Formation and propagation of streamers in gas

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RD51 Collaboration Meeting - 11/03/2016 - CERN

Notice

http://e-collection.library.ethz.ch/view/eth:6303

This work was (more than) inspired by a simulation of Paulo Fonte of streamers

With one fundamental difference: formation and propagation of streamers rely on electron diffusion only

P. Fonte computed the diffusion assisted streamer too (and before)

https://indico.cern.ch/event/89325/session/0/contribution/16/attachments/1089488/1554083/Calculation_of_streamer_development.pdf
Nice talks and references

Introduction

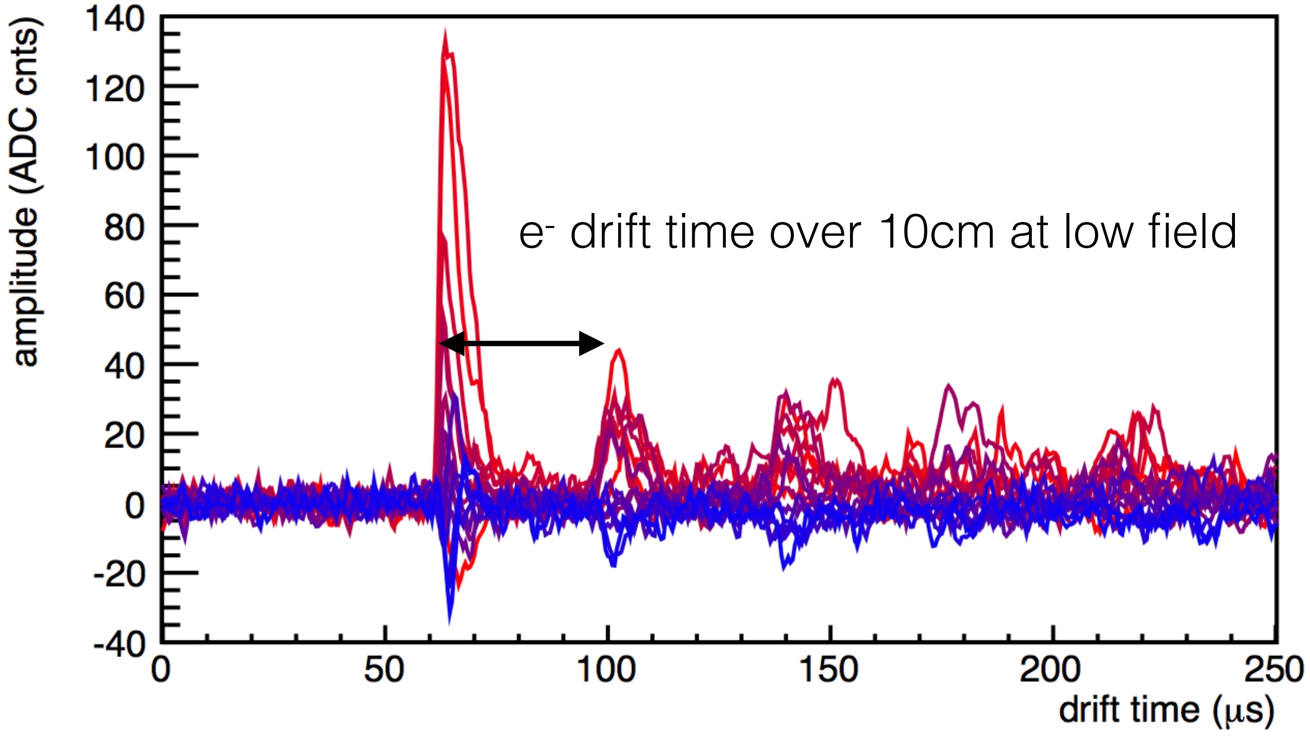
Discharge is a generic term associated to a specific class of problems in gaseous detectors

Several kind of discharges:
Corona, Glow, Paschen, Arc, Streamer, …

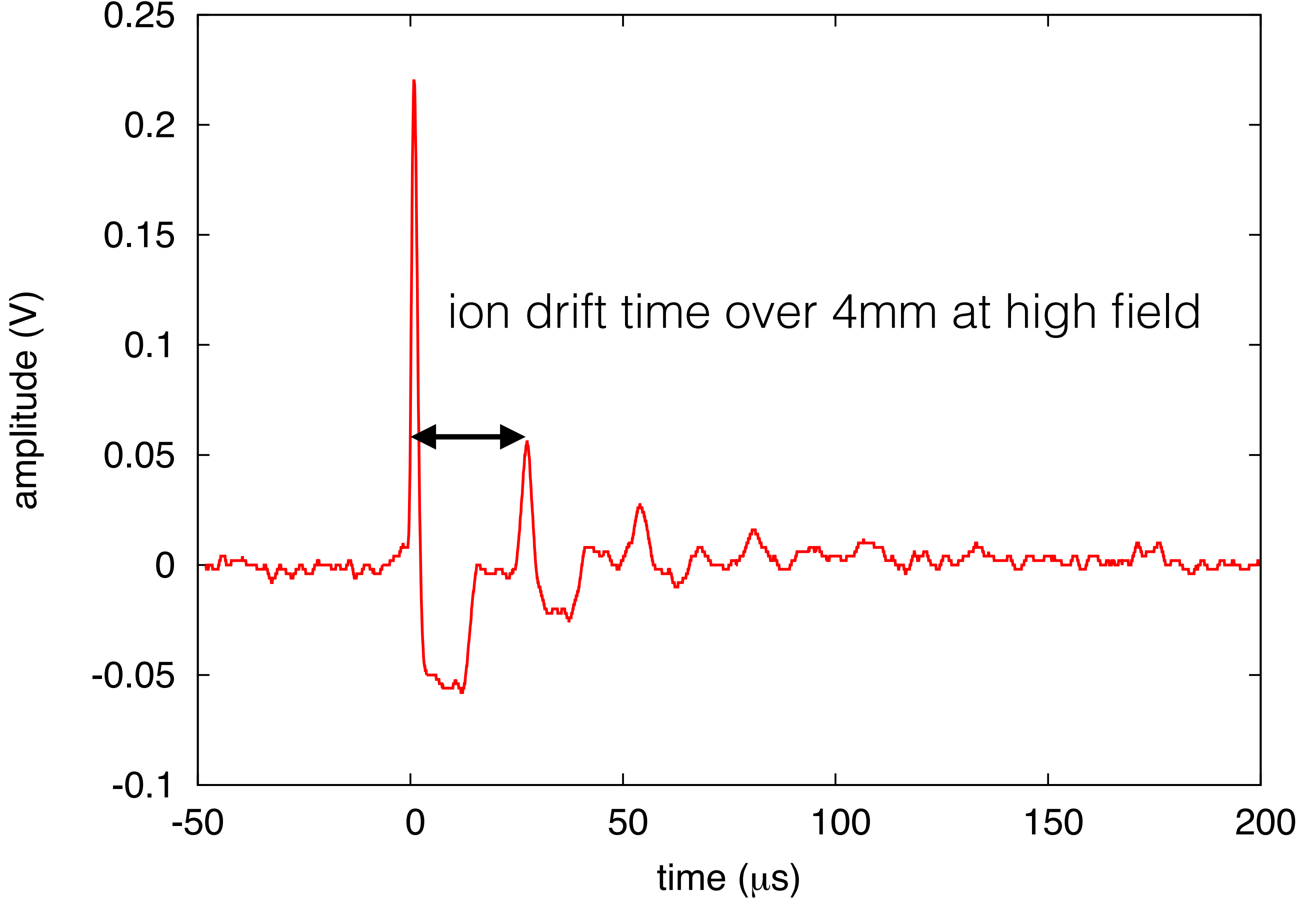
Each manifesting in *specific* situations and having distinct characteristics

À la Paschen

Photon feedback:
Exposed electrodes
in pure argon



Ion feedback:
Low pressure
quenched gas



Current diverges if next peak larger than the previous

Typically: event induced, increase of currents, **slow**

Streamer

Most relevant discharge (or discharge ignition) type for gaseous detectors in normal operation (personal opinion)

Sudden and **fast** (ns) evolution

Propagation also towards the cathode

Possibly with a precursor

Streamer

Driven by electric field distortions due to large charge densities (Raether)

Rely on gas photo-ionisation and electron drift and diffusion

Hereafter photo-ionisation is neglected: computation developed for pure argon, where scintillation photons are not able to ionise argon atoms

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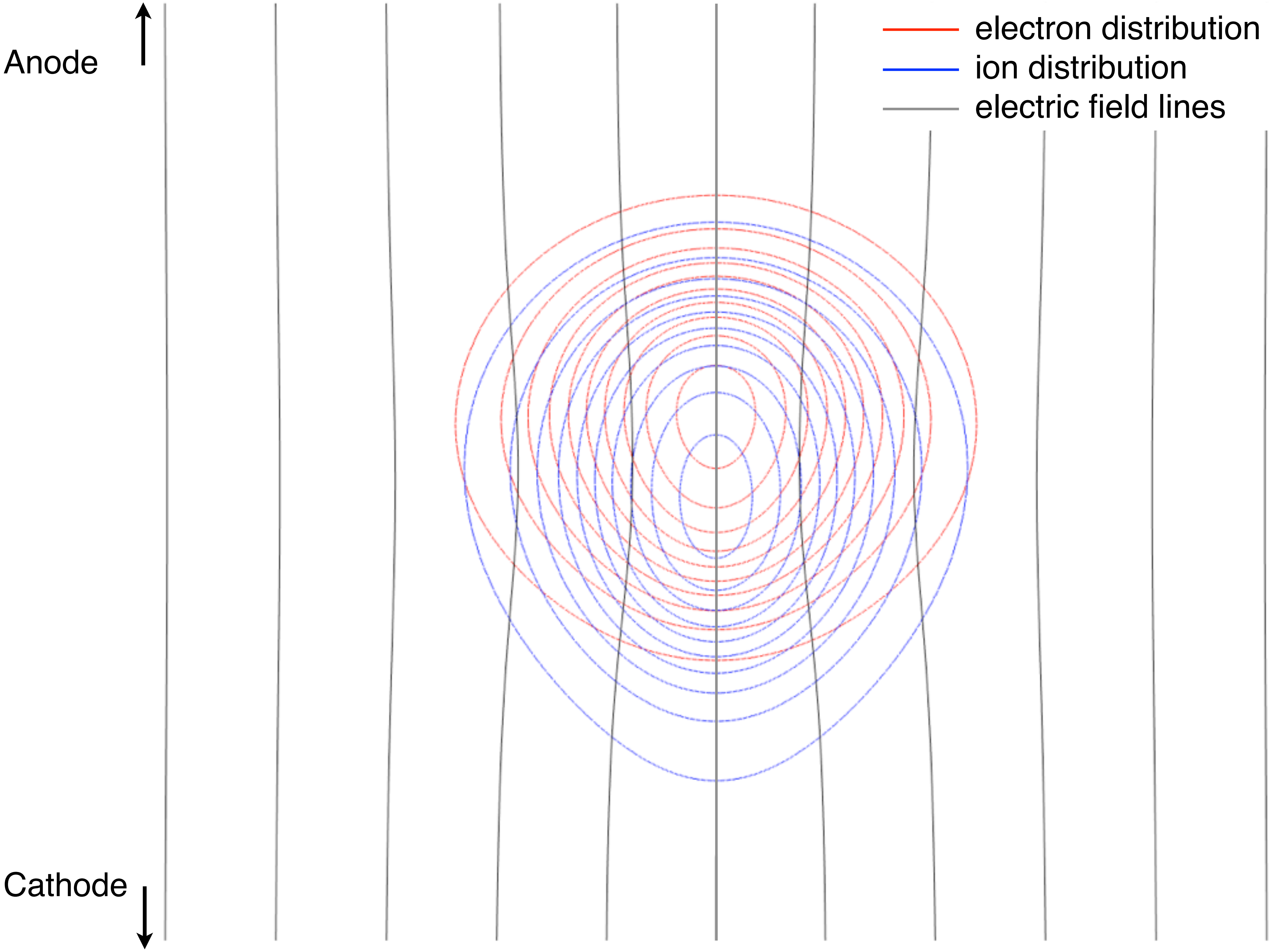
Streamer



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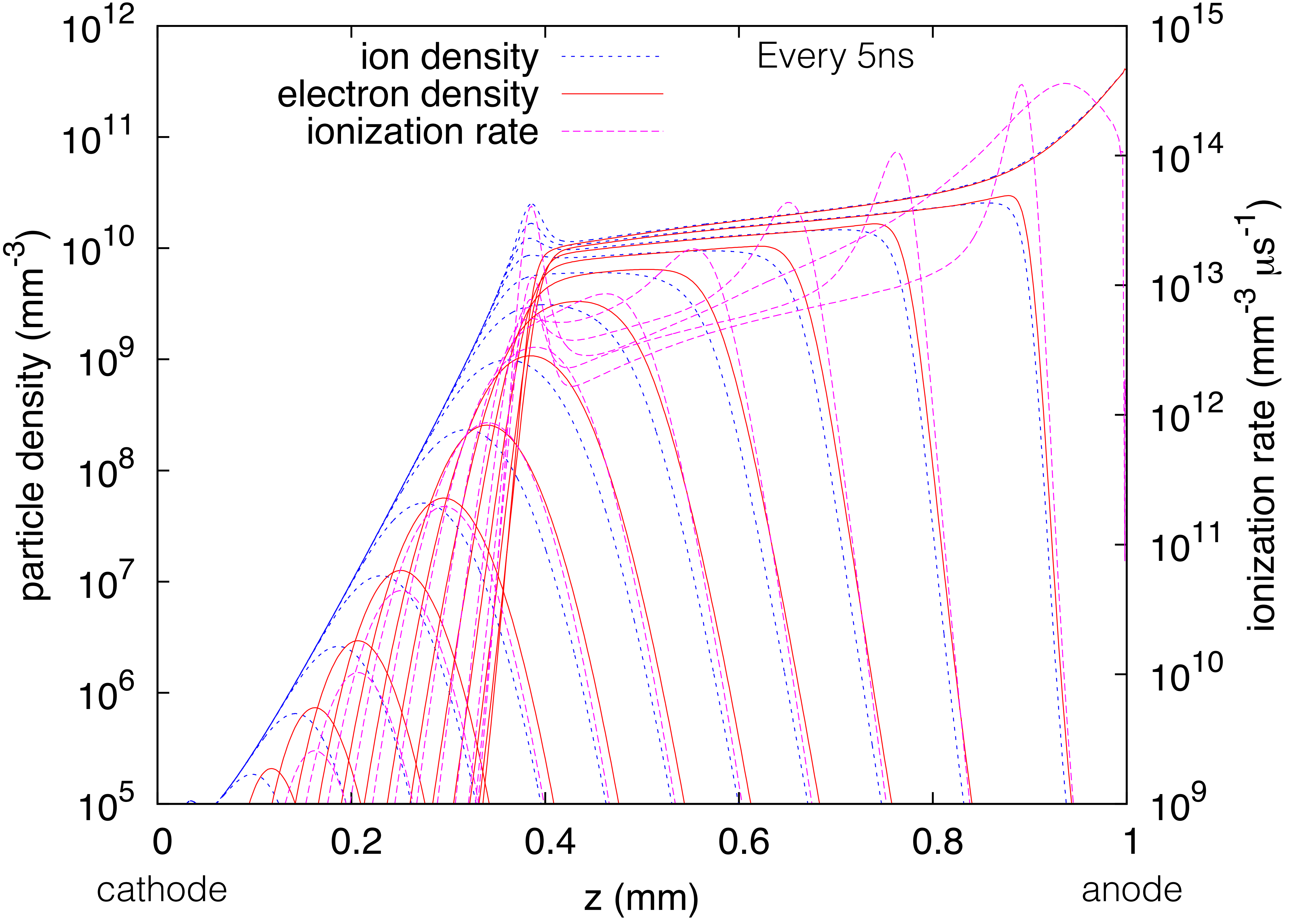
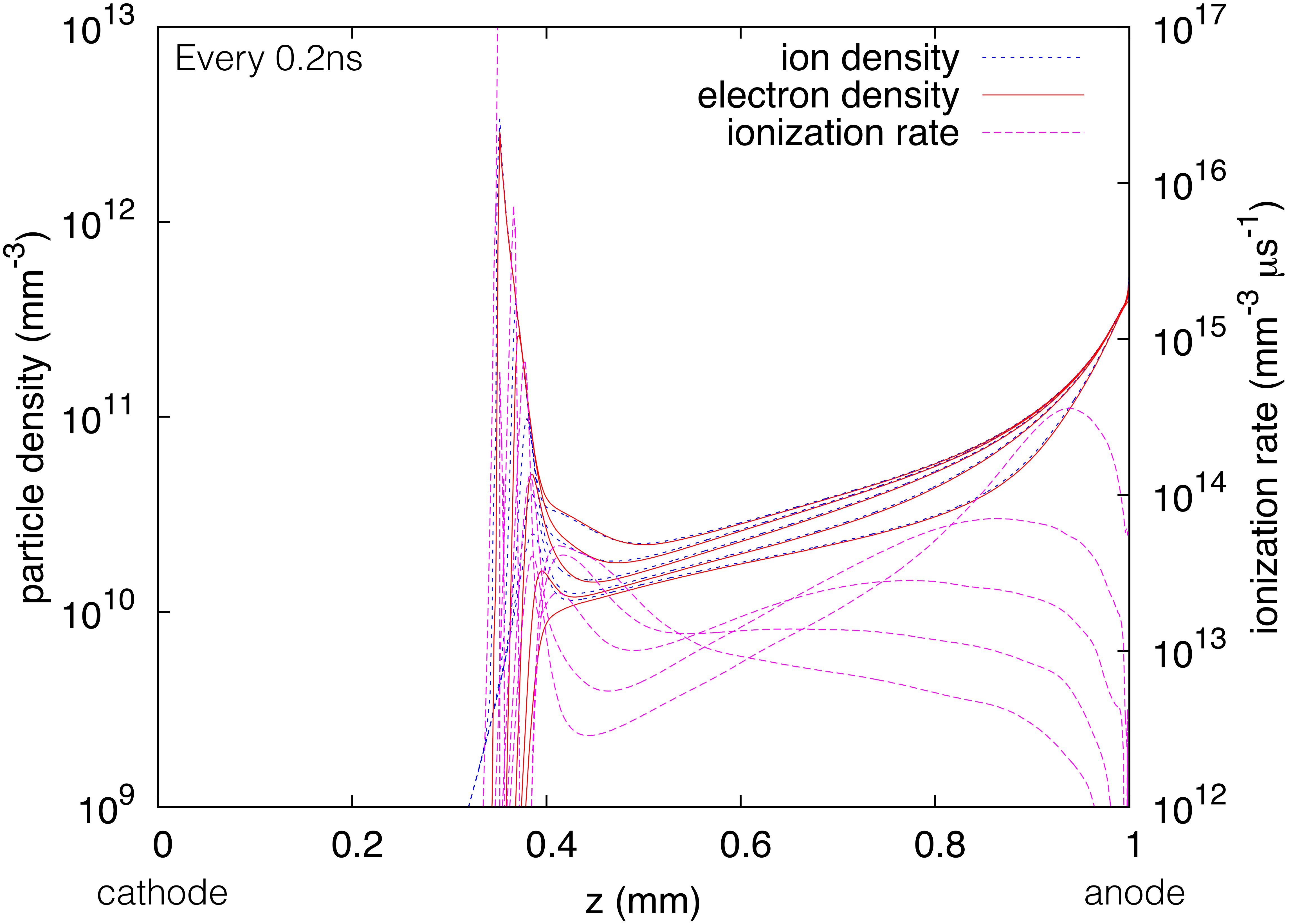
Streamer



Streamer


Every 0.2ns
ion density
electron density
ionization rate
particle density (mm^{-3})
ionization rate (mm^{-3} μs^{-1})
10^{13}
10^{12}
10^{11}
10^{10}
10^{9}
10^{17}
10^{16}
10^{15}
10^{14}
10^{13}
10^{12}
0
0.2
0.4
0.6
0.8
1
cathode
z (mm)
anode

The model

$$\vec{\nabla} \cdot \epsilon \vec{\nabla} V = -q_e(\rho_i - \rho_n - \rho_e)$$

$$\frac{\partial \rho_e}{\partial t} = \alpha |\vec{W}_e| \rho_e - \eta |\vec{W}_e| \rho_e - K \rho_i \rho_e - \vec{\nabla} \cdot (\vec{W}_e \rho_e - D_e \vec{\nabla} \rho_e)$$

$$\frac{\partial \rho_i}{\partial t} = \alpha |\vec{W}_e| \rho_e - K \rho_i \rho_e - \vec{\nabla} \cdot (\vec{W}_i \rho_i - D_i \vec{\nabla} \rho_i)$$

$$\frac{\partial \rho_n}{\partial t} = \eta |\vec{W}_e| \rho_e - \vec{\nabla} \cdot (\vec{W}_n \rho_n - D_n \vec{\nabla} \rho_n)$$

Unknowns: V, ρ_e, ρ_i, and ρ_n

Input (field dependent): α, η, K, D_x, W_x

It can be made more complete and complex, but

The model

$$\vec{\nabla}\cdot\epsilon\vec{\nabla}V = -q_e(\rho_i - \cancel{\rho_n} - \rho_e)$$

$$\frac{\partial\rho_e}{\partial t} = \alpha|\vec{W}_e|\rho_e - \eta|\vec{W}_e|\rho_e - \cancel{K\rho_i\rho_e} - \vec{\nabla}\cdot(\vec{W}_e\rho_e - D_e\vec{\nabla}\rho_e)$$

$$\frac{\partial\rho_i}{\partial t} = \alpha|\vec{W}_e|\rho_e - \cancel{K\rho_i\rho_e} - \vec{\nabla}\cdot(\vec{W}_i\rho_i - \cancel{D_i\vec{\nabla}\rho_i})$$

$$\cancel{\frac{\partial\rho_n}{\partial t} = \eta|\vec{W}_e|\rho_e - \vec{\nabla}\cdot(\vec{W}_n\rho_n - D_n\vec{\nabla}\rho_n)}$$

Unknowns: V, ρ_e, and ρ_i

COMSOL

Finite Element Analysis software able to find an approximate solution for a coupled system of PDEs on an (almost) arbitrary (3D, 2D, and 1D) mesh

Coefficients are arbitrary

$$\underset{\text{mass}}{e_a}\frac{\partial^2 u}{\partial t^2} + \underset{\text{damping}}{d_a}\frac{\partial u}{\partial t} + \nabla\cdot(-\underset{\text{diffusion}}{c}\nabla u - \underset{\substack{\text{conservative}\\\text{convection}}}{\alpha} u + \underset{\substack{\text{flux}\\\text{source}}}{\gamma}) + \overset{\text{convection}}{\beta}\cdot\nabla u + \underset{\text{absorption}}{a}u = \overset{\text{source}}{f}$$

Approximations

Absence of gas photo-ionisation

Atoms are ionised only once

No impurities/contaminants

Potentials at the electrodes are constant

Approximations

Single hole in axial symmetric geometry

Dynamic equilibrium of the charging up

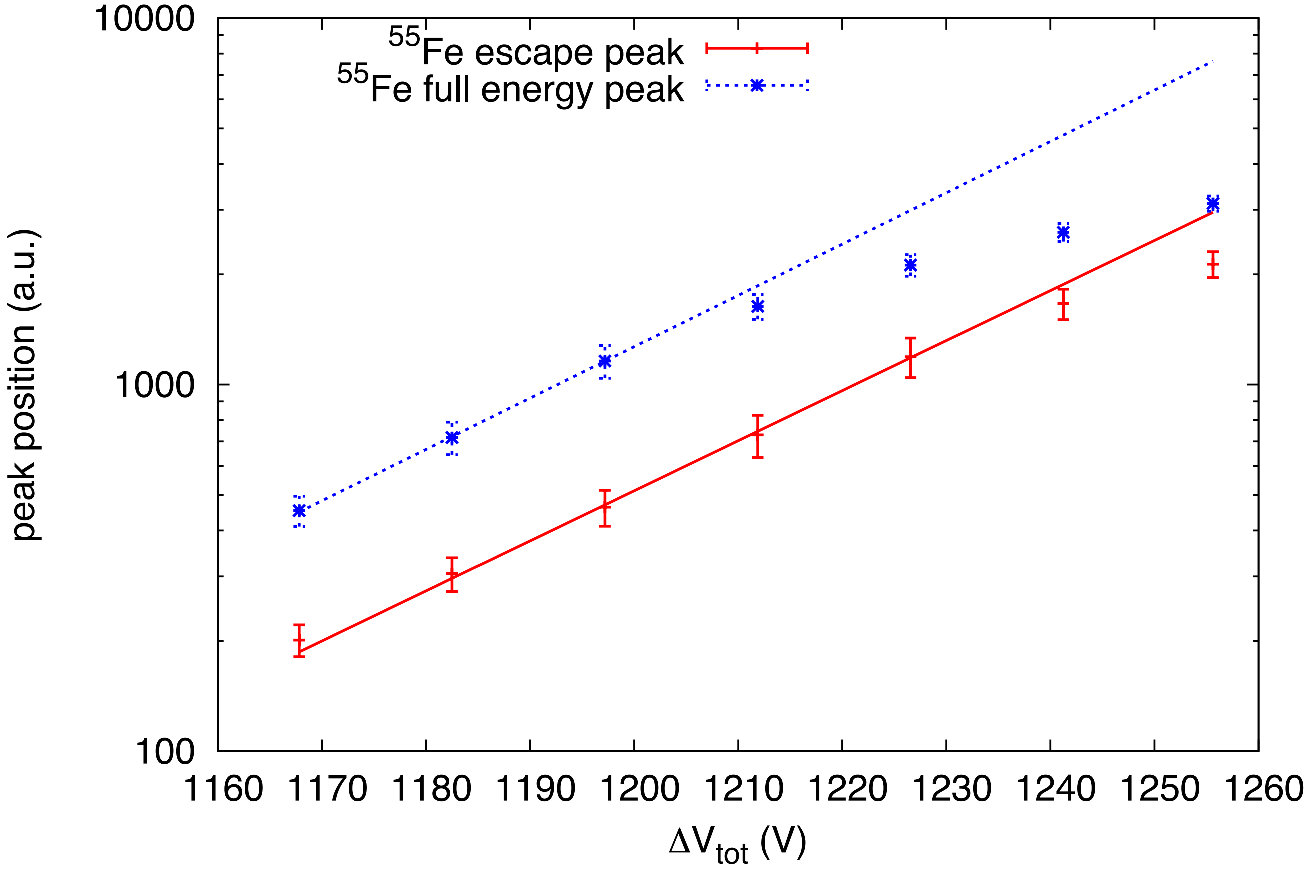
Electric field smooth enough

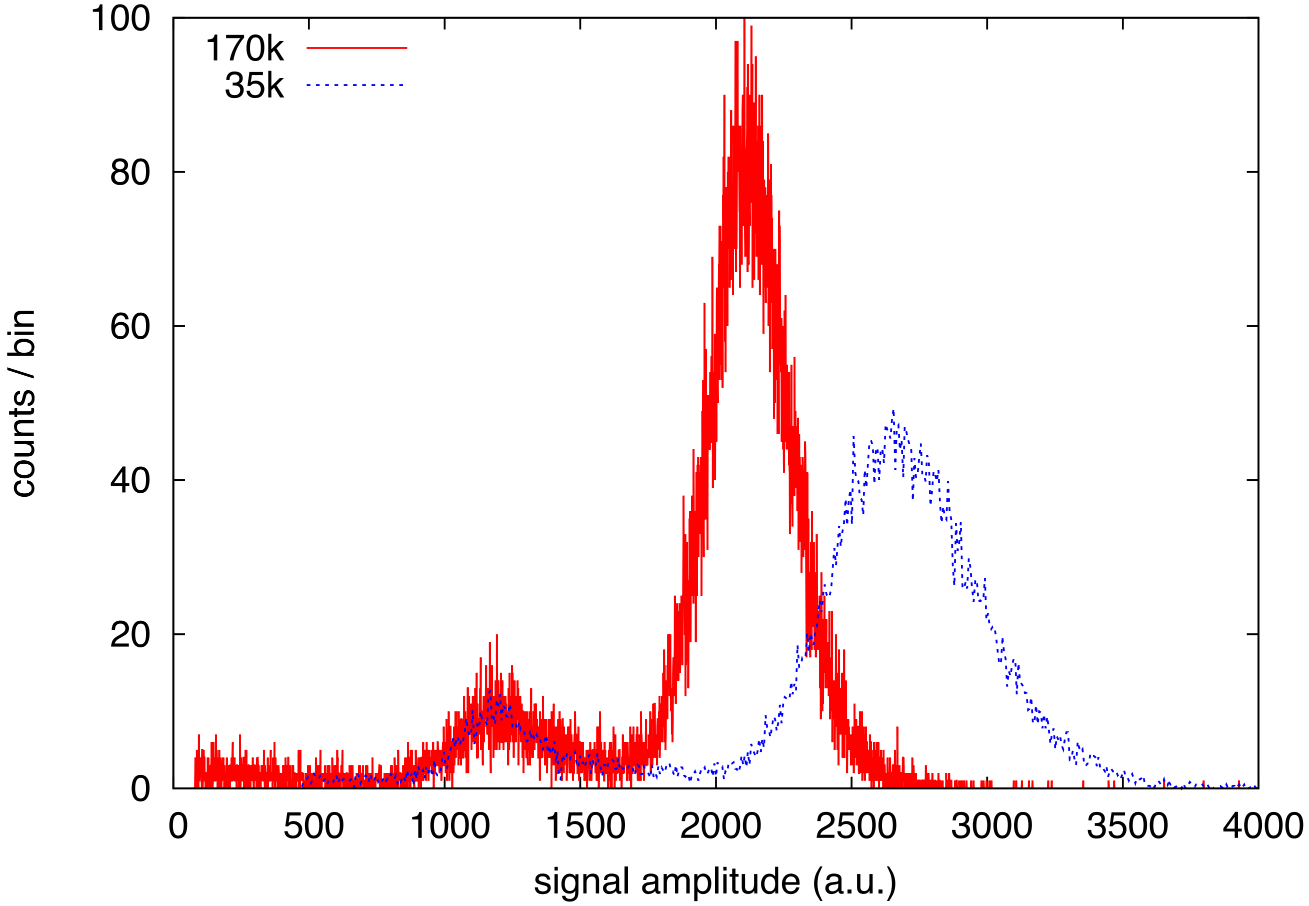
Perfect hole with no defects

No stochastic process: *average* streamer arXiv:1512.04968

Amplification and saturation

Triple GEM data



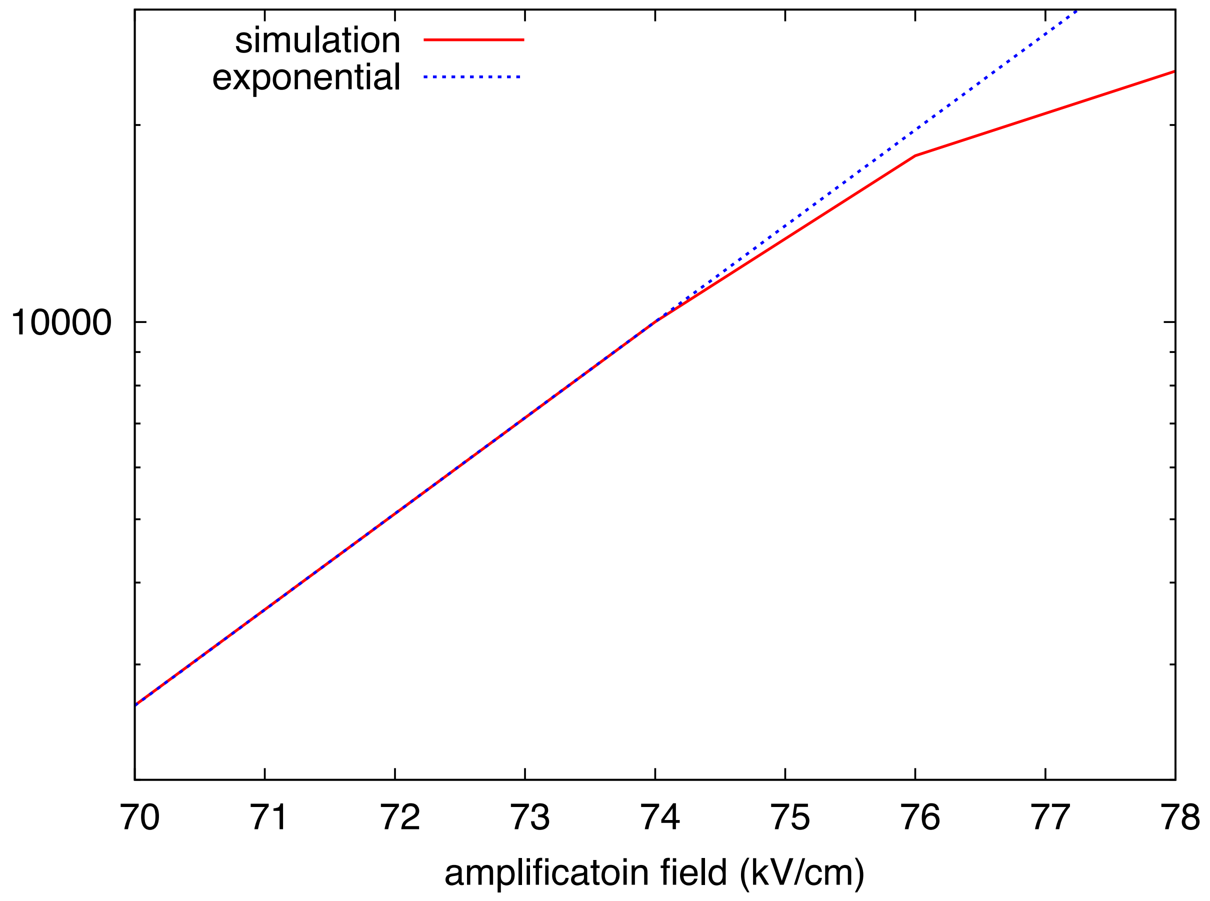


Saturation: deviation from the exponential
Saturation involves the full energy peak first
Prelude of a discharge

Each avalanche quenches its growth
Resolution *improves*:
large avalanches cannot grow,
small avalanches can still grow

Amplification and saturation

Simulation of a single avalanche in a GEM

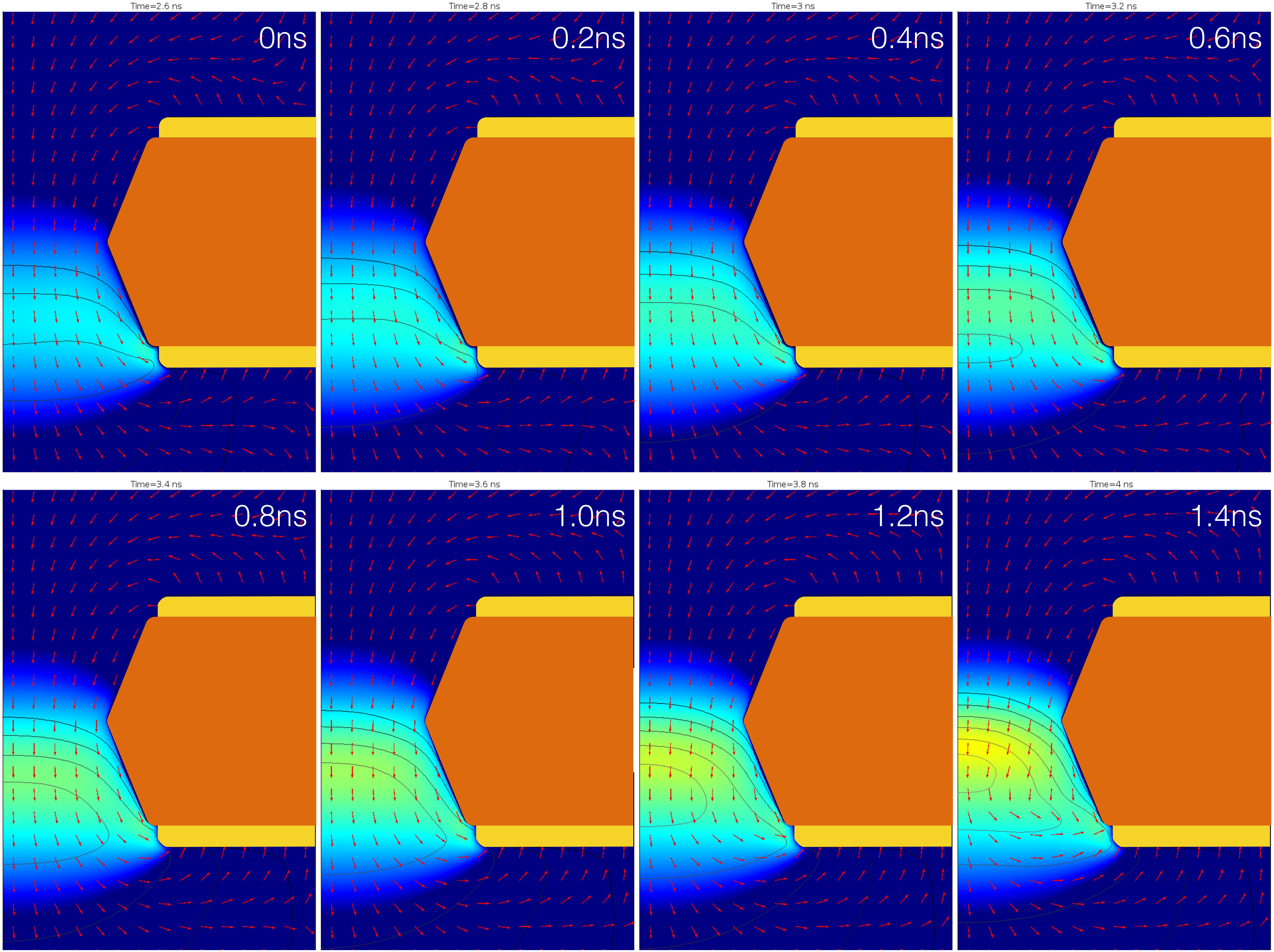


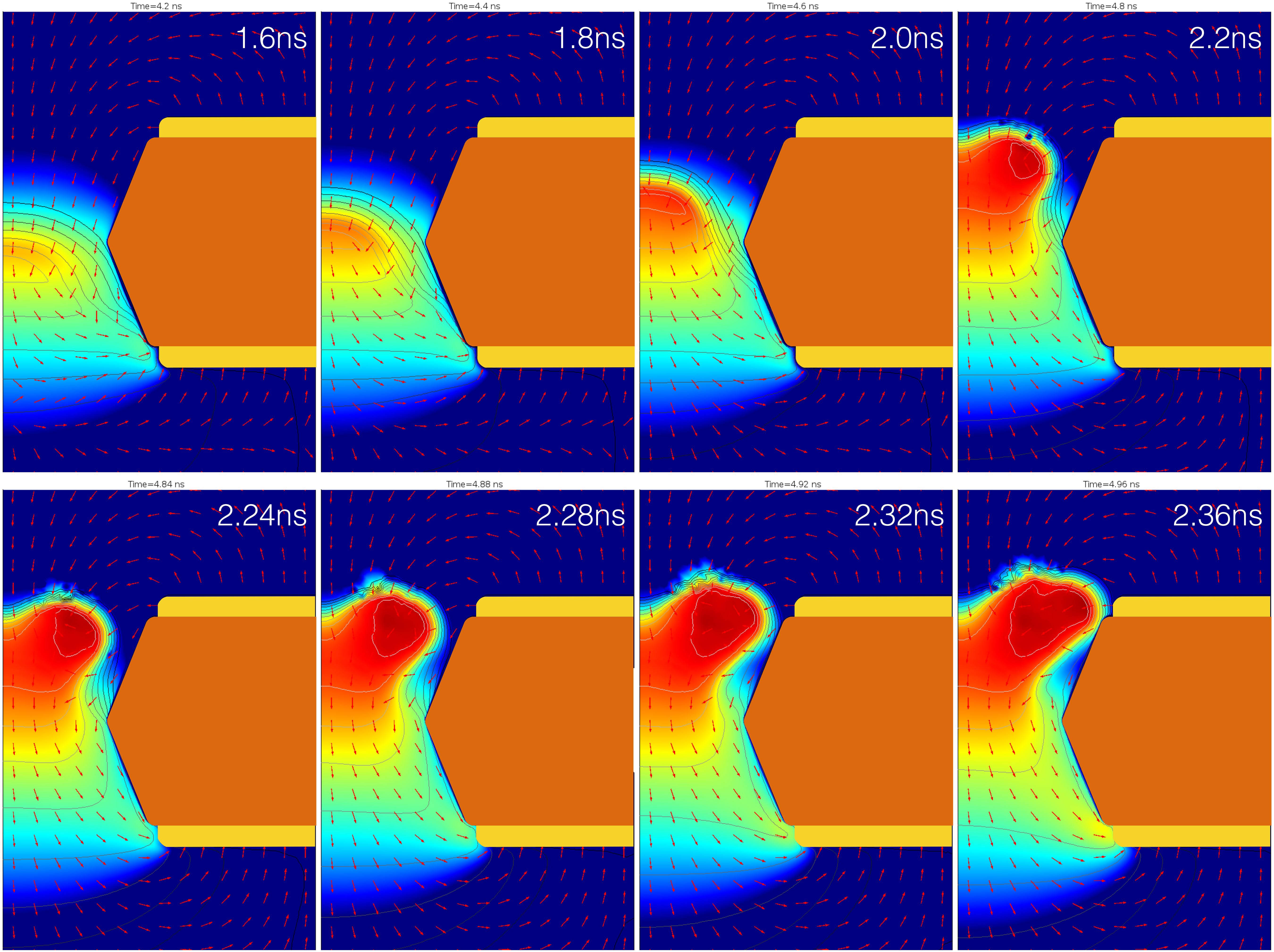
Ions moving towards the entrance of the hole reduce the amplification field affecting the multiplication of the forthcoming electrons

Within the same computation framework, the saturation is *qualitatively* reproduced

Absolute gain mismatch is related to e^- diffusion in several holes, not included in the computation

There is a maximum achievable gain in simulation too…


Time=2.6 ns
0ns
Time=2.8 ns
0.2ns
Time=3 ns
0.4ns
Time=3.2 ns
0.6ns
Time=3.4 ns
0.8ns
Time=3.6 ns
1.0ns
Time=3.8 ns
1.2ns
Time=4 ns
1.4ns


Time=4.2 ns
1.6ns
Time=4.4 ns
1.8ns
Time=4.6 ns
2.0ns
Time=4.8 ns
2.2ns
Time=4.84 ns
2.24ns
Time=4.88 ns
2.28ns
Time=4.92 ns
2.32ns
Time=4.96 ns
2.36ns

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Observations

LEM geometry in pure argon

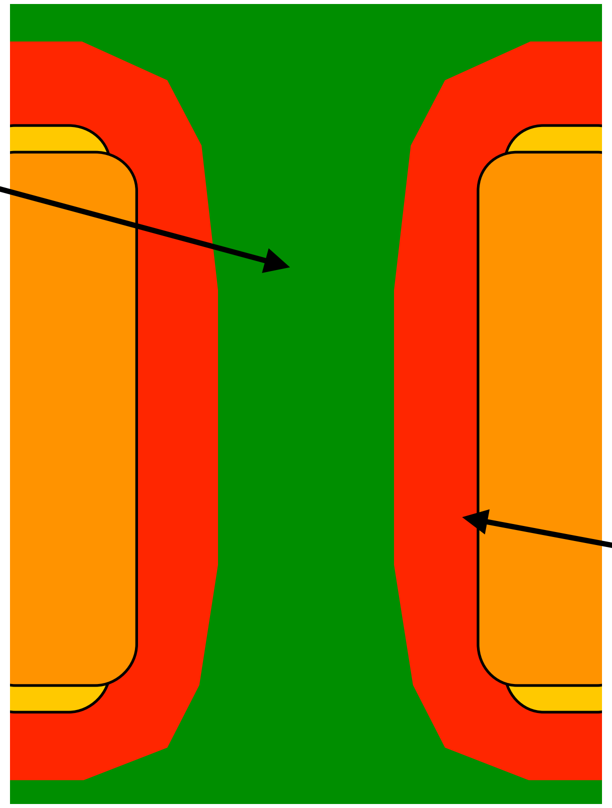
n_e^0	E_0 (kV/cm)	n_{ion}
10	23.8	1.67×10^7
100	22.5	1.68×10^7
1000	21.1	1.71×10^7

Discharge occurrence

The spark limit is well defined by the total ion/electron pairs (per hole) produced in agreement with the Raether limit (gas and geometry dependent)

Observations

LEM geometry in pure argon



Low gain region:
amplification region

High gain region:
streamer region

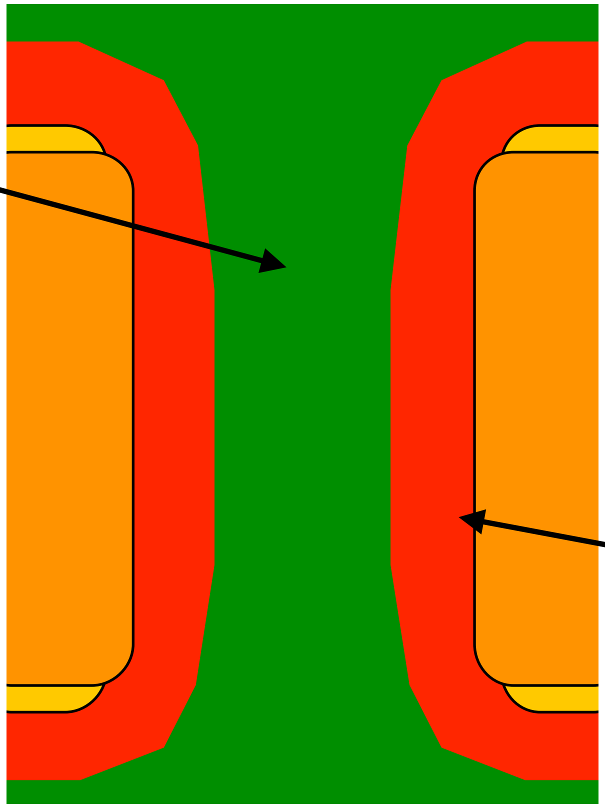
Gain in the amplification region limited by discharge in the streamer region

rim (μm)	E_0 (kV/cm)	E_{max} (kV/cm)	G
30	22.2	73.9	1.86×10^5
50	22.9	69.3	3.13×10^5
70	23.4	67.0	4.20×10^5

Increasing the rim: decrease of the maximum field

Observations

LEM geometry in pure argon



Low gain region:
amplification region

High gain region:
streamer region

Gain in the amplification region limited by discharge in the streamer region

dielectric (mm)	E_0 (kV/cm)	G
1.0	22.9	3.13×10^5
0.8	25.3	1.20×10^5
0.6	29.3	3.86×10^4

Decreasing the thickness: worsening the field uniformity

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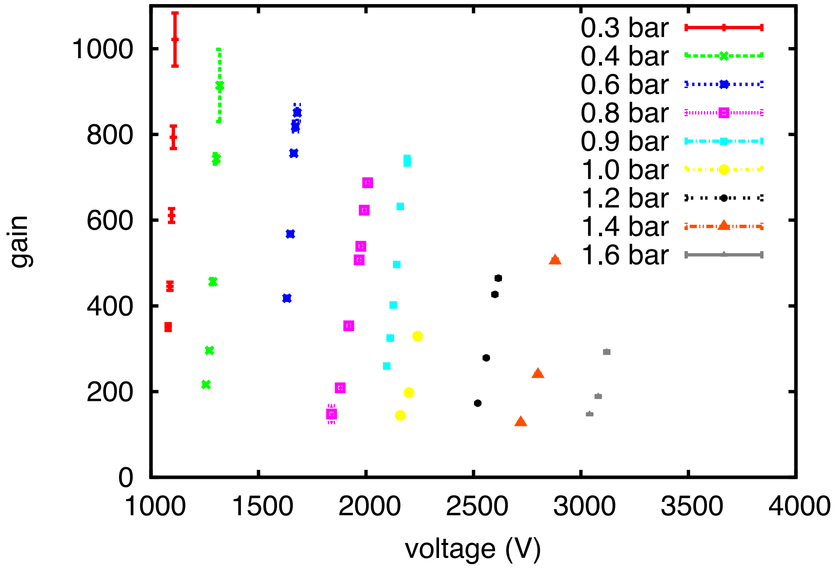
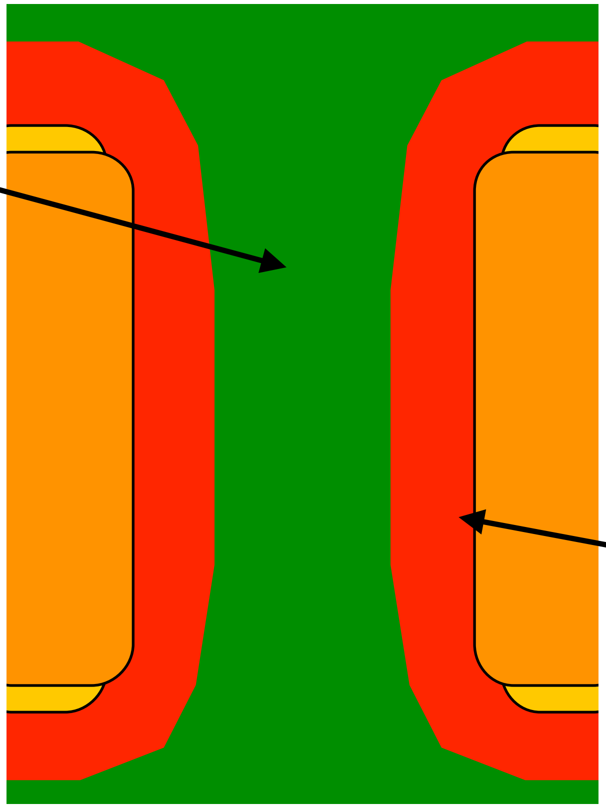
Observations

LEM geometry in pure argon

Low gain region:
amplification region





High gain region:
streamer region

Gain in the amplification region limited by discharge in the streamer region

P (atm)	E_0 (kV/cm)	G
0.8	19.8	3.88×10^5
1.0	22.9	3.13×10^5
2.0	35.7	7.20×10^4
3.0	46.9	3.10×10^4

Increasing the pressure: increase of $\frac{G_{hi}}{G_{lo}} = \frac{e^{\int_{hi} \alpha_{hi}}}{e^{\int_{lo} \alpha_{lo}}} \simeq e^{A\rho(x_{hi}e^{-B\rho/E_{hi}} - x_{lo}e^{(-B\rho/E_{lo})})}$

Summary

Computation of streamer in gas

Diffusion assisted streamers:
no need of gas photo-ionisation

Qualitative data comparison possible, i.e.
density decrease maximum gain, …

GEM saturation simulated within the same framework