



# 2D simulation of the positive streamer in SF<sub>6</sub>: Effect of high attachment rate in atmospheric and sub atmospheric pressure.

– Electrostatic and Dielectric Materials team –  
Grenoble Electrical Engineering Lab (G2Elab)  
5<sup>TH</sup> October, 2021

**By: Francis BOAKYE-MENSAH**

**Collaborators: Nelly BONIFACI, Rachelle HANNA, Innocent NIYONZIMA, Igor TIMOSKIN**

*[francis.boakye-mensah@g2elab.grenoble-inp.fr](mailto:francis.boakye-mensah@g2elab.grenoble-inp.fr)*



financé par  
**IDEX Université Grenoble Alpes**



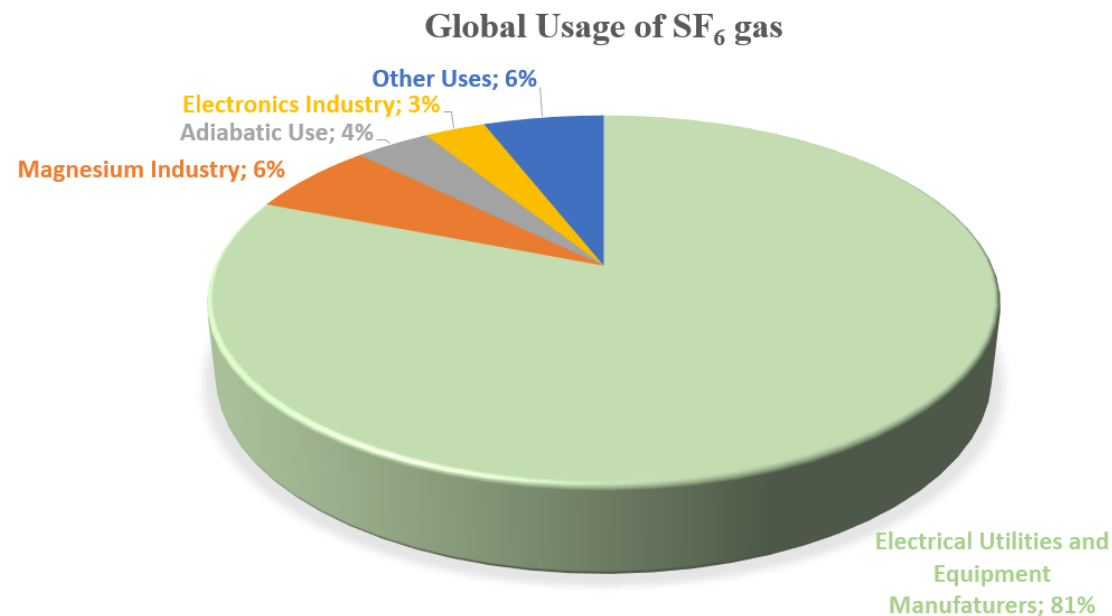
**InnoEnergy**  
Knowledge Innovation Community



# Introduction

## Motivation

- Industrial applications of SF<sub>6</sub> and the need to replace it in electro technical applications
- Strong greenhouse warming potential (23900 on a 100 year time horizon)
- Search for replacement ongoing for 20 years especially in medium voltage applications with compressed air a promising candidate.



# Outline

## ❑ Background

- Streamer Modelling

## ❑ Model Implementation

## ❑ Results and Analysis

- Streamers in Air and SF<sub>6</sub> at atmospheric pressure
- Streamers in Air and SF<sub>6</sub> at sub atmospheric pressure

## ❑ Conclusion

## Streamer Modelling – Plasma Fluid Model

- Hydrodynamic model + Individual Reactions

Diffusion

- Mass conservation equations for electrons and ions:

$$\frac{\partial n_{xl}}{\partial t} + \nabla \cdot (-D_x \nabla n_{xl} - \mu_x n_{xl} E) = R_{xl}$$

Drift

$$n_{xl} = \ln(n_{e,p,n})$$

Rate Processes

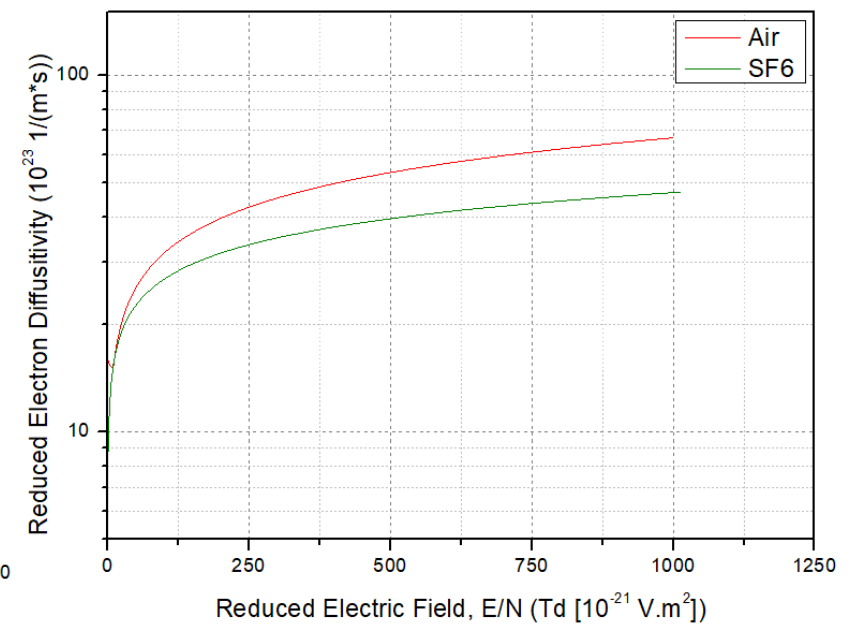
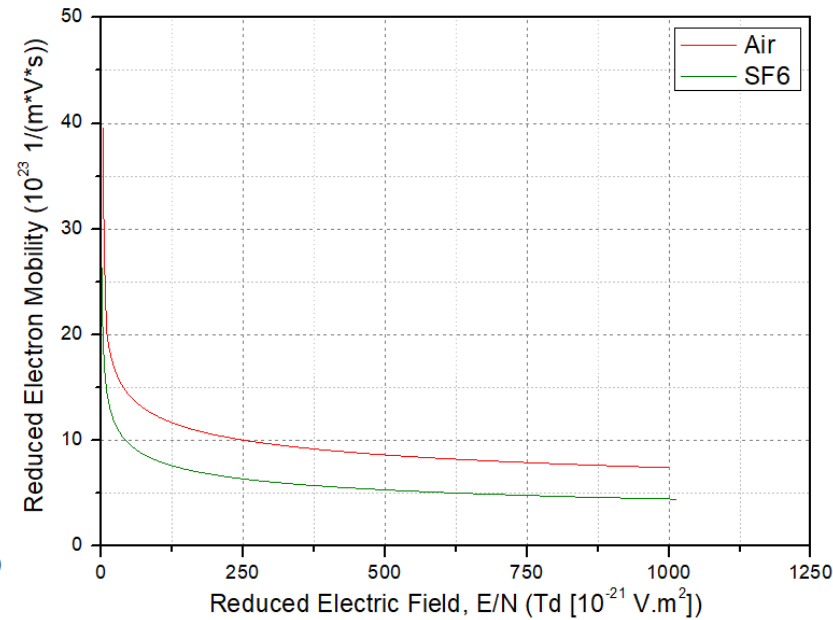
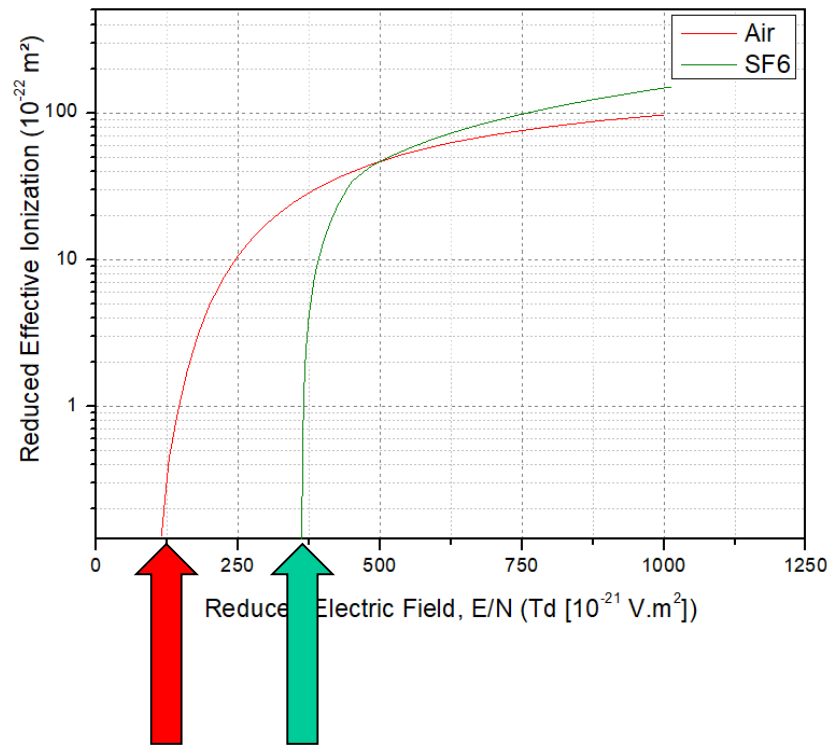
Space Charge

- Poissons equation for electric potential  $\phi$ :

$$\nabla \cdot (\epsilon_0 \epsilon_r \nabla \phi) = -e(n_p - n_e - n_n), \vec{E} = -\nabla \phi$$

- Photoionization model / Background ionization term.

## Streamer Modelling – Swarm Parameters



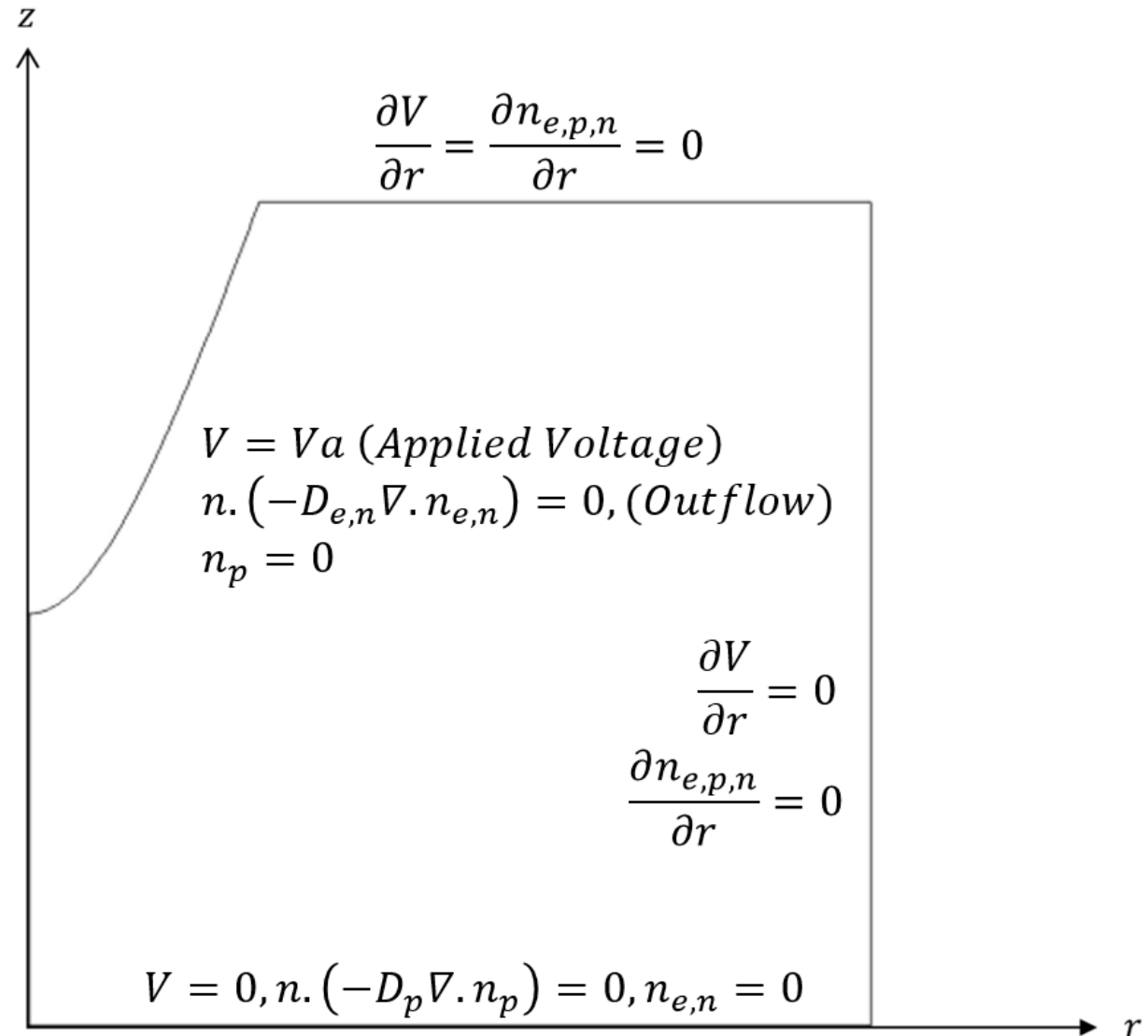
**120 Td**   **362 Td**

\*Air = Lowke (1997), Ducasse (2008); SF<sub>6</sub> = Morrow (1986)\*

## Model Implementation

COMSOL<sup>®</sup> (FEM) → Plasma Module

- Log Formulation
- Point to Plane Geometry
- Appropriate Boundary Conditions
- Nano-second timescale → AMR
- Time stepping: BDF
- Solver: Direct, Fully Coupled



Background

Implementation

Comsol | Afivo

Results

1 bar | 0.1 bar

Conclusion

## Results

Streamers in Air and SF<sub>6</sub> at atmospheric pressure

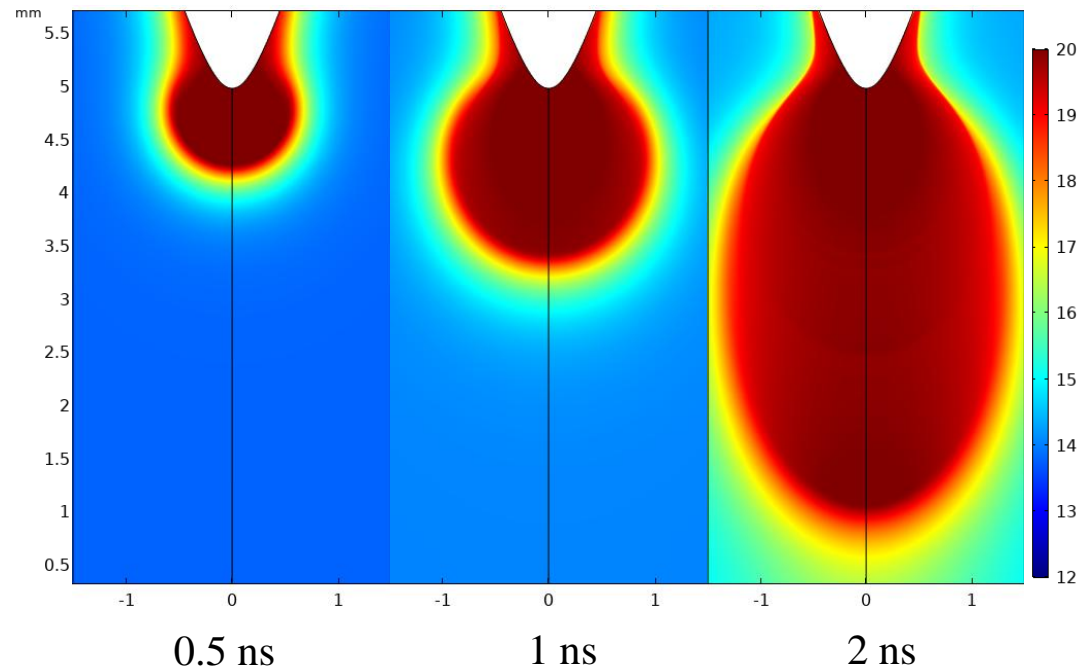
Radius of curvature: 0.1 mm

Gap Distance: 5 mm

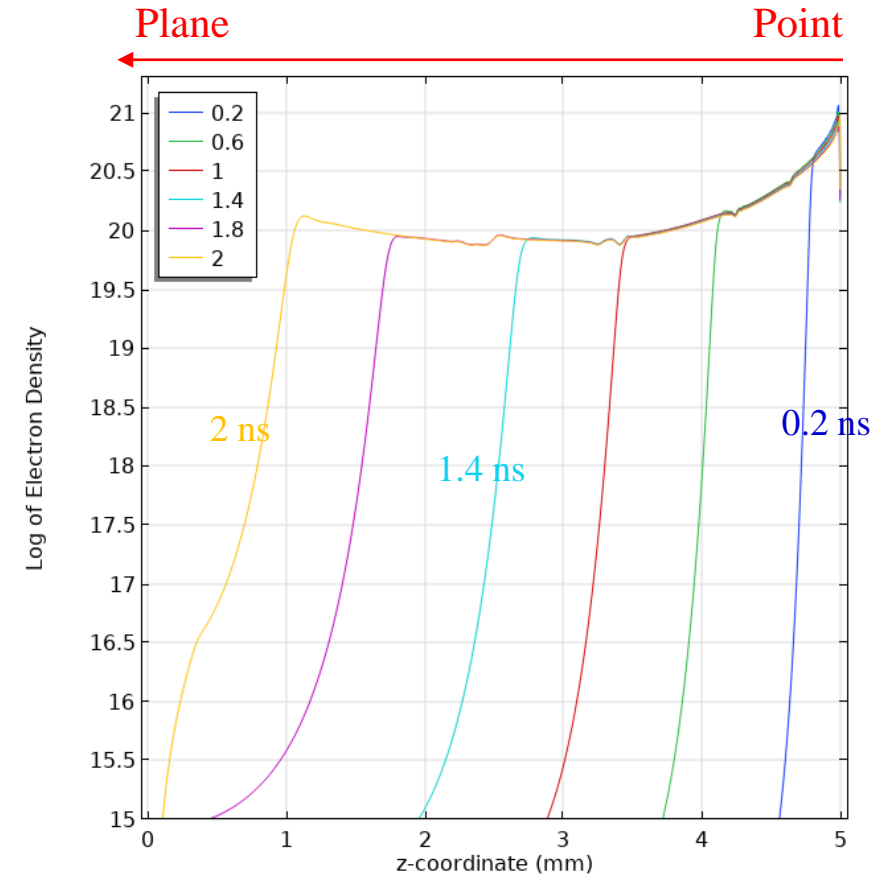
Background Ionization:  $S_b = 1e23$  (1/m<sup>3</sup>.s)

## Streamer in Air at Atmospheric Pressure (Electron Density)

$V_0 = +20$  kV,  $d = 5$  mm,  $r_c = 0.1$  mm,  $S_b = 1e23$  (1/m<sup>3</sup>.s)



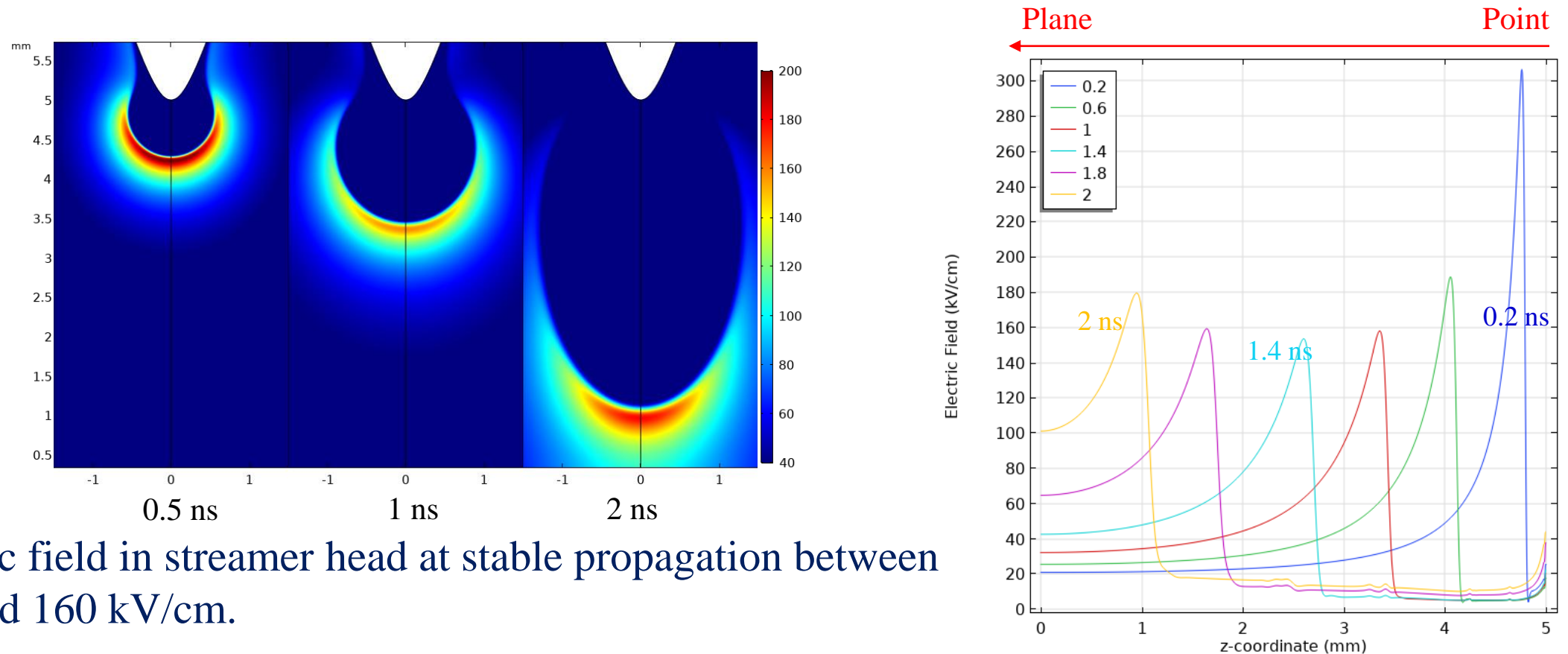
- Two phases: Initiation and Radial Expansion phase; Propagation phase.
- Electron density in streamer  $\sim 10^{20}$  m<sup>-3</sup>





## Streamer in Air at Atmospheric Pressure (Electric Field)

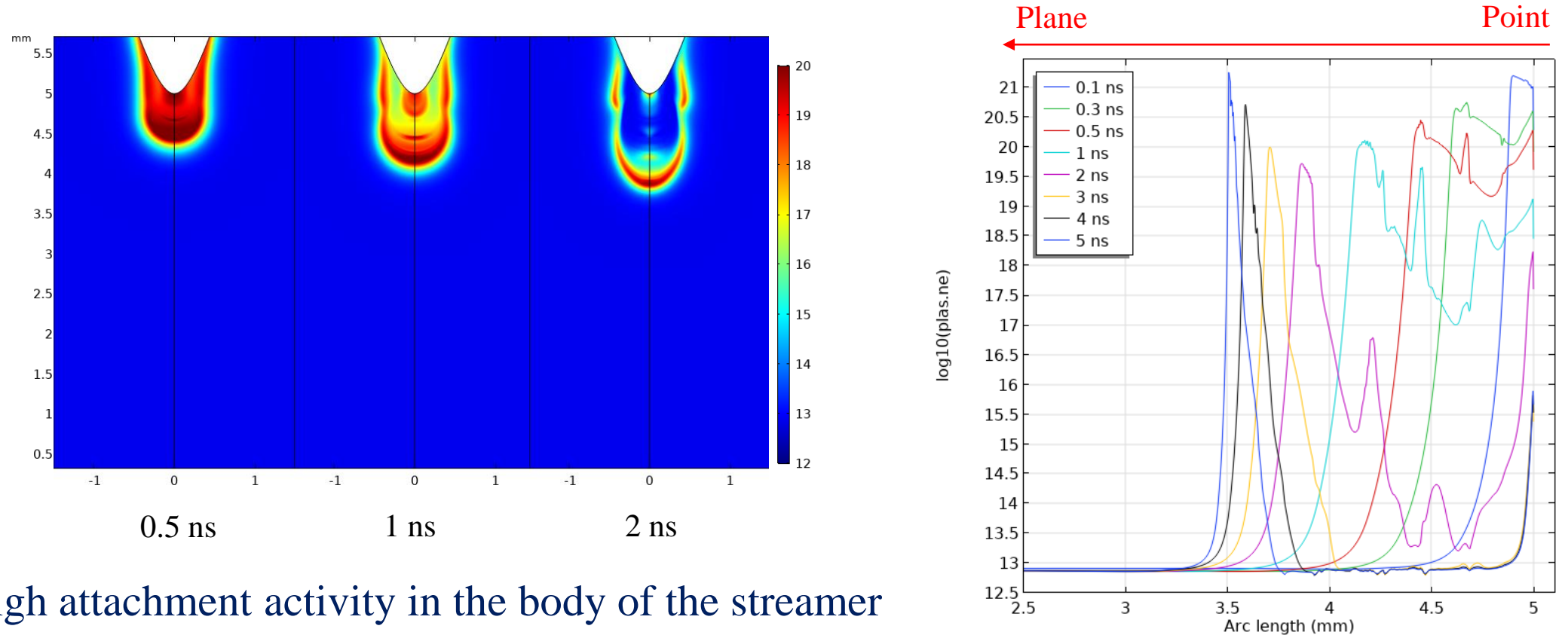
$V_0 = +20$  kV,  $d = 5$  mm,  $r_c = 0.1$  mm,  $S_b = 1e23$  (1/m<sup>3</sup>.s)



- Electric field in streamer head at stable propagation between 140 and 160 kV/cm.
- Interaction with cathode results in increase in electric field.
- Channel radius of  $\sim 900$   $\mu\text{m}$  and streamer velocity 2.27 mm/ns.

## Streamer in SF<sub>6</sub> at Atmospheric Pressure (Electron Density)

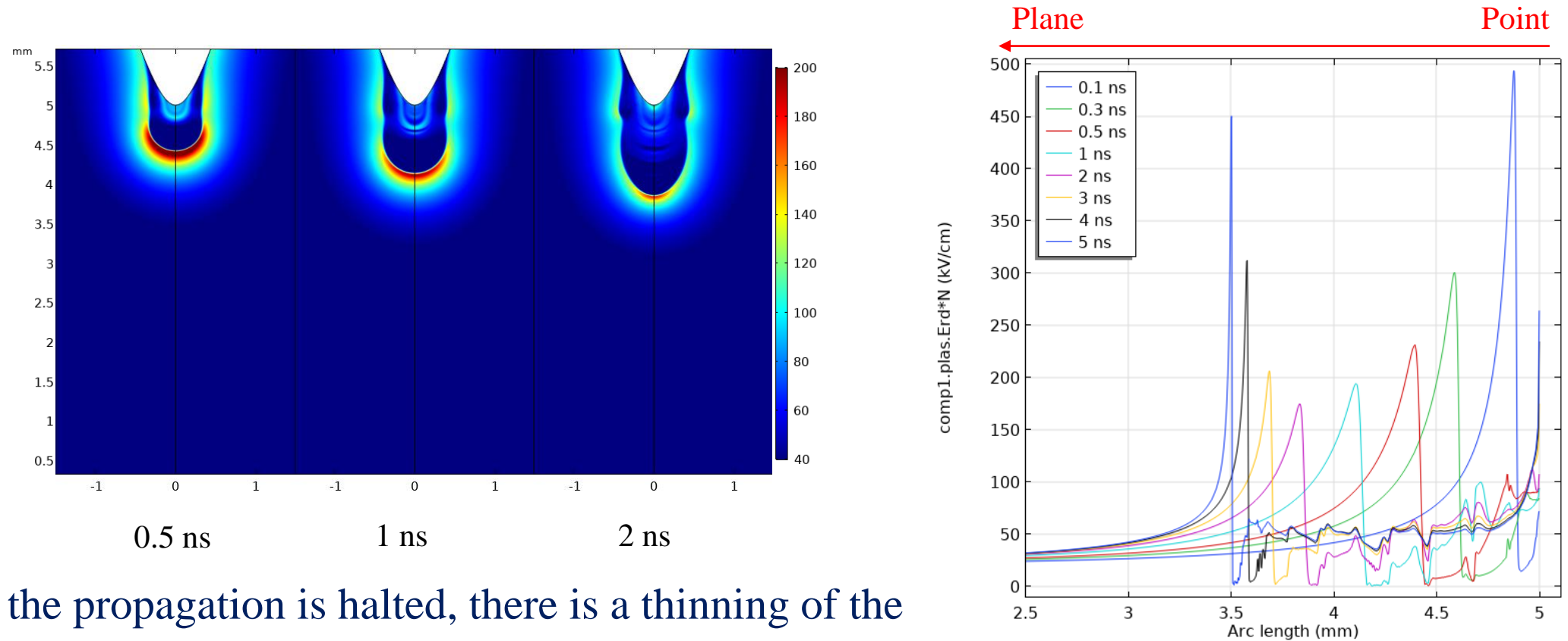
$V_0 = +20$  kV,  $d = 5$  mm,  $r_c = 0.1$  mm,  $S_b = 1e23$  (1/m<sup>3</sup>.s)



- High attachment activity in the body of the streamer eventually leading to a stop in propagation.
- Gradual loss of conduction channel.

## Streamer in SF<sub>6</sub> at Atmospheric Pressure (Electric Field)

$V_0 = +20$  kV,  $d = 5$  mm,  $rc = 0.1$  mm,  $S_b = 1e23$  (1/m<sup>3</sup>.s)



- When the propagation is halted, there is a thinning of the streamer head and an increase in electric field.
- Electric field in channel  $< 90$  kV/cm required for propagation.

## Streamer in SF<sub>6</sub> at Atmospheric Pressure

### Conclusion

- Streamer in Air with comparable results to literary works; velocity of 1 mm/ns.
- Streamer in SF<sub>6</sub> halts propagation about 1 mm into the 5 mm gap as opposed to in air where it crosses the gap.
- High loss processes in highly electronegative gases result in less conductive streamer channels and in the case of SF<sub>6</sub>, the total loss of conduction.
- To maintain propagation in SF<sub>6</sub>, the field in the channel should be equal to the field at which ionization = attachment.
- This is ~90 kV/cm in SF<sub>6</sub> at atmospheric pressure and from the simulations, fields of ~50 kV/cm are observed.
- In air, field is ~30 kV/cm but because of lower attachment rates, propagation can still occur even with lower fields in channel, fields of ~10 kV/cm observed in simulations.

Background

Implementation

Comsol | Afivo

Results

1 bar | 0.1 bar

Conclusion

## Results

Streamers in Air and SF<sub>6</sub> at sub-atmospheric pressure

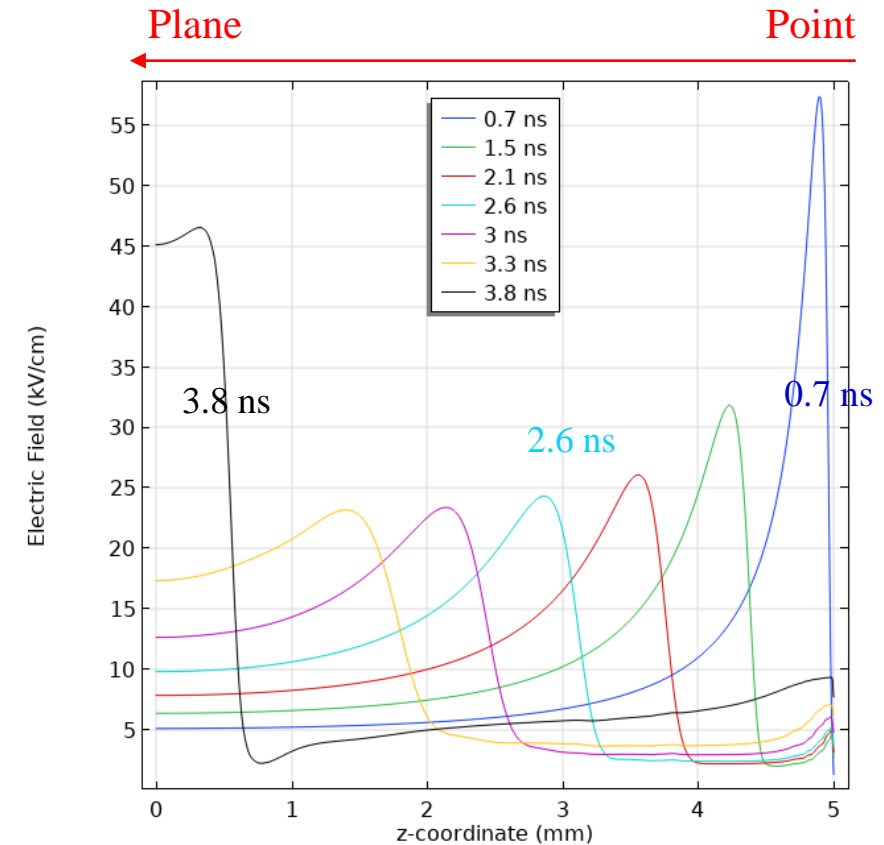
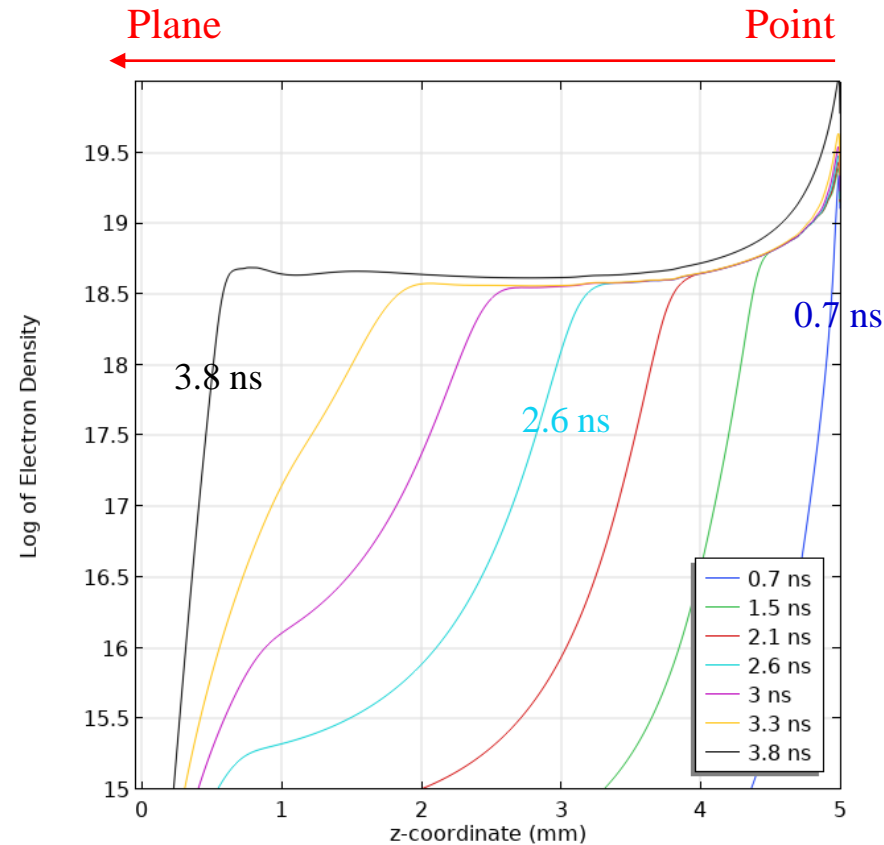
Radius of curvature: 0.1 mm

Gap Distance: 5 mm

Background Ionization:  $S_b = 1e23$  (1/m<sup>3</sup>.s)

## Streamer in Air at 0.1 bar (Electron Density and Electric Field)

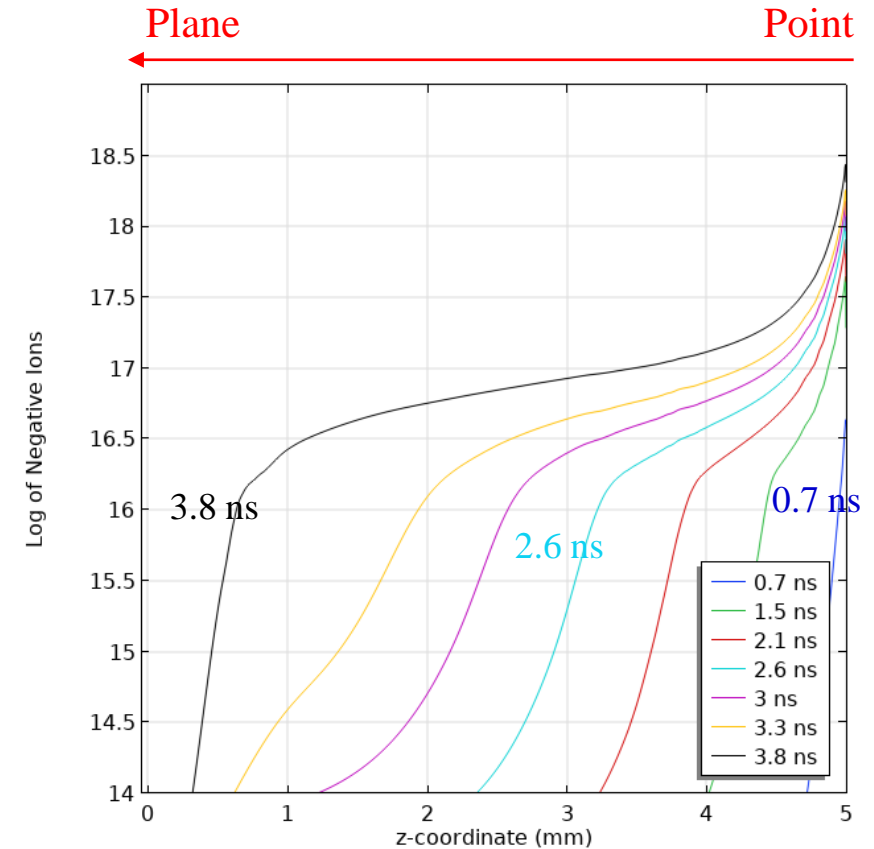
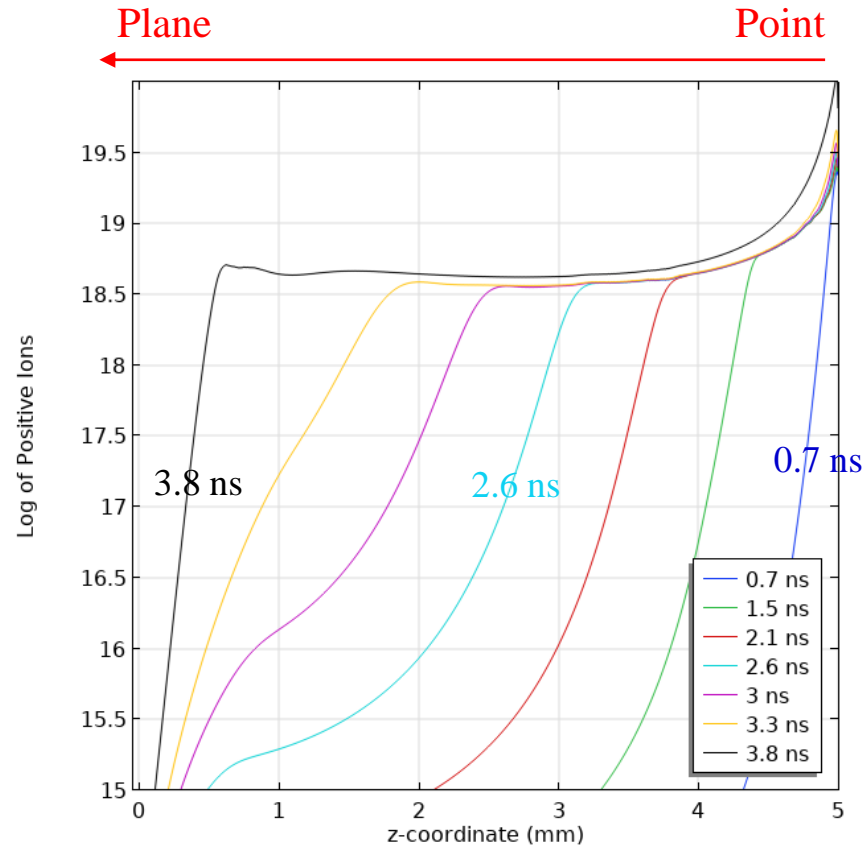
$V_0 = +5$  kV,  $d = 5$  mm,  $rc = 0.1$  mm,  $Sb = 1e23$  (1/m<sup>3</sup>.s)



- Electric field in streamer head is between 23 and 27 kV/cm.
- Channel radius of  $\sim 1.6$  mm and streamer velocity 1.3 mm/ns

## Streamer in Air at 0.1 bar (Ion Densities)

$V_0 = +5$  kV,  $d = 5$  mm,  $rc = 0.1$  mm,  $Sb = 1e23$  (1/m<sup>3</sup>.s)

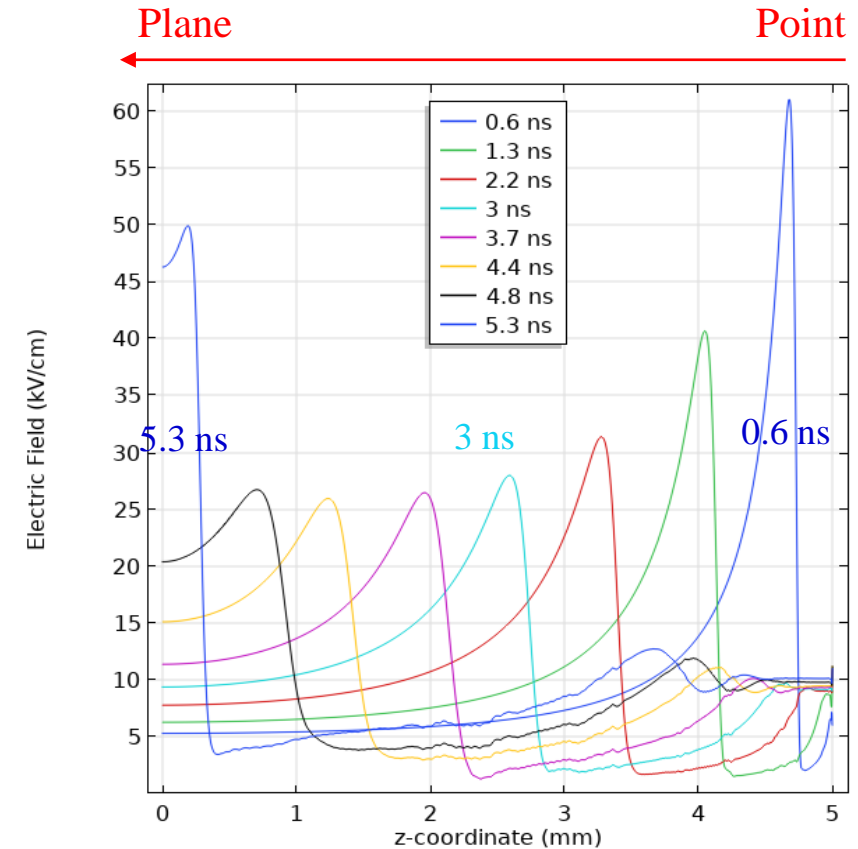
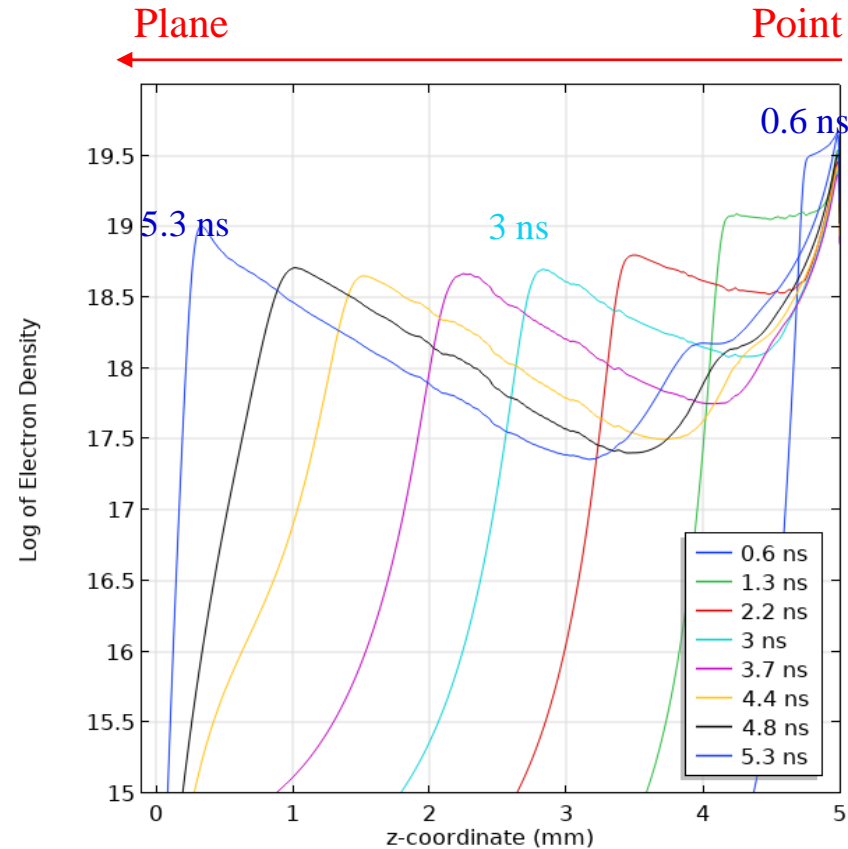


- Higher ionization rate compared to attachment rate results in a 2 order of magnitude difference between positive ion density and negative ion density



## Streamer in SF<sub>6</sub> at 0.1 bar (Electron Density and Electric Field)

$V_0 = +5$  kV,  $d = 5$  mm,  $rc = 0.1$  mm,  $Sb = 1e23$  (1/m<sup>3</sup>.s)

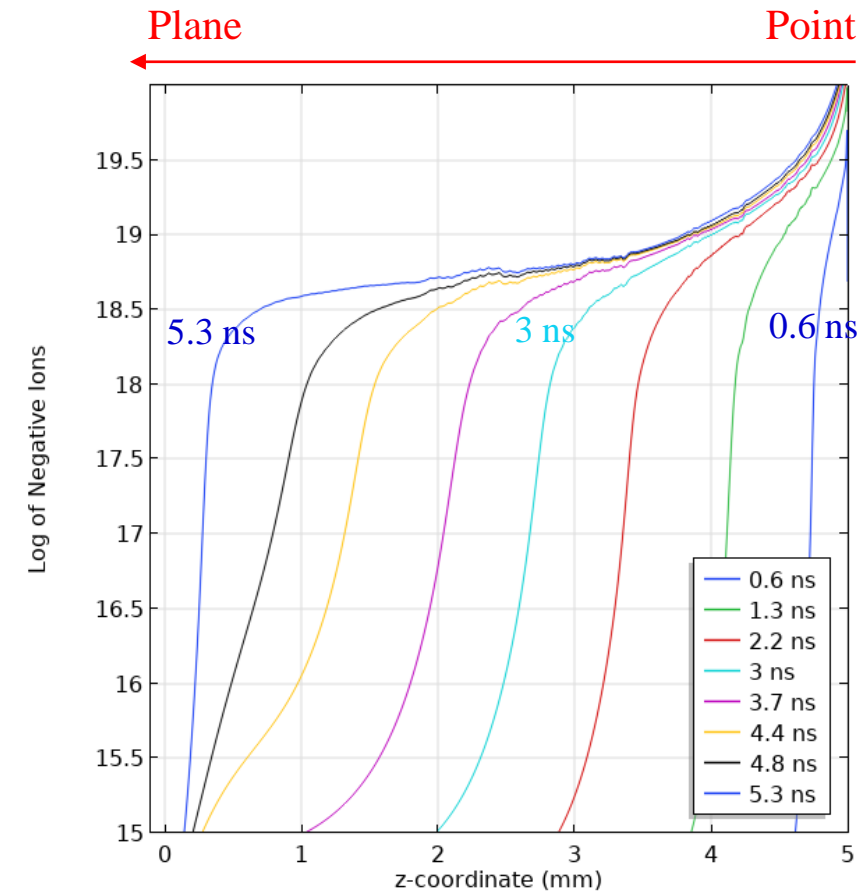
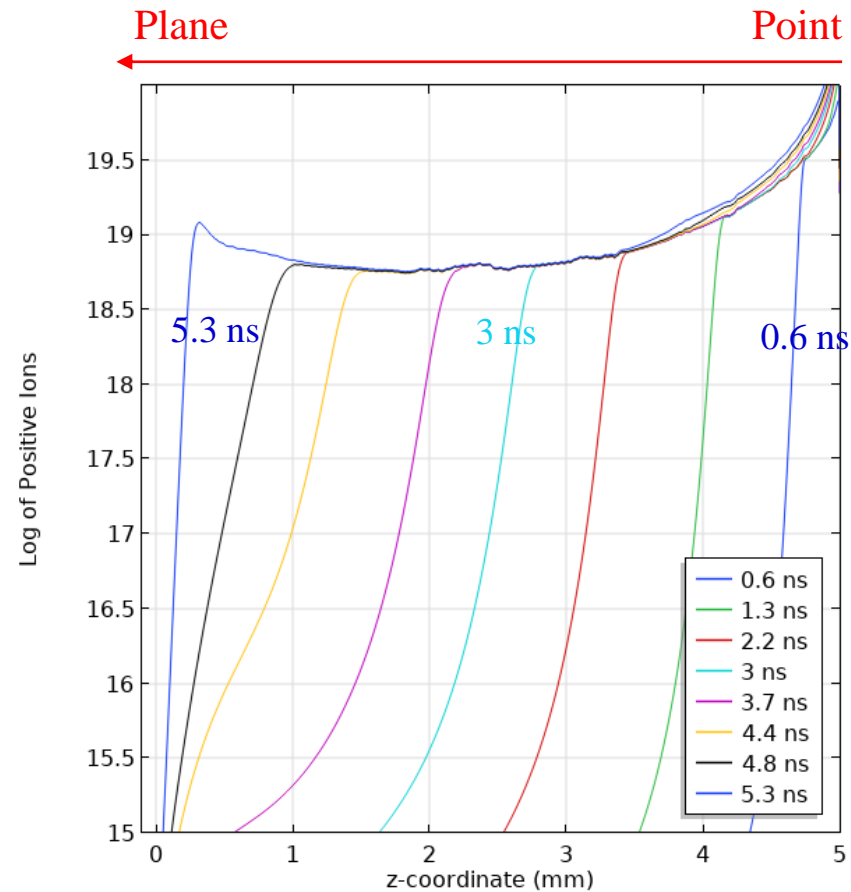


- Electric field in streamer head is between 25 and 30 kV/cm.
- Channel radius of  $\sim 800$   $\mu\text{m}$  and streamer velocity 0.96 mm/ns.



## Streamer in SF<sub>6</sub> at 0.1 bar (Ion Densities)

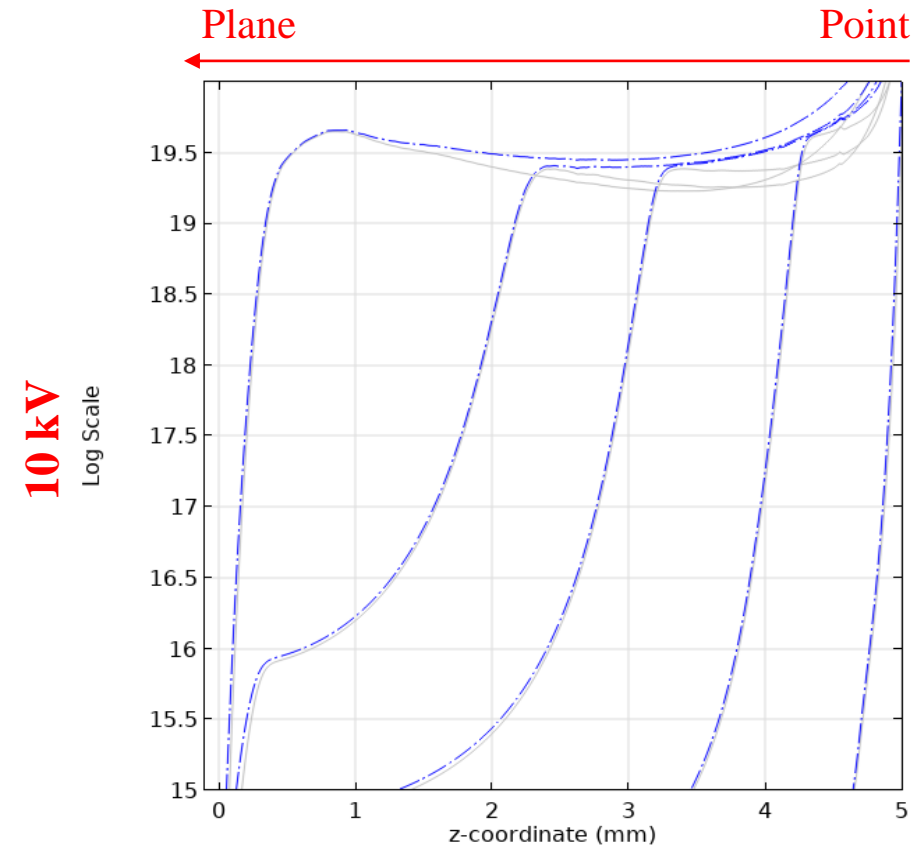
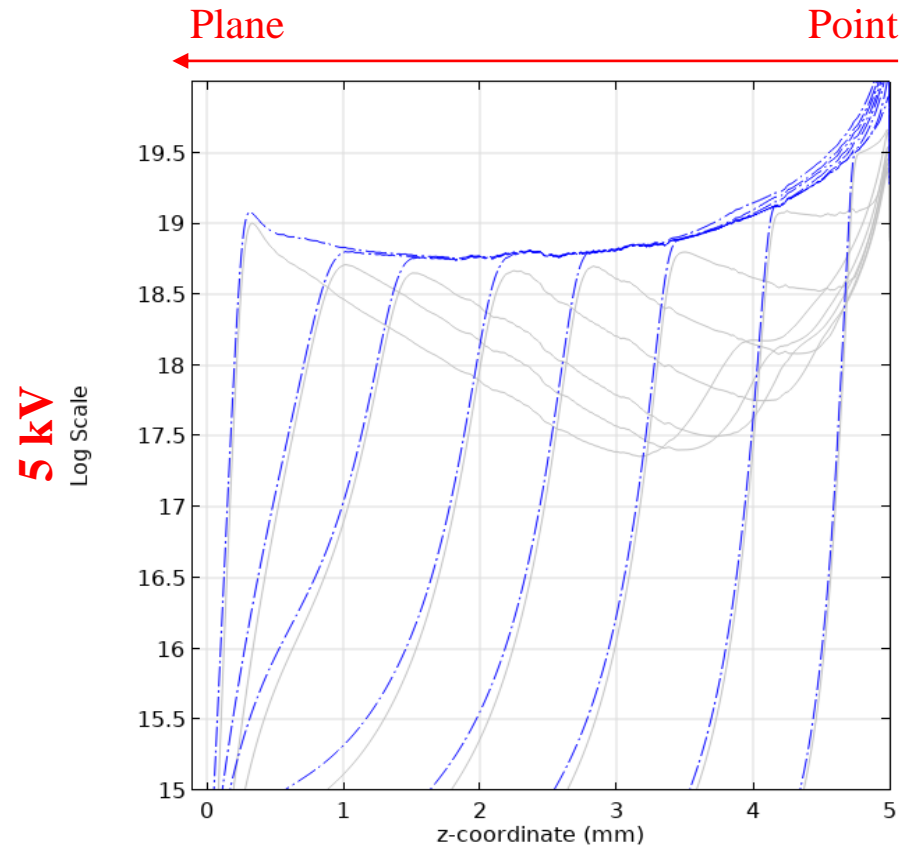
$V_0 = +5$  kV,  $d = 5$  mm,  $rc = 0.1$  mm,  $Sb = 1e23$  (1/m<sup>3</sup>.s)



- Both ion densities of the same order of magnitude.
- Positive ion density almost constant. Negative ion density increases marginally with time. 14/18

## Streamer in SF<sub>6</sub> at 0.1 bar (Positive Ion and Electron Densities)

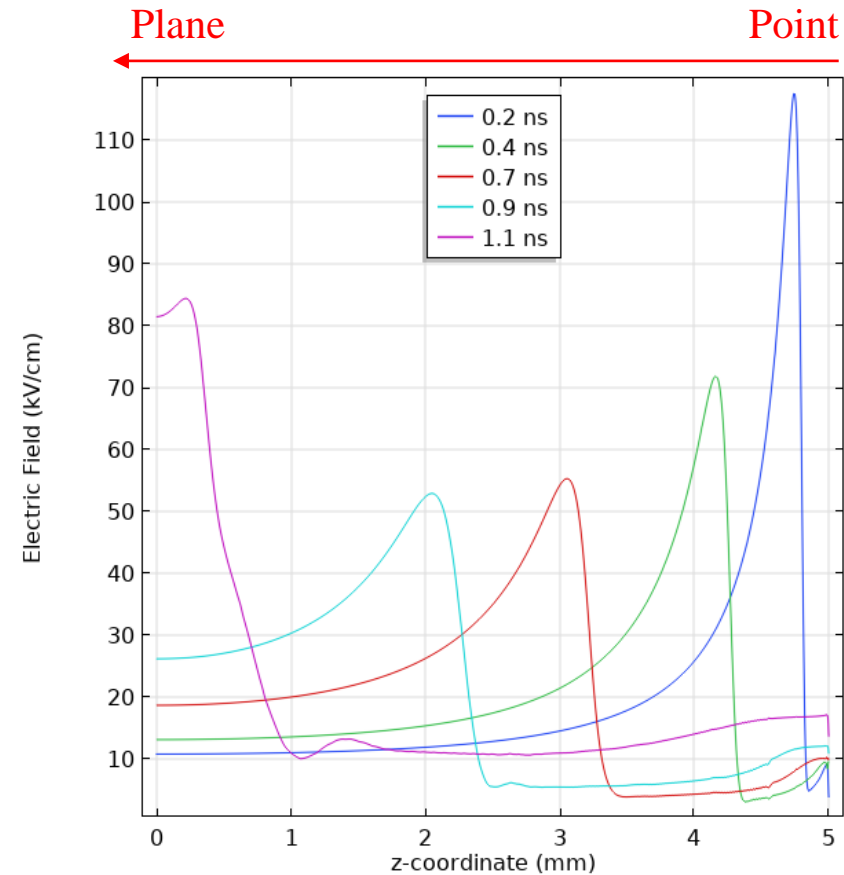
$V_0 = +5 \text{ kV}, +10 \text{ kV}, d = 5 \text{ mm}, r_c = 0.1 \text{ mm}, S_b = 1e23 \text{ (1/m}^3\cdot\text{s)}$



- Higher applied voltages result in higher electron density in the streamer channel because of an increase in the effective ionization

## Streamer in SF<sub>6</sub> at 0.1 bar (Electric Field)

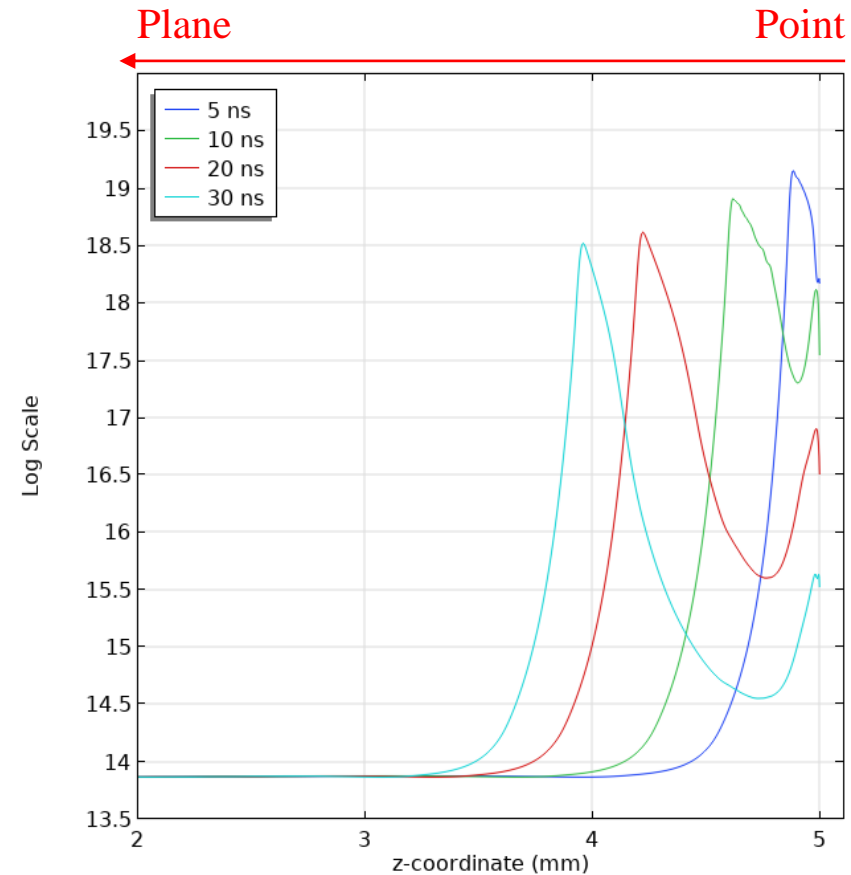
$V_0 = +10$  kV,  $d = 5$  mm,  $rc = 0.1$  mm,  $S_b = 1e23$  (1/m<sup>3</sup>.s)



- Higher electric fields in the streamer head observed with increased applied voltage.
- At stable propagation, electric field in streamer head between 50 and 60 kV/cm

## Streamer in SF<sub>6</sub> at 0.1 bar (Electron Density)

$V_0 = +2$  kV,  $d = 5$  mm,  $rc = 0.1$  mm,  $Sb = 1e23$  (1/m<sup>3</sup>.s)



- Same reduced electric field at at 0.1 bar and 1 bar, the loss of the conduction channel and the halt of the streamer propagation was observed.

- On summarising:
  - ✓ The drift diffusion approach for streamer modelling cannot accurately capture the discharge in SF<sub>6</sub> at 1 bar due to the stepped leader transition.
  - ✓ In lower pressures, < 0.3 bar, the hydrodynamic approach can be used to analyse streamer discharges as have been done for 0.1 bar.
  - ✓ High electronegativity of SF<sub>6</sub> plays a role in the discharge formation as it results in higher loss processes in the channel and a reduction in its conduction.
  - ✓ Comparing to streamers in air at same pressure, the diameter is about half that of air but the velocity of the streamer in both gases is ~1 mm/ns.
  - ✓ When the reduced electric field is scaled according, similar behaviour at atmospheric pressure is observed for sub atmospheric pressure also.
- Perspectives
  - Using hydrodynamic approach to quantify streamer to leader transition
  - Leader propagation in SF<sub>6</sub> gas.



financé par  
**IDEX Université Grenoble Alpes**



**InnoEnergy**  
Knowledge Innovation Community