Detector Physics of Resistive Plate Chambers

Christian Lippmann

Work in collaboration with Werner Riegler (CERN)

- ***Introduction***
- ***Simulation of RPCs***
  - ***Time Resolution***
  - ***Efficiency***
  - ***Charge Spectra***
  - ***Detailed 2-D simulations of single avalanches***
  - ***Rate effects***
- ***Summary***

Over the last years we have published several articles on RPC detector physics:

[0] Rate Effects in Resistive Plate Chambers,
Conference proceedings, RPC2005, Seoul, C. Lippmann, W. Riegler and A. Kalweit

[1] Detailed RPC Avalanche Simulations,
NIM A 533 (2004) 11-15, C. Lippmann and W. Riegler

[2] The Physics of Resistive Plate Chambers,
NIM A 518 (2004) 86-90, W. Riegler and C. Lippmann

[3] Space Charge Effects in Resistive Plate Chambers,
CERN-EP/2003-026, accepted for publication in NIM A, C. Lippmann, W. Riegler

[4] Detector Physics of RPCs,
Doctoral Thesis, C. Lippmann, May 2003 (CERN, University of Frankfurt)

[5] Detector Physics and Simulation of Resistive Plate Chambers,
NIM A 500 (2003) 144-162, W. Riegler, C. Lippmann, R. Veenhof

[6] Induced Signals in Resistive Plate Chambers,
NIM A 491 (2002) 258-271, W. Riegler

[7] Signal Propagation, Termination, Crosstalk and Losses in Resistive Plate Chambers,
NIM A 481 (2002) 130-143, W. Riegler, D. Burgarth

[8] Detector Physics of Resistive Plate Chambers,
Proceedings of IEEE NSS/MIC (2002), C. Lippmann, W. Riegler

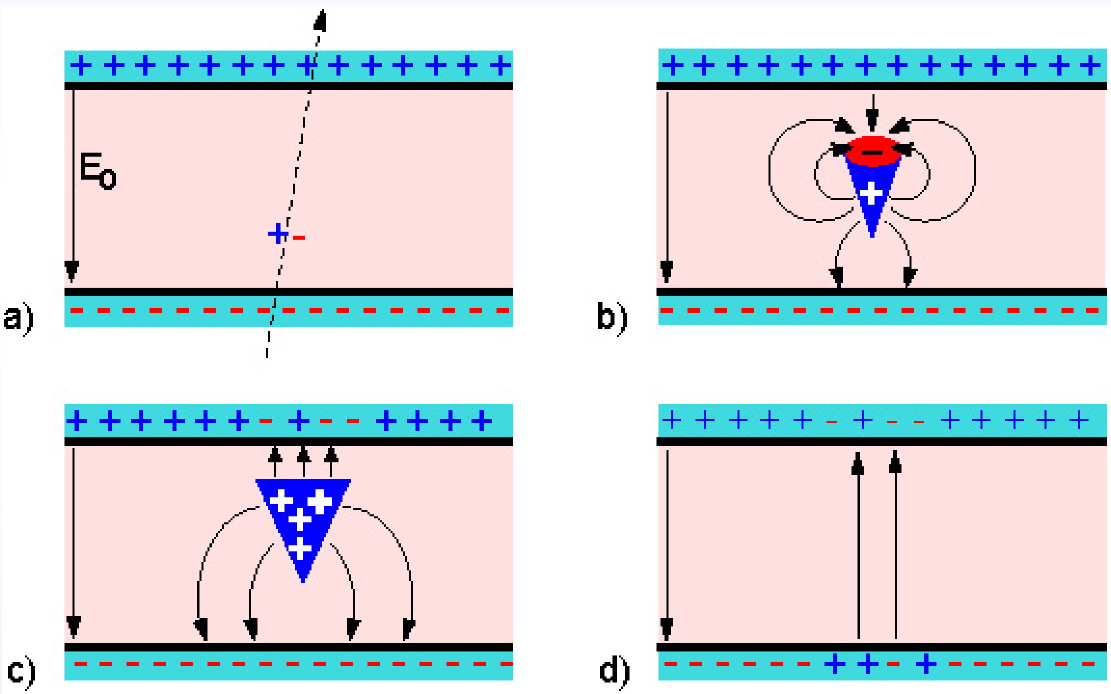
[9] Static Electric Fields in an Infinite Plane Condenser with One or Three Homogeneous Layers,
NIM A 489 (2002) 439-443, CERN-OPEN-2001-074, T. Heubrandtner, B. Schnizer, C. Lippmann, W. Riegler

Only some of this material is covered in this talk!

Introduction

RPCs

R. Santonico, R. Cardarelli, NIM 187 (1981) 377, NIM A 263 (1988) 20



a) **ionisation**

b) **Avalanche (space charge effects!)**

c) **Slow ion drift (in RPCs electrons induce the signal!)**

d) **Charge sticks in resistive plates after avalanche (rate effects!)**

time constant: $\tau = \rho\, \varepsilon_0\, \varepsilon_r$

ρ = Volume resistivity

ε_0 = Dielektr. constant

ε_r = rel. permittivity

Working Modes

1) Avalanche mode
2) Streamer mode: photons contribute to the avalanche development
3) Sparks: A conductive vhannel is formed, the electrodes are discharged (Pestov counter)

Why Resistive Electrodes?

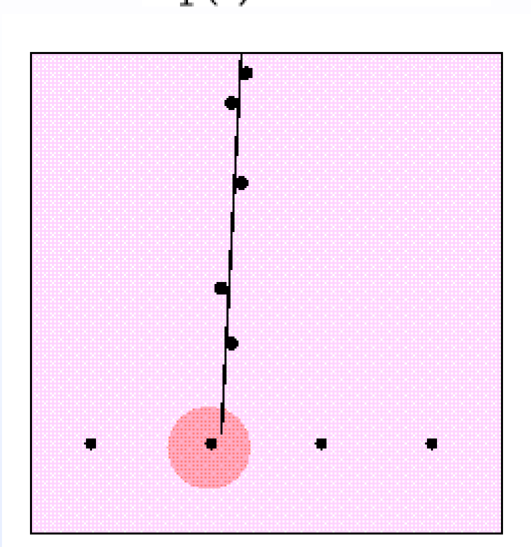
- In Parallel Plate Avalanche Chambers (2 parallel metal electrodes) sparks lead to the discharge of whole detector (**breakdown**):
  - Can destroy electronics
  - Recharging needs time $\Rightarrow$ deadtime

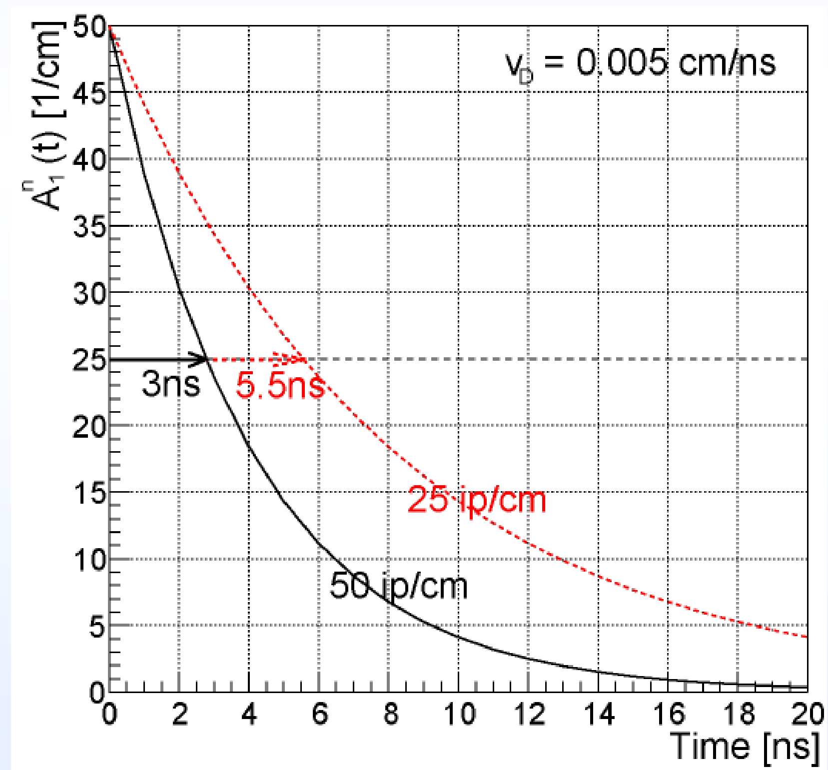
Reminder: Time Resolution of Wire Chambers

- Limited time resolution of Wire and Micropattern Chambers (GEM, …)
- Space distribution of the cluster closest to anode:
  - Exponential distribution

$$A_1^n(x) = ne^{-nx}$$

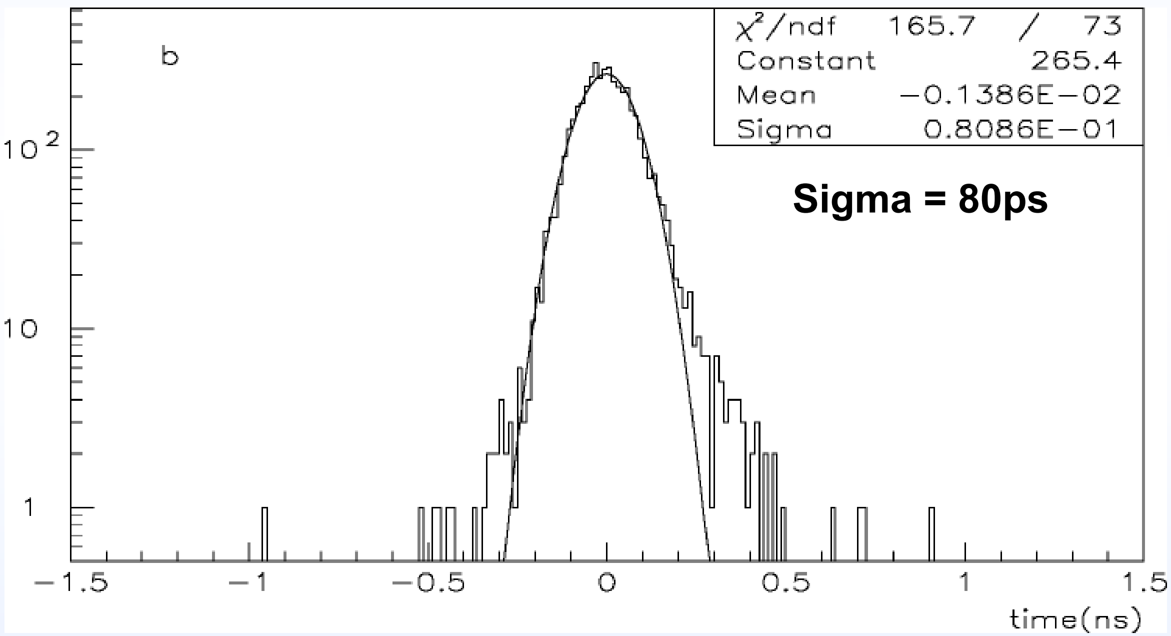
- Drift time distribution of that cluster: $A_1^n(t) = ne^{-nv_D t}$





Time Resolution of RPCs

- Compared to Wire Chambers RPCs reach much better time resolutions because the avalanche growth starts instantly
- Fast signal induction during avalanche development



V. Ammosov et al, Four-gap glass RPC as a candidate to a large area thin time-of-flight detector, CERN, 2002, http://harp.web.cern.ch/harp/

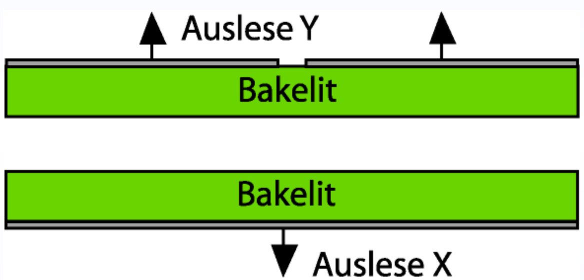
Existing RPC technologies

Trigger RPCs and Timing RPCs

Three different configurations

Trigger RPC

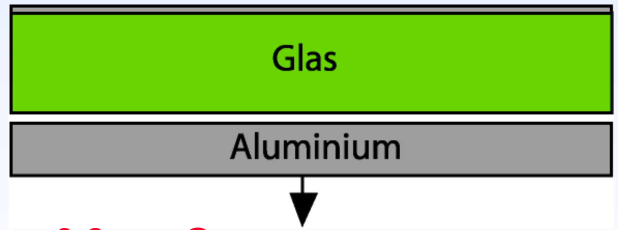
R. Santonico, R. Cardarelli



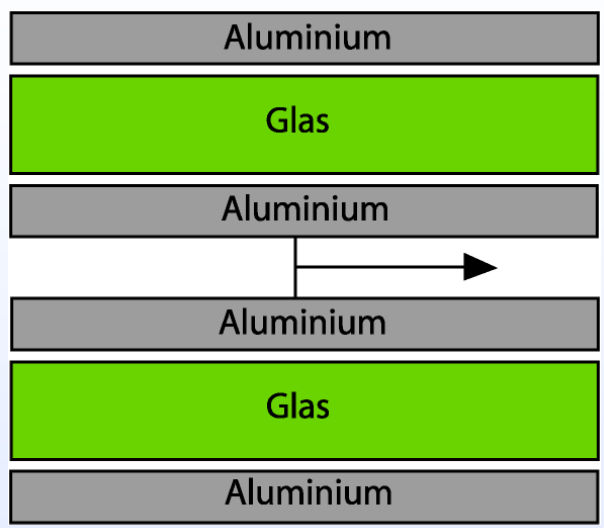
- **2mm Gas gaps**
- **Resistive material: 2mm Bakelite, $\rho \approx 10^{10}\ \Omega$cm**
- **$C_2F_4H_2$/ i-C_4H_{10}/ SF_6 (96.7/3/0.3)**
- **HV: 10kV $\Rightarrow$ E: $\approx$50kV/cm**

Timing RPC

P. Fonte, V. Peskov et al.

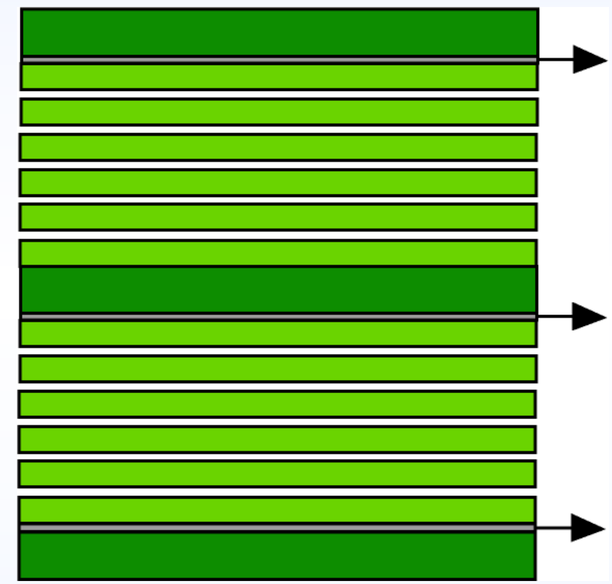


- **0.3mm Gas gaps**
- **Resistive material: 3mm glas, $\rho \approx 2\text{x}10^{12}\ \Omega$cm**
- **2mm Aluminium**
- **$C_2F_4H_2$/ i-C_4H_{10}/ SF_6 (85/5/10)**
- **HV: 3(6)kV $\Rightarrow$ E: $\approx$100kV/cm**



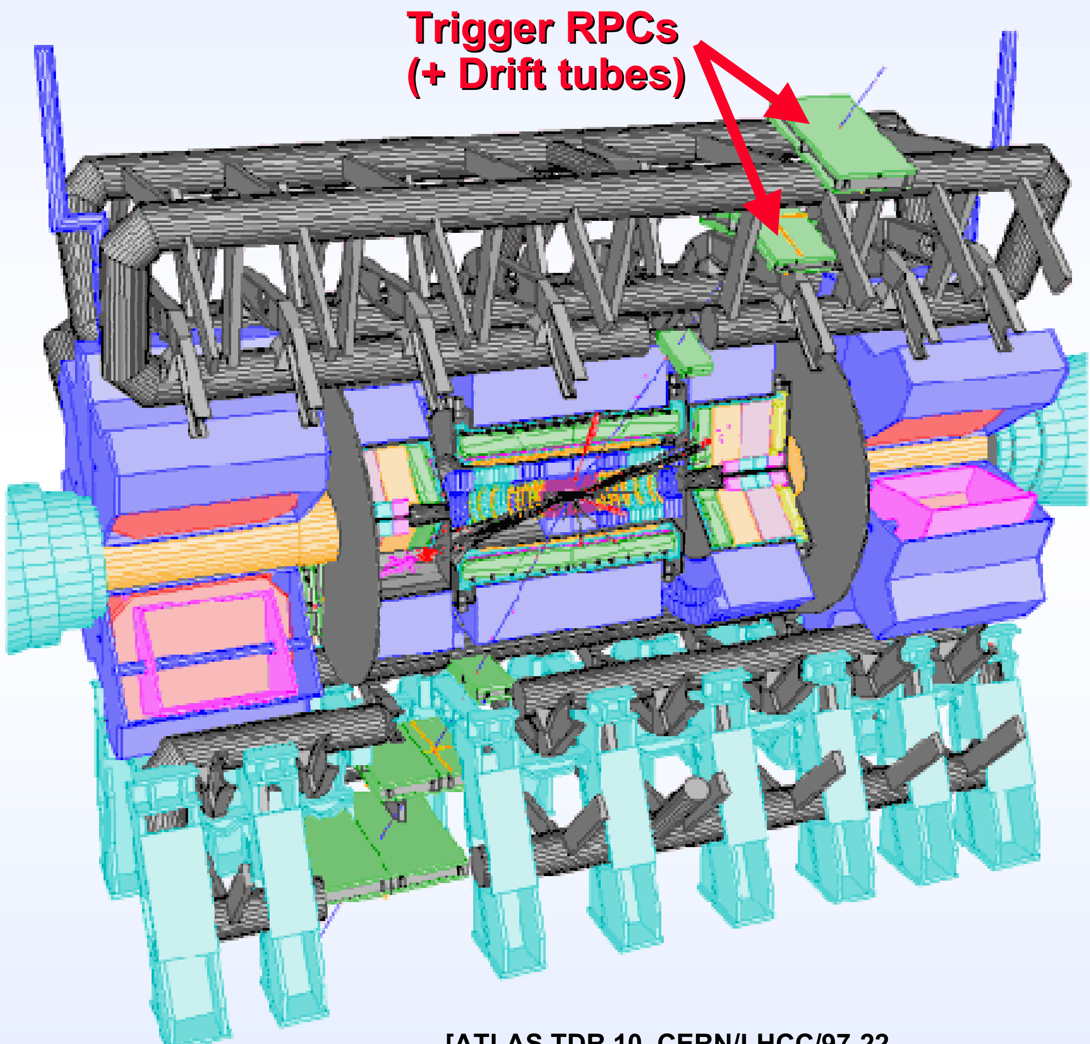
Multi Gap Timing RPC

M.C.S. Williams et al.



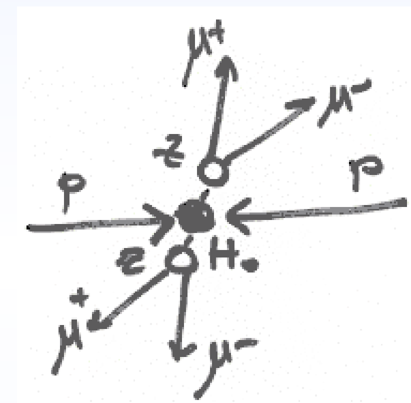
- **0.25mm Gas gaps**
- **Resistive material: 0.4mm Glas, $\rho \approx 10^{13}\ \Omega$cm**
- **$C_2F_4H_2$/ i-C_4H_{10}/ SF_6 (90/5/5)**
- **HV: 12.5kV $\Rightarrow$ E: $\approx$100kV/cm**

An Experiment with Trigger RPCs: ATLAS at CERN



[ATLAS TDR 10, CERN/LHCC/97-22,
http://atlas.web.cern.ch/Atlas/Welcome.html]

- p-p collisions at 14TeV,
- Search for Higgs particle H_0:



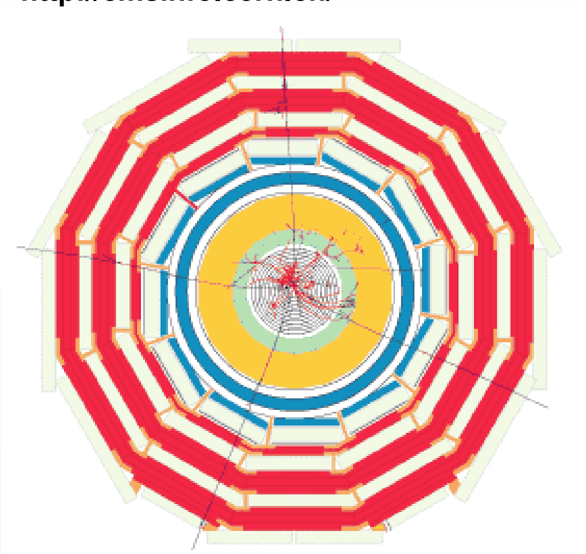
- **Trigger RPCs** in muon system
  - Avalanche mode
  - Area: 3650m^2
  - 355.000 channels
  - Efficiency: >95%
  - Time resolution: <3ns
  - Rate capability: bis 1kHz/cm^2

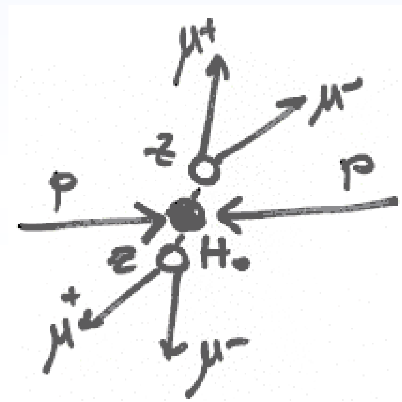
An Experiment with Trigger RPCs: CMS at CERN

- CMS (Compact Muon Solenoid)
- Similar to ATLAS
- Area: 3100m^2

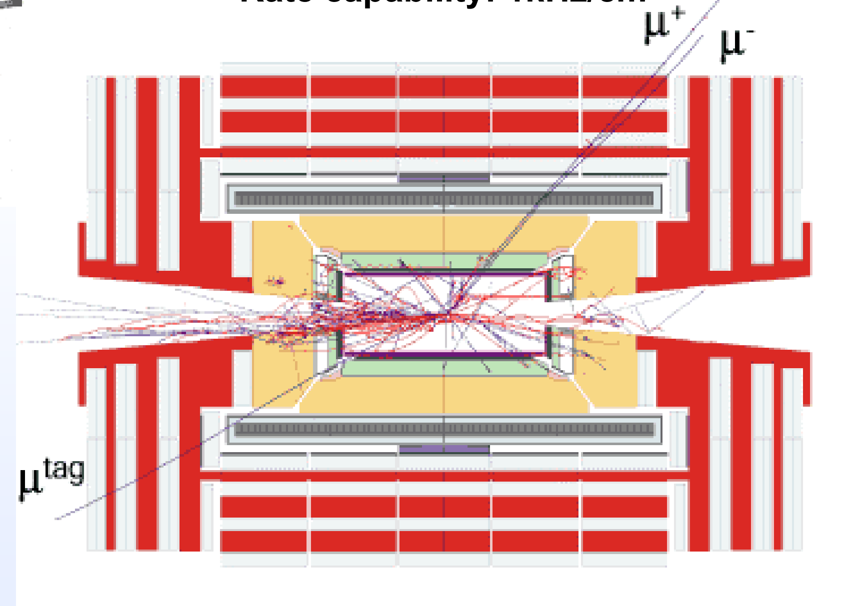
CMS TDR 3, CERN/LHCC 97-32

http://cmsinfo.cern.ch/

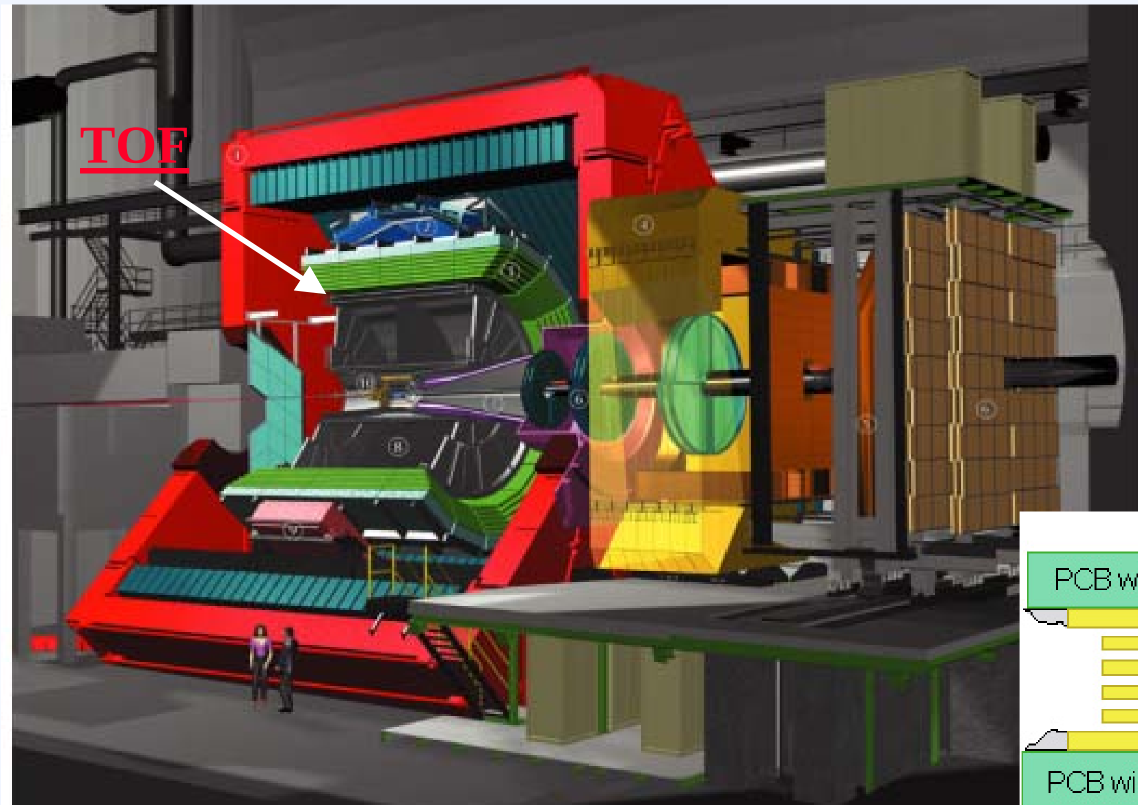




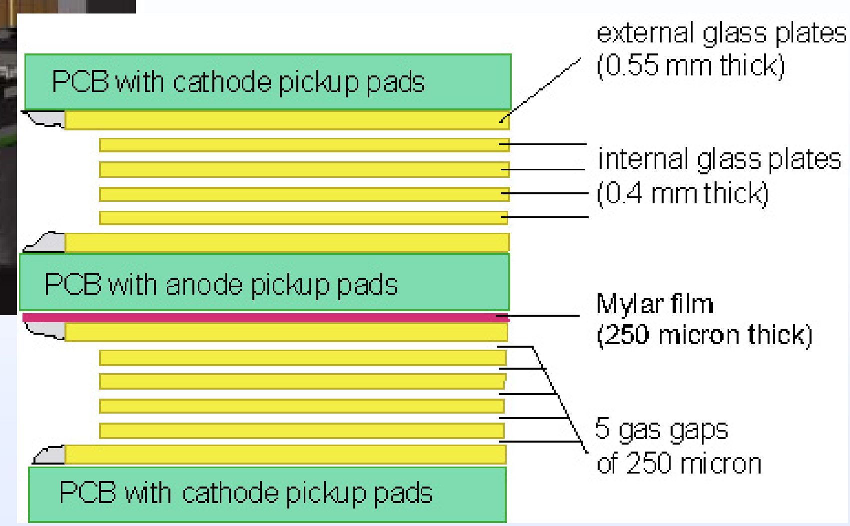
- They also use **Trigger RPCs**
  - Avalanche mode
  - Bakelite
  - 2mm gaps
  - E ≈ 50kV/cm
  - Gas: Freon + Isobutane
  - Time Resolution < 3ns
  - Efficiency > 95%
  - Rate capability: 1kHz/cm^2



An Experiment with Timing RPCs: ALICE at CERN



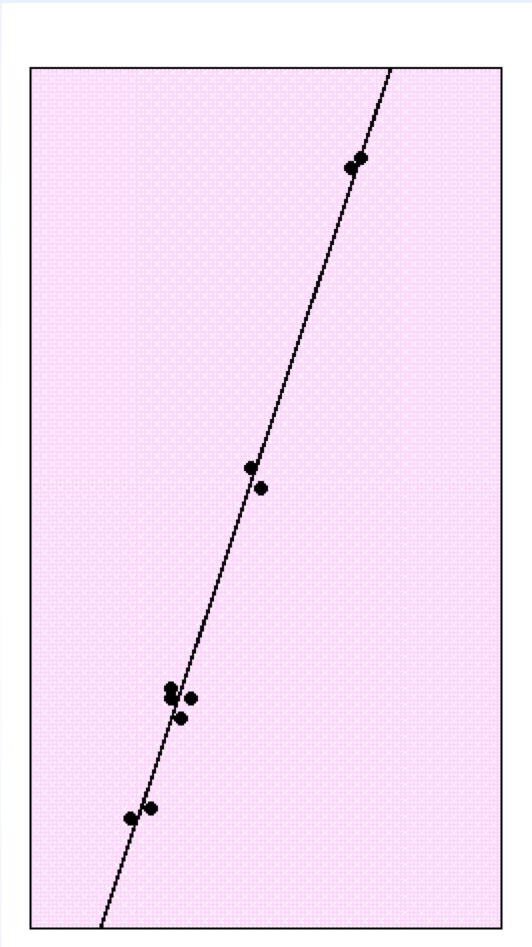
- **Multigap Timing RPCs are used to identify particles (e/π-, π/K-, K/p- Separation) via time-of-flight (TOF)**
  - **Area: 176m^2**
  - **160.000 channels**
  - **efficiency: >98%**
  - **Time resolution: <70ps**
  - **Rate capability: up to 50Hz/cm^2**



[http://alice.web.cern.ch/Alice]

Motivation for our work on RPCs

Important for efficiency: The Primary Ionization



- **Coulomb interactions of charged particles with gas molecules**
- **Mean number of events per cm (HEED):**

Gas	Helium	Argon	Xenon	i-C_4H_{10}
n (events/cm)	4.2	23	44	84

- **Events are Poisson distributed around the mean number n:**

$$P_k^n = \frac{n^k}{k!} e^{\;n}$$

n = average number of events
k = actual number of events

- **Maximum detection efficiency:**

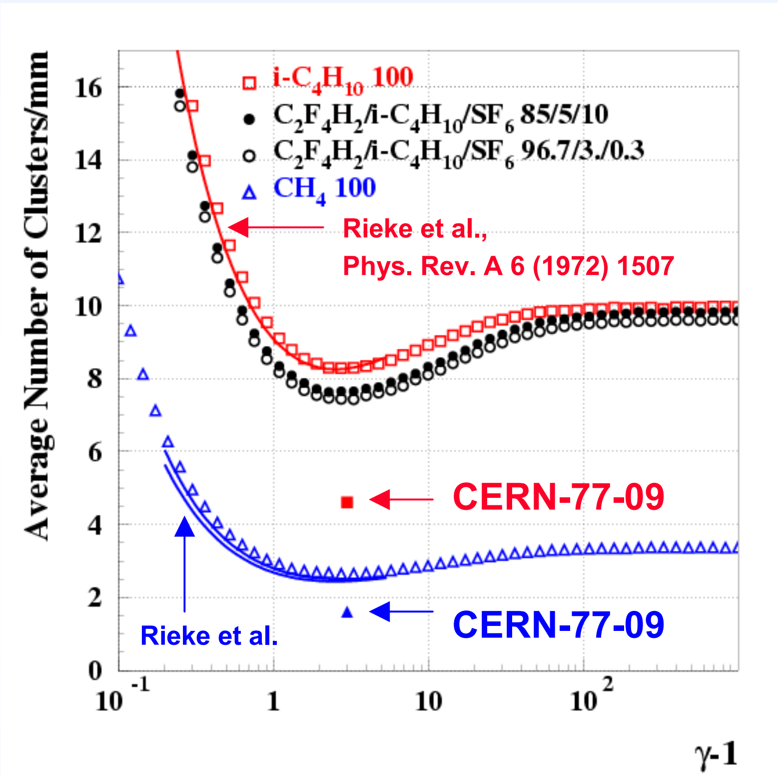
Gas	gap thickness	Eff (%)
Helium	0.3mm	12
	2mm	57
i-C_4H_{10}	0.3mm	92
	2mm	100

$$\text{Eff} = 1 - e^{-n}$$

- **n (events/cm) is very important for efficiency**

http://consult.cern.ch/writeup/garfield/examples/gas/Welcome.html#stat

Primary ionisation parameters (HEED) [5]



- Average number of primary ionisation clusters / mm
- $C_2F_4H_2$ gas:

  For 7GeV pions ($\gamma \approx 50$) we find about 10/mm

Motivation for our work [1-9]

For RPCs with 0.3mm gas gaps filled with pure Isobutane or a $C_2F_4H_2$ mixture one measures ≈75% efficiency.

This needs about 10 primary ionisation clusters per mm and a Townsend coefficient around 100/mm.

An often used value for Isobutane is 5 primary ionisation clusters per mm [SAULI, CERN 77-09] .

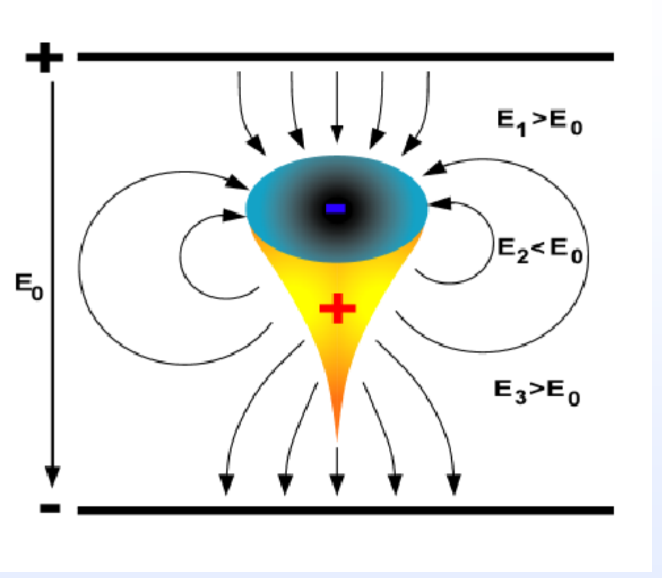
Why are the RPCs efficient then?

Even if 10 clusters/mm and a Townsend coefficient of 100/mm are correct: The expected induced charge would be around 5 x 10^7 pC, while 0.5 pC is measured!

Could a Space charge effect lead to such a charge (gain) suppression?

If there are regions with reduced gain due to space charge, there must also be regions with increased gain. Is stable operation possible? Can the measured average induced charges be explained?

Detailed understanding was nor there, when we started our work.



Simulation of RPCs

Procedure and Results

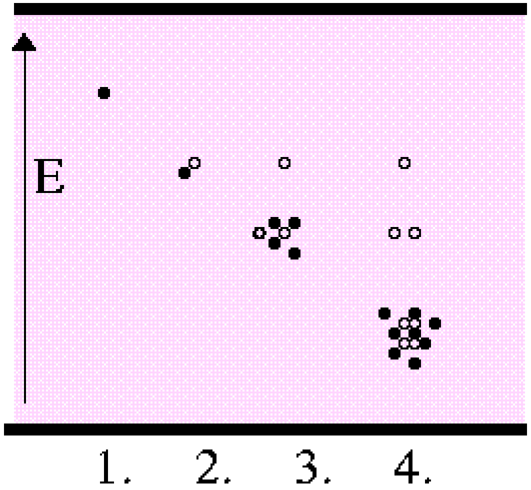
Simulation procedure:
One dimensional simulation [5]

1. The gas gap is divided into several steps.
2. The primary clusters are distributed onto the steps.
3. The charges in the gas gap are multiplied and drifted towards the anode.
4. The induced signal is calculated.
5. Steps 3 – 4 are repeated until all electrons have left the gas gap.

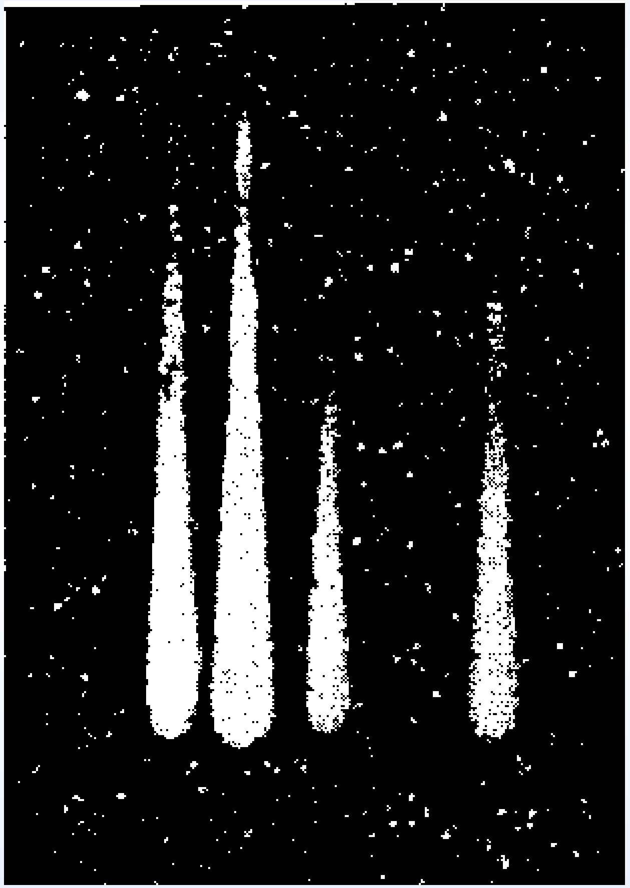
- No Diffusion
- No Space Charge Effect
- No Photons

1.5D Simulation

Average avalanche multiplication in an uniform field



- **Combined Cloud Chamber – Avalanche Chamber:**



H. Raether, Electron avalanches and breakdown in gases, Butterworth 1964

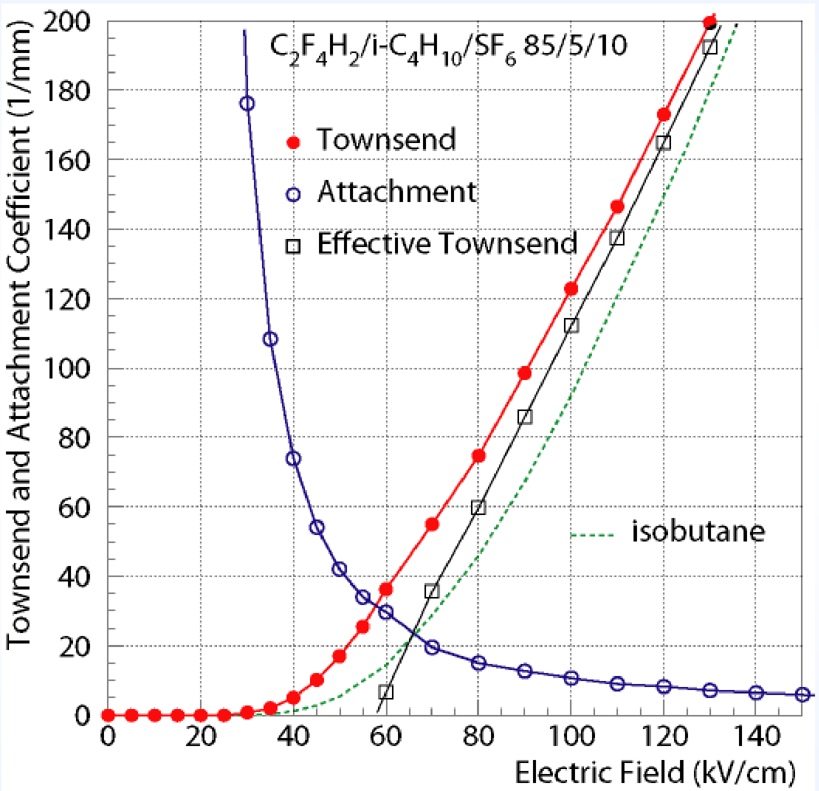
α = Townsend Coefficient
η = Attachment Coefficient

$$dn = [\alpha - \eta]\, n\, dx \quad \Rightarrow \quad \overline{n}(x) = n_0 e^{(\alpha-\eta)x}$$

But: $\alpha = \alpha(E) \qquad \eta = \eta(E)$

E constant? Space Charge Fields?

Gas parameters (IMONTE) [5]



- **Effektive Townsend Coefficient for Timing RPC:**
  ≈ 110/mm

Avalanche fluctuations [5]

[W. Legler, 1960: Die Statistik der Elektronenlawinen in elektronegativen Gasen bei hohen Feldstärken und bei grosser Gasverstärkung]

Assumption: Probability to ionise does not depend on last ionisation

$$\frac{dP(n,x)}{dx} = -P(n,x)n(\alpha+\eta) + P(n-1,x)(n-1)\alpha + P(n+1,x)(n+1)\eta$$

General solution:

$$\overline{n}(x) = e^{(\alpha-\eta)x} \qquad k = \frac{\eta}{\alpha}$$

$$P(n,x) = k\frac{\overline{n}(x)-1}{\overline{n}(x)-k} \qquad n = 0$$

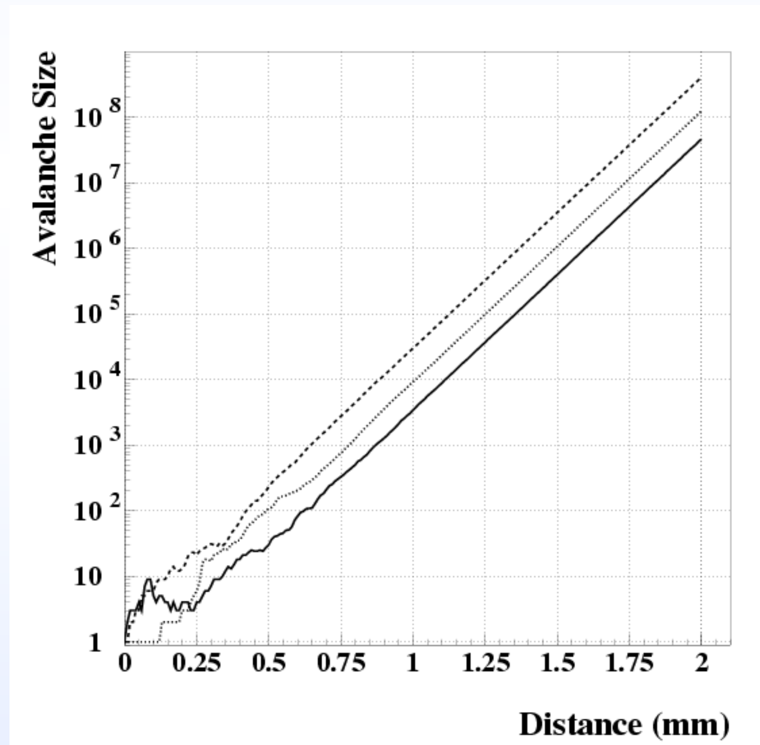
$$= \overline{n}(x)\left(\frac{1-k}{\overline{n}(x)-k}\right)^2\left(\frac{\overline{n}(x)-1}{\overline{n}(x)-k}\right)^{n-1} \qquad n > 0$$

Variance:

$$\sigma^2(x) = \left(\frac{1+k}{1-k}\right)\overline{n}(x)\left(\overline{n}(x)-1\right)$$

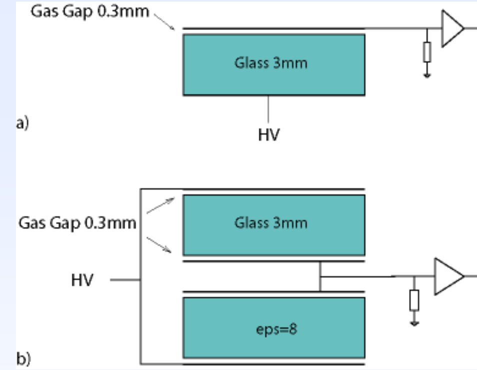
α = Townsend coefficient,
η = Attachment coefficient

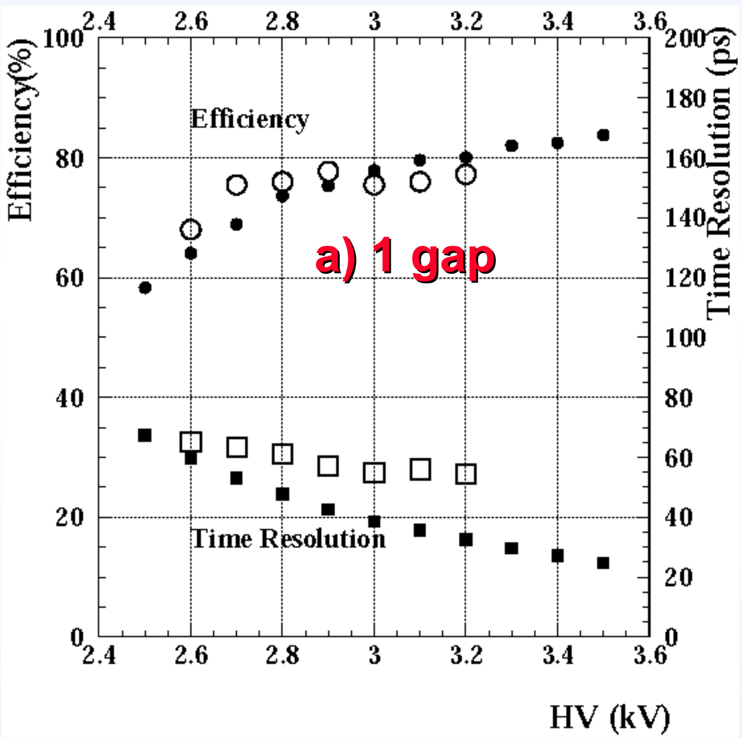
Three simulated avalanches initiated by one electron:

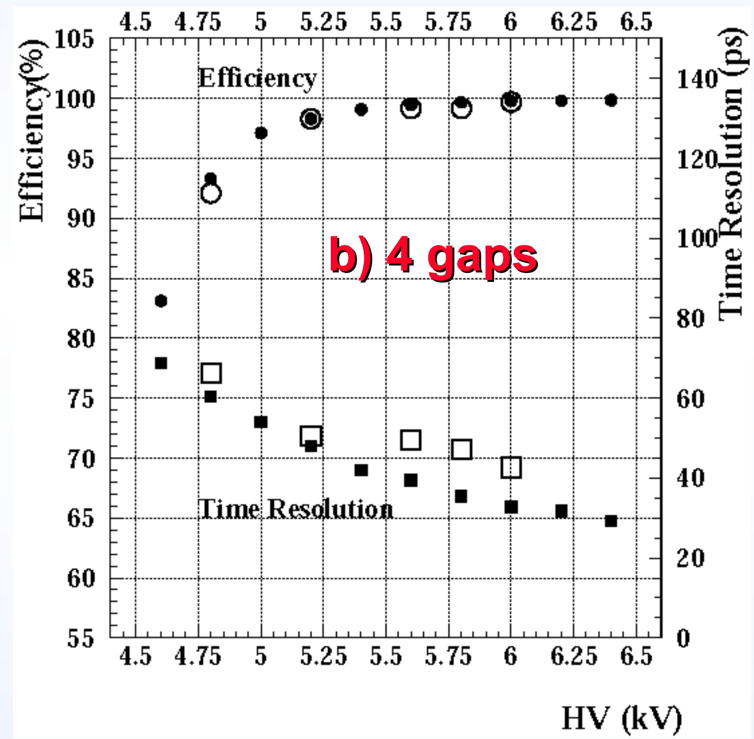


1D-Simulation results: Efficiency and time resolution [5]

Example: Timing RPC







- **Open Symbols: Measurements, filled symbols: Simulations**
- **(7GeV Pionen, 20fC Threshold, 200ps amplifier rise time, 1fC Noise, T=296.15K, p=970mb)**

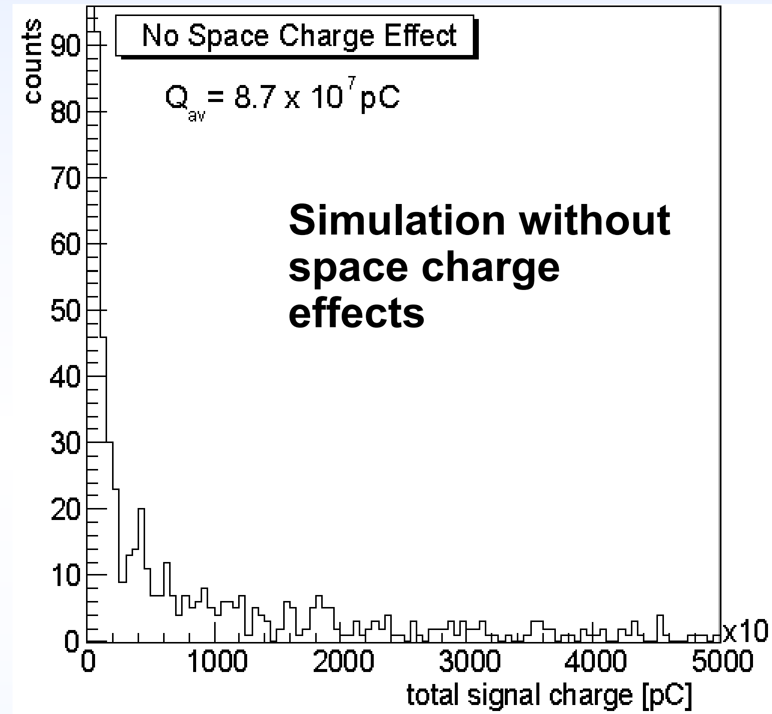
Problem: Avalanche charges (no space charge effect simulated)

Average induced charge (0.3mm Timing RPC):

	simulated	measured
Q_{ind}=	$5 \cdot 10^7$pC	0.5 pC

Average induced charge (2mm Trigger RPC):

	simulated	measured
Q_{ind} =	$8 \cdot 10^3$pC	2 pC

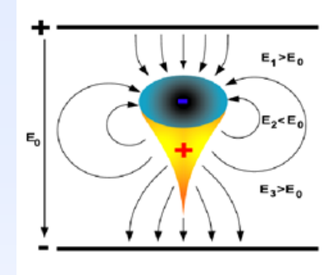


Simulated spectrum is exponential!

Measurements on the other hand show peak!!

⇒ Saturation due to space charge effect?

1.5D Simulation Procedure: Space charge is included

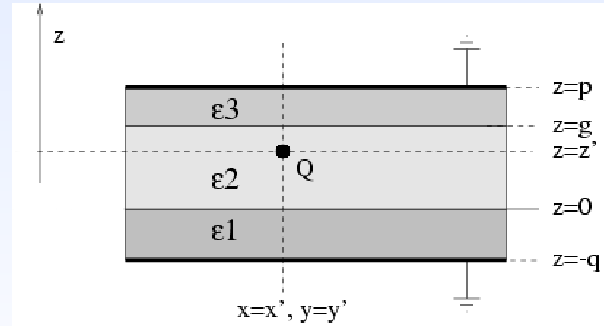


1. The gas gap is divided into several steps.
2. The primary clusters are distributed onto the steps.
3. The electric field of the space charge is calculated and added to the applied external field. This is where the transversal diffusion enters.
4. The Townsend and attachment coefficients and the drift velocity at each step are calculated.
5. The charges in the gas gap are multiplied and drifted towards the anode.
6. We also include longitudinal diffusion. The charges are redistributed onto the steps.
7. The induced signal at this time step is calculated.
8. Steps 3 – 7 are repeated until all electrons have left the gas gap.

- No photons

Field of space charge [9]

Analytical solution for the electric field of a point charge in an RPC.



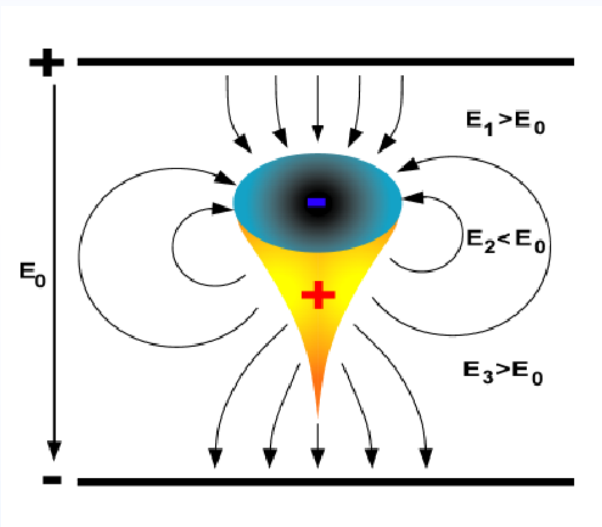
$$\Phi(\rho,\phi,z) = \frac{Q}{4\pi\varepsilon_2}\Big[\frac{1}{\sqrt{P^2+(z-z')^2}} + \frac{(\varepsilon_2-\varepsilon_3)}{(\varepsilon_2+\varepsilon_3)\sqrt{P^2+(2g-z-z')^2}} - \frac{(\varepsilon_1-\varepsilon_2)}{(\varepsilon_1+\varepsilon_2)\sqrt{P^2+(z+z')^2}}$$

$$+ \frac{1}{(\varepsilon_1+\varepsilon_2)(\varepsilon_2+\varepsilon_3)} \int_0^\infty d\kappa\; J_0(\kappa P)\, \frac{R(\tau,z,z')}{D(\kappa)}\Big], \qquad 0 \le z \le g$$

$$\begin{aligned} D(\kappa) = {} & (\varepsilon_1+\varepsilon_2)(\varepsilon_2+\varepsilon_3)\,(1-e^{-2\kappa(p+q)}) - (\varepsilon_1-\varepsilon_2)(\varepsilon_2+\varepsilon_3)(e^{-2\kappa p}-e^{-2\kappa q}) \\ & - (\varepsilon_1+\varepsilon_2)(\varepsilon_2-\varepsilon_3)(e^{-2\kappa(p-g)}-e^{-2\kappa(q+g)}) + (\varepsilon_1-\varepsilon_2)(\varepsilon_2-\varepsilon_3)(e^{-2\kappa g}-e^{-2\kappa(p+q-g)}) \end{aligned}$$

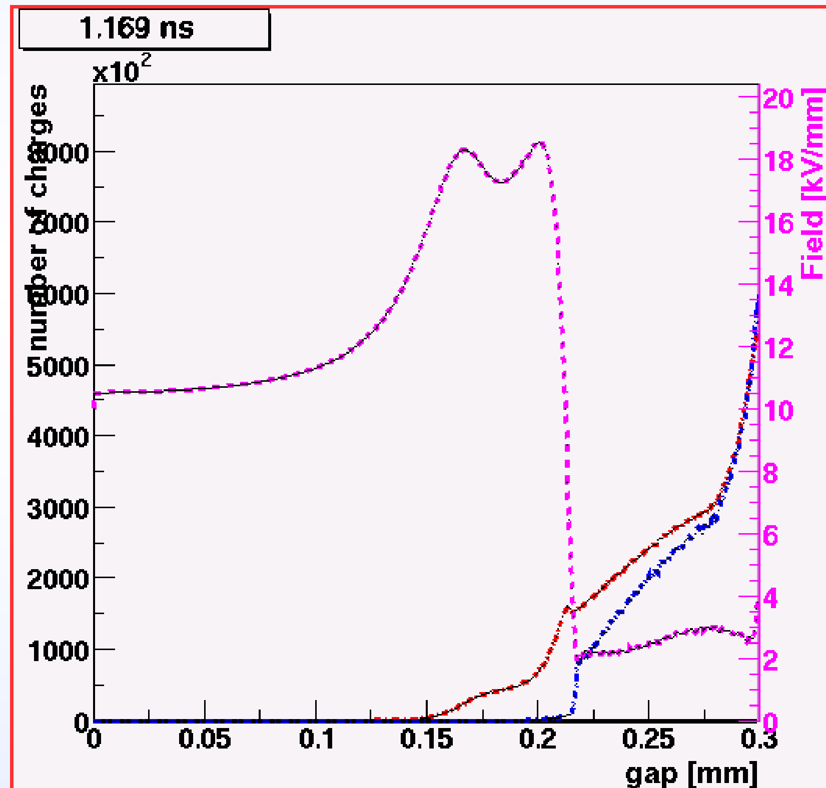
$$\begin{aligned} R(\kappa;z,z') = {} & (\varepsilon_1+\varepsilon_2)^2(\varepsilon_2+\varepsilon_3)^2\;\left[e^{\kappa(-2p-2q+z-z')} + e^{\kappa(-2p-2q-z+z')}\right] \\ & -(\varepsilon_1+\varepsilon_2)^2\,(\varepsilon_2-\varepsilon_3)^2\,e^{\kappa(-4g-2q+z+z')} - 4\varepsilon_1\varepsilon_2(\varepsilon_2+\varepsilon_3)^2\,e^{\kappa(-2q-z-z')} \\ & -(\varepsilon_1-\varepsilon_2)^2\,(\varepsilon_2+\varepsilon_3)^2\;e^{\kappa(-2p-z-z')} - \left(\varepsilon_1{}^2-\varepsilon_2{}^2\right)(\varepsilon_2-\varepsilon_3)^2\;e^{\kappa(-4g+z+z')} \\ & +\left(\varepsilon_1{}^2-\varepsilon_2{}^2\right)(\varepsilon_2+\varepsilon_3)^2\;\left[-e^{\kappa(-2p-2q-z-z')} + e^{\kappa(-2p+z-z')} + e^{\kappa(-2p-z+z')}\right] \\ & -4\left(\varepsilon_1{}^2-\varepsilon_2{}^2\right)\varepsilon_2\varepsilon_3\;e^{\kappa(-2p-2q+z+z')} - 4(\varepsilon_1+\varepsilon_2)^2\varepsilon_2\varepsilon_3\;e^{\kappa(-2p+z+z')} \\ & +(\varepsilon_1-\varepsilon_2)^2\left(\varepsilon_2{}^2-\varepsilon_3{}^2\right)\;e^{\kappa(-2g-z-z')} + 4\varepsilon_1\varepsilon_2\left(\varepsilon_2{}^2-\varepsilon_3{}^2\right)\;e^{\kappa(2g-2p-2q-z-z')} \\ & +(\varepsilon_1+\varepsilon_2)^2\left(\varepsilon_2{}^2-\varepsilon_3{}^2\right)\left[-e^{\kappa(-2g-2q+z-z')} - e^{\kappa(-2g-2q-z+z')} + e^{\kappa(-2g-2p-2q+z+z')}\right] \\ & +\left(\varepsilon_1{}^2-\varepsilon_2{}^2\right)\left(\varepsilon_2{}^2-\varepsilon_3{}^2\right)\left[e^{\kappa(-2g-2q-z-z')} - e^{\kappa(-2g+z-z')} - e^{\kappa(-2g-z+z')} + e^{\kappa(-2g-2p+z+z')}\right] \end{aligned}$$

Space charge effect: Example avalanche [3,4]



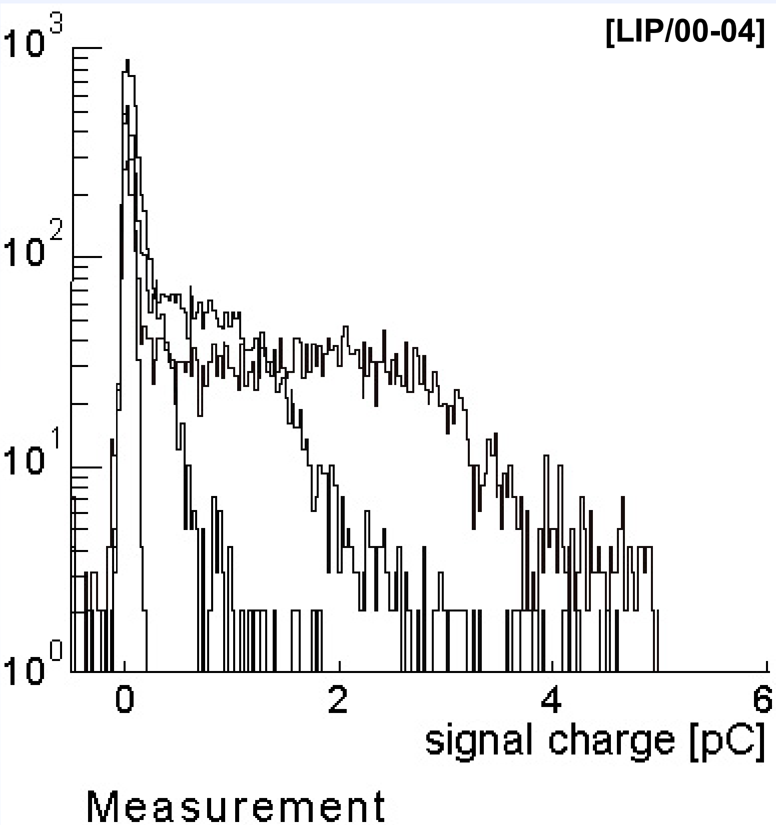
0.3mm Timing RPC, HV=3kV

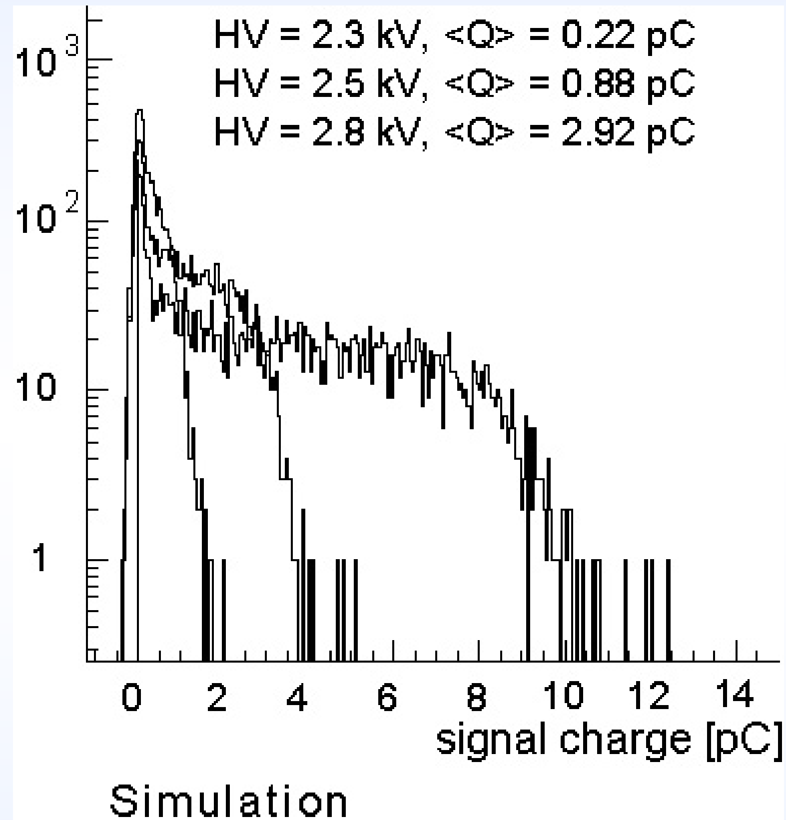
Electrons, positiv Ions, negativ Ions, Field



Results: charge spectra [3,4]

Example: Timing RPC



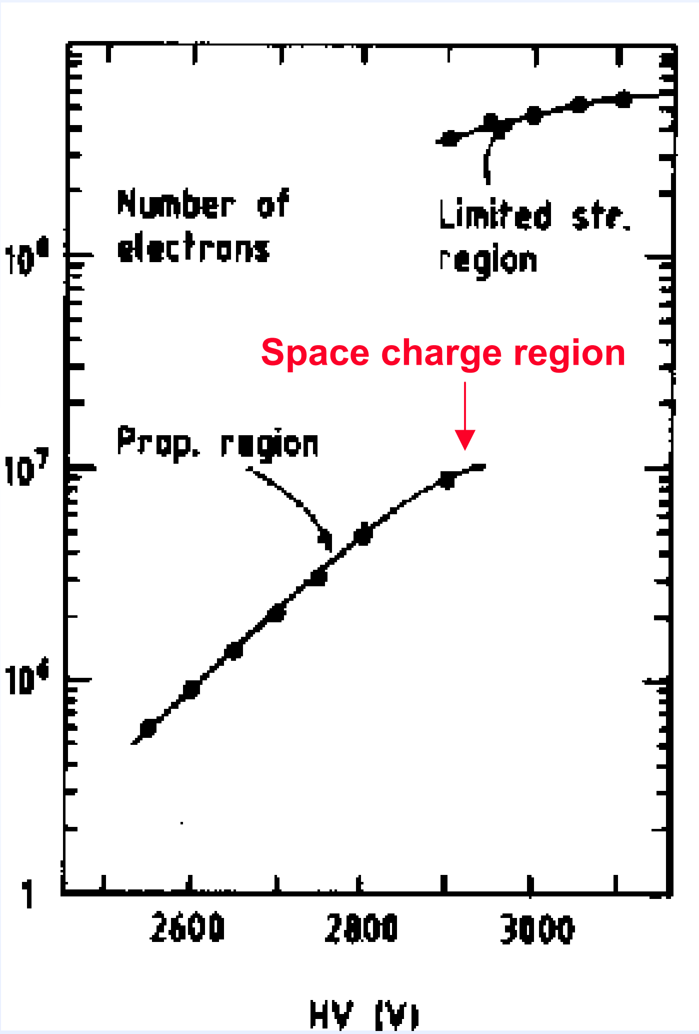


- **Difference about a factor 2.**
- **Compared with factor 10^7 without space charge effect it is good!**
- **(7GeV pions, T=296.15K, p=970mb)**

1.5D Simulation

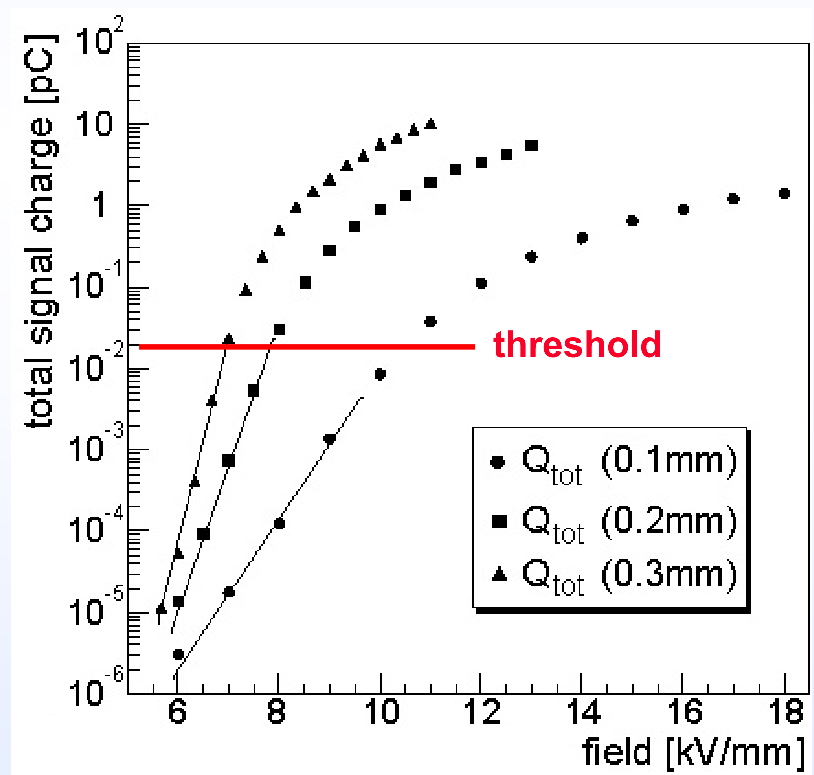
Working modes of wire chamber and RPC

MWPC/ Geiger-Müller-Rohr:

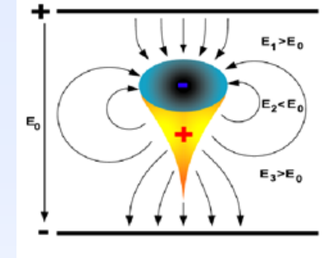


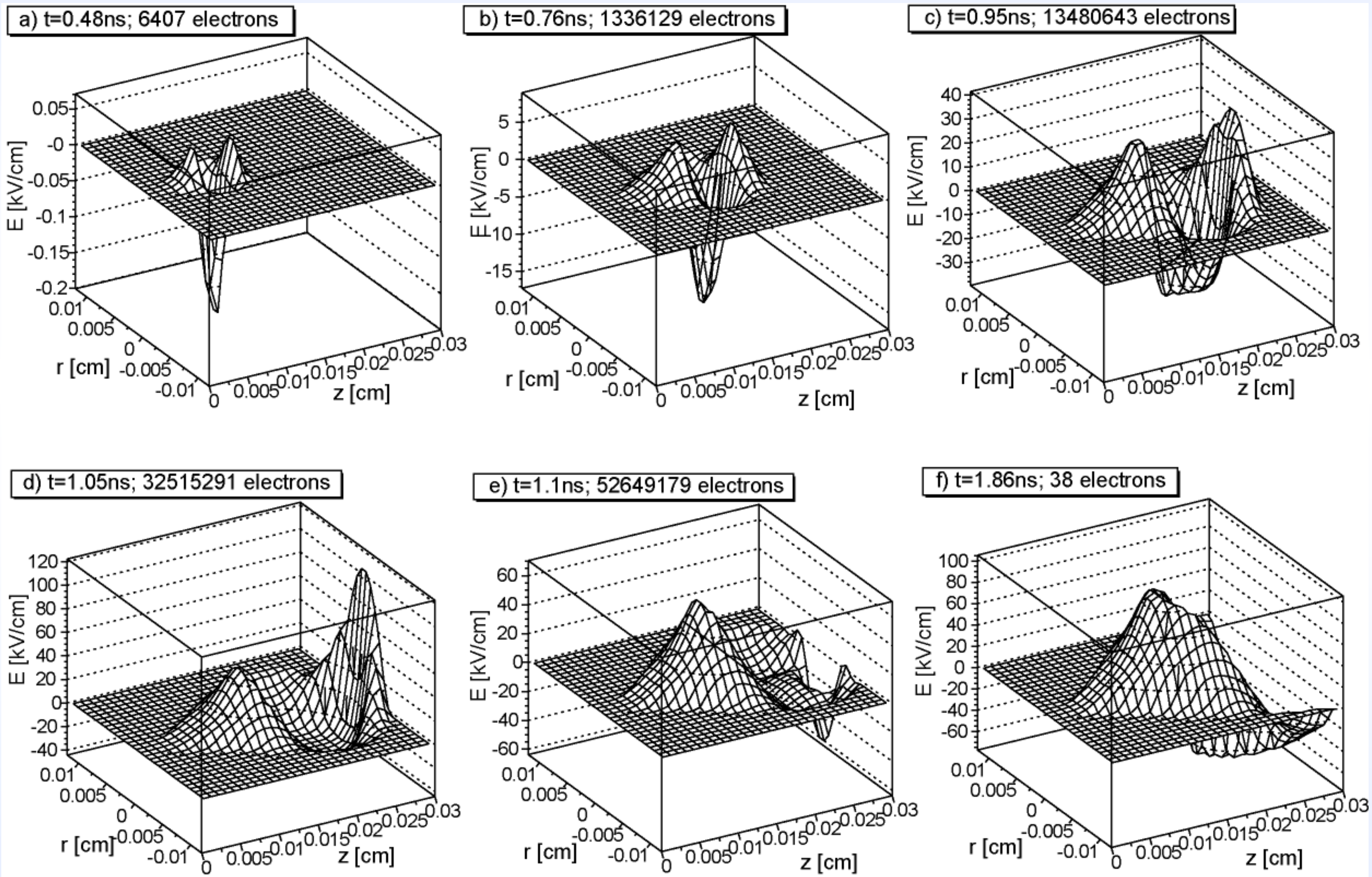
[NIM 200, 345 (1982)]

- **Timing RPC (Simulation)**
- **Homogeous applied Field**
- **Proportional region is below threshold (not measurable)**
- **Wide space charge region**



Even better: 2D- Simulations [1]
space charge field





The space charge field gets as strong as the applied electric field!

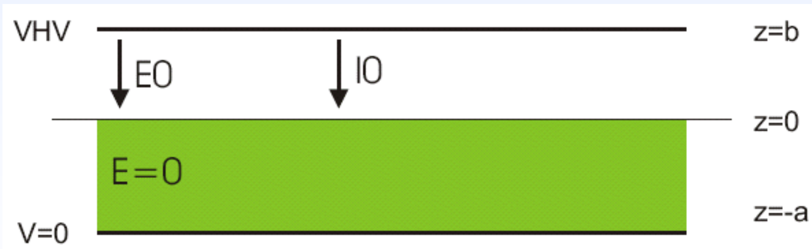
Rate effects [0]

Cause

Simulation procedure and Results

DC current model

RPC with a gas gap of thickness b and resistive plate of thickness a and volume resistivity $\rho = 1/\sigma$



$$E_0 = V_{HV}/b$$

A current I_0 on the surface causes a voltage drop of $\Delta V = a*\rho*I_0$ across the gas gap.

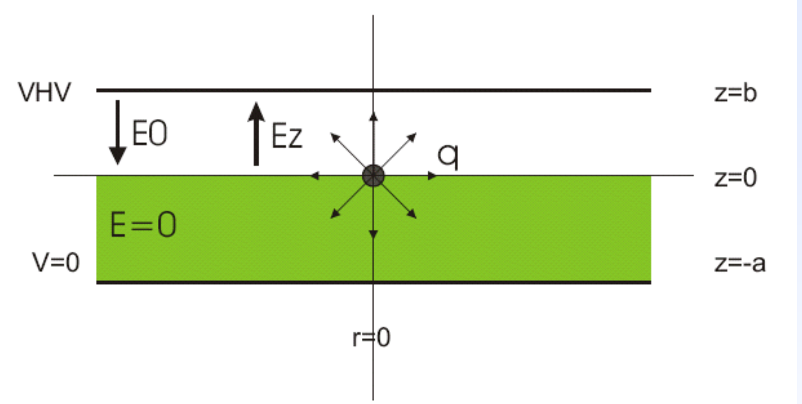
An avalanche charge Q (pC) at rate R (Hz/cm²) gives a current of $I_0=R*Q$ (A/cm²).

The resistive plate represents a resistance of $a*\rho$ (Ω cm²) between gas gap and metal.

The voltage drop is therefore $\Delta V = \rho*a*I_0 = \rho*a*R*Q$ and the electric field drops by

$$\Delta E_{gap} = -\rho*a/b*R*Q$$

Exact calculation



Without particles traversing the RPC the field in the gas gap is V_{HV}/b and the field in the resistive plate is zero.

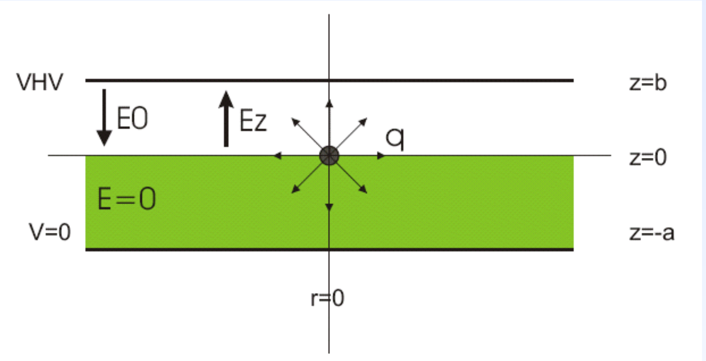
The charge sitting on the surface of the resistive plate decreases the field in the gas gap and causes an electric field in the resistive plate.

The electric field in the resistive plate will cause charges to flow in the resistive material which 'destroy' the point charge.

This causes a time dependent electric field E(x,y,z,t) in the gas gap which adds to the externally applied field E_0.

The electric field in the gas gap due to high rate is then simply given by superimposing this solution for the individual charges.

Point charge in RPC

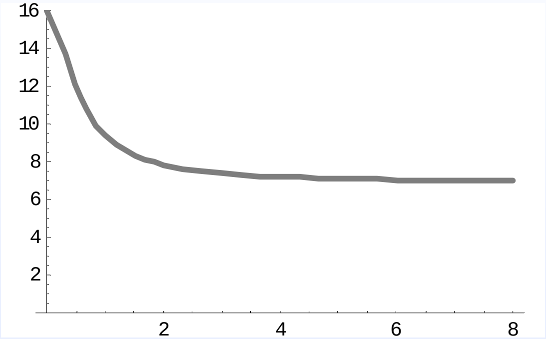


Point charge placed at position r=0, z=0 at time t=0, permittivity ε_1, conductivity σ

$$E_z(r,z,t) = \frac{q}{2\pi(\varepsilon_0+\varepsilon_1)} \frac{z}{(r^2+z^2)^{\frac{3}{2}}} e^{-t/\tau_1} + \frac{q}{2\pi}\int_0^\infty J_0(kr)\left[f_1(k,z)\,e^{-t/\tau_2(k)} - f_2(k,z)\,e^{-t/\tau_1}\right] dk$$

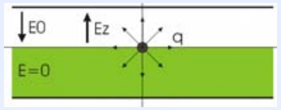
$$\tau_1 = \frac{\varepsilon_0+\varepsilon_1}{\sigma} \qquad \tau_2(k) = \frac{\varepsilon_0 \cosh(kb)\sinh(ka) + \varepsilon_1 \cosh(ka)\sinh(kb)}{\sigma\ \cosh(ka)\sinh(kb)}$$

τ_2(k)



k

Charge decays with a continuous distribution of time constants between τ (charge sheet in RPC) and τ_1 (point charge at infinite half space).



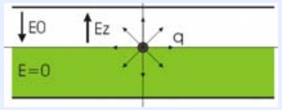
Method for Monte Carlo Simulations

A <u>single gap</u> RPC of area A = 3*3 cm^2 is simulated.

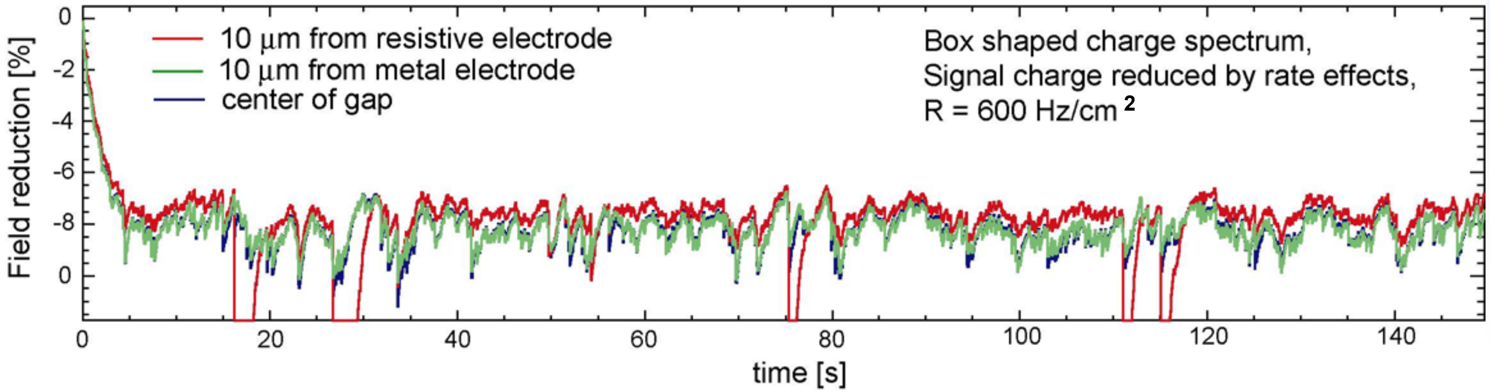
For each time step (Δt) a new number of charges (Δt*R*A) is distributed randomly on the surface of the resistive plate.

The z-component of the electric field of all charges in the resistive plates is calculated at always the same position (center of RPC area, center of gap or close to electrodes) at all time steps and added to the applied field: $E_{tot} = E_0 + \sum E_z(r,z,t)$.

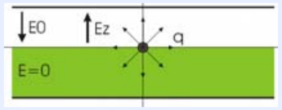
All charges are kept until their field contribution has fallen below 10^{-26} V/cm (up to 60s for Timing RPC).



Monte Carlo for Timing RPCs

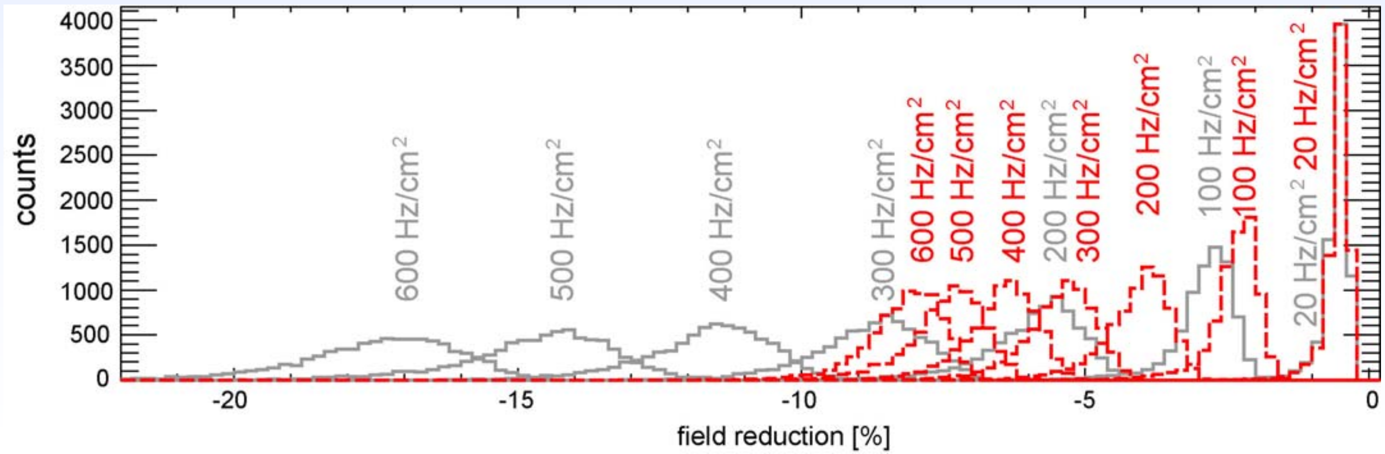


Fluctuations of the electric field at three different z-positions in the gap.

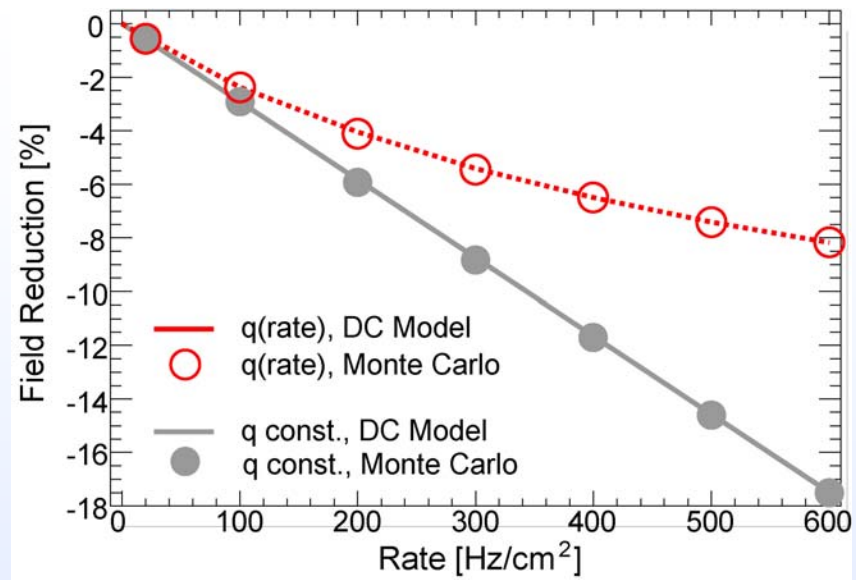


Monte Carlo for Timing RPCs: Results

Total avalanche charge changes as the electric field is reduced by rate:



The average field reduction in the gap center is exactly the same as the one calculated from the DC model.



Summary / Conclusions

RPCs are used heavily in high energy physics experiments:

- 3650m^2 Trigger RPCs in ATLAS,
- 176m^2 Timing RPCs in ALICE.

The detector physics (time resolution, efficiency, charge spectra) are well understood.

Space charge effects can be calculated by using the exact solutions for the electric field of a point charge in the gas gap of an RPC.

A strong space charge effect is always present (different than for MWPCs).

Rate effects in RPCs can be calculated by using the exact time dependend solutions for the electric field of a point charge on the resistive plate of an RPC.

Rate effects: The electric field fluctuates due to the particle flux around a mean value which is equal to the value derived with a simple ohmic law model.