

Design and construction of RPC detectors

G. AIELLI

RPC technical challenges vs. construction

Features challenges and limits of RPCs

3

G. Aielli - ISU
10/15/2026

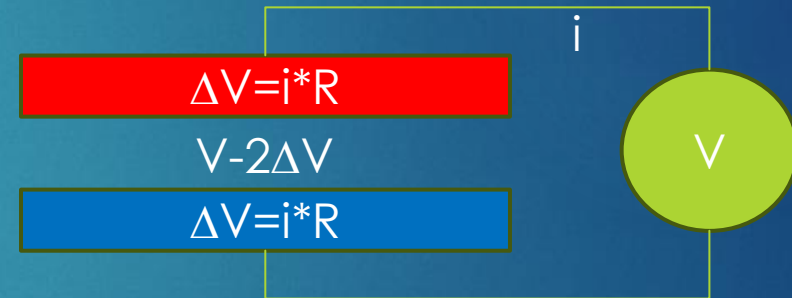
- ▶ RPCs are fast and time sharp
 - ▶ Been used for many applications where timing is crucial
- ▶ “Easy” and “Cheap”
 - ▶ So they are often built in very large modules
 - ▶ As thin as possible gas gaps for better timing
- ▶ Most wanted: large-size, thin, fast signal devices,
- ▶ ...and yes, with very sensitive electronics...
- ▶ Competing requirements challenge:
 - ▶ mechanical:
 - ▶ Uniformity of gas change, rigidity, planarity, surface roughness and large surface
 - ▶ Electronic:
 - ▶ External and self-induced noise, reflections, sensitivity of electronics to all that
- ▶ We will touch those points in the next slides

Resistive Plate Chamber

4

G. Aielli - ISU
10/15/2026

- ▶ One of the primary features of the RPC is the resistive electrodes
- ▶ Requirements:
 - ▶ Uniformity: a continuous piece of material industrially produced
 - ▶ a volume resistivity ranging in between $10^8 - 10^{12} \text{ Ohm cm}$
 - ▶ Relative Dielectric constant around 5-7
 - ▶ The resistivity should be stable in the detector lifetime $\rightarrow$ carriers non depleted
 - ▶ A continuous resistive layer is needed to localize the discharge, but it limits the rate capability: in presence of a uniform background, the voltage drop is $\Delta V = IR = \langle Q \rangle (pC) \cdot f (Hz) \cdot \rho (Ohm cm) \cdot \frac{d}{s} (cm^{-1})$

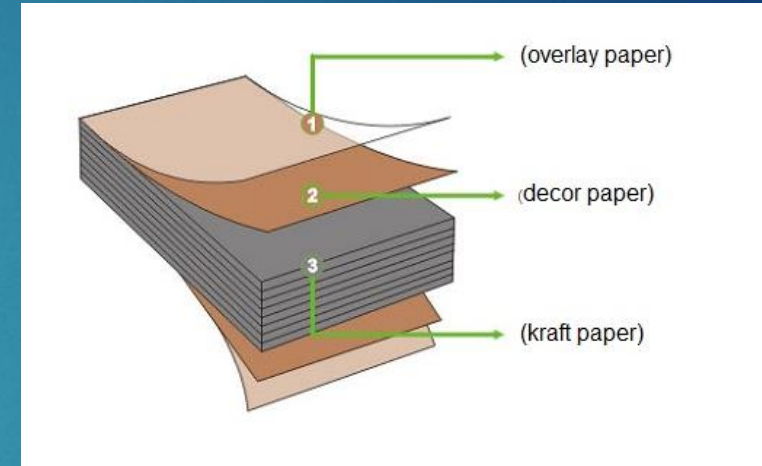


- ▶ Having $d=1 \text{ mm}$ of electrode thickness and $\rho = 10^{10} (Ohm cm)$, a current of $10 \mu A$ given by a 1 MHz/m^2 of MIPS producing in average 10 pC of avalanche charge, would produce a field of 1 V/mm in the electrode
 - ▶ To be compared to the typical applied field of about 5000 V/mm
- ▶ The field in the electrode should be “small” to have most of the field on the gas. Vice versa this limits the rate capability (through the voltage drop) and the longevity by depleting the electrode

Resistive Plate Construction

5

- ▶ Such resistivity range is not common for large plates of materials. Most commonly used material:
 - ▶ High Pressure Laminate ranging between 10^9 and 10^{12} Ohm cm
 - ▶ Low cost per unit surface
 - ▶ High mechanical stability
 - ▶ Carriers are water ions (internal water concentration goes in equilibrium with the environment)
 - ▶ The plate is in between 1 and 2 mm
 - ▶ It is produced by pressing together at high temperature a core of several layers of kraft paper impregnated with phenolic resin, finished externally with melamine impregnated paper.
 - ▶ The hot press produces the resin polymerization
 - ▶ The melamine provides a harder surface and carries most of the resistivity

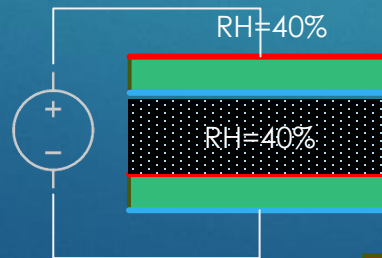
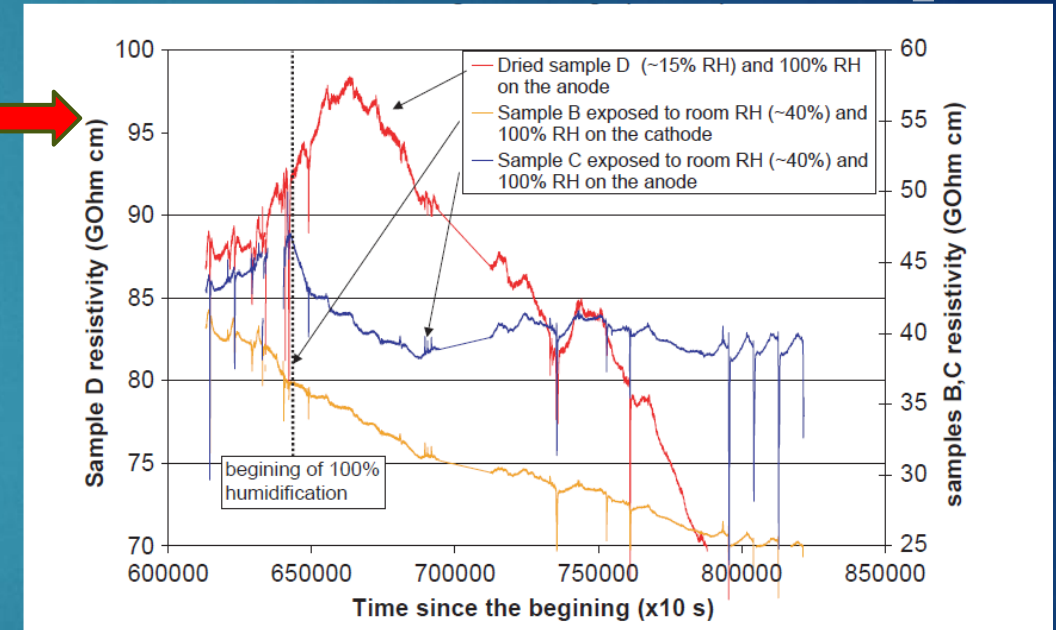
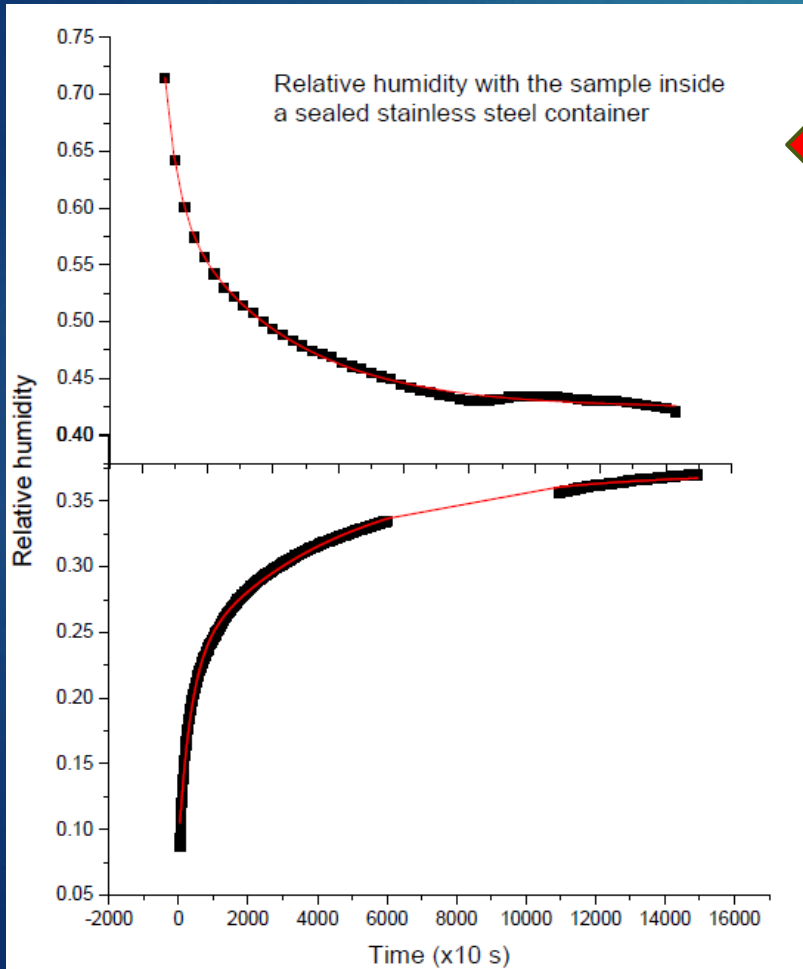


Resistive Plate Endurance

6

- ▶ HPL is hygroscopic
- ▶ It behaves as porous water container setting surrounding environment to an equilibrium point around 40% RH

- HPL ELECTRICAL CONDUCTION IS MEDIATED BY WATER IONS
- A CONSTANT AVAILABILITY OF WATER MOLECULES AT THE ELECTRODE ANODIC FACE, GUARANTEES A STABLE CONDUCTIVITY



- TO EXPOSE THE ANODE SIDE OF EACH RPC ELECTRODE, BOTH ENVIRONMENT AND GAS MUST BE KEPT AT CONSTANT RH (AROUND 40%)

Resistive Plate Construction

7

G. Aielli - ISU
10/15/2026

- ▶ The other commonly used material is glass
- ▶ **Soda-lime glass:** The typical resistivity is $10^{12} \Omega$.
 - This is the most commonly used type of glass in RPC detectors.
 - It provides a good combination of:
 - **Surface resistivity uniformity**, which is crucial for the consistent operation of the chamber.
 - **Mechanical stability**, to maintain the flatness of the plates.
 - It is relatively inexpensive and easy to process.
- ▶ Drawbacks are the weight, fragility, and high resistivity, making it suitable for cosmic rays experiments.
- ▶ Must be operated with a dry gas if in presence of fluorinated gases, since glass is very sensitive to HF
- ▶ Advantage: more rigid and higher mechanical precision than HPL → suitable for very thin electrodes
- ▶ It is the election material for the micro-multi gap RPCs where the electrode thickness is of the order of 0.2 mm

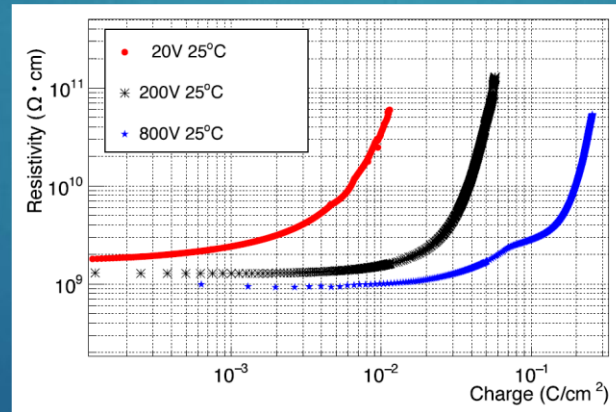


Resistive Plate alternatives

- MRPC → EXTREME EXPLOITATION OF THE DETECTOR GEOMETRY TO EXTRACT THE MOST OF $\langle Q \rangle$
 - E.G. ALICE: 10 GAS GAPS OF 0.25MM WITH 0.4 MM ELECTRODES
- MAIN LIMITATION → THIN FLOAT GLASS LIMITED TO $< 1 \text{ kHz/cm}^2$ DUE TO $\rho \sim 10^{12} \Omega/\text{cm}$.
- NEW MATERIALS WITH LOW RESISTIVITY (DOWN TO $10^9 - 10 \Omega/\text{cm}$) → (CERAMICS, PLASTICS, GLASS,...)

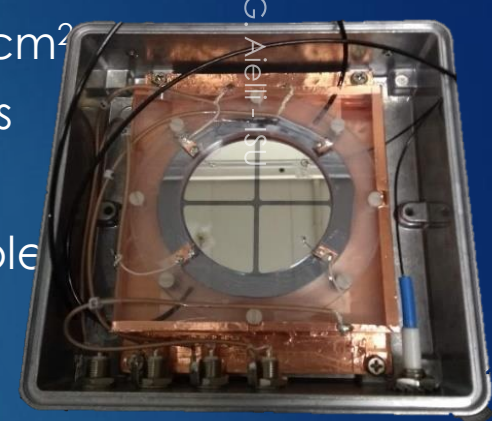
(10.1016/J.NIMA.2006.12.027, 10.1016/J.NIMA.2010.08.076, 10.1016/J.NIMA.2020.363483, 10.1088/1748-0221/14/09/C09007, [HTTP://CDS.CERN.CH/RECORD/2319919](http://cds.cern.ch/record/2319919))

- CARRIER DEPLETION EFFECTS → R&D NEEDED
- MATERIAL NON-HOMOGENEITIES FOR LARGE SIZES
- THINNING ELECTRODES STILL POSSIBLE.
- FORCED (NO DIFFUSION) GAS DISTRIBUTION
- LARGE MARGIN ACHIEVABLE BY LOWERING $\langle Q \rangle$



A new device: single gap semi-conductor RPC
[electronic carriers can not be depleted]

- ▶ Counting rate $> 40 \text{ kHz/cm}^2$
- ▶ 0.6 mm GaAs electrodes
- ▶ Resistivity $1.4 \times 10^8 \Omega/\text{cm}$
- ▶ 1 MHz/cm² seems possible
- ▶ Active area 6.25 cm^2
- ▶ [10.1088/1748-0221/15/12/C12004](https://doi.org/10.1088/1748-0221/15/12/C12004)



FFC TARGET → improve by a further order of magnitude by lowering R

Resistive Plate Chamber - surface

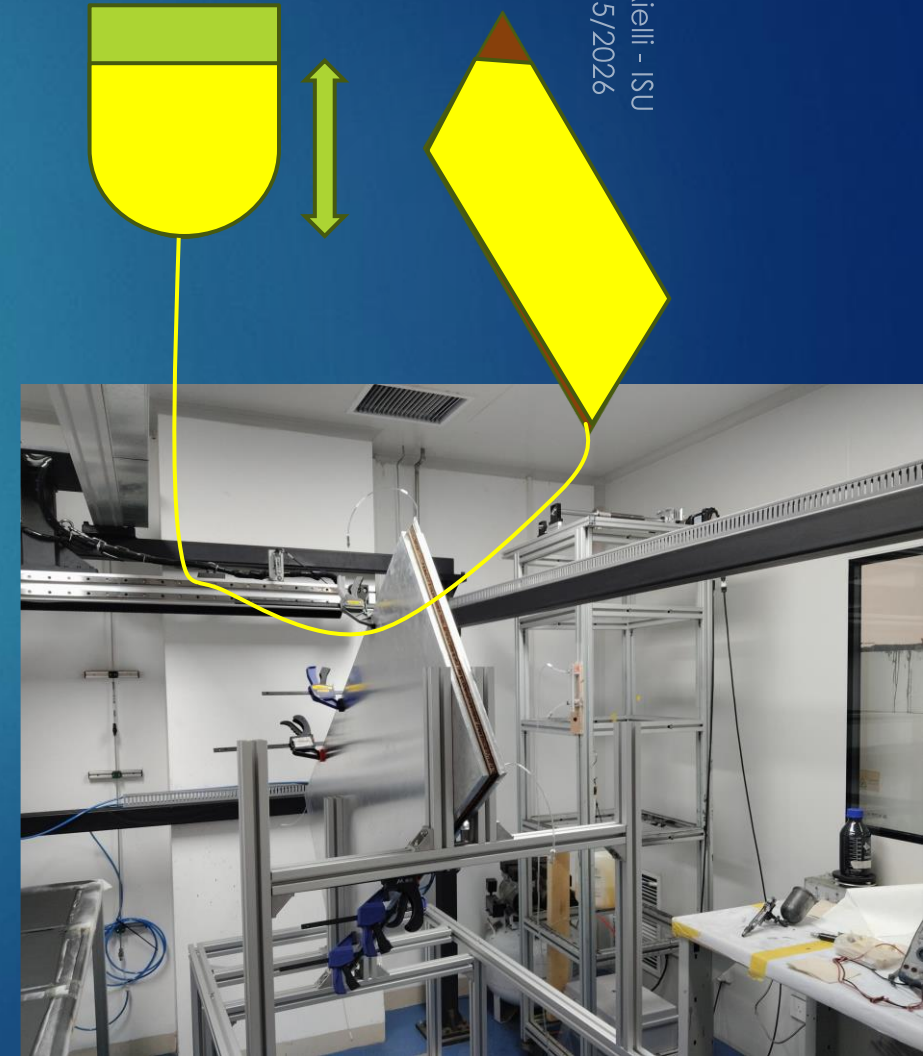
9

- ▶ The other characterizing feature is the uniform and strong electric field → plate configuration.
- ▶ The advantage is the production of a signal without delay and the naturally achieved 3D+t localization of the hit with high space-time resolution, on large surfaces.
- ▶ The disadvantage is that it is difficult to maintain such a configuration in a stable way, due to the spontaneous electron emission from the electrode surface, by edge effect (cold electron extraction)
- ▶ The resistive plate prevents the lateral propagation of the discharge, but the spontaneous discharges may overwhelm the detector response
 - ▶ This is affecting in particular HPL electrodes → the surface finishing is determined mechanically determined by the press iron plate finishing. Moreover, HPL is a multilayer polymer. The expected local roughness distribution is wide, with an average of the order of 1 μm
 - ▶ Glass is a liquid so naturally smooth (roughness from 10 to 100 nm)
 - ▶ silicon is a crystal cut along a specific layer (roughness of the order of a few nm)

Resistive **Plate** Chamber – HPL case

10

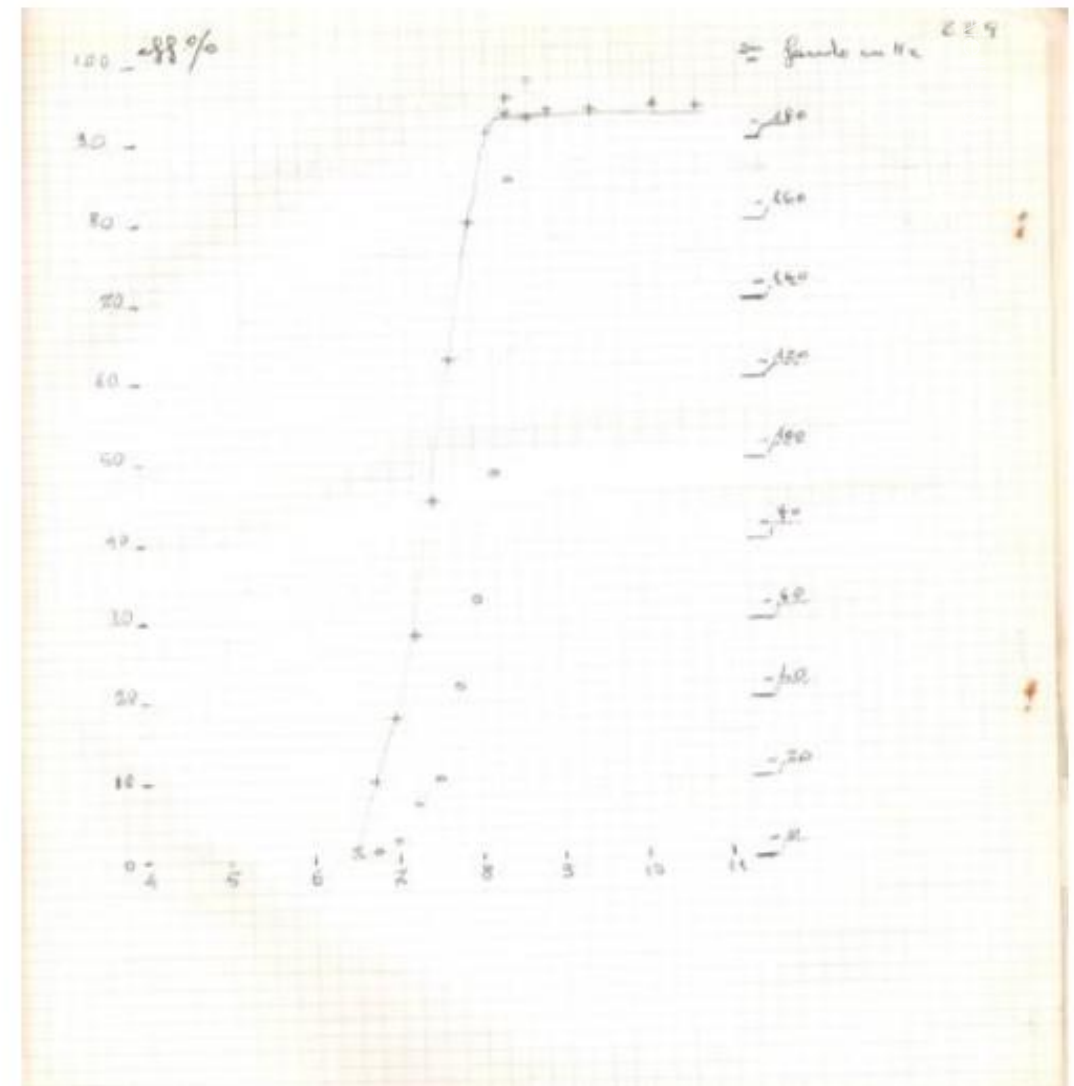
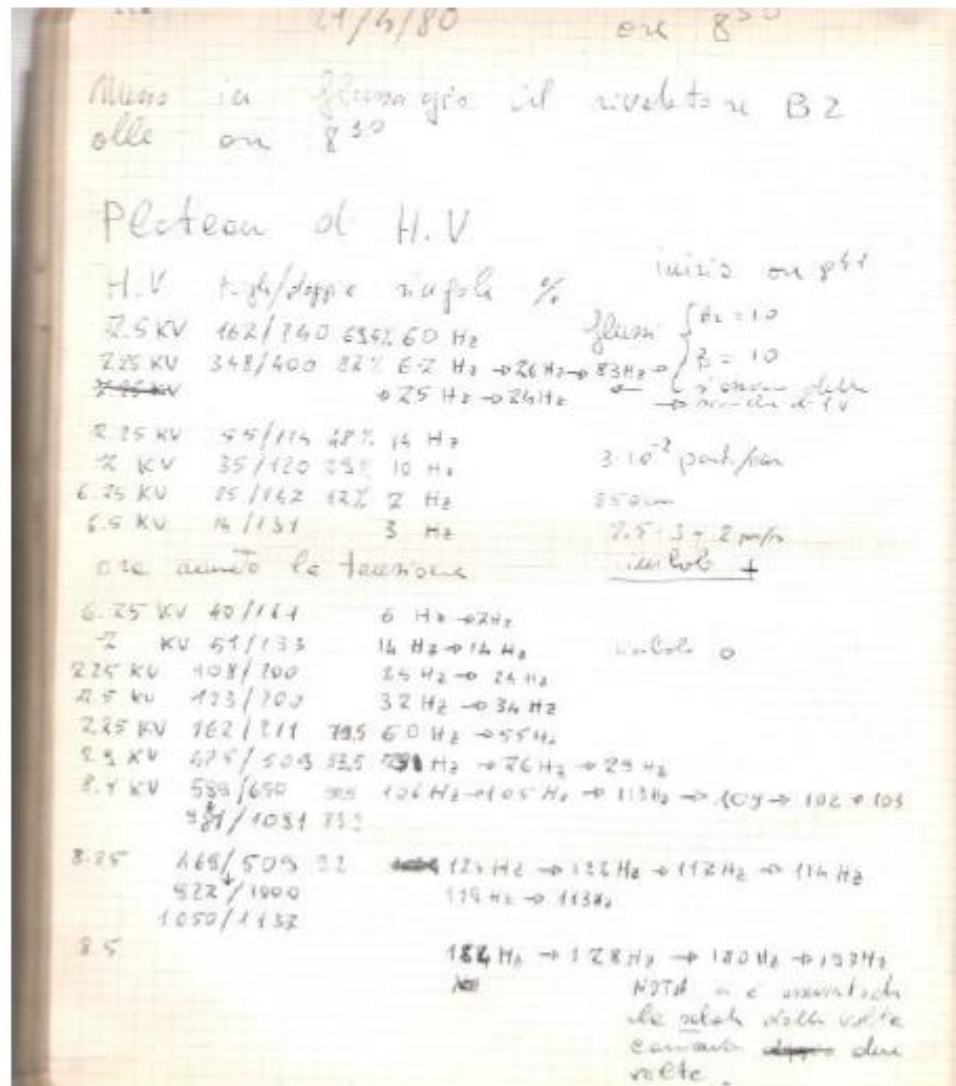
- ▶ HPL was the first material used for RPCs
- ▶ A very special procedure has been invented to have a glass-like finishing
- ▶ Varnishing the internal surface with a few μm layer of linseed oil
 - ▶ Linseed oil was the “secret” of the Flemish painters in the XVI century...
 - ▶ Upon polymerization, linseed oil forms a hard and glossy surface, and its resistivity is similar to the one of HPL
 - ▶ Oiling is applied by slowly filling and emptying gas volumes vertically held, with a mixture of linseed oil and heptane, and subsequently stimulating the polymerization (oxygen driven) by flushing the gas volumes with clean air.
 - ▶ The polymerization lasts a few days and is performed at $T > 30^\circ\text{C}$



G. Aielli - ISU
10/15/2026

First plateau using linseed oil (by R. Cardarelli)

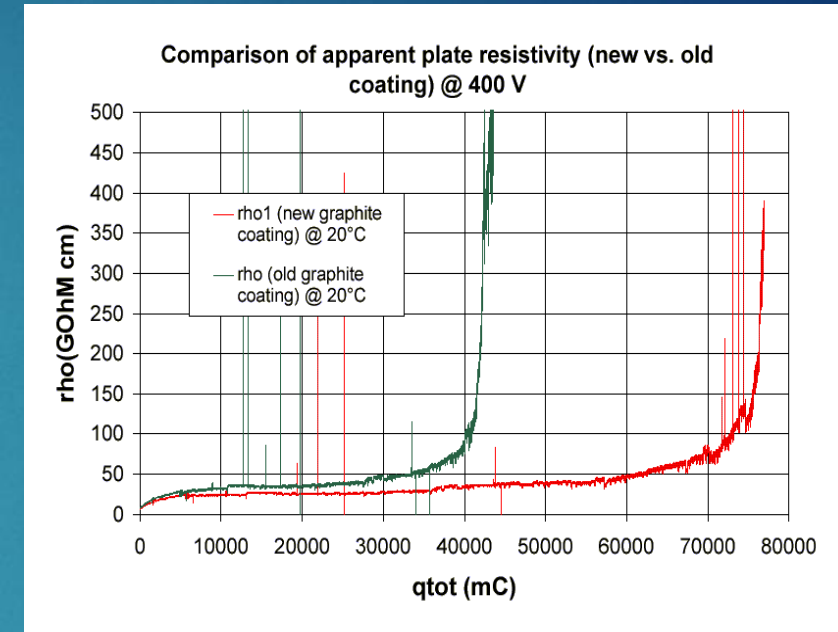
11



Resistive Plate – ohmic contact

12

- ▶ The external face of the electrodes are treated with a graphite layer with a surface resistivity $\ll$ of the HPL one
- ▶ This represents an ohmic contact and has the function of distributing the electric potential uniformly on the surface
- ▶ Its surface resistivity is of the order of 100 kOhm/□
 - ▶ Typical $\tau = RC = 10 \text{ pF} \cdot 100 \text{ kOhm} = 10^{-6} \text{ s}$
 - ▶ Sufficiently slow to be transparent to the prompt avalanche signal ($\tau \approx 1 \text{ ns}$)
- ▶ The graphite contact is progressively damaged by the electro-chemical reactions, using a thick layer, we demonstrate that the system can withstand the full ATLS program



Choice of the graphite: it is possible to obtain the same resistance per square with different amounts of graphite per unit surface, by adding a resin as a filler in between the graphite grains. Such a thicker structure is more resilient to chemical damage

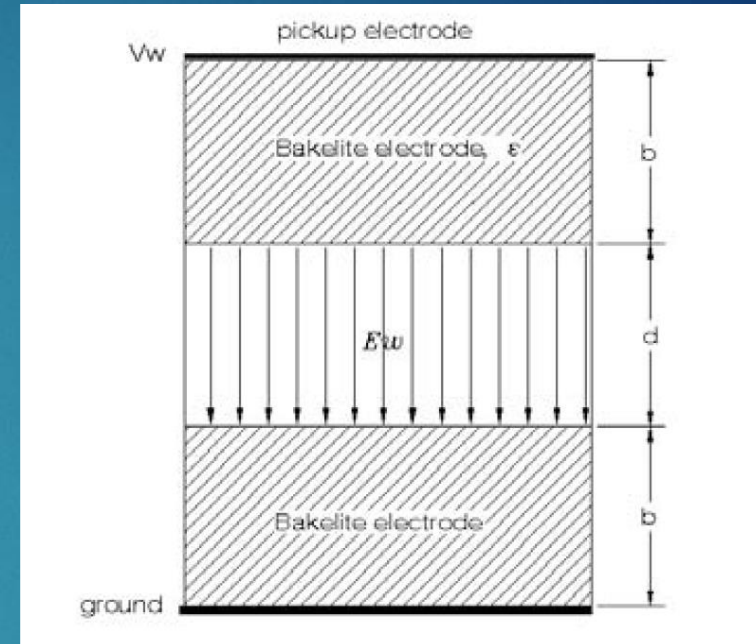
Resistive Plate – electrode thickness

13

- ▶ The electrode thickness should be idealistically as thin as possible since the signal induction is given by the weighting field through the Ramo theorem as:

$$i(t) = \frac{E_w}{V_w} v e_0 N(t) \quad \text{Where} \quad \frac{E_w}{V_w} = \frac{1}{\frac{2b}{\epsilon} + d}$$

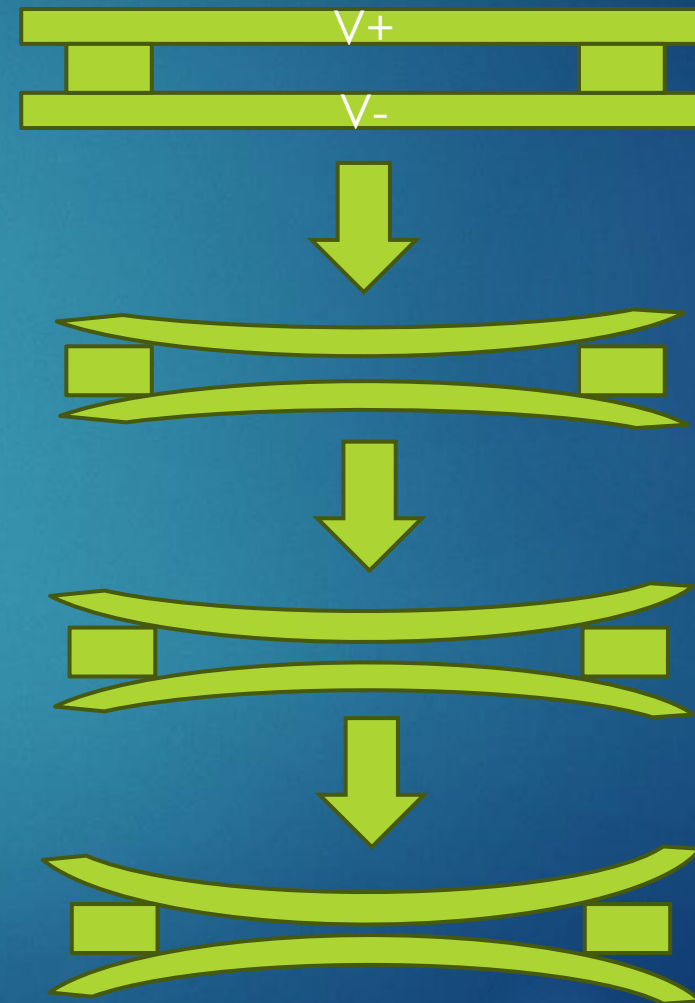
- ▶ Since ϵ is about 7 the electrode thickness contribution is reduced:
- ▶ Example: $b=1\text{mm}$ $d=2\text{mm}$ $\rightarrow$ 77% we have a reduction of 23% for the signal with respect to a zero thickness electrode
- ▶ On the other side a too thin electrode becomes mechanically unstable due to the electrical force in between the electrodes
- ▶ Practical ranges are in between 1.4 and 2 mm



Discussion on the mechanical stability

14

- ▶ When the electric field is on the plates are attracted by electrostatic force
- ▶ Elements to consider:
 - ▶ Material rigidity
 - ▶ Material thickness
 - ▶ Distance and size of the spacers
 - ▶ Fixing of plate and spacer
 - ▶ Intensity of the field
- ▶ The residual gas gap is smaller
 - ▶ In extreme cases it may trigger a pull-in effect due to the increase of E
 - ▶ The design should be such to make this effect negligible



An example

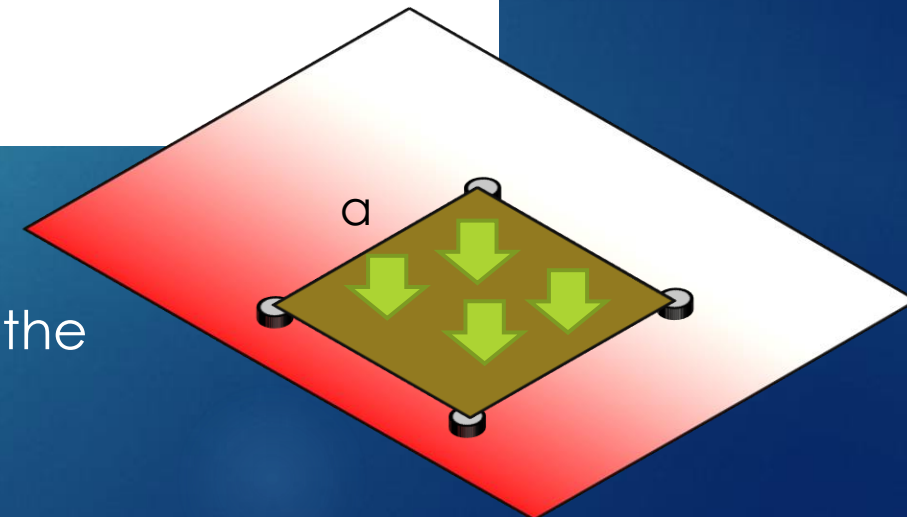
15

G. Aielli - ISU
10/15/2026

- **Cell geometry:** square side $a = 70 \text{ mm} = 0.07 \text{ m}$. Four **support pads** at the corners, $\varnothing 7 \text{ mm}$, bonded with **Araldite 411** as a thin layer ($\approx 5 \text{ }\mu\text{m}$). This yields a near-ideal local clamp over the pad area; edges are free.
- **Initial gap:** $d_0 = 1.0 \text{ mm}$.
- **Applied voltage:** $V = 6.0 \text{ kV}$ (initial average field $E_0 = V/d_0 = 6 \text{ kV/mm}$).
- **Gas:** target dielectric strength $E_{bd} \approx 7 \text{ kV/mm}$.
- **Materials** (typical):
 - HPL: $E \approx 9 \text{ GPa}$, $\nu \approx 0.30$
 - Soda-lime glass: $E \approx 70 \text{ GPa}$, $\nu \approx 0.22$
- **Thickness range:** $h \in [1.4, 1.5] \text{ mm}$ (constraint: $< 1.5 \text{ mm}$).
- **Vacuum permittivity:** $\epsilon_0 = 8.854 \times 10^{-12} \text{ F/m}$.

E is the Young modulus
 ν is the Poisson coefficient

- Typical literature value are used
- For a more predictive calculation one should measure the material rigidity E directly



Physical model

16

- For more accurate results, one should measure directly D on a realistic mock-up
- By using different loads it is also possible to verify the linear deflection law
- Notice that the deflection grows with the 4th power of a and decrease with the 3rd power of h
- Implication on the spacers grid density

Electrostatic load

For local gap d , the field is $E = V/d$. The **electrostatic pressure** (Maxwell stress) is

$$p = \frac{1}{2} \varepsilon_0 E^2 = \frac{1}{2} \varepsilon_0 \left(\frac{V}{d} \right)^2.$$

At the initial distance d_0 : $p_0 = \frac{1}{2} \varepsilon_0 (V/d_0)^2$.

Thin plate (Kirchhoff-Love)

Flexural rigidity:

$$D = \frac{E h^3}{12(1 - \nu^2)}.$$

Linear deflection under uniform pressure (square plate with 4 local clamps at corners):

$$w_0 = \alpha \frac{p_0 a^4}{D}.$$

Physical model - extrapolation

17

G. Aielli - ISU
10/15/2026

Electro-mechanical self-consistency

With two identical plates, the center gap reduction is $\delta = 2w$. Since $d = d_0 - 2w$, the load increases as the plates approach. Defining $x := 2w/d_0$, the center equilibrium solves the **cubic**

$$\boxed{x(1-x)^2 = K \alpha}, \quad K = \frac{2 a^4 p_0}{d_0 D} = \frac{24 (1 - \nu^2) a^4 p_0}{d_0 E h^3}.$$

Residual gap at the center: $g = d_0(1 - x)$. **Center field:** $E_c = E_0/(1 - x)$.

Design constraints

1. **Gap thinning limit:** $x \leq x_{\max}$. Example: "3%" $\Rightarrow x_{\max} = 0.03$.
2. **Gas dielectric limit:** $E_c \leq E_{bd} \Rightarrow x \leq 1 - E_0/E_{bd}$. For 6 vs 7 kV/mm: $x \leq 0.1429$.
3. **Stability (no pull-in):** the cubic has a stable solution if $K \alpha \leq 4/27 \Leftrightarrow w_0/d_0 \leq 2/27$.

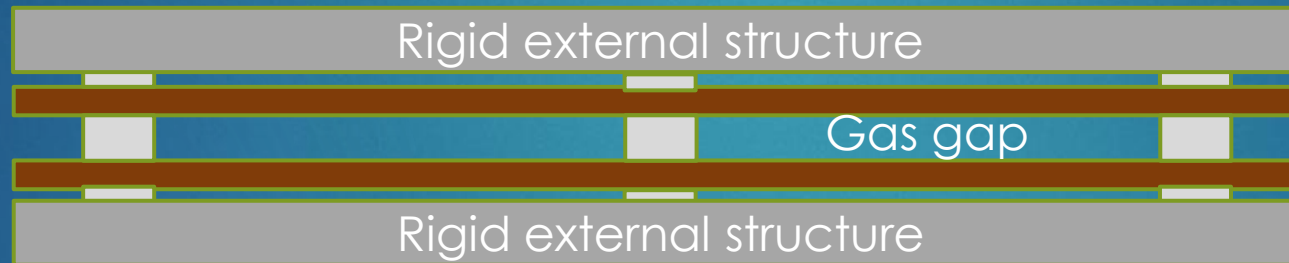
- ▶ One can play with the model to find the most desired optimization
- ▶ Changing a , h in particular and making statistical consideration on the stability of the expected values for D

Mechanical stability – overpressure

18

G. Aielli - ISU
10/15/2026

- ▶ The internal pressure of the gas
 - ▶ static pressure of the gas column (2.3 mbar/m for TFE)
 - ▶ Dynamic pressure due to the gas flow
- ▶ A small but continuous stress for the time life of the experiment
- ▶ Neutralized by applying an external force to prevent spacer detachment



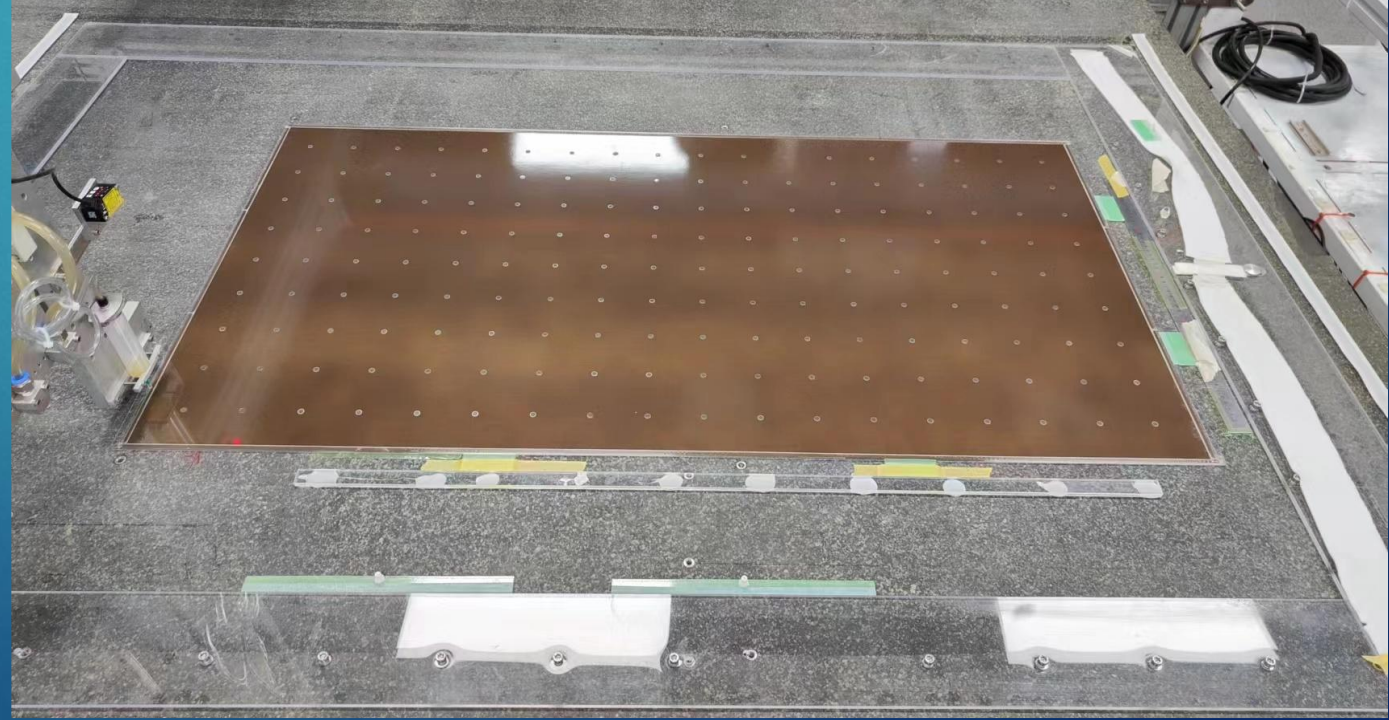
- ▶ The force is applied just on the internal spacers, through external thin spacers preventing the contact with the gas gap
- ▶ If the gas is “light” and the flow is “low” the design of the mechanical frame can be greatly simplified

Resistive Plate Chamber gas gap

19

G. Aielli - ISU
10/15/2026

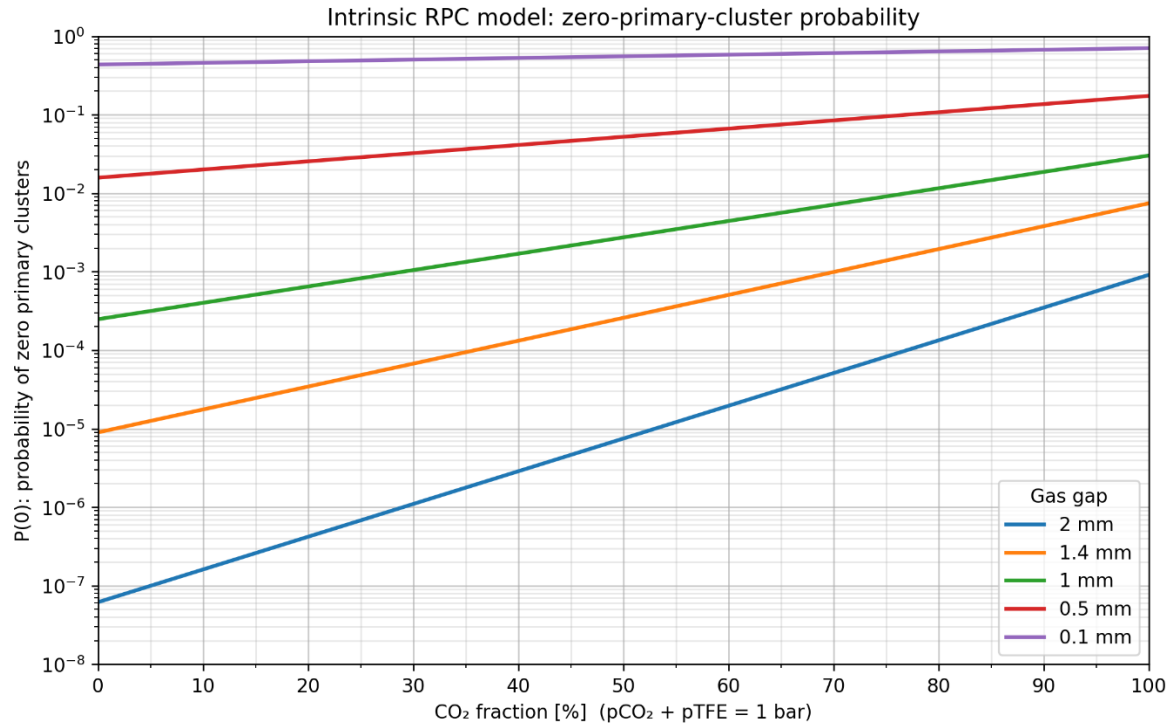
- ▶ We consider a chamber as a closed and defined gas volume
 - ▶ The electrodes are kept at constant distance by a set of spacers placed at a distance such that the catenary profile in between 2 spacers is $\ll$ of the gas gap
 - ▶ Having a more or less thin gas gap has pros and cons
- ▶ Pro:
- ▶ higher time resolution
 - ▶ Lower applied voltage
 - ▶ The same charge, produces a higher saturation of the field
 - ▶ Higher space resolution
- ▶ Cons:
- ▶ Less statistics of primaries $\rightarrow$ the bottom line is $P(0) = e^{-\frac{d}{\lambda}} \leq Eff$ where λ is the ionization mean free path
 - ▶ Higher mechanical sensitivity
 - ▶ Higher FE amplifier performance



Primary Poisson probability and the useful gas gap

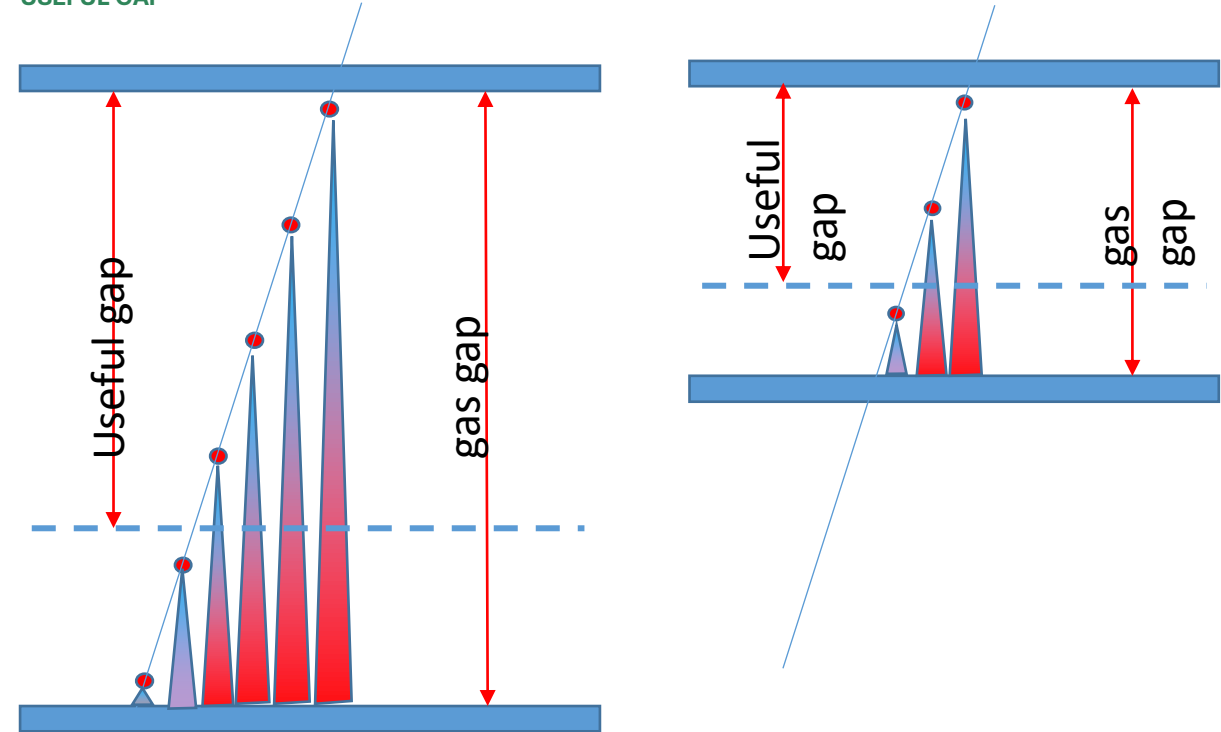
The total gaseous target sets $P(0)$; only ionizations inside the useful region can generate a detectable avalanche.

PRIMARY-CLUSTER POISSON LIMIT



$P(0)$ depends mainly on the total gaseous target: the gap thickness and the mixture density.

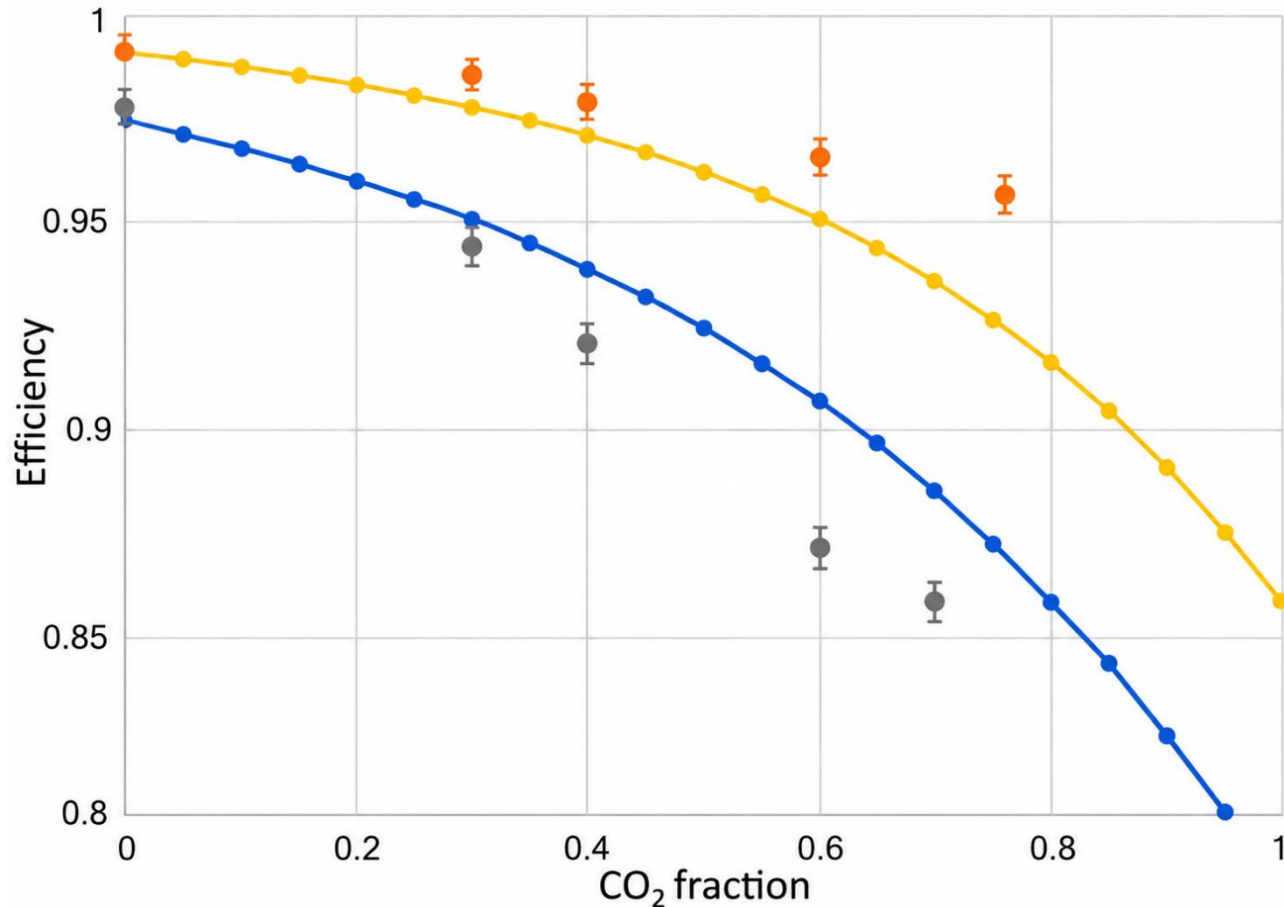
USEFUL GAP



The useful gap is empirical: it is the region where an ionization can develop into an avalanche large enough to be detected.

Consequence: Poisson $P(0)$ is smaller than the observed inefficiency because not every primary ionization lies inside the useful gap.

Effective maximum efficiency and constrained Poisson



1. Effective maximum efficiency

An empirical working value rather than a rigorous limit. Efficiency may still increase with HV, but at increasing operating cost.

2. Constrained Poisson prediction

The Poisson maximum from primary-cluster statistics versus gas composition, normalized to the Standard-mixture measured efficiency and assuming 100% acceptance.

3. Direct comparison

The Poisson curve follows the decrease approximately, but shows a growing quantitative difference and a different functional shape.

Equation placeholder: constrained Poisson normalization

Takeaway: the primary Poisson constraint is a baseline; detector-dependent response is required to describe the measured effective plateau.

Front-end electronics sensitivity test

TEST CONFIGURATION

- **Chamber:** ATLAS-like layout [*]
- **Geometry:** 2 mm gas-gap doublet with one test chamber and one monitoring chamber
- **Test readout:** vertical strips equipped with ATLAS electronics
- **Reference readout:** horizontal strips equipped with a high-sensitivity analog preamplifier, the baseline for the Phase-1 and Phase-2 upgrades

GIF++ EXPOSURE AND MEASUREMENTS

- **Beam and source exposure**
- Efficiency under irradiation
- V–A curve

EXAMPLE GAS MIXTURE

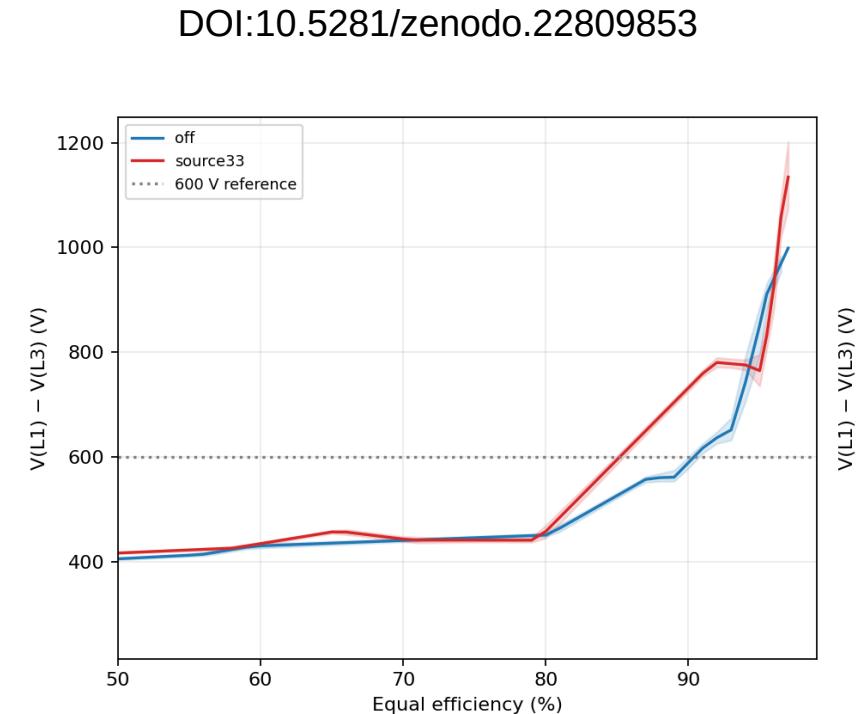
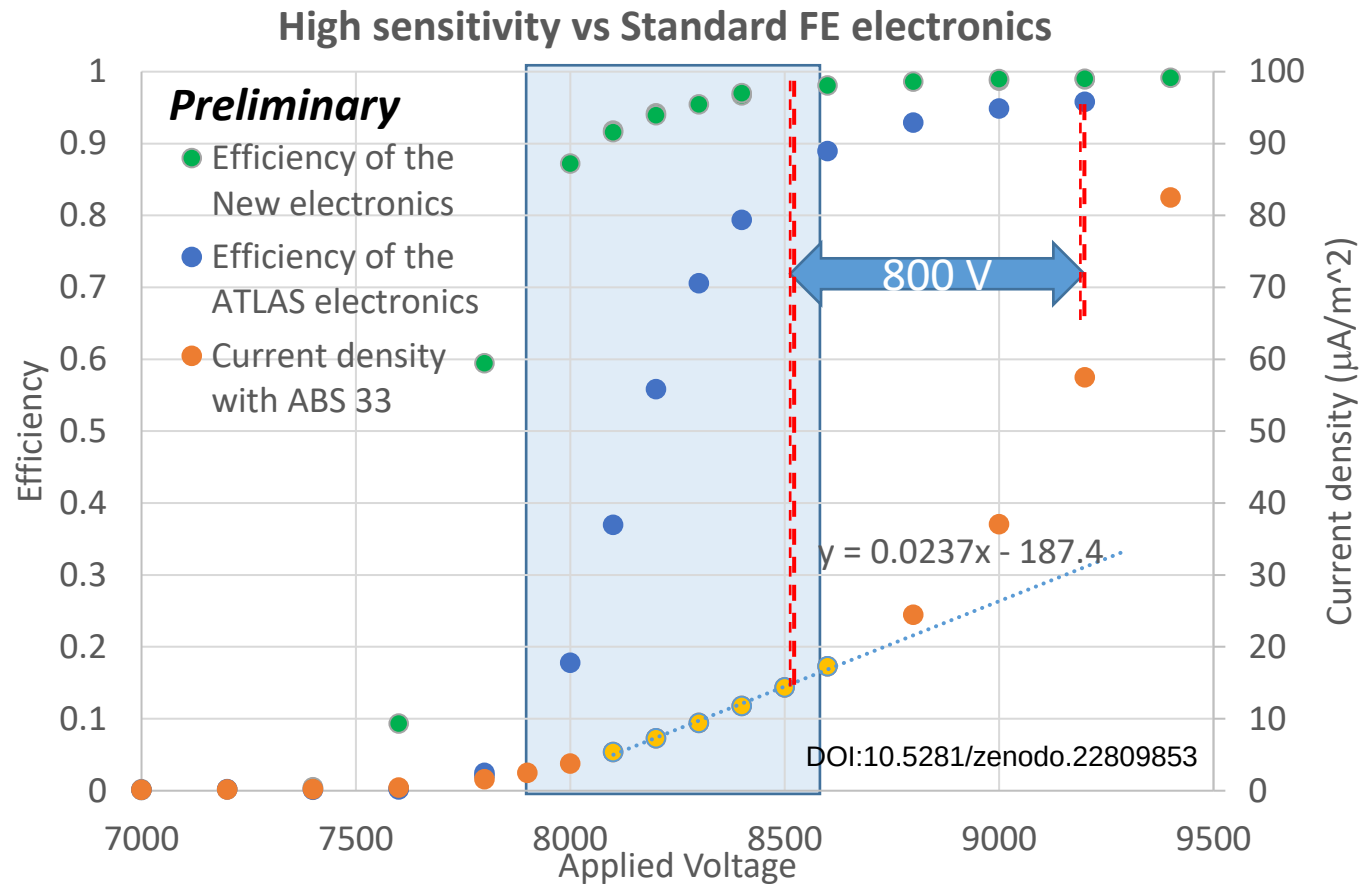
0% R134a 88% CO₂ 10% i-C₄H₁₀ 2% R1233zd

Flammable and freon-free. Example only, not (yet) an official proposal.

OBJECTIVE Compare the two amplifiers event by event on the same avalanche signal.

Both electronics record each avalanche simultaneously.

Voltage separation new vs. standard FE

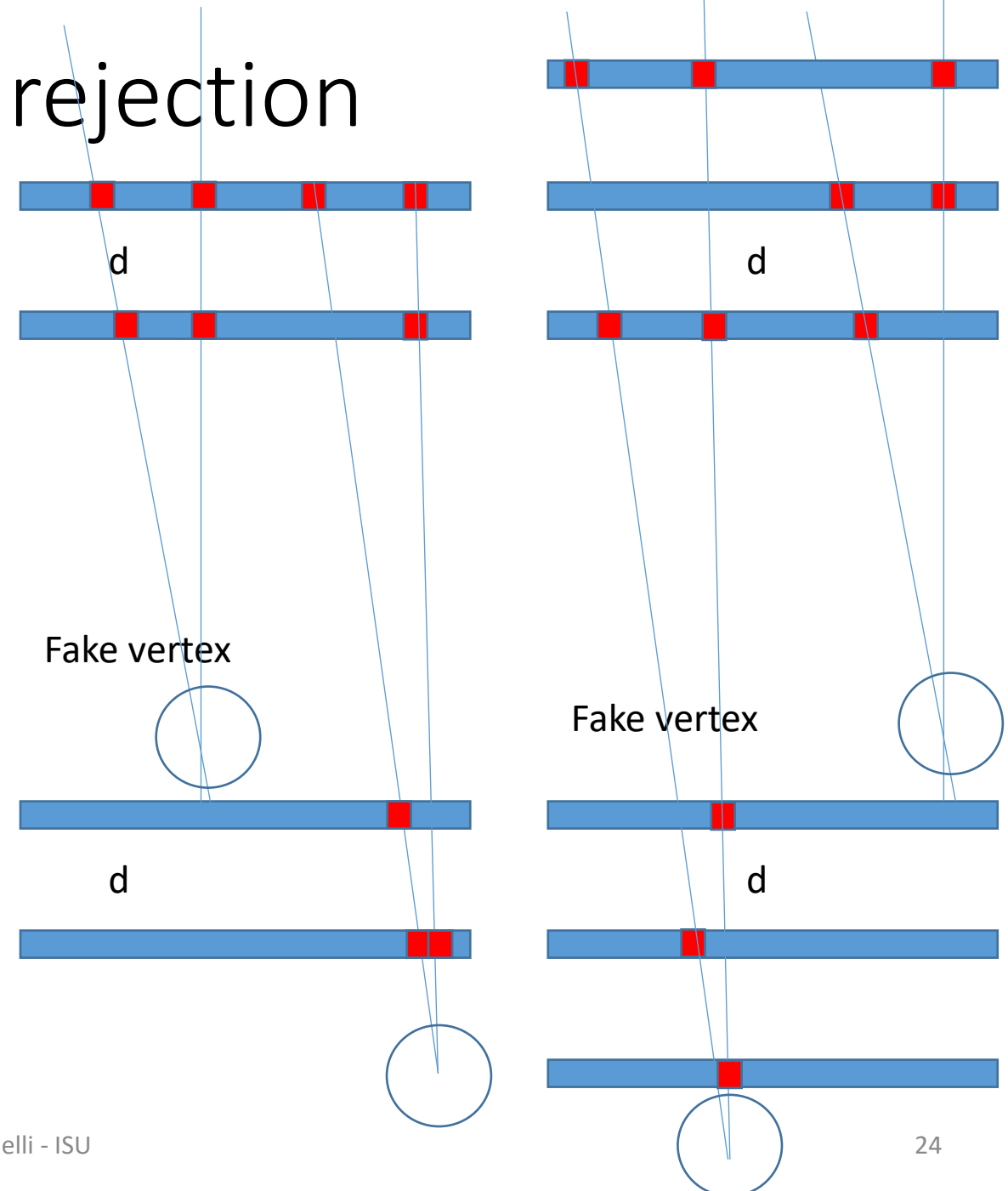
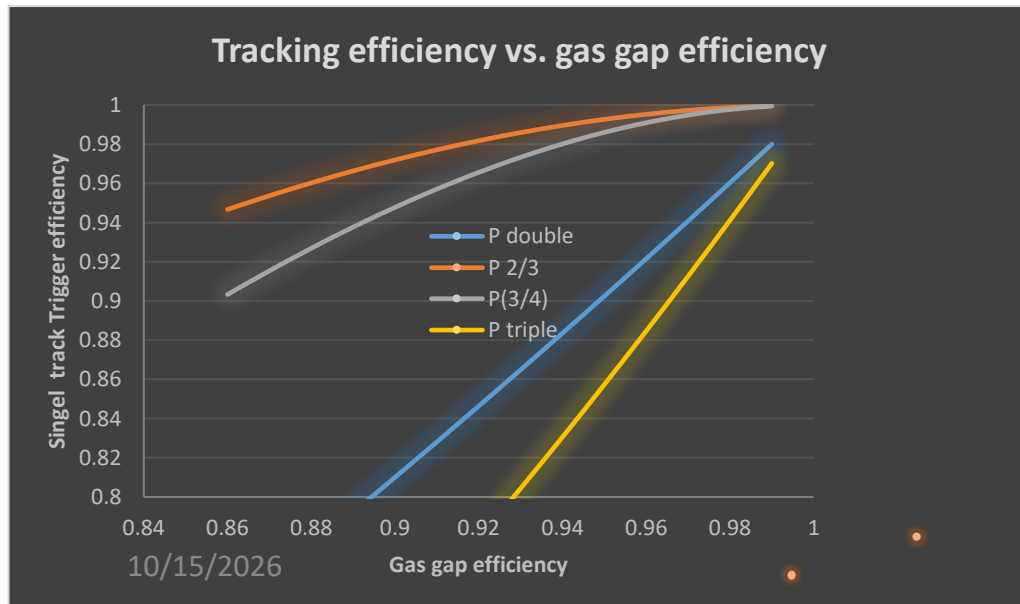


We observe that

- this freon free mixture, is unsuitable for a standard ATLAS chamber working at Efficiency > 90%
- The sensitivity of the new electronics allows to catch very small signals lowering by more of 600V the working point → the mixture becomes fully workable in saturated avalanche regime

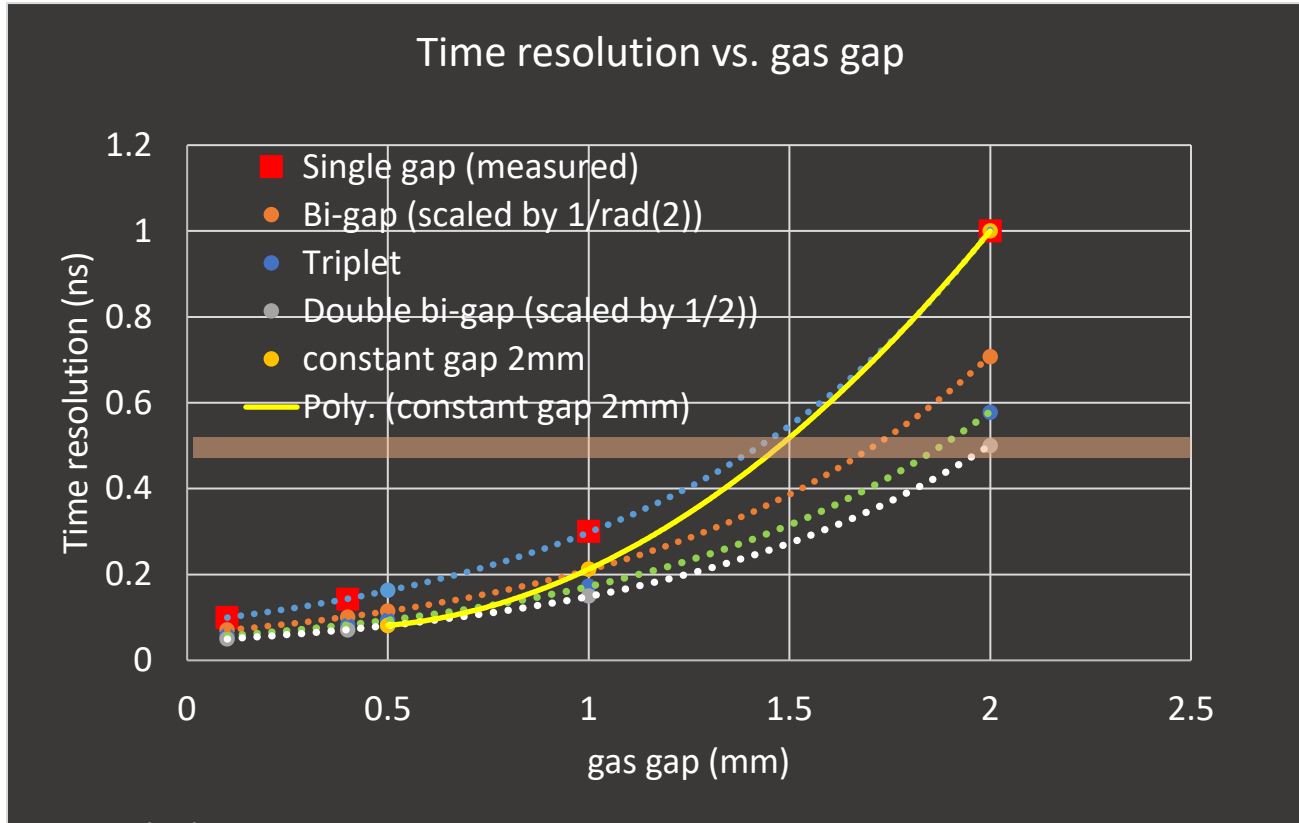
Efficiency and Fake tracks rejection

- Balance of Efficiency and fake rejection:
 - OR of layers boosts the efficiency and noise
 - AND of layers boosts the fake rejection at expense of efficiency
 - Majority (2oo3 3oo4) achieve both at expense of cost and bulkiness
- The physics target influences the performance goals:
 - Muon spectrometers are sensitive to single muons and rely on at most one hit per layer
 - Vertex detectors can rely on at least 2 tracks, the signal is intrinsically much stronger



RPC design – time resolution

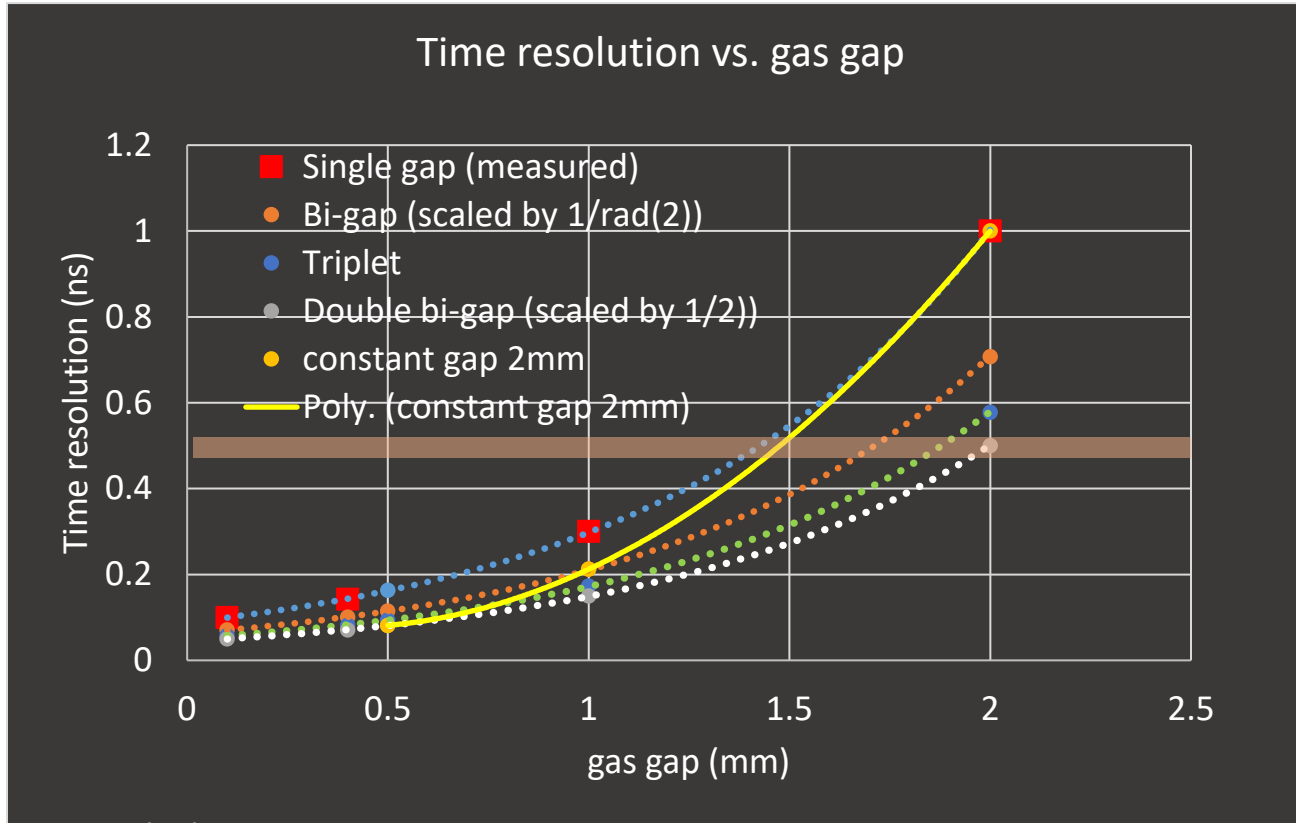
- Time resolution taken for single gas gap and scaled for the number of gas gaps
- Standard mixture
- The yellow line is for total gas gap = 2 mm



- Time resolution Depends mainly on:
 - Gas gap thickness $\rightarrow$ resolution scales regularly with gas gap thickness
 - Number of gas gaps (suppressing fluctuations as $1/\sqrt{n}$)
 - The gas drift velocity
- Dependence on electronics
 - To make the electronic noise contribution negligible for the time resolution it should be $\ll$ intrinsic signal fluctuations

RPC design – time resolution

- Time resolution taken for single gas gap and scaled for the number of gas gaps
- Standard mixture
- The yellow line is for total gas gap = 2 mm



Overall performance

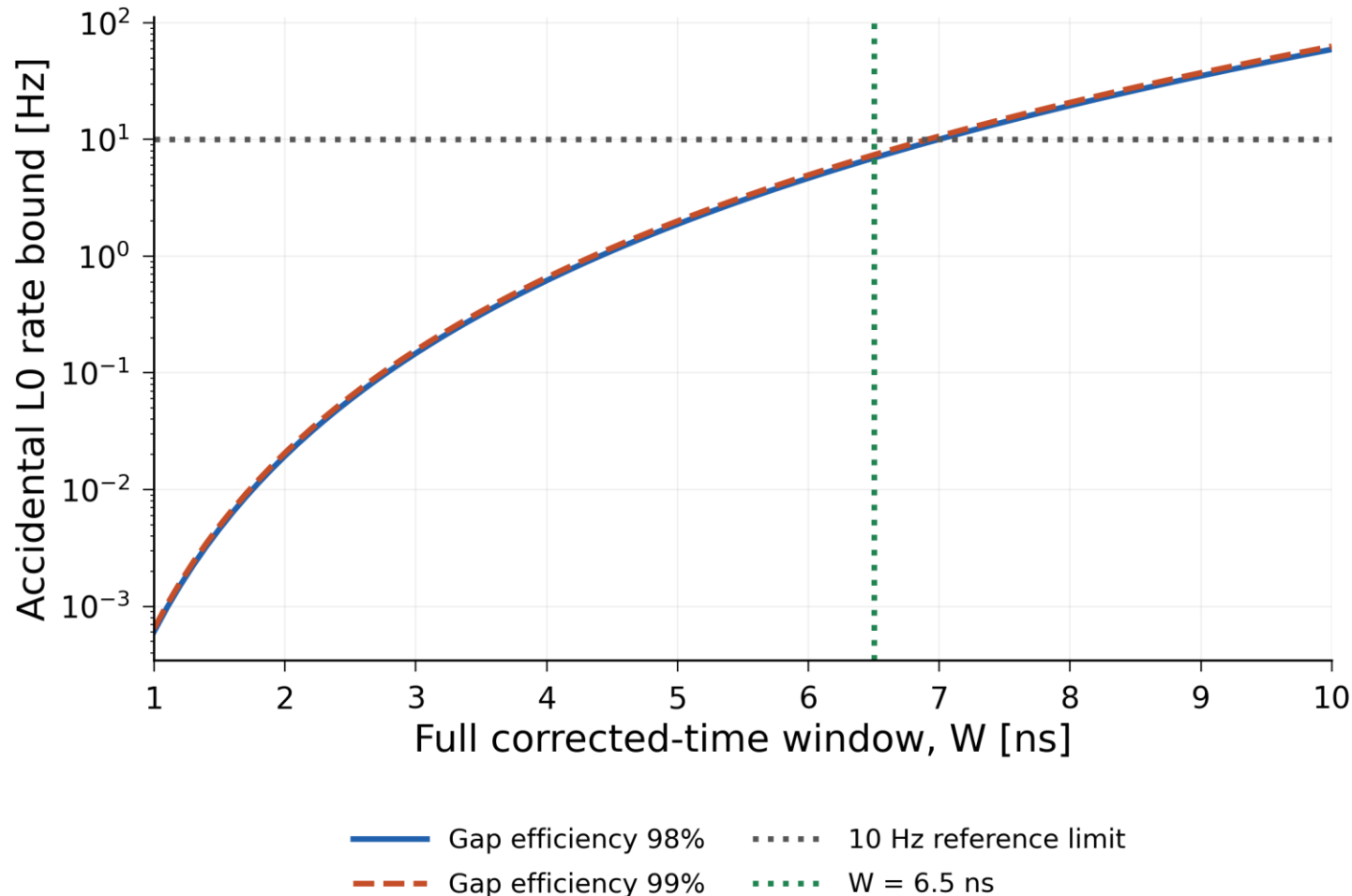
- Target: > 2mm
- Time res.: > 0.5 ns

Possible solutions:

1. Triplet with $1.5 \text{ mm} < \text{gas gap} < 1.7 \text{ mm}$
 - Double hit $\rightarrow 0.5 \text{ ns}$
 - Triple hit $\rightarrow 0.4 \text{ ns}$
2. Doublet with gas gap = 2 mm
 - R&D needed to improve single gas gap time resolution to 0.7 ns
 - Single hit $\rightarrow$ negligible fraction
 - Double hit $\rightarrow 0.5 \text{ ns}$
3. Doublet with a 1+1mm bi-gap
 - Single hit $\rightarrow 0.2 \text{ ns}$
 - Double hit $\rightarrow 0.13 \text{ ns}$

Six-hit RPC trigger: window dependence

1600 m² detector · stations at 25 and 26 m · adjacent gaps separated by 2 cm



At least six local hits are required across four gaps, with at most two contributions per gap. Rates sum 36 adjacent-pad combinations over the detector. For sparse occupancy, the accidental bound scales approximately as W^5 ; exact Poisson values are plotted. W is a full sliding width after nominal light-flight offsets. Independent Poisson hits: 100 ϵ Hz/cm² per gap. No ATLAS selections are applied.

Next RPC design recipe

28

G. Aielli - ISU
10/15/2026

1. Select target efficiency → 99%
2. Select desired amount of CO₂ → > 90%
3. Determine the total gas thickness needed per efficient unit → 2mm
4. Select the target Time resolution:
 - ▶ 1 ns → single 2 mm gas gap → simple robust and low cost
 - ▶ 400 ps → 1.4+1.4mm bi-gap --> CMS phase2 established resolution to be verified
 - ▶ 200 ps → 1+1mm bi-gap --&to ATLAS phase2 established resolution to be verified
 - ▶ 80 ps → 2 x 0.5x0.5 mm bi-gap → critical R&D is necessary

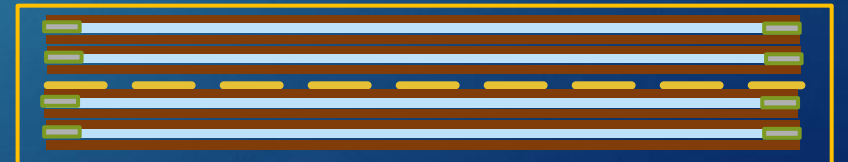
2mm



2X1



0.5x4



Resistive Plate Chamber vs. amplifier

29

G. Aielli - ISU
10/15/2026

State of the art FE →
noise = 4000 e- RMS

Threshold on the injected signal →
20000 e- RMS

Assuming to lose a factor 40 on the
induction →
avalanche geometry x Ramo x readout strip

$8 \cdot 10^5$ electrons for the minimum
detectable signal

Rough assumptions on charge distribution for saturated avalanches

- mode $\approx$ average $\approx 3 \times$ minimum
- Max $\approx 15 \times$ minimum

▶ Two parameters are important to determine the maximum rate capability:

- ▶ FE threshold
- ▶ Asymmetry of the charge distribution
- ▶ A perfectly saturated avalanche would produce a gaussian distribution

Gas gap optimization parameters:

- As small as possible to achieve saturation with proportionally fewer electrons → 0.1 mm
- Deep saturation also increases the induction efficiency
- Below 1 mm gas gap $P(0)$ is not negligible, and part of the advantage is lost due to the necessity of amplifying very unfavorable primary electrons (placed close to the anode) by increasing the electric field
- Therefore, the MRPC use many tiny gas gaps

- Ideal case ~ 0.4 pC
- 7.5 times better of the single gap state of the art (3 pC real case)

Worsening of FE performance
proportionally reflects on $\langle Q \rangle$
Correlation between
narrower gas gap and FE
threshold

Resistive Plate Chamber S/N

30

G. Aielli - ISU
10/15/2026

- ▶ The RPC is typically a very large structure (a few m^2)
- ▶ A signal or a disturbance takes a few tens of ns to travel end to end
- ▶ The amplifier and discriminator produce typically a fast transient resulting in a very high instantaneous current injected on the ground. This under any aspect is seen as a signal if the ground scheme is not able to dissipate or compensate it
- ▶ There are the following types of noise:
 - ▶ Self-induced current coupled noise (diaphonicity), the one above
 - ▶ External noise coming from the environment, this can be dominant if the faraday cage is not strong enough
 - ▶ Intrinsic electronic noise, of the order of a few hundred to a few thousand of electrons
 - ▶ The first 2 are generally dominant unless the grounding is able to suppress them

Different RPC layout brought to different operative thresholds:

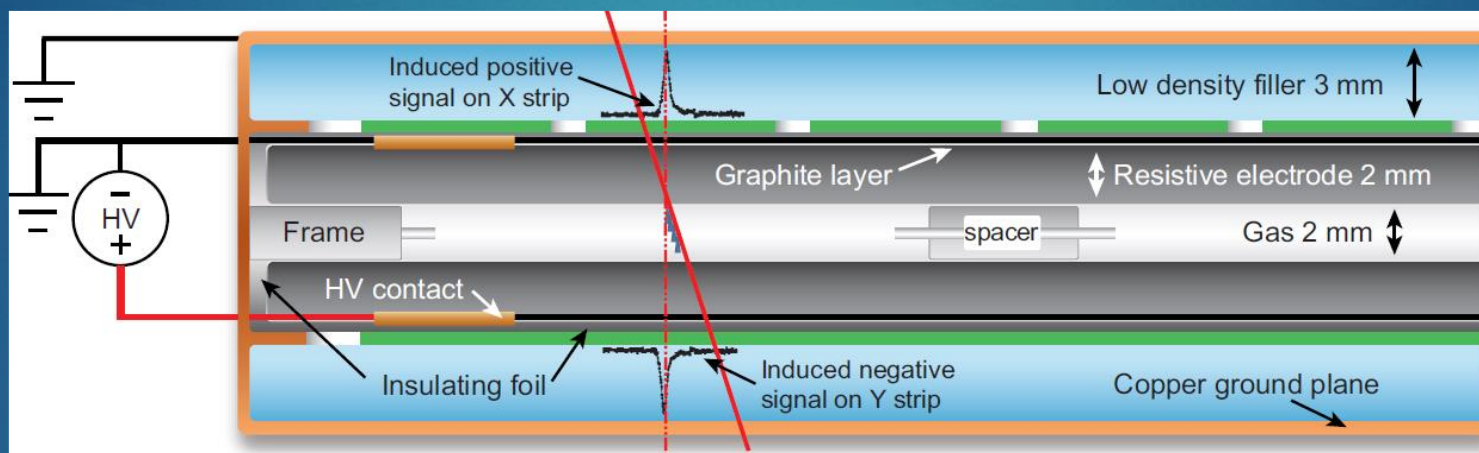
- ▶ Legacy ATLAS – 20 fC one 2 mm gas gap
- ▶ Legacy CMS – 40 fC two 2 mm gas gaps
- ▶ Upgrade ATLAS 5 fC one 1 mm gas gap
- ▶ Upgrade CMS 40 fC two 1.4 mm gas gaps

The RPC chamber: a stripline having the detector as dielectric

31

G. Aielli - ISU
10/15/2026

- At the very origin of RPCs this was the driving concept for exploiting RPCs timing performance (R. Cardarelli private communication)



- A large timing detector couldn't be nothing but a fully matched stripline where the RPC is an "active" dielectric generating the signal internally
- The strip line was meant to propagate without distortion the signal to the FE electronics, also matched to the line

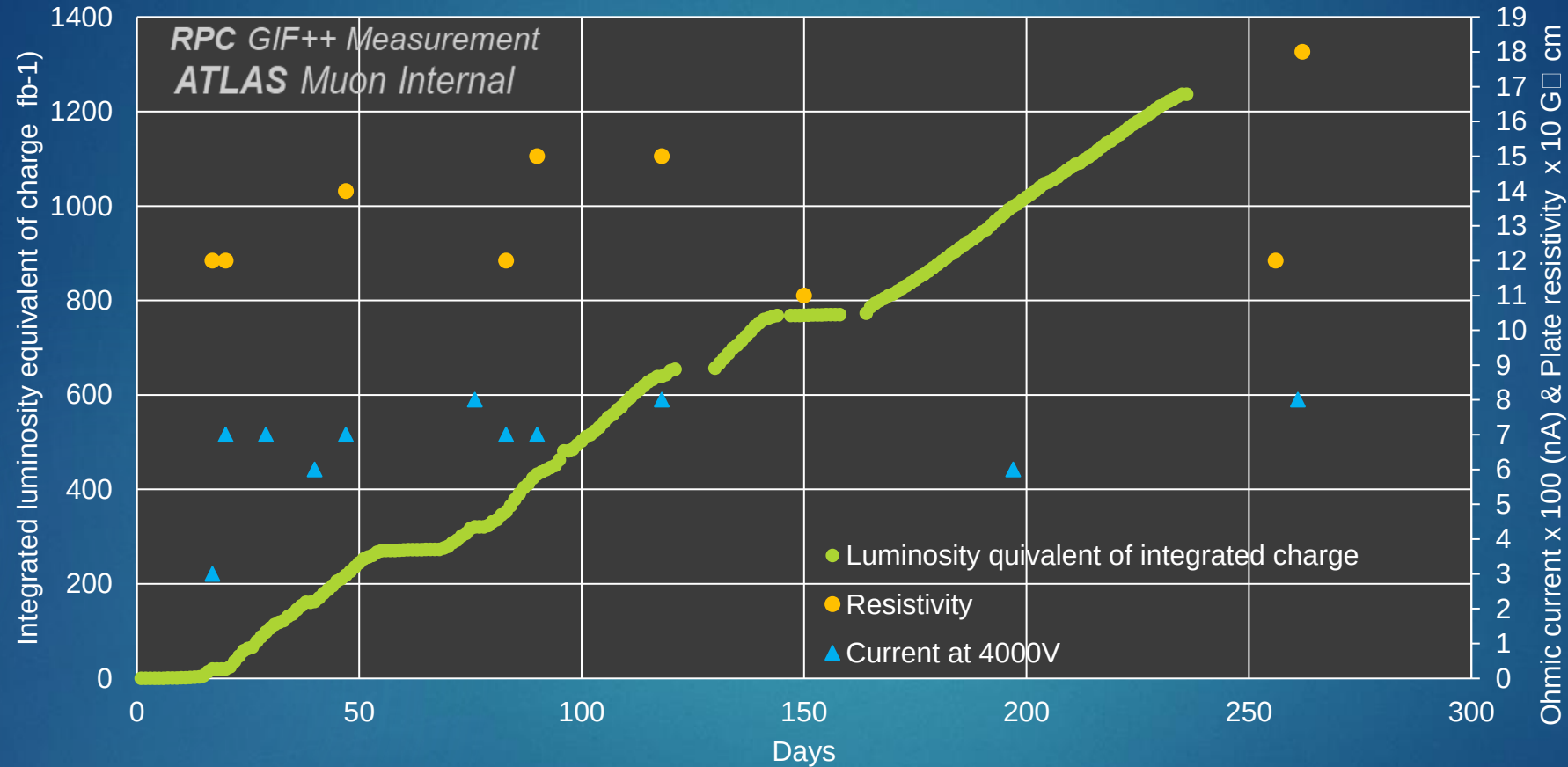
Consideration on Ageing

CURRENT IT IS USED AS A PROXY FOR AGEING EFFECTS BUT THE SAME
CURRENT MAY HAVE VERY DIFFERENT EFFECTS

Ageing Test with 30% CO₂ + 0.5 % SF₆

33

Ageing Test of ATLAS-like RPC Under Irradiation



G. Aielli - ISU
10/15/2026

- Target → Full HL-LHC program corresponds to ~ 3000 fb⁻¹
- Approximately 42% of this target has been reached, corresponding to about 1250 fb⁻¹

Results:

- ▲ The ohmic current remains excellent and stable over time.
- The electrode resistance was initially high, then increased by approximately 25% after the first exposure to radiation, and has remained stable since.

Comparison of STD & New RPC Gas Mixtures in ATLAS Cavern

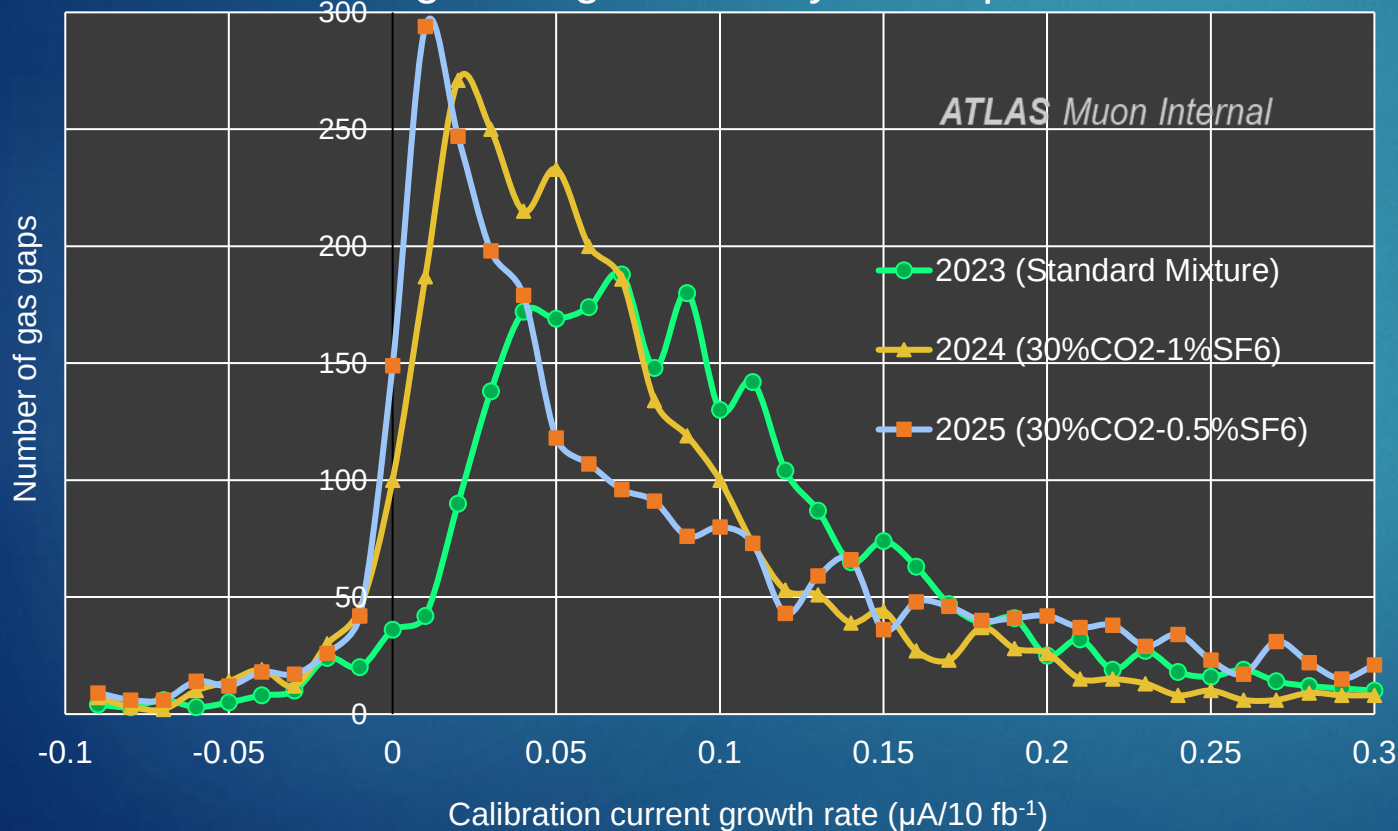
34

Calibration current): Current measured at the operating voltage without beam-induced background. For a stable detector, it should remain constant with accumulated charge

I_{calib} growth rate $\approx 0 \rightarrow$ **no current increase with accumulated charge**

G. Aielli - ISU
10/15/2026

RPC calibration current growth rate for integrated average charge in steady LHC operation



Results:

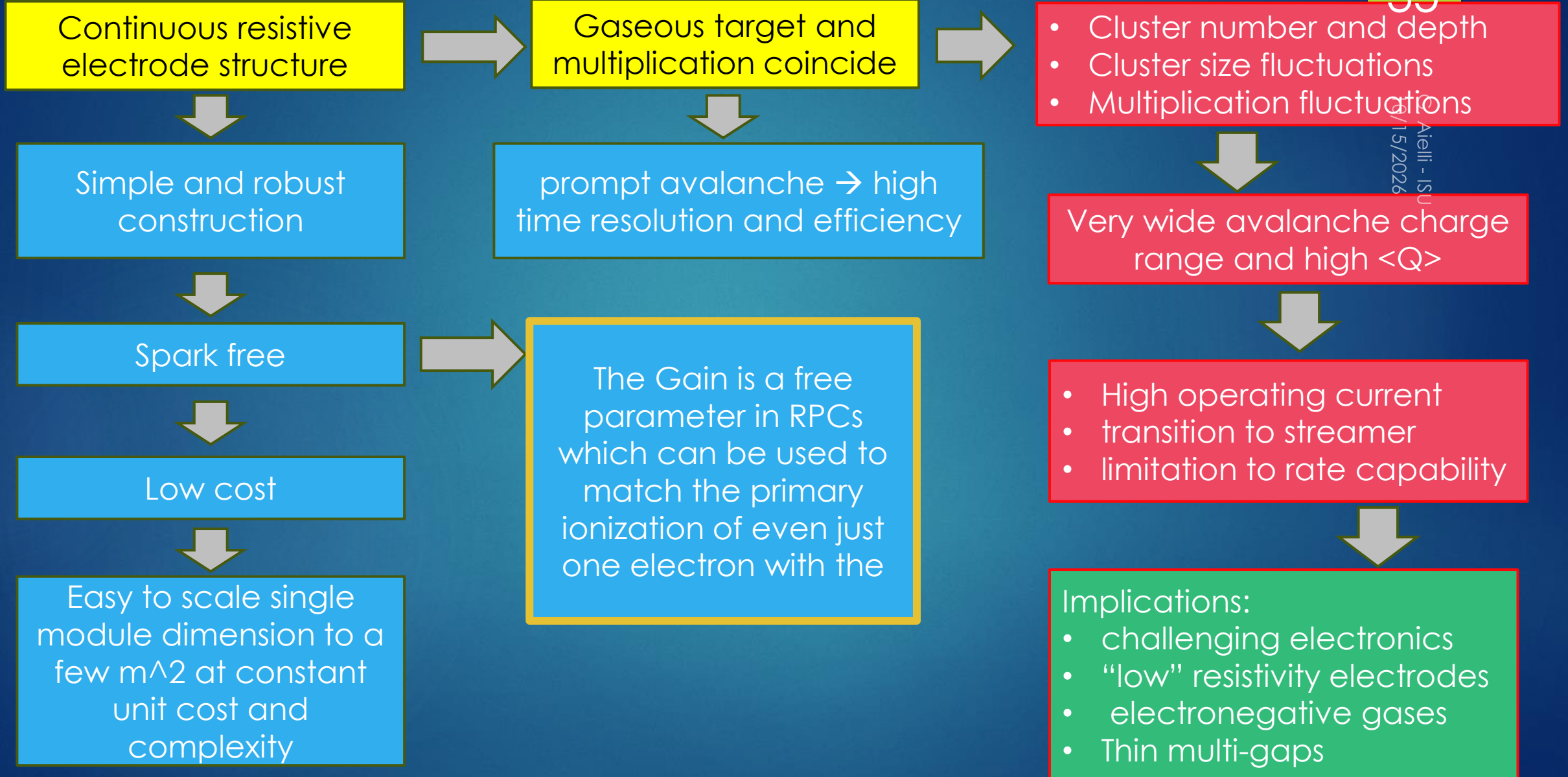
- The mixtures with reduced fluorinated-gas content show distributions more concentrated around zero
 $\rightarrow$ **smaller increase in the rate of I_{calib} .**
- Halving the SF₆ fraction further reduces I_{calib} , due to **lower dark-current contribution.**

The luminosity delivery rate in the selected periods:

in 2023 was $0.31 \text{ fb}^{-1}/\text{week}$

in 2024 and 2025 were $0.54 \text{ fb}^{-1}/\text{week}$

RPC Strength vs. weakness diagram



RPC construction sites

Summary of the gas gaps production sites

37

G. Aielli - ISU
10/15/2026

Classic RPCs – main sites (known to me)

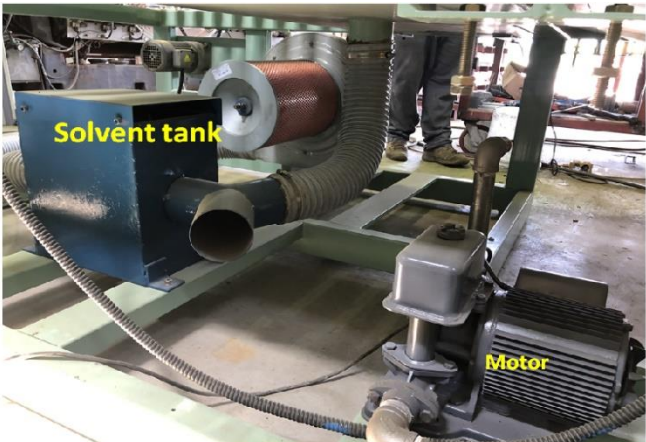
- ▶ GTE (Colli – FR) it is the historical site where most of the classic RPCs have been built (ATLAS-CMS-ARGO-OPERA-BaBar etc)
- ▶ Production in Korea for CMS (see next slides)
- ▶ Production at MPI for ATLAS (new entry)
- ▶ Production at USTC (new entry)

MRPCs

- ▶ Smaller productions – lab driven

Outsourcing to private companies

Brushing and washing with MEK for HPL



Brushing scheme
✓ Two PE brushes (top)
✓ Two metal brushes (bottom)

PE brush

PE brush

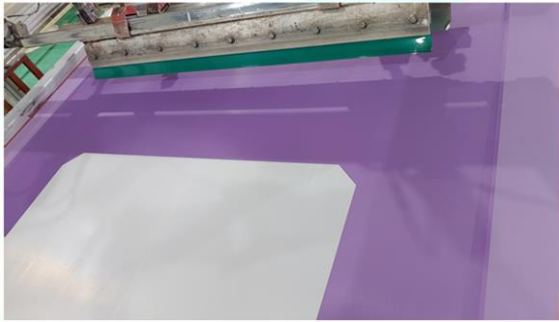
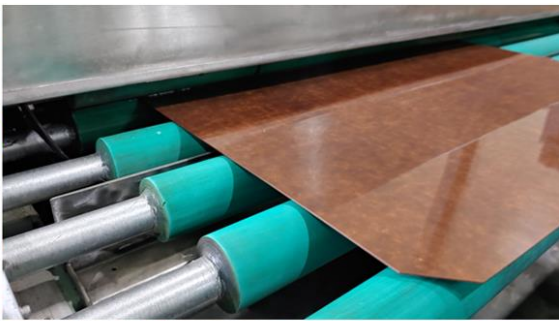
Wire brush

Wire brush



Graphite printing facility

More uniform surface resistivity ranging from 300 to 700 kΩ/sq



Outsourcing to private companies

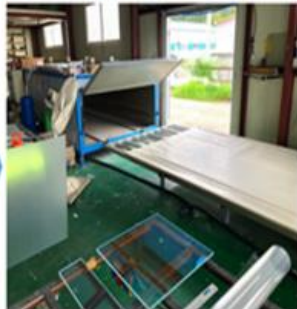
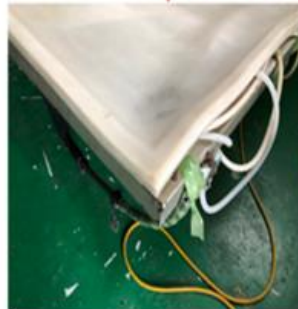
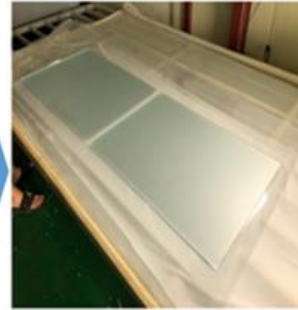
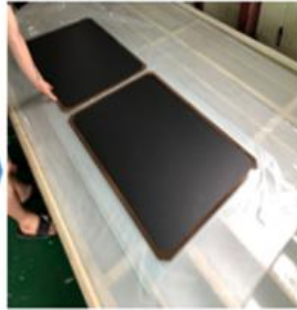
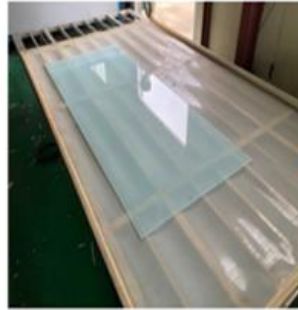
PET-film coating procedure (new)

Glue extrusion facility for PET coating @KODEL



NEW

Vacuum gluing facility @Yurim



Pet-film 3mm

EVA glue film on HPL

Steps

- 1) Place 250- μ m thick EVA glue film on HPL
- 2) Place 190- μ m thick PET film on the EVA-film covered HPL
- 3) Insert ~ 5 layers in a vacuum chamber
- 4) Increase the temperature to 90°C for 60 mins.
- 5) Cure adhesiveness of the glue on PET @90 °C for 60 mins
- 6) Gradual decrease of vacuum temperature for 60 mins

Gluings RPC electrodes (gas gaps)



Gas Nozzle

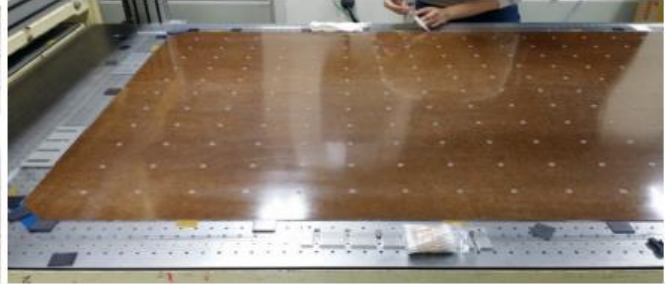
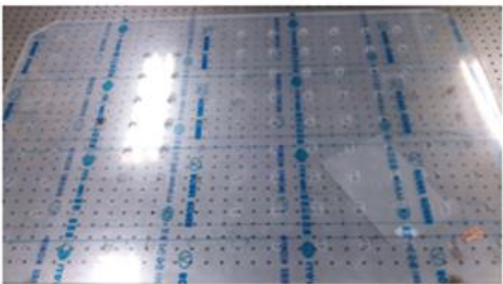
Gluings tables and pressure devices



Metric tables and multi-layer air pouches for gluing and glue hardening for gaps

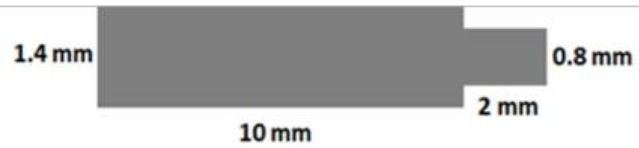
Air pouches uniformly press the whole surface of the gap with a pressure of 30 hPa (equivalent to 300 kg m⁻²).

Spacer jig



Gap supporting m

peripheral strip spacers



gas-inlet profiles

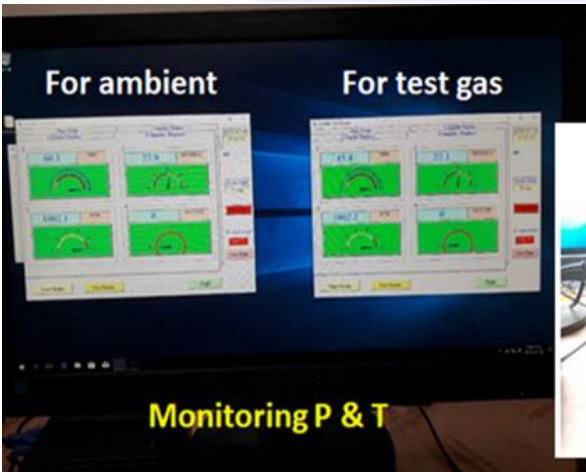


circular spacers



Epoxy glue (3M DM460):
hardening time ~ 24 h
Requiring epoxy out gassing for additional 48 hours before oil varnishing

At KODEL



QC2 step2: three-step HV tests

- 1) 1st HV scan test
- 2) Long-term test for 120 hours
- 3) 2nd HV scan test

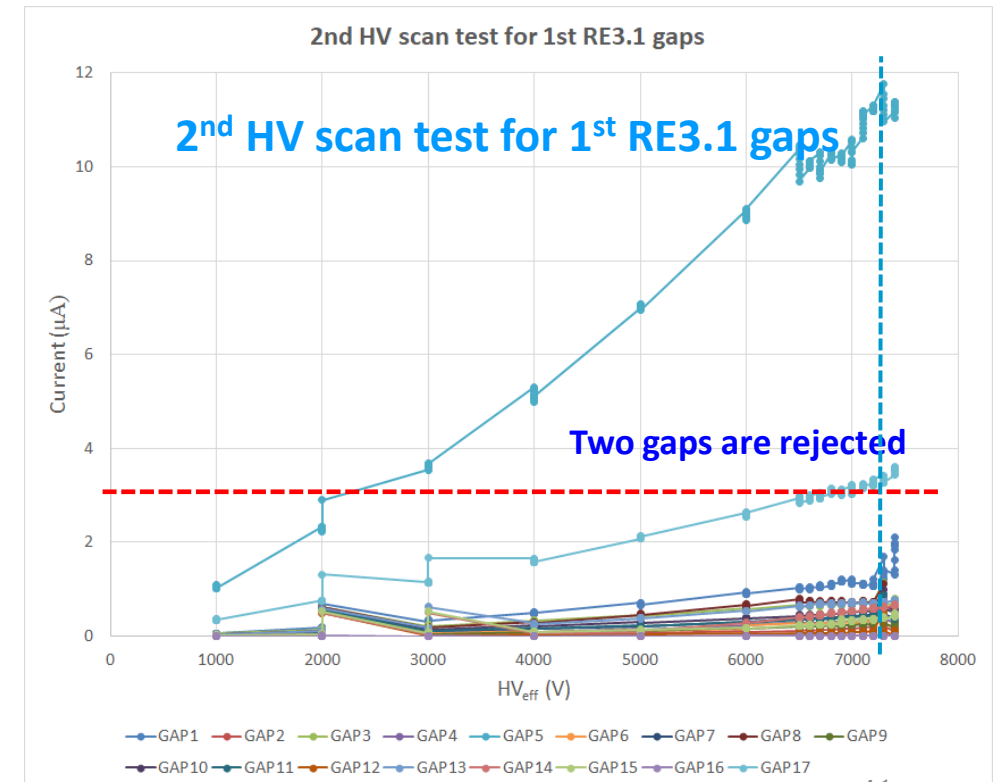
Operational gas = 95.2% TFE + 4.5% isobutene + 0.3 SF₆ with Gas humidity = 40%

Requirements:

For Ohmic current: current limit = 0.5 μ A @5.0 kV

For operation: current limit = 2 μ A at effective HV (7.5 kV)

- QC data for HV tests: csv excel format for currents, P, T, H (gas & ambient)



MPI: qualification of 2 industrial producers



Website: <https://www.mirion.com/>



Website: <https://www.ptsmaschinenbau.com/>

The 2 producers are followed up directly by MPI personnel and based on the same design and equivalent procedure been implemented by INFN at GTE

- PHASE-0: Optimization of the production steps in interaction with companies
- PHASE-1: Qualification of companies with test-sample prototypes
- PHASE-2: Qualification of companies with both small- and real-scale prototypes
- The series production is planned to start for September 2024

← **we are HERE!**

Certification plan

- Small- and real-scale RPCs will undergo long-term irradiation for half a year in the CERN GIF++
- Small and real scale prototypes per each company + dummies for oiling QC
- Small scale RPC are produced and just started irradiation at GIF++
- Real scale prototypes are under construction

Factory Acceptance Tests

An extensive Quality Assurance and Quality Control (QA/QC) program has been established to guarantee high quality and reliability of the gas volume production:

QA/QC step 1: HPL production test

- Visual inspection of surface, volume resistivity meas., thickness meas.

QA/QC step 2: Electrode production test

- Visual inspection and surface resistivity meas. of the graphite coating.
- Test of absence of bubbles between the insulating PET foil and the graphite coating.

QA/QC step 3: Gas gap production test

- ... see next slides!



visual inspection



volume resistivity meas.



thickness meas.

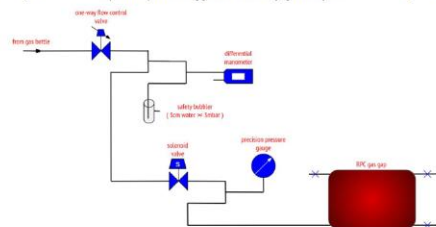
Gas tightness measurement

Objective:

Identify the gas leak rate of the gas gap by monitoring the drop of the internal over-pressure as a function of time and check the gas tightness

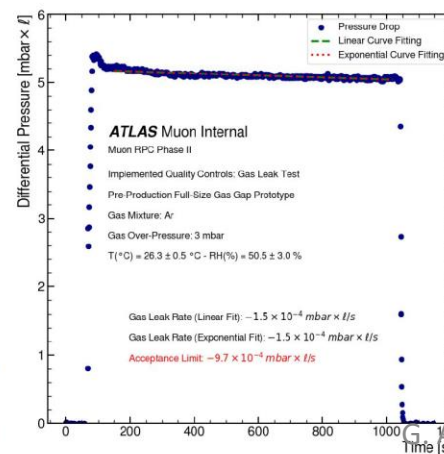
Methodology:

- The internal pressure of the gas volume is increased by up to 3 mbar above atmospheric pressure using a controlled gas supply.
- The internal pressure is monitored for 15 min. after closing the gas volume.



Analysis:

- The experimental data are modeled using both linear and exponential fits to determine the gas leak rate of the gas volume
- The gas volume passes the gas tightness test if the gas leak rate of the gas gap + gas system does not exceed: $-9.7 \times 10^{-4} \text{ mbar} \times \text{l/s}$.



Spacer traction test & Spacer height measurement

Objective:

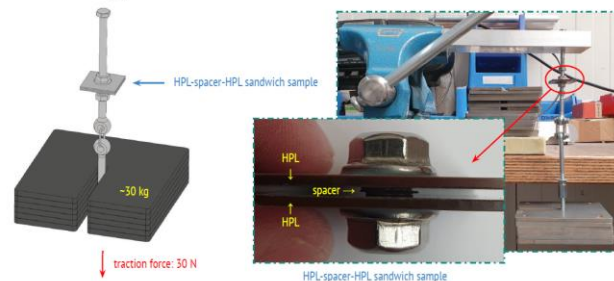
Ensure the reliability of glued pillars on HPL plates for assembled gas volume.

Methodology:

- For each gas volume, a $3 \times 3 \text{ cm}^2$ HPL-spacer-HPL sandwich sample is prepared at the end of each gluing phases.
- A traction force of 30 N is applied to each sample to ensure that no disconnection occurs.
- If no disconnection occurs at 30 N, the applied force is gradually increased until the pillar breaks.

Analysis:

The breaking point occurs at a traction force $\geq 100 \text{ N}$.



Objective:

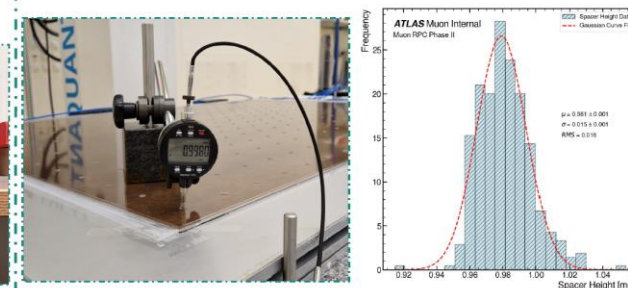
Ensure precise compliance with spacer height during the gas gap gluing phase, serving as an indirect verification of accurate gas gap dimensions.

Methodology:

Following the initial gluing step, the spacers remain accessible, allowing for precise measurement of their heights relative to the HPL plate using a digital drop indicator.

Analysis:

All spacer heights are within the 1 mm gas gap specification, with a spread well below $20 \mu\text{m}$.



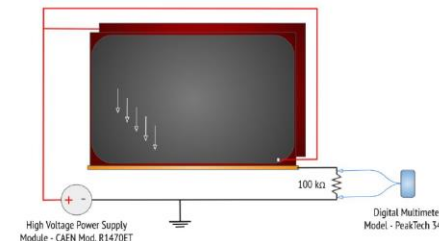
Leakage current measurement

Objective:

Measure the leakage current within the HPL electrodes of the gas volume to ensure proper insulation and minimal leakage.

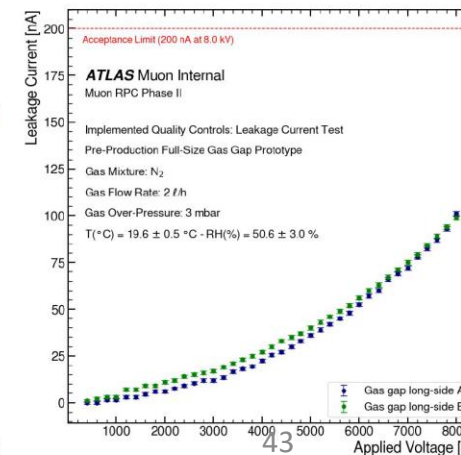
Methodology:

- The HPL electrodes are subjected to the same voltage as the HV power supply.
- A copper-coated aluminum bar, grounded through a 100 kΩ resistor, is brought into contact with the long side of the gas gap under test.
- The leakage current flow to ground is measured using a digital multimeter, by monitoring the voltage drop across the resistor.



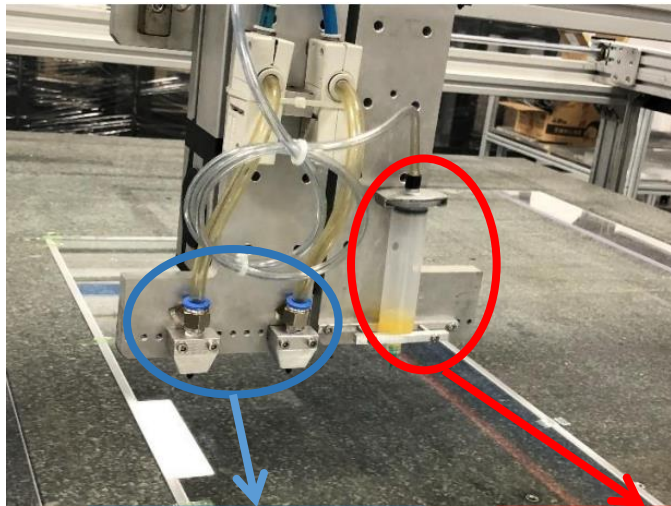
Analysis:

The gas volume passes the leakage current test if the leakage current not exceed 200nA at the maximum applied voltage of 8 kV on both HPL electrode.



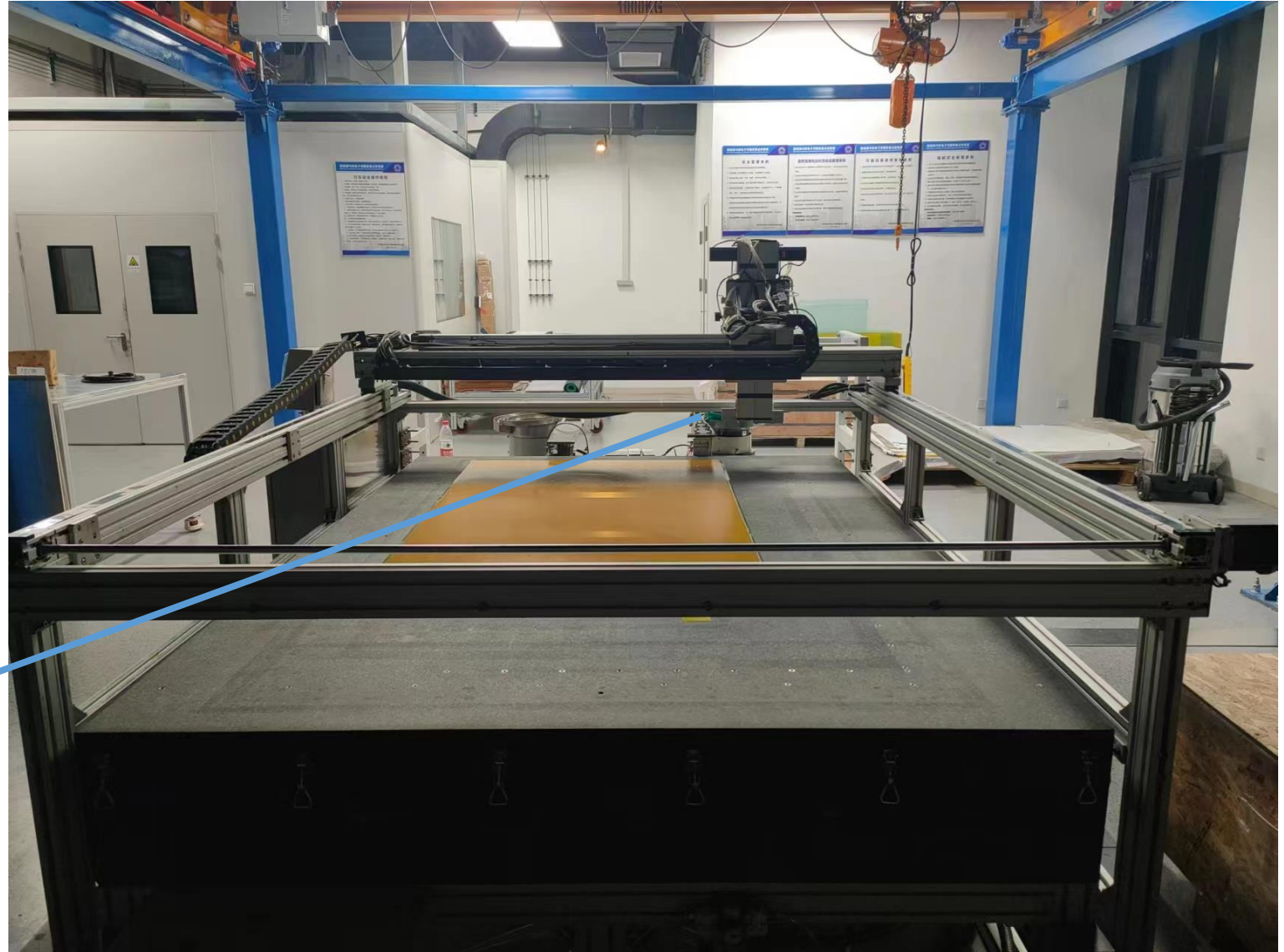
The platform of gas gap production at USTC

- A marble table as base:
2.5m×1.8m
- A head stock supported by a gantry moving in 2-dimentional
- 9 holes among the table are connected to the vacuum system.



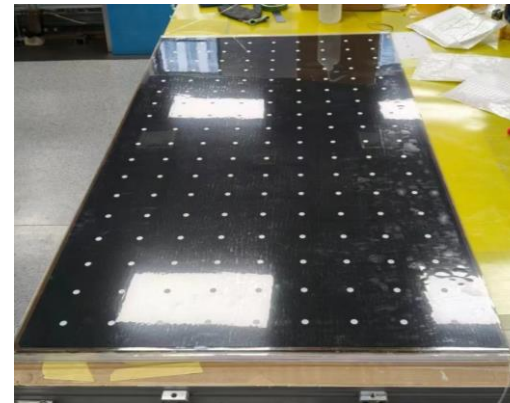
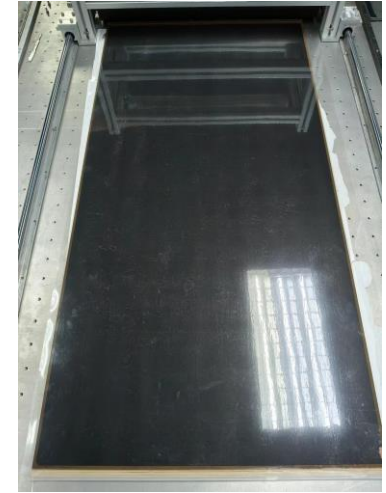
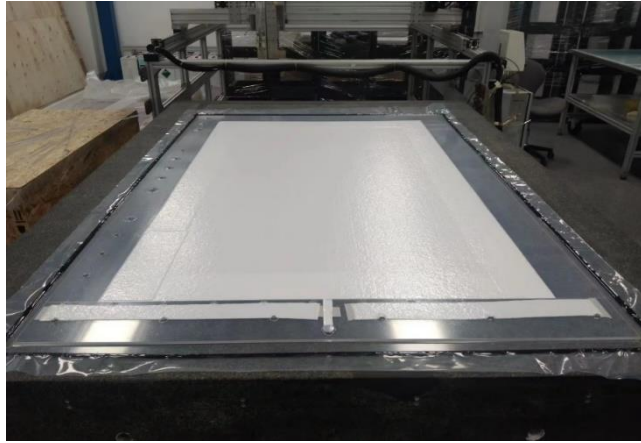
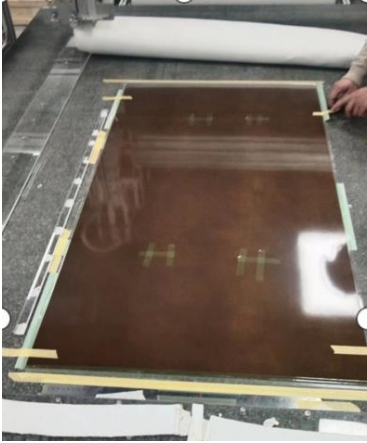
10/15/2026
Spacer pickers

Glue syringe



G. Aielli - ISU

Production steps



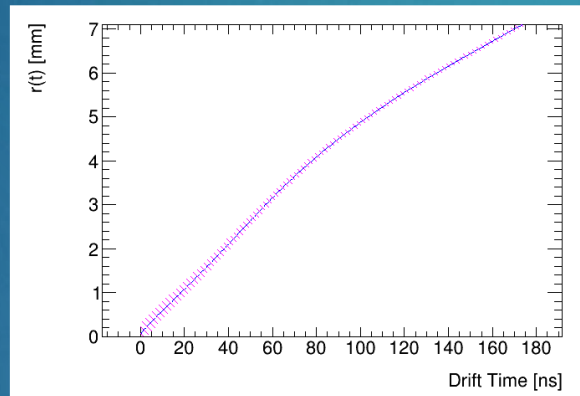
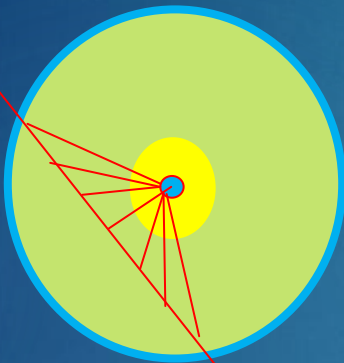
Backup

Space resolution principles

- ▶ Space resolution is driven by 2 factors
 - ▶ Intrinsic localization of the event
 - ▶ Precision of the chamber geometry

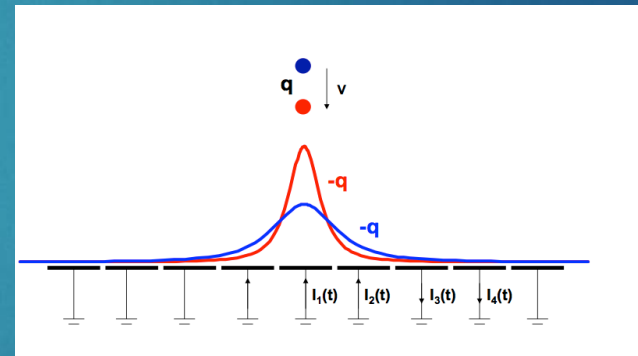
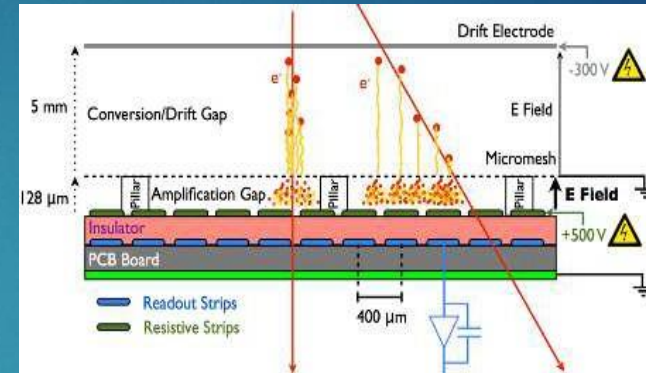
Wire chamber

$$E \approx \frac{1}{r}$$



- ▶ Tubes and MWPC exploit the R-t relation of the ions drifting in the gas and rely on their metallic bulks which can be easily machined to offer a precise reference frame. Can obtain high precision with low channel density

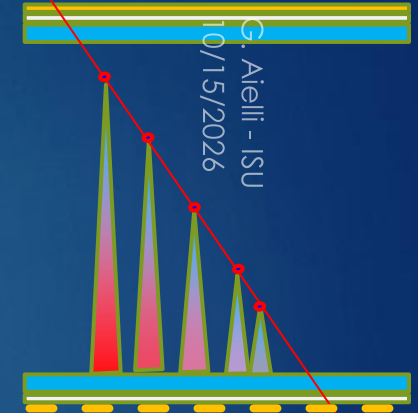
MPGD



- ▶ RPCs and MPGD exploit electrostatic induction of the moving charges to calculate the charge centroid. The resolution is driven by the readout system segmentation and mechanical precision preserving it on large multi-layer chambers made of composite materials. Can obtain high precision with high channel density

47

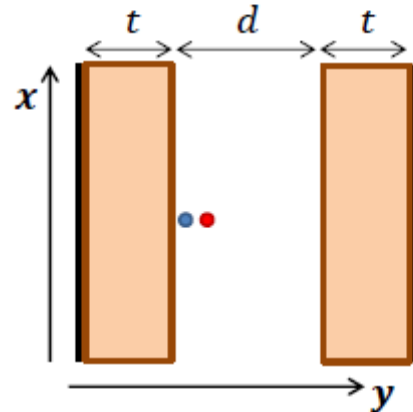
RPCs



The Physical model

An induced charge distribution model

The main limitation of this model is that it does not take into account the presence of the resistive electrodes. It also neglects the presence of other parameters, as graphite painting.



Considering the presence of the electrodes, the parameter δ can be written as

$$\delta \cong \frac{d + 2t}{\pi}$$

*C. Lu, Princeton University, Princeton, NJ 08544, USA
SNIC Symposium, Stanford, California – 3-6 April 2006

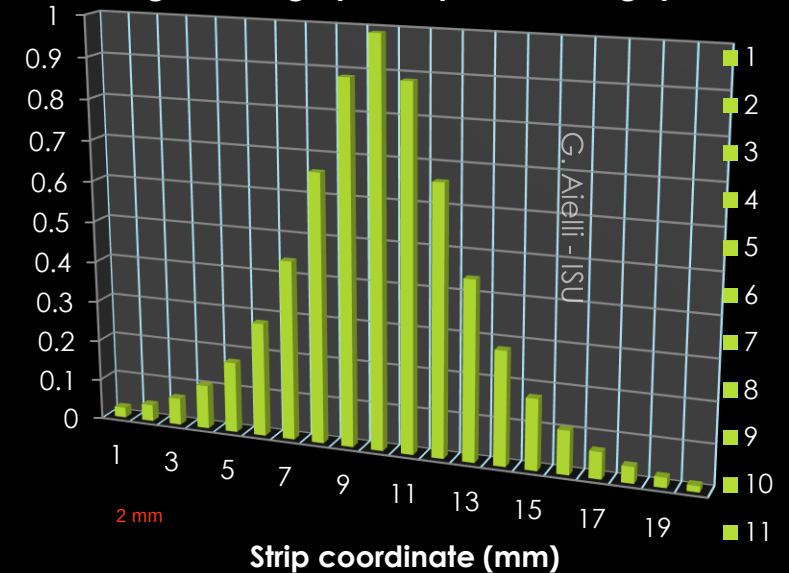
For simplicity, when the thickness of the electrode is similar to the gas gap and smaller than the strip pitch, the effect of the charge displacement with respect to the middle of the gap is negligible. This offers the possibility to use the model.

$$\sigma = \frac{q_{ind}}{2\pi\delta} \frac{1}{\cosh\left(\frac{x - x_0}{\delta}\right)}, \quad \delta \cong \frac{d + 2t}{\pi}, \quad q_{ind} = q \frac{\Delta y_{el}}{d + \frac{2 \cdot t}{\epsilon_r}}$$

L. Paolozzi, RPC2014 - Beijing

4

Integral charge per strip for a RPC gap



$$\sigma(x, \bar{x}) = \frac{A}{\cosh[(x - \bar{x})/\delta]}$$

$\Rightarrow$ integration over each strip

$$Q_i = \int_{x_1}^{x_2} \frac{A}{\cosh[(x - \bar{x})/\delta]} dx =$$

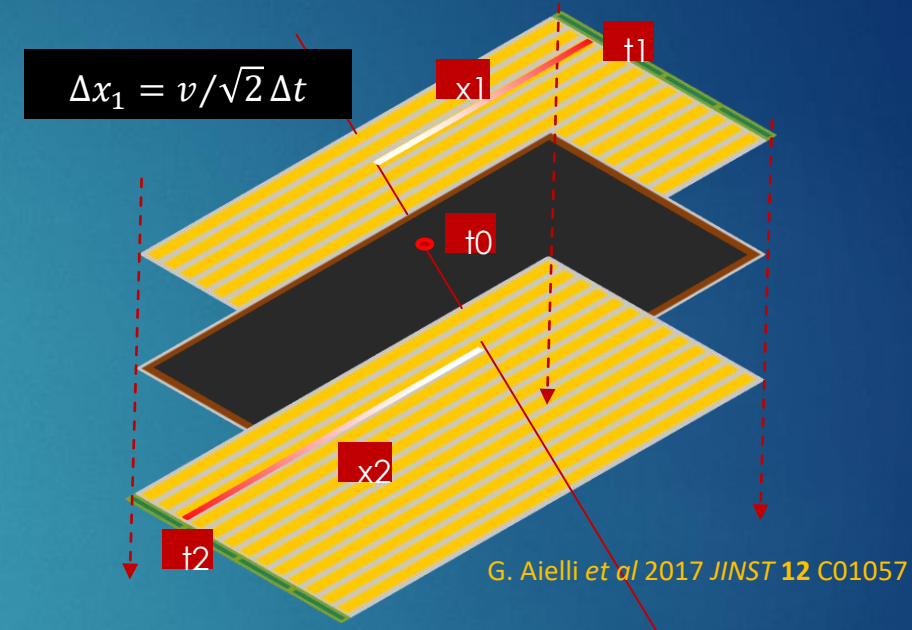
$$= A\delta \cdot \operatorname{arctg}\left[\left(e^{(x-\bar{x})/\delta}\right)\right]_{x_1}^{x_2}$$

Yet another method: strip drift time

G. Aielli - ISU

CHALLENGING READOUT FOR FUTURE COLLIDERS

- FAST LEADING SIGNALS FOR THIN GAS GAPS
- NEW GENERATION OF INEXPENSIVE ~ 1 ps TDCs
- PROPAGATION SPEED 15 CM/NS
- 100 μ m PRECISION IS THE TARGET
- CAN BE REPLICATED IN 2D
- ACCURATE RECONSTRUCTION OF MULTIPLE TRACKS



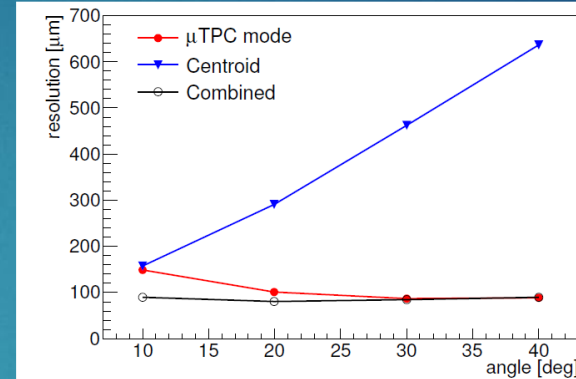
Space resolution performance

50

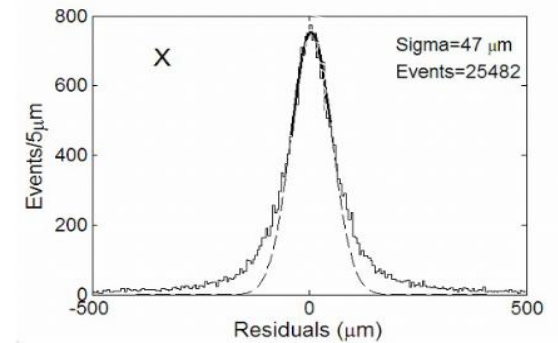
RPCs and MPGDs

- ▶ ATLAS MMGAS
 - ▶ resolution $\sim 100\mu\text{m}$ with 0.4 mm strips
- ▶ The drift gap is large $\rightarrow$ impact angle worsen resolution corrections needed (micro-TCP method)
- ▶ Affected by the B field
- ▶ A lot of care needed in construction
- ▶ Proof of principle on a small MRPC
 - ▶ resolution $\sim 50\mu\text{m}$ with 4 mm strips
 - ▶ RPC less sensitive to the angle $\rightarrow$ smaller gas gaps and a single dominant cluster
- ▶ 1m² 1mm gas gap ATLAS prototype reaching 1mm space resolution with 2.7cm strip pitch! Up to 10 kHz/cm² at GIF++
- ▶ Space resolution is not a classic RPCs performance, though physics is not preventing it...

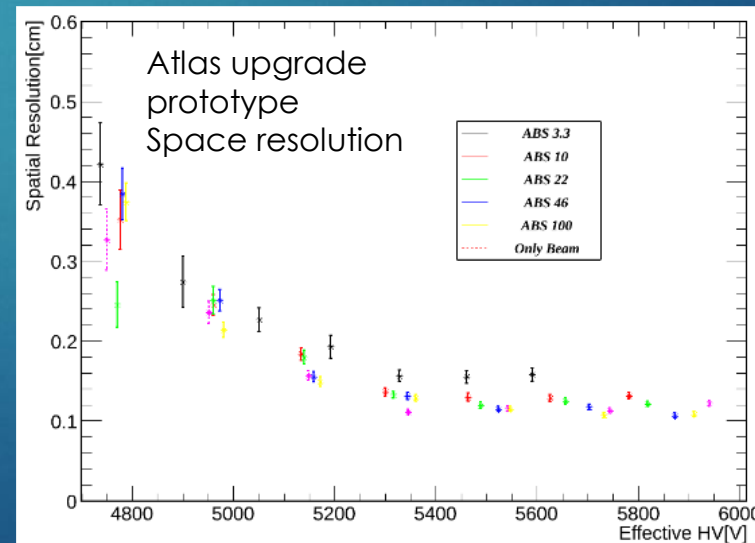
MMGAS



MRPC



Planar technologies need further R&D for a simple and reliable structures to emulate DTs



Time resolution principles

51

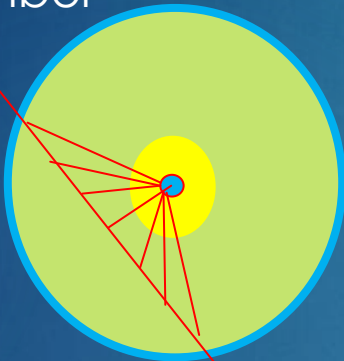
- ▶ Time resolution is driven by
 - ▶ Avalanche statistical fluctuations
 - ▶ Drift time (velocity x gap size)
 - ▶ Electronics noise



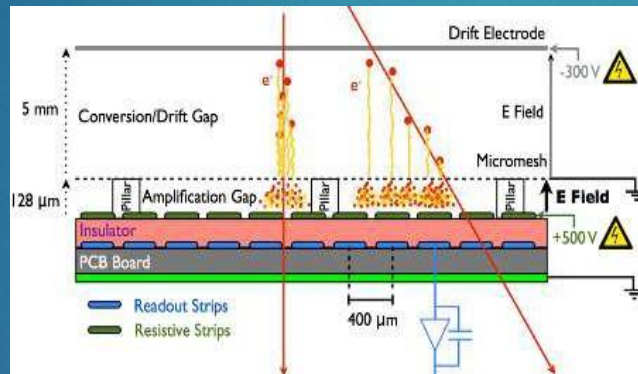
G. Aielli - IS
10/15/2026

Wire chamber

$$E \approx \frac{1}{r}$$



MPGD

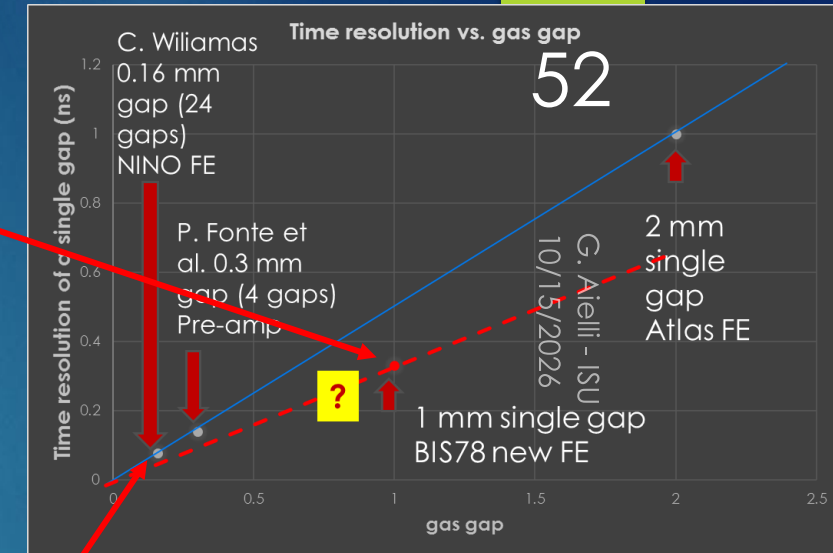
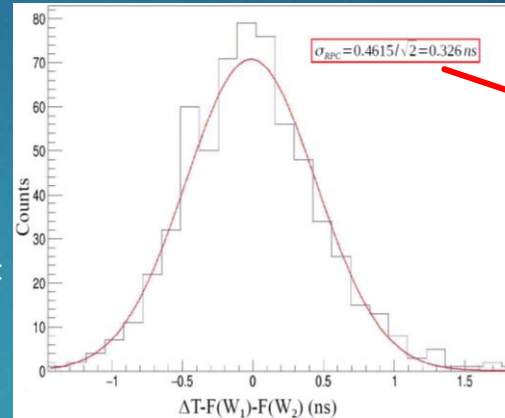


- ▶ MWPC and MPGD work on similar principles: the separation of the drift and multiplication introduces irreducible uncertainty on the time resolution, dependent on the drift width
- ▶ RPCs and MRPCs drift and multiplication space coincide. The multi-micro gap RPC segments the gas gap to further reduce the drift time

RPC time resolution

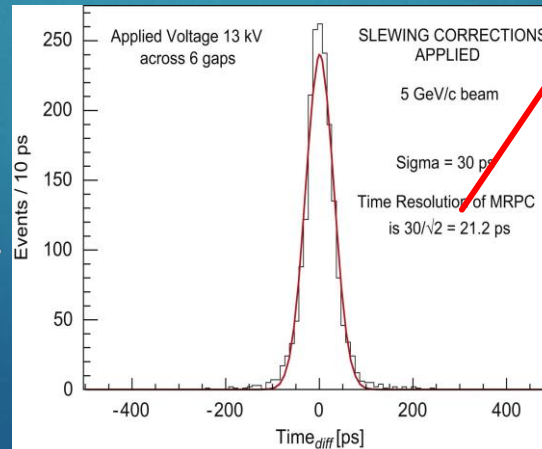
Time resolution is one of the main RPC features

- ▶ Golden standards: **MRPCs ~50 ps** -- **RPCs ~500 ps**
- ▶ complex physics behind: cluster statistics, multiplication dynamics, electronic noise
- ▶ Empirically smaller gas gaps → higher resolution
 - ▶ Smaller gas gaps can be operated at higher electric field and have a faster multiplication dynamics compressing noise fluctuations
- ▶ As one learn from other detectors the electronics noise plays a role



CHALLENGE: RESOLUTION BEYOND 50 PS

- WITH MORE AND THINNER GAS GAPS, E.G., 20 PS WITH 24, 0.16 MM GAPS
[10.1016/J.NIMA.2008.06.013]
- THINNER ELECTRODES → HIGHER SIGNAL
- LOW NOISE HIGH RESOLUTION FEE (PICO TDC) <https://kt.cern/technologies/picotdc>



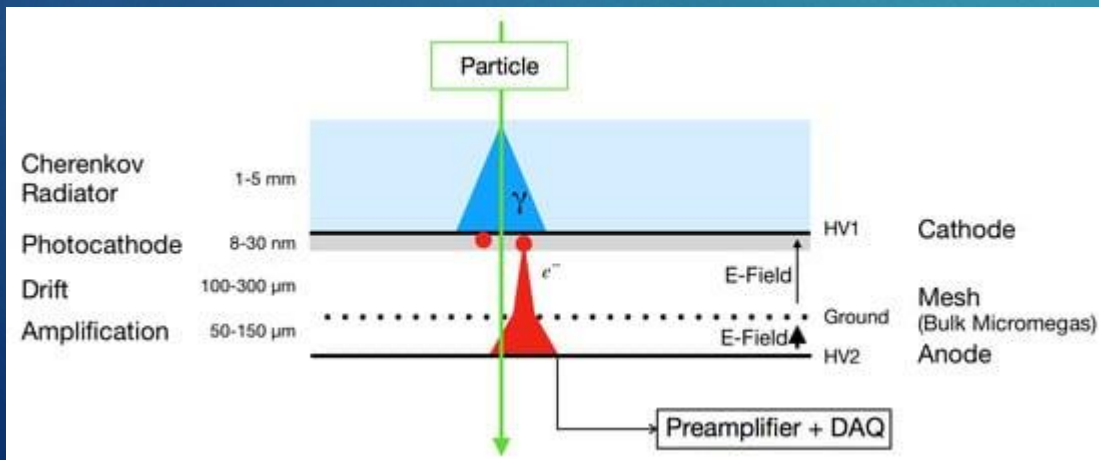
INNOVATIVE APPROACH →

- GOING BEYOND THE GAS GAP WIDTH LAW
- EXTRACT HIDDEN INFORMATION BEYOND DISCR. AND SLEW CORRECTION
- PROMISING THE USE OF DNN TO FILTER THE COMPLEX AVALANCHE DYNAMICS → 16 PS ACHIEVED! [ARXIV:2005.03903V1 [PHYSICS.INS-DET] 8 MAY 2020]

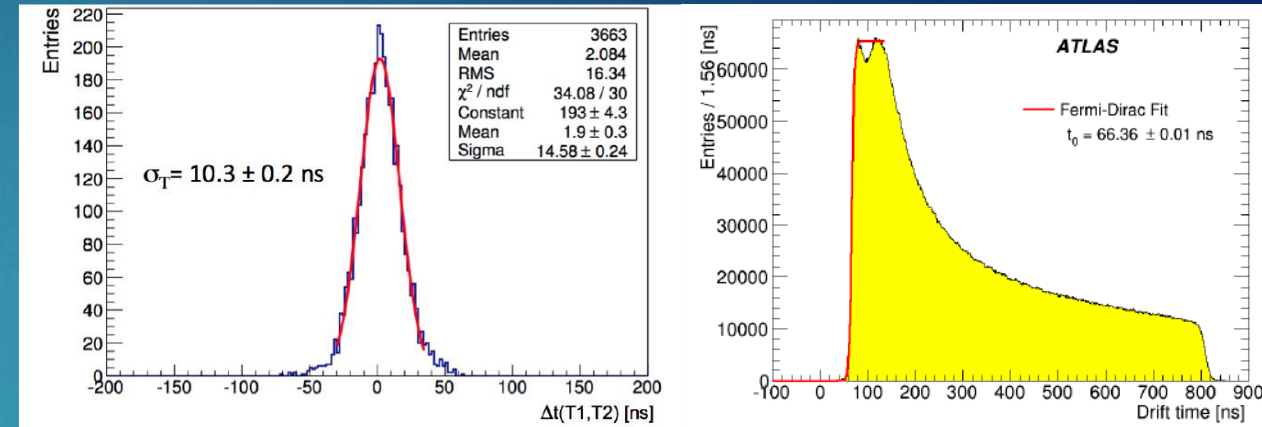
Drift based detectors time resolution

53

- ▶ DT drift spectrum is by construction unsuitable for timing as a long drift time is used for high space accuracy
- ▶ ATLAS Thin gap chambers $\rightarrow$ 6-7 ns
- ▶ Typical Micromegas, GEM, μ RWELL 10 ns
- ▶ A proposal to get rid of the drift variations is to hybridize a MMGAS with a photocathode and a Cherenkov radiator. Resolution $\sim$ 50 ps driven just by the single avalanche process, like in MRPC



Atlas MMGAS



Atlas sMDT

- ▶ Drift detectors are limited in time resolution and an optimal strategy is combining a drift detector with an RPC to have a combined performance.
- ▶ MPGD have a barely sufficient resolution for identifying the BC at 25 ns but it can be improved by using multiple layers for the 5ns scenario
- ▶ The idea to combine a Cherenkov and a MMGAS can provide a good timing in the very high rate regions (why not an RPC?)

Present limits – rate and longevity

54

Rate capability [RPCs and MPGDs]

- ▶ Electrode resistivity to prevent discharges in RPCs and MPGDs but limits rate capability:

- ▶ $\Delta V = \langle Q \rangle \times \text{freq.} \times R$

- ▶ $\langle Q \rangle$ is very favorable in MPGDs

Longevity: Bulk materials insensitive to radiation, but

- ▶ radicals produced in RPC avalanches affect the electrodes
- ▶ High ionization may induce discharges in MPGDs progressively damaging the detector

Rate capability (drift chambers)

- ▶ Limited by the space-charge effect
- ▶ Effect reduced with $R^3 \rightarrow R=1/2 \rightarrow \text{rate} = 8x$ (drift time $\times$ cross section)

Longevity: Bulk materials insensitive to radiation, but

- ▶ Gas purity is very important to avoid ageing
- ▶ no discharges possible (geometrical quenching)
- ▶ No observed ageing in such conditions

- LOWERING R IMPROVES RATE CAPABILITY ONLY

- LOWER RESISTIVITY MATERIALS
 - THINNER ELECTRODES

- ACHIEVING HIGH RATE BY BRUTE FORCE REDUCTION OF R (WITHOUT REDUCING AT THE SAME TIME THE E FIELD) MAY LEAD TO INSTABLE DETECTORS

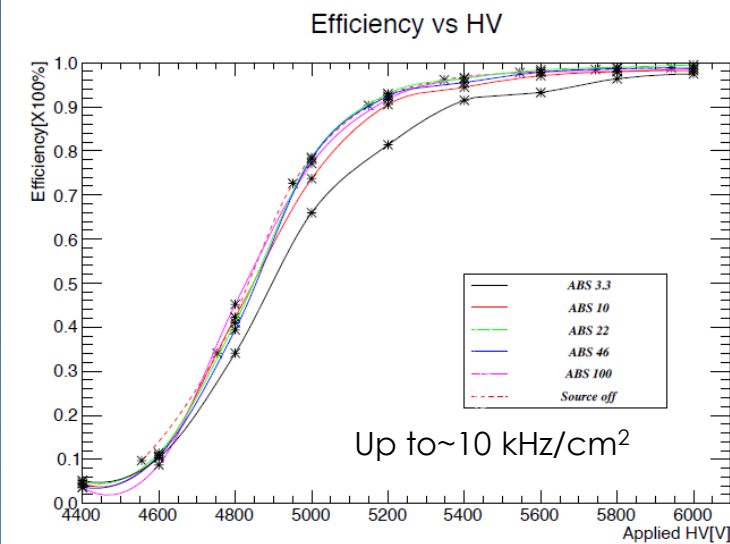
- REDUCTION OF $\langle Q \rangle$ IMPROVES RATE CAPABILITY AND LONGEVITY AT THE SAME TIME

- BY IMPROVING THE S/N ON THE FE ELECTRONICS
 - BY IMPROVING THE SIGNAL COLLECTION EFFICIENCY

Keeping the gas clean is the key to preserve the electrode longevity

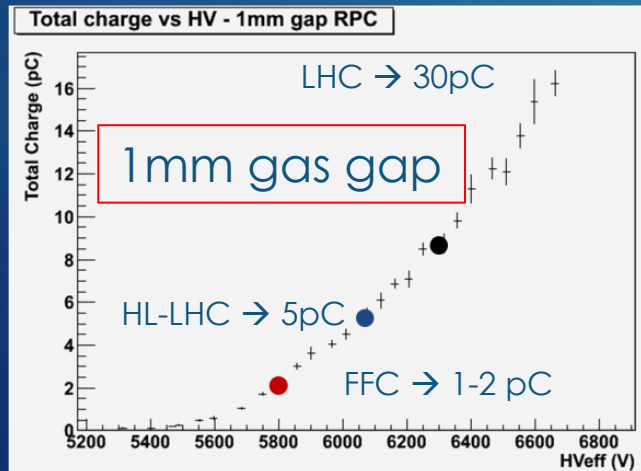
High rate for single gap RPCs

- ▶ limited by Ramo theorem ($\sim 1/20$ of $\langle Q \rangle$ is usable)
- ▶ low resistivity electrodes made of HPL ($\sim 10^{10} \Omega \text{ cm}$)
- ▶ SiGe FE tech. with 4k e- noise to reduce $\langle Q \rangle$
- ▶ Reaching up to 10 kHz/cm² in production chambers
- ▶ Suitable for safe operation with eco-gas mixture



FFC full TARGET $\rightarrow$ improve by a further order of magnitude by increasing S/N and lowering R:

Last generation SiGe hetero-junction technologies (ft 0.7 THz) announce a further $\times 10$ leap in the FE $\rightarrow$ 500 e- noise reduction

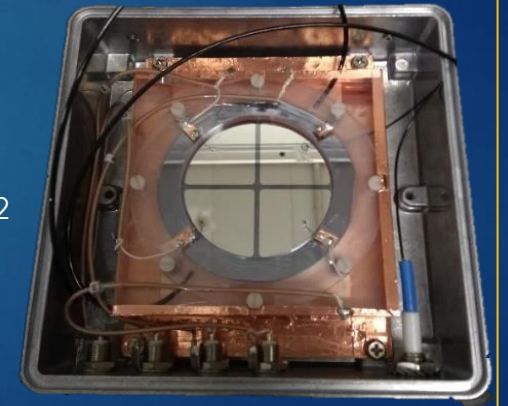


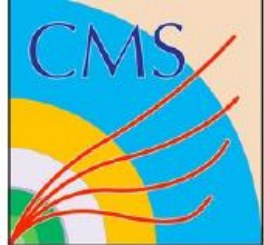
For further exploiting the electronics:

- Faster avalanche
- Very efficient grounding

A new device: single gap semi-conductor RPC
[electronic carriers can not be depleted]

- ▶ 0.6 mm GaAs electrodes
- ▶ Resistivity $1.4 \times 10^8 \Omega \text{ cm}$
- ▶ Tested up to $> 40 \text{ kHz/cm}^2$
- ▶ $> 1 \text{ MHz/cm}^2$ is possible
- ▶ Active area 6.25 cm^2
- ▶ [10.1088/1748-0221/15/12/C12004](https://doi.org/10.1088/1748-0221/15/12/C12004)

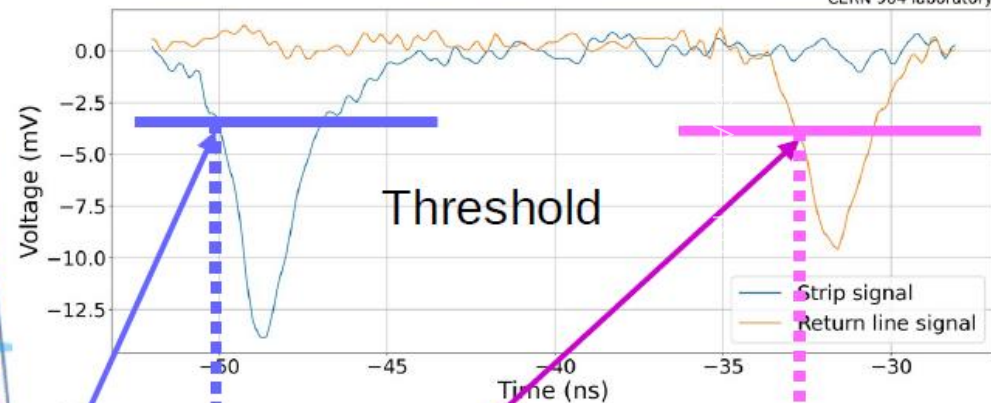
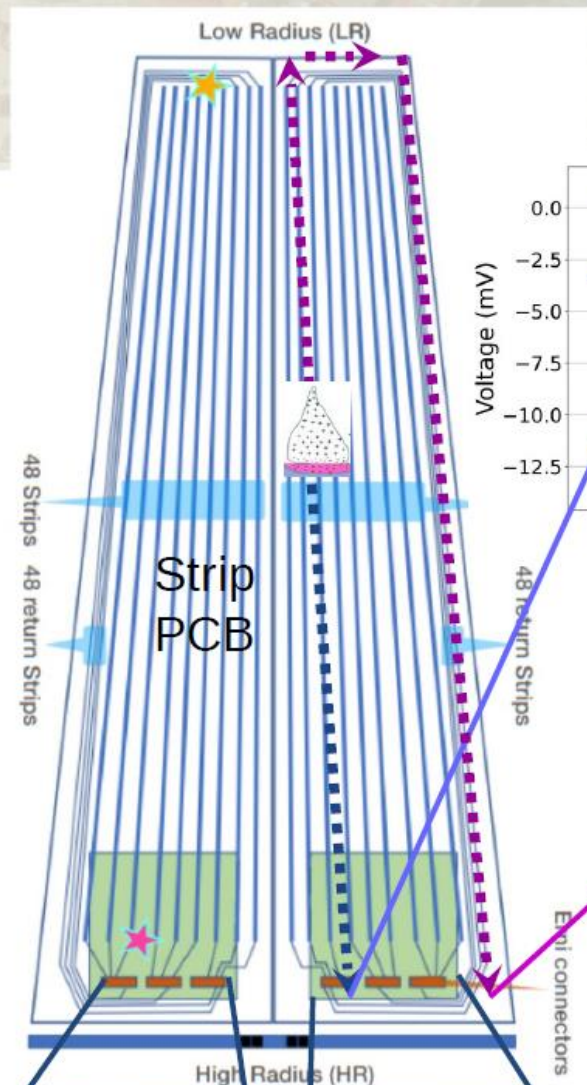
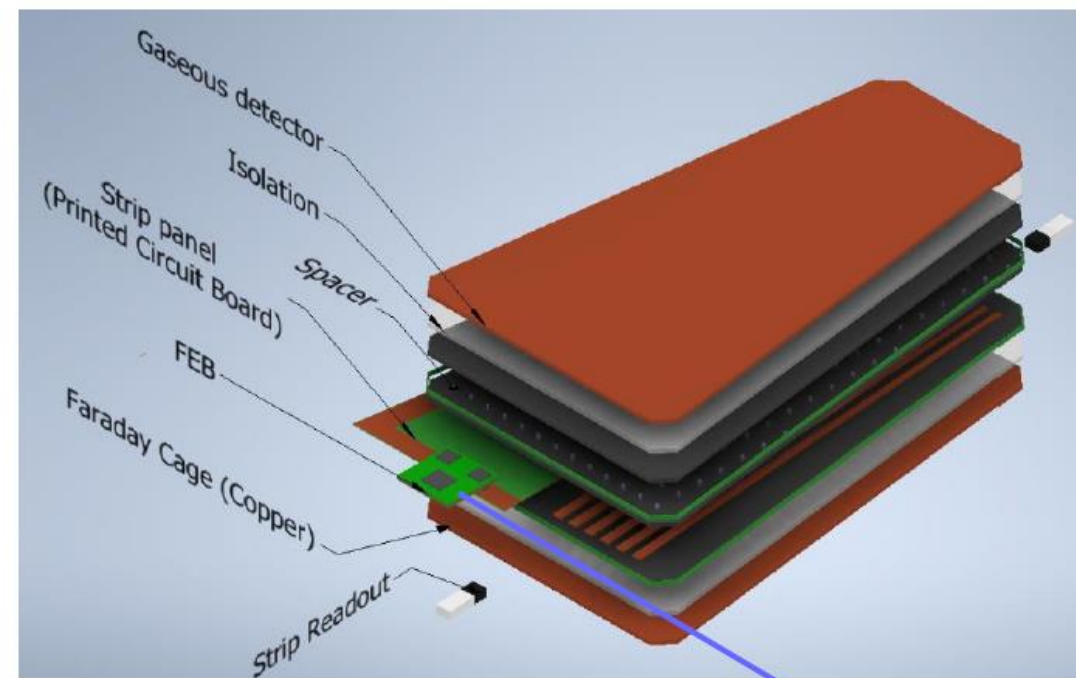




1.3) iRPC

readout

CERN 904 laboratory



- Strip pitch : 0.5 – 1 cm
- Double sided readout of long strips using timing to localise the signal position

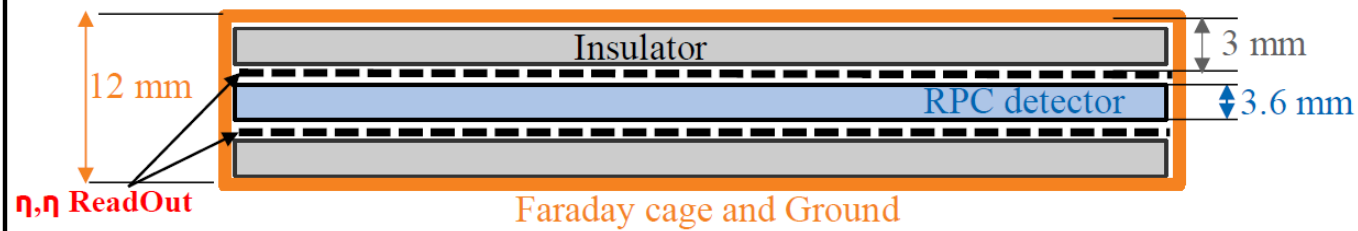
$$\Delta T = T_{HR} - T_{LR}$$

$$\sigma_{\Delta T} \sim 150 \text{ ps} \rightarrow \sigma_{\eta} \sim 1.5 \text{ cm}$$



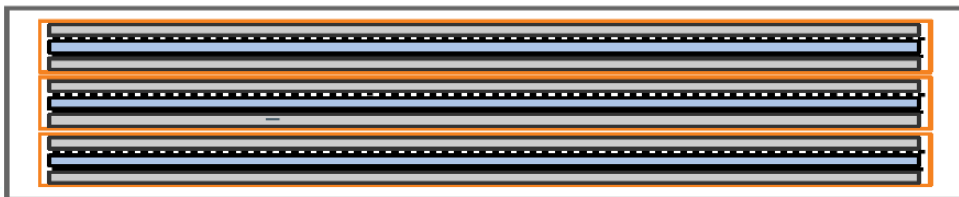
BI RPC Challenges – Physical encumbrance & new detector structure

BI RPC singlet layout



RPC triplet layout

- 3 independent singlets
- Up to 36 x 8 η FE chs



	ATLAS RPC currently installed	ATLAS New generation RPC
Detector	Mono gas gap	Mono gas gap
Gas Gap width	2 mm	1 mm
Electrode Thickness	1.8 mm	1.3 mm
Gas Mixture	95% TFE, 4.7% i-C4H10, 0.3% SF6	95% TFE, 4.7% i-C4H10, 0.3% SF6
Time Resolution	1 ns	0.4 ns

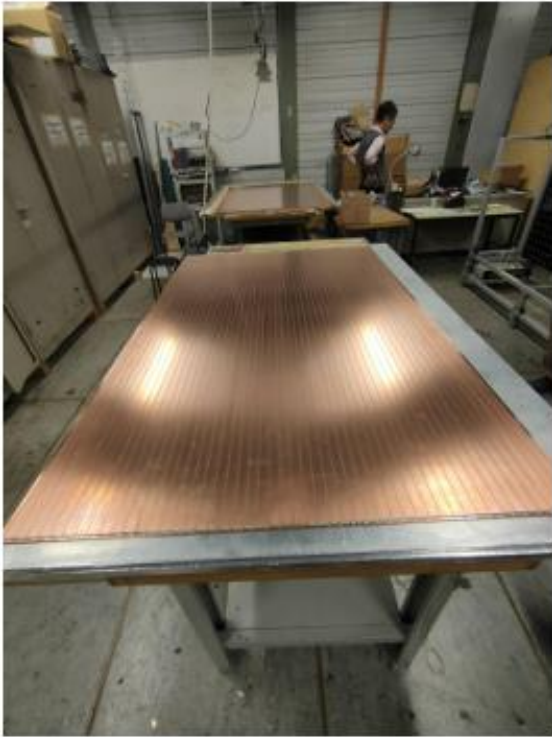
The available space in the ATLAS muon-spectrometer inner barrel implies mainly:

- Few centimeters space (in the orthogonal direction wrt the beam) for the full detector placement along with most of its services
 - Some fully inaccessible zones
 - No room for the electronics on the detector phi side due to geometrical factors and impossibility to overlap the detectors
- Detector and services structures re-design**
- Parallel strips readout** (second coordinate measured with the time arrival difference at the detector edges)

The time resolution < 100 ps of the TDC embedded in the FE allows the reconstruction of the second coordinate with 1 cm space resolution.

BIS singlets assembly (Training @ BB5)

58



Step1:
Put the readout pannel in
the table with strip pannel
on the top



Step2:
Put the gas gap on the top
of the readout pannel



Step3:
Put another readout pannel
on the top of the gas gap



Step4:
Use the Aluminium tape
to fix those three layers
to form the singlet