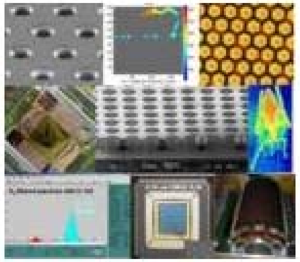


2nd RD51 Collaboration Meeting

13-15 October 2008

The physics of streamers and discharges

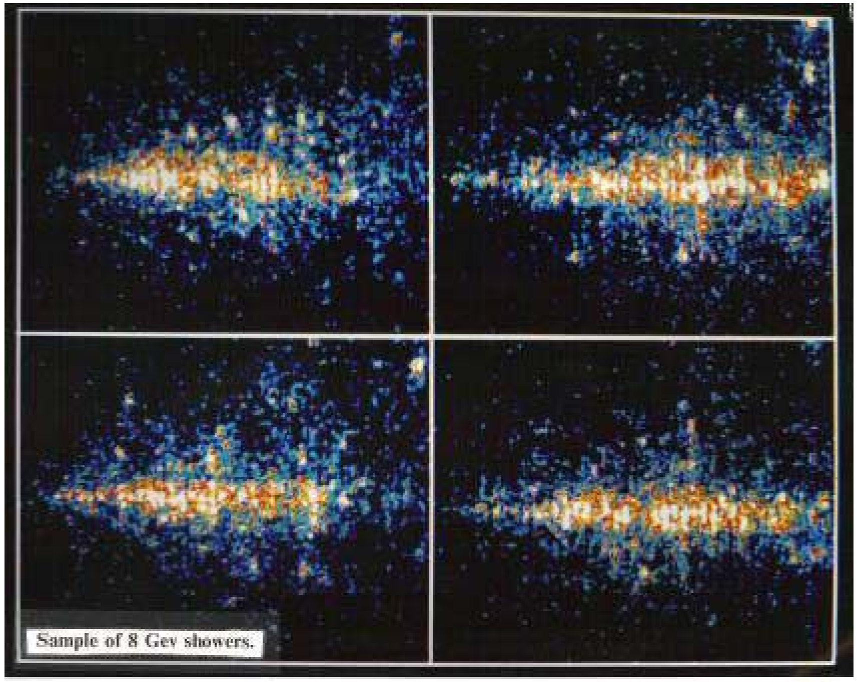
P.Fonte

LIP

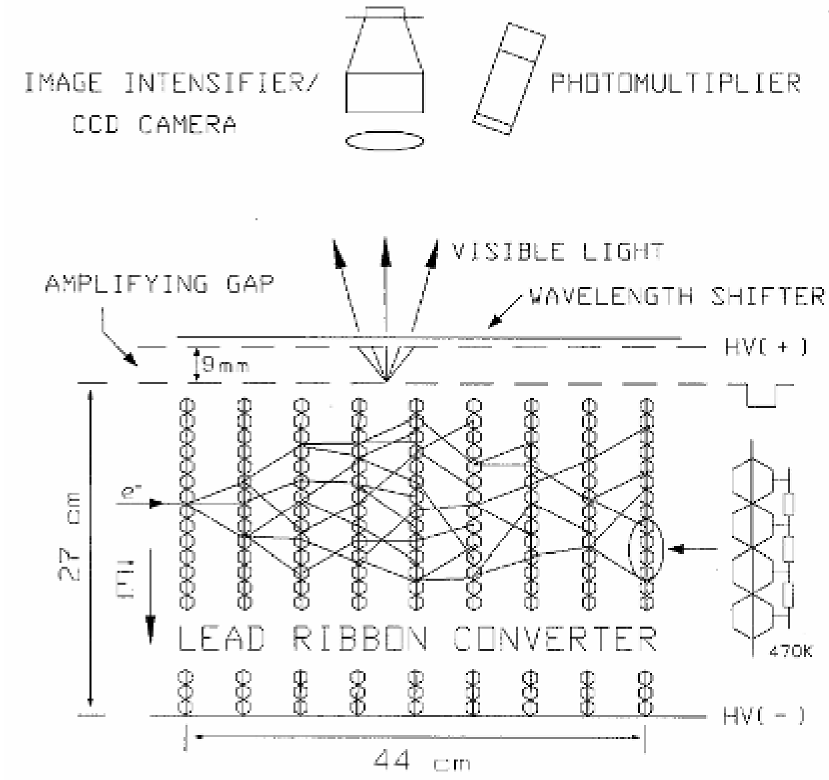
My view, not a review.

Nostalgic anecdote

DELPHI's HPC



Imaging HPC (1989)



Sparked disastrously owing to the alpha particles emitted by the lead converter.

Sparked also my lasting interest in breakdown phenomena in gaseous detectors, most of the way in partnership with V. Peskov.

Outlook

- Known and suspected fundamental breakdown onset modes:
  slow, fast, rate-induced?
  - Experimental evidence
  - Physical origin (or speculations about…)
  - Suppression

- Streamer simulation
  - Detailed physics
  - Simulation strategies
  - Results

- The discharge
  - Phenomenology
  - Suppression

Slow breakdown - experimental evidence

[RAE64]

CO_2, 2 cm gap,
148 Torr

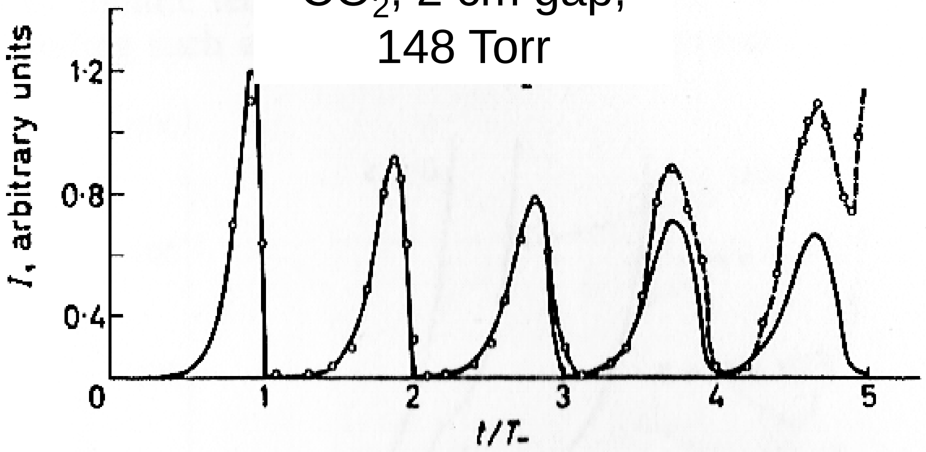
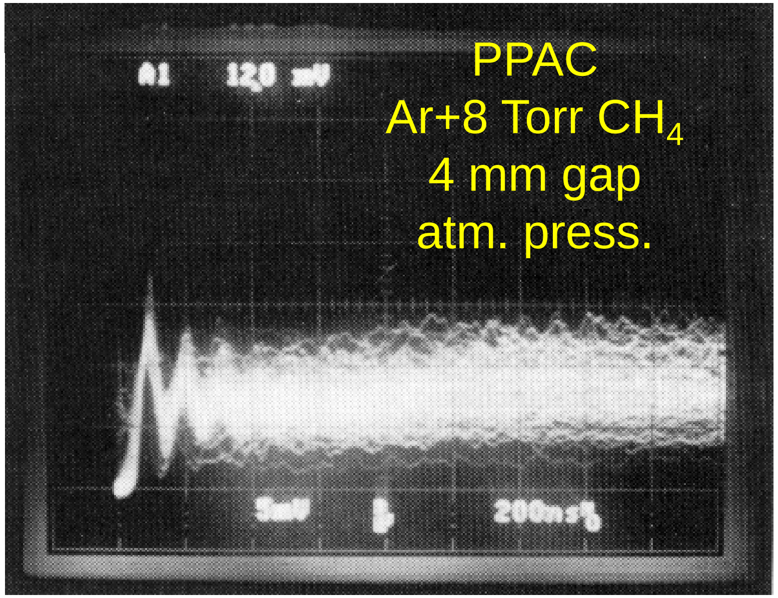


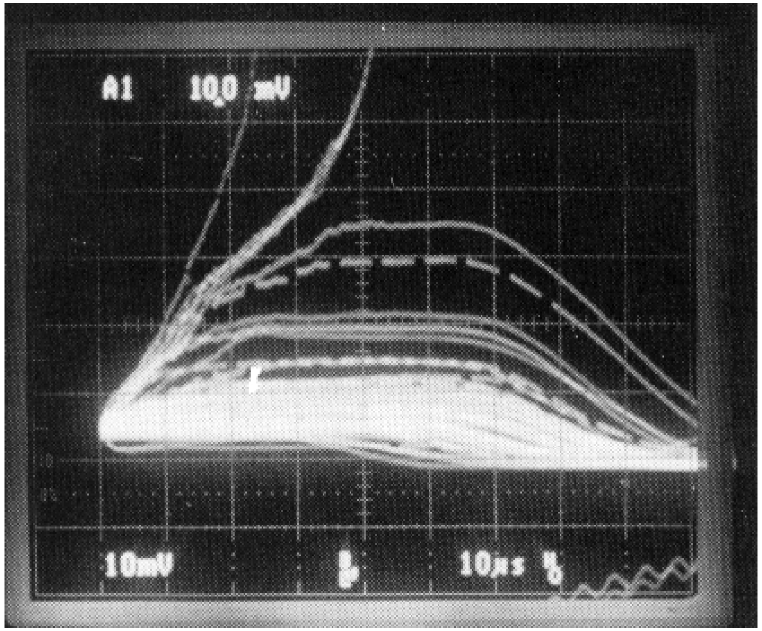
Figure 5.5. Series of photosuccessors in CO_2 started by an alpha-particle at $\mu_0 \cong 1$. ($E/p = 50{\cdot}2$; $pd = 124$ Torr·cm; $d = 2$ cm; $\alpha d = 15{\cdot}3$; $T_- = 115 \times 10^{-9}$ sec). The first maximum corresponds to $I_- \cong 200$ μA. ○ observed, —— calculated without space charge. The comparison shows that the fourth generation is heightened by the space charge effect; thus μ becomes > 1[13]

Extremely unstable situation.

[FON91a]

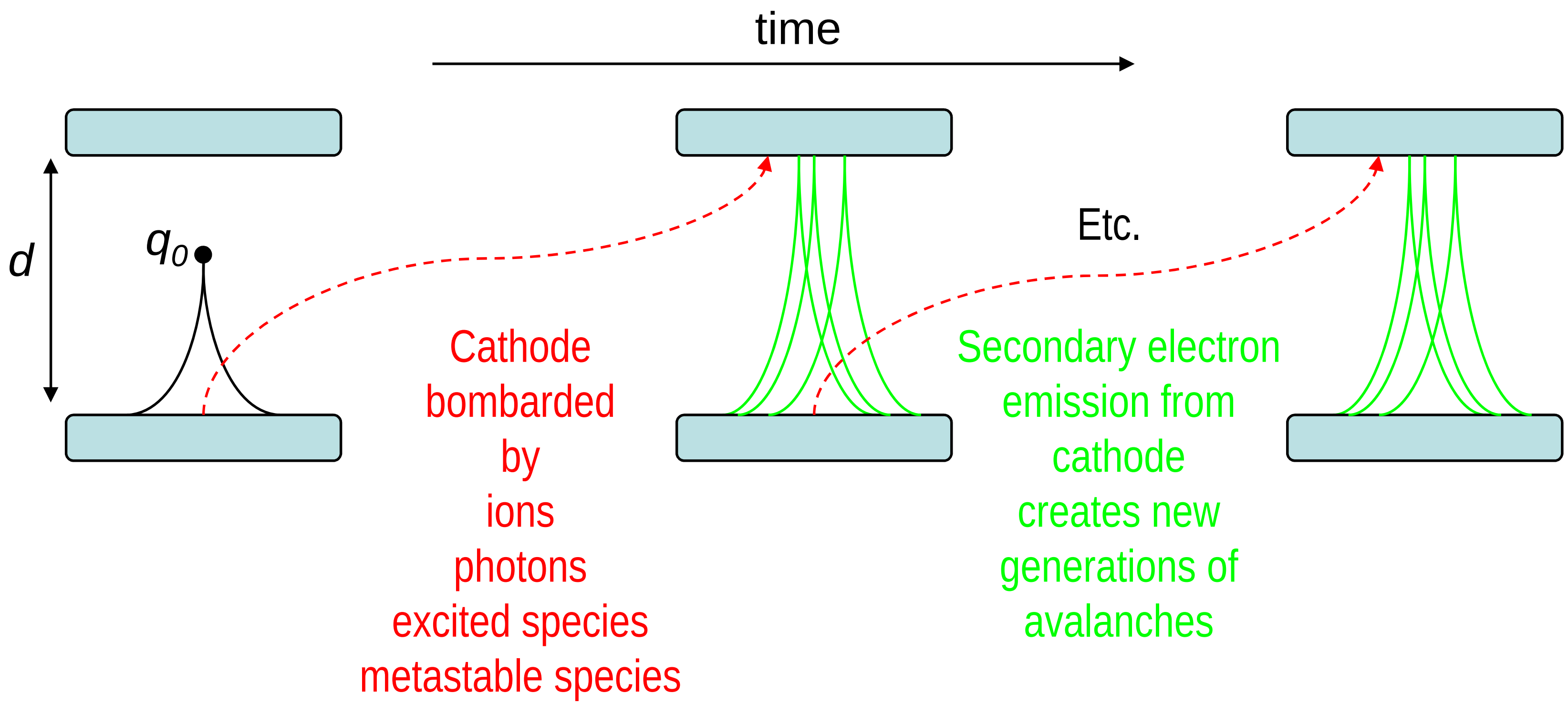
PPAC
Ar+8 Torr CH_4
4 mm gap
atm. press.





Slow breakdown – physical origin

(Townsend's "generations" mechanism)



A very elaborate theory exists (for instance [DAV73] chap. 2).

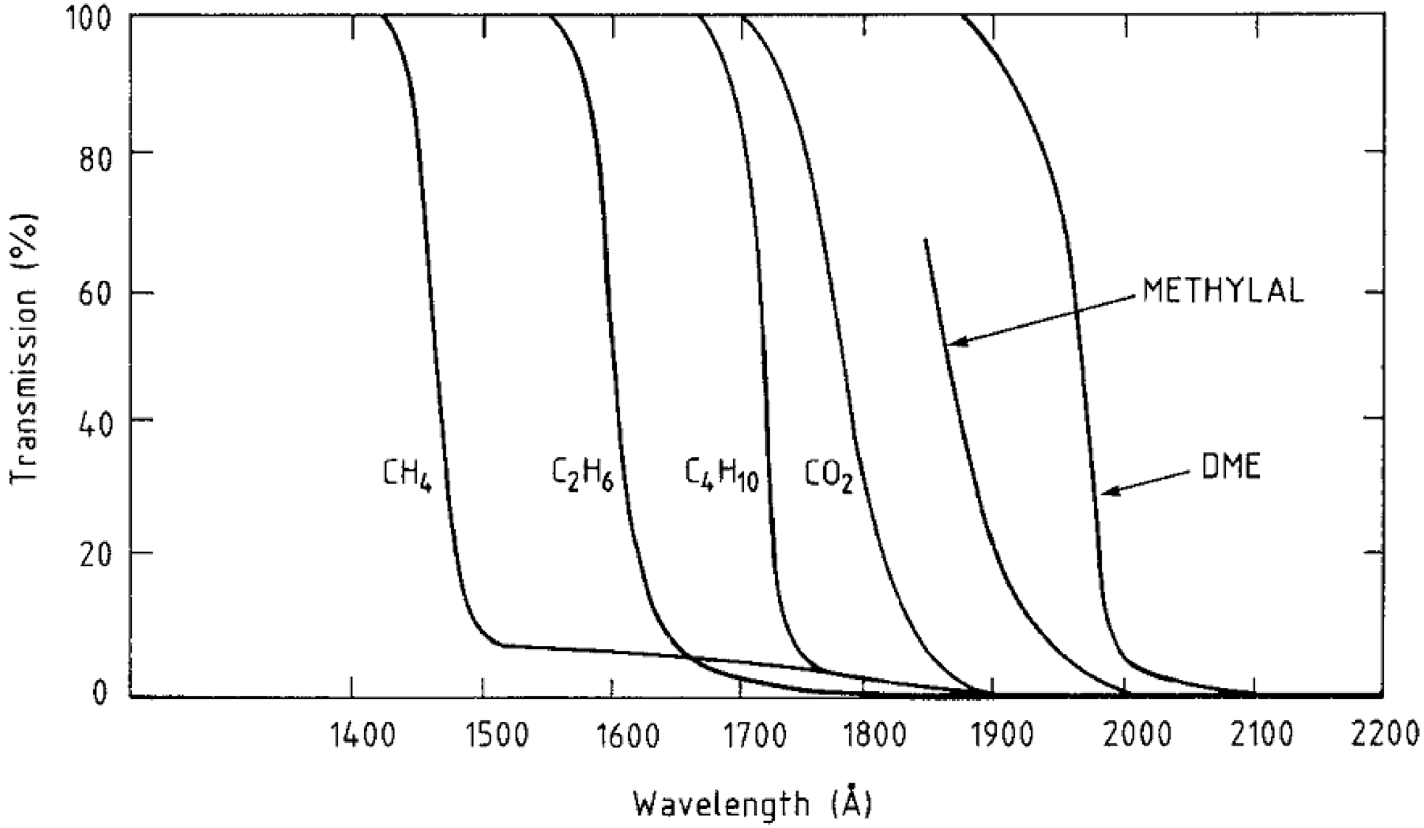
The stability condition is $\eta G < 1$ where $G = e^{\alpha d}$ is the gas gain and η is the secondary electron yield per electron in the avalanche. But there is also an overlaying statistics.

In detectors photon feedback generally dominates and the characteristic time is the electron's drift time from cathode to anode.

Slow breakdown – "quenching"

Gas "quenching": adding complex molecules to the gas mixture

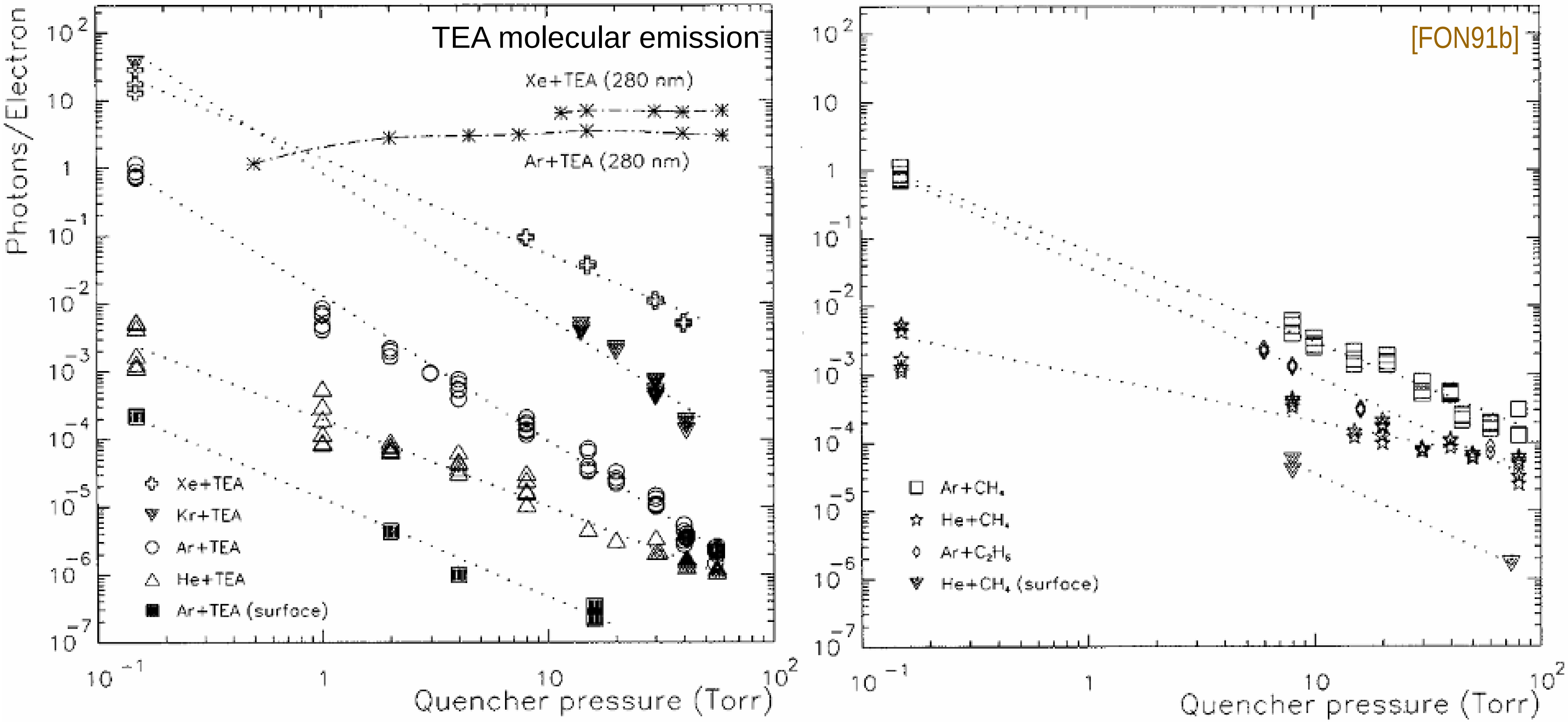
Photoabsorption of the emitted photons in the UV
(depends on details of the quencher gas)



Slow breakdown – “quenching”

Emission suppression: less dependent on details

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

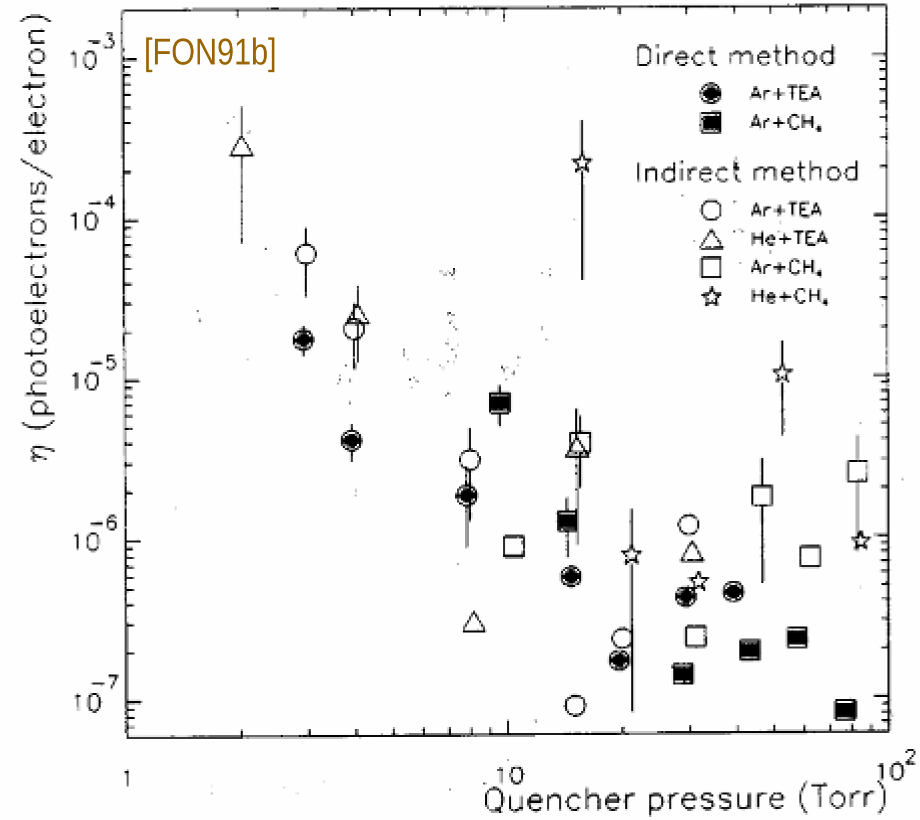


There is some evidence that the emission originates mainly from fragments (likely carbon atomic emission lines) at λ>140nm.

Photoemission strongly suppressed for quencher concentration 1-10%.

Slow breakdown – “quenching”

Altogether: efficient photon feedback suppression



Secondary photons/electron

PPAC
Stainl. steel mesh cathode
4 mm gap
atm. press.

No matter the nature of the quencher, photon feedback is very effectively suppressed by a few percent concentration.

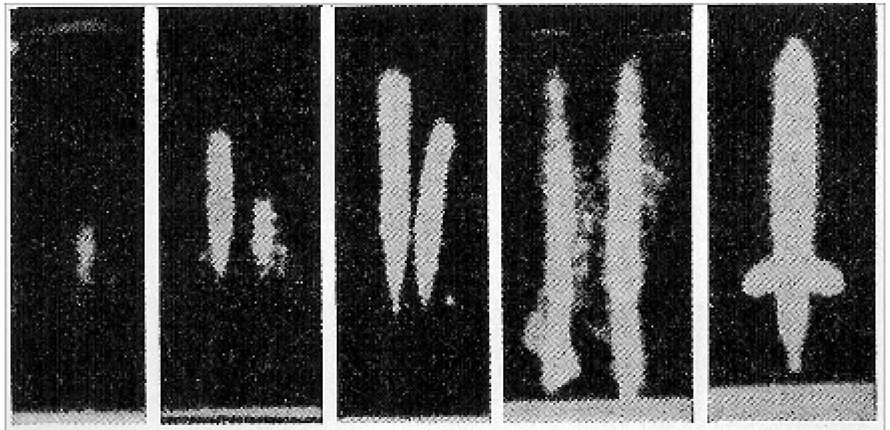
Slow breakdown is normally not a problem for stability, except in presence of very photosensitive surfaces (e.g. CsI photocathode)

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



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

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

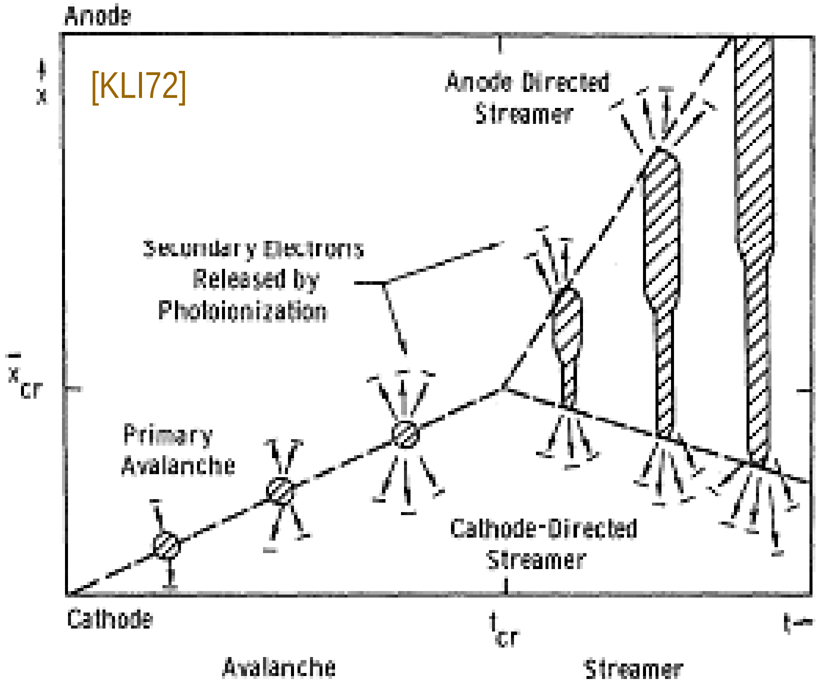


FIG. 6. Schematic representation of the qualitative description of streamer development given by Wagner. (Based on Figs. 22 and 27 of Ref. 11.) Anode- and cathode-directed streamer propagation begins at $t_{critical}$ when the avalanche position equals $\bar{x}_{critical}$.

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

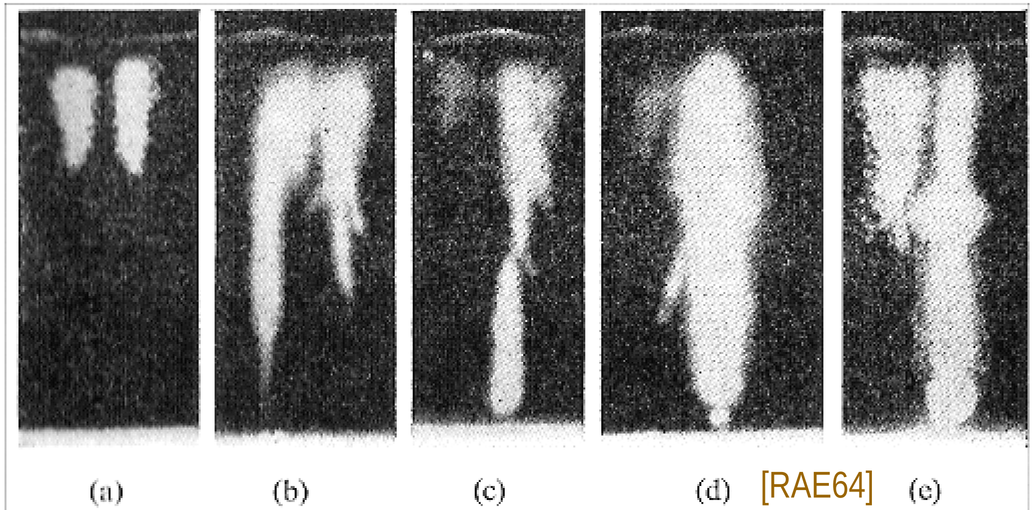


Figure 5.10. Development of the cathode directed streamer (with increasing pulse length). From the head of the avalanche (near the anode) (a) starts the cathode directed streamer ((b) (c)) till a plasma channel connects cathode and anode (d, e). These branched streamers resemble the discharge figures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

Is it relevant for detectors?

Fast breakdown - experimental evidence

Very fast process featuring a "precursor" pulse

[RAE64]

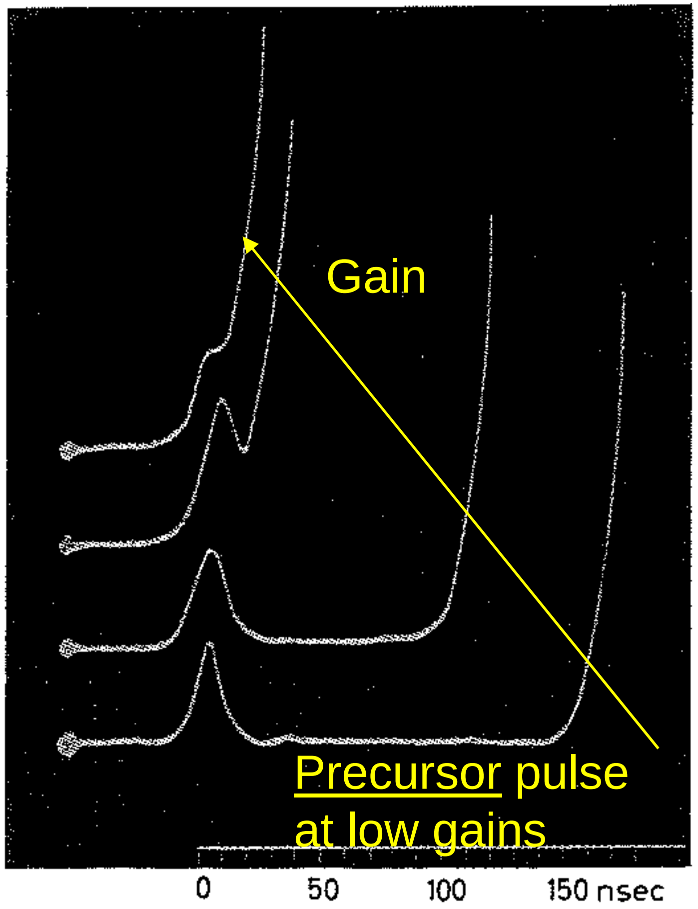
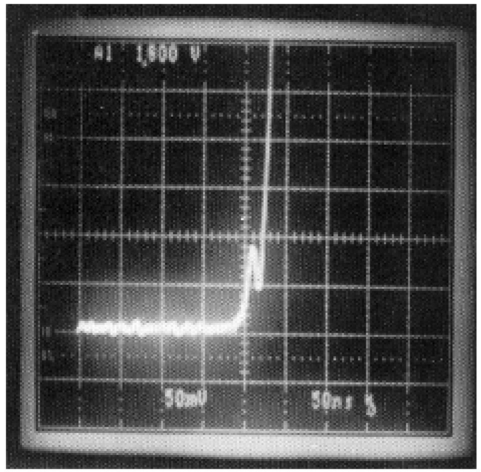


Figure 5.14. Current oscillograms of static breakdown in methylal. Optical method. $E/p = 64{\cdot}4$, $pd = 230$ Torr cm, $d = 0{\cdot}8$ cm, $T_{-} = 90$ nsec $RC = 5$ nsec[36]

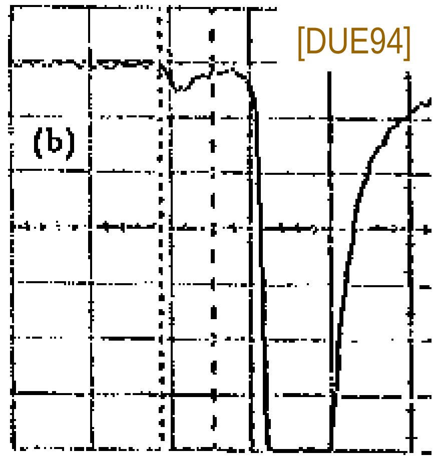
PPAC

[FON91]



A signature of low-gain cathode streamer-only breakdown

RPC



[DUE94]

single-wire

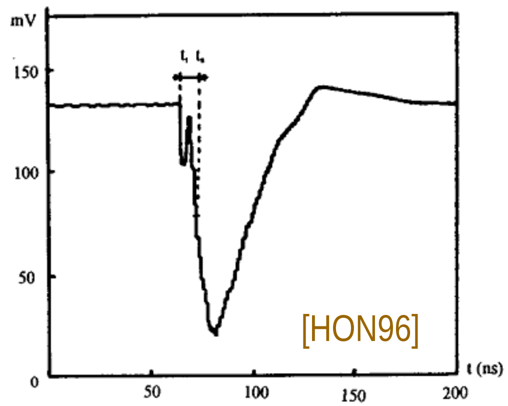
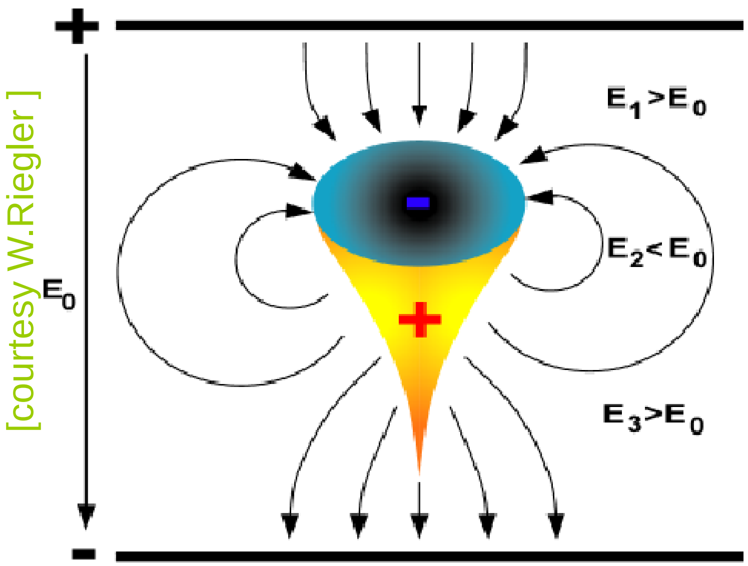


Fig. 1. The pulse shape of the SQS electrical signal $V = 2.45$ kV, Methylal/(Methylal + Ar) = 16.6%.

Fast breakdown – physical origin

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

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



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)

Details later

Raether limit – parallel fields

[RAE64]

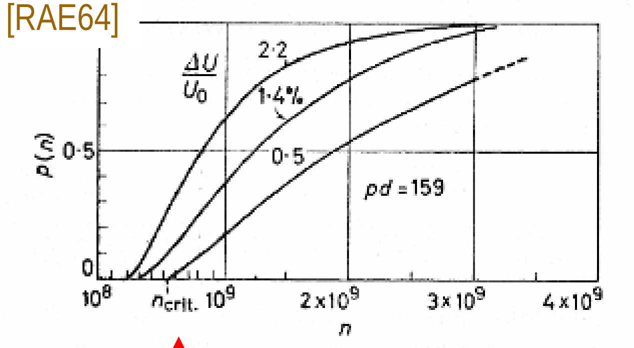
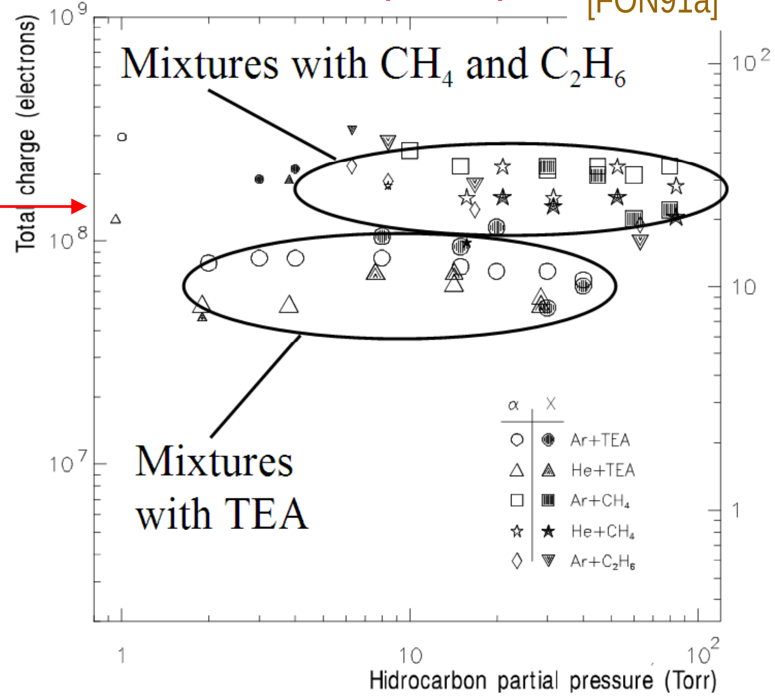


Figure 5.16. Probability p(n) that an avalanche produces a streamer as function of n; ether, $d = 0{\cdot}8$ cm, $p = 199$ Torr[37]

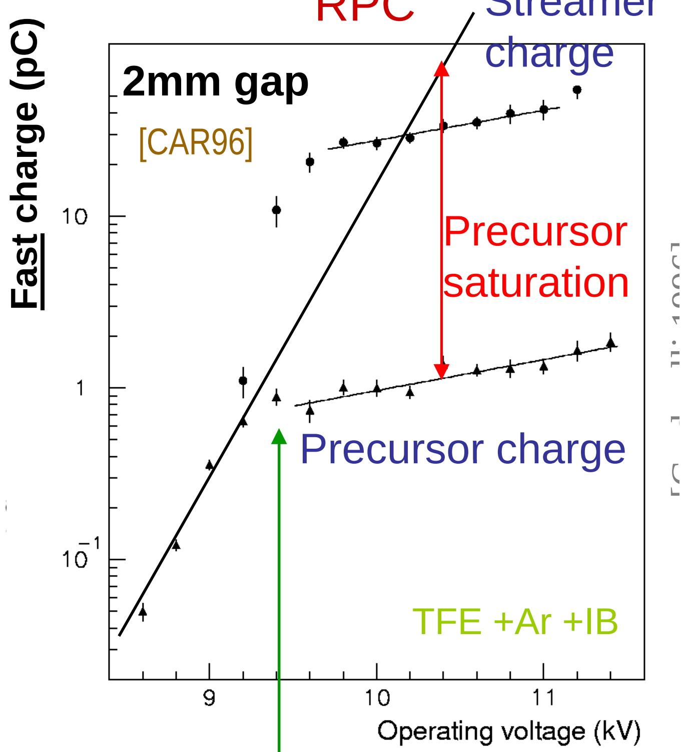
A charge-dominated process

The famous "Raether limit" of ~10^8 electrons

PPAC (4mm) [FON91a]



RPC



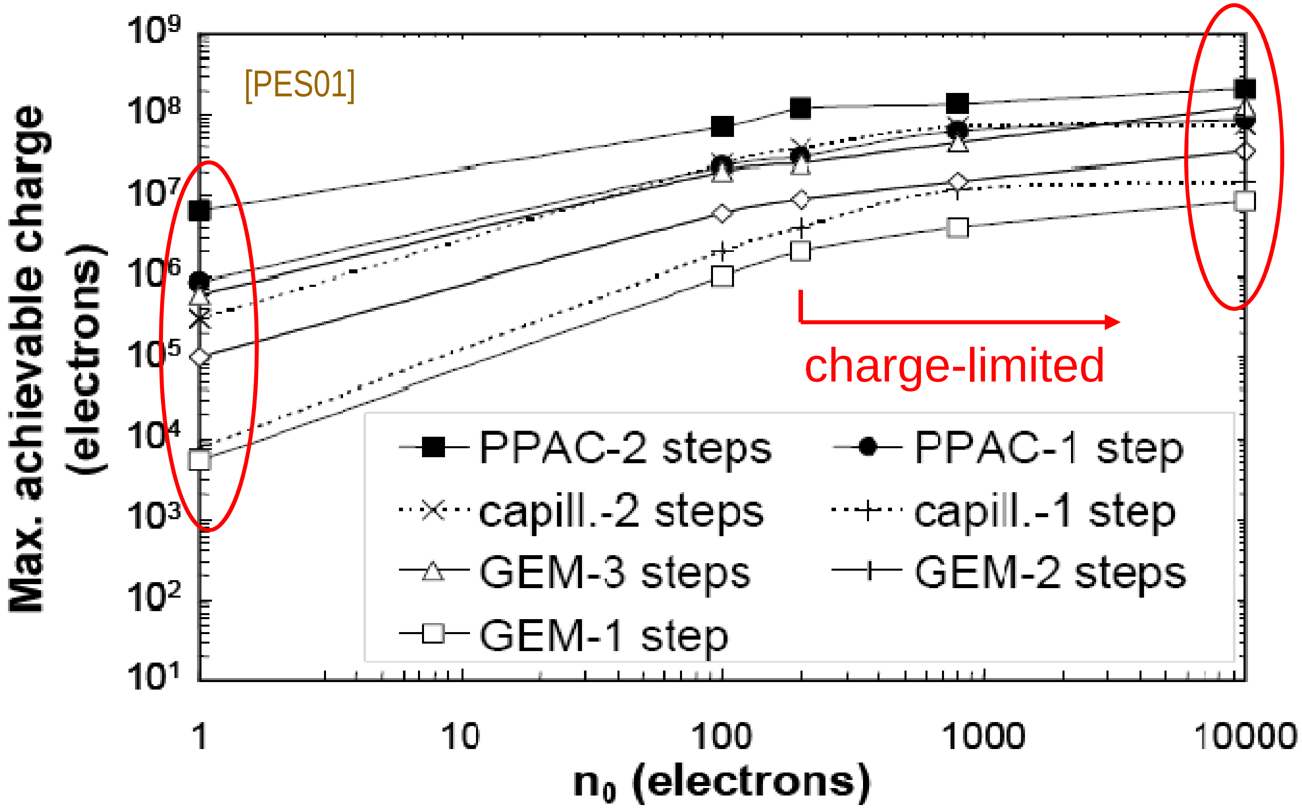
Avalanche gain saturation corresponds to the onset of streamers.

No "limited proportionality" in parallel fields (except in SF_6).

Raether limit – micropattern detectors?

Geometry dependence + multistep

Reduction at high gain
Likely owing to:
 -avalanche statistics
 -Corona discharge



For n_0>~200 electrons the Raether limit applies, but depends on geometry.
For n_0<~200 electrons other factors start to dominate, such as:
 avalanche gain fluctuation
 Corona discharge from sharp edges

Streamer suppression

By spatial variation of the applied field: SQS mode (wire counters)

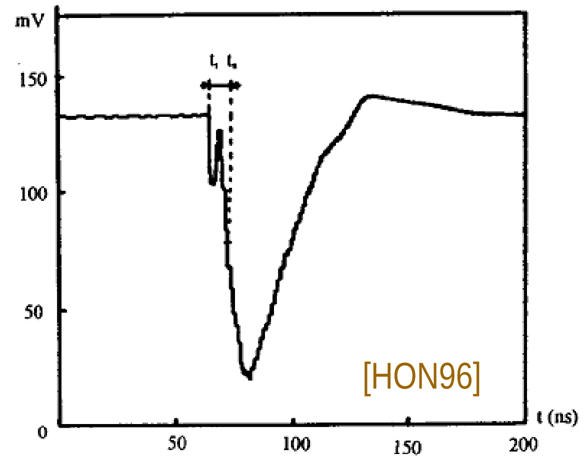
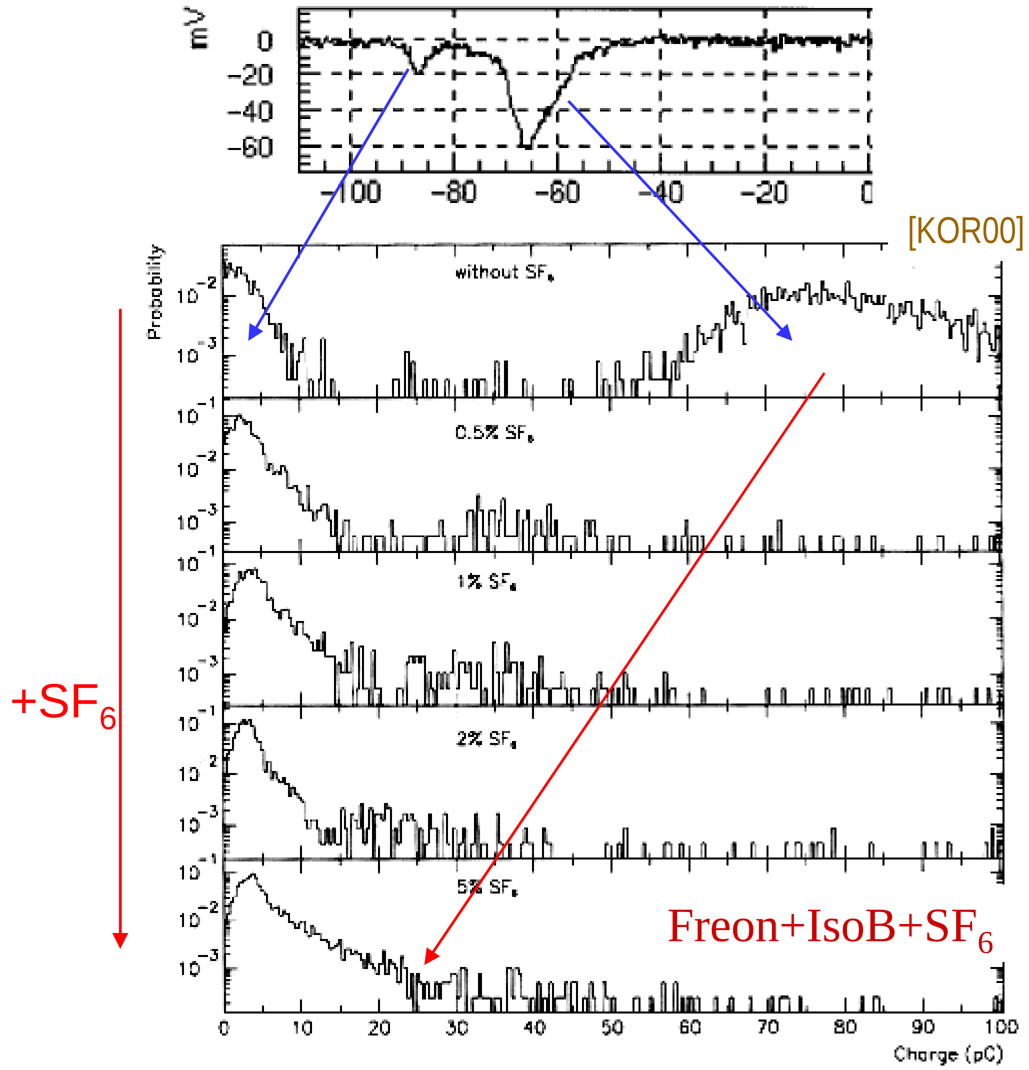


Fig. 1. The pulse shape of the SQS electrical signal $V = 2.45$ kV, Methylal/(Methylal + Ar) = 16.6%.

By poisoning the gas with SF_6 (RPC only – not tried on PPC)



Streamer enhancement…

dielectric surfaces favour the streamer propagation

SQS

Direct spark

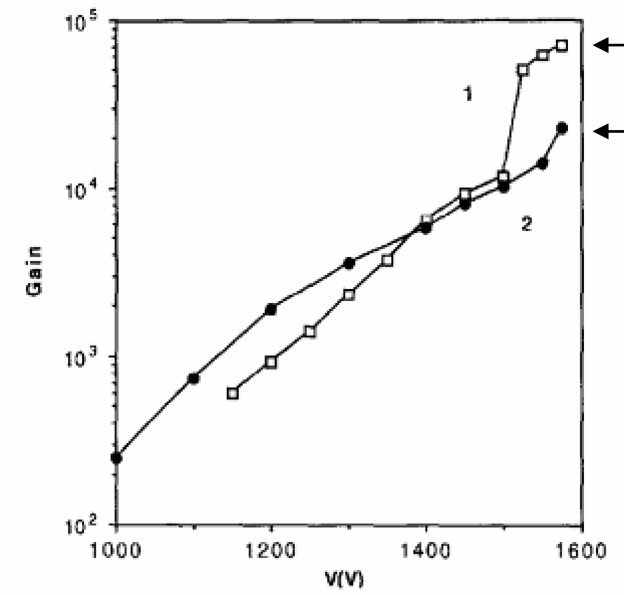
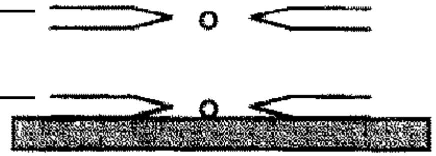


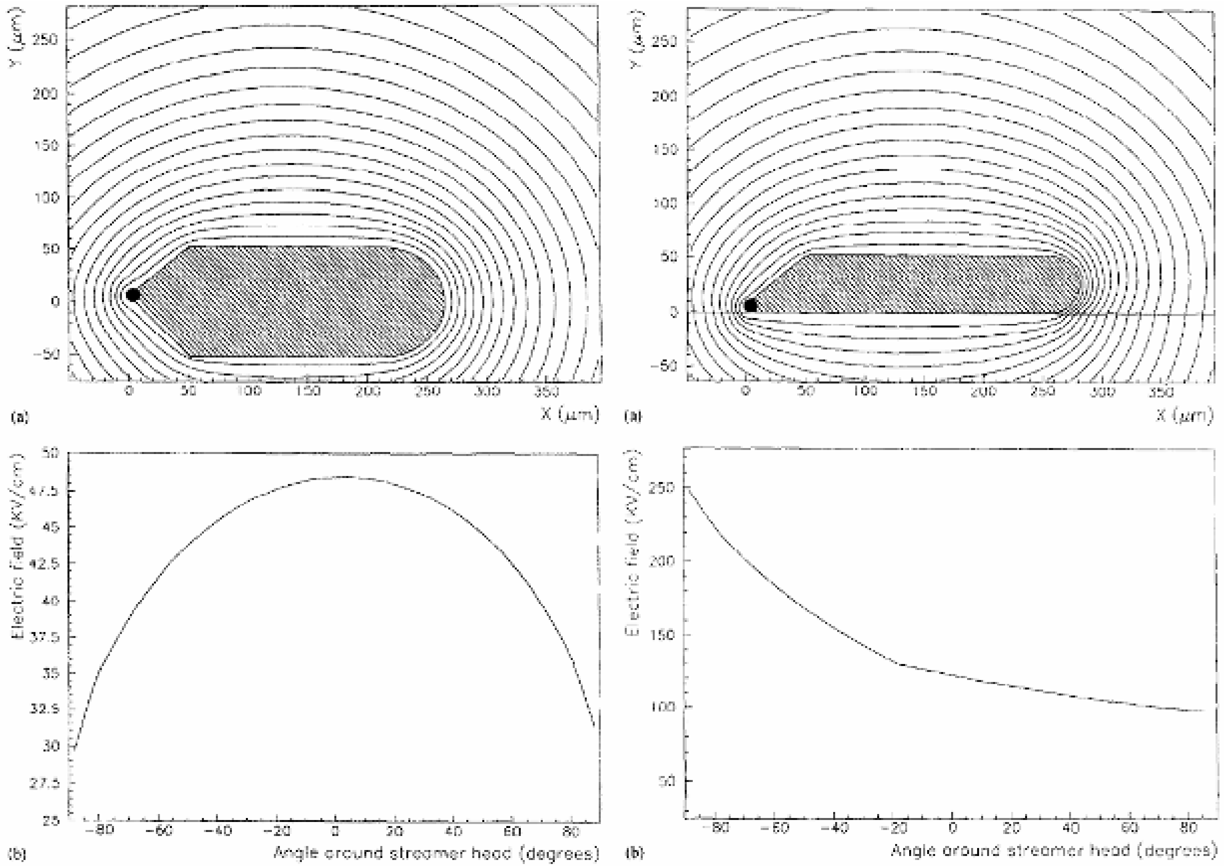
Fig. 3. Amplitudes of Fe^{55} signals versus applied voltage for the blade chamber with a 3 mm gap; without substrate (1) and with substrate (2).



Blade detector

Blade detector on substrate

[PES97]



Rate-induced breakdown? – experimental evidence

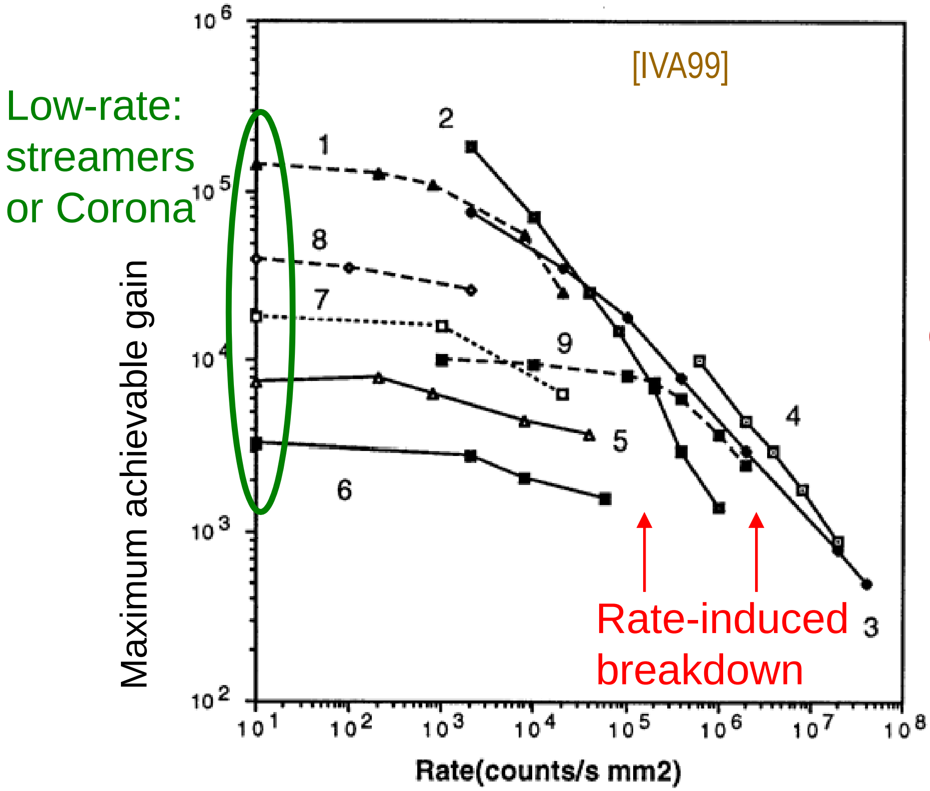


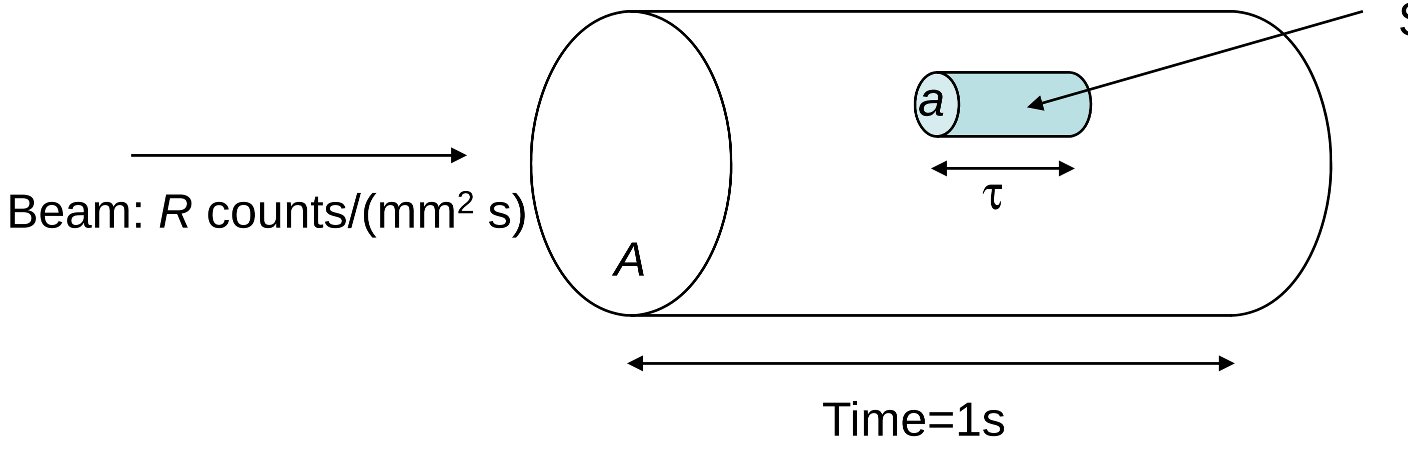
Fig. 1. The maximum achievable gain (curves 1–6), as a function of X-ray flux for various detectors: (1) thick-wire MWPC, (2) PPAC with 3 mm gap, (3) PPAC with 0.6 mm gap, (4) MICROMEGAS (from Ref. [13]), (5) CAT, (6) GEM. (7–9) Space-charge gain limit as a function of rate for other MWPCs: (7) "standard"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

Qualitatively similar data measured by several authors

Can we interpret such plots solely in terms of statistics + Raether limit? (superimposition of avalanches exceeding Raether limit)

Is there a new breakdown mode?

Breakdown statistics via superimposition and Raether limit



For instance:
$A = 1\ cm^2$
$a = 1\ mm^2$
$\tau = 1\ \mu s$ (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 $P(spark)=S\sim10^{-2}$ /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 $\lambda=Ra\tau$: $\lambda=R\times1\times10^{-6}$.

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.

Rate-induced breakdown? – experimental evidence

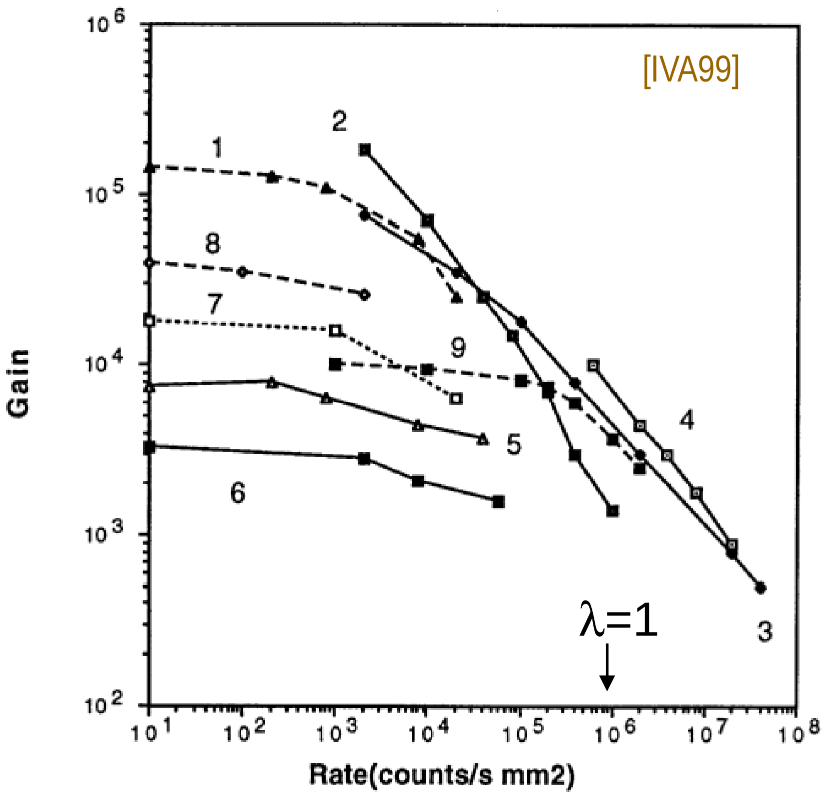
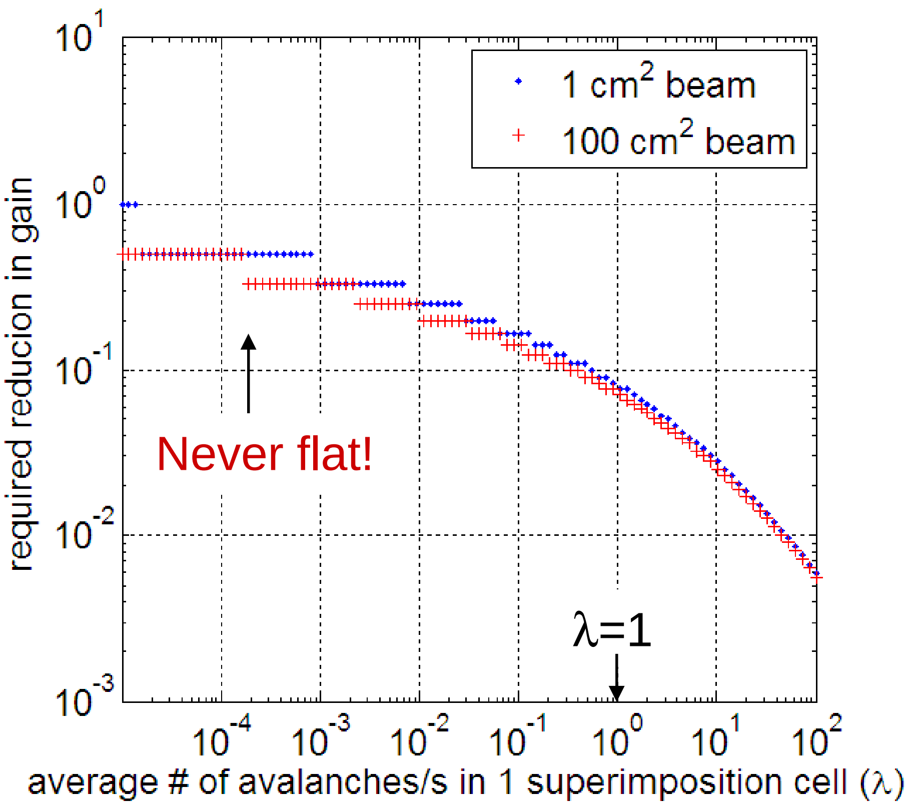


Fig. 1. The maximum achievable gain (curves 1–6), as a function of X-ray flux for various detectors: (1) thick-wire MWPC, (2) PPAC with 3 mm gap, (3) PPAC with 0.6 mm gap, (4) MICROMEGAS (from Ref. [13]), (5) CAT, (6) GEM. (7–9) Space-charge gain limit as a function of rate for other MWPCs: (7) "standard"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

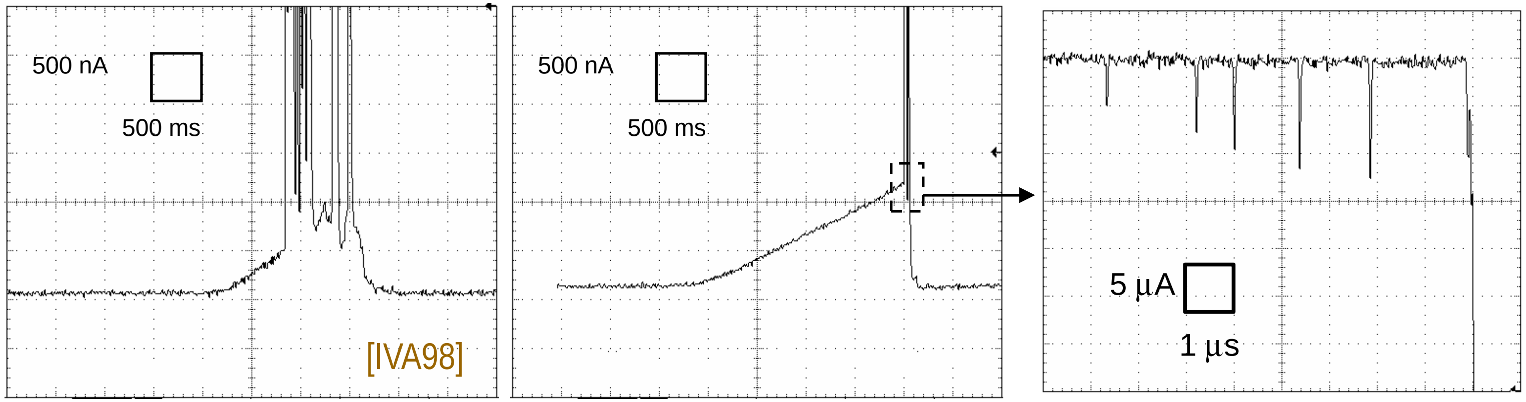


Mere statistics seem to qualitatively reproduce the data!

BUT…

Rate-induced breakdown? – spurious pulses

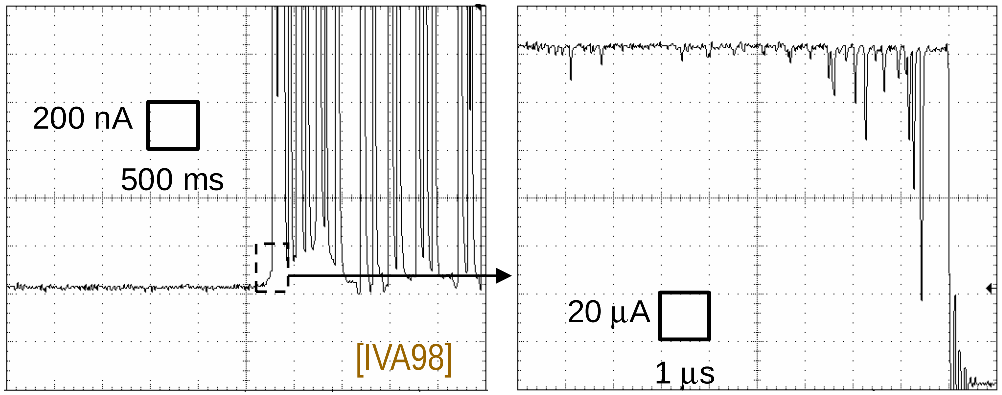
PPAC - high rate, low gain – *single sparks*



PPAC - medium rate - higher gain

continuous sparking regime

+ memory effect (cannot reach same gain for hours)



afterpulses after irradiation

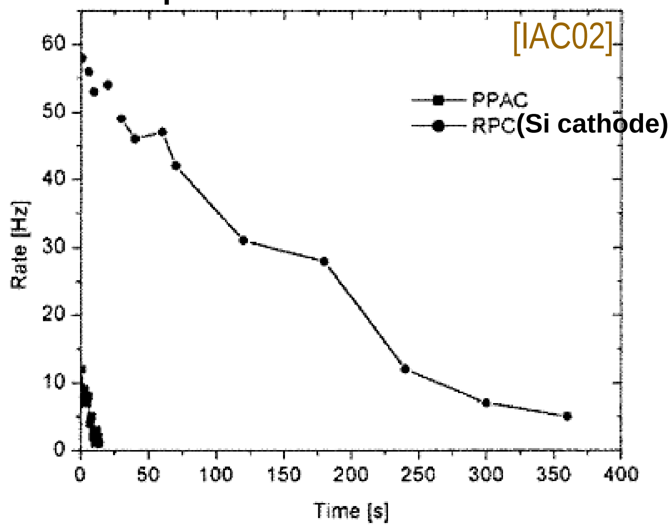
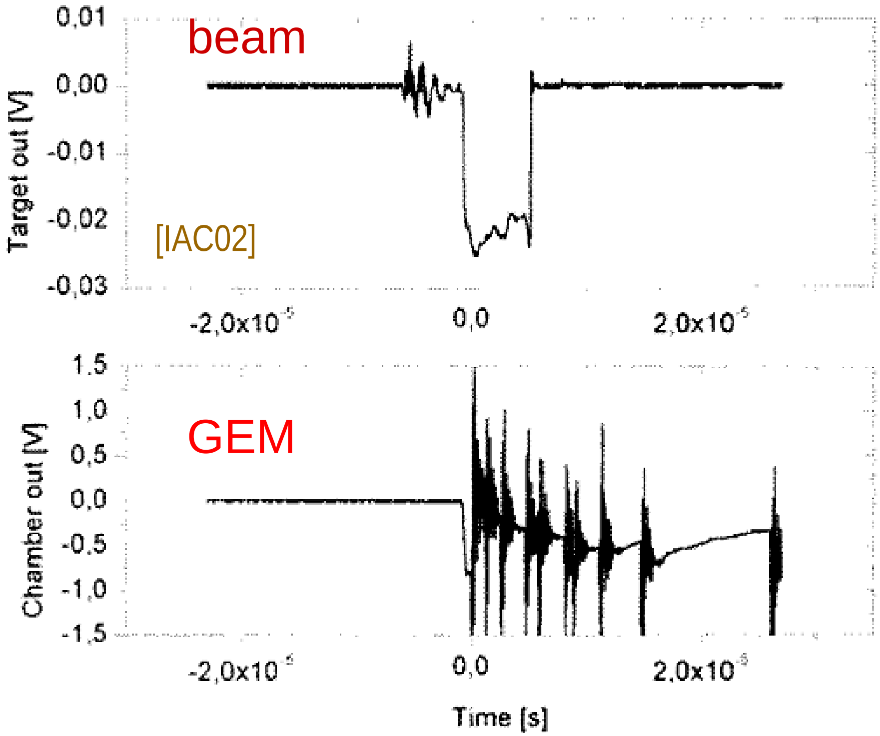


Fig. 11. The rate of the afterpulses for the PPAC (Cu-electrodes) and the RPC (Si). Gas mixture Xe (20%)+Kr (40%)+CO_2 (20%) at 1 atm.

Rate-induced breakdown? – spurious pulses



Rate-induced breakdown? – possible physical origin

Peskov's "cathode jets"

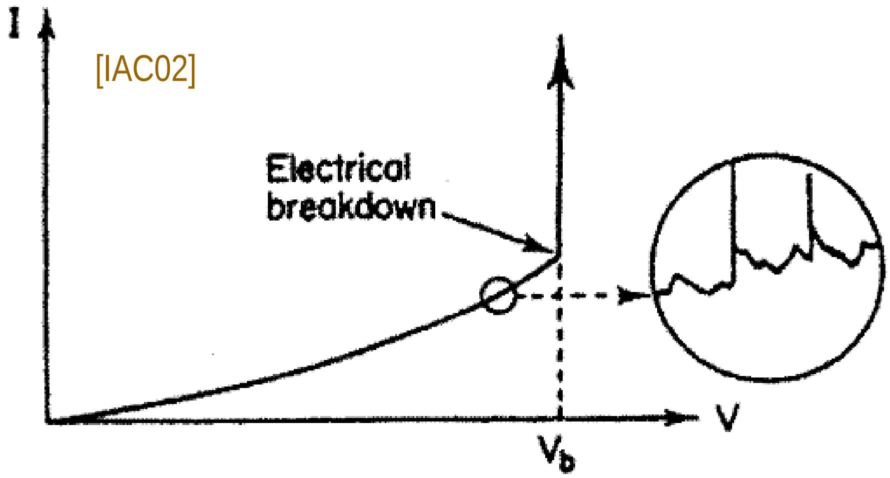


Fig. 14. Current–voltage curve in the case of electrical breakdown in vacuum (from [17]). Enlargement shows pulses due to the explosive field emission.

Explosive field emission from dielectric insertions in the metal.
Similar to the vacuum breakdown phenomenon.

Streamer calculation strategies: continuous approach

Charge transport

good reference: [DAV73]

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

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

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

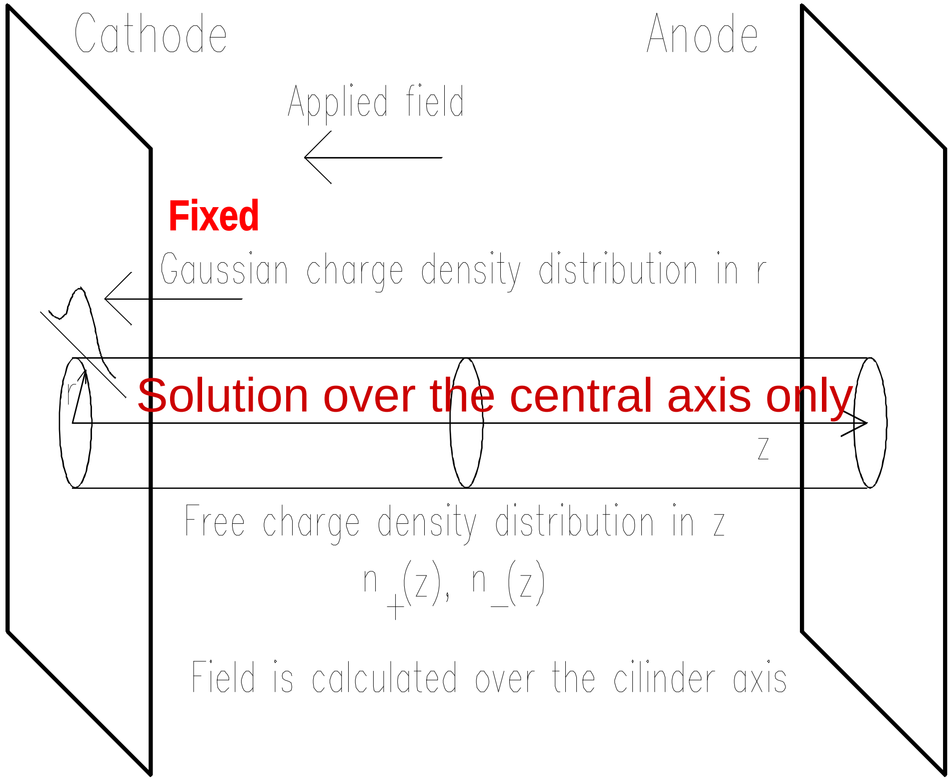
λ = photon's mean free path

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

All this for each relevant emission wavelength…

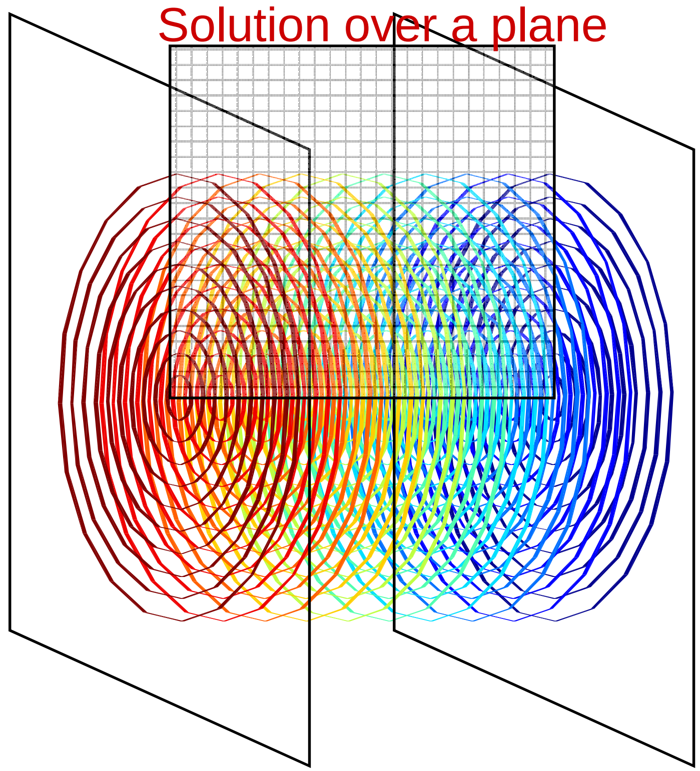
Some simplification from symmetry

The minimum model: “1.5D” (discs)



Started by Davies et al. in the 60’s

Much better: “2D” (rings=axial simetry)



Unfortunately, still a bit artificial for many detectors.

Numerical strategies for continuous approach

Method of “characteristics”

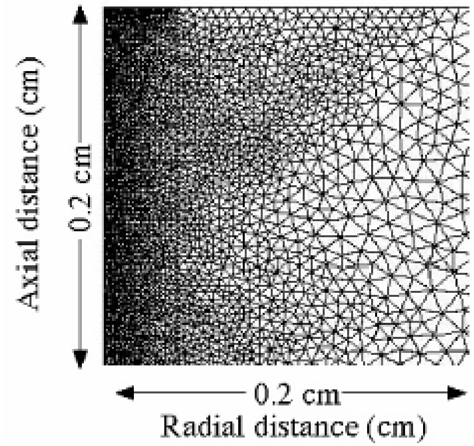
Integrate the equations along “characteristic lines” that correspond to the path of the charges

Equations become a set of uncoupled ordinary differential equations and analytical solution exists for non-space charge regime.

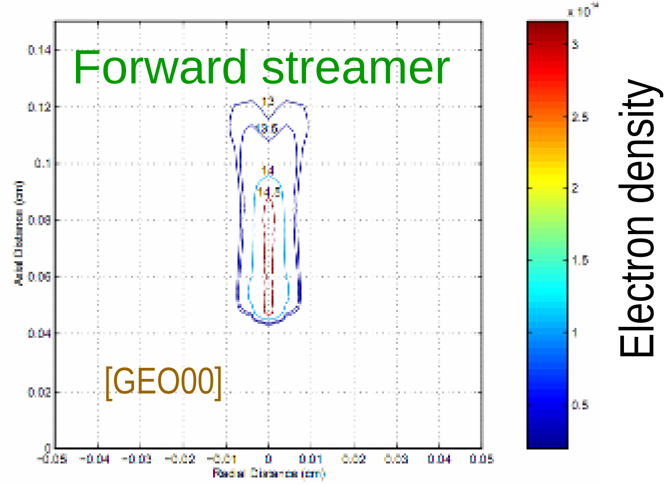
For space-charge regime: small time steps and recalculate the field at each step

Finite elements

Solve the differential equations on the vertices of a mesh.



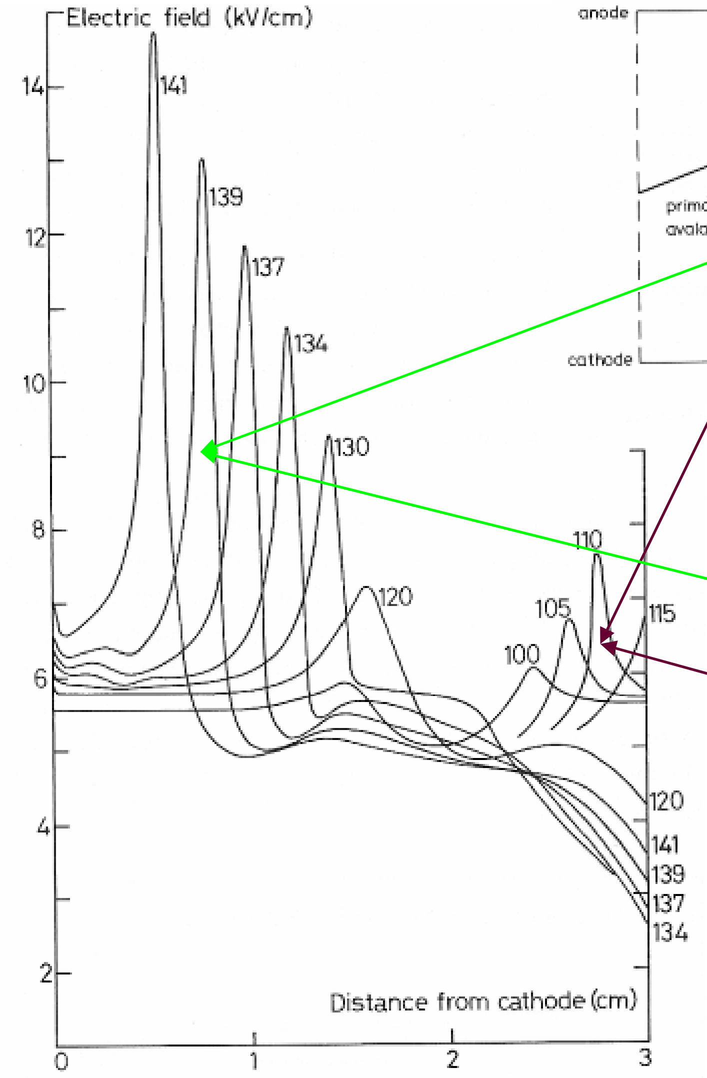
“2D”
axial symmetry



Promising!

Streamer (a&c) simulation in spark chamber

[DAV73]



Electric field at various times corresponding to the curves

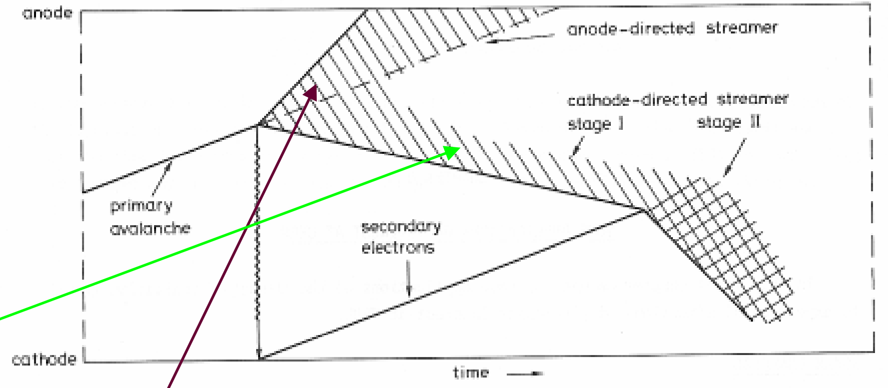


Fig. V.1 Wagner's interpretation of a typical streak photograph.

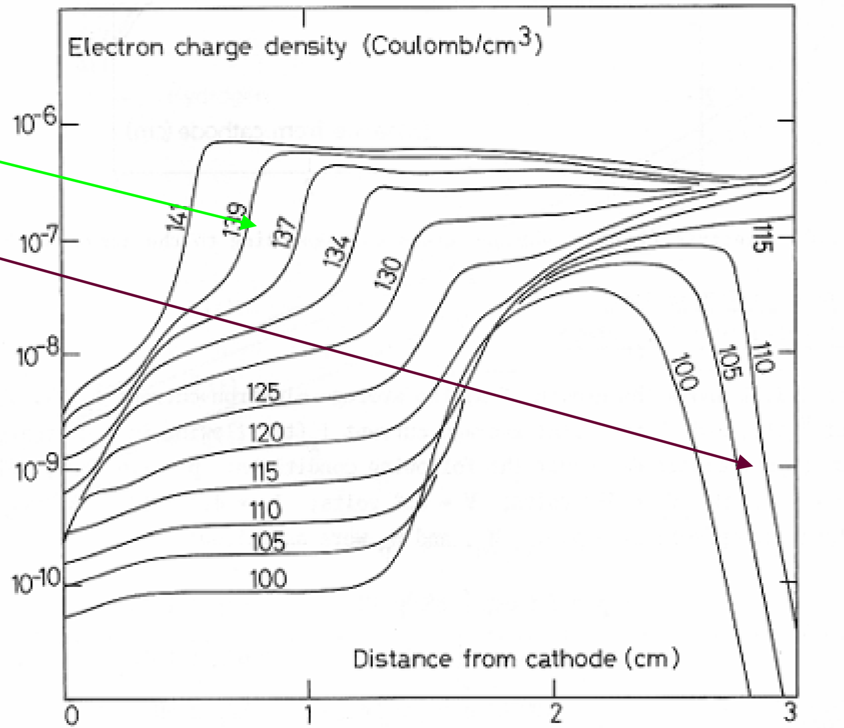
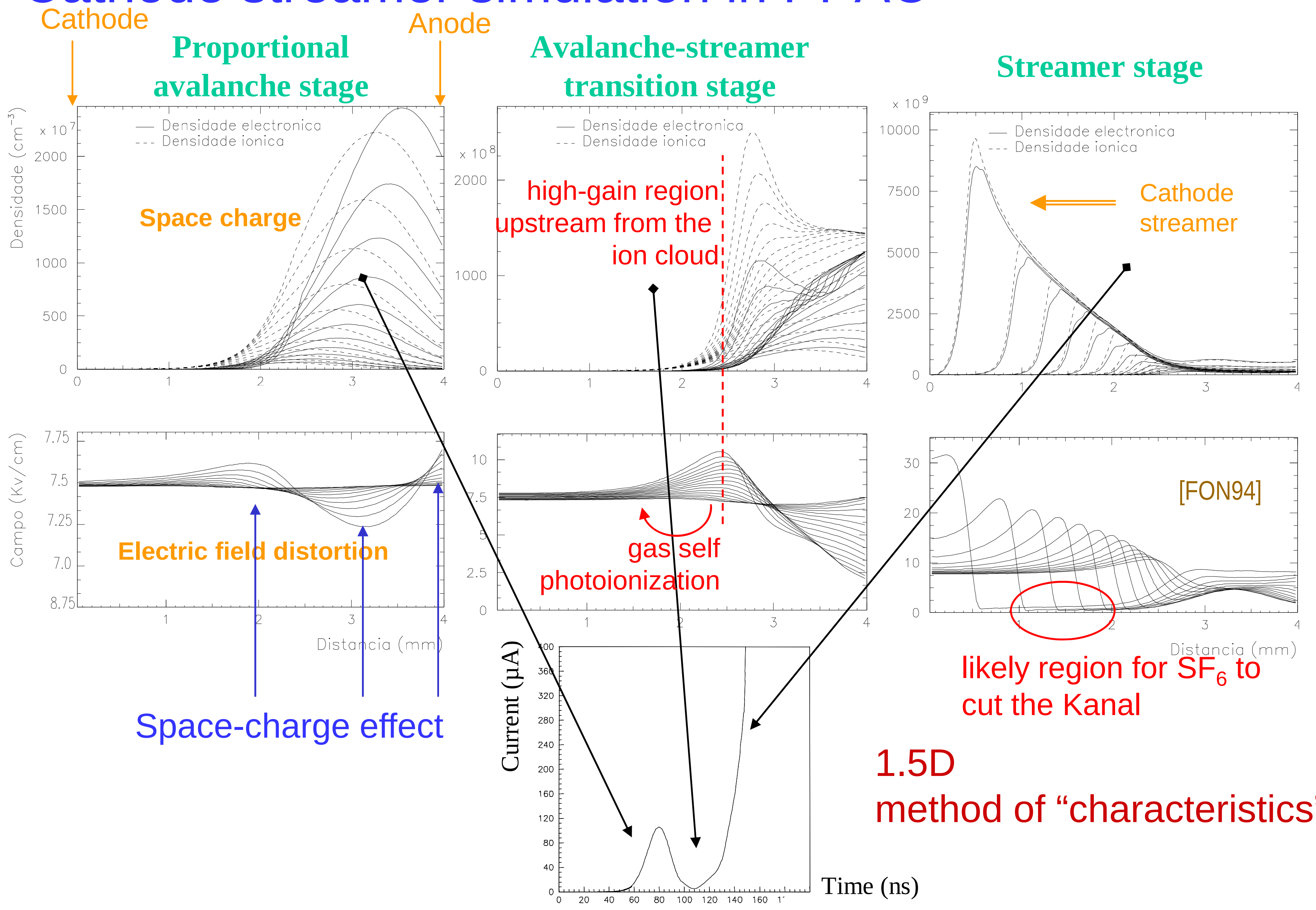


Fig. III.9 The development of a discharge allowing for the distortion of the field. The time in nanoseconds is indicated on the curves.

1.5D, method of “characteristics”

Cathode streamer simulation in PPAC



1.5D
method of "characteristics"

Cathode streamer simulation in PPAC

Cathode　　　Anode

Proportional avalanche stage　　**Avalanche-streamer transition stage**　　**Streamer stage**

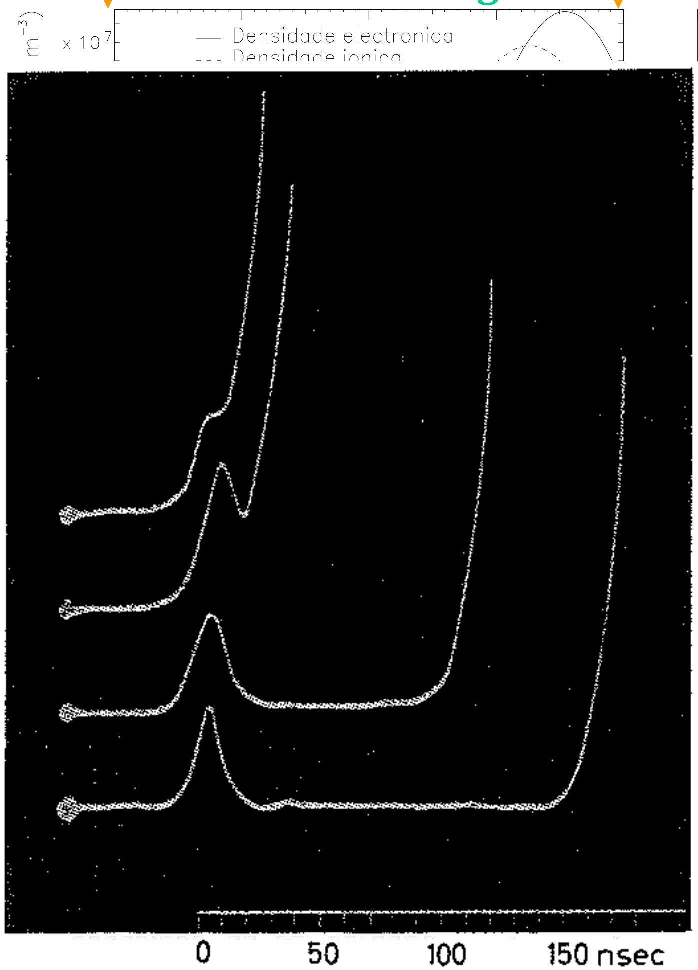
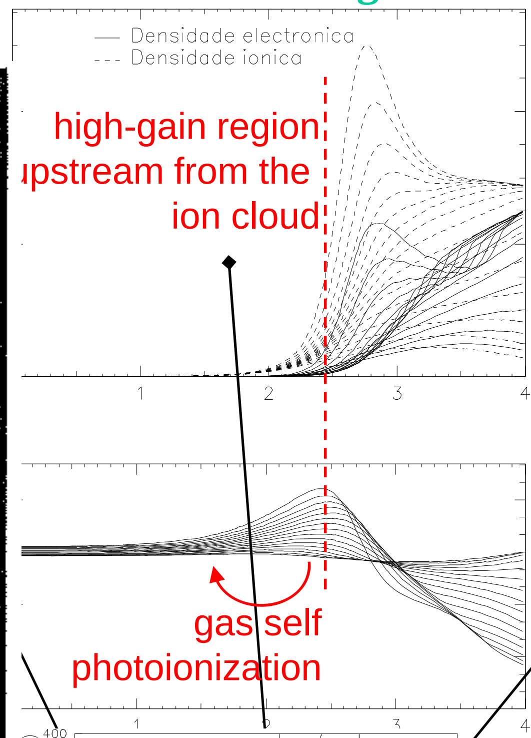
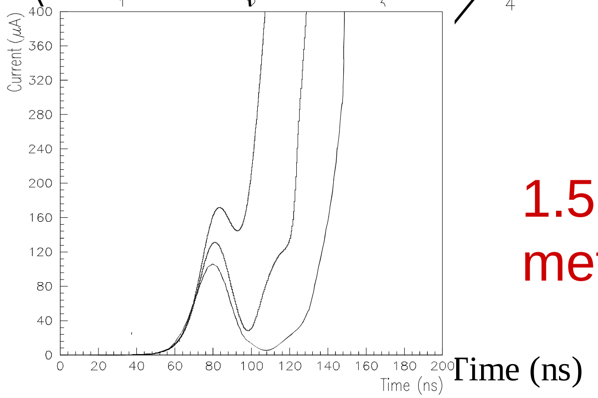
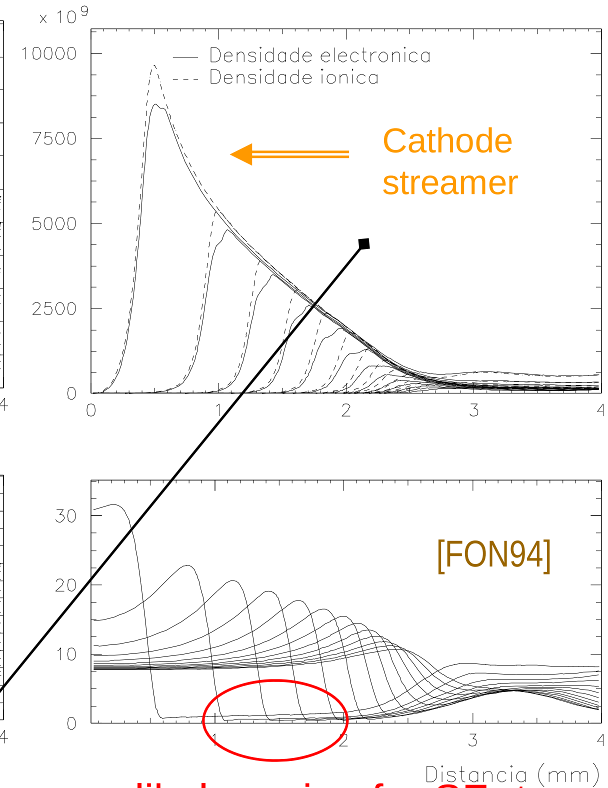


Figure 5.14. Current oscillograms of static breakdown in methylal. Optical method. $E/p = 64{\cdot}4$, $pd = 230$ Torr cm, $d = 0{\cdot}8$ cm, $T_{-} = 90$ nsec $RC = 5$ nsec[36]







likely region for SF_6 to cut the Kanal

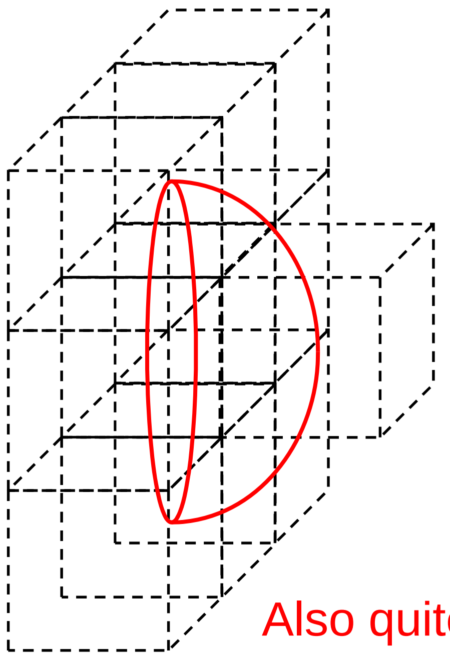
1.5D
method of "characteristics"

Another approach: particle-in-cell

A "mesoscopic" MonteCarlo where mini-avalanches are propagated from cell-to-cell in a mesh.

Symmetries can be also applied.

Incorporates naturally avalanche statistics.



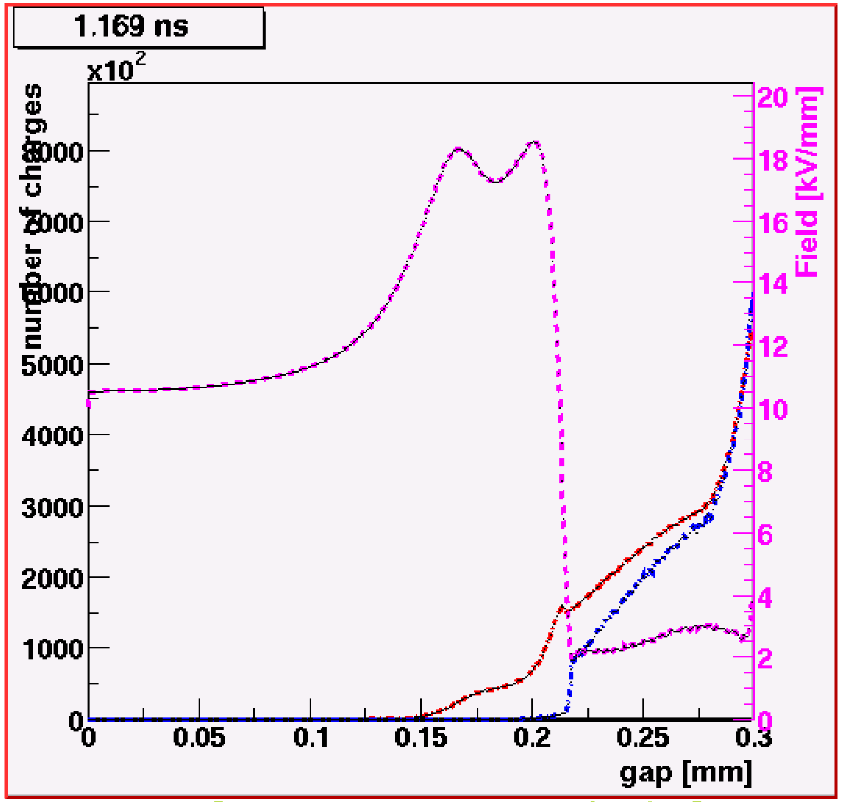
[LIP04]

1.5D approximation

0.3mm timing RPC, 3kV

Space-charge only
no cathode streamer

electrons, positive ions, negative ions, field



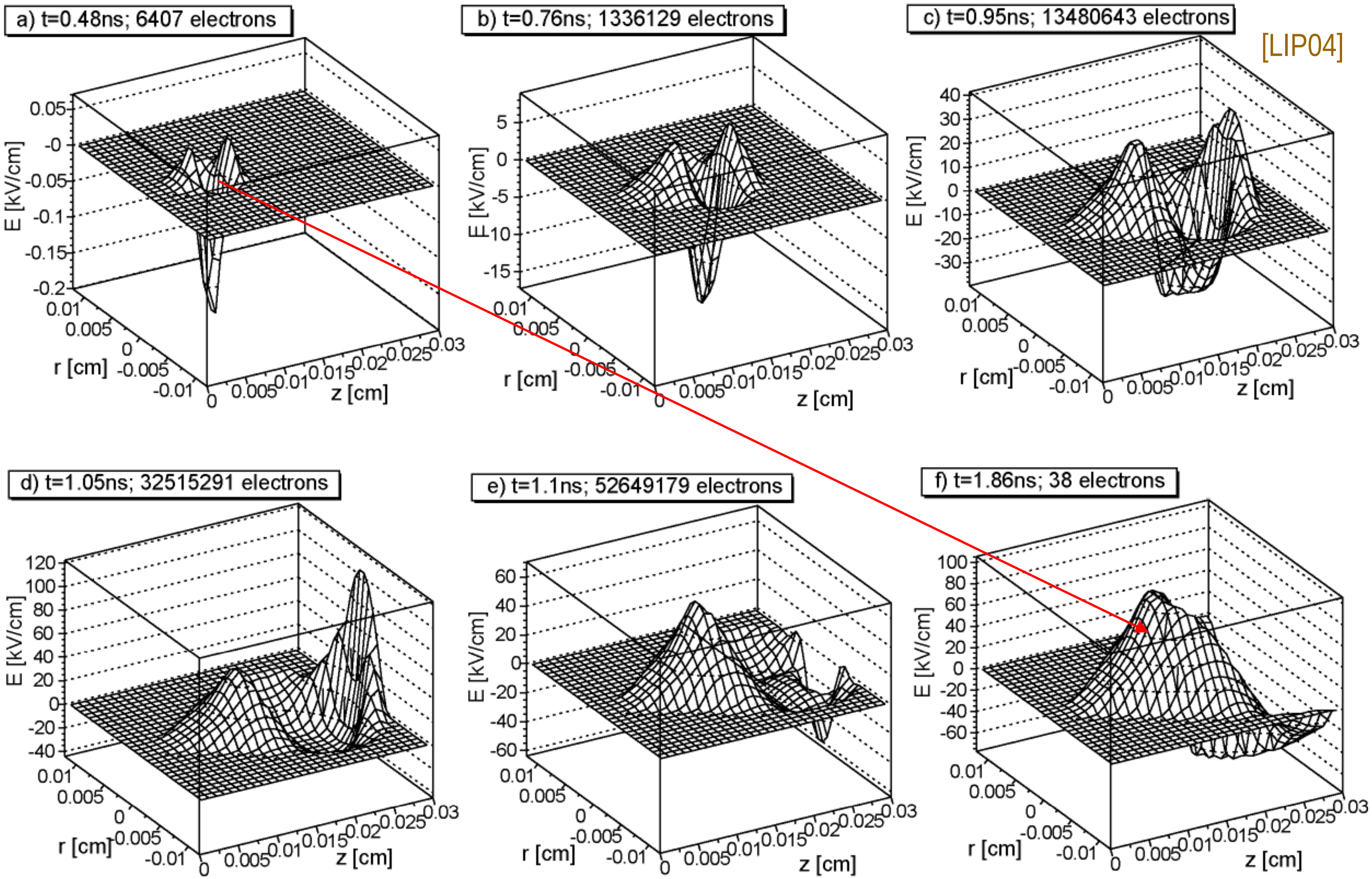
[Courtesy Werner Riegler]

Also quite formidable: huge number of cells.
3D prohibitive

2D particle-in-cell simulation

Electric field in a single electron avalanche, 0.3mm timing RPC, 2.8kV

Space-charge only
no cathode streamer



Strong widening of the electron cloud.

Discharge stages

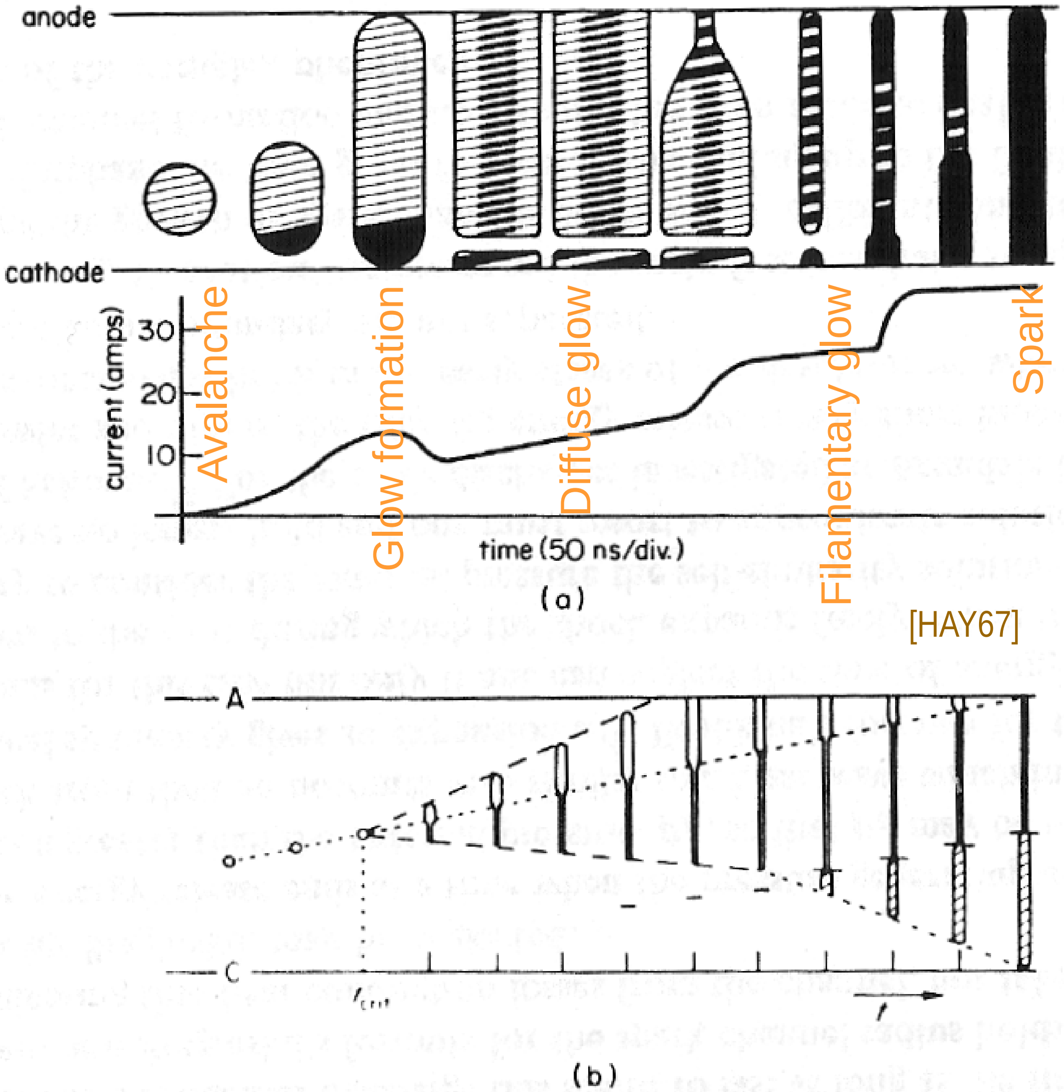


Figure 22. **Schematic representations of main features of spark channel development (a) at low percentage overvoltage, (b) at high percentage overvoltage.**

Slow breakdown: many stages

(very) Fast breakdown: spark grows directly from the anode & cathode streamers

Detectors not quite any of these (GEM maybe excepted)

Discharge from cathode streamer

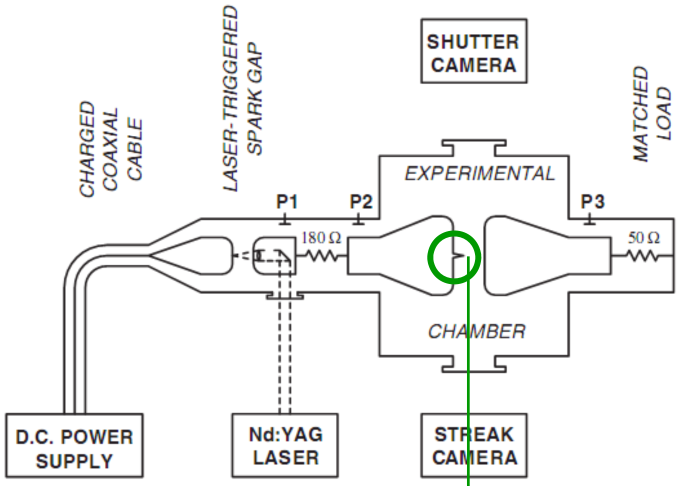
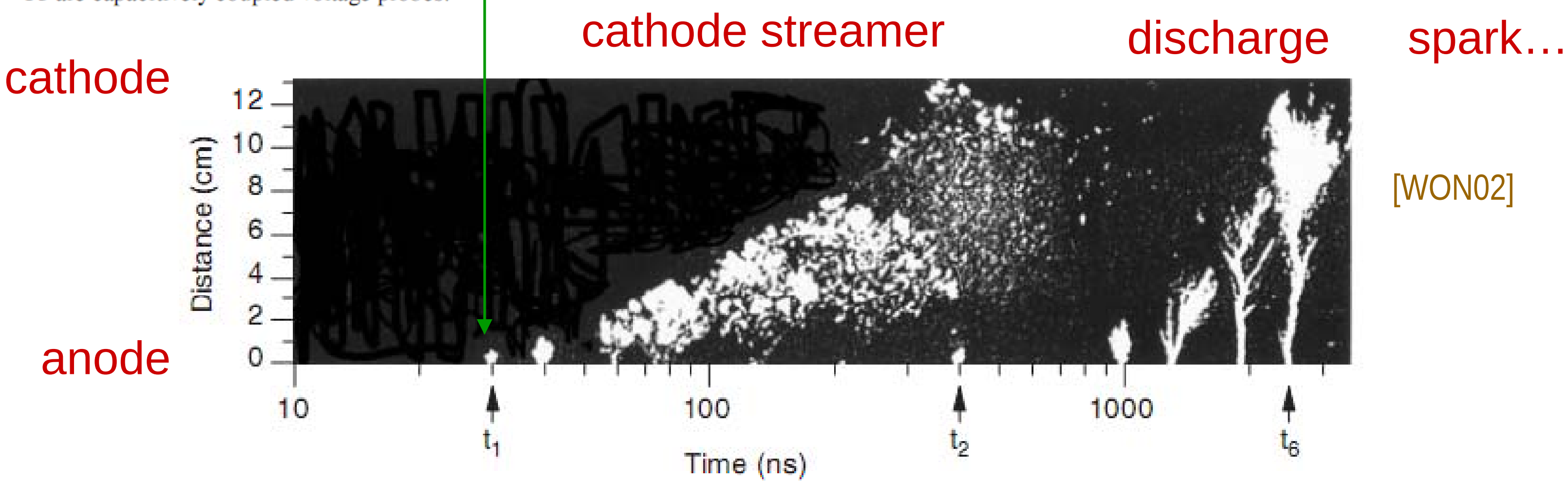


Figure 1. Schematic diagram of the experimental setup. P1, P2, and P3 are capacitively coupled voltage probes.

Process may be stopped by external current limitation.

Resistive electrodes or very small electrode segments with individual resistors



[WON02]

Figure 13. Typical sequence of shutter photographs of the cathode-directed streamer in point-plane gap, and fill gas pure N_2, at atmospheric pressure. The shutter was open for 10 ns. The point extended 0.9 cm into the gap, the distance from the tip of the point to the opposite electrode was 13.4 cm. The voltage was 98 kV with 20 ns risetime. (From Dale, fig 5.39 in [33].)

Summary

My view, not a review.

- What causes breakdown
  - Imperfections (sharp edges, etc) ⇒ Corona discharge.
  - In photosensitive detectors: photon feedback.
  - At low rate mainly the space-charge ("Raether") limit ⇒ streamers
    - by its physical origin, it must depend on
      - specific geometry of the detector (lower for denser avalanches)
      - avalanche statistics (lower for low n_0)
      - number of amplification steps (spreading the charge around)
  - At high rate: maybe ion-bombardment induced electron jets from cathodes, maybe merely superimposition statistics+Raether limit

- Streamer physics and simulation
  - Subject is pursued since the 60's.
  - Several methods and simplification strategies were devised.
  - There is a good understanding of the process.
  - Some doubts persist about the cathode-streamer feedback mechanism
  - Full 3D solutions still missing.

- The discharge (final breakdown stages)
  - Well studied. (Interesting for electrical engineering.)
  - Likely, suppression only by external current limitation.

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