



Numerical simulation of cathode directed streamer discharges in Air and CO₂.

– Electrostatic and Dielectric Materials team –
Grenoble Electrical Engineering Lab (G2Elab)
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By: Francis BOAKYE-MENSAH

Collaborators: Hani FRANCISCO, Ute EBERT, Nelly BONIFACI, Rachelle HANNA, Innocent NIYONZIMA

francis.boakye-mensah@g2elab.grenoble-inp.fr



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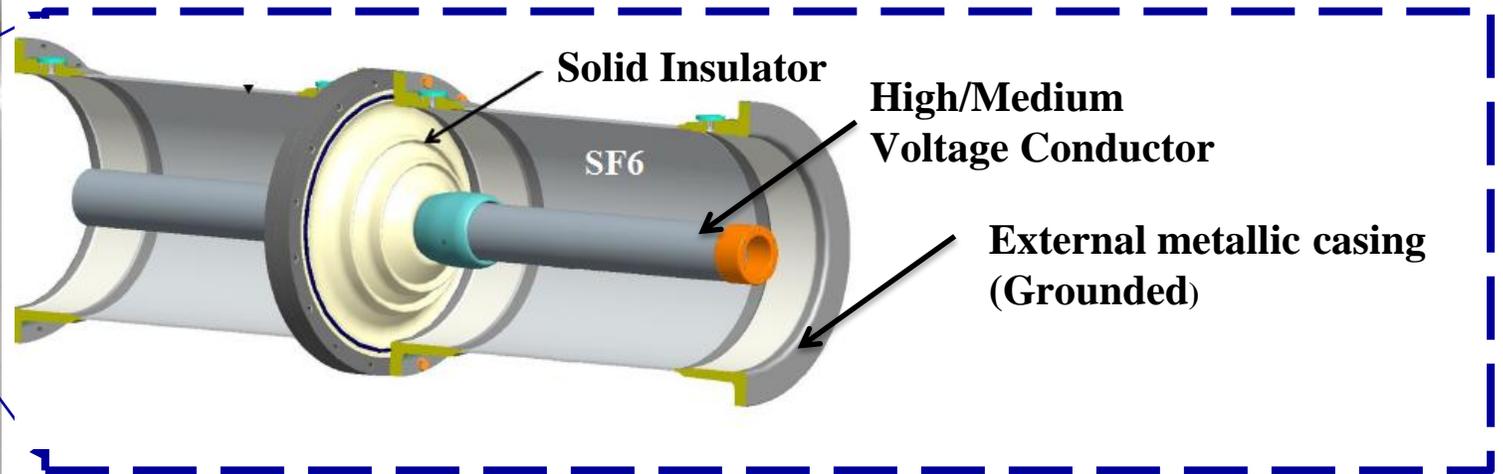
Introduction

Motivation

- Replacement of SF₆ in medium voltage GIS.
- 80% of SF₆ gas used in electrical manufacturing.
- Industrial interest in Air and CO₂ or a mix of the two gases as possible alternatives.



GIS



Outline

Part 1: Background

- Streamer Modelling

Part 2: Model Implementation

- COMSOL
- AFIVOSTreamer

Part 3: Results and Analysis

- Comparison between COMSOL and AFIVO for streamers in Air in short gaps
- Streamers in Air and CO₂ in COMSOL
- Comparison between simulation results and experiments in AFIVO

Part 4: Conclusion

Streamer Modelling – Plasma Fluid Model

- Hydrodynamic model + Individual Reactions
- Mass conservation equations for electrons and ions:

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

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

Diffusion

Drift

Rate Processes

Space Charge

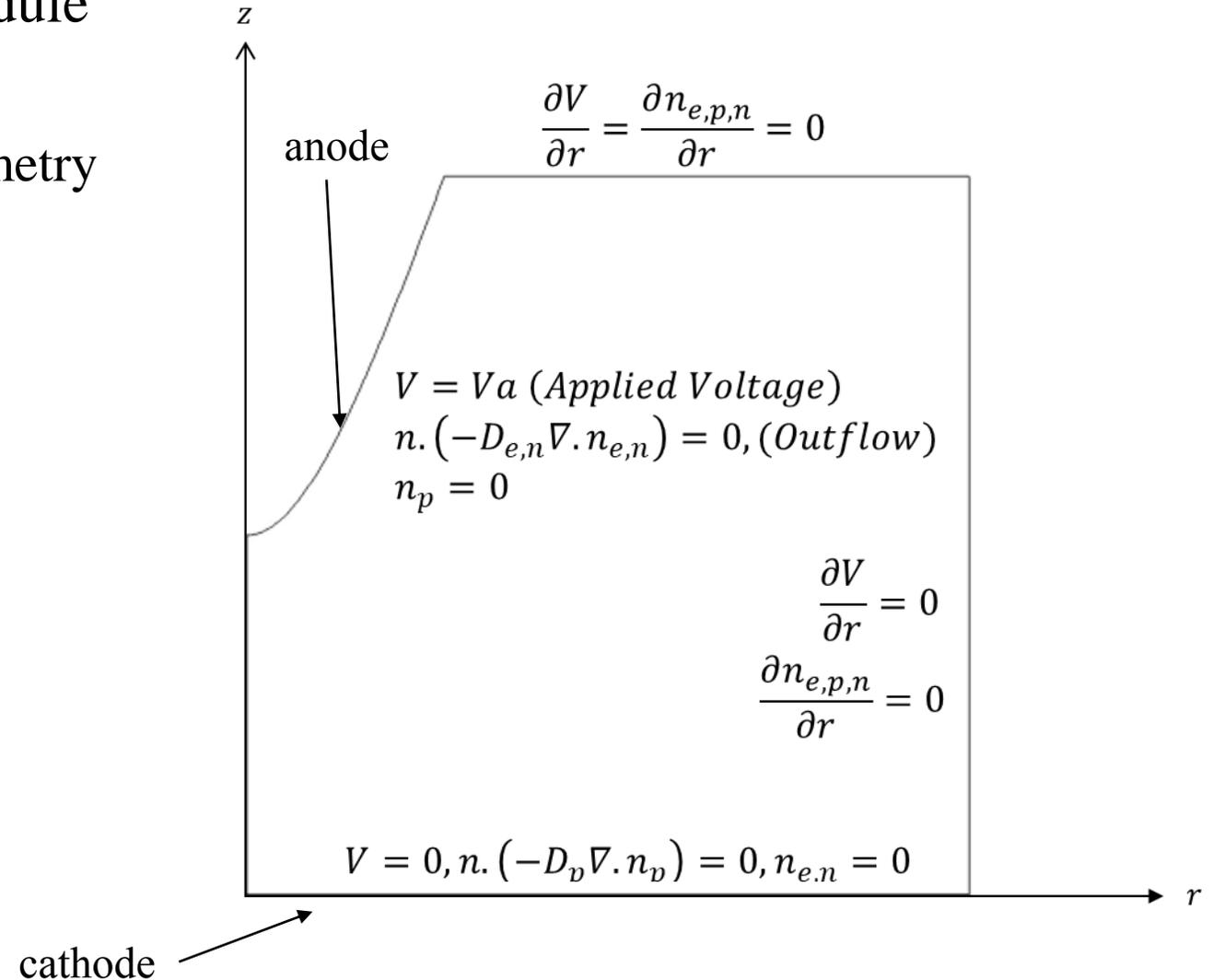
- Poissons equation for electric potential ϕ :

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

- Photoionization model / Background ionization term.

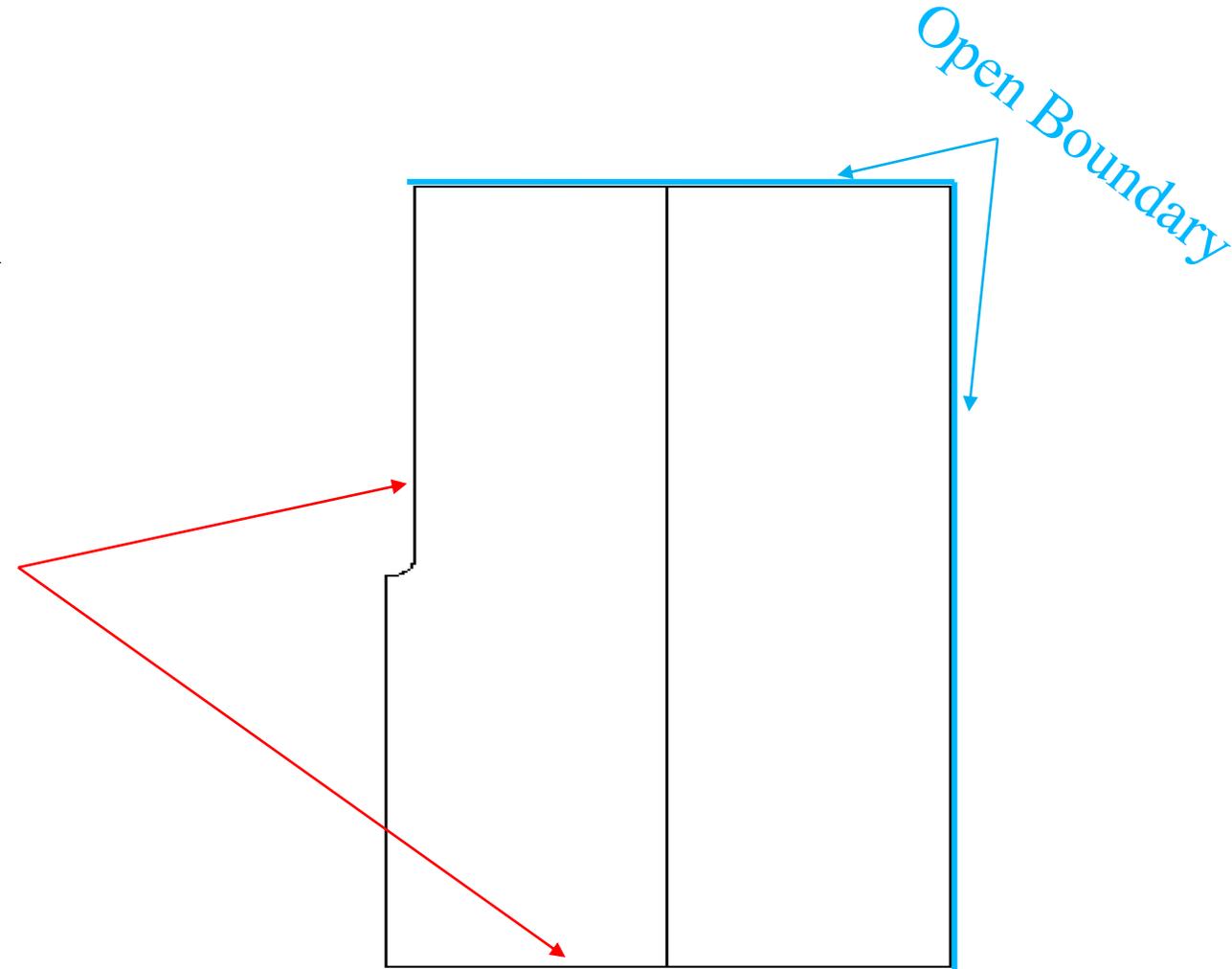
COMSOL® (FEM) → Plasma Module

- Single Discharge using axial symmetry
- Log Formulation
- Point to Plane Geometry
- Appropriate Boundary Conditions
- No photoionization



AFIVOSTREAMER (FVM)

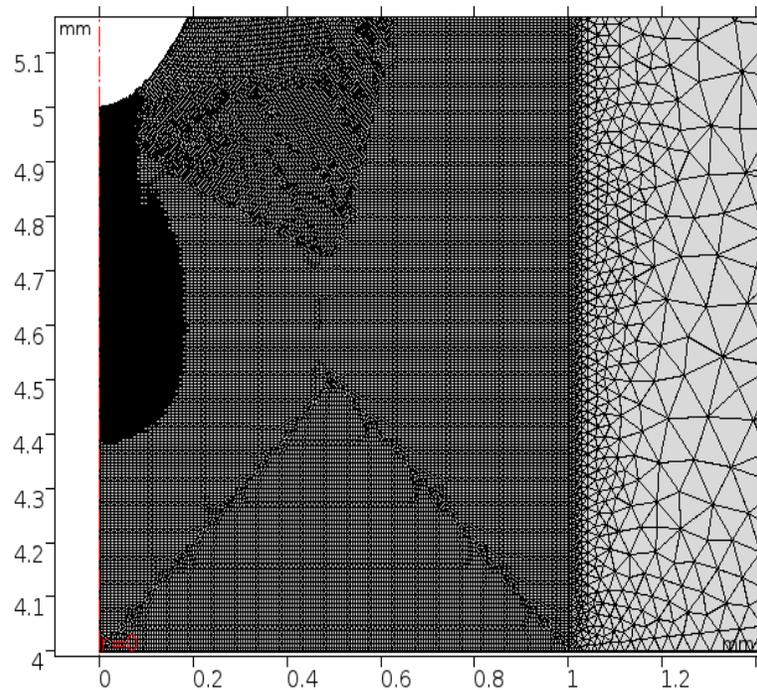
- Open Source Code for Plasma Fluid Simulations
- Collaboration with CWI Amsterdam
- Point to Plane Geometry (Fileted)
- Boundary Conditions = **Dirichlet_zero**
- Photoionization using Zheleznyak's Model



J. Teunissen and U Ebert, Simulating streamer discharges in 3D with the parallel adaptive Afivo framework (2017).

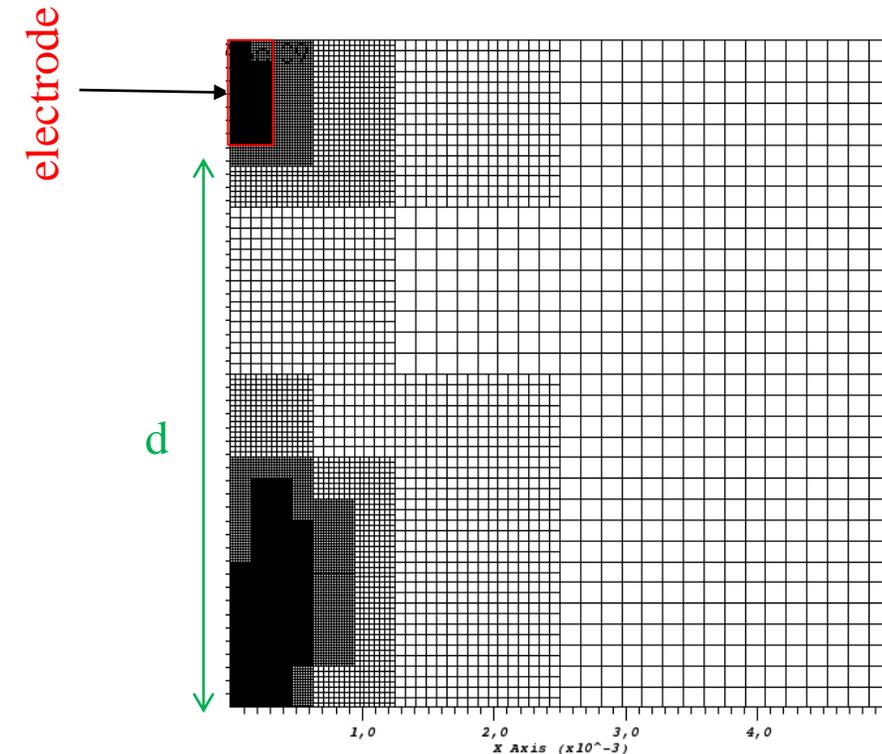
Mesh Refinement

COMSOL[®] : Adaptive Mesh



Reaction Rate + Domain Partitioning

AFIVOSTREAMER : Adaptive Quadtree/Octree



Mesh derefined in regions of non-interest

Background

Implementation

Results

Conclusion

Comsol | Afivo

Comparison | Comsol | Afivo

Part 3a: COMSOL vs AFIVO

Comparison of Streamer Model in AFIVO and COMSOL

Gap Distance: 2 mm

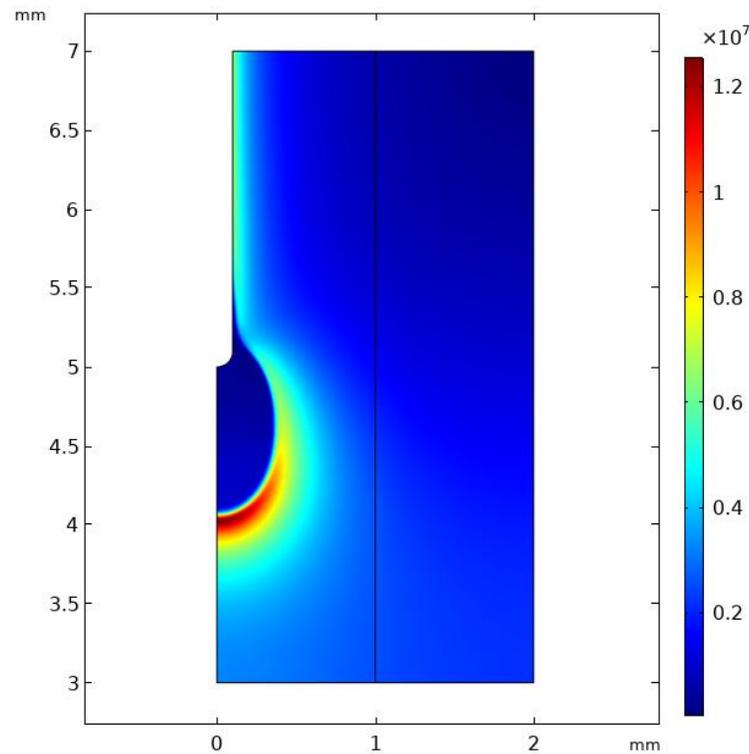
Radius of Curvature: 0.1 mm

Electrode Shape: Fileted

Comparison of Streamer Model in **AFIVO** and **COMSOL**

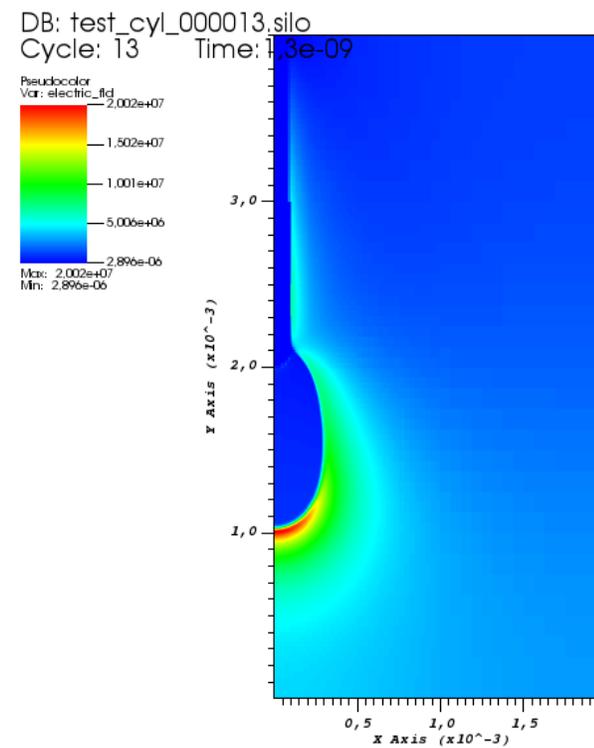
$E_{\text{laplacian}} = 377 (+10)$ kV/cm, $d = 2$ mm, $r_c = 0.1$ mm, $n_{e0} = 1^{e15}$ m⁻³, Photoionization

Cmsol at 2.7 ns



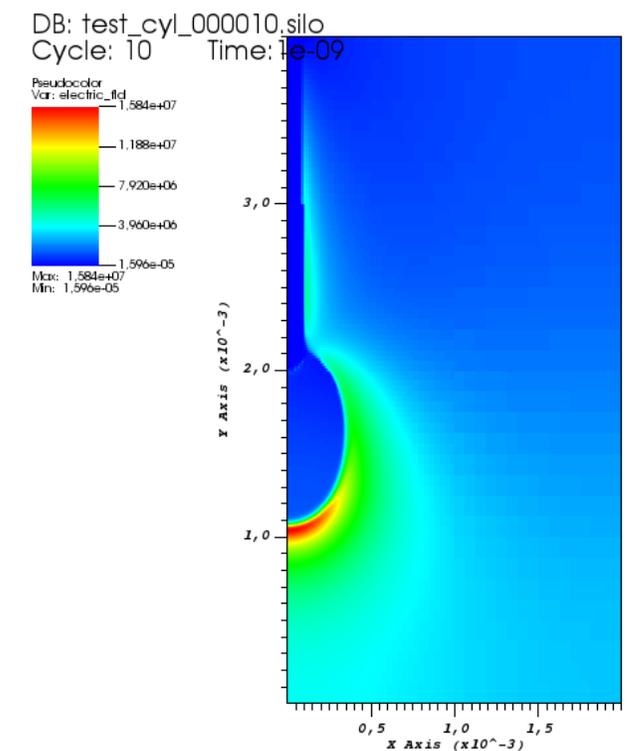
$E_{\text{max}} = 1.25^{e7}$ V/m

Afivo no photo at 1.3 ns



$E_{\text{max}} = 2.0^{e7}$ V/m

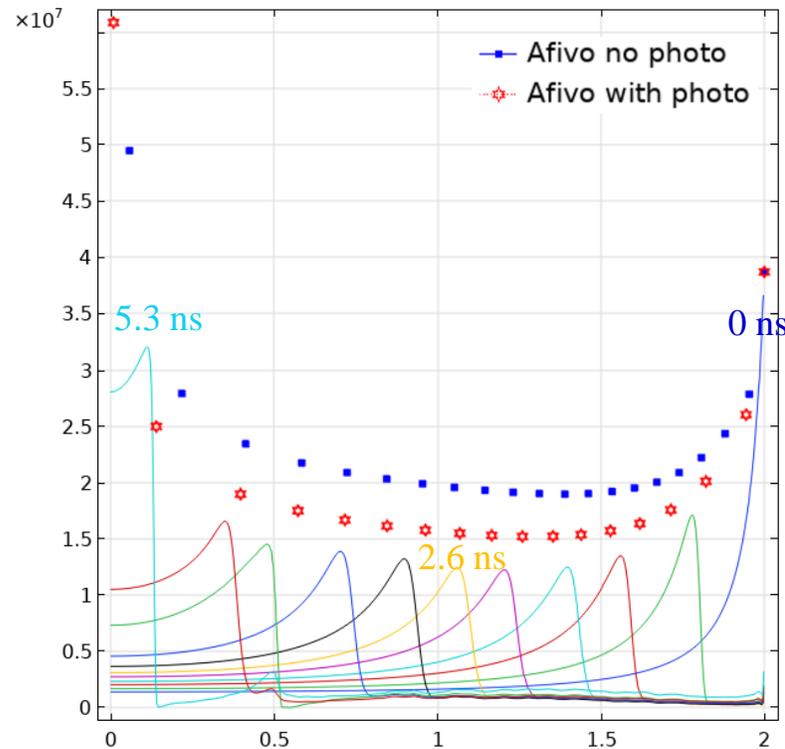
Afivo with photo at 1 ns



$E_{\text{max}} = 1.6^{e7}$ V/m

Comparison of Streamer Model in **COMSOL** and **AFIVO**

$d = 2 \text{ mm}$, $r_c = 0.1 \text{ mm}$, $S_b = 1e23 \text{ (1/m}^3\cdot\text{s)}$ / Photoionization



	COMSOL	AFIVO no photoionization	AFIVO with photoionization
Voltage/ Field Amplitude	6.3 kV	2^6 V/m	2^6 V/m
Electric Field at $t = 0 \text{ ns}$	377 kV/cm	387 kV/cm	387 kV/cm
Electric Field (1 mm)	130 kV/cm	200 kV/cm	158 kV/cm
Streamer Velocity	0.45 mm/ns	0.95 mm/ns	1.18 mm/ns
Streamer Radius (at 1 mm)	0.4 mm	0.3 mm	0.35 mm

- For same electrode configuration and maximum electric field, Afivo is characterized by high fields in the streamer head and thus higher velocities

Comparison: COMSOL vs AFIVO

COMSOL	AFIVO
GUI	Code Based Implementation
Electrode Flexibility	Rigid electrode types
Shorter Gaps, Limited by Computational Power	Longer Gaps Possible
Long Simulation Times	Relatively Shorter Simulation Times

Part 3b: COMSOL Results

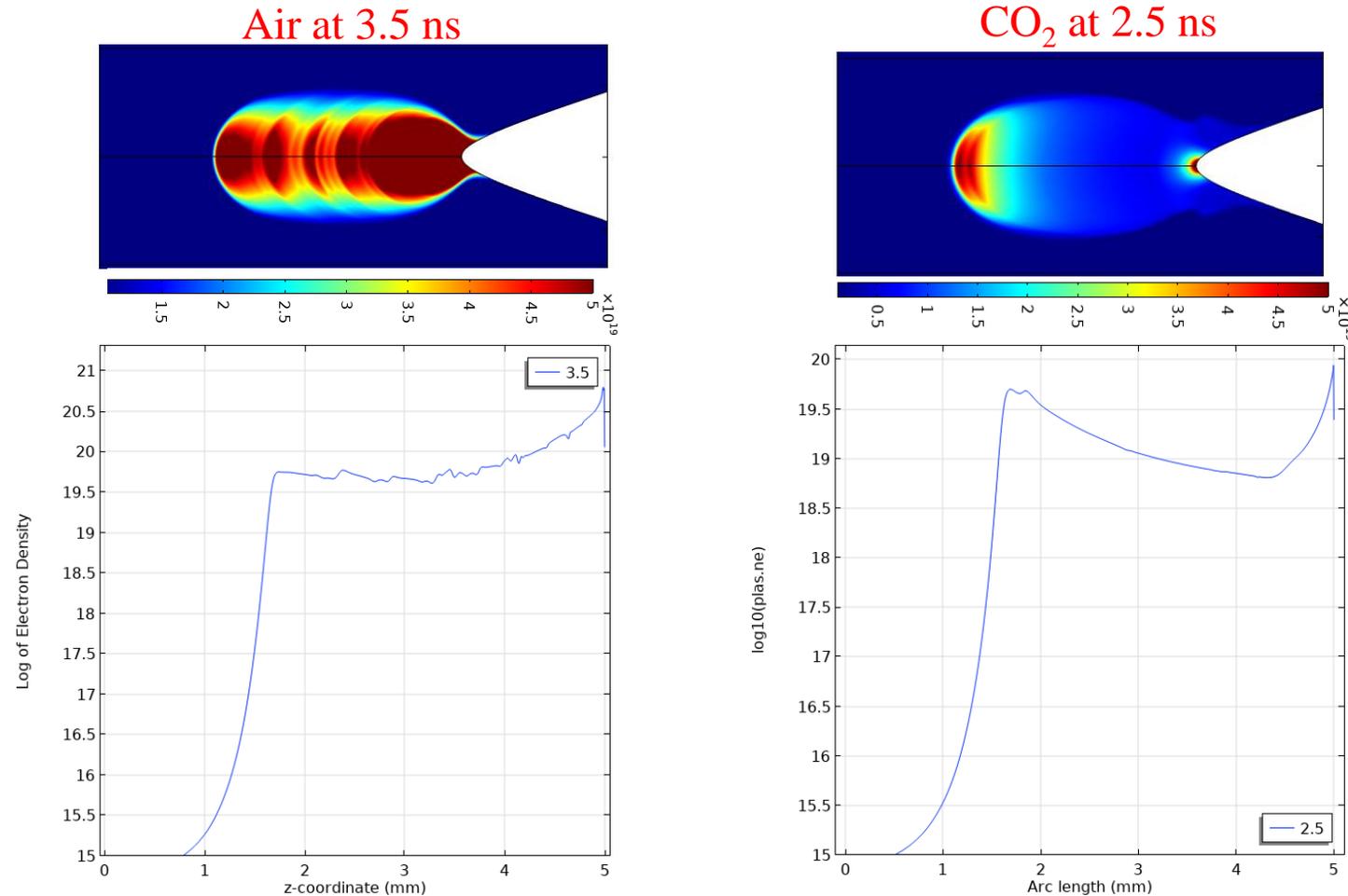
Streamers in Air and CO₂

Radius of curvature: 0.1 mm

Gap Distance: 5 mm

Background Ionization: $S_b = 1e23$ (1/m³.s)

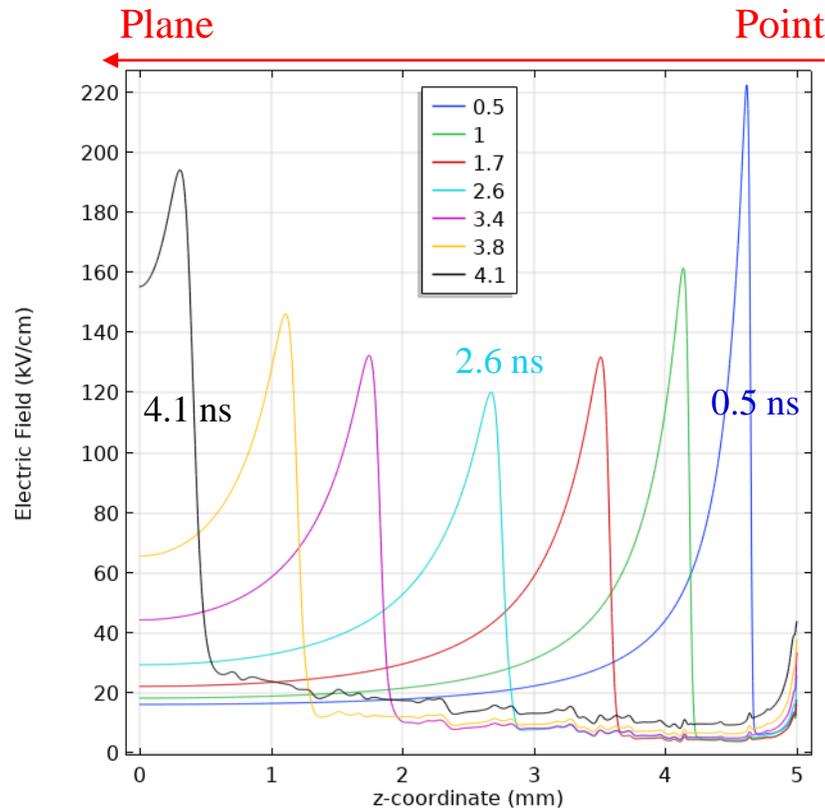
Electron Density Profiles in different gases at Atmospheric Pressure
 $V_0 = +15$ kV, $d = 5$ mm, $rc = 0.1$ mm, $Sb = 1e23$ (1/m³.s)



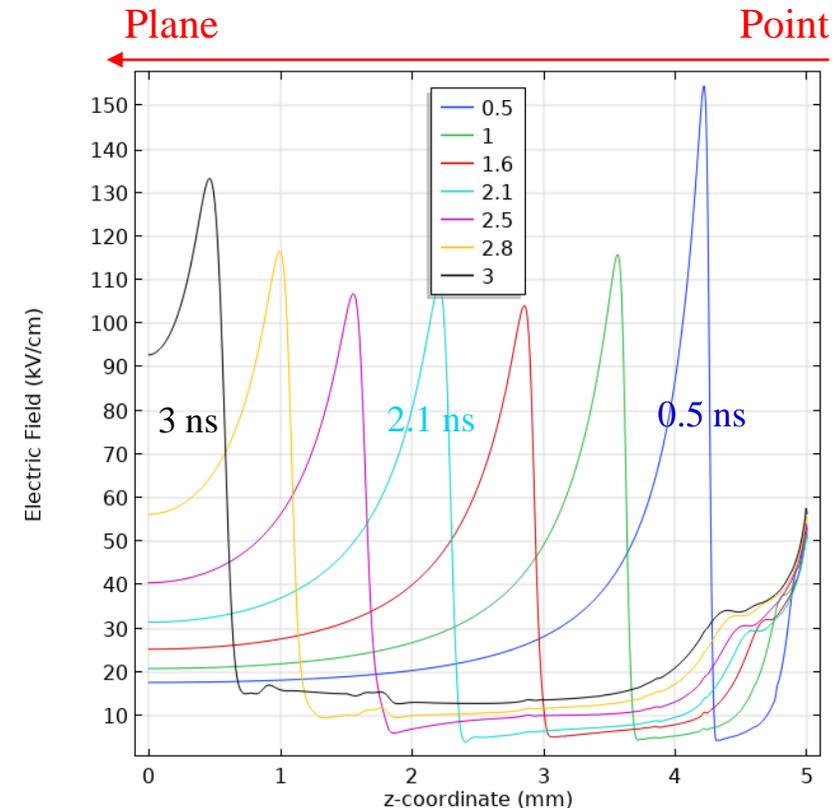
- Loss processes determine the magnitude of electrons in the streamer channel.

Electric Field Distribution for Streamers in Air and CO₂ at Atmospheric Pressure

$V_0 = +15$ kV, $d = 5$ mm, $rc = 0.1$ mm, $Sb = 1e23$ (1/m³.s)



Electric Field Air

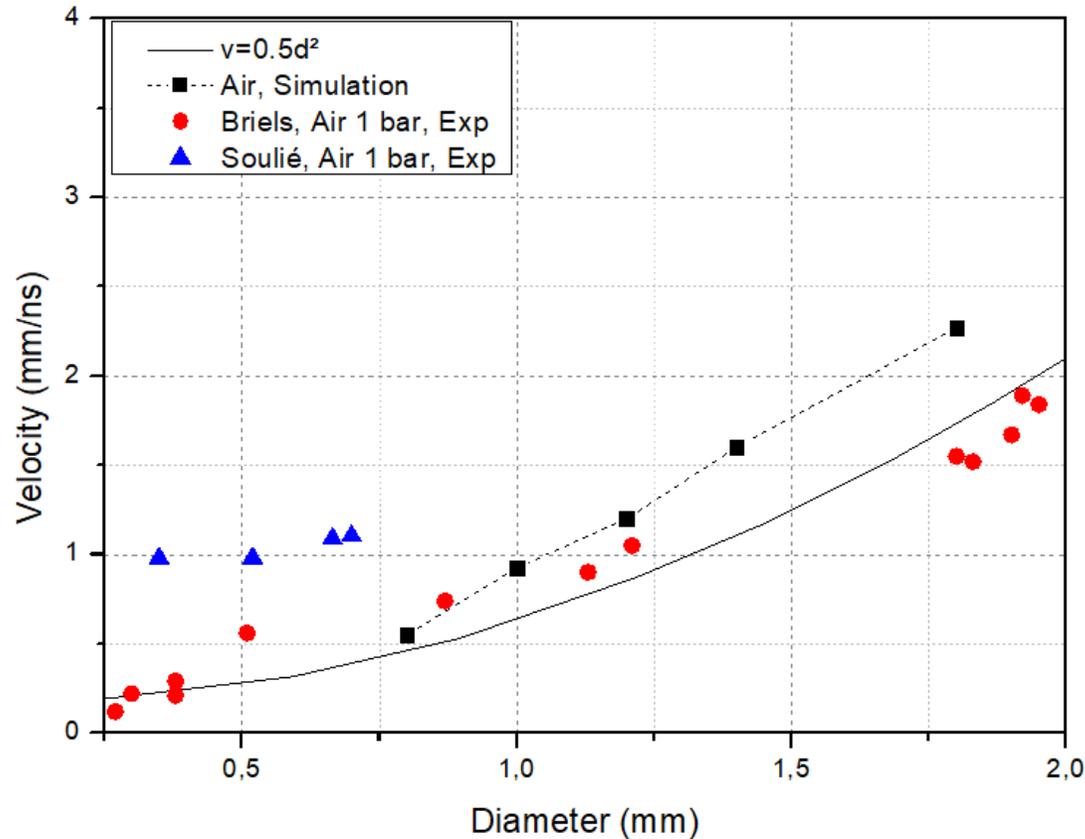


Electric Field CO₂

- Lower electric field in the streamer in CO₂ signifying the ease of propagation in the gas.
 - The computed velocity in CO₂ is 1.6 mm/ns and 1.2 mm/ns in Air

Streamer in Air at 1 bar (COMSOL)

$V_0 = +11$ to 20 kV, $d = 5$ mm, $r_c = 0.1$ mm, $S_b = 1e23$ (1/m³.s)



	COMSOL	BRIELS	SOULIE
Needle Radius (μm)	100	15	200
Gap Distance (mm)	5	40	50
Voltage Range (kV)	11 – 20	5 – 96	38 – 68
Voltage Type	Instantaneous	Pulsed	Lightning Pulse
Rise Time (ns)	–	15 – 150	800

- Correlation between simulation results and experimental results from Briels.
- The deviation between the results of Soulié and the simulation results ???

Part 3c: **AFIVO** Results

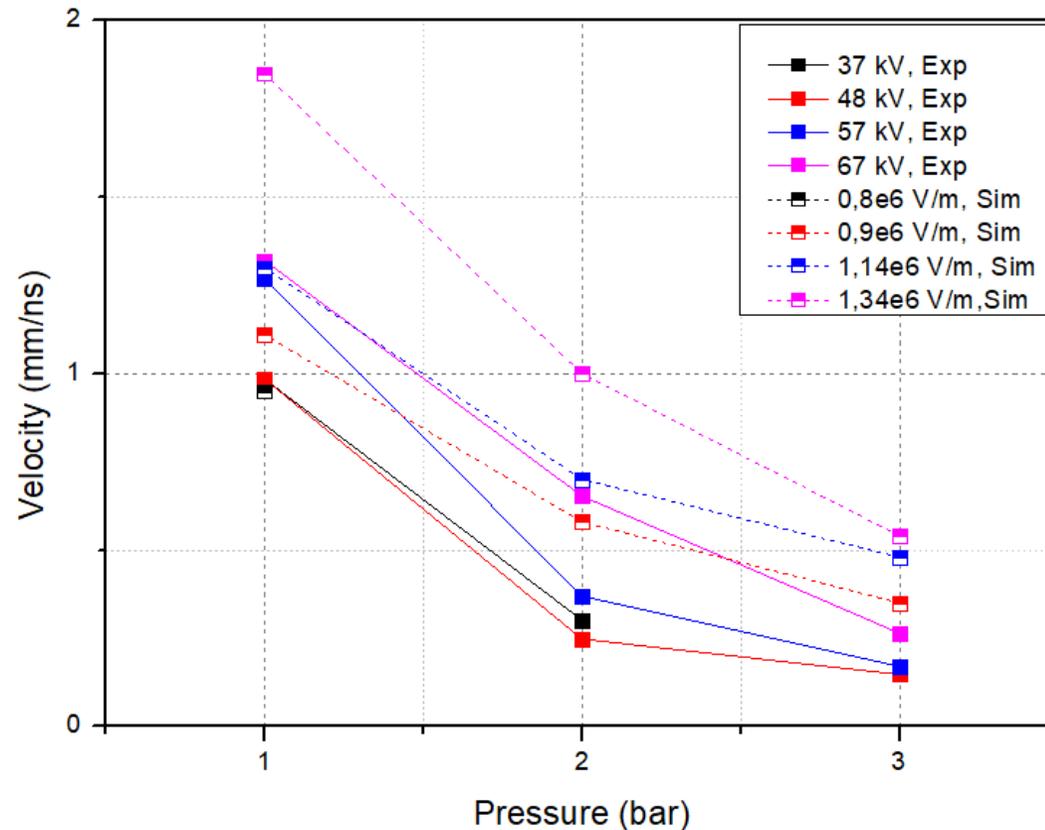
Experimental Comparison of Streamers in Air and CO₂

Gap Distance: 50 mm

Radius of Curvature: 0.2 mm, 0.5 mm

Influence of Pressure on Streamer in Air for longer gaps (AFIVO)

$d = 50 \text{ mm}$, $rc = 0.2 \text{ mm}$, Photoionization model present

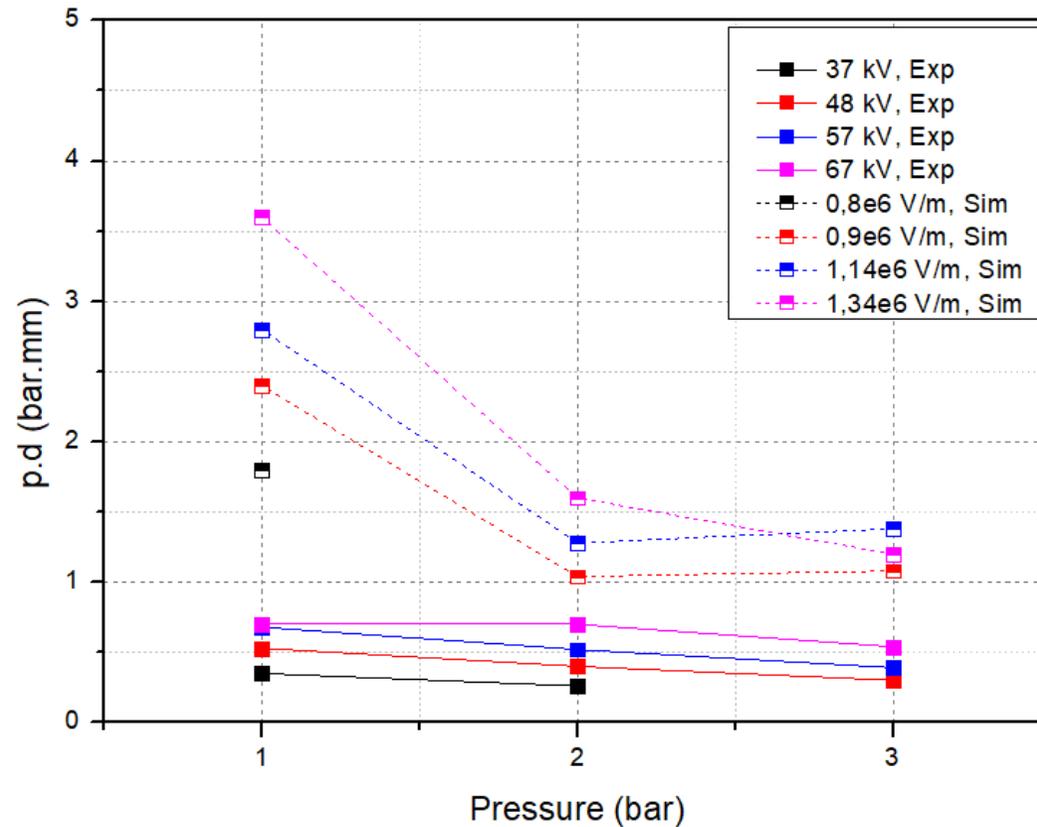


	AFIVO	SOULIE
Needle Radius (μm)	200	200
Gap Distance (mm)	50	50
Voltage Range (kV)	40 – 87	37 – 87
Voltage Type	Instantaneous	Lightning Pulse
Rise Time (ns)	–	800

- Simulation and experimental comparison of velocity with increasing pressure.
 - At atmospheric pressure, streamer velocity is $\sim 1 \text{ mm/ns}$.

Influence of Pressure on Streamer in Air in longer gaps (**AFIVO**)

d = 50 mm, rc = 0.2 mm, Photoionization model present

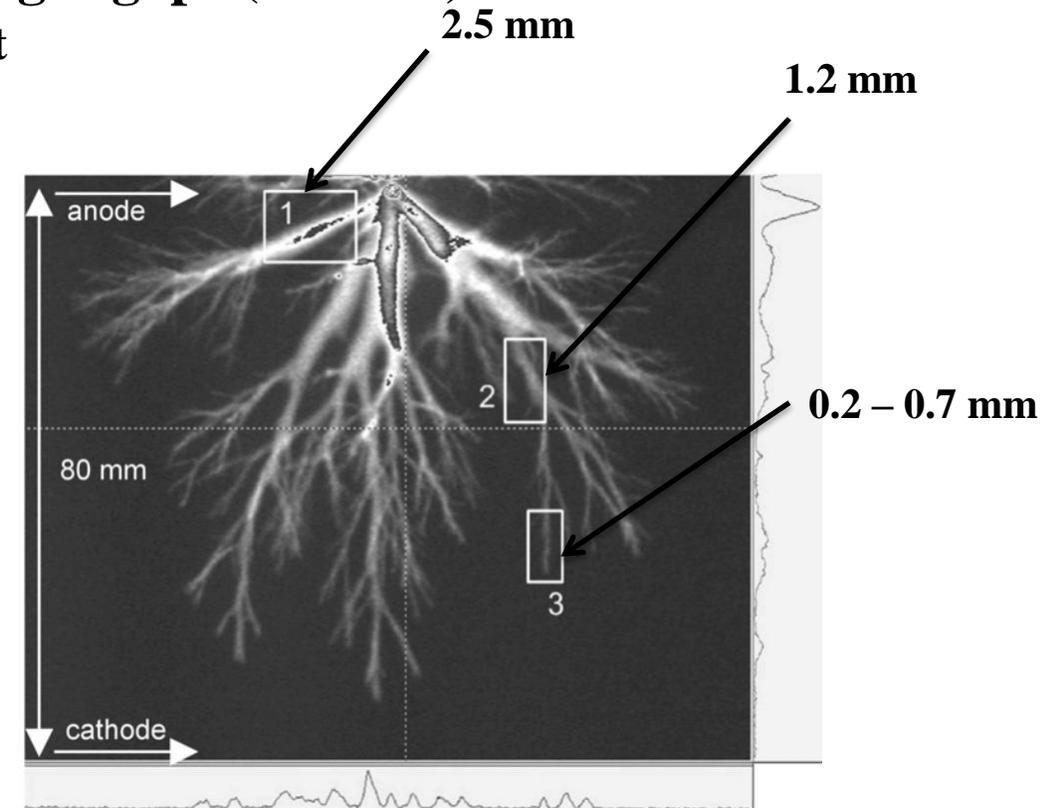
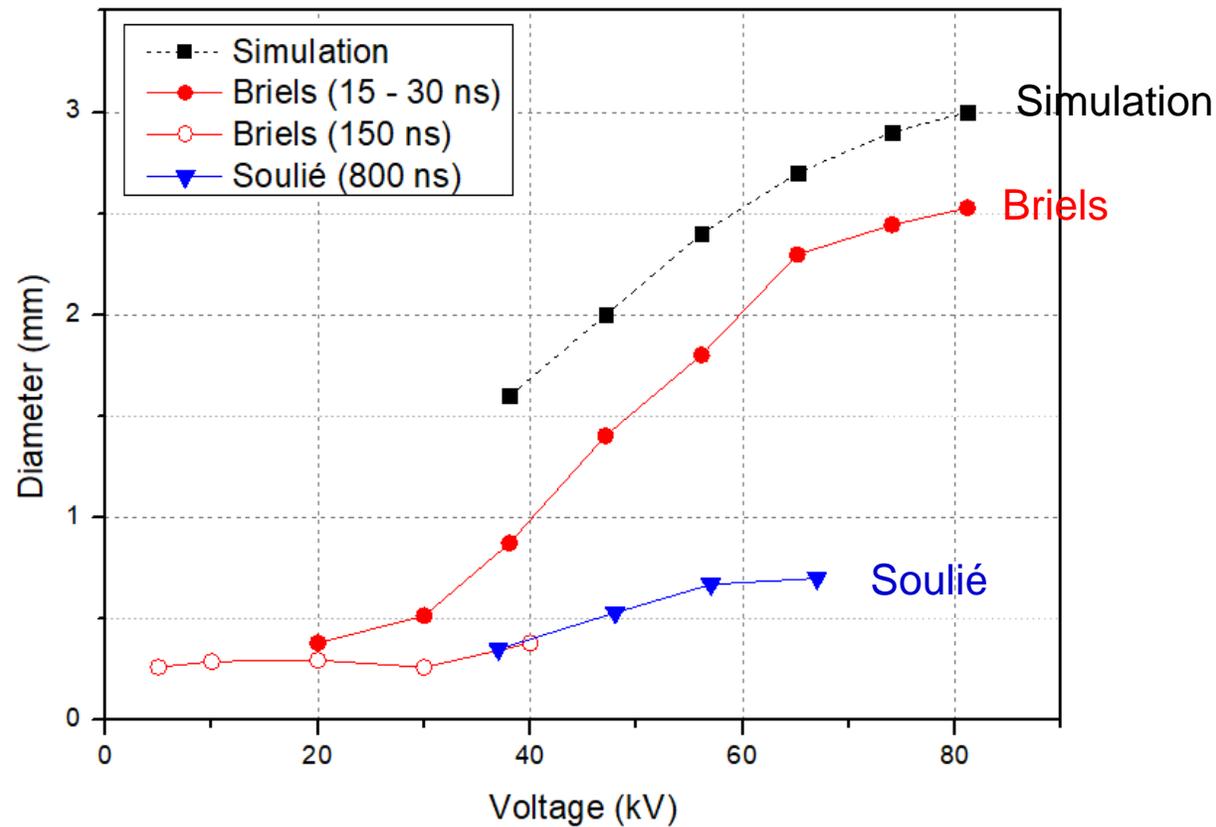


	AFIVO	SOULIE
Needle Radius (μm)	200	200
Gap Distance (mm)	50	50
Voltage Range (kV)	40 – 87	37 – 87
Voltage Type	Instantaneous	Lightning Pulse
Rise Time (ns)	–	800

- Simulation and experimental comparison of reduced diameter with pressure.
 - Higher diameters realised in simulations.

Influence of Pressure on Streamer in Air in longer gaps (AFIVO)

$d = 40 \text{ mm}$, $r_c = 0.15 \text{ mm}$, Photoionization model present



Courtesy: Briels 2008

- Diameter highly dependent on rise time of voltage, where and how it is measured.

- On summarising:
 - ✓ Plasma fluid model for streamer discharges in air for short gaps in COMSOL.
 - ✓ Applied voltage has a direct proportionality on streamer diameter and propagation velocity.
 - ✓ Consistency between simulation results and empirical computations for diameter and velocity.
 - ✓ Model validation, COMSOL: <https://hal.archives-ouvertes.fr/hal-02966589/document>
 - ✓ AfivoStreamer used for long gap simulations.
 - ✓ Density has inverse proportionality effect on velocity and diameter as the electric field in the head required to sustain the propagation increases.
 - ✓ Repository for AfivoStreamer: <https://gitlab.com/MD-CWI-NL/afivo-streamer>
- Perspectives
 - ❑ Streamers in Air/CO₂ mixtures



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