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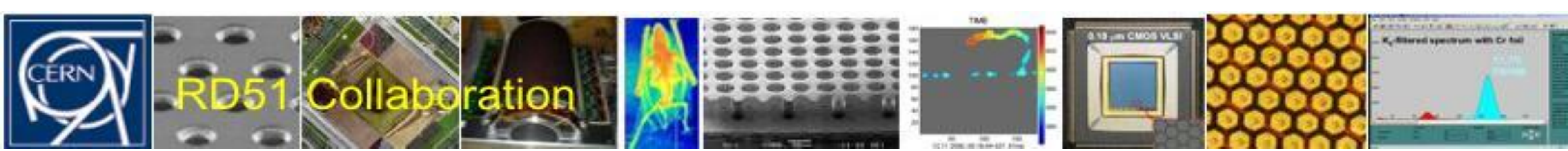
MPDG and μ–RWELL R&D at LNF

G. Morello on behalf of DDG group

53rd LNF Scientific Committee

May 9th, 2017



MPDG at LNF

Activities at LNF involving construction and development of **MicroPattern Gaseous Detectors**:

Past:

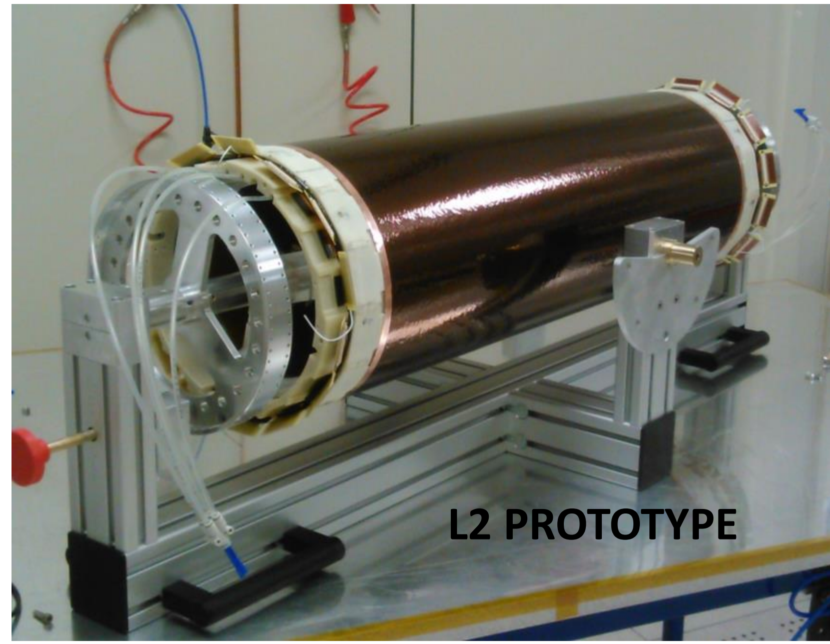
- **Planar triple-GEMs** for **LHCb** muon system trigger
- **Cylindrical triple-GEMs** for **KLOE-2** tracking system

Future upgrades:

- **MicroMegas** for the new **ATLAS** small wheels
- **Large area triple-GEMs** for the **CMS** GE1/1 region
- **Cylindrical triple-GEMs** for **BESIII** experiment
- **Micro-Resistive WELL** (**µ-RWELL**) proposed for **CMS** upgrades (GE2/1) and LHCb

Cylindrical GEMs

- First **CGEM bundle** ever built, equipped with a digital FEE on a X-V strips-pads readout.
- Standard gas-gaps 3/2/2/2
- Operated with Ar/iC_4H_{10} 90/10 gas mixture to decrease the discharge probability
- The project pushed CAEN to develop a dedicated floating HV board

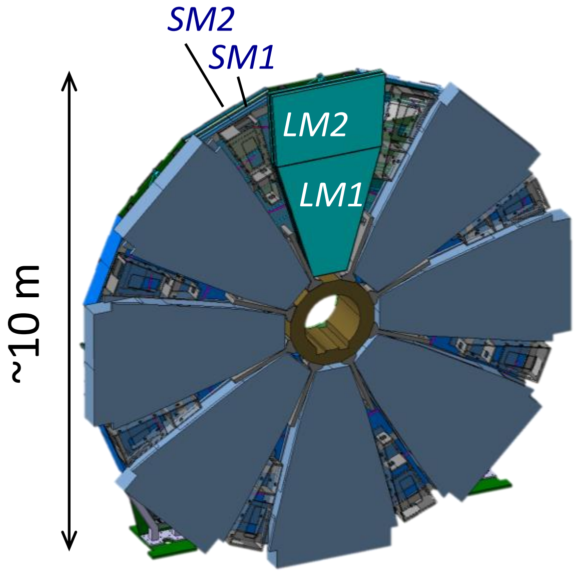


The BESIII-Italy collaboration is realizing three cylindrical GEMs to replace the inner part of the Drift Chamber.

- Non standard-gaps 5/2/2/2
- Analog FEE for charge analysis
- Requirements: 130 μm on r-φ plane in 1 T axial magnetic field, 2 mm along z

ATLAS upgrade

The ATLAS collaboration is building a New Small Wheel (NSW) with sTGC and MM.
Frascati is heavily involved in MM construction, focusing the efforts of other INFN sections.



Each NSW has 16 sectors
8 Large + 8 Small

- 15% P_T resolution at 1 TeV

→ ~100 μm resolution per plane

- Keep single muon trigger under control

→ 1 mrad online angular resolution

About 15kHz / cm^2 at $L \approx 5 \times 10^{34}\ cm^{-2}s^{-1}$

Challenge in MM construction:

alignment of the strips on each detection layer

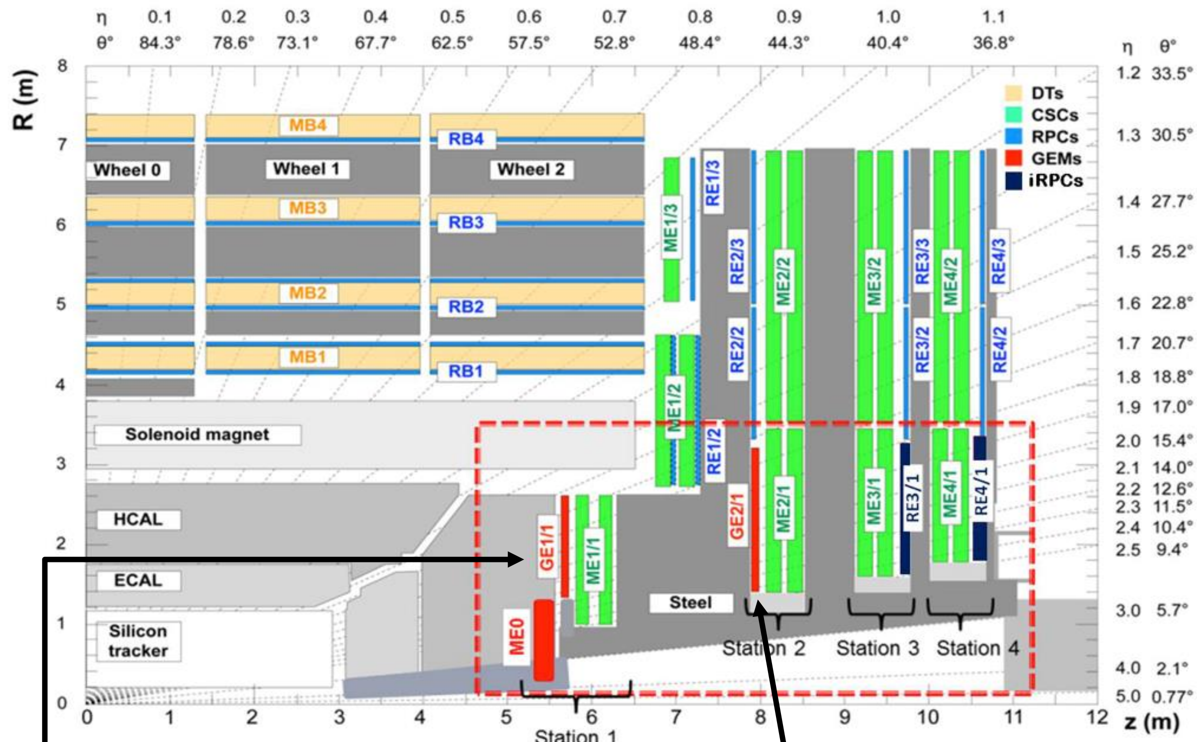
30 μm RMS in η

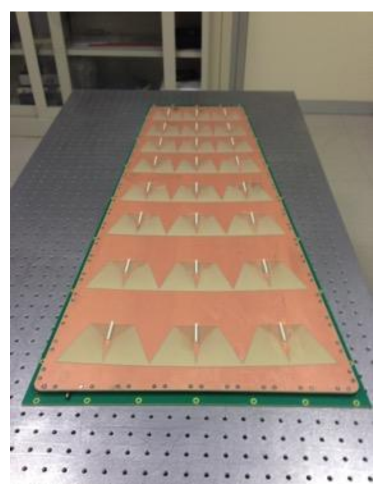
80 μm RMS in z

Preliminary results from the 2015 H8 Test Beam: Spatial resolution of 81 μm on the 'precision coordinate' f(η), 2.4 mm on the second coordinate

CMS upgrade

- **CMS-LNF group** has the responsibility to coordinate the CMS GEM general production in the different production sites (CERN, INFN, USA, India and Pakistan)
- **CMS-LNF group** contributed in the definition CMS GEM final design, proposing several mechanical and design solutions studied during the test on prototypes in the framework AIDA2020





GE1/1

- Total number of chambers to be produced @ LNF = 40
- Chambers with a size ~ 130x50 cm^2

GE2/1

- 36 Super Chambers each covering 20°
- Layout similar to GE1/1, but with a larger surface
- **GEM or μ-RWELL?**

LHCb upgrade

Requirements @ $2\times10^{34}cm^{-2}\,s^{-1}$

- **Rate** up to 3 **MHz/cm²** **with an additional filter in front of M2**
- **Efficiency** for single gap **> 95%** within a BX (25 ns)
- **Long stability** up to **6 C/cm²** accumulated charge in **10 y** of operation
- **Pad cluster size < 1.2**

	Expected max rate MHz/cm² (*)	Active area cm²	Pad Size cm² (*)	Rate/Pad MHz	# pad/gaps	# gaps	#chambers (with 2 gaps)
M2R1	3	30x25	0.63x0.77	1.5	1536	24	12
M2R2	0.5	60x25	1.25x1.58	1	768	48	24
M3R1	1	32.4x27	0.67x1.7	1	768	24	12
M3R2	0.15	64.8x27	1.35x3.4	0.7	384	48	24

(*) **average rate is about 50% of maximum rate**

(*) X, Y/4 w.r.t. present logical pads in M2R1-R2; **a factor 2 more in Y, to halve the rate/Pad**
X, Y/2 w.r.t. present logical pads in M3R1 and M3R2

in this framework the **GEM detector** is still **a valid option,**
however we are proposing a new detector ➔ **the μ-RWELL**

The μ-RWELL: motivations

Because of the micrometric distance between electrodes, every MPGD suffers from spark occurrence that can damage the detector or the FEE.

The R&D on μ-RWELL is mainly motivated by the wish to improve

- stability under heavy irradiation

And simplify as much as possible

- construction/assembly procedures

Consequently reducing the costs of the device.

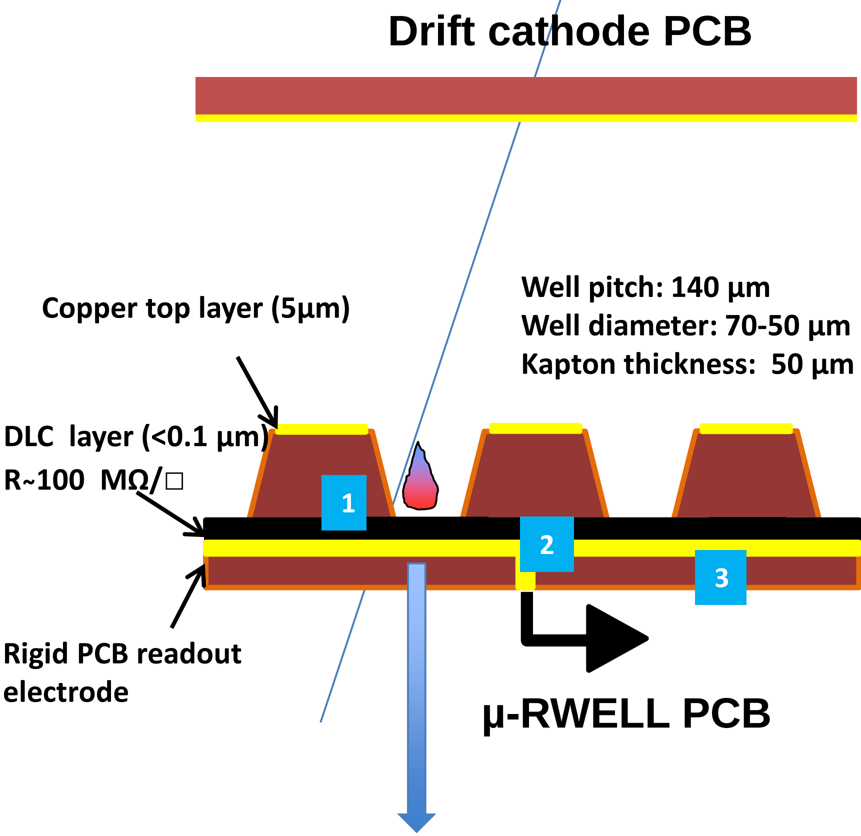
The detector architecture

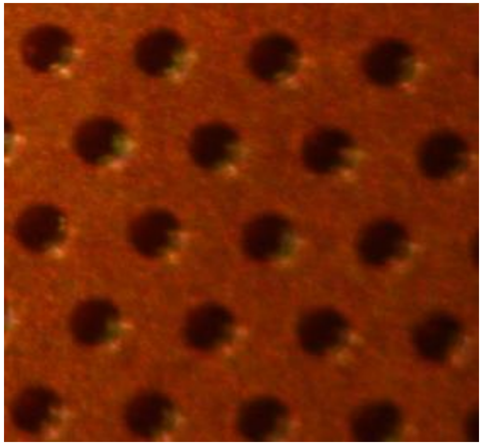
The **μ-RWELL is composed of** only **two elements**:
the **μ-RWELL_PCB** and the **cathode**

The **μ-RWELL_PCB, the core of the detector,** is realized by **coupling:**

1. a "WELL patterned kapton foil" as **"amplification stage"**
2. a **"resistive sheet"** for the discharge suppression & current evacuation
   i. **"Single resistive layer" (SL)** < 100 kHz/cm^2**:** single resistive layer → surface resistivity ~100 MΩ/☐ (CMS-phase2 upgrade; SHIP)
   ii. **"Double resistive layer" (DL)** > 1 MHz/cm^2: more sophisticated resistive scheme must be implemented (MPDG_NEXT- LNF) suitable for LHCb-Muon upgrade
3. a **standard readout PCB**

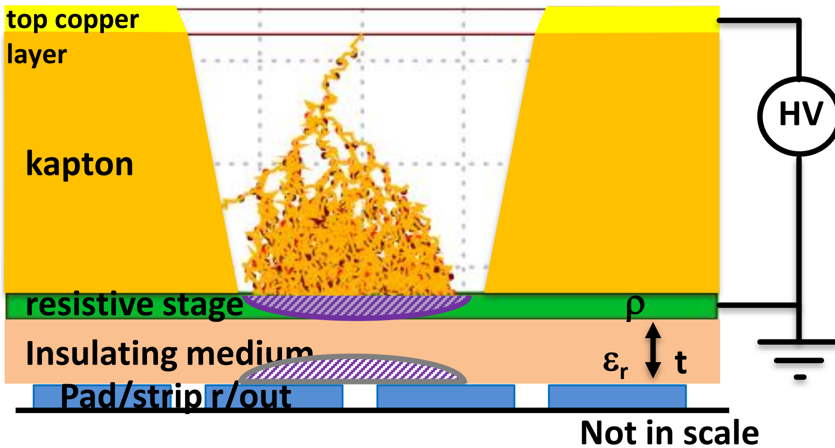
G. Bencivenni et al., 2015_JINST_10_P02008





(*) DLC = Diamond Like Carbon
High mechanical & chemical resistant material

Principle of operation



Applying a suitable voltage between top copper layer and DLC the "**WELL" acts as multiplication channel for the ionization.**

The charge induced on the resistive foil is dispersed with a *time constant, τ = ρC* , determined by

- the ***surface resistivity, ρ***
- the ***capacitance per unit area,*** which depends on the **distance between the resistive foil and the pad readout plane, *t***
- the ***dielectric constant*** of the insulating medium, ε_r ***[M.S. Dixit et al., NIMA 566 (2006) 281]***

- **The main effect of the introduction of the resistive stage is the suppression of the transition from streamer to spark**
- As a drawback, the **capability to stand high particle fluxes is reduced**, ***but an appropriate grounding of the resistive layer with a suitable pitch solves this problem (see High Rate scheme)***

The µ-RWELL

Main features:

simple assembly:

- ***only two components*** → ***µ-RWELL_PCB + cathode***
- no critical & time consuming **assembly** steps:
  - ***no gluing***
  - ***no stretching*** **(**→ no stiff & large frames needed)
  - ***easy handling***
- ***suitable for large area with PCB splicing technique w/small dead zone***

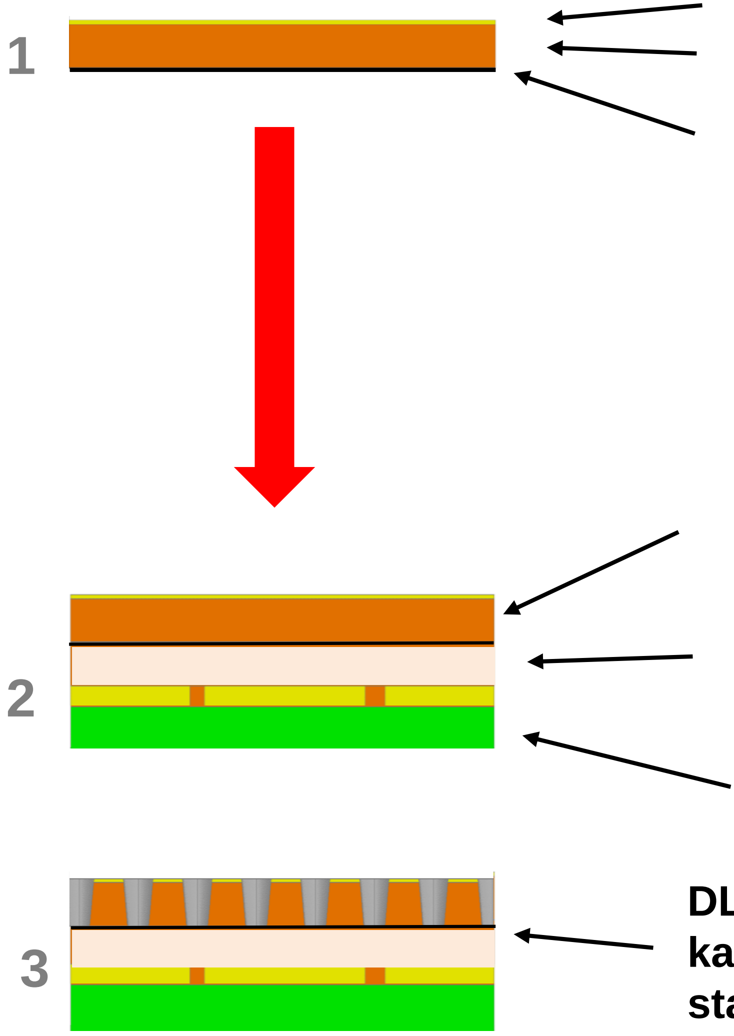
cost effective:

1 PCB r/o, 1 µ-RWELL foil, 1 DLC, 1 cathode and very low man-power

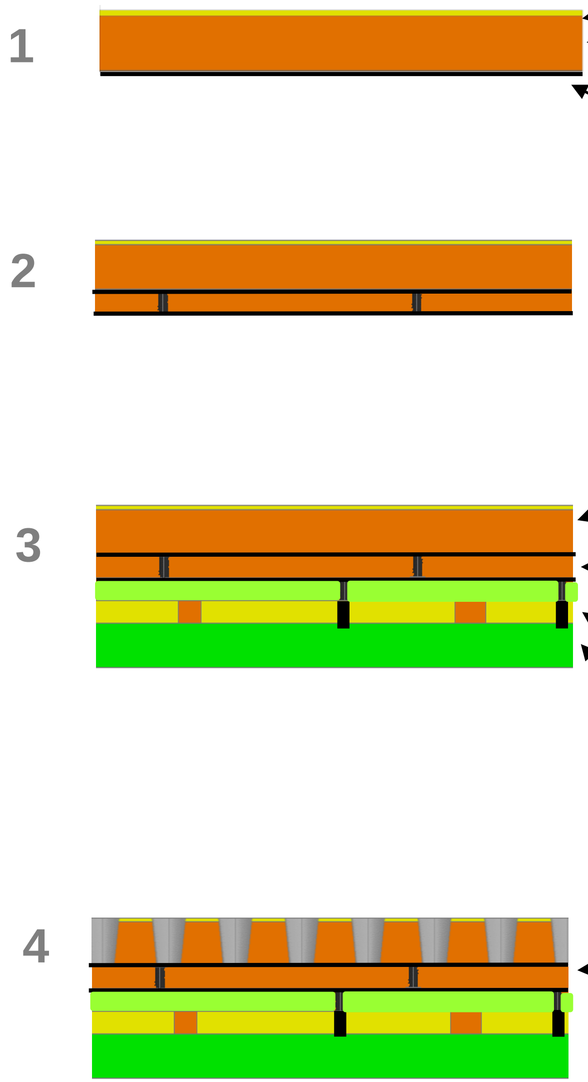
easy to operate:

very simple HV supply → only ***2 independent HV channels*** or a trivial ***passive divider*** (while 3GEM detector → 7 HV floating/channels)

The low rate scheme (CMS/SHiP)



The high rate scheme (LHCb)



Copper layer 5 µm

Kapton layer 50 µm

DLC layer: 0.1 – 0.2 µm
(10-200 MΩ/☐)

2^{nd} resistive kapton layer with ~ $1/cm^2$ "*through vias*" density

DLC-coated kapton base material

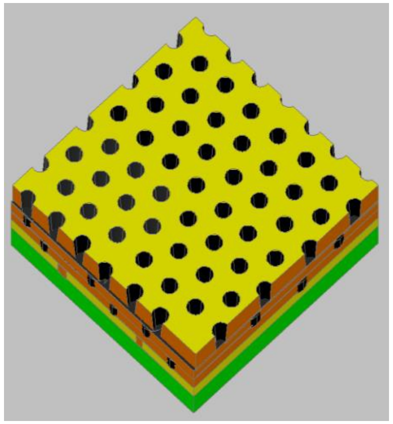
2^{nd} resistive kapton layer

insulating layer

pad/strips readout on standard PCB

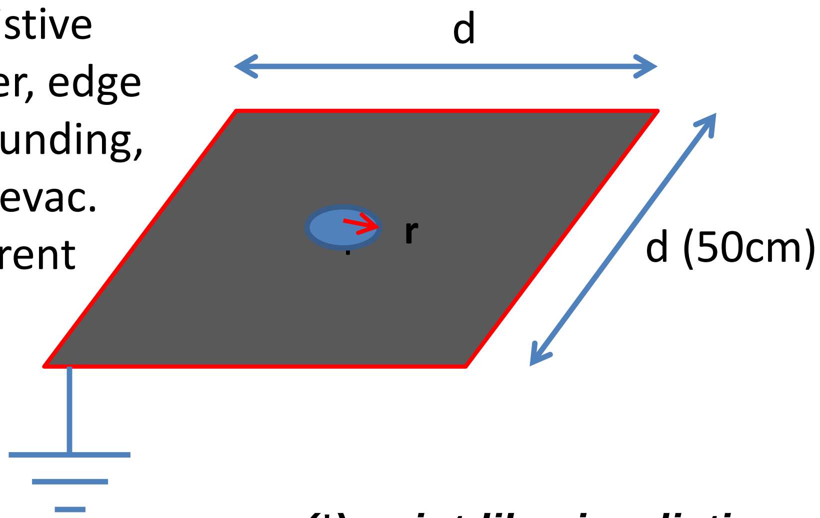
***"through vias"* for grounding**

DLC-coated base material after copper and kapton chemical etching (WELL amplification stage)

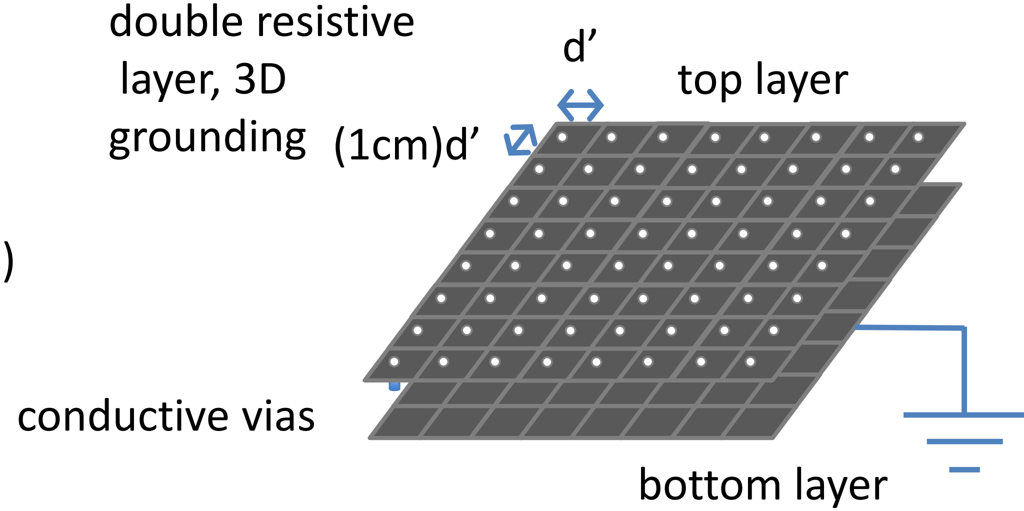


Towards a High Rate scheme

single resistive layer, edge grounding, 2D evac. current



double resistive layer, 3D grounding



(*) point-like irradiation, r << d
Ω is the resistance seen by the current generated by a radiation incident in the center of the detector cell

$\Omega \sim \rho_s \times d/2\pi r$

$\Omega' \sim \rho_s' \times 3d'/2\pi r$

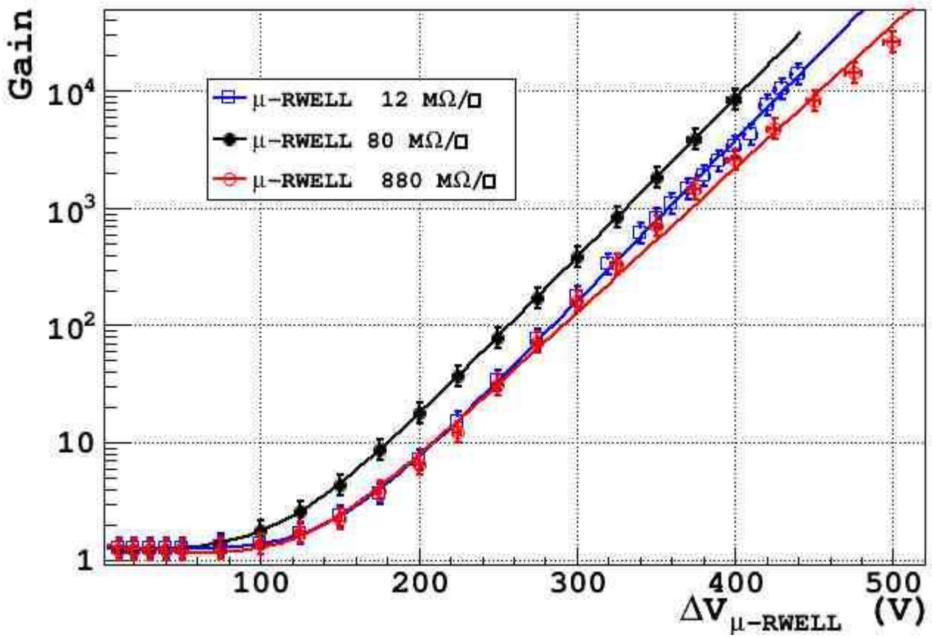
$\Omega/\Omega' \sim (\rho_s/\rho_s') \times d/3d'$

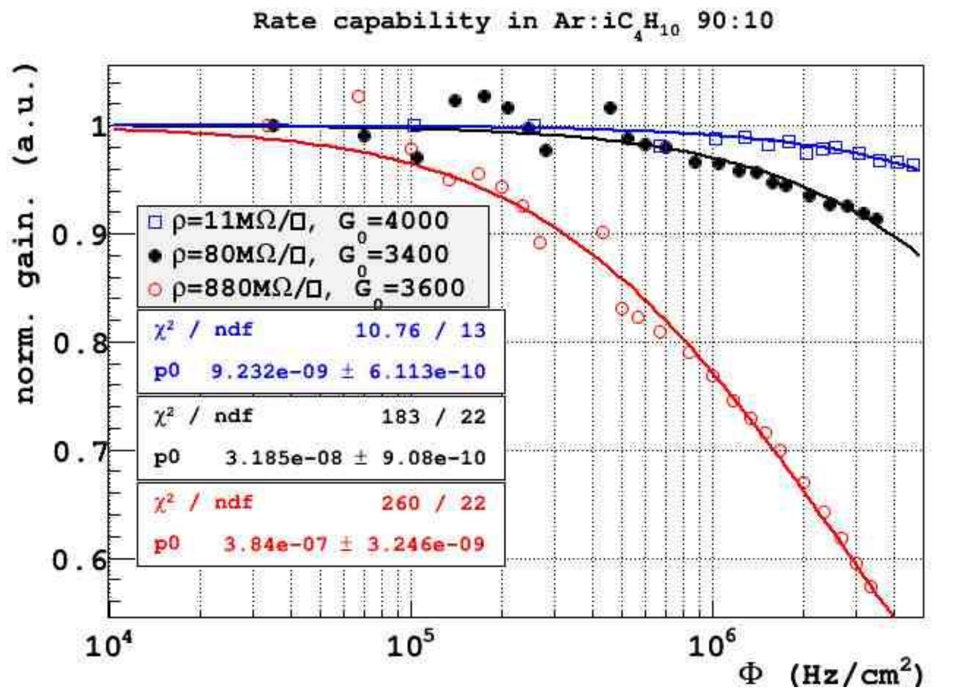
If $\rho_s = \rho_s'$ → $\Omega/\Omega' \sim \rho_s/\rho'_s * d/3d' = 50/3 = 16.7$

(*) Morello’s model: appendix A-B (G. Bencivenni et al., 2015_JINST_10_P02008)

The μ-RWELL performance: X-rays test

The prototypes, with different surface resistivities, have been tested with X-rays for first measurements in current mode (gain and rate capability **under local irradiation**).





Detectors safely reach a gain ≥ 10000

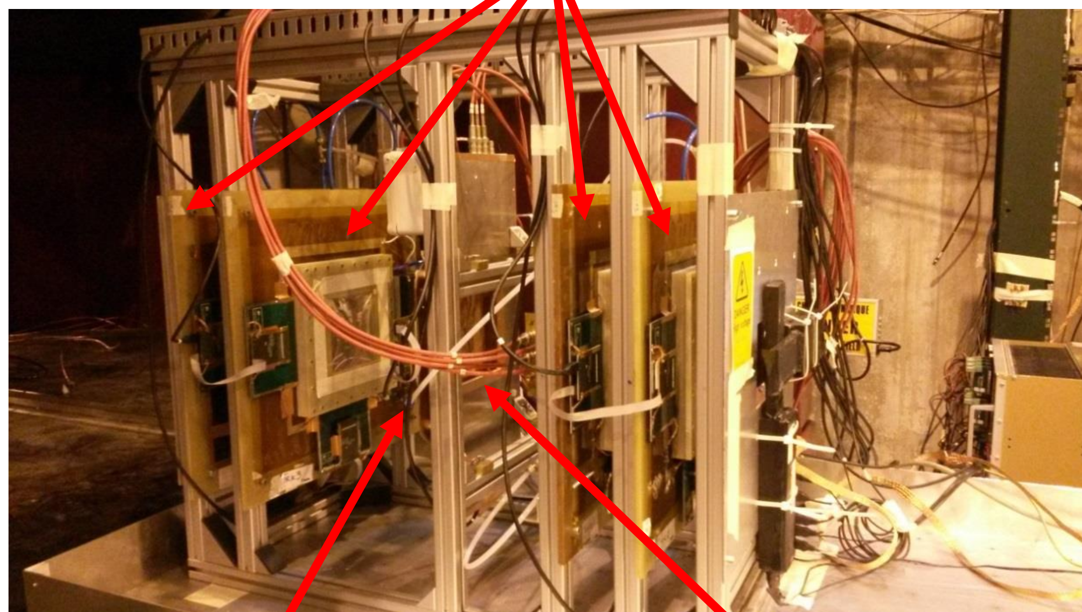
$\Phi_{0.97}$ = 850 kHz/cm²; **$\Phi_{0.97}$ = 77 kHz/cm²;**
$\Phi_{0.97}$ = 3.4 MHz/cm²;

Under global irradiation we expect a lower rate capability for single layer scheme

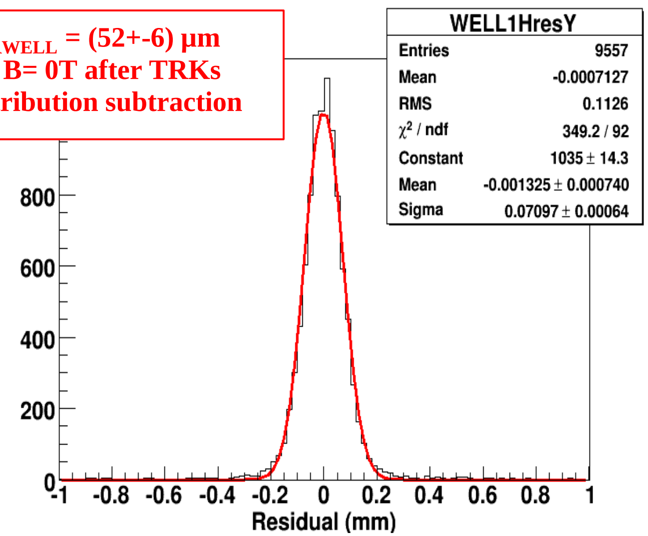
The µ-RWELL performance: Beam Tests

H4 Beam Area (RD51)
Muon beam momentum: 150 GeV/c
Goliath: B up to 1.4 T

GEMs trackers



σ_{RWELL} = (52+-6) µm
@ B= 0T after TRKs
contribution subtraction



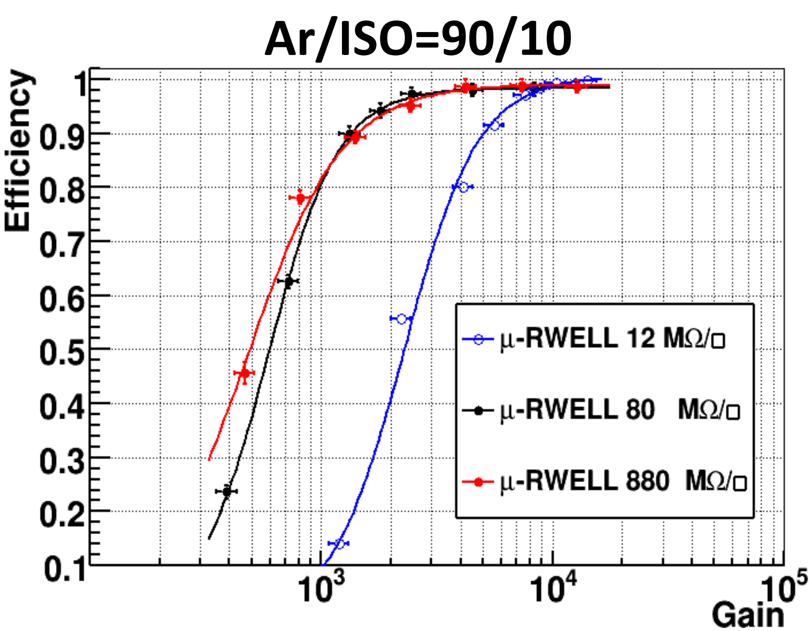
BESIII gem chambers

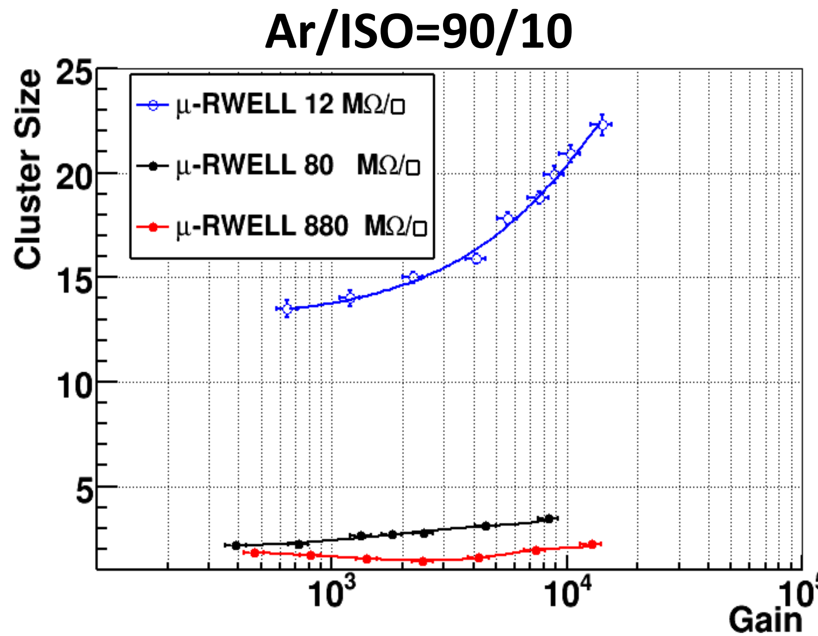
µ-RWELL prototype 12-80-880 MΩ/□; 400 µm pitch strips with APV25 FEE for CC analysis.

Ar/iC_4H_{10} 90/10

The µ-RWELL performance: Beam Tests

Analysis performed with the CC method, 400 µm strips pitch



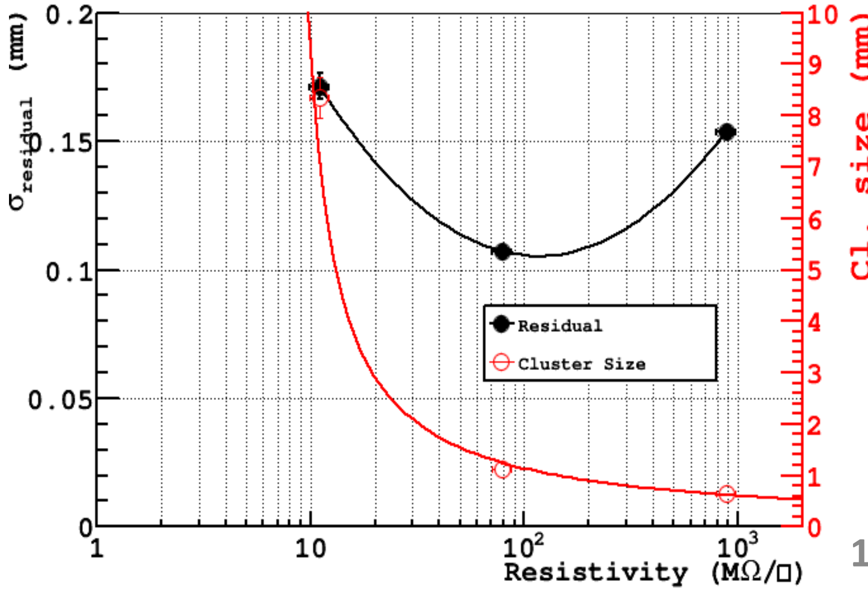


At low resistivity the spread of the charge (cluster size) on the readout strips increases, thus requiring a higher gain to reach the full detector efficiency.

The residuals exhibit a minimum width around 100 MΩ/□.

At low resistivity the charge spread increases → worse spatial resolution

At higher resistivity → ~ 1 fired strip

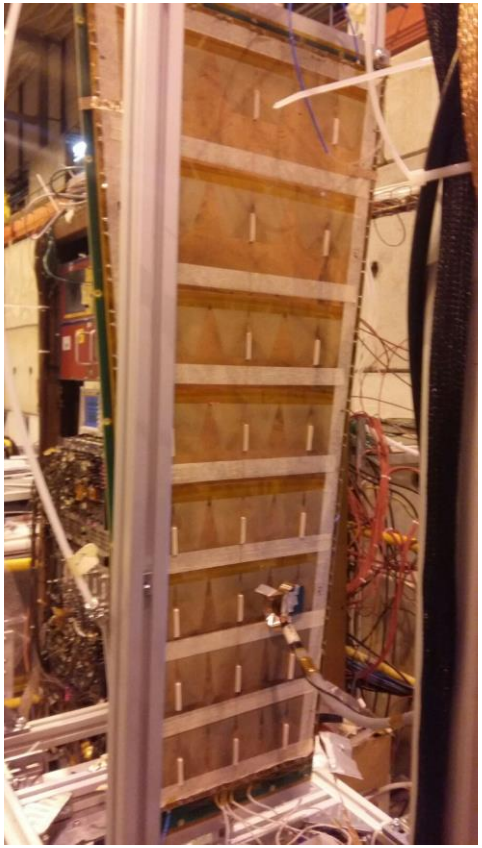


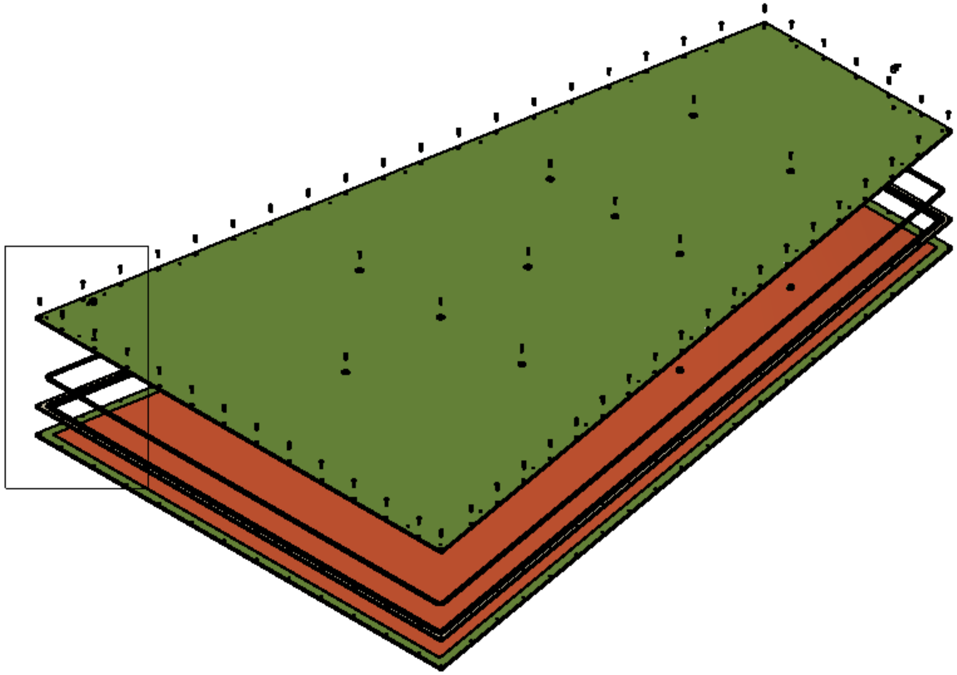
The LARGE AREA µ-RWELL

In the framework of the **CMS-phase2 muon upgrade** we are developing **large size µ-RWELL.**
The **R&D** is performed in strict collaboration with **Italian industrial partners (ELTOS & MDT).**
The work is performed in **two years** with following schedule:

1. Construction & test of the first **$1.2x0.5m^2$ (GE1/1) µ-RWELL** **2016**
2. Mechanical study and mock-up of $1.8x1.2\ m^2$ (GE2/1) µ-RWELL **2016-2017**
3. Construction of the first **$1.8x1.2m^2$ (GE2/1) µ-RWELL (only M4 active)** **01-09/2017**

~40 times larger than small protos !!!





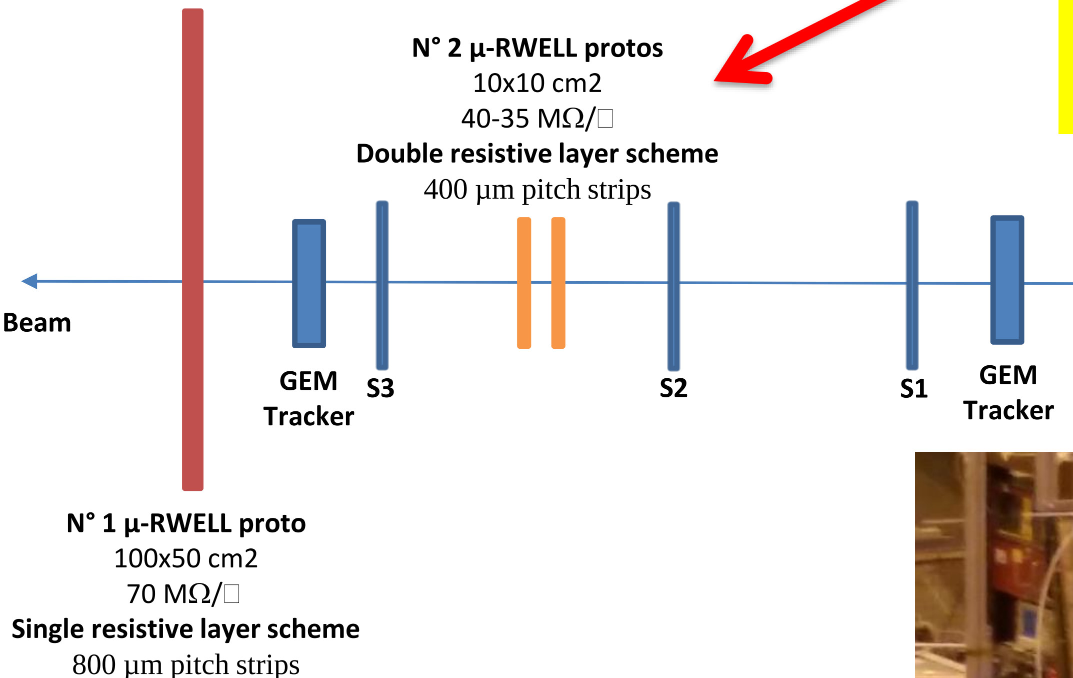
$1.8x1.2m^2$ (GE2/1) µ-RWELL

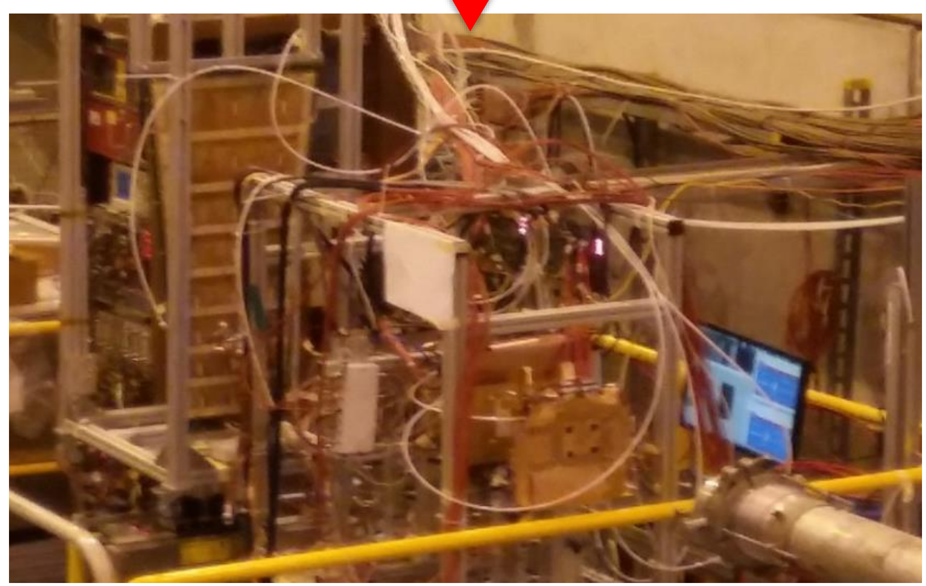
Test beam Setup

H8 Beam Area (18th Oct. 9th Nov 2016)

Muon/Pion beam: 150 GeV/c

3 μ-RWELL prototypes
40-60-70 MΩ /□
VFAT (digital FEE)
$Ar/CO_2/CF_4$ = 45/15/40

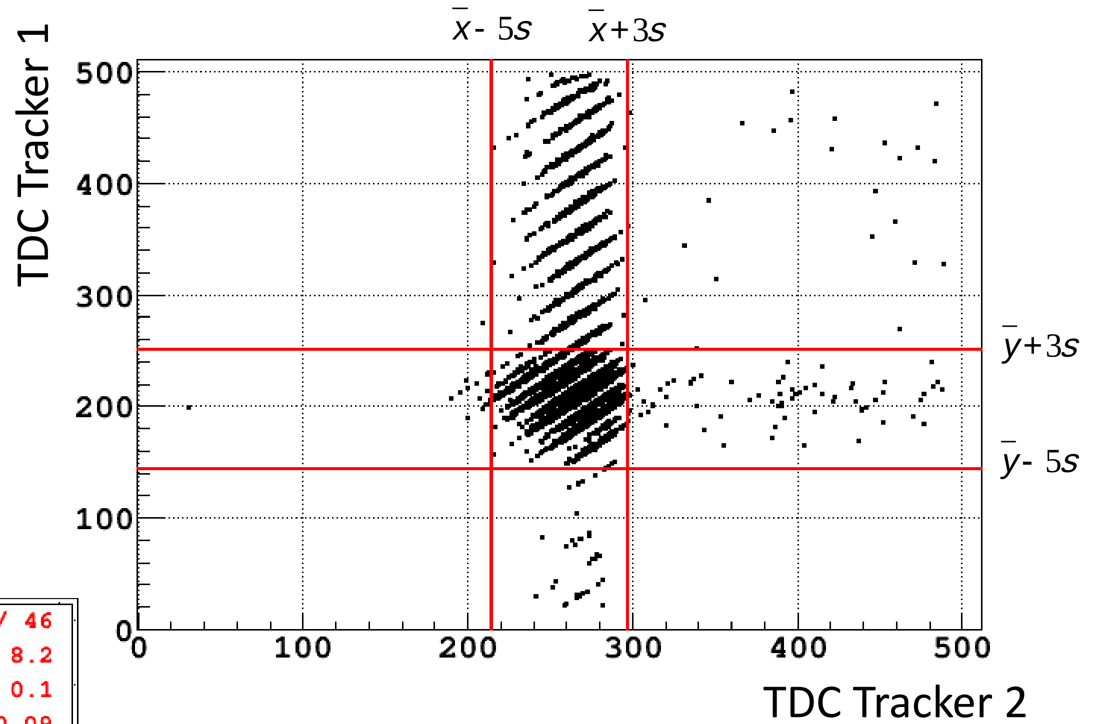


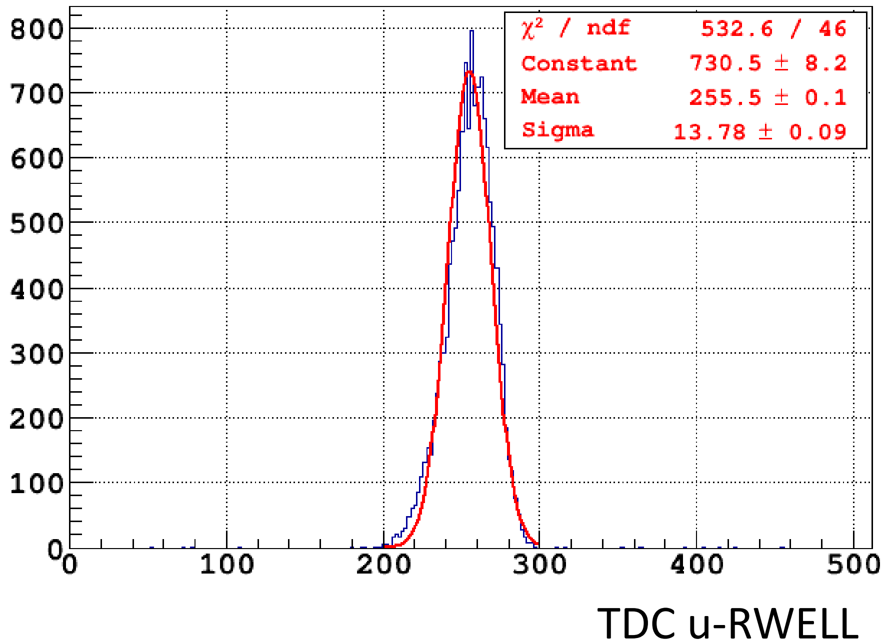


The goal is the <u>time resolution measurement</u> due to intrinsic process in the gas, mainly limited by FEE performance

Efficiency & time resolution measurement

The efficiency has been evaluated asking for **TDC coincidence** selected in a proper range.
Then the ratio of the triplets on the doublets gives the value.

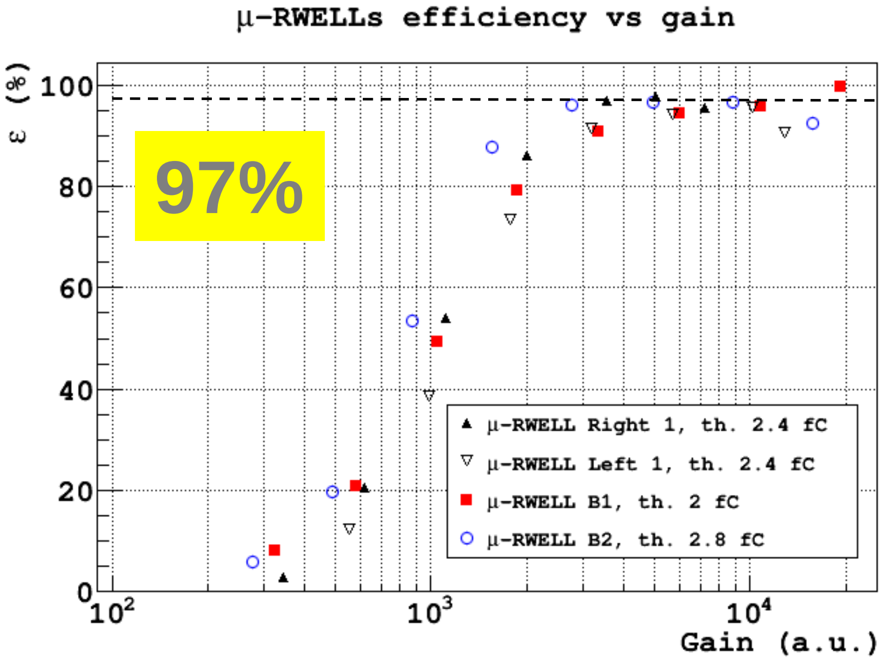


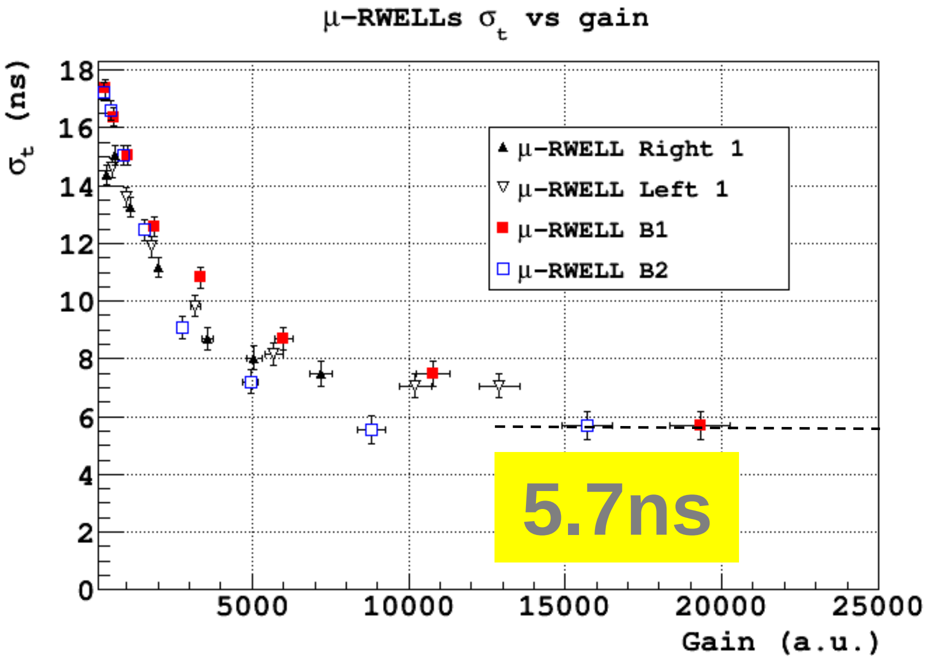


The TDC distribution is then fitted with a simple gaussian and the sigma is then **deconvoluted** by the contribution of the VFAT.

$$\sigma_t^2 = \sigma_{TDC}^2 - \left(\frac{25}{\sqrt{12}}\right)^2$$

Efficiency & time resolution measurement





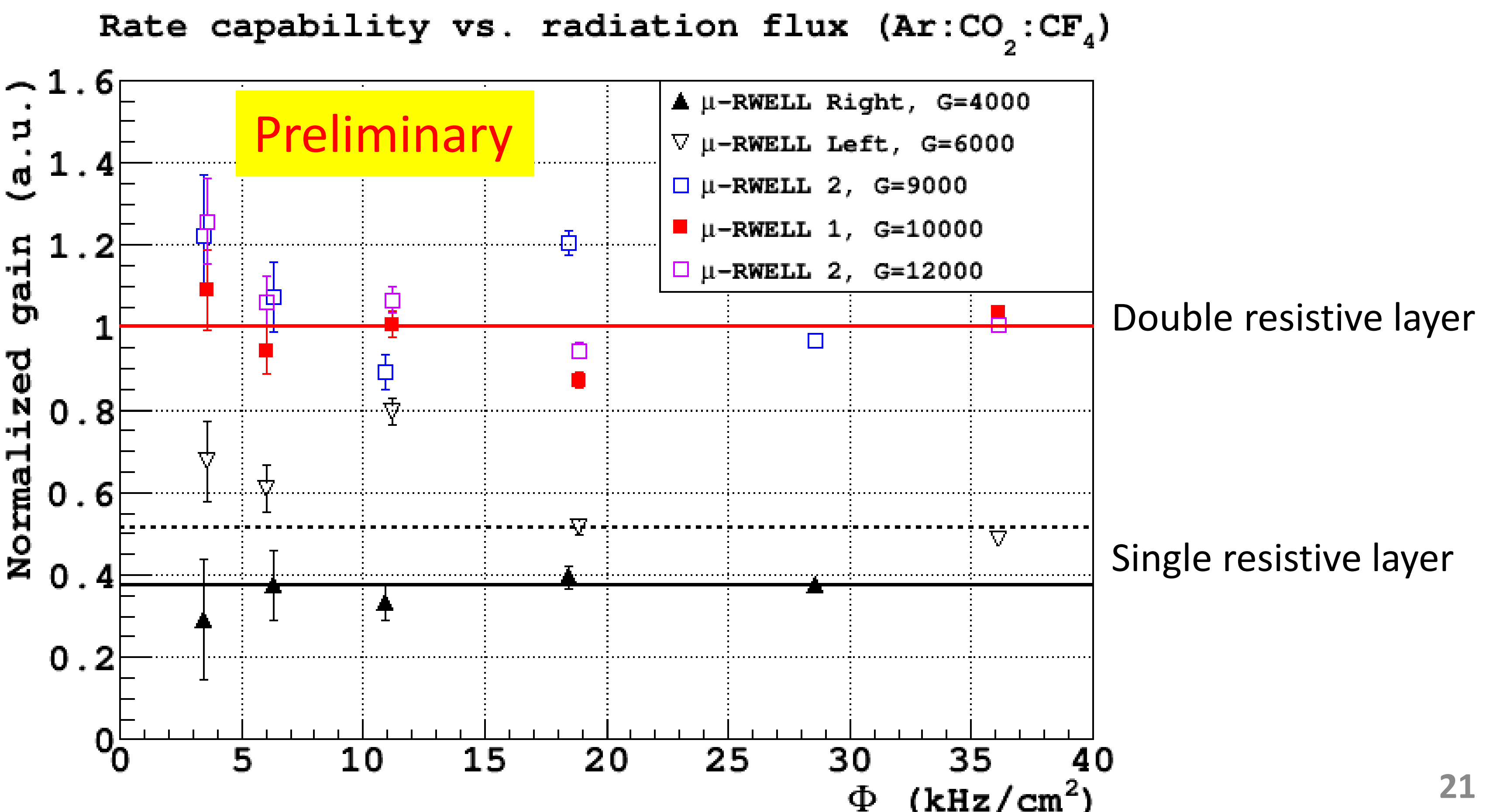
To be compared with a measurement done with GEM by LHCb-LNF in 2004 (LHCb) giving a σ_t = 4.5 ns with VTX chip [1].

Different chambers with **different dimensions and resistive schemes** exhibit a **very similar behavior** although realized in **different sites** (large detector partially realized outside CERN).

[1] G. Bencivenni et al, "Performance of a triple-GEM detector for high rate charged particle triggering", NIM ***A*** *494 (2002) 156*

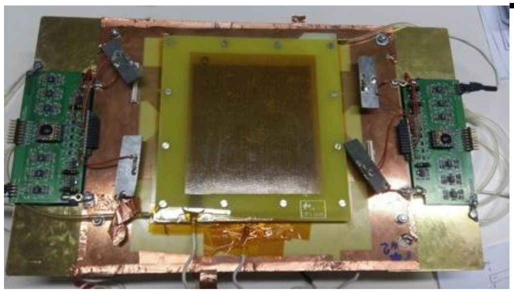
Performance vs Rate

The detector rate capability (with Ed=3,5 kV/cm) has been measured in current mode with a pion beam and irradiating an area of ~ 3 x 3 cm^2 (FWHM)

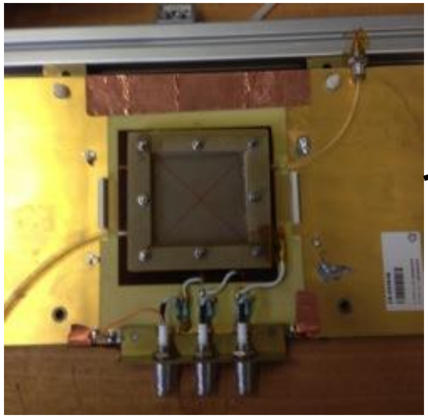


Ageing test: GIF++ (LNF, INFN-BO)

- To validate the (DLC-based) detector in the GE2/1 region, it is necessary (mandatory) to study the behaviour of the chamber under heavy irradiation.
- The detector, working at a gain 4000 (efficiency plateau) in Ar/CO2 70/30, will integrate about 2.5 mC/cm^2
- We plan to integrate 25 mC/cm^2 in about 60 days (10 years with s.f. 10)
- The setup has been completed with two more µ-RWELL:



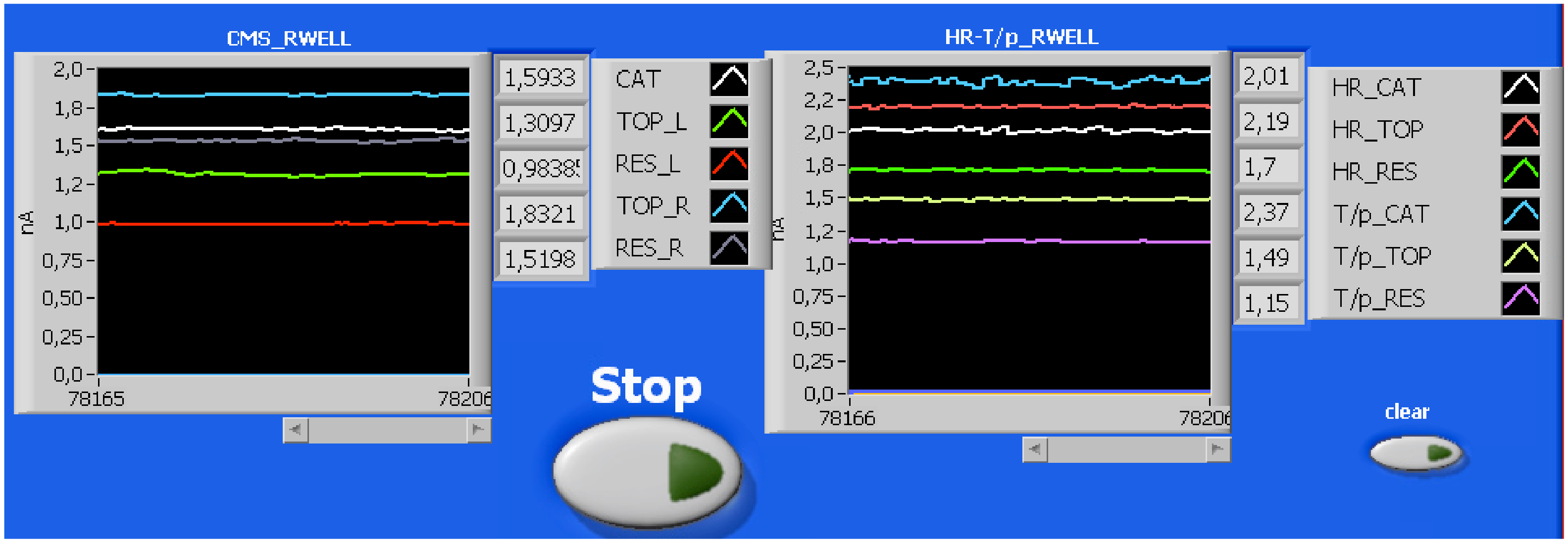
Double resistive layer scheme (high rate)



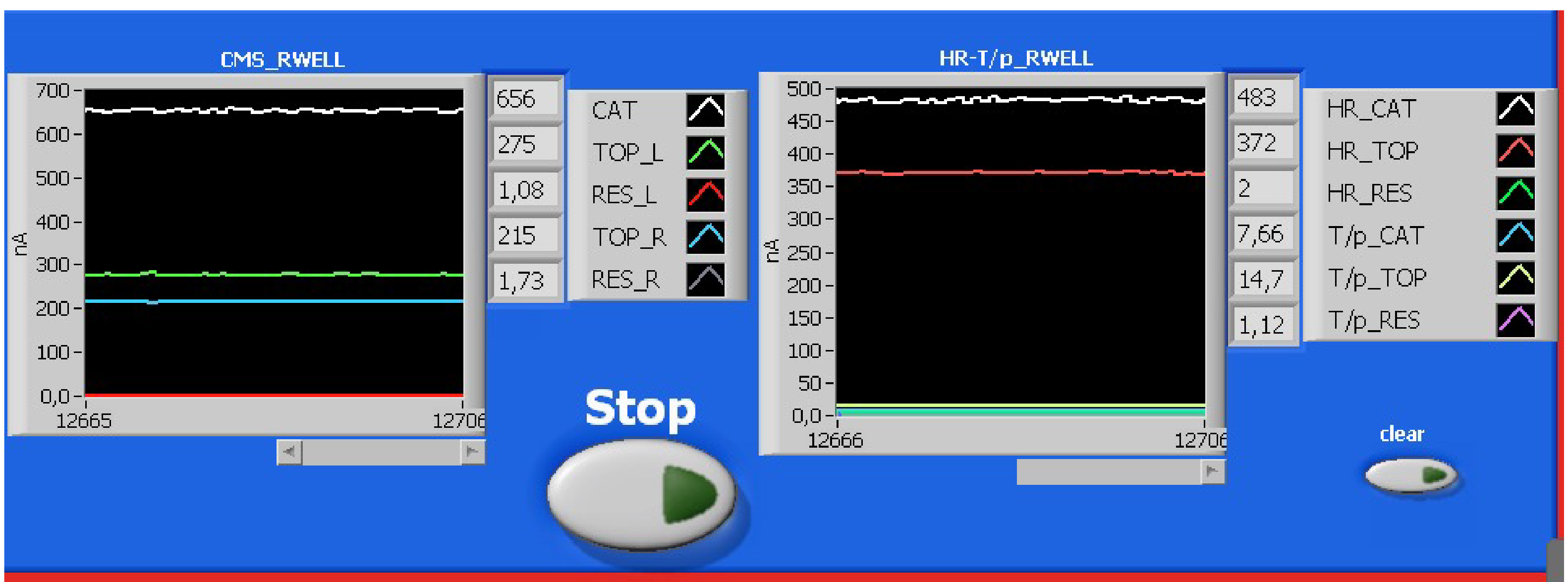
Single layer scheme (reference chamber)

Ageing test: GIF++ (LNF, INFN-BO)

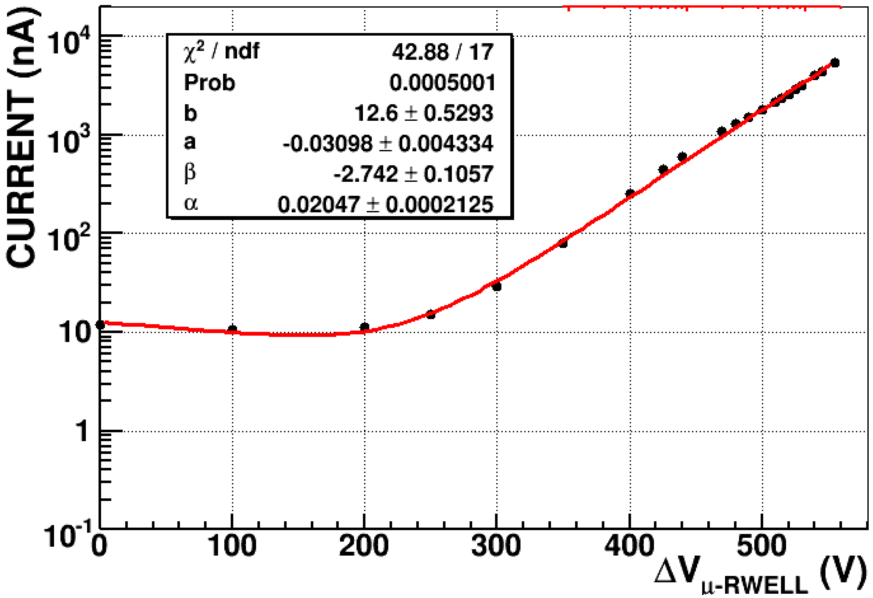
Source off

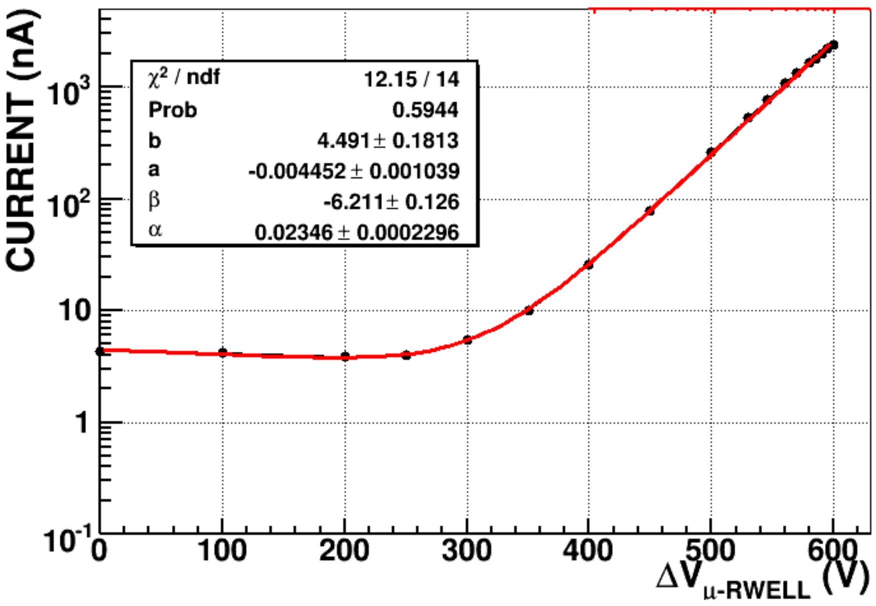


Source on



Ageing test: GIF++





I(g=4000) ~ 5 nA/cm2 corresponding to an **equivalent mip rate of ~ 60-90 kHz/cm2** evaluated on sectors #3

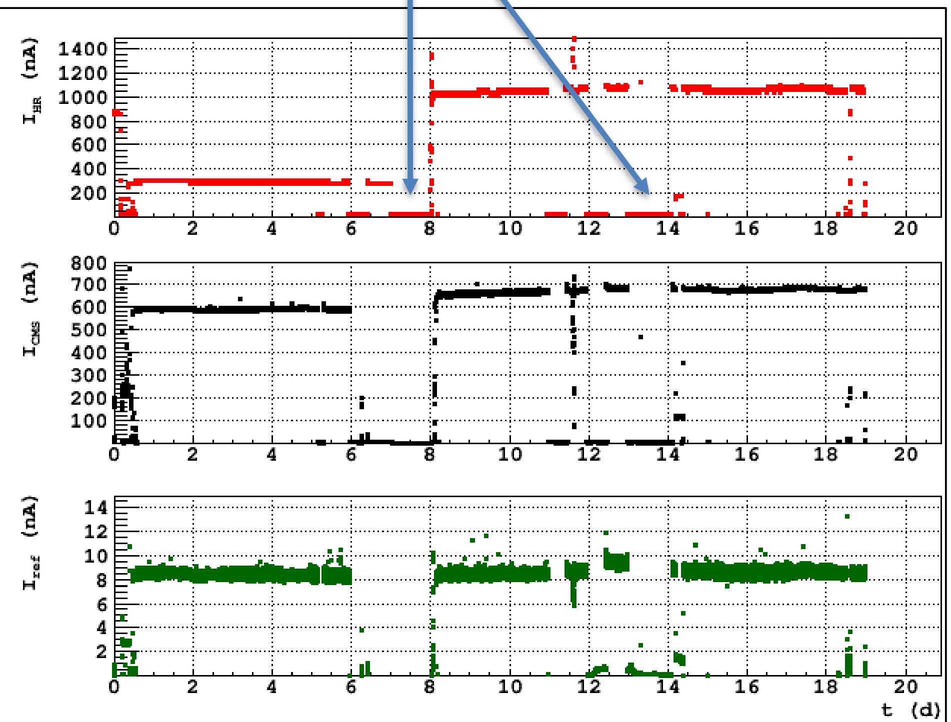
I(g=4000)~ 10 nA/cm2 corresponding to an **equivalent mip rate of ~ 250 kHz/cm2**

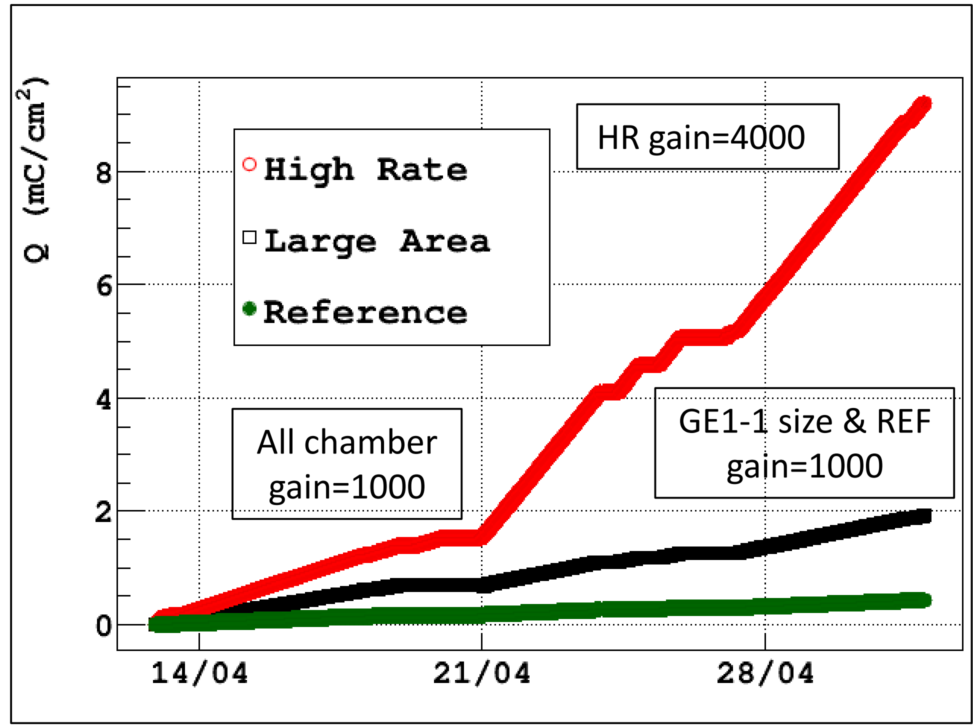
Ageing test: GIF++

Source off

Low gain

High gain

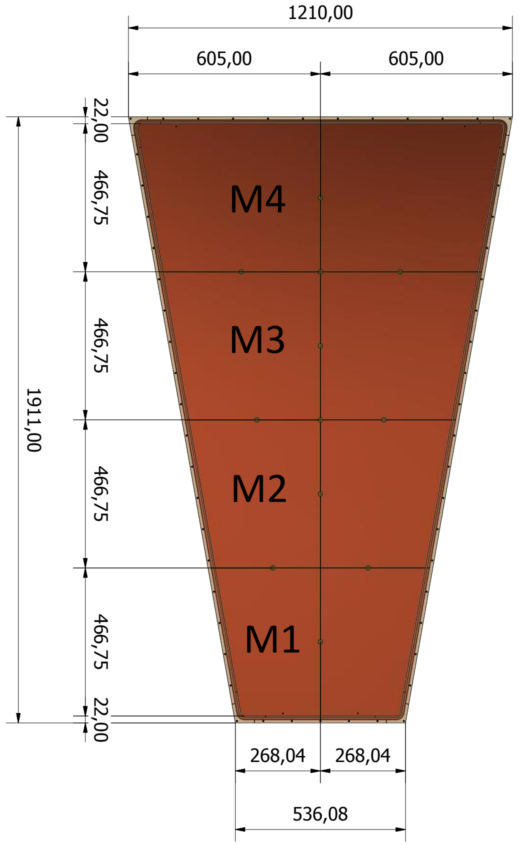




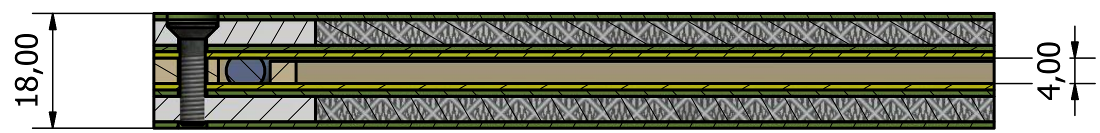
Currents quite constant during the operating time gates

The large area has integrated 1.92 mC/cm2 up to May 2nd.

GE2/1 μ-RWELL: mechanical studies

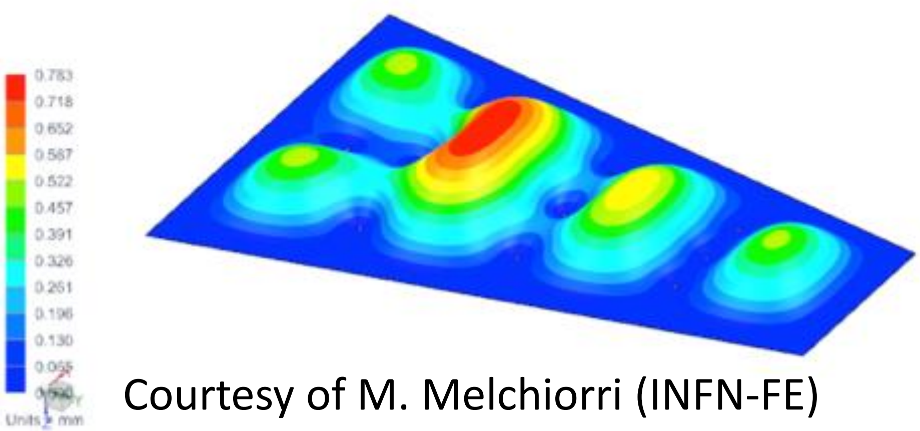


A very large μ-RWELL with the dimensions close to the GE2/1 chamber is going to be realized at LNF, in collaboration with INFN-BA and INFN-BO with M4 operating detectors.
The dimensions of the chamber suggest preliminary studies on the mechanical aspect of the project.



The active volume is limited by two honeycombed panels, which composition has been validated by ANSYS simulations.

The largest deformation (0.78 mm) at 8 mbar has been obtained with 3 mm thick honeycomb glued between two 1 mm thick fiberglass skins with the presence of 10 pillars.

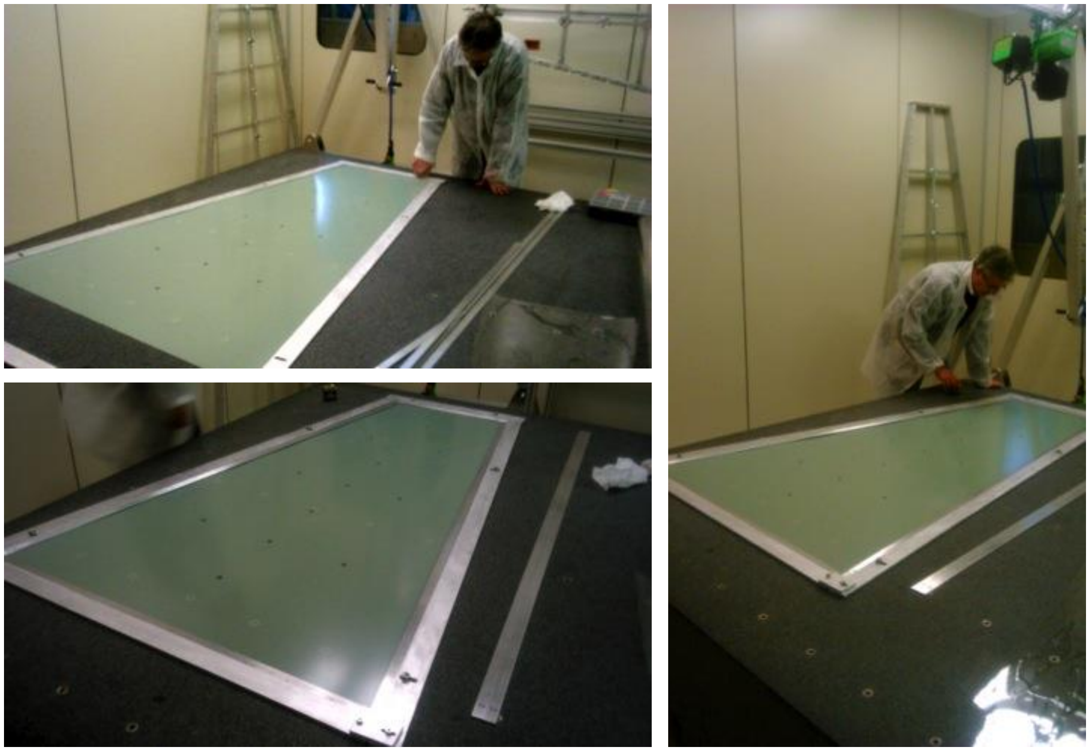


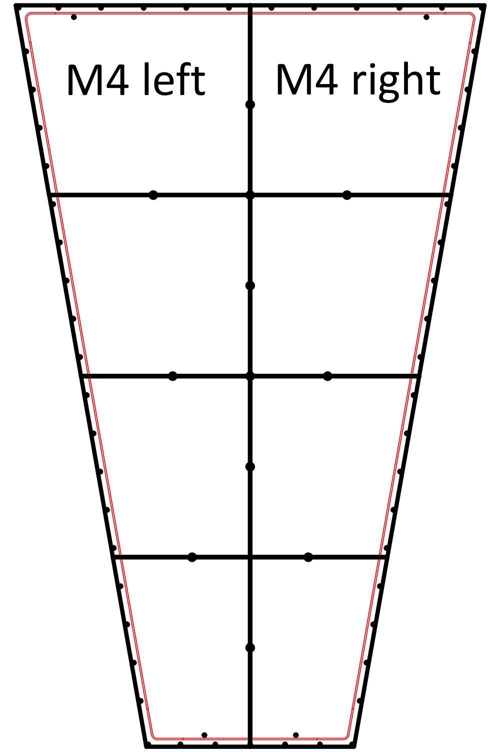
Courtesy of M. Melchiorri (INFN-FE)

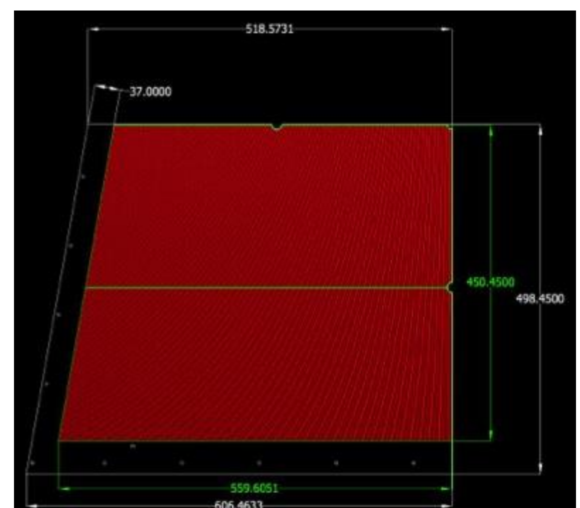
After these results:

- the thickness of the honeycomb increased up to 4 mm
- the number of pillars in the active volume increased to 12
- **Expected maximum deformation: < 0.2 mm per panel (5 mbar) → < 10% on conversion drift gap**

Mock-up







The two external panels are ready.
ELTOS just this week is producing the M4 PCB that will be sent to CERN for the chemical etching

Conclusions

- LNF is strongly involved into the upgrade of LHC apparatuses with MPDG technology

- A new MPGD, based on the μ-RWELL technology, has been conceived and developed at LNF. The detector shows:
  - gas gain > 10^4
  - intrinsic spark protection
  - rate capability > 1 MHz/cm^2 (HR version)
  - space resolution < 60μm
  - time resolution < 6 ns

- A large-size prototype has been built, qualified and installed at GIF++ for DLC ageing test

- The final CMS prototype is going to be realized and tested

- A well defined roadmap towards Technological Transfer to industry has been planned

SPARE

A brief history of MPGDs

- **G. Charpak et al.**, *The use of multiwire proportional counters to select and localize charged particles*, Nucl. Instr. Meth. **62** (1968) 262-268.
- **A. Oed**, *Position-sensitive detector with microstrip anode for electron multiplication with gases*, Nucl. Inst. Meth. **A 263** (1988) 351-359.
- **Y. Giomataris et al.**, *Micromegas: a high-granularity, position sensitive gaseous detector for high particle flux environments*, Nucl. Inst. Meth. **A 376** (1996) 29.
- **F. Bartol et al.**, *The C.A.T. Pixel Proportional Gas Counter Detector,* J. Phys. III France **6** (1996)
- **F. Sauli**, *GEM: A new concept for electron amplification in gas detectors,* Nucl. Inst. Meth. **A 386** (1997) 531.
- **R. Bellazzini et al.**, *The WELL detector*, Nucl. Inst. Meth. **A 423** (1999) 125.
- **G. Bencivenni et al.**, *A novel idea for an ultra light cylindrical GEM based vertex detector*, Nucl. Inst. Meth. **A 572** (2007) 168.
- **P. Fonte et al.**, *Advances in the Development of Micropattern Gaseous Detectors with Resistive Electrodes,* Nucl. Inst. Meth. **A 661** (2012) 153.
- **G. Bencivenni et al.**, *The micro-Resistive WELL detector: a compact spark-protected single amplification-stage MPGD*, JINST **10** (2015) P02008.

The μ-RWELL: motivations

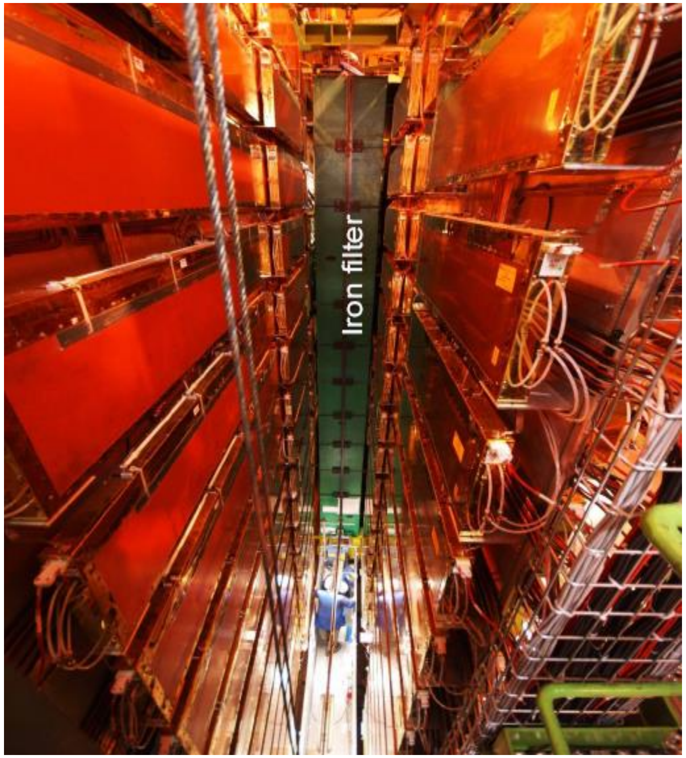
Because of the micrometric distance between electrodes, every MPGD suffers from spark occurrence that can damage the detector or the FEE.
A resistive readout quenches the discharge:

- The Raether limit is overcome
- The charge is deposited on the resistive layer
- The charge density spreads with ***τ = RC*** (**M.Dixit**, NIM **A 518** (2004) 721)
- The resistive layer is locally charged-up with a potential ***V=Ri***, reducing the ΔV applied to the amplification stage
- The amplification field is reduced
- The discharge is locally suppressed

Obviously this has a drawback correlated to high particle fluence, that's why we studied the performance of the detector as a function of the resistivity

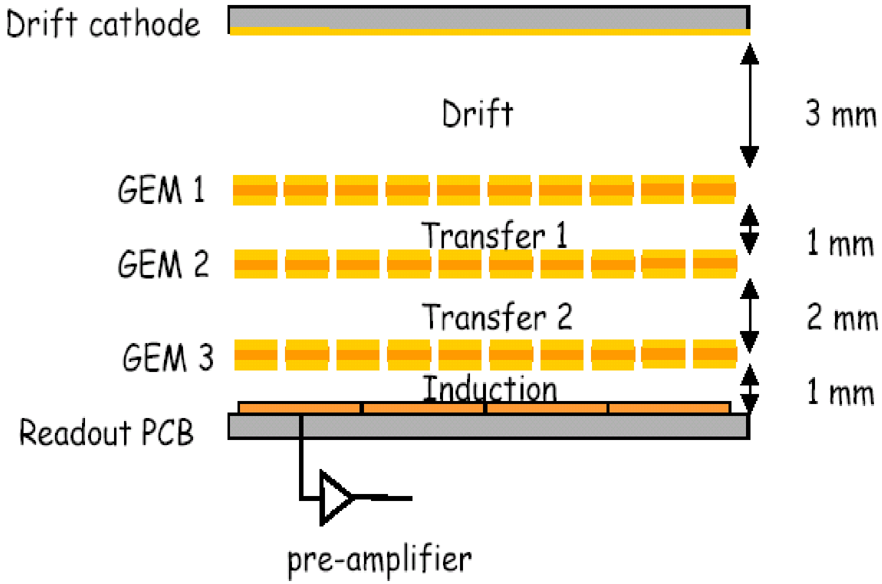
GEMs for LHCb

The **LHCb muon system** provides high p_T muon trigger at low angles, their identification at HLT and offline reconstruction.
Composed of 5 stations (1380 **MWPC**) separated by iron walls, the M1 central region there has been equipped with **GEM detectors**.



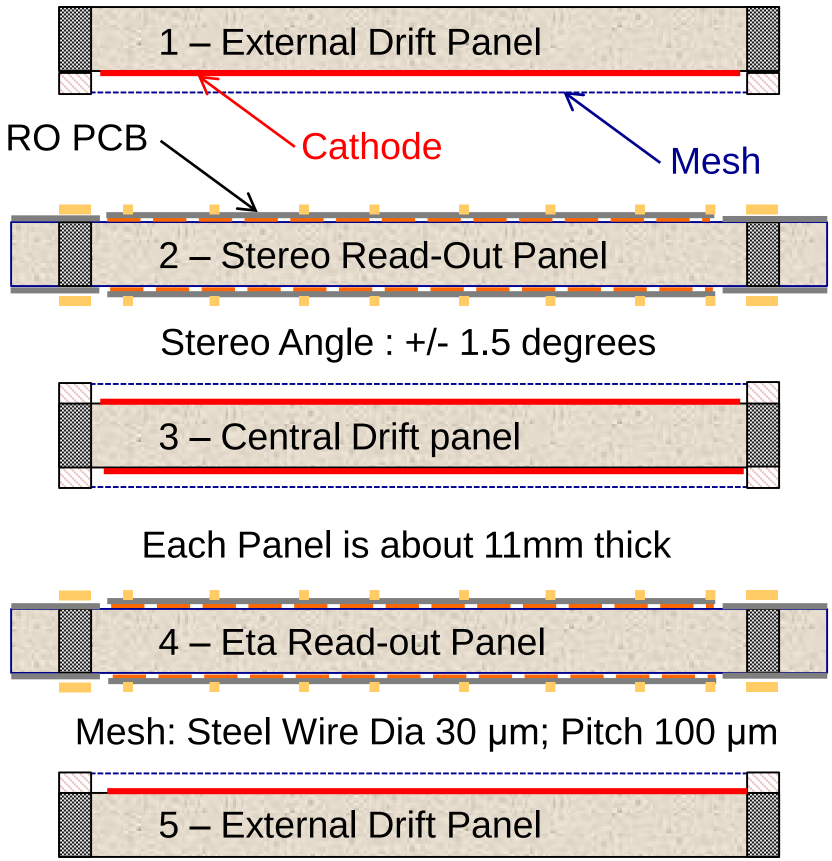
LHCb is one of the first experiments using **GEMs**.
Their features are:

- 20 x 24 cm^2 active area
- Non-standard gaps: 3/1/2/1 mm, to decrease the probability that ionization in T1 can trigger the discriminator
- Innovative gas mixture: $Ar/CO_2/CF_4$ 45/15/40, providing high time resolution (4.5 ns) and no aging effect after 2.2 C/cm^2 integrated during R&D



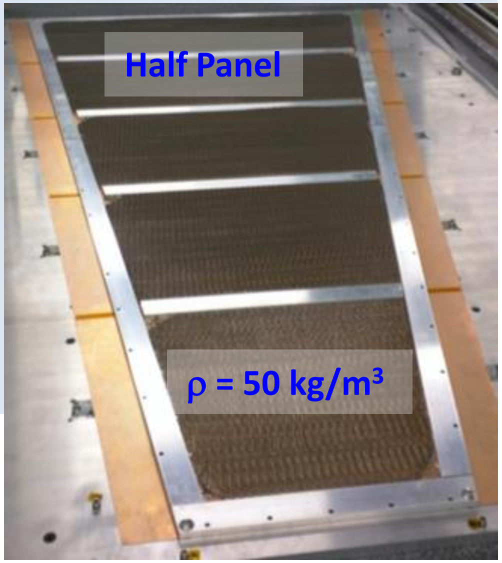
ATLAS upgrade

MM Quadruplet Exploded View



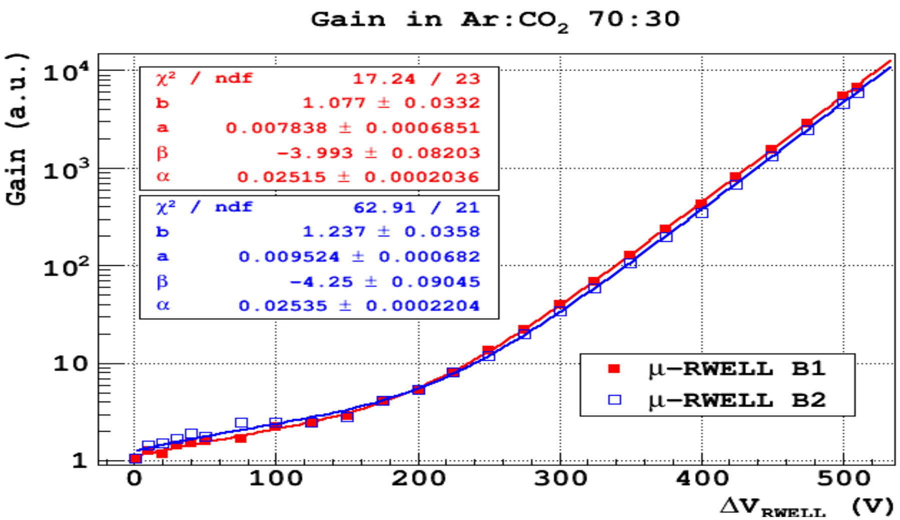
Building Large Area MM

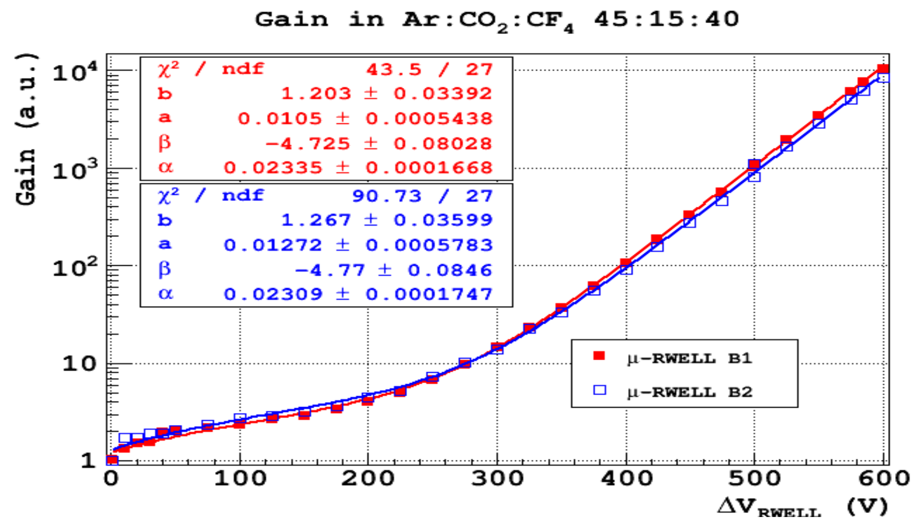
- Panel is a sandwich of 0.5 mm PCB skin with honeycomb in the middle and frames in the perimeter and in the joint of two adjacent PCB. Honeycomb and frames are in Al.
- Different Panels are needed for a Quadruplet
  - RO Panels (Eta and Stereo)
  - N.2 External Drift Panels
  - One Central Drift Panel
- For each gas layer a unique Mesh is glued on the drift panel, using a custom frame that define the 5 mm height.
- Slow bi-component epoxy is used as glue.

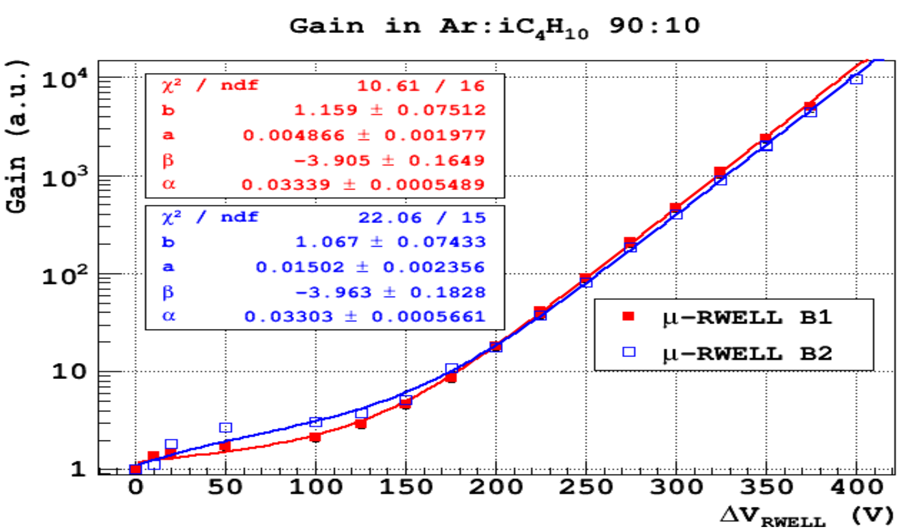


X-ray measurements

Two prototypes with the **double resistive layer scheme** (ρ=40 MΩ/☐) have been completed last Summer; the detectors have been tested with a 5.9 keV X-rays flux **(local irradiation)**.



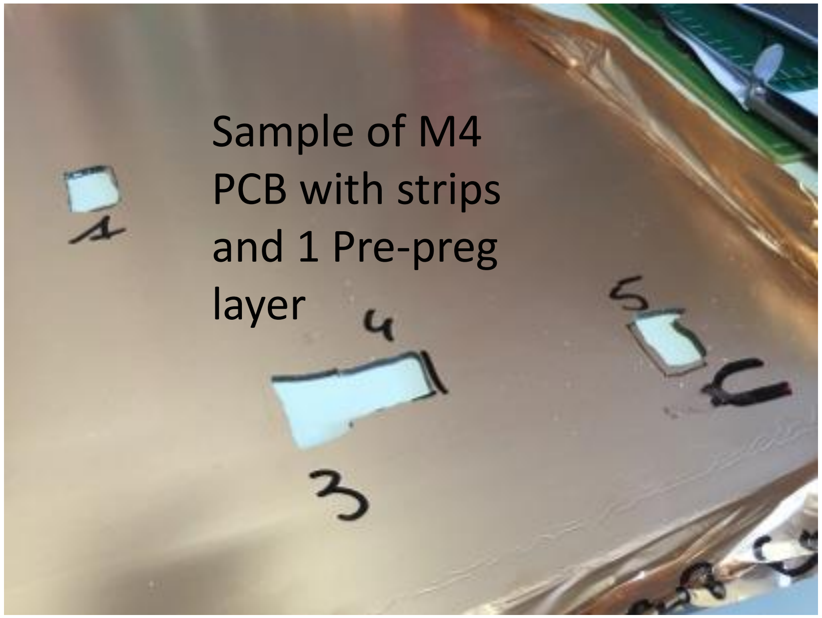


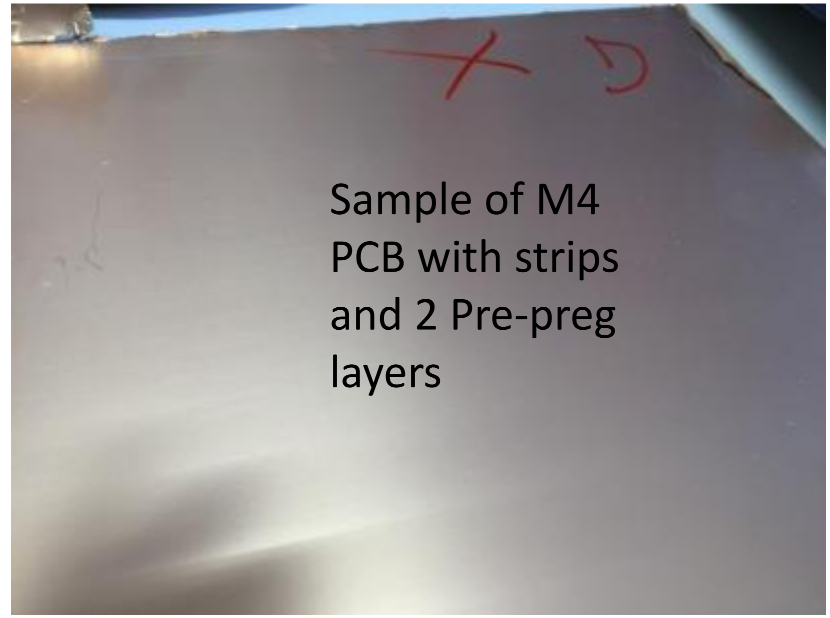


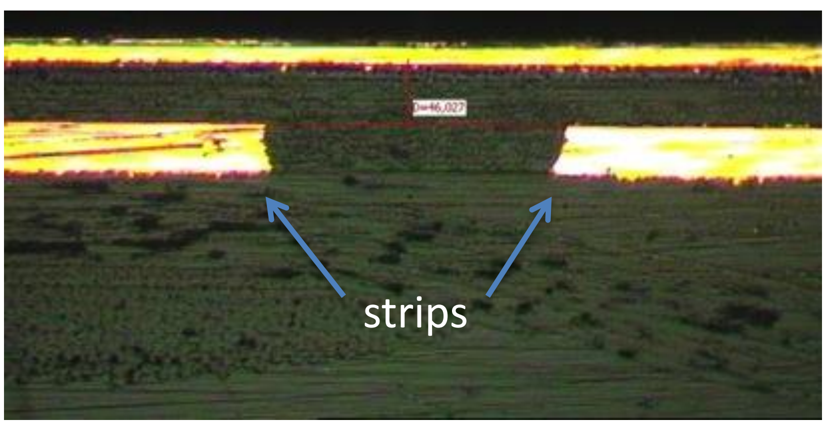
Measurement performed in current mode.
Gain measured up to 10000.
Similar behaviour for the two chambers.

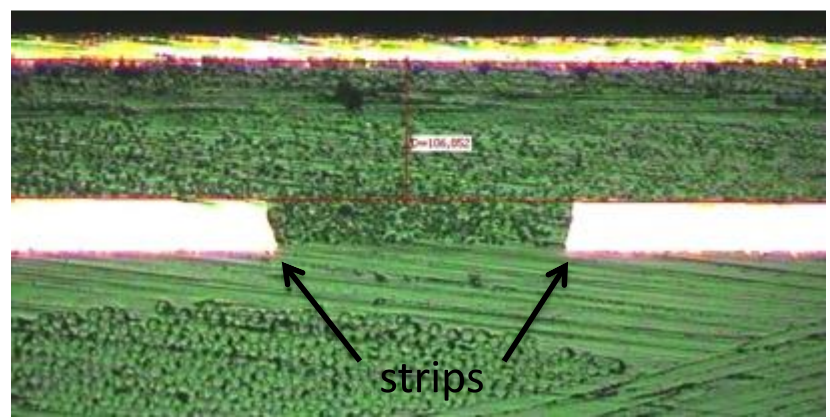
ELTOS tests

From ELTOS tests, it is quite visible that without PACOFLEX the surface is very flat.









Metallographic cross sections: on the left we have an example with one pre-preg layer (50 um), on the right with two pre-preg layers (100 um)

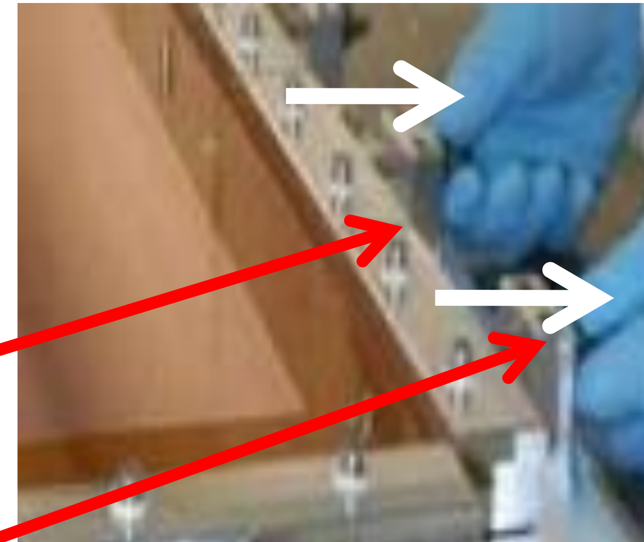
Technology improvements: NS2 assembly

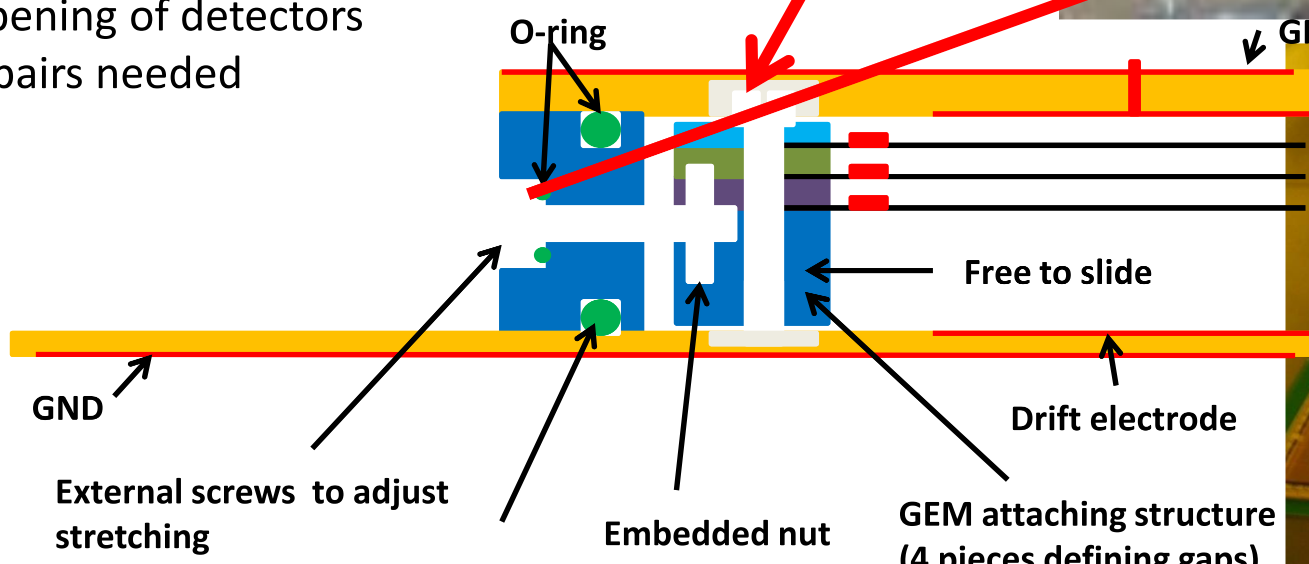
Rui de Oliveira at CERN developed a new detector assembly scheme inspired to LHCb-GEM “stretching technique” of GEM foils, that is suitable for mass-production and industrialization of the whole construction process.
The idea is to re-scale and adapt the design of the GEM stretching tool in order to be embedded inside the detector itself.

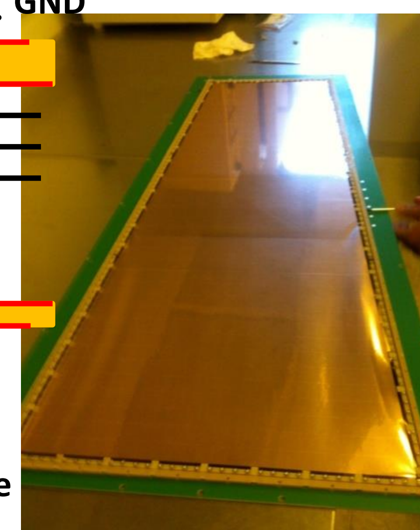
Advantages:

- No gluing, nor soldering
- No spacers in the active area
- Re-opening of detectors if repairs needed

LHCb-LNF

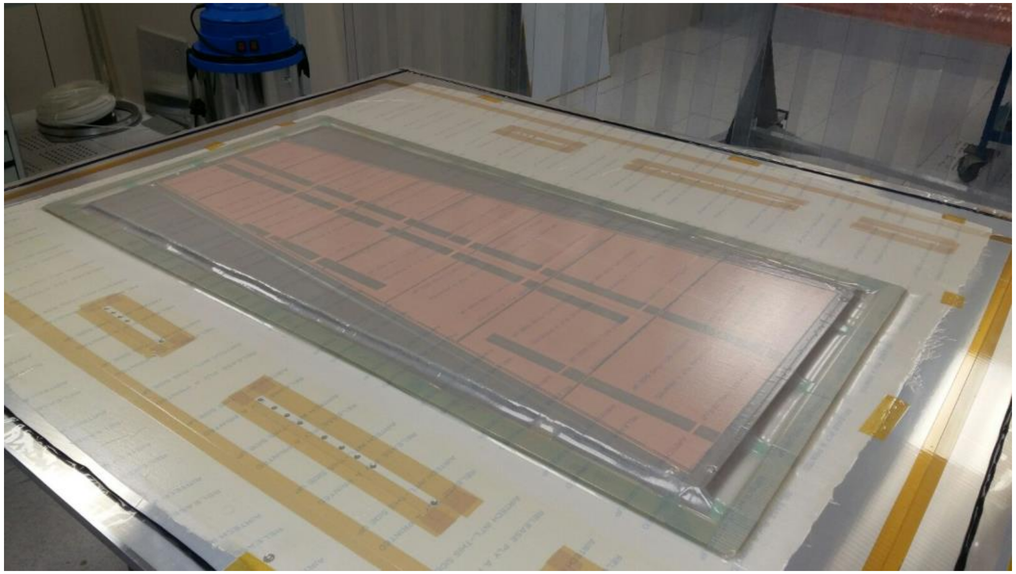






The LARGE AREA μ-RWELL

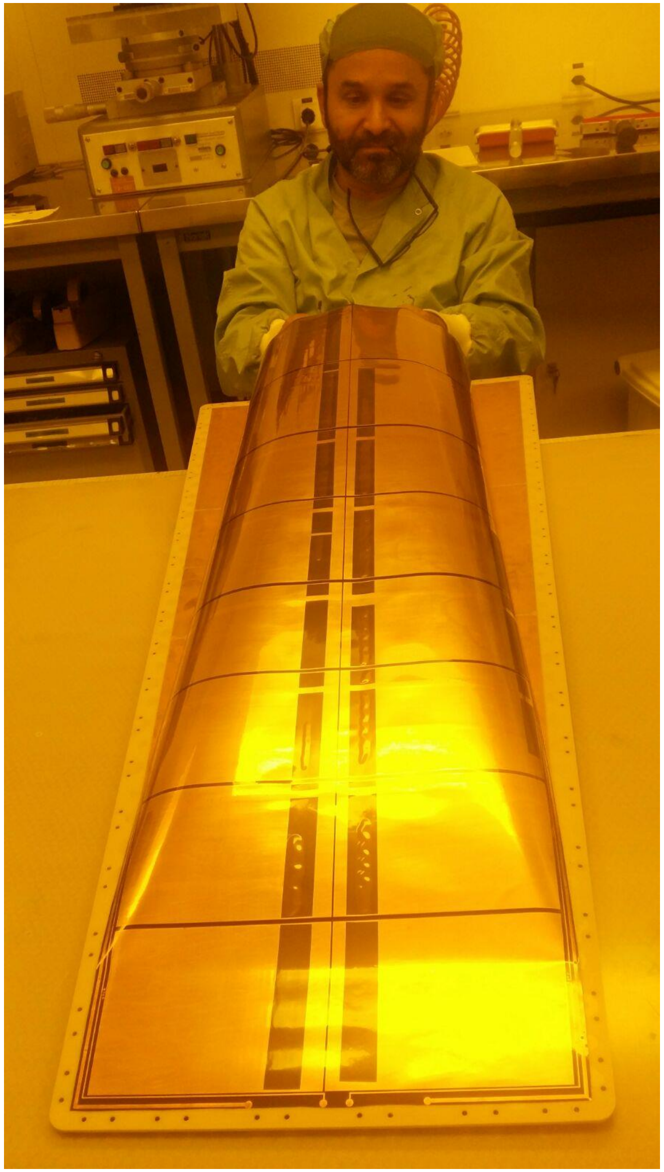
- A large area prototype, following the **single resistive layer scheme**, has been realized for tests. The amplification stage suffered delamination (copper removal) in some sectors during the etching process. The origin of the problem is the combination of a wrong operation done by Eltos with the choice of a corrupted base material.
- The amplification stage has been glued on the readout PCB with the **vacuum bag technique**.
- The detector has been completed with a frame and a cathode



The LARGE AREA µ-RWELL

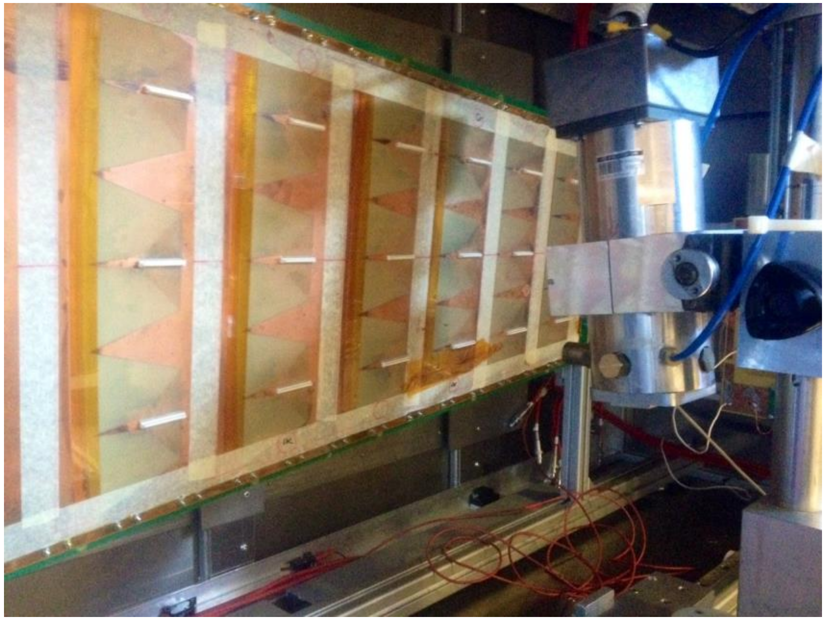
- Anyway the HV sectors drew in some cases anomalous currents and we needed an intervention by Rui.
- The whole stack composed of readout and u-RWELL has been washed in a ultrasonic bath, with the consequence of a separation of the foil from the PCB.
- After supplying up to 1 kV, four sectors were labeled as “good”

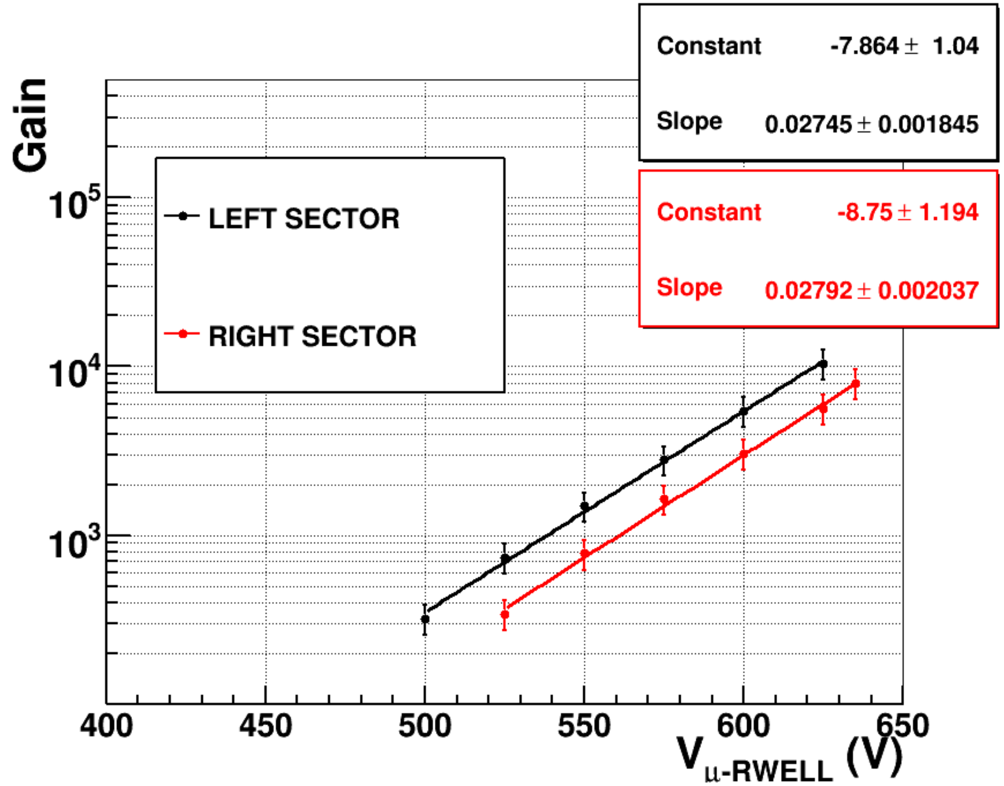
  (R >10 GΩ when ΔV = 500 V).
- The foil has been glued again on the PCB with a 50 um thick **FILM GLUE** produced by **3M company**.



Detector Gain

The prototype has been characterized by measuring the **gas gain, rate capability** in **current mode** with an **5.9 keV X-rays (local irradiation, ~1cm² spot)**.





A shift of ~ 25 V has been measured between the two sectors probably due to the different geometry of the amplification stage (to be confirmed with microscope check – left/right asymmetry)

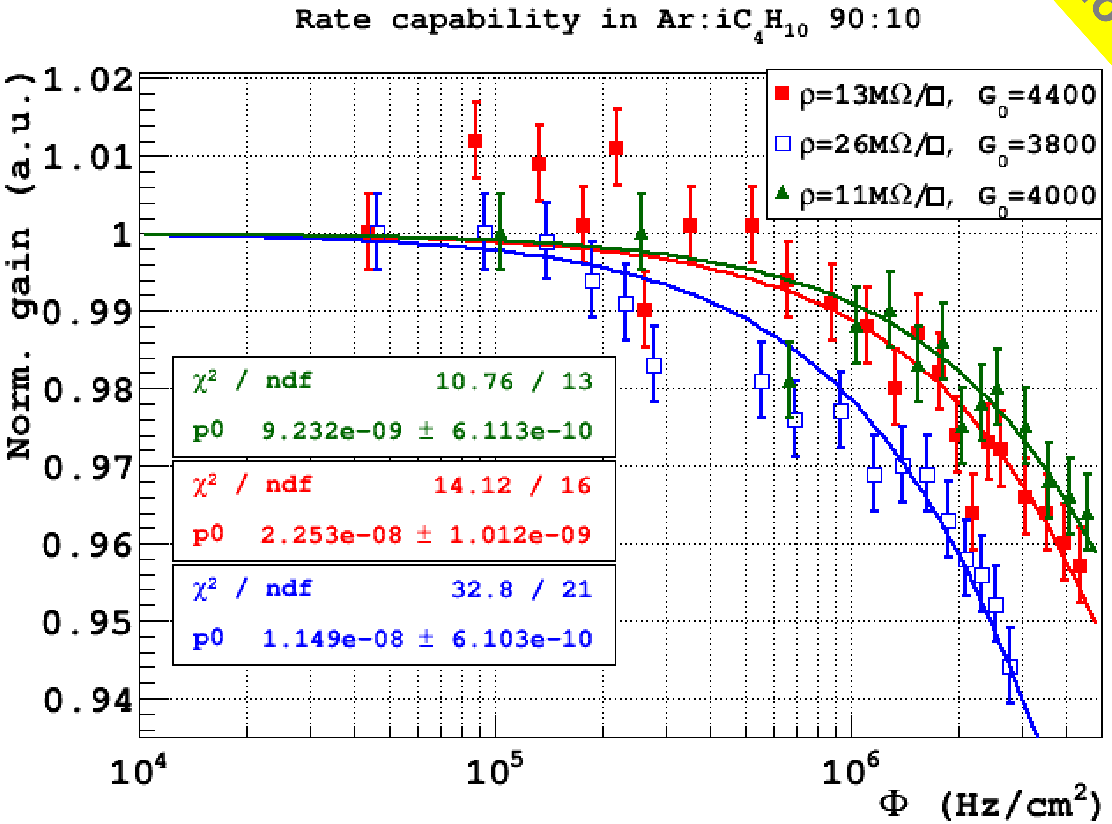
GEM detector currently running @ HEP

Experiment	Instrumented area (m^2)	Gas Mixture	Gain	Flux (MHz/cm^2)	HV-type	# lost sector for shorts	% damaged area	Front-End Electronics
COMPASS	2	Ar/CO_2	4000	<1	HV passive divider	???		APV25
LHCb	0.6	$Ar/CO_2/CF_4$	8000	1	HV active divider	5 (All on GEM #1)	1%	CARIOCA -GEM
TOTEM	0.6	Ar/CO_2	8000	<1	HV passive divider	6	percent level	VFAT2
KLOE2	4	$Ar/i\text{-}C_4H_{10}$	12000	0,01	7 independent ch; then active divider	61 (8 GEM#1, 28 GEM#2, 25 GEM#3)	5%	GASTONE

A damaged GEM sector could required for the replacing of a whole a detector gap !!

Rate capability with X-rays (double layer)

Double resistive layer w/ 1x1 cm² *through-vias* grounding pitch

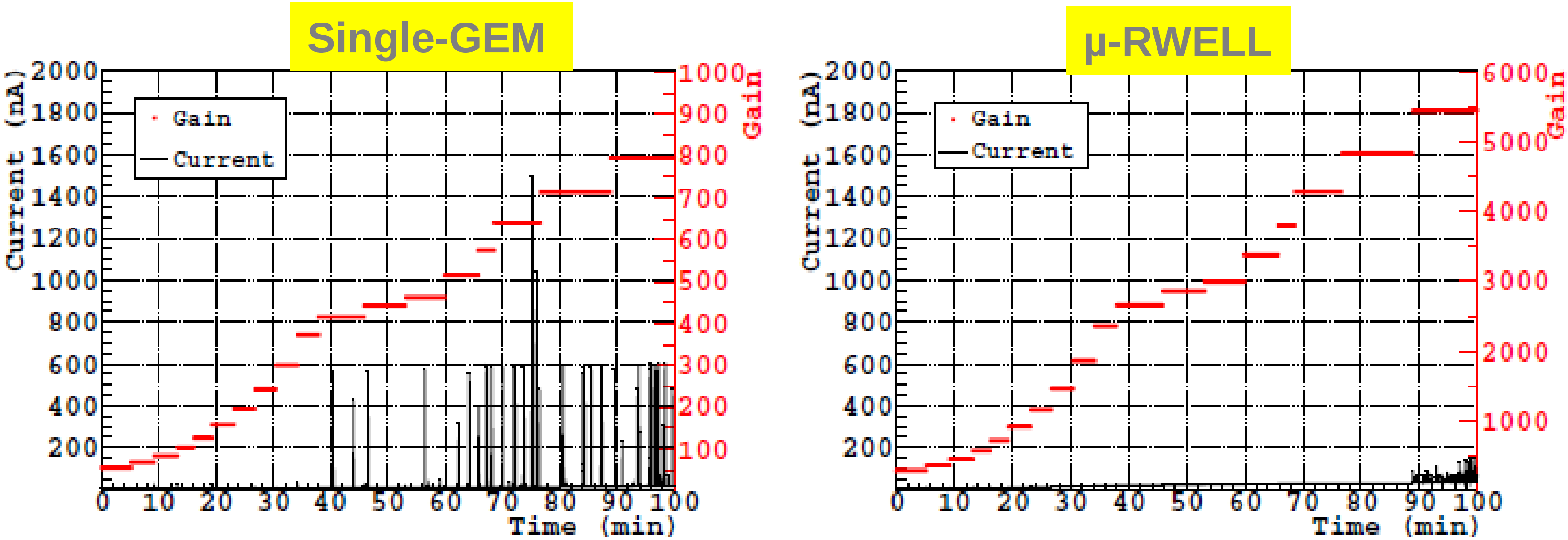


Φ = 3.4 MHz/cm²; Φ = 2.8 MHz/cm²; Φ = 1.6 MHz/cm²

Local irradiation is practically equivalent to global irradiation

The µ-RWELL performance

Discharge study: µ-RWELL vs GEM



- discharges for µ-RWELL of the order of few tens of nA (<100 nA @ max gain)
- for GEM discharges the order of 1µA are observed at high gas gain