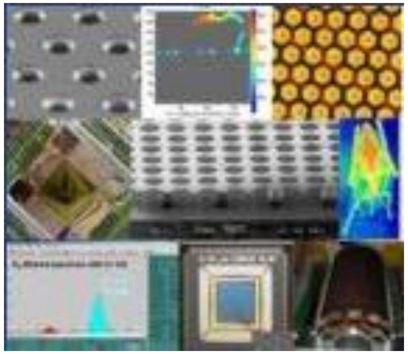


5th RD51 Collaboration Meeting

24-27 May 2010 *Freiburg, Germany*

Calculation of streamer development in MPGDs in an axisymmetric hydrodynamic model

P.Fonte

LIP

FEDER

QUADRO DE REFERÊNCIA ESTRATÉGICO NACIONAL
PORTUGAL 2007.2013

COMPETE
PROGRAMA OPERACIONAL FACTORES DE COMPETITIVIDADE

Fundamental detector limits

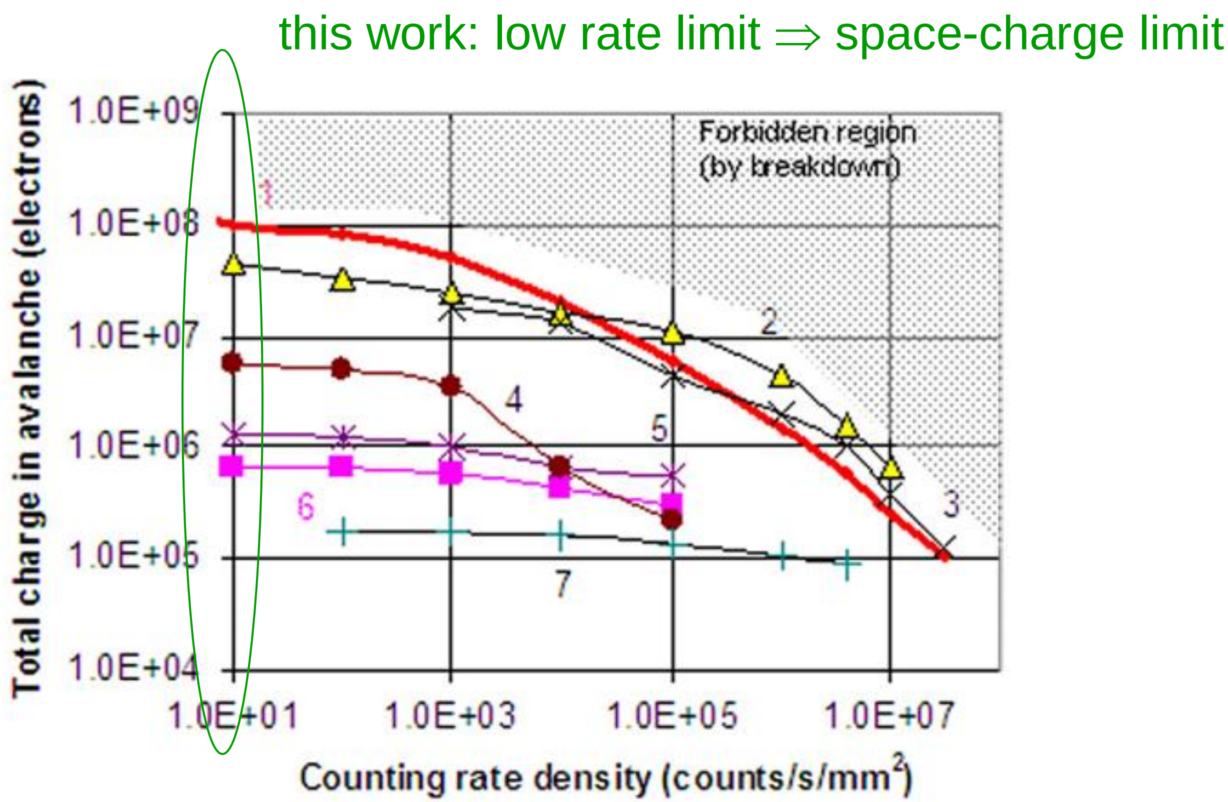


Figure 4. The maximum achievable gain, limited by breakdown, as a function of the x-ray flux for various detectors: (1) PPAC with 3 mm gap; (2) MICROMEGAS; (3) PPAC with 0.6 mm gap; (4) microstrip gas chamber with 1 mm strip pitch; (5) microstrip gas chamber with 0.2 mm strip pitch; (6) GEM; (7) microgap detectors with 0.2 mm strip pitch. Large counting rate densities require a reduction in the gas gain to prevent breakdown. See [52–55] and references therein for the original data and details. All data were converted to total avalanche charge.

Fast breakdown - experimental evidence

Very fast process featuring a "precursor" pulse

[RAE64]

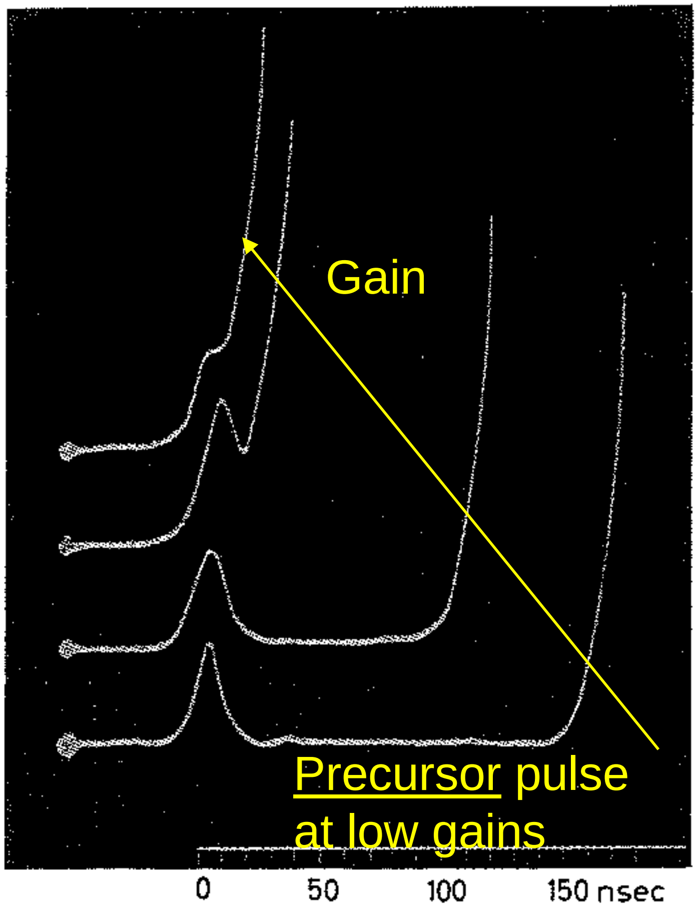
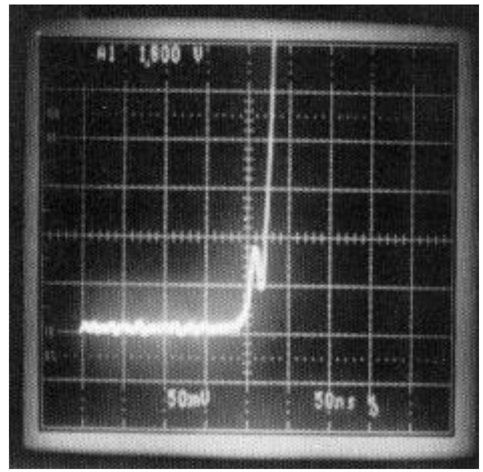


Figure 5.14. Current oscillograms of static breakdown in methylal. Optical method. $E/p = 64{\cdot}4$, $pd = 230$ Torr cm, $d = 0{\cdot}8$ cm, $T_- = 90$ nsec $RC = 5$ nsec[36]

PPAC

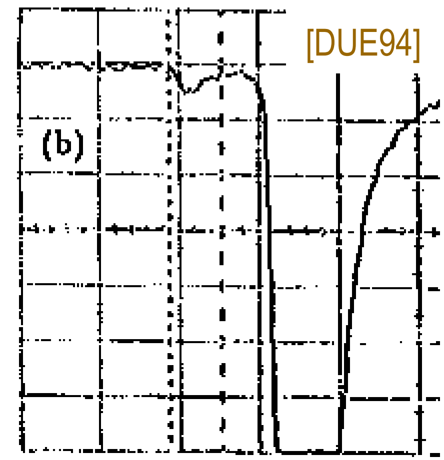
[FON91]



A signature of low-gain cathode streamer-only breakdown

RPC

[DUE94]



single-wire (SQS mode)

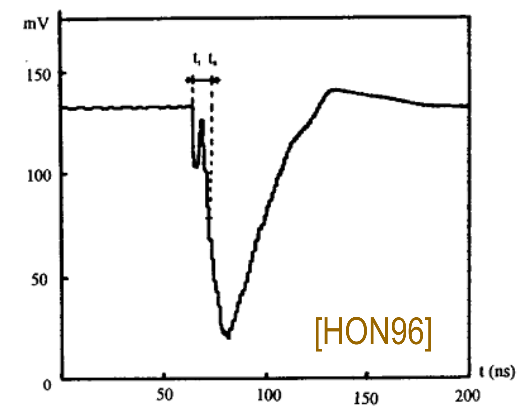


Fig. 1. The pulse shape of the SQS electrical signal $V = 2.45$ kV. Methylal/(Methylal + Ar) = 16.6%.

Fast breakdown - experimental evidence

Cloud chamber observations (vapours, ~1cm gap)

High gain – anode and cathode streamers

Avalanche head	Anode streamer almost at anode	Anode streamer almost at anode	Cathode streamer develops	Channel established

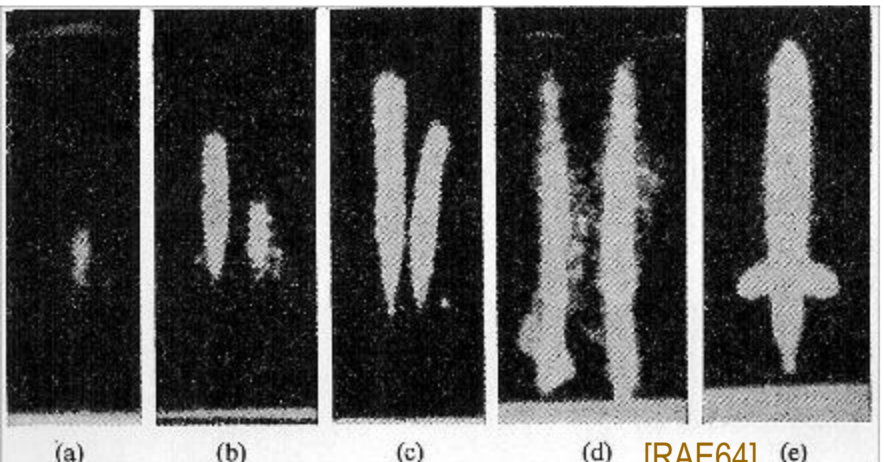


Figure 5.9. Development of one avalanche into a streamer, photographed in the cloud chamber (air, 270 Torr). The expansion ratio was reduced, so that in (a) only the head of the avalanche, as the region of the highest ion density, is visible as a track. If the voltage is slightly raised (at constant voltage pulse duration), an 'anode directed' streamer develops out of the avalanche head (b, c). Further increase of the voltage produces the development of the 'cathode directed' streamer, so that a plasma channel bridges the two electrodes. Therein occurs the spark. The same stages pass, if the voltage pulse height remains constant and the pulse duration is increased[16]

Interpretation

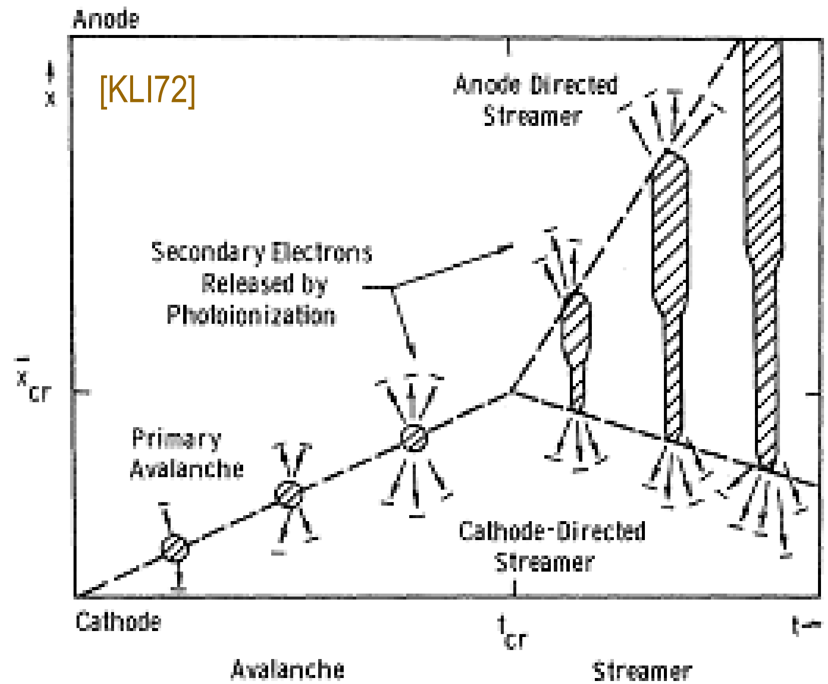
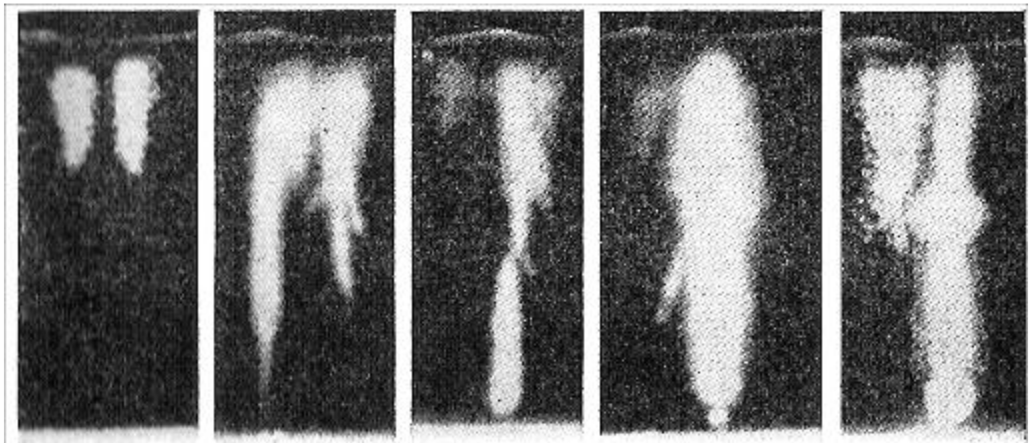


FIG. 6. Schematic representation of the qualitative description of streamer development given by Wagner. (Based on Figs. 22 and 27 of Ref. 11.) Anode- and cathode-directed streamer propagation begins at $t_{critical}$ when the avalanche position equals $\bar{x}_{critical}$.

Fast breakdown - experimental evidence

Lower gain – only cathode streamer

From avalanche head near the anode starts the cathode stremaer	Cathode streamer almost at anode +streamer branches	Cathode streamer reaches anode	Channel established	Channel established



(a) (b) (c) (d) [RAE64] (e)

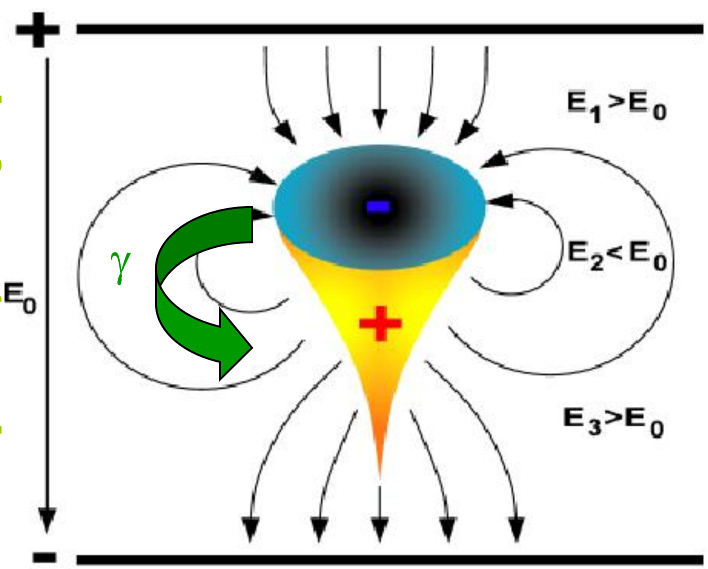
Figure 5.10. Development of the cathode directed streamer (with increasing pulse length). From the head of the avalanche (near the anode) (a) starts the cathode directed streamer ((b) (c)) till a plasma channel connects cathode and anode (d, e). These branched streamers resemble the discharge figures going out from a positive point, see *Figure 5.12*[18]

Fast breakdown – accepted physical origin

(Meek and Raether's "streamer"/"Kanalaufbau" mechanism)

Photon-mediated local feedback in a strong space-charge field

[courtesy W.Riegler]



Higher field: anode (forward) streamer

Lower field: safe, but lowers avg. gain

Higher field: cathode streamer
(but needs a secondary process)

Streamers are triggered when the space-charge field becomes comparable to the applied field:
a charge-dominated,
geometry-dependent process.

Complex physical process, involving:

electron transport in variable fields
electron multiplication in high fields
space-charge distorted electric field
emission of photons able to photoionize the gas at a certain distance (gas self-photoionization)

Hydrodynamic approach to streamer calculation

Charge transport

good reference: [DAV73]

$$\frac{\partial n_e(\vec{r},t)}{\partial t} = \overbrace{\underbrace{S}_{\text{other sources}} + \underbrace{(\alpha - \eta)\left|\vec{W}_e\right| n_e}_{\text{multiplication attachment}}}^{\text{creation}} \overbrace{- \underbrace{\vec{\nabla}\cdot(\vec{W}_e n_e)}_{\underbrace{\vec{W}_e\cdot\vec{\nabla} n_e}_{\text{drift}} + \underbrace{n_e \vec{\nabla}\cdot\vec{W}_e}_{\text{pile-up}}} + \underbrace{D_e \nabla^2 n_e}_{\text{diffusion}}}^{\text{transport}}$$

electrons

$n(\vec{r},t)$ = charge density in space and time

$\vec{W}(\vec{E})$ = velocity of charges

$\vec{E}(\vec{r},t)$ = electric field: applied + space charge

α = first Townsend coefficient

D = diffusion coefficient

$$\frac{\partial n_{i+}(\vec{r},t)}{\partial t} = S + \alpha\left|\vec{W}_e\right| n_e$$

$$\frac{\partial n_{i-}(\vec{r},t)}{\partial t} = \eta\left|\vec{W}_e\right| n_e$$

Ions, assuming stationary ions

Space-charge + applied field

$$\nabla^2 V = -\frac{e}{\varepsilon_0}(n_{i+} - n_e - n_{i-})$$

Boundary conditions

initial densities: $n_{e,i\pm}(\vec{r},0)$

behaviour of charges at the electrodes

Electrostatic B.C.

Slight drawback: no avalanche statistics

Gas self-photoionization as a secondary process

It is possible that just transport accounts for the forward (anode) streamer but for the cathode streamer (growing backwards) something else is needed.

e.g. photoemission proportional to the electron multiplication

$$\frac{\partial n_f(\vec{r},t)}{\partial t} = \delta \left|\vec{W}_e\right| n_e$$

photon creation

+ gas **self-photoionization** source term

$$S(\vec{r},t) = \frac{Q}{\lambda} \int_{Volume} \frac{\partial n_f(\vec{r}\,',t)}{\partial t} \Omega(\vec{r} - \vec{r}\,') e^{\left|\vec{r}-\vec{r}\,'\right|/\lambda} d\vec{r}\,'$$

distribute the photons around and ionize the gas

δ = photon yield per electron

Ω = solid angle fraction from emission to absorption point

Q = quantum efficiency

λ = photon's mean free path

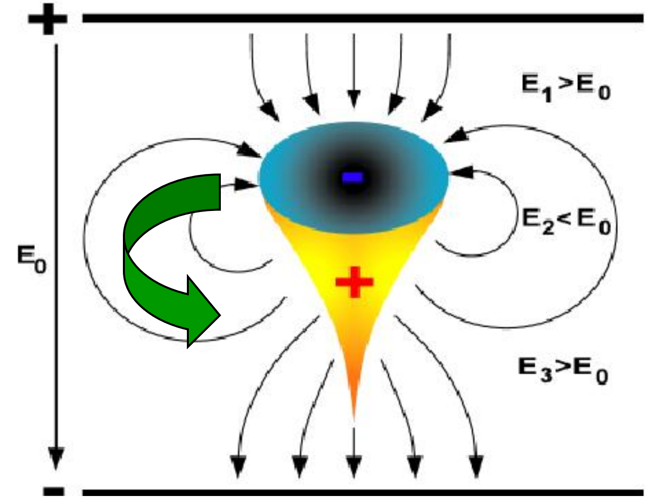
All this for each relevant emission wavelength…

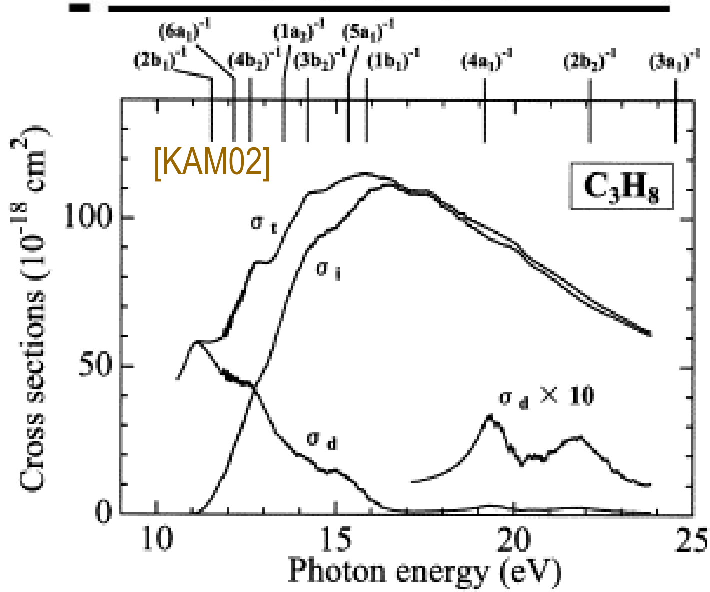
Gas self-photoionization as a secondary process?

- Streamer breakdown seems to be an universal phenomenon. (Generations of electrical engineers and detector physicists couldn't find a way to avoid it.)
- However, self-photoionization hardly allows an universal situation. Essentially every mixture requires its own theory!
  - Depends on the details of photoemission, photoabsorption and photoionization spectra and that must be considered for every component of a gas mixture;
  - Photoemission yields are essentially unknowable. Both hard to measure and hard to calculate. Yield depends on competing deexcitation processes: very mixture-dependent.
- In pure propane, for instance, at atm. pressure the absorption length at the edge of the photoionization band is only ~10µm. Hardly enough for closing a gain loop, even without considerations about yield.

IS THERE ANY OTHER WAY?

Closing the gain loop by self-photoionization?





Diffusion as a streamer-supporting process

PHYSICAL REVIEW E VOLUME 55, NUMBER 2 FEBRUARY 1997

Propagation and structure of planar streamer fronts

Ute Ebert and Wim van Saarloos
Instituut-Lorentz, Universiteit Leiden, Postbus 9506, 2300 RA Leiden, The Netherlands

Christiane Caroli
Université Paris VII, GPS Tour 23, 2 place Jussieu, 75251 Paris Cedex 05, France

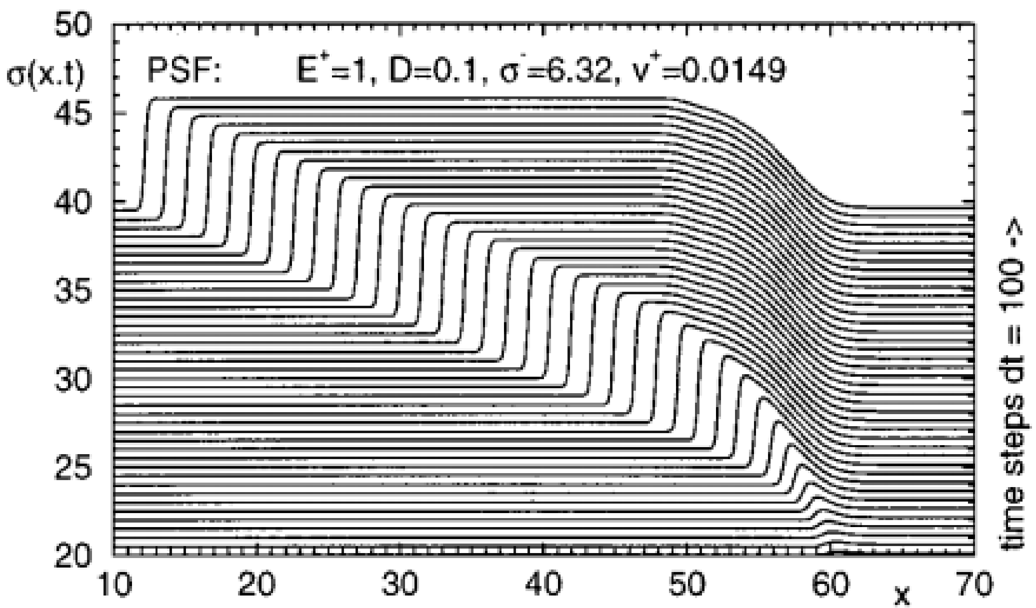


FIG. 10. Emergence of the uniformly translating PSF on the left for $D=0.1$. Initial conditions identical with Fig. 9. The time range $t=4000-8000$ after an initial perturbation at $t=0$ and $x_0=60$ is shown in time steps of $\Delta t=100$. (Numerical grid size $\Delta x=0.01$ and $\Delta\tau=0.5$.)

Analytical and numerical proof that diffusion alone provides a sufficient mechanism for positive streamer front (PSF) propagation in some simplifying (but quite reasonable) conditions.

Simplified hydrodynamic model

$$
\begin{cases}
\dfrac{\partial n_e}{\partial t} = \alpha \left|\vec{W}_e\right| n_e - \vec{\nabla}\cdot(\vec{W}_e n_e) + D_e \nabla^2 n_e \\
\dfrac{\partial n_{i+}}{\partial t} = \alpha \left|\vec{W}_e\right| n_e \\
\nabla^2 V = -\dfrac{e}{\varepsilon_0}(n_{i+} - n_e)
\end{cases}
$$

$n_{e,i+}(\vec{r},t)$ = charge density in space and time

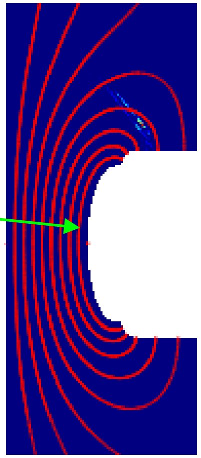
$\vec{E}(\vec{r},t)$ = electric field = $\vec{\nabla} V(\vec{r},t)$

$\vec{W}_e(\vec{E})$ = electron velocity

$\alpha(\vec{E})$ = first Townsend coefficient

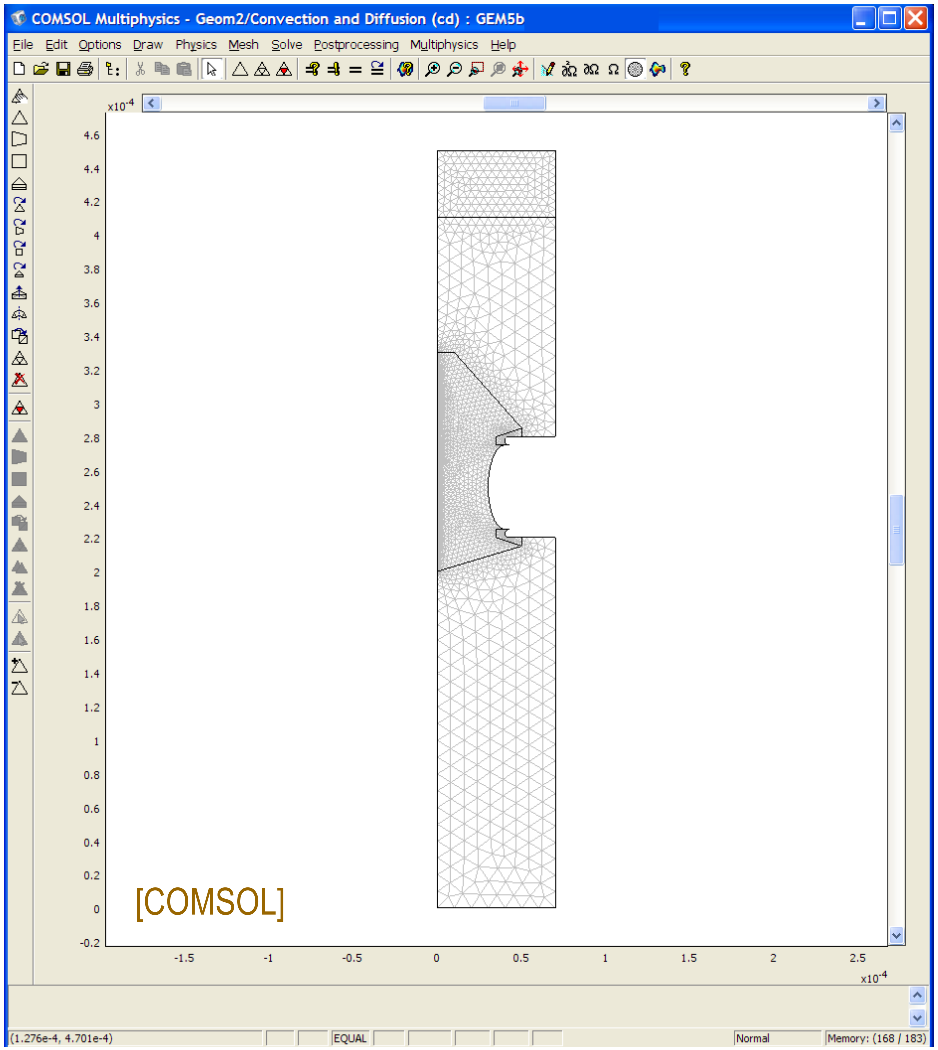
$D_e(\vec{E})$ = electron diffusion coefficient

- Only electrons and positive ions
- No positive ion movement (in such short time span)
- No attachment
- **No photons**
- Assume <u>axial symmetry</u> (minimal condition for realism): 2D calculation
- Applied field: boundary conditions on the potential
- Dielectrics: tangent $\vec{E}$ (no charge flow into the surface)



Numerical approach: finite elements

Used the commercial program *COMSOL Multiphysics*



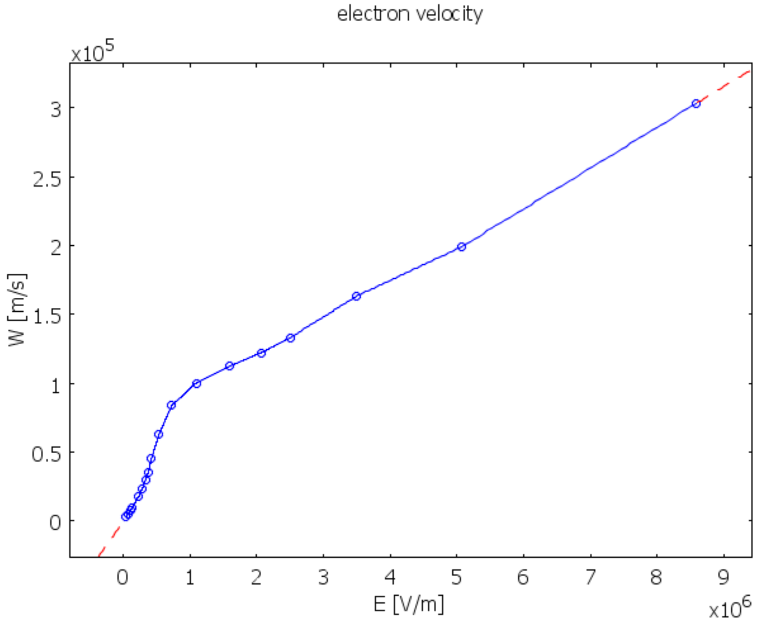
Solves a coupled set of a basic differential equation,

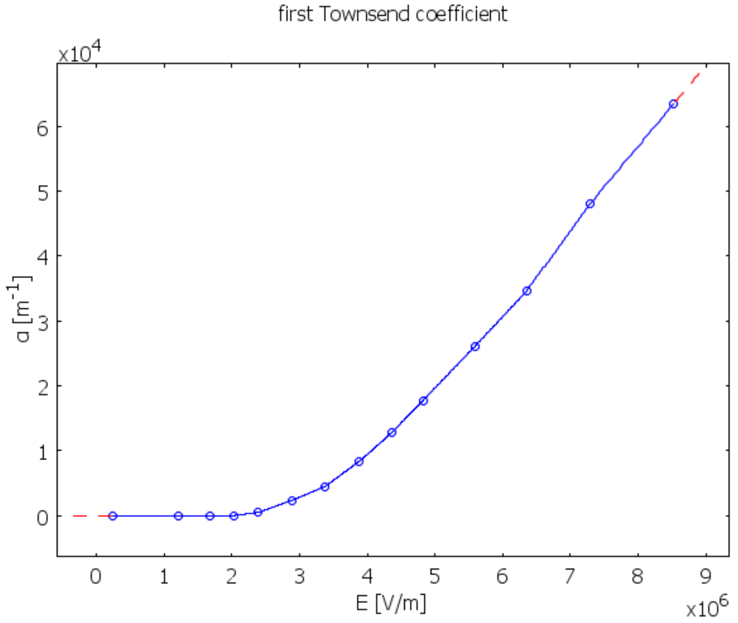
$$\begin{cases} e_a \dfrac{\partial^2 u}{\partial t^2} + d_a \dfrac{\partial u}{\partial t} + \nabla \cdot (-c\nabla u - \alpha u + \gamma) + \beta \cdot \nabla u + au = f & \text{in } \Omega \\ \mathbf{n} \cdot (c\nabla u + \alpha u - \gamma) + qu = g - h^T \mu & \text{on } \partial\Omega \\ hu = r & \text{on } \partial\Omega \end{cases}$$

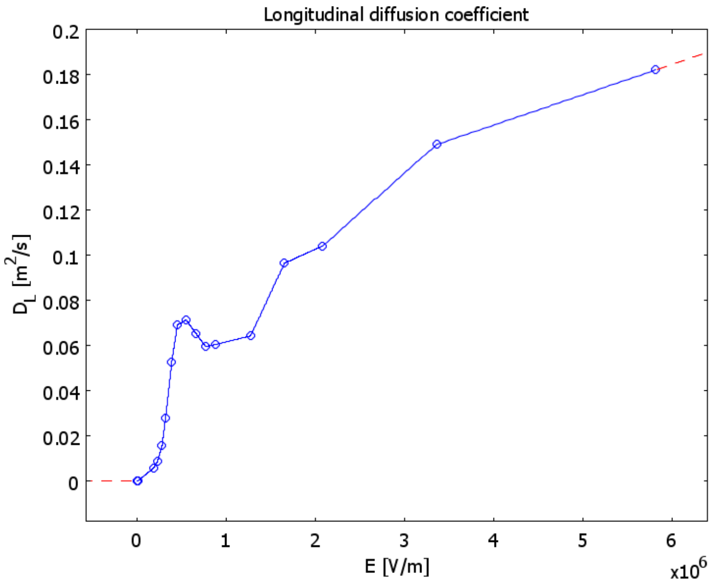
with arbitrary coefficients (any function of any variable) in a mesh (finite elements).

Covers most cases needed for applied physics.

Gas: pure CO_2 @ atm. pressure







[HER02]

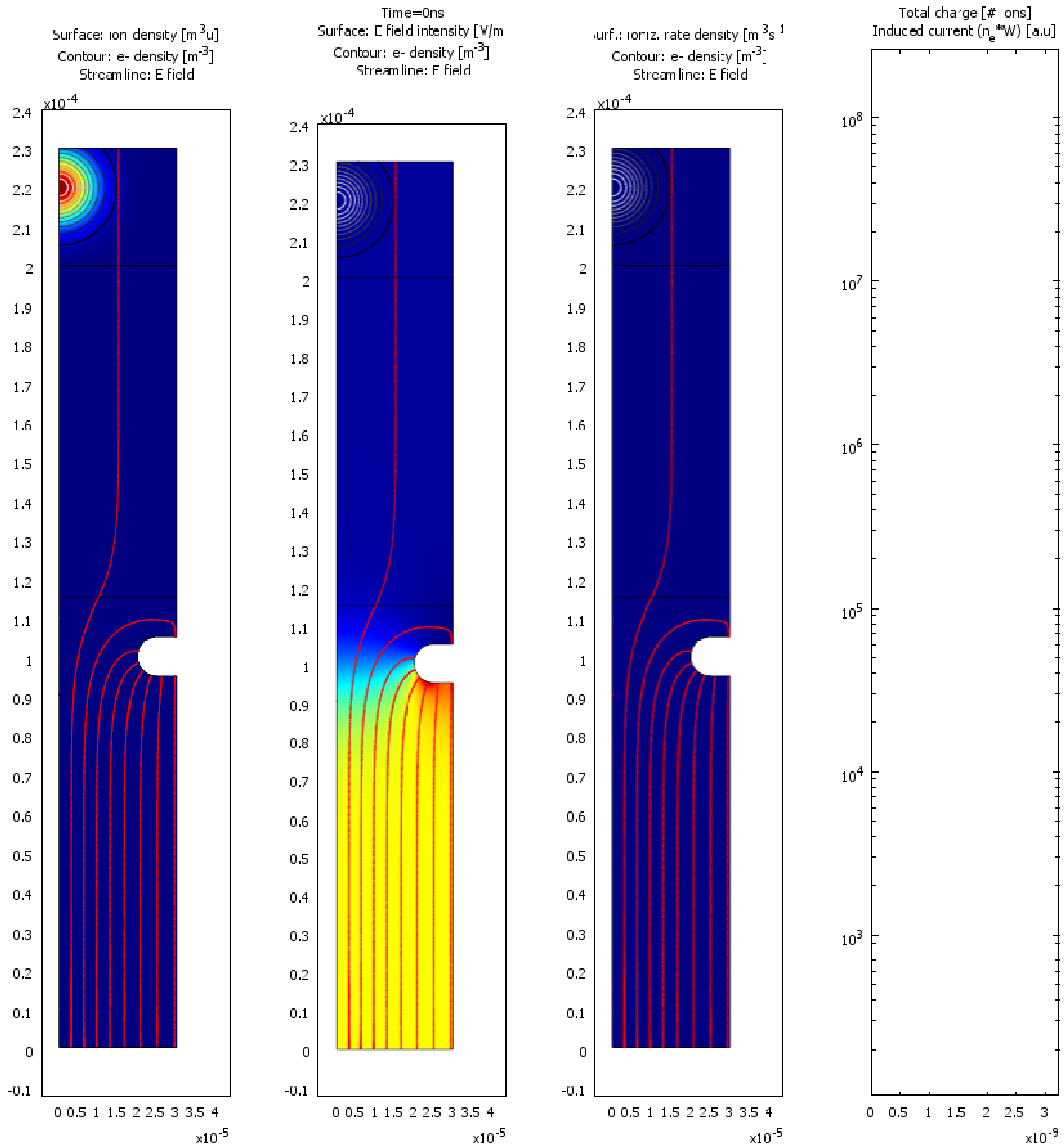
MICROMEGAS

hole: 40 µm
gap: 100 µm
N_0=100 e^-

Total induced current

$$\propto \int_{Volume} \left|\vec{j}\right| dV = \int_{Volume} n_e \left|\vec{W}_e\right| dV$$

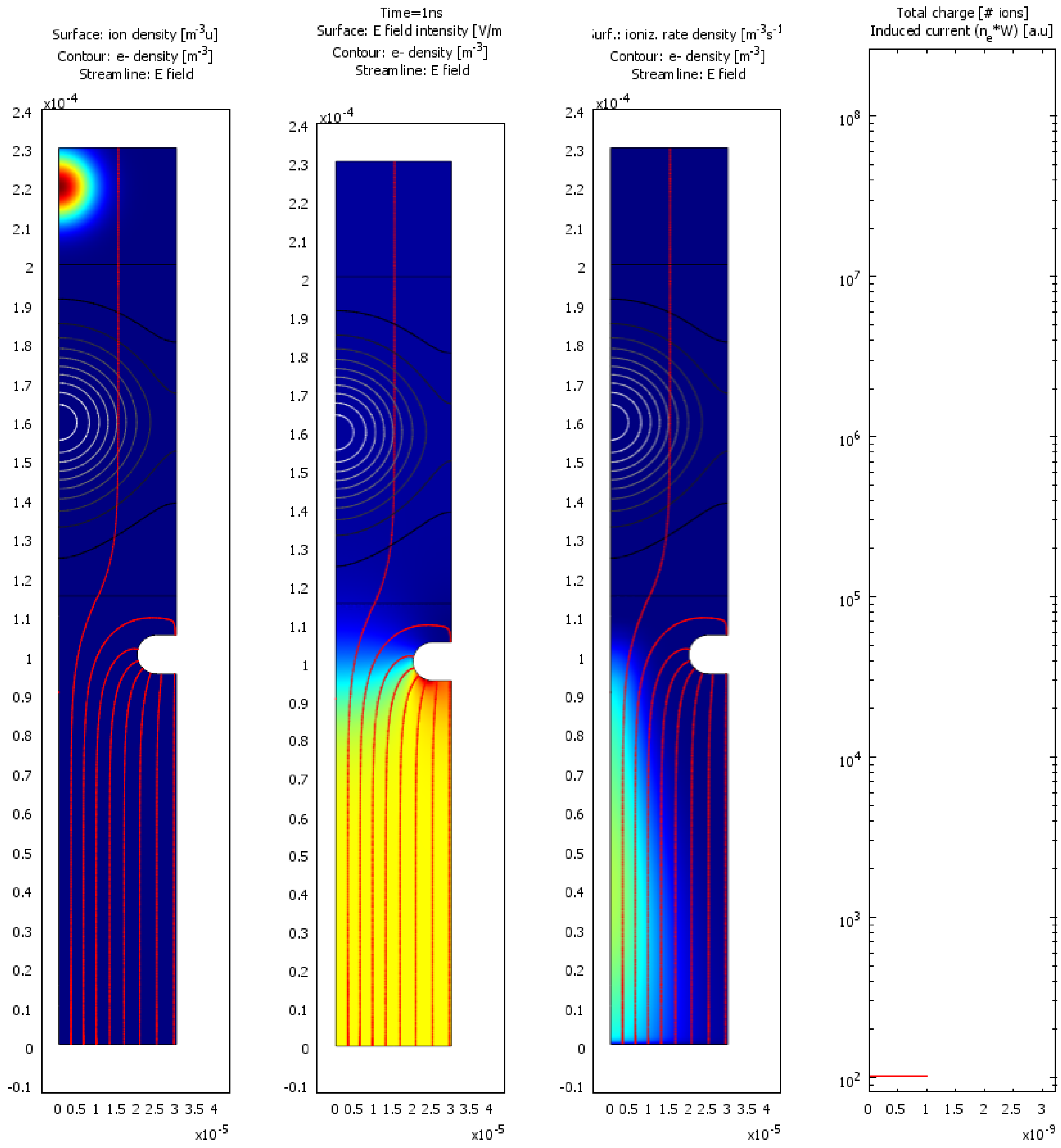
The details depend on which electrodes we are actually collecting this current.



MICROMEGAS

hole: 40 µm
gap: 100 µm
N_0=100 e^-

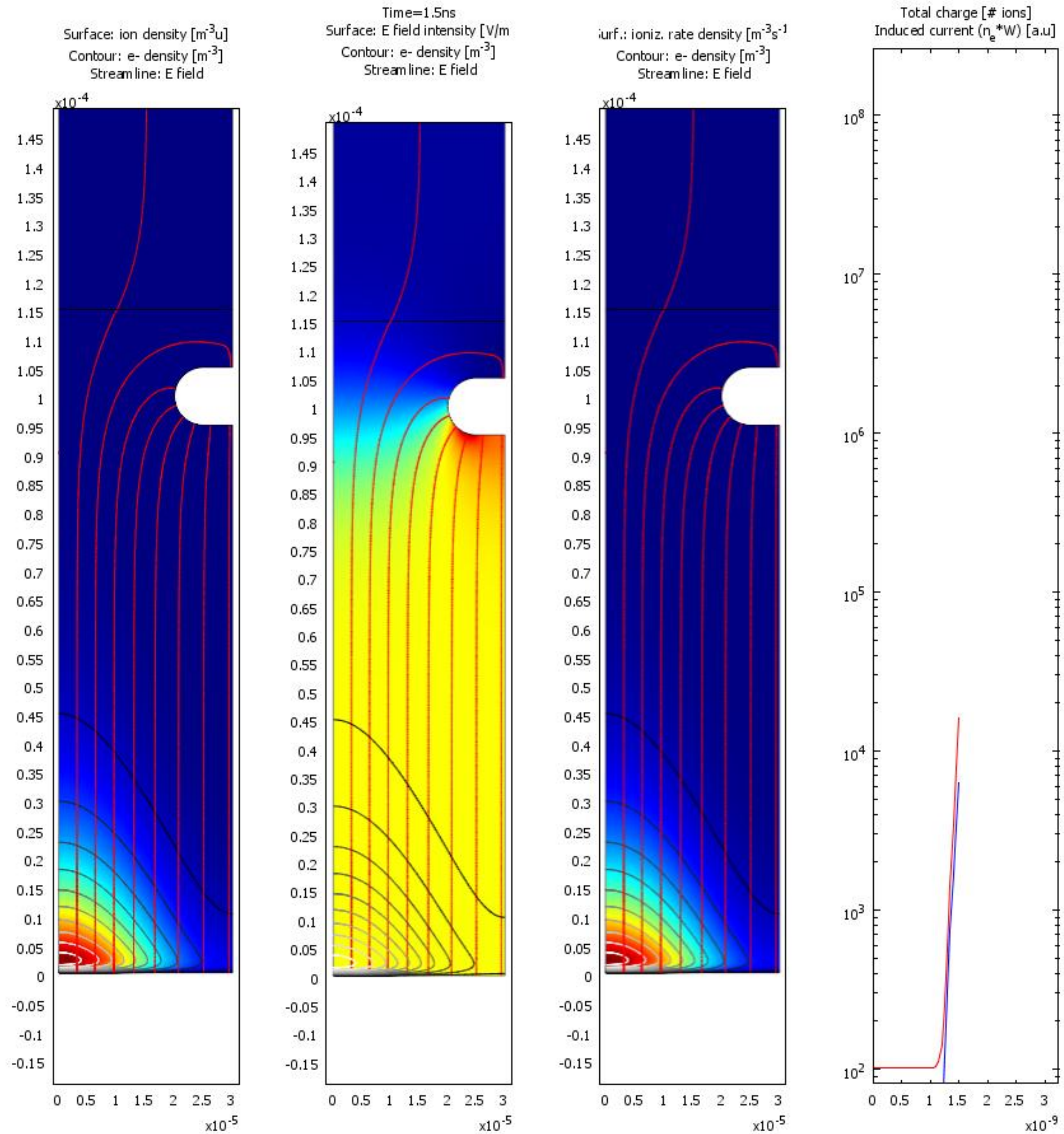
Start of multiplication while most of the electrons are still in the drift region



MICROMEGAS

hole: 40 µm
gap: 100 µm
N_0=100 e^-

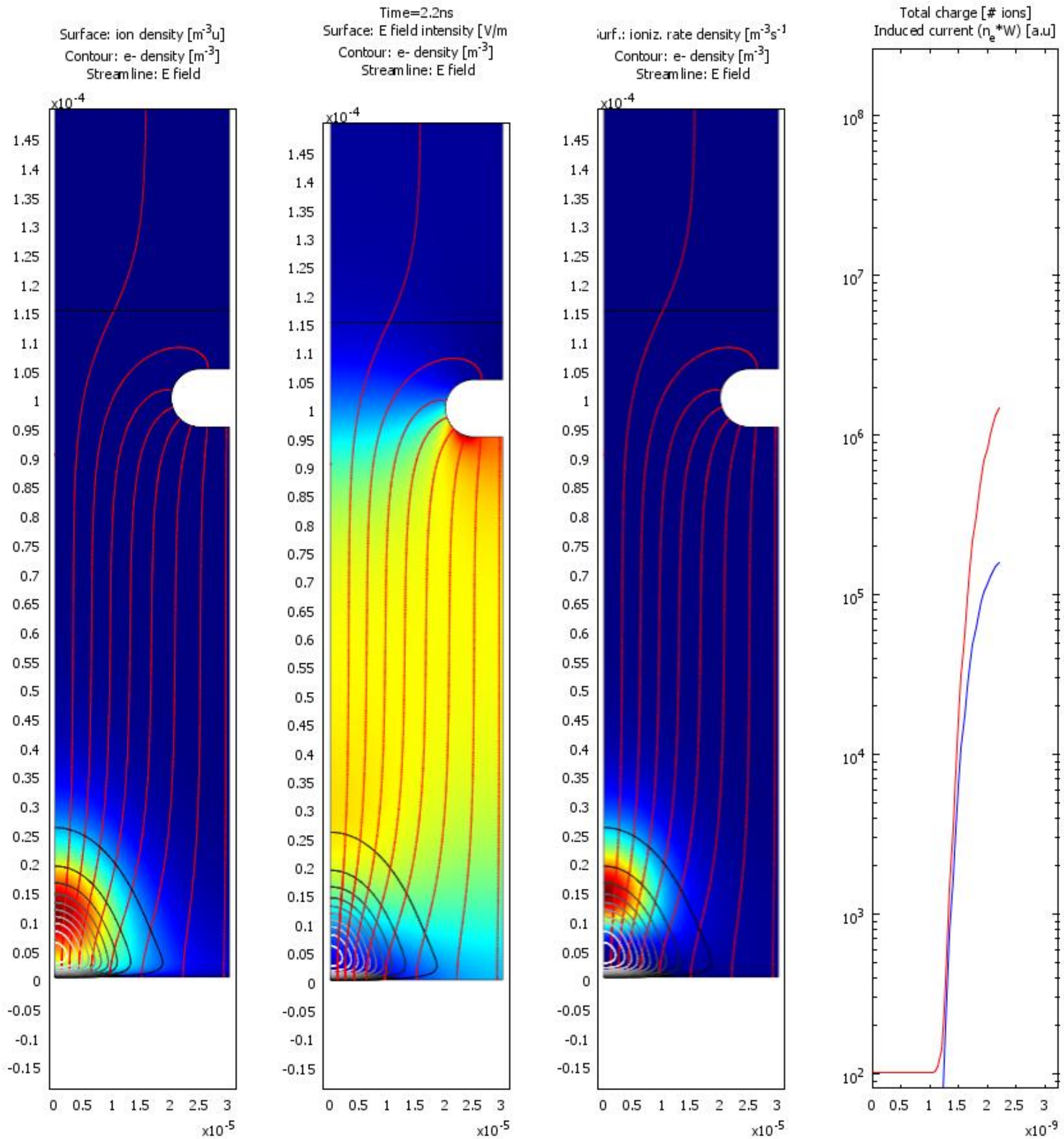
Proportional gain



MICROMEGAS

hole: 40 µm
gap: 100 µm
N_0=100 e^-

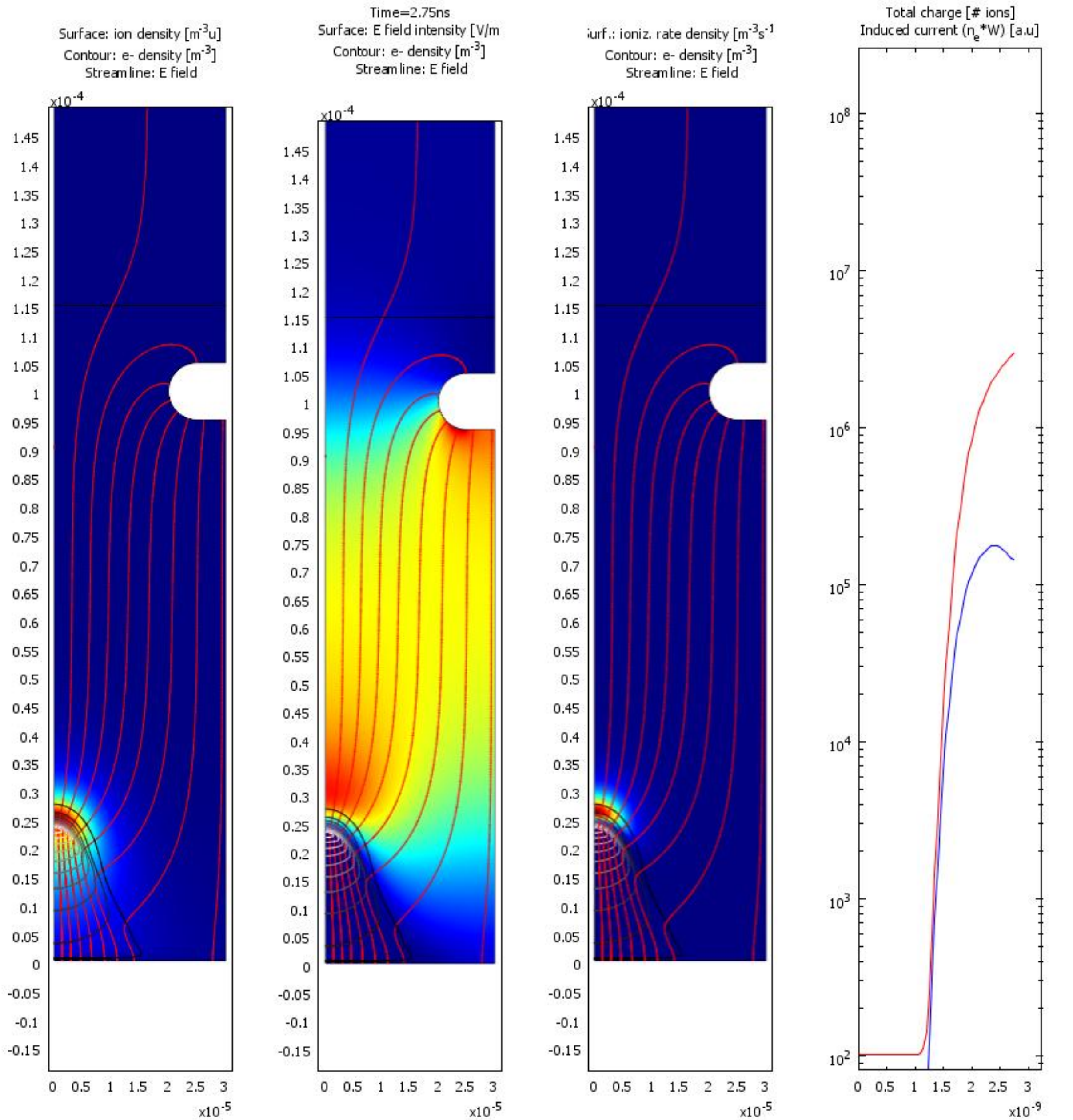
Onset of space-charge: maximum multiplication region moves away from anode owing to space-charge.
This is not a streamer yet.
Depends on the inflow of electrons from the drift for growth.



MICROMEGAS

hole: 40 µm
gap: 100 µm
N_0=100 e^-

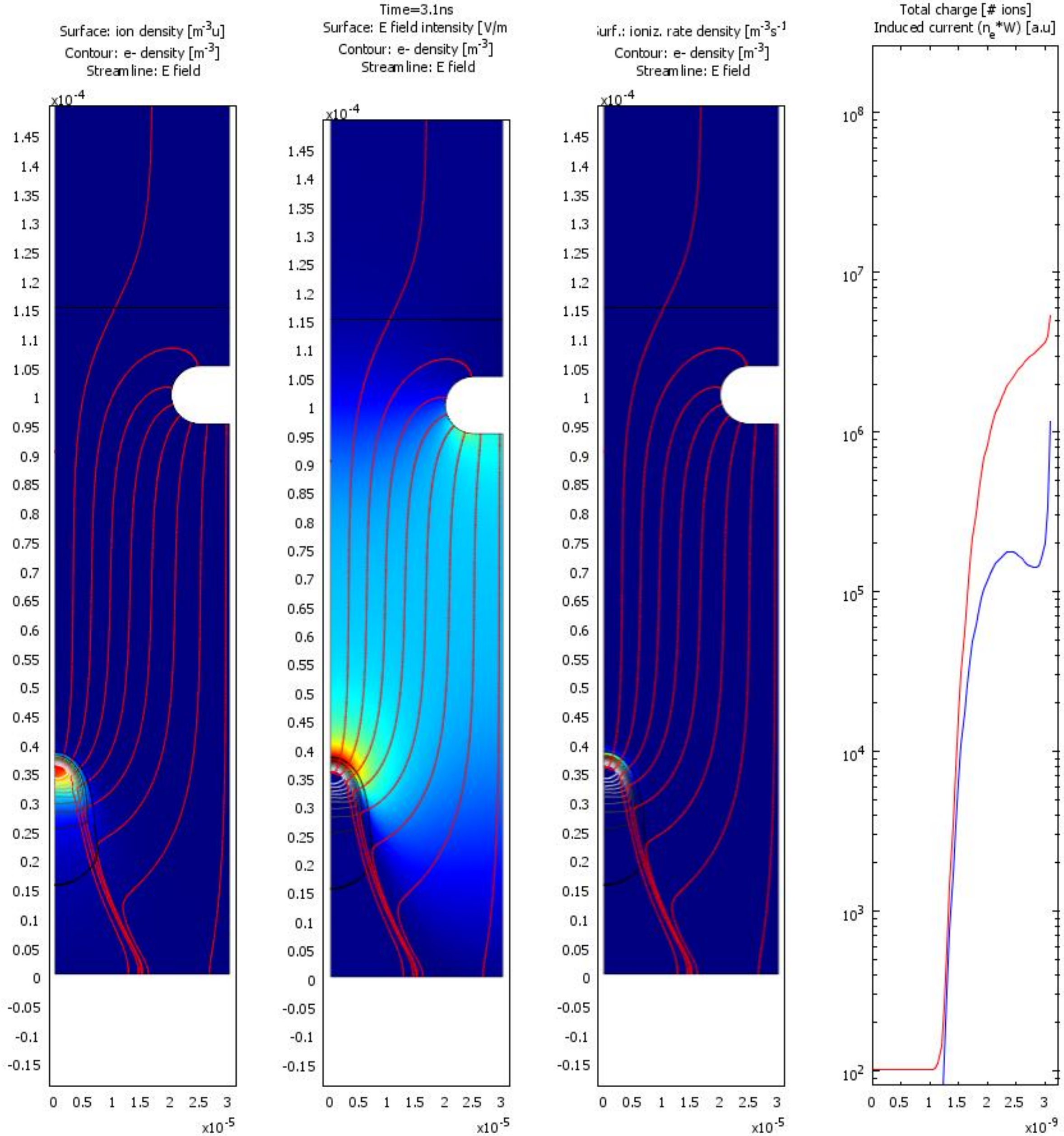
The induced current actually decreases because the multiplication of the inflow of electrons is not enough to compensate for the electron losses to the anode.



MICROMEGAS

hole: 40 µm
gap: 100 µm
N_0=100 e^-

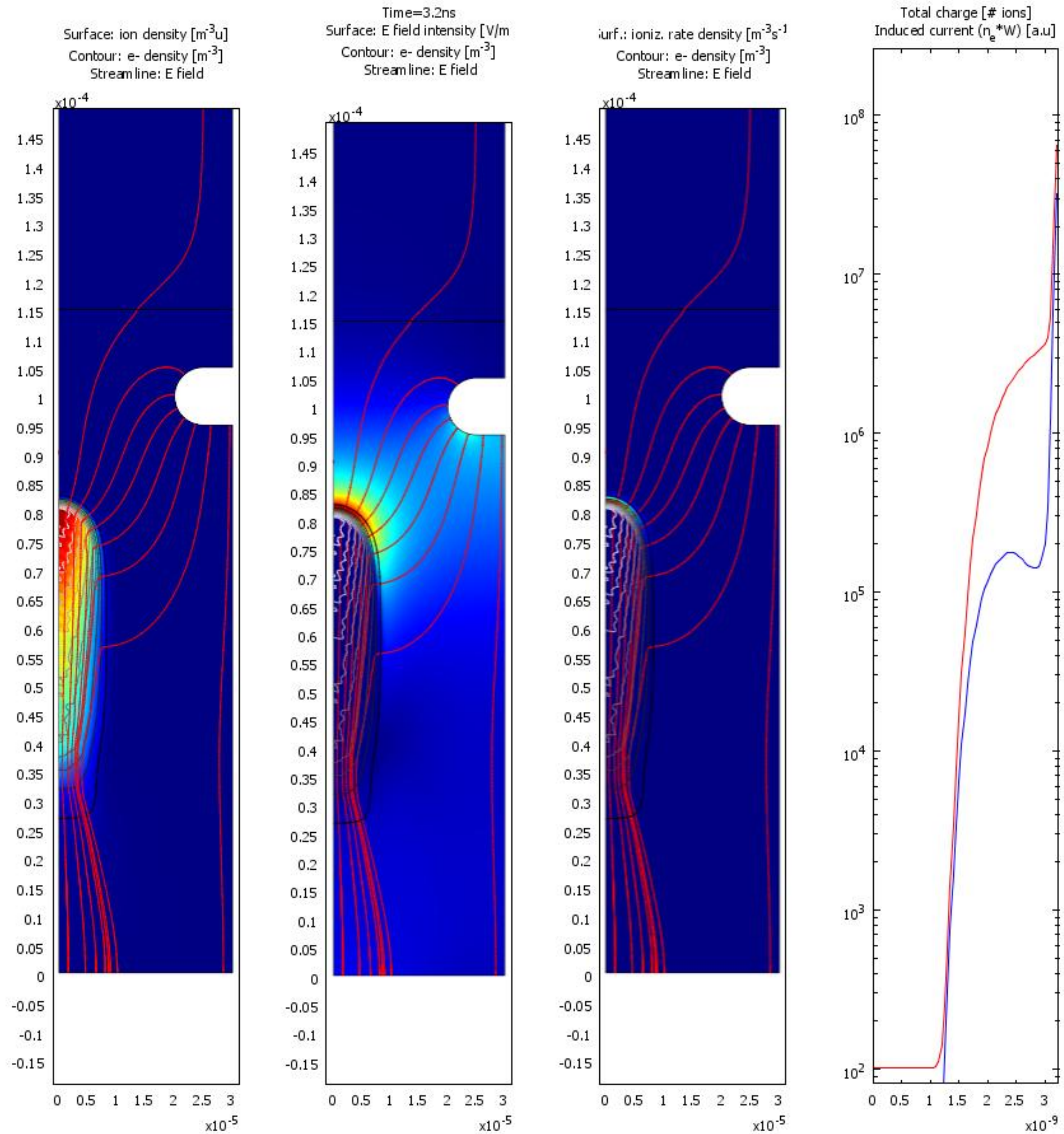
A streamer structure is formed on the tip of a plasma conductive “needle”.
The current increases and the structure known as “the precursor” is formed.



MICROMEGAS

hole: 40 µm
gap: 100 µm
N_0=100 e^-

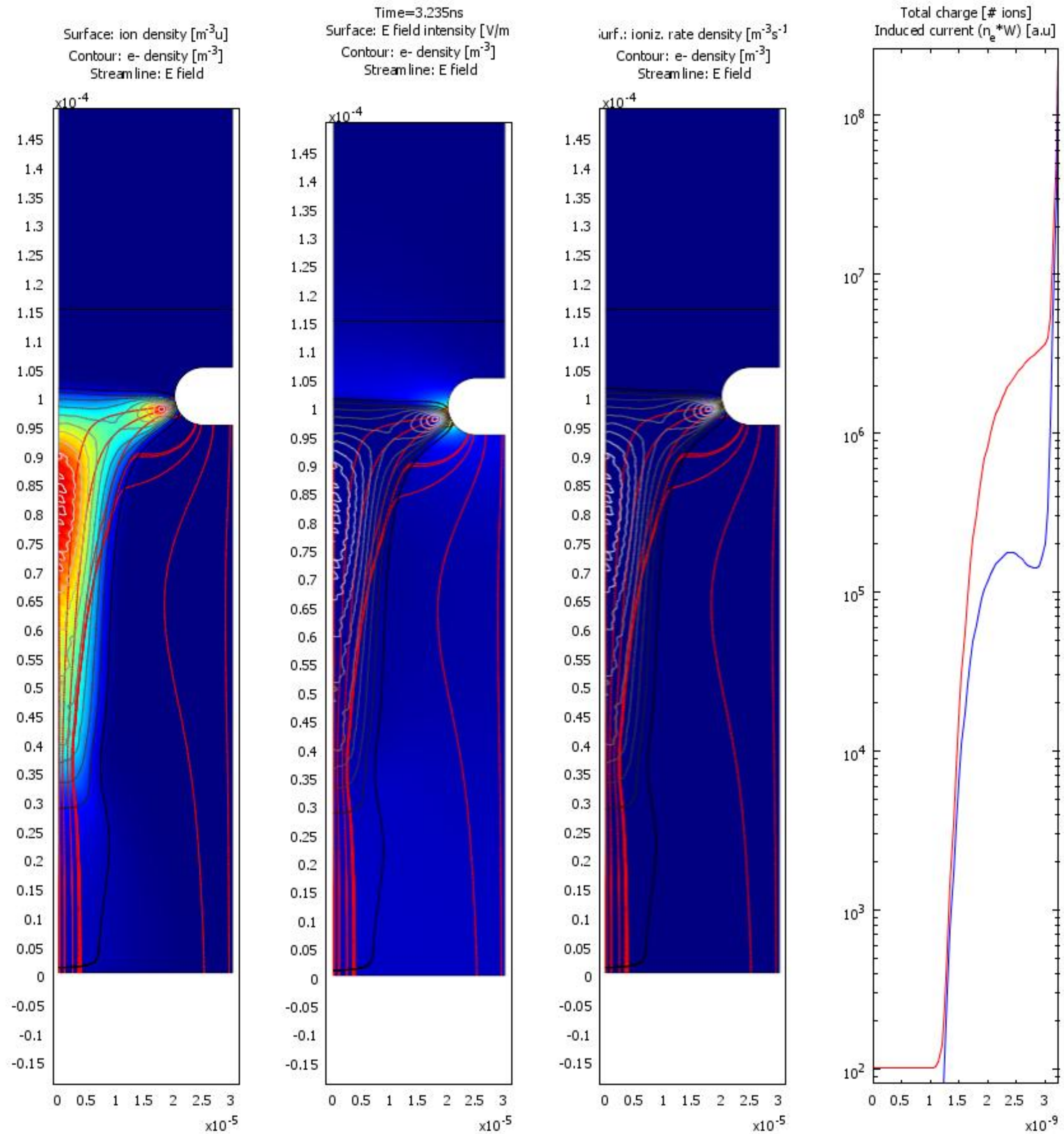
The streamer is self-sustained and propagates towards the cathode at very high speed.



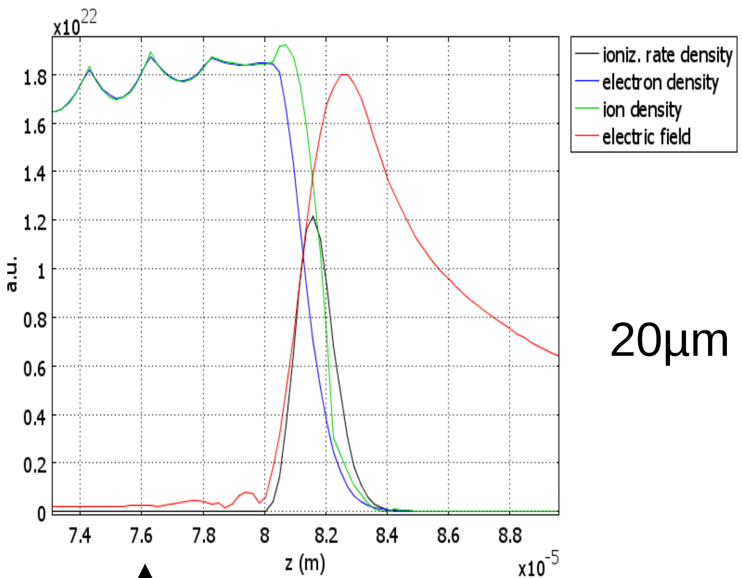
MICROMEGAS

hole: 40 µm
gap: 100 µm
N_0=100 e^-

The streamer branches sideways towards the mesh, bridging anode and cathode with a conductive plasma path.
Further discharge stages will follow, eventually ending with a spark.



Structure of the diffusion-assisted streamer

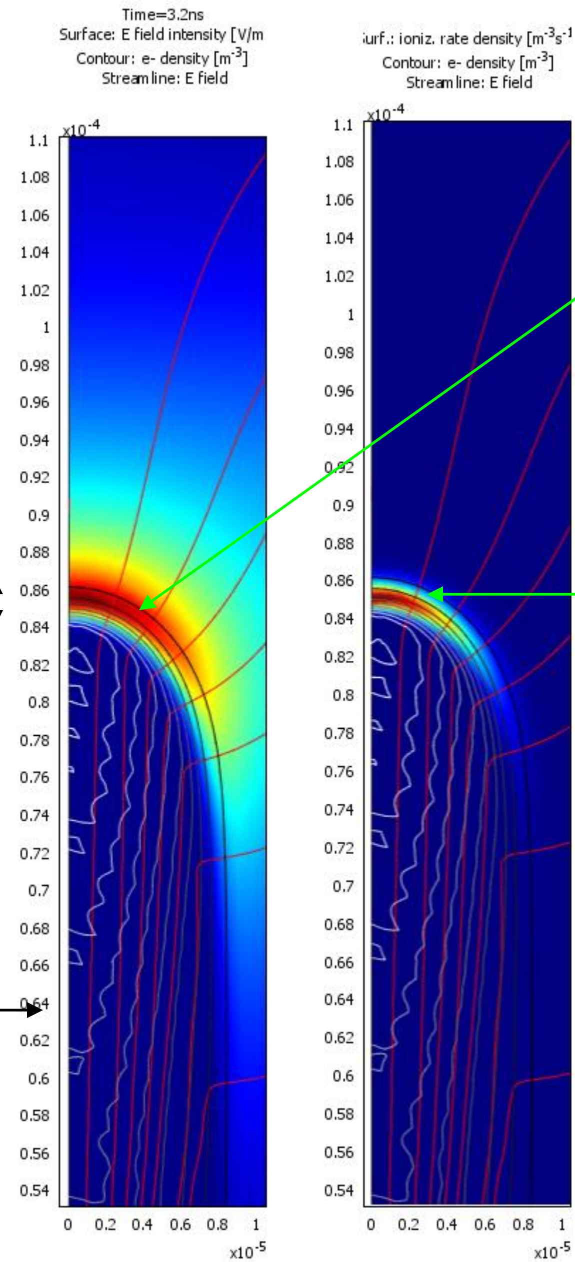


Very low field region

⇓

the anode potential appears at the tip of the streamer

20µm ↕



Owing to the strong density gradient some electrons actually diffuse against the E field into the high gain region on the tip of the streamer.

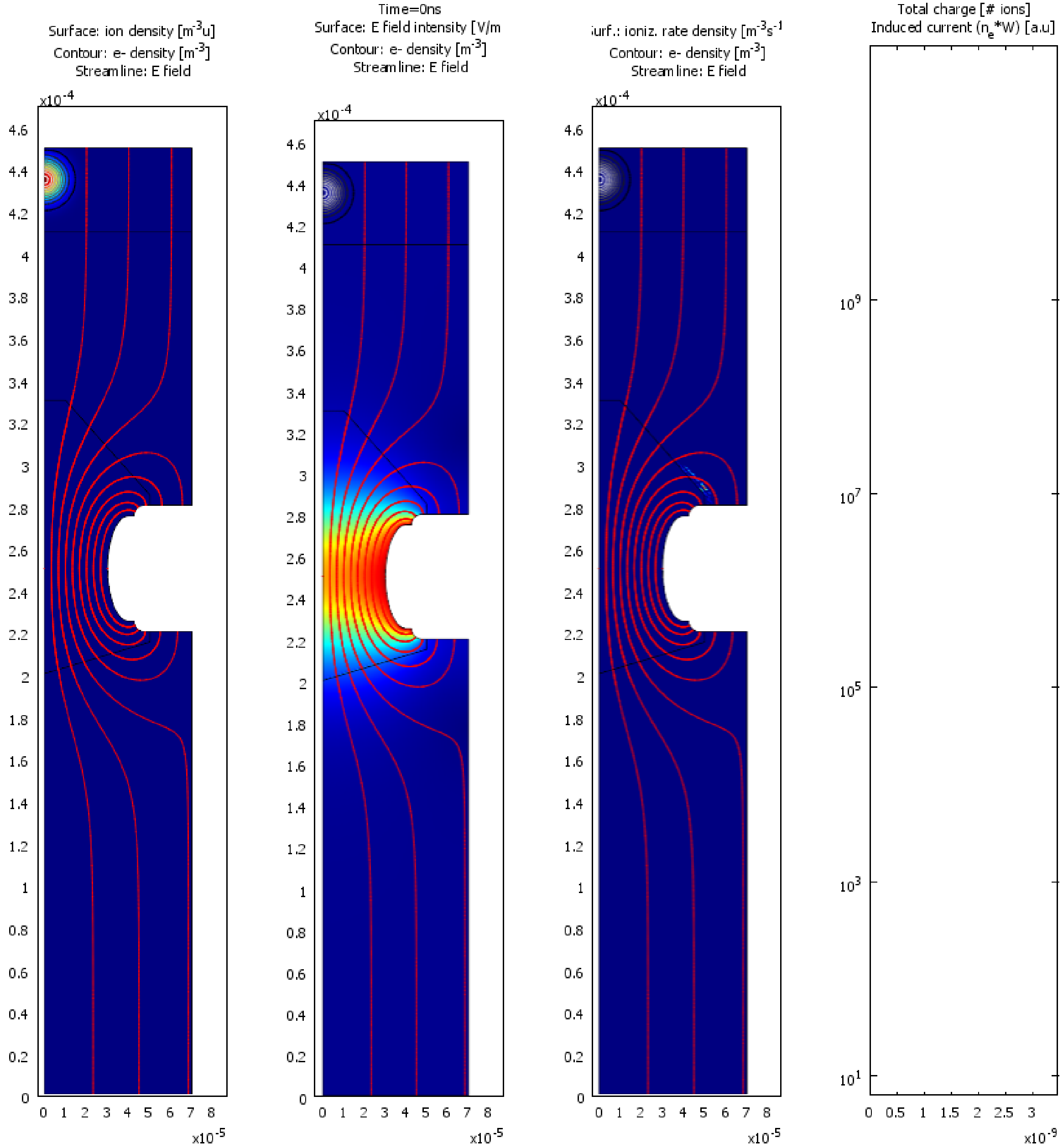
Above a certain gain threshold this structure is self-sustained.

A thin active region forms upstream of the ion density maximum, moving the maximum upwards at high speed.

The movement of the streamer is the movement of the density maximum, not a physical velocity of an object.

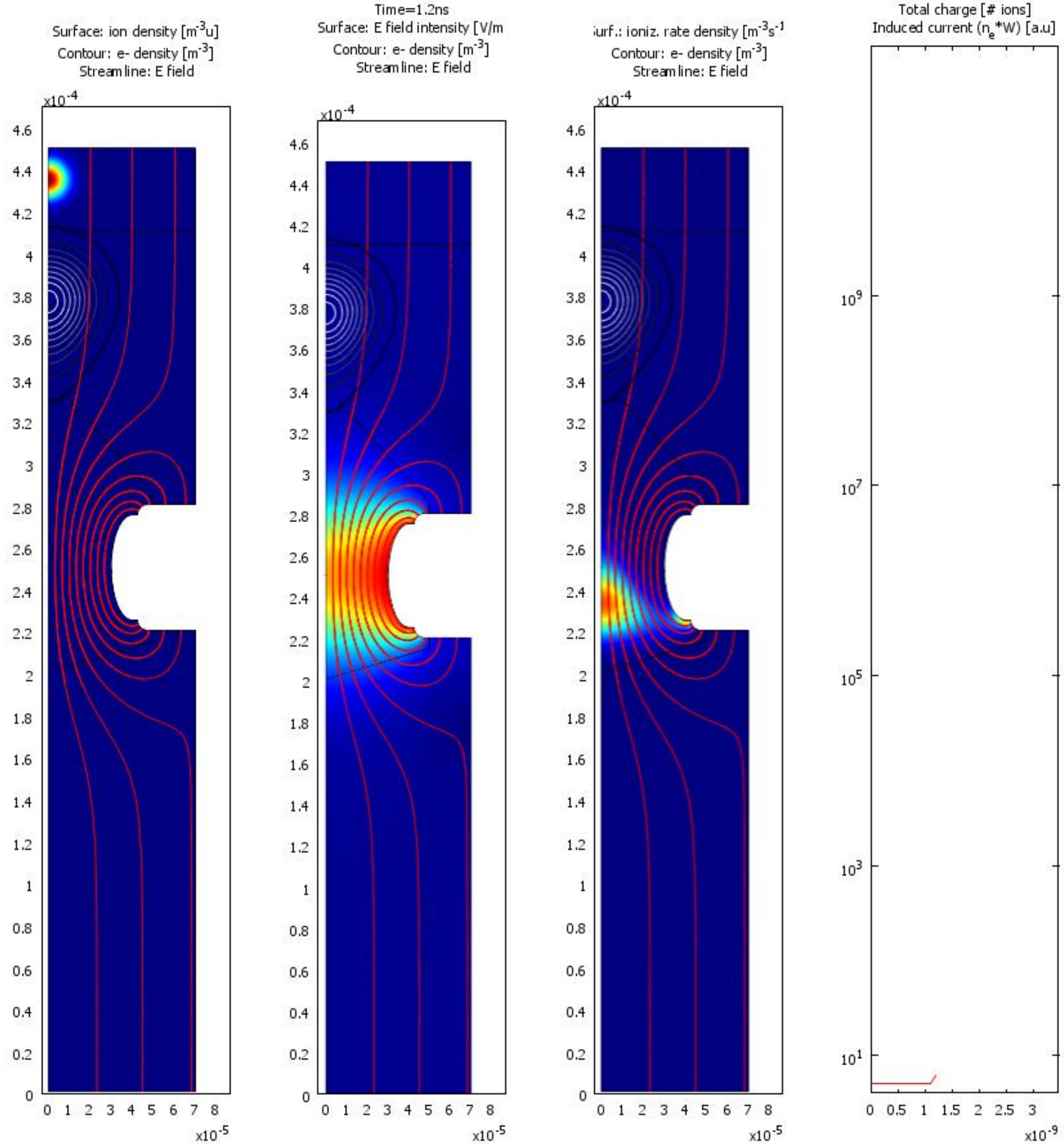
GEM

hole: 60 µm
gap: 100 µm
N_0=100 e^-
V=1250V



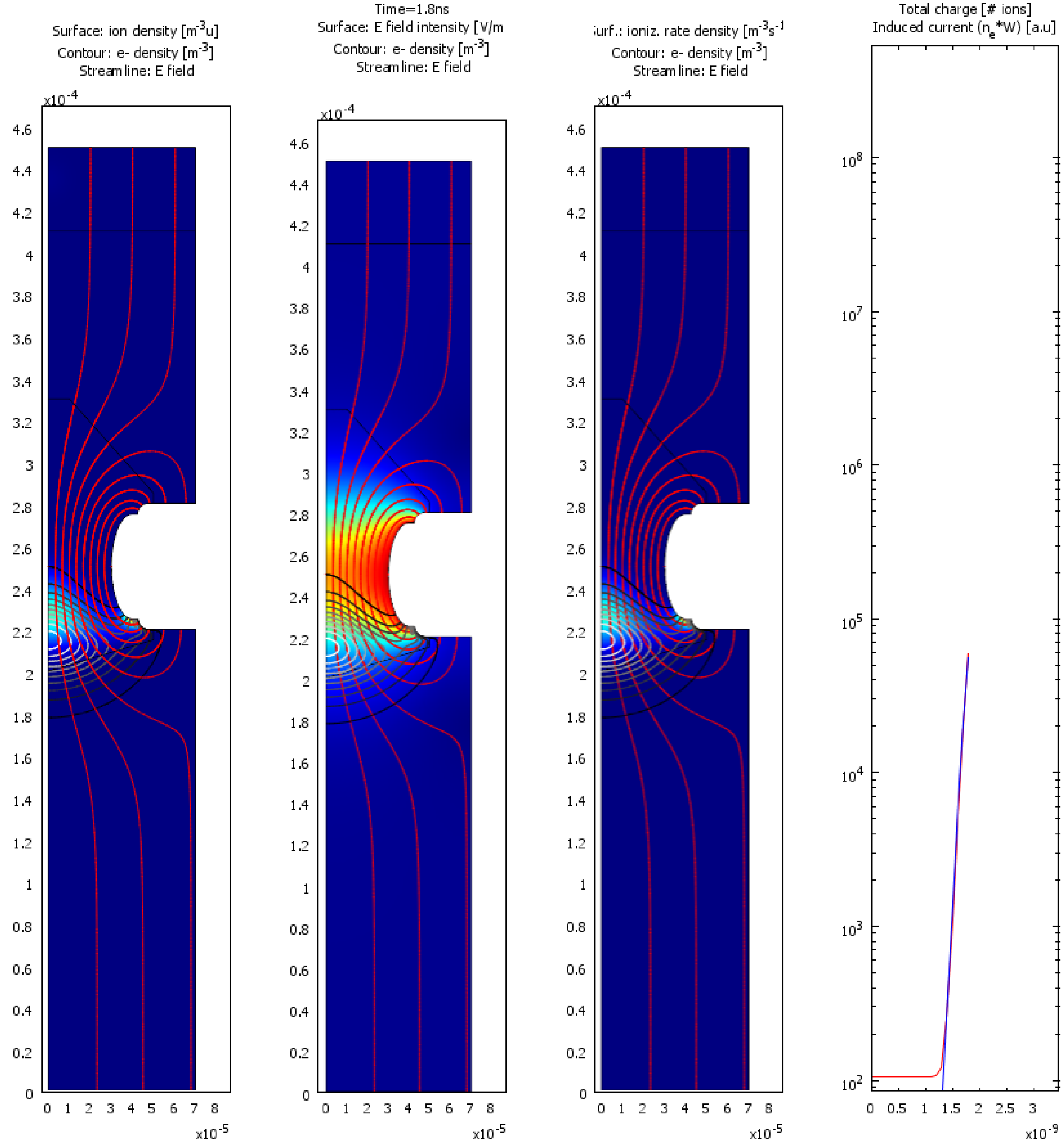
GEM

hole: 60 µm
gap: 100 µm
N_0=100 e^-
V=1250V



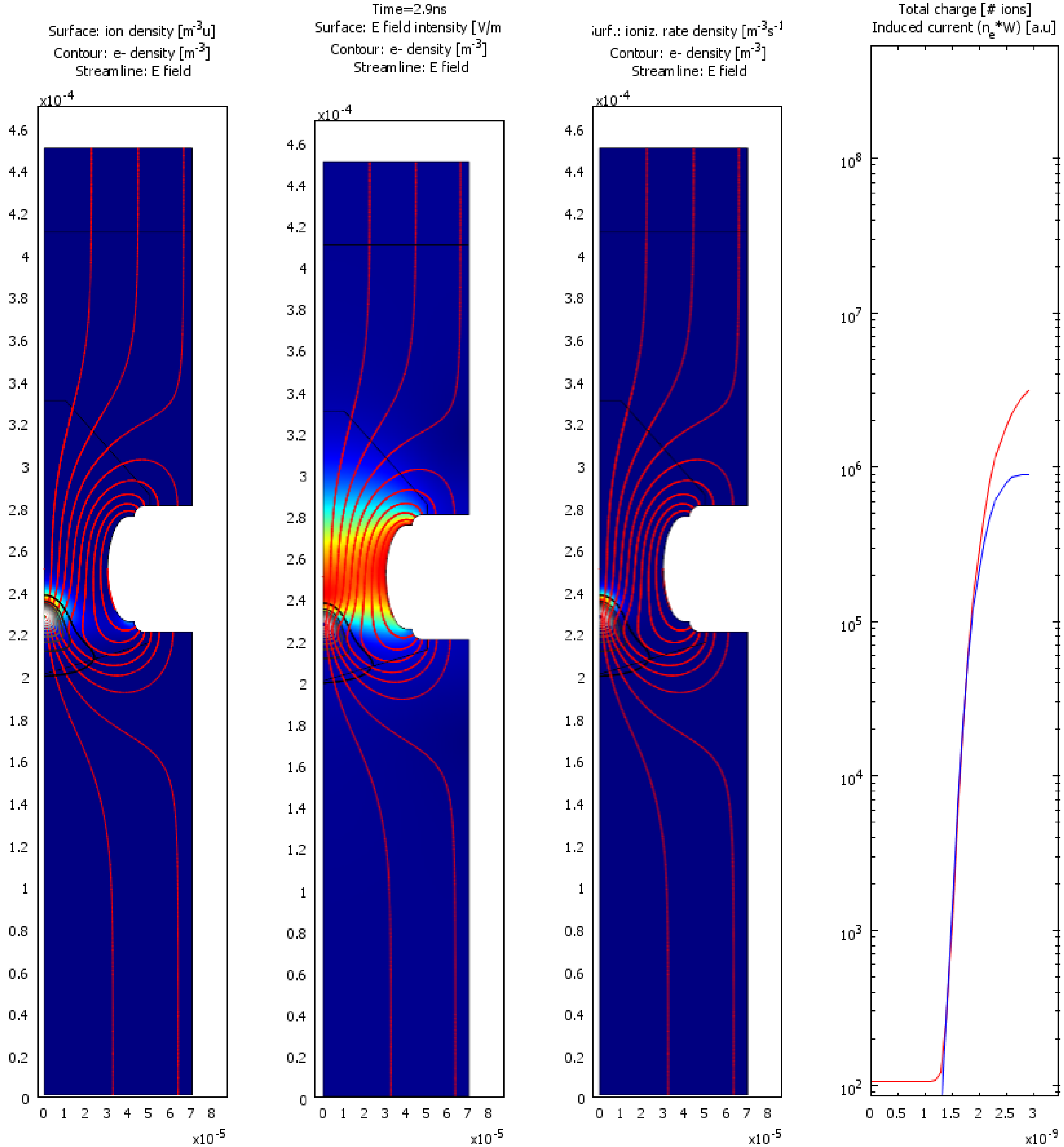
GEM

hole: 60 µm
gap: 100 µm
N_0=100 e^-
V=1250V



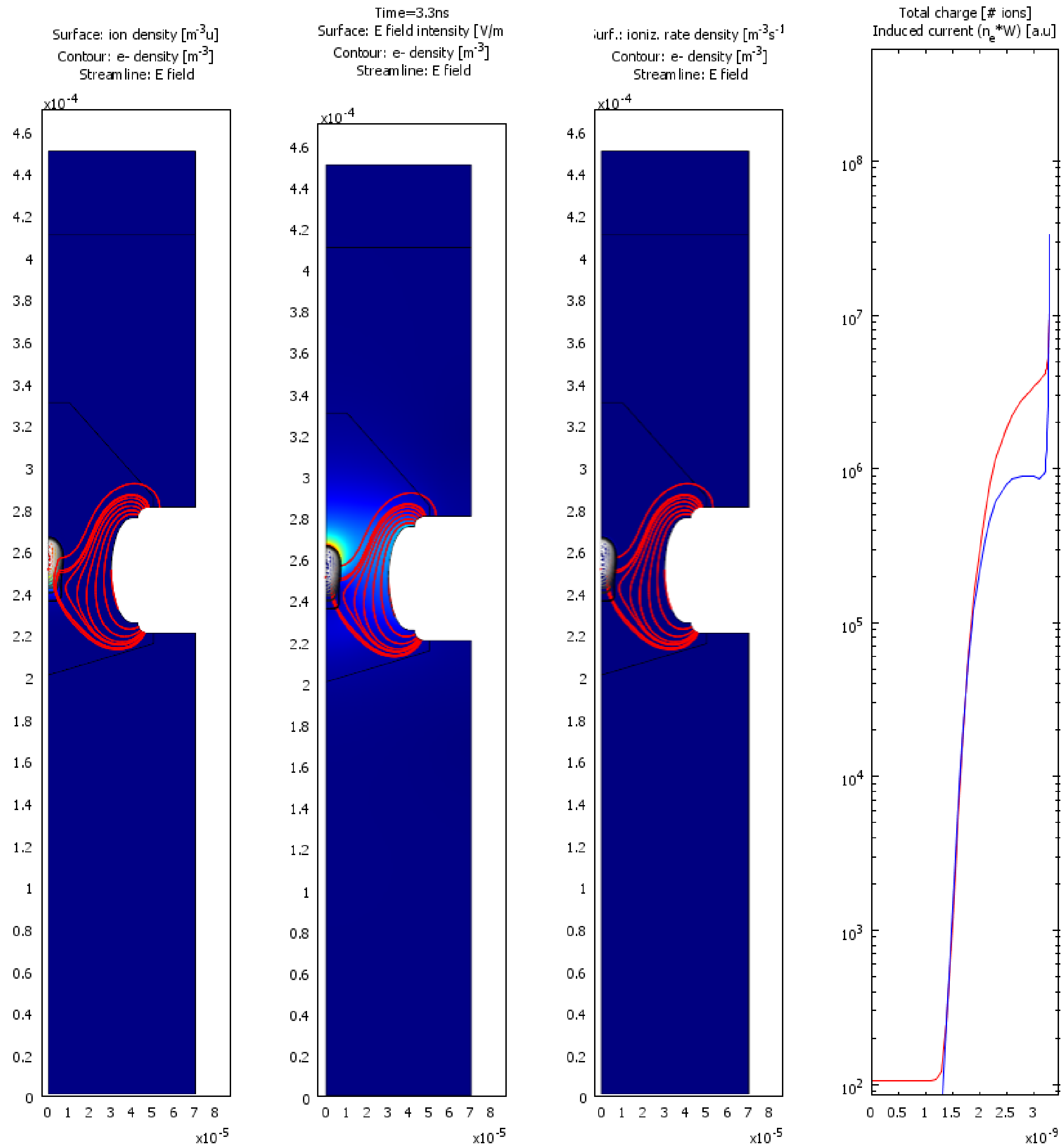
GEM

hole: 60 µm
gap: 100 µm
N_0=100 e^-
V=1250V



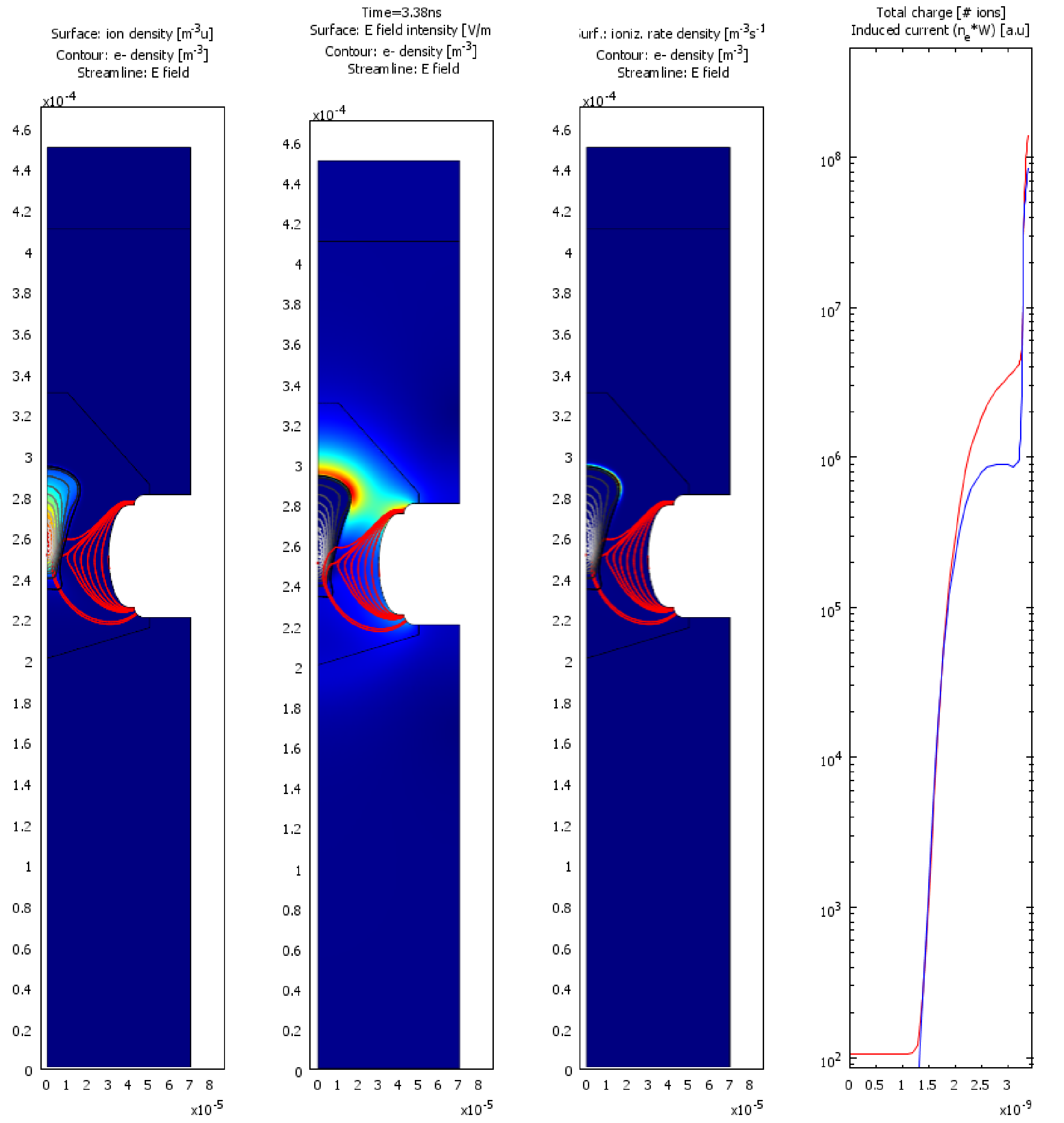
GEM

hole: 60 µm
gap: 100 µm
N_0=100 e^-
V=1250V



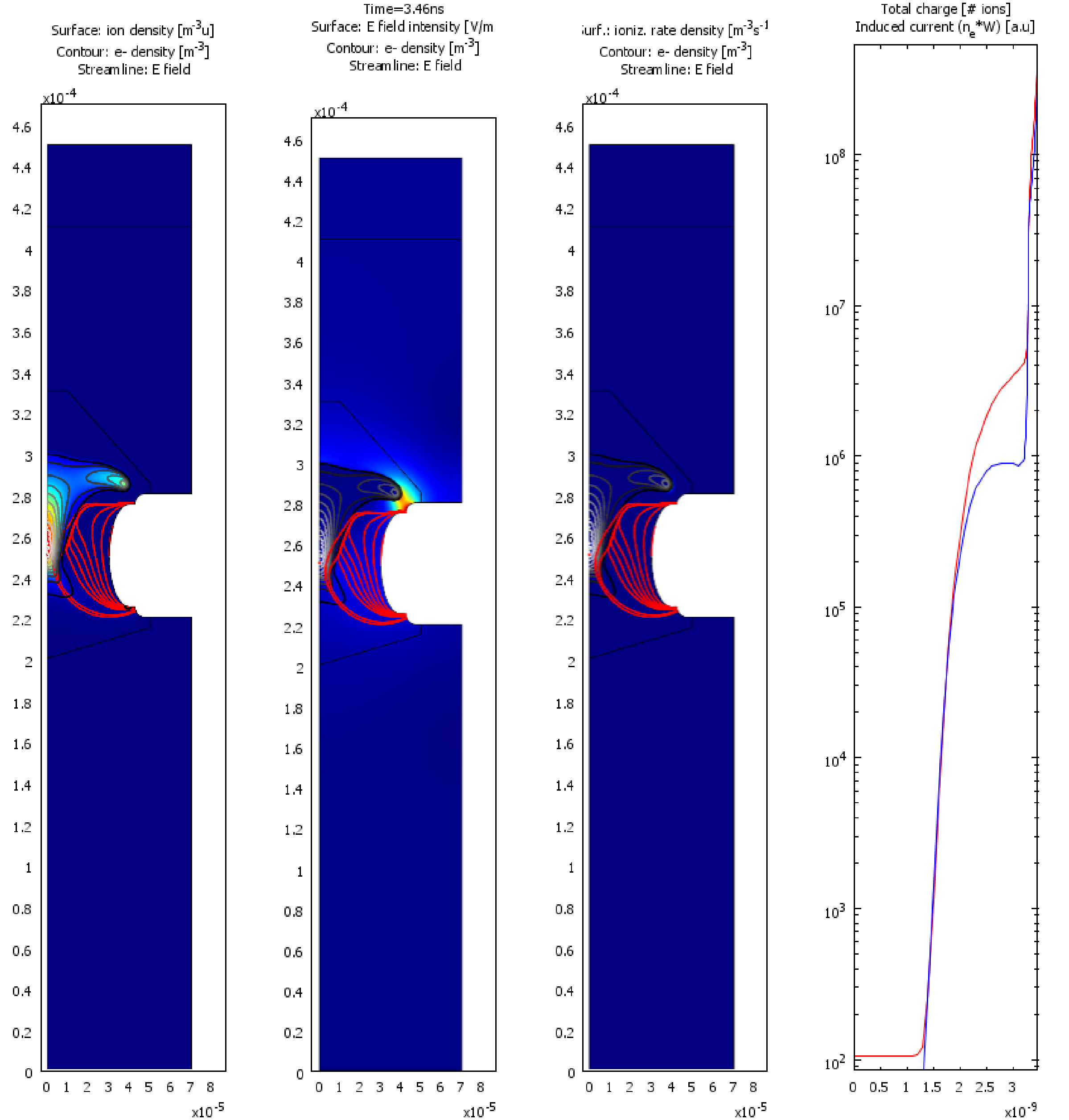
GEM

hole: 60 µm
gap: 100 µm
N_0=100 e^-
V=1250V



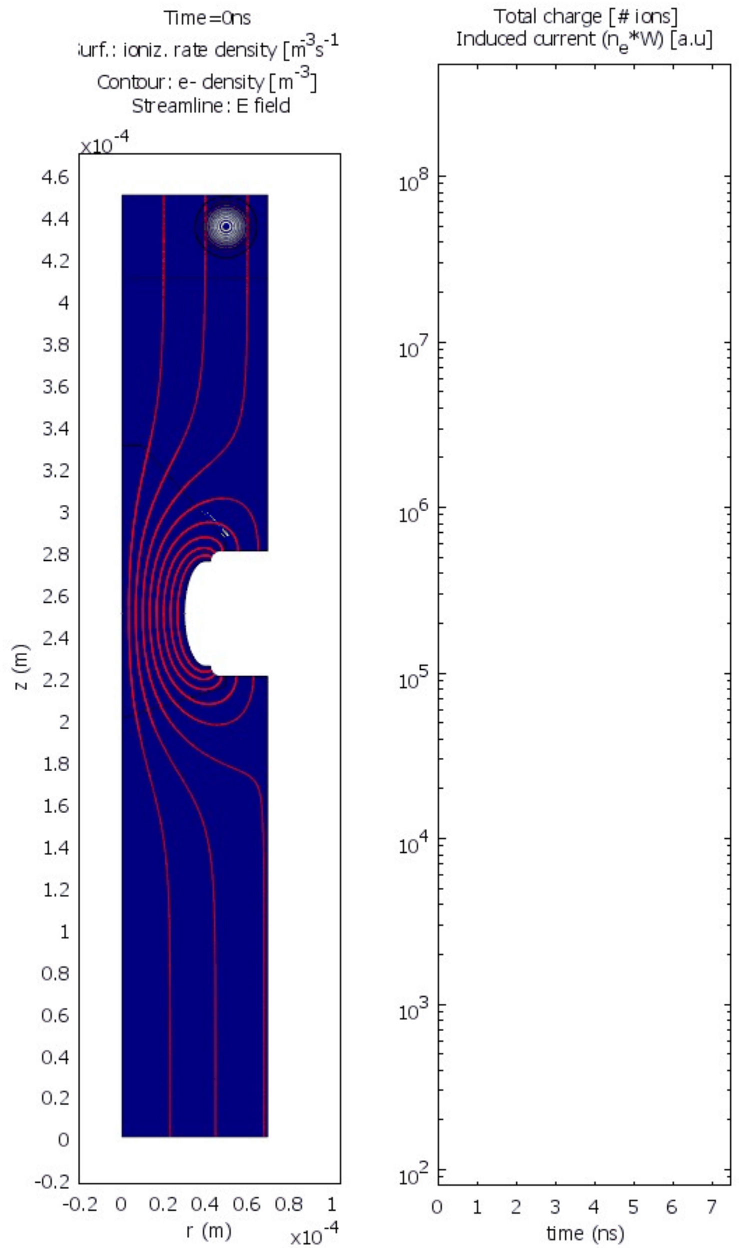
GEM

hole: 60 µm
gap: 100 µm
N_0=100 e^-
V=1250V



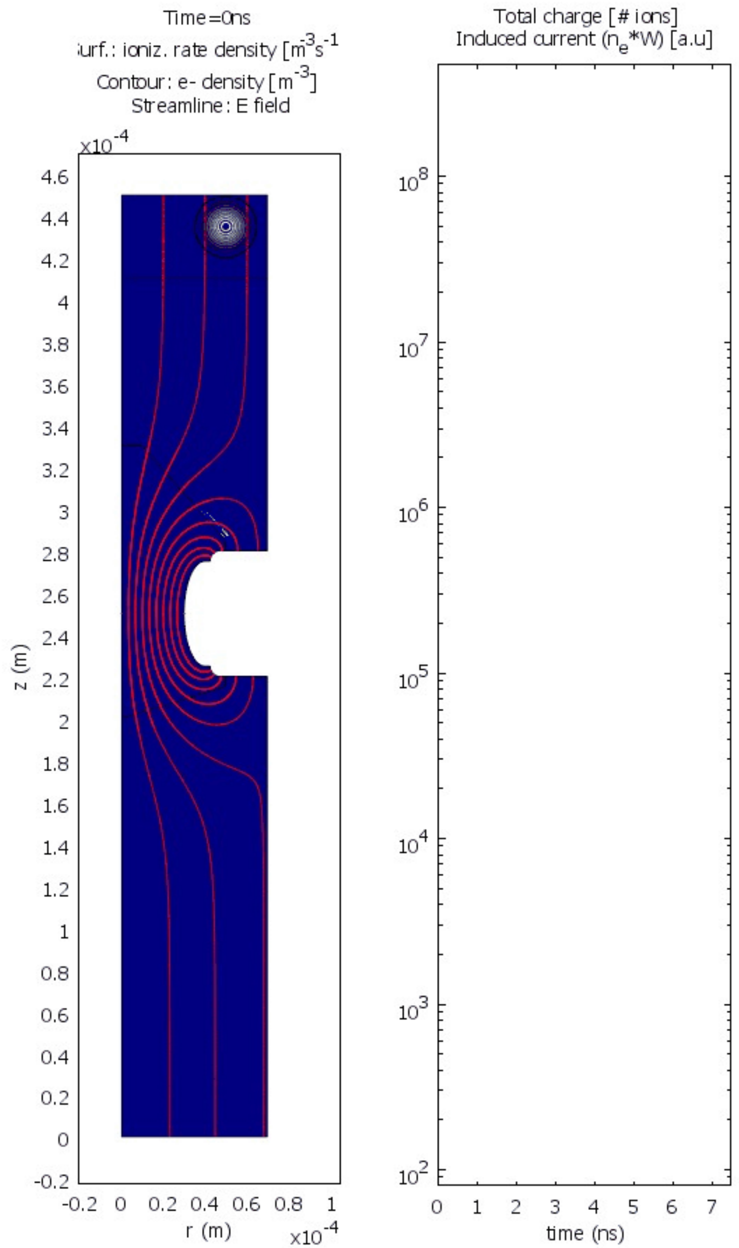
GEM lateral (ring) avalanche

hole: 60 µm
gap: 100 µm
N_0=100 e^-
V=1250V



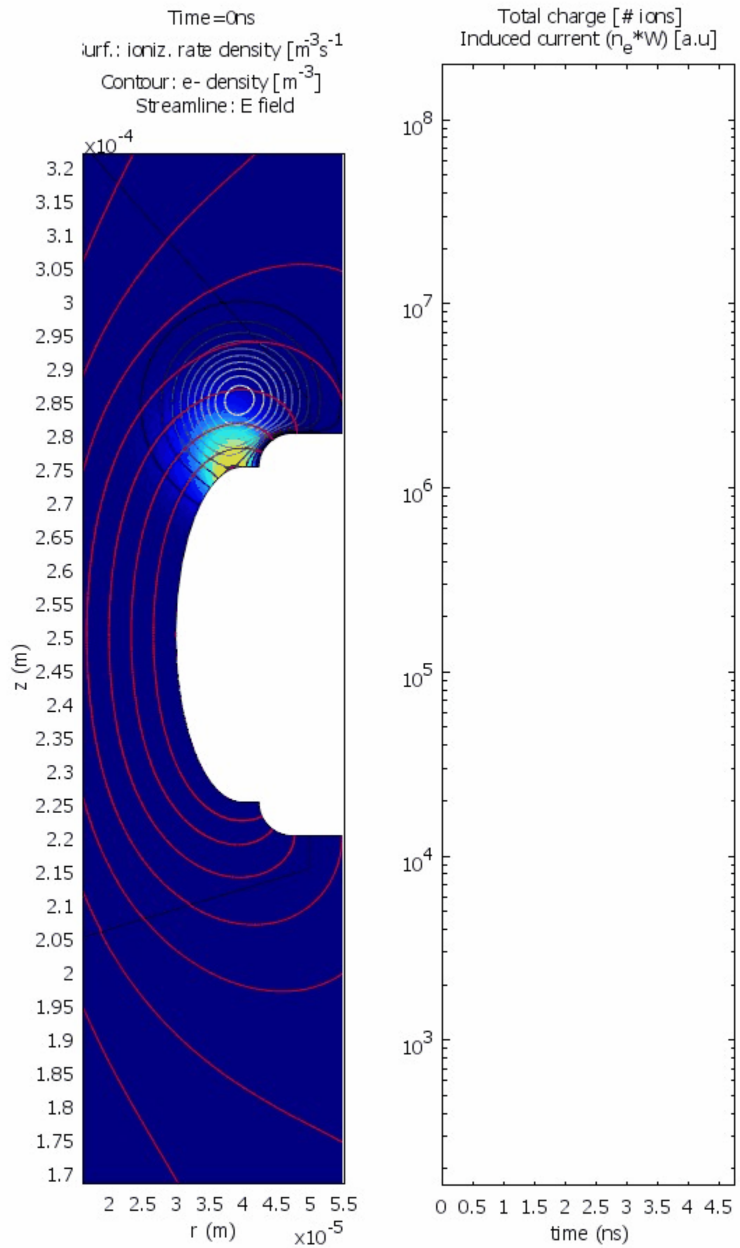
GEM lateral (ring) avalanche

hole: 60 μm
gap: 100 μm
N_0=100 e^-
V=1250V



GEM
surface avalanche

hole: 60 µm
gap: 100 µm
N_0=100 e^-
V=1150V

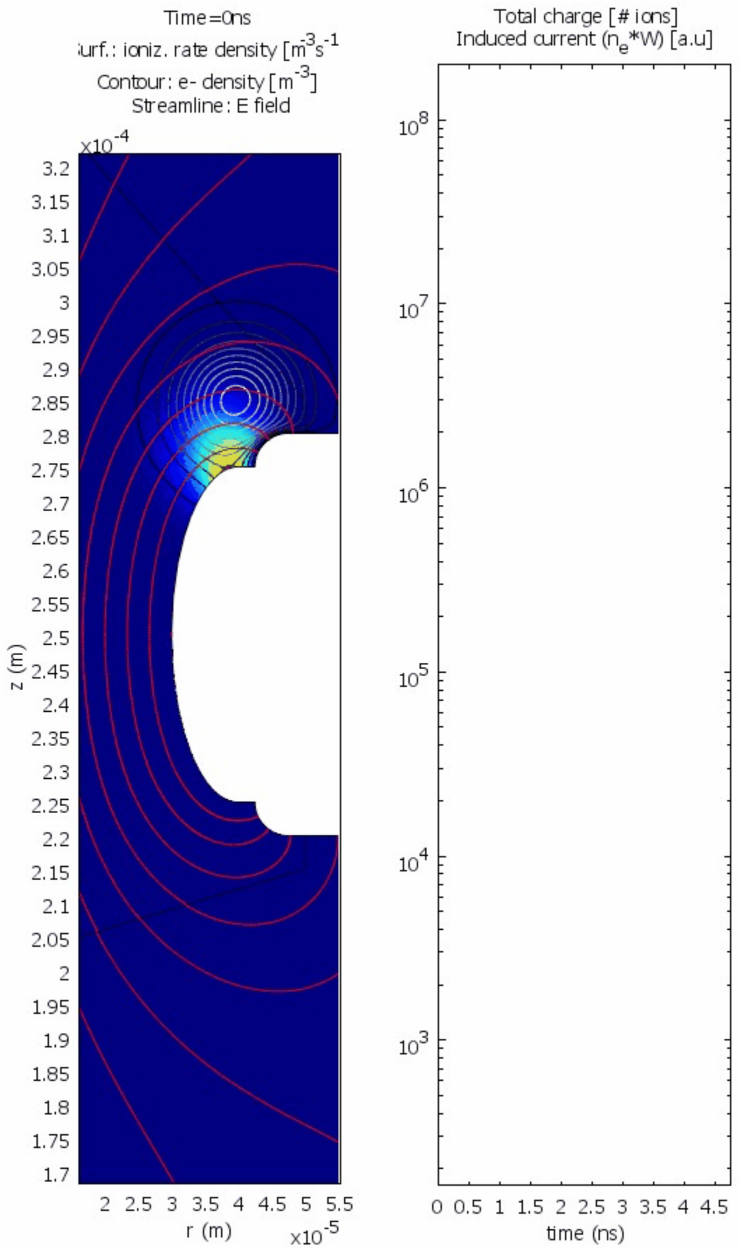


GEM
surface avalanche

hole: 60 µm
gap: 100 µm
N_0=100 e^-
V=1150V

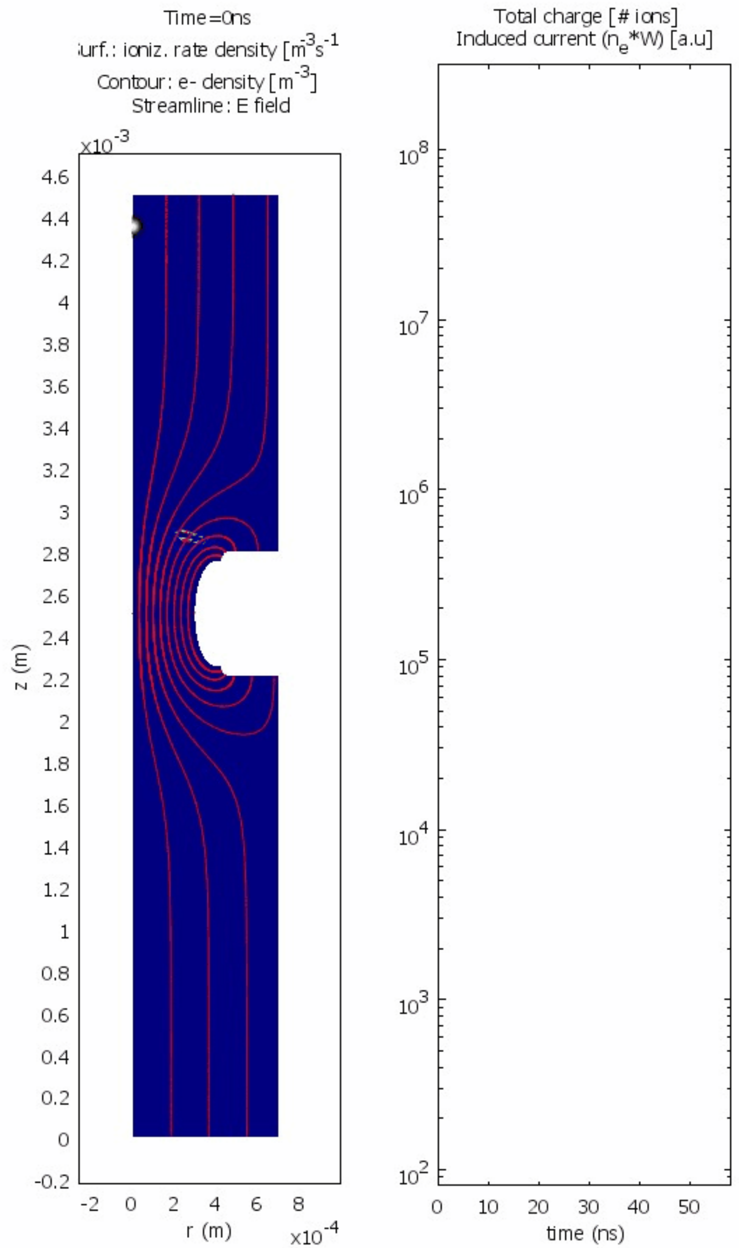
This happens 100V below the streamer limit in the space, limiting the practical GEM gain.

Solved by multistepping.



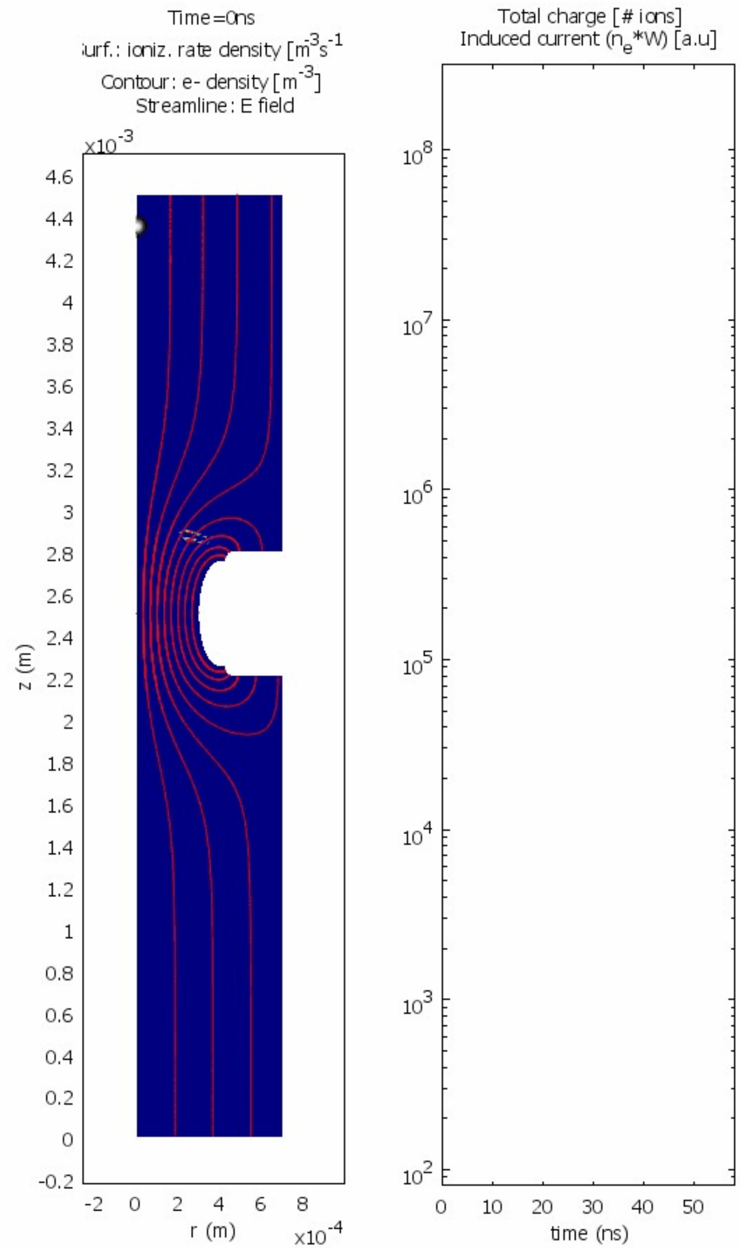
THGEM (GEMx10)

hole: 600 µm
gap: 1 mm
N_0=100 e^-
V=4600V



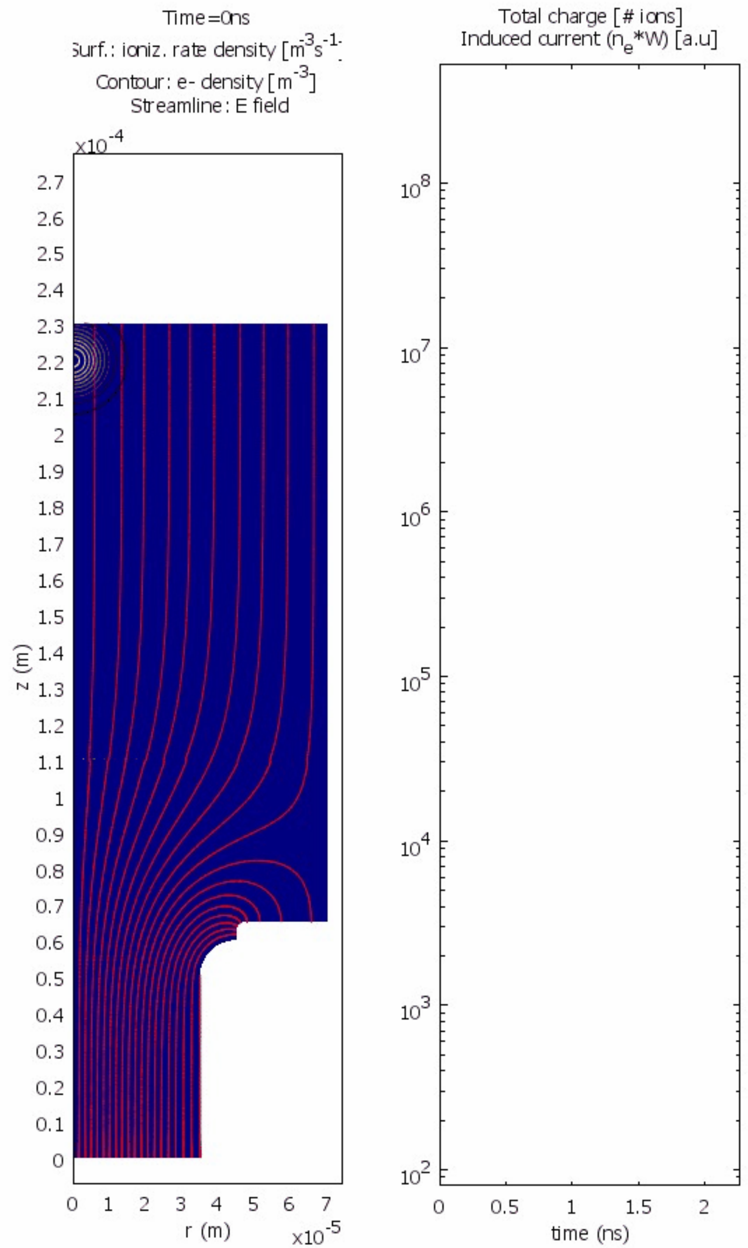
THGEM (GEMx10)

hole: 600 μm
gap: 1 mm
N_0=100 e^-
V=4600V



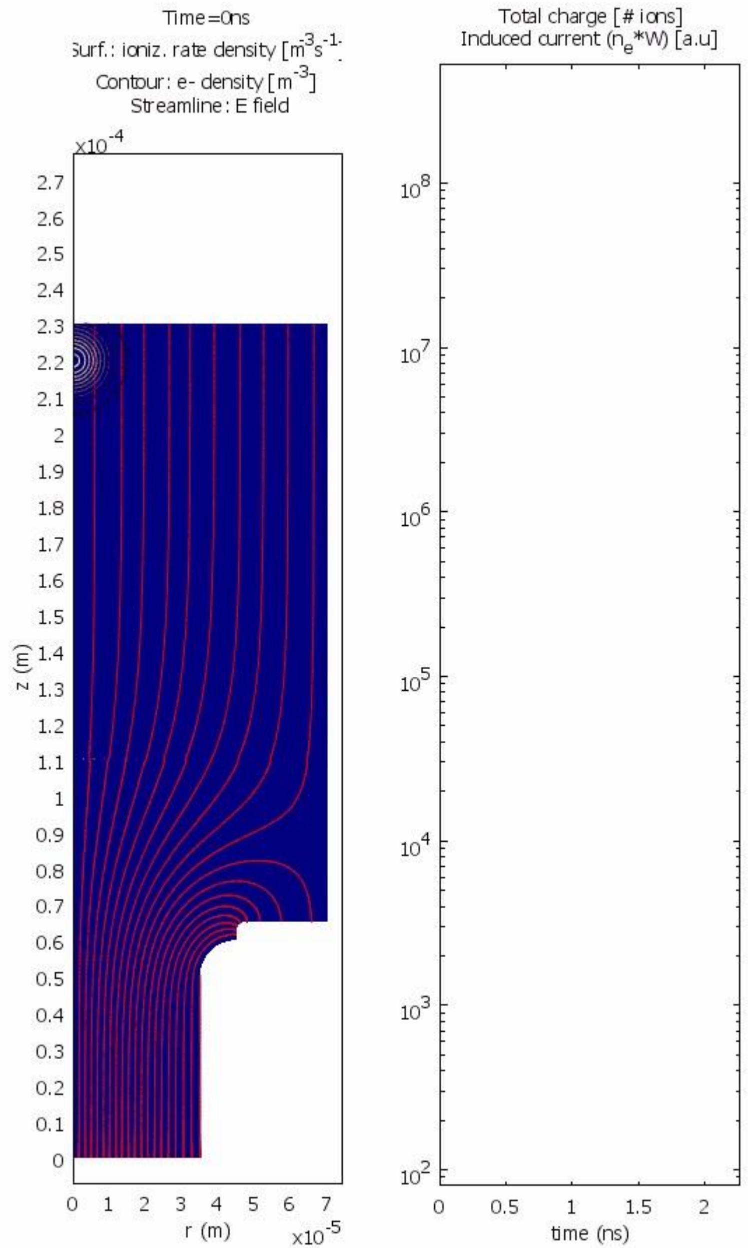
CAT

diameter: 70 µm
height: 650 µm
N_0=100 e^-

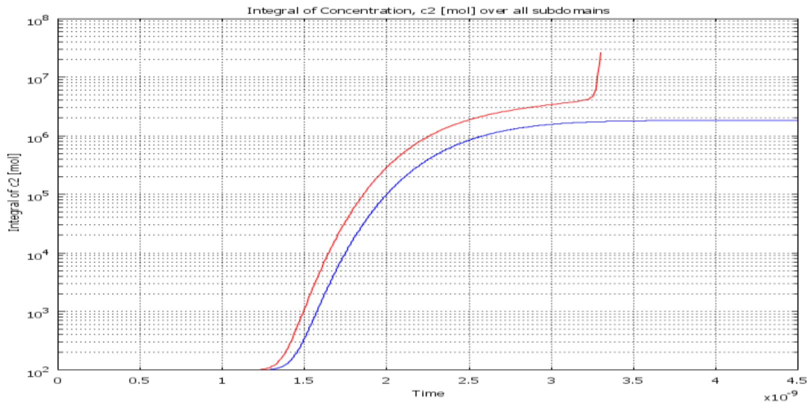


CAT

diameter: 70 µm
height: 650 µm
N_0=100 e^-



Determination of the space-charge limit



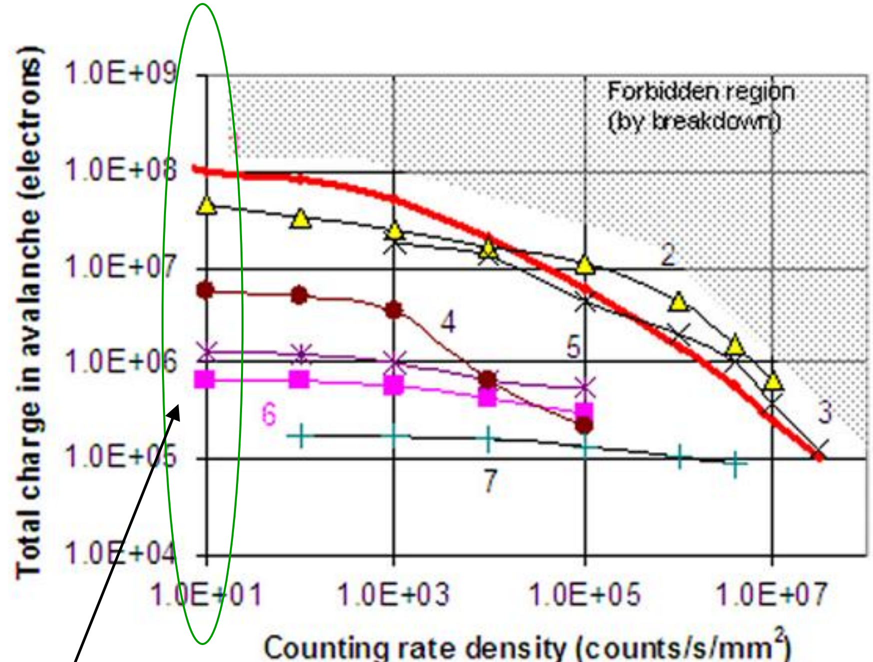
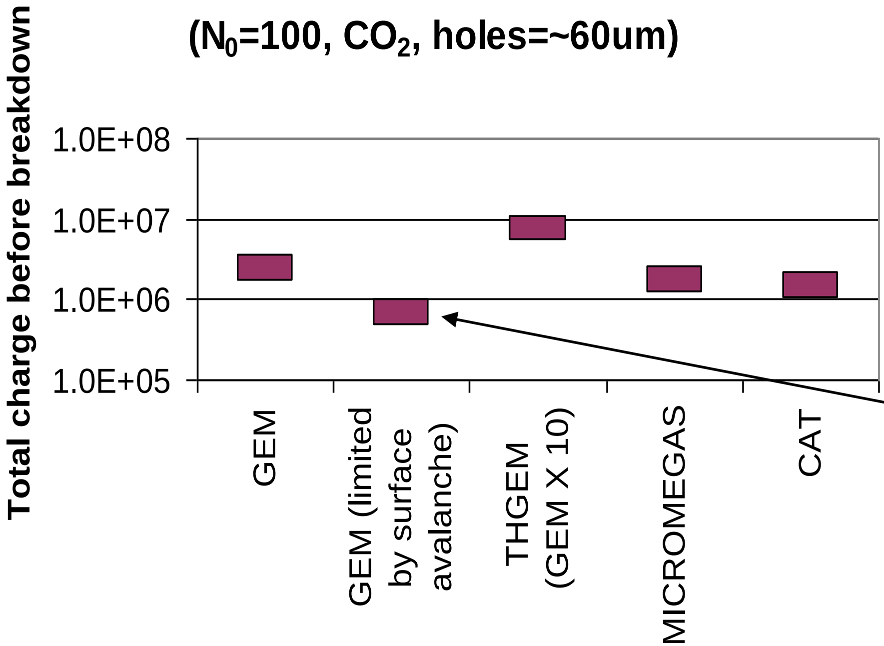


Figure 4. The maximum achievable gain, limited by breakdown, as a function of the x-ray flux for various detectors: (1) PPAC with 3 mm gap; (2) MICROMEGAS; (3) PPAC with 0.6 mm gap; (4) microstrip gas chamber with 1 mm strip pitch; (5) microstrip gas chamber with 0.2 mm strip pitch; (6) GEM; (7) microgap detectors with 0.2 mm strip pitch. Large counting rate densities require a

BREAKDOWN LIMIT
(N_0=100, CO_2, holes=~60um)



~ OK for GEM
Much lower for MM.
(maybe not the same exact geometry, gas, etc)

Streamer-resistant detectors?

single-wire (SQS mode)

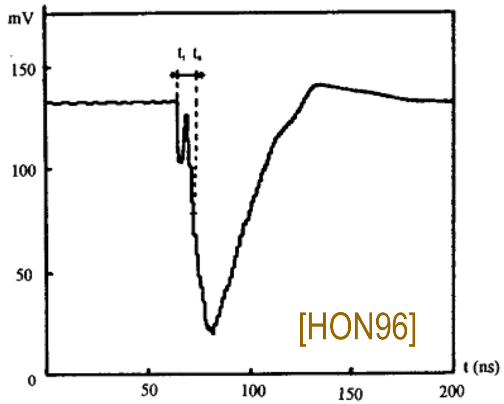
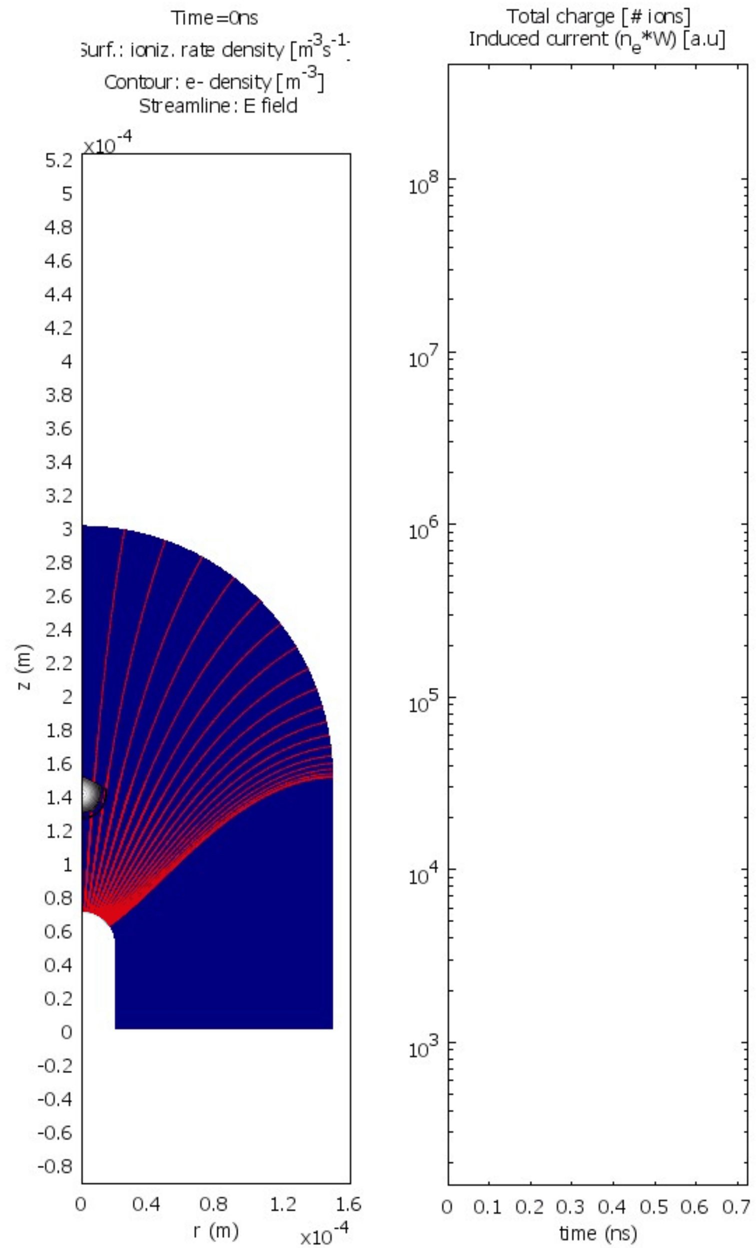


Fig. 1. The pulse shape of the SQS electrical signal $V = 2.45$ kV, Methylal/(Methylal + Ar) = 16.6%.

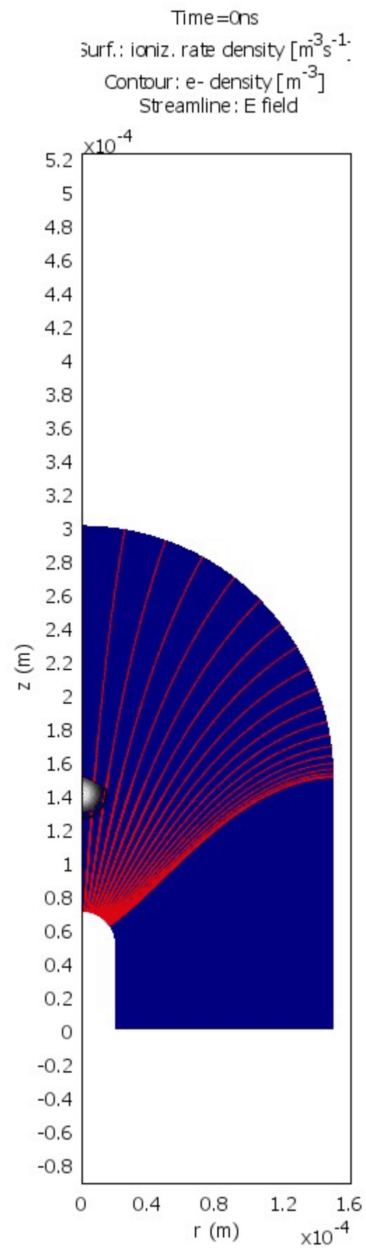
Could there be a self-quenching streamer (SQS) mode in MPGDs?

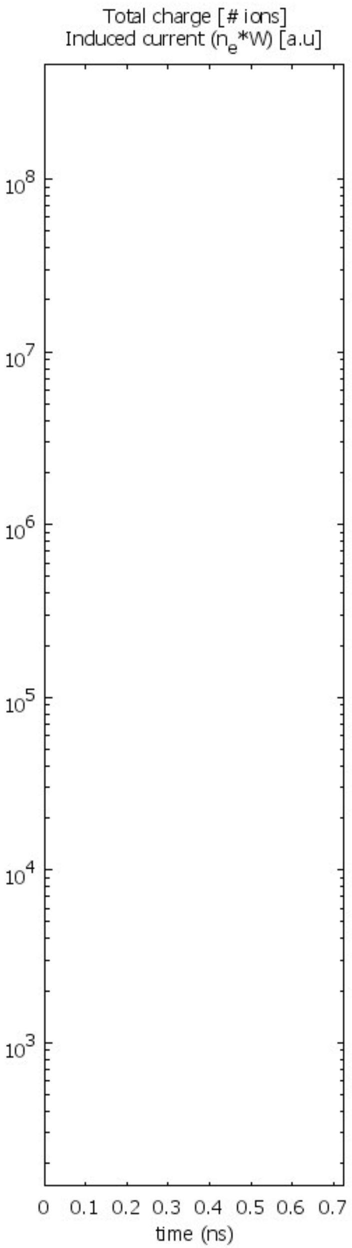
SQS around needles

diameter: 40 µm
N_0=100 e^-



SQS around needles





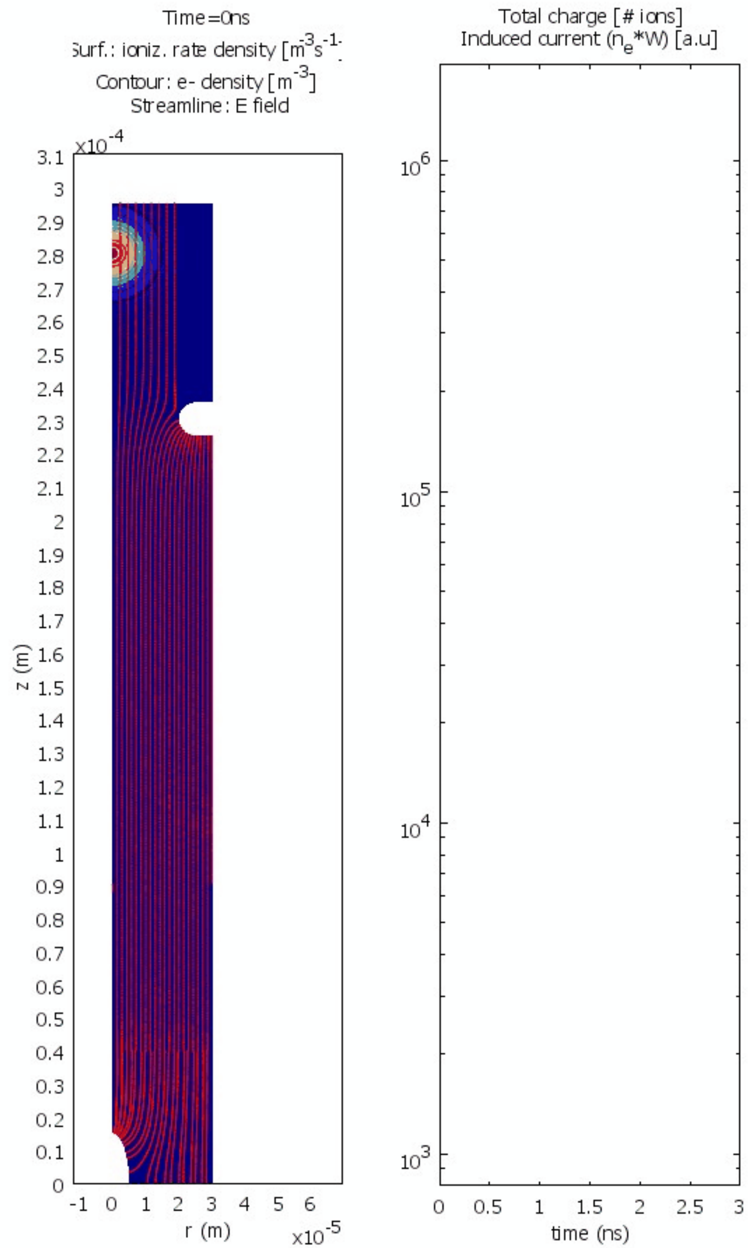
Array of needles
+ InGRID

diameter: 10 µm

N_0=1000 e^-

Or course:

needle ⇒ low rate capability

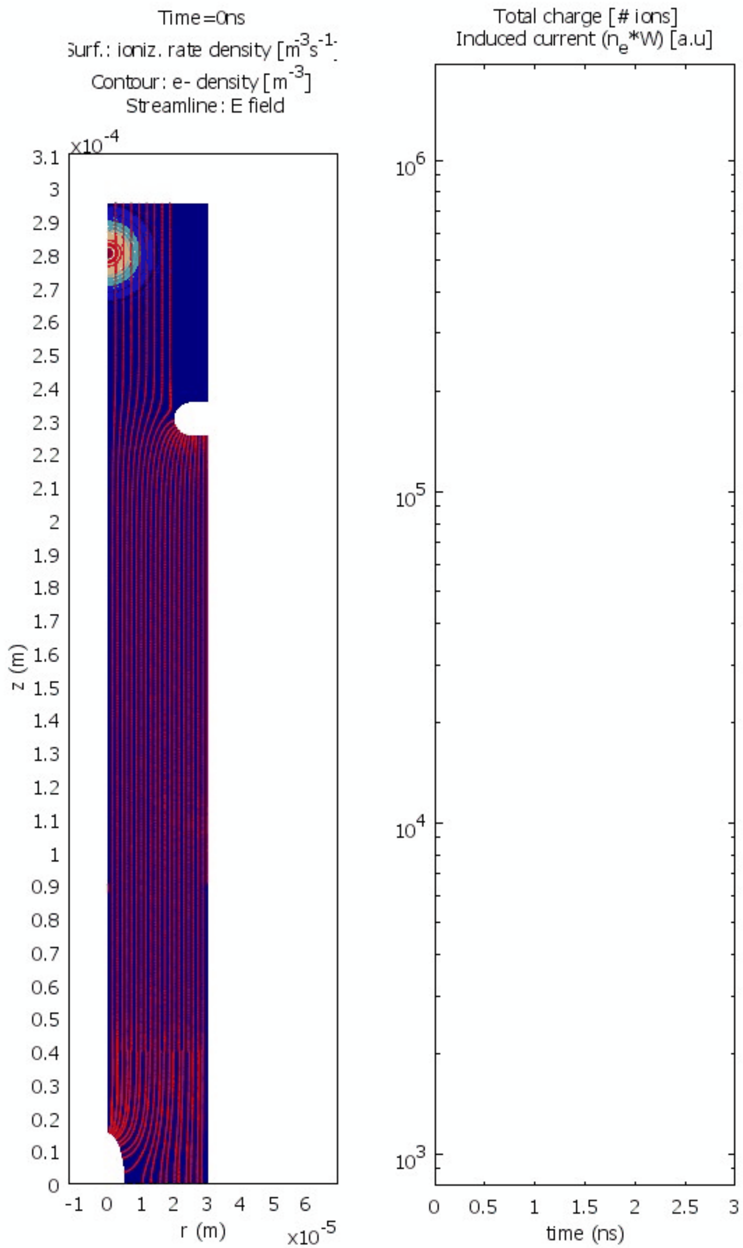


Array of needles + InGRID

diameter: 10 µm

N_0=1000 e^-

It seems there is indeed an SQS regime in the needle

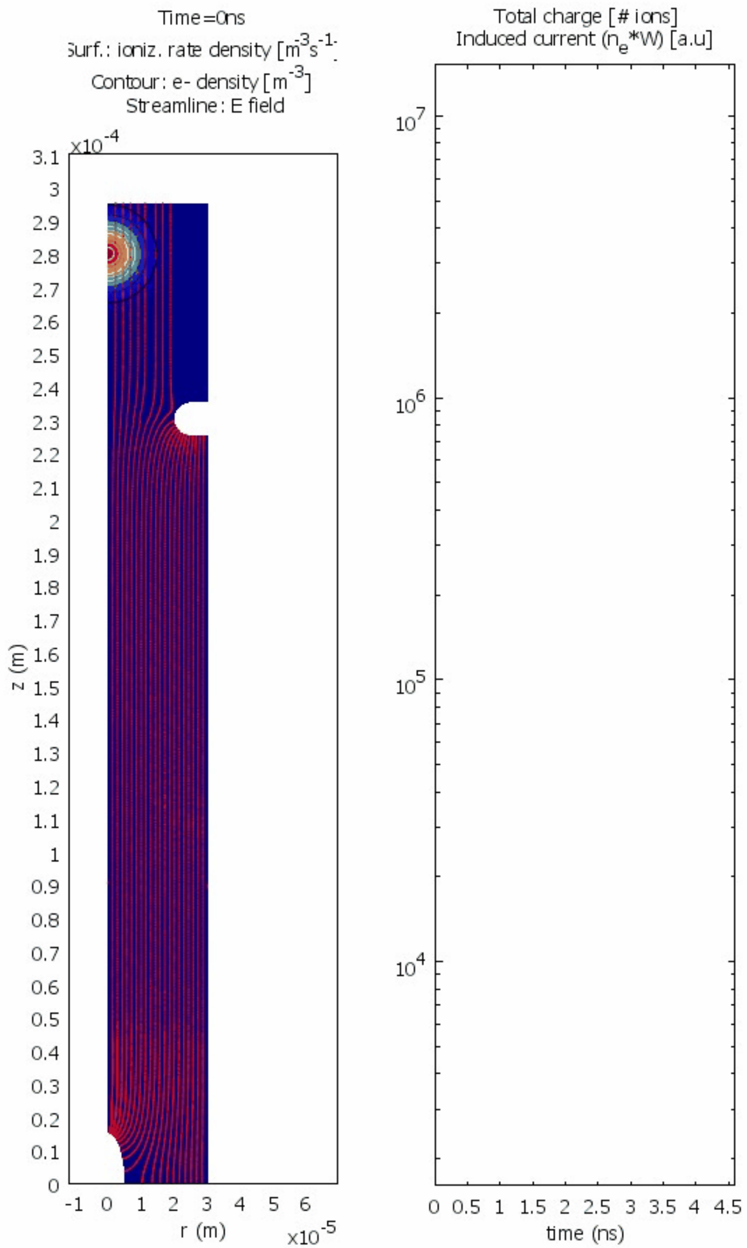


Array of needles
+ InGRID

diameter: 10 µm

N_0=2000 e⁻

Larger charge

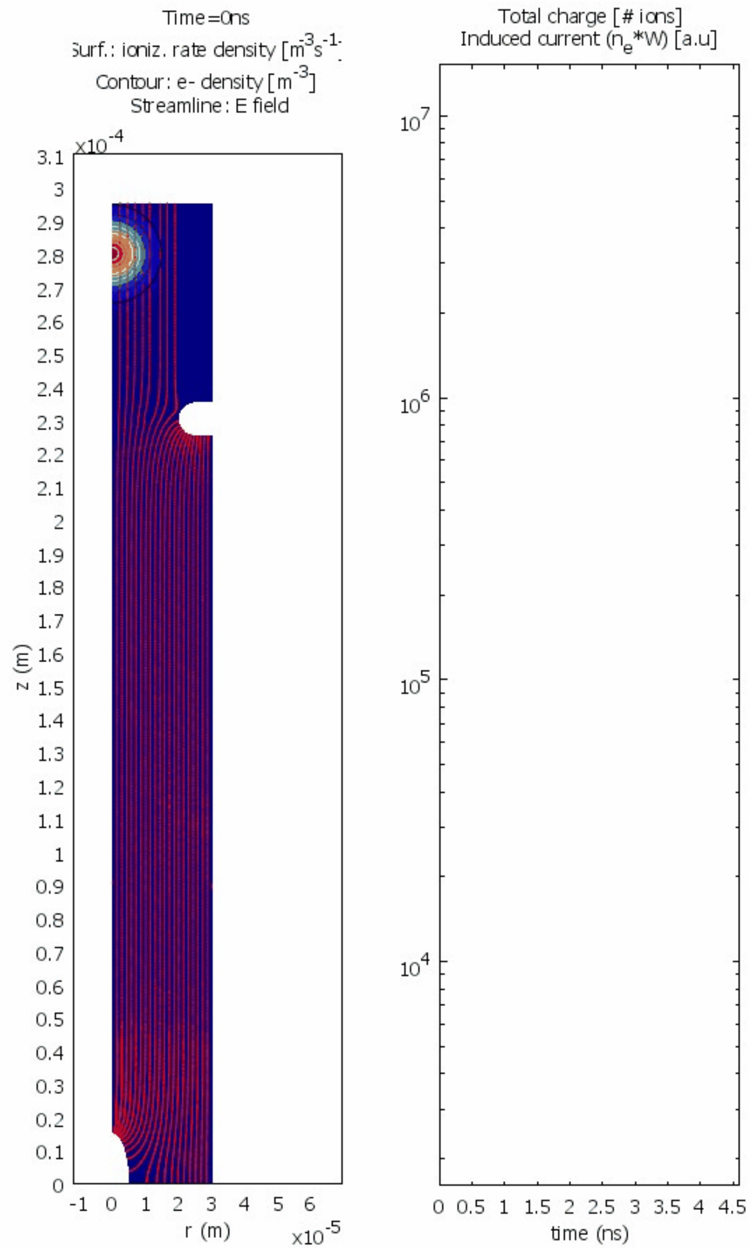


Array of needles + InGRID

diameter: 10 µm

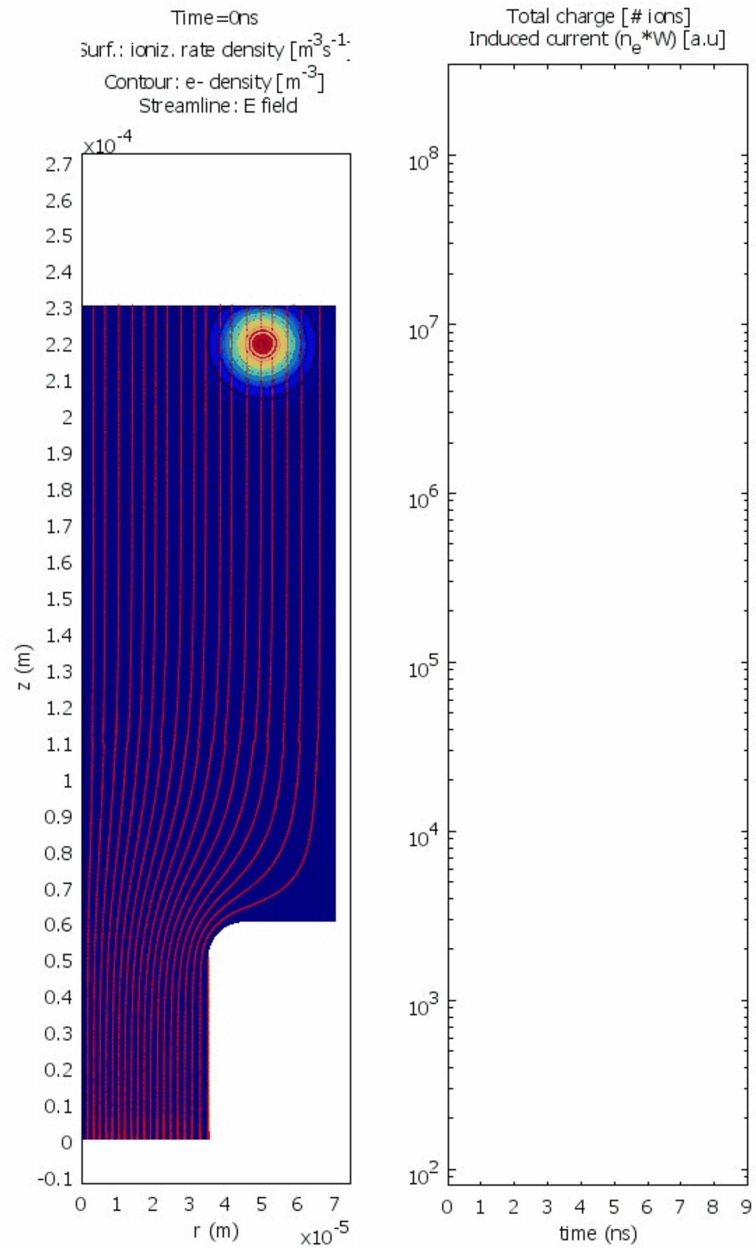
N_0=2000 e^-

It seems there is indeed an SQS regime in the needle, but there is still too much parallel-field gain.



Cathodeless CAT

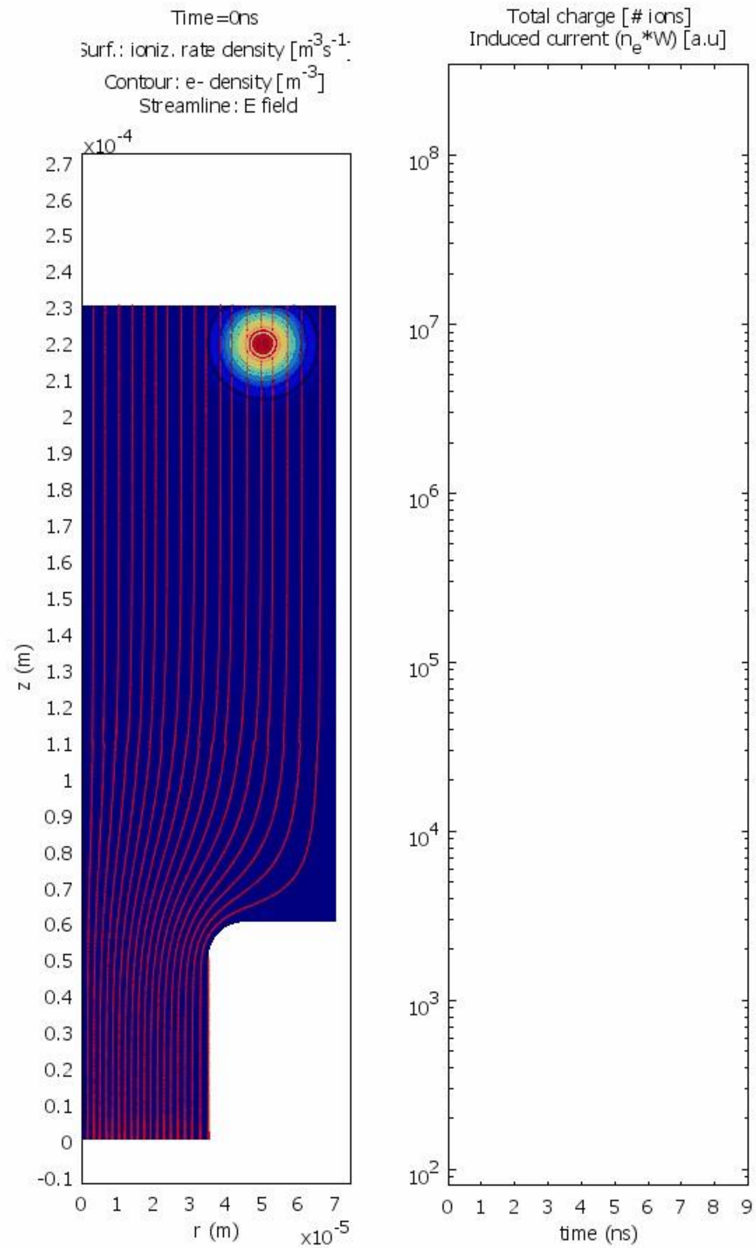
Will the streamer be able to grow out of the hole?



Cathodeless CAT

Not completely successful, but it sparks at a rather large charge.

Maybe such geometries can be optimized for SQS mode.



Summary

- Streamers can be supported by diffusion alone
- This seems to be qualitatively more in agreement with the empirical observations in detectors than the classical mechanism based on self-photoionization
- The corresponding hydrodynamic model seems to describe qualitatively fast breakdown in detectors
- Gives correct breakdown limit for GEM
- Seems to reproduce SQS in needles
- Useful tool for detector design and optimization. No SQS so far…

- Further work
    - detailed comparisons with careful spark-limit measurements

References

[COMSOL] www.comsol.se

[DUE94] I. Duerdoth et al., Nucl. Instrum. and Meth. A 348 (1994) 303

[FON91] P. Fonte et. al., Nucl. Instrum. and Meth. A310 (1991) 140

[FON10] P.Fonte and V.Peskov, arXiv:0911.0463v1.

[HER02] J.L.Hernandez-Avila et al., J.Phys.D:Appl.Phys. 35 (2002) 2264–2269

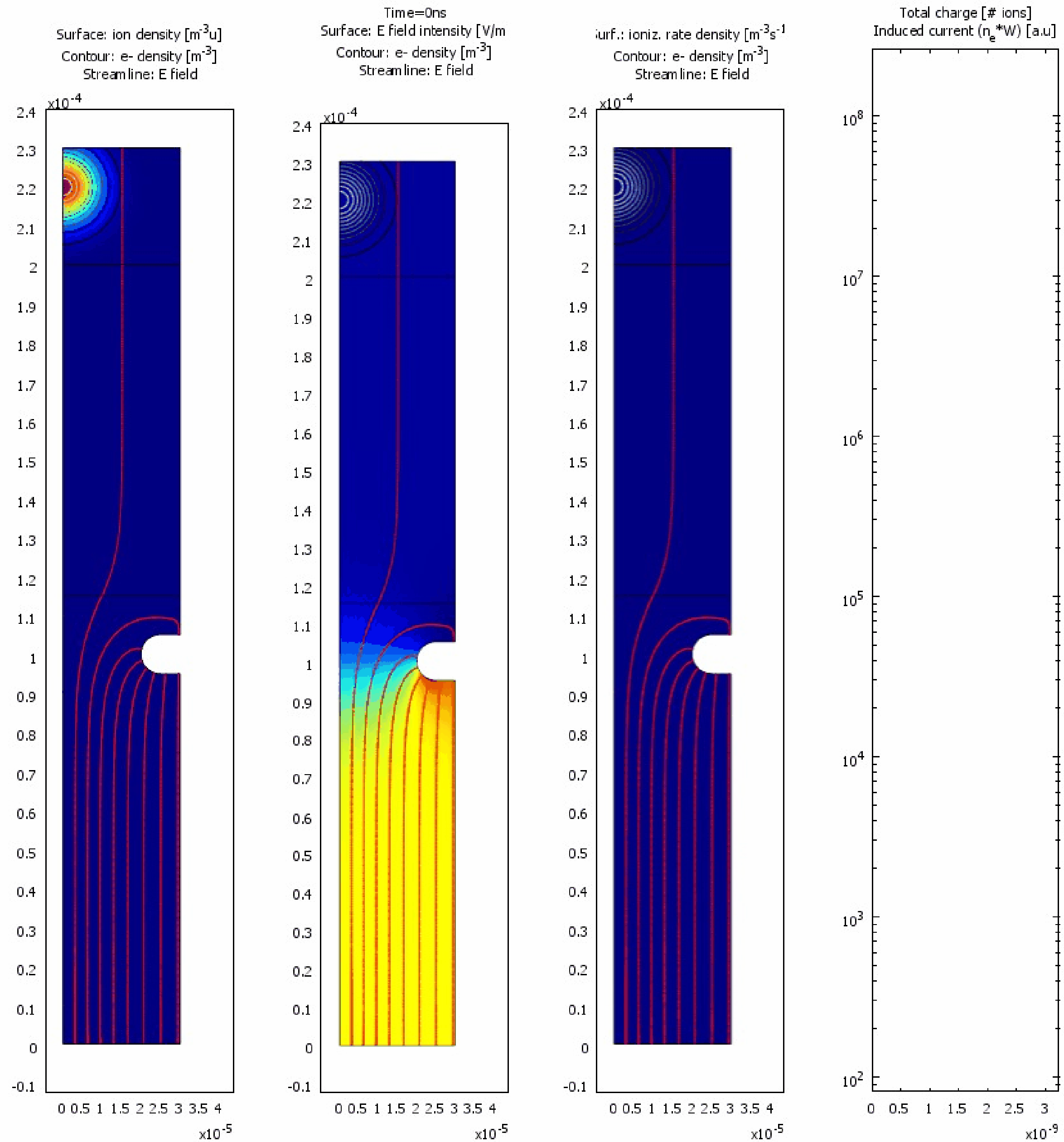
[HON96] C. Hongfang et al., Nucl. Instrum. and Meth. A373 (1996) 430

[KAM02] Kameta K et al., J. of Electr. Spectr. and Related Phenomena (2002) 123

[KLI72] Kline and Siambis, Phys. Rev. A 5 (1972) 794

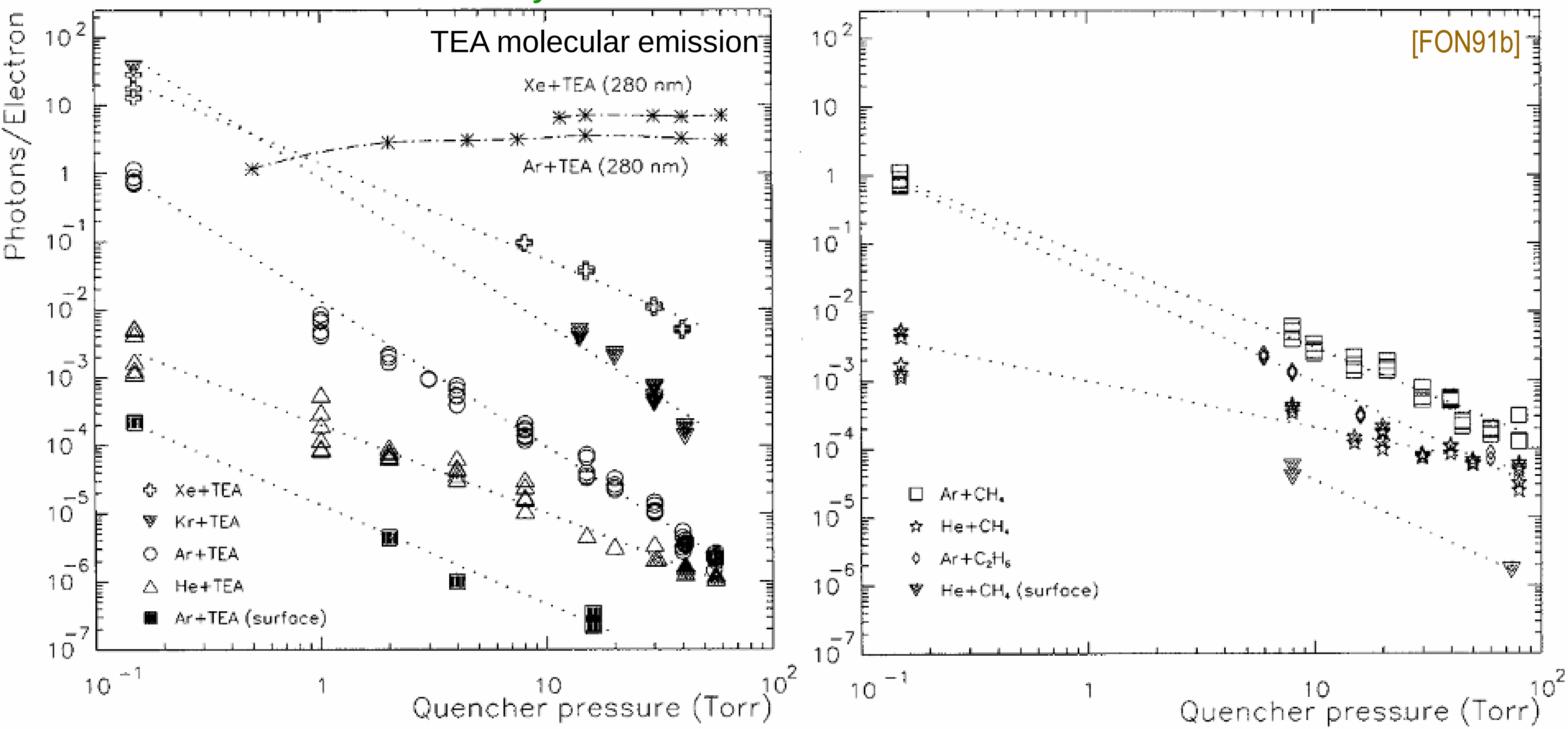
MICROMEGAS

hole: 30 µm
gap: 100 µm
N_0=100 e^-



Emission suppression by "quenchers"

Photon yields in PPAC in the band:120-170nm



There is some evidence that the emission originates mainly from fragments (likely carbon atomic emission lines) at λ>140nm.

Photoemission strongly suppressed for quencher concentration 1-10%

If "quenching" was the answer, people ought to have found a sparkless gas, or at least one that would strongly expand the sparking limit.