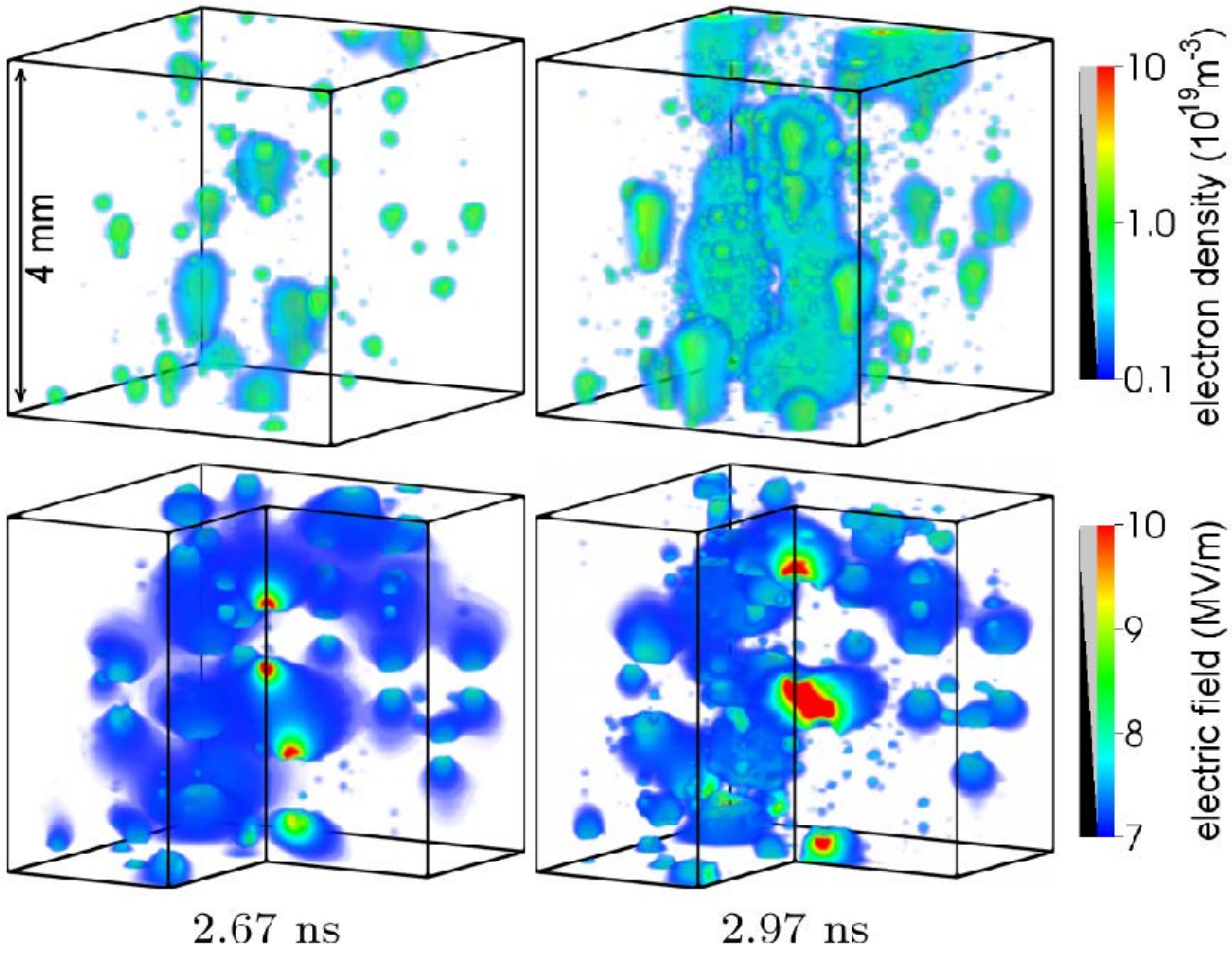
Air, overvolted gap (70 kV/cm) with one free electron initially, no O_2^-



New spots due to single photoionization events

Double headed streamer as in 2D fluid models!

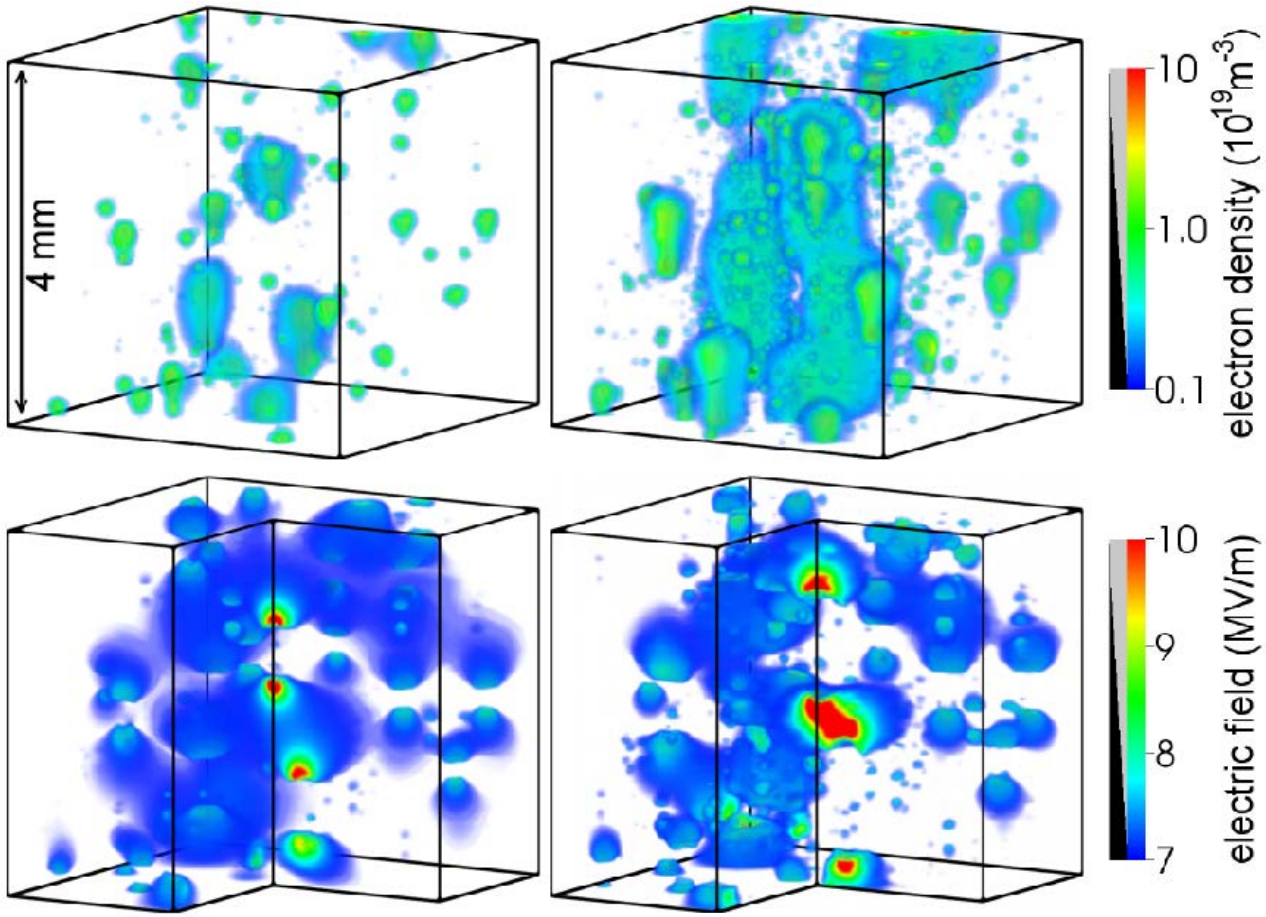
Air, overvolted gap (70 kV/cm) with one free electron initially, and 10^3 O_2^-/cm^3



Global breakdown due to electron detachment!

[Sun, Teunissen, Ebert, Geophys. Res. Letters **40**, 2417 (2013)]

Air, overvolted gap (70 kV/cm) with one free electron initially, and 10^3 O_2^-/cm^3



Ionization screening time $\tau_{is} \approx \ln\left(1 + \frac{\alpha\epsilon_0 E_0}{e n_0}\right)/(\alpha v_d)$

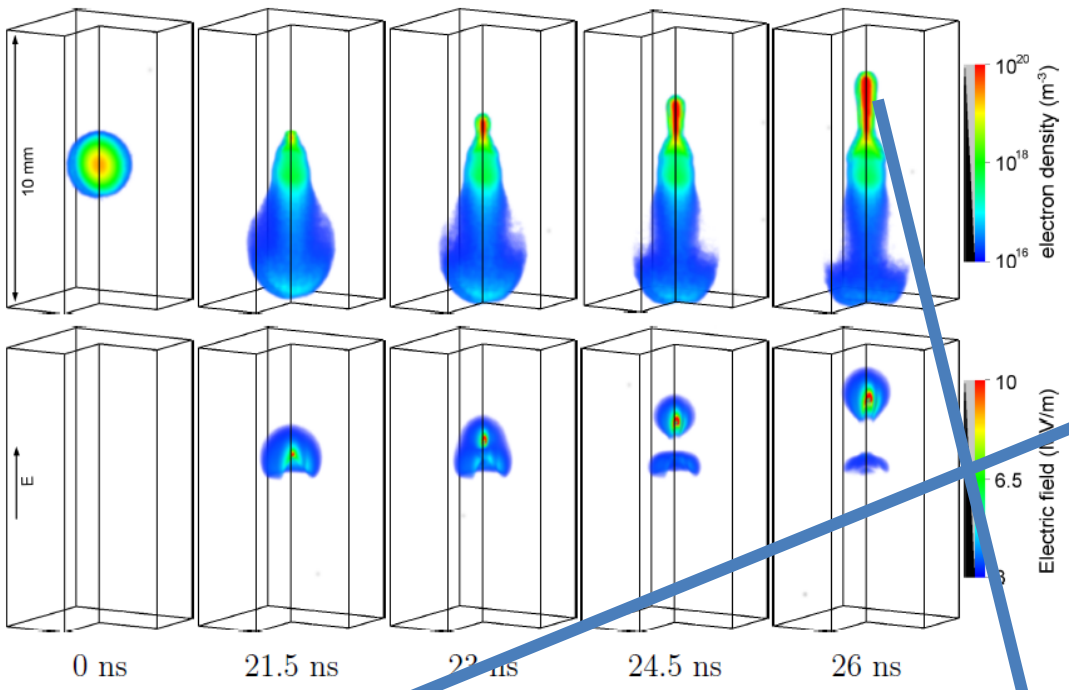
For vanishing impact ionization, τ_{is} → Maxwell relaxation time.

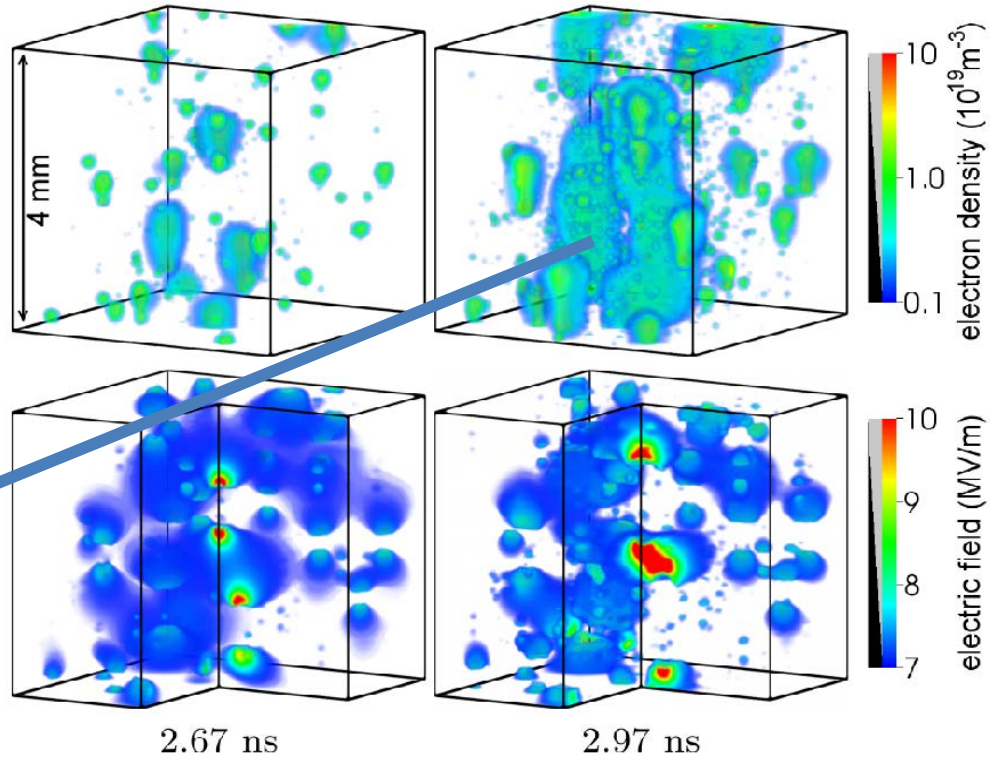
[Sun, Teunissen, Ebert, GRL 2013; Teunissen, Sun, Ebert, J Phys D, to appear]

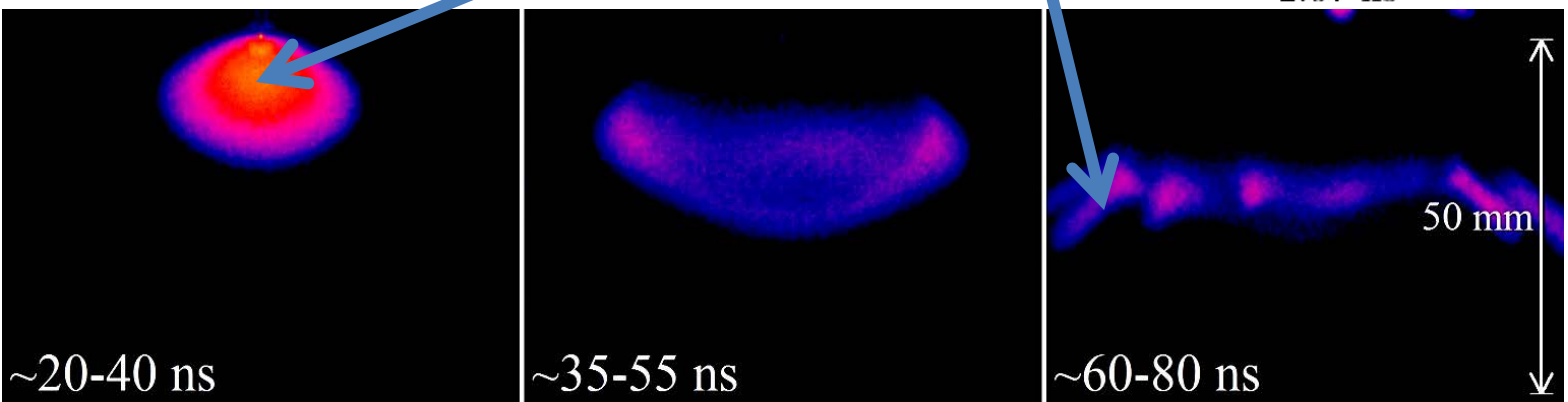
No immediate double-headed streamers in air due to natural O_2^- and detachment

Undervolted:
Only positive streamers

Overvolted:
Global breakdown







Streamers, leaders, radiation:

- X-rays, γ-rays, positrons generated by streamer processes and lightning leaders
- Observations of growth of meter-long sparks with streamers and leaders
- Streamer tree model with consistent charge transport: field inversion

Inception, morphology, memory effects:

- Inception near electrode: from cloud to streamers, dependence on N_2:O_2 ratio and on voltage frequency
- Double pulse experiment and “memory due to ions”
- Streamers can move perpendicular to the electric field

Pulsed positive discharges in air: Streamers and beyond

www.cwi.nl/~ebert

for publications and numerical codes