Discharge phenomena in gaseous detectors

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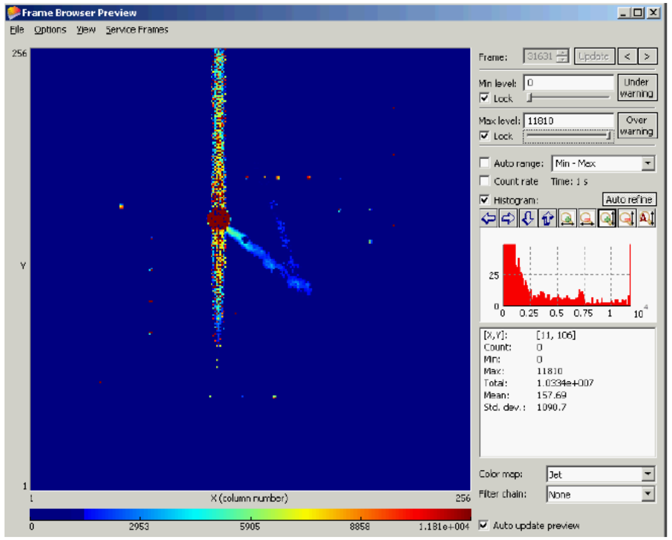


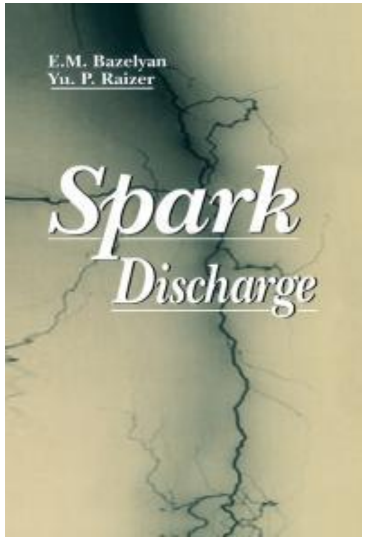
Discharge phenomena in gaseous detectors

V. Peskov

CERN

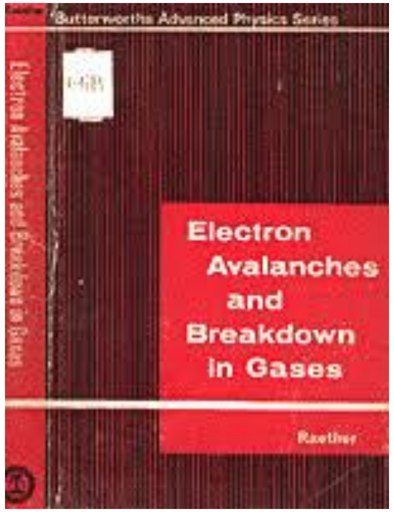
…discharges in gaseous detectors give a continue headache in our community…

Why this old problem was not solved yet?



The possible answer is that discharges in gases, in general, are quiet complicated phenomena and <u>many details are not still fully understood</u>

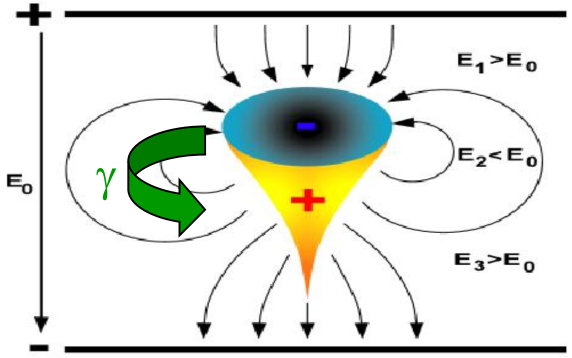
(see, for example E.M Bazelyan, Y.P. Raizer, "Spark Discharge")



However, gaseous detectors represent, probably, the simplest (!) case

The main foundlings/understanding are summarized in

H. Raether "Electron avalanches and breakdown in gases"



The aim of this talk is to give an exhaustive information about these phenomena

The talk consists from 3 parts:

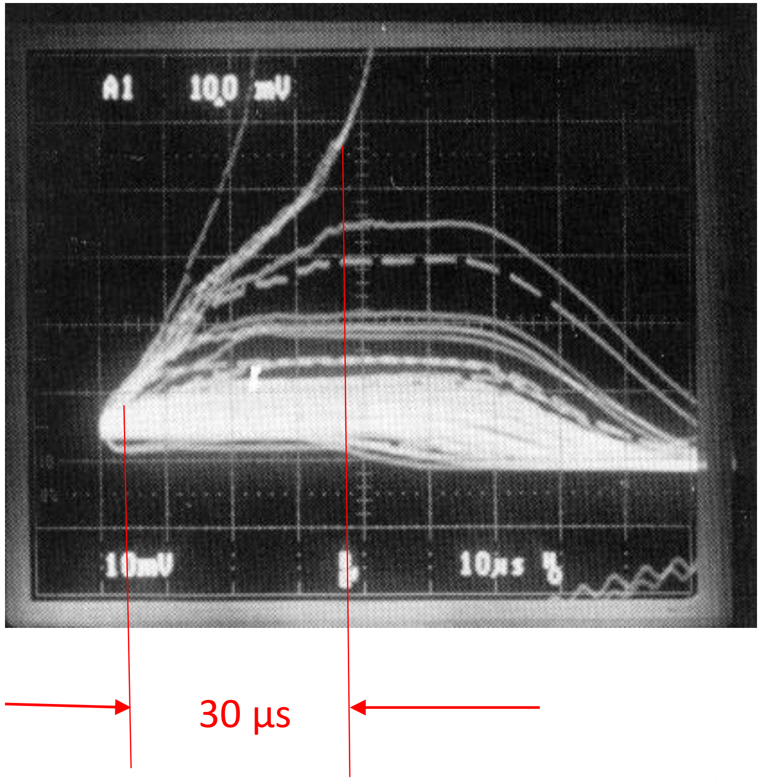
1. What is known (before MPGD era)
2. New findings (happened during MPGD era)
2. Possible ways of discharges prevention/protection in MPGD

Part I

What was well known about discharges in gaseous detectors before MPGD era

I.1. “Slow” and “fast” breakdowns

According to the commonly accepted classification, discharges in gaseous detectors can be dived on two main categories: a so called “slow” and ”fast”. We will quickly review them with an emphasis on some still not fully understood features (to be marked though the presentation as) 



I.1. Slow breakdown

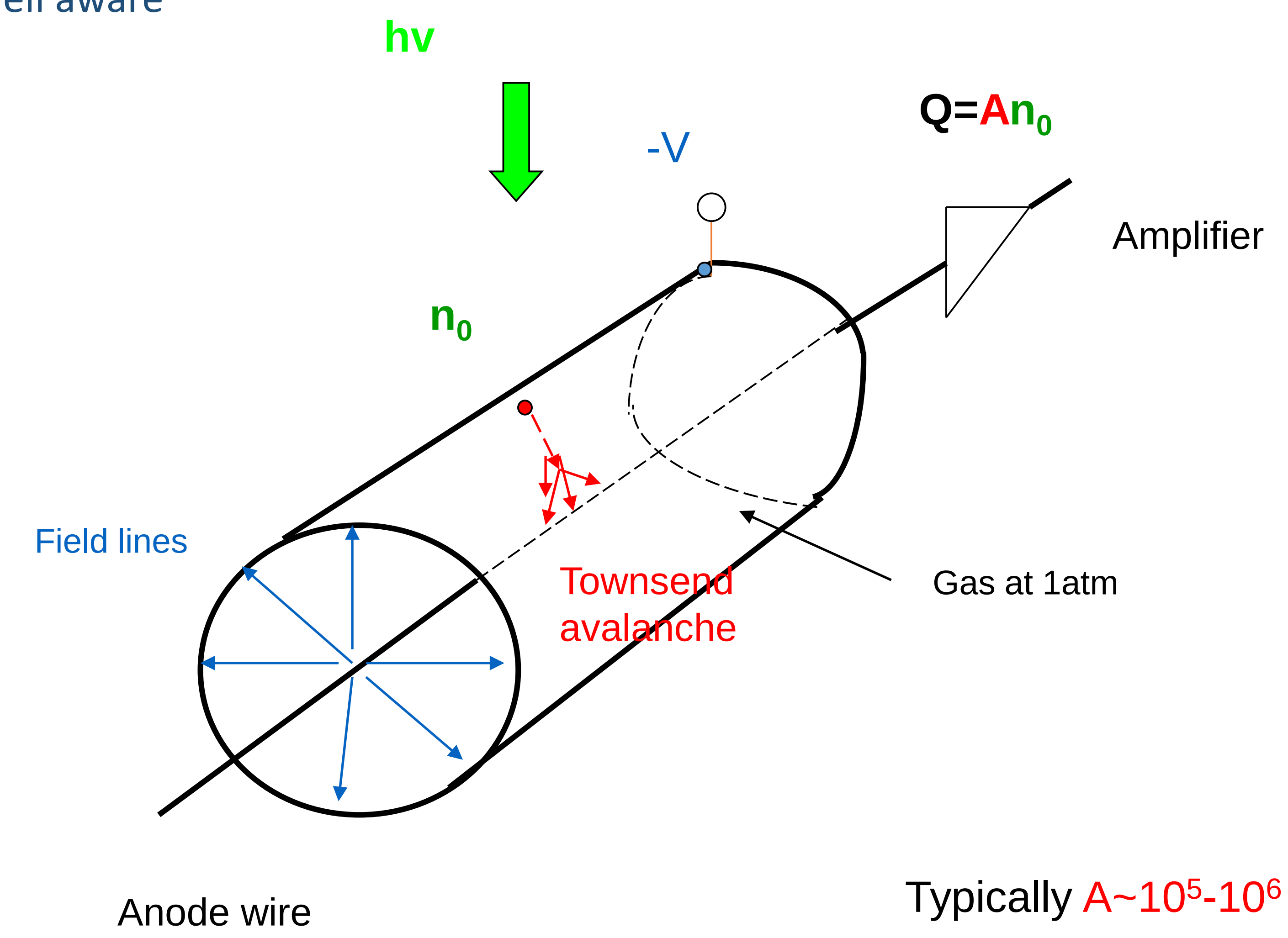
(a discharge which develops relatively slow, typically > 10μs)

Usually occurs in a single -wire counter (with a <u>thin</u> anode wire) or in detectors combined with high efficient photocathodes

H. Raether "Electron avalanches and breakdown in gases"
<u>The latest studies</u>: P. Fonte et al., NIM, A305, 1991, 91

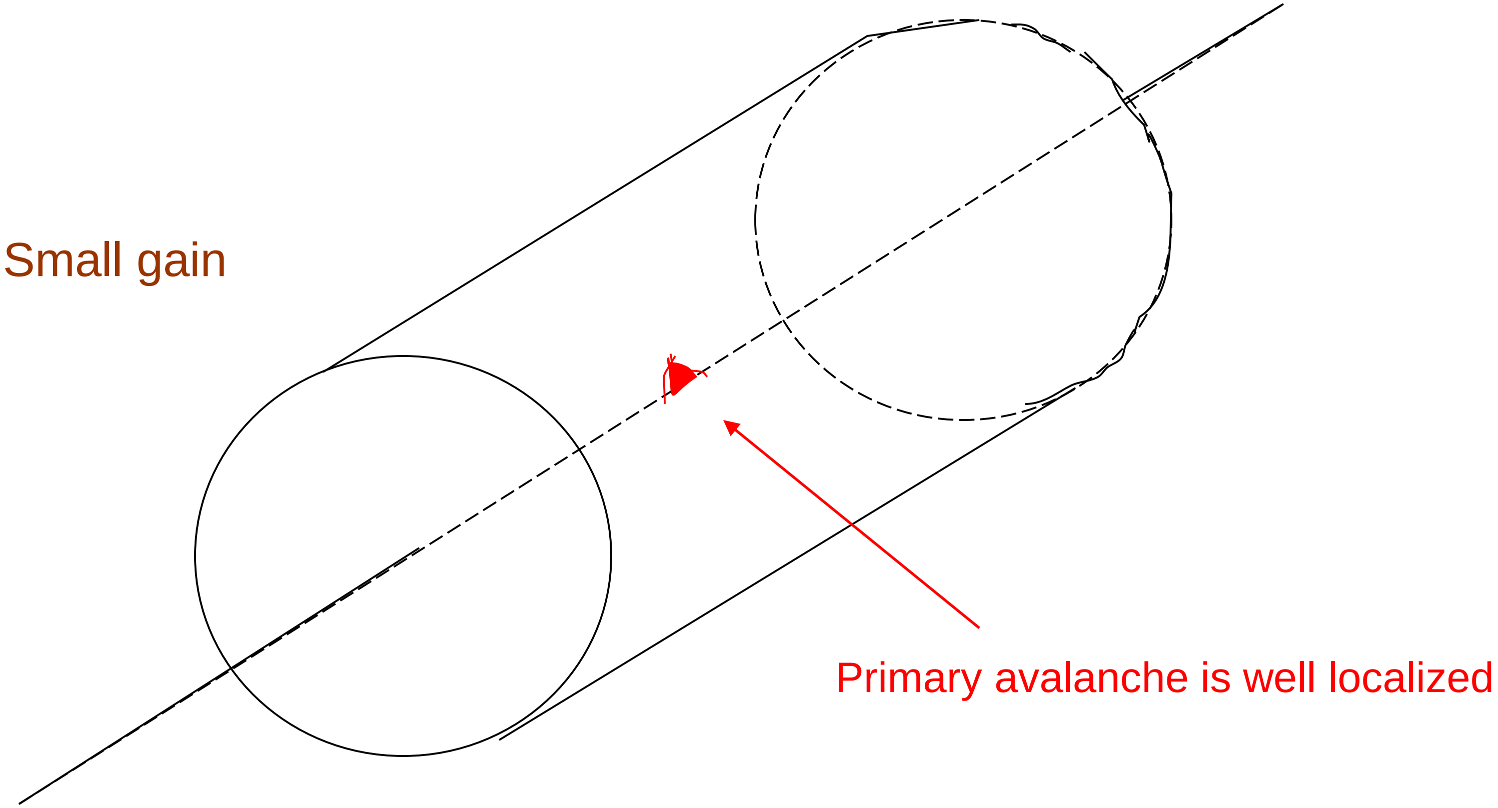
…let`s review it very shortly/schematically because this auditorium is well aware about all this…

Lets consider two cases:
unquenched
and
quenched gases

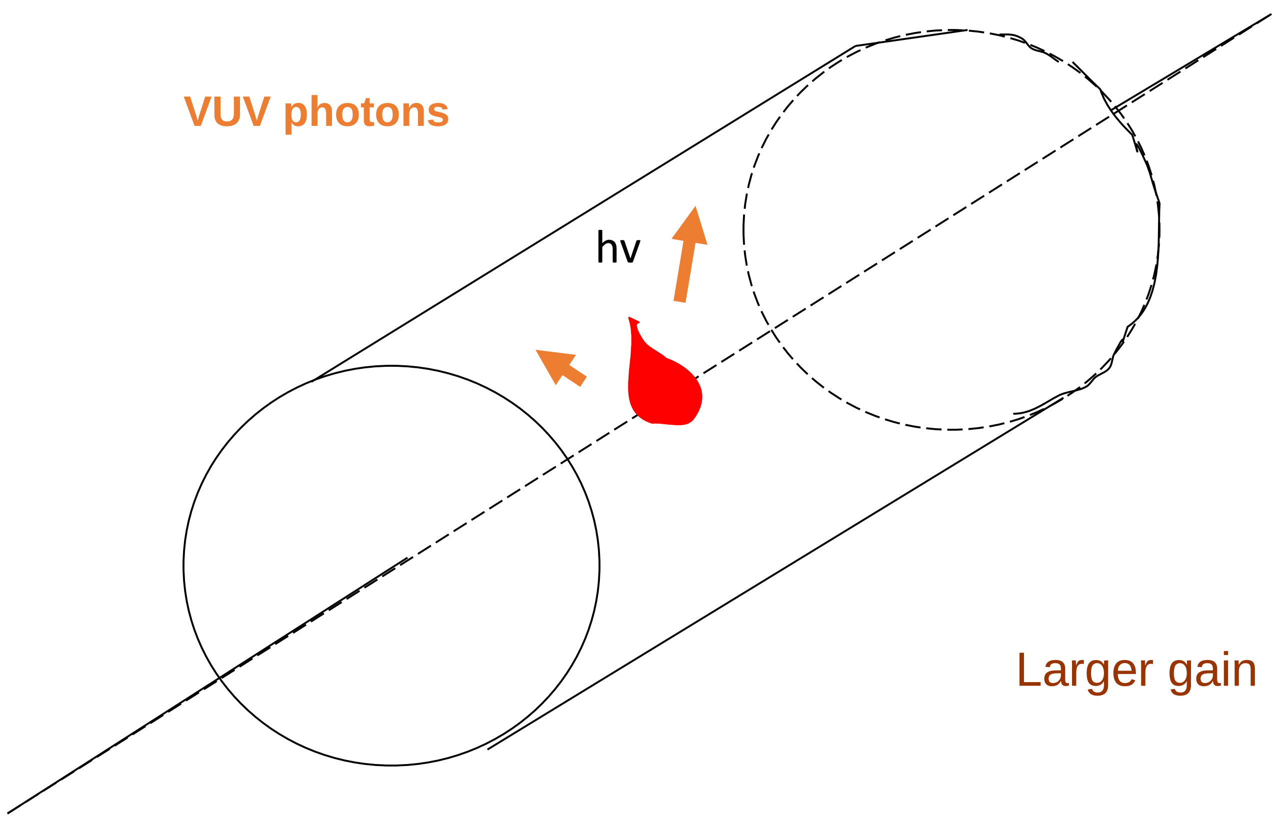


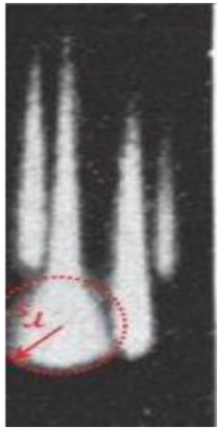
Typically $A \sim 10^5 - 10^6$

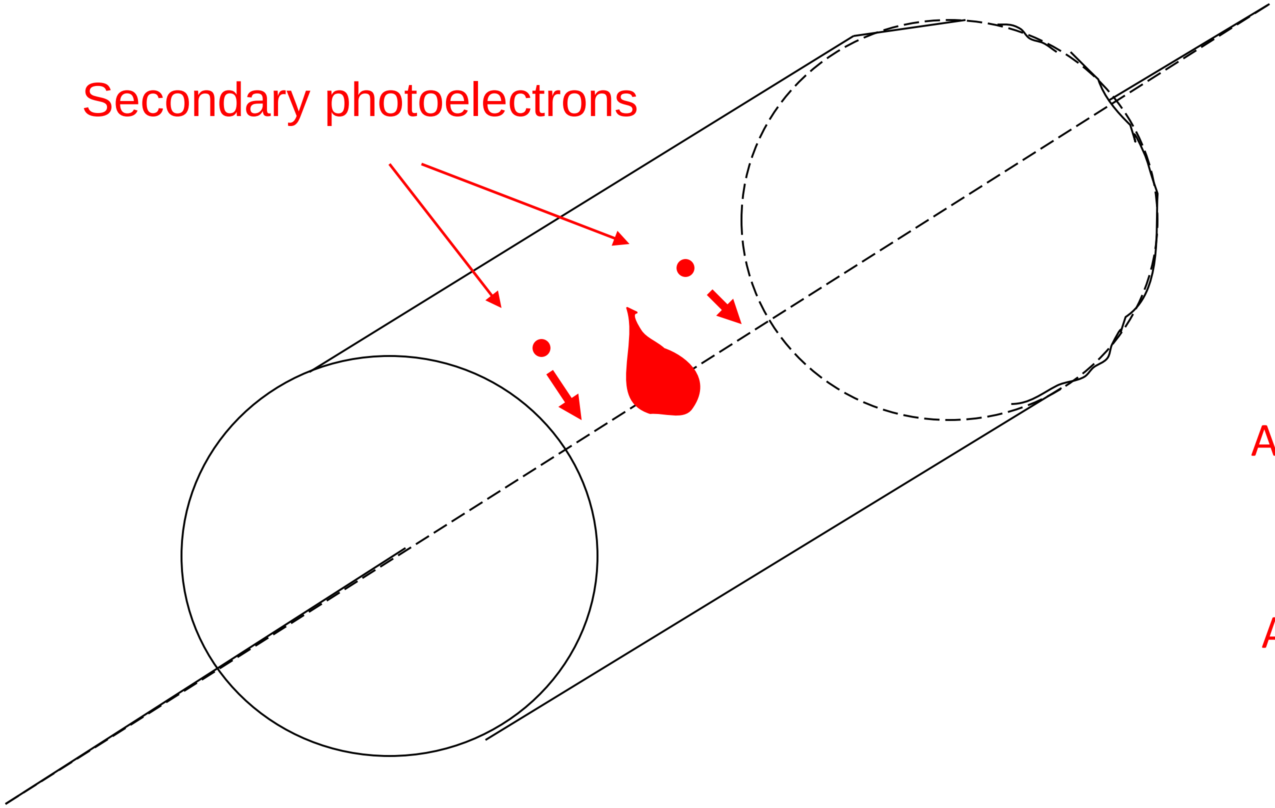
Small gain



Discharge development in a thin wire detector filled with unquenched or poorely quenched gases


VUV photons
hν
Larger gain



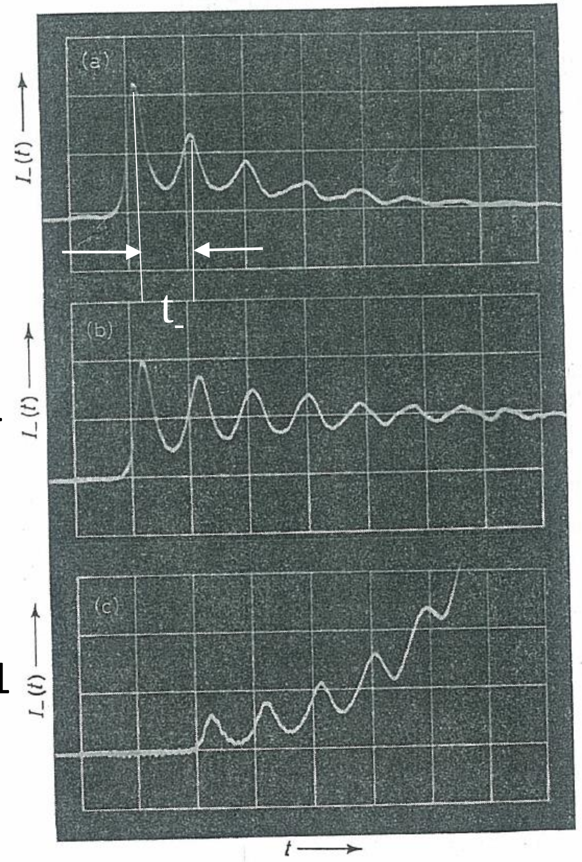


An example of chain of feedback pulses

$A\gamma_{ph} < 1$

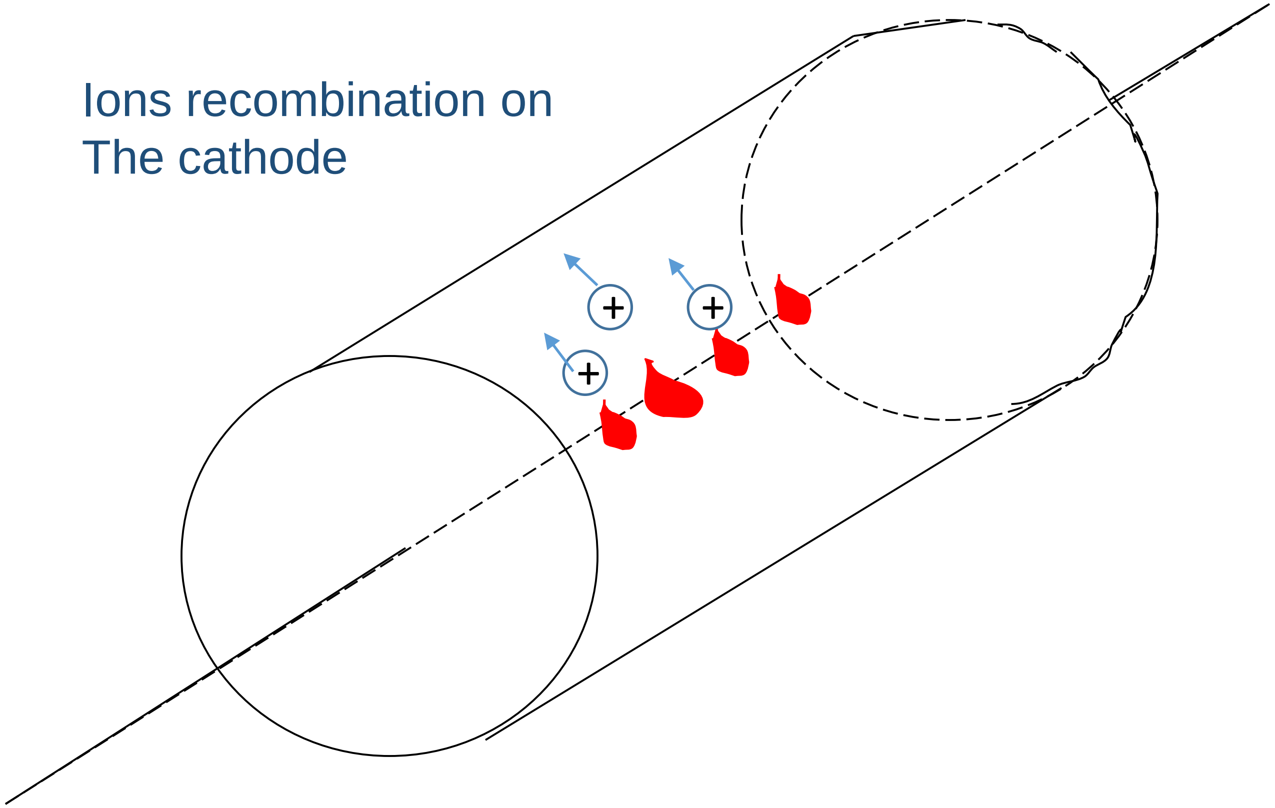
$A\gamma_{ph} \sim 1$

$A\gamma_{ph} = 1$



γ_{ph} is the probability of secondary processes due to the photoeffect from the cathode (or photoionization in some cases)

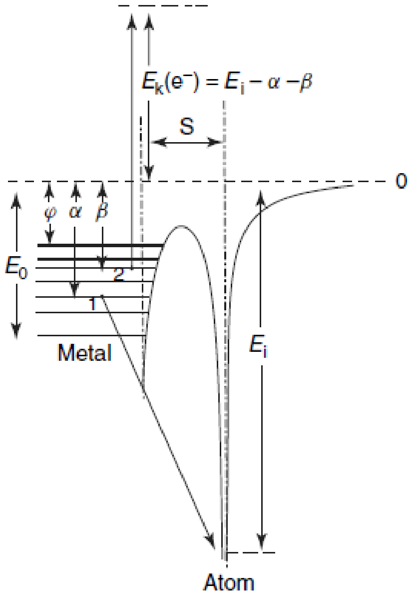
Ions recombination on
The cathode



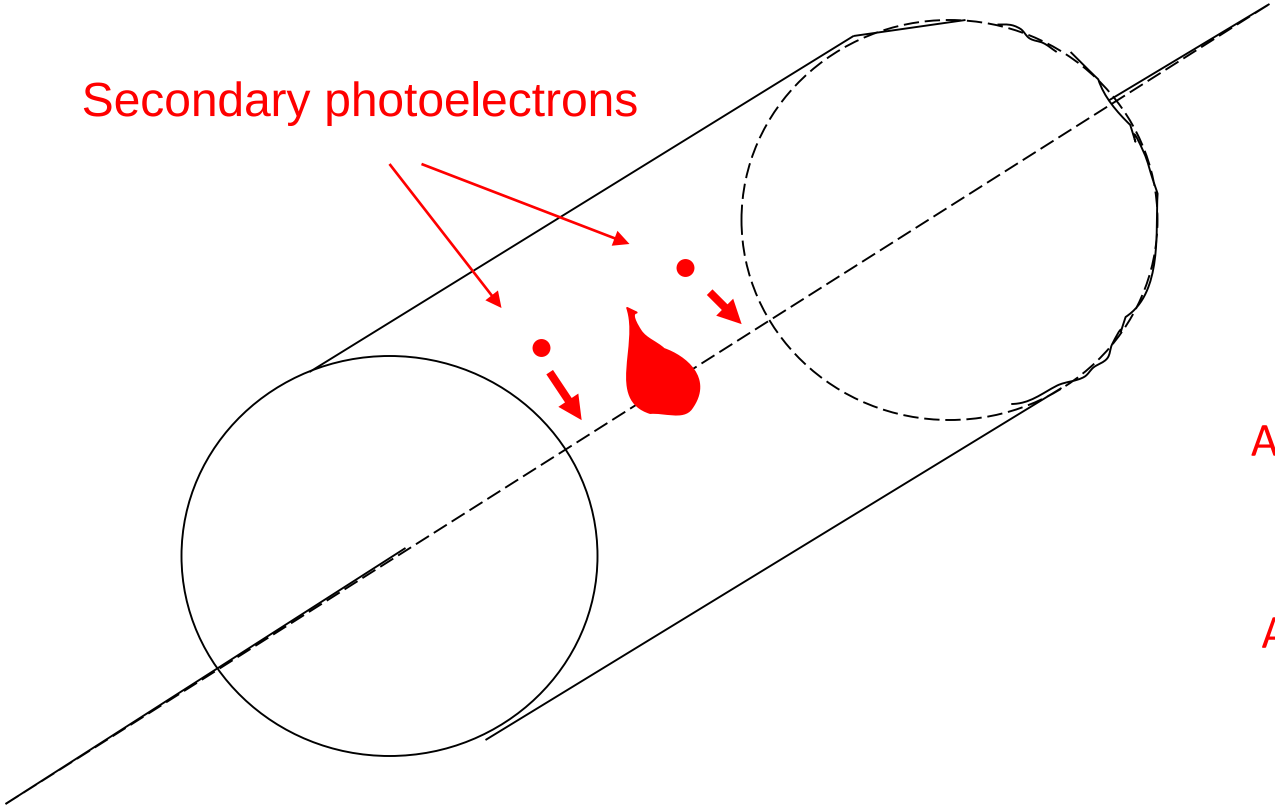
Electrons from the cathode are extracted if

$E_i - 2\varphi,$

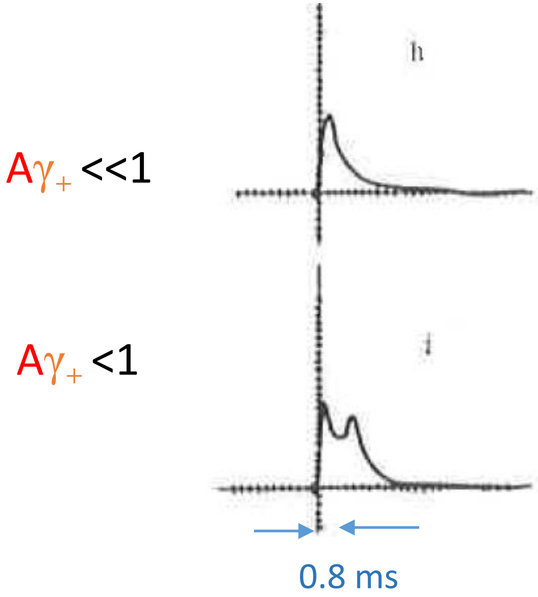
where E_i -gas ionization potential
φ -the cathode work function



γ_+ is the probability of secondary processes due to ion recombination on the cathode

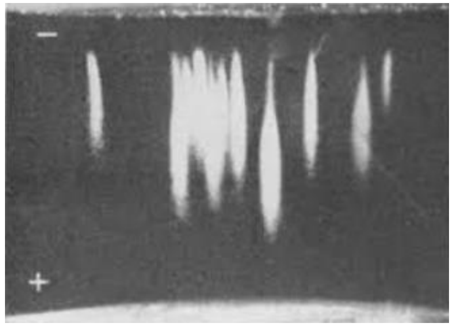


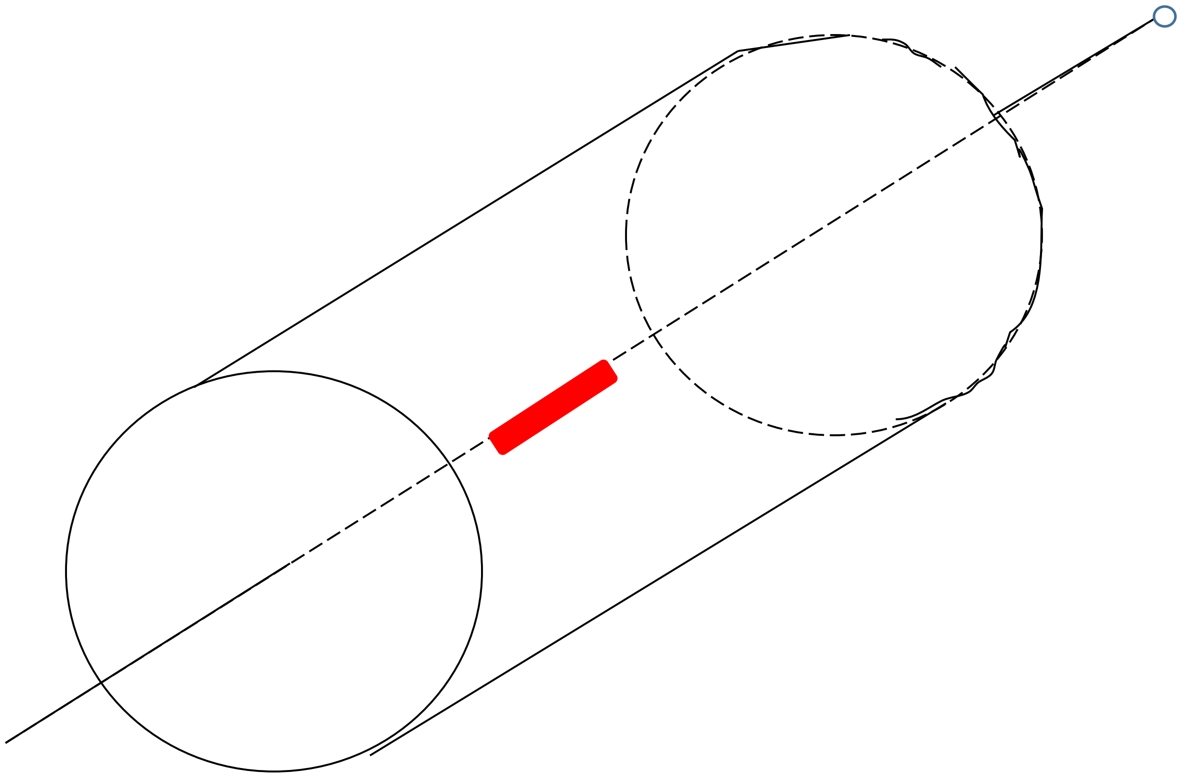
An example of chain of
Ion feedback pulses in CH4



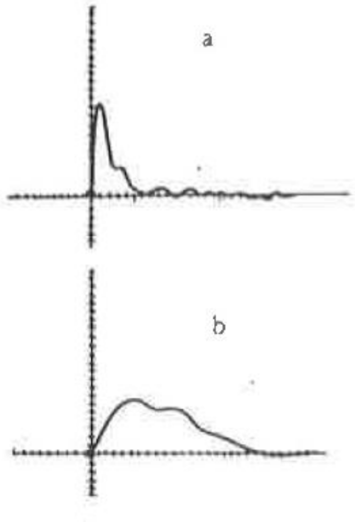
V. Peskov, Sov. Phy. Tech Phys. Phys., 20, 1975, 791

Aγ ⟶ 1 Unstable corona





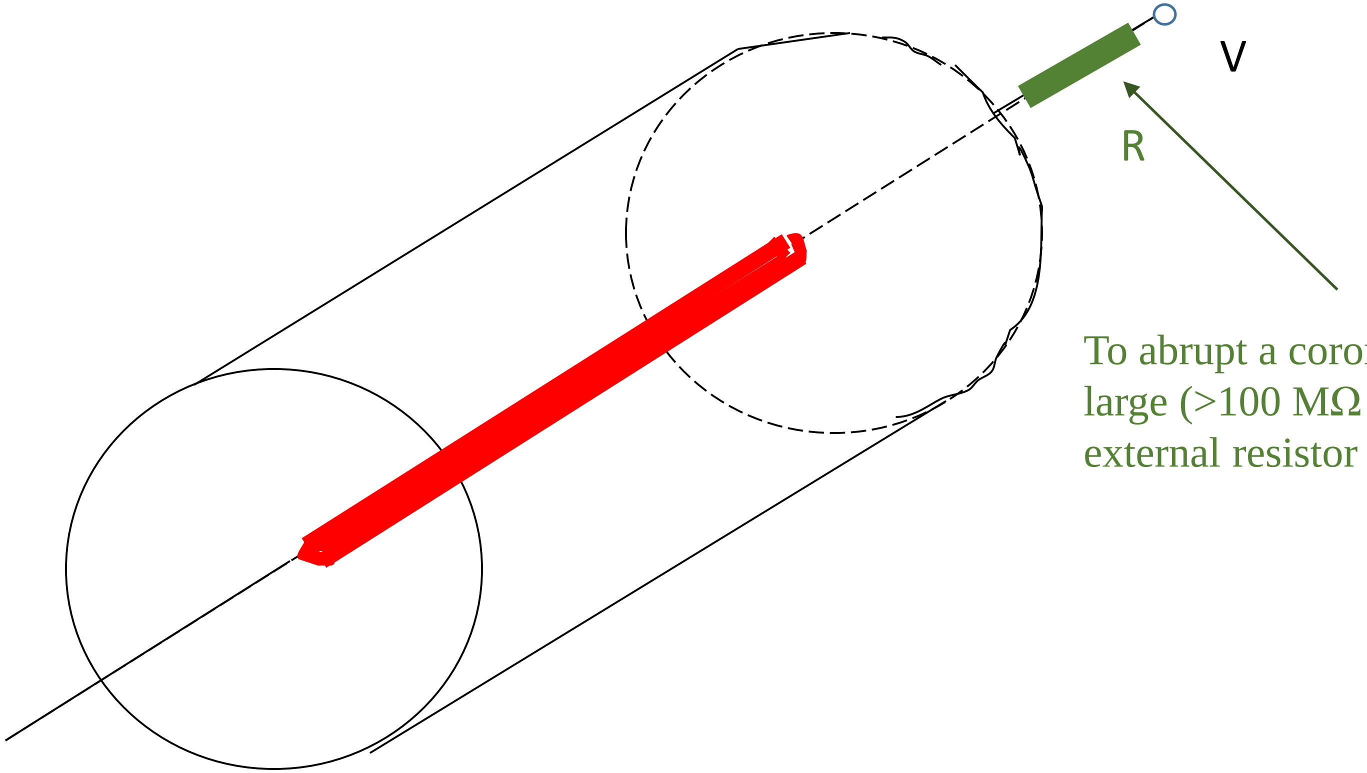
Unstable corona pulses in pure He at 1 atm



V. Peskov, Sov. Phy. Tech Phys. Phys., 20, 1975, 791

In unquenched gases the unstable corona exist in a very narrow voltage interval

$A\gamma=1$ → corona discharge (it is not damaging)



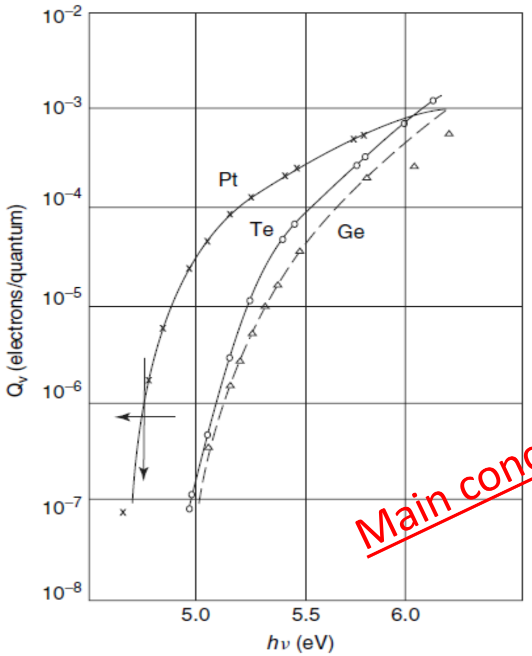
To abrupt a corona discharge a large (>100 MΩ external resistor should be used

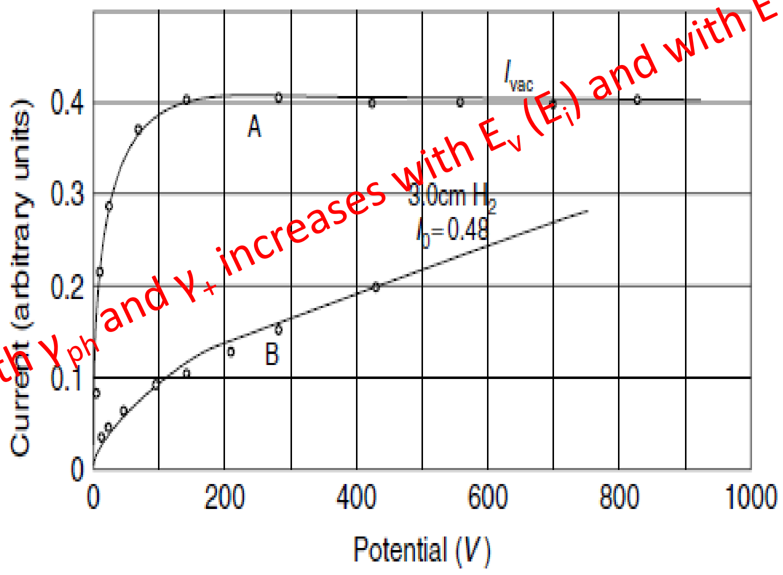
(it appears in unquenched gases, when $A\gamma_{ph}=1$ or $A\gamma_{+}=1$, what comes first)

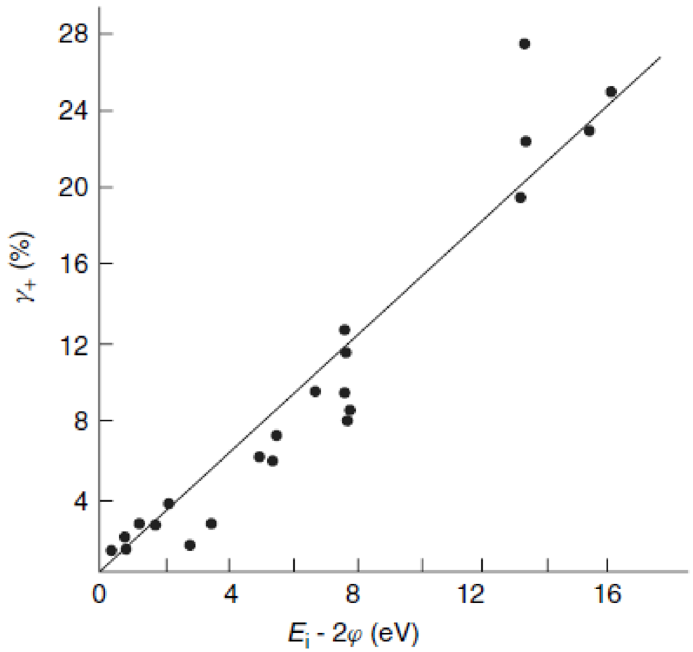
Note that both γ_{ph} and γ_+ are multiparameter functions:

$\gamma_{ph}=\int Q_s(E, E_v)\, S(E_v)\,)\{-\exp[-K(E_v)RN]\}dE_v$ –
for the surface photoeffect and $\gamma_{ph}=\iint Q_v(E, E_v)\, S(E_v)\{1-\exp[-K(E_v)RN_v]\}dE_v$-
for the volume photoionization. (solid angle features are ignored
for simplicity)

$\gamma_+=b(E)(E_i-2\varphi)$,





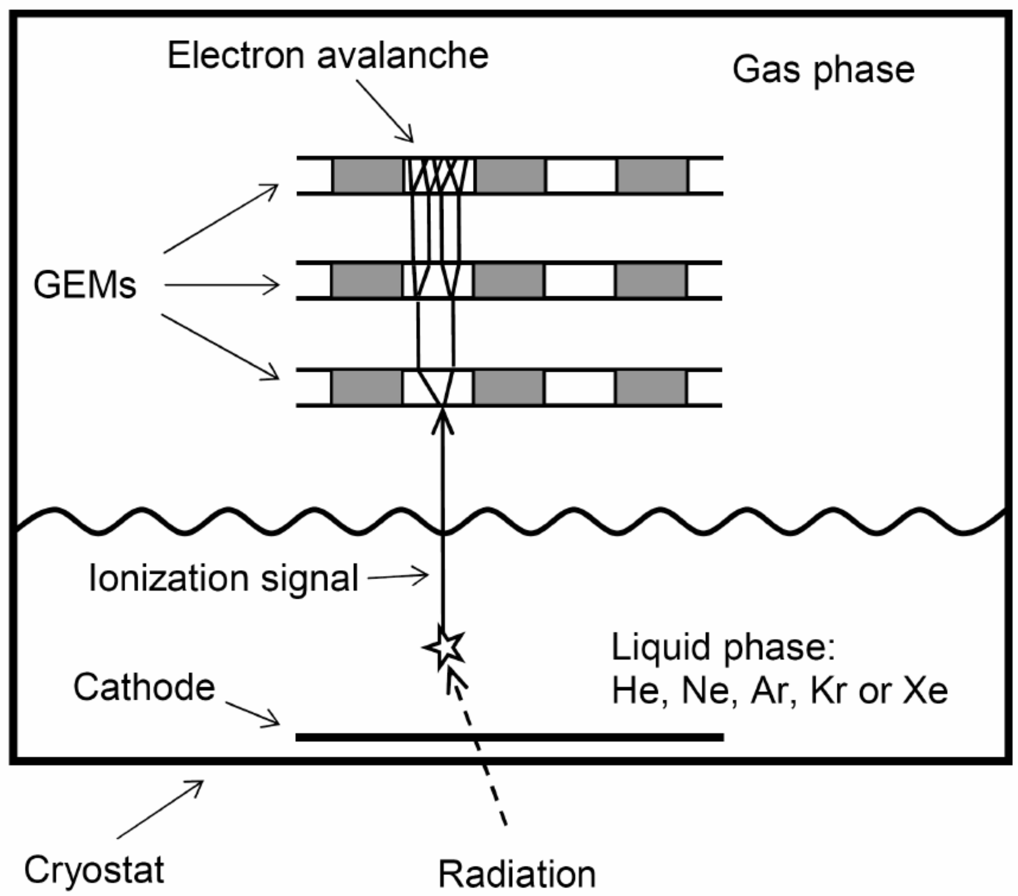


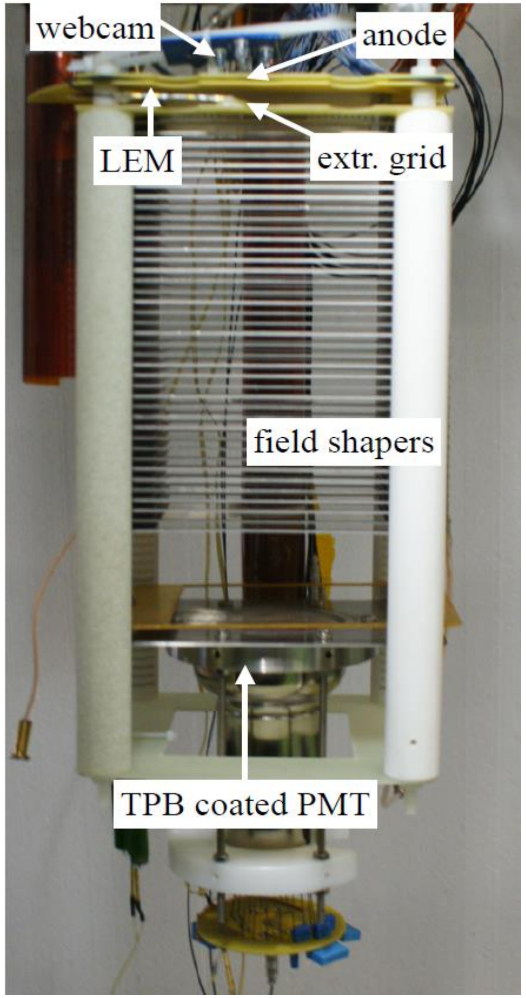
Main conclusion: both γ_{ph} and γ_+ increases with E_v (E_i) and with E near the cathode

where E_v-photon energy, $S(E_v)$ avalanche emission spectra, K(Ev)-absorption coefficient, Q_s-the cathode quantum efficiency, Q_v-the photionization quantum efficiency R-radius), b(E) is a gas depended coefficient, E is electric field near the cathode

See, for example : E. Nappi et al., Imaging gaseous detectors and their applications, Wiley, 2013

Operation of GEM in clean noble gases





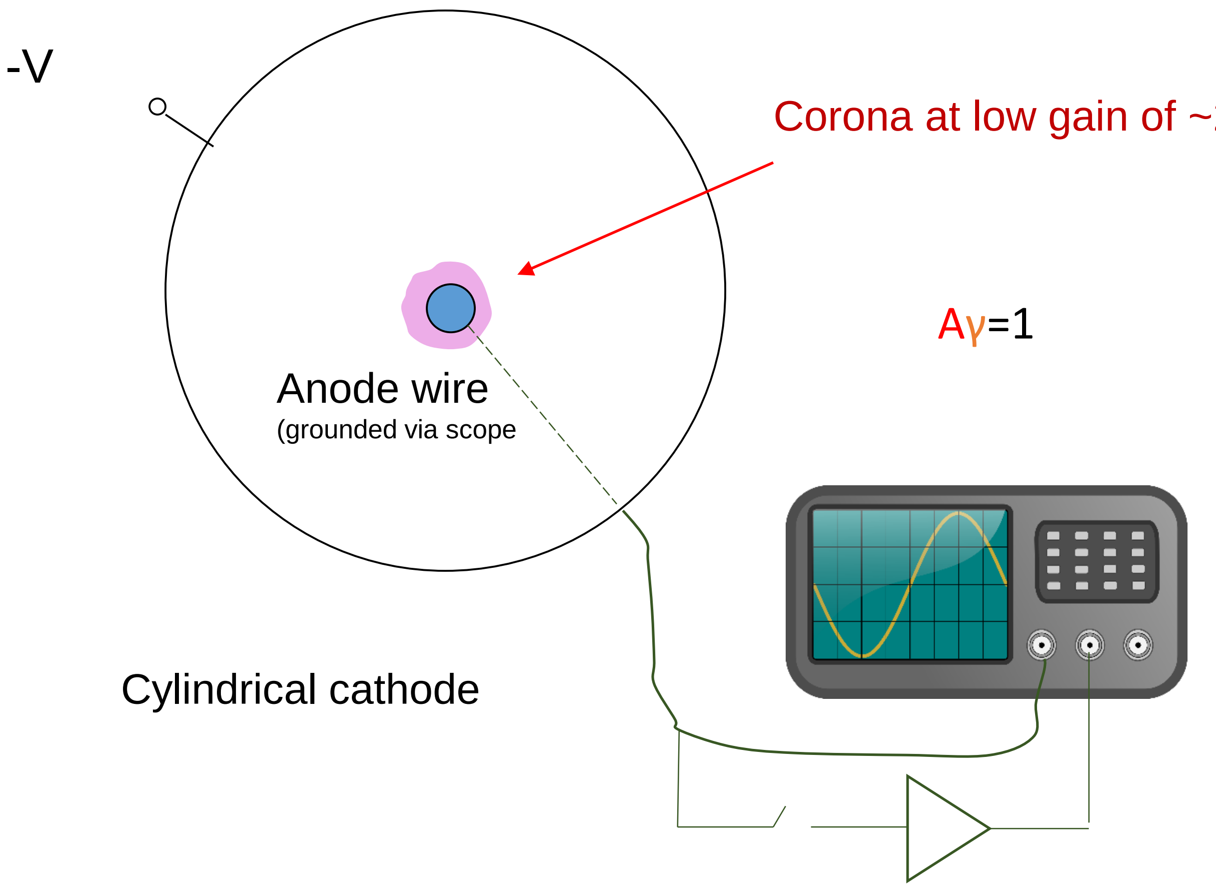
In ultraclean He and Ne the maximum achievable gain was below 10

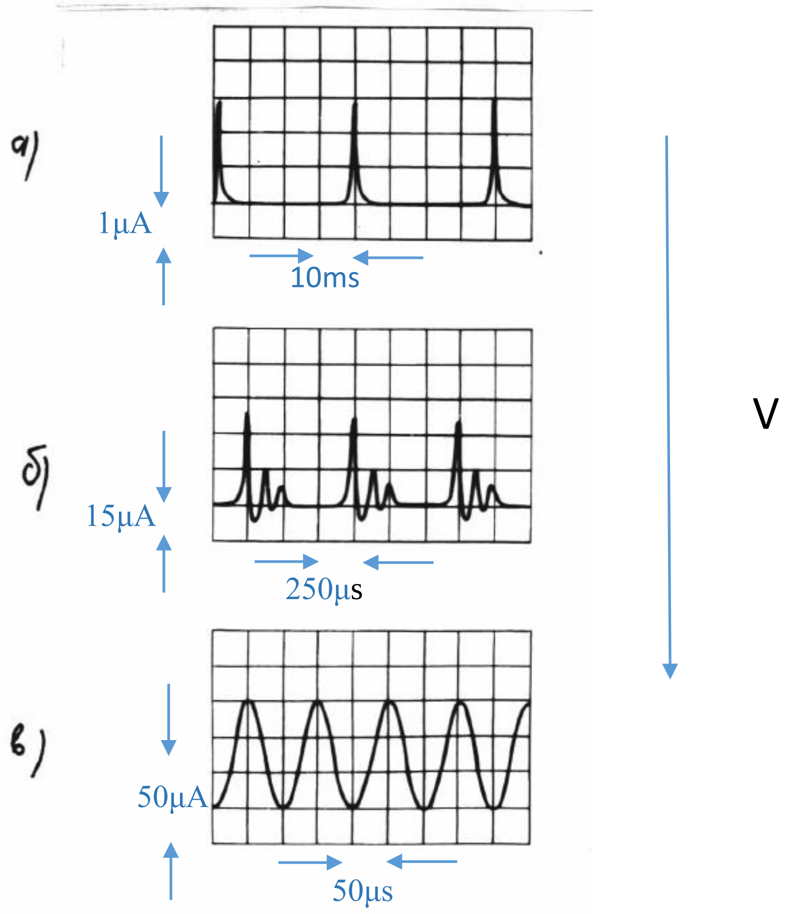
See R. Galea et al., IEEE Trans. Nucl.Sci 53 2006, 2260, J. Miyamoto et al., JINST 5 2010, P05008, A. Buzulutskov et al., NIM, 2005, 487

By the way, an exotic effect was observed in very pure (< 10^{-5}%) noble gases at high-pressure- - ionization instability of a corona (and other discharges)- a kind of a “slow breakdown” presumably due to the ionization via excites states (?)

See Appendix for more details

Ionization instability of a corona discharge in ultraclean noble gases

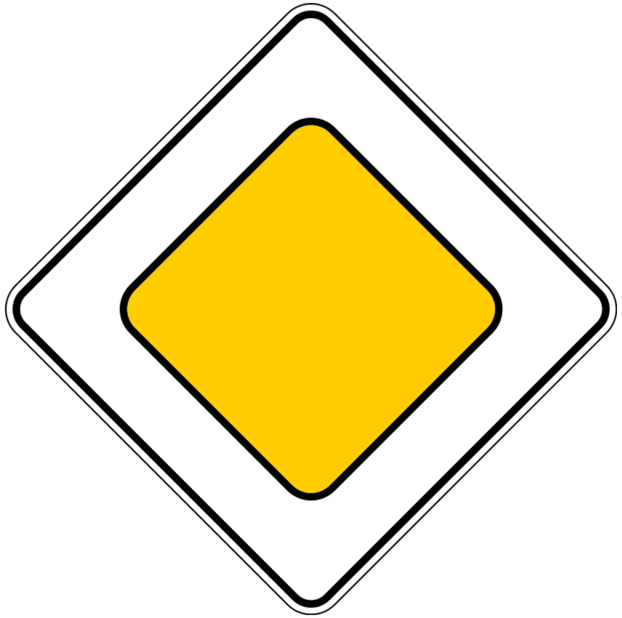




V. Peskov, Sov. Phy. Techn. Phys. 20, 1975, 1584

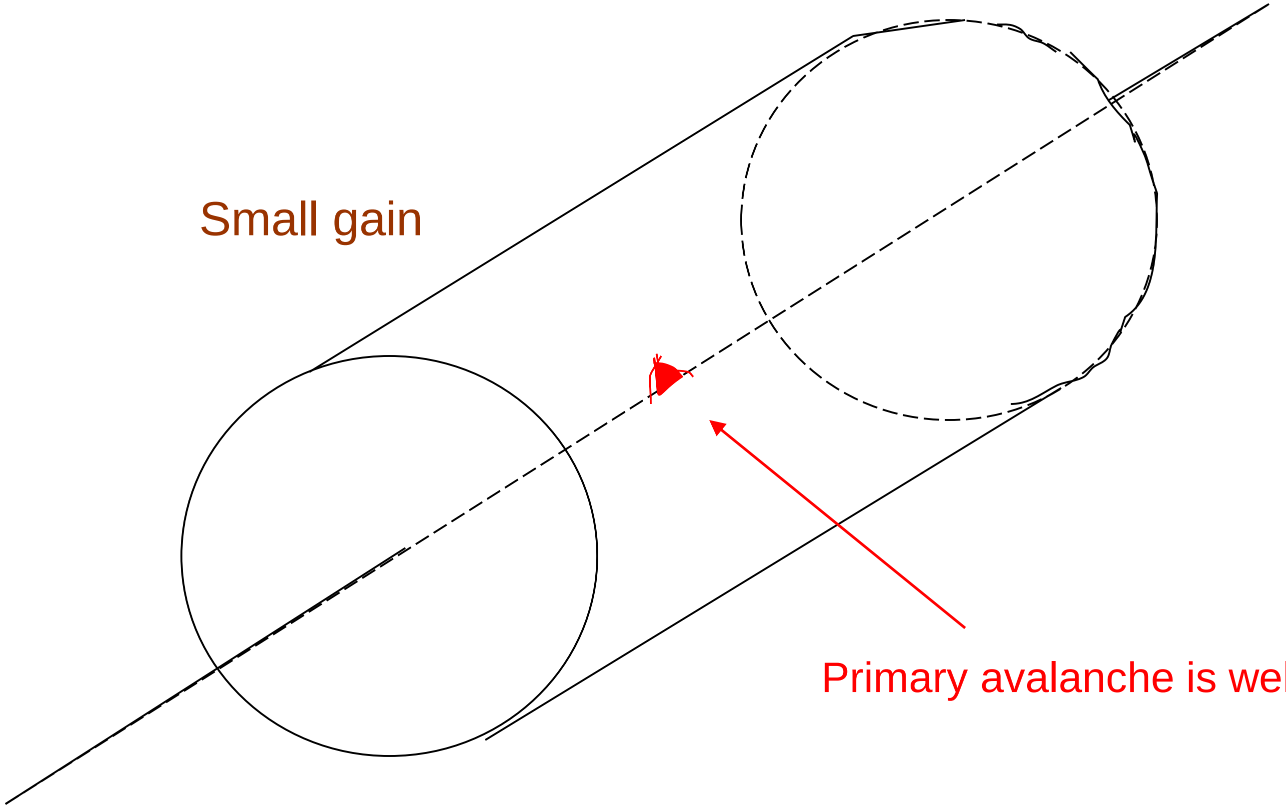
Such signals were observed in ultraclean He at p>5atm and Xe at P>3atm

...but lets now back to slow breakdown and corona discharge in a single-wire counter filled with <u>quenched gases</u>



Position of wire

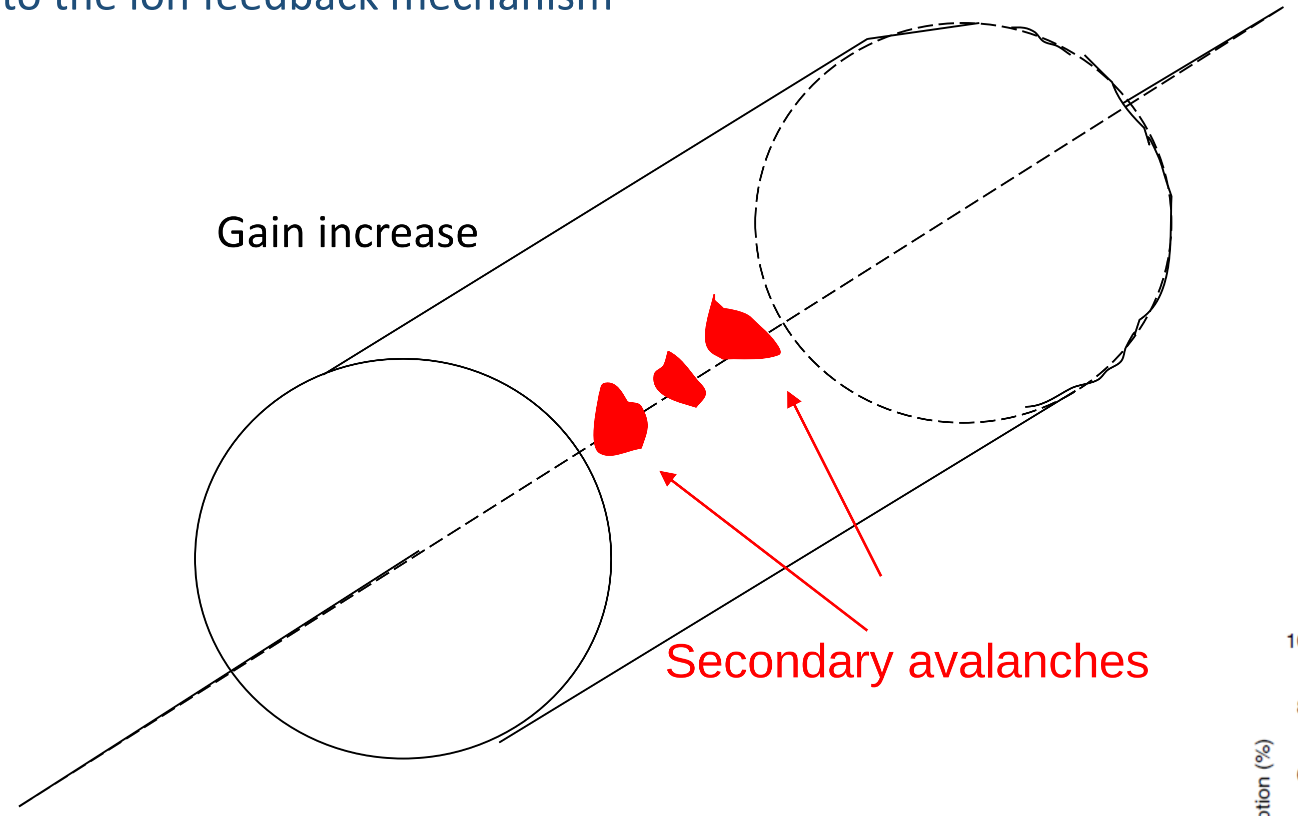
Small gain



Primary avalanche is well localized

Discharge development in a thin wire detector filled with quenched gases

In quenched gases: propagation along the wire is due to photons and electron diffusion, but a corona discharge –mainly due to the ion feedback mechanism



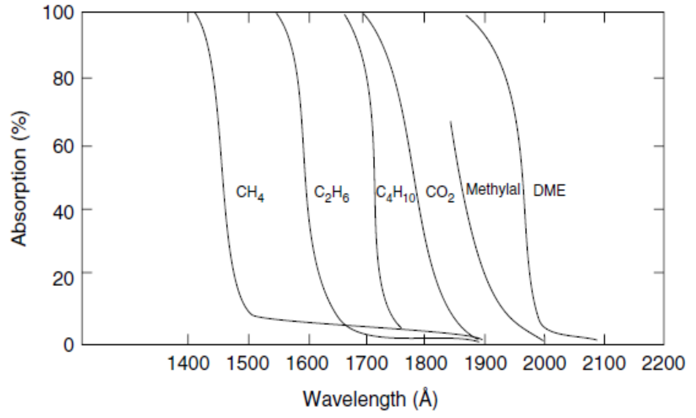
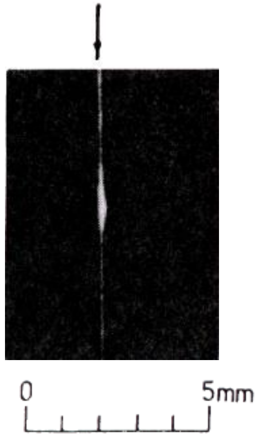
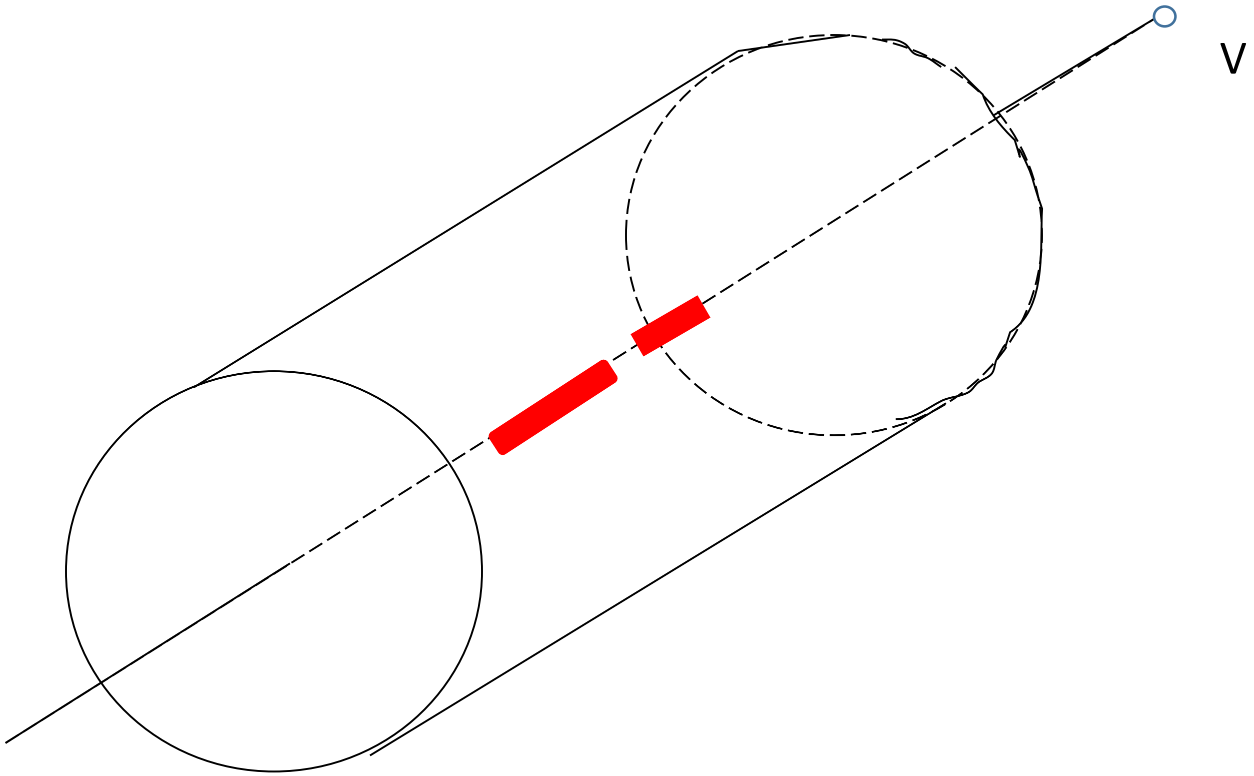


Figure 5.14 Absorption curves $(1/T_v(\lambda))$ for quenchers at 1 atm for gas thicknesses longer than 5cm (from Ref. [13]).

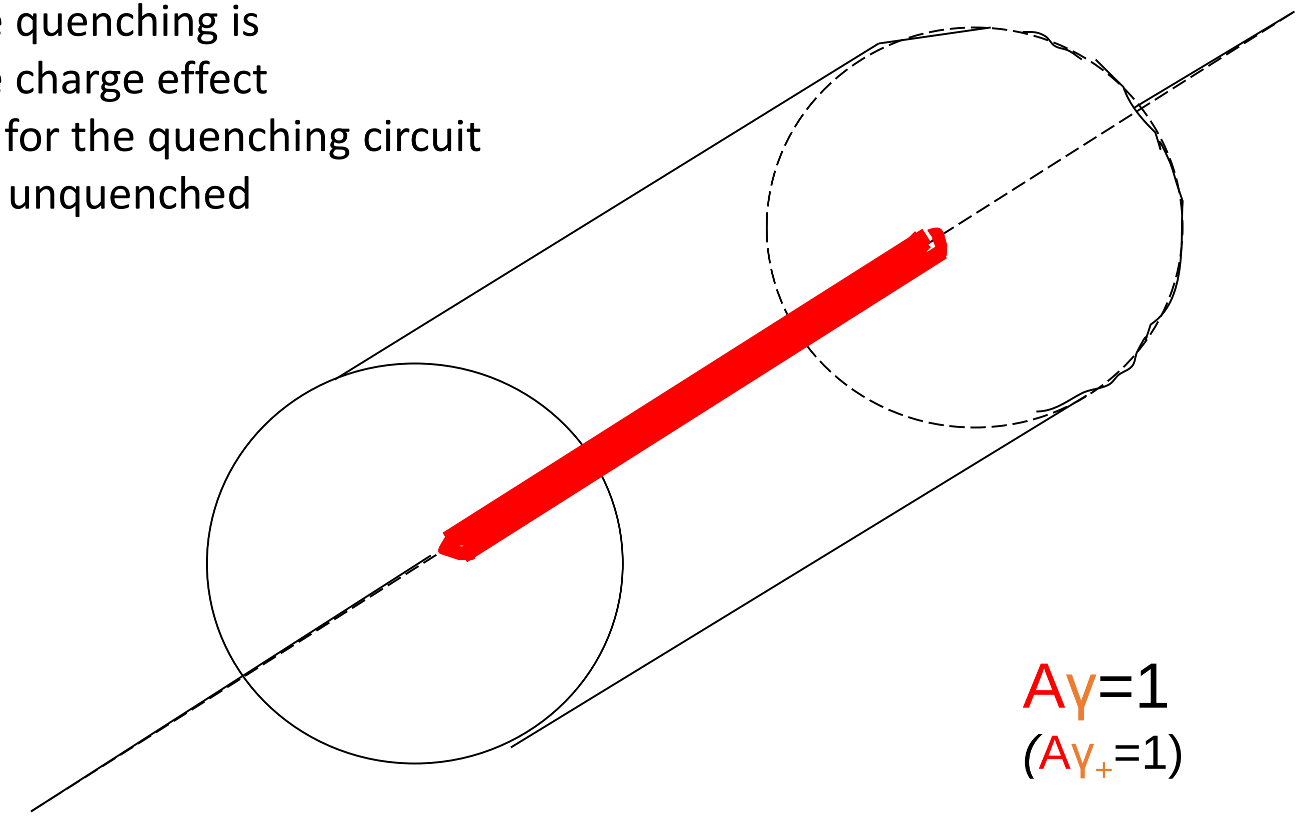
$A\gamma \longrightarrow 1$ Unstable corona





Geiger mode in quenched gases

Geiger discharge quenching is due to the space charge effect (and so no need for the quenching circuit as it was used in unquenched gases)

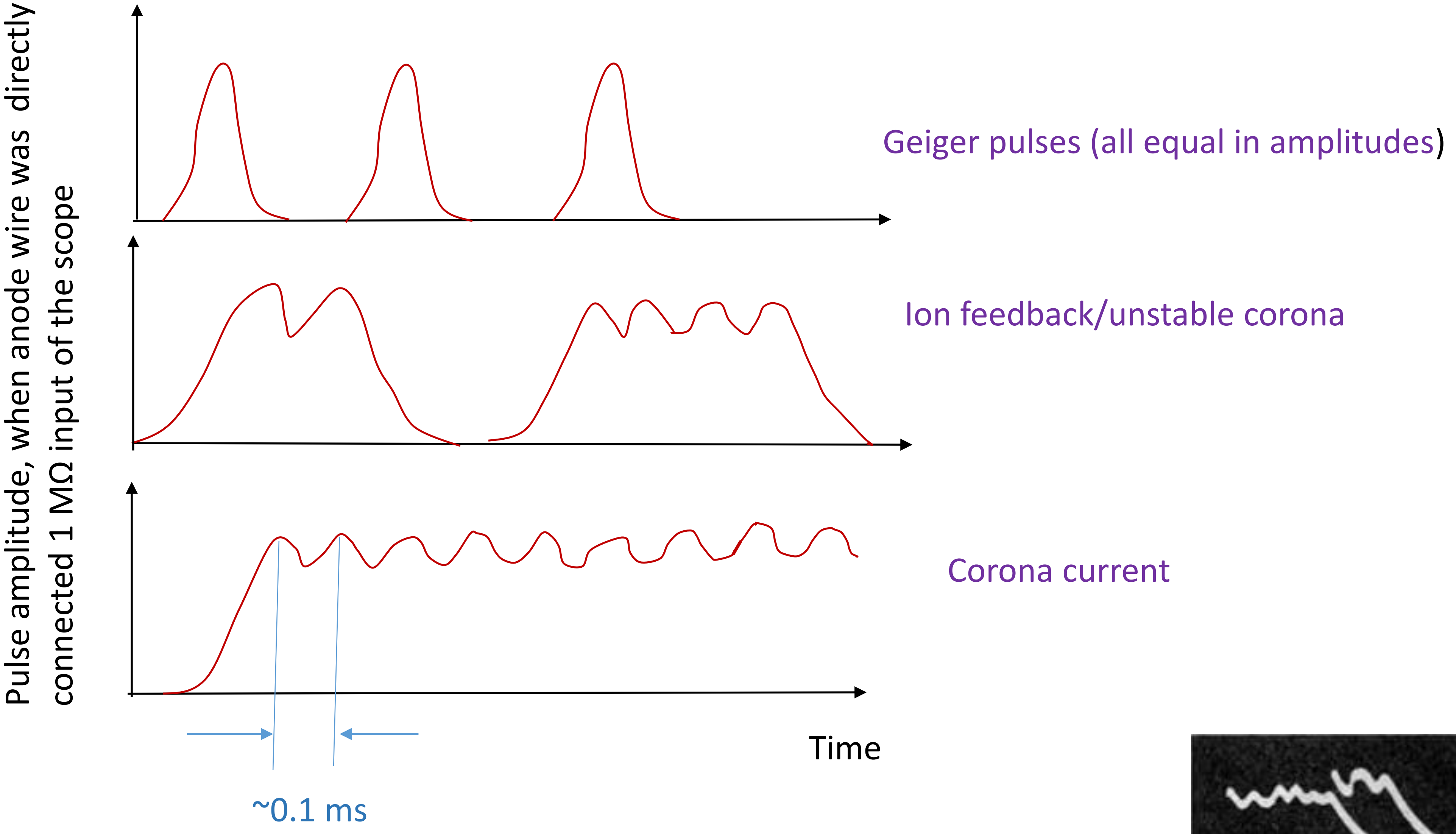


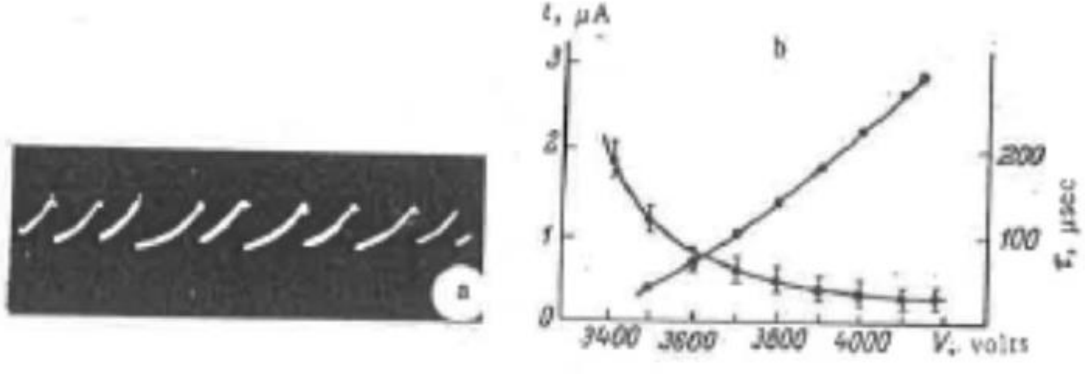
$A\gamma=1$

$(A\gamma_{+}=1)$

$c_{front}=10^{6}\text{-}10^{7}$ cm/s

Geiger discharge is not damaging. One can observed signals~1V directly on 1MΩ input of the scope (no amplifier is needed)


Pulse amplitude, when anode wire was directly connected 1 MΩ input of the scope
Geiger pulses (all equal in amplitudes)
Ion feedback/unstable corona
Corona current
Time
~0.1 ms



A note: at certain conditions one can observe instabilities in form of periodical current oscillations: this is the oscillation of the space charge

Note: a corona counter was suggested by one Russian group for alpha particles detection in a strong radiation background

Current oscillations in a positive corona discharge

V. D. Peskov

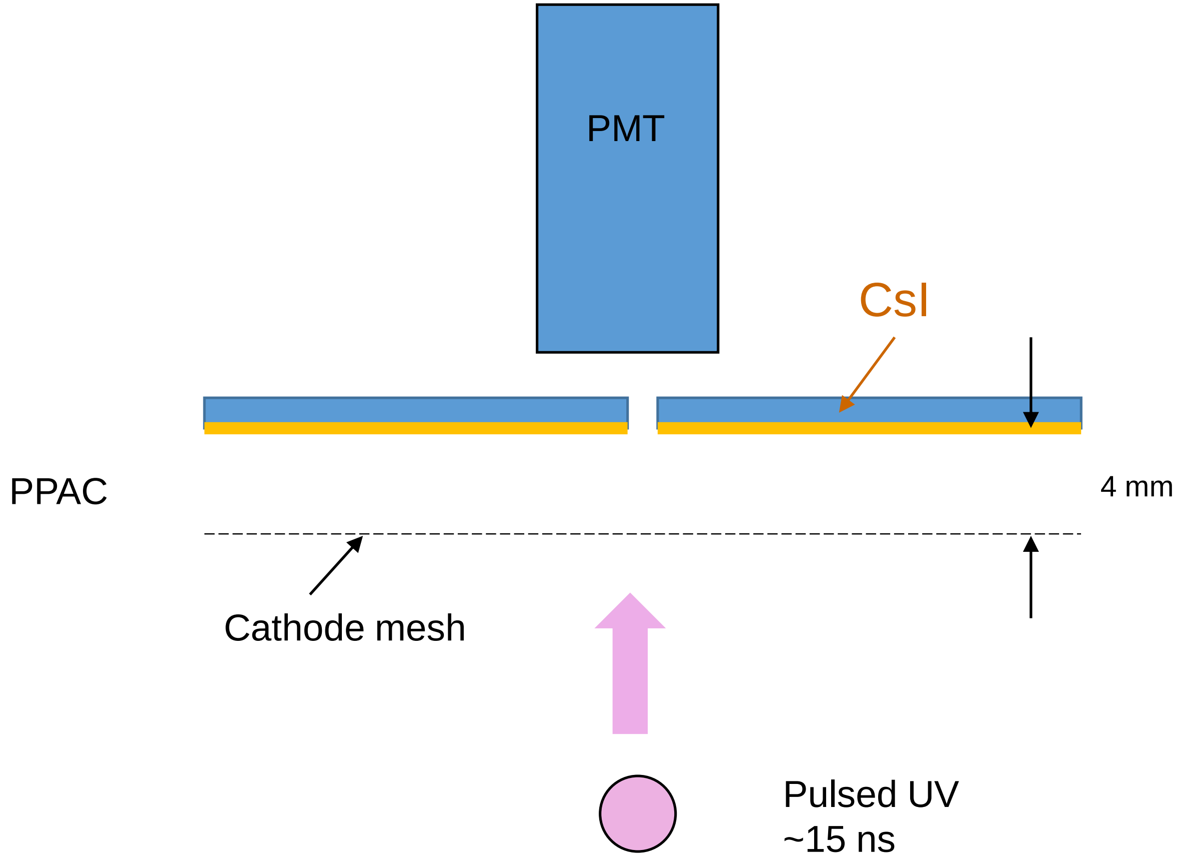
Institute of Problems in Physics, Academy of Sciences of the USSR, Moscow

(Submitted December 4, 1974)

Zh. Tekh. Fiz. **45**, 2552–2556 (December 1975)

Periodic current oscillations have been detected in positive corona discharges in He, Ar, H_2, N_2, CH_4, and their mixtures at pressures from 0.1 to 3 atm. The frequency of these oscillations is proportional to the voltage applied to the counter and ranges from 10^4 to 10^6 Hz. In mixtures there is a definite impurity concentration (~1%) at which the oscillation amplitude is a minimum. The oscillations are attributed to space charge fluctuations in the corona gap. The oscillation amplitude depends on the pressure and the gas and is the lower, the greater the role of stepwise ionization in the discharge mechanism.

An example of a slow breakdown studies in detectors filled with quenched gases and combined with photocathodes



G. Charpak et al., NIM A307,1991,63

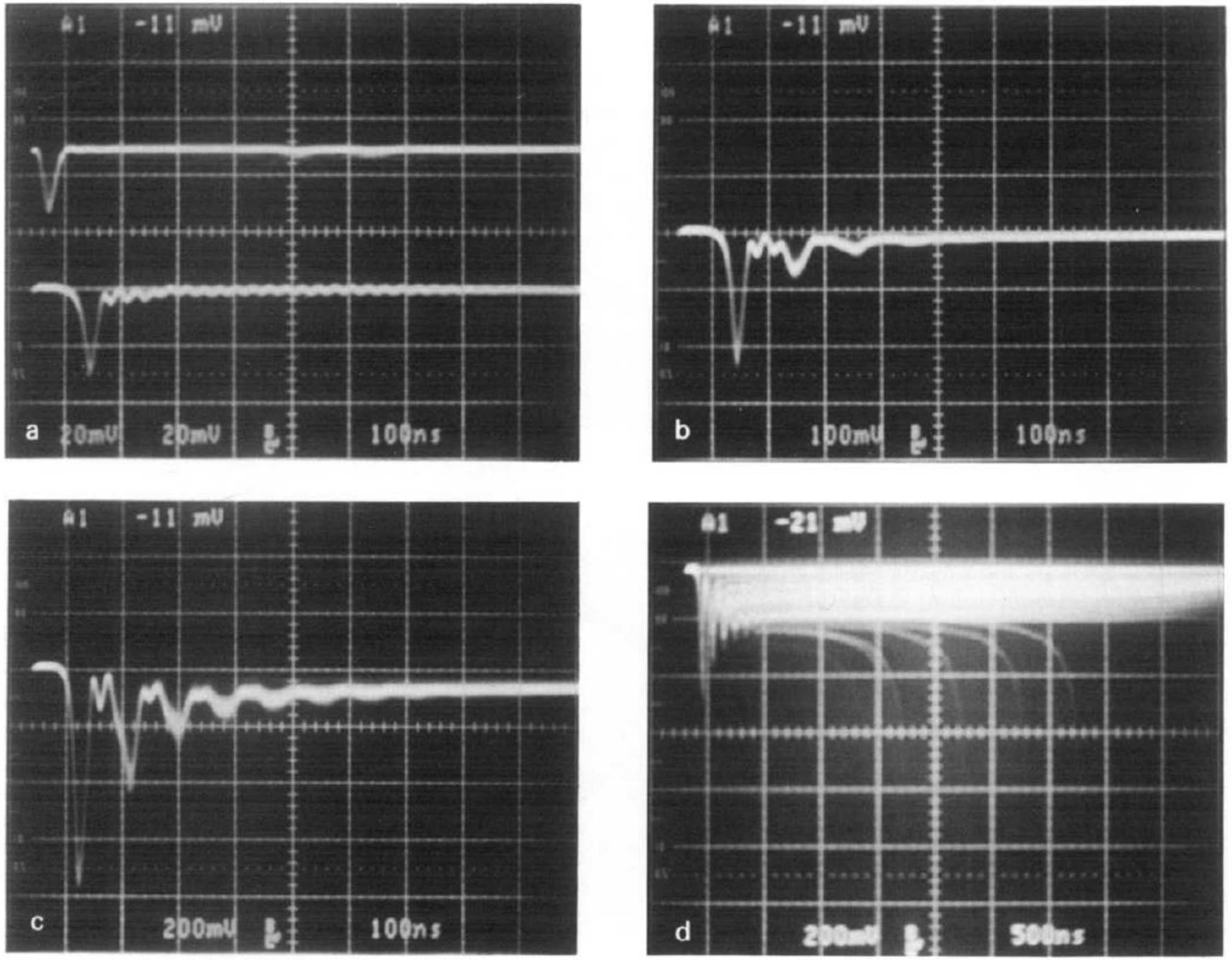


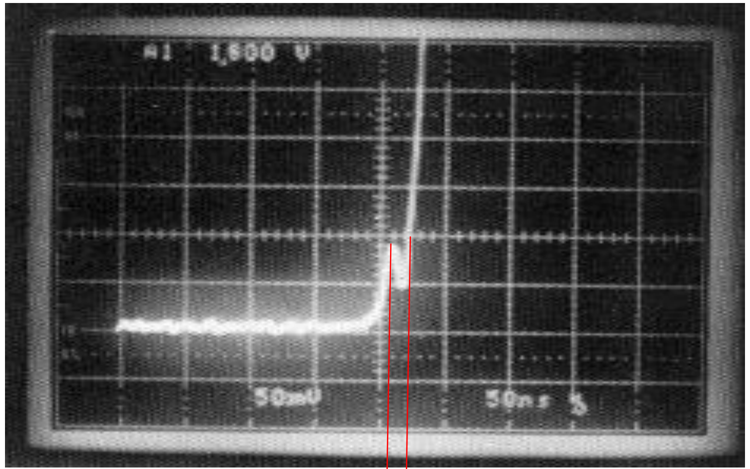
Fig. 2. Typical chamber signals, as detected with a fast current preamplifier: (a) chamber signal delayed after the PM signal (top) by the avalanche time, (b) ~ 25% feedback – our standard level for feedback measurements, (c) many feedback successors, (d) slow breakdown.

Ususally $A\gamma_{ph}$=1

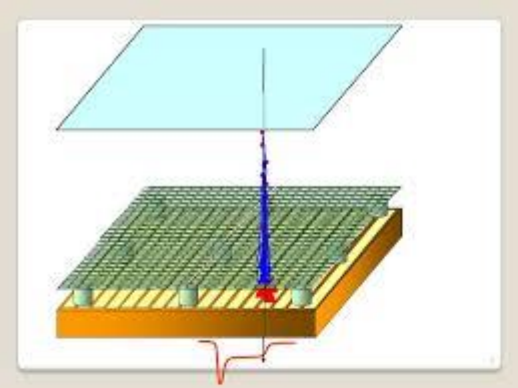
G. Charpak et al., NIM A307,1991,63

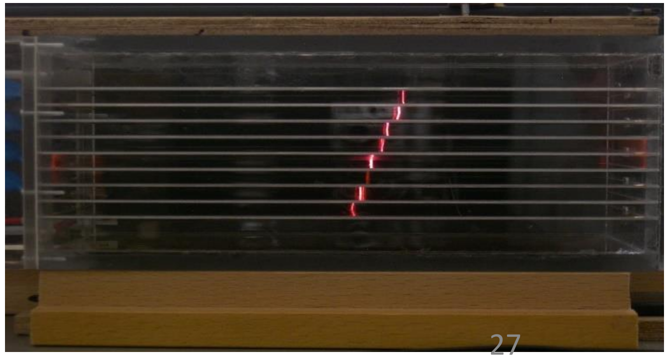
I.2. Fast breakdown

(happening very fast: in 1-10 ns scale)



20 ns





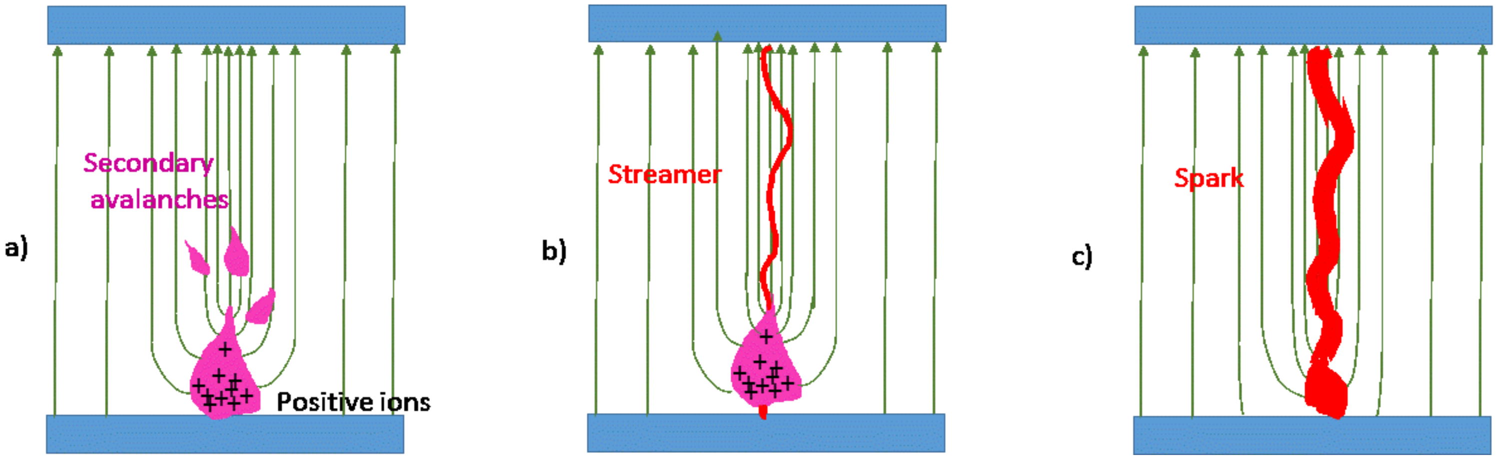
Usually occurs in PPAC and in MPGDs

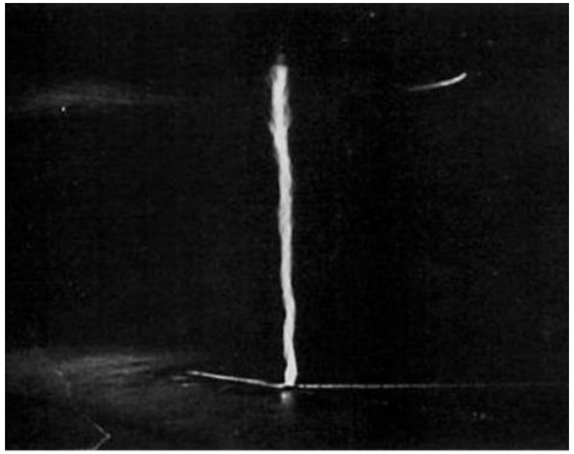
H. Raether "Electron avalanches and breakdown in gases"
P. Fonte et al., NIM, A305, 1991, 91

Typical time ≤ ns

Appeared at a total charg in avalanche An_0~10^8 electrons–a so-called Raether limit

(A –gas gain, n_0-primary ionization)





Avalanche transit to a streamer in the case of a strong space charge effect in the primary avalanch

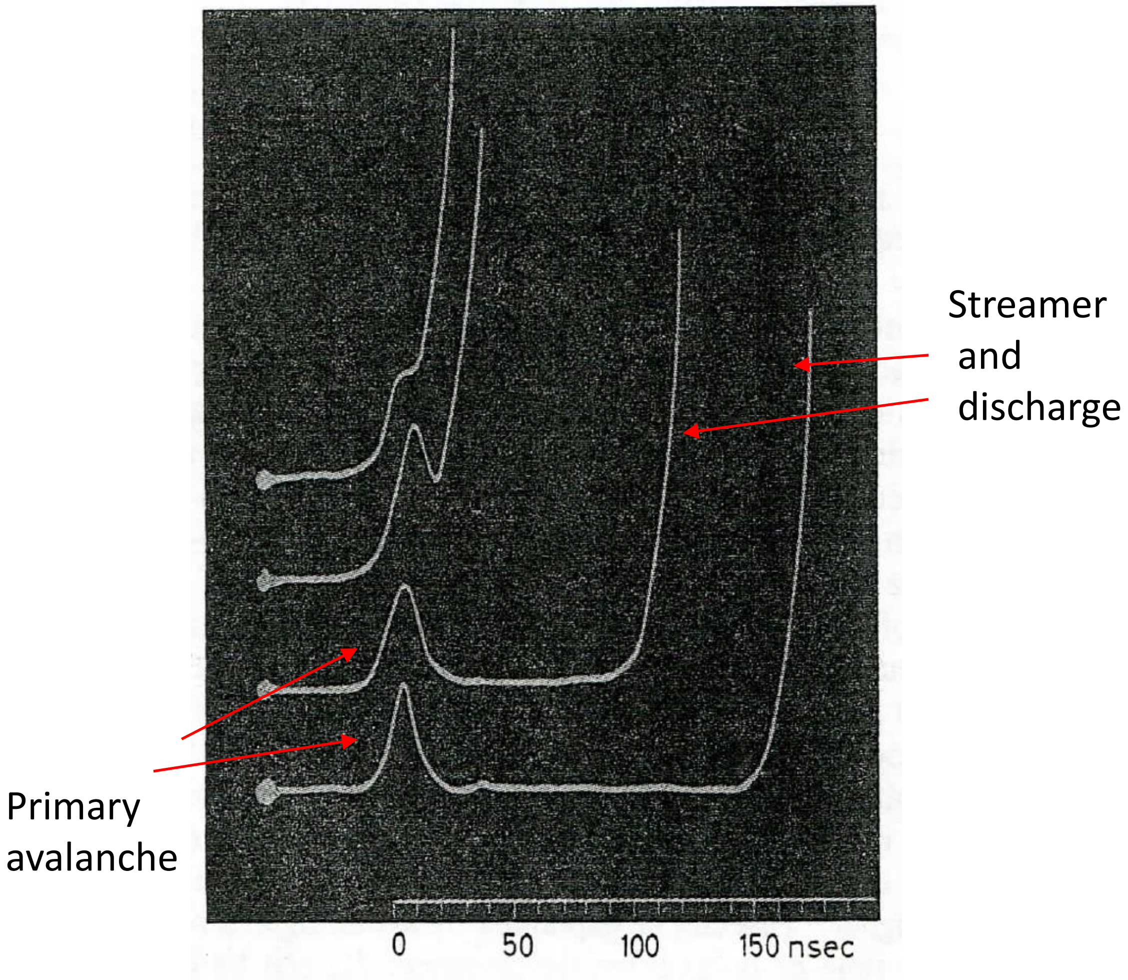
Animation of spark development when the total charge in the avalanche reaches the Raethet limit:

a) filed lines close to the avalanche experience a focusing effect and some secondary avalanches start

b) moving towards the positive ions “body”, b) a thin plasm filament-a streamer- is formed,

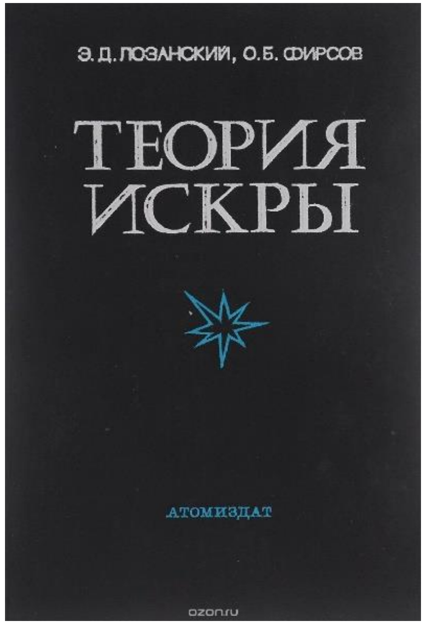
c) when the streamer reaches the electrodes, a spark happens

Typically it happens in electric field with parallel field lines



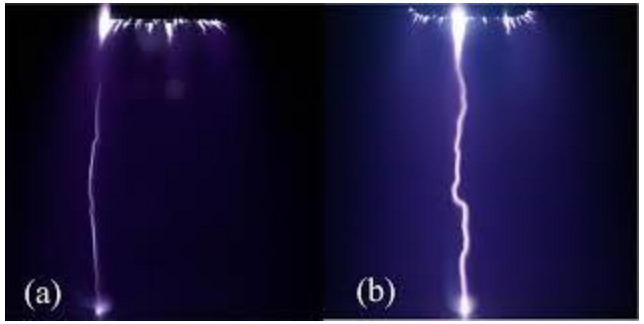
Current oscillograms of static breakdown in methylal at various overvoltages increased from the lowest to upper curves (*from Raether book*)

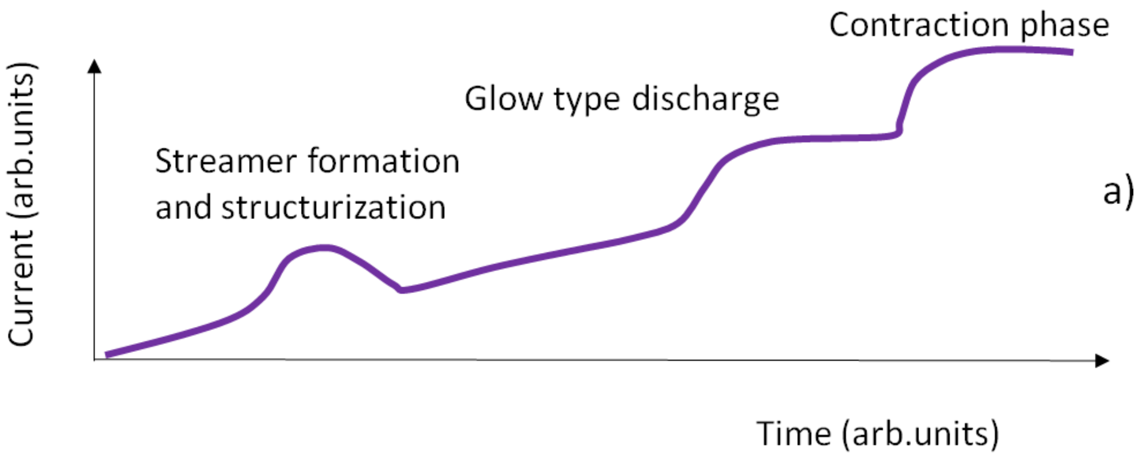
An analytical model of streamer was developed by E. Lozanski and O. Firsov



Validation of the Rather limit in the case of gaseous detectors was done in work:
P. Fonte et al., NIM, A305, 1991, 91

How a streamer transits to a spark?





In a stationary case:

$n_e v_e = N_+ V_+$ (1)

Self -supporting current will exist if:

$N_+ \gamma_+ = n_e$ (2)

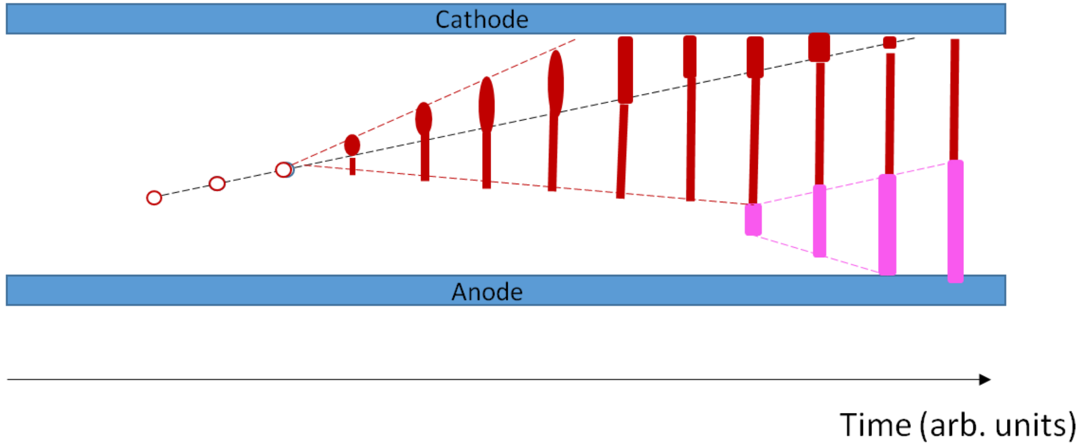
In quenched gases typically

$\gamma_+ < 10^{-6}$ (3)

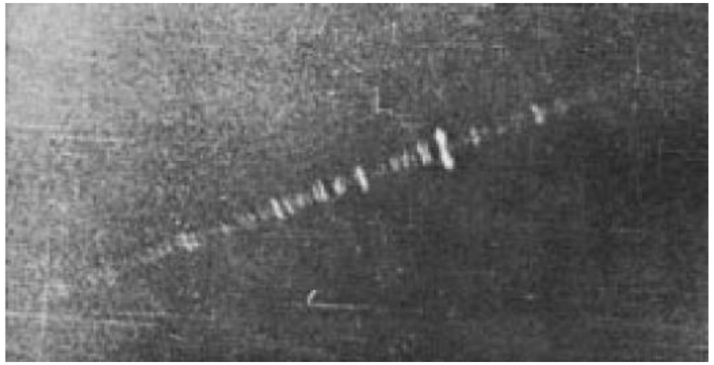
Because of $v_e/V_+ \approx 10^3\text{-}10^4$ (4),

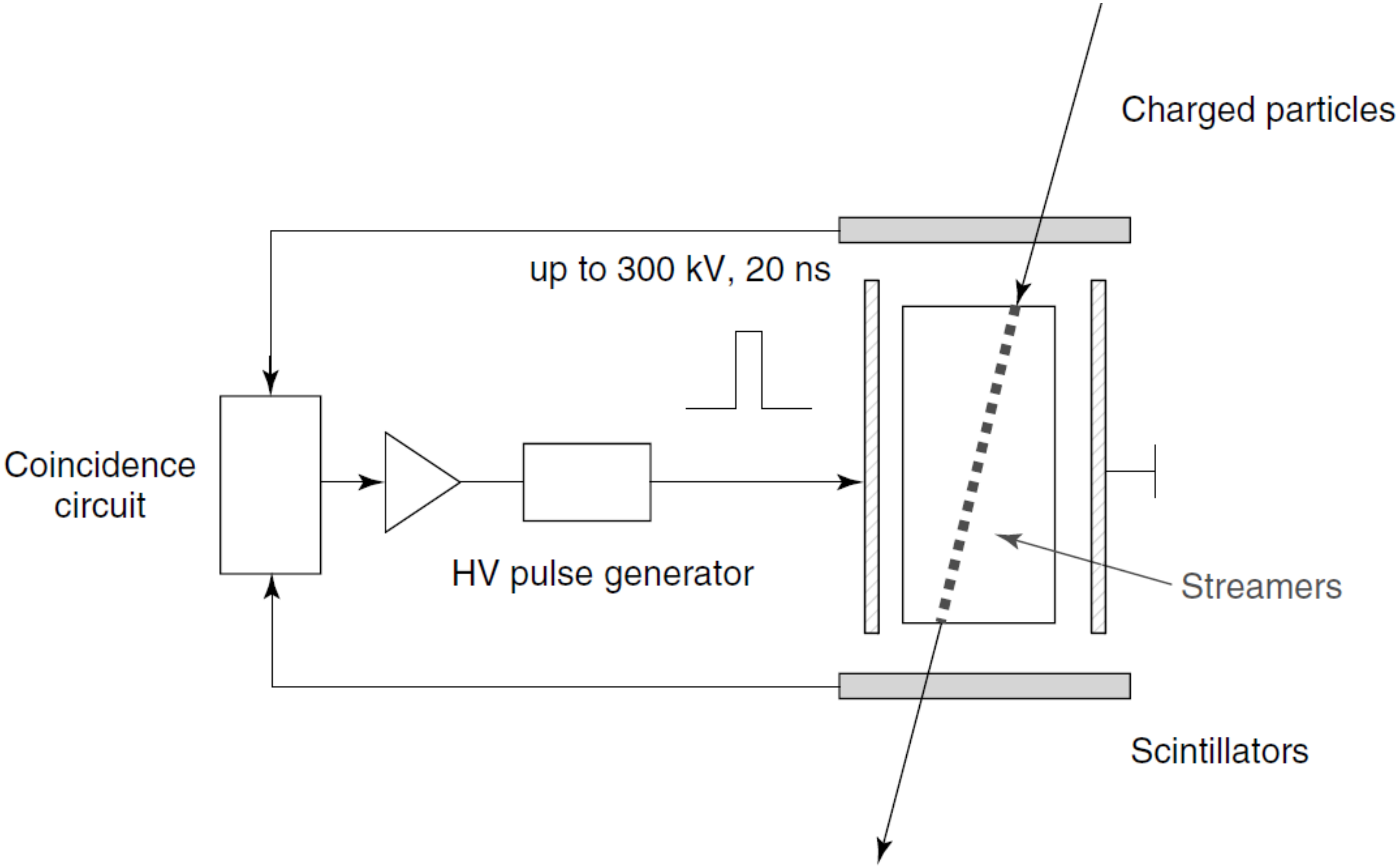
Than to satisfy a condition (2) multiplication is necessary in the region between the streamer head and the metal surface. This leads to a formation of a short-term glow discharge

b)

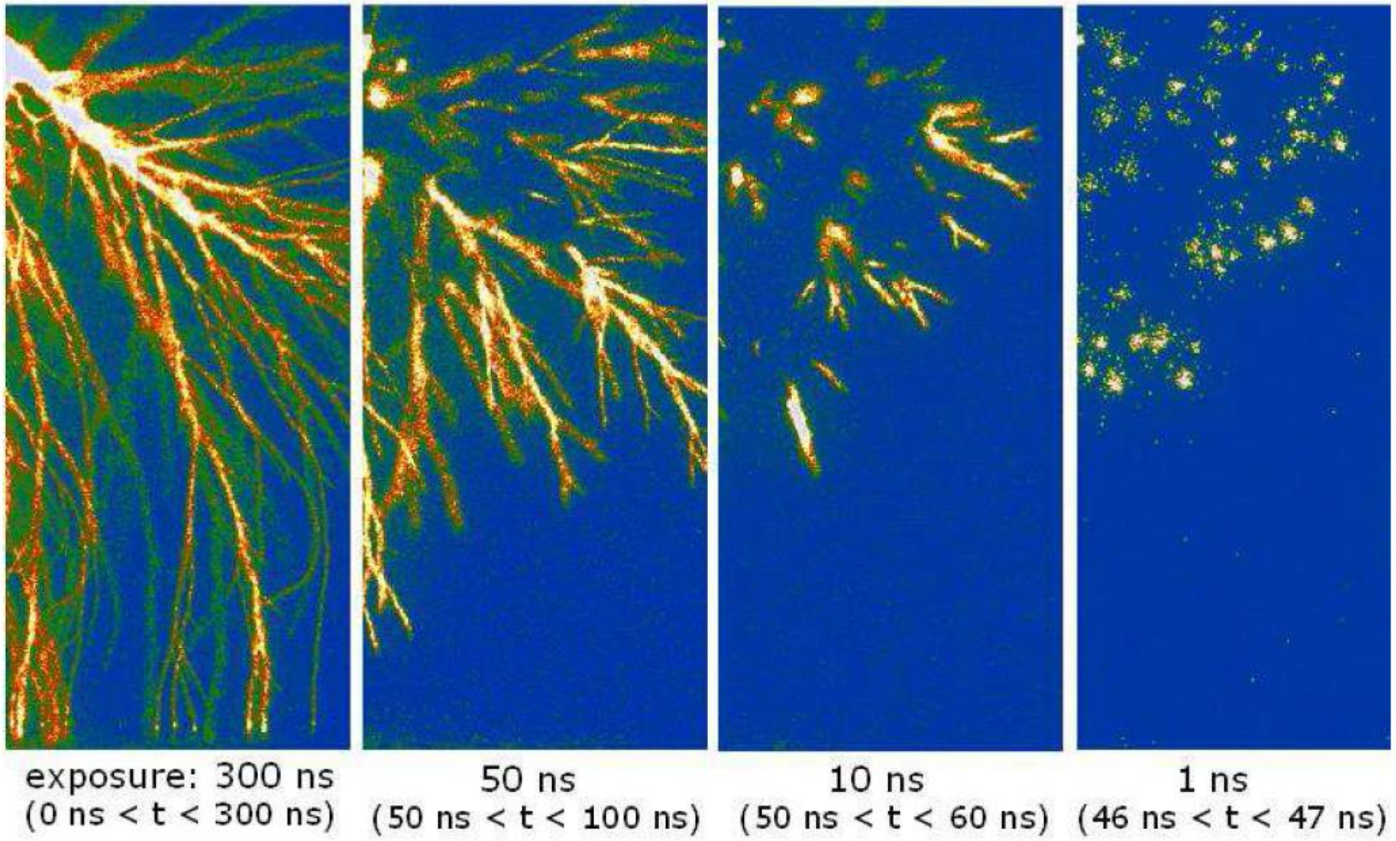


Understanding these processes lead to a nice application: streamer chamber





G.E. Chikovani et al., NIM 29, 1964, 261
B.A. Dolgoshein et al ., NIM 26, 1964, 345

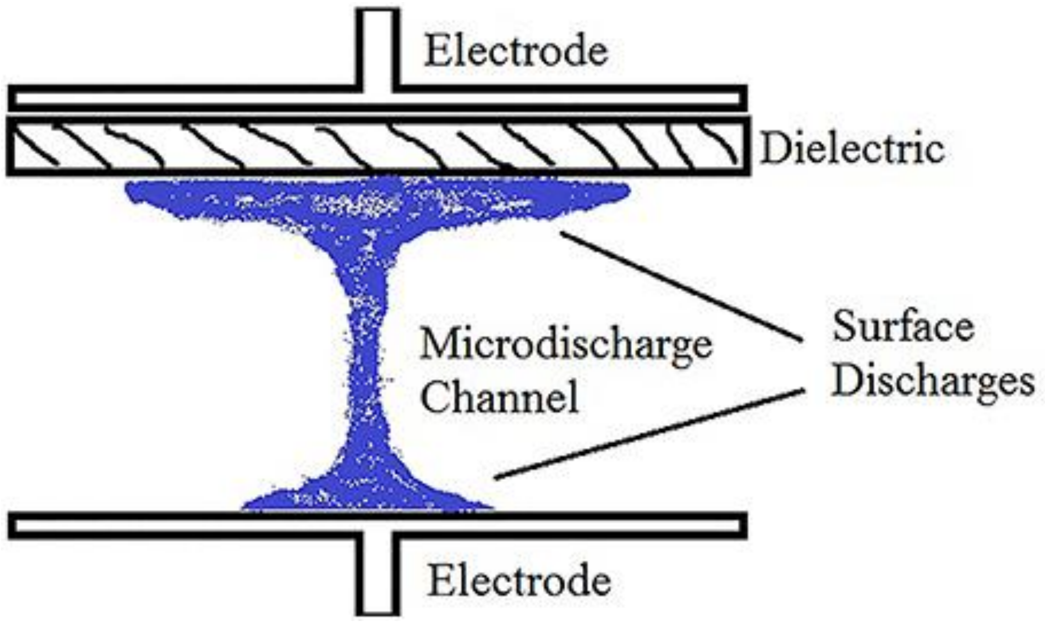


(From U. Ubert et al., Plasma Source and Technologies, ArXivePhys0604023v)

Experimental proof of photoeffect contribution in streamer creation

However, not in all gases emission from avalanche is able to ionize the gas. To overcome this Losanski and Firsov suggested to include into the consideration electron diffusion

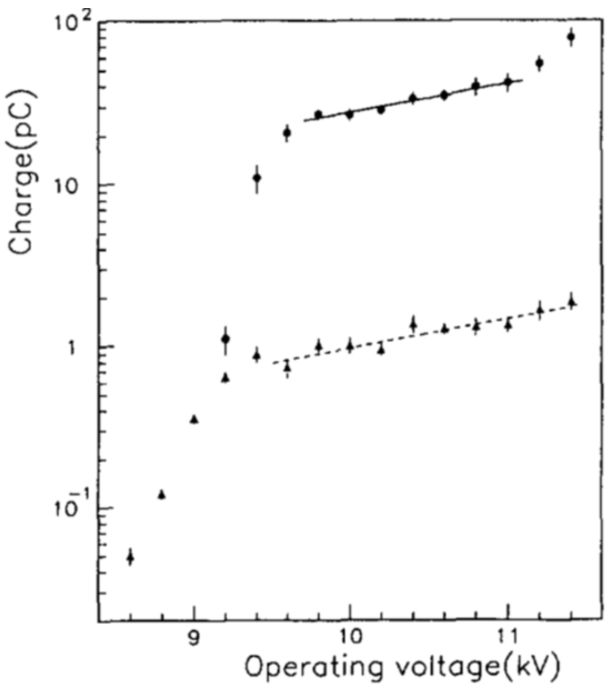
Streamers in RPCs

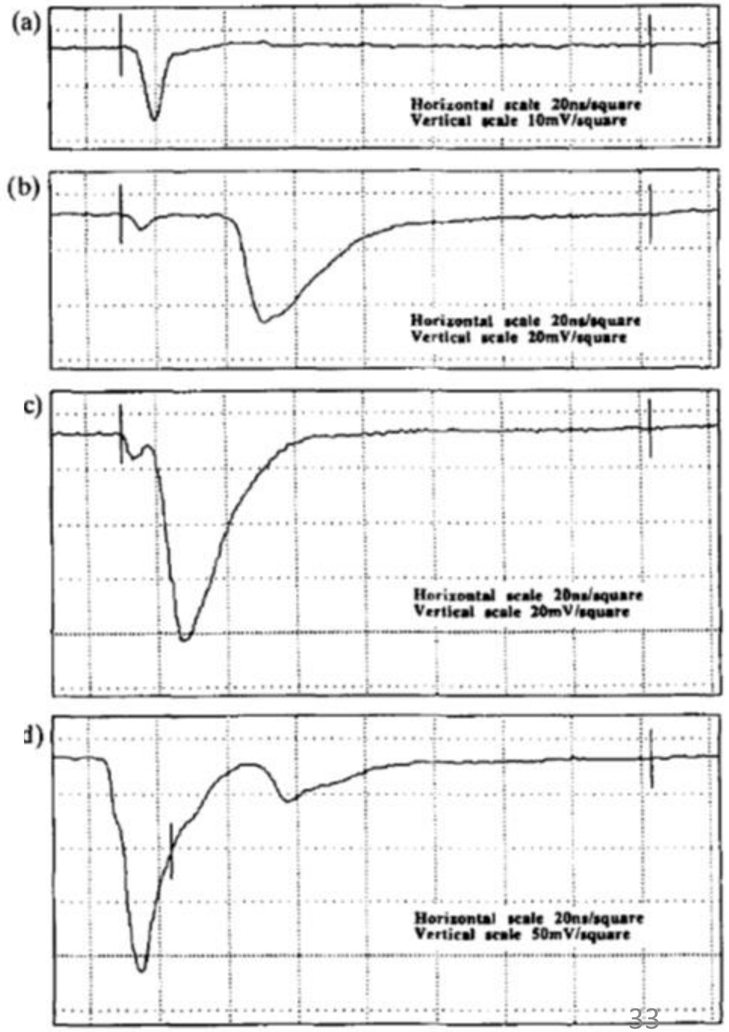


[Requires more studies:]()

Streamer interaction with a high resistivity surface

Role of spacers and leaks along the surface

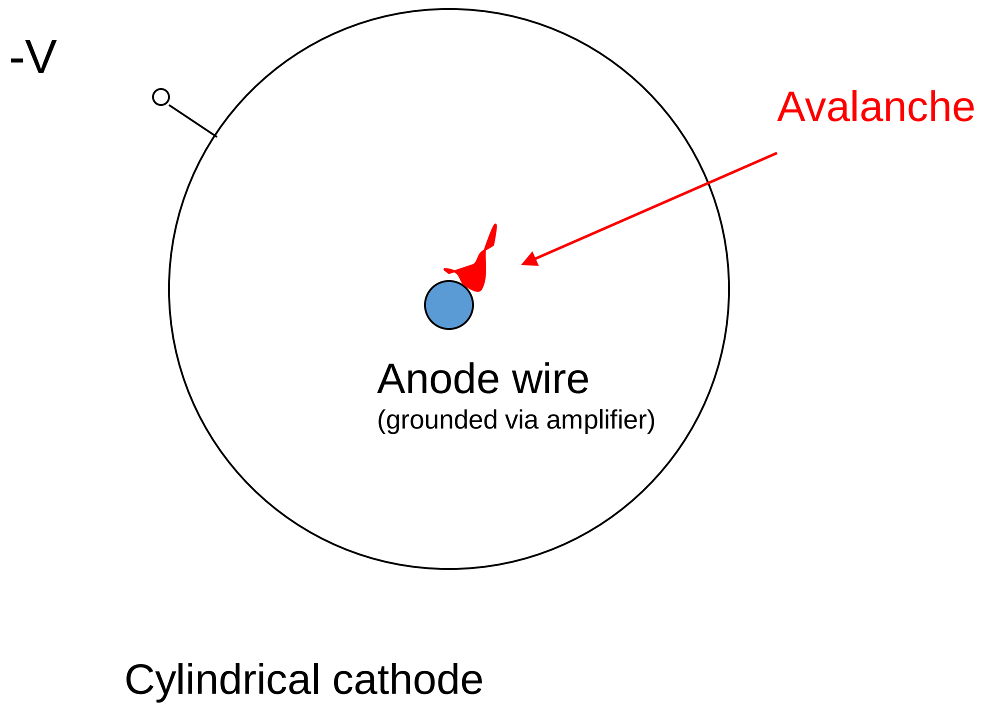




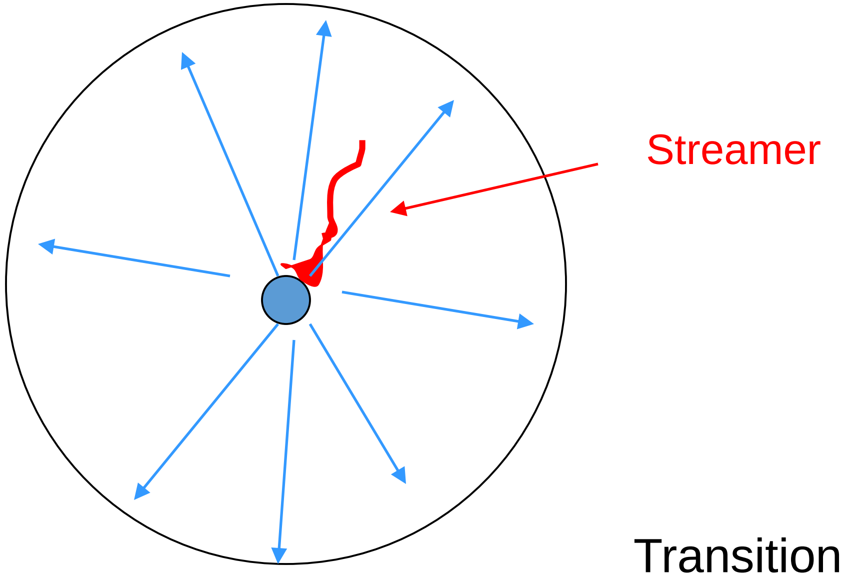
I.3. Self-quenched streamers

(...may related to MPGDs - see later!)

Discharges in thick wire detectors



Self-quenched streamer

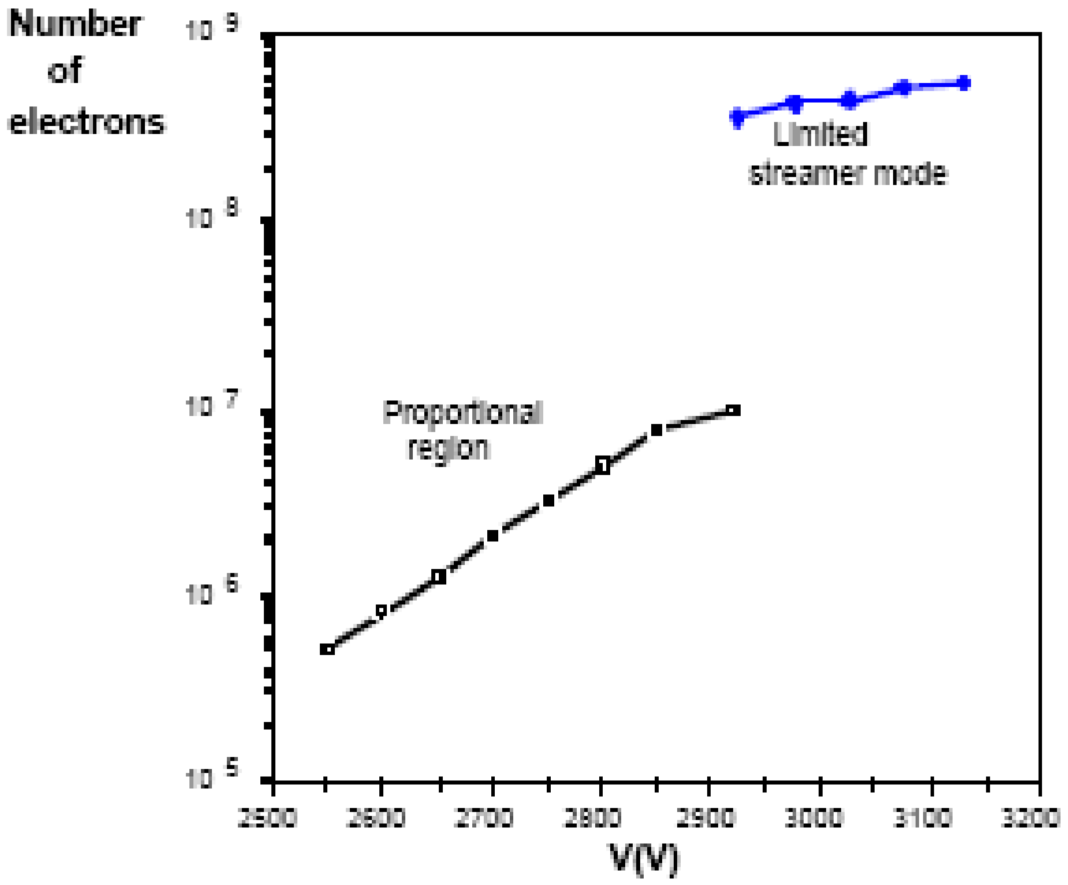


Streamers <u>cannot propagate</u> to the cathode because the electric field drops as 1/r

Transition to streamer occurs when $An_0 \geq Q_{max} = 10^8$electros

Streamers give huge amplitudes, but the are not harmful sinc they do not touch the cathode

Signal’s amplitude in proportional and streamer modes



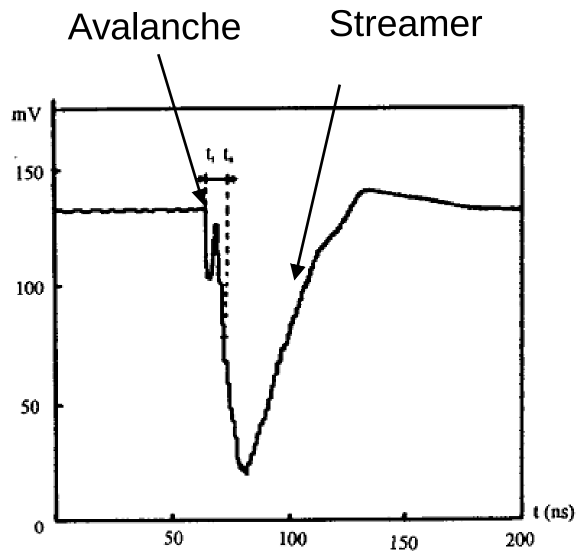
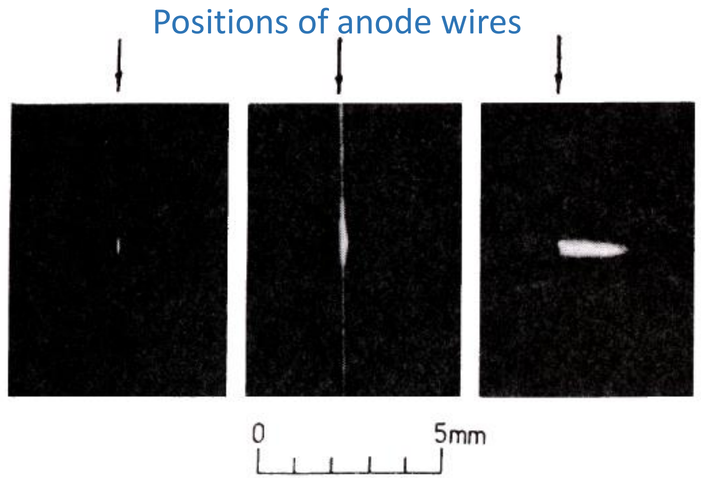


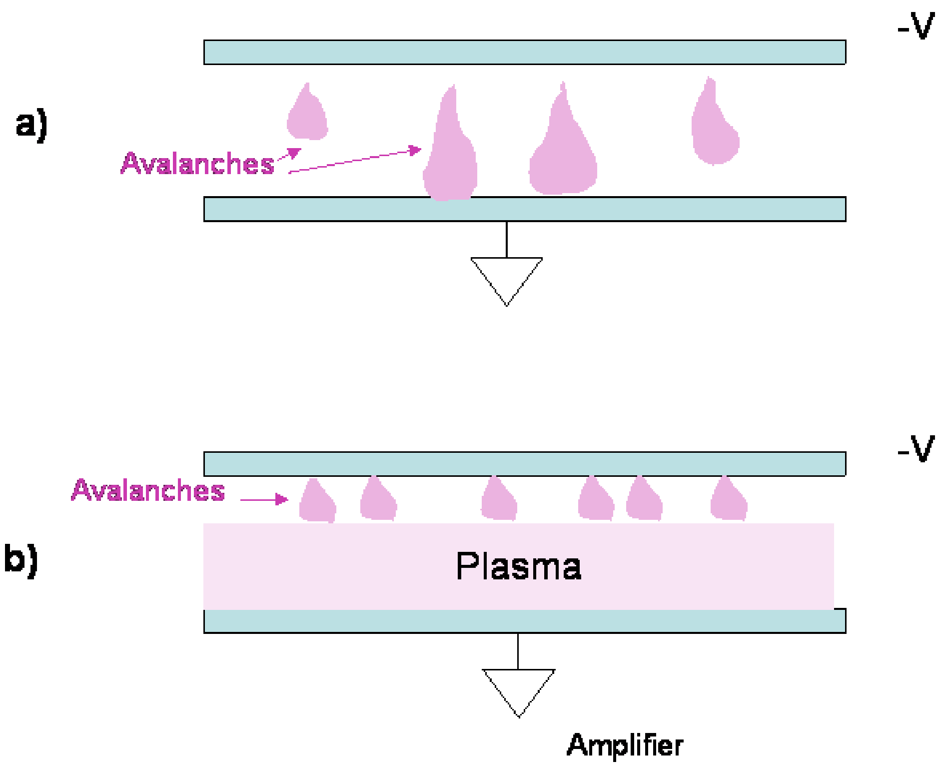
Fig. 1. The pulse shape of the SQS electrical signal $V = 2.45$ kV, Methylal/(Methylal + Ar) = 16.6%.



I.4. Mixed breakdown

Could be different scenarios of such mixed breakdowns

Typical time…up to ms or even more



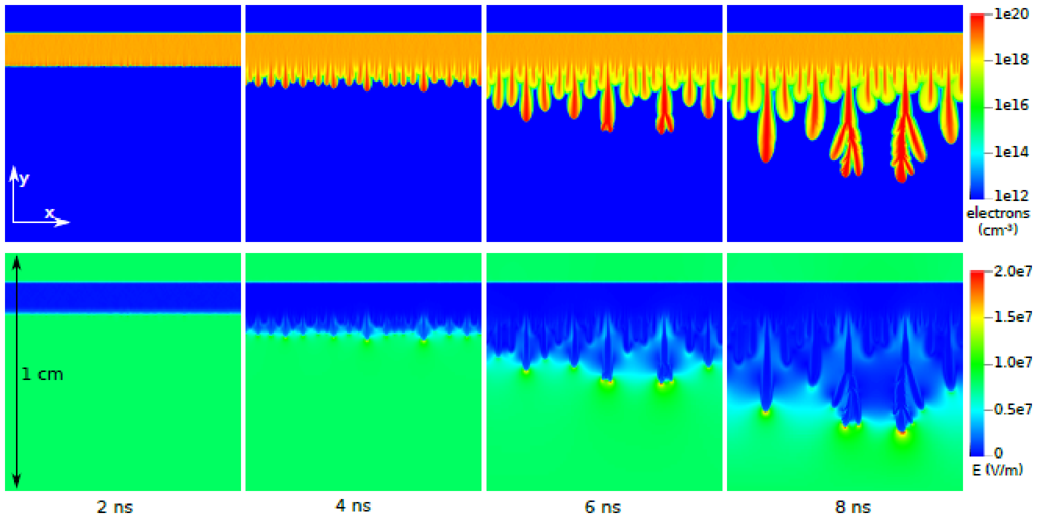


Figure 8: The evolution of the electron density (top) and electric field (bottom) in a 2D electric discharge simulation in nitrogen at standard temperature and pressure. The discharge started from a pre-ionized layer, which destabilizes into streamer channels. A zoom-in of the mesh around a streamer head at $t = 8$ ns is shown in figure 9.

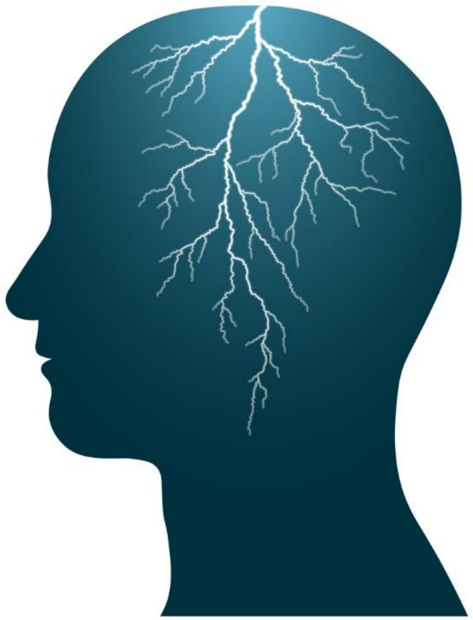
Conditions:

$A\gamma_{ph}=1$
or
$A\gamma_{+}=1$

Free electron can be emitted from the cathode as a result of the ion recombination with a probability γ_+ or due to the photo processes- γ_{ph}

Let’s now move to the central part of this presentation:

Part II. New findings (happened during MPGD era)



RD51 collaboration made a remarkable progress in discharge understanding

II.1.Raether limit for MPGDs:

It was shown* that a similar limit applies for every micropattern detectors: GEMs, MICROMEGAS and others:

$$A_{max}n_0=Q_{max}=10^6\text{-}10^7 \text{ electrons,}$$

where n_0 is the number of primary electrons created in the drift region of the detector

(Q_{max} depends on the detector geometry and the gas composition)

*(*see I. Ivaniochenkov et al., NIM A422,1999,300 and V. Peskov et al., IEEE Nucl. Sci. 48, 2001, 1070)*

Now it is loos like evident, but some time ago it was not the case…

Alternative explanation

Sauli model:

Figure 11.Computed field lines and equal gain contours in an MSGC. As can be seen the primary electrons released close to the cathode edge nay experience quite high gas multiplication (Bouclier, 1995).

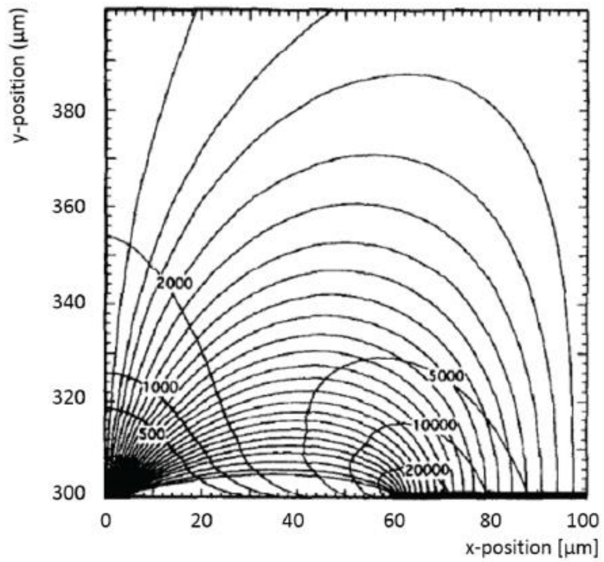
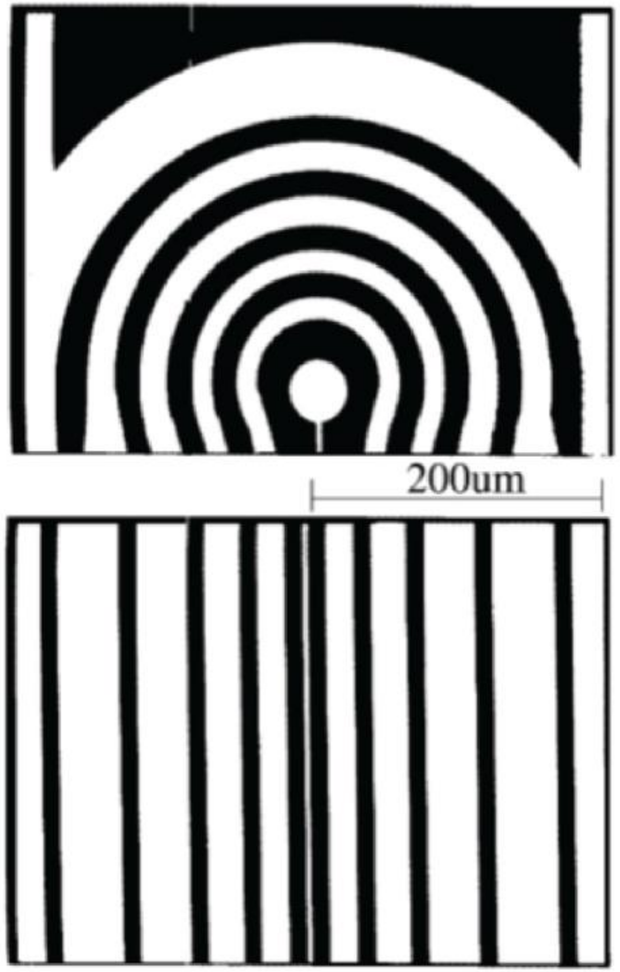


Figure 14. Photograph of the MSGC with segmented cathode (Takahashi, 2002)

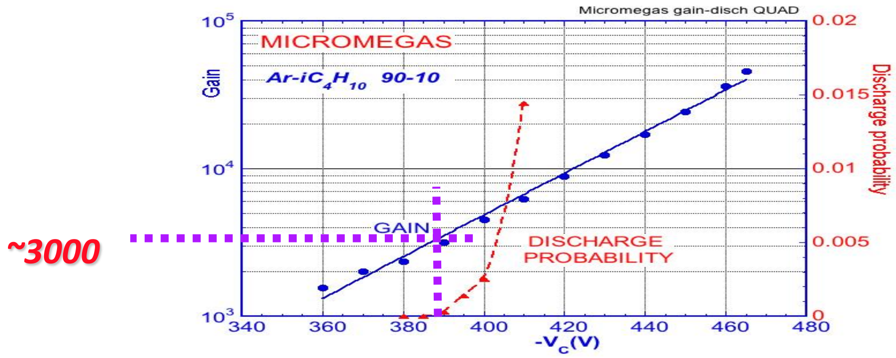


MPGD CERTIFICATION

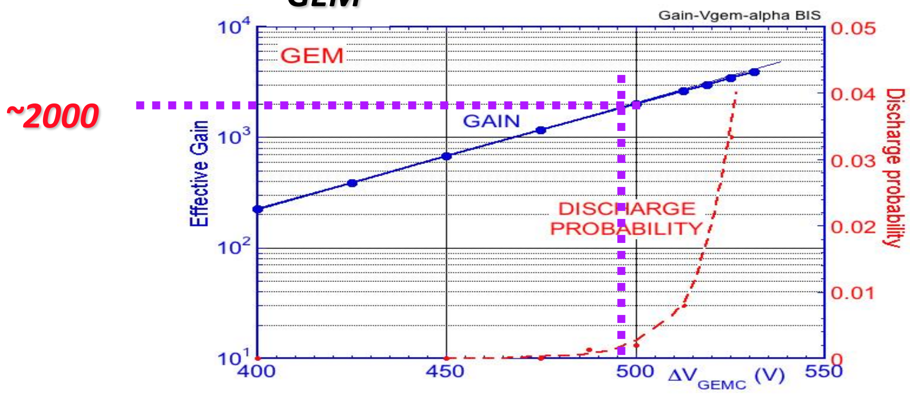
The maximum gain before discharge is almost the same for all MPGD tested:

DETECTOR	MAX GAIN	MAX CHARGE
MSGC	2000	$4\ 10^7$
ADV PASS MSGC	1000	$2\ 10^7$
MICROWELL	2200	$4.4\ 10^7$
MICROMEGAS	3000	$6\ 10^7$
GEM	2000	$4\ 10^7$

MICROMEGAS



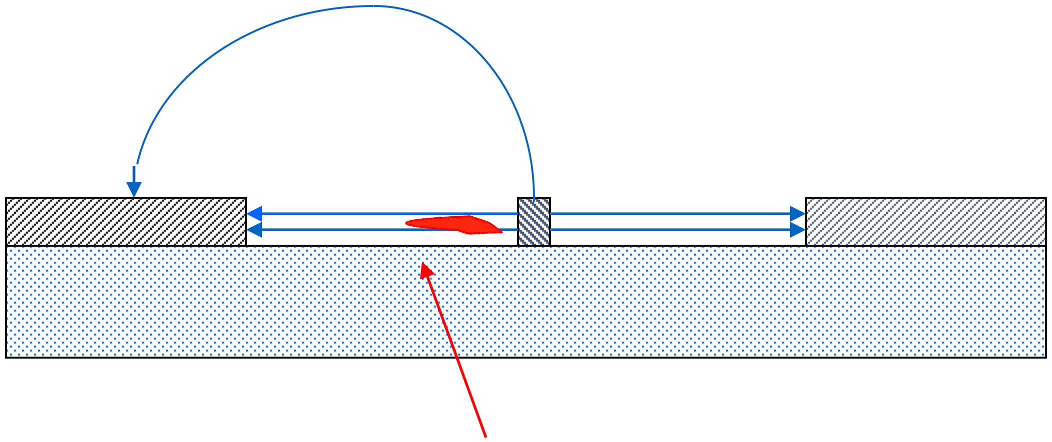
GEM



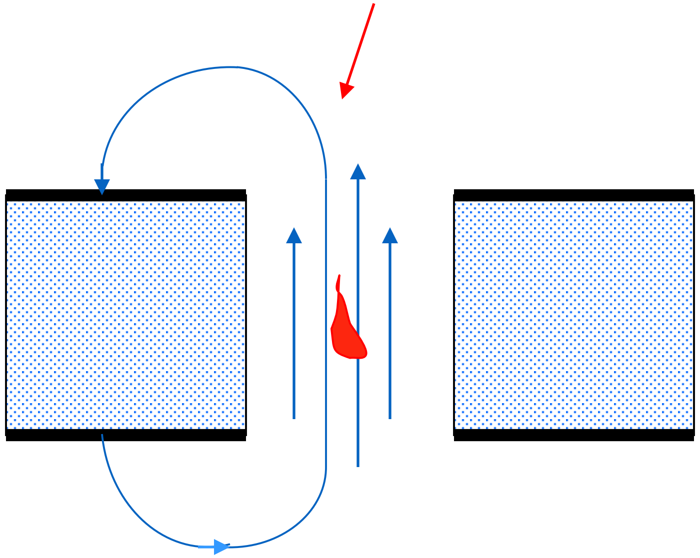
S. Bachmann et al, Nucl. Instr. and Meth. A479(2002)294

F. Sauli, Report at the RD51 collaboration meeting in Amsterdam, 2008

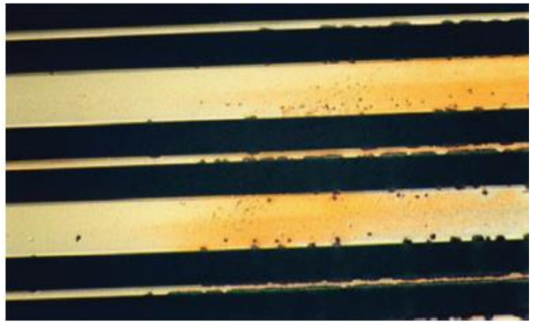
Why there are sparks in micropattern gaseous detectors?



Regions with parallel fields lines where any streamer, if appear, is unquenched and may reach the cathode

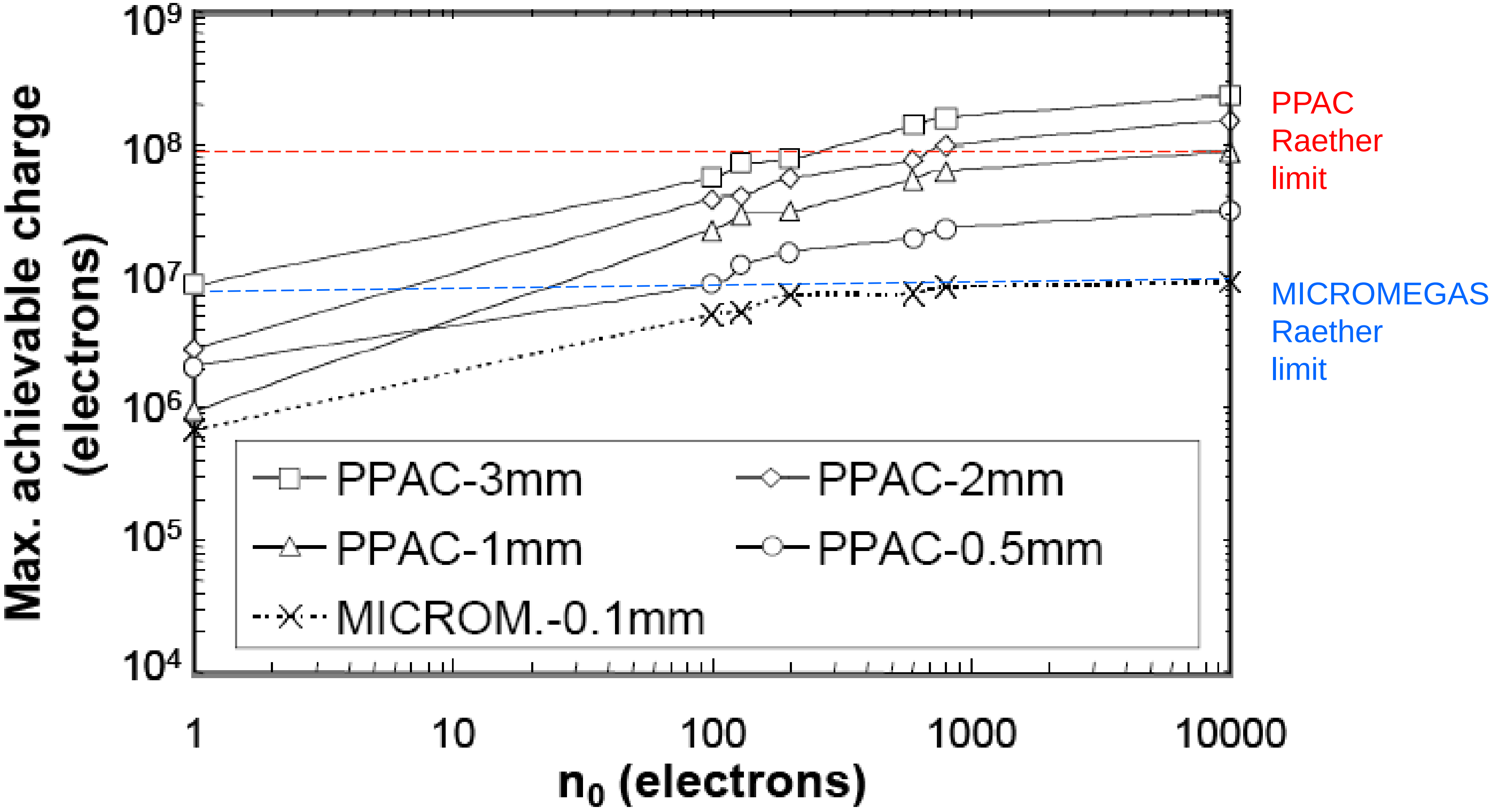


Numerous studies showed that in micropattern gaseous detectors sparks develop in the region of the avalanche gap, where the field lines are parallel each other. Therefore, the spark probability could be dramatically reduced if a radial shape electric field could be formed in the avalanche gap by some means.



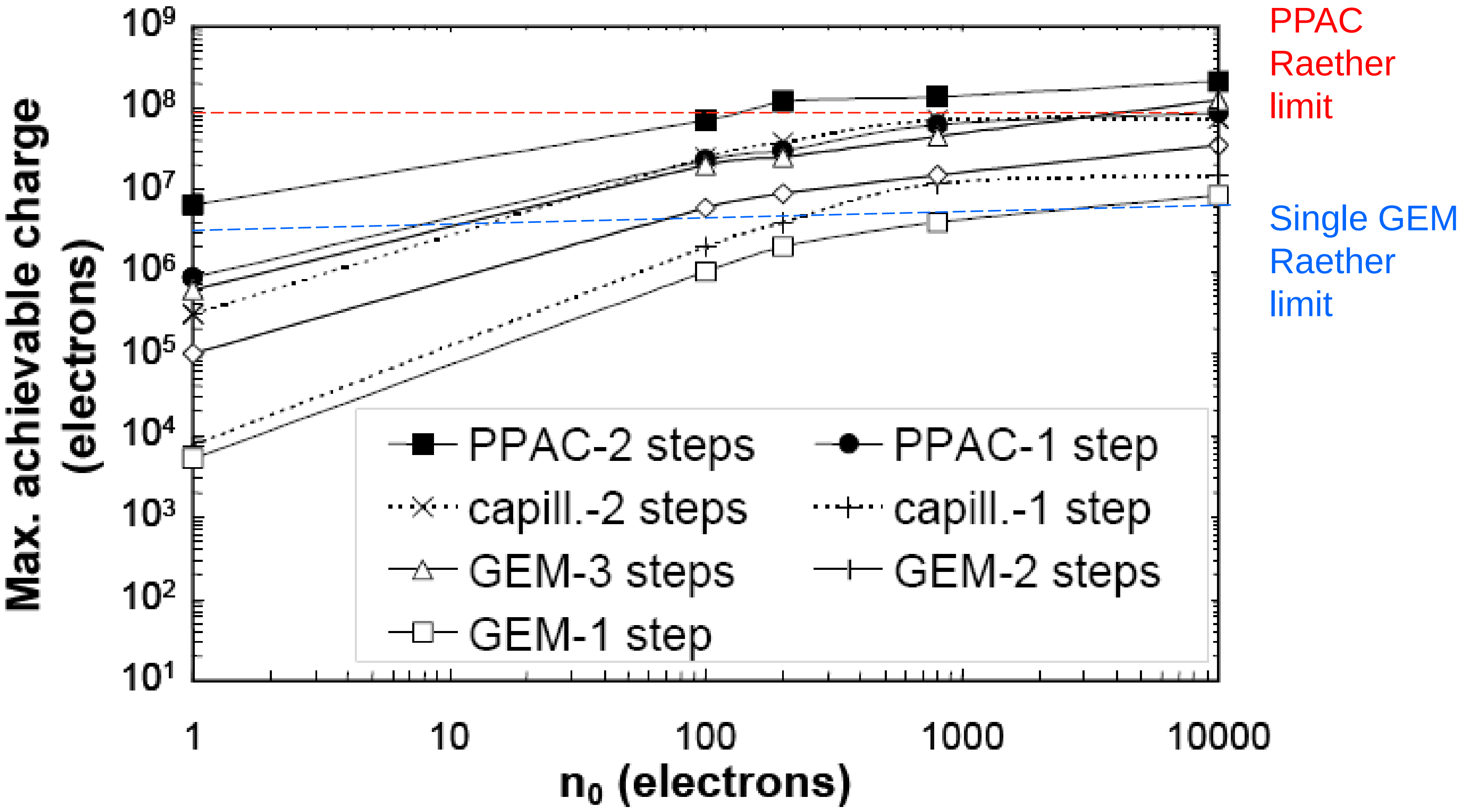
Because there are regions with parallel field lines, so streamers develop there by the same mechanism as in PPAC

Raether limit for PPAC and MICROMEGAS is reached at n_0>50 electrons



V. Peskov et al., IEEE Nucl. Sci. 48,2001,1070

..similar for GEM-type detectors



For n_0>50 electrons "Rather" limit works well, however for n_0<20 electrons other factor starts dominating like field emission from sharp edges, gain fluctuation…

V. Peskov et al., IEEE Nucl. Sci. 48,2001,1070

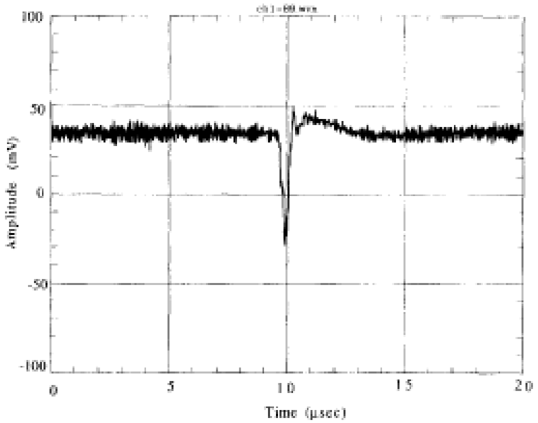


Fig. 4. Typical streamer current pulses for E-MSGCs with substrates.

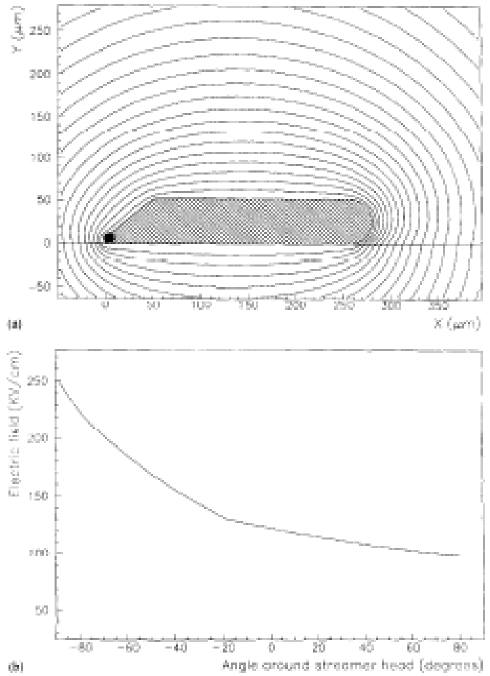


Fig. 16. Field calculations for a streamer close to the substrate surface (this case corresponds to the E-MSGC with substrate and the MSGC): (a) field map; (b) field around the tip.

V. Peskov et al., NIM A397,1997, 243

An important contribution to the Raether limit studies was done by the RD51 community

Just a couple of examples…

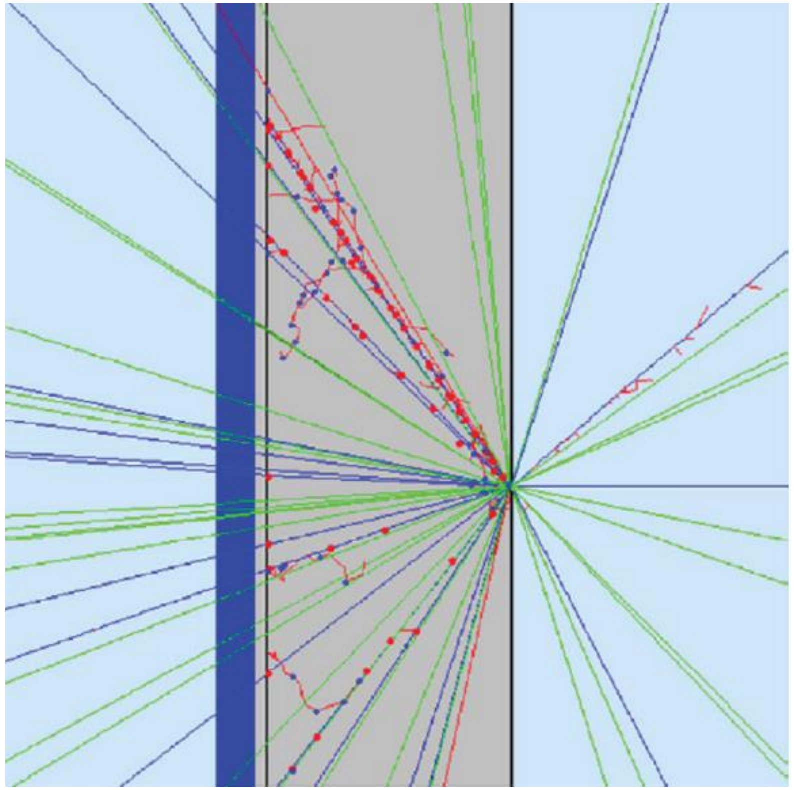
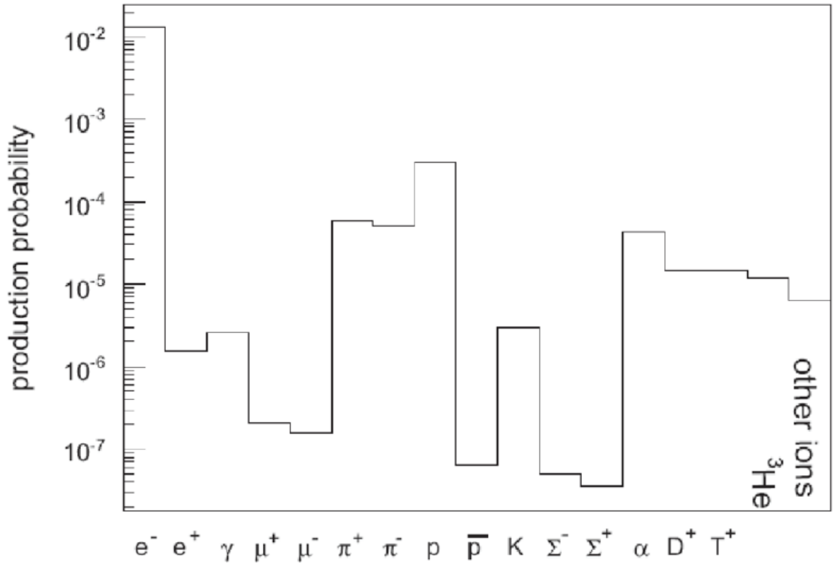
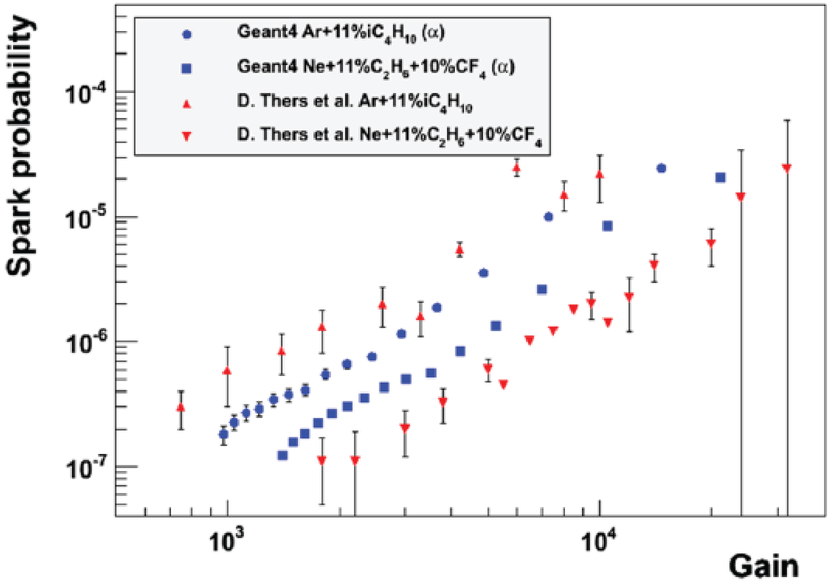


Figure 29. A simulated interaction between a 15Gev/c pion arriving from the right and nucleus in the MICROMEGAS drift electrode. Besides secondary photons and electrons, a low energy proton is created which is heavily ionizing (along the red dotted track). Regions of large deposited energy are represented by red and blue dots (Procureur, 2010a).





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Charge density as a driving factor of discharge formation in GEM-based detectors

P. Gasik [a,b,*], A. Mathis [a,b,*], L. Fabbietti [a,b], J. Margutti [a,c,1]

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A R T I C L E   I N F O

Keywords:
Gas electron multiplier
GEM
Gas discharges
Breakdown
Streamer

A B S T R A C T

We report on discharge probability studies with a single Gas Electron Multiplier (GEM) under irradiation with alpha particles in Ar- and Ne-based gas mixtures. The discharge probability as a function of the GEM absolute gain is measured for various distances between an alpha source and the GEM. We observe that the discharge probability is the highest when the charge deposit occurs in the closest vicinity of the GEM holes, and that the breakdown limit is lower for argon mixtures than for neon mixtures.

Our experimental findings are in line with the well-grounded hypothesis of the charge density being the limiting factor of GEM stability against discharges. A detailed comparison of the measurements with GEANT4 simulations allowed us to extract the critical charge density leading to the formation of a spark in a GEM hole. This number is found to be within the range of $(5-9) \times 10^6$ electrons after amplification, and it depends on the gas mixture.

Practical outcome:

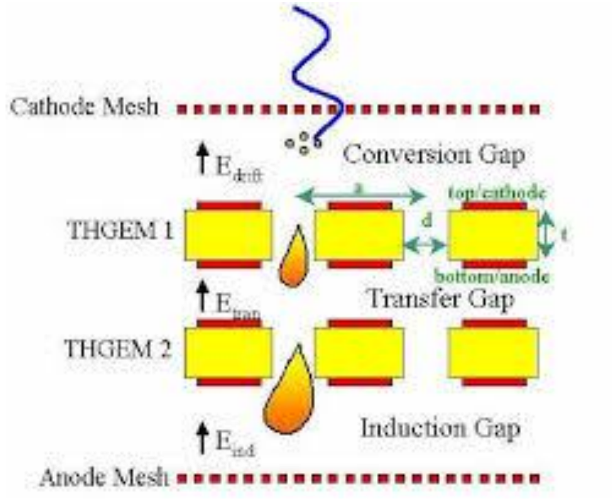
RD51 collaboration founded that the Raether limit in micropattern detectors depends on many factors, e.g.:

geometry,

gas composition,

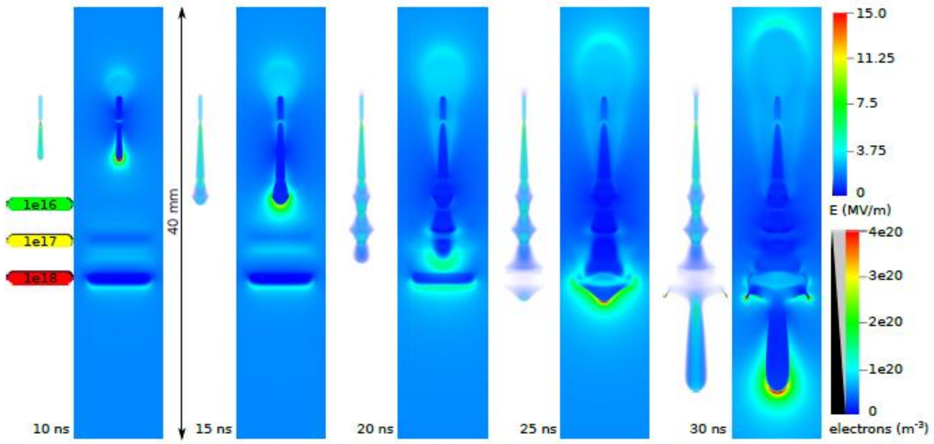
ionization density, etc

This gives a tool for the detector optimization



For example, in multistep GEM the Raether limit increases with the number of steps (due to the electron diffusion effect (*see P. Fonte et al, NIM A416,1998, 23*). Moreover, in this mode the voltage on each GEM is reduces, allowing to avoid breakdowns due to the detector defects sharp edges, durt, etc

II.2. Streamers understanding and simulation



Nowadays streamer dynamic based on photoeffect model are simulated in many paper

Streamer are treated as an ionization wave

However, one of first (probably the first!) such impressive simulations were done in our community by P. Fonte

Streamer calculation strategies: continuous approach

Other sources

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 (very debatable process)

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

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

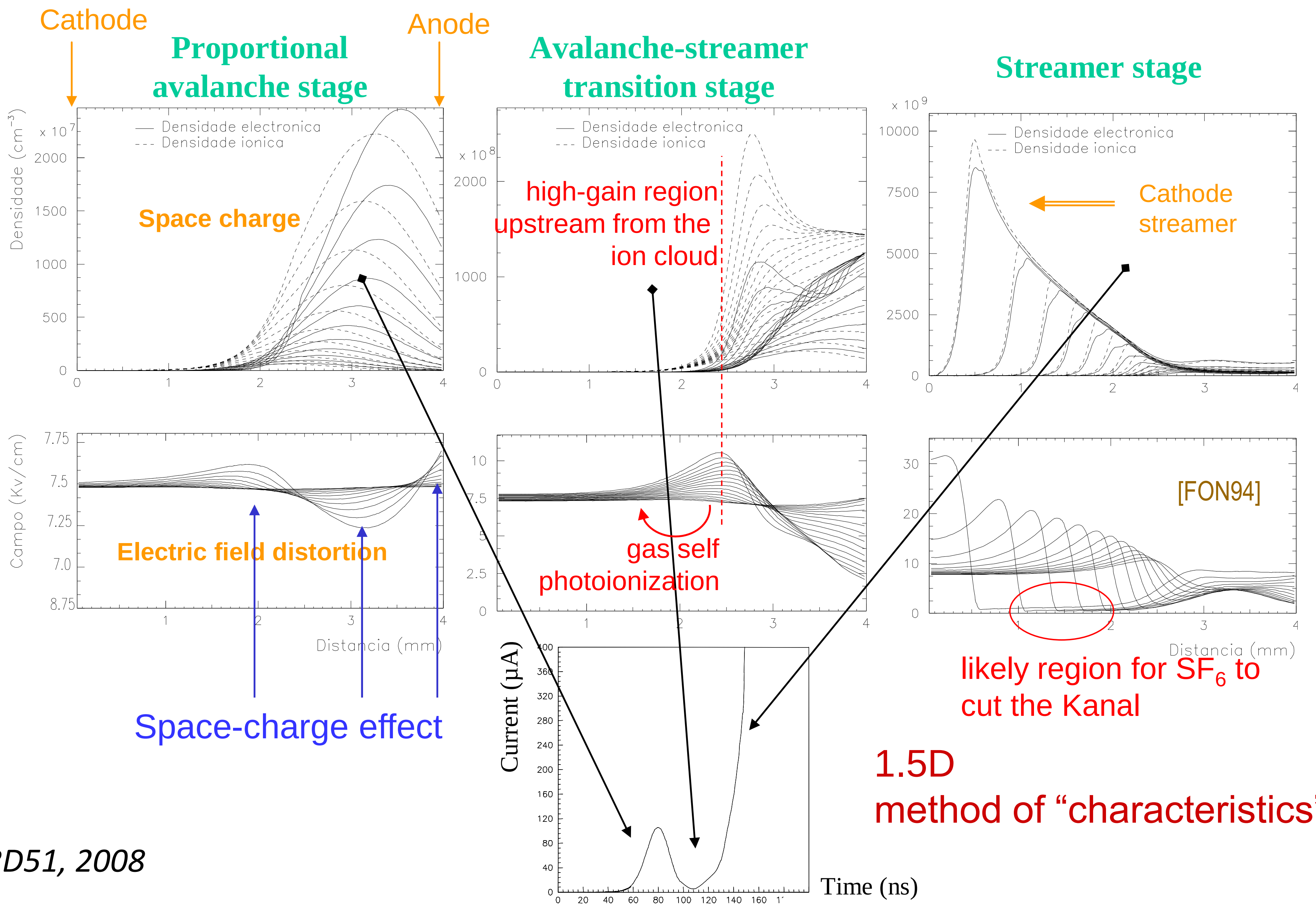
λ = photon's mean free path

Quite formidable!
Don't know of any practical 3D calculation.

All this for each relevant emission wavelength…

From P. Fonte, RD51, 2008

Cathode streamer simulation in PPAC



1.5D
method of "characteristics"

From P. Fonte, RD51, 2008

II.3. A new model: 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

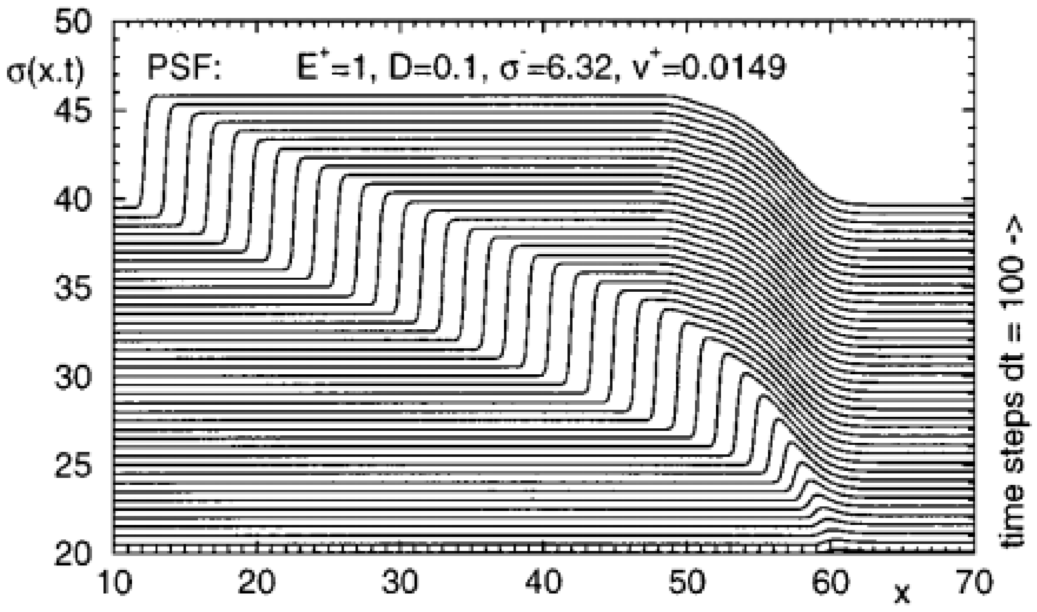


FIG. 10. Emergence of the uniformly translating PSF on the left for $D=0.1$. Initial conditions identical with Fig. 9. The time range $t=4000$–8000 after an initial perturbation at $t=0$ and $x_0=60$ is shown in time steps of $\Delta t=100$. (Numerical grid size $\Delta x=0.01$ and $\Delta\tau=0.5$.)

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

Fonte, RD51, 2010

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

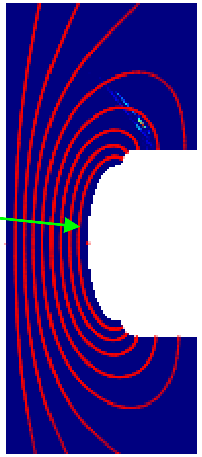
$\vec{E}(\vec{r},t) =$ electric field$=\vec{\nabla} V(\vec{r},t)$

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

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

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

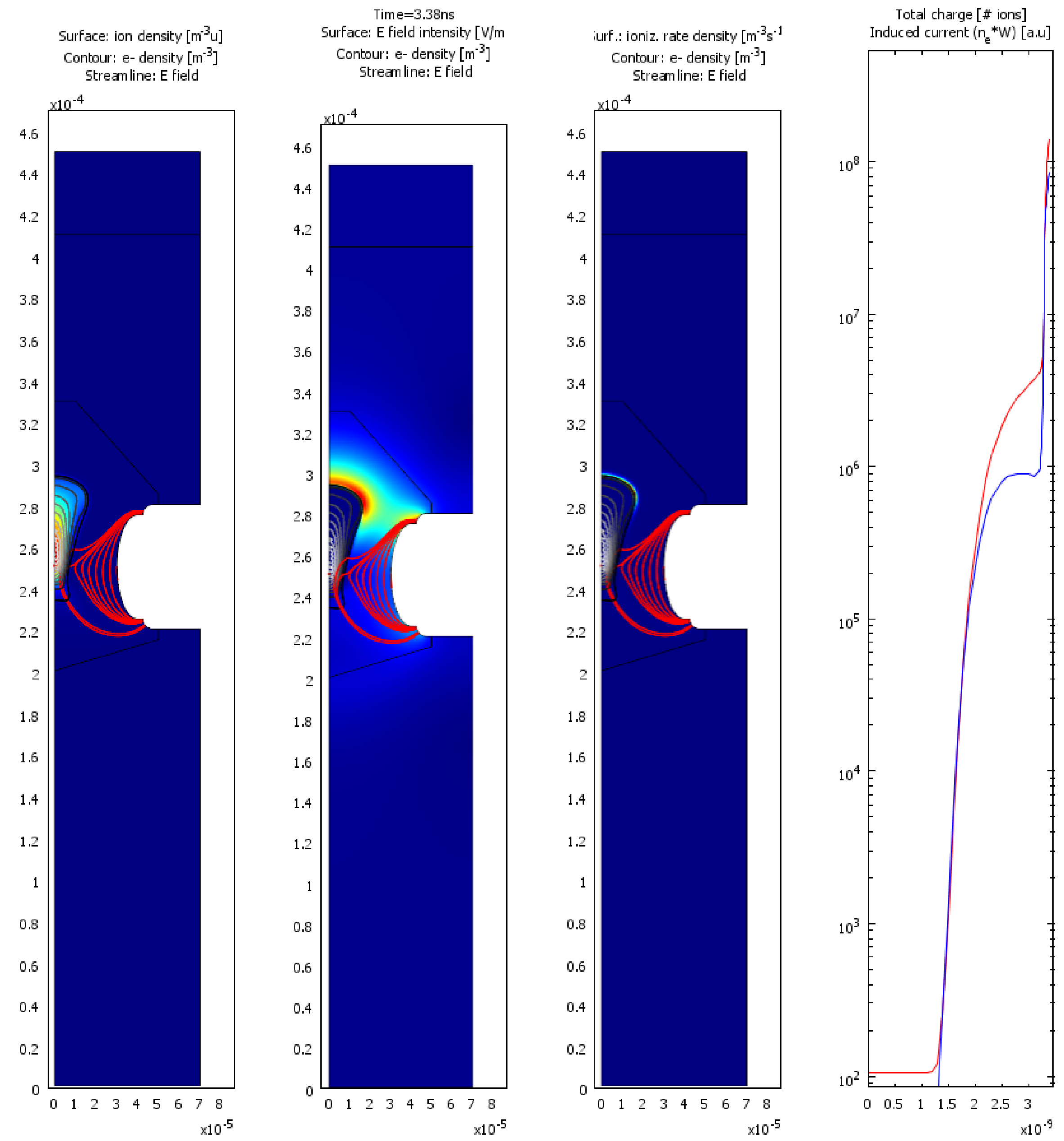
- Only electrons and positive ions
- No positive ion movement (in such short time span)
- No attachment
- **No photons**
- Assume <u>axial symmetry</u> (minimal condition for realism):
  2D calculation
- Applied field: boundary conditions on the potential
- Dielectrics: tangent $\vec{E}$ (no charge flow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



Fonte, RD51, 2010

GEM

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



For details, please see P. Fote talk at this Workshop

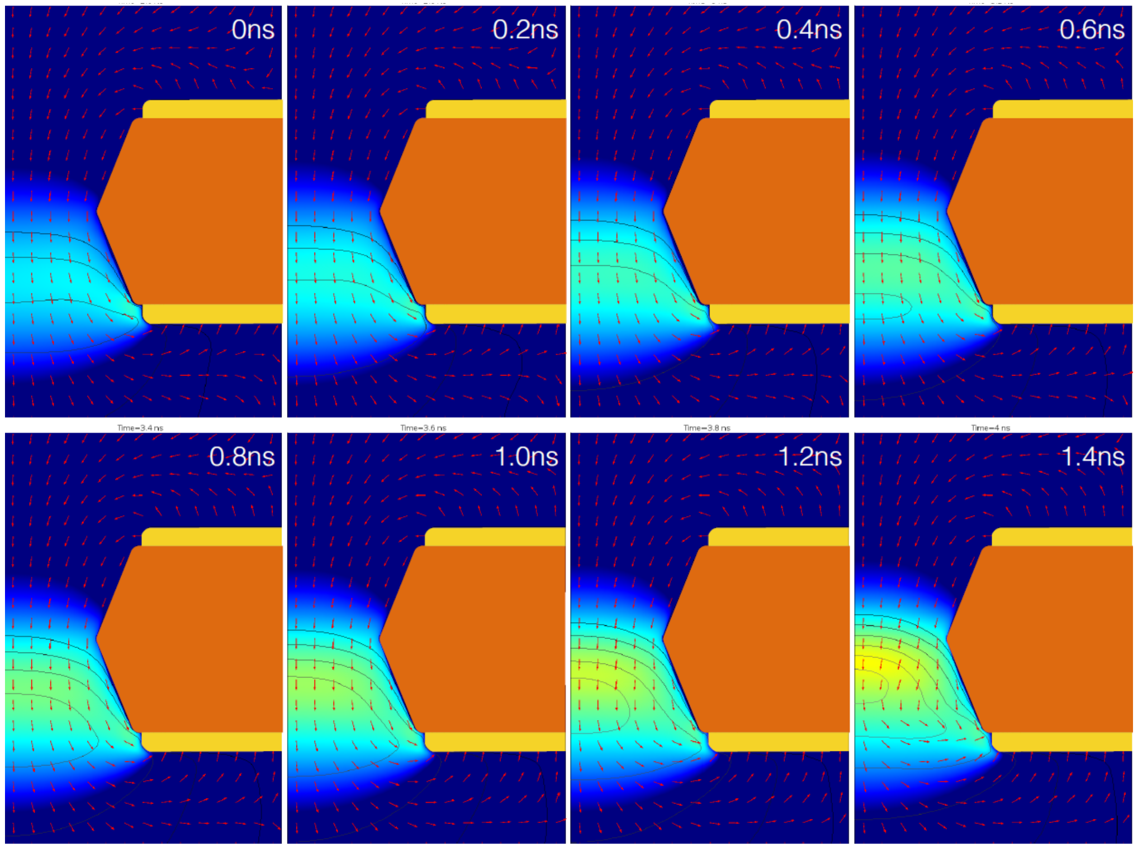
Summary

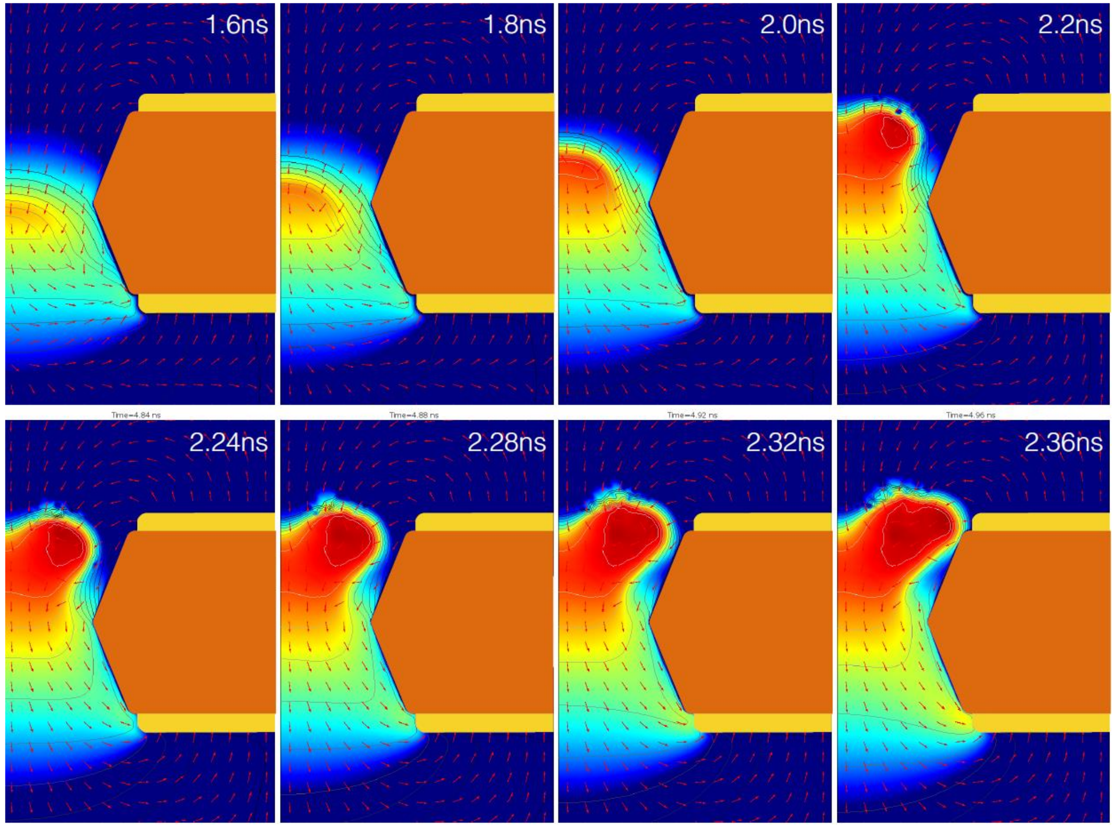
- Streamers can be supported by diffusion alone
- This seems to be qualitatively more in agreement with the empirical observations in detectors than the classical mechanism based on self-photoionization
- The corresponding hydrodynamic model seems to describe qualitatively fast breakdown in detectors
- **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

Fonte, RD51, 2010

Recent impressive calculation from F. Resnati





Filippo conclusions:

Summary

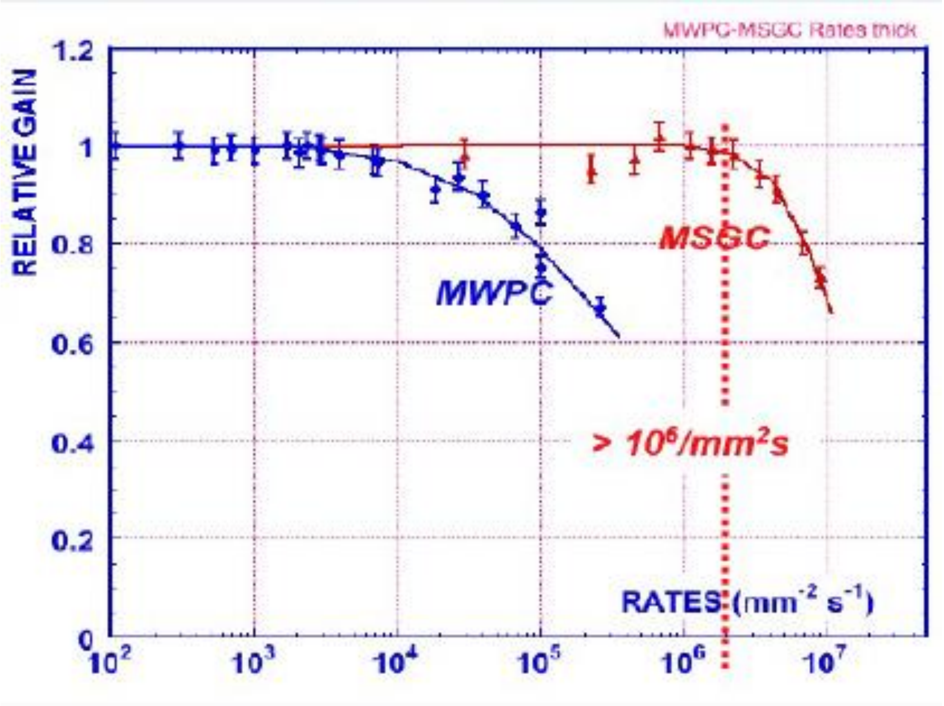
Computation of streamer in gas

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

II.3.Undestandin of a rate effect in MPGD



What determines the limit?

II.2. Rate dependence of the max. achievable gain on counting rate.

Example Parallel plate detector (PPAC or MacroMEGAS)

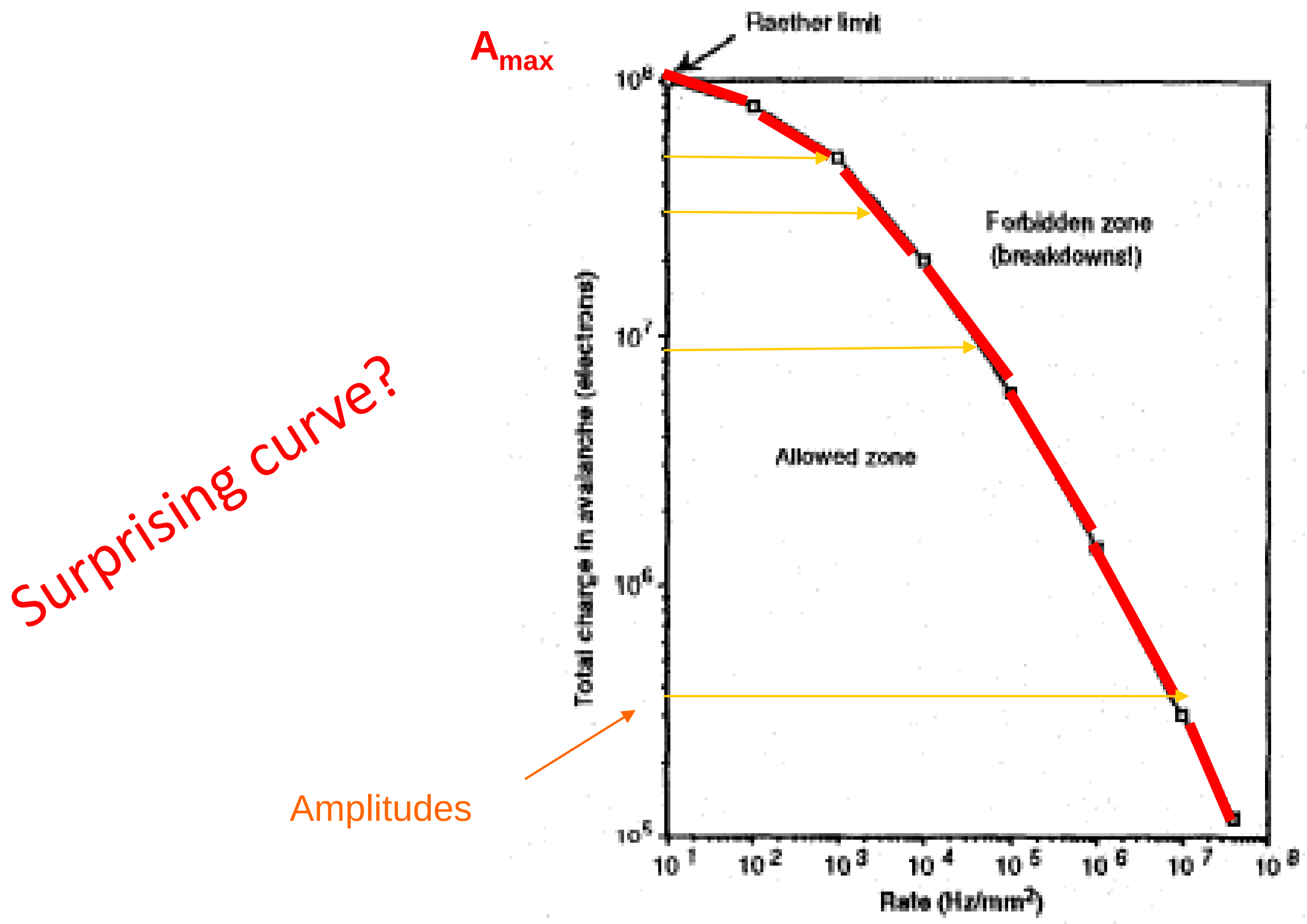
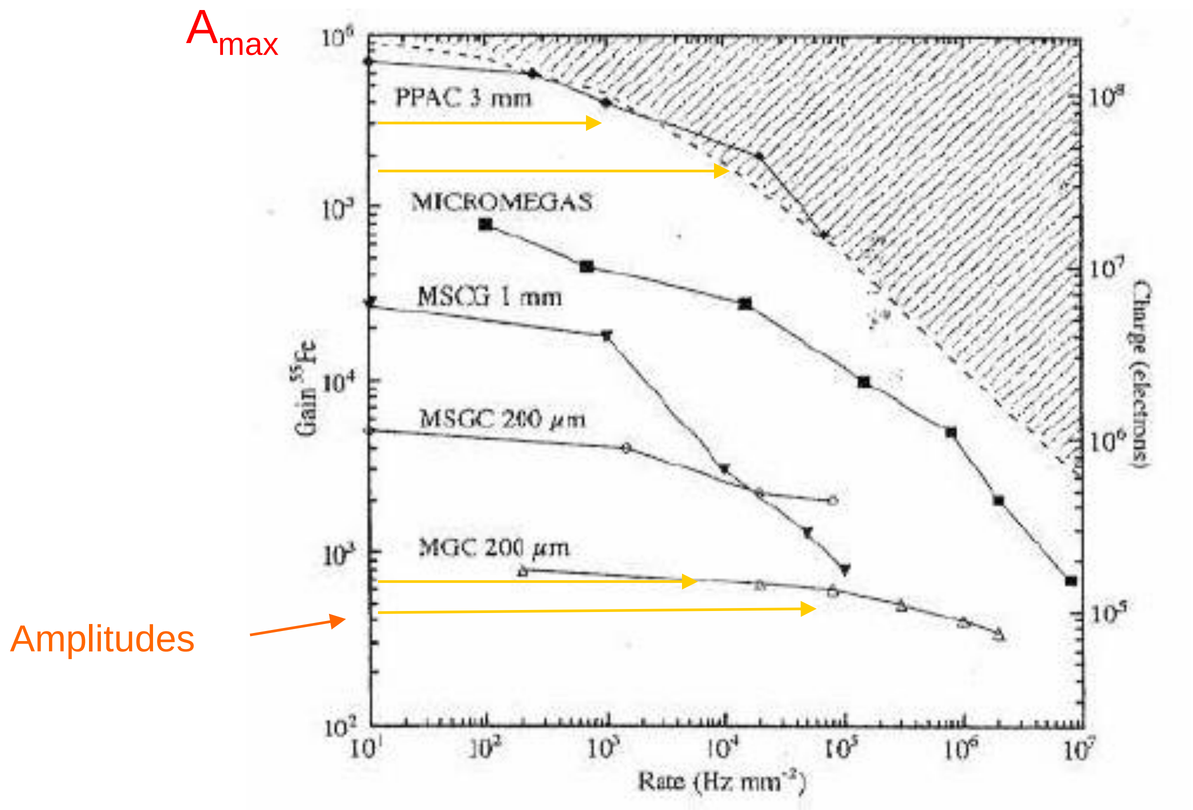


Figure 1: General curve reflecting gain limitation with rate for gaseous detectors.

P. Fonte et al IEEE Nucl. Sci 46,1999,321

Signal amplitude does <u>not drop with rate</u>, however there is a <u>rate limit</u> for each amplitude

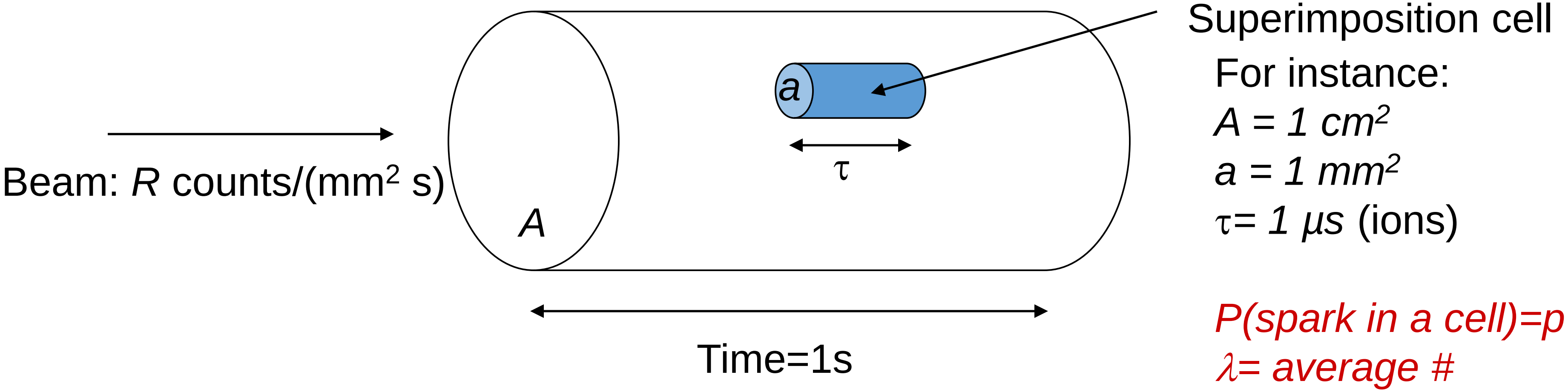
II.3. Rate limit of micropattern gaseous detector
(max. achievable gain vs. rate)



P. Fonte et al,
NIM A419,1998,405

For each micropattern detector the pulse amplitude remains practically unchanged with rate, however the maximum achievable gain drops with the rate

Breakdown statistics via superimposition and Raether limit



For instance:
A = 1 cm^2
a = 1 mm^2
τ = 1 μs (ions)

P(spark in a cell)=p
λ= average # avalanches/cell

There are $N=A/a \times (1s)/\tau$ superimposition cells: $N=10^8$.

We want to observe a relatively low absolute spark rate $P(spark)=S \sim 10^{-2}$ /s

$S=1-P(not\ spark)=1-(1-p)^N \Rightarrow p \approx S/N$: $p=10^{-10}$.

The number of avalanches n in each cell is Poisson-distributed with average $\lambda=Ra\tau$:
$\lambda=R \times 1 \times 10^{-6}$.

There will be a spark if $nq>Q_R$, q=is the average avalanche charge and Q_R the Raether limit.

Then, the required gain reduction owing to superimposition is $1/\tilde{n}$, with $\tilde{n}$ the percentile $1-p$ of the Poisson distribution with average λ.

P. Fonte et al., arXiv:0909.2681

Rate-induced breakdown? – experimental evidence

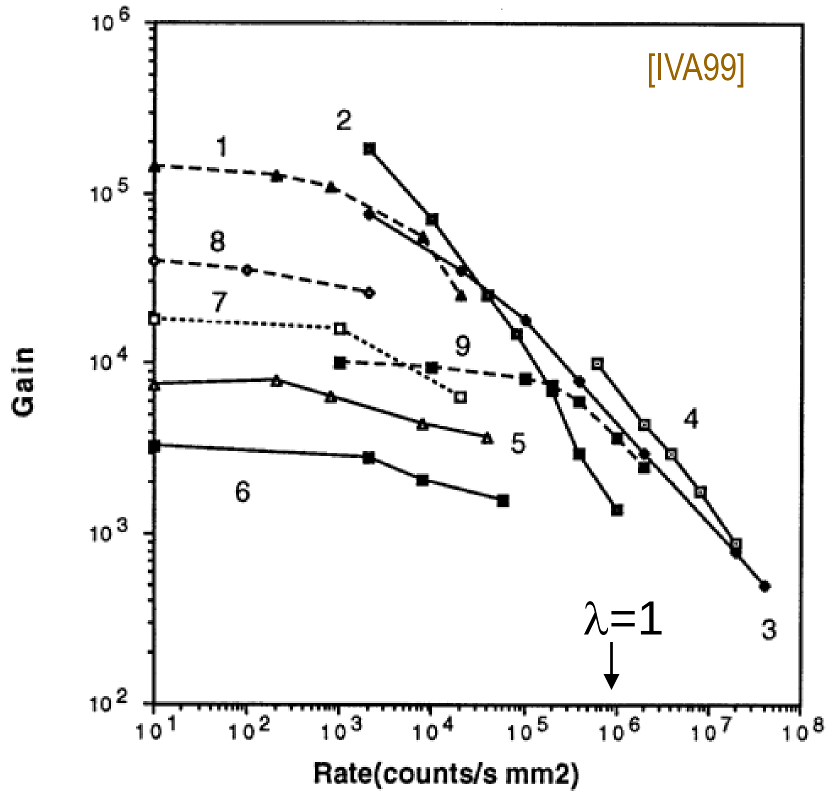
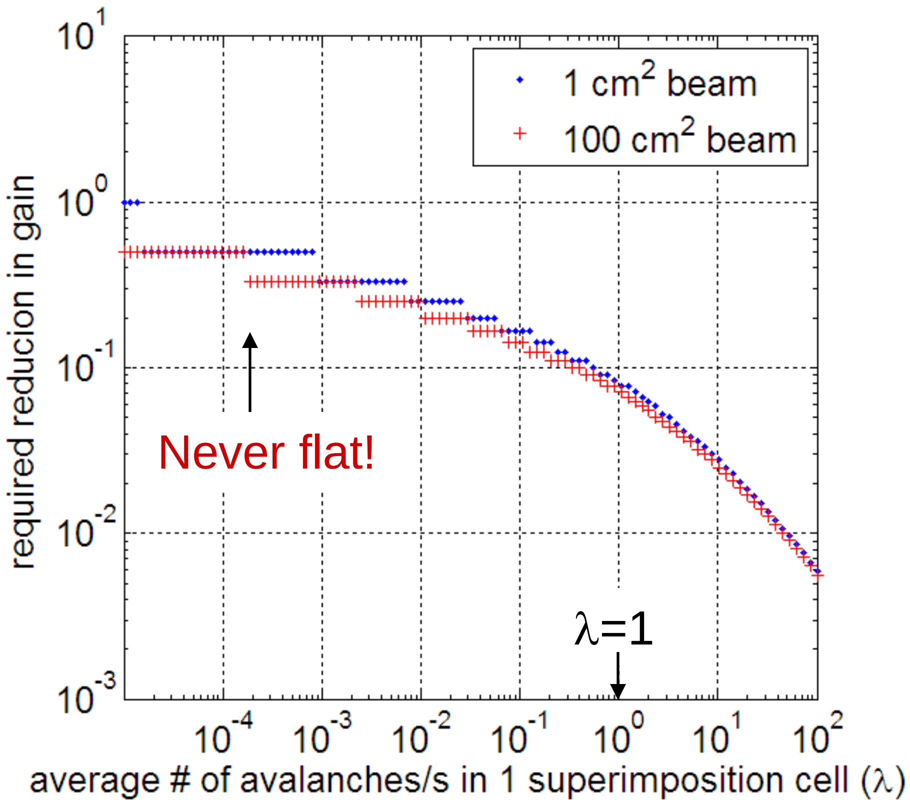


Fig. 1. The maximum achievable gain (curves 1–6), as a function of X-ray flux for various detectors: (1) thick-wire MWPC, (2) PPAC with 3 mm gap, (3) PPAC with 0.6 mm gap, (4) MICROMEGAS (from Ref. [13]), (5) CAT, (6) GEM. (7–9) Space-charge gain limit as a function of rate for other MWPCs: (7) "standard" MWPC, (8) MWPC replotted (from Ref. [14]), (9) thin-gap MWPC (from Ref. [15]).

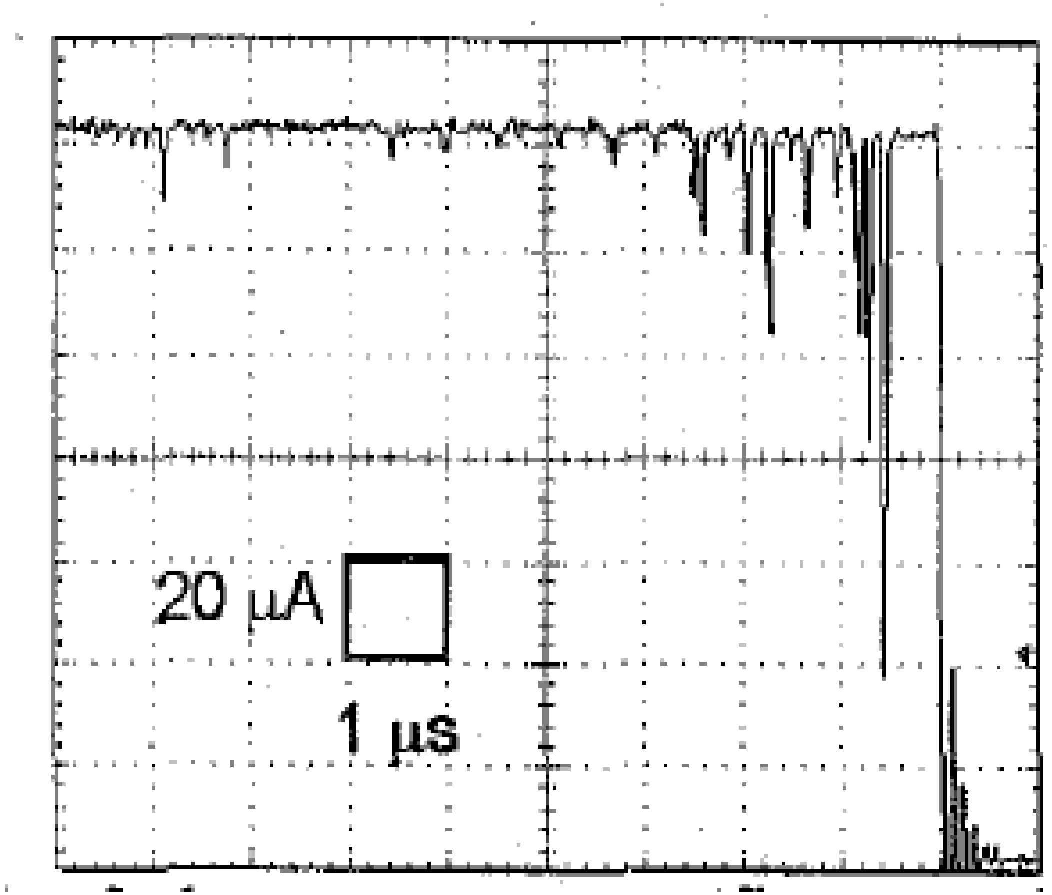


Mere statistics seem to qualitatively reproduce the data!

P. Fonte et al., arXiv:0909.2681

Could be also a contribution from sporadic jets of electrons (?)

What is the origin of these gigantic pulses appearing just before the fast breakdown?

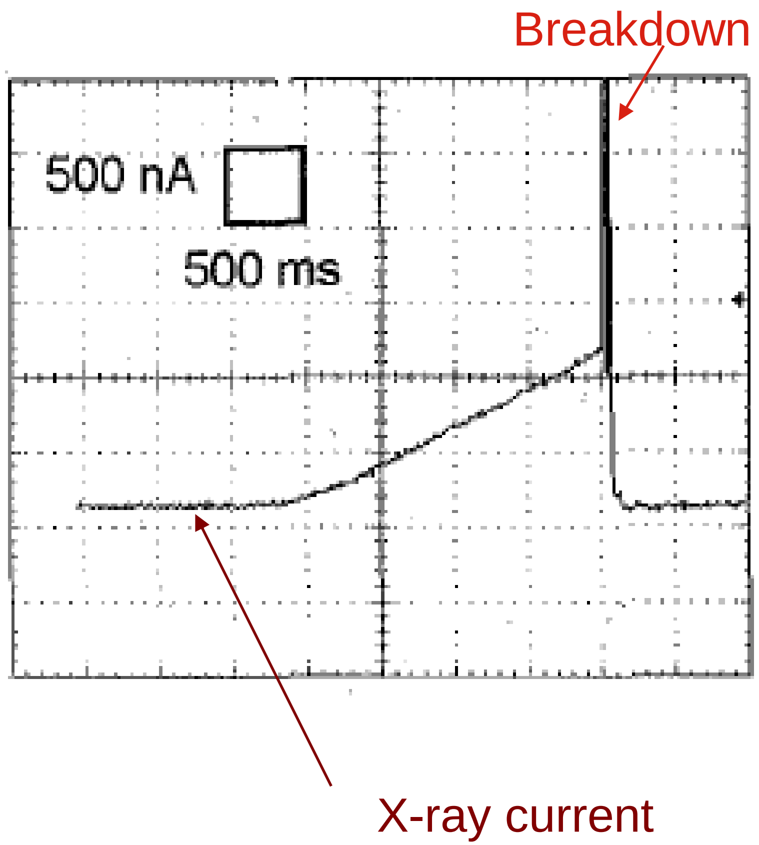


I. Ivaniochenkov et al., IEEE Trans Nucl. Sci., 45, 1998, 258

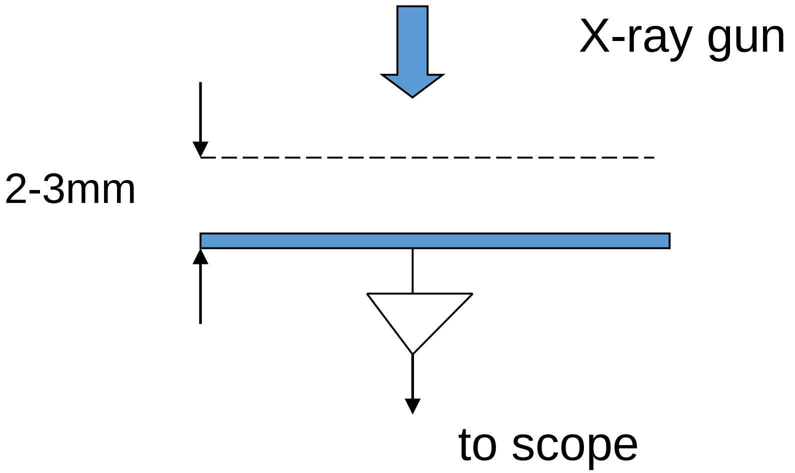
This observation lead us to a conclusion that there could be some new phenomenon:

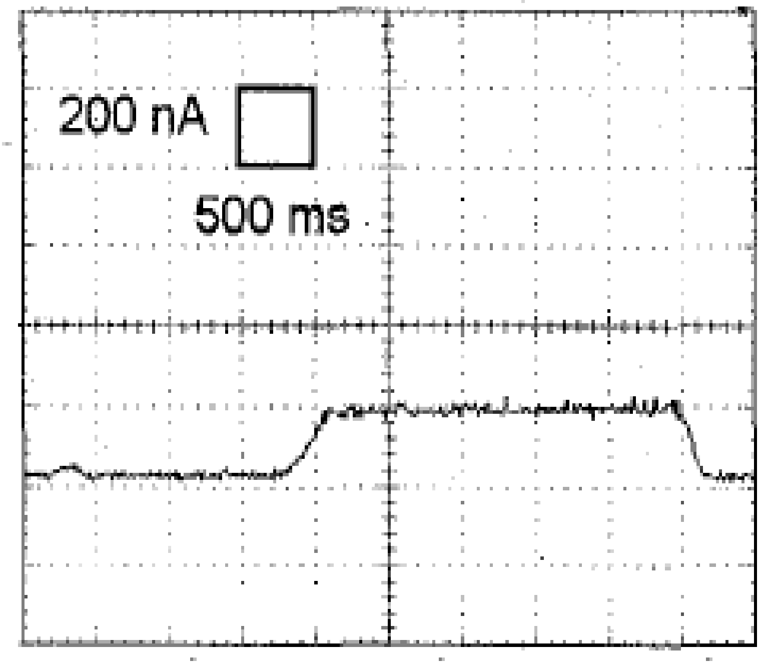
II.4. Discharge preparation mechanisms

C. Iacobaeus et al., IEEE Trans Nucl. Sci, 49, 2002, 1622



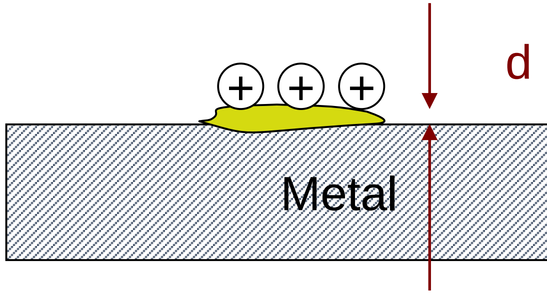
Y. Ivanchenkov et al, IEEE, 45,1998, 258





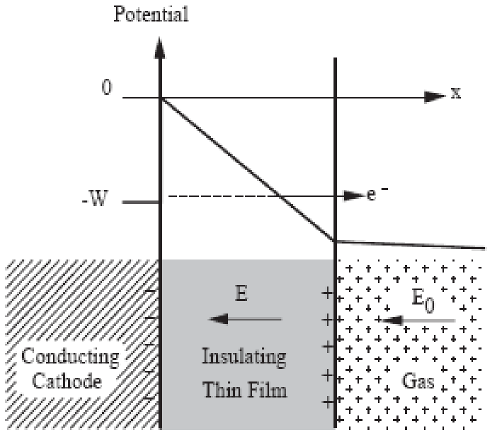
Similar effect is often describes in aging papers
(see for example *Aging Workshop*, *NIM A515, 2003*)

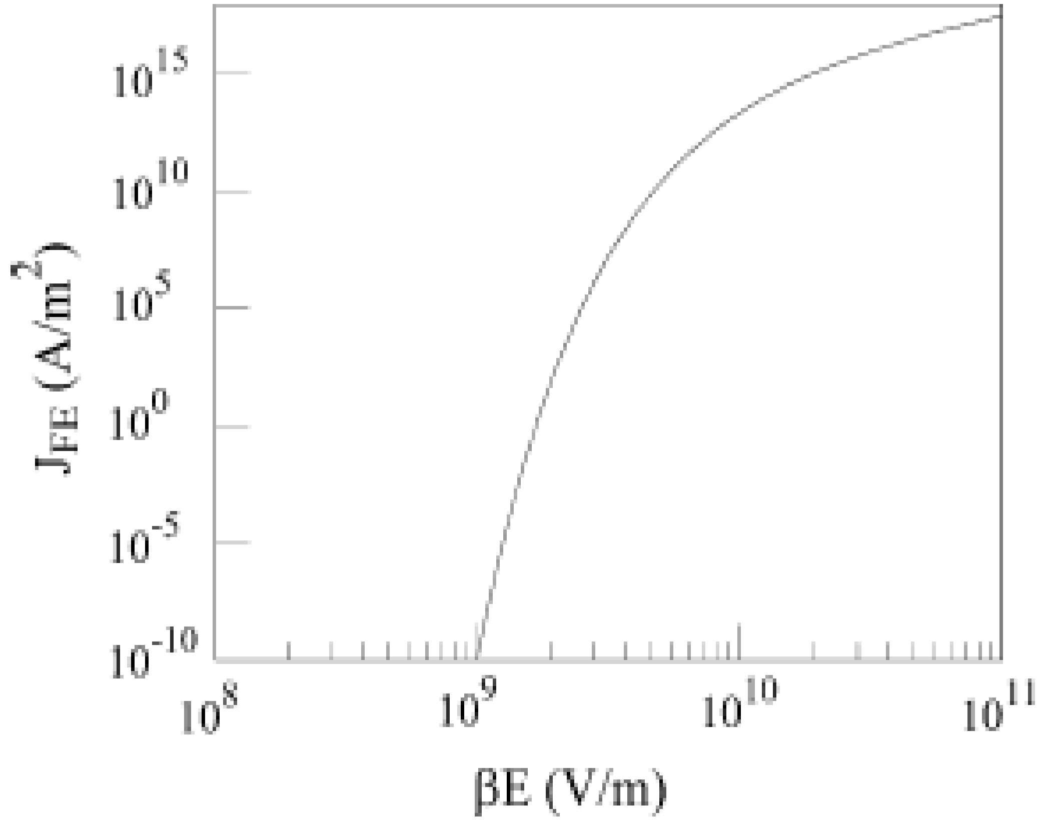
Usual explanation is via Malter effect..



$J_{fe}=5.4\times10^{-5}(\beta E)^2\exp(-5.43\times10^{10}/\beta E)$

E=σ/d





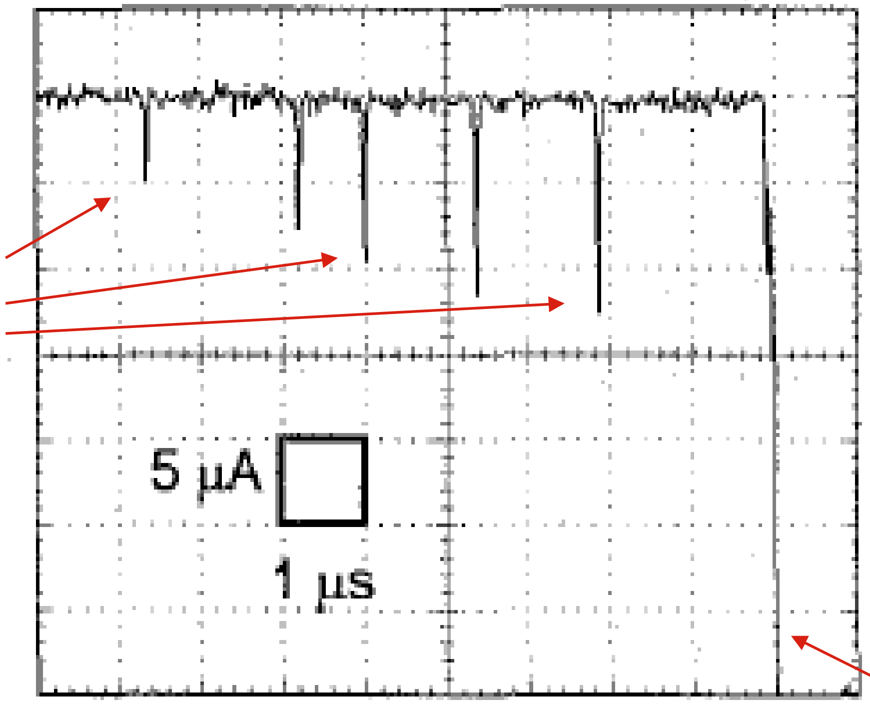
But it is not so simple…

Classical Malter effect predicts single electron emission

(see L. Malter , Phys. Rev, 49,1936, 478)

However, in most cases a slow current increase is just an integral of high amplitude pulses (*I. Ivanchenkov et al, IEEE, 45,1998, 258)*
:

“preparation” pulses, each contains a huge number of electrons-jets



Breakdown

This strongly contradict to the classical Malter effect

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Nuclear Instruments and Methods in Physics Research A 535 (2004) 632–643

NUCLEAR INSTRUMENTS & METHODS IN PHYSICS RESEARCH

Section A

www.elsevier.com/locate/nima

Model of high-current breakdown from cathode field emission in aged wire chambers☆

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Received 18 March 2004; accepted 26 June 2004

Available online 13 August 2004

Some of the results presented in this paper were interpreted via the <u>jets mechanism</u>

Explosive field emission

Besides classical field emission calculated by Zommerfeld and others there is another phenomena -<u>explosive field emission</u>

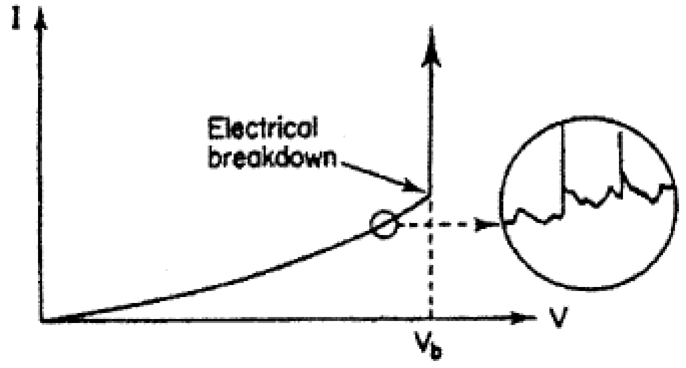
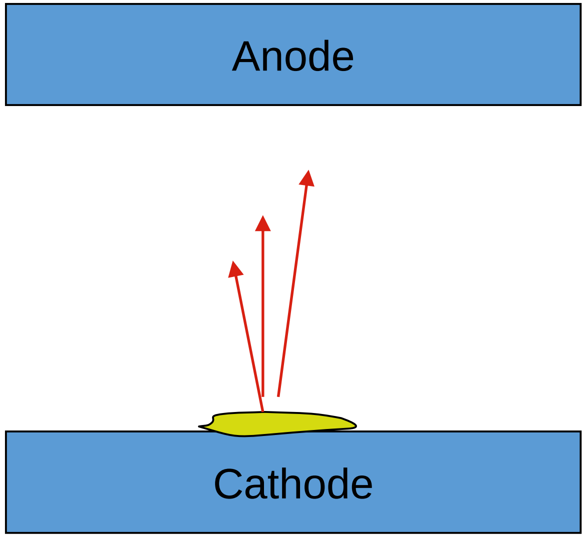
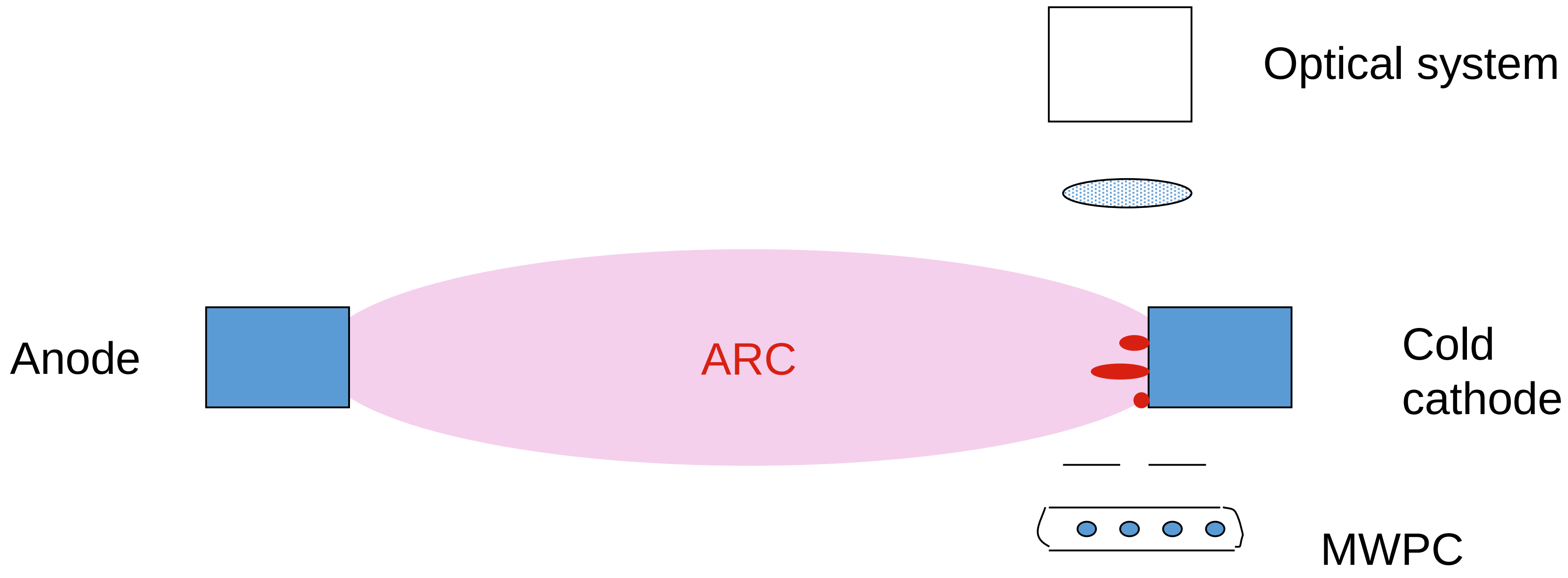


Fig. 14. Current–voltage curve in the case of electrical breakdown in vacuum (from [17]). Enlargement shows pulses due to the explosive field emission.



R. Latham, "High voltage vacuum insulation", new Yoork,1995

Explosive electron emission was also observed from cold cathodes of some gaseous discharges, for example arcs (*Rachovski phenomena*)



See: G.A. Lubimov, V.I. Rahovski, Uspekh. Phys. Nauk, 125, 1978, 665,

V. Peskov Journ, de Physique Coll. C7, suppl#7, 1979,C7-333

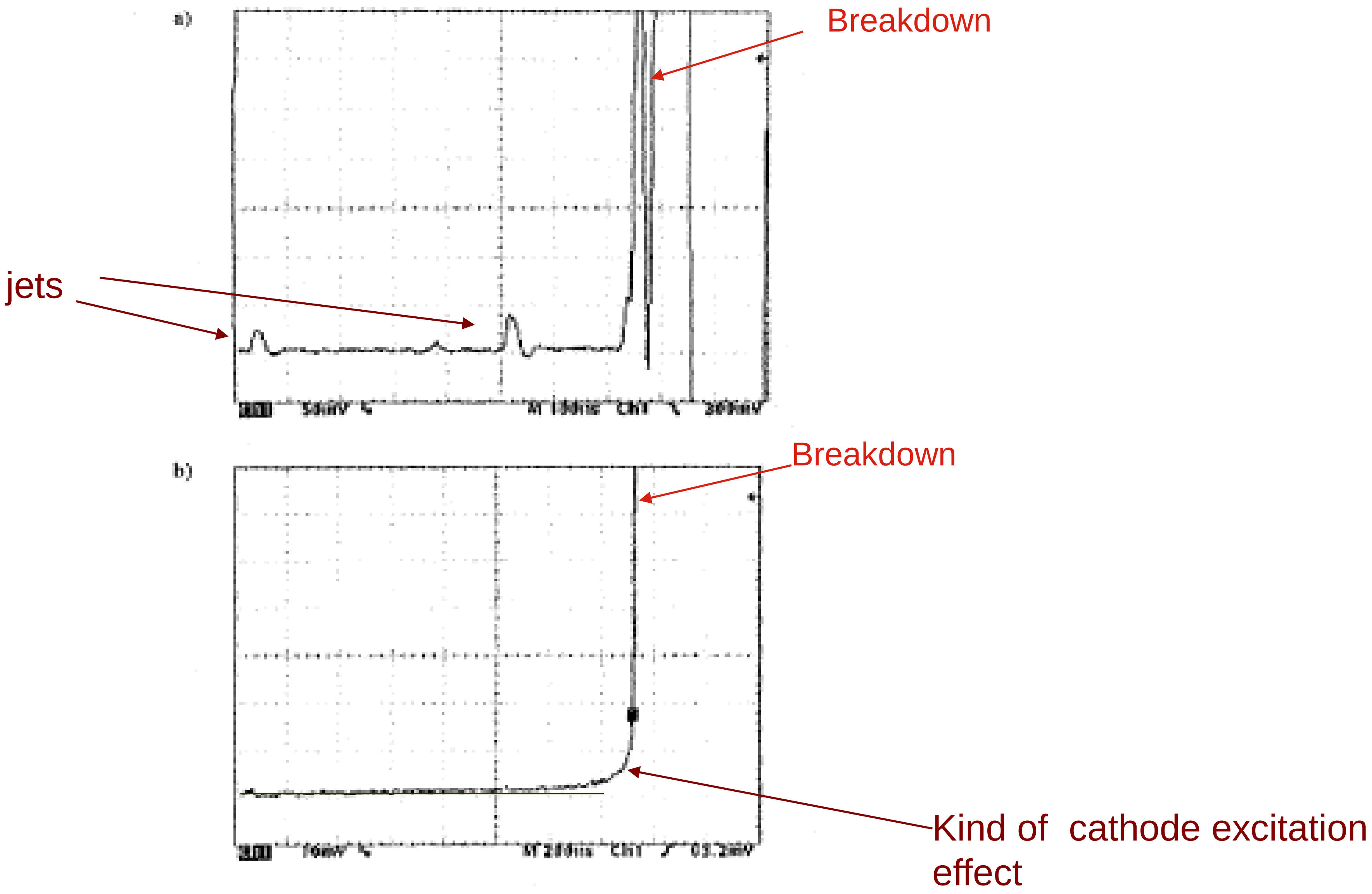


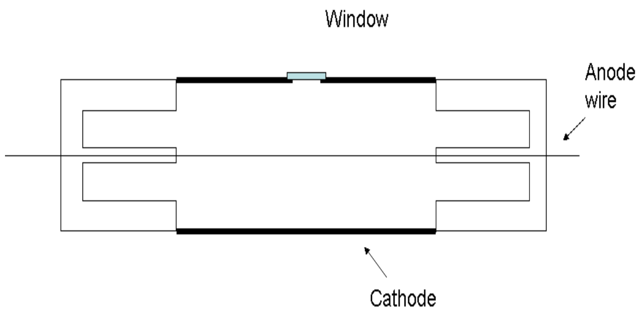
Figure 2a), b): Two typical oscillograms showing a preparation mechanism immediately preceding a high-rate breakdown.

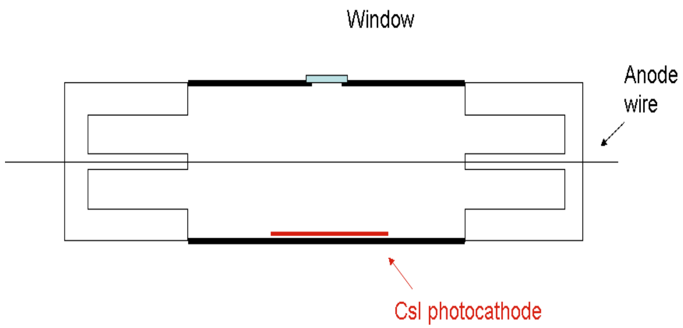
P. Fonte etal., IEEE Nucl Sci,46,1999,321

II.4.Cathode excitation

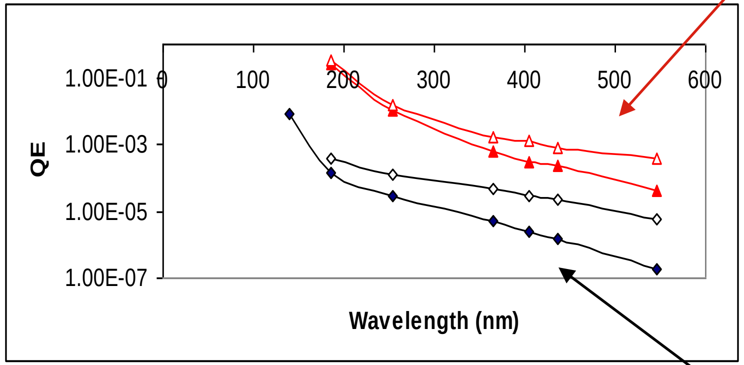
(a glance from another angle)

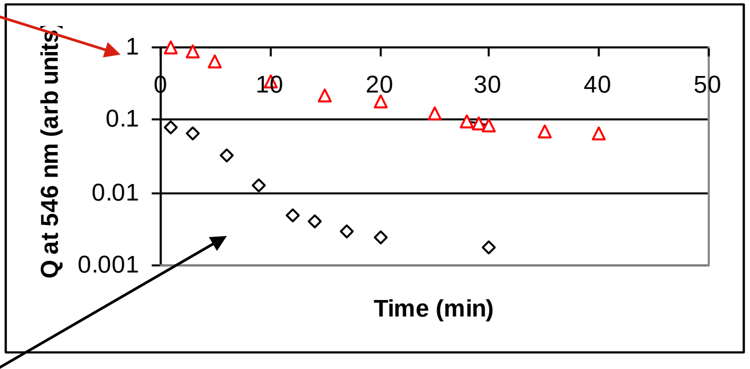
Changes in QE after intense ion bombardment





CsI





SS

P. Fonte et al., arXiv:0909.2681

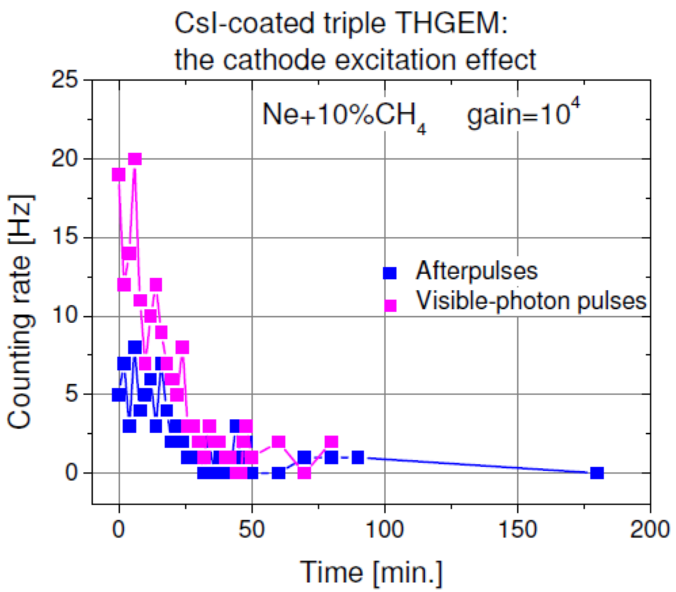


Figure 10. Counting rate of spurious pulses and visible-light induced pulses vs. time after induction of cathode excitation effect; CsI-coated triple THGEM; gas mixture: Ne+10%CH_4; gas gain $\sim 10^4$.

Results obtained in Breskin group

(JINST 5 P11004, 2010)

…can explains COMPASS experience?…

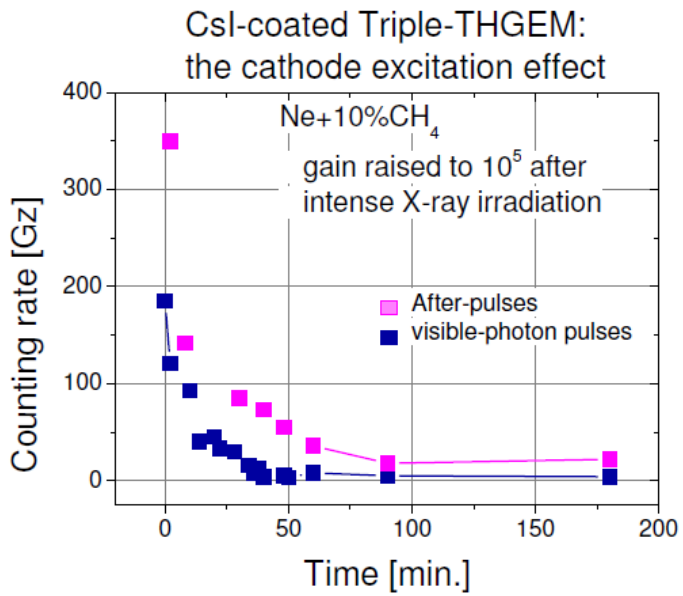


Figure 11. Counting rate of spurious pulses and visible-light pulses vs. time after cathode excitation induction at gain 10^4, followed by a 10-fold gain increase. CsI-coated triple THGEM, Ne+10%CH_4 mixture, gas gain $\sim 10^5$.

[13] S. Dalla Torre, *Status and perspectives of gaseous photon detectors*, available online at:
http://indico.in2p3.fr/contributionDisplay.py?contribId=102&confId=1697;
F. Tessarotto, *The experience of building and operating COMPASS RICH-1*, presented at the *7th International Workshop on Ring Imaging Cherenkov detectors (RICH 2010)*, Cassis France, May2–7 2010, available online at:
http://indico.in2p3.fr/contributionDisplay.py?contribId=35&sessionId=37&confId=1697.

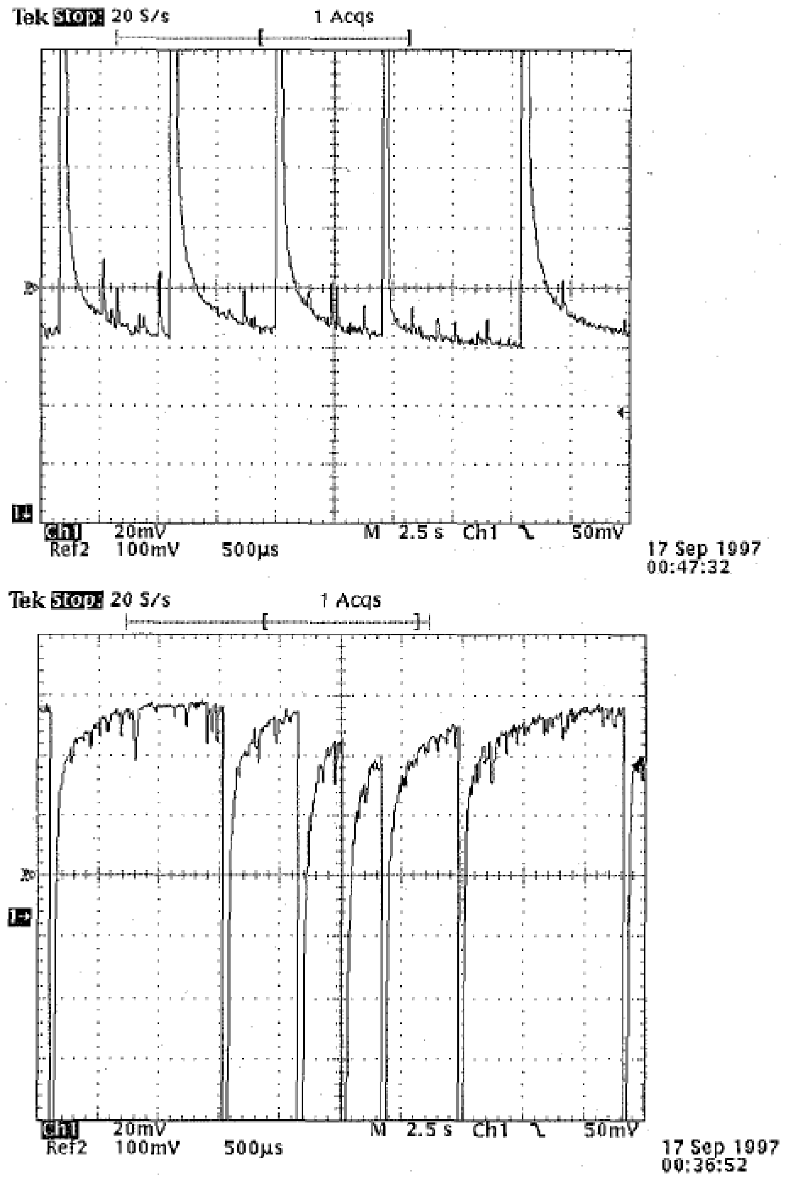
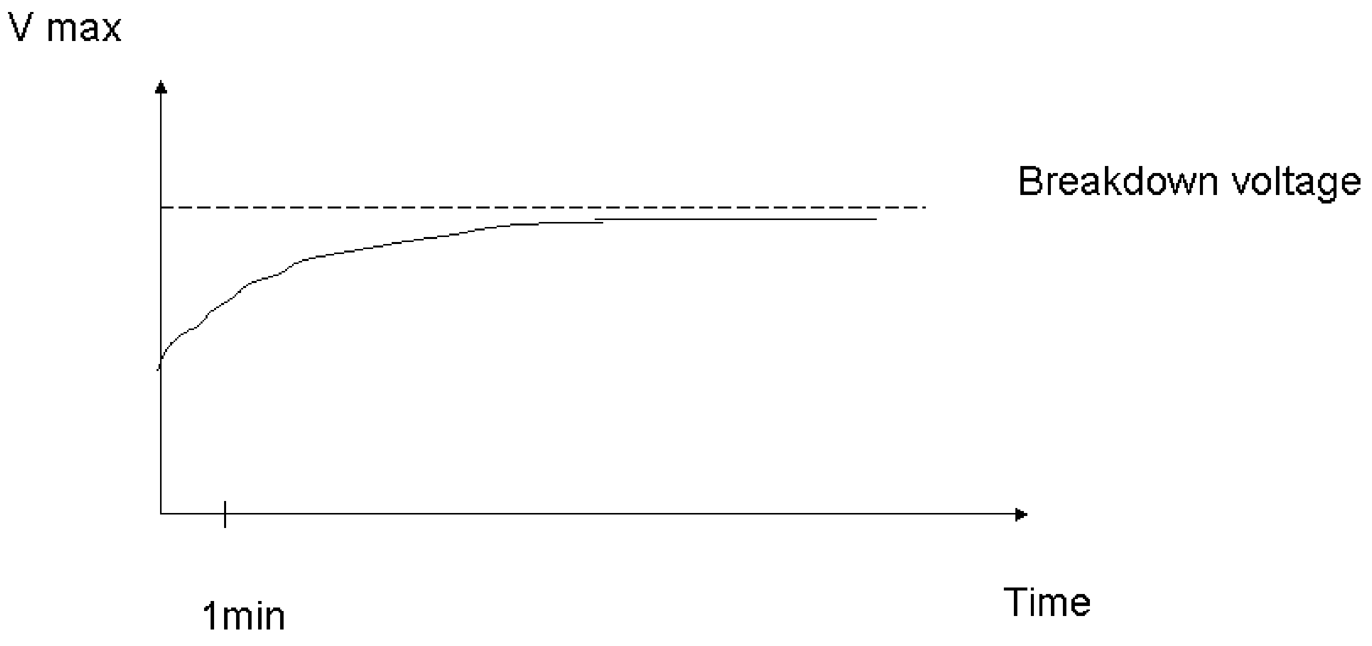


Figure 4: Afterpulses with amplitudes corresponding to ~10 primary electrons which appear after sparks (saturated amplitude pulses) in a resistive plate chamber made from melamine and metallic electrodes at different polarities of high voltage: a) positive voltage on melamine electrode, b) positive voltage on metallic electrode.

Afterpulses can contain many electrons per burst!

V. Peskov et al IEEE Trans Nucl Sci45, 1998, 244



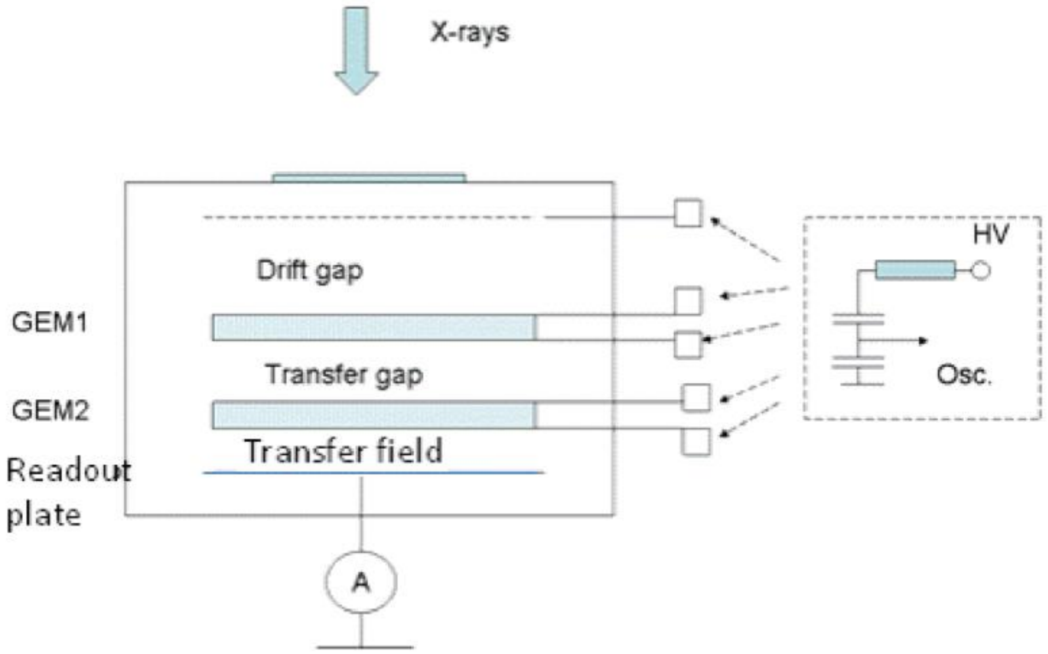
This curve is typical for many gaseous detectors, including MPGDs (check with your experience!)

Is not this an indirect indication of a cathode excitation mechanism or jets emission?

A hot topic today!

II.5. Studies of breakdowns in cascaded GEM

II.5.1.Discharge propagation between two GEMs (early studies)



Wallmark, A. (2000). *Operating range of a gas electron multiplier*. (Master Thesis). KTH-Karolinska Institute. Stockholm, Sweden.

Delay time measurements

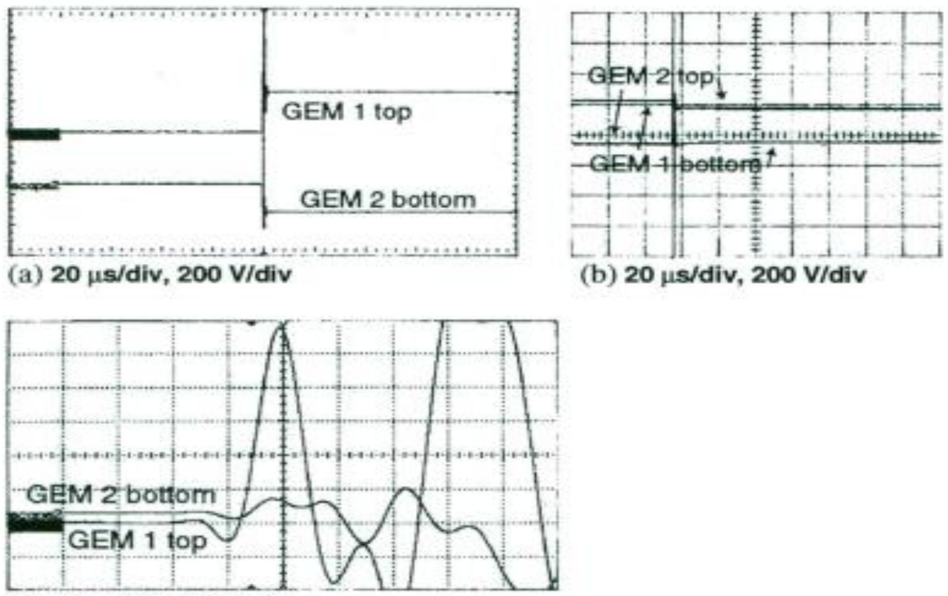


Figure 5-12 A breakdown occurs both in GEM 1 and in GEM 2. (c) is an enlarged version of (a). Since signals from both the GEMs are shown on the same oscilloscope in (c) it is

With an accuracy ~10 ns no delay between breakdowns in two neighbouring GEMs was observed.

This offers photon assistance mechanism for the discharge propagation

It was found that breakdown propagation is independent on the electric strength between the GEMs. For example, in several occasions the propagation could occur at reversed fields between the GEMs, i.e. a larger negative potential on GEM2 top than on GEM1 bottom.

Also, when the distance between the GEMs was small, for example 3 mm, a breakdown could propagate upwards, to GEM1 if the discharge was initiated in GEM2.

However, this propagation from GEM2 to GEM1 was not observed in the case of large transfer gap, for example 26 mm and more.

Studies were also performed in Sauli group (*S. Bachmann et al, NIM A479,2002,294*)

From GEM1 to GEM2

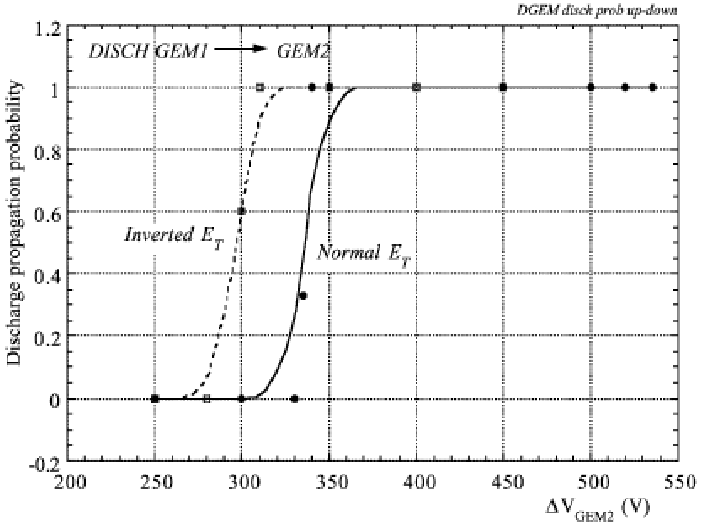


Fig. 13. Discharge propagation probability between first and second GEM in a cascade, as a function of voltage on the second, for normal and inverted transfer fields.

From GEM2 to GEM1

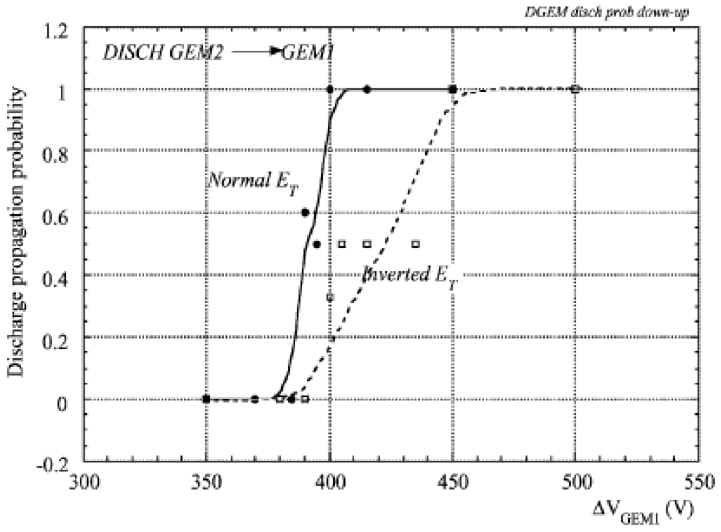
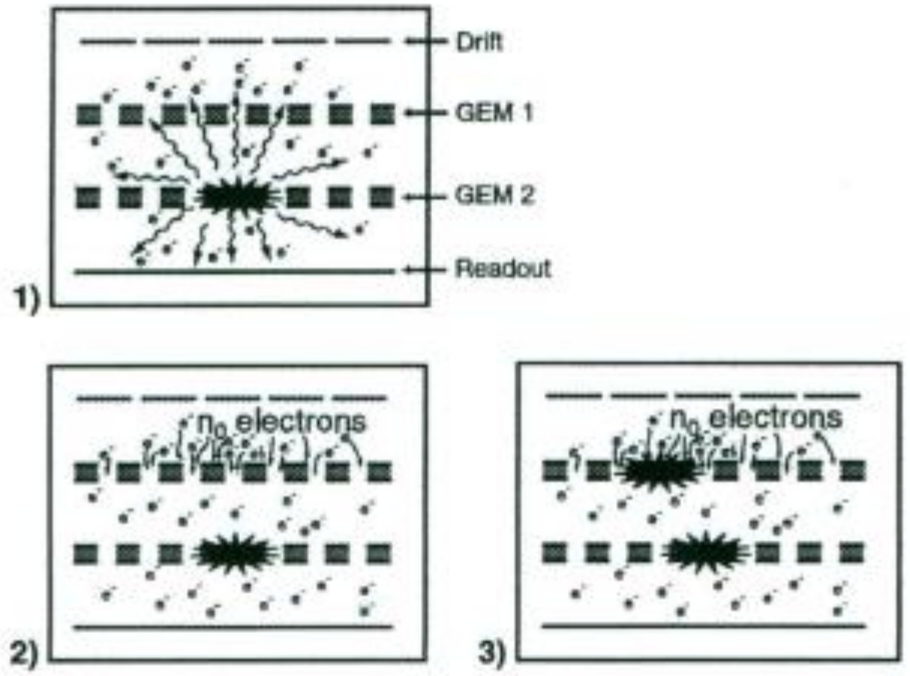


Fig. 14. Discharge propagation probability between second and first GEM in a cascade, as a function of voltage on the first, for normal and inverted transfer fields.

" the predominance of a fast propagation mechanism between GEMs is confirmed by the observation that discharges can propagate between two multipliers, even if the electric field is inverted in the transfer region. "

Our main observation were confirmed, but in a more qualitative way

Photon assistance mechanism of discharge propagation



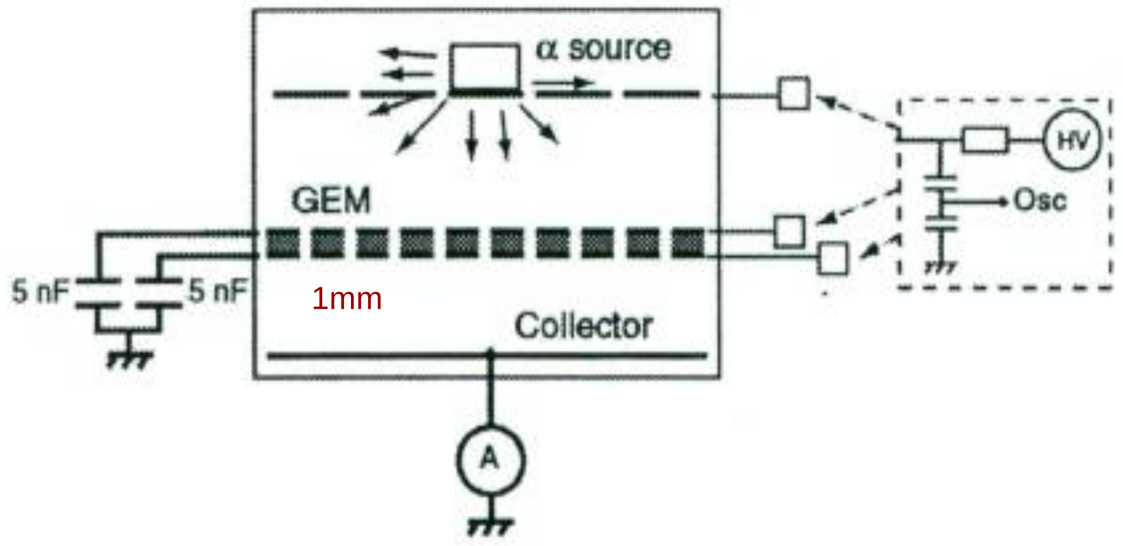
Mostly confirmed by ALICE group studies
(see , for example A. Deisting Thesis, 2018)

A schematic drawing illustrating discharge propagation from GEM2 to GEM1.
The UV photons from the discharge in the GEM2 photoionize gas in the entire detector, including the drift region. The secondary electrons trigger a breakdown in GEM1

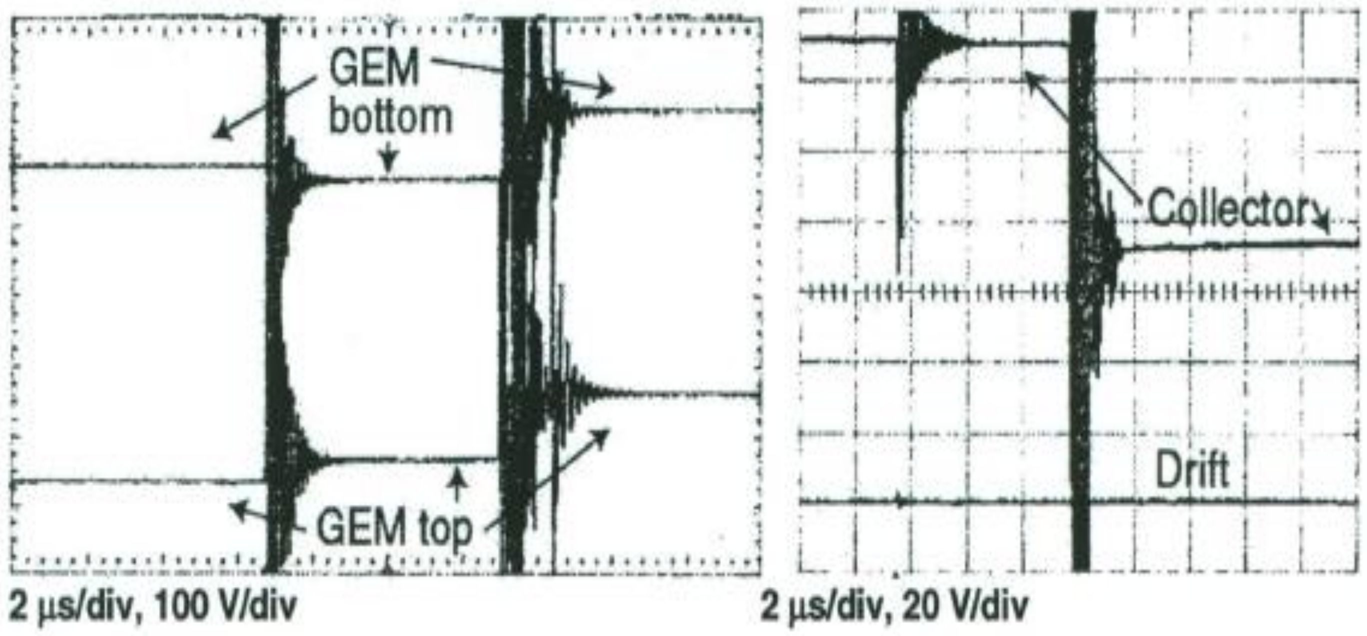
II.5.2. Delayed breakdown

II.5.2a.Early studies

To observe this phenomena a large discharge energy is required, so capacitors were connected (to model a large-area GEM)



A setup for studies of breakdown propagation when GEM electrodes were connected to ground via 5nF capacitors

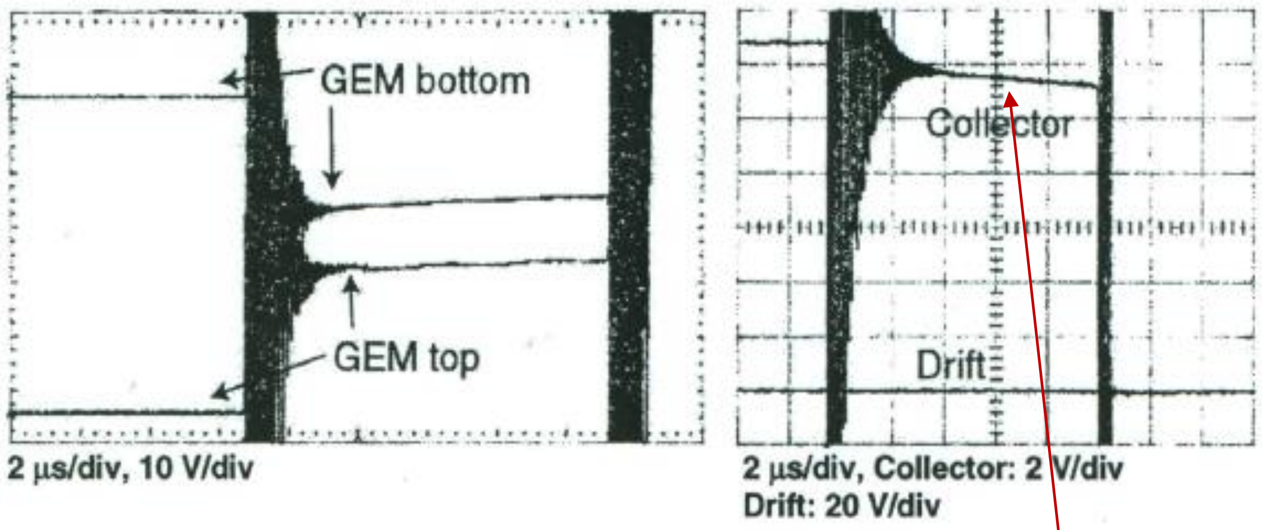


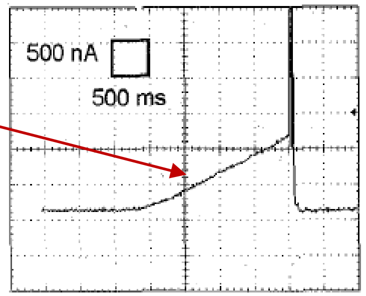
Delay time varied between
1.5 to 25μs

Note that electron drift time was~15ns
and full ions collection time 6-9μs

Two breakdowns following each other: the breakdown in the GEM was followed with some delay by a discharge propagation to the collector

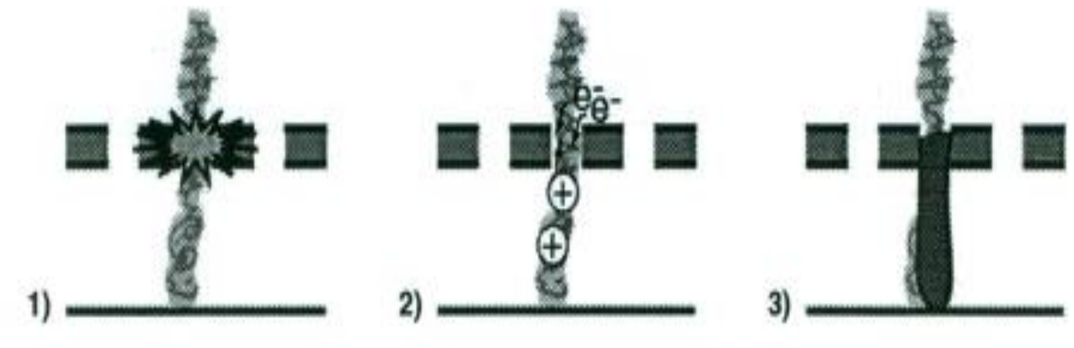
Close inspection reveal some similarity to the "cathode excitation" effect





A kind of preparation mechanism
(see above)?

First hypothesis, pretending to explain of the delayed breakdown

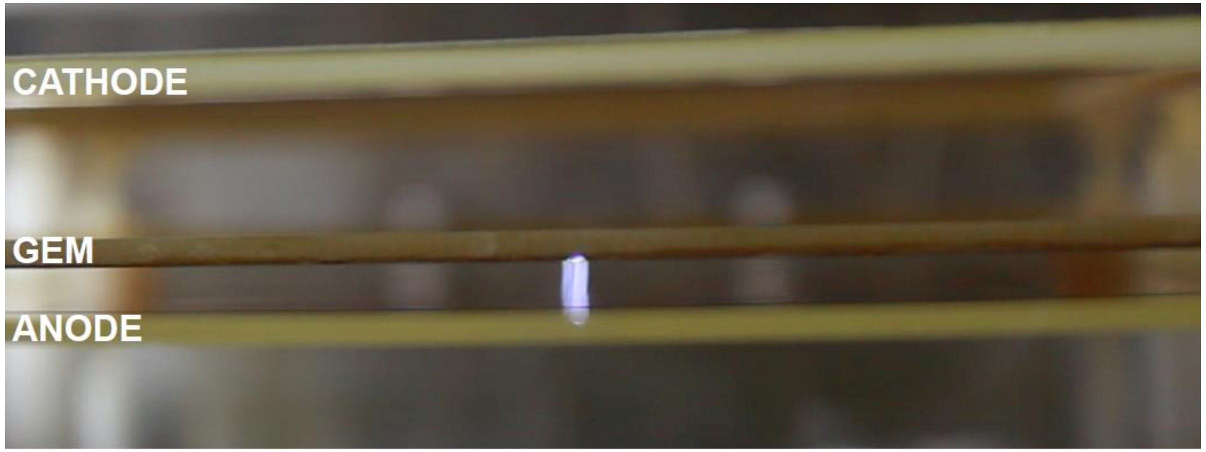


A schematic illustration of the delayed breakdown. When there is a spark in GEM triggered by alpha particles, the cathode will emit for some tile electrons due to the slow collected ions from the alpha track. This may cause another breakdown in the space between the GEM and the collector due to the combination of two effects: ion feedback and jets

II.5.2b. Resent impressive ALICE TPC upgrade group results

(performed at CERN in Chilo Garabatos group, and in Munich in Piotr Gasik group)

See ,for example, talks at this Workshop:
A.Deisting,
A. Utrobicic
L. Lauther

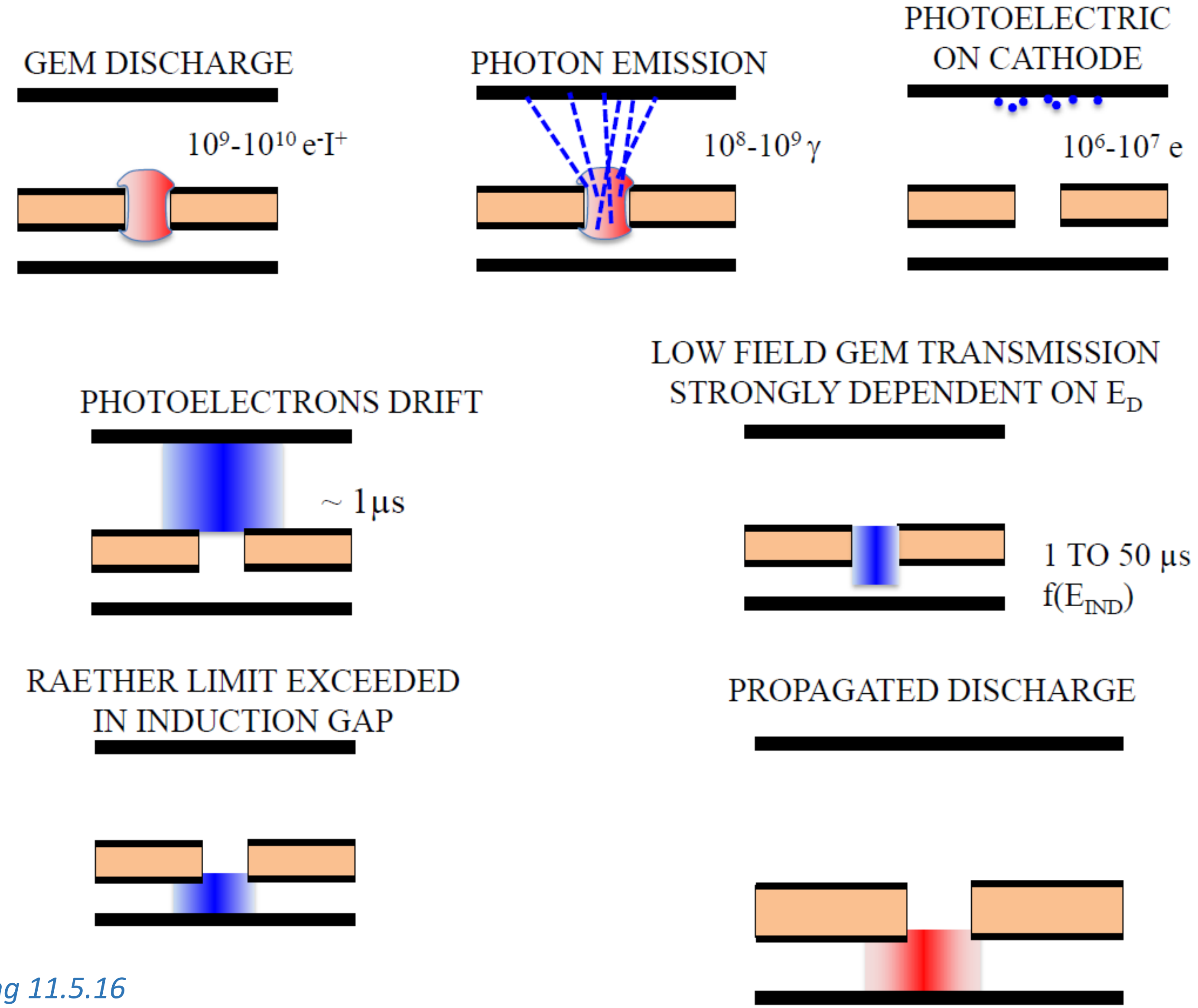


Our old explanation of the slow breakdown was not fully confirmed

Which is good: some new ideas are needed!

…so another explanation is needed!

F. Sauli model



C. Garabados model

Private communication

Alternative explanations:

Possible ways to solve the delayed breakdown puzzle

Scenarios:

1.Only instant primary ionization in the cloud:

Fast collection of ions, extraction of electron from the cathode due to the γ+ or jets

2. Thermal ionization wave in a relatively weak electric field

(high E/N so plasma can support itself)

Presented here just in order **to trigged a brainstorm!**

What is necessary to discharge a capacitor in a gas?

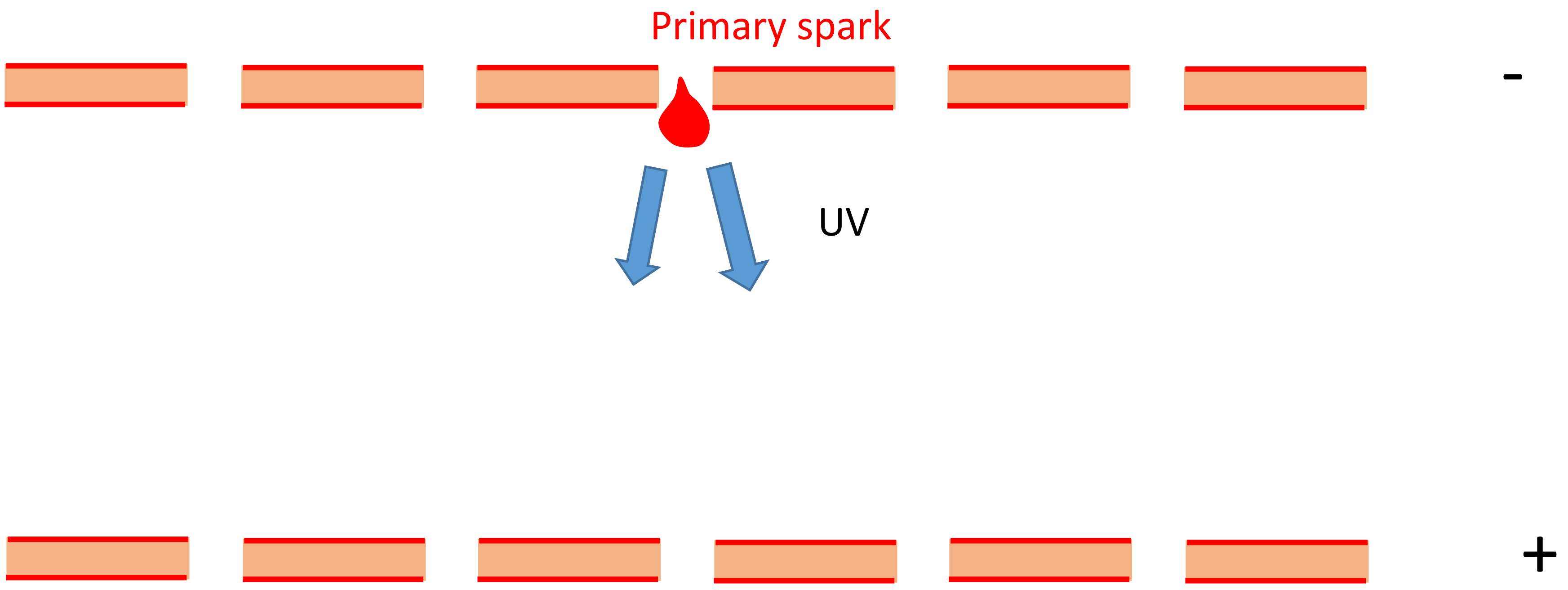
For this is necessary to have a source of electrons. Possibilities:

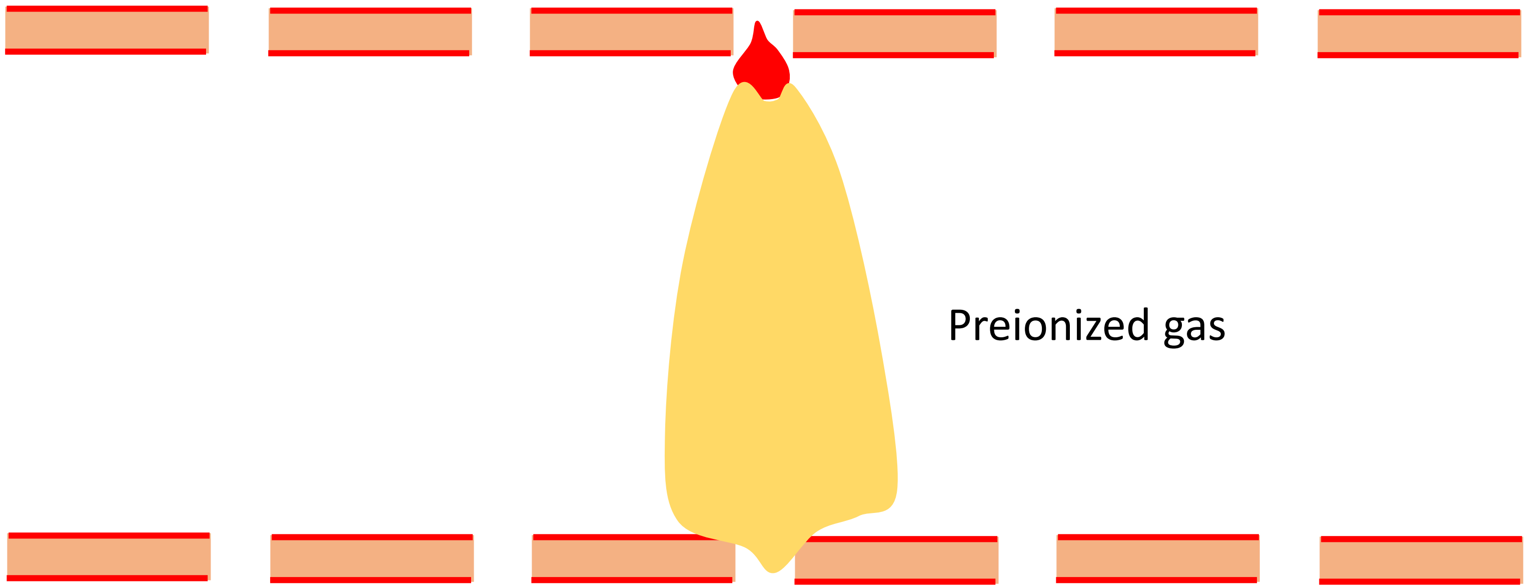
1. Their creation on the cathode surface
2. Creation in the volume (volume ionization)
3. Combination of both effects

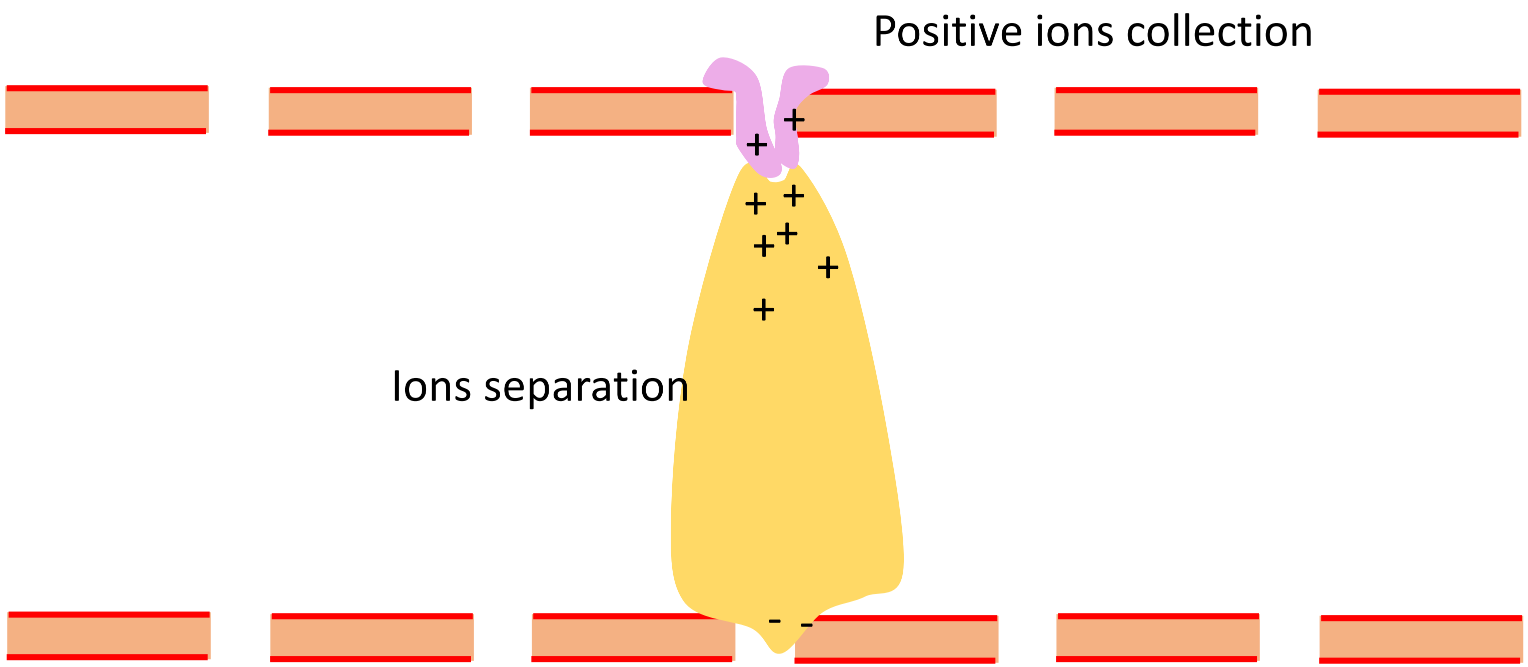
Scenario 1

Only instant primary ionization in the cloud

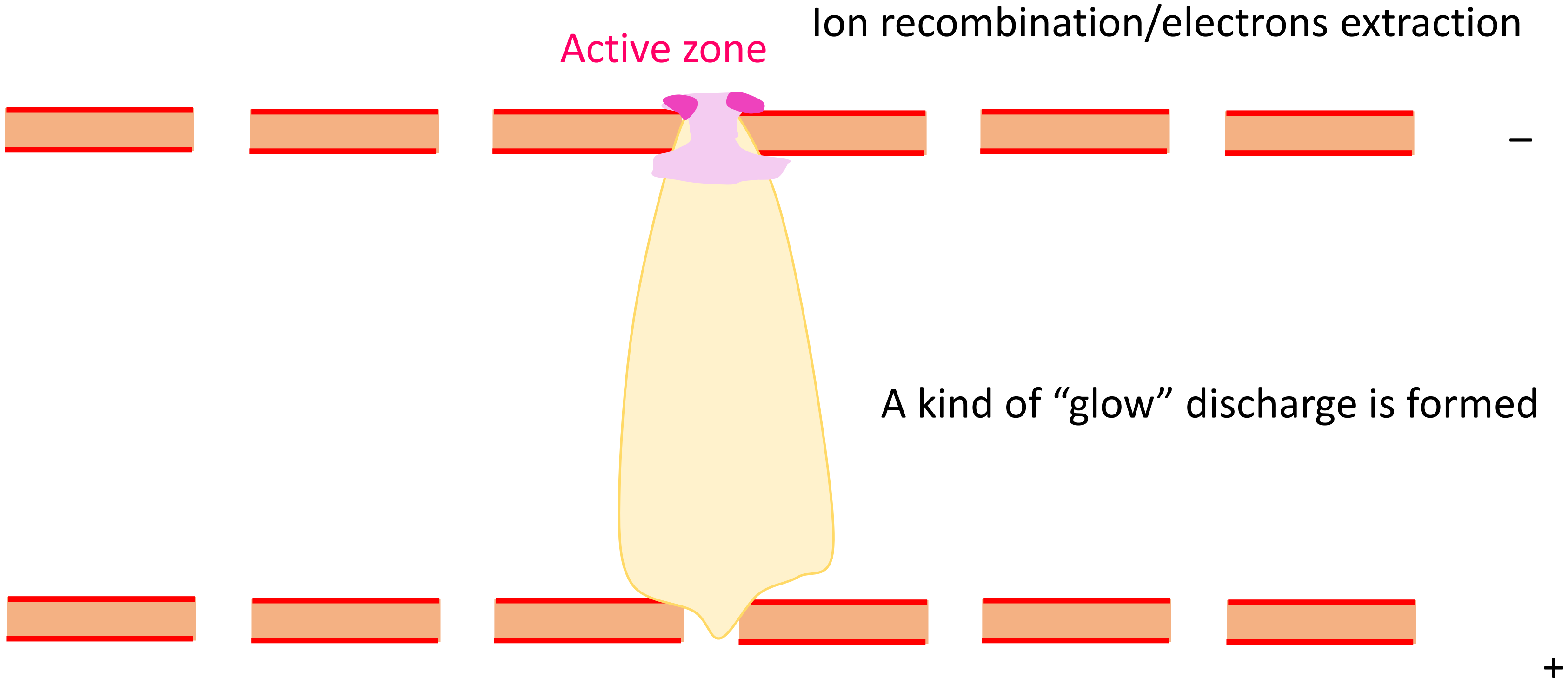
Readout plate at positive potential




Preionized gas


Positive ions collection
Ions separation

Readout plate at positive potential



In a “stationary” case:

$n_e v_e = N_+ V_+$ (1)

Self -supporting current will exist if:

$N_+ \gamma_+ = n_e$ (2)

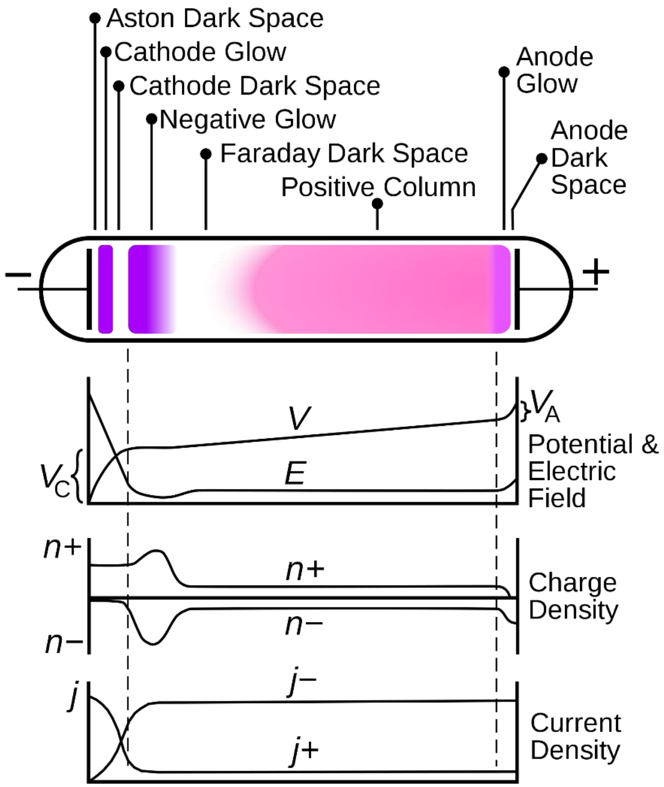
In quenched gases typically

$\gamma_+ < 10^{-6}$ (3)

Because of $v_e/V_+ \approx 10^3 - 10^4$ (4),

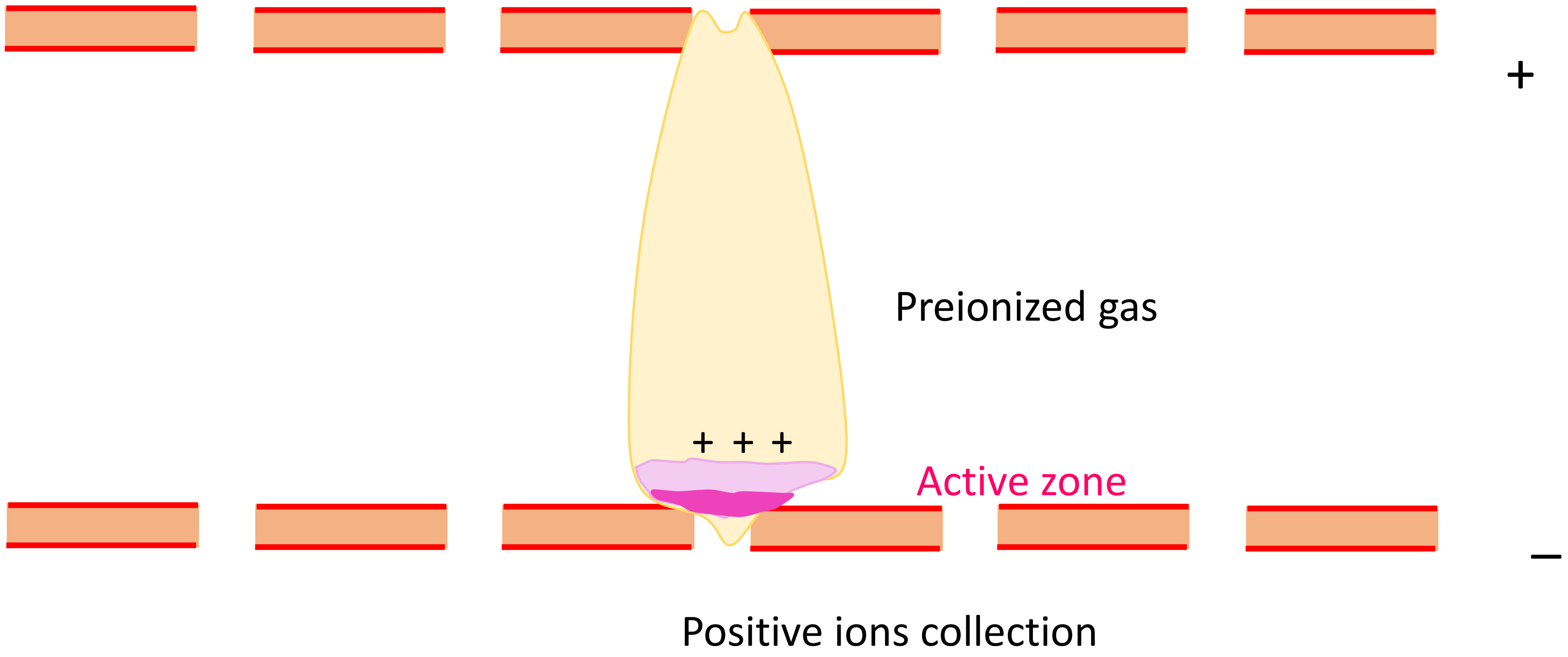
Than to satisfy a condition (2) multiplication is necessary, which leads to a glow discharge structure, like it happens in streamers.

Electron jets may, in principle, also efficiently contribute



Therefore, if one neglects the thermal effect and ionization from the excites states, than the creation of electrons in the cathode is essentially through the ion recombination $N_+\gamma_+$ enforced in the increased local electric field or by the via electron jets

Let’s consider now the readout plate at negative potential

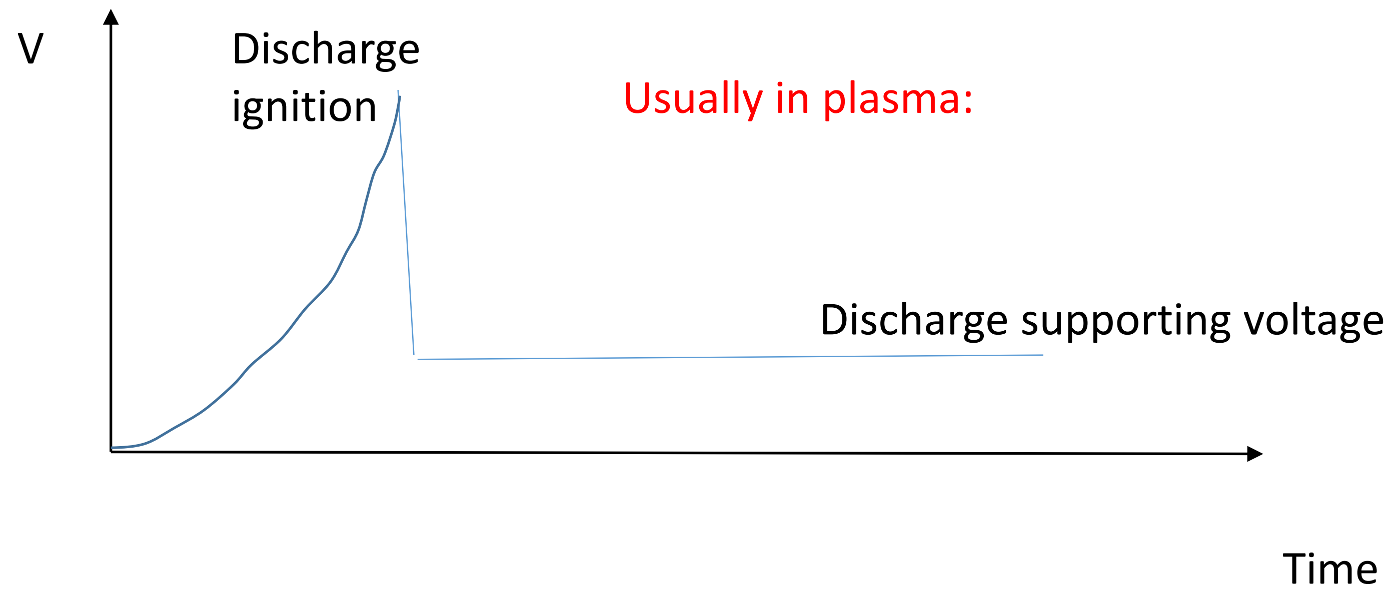


Scenario 2

Temperature wave in preionized gas:

thermal ionization in a relatively weak electric field

Usually in plasma:



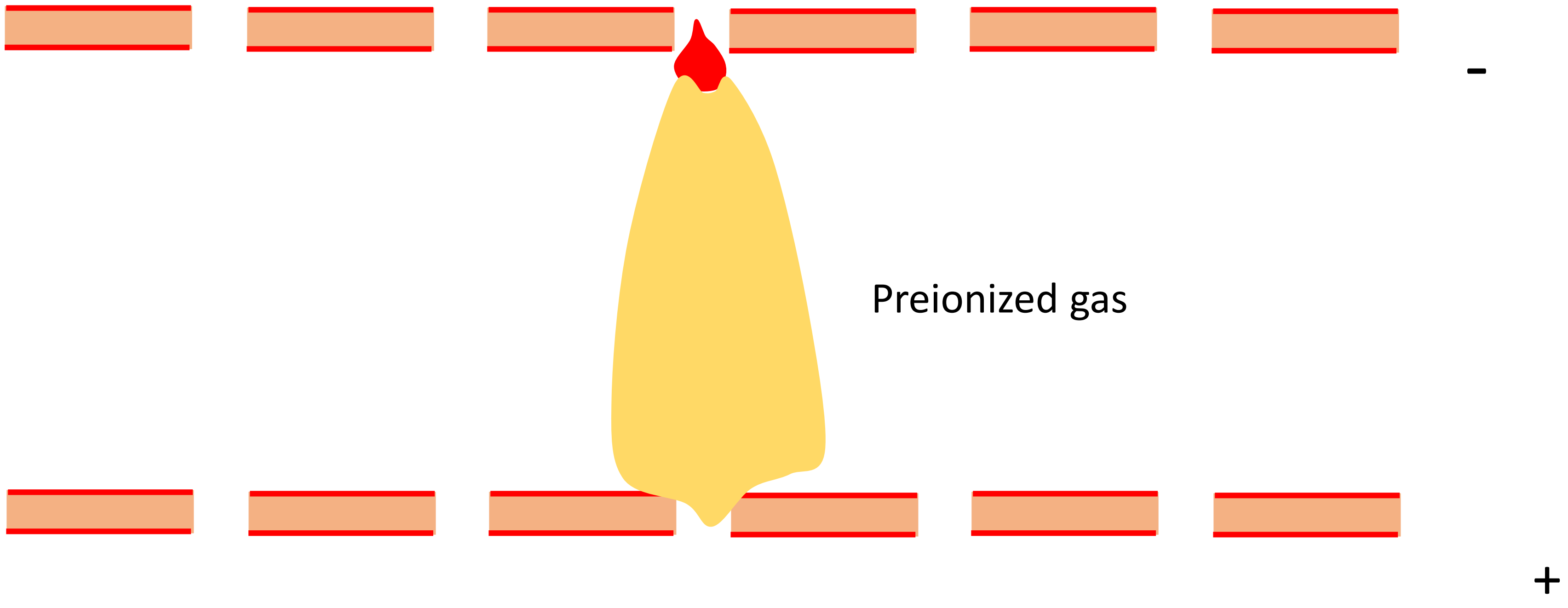
Reasons:

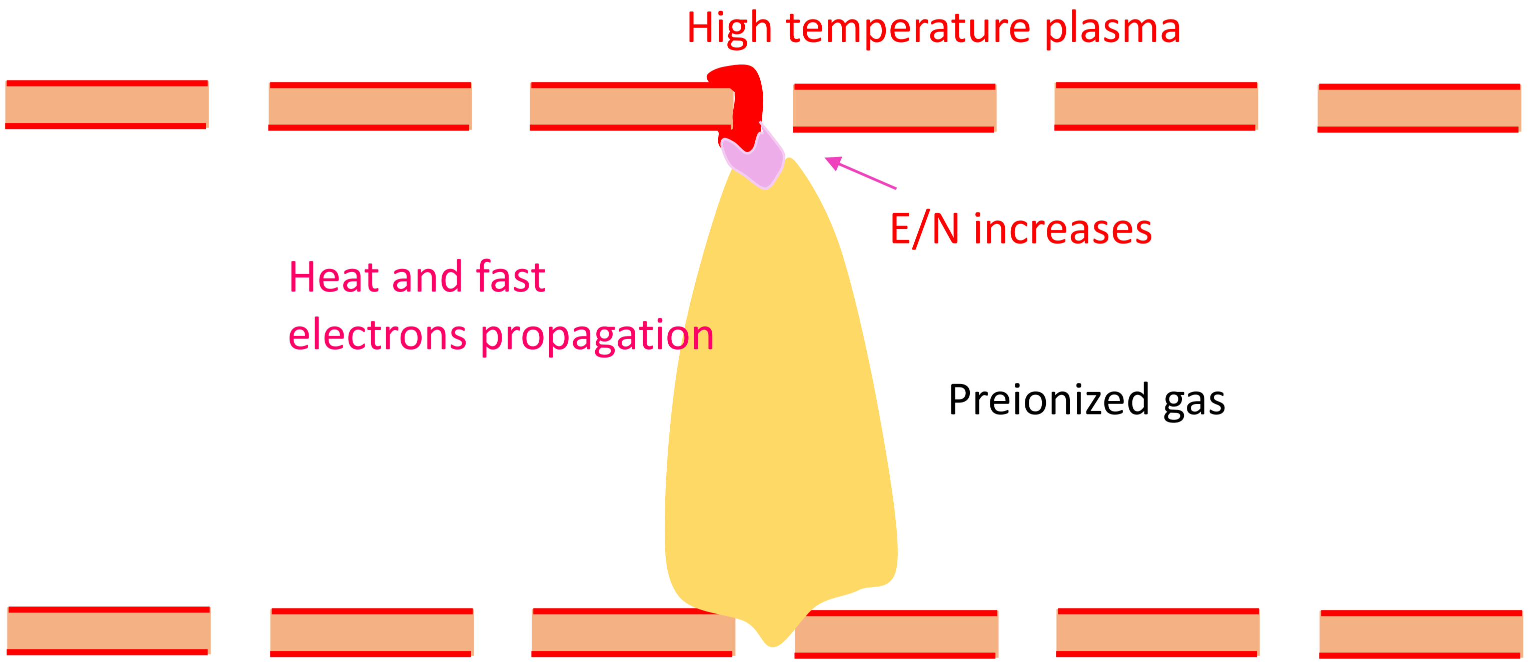
1.Temperture effect-lower density, higher E/N

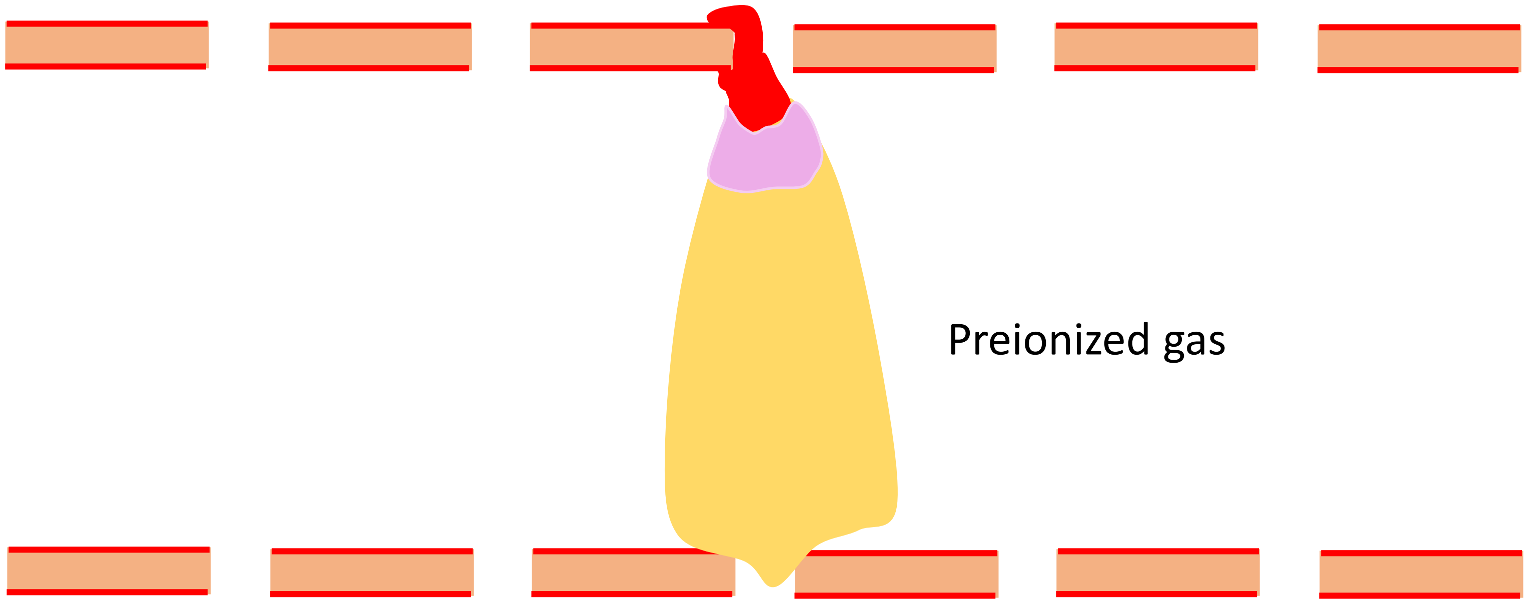
2. Electrons –electron collisions leading to the thermalization and appearing a high -energy tail

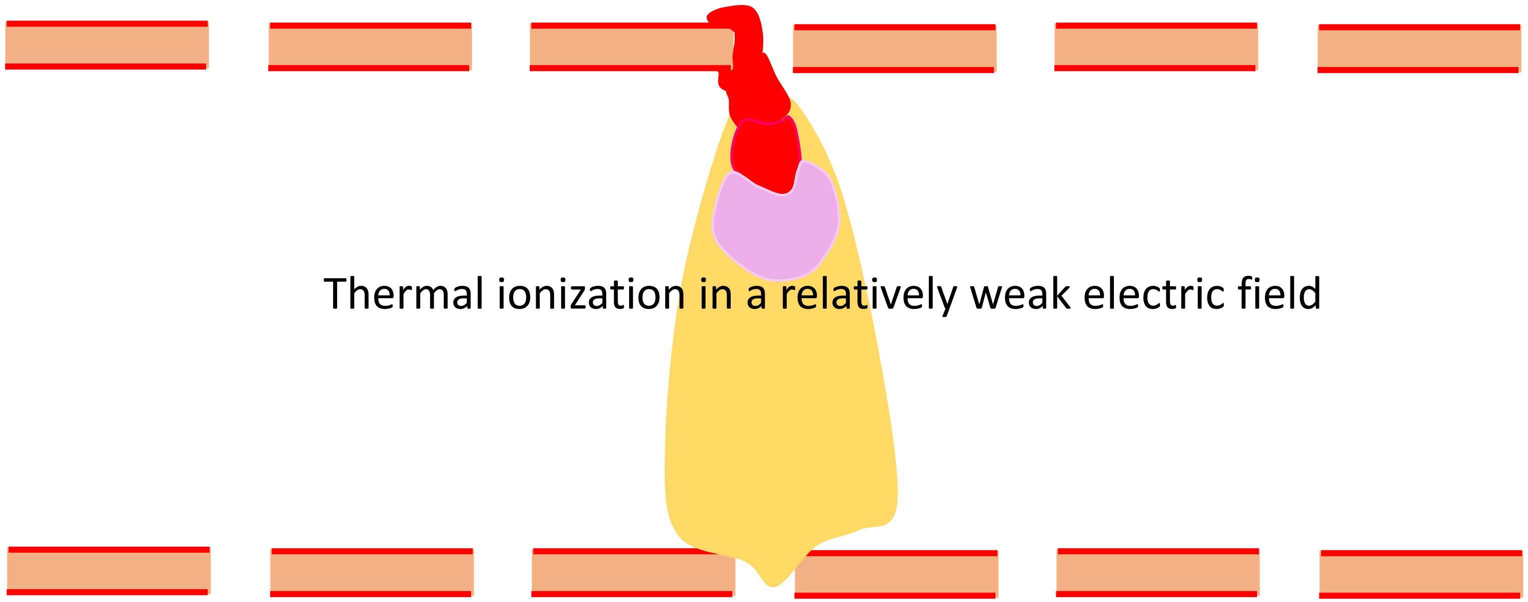
3. Multistep ionization and light contribution

Collection electrode at a positive potential




High temperature plasma
E/N increases
Heat and fast
electrons propagation
Preionized gas


Preionized gas



Thermal ionization in a relatively weak electric field

What ever is the correct explanation, but practical solution is on the way by the resistive chain optimization

(P. Gasik, private communication)

III. Possible ways of discharges prevention/protection in MPGD

RD51 collaboration found efficient ways of protection against discharges

Well working approaches:

III.1.Electrodes segmentation (nowadays is routinely implemented)

III.2.Resistive chain optimization (example of the power of the method is Gasik group achievements)

III.3.Use of resistive electrodes and optimization their network (in fast progress)

III.4 Dream: MPGD almost without sparks

Let me focus on III.3 and III.4

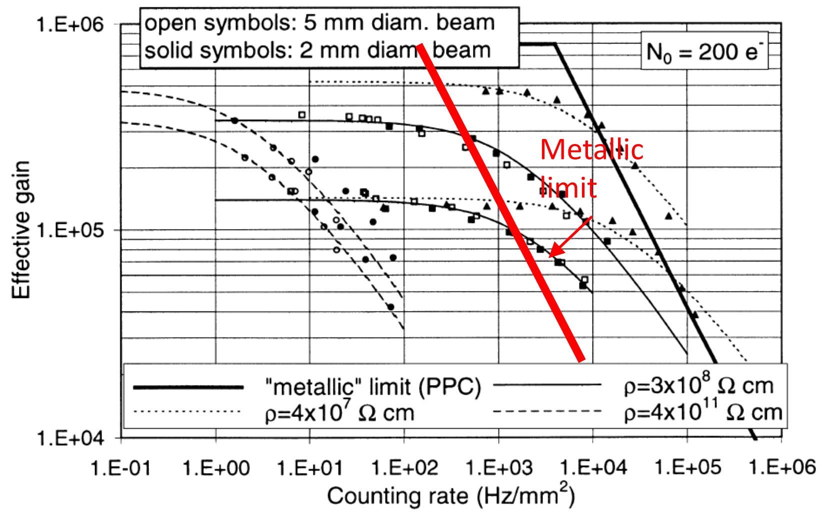
III.3. Strait forward solution: spark-protected high-rate micropattern detectors

There are currently very encouraging developments: resistive electrode GEM, resistive MICROMEGAS, resistive microwell, microdot etc. Rate capability ~10^4 Hz/cm^2

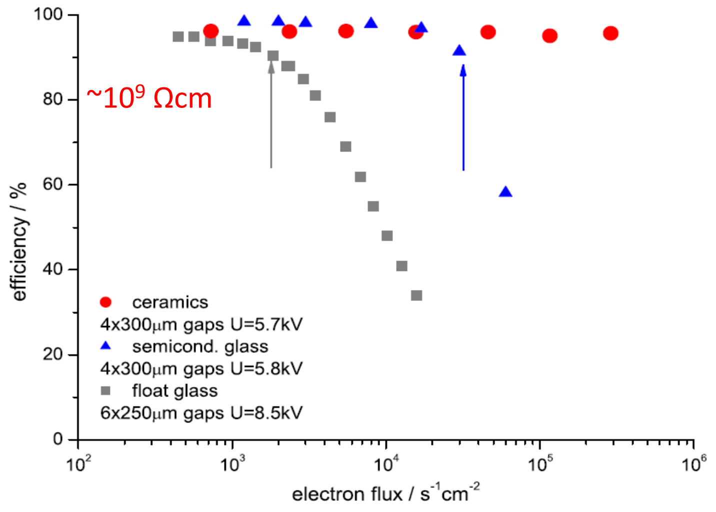
Aim of further developments: improve rate capability of micropattern detectors with resistive electrodes

Methodology: search a for appropriate low resistivity coatings and their exhaustive tests

Encouragement: success in development high rate RPCs



P. Fonte et al., NIM A431, 1999,154



L. Naumann te al., NIM A635, 2011, S113

High-rate RPCs (GaAs, ~10^8 Ωcm) we already successfully used in mammographic scanners

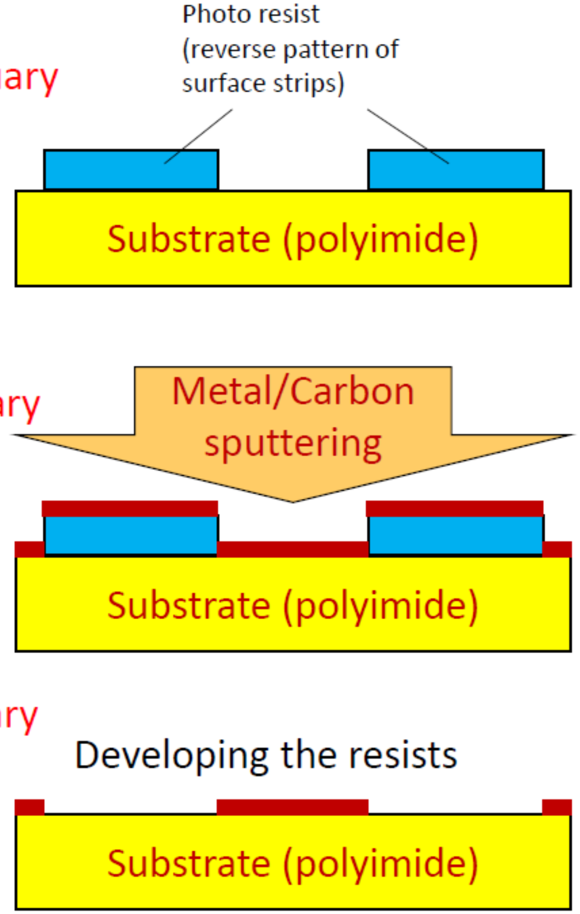
(T. Francke et al., NIM A471, 2001, 85; A. Maidment et al Proc. SPIE Intern Sympos. on Med Imaging, 2006)

New promising materials are coming

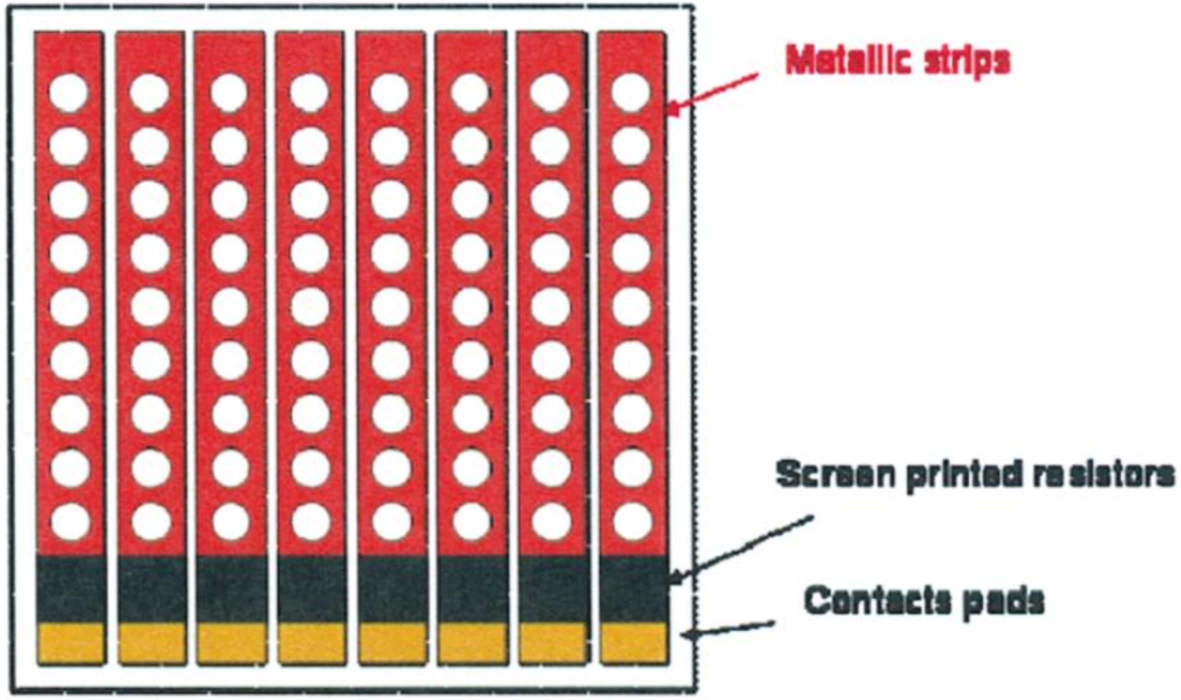
Mid-end of January
(Raytech)

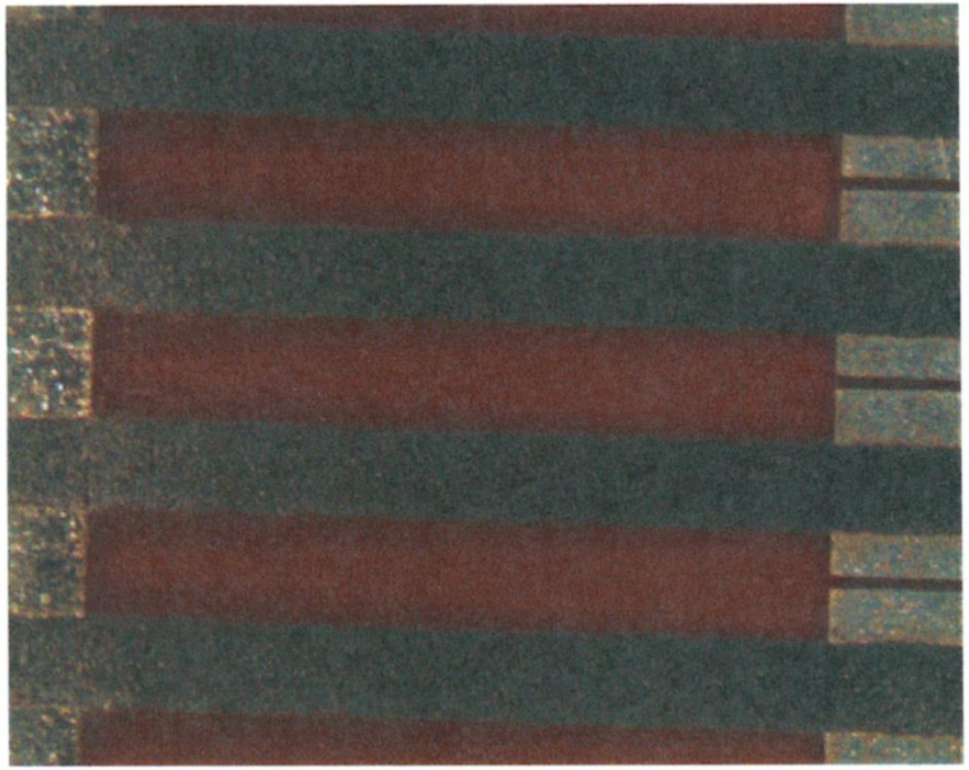
5th – 13th February
(Be-Sputter)

9th – 20th February
(Raytech)



There are many ways how to optimize resistive electrodes approach

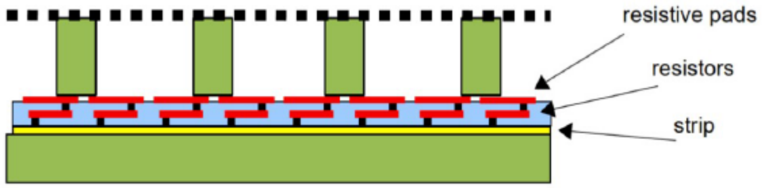


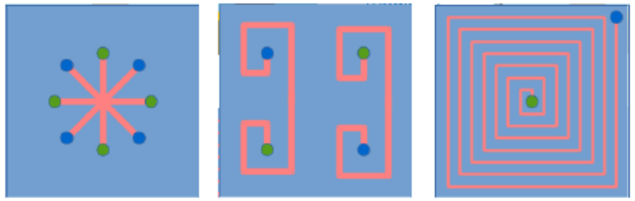


… just a couple of examples

Resistive patterns

- We tried different resistive pattern with different Q evacuation schemes
- And adopted the embedded resistor (de Oliveira et al. in 2010)
  - Pioneered by COMPASS Saclay group (2009 JINST 12 P12004)
  - Now, interest for ATLAS (M. Iodice et al., 2017 JINST 12 C03077)
  - In between, us.
- Allows segmentation of readout anode plane into pads (no Q spread)
- Control of the resistance through R-pattern
  $\rightarrow$ minimal charge-up & spark suppression





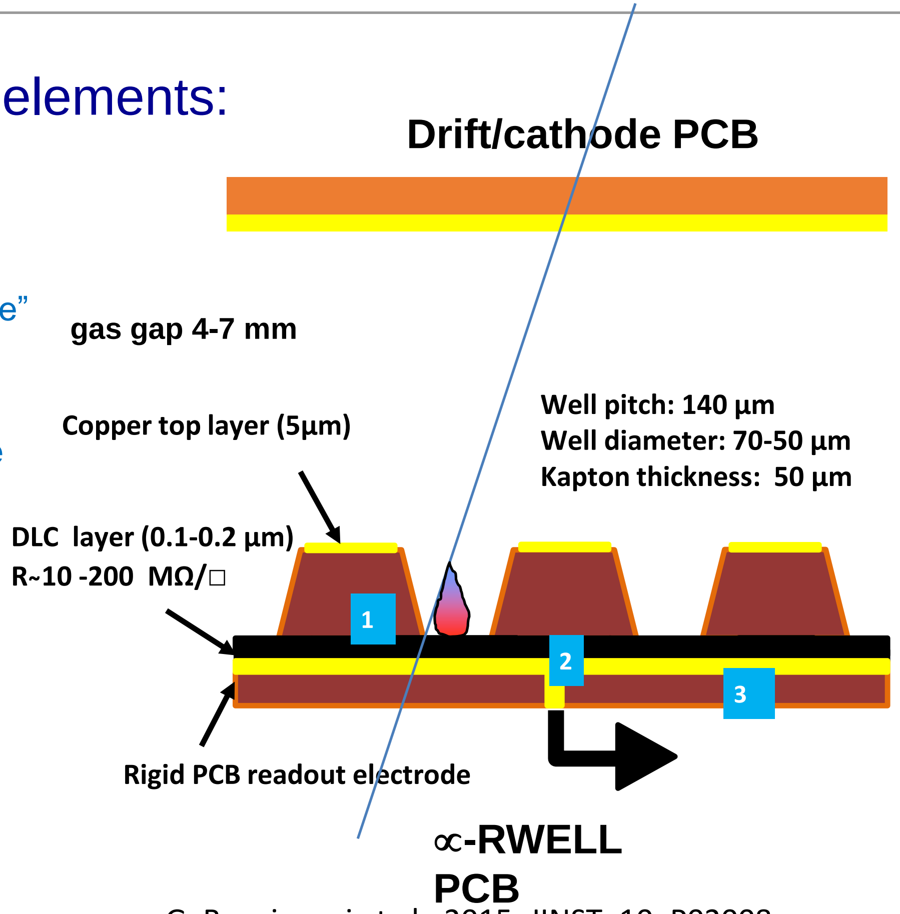
4

The μ-RWELL technology

The μ-RWELL detector is composed of two elements: the **cathode** and the **∝-RWELL_PCB .**

The **∝-RWELL_PCB** is realized by **coupling:**

1. a “**suitable WELL patterned kapton foil** as “amplification stage”
2. a **“resistive stage”** for the discharge suppression & current evacuation
   i. **“Low particle rate” (LR) ~ 100 kHz/cm²: single resistive layer → surface resistivity ~100 MΩ/☐ (CMS-phase2 upgrade - SHIP)**
   ii. **“High particle rate” (HR) > 1 MHz/cm²: more sophisticated resistive scheme must be implemented (MPDG_NEXT- LNF & LHCb-muon upgrade)**
3. a **standard readout PCB**



G. Bencivenni et al., 2015_JINST_10_P02008

Collaboration of INFN, CERN, Eltos

Major **advantages** wrt. GEM

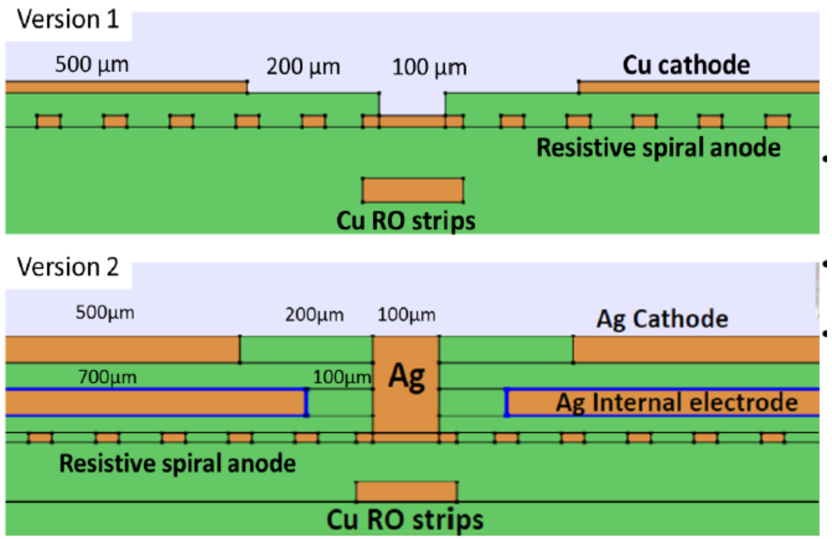
- 1 kapton foil instead of 3
- No stretching
- Spark safe

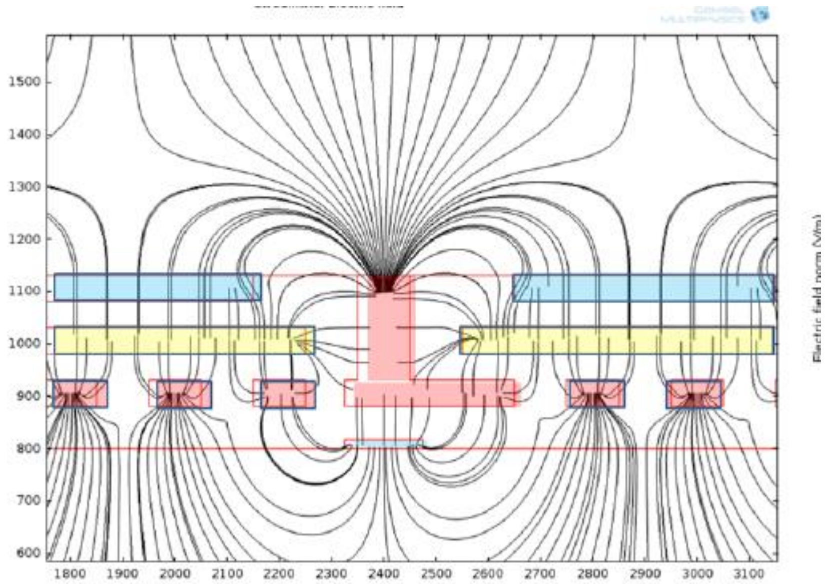
III.4. Possible ways to minimize a spark probability

III.4.1.Multilayer printed circuit technology

Aim: development of special 3D multiplication structures, ensuring radial shape of electric field in the avalanche gap.

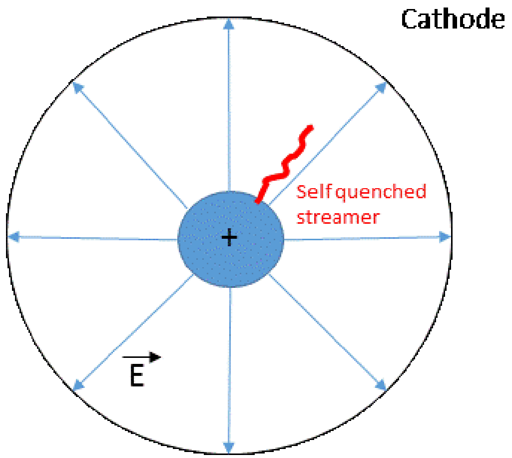
Methodology: field shaping with an array of inner strips, appropriately bias by voltages; manufacturing and tests of 3D structures, combined with inner strips



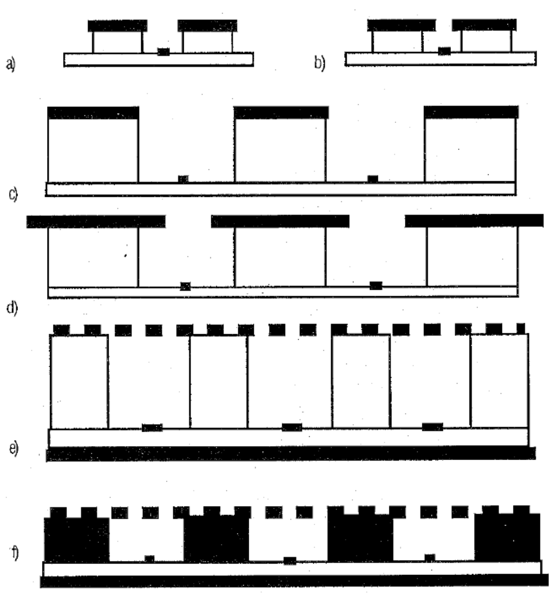


V. Cairo et al, JINST 9 C11022, 2014

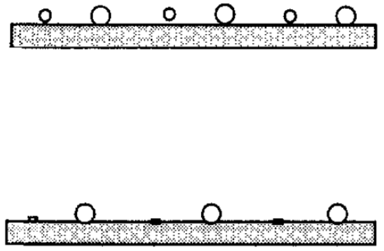
III.4.2. 3D micropattern structures



Aim: development of special 3D multiplication structures, ensuring radial shape of electric field in the avalanche gap.



Detectors showing exceptionally high gains



Possibility: suspended wires supported by pillars

!

Numerous studies showed that in micropattern gaseous detectors sparks develop in the region of the avalanche gap, where the field lines are parallel each other. Therefore, the spark probability could be dramatically reduced if a radial shape electric field could be formed in the avalanche gap by some means.

V. Peskov et al., NIM A392,1997,89

V. Peskov et al, IEEE Nucl . Sci., 45,1998,244

Conclusions:

- **What was known before MRGD era:**

Slow breakdown

Fat breakdown

Limited streamer discharge

- **What was founded during MRGD era:**

Rather limit for MPGDs

Rate effect

Surface streamers

Streamers understanding and simulations

Discharge preparation effects

Cathode excitation effect

Delayed breakdown in GEMs

- **How MPGD can be protected:**

Segmentation

Optimization of resistive chain

Resistive electrodes

- **Guidelines to reduce discharge probabilities**

3D structures of electrodes for radial electric field creation

Biasing of inner electrodes for the field line optimization

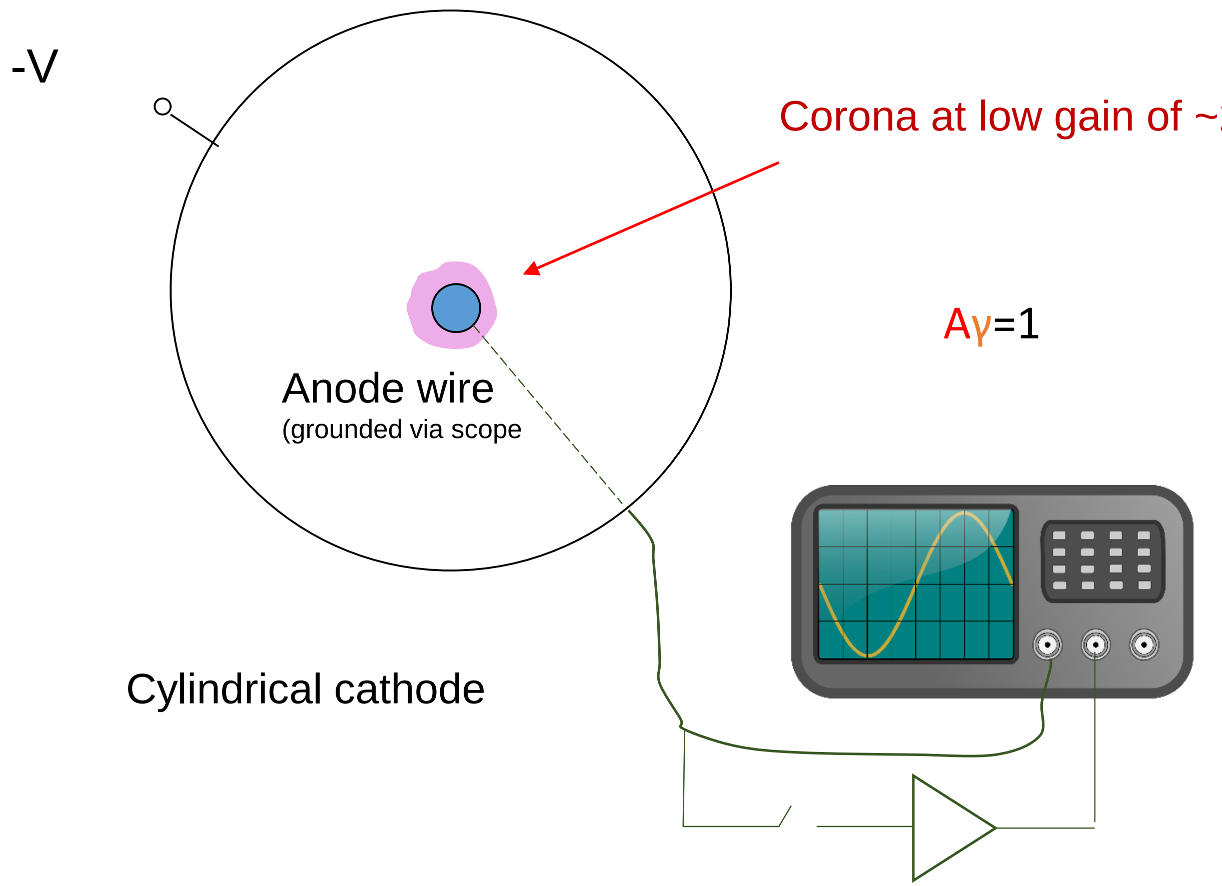
Although some "headache" associated with breakdowns in gaseous detectors, unfortunately is still remains, a considerable progress in understanding these phenomena was achieved by the **RD51 collaboration**

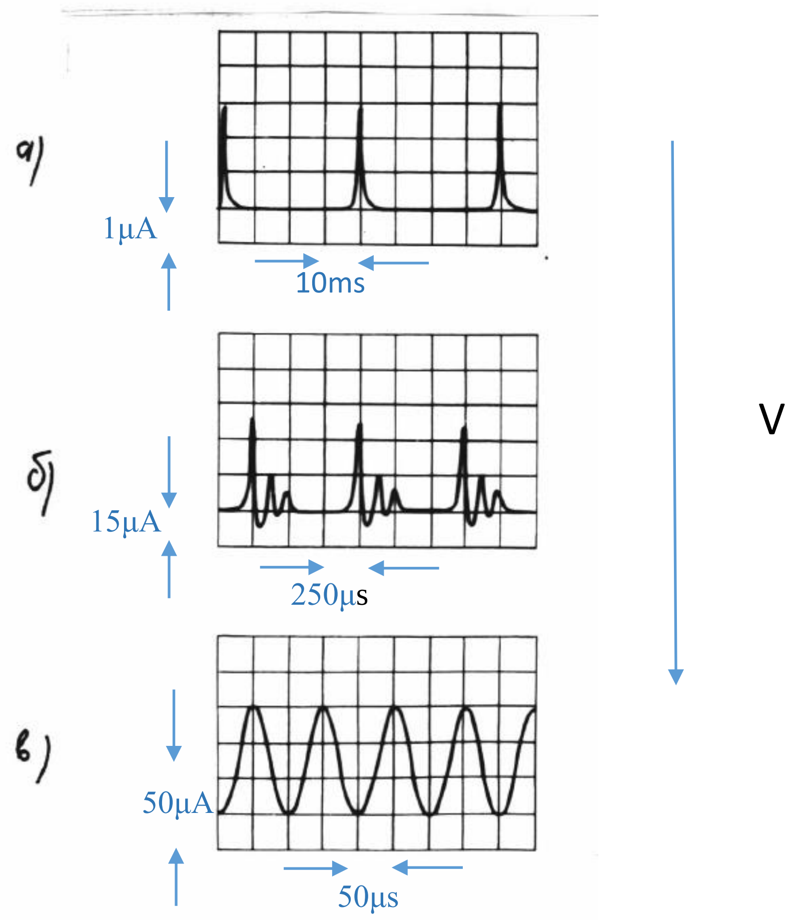
Appendix
(for additional reading)

A kind of a “slow breakdown” in preionized/ excited ultraclean gases

Since this workshop is related to the gaseous detectors stability, let me make a short deviation and mention some feature concerning corona discharges and kind of <u>slow</u> breakdowns (???)

Ionization instability of a corona discharge in ultraclean noble gases

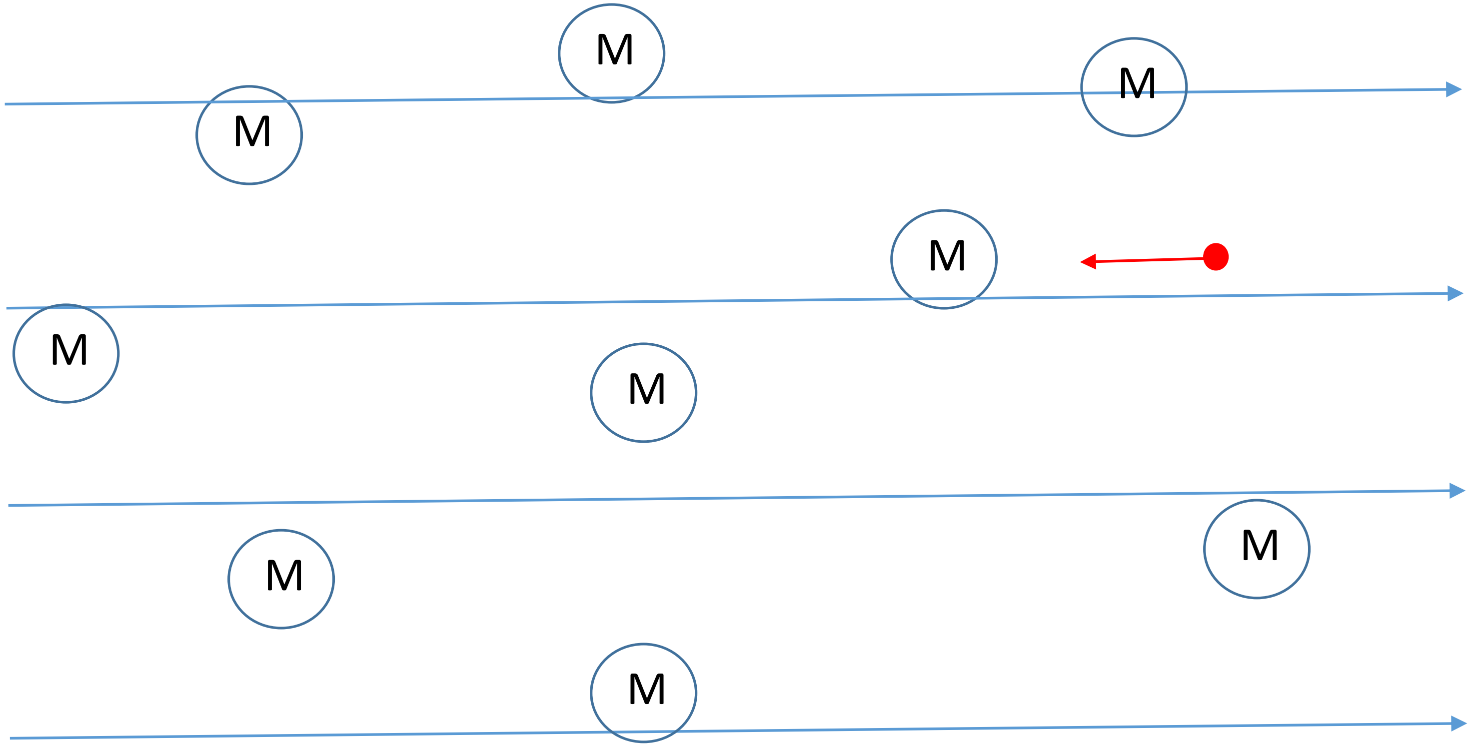




V. Peskov, Sov. Phy. Techn. Phys. 20, 1975, 1584

Such signals were observed in ultraclean He at p>5atm and Xe at P>3atm

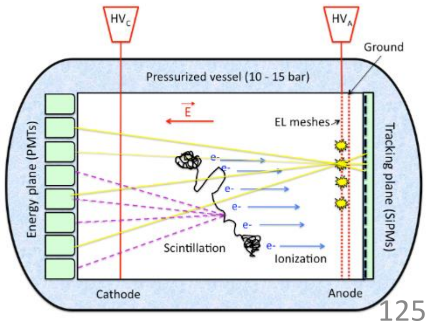
A hypothesis: this instability is connection to the accumulation of excited states

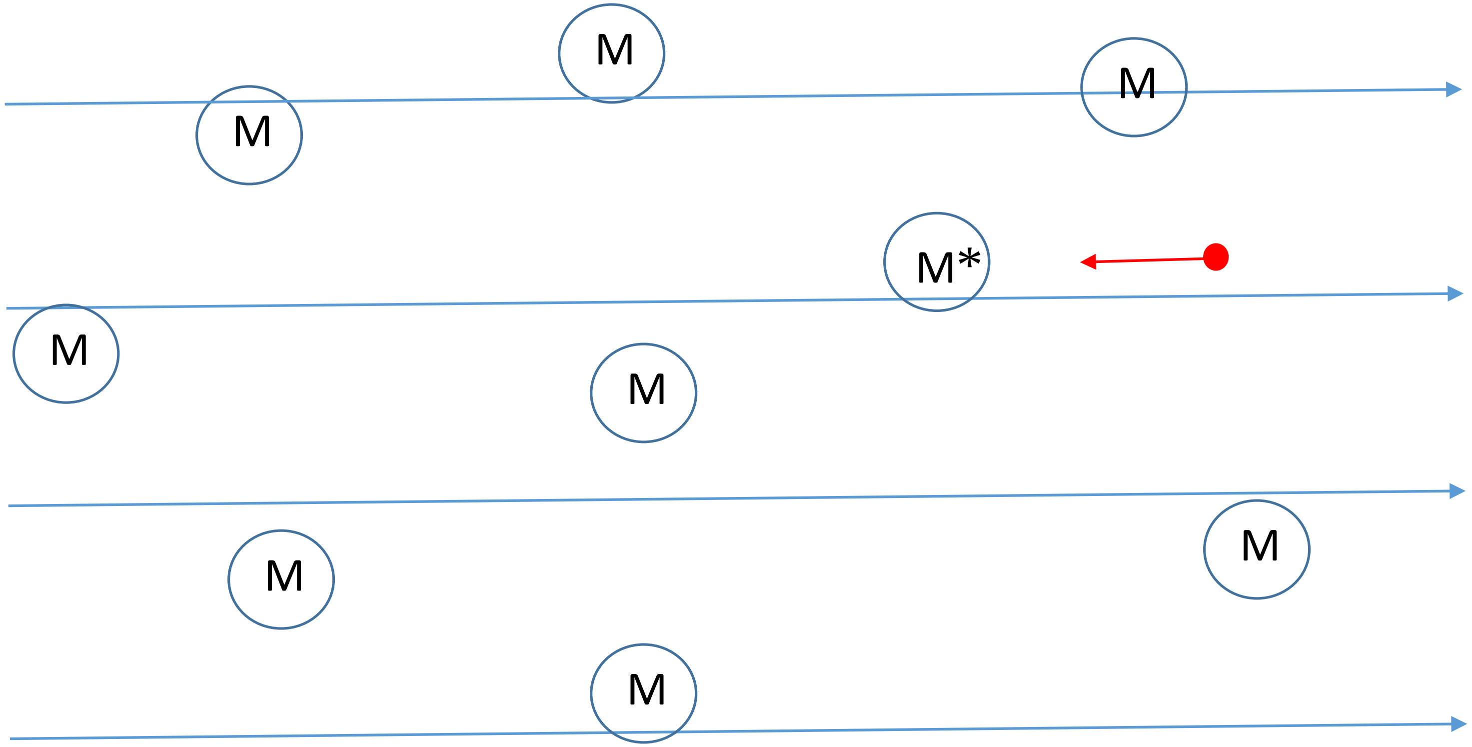


$e^- + R \rightarrow R^* + e^-$	*impact excitation*
$R^* + R \rightarrow R_2^{*,v}$	*excimer formation*
$R_2^{*,v} + R \rightarrow R_2^* + R$	*relaxation*
$R_2^* \rightarrow R + R + h\nu$	*VUV emission*

$e^- + R \rightarrow R^+ + 2e^-$	*ionization*
$R^+ + R + R \rightarrow R_2^+ + R$	
$e^- + R_2^+ \rightarrow R^{**} + R$	*recombination*
$R^{**} + R \rightarrow R^* + R + \text{heat}$	
$R^* + R + R \rightarrow R_2^* + R + \text{hea}$	
$R_2^* \rightarrow R + R + h\nu$	*VUV emission*

In a weak electric field mainly excited states are produced by drifting electrons
(on this principle gaseous scintillation detectors are operating)



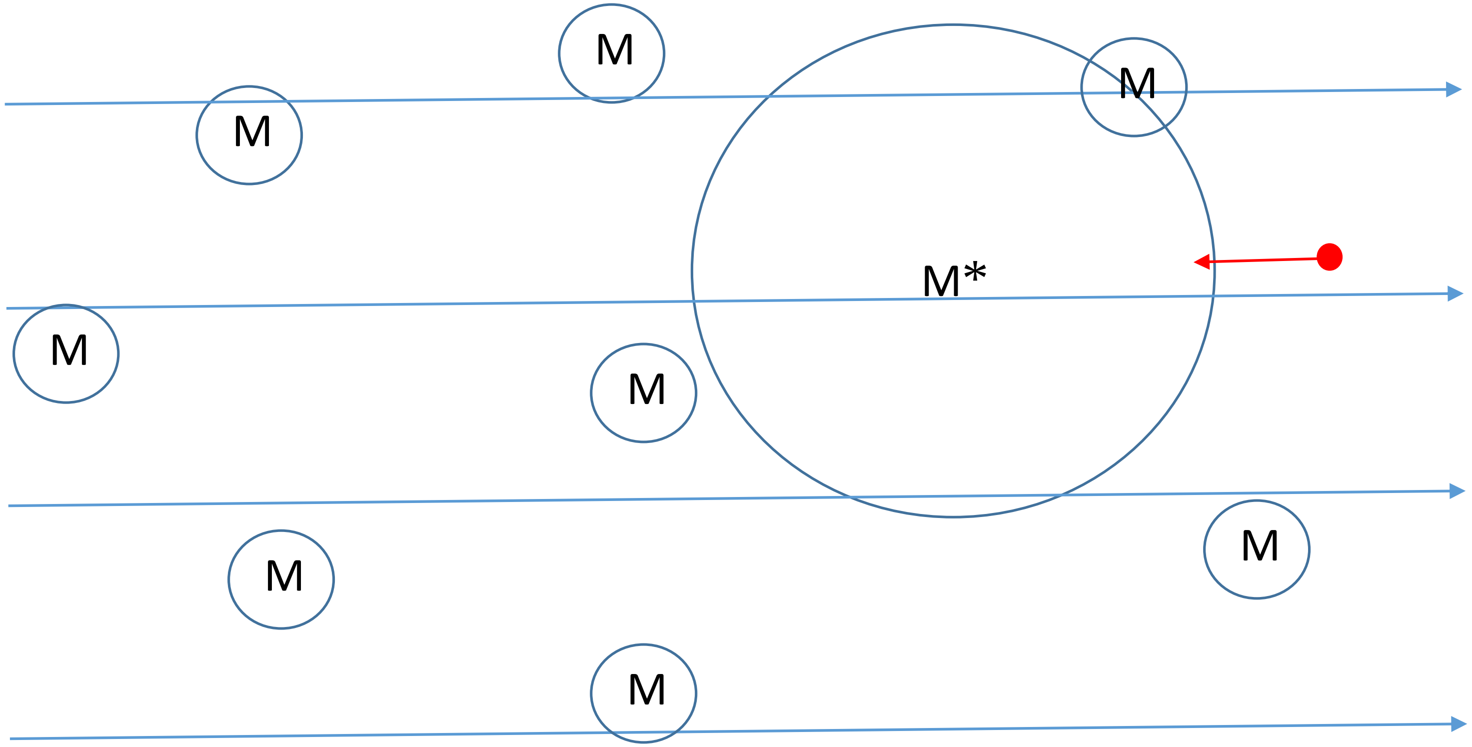


$e^- + R \rightarrow R^* + e^-$	*impact excitation*
$R^* + R \rightarrow R_2^{*,v}$	*excimer formation*
$R_2^{*,v} + R \rightarrow R_2^* + R$	*relaxation*
$R_2^* \rightarrow R + R + h\nu$	*VUV emission*

$e^- + R \rightarrow R^+ + 2e^-$	*ionization*
$R^+ + R + R \rightarrow R_2^+ + R$	
$e^- + R_2^+ \rightarrow R^{**} + R$	*recombination*
$R^{**} + R \rightarrow R^* + R + \mathrm{heat}$	
$R^* + R + R \rightarrow R_2^* + R + \mathrm{hea}$	
$R_2^* \rightarrow R + R + h\nu$	*VUV emission*

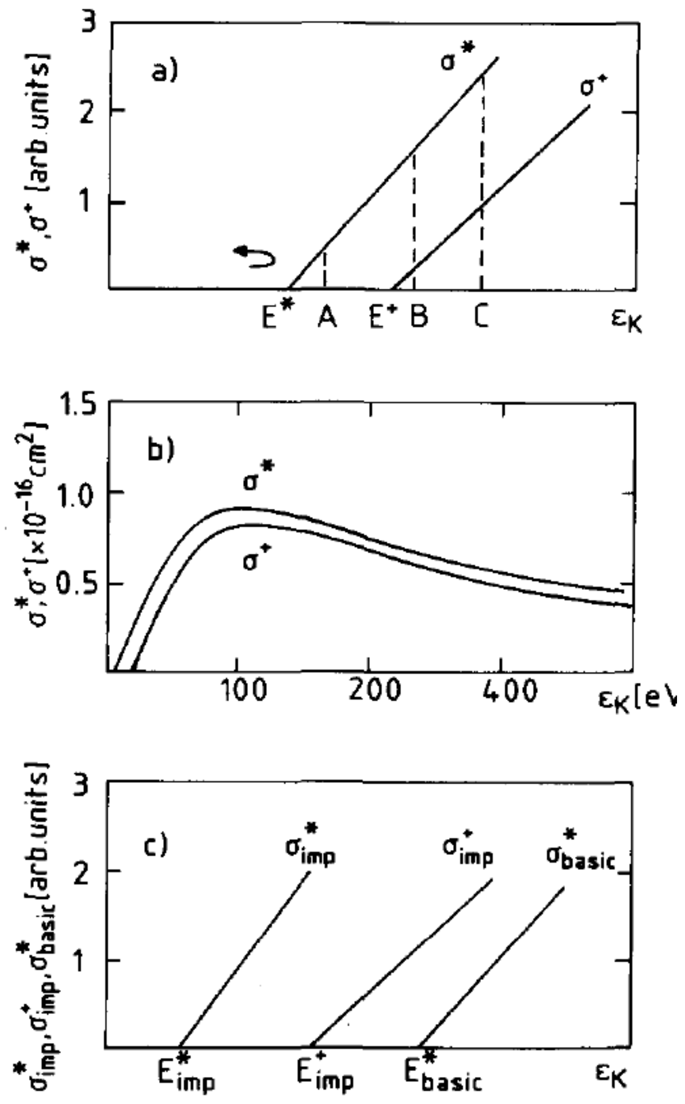
But in scintillation chambers there is just a short passing of primary electrons through the scintillation volume

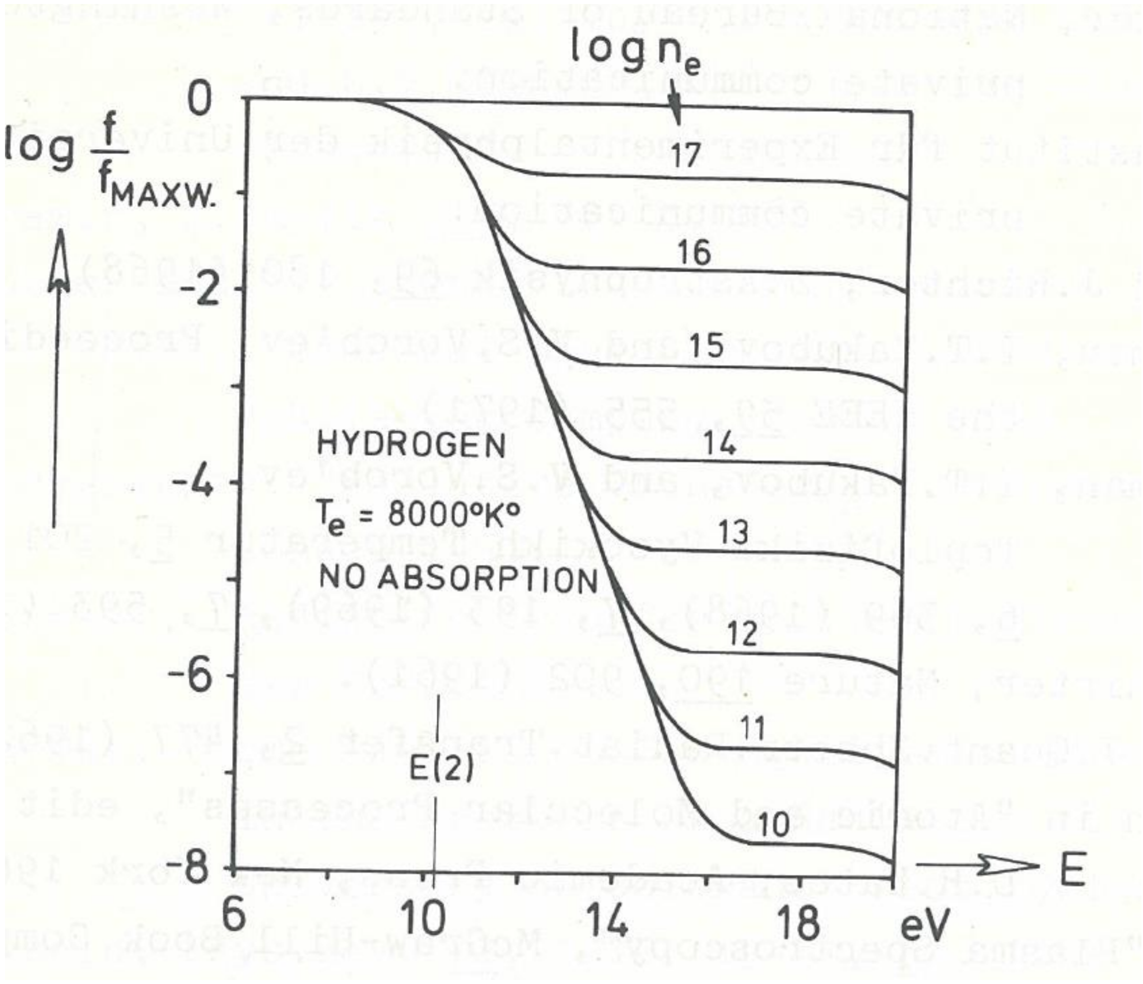
In corona discharge the current is continuous, allowing electrons to occasionally ionize excite states



A Crosss section of ionization from the excited atom/molecue dramatically increases, fore example in hydrogen as n^4, where n is the level number

What facilitate excited states accumulation?





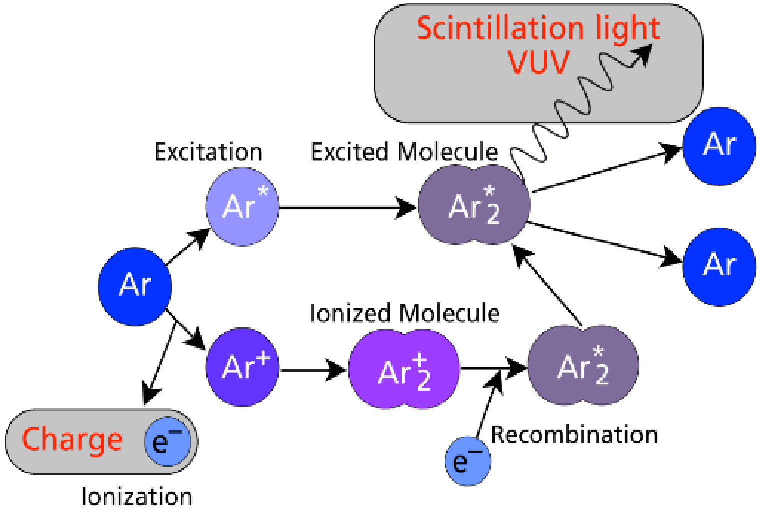
1) In low E excitation rate>> ionization

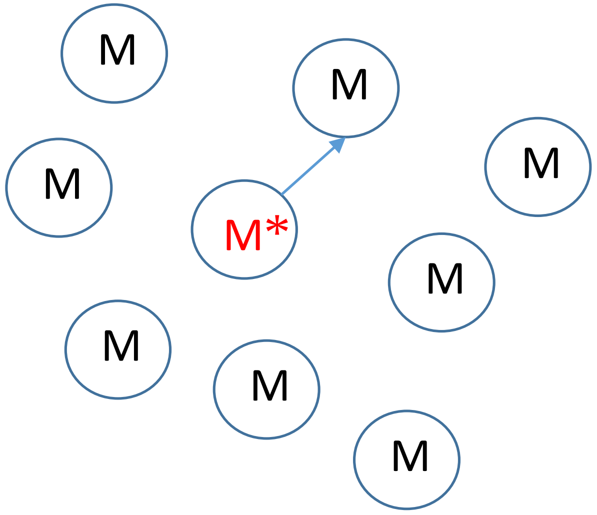
2) Electron tail cut

What facilitate accumulation of excite states?

Diffusion of resonance radiation

3)Diffusion of resonance radiation – a well know effect in atomic spectroscopy





Resonance line

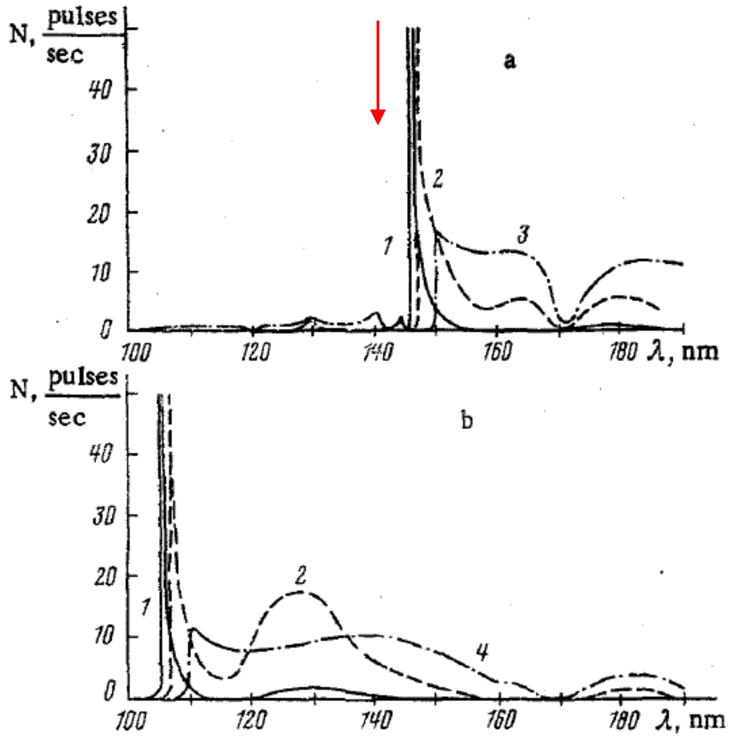


Fig. 3. Emission spectrum of a continuous sequenc of Townsend avalanches in Xe (a) and Ar (b) initia ed by an ^{55}Fe specimen; p =0.1 (1), 1 (2), 10 (3), and 25 atm (4). The diameter of the anode wire is 0.1 mm. The multiplication factor is roughly 100.

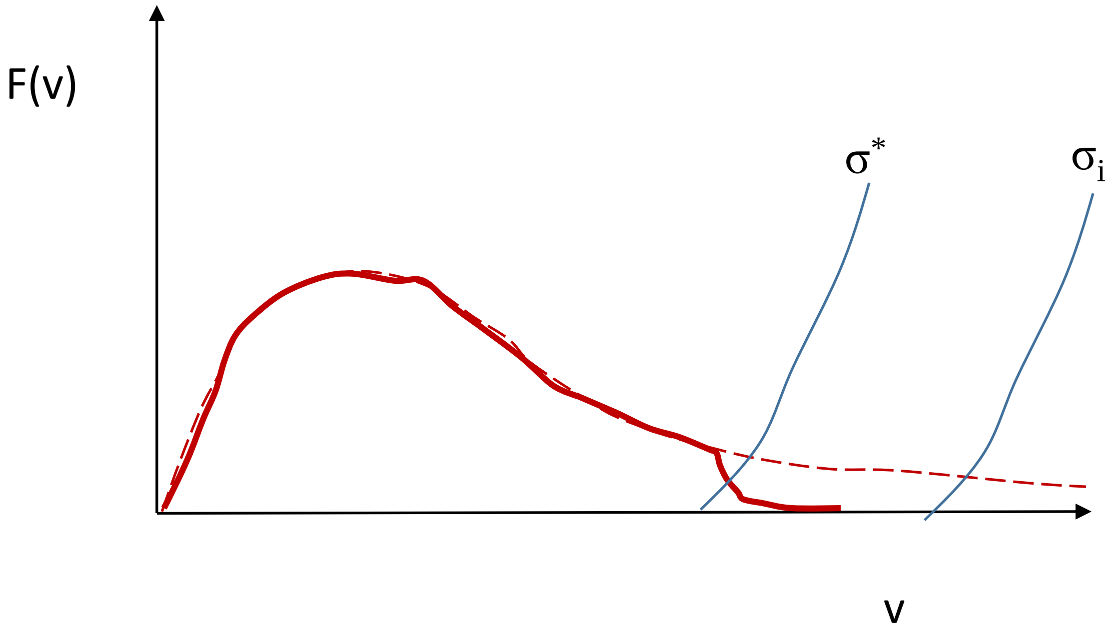
Condition of the instability caused by step ionization

$$n_e = k_i \int_{Ei}^{\infty} f(E)\, \sigma_i(E) N dE$$

If

$$k_i \int_{E^*}^{\infty} f(E)\sigma^*(E)\, N^* dE > k^* \int_{Ei}^{\infty} f(E)\sigma_i(E)\, N\, dE$$

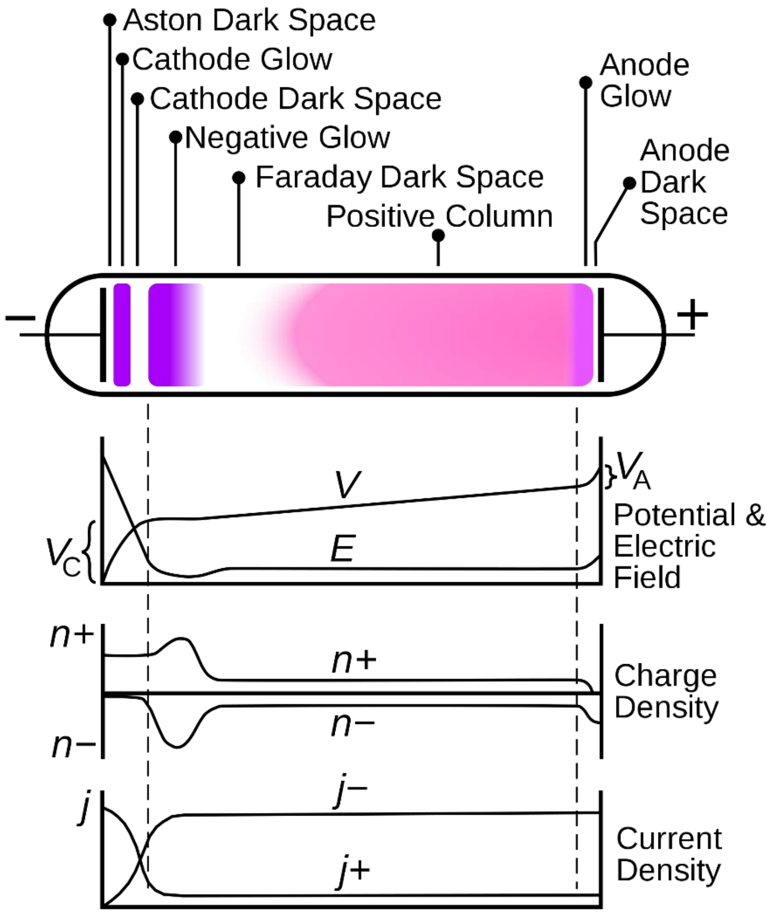
Ionization from excites states will dominate



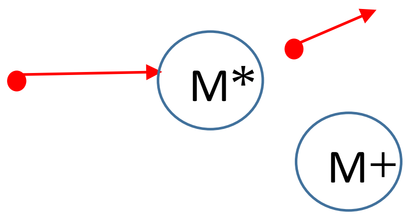
Note that $\sigma^* >> \sigma_i$ and number of electrons capable to ionize from excited level is much higher than from the ground state

There some experimental proofs and supporting calculations (see for example *https://link.springer.com/article/10.1134/1.1427998*)

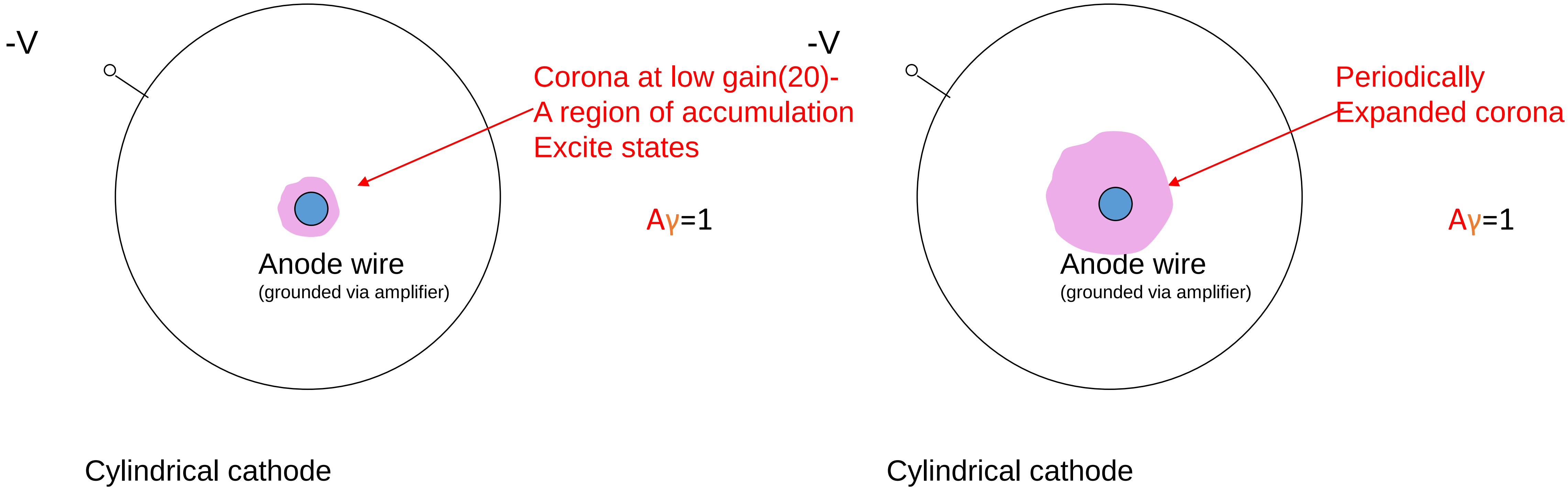
In plasma physics this process is called a step ionization



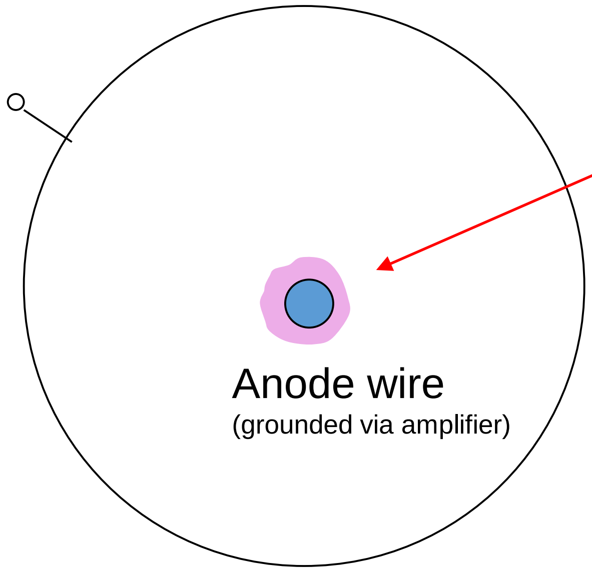
It is well known that a positive column in a glow discharge, where E/ is very low, is supported via step ionization of excites states

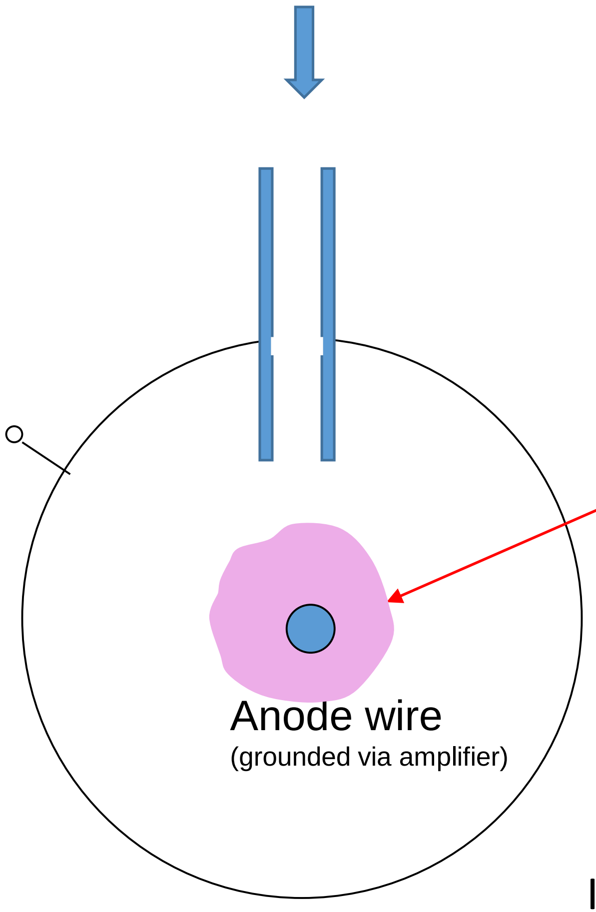


A critical role of excited and metastable states in streamer formation was discussed in paper: *L.S. Zhang, NIM 247,1986,343*

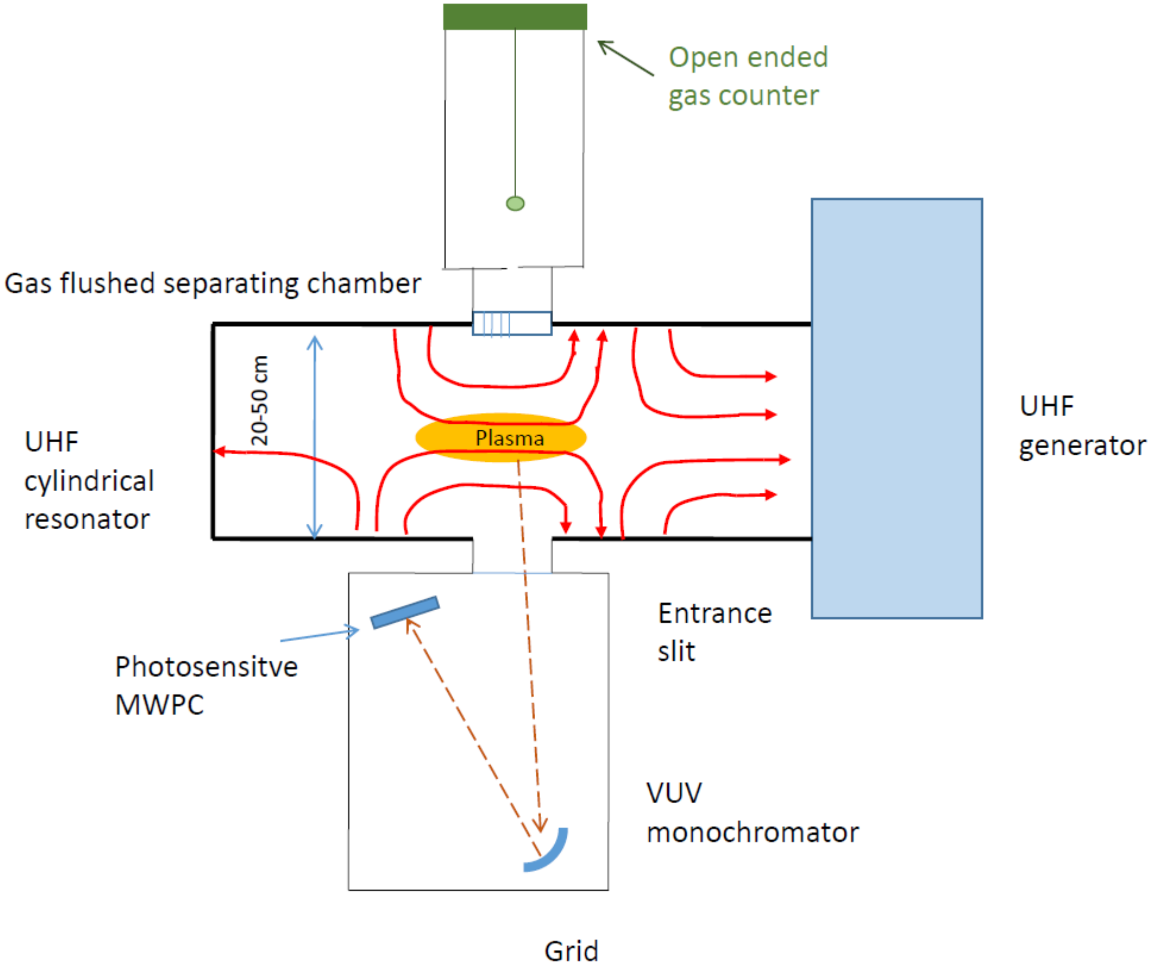

-V
Corona at low gain(20)-
A region of accumulation
Excite states
Aγ=1
Anode wire
(grounded via amplifier)
Cylindrical cathode
-V
Periodically
Expanded corona
Aγ=1
Anode wire
(grounded via amplifier)
Cylindrical cathode

Indirect confirmation



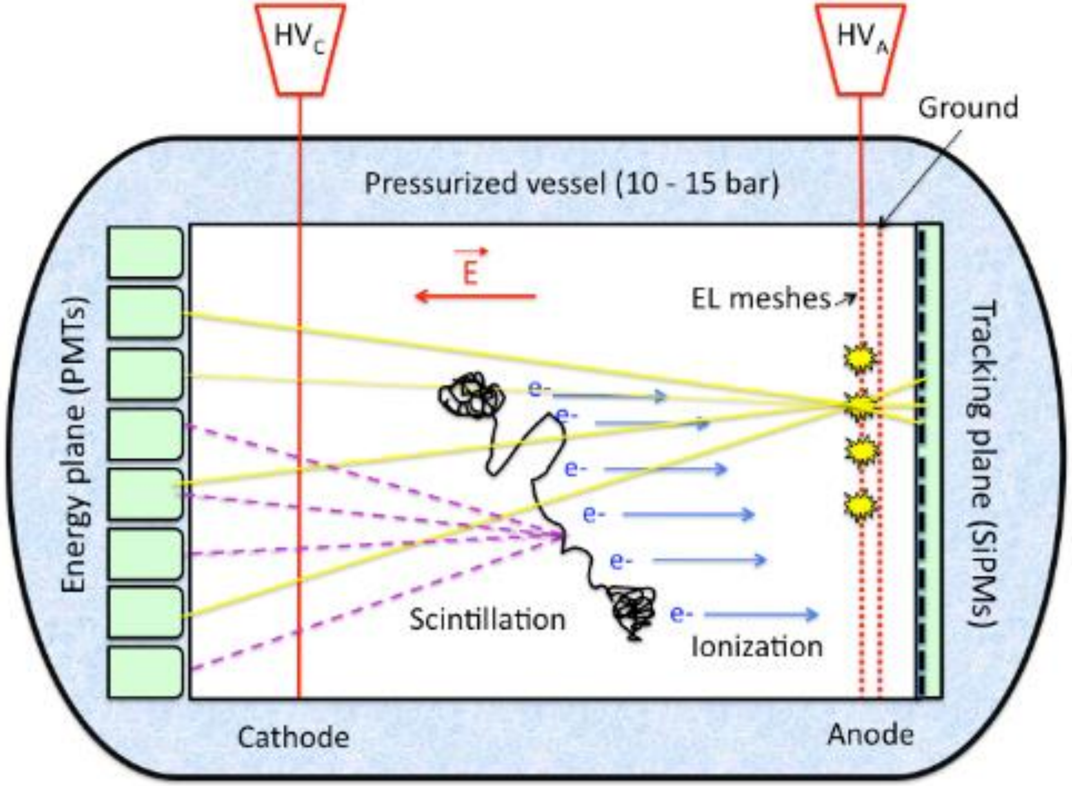


Understanding all the processes was critical for the successful operation of open-ended counters in plasma studies

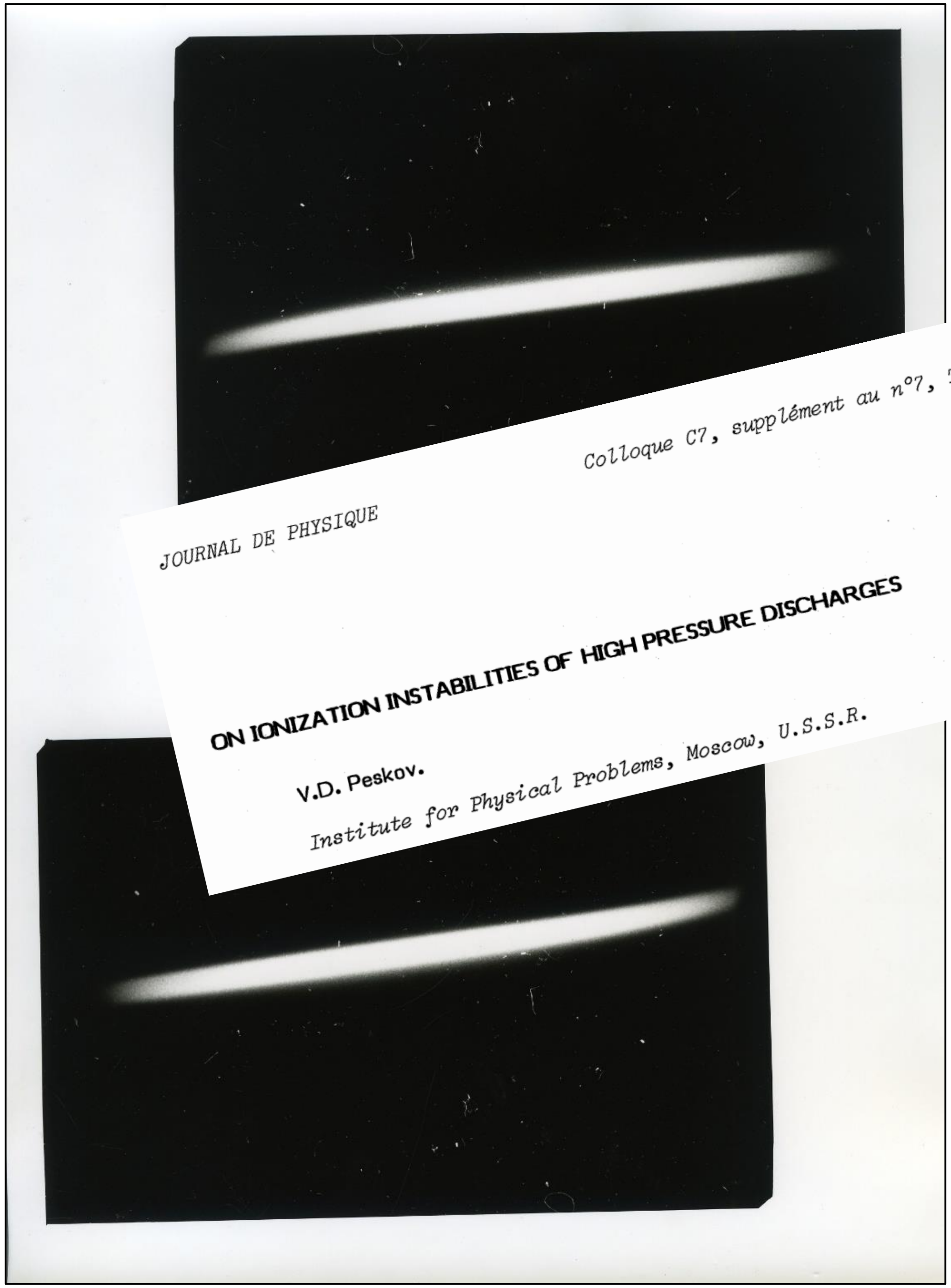


It also explains why the maximum achievable gain in clean He was around 10, whereas us in Ar and Xe it could reach values of of 100-1000…

Explains occasional breakdowns in high-pressure scintillation chambers



Observations of large- scale instability in very pure (< 10^{-5}%) noble gases at high-pressure, most probably also related to the excited states



JOURNAL DE PHYSIQUE Colloque C7, supplément au n°7, Tome 40, Juillet 1979, page C7- 335

ON IONIZATION INSTABILITIES OF HIGH PRESSURE DISCHARGES

V.D. Peskov.

Institute for Physical Problems, Moscow, U.S.S.R.

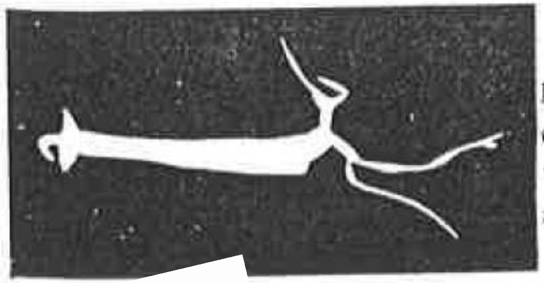


Fig. 3. Photograph of microwave corona in argon. This discharge has the form of a continuously growing and vanishing plasma filament.

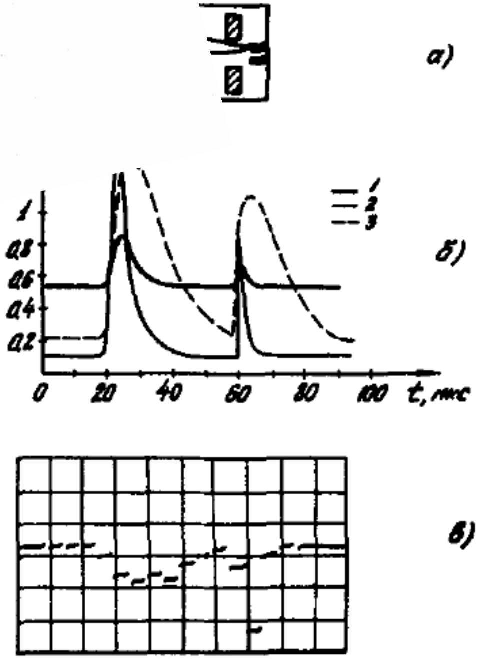


Fig.2 a) scheme of first type of instability, b) oscillograms of arc current (1), lines (2), and molecular (3) radiation at the moment of breakdown, c) oscillogram [5] of signals from coordinate counter passed 10 μs after breakdown

Measurements shows that it is a kind of "slow breakdown"!