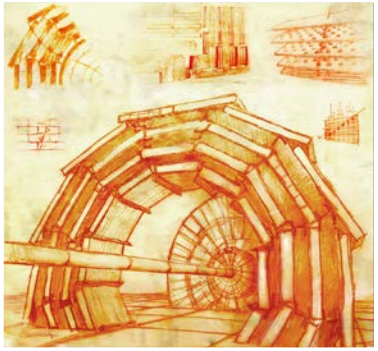
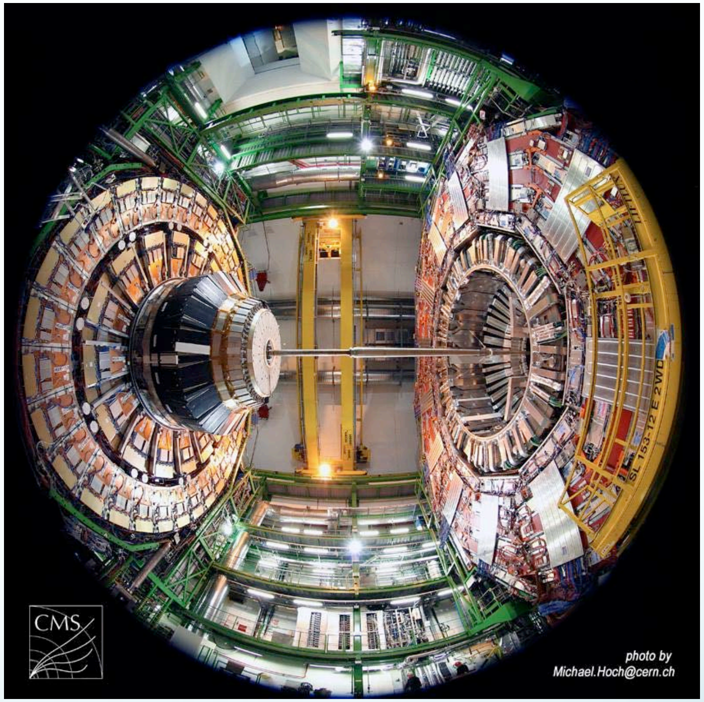


The Resistive Plate Chambers



G. M. I. Pugliese

(CERN, INFN and Politecnico of Bari)

The 2nd Omani School of High Energy Physics
28 March – April 4th, 2018

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Please contact me for any questions

G. Pugliese

Outline of my lessons

1. The Resistive Plate Chamber detector

- Physics and principle of operation
- The evolution of the RPC technology:
  1st , 2nd and 3th generation of RPC

…Today talk

2. RPC detectors running at HEP experiments

…Tomorrow talk

2. RPC detectors future application in HEP and life

.. Monday talk

Brief History of the Resistive Plate Chamber

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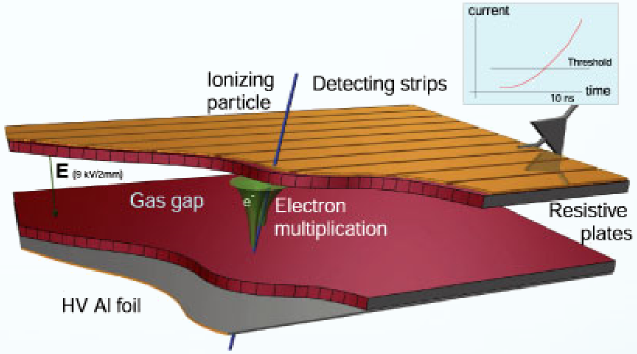
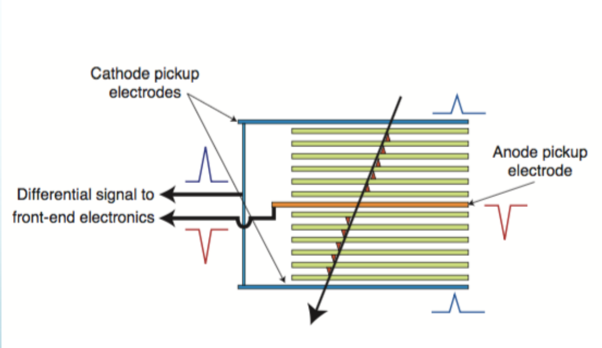
1981: R. Santonico published the paper "Development of Resistive Plate Counters``, Nucl. Instrum. Meth. N.187 https://doi.org/10.1016/0029-554X(81)90363-3

1992: **2nd generation** of RPCs developed for LHC experiments



1995: **Multi-gap RPCs** developed by C. Williams



2015: **3rd generation of** RPC developed for HL-LHC

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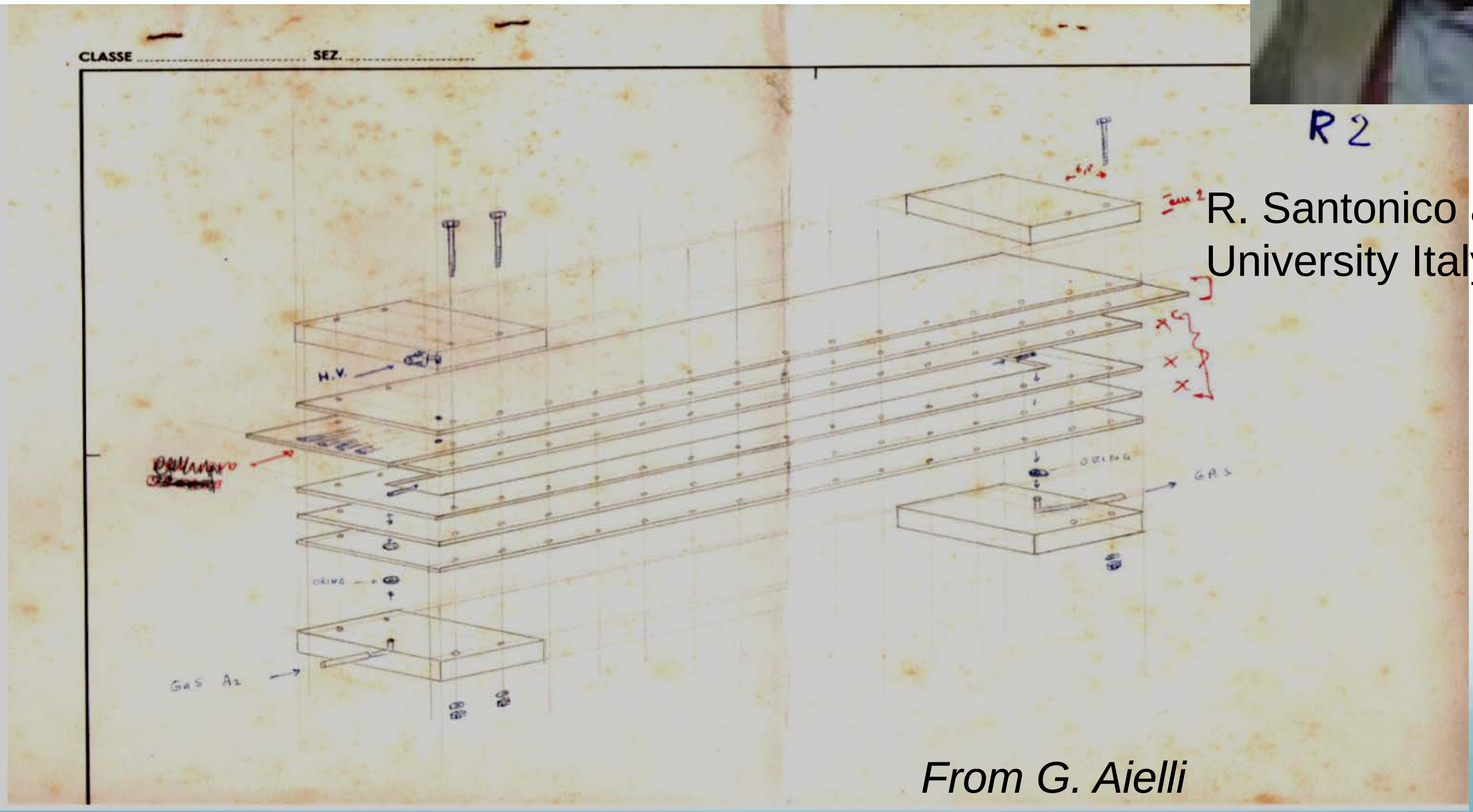
1st generation of RPC

The first prototype 16/2/1980



R. Santonico at Roma 2 University Italy

From G. Aielli

The importance of the surface

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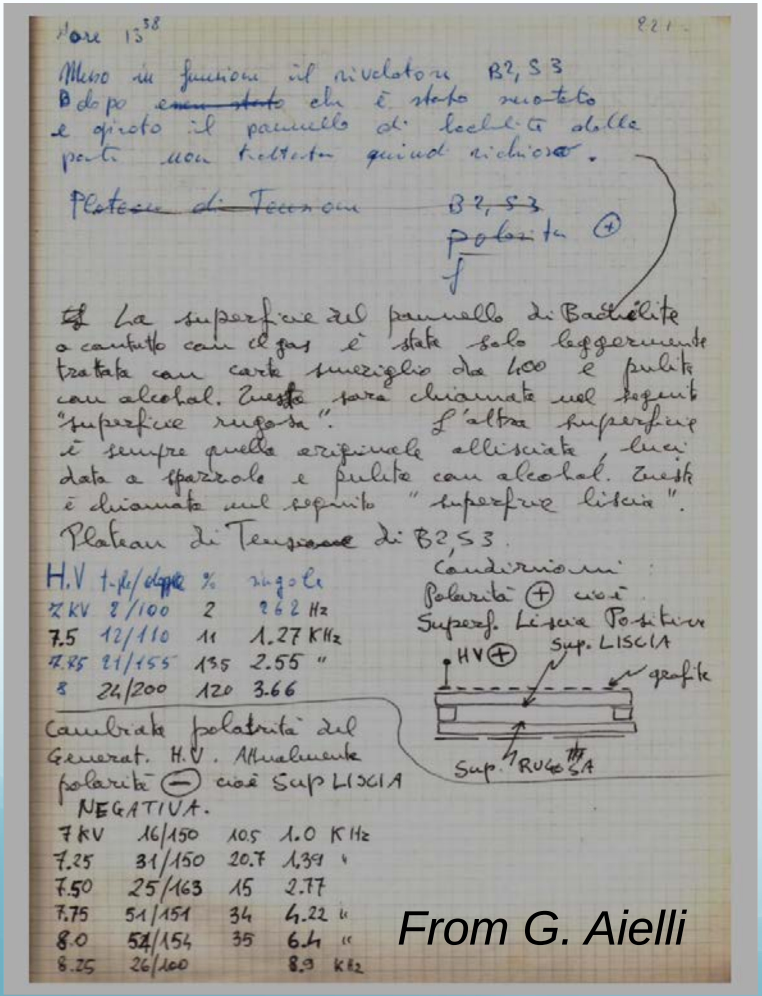
More roughness → more noise
→ more current → less efficiency

less roughness → less noise
→ less current → more efficiency

19/4/1980



Ore 13^{38} 221

Messo in funzione il rivelatore B2, S3 dopo ~~essere stato~~ che è stato smontato e girato il pannello di bachelite dalle parti non trattate quindi richiuso.

~~Plateau di Tensione B2, S3~~
polarità (+)

La superficie del pannello di Bachelite a contatto con il gas è stata solo leggermente trattata con carta smeriglio da 400 e pulita con alcohol. Questa sarà chiamata nel seguito "superficie rugosa". L'altra superficie è sempre quella originale allisciata, lucidata a spazzola e pulita con alcohol. Questa è chiamata nel seguito "superficie liscia".

Plateau di Tensione di B2, S3

Condizioni:
Polarità (+) cioè
Superf. Liscia Positiva

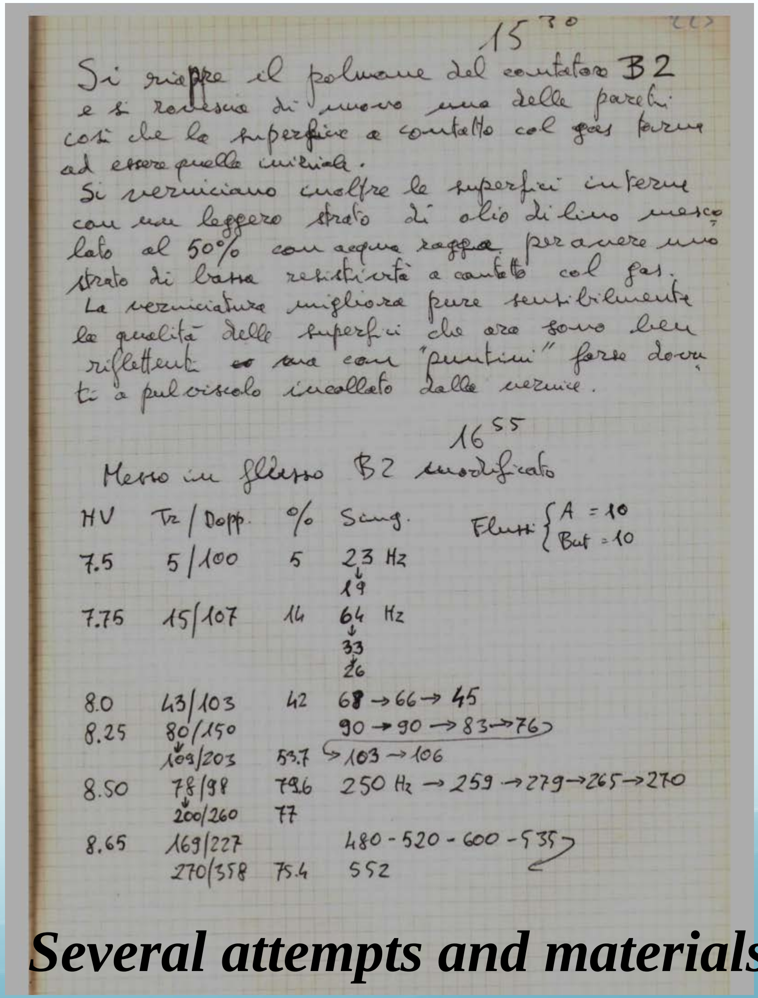
H.V	triple/doppie	%	singole
7 KV	2/100	2	262 Hz
7.5	12/110	11	1.27 KHz
7.75	21/155	13.5	2.55 "
8	24/200	12.0	3.66

Cambiata polarità del Generat. H.V. Attualmente polarità (−) cioè Sup LISCIA NEGATIVA.

7 KV	16/150	10.5	1.0 KHz
7.25	31/150	20.7	1.39 "
7.50	25/163	15	2.77
7.75	51/151	34	4.22 "
8.0	54/154	35	6.4 "
8.25	26/100		8.9 KHz

From G. Aielli

20/4/1980



15^{30} 222

Si riapre il polmone del contatore B2 e si rovescia di nuovo una delle pareti così che la superficie a contatto col gas torna ad essere quella iniziale.
Si verniciano inoltre le superfici interne con un leggero strato di olio di lino mescolato al 50% con acqua ragia per avere uno strato di bassa resistività a contatto col gas.
La verniciatura migliora pure sensibilmente la qualità delle superfici che ora sono ben riflettenti ma con "puntini" forse dovuti a pulviscolo incollato dalla vernice.

16^{55}

Messo in flusso B2 modificato

Flussi: A = 10, But = 10

HV	Tr / Dopp.	%	Sing.
7.5	5/100	5	23 Hz ↓ 19
7.75	15/107	14	64 Hz ↓ 33 ↓ 26
8.0	43/103	42	68 → 66 → 45
8.25	80/150 ↓ 109/203	53.7	90 → 90 → 83 → 76 → 103 → 106
8.50	78/98 ↓ 200/260	79.6 / 77	250 Hz → 259 → 279 → 265 → 270
8.65	169/227 / 270/358	75.4	480 - 520 - 600 - 535 → 552

Several attempts and materials….

Linseed oil → the first RPC works!

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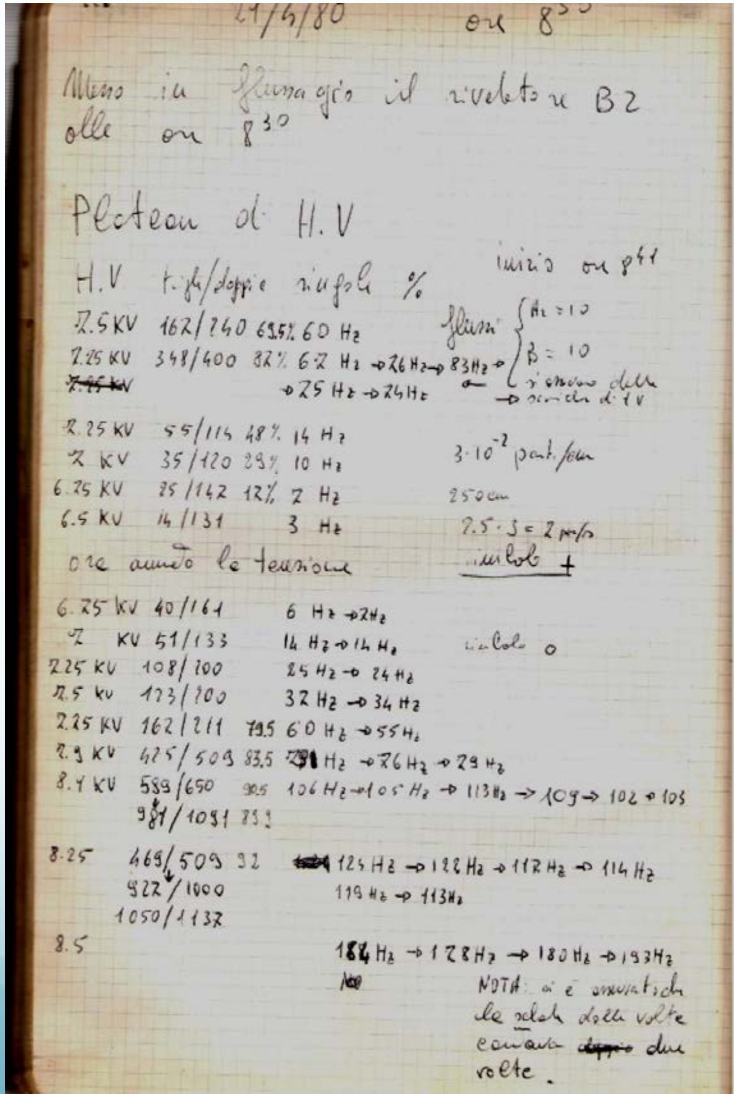
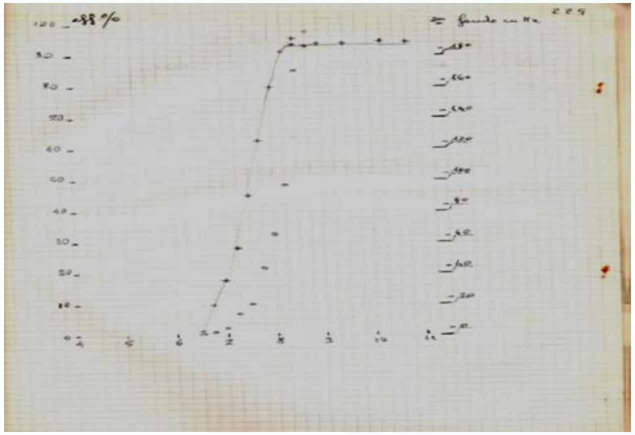




Linseed oil:
Mixture of triglycerides, formed by one molecule of glycerol and three molecules of linear fatty acids. The oil is cured forming a hard stable film because of oxidation followed by polymerization.

If you look on Wikipedia..
The Linseed oil is used as a painting medium. It was a significant advantage in the technology of oil painting!

From G. Aielli

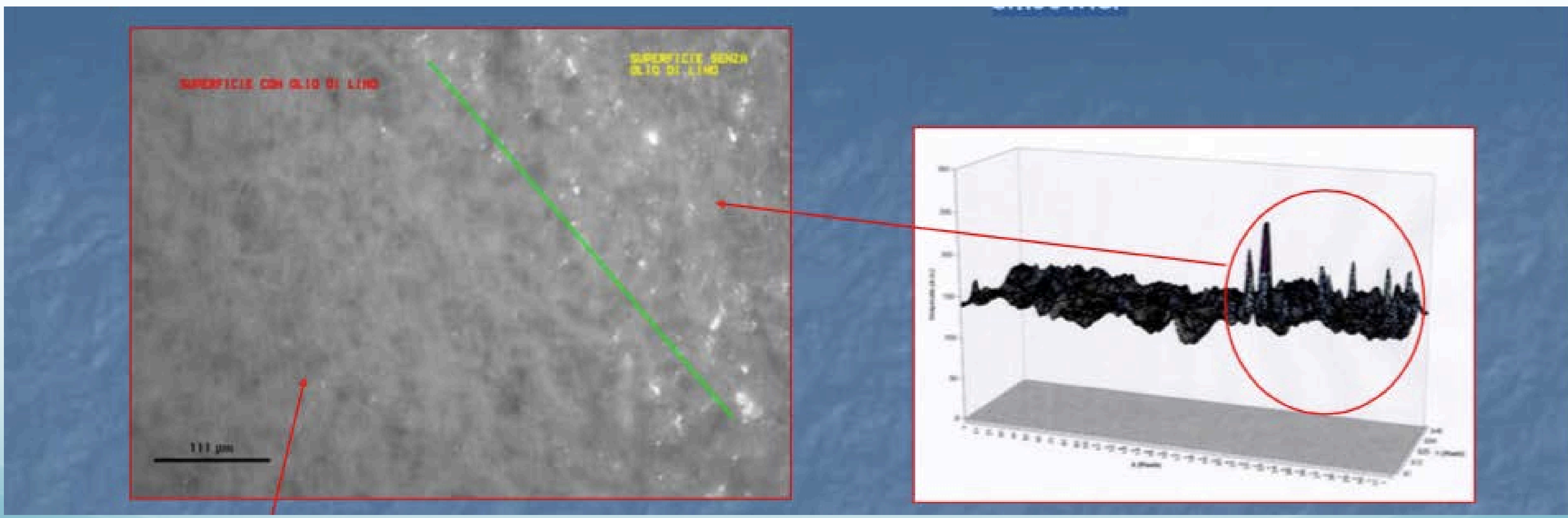
G. Pugliese

RPC: the linseed Oil

Why Electrodes are "cured" with linseed oil ?

Linseed oil makes the surface smoother

The smoother the surface, the lower the intrinsic noise of the detector



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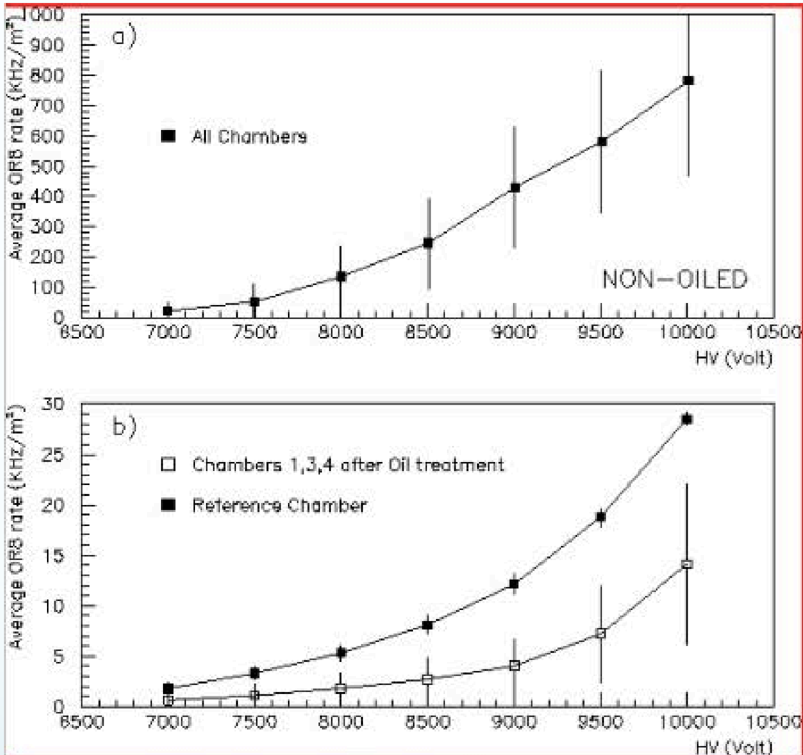
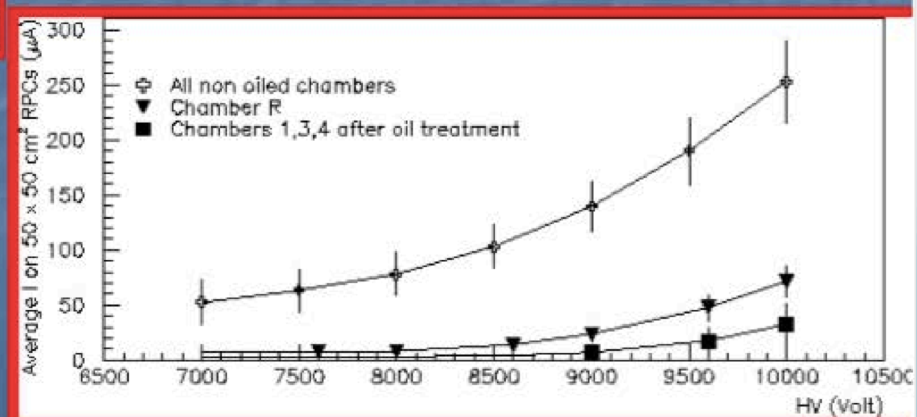
RPC: the linseed Oil



Reduced Currents and Noise rate



RPC basic elements
(as in the original design)

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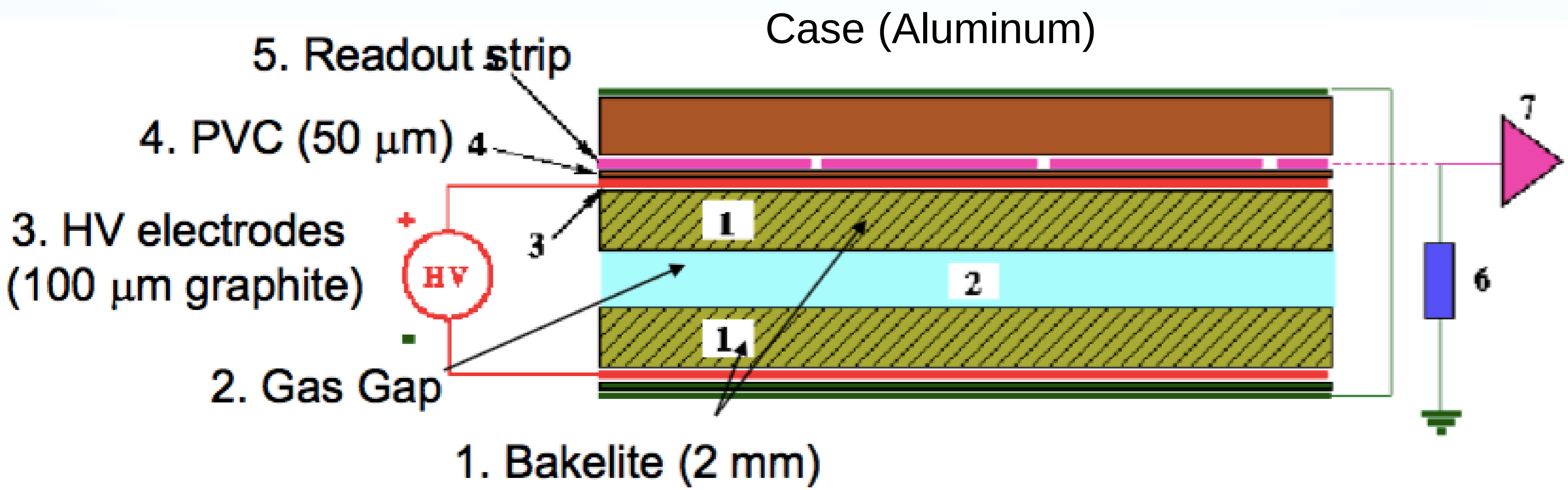
Gas mixture:
Argon, Iso-butane and Freon
at P ≈ 1 Atm

High Voltage contact: graphite coating on electrode outer surfaces

Pick up strips are used to collect the signal: **Al/Cu, ~cm**



Resistive Electrodes (**ρ≈10^{10}-10^{12} Ωcm**): **High Pressure Laminates (HPL)** "Bakelite" made by Kraft paper impregnated with melamine/phenol resins.
Internal electrode surface covered with a **thin linseed oil layer (~µm)**

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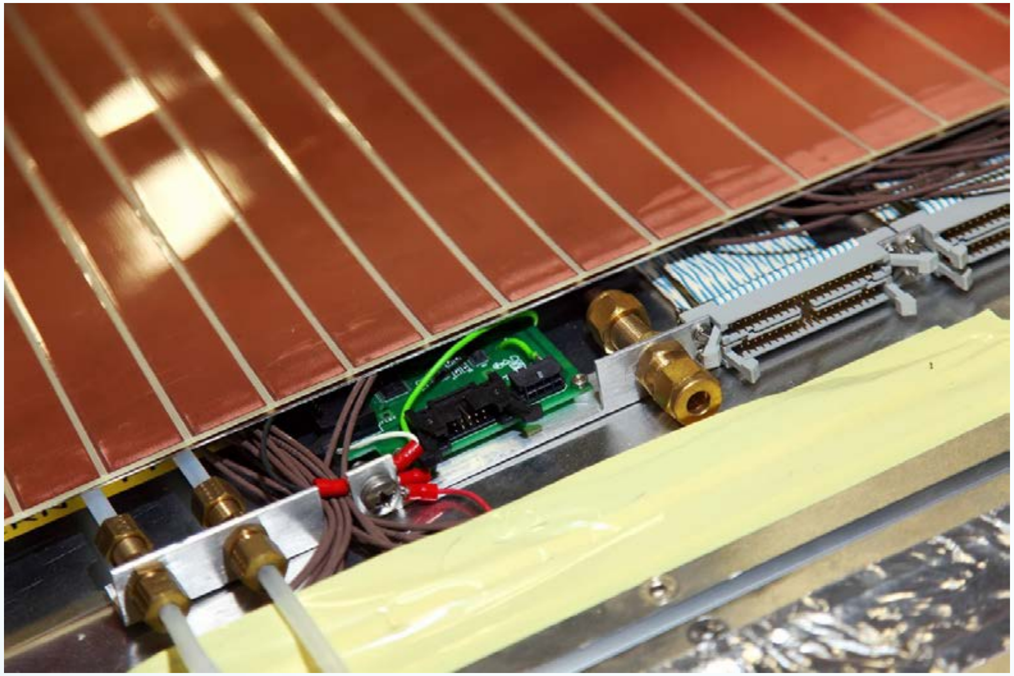
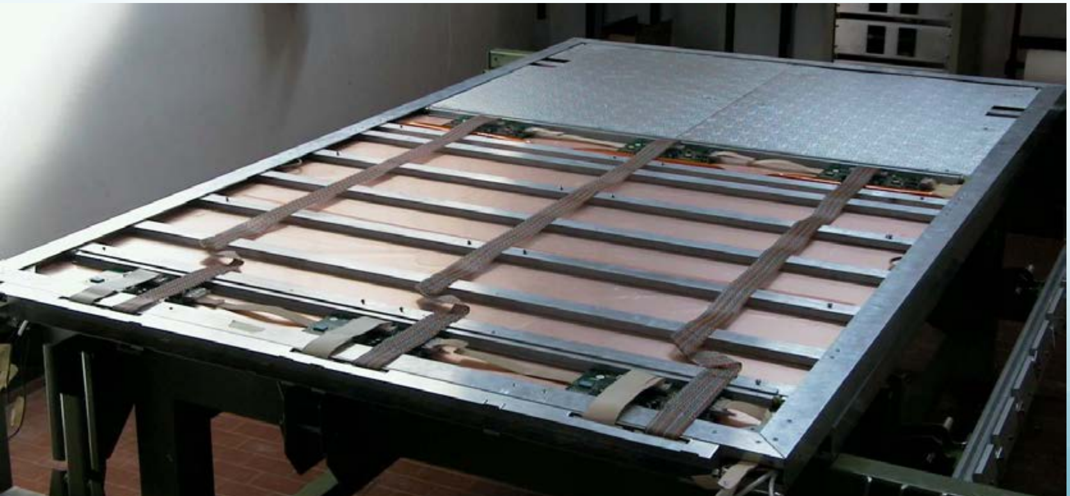
Some pictures of the RPC



Kraft Puricelli production site



Kraft paper

Applications of the fist generation of the RPC

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The first generation of RPC detectors has been used in several HEP experiments:

‘85: Nadir – 120 m^2 (Triga Mark II – Pavia)

‘90: Fenice – 300 m^2 (Adone – Frascati)

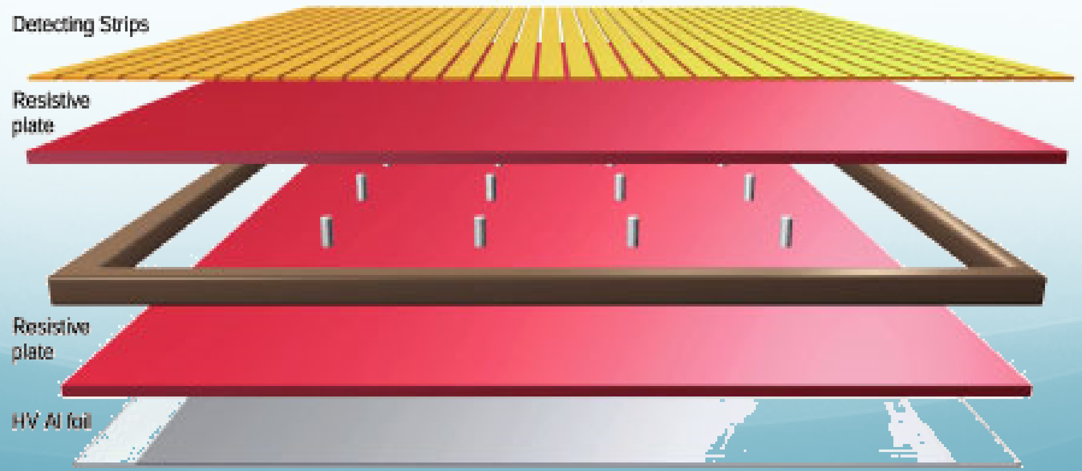
‘90: WA92 – 72 m^2 (CERN SPS)

‘90: E771– 60 m^2; E831 – 60 m^2 (Fermilab)

1994-1996: L3 – 300 m^2 (CERN-LEP)

1996-2002: BaBar – 2000 m^2 (SLAC)

Very large area of muon detection



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Significance of the fist generation of the RPC

Why the RPCs have been extensively used in several HEP experiments?

- **Golden parameter:** the time resolution (≈1 ns)
- **High muon efficiency** of the order of > 96% and **long term stability**

- **The cost** of RPC is much smaller as compared to other fast detector (like the scintillators)
- It is **easy** to construct and operate
- Simple signal pick up and readout system (just “strips”)
- Two dimensional readout (x and y)

BUT

rate capability < 50 Hz/cm^2

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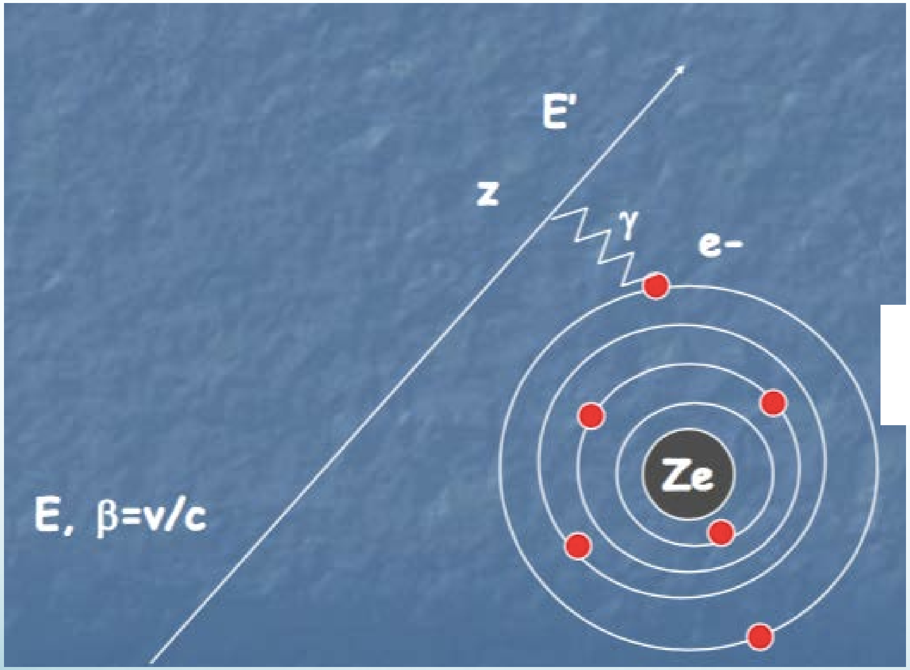
RPCs are.. gas detectors

So the story begins with… the interaction of a charged particle within the gas where it **ionizes** the gas molecules by losing energy:



The mean rate of energy loss is well-described by the "Bethe-Bloch" formula:

$$-\left\langle \frac{dE}{dx} \right\rangle = K z^2 \frac{Z}{A} \frac{1}{\beta^2} \left[\frac{1}{2} \ln \frac{2 m_e c^2 \beta^2 \gamma^2 T_{\max}}{I^2} - \beta^2 - \frac{\delta(\beta\gamma)}{2} \right]$$

The gas mixture represents the sensitive medium!

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The ionization

Ionizing particles passing through the gas are producing **primary ionization.** Quite often their kinetic energy is enough to generate **secondary ionization.**

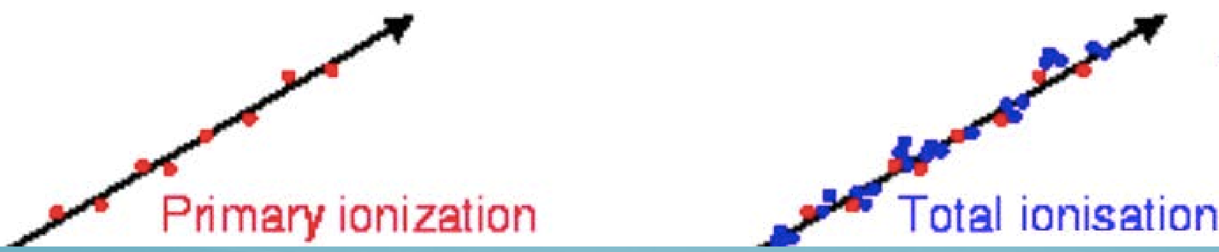
$$n_T = \frac{\Delta E}{W_i}$$

n_T: total number of ion/electron pairs generated

ΔE: total energy loss

W_i: mean energy needed to create ion/elect pair

The mean number of electron/ion pairs created is proportional to the energy deposited in the gas gap



$$n_{total} \approx 3 \ldots 4 \cdot n_{primary}$$

Primary Ionization

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Ionization process is **a statistic process.** The collisions with the gas atoms are randomly distributed and characterized by **the mean free path λ_I.**

$$\lambda_I = \frac{A}{N_A \rho \sigma_I}$$

N_A Avogadro number (moli^{-1})

ρ gas density (gr cm^{-3})

A gas mass number (gr moli^{-1})

σ_I ionization cross section (cm^2)

$\alpha = 1/\lambda$ = first Townsend coefficient
(the average number of ion/e pairs produced per units length)

The "average number of collisions" along a path L will be:

$$\mu = \frac{L}{\lambda_i}$$

Number of primaries is distributed following a Poisson distribution. The probability of having k collisions when μ is the average is:

$$P(\mu,k) = \frac{\mu^k}{k!} e^{-\mu}$$

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Ionization and gap thickness

Maximum detection efficiency is limited!!
The inefficiency is given by the probability to have k= 0 collision:

$$P(\frac{L}{\lambda},0) = e^{-\frac{L}{\lambda}} = 1 - \varepsilon$$

GAS (STP)	Helium	Argon	Xenon	CH_4	DME
dE/ dx (keV/ cm)	0.32	2.4	6.7	1.5	3.9
n (ion pairs/ cm)	6	25	44	16	55

$$\lambda = \frac{1}{n} = \frac{1}{25} = 0.04 \text{ cm}$$

$$L = 1 \text{ cm}$$

$$\mu = \frac{L}{\lambda} = Ln = 25 \Rightarrow$$

average number of collisions in L

An Ar detector 1 cm wide will have an inefficiency →

$$1 - \varepsilon = P(\frac{L}{\lambda},0) = 1.5 \times 10^{-11}$$

..ok good ..can we reduce the thickness? →

$$L = 1 \text{ mm}, \ \mu = \frac{L}{\lambda} = \frac{0.1}{0.04} = 2.5$$

$$1 - \varepsilon = P(\frac{L}{\lambda},0) = e^{-\mu} = 0.08 = 8\,\%!!$$

….not too much!!

For narrow gaps the **inefficiency** can be significant!!

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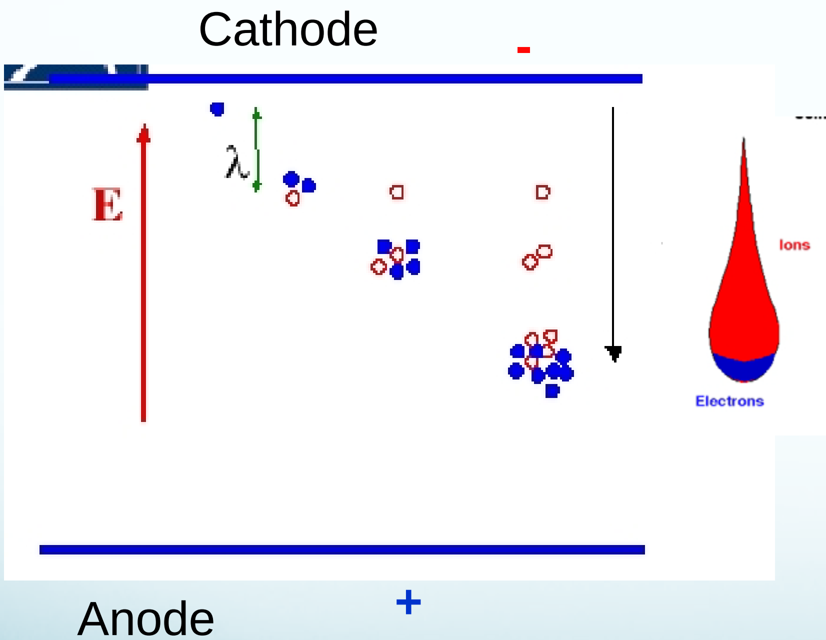
Gas multiplication process

Due to the **strong electric field (≈ kV/cm),** **electrons** are accelerated towards the anode and **ions** towards the cathode (with a lower velocity) to enough high energy capable to further ionization starting the multiplication process.



The charge distribution is like a liquid drop with electrons grouped near the head and slower ions tailing behind: called "**avalanche".**

Gas multiplication process (cont.)

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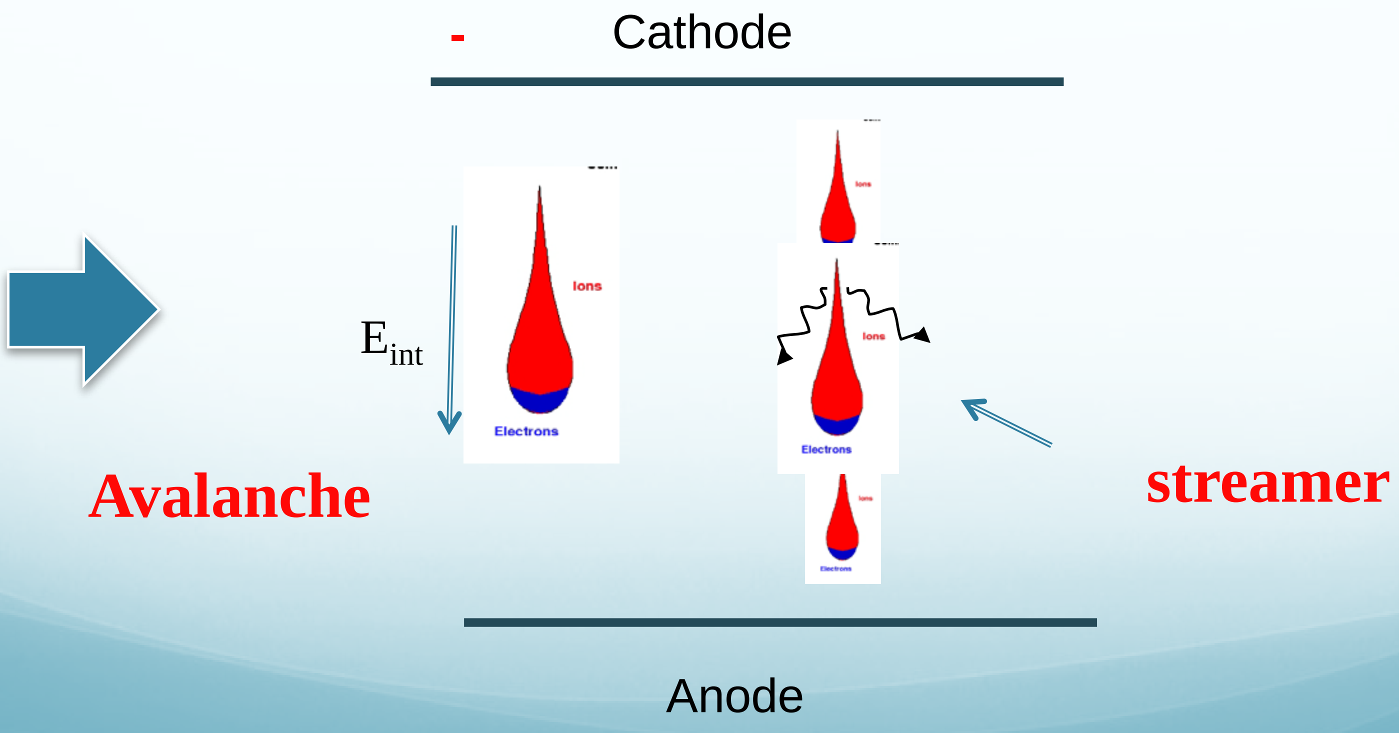
When the $E_{int} = E_{appl....}$ the multiplication process stop.

Ion and electrons recombine with photon emission.

New secondary avalanches can be produced, forming a streamline of continuous flow of charges from one electrode: the "**streamer**"



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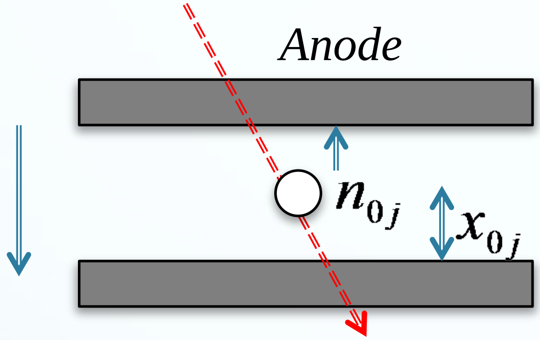
Gas multiplication process

The number of electron produced during the multiplication process can be calculated using a simple model (statistical correction should be taken into account):



Consider the first cluster j due to the primary ionization

n_{0j} and x_{0j} the inizial size and position

The number of produced electrons:

$$n_e(x) = n_{\mathbf{0}j} e^{\eta(x - x_{jo})}$$

η = α-β = effective Townsend coefficient
α = 1/λ = first Townsend coefficient
β= attachment coefficient

A gas electronegative can cause the production of ion⁻ (attachment processes) reducing the number of electrons

$$Q_e(x) = q_{ele} n_{0j} e^{\eta(x - x_{oj})}$$

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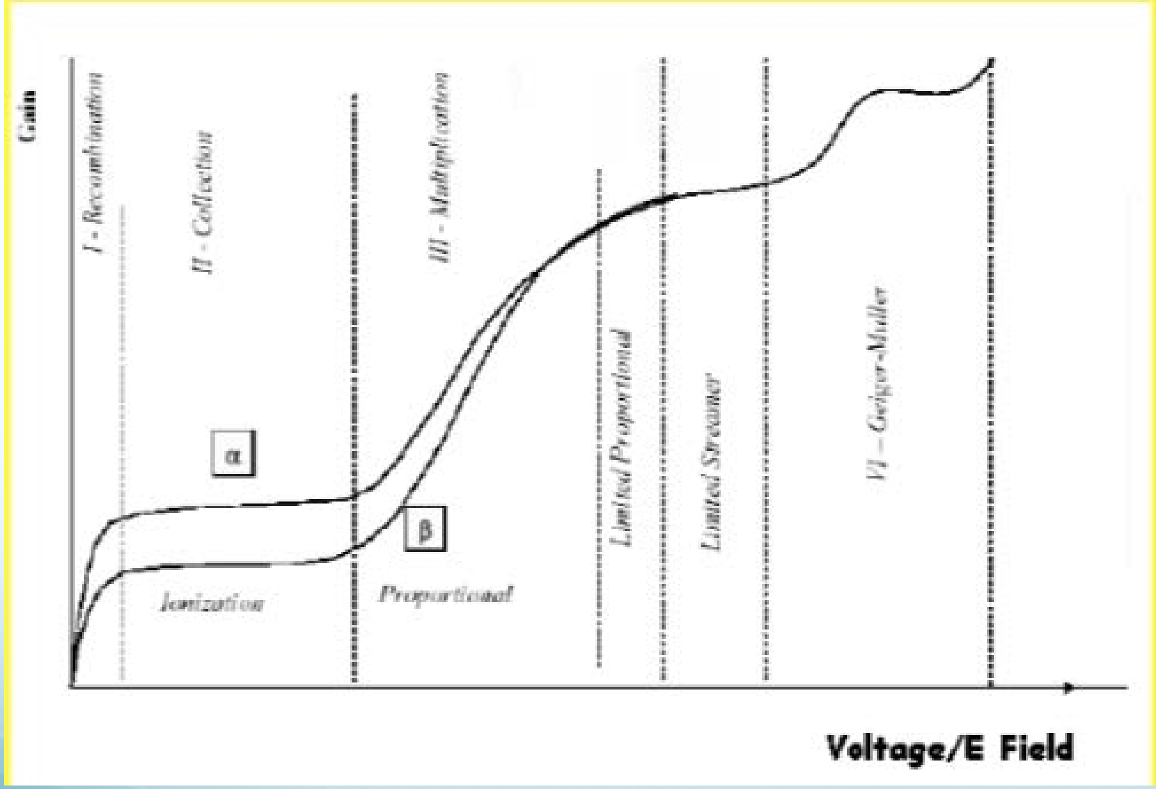
Gas multiplication gain

The gas multiplication gain

$$M = \frac{n_e}{n_{0j}} = e^{\eta(x - x_{oj})}$$



The **intensity of the field** (i.e. the applied voltage) rules the **various amplification mechanisms in the gas.**

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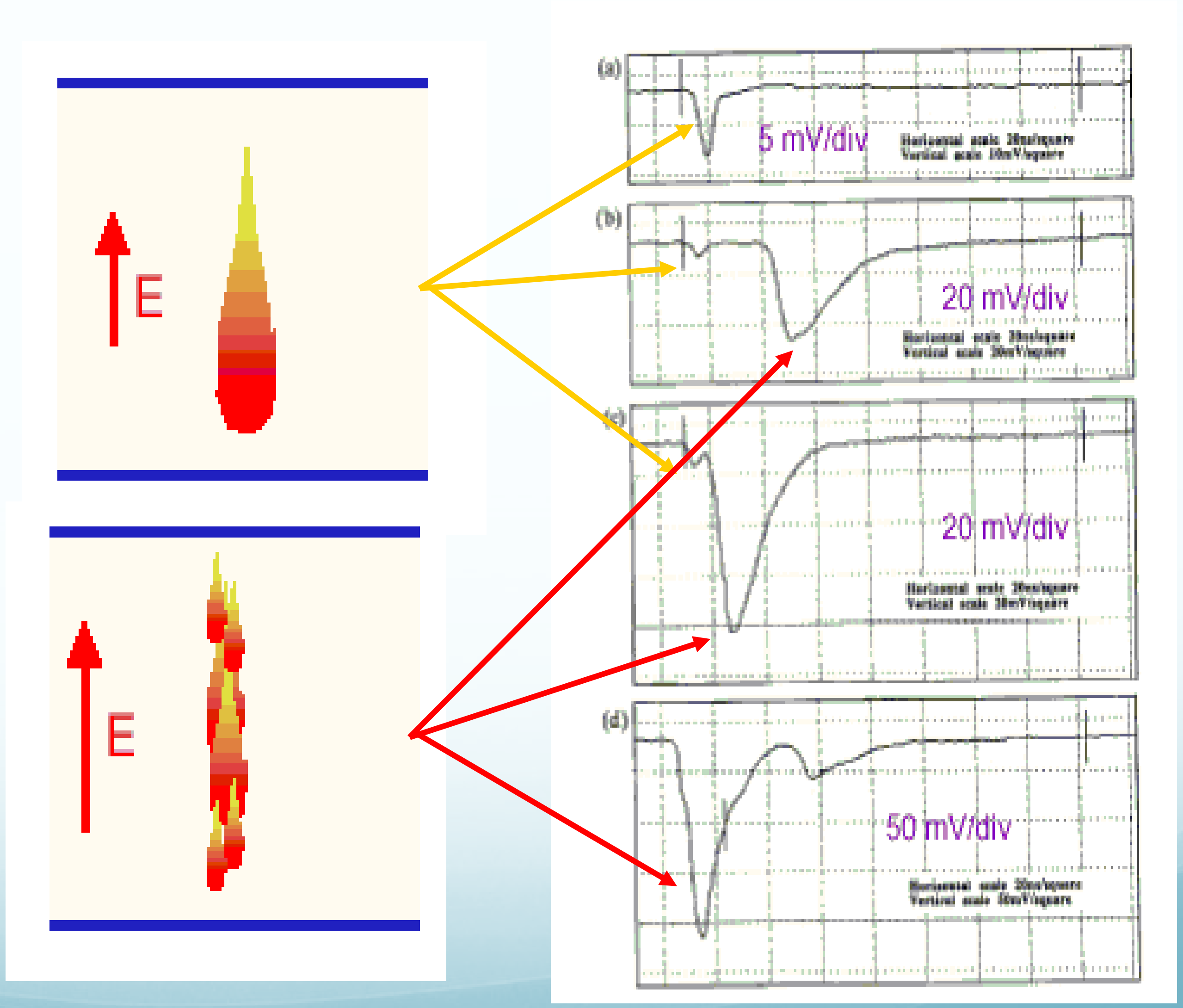
RPC signal example

Avalanche signal

Streamer signal



Signal generation in an RPC

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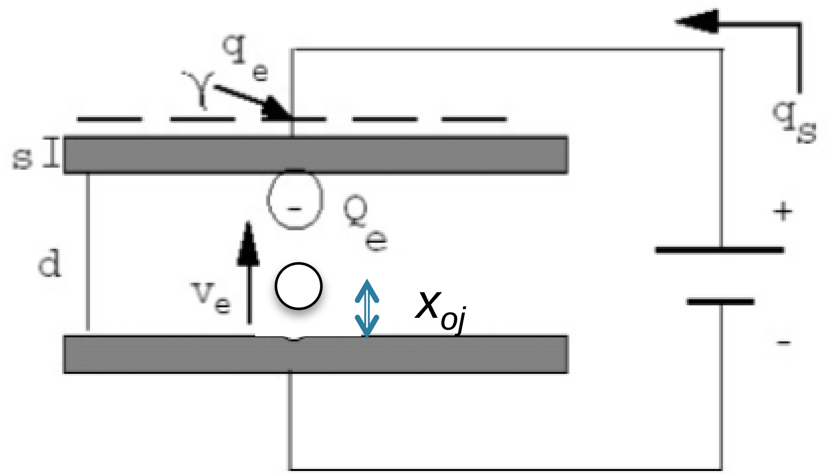
Signal is induced by the charges (electrons and ions) **MOVEMENT** in the gap (the readout strips are completely separated from gas gap)



Simple model of charge formation

the cluster of n_j electrons starts the avalanche

Q_e electronic charge developed

The "fast" charge q_e

$$q_e(x) \cong \frac{Q_{ele}^{tot}}{\eta d} \frac{\varepsilon_r d / s}{2 + \varepsilon_r d / s}$$

To be noted:

- The fast charge is a fraction of the total charge
- It depends by the geometrical parameters, electrodes material and the gas

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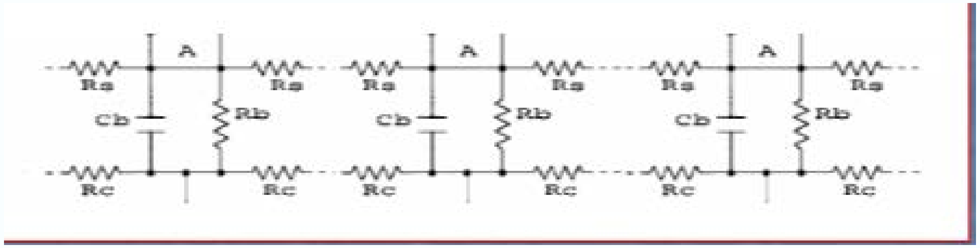
Resistive Plate Chamber

RPC circuit made of elementary cells



Discharging time linked to drift velocity and multiplication factor

$$\tau_{dis} = \frac{1}{\eta v_d} \approx 10ns$$

Time constant for recharge the elementary cell is related to the RC constant

$$\tau_{REC} = \rho\varepsilon_0\left(\varepsilon_r + \frac{2d}{g}\right) \approx 10ms$$

$\tau_{dis} \ll \tau_{rec}$

Self-extinguish mechanism

The arrival of the electrons on the anode is reducing the electric field and therefore the discharge will be locally extinguished.

After the first charge development the electrodes behave like an insulator

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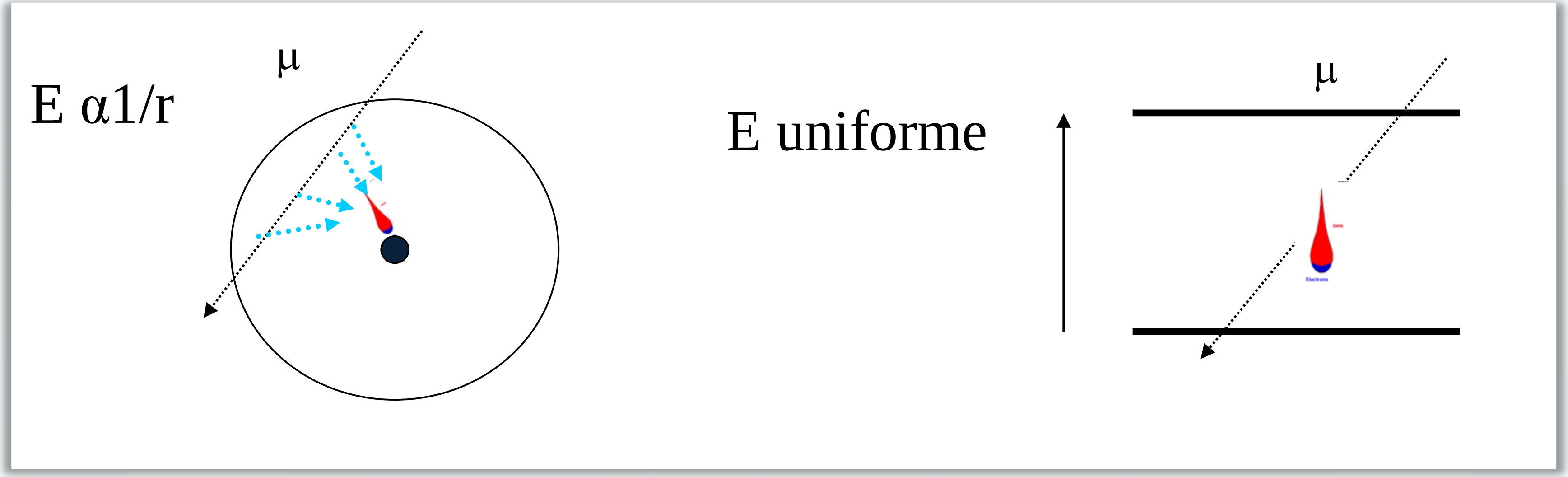
Resistive Plate Chamber



Drift chambers (cylindrical geometry) have an important limitation:
primary electrons have to drift close to the wire before the charge multiplication starts

→ **limit in the time resolution**

In a parallel plate geometry the charge multiplication starts immediately so all the gas volume is active.
→ **much better time resolution (~ 1 ns)**

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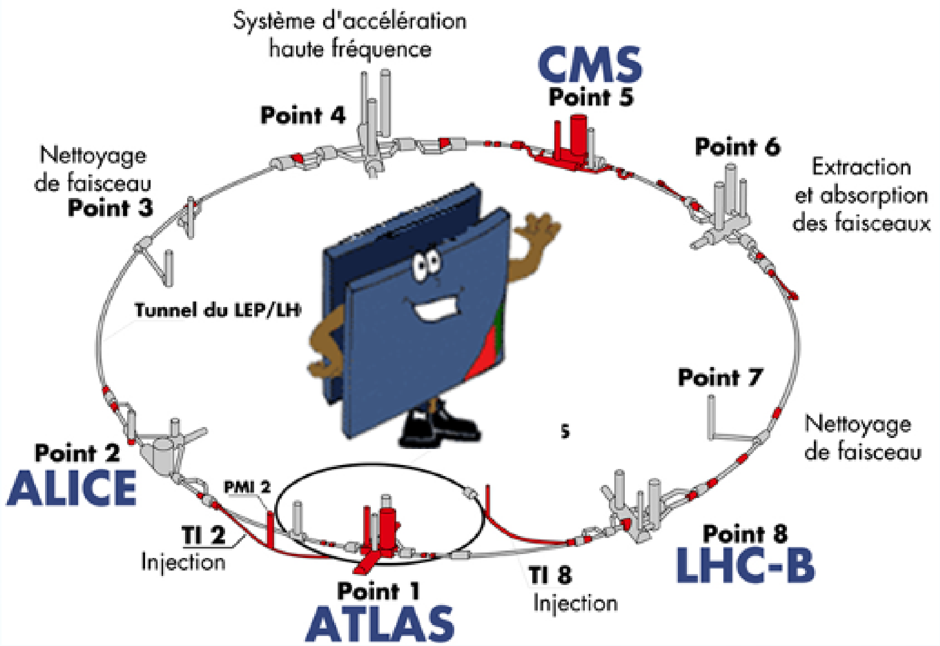
RPC at LHC



New detector need to sustain the expected background condition for 10 LHC year!

Detector requirements:

- **Maximum rate* ≈ 300 - 500 Hz/cm^2**
- **Improved time resolution (<ns) for TOF applications**

***** *at the nominal LHC luminosity 10^{34}cm^{-2} s^{-1}***

2^{nd} generation of RPC

2nd generation of "classic" RPC

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In late '90, a new generation of RPC has been developped:

- **New working mode: *Avalanche mode (saturated avalanche)***
- New gas mixture: Freon-based mixture
- Total charge ~ 20-40 pC (from 0.1 – 1 nC)
  - lower current in the detector → better longevity

- **New electronics** in order to transfer a large fraction of the amplification from the gas to the electronics

→ **good rate capability ~ 500 Hz/cm^2 with high efficiency (> 95 %) and stable conditions for 10 LHC years**

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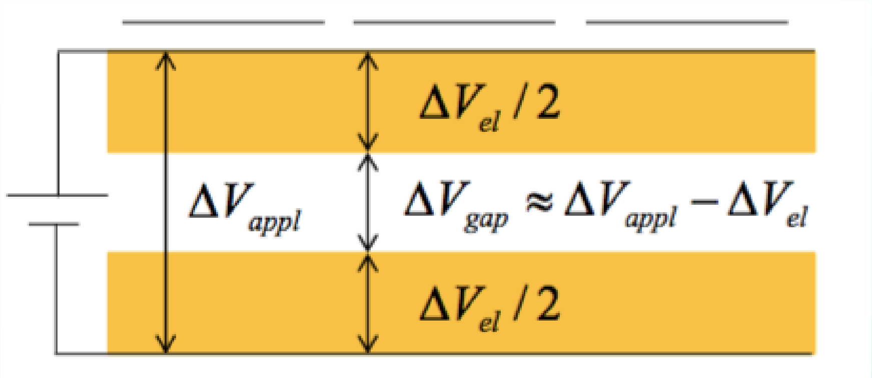
The issue of the rate capability

In the static limit the voltage applied to the chamber ΔV_{gap} is entirely transferred to the gas; but, for a working current I, part of this voltage is needed to drive the current in the electrodes

$$\Delta V_{gap} = \Delta V_{appl} - RI = \Delta V_{appl} - \Delta V_{el}$$



$$\Delta V_{el} = \rho \, d \, \Phi \, \langle Q \rangle$$

Electrode resistivity

Electrode thickness

Particle flux counts/cm^2

To increase the rate capability (i.e the particle flux) we can play with ρ, d and the average charge.

Change of the Operation mode

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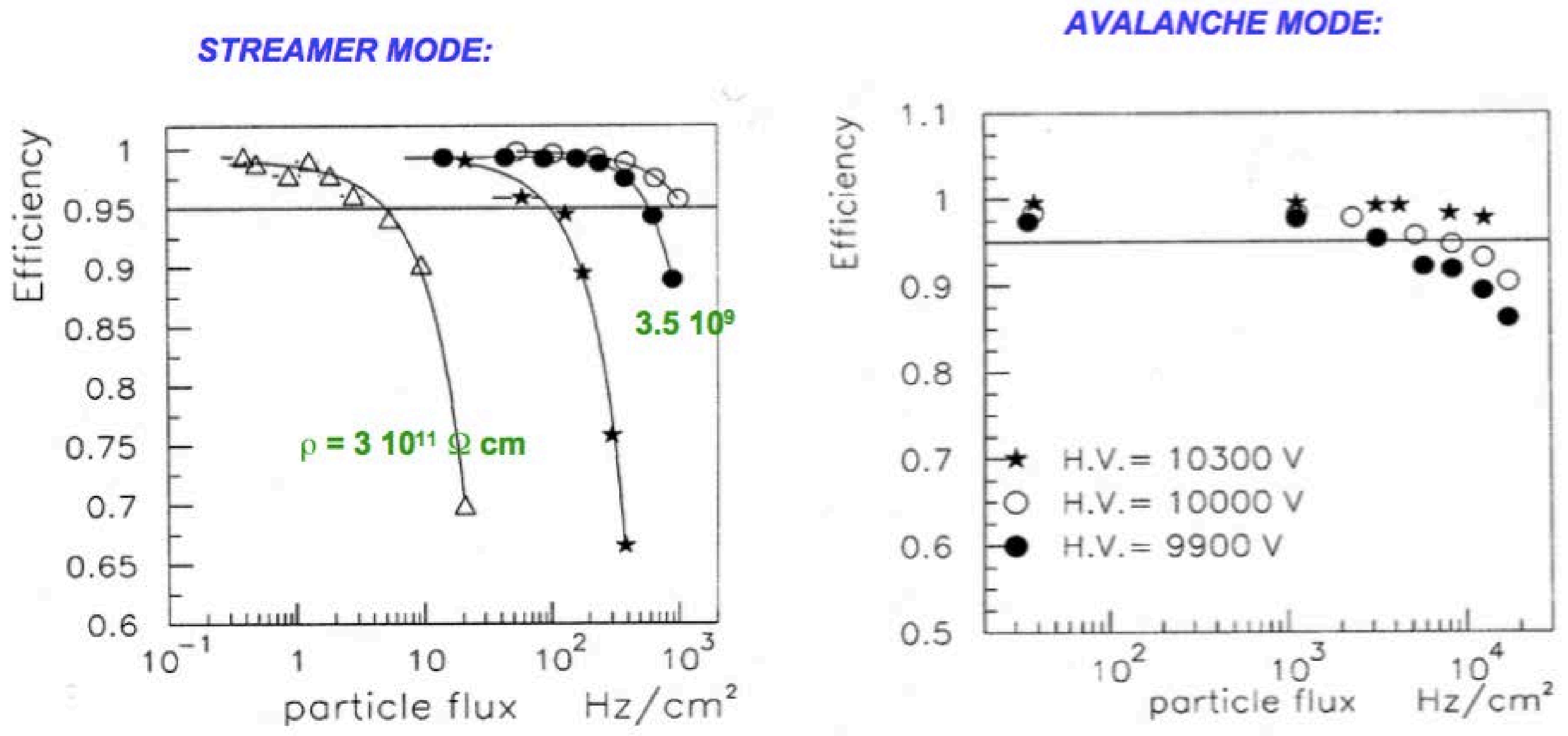

R. Arnaldi et al, Nucl. Physics B (Suppl) 78 (1999) 84

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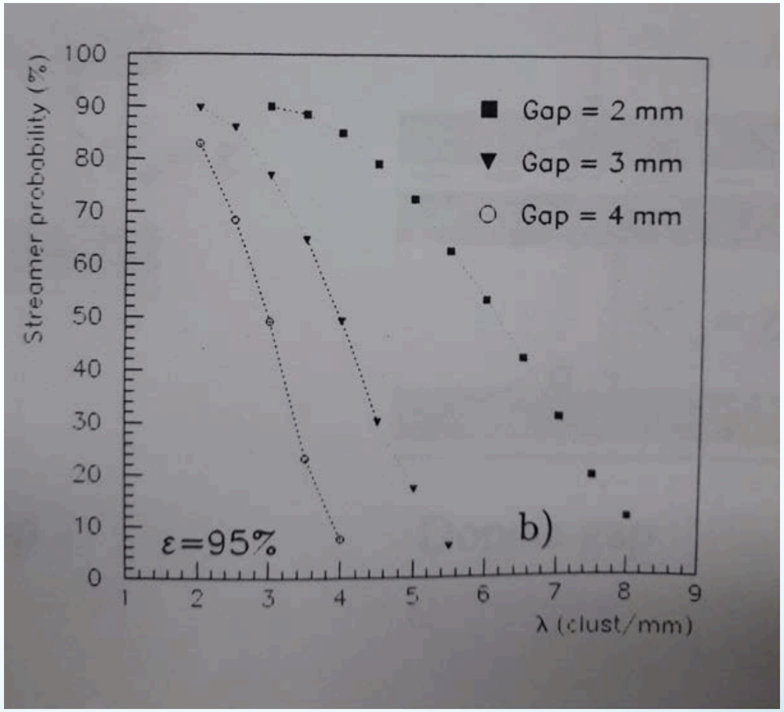
The new gas mixture

Magic gas mixture:

C2H2F4 (95.4%), Iso-butane = 4.5%, SF6 = 0.3 %



In a **streamer mode**, the main gas components should provide a **robust first ionization** signal and a **large avalanche multiplication** for a low electric field→ Argon based gas mixture (λ = 2.5 mm^{-1})

In **avalanche mode,** the main component has to have high primary ionization but with small free path for electron capture. The high electronegative attachment coefficient limits the avalanche electron number → Freon ($C_2H_2F_4$) based gas mixture (λ = 5 mm^{-1})

Plus….a "**quenching gas**" like the **iso-butane** which has an high probability for absorbing ultra violet photons

The new gas mixture (3)

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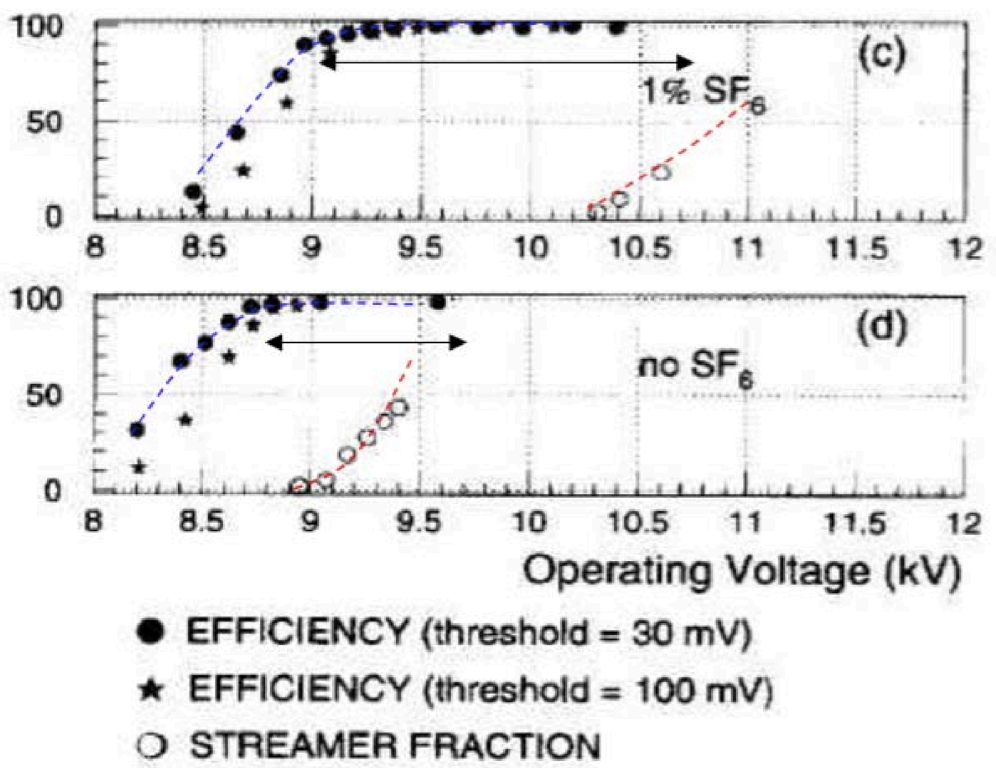
… and a **strong electronegative** gas the **SF6** is also used to control the excess number of electrons and extends the separation between streamer and avalanche



R. Santonico, Scient. Acta XII N2(1997)1

P. Camarri et al, Nucl. Instr. and Meth. A414(1998)317

2nd generation RPC Performance

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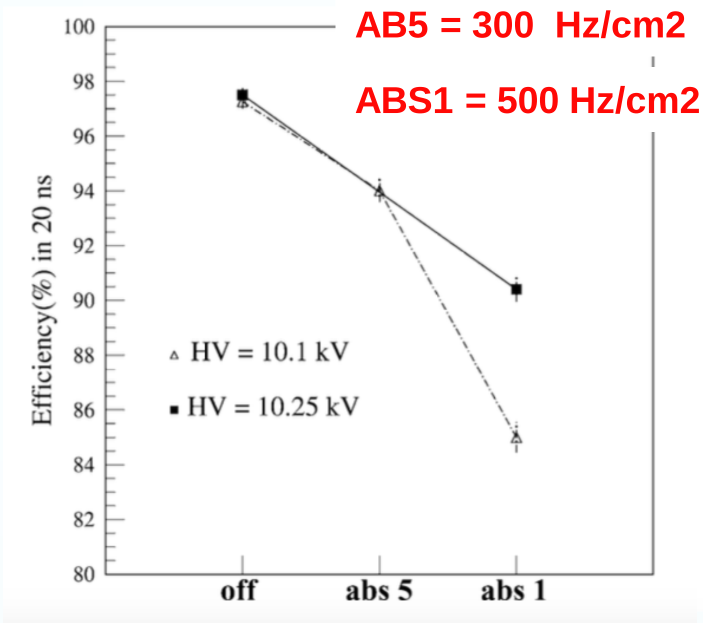
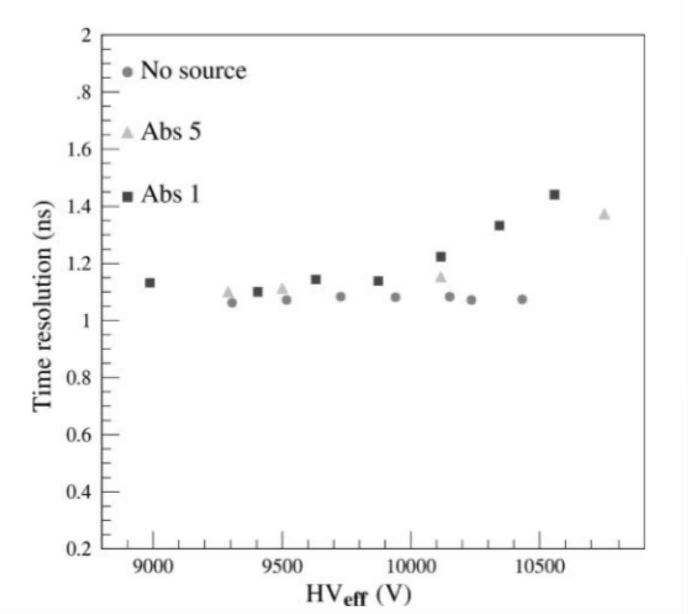
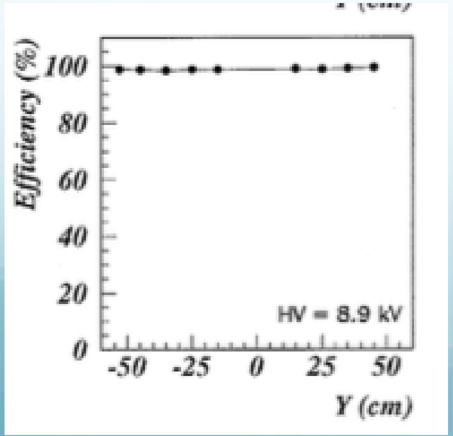
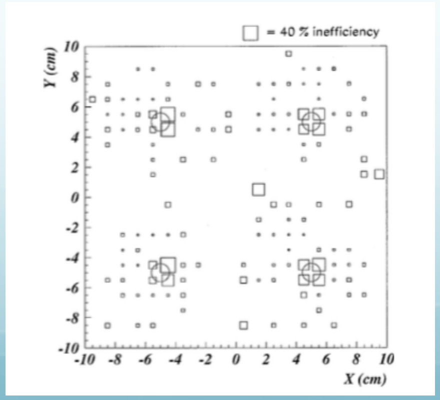


Efficiency vs gamma hits rate



Time resolution vs HV at different gamma background



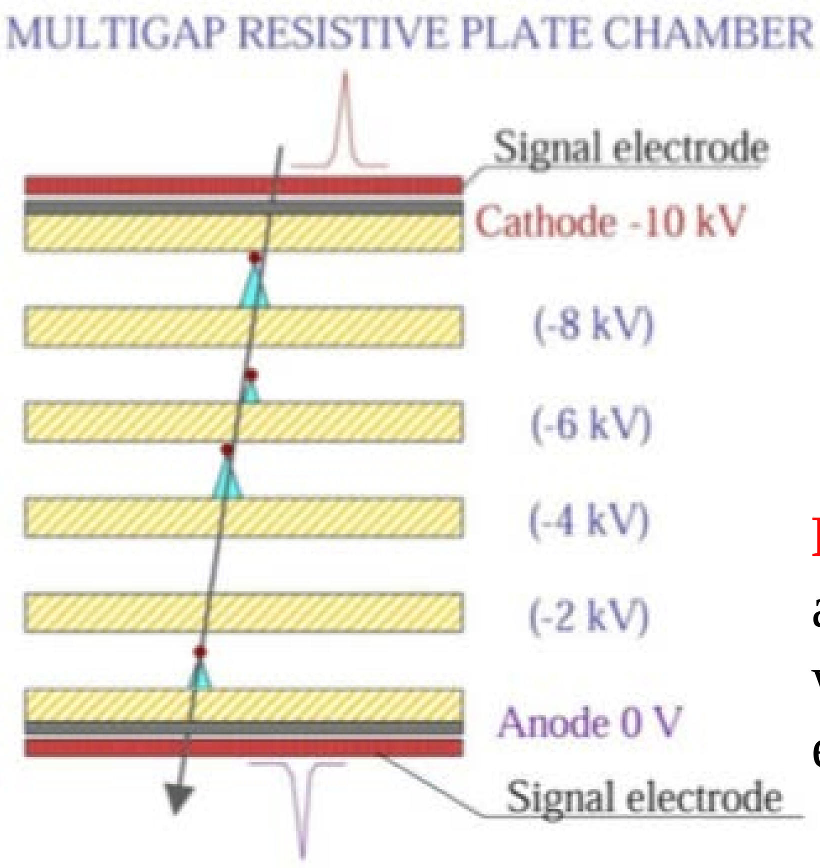


Uniform efficiency!

Multi-gap timing RPC

G. Pugliese

Multi-gap **timing** RPCs: developed by C. Williams for ALICE experiments



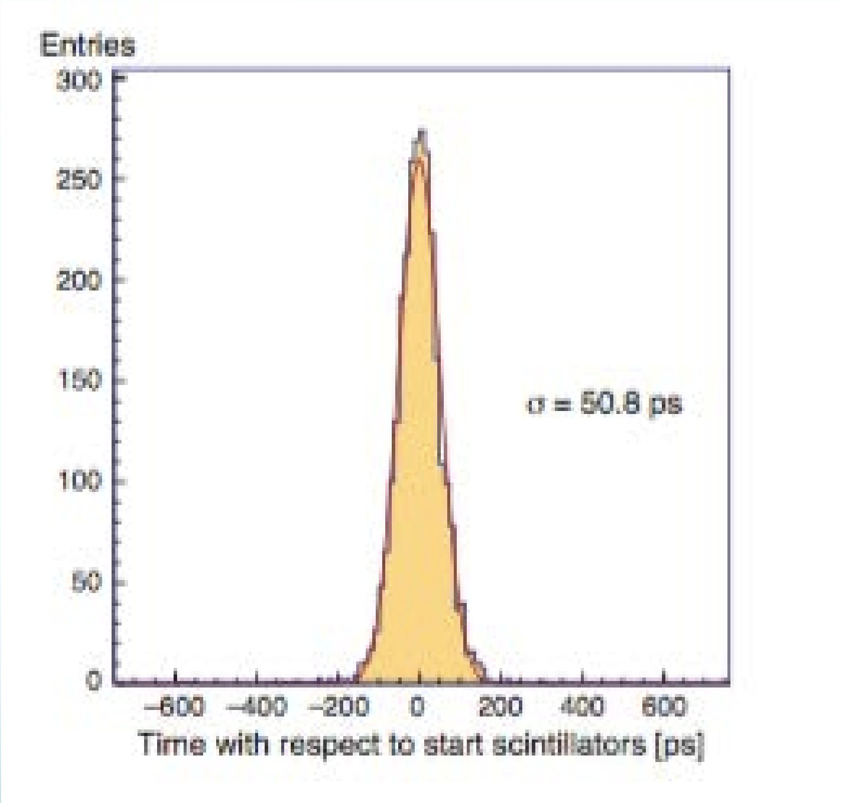
The **key point** to improve the timing is to use very thin gas gaps, in a multi-gap structure, to compensate the reduced primary ionization in the gas (high inefficiency).

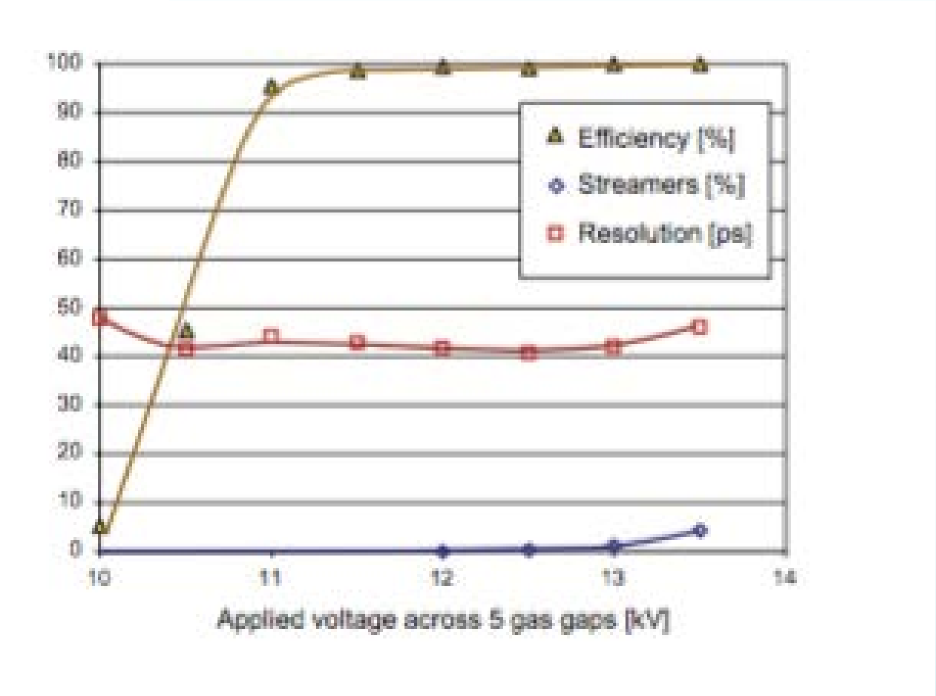
Design: the multi-gap is characterized by a number of floating (glass) electrodes whose potentials scale in such a way to equalize the field in all gaps.

Compared with the single gap design the average charge induced on the pick up electrodes does not change but gives a narrower charge distribution

Performance of Multi-gap RPC

ALICE MRPC





Time resolution ≈ 50 ps

Efficiency and time resolution as a function of the high voltage.
The plateau is more than 2 kV long before the onset of streamers

New challenge: the HL-LHC

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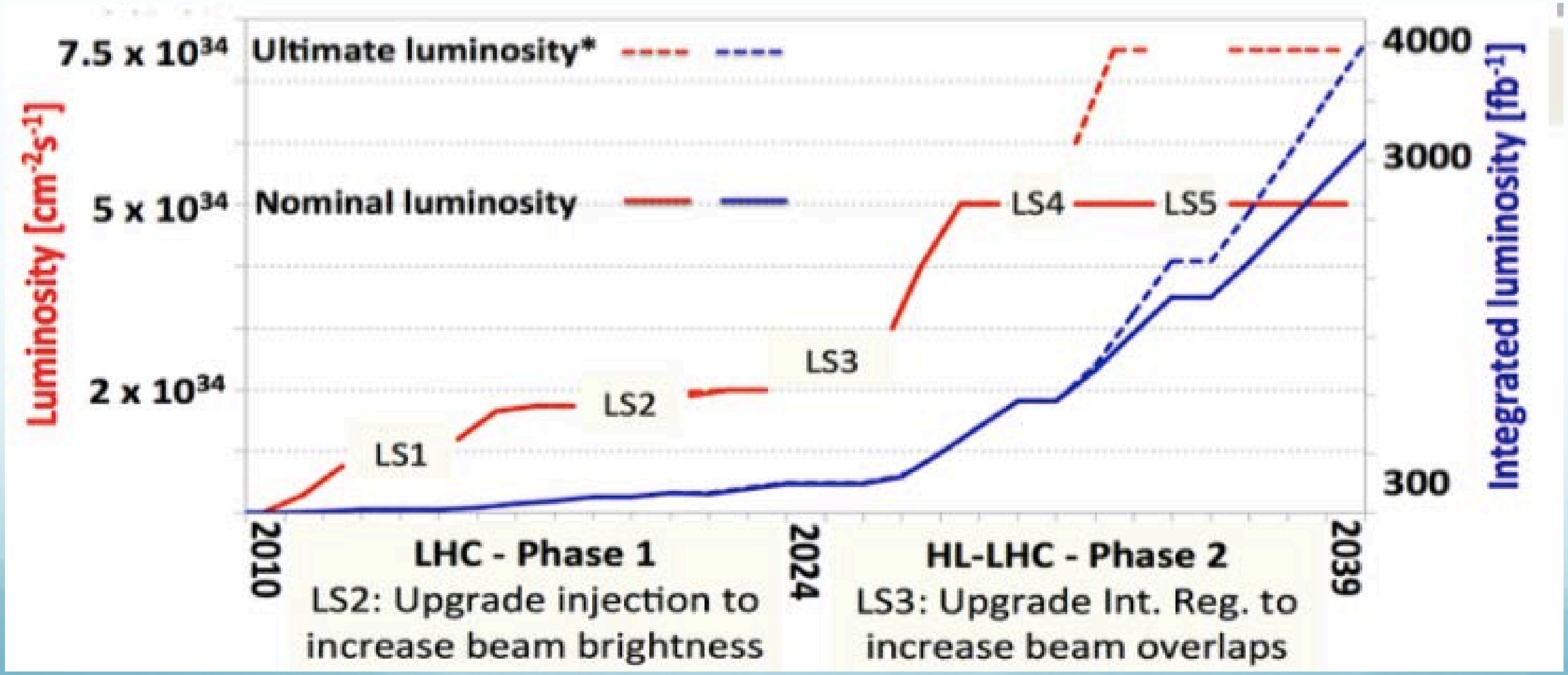
European Strategy for Particle Physics

"***Europe's top priority* should be the *exploitation* of *the full potential of the LHC*, including the high luminosity upgrade of the machine and the detectors with a view to collecting 10 times more data than in the initial design, by around 2030**"



We are here

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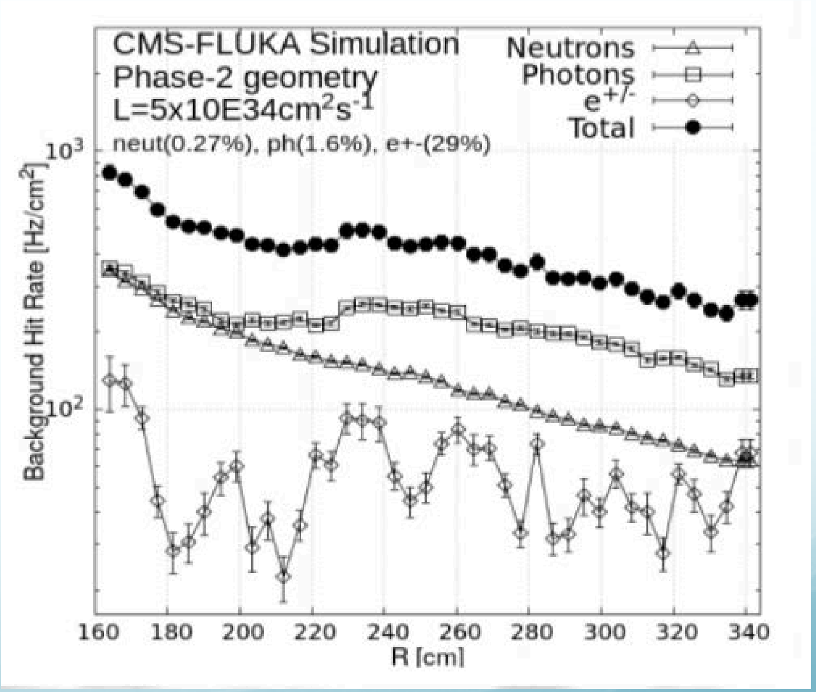
The challenges for the RPC systems in the LHC experiments

➢ Confirm muon system performance at HL-LHC conditions: the RPC systems have to run at **5 times the expected LHC intensity** and for **30 years (instead of 10)** *..the longevity will be covered tomorrow..*

➢ New RPC chambers needed to extend the CMS muon coverage up to $|\eta| < 2.8$ or to improve the trigger perfomance (ATLAS)

➢ **Rate capability ≈ 1-2 kHz/cm²**



3th generation of RPC

Further improve the rate capability

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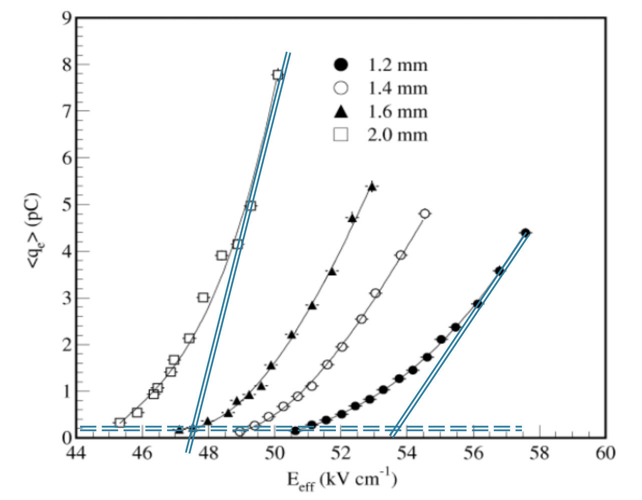
All relevant detector improvement factors have been investigated **to improve rate capability:**

- Reduced electrode resistivity
- **New detector geometry: gas gap and electrodes thickness**
- New Front-End electronics

The key points is to reduce:

- the charge
  - thinner gas gaps: from 2 mm to 1 mm
  - lower electronics threshold

- Thinner electrodes: from 2 mm to 1mm



$$\Delta V_{el} = \rho \, d \, \Phi <Q>$$

The role of the electrodes thickness

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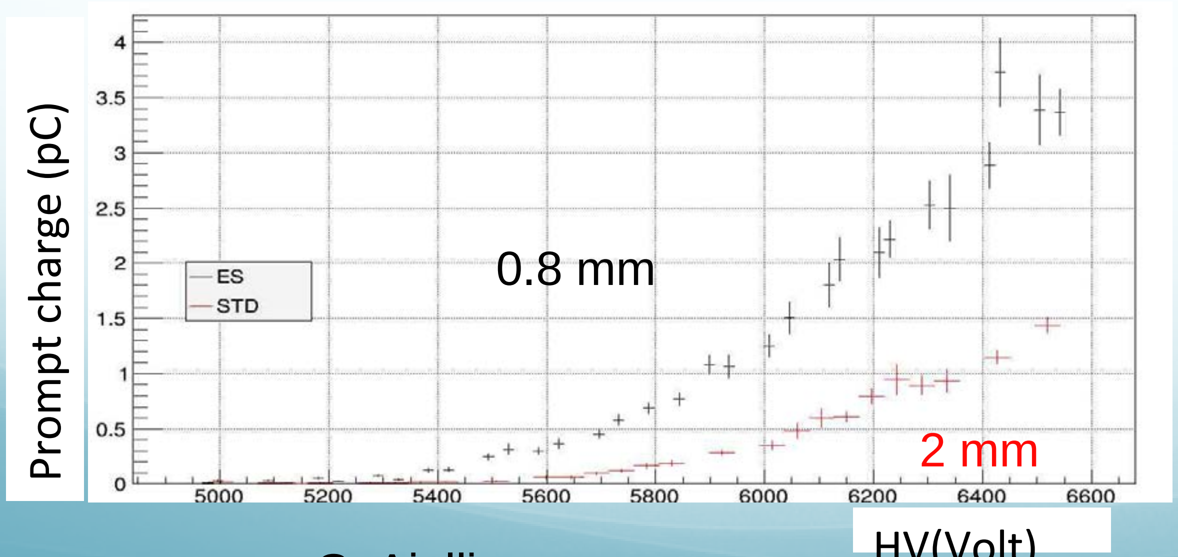

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More than a factor of 2 of collected signal

$$q_e(x) \cong \frac{Q_{ele}^{tot}}{\eta d} \frac{\varepsilon_r d / s}{2 + \varepsilon_r d / s}$$

CMS improved RPC performance

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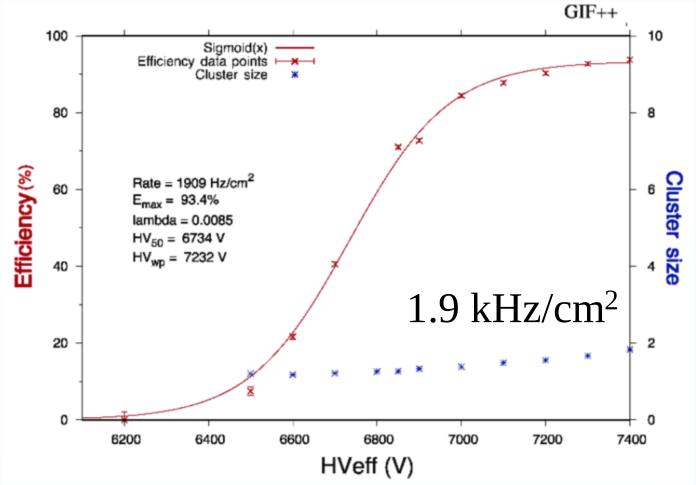
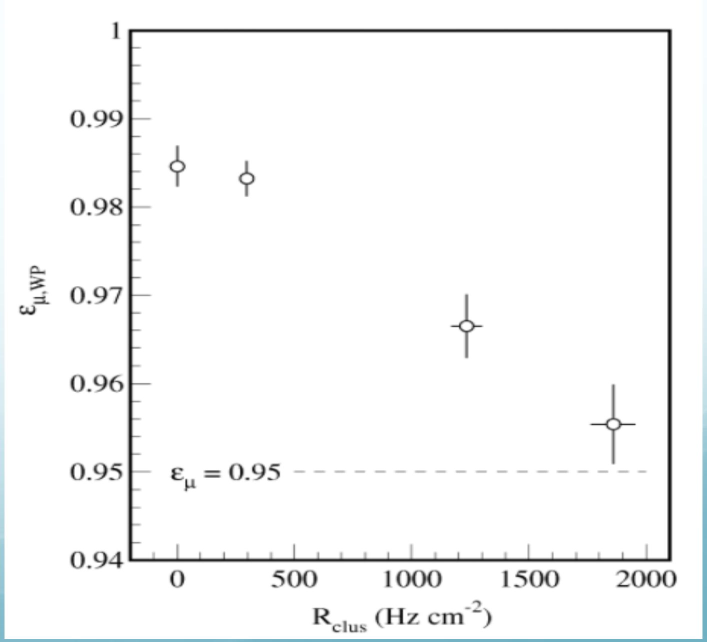
	New RPC	RPC
High Pressure Laminate thickness	1.4 mm	2 mm
Num. of Gas Gap	2	2
Gas Gap width	1.4 mm	2 mm
Resistivity (Ωcm)	0.9 - 3 x 10^{10}	1 - 6 x 10^{10}
Charge threshold	50 fC	150 fC
η segmentation	2D readout	3 η partitions





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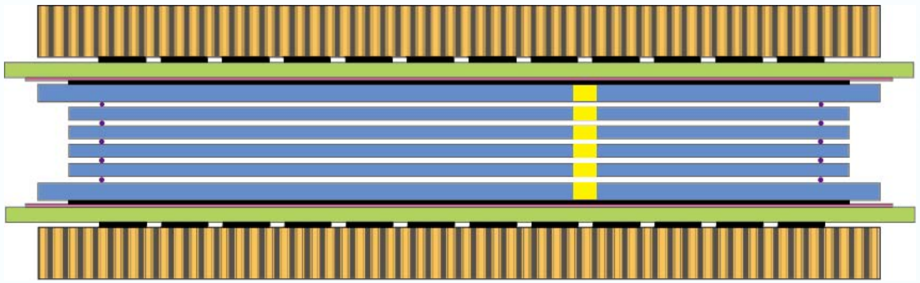
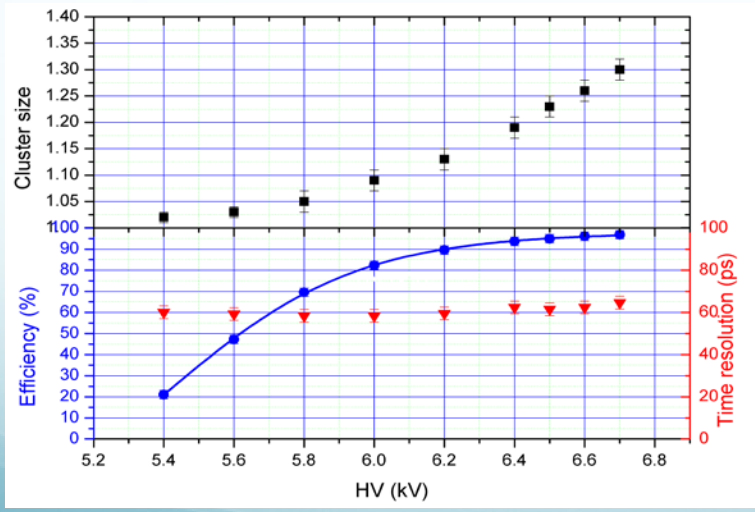
“New” Multi-gap GRPC

New Multi-gap GRPC build using
low resistive glasses (~ 10^{10} Ωcm)

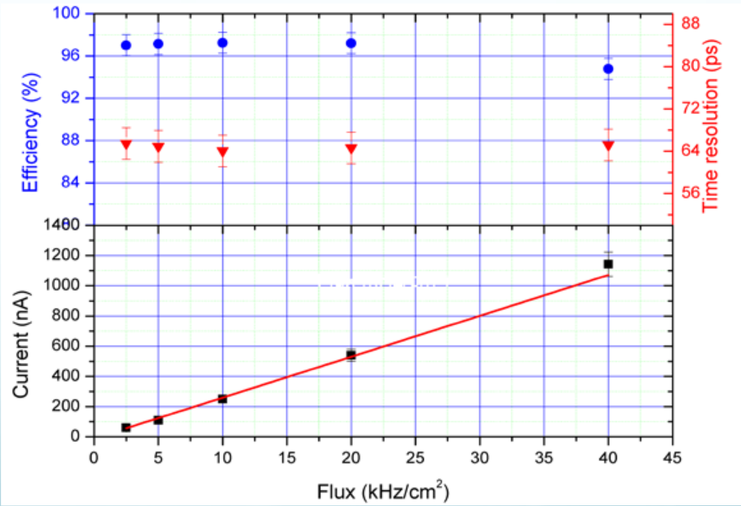
Rate capability: Eff ~95% up to 20 kHz/cm²
Time resolution ~60 ps



Thickness electrode: 0.7 mm
Gap geometry: 5 gas gaps with width of 250 μm
Gas Mixture: 90% TFE + 5% isoC_4H_{10} + 5% SF_6



Cluster size, efficiency and time resolution as function of the applied HV.



Efficiency, time resolution and current as function of the beam flux.

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Conclusions: the RPC from 1981 to nowadays

- **Rate capability** from 10 Hz/cm^2 to 30000 Hz/cm^2
- **Time resolution** from 1 ns to 60 ps
- **Space resolution** from 1 cm to 0.01cm
- But performance is not all: the increase is obtained while keeping the same simple structure which always allowed to scale the detector to large surfaces

The Secret?

- Simple physics laws and right choice of materials do most of the job
- The physical event is very local in space-time. A discharge (local) can never evolve in spark (global)
- Better electronics → better performance → widely span over the avalanche dynamical range

Spare

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RPC: basics

Why we need high (volume) resistivity electrodes ?

- To localize the discharge that takes place inside the detector (better on this later on)
- Only a limited area around the discharge remains inefficient to the next event

The same mechanism is also done by the gas mixture that contains iC_4H_{10} as a UV quencher and SF_6 as electron quencher

Why we need a semi conductive layer?

- To see the induced signal into the pick-up strips (signal is affected by the surface resistivity of the semi conductive layer)

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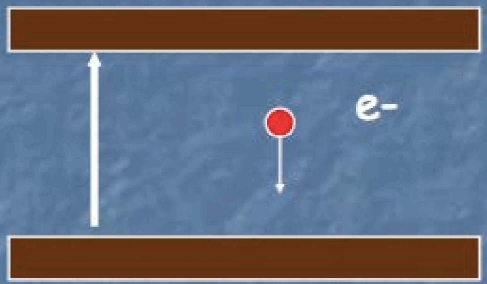

$$i = -q\vec{E}_w \cdot \vec{v}$$

Now v and E have opposite versus and

We have also a different $E_w = k/d$, k depending on the geometry and on the material of the electrodes...

$$i(t) = q(t)\frac{k}{d}v(t) = q_0 e^{\alpha v t}\frac{k}{d}v$$

$$Q_i(t) = \int i(t)dt = q_0\frac{k}{\alpha d}(e^{\alpha v t} - 1) \approx q_0\frac{k}{\alpha d}e^{\alpha v t}$$

It is interesting to note that the ratio of the induced charge and the total charge inside the detector is

$$\frac{Q_i}{Q_{tot}} = \frac{k}{\alpha d}$$

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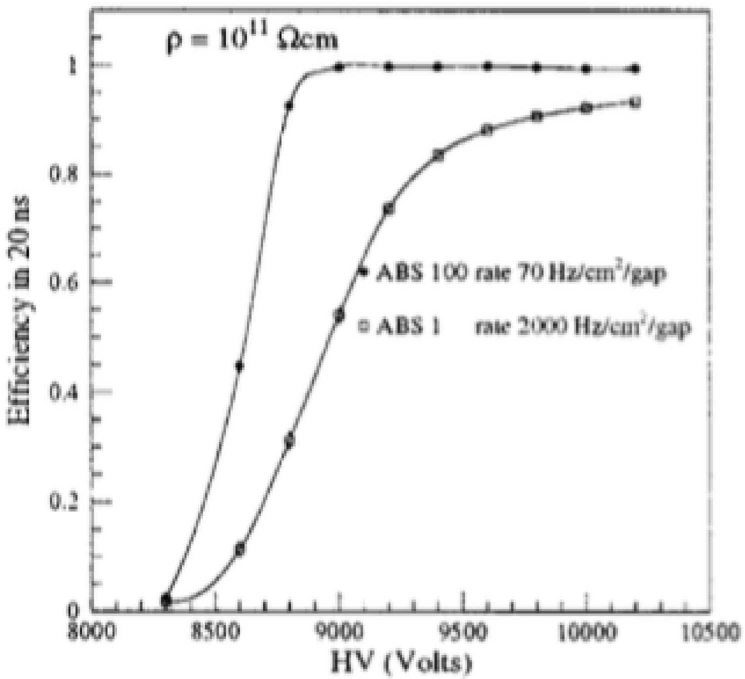
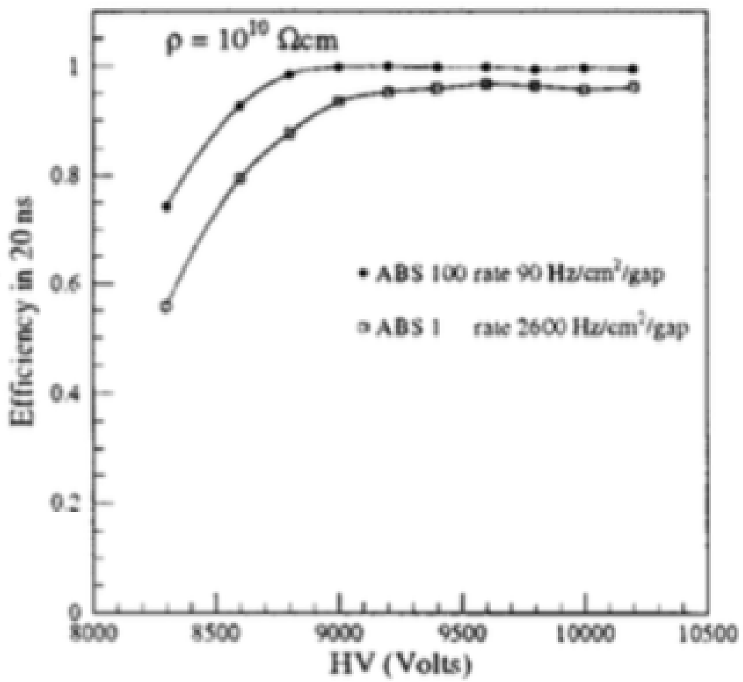
Reduced resistivity





M. Abbrescia et at. NIM, 434 (1999), 244-253