Detector stability (ageing, discharge issues) and rate capability: resistive electrodes

ECFA Detector R&D Roadmap Symposium of Task Force 1 Gaseous Detectors
29 April 2021
SESSION: Challenges and new developments

M. Iodice (INFN Roma Tre)

Focus of the talk

- High performance, High stability, Long term operation and High-rate capability Gaseous Detectors

- Detectors with resistive electrodes
  - RPC (see G. Aielli's talk + some hints in backup)
  - Wire Detectors: TGC and sTGC (P. Wintz' talk + some hints in backup)
  - MPGD

Many thanks for useful inputs to:
G. Bencivenni, G. Cibinetto, F. Fallavollita, P. Iengo, G. Mikenberg, E. Oliveri, P. Verwilligen, …

Why resistive electrodes

High performance → **high gain** (efficiency, spatial resolution, timing,…)
High gain, often limited by onset of discharges → **Stability issues**

Occurrence of discharges due to:

- Mechanical imperfections (issues mostly for large area detectors)
- Micrometric structures in MPGD
- Transition from avalanche to streamer mode which might occur when too many primary electrons are released in the gas (exceeding the Raether limit, rate induced, jets, …)

→ Diverging processes can be quenched by means of **resistive electrodes**.
Progressive charge-up of the anode by avalanche electrons reduces locally the electric field and quenches the spark at an early stage of development

MPGD

Micro-Pattern Gaseous Detectors (MPGD) are among the most promising technologies for gaseous particle detectors at future accelerators.
Their features (see talk by E. Oliveri) can be exploited where extreme operation conditions are required.

The biggest "enemy" of standard MPGDs are the discharges.
Due to the fine structure and the typical micrometric distance of their electrodes, MPGDs generally suffer from spark occurrence that can eventually damage the detector and the related FEE.

First Large size MICROMEGAS in COMPASS

discharge rate ~0.1 discharge/s with a beam of 10^7 hadron/s.

D Neyret et al 2012 JINST 7 C03006

D. Thers et al., Nucl. Instr. and Meth. A 469 (2001) 133

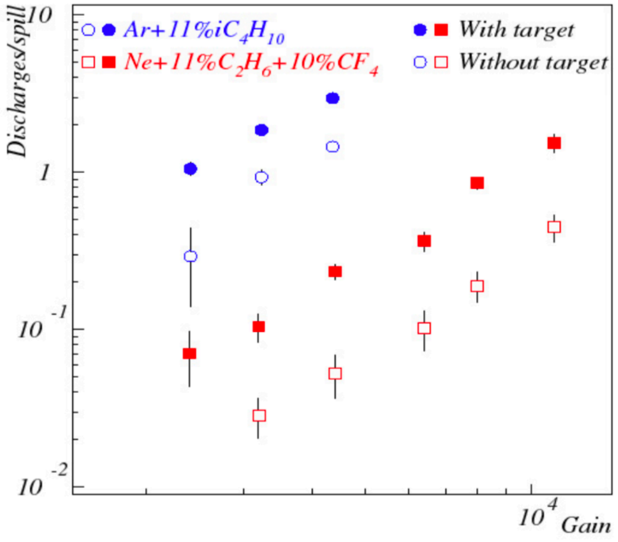
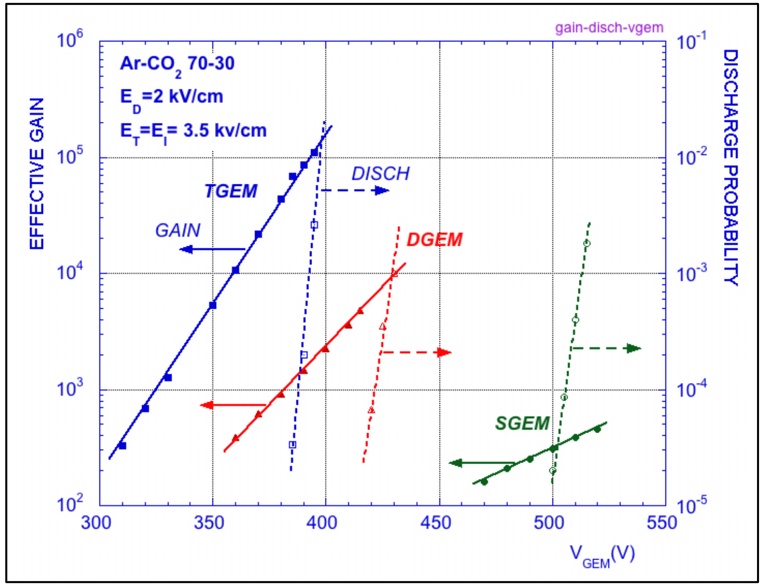
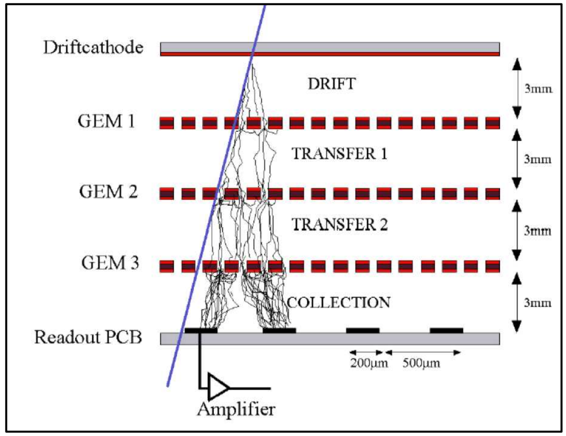


Fig. 3. Number of discharges per spill measured with the nominal COMPASS muon beam, with and without target.





S. Bachmann et al., NIMA A479(2002) 294

Resistive MPGD

The implementation of resistive electrodes represents the breakthrough in the MPGD technology

MAIN Goals of resistive protections:

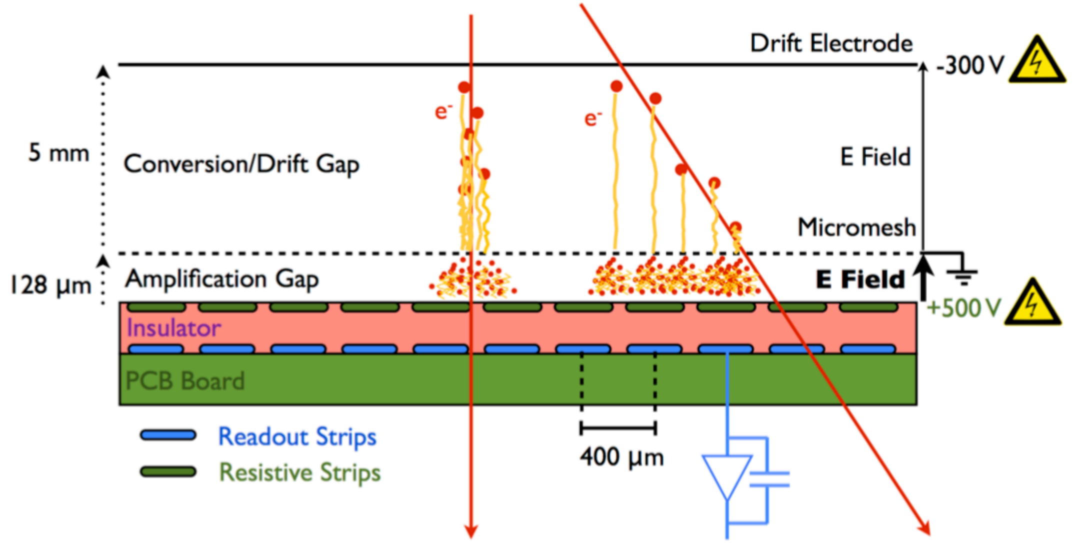
- Drastically reduce the sparks intensity
- Improve the spatial resolution by charge spreading (not discussed here)
- Keep best "existing" MPGDs features:
    - Rate
    - Space, Time, Energy resolution
    - Low material budget

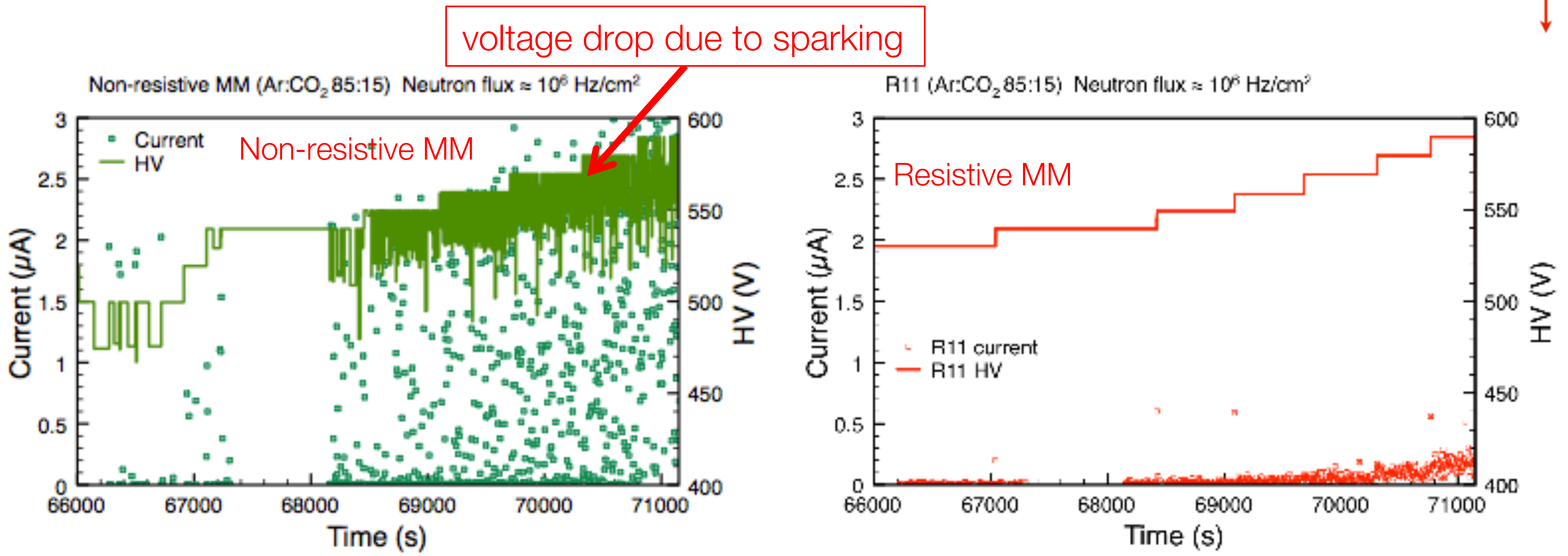
See e.g., Paul Colas "Charge spreading with a Resistive-Capacitive coating", New Horizons in Time Projection Chambers https://indico.cern.ch/event/889369

ONLY SOME EXAMPLES GIVEN IN THE FOLLOWING SLIDES
By far not exhaustive of all the great multitude of R&D currently ongoing

Resistive Micromegas – ATLAS R&D technology breakthrough

- The discharge problem has been overcome with the implementation of a layer of resistive strips by screen printing facing the amplification gap, capacitively coupled with the copper readout strips.
- In case of spark, the electric field locally drops down damping the discharge





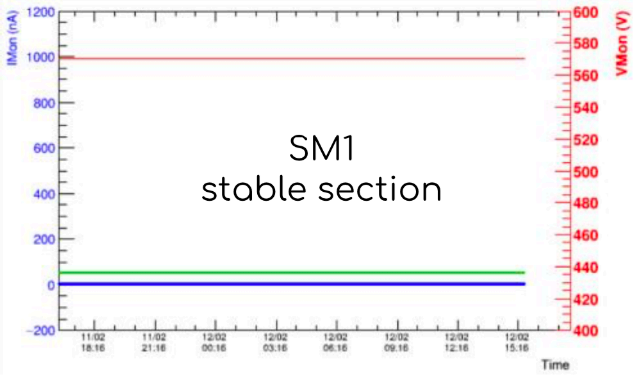
T.Alexopoulos et al. "A spark-resistant bulk-micromegas chamber for high-rate applications" NIM A 640 (2011) 110

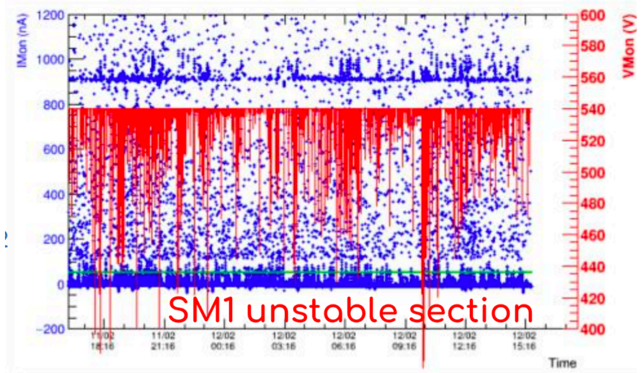
Resistive Micromegas – the ATLAS Experience

STABILITY / DISCHARGES ISSUES …to make an extremely long story very short:

See e.g., I. Gnesi INSTR 2020

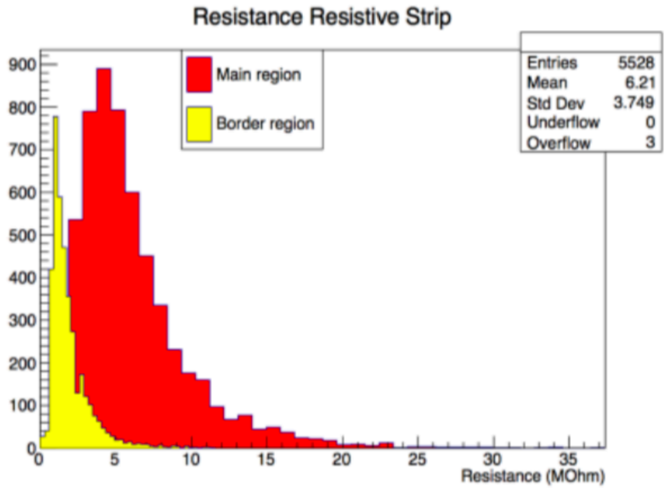
An ATLAS MM Module is divided in many HV sections. First modules showed significant issues of stabilities

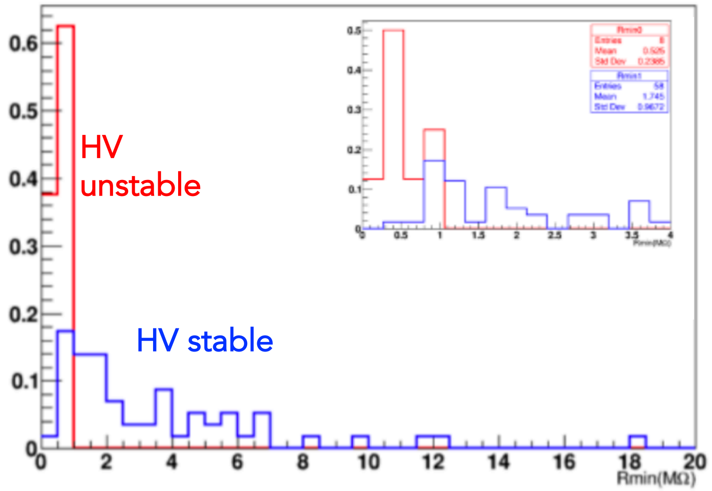




Main issues identified to be:

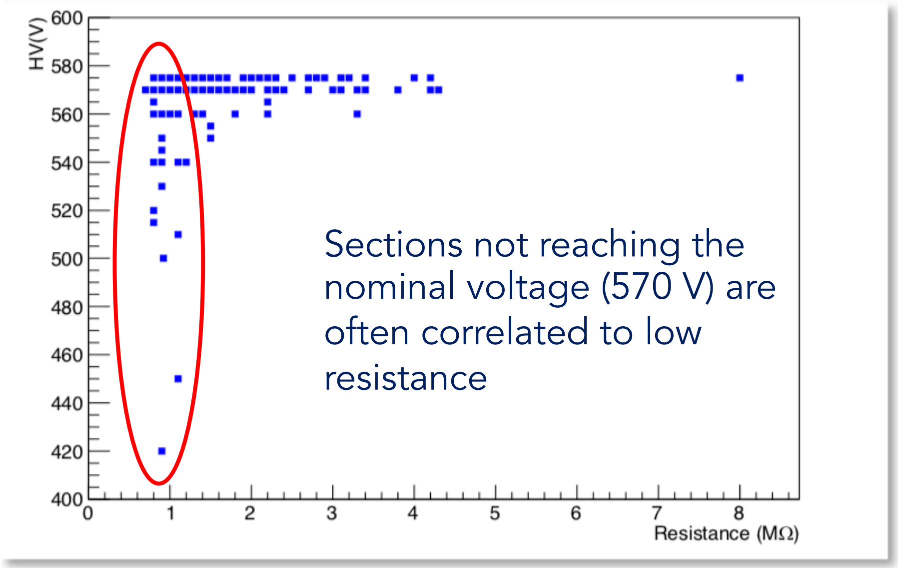
- Residual ionic contamination of boards and panels from industrial processing and handling => **improve the cleaning procedures**
- Possible effects from mesh mechanical imperfections => **implement mesh polishing**
- Clear correlation of currents with humidity => **increase gas flow rate and keep humidity under control**
- TOO LOW RESISTANCE in localized zones (edge of the HV section)





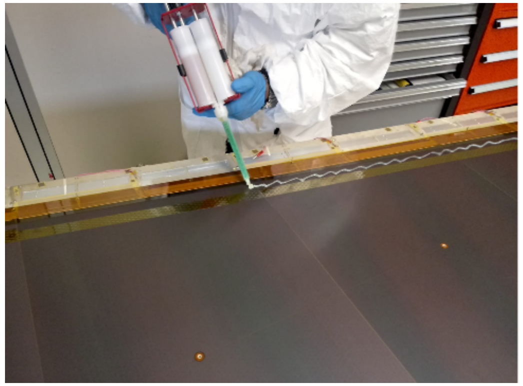
Resistive Micromegas – the ATLAS Experience

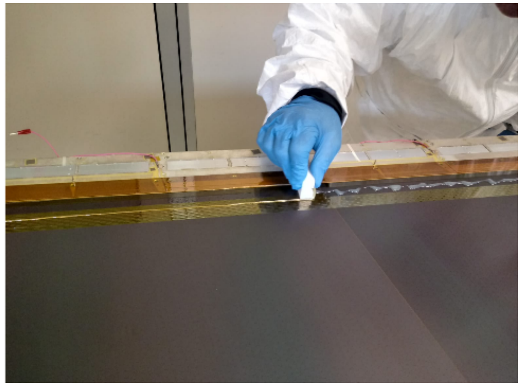
Clear correlation between unstable sectors and R_{min}



- The minimum resistance measured near the edge of the active area is sometimes very low ($R_{min} < 0.4$ MΩ)
- Known effect (aka DOCA – Distance of closest approach to ground) → see G. Bencivenni et al., JINST 063P 0319
- **Lesson learned: R_{min} , DOCA are key parameters !**

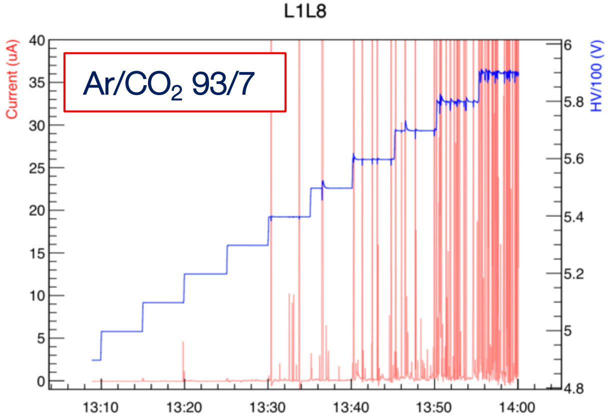
Mitigation of the problem by edge passivation

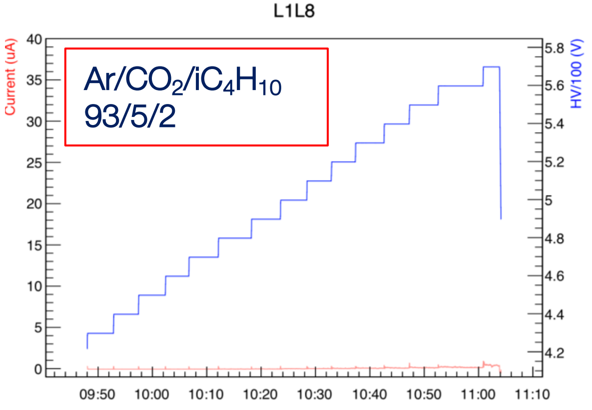




Slightly reduces the active area

NEW GAS MIXTURE: $Ar/CO_2/iC_4H_{10}$ 93/5/2





Much higher stability with 2% of isobutane

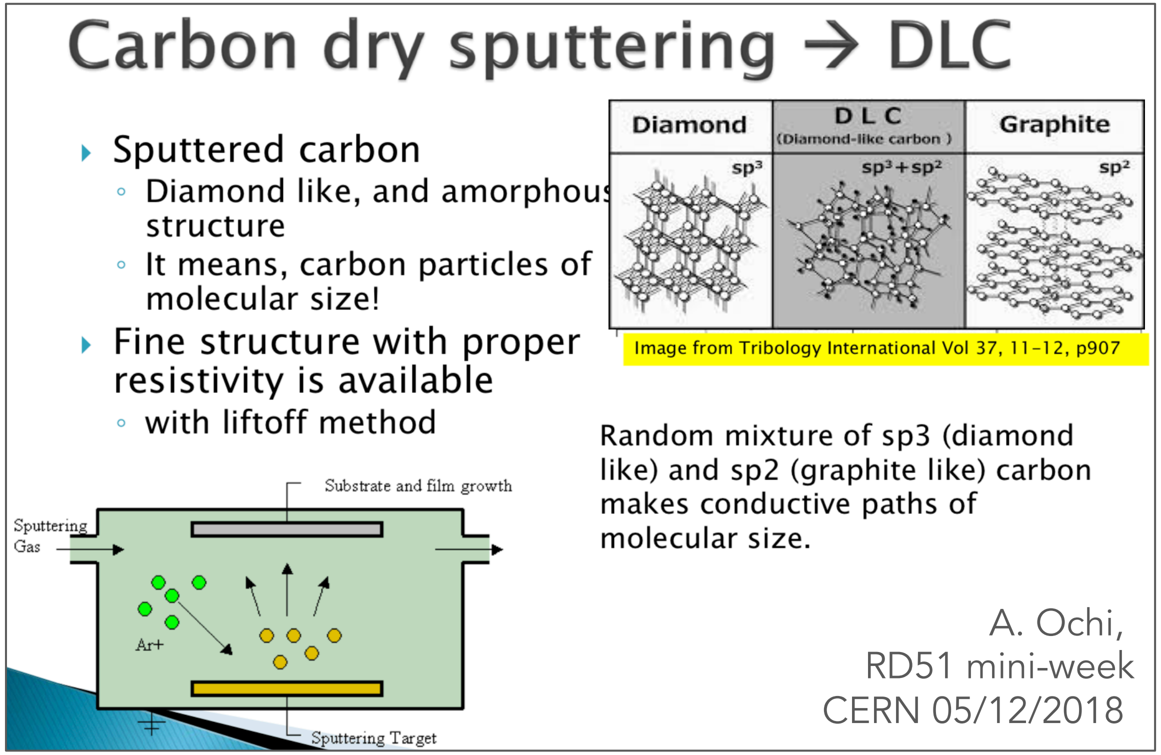
AGEING studies ongoing

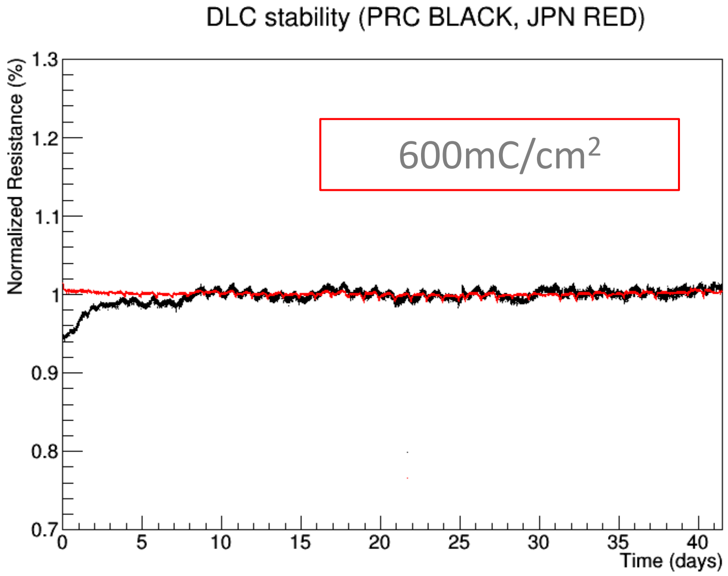
See also: G. Puill, et al., IEEE TRANS NUCL SCI, 46 (1999) 1894

Current developments on Resistive MPGD - DLC

- Diamond Like Carbon (DLC) coatings: properties of DLC have offered new possibilities opening the way to develop new detector structures.
- Stable and mechanically robust material

For DLC see also:
RD51 DLC Workshop Report
RD51-NOTE-2021-002
and references therein



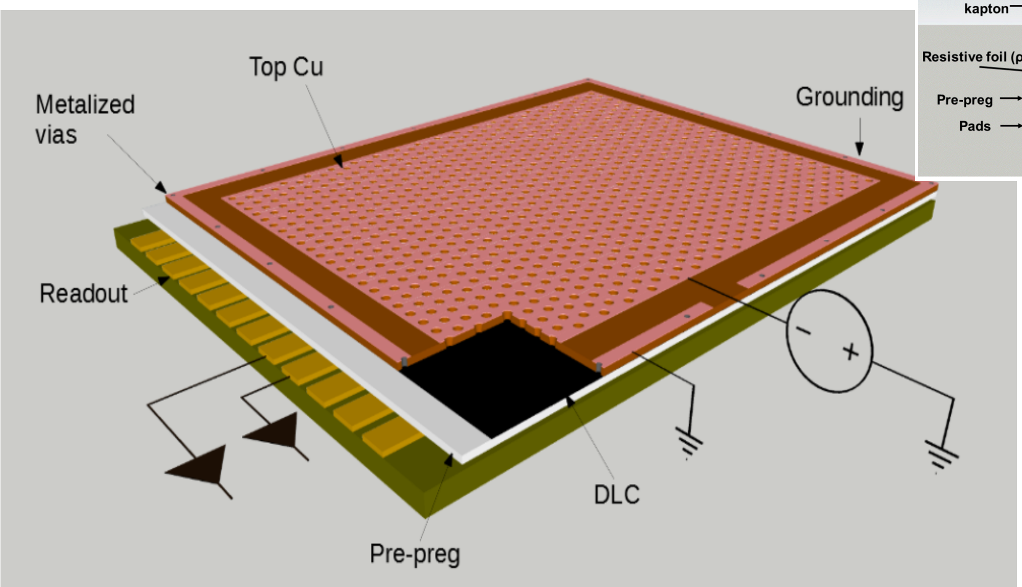


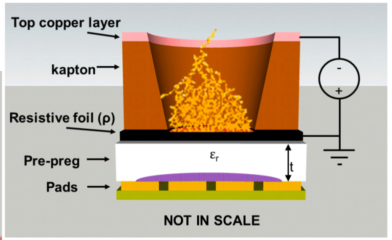
Measurements taken with bare DLC foils applying a DC Voltage in order to induce a continuous current flow over the DLC surface

The μ-RWELL: a DLC based resistive detector

The core of a μ-RWELL detector is the **μ-RWELL-PCB** realized by coupling 3 elements:

- a WELL patterned Kapton foil acting as amplification stage (GEM-like)
- a resistive DLC layer
- a standard readout PCB



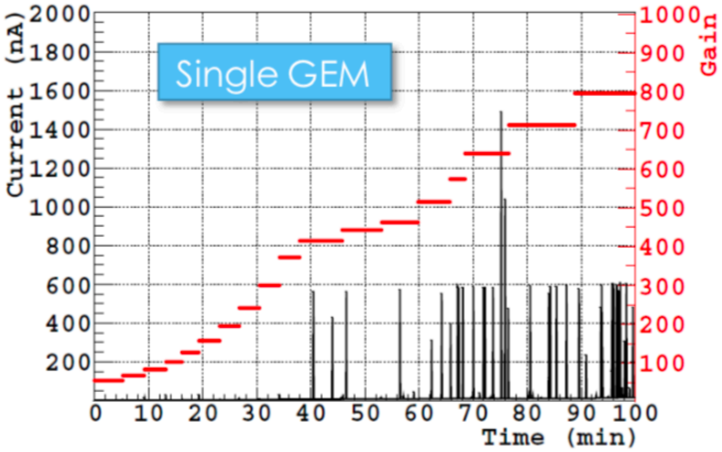


Single Resistive Layer (SRL)

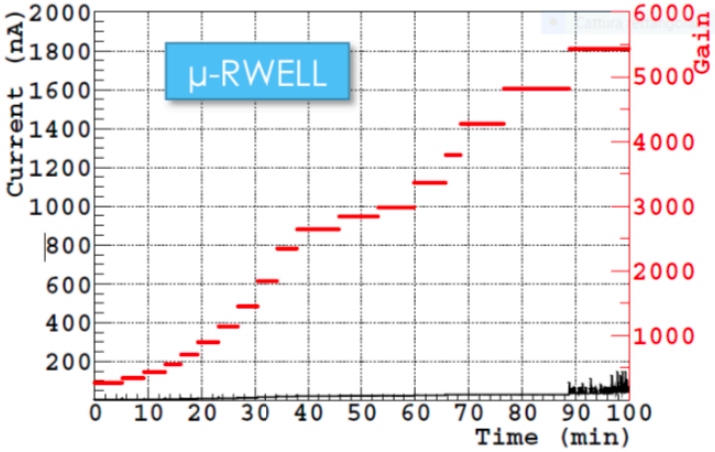
- G. Bencivenni et al., JINST 063P 0319
- M. Giovannetti at INSTR2020

- 2-D current evacuation scheme based on a single resistive layer
- conductive grounding line all around the perimeter of the active area
- Limitation for large area: the signal amplitude depends on the particle incident point → **limited rate capability - O(10kHz/cm2)**

Comparison between the Current drawn by a Single GEM and a uRWELL at various GAIN

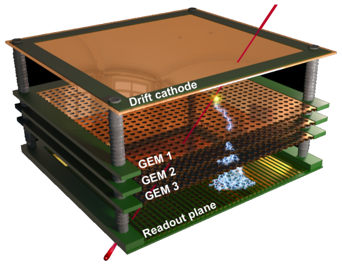


for GEM discharges are of the order of 1μA at Gain<1k



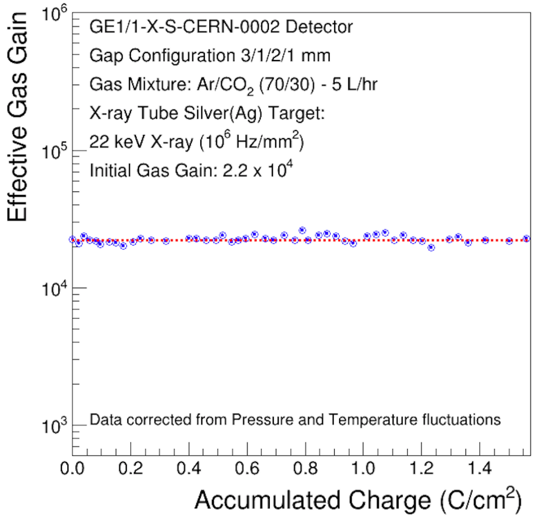
for μ-RWELL discharges are of the order of few tens of nA at Gain > 5k

GEM



CMS-GEM ME0

(F. Fallavollita)

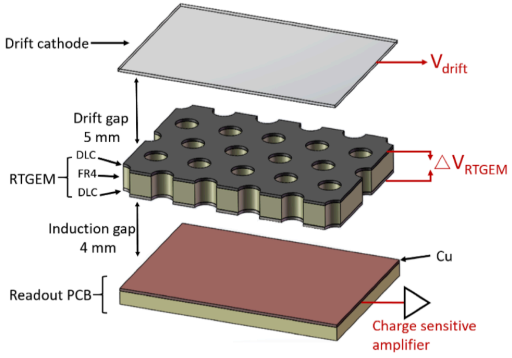


- The main solution adopted to obtain high gain, high performance with GEM is the multi-stage amplification scheme
  - E.g., Triple GEM successfully employed in many experiments and now large area 3-4-GEM under installation in CMS and ALICE (TPC) at LHC
  - Good stability, high gain (>2x10^4), high-rate capability (100's kHz/cm^2)

NO aging observed up to ~ 1.5 C/cm^2

R&D on Resistive GEM (improve spark protection and reduce X0)

Resistive Thick GEM (RETGEM)



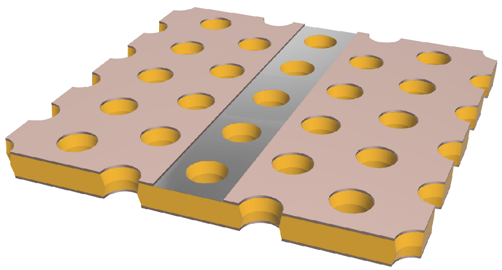
A DLC version

G. Song *et al* 2020 *JINST* **15** P11013

See also
R. Oliveira, V. Peskov, et al.
NIM A576 (2007) 362

DLC in SECTORS SEPARATION:

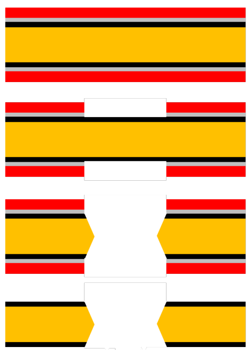
preserve the electric field line uniformity



F. Sauli "RESTORING EFFICIENCY IN GEM SECTOR SEPARATIONS"
https://indico.cern.ch/event/843711/
And A.P. Marques, et al. NIM A 961 (2020) 163673

ONGOING R&D

Full DLC GEM

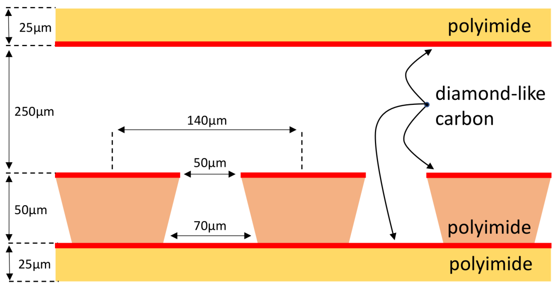


Still ISSUES with low adhesion of Cr on DLC

R. De Oliveira, RD51 October2019
https://indico.cern.ch/event/843711/

FTM Fast Timing Mpgd

(see talk by P. Verwilligen)



FTM effort: Full resistive kapton 50 µm with DLC
Next step: GEM

GEM

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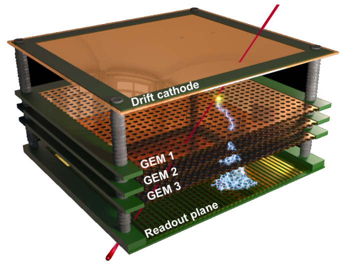
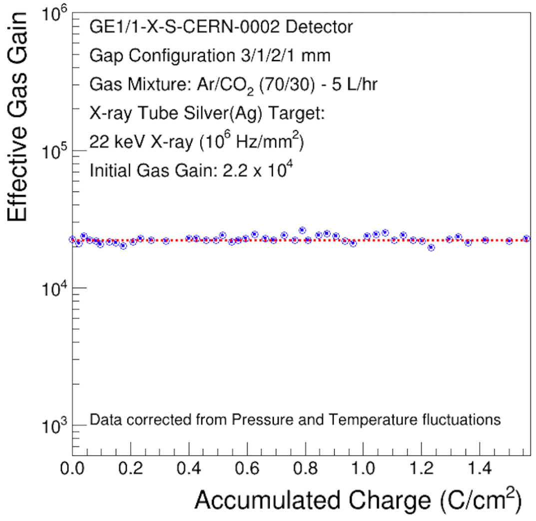


CMS-GEM
ME0
(F. Fallavollita)



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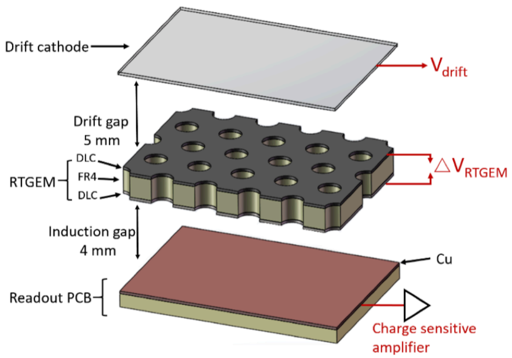

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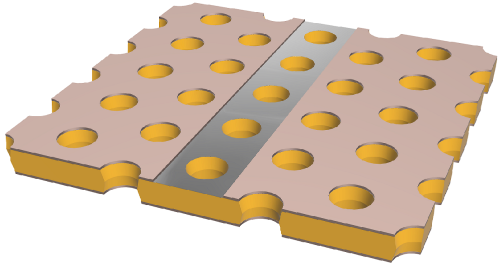

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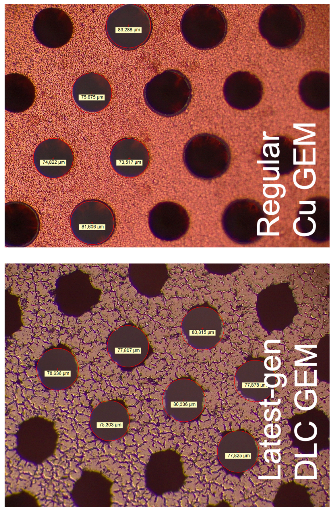
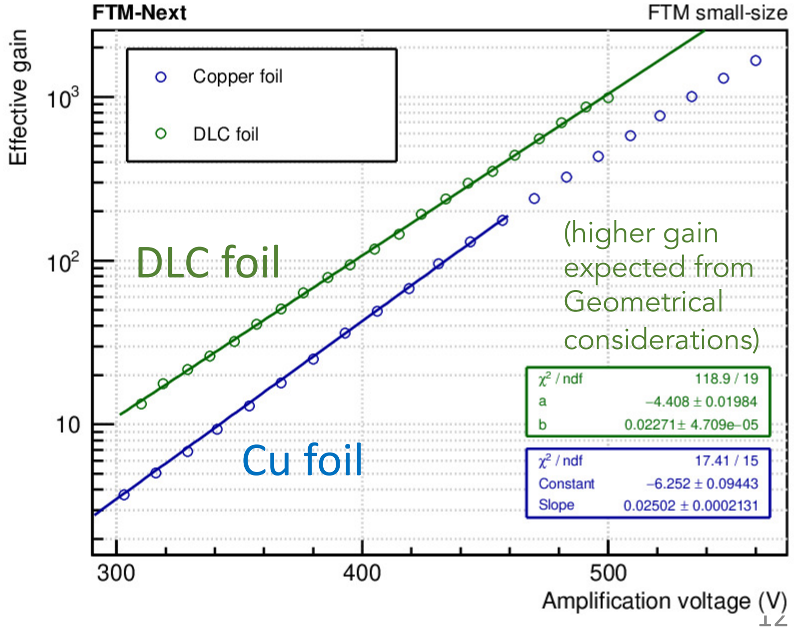
ONGOING R&D

Full DLC GEM



FTM Fast Timing Mpgd



Challenges for future R&D on resistive MPGD

- **HIGH RATE: Stable** and efficient **operation** up to particle fluxes of 10 MHz/cm^2 (and beyond)
- **Radiation hard** and effective **spark quenching** up to integrated charges of tens of C/cm^2
- **Low occupancy**: high granularity readout to operate efficiently at high rate
  - Pixels/pads readout of order of few mm^2
  - fully integrated electronics
- **High gain** for improved performance, single-electron detection & Fast Timing
- **Good spatial resolution** (~50um and below)

…and… **Gas** optimisation, Fast **timing,** Improved **Electronics, Low material budget, Reliable** and **cost-effective** production process

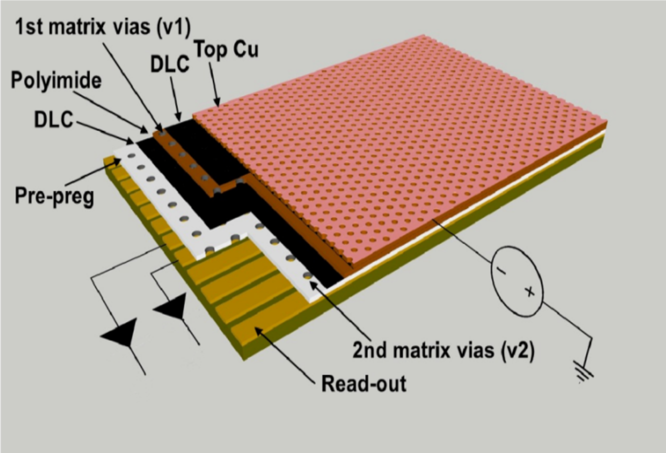
Resistive schemes for HIGH RATES

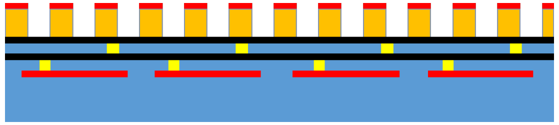
R. De Oliveira INSTR2020
R. De Oliveira, RD51 Coll Meeting Oct. 2019
https://indico.cern.ch/event/843711

Resistive electrodes are inherently unsuitable for HIGH RATES (ohmic voltage drop).
Need to develop new, more complex resistive schemes, eventually implementing standard techniques of PCB production

- Keep sufficient local surface resistivity to quench sparks
- with low resistance to grounding

Double DLC μRwell





Concept of the Double DLC layer with conductive vias to ground every few mm

Different μRwell structures

- 1"DLC+" with Silver or Cu evacuation Grid

- 1 "DLC" with Drill and fill method

- 2 "DLC+" Sequential Build Up

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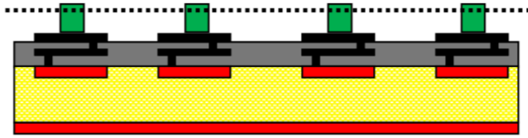
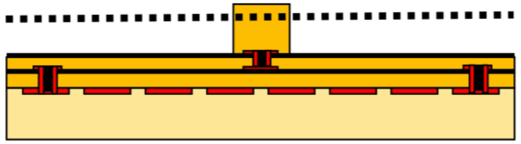
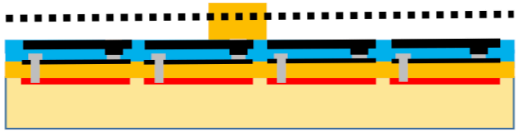
Different Resistive protection approach with SMALL PAD Micromegas



- 2 layers screen printed resistors



- 2 "DLC+" layers → SBU



- MIX "DLC" and screen printed

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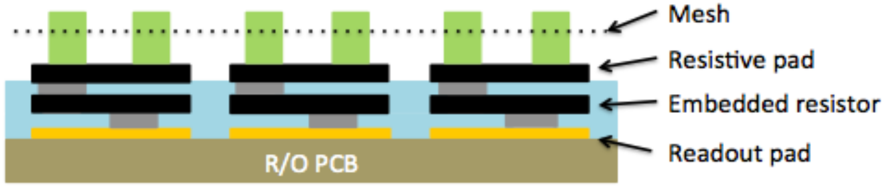
DLC+ is a DLC with Cu/Cr coating allowing for standard lithographic production (backup slide)

Pad-patterned schemes – the embedded resistor approach

Schemes with fully independent pads offer several advantages:

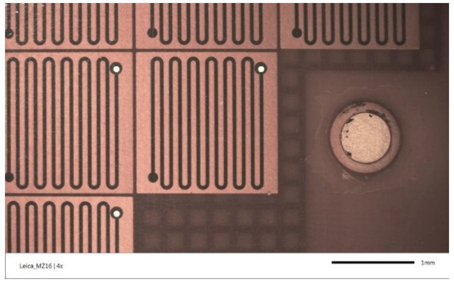
- Very high rates
- Resistance independent from the position
  → constant behaviour as a function of irradiated area

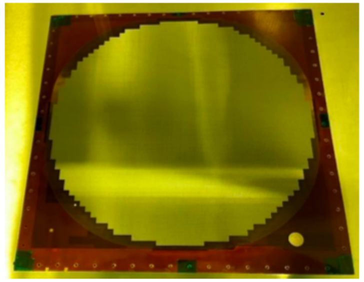


1. Resistive Micromegas for SDCAL (pads 10x10 mm^2)
   (M. Chefdeville et al., NIM A (2021) 510–511)
2. Pad miniaturisation for COMPASS R&D (pads 0.7x2.6 mm^2)
   (F. Thibaud et al., 2014 JINST 9 C02005)
3. Small Pads MM – improving COMPASS R&D new resistive schemes (0.8 x 2.8 mm^2) (M. Alviggi, JINST 12 C03077 (2017))

Screen printing

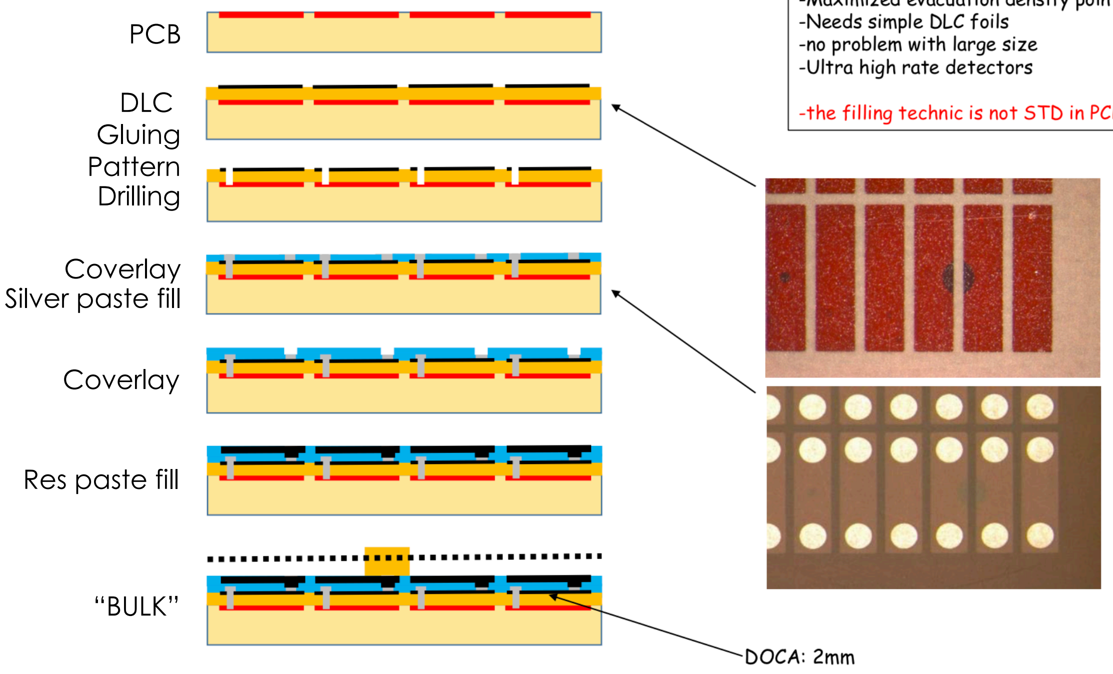
Shapes (Resistance) defined by photolitographic processes





5 ILC DHCAL
50cm diameter
pads 1cm x 1cm
5M/Pad

MIX method: DLC+paste filling



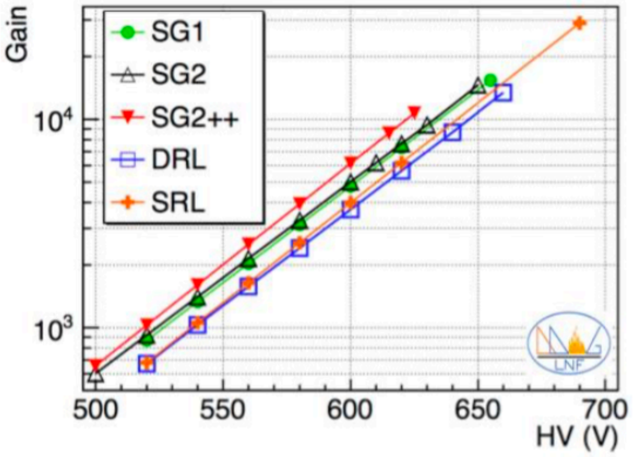
-Large DOCA
-Maximized evacuation density points
-Needs simple DLC foils
-no problem with large size
-Ultra high rate detectors

-the filling technic is not STD in PCB world

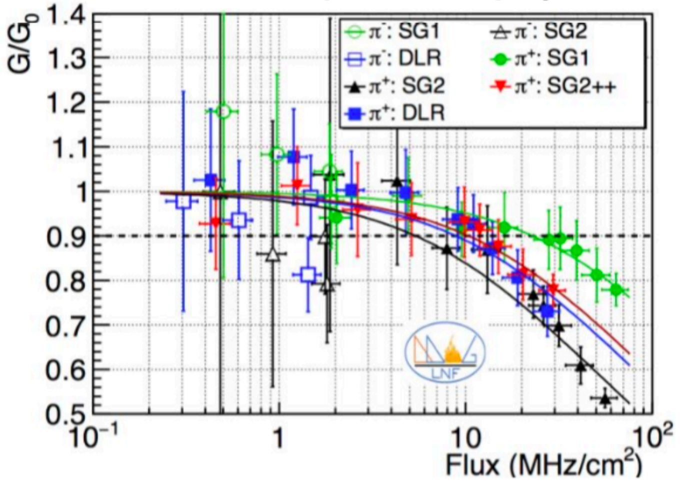
PERFORMANCE - uRWell

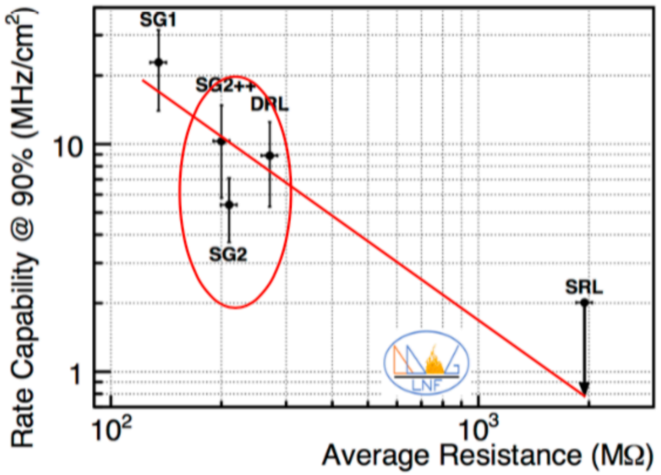
- M. Giovannetti at INSTR2020

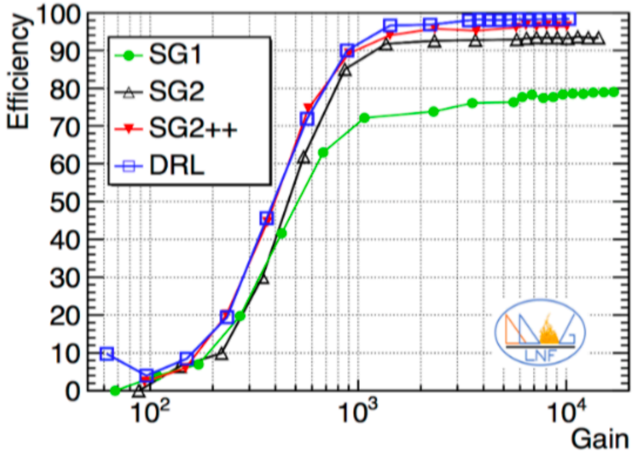
Gain up to ~ 10^4

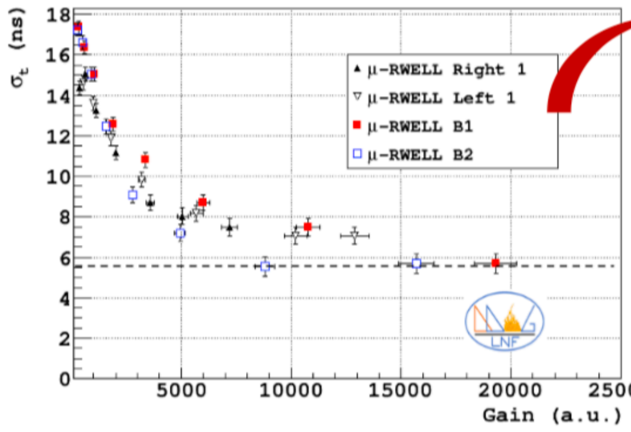


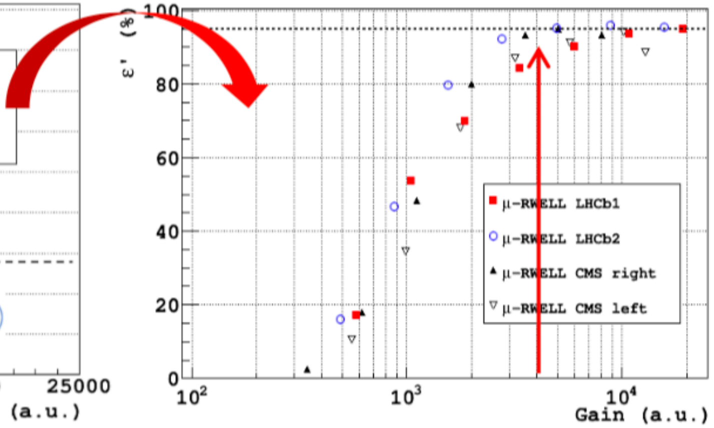
Rate capability (@ G = 5000) ~ 5-10 MHz/cm²











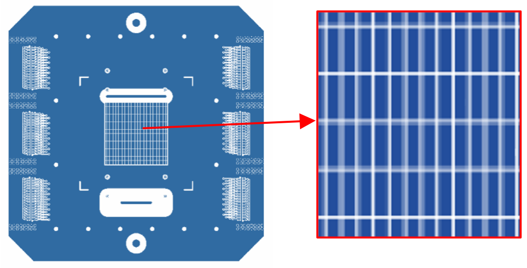
Efficiency ~ 98%

σ_t ~ 5-6 ns

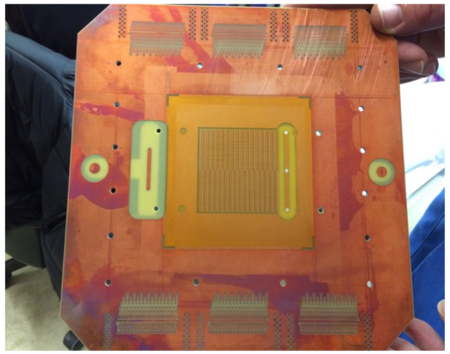
Efficiency in 25 ns

PERFORMANCE – High-rate High-granularity Micromegas

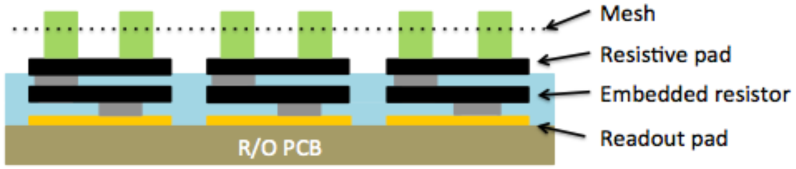
ONGOING R&D



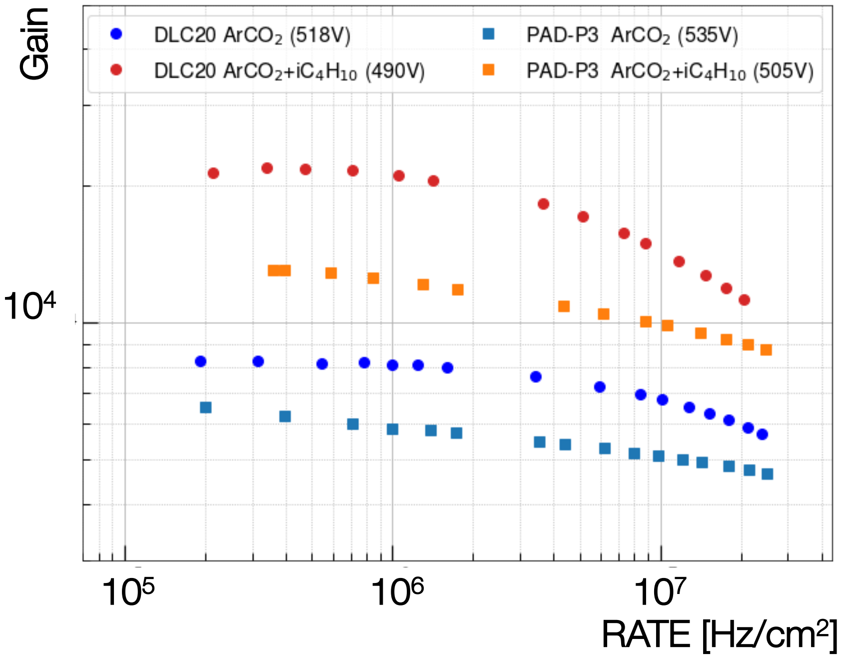
Pixelated readout pads of 0.8 x 2.8 mm^2



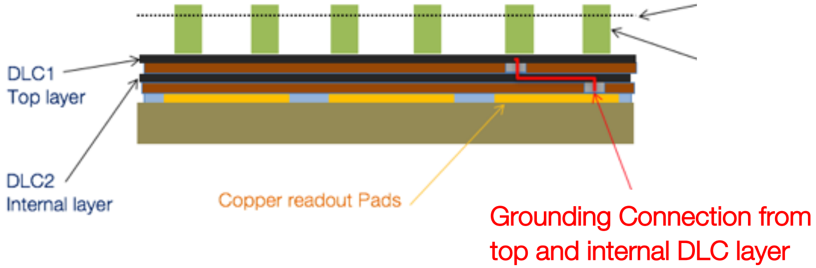
Pad-patterned

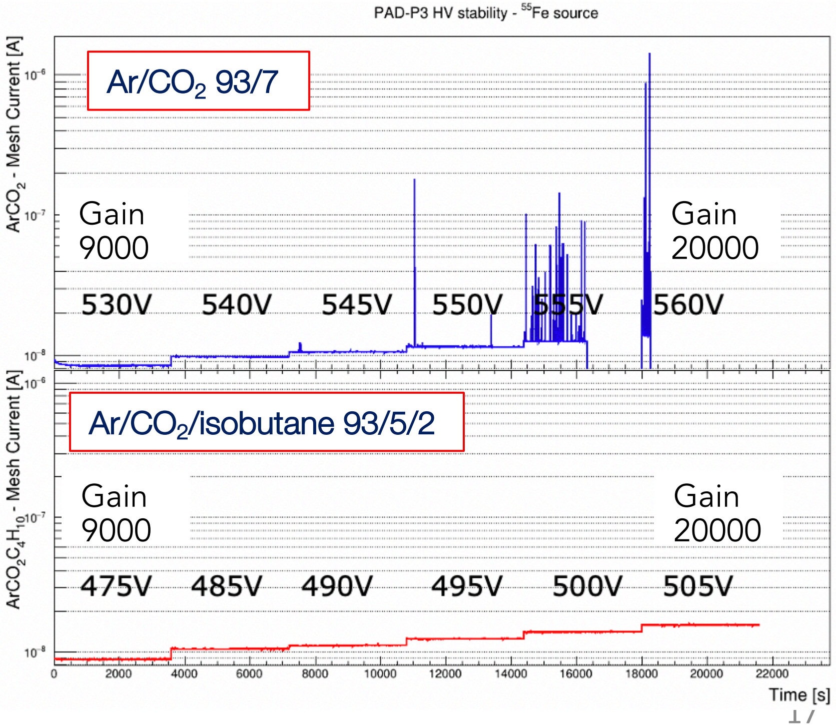


Rate capability ~5-10 MHz/cm^2 at Gain ~$2x10^4$



Double DLC





- M. Alviggi, et al. JINST 12 C03077 (2017)
- M. Iodice at INSTR 2020, and RD51 mini-week 15-19 February 2021

Concluding Remarks

- An intense and promising R&D activity is underway on resistive gas detectors (only a very limited and partial overview reported in this talk)
- As of today, not a single technology clearly predominant. R&D should proceed along multiple roads
- Need transfer of technology to **research institutes** and **PCB Industries**
- Today, there is a large interest in Diamond Like Carbon (DLC) coatings. The DLC production techniques must be, however, further advanced:
  - Uniformity and quality - Resistivity values from a few hundreds kΩ/□ to GΩ/□.
  - study of DLC mechanical etching (scrabbing) technologies to create high quality resistive patterns.
- Exploit sputtering production for different coatings (Cu/Cr clad DLC, B4C, ITO for transparent MPGD)
- Beyond DLC, future R&D on new resistive materials must be pursued (e.g., graphene) and do not abandon the screen-printing technique (good for large simple production - control of resistivity needs R&D)
- **Fully resistive MPGD would further improve their stability.**
  At the same time reducing the material budget (crucial challenge for the future)

BACKUP

RPC (see talk by G. Aielli)

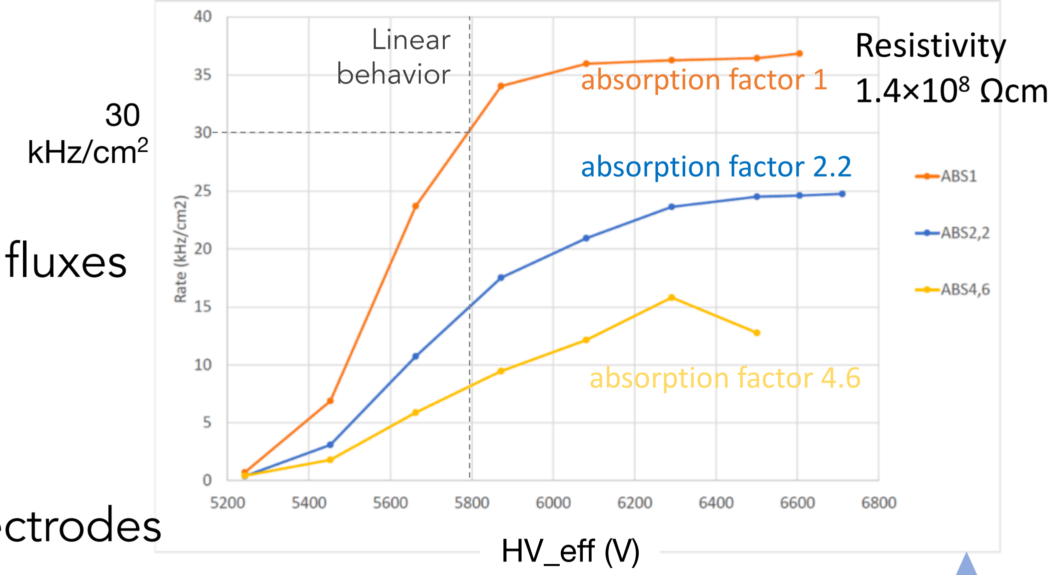
RPCs have great potential for future development:

- good spatial and temporal resolution; low cost for large surfaces and a relatively simple construction

The main limitation of RPC is the rate capability.

Three MAIN approaches pursued:

- **New materials:**
  - optimization of resistivity AND to prevent ageing under high fluxes
- **New geometries (thin electrodes, multiple gaps)**
- **Low-noise FEE**



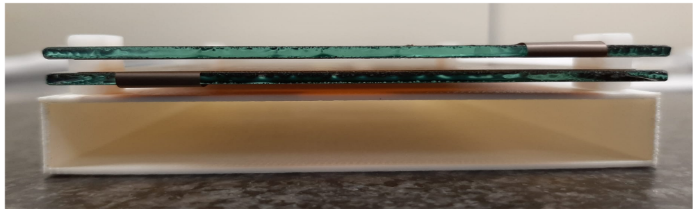
Among the ongoing developments: RPC with semiconducting electrodes

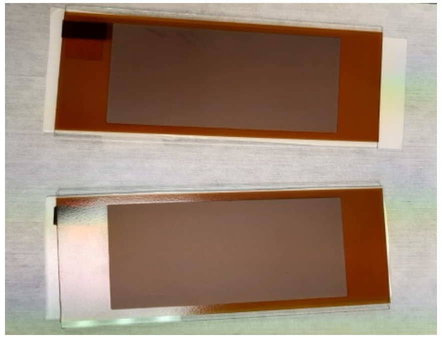
- The idea of using electronic semiconductors as RPC electrodes is mainly motivated by their lower resistivity which allows to increase the RPC rate capability
- Small size RPCs with Silicon and GaAs electrodes successfully tested. Rate capability ~30-40 kHz/cm^2 with excellent potentialities for higher rates *[A. Rocchi et al 2019 JINST 14 C12005]*

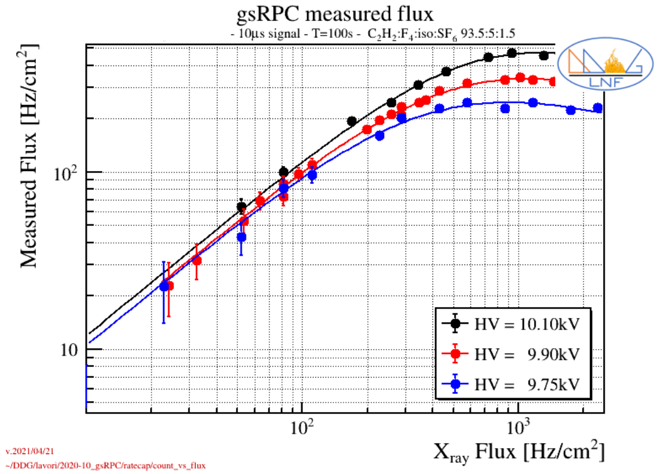
NEW: G. Bencivenni et al. Surface Resistive Plate Counter sRPC manufactured with ***DLC*** *coating technique (see Backup slides) and P. Iengo Development of a resistive plate device with micro-pattern technique" (****Screen Printing****) NIM, A 958 (2020) 162779*

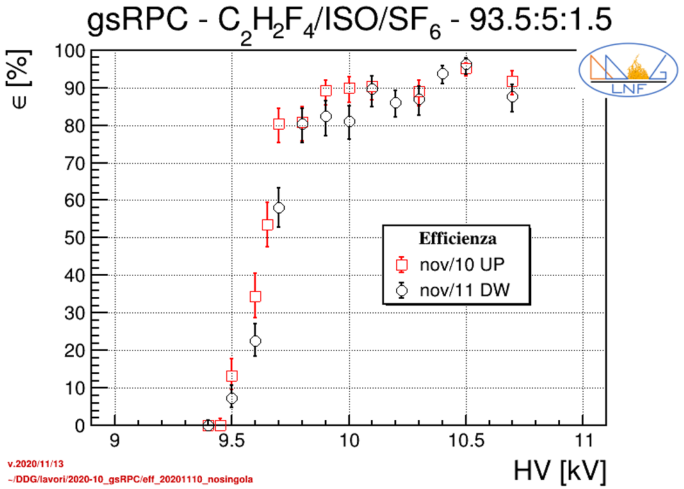
Surface Resistive Plate Counter sRPC

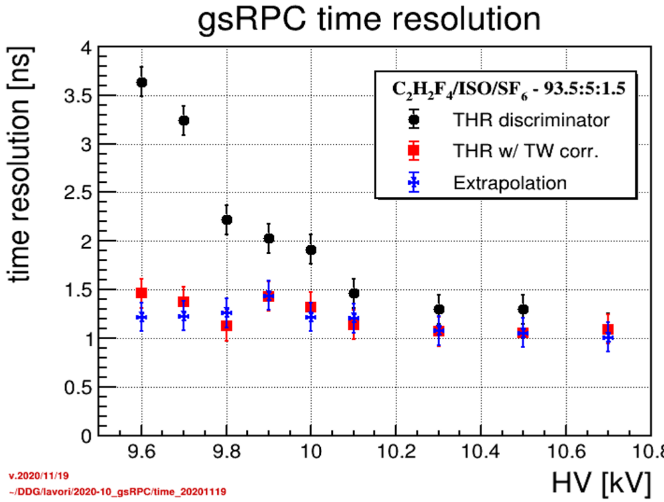
- The **sRPC** is based on **surface resistivity thin electrodes** (1-10 GΩ/sq) manufactured with **industrial DLC coating techniques** on flexible or semi-rigid supports,
- a completely different concept w.r.t. traditional RPCs characterized by volume resistivity











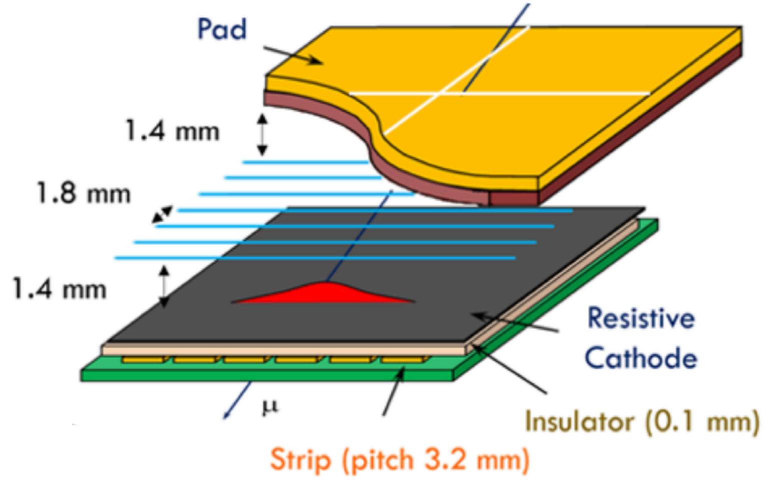
- The detector can be operated in a stable and efficient way over a wide voltage range (>1 kV)
- Typical **time resolution of 1 ns**
- Rate capability of **1 kHz/cm²** (m.i.p. ~ 3□X-ray) obtained with a 2 mm gas gap
- Exploiting the technology developed for resistive MPGDs should allow the development of sRPC achieving very high particle rates (>10 kHz/cm2)

Brevetto in Italia N. 102020000002359 (submitted to INFN 10 Sept 2019 - deposited to Ufficio Brevetti 6 Feb 2020)
INFN – "ELETTRODO PIANO A RESISTIVITÀ SUPERFICIALE MODULABILE E RIVELATORI BASATI SU DI ESSO."

Thin Gap Chambers (TGC)

Successfully employed in large experiments
In ATLAS: "low-rate" and "high-rate" (sTGC)

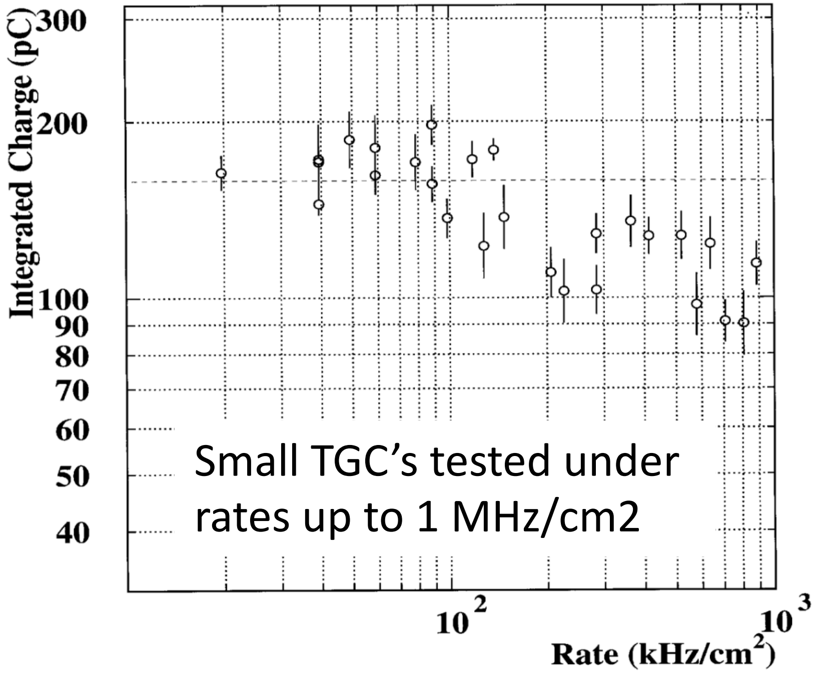
- CSC-like structure
- Anode wires sandwiched between 2 high resistive layers.
- Readout behind resistive layers (strips, pads)
- ATLAS TGC "low-rate" O(kHz/cm2): R = 0.5 and 1 MΩ/sq
- ATLAS small-strips TGC "high-rate" (10's kHz/cm2): R = 100 and 200 kΩ/sq



Resistive layer applied by Carbon Spray

RATE CAPABILITY: up to 100 kHz/cm^2 for local irradiation

- **limited to 30 kHz/cm^2 for LARGE AREAS**
- Also limited by granularity → high occupancy

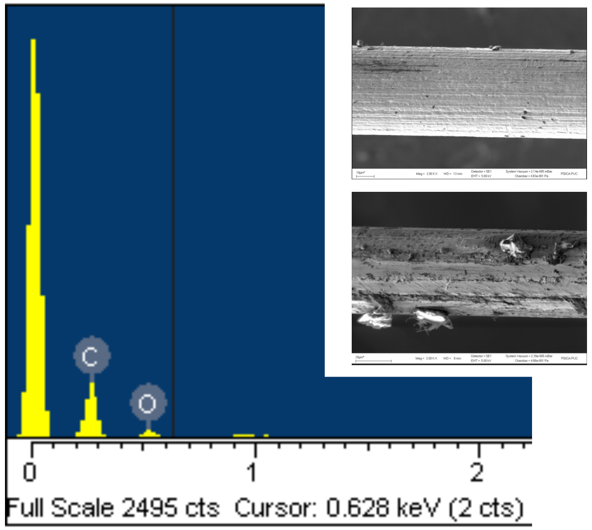


Thin Gap Chambers (TGC)

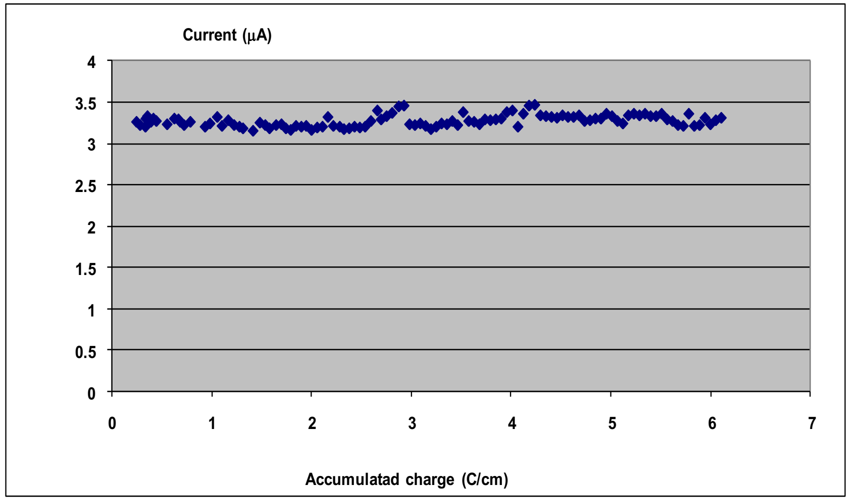
TGC STABILITY and AGEING

- Gas: CO_2 – n-Pentane (55%-45%): n-Pentane increases the ionization, while absorbing the photons in the avalanche.
- In the TGC has proven to perform "much better" than isobutane
- A small chamber has accumulated 6 Coulomb/cm, without any deterioration= 20 years at HL-LHC with safety factor 5.

Anode and cathodes analyzed:
Deposits: mainly Carbon and Oxygen

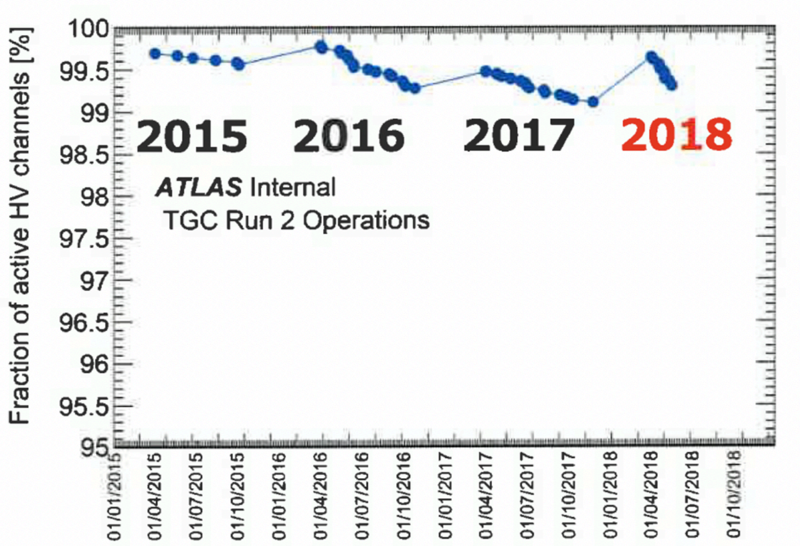


No signs of ageing



IN ATLAS

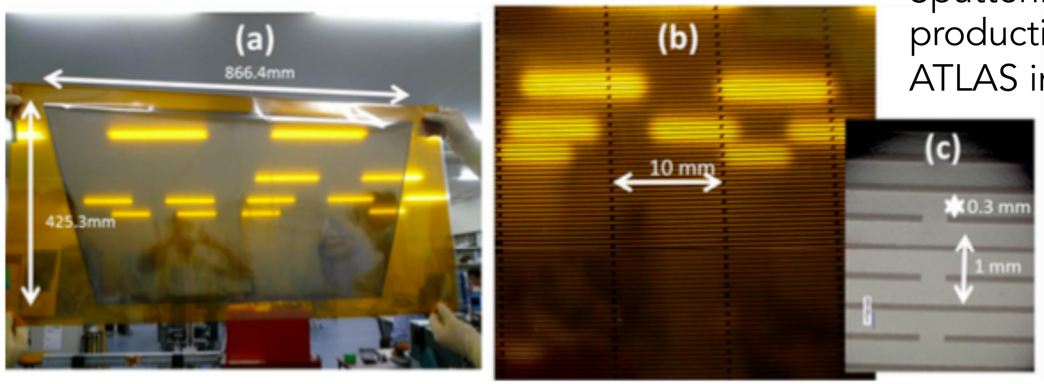
- 4,000 large area TGC's
- Very stable, though with several trips during physics runs
- >99% active HV channels



The ATLAS Resistive Micromegas

Choice of the technique for the resistive layer

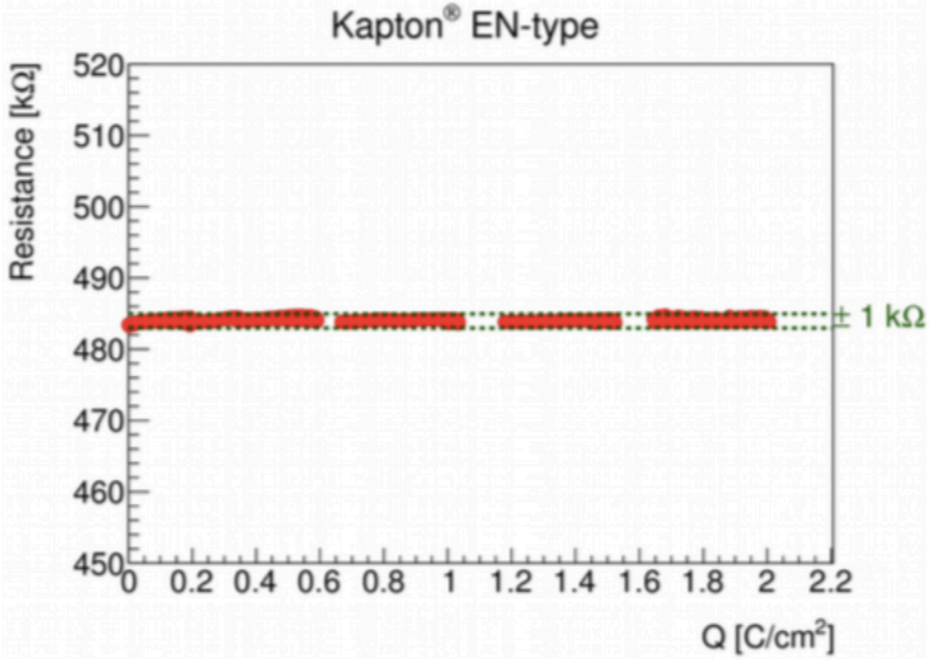
- **DLC sputtering** Vs **screen-printing**
- Both evaluated and considered valid for ATLAS MM



Sputtering production for ATLAS in Japan

A. Ochi, PoS(TIPP2014)351

Choice finally made on **screen printing technique**, mostly motivated by the lower cost, also by some evidence on mechanical poor DLC adhesion after treatment (liftoff) to pattern the (interconnected) strips

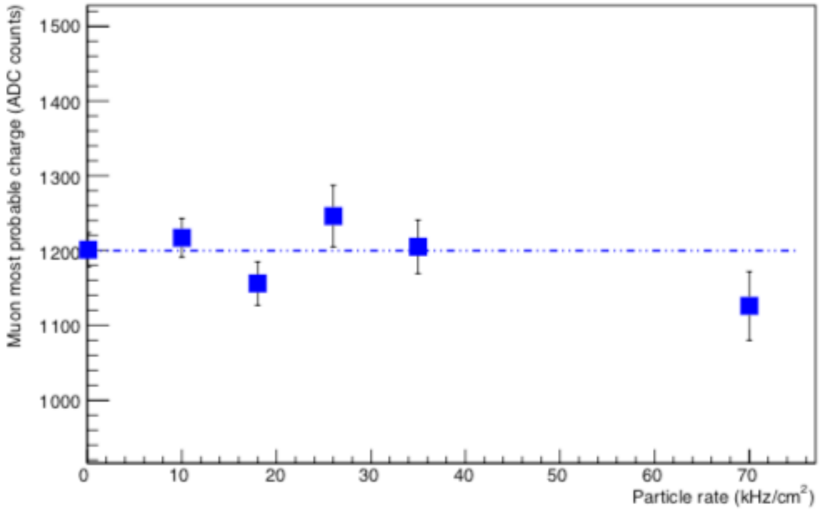


Resistive screen-printing on Kapton
Measurement of stability done up to 2 C/cm2 equivalent charge applying a DC Voltage in order to induce a continuous current flow over the resistive surface (analogous to plot for DLC on slide 11)

Resistive Micromegas – the ATLAS Experience

RATE CAPABILITY AND AGEING

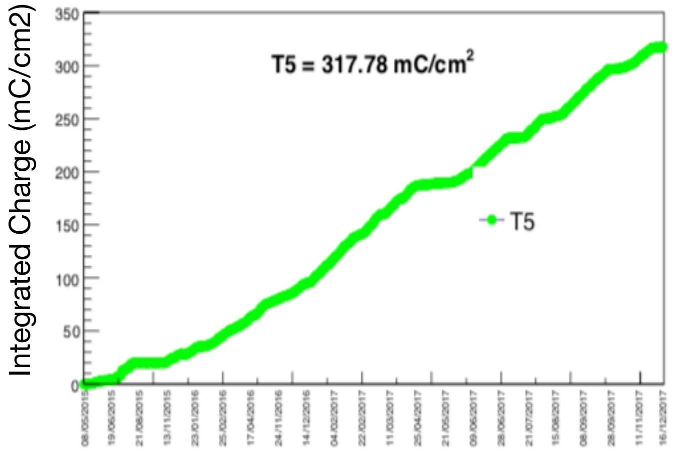
- Studies carried out at GIF++ at CERN (14TBq Cesium source) [ref]
- Two Small size MM Resistive Prototypes (“ATLAS style”)
  - Resistive strips with ~few MΩ/sq
  - Operated with the **“ageing safe” gas mixture Ar/CO2 93/7**

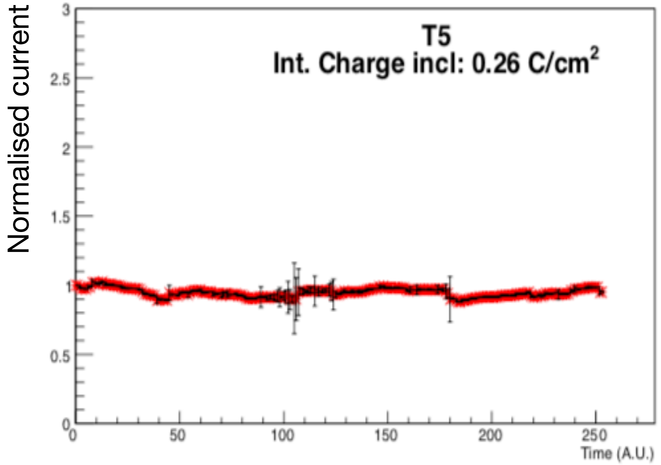


- RATE CAPABILITY: measured gain drop of ~10% at 70 kHz/cm2

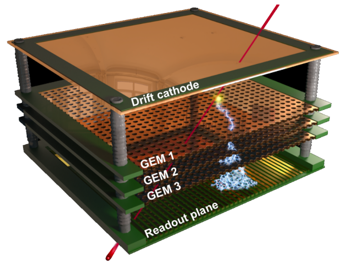
- In 2015-2017 more than 0.3 C/cm^2 have been accumulated (more than what expected in 10 years of HL-LHC in the NSW)

→ no ageing effects have been observed in gas gain, efficiency and current stability

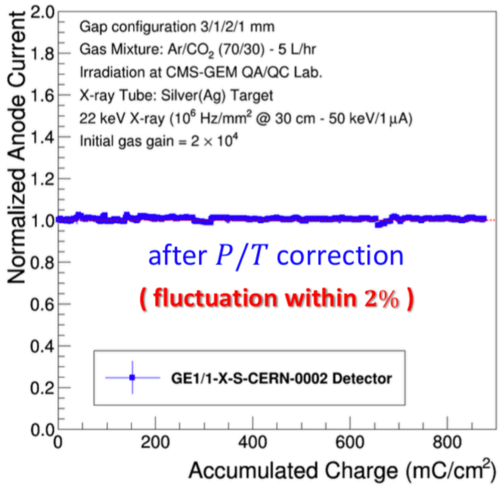




GEM



CMS-GEM ME0 (F. Fallavollita PhD Thesis)

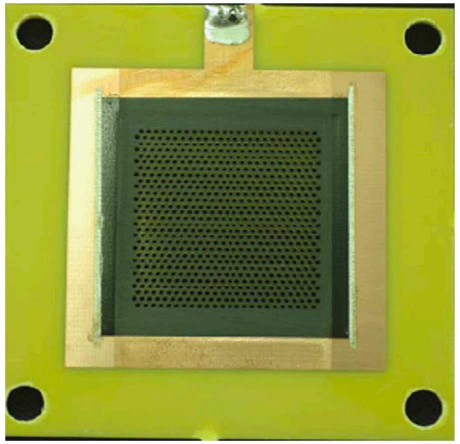


NO aging observed up to ~ $875\ mC/cm^2$

- The main solution adopted to obtain high gain, high performance with GEM is the multi-stage amplification scheme
  - E.g., Triple GEM successfully employed in many experiments and now Large area T-GEM under installation in CMS and ALICE (TPC) at LHC
  - Good stability, high gain (>2x10^4), high-rate capability $\mathcal{O}$(MHz/cm^2)
  - Yet, construction not straightforward, especially for large surfaces

R&D on Resistive GEM

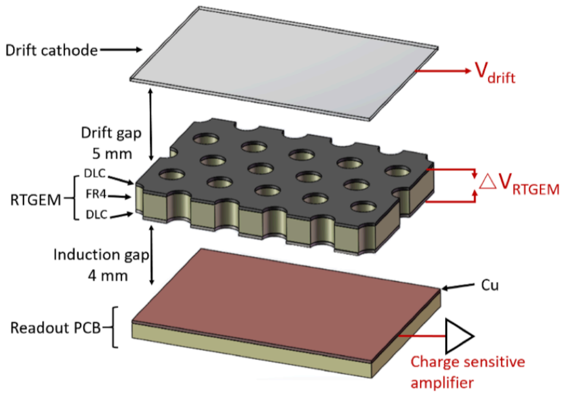
Resistive Thick GEM



R. Oliveira, V. Peskov, et al. NIM A576 (2007) 362
And https://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=5658074

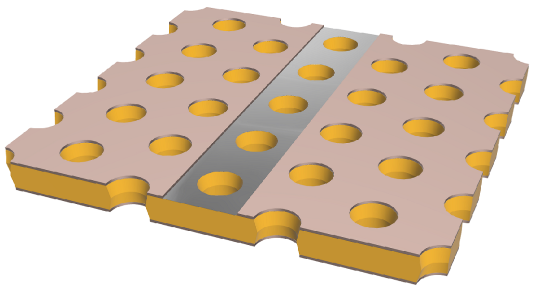
RETGEM with DLC

G. Song *et al* 2020 *JINST* **15** P11013



DLC layers in sector gaps

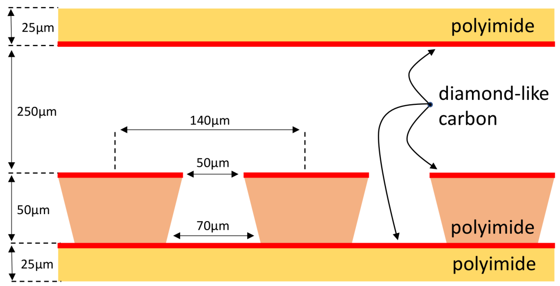
preserve the electric field line uniformity



F. Sauli "RESTORING EFFICIENCY IN GEM SECTOR SEPARATIONS"
https://indico.cern.ch/event/843711/

FTM (see talk by P. Verwilligen)

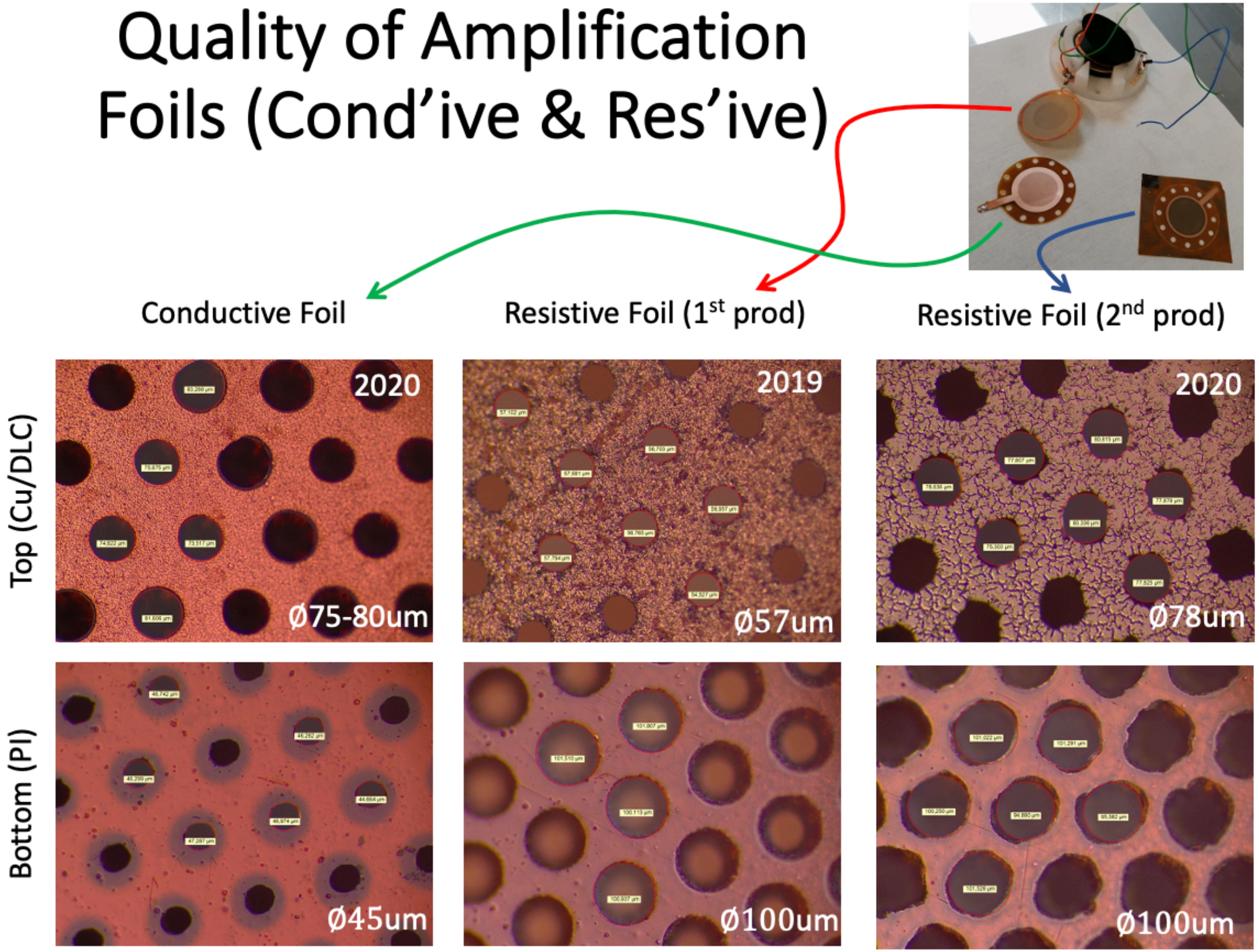
Fast Timing Mpgd



FTM effort: Full resistive kapton 50 μm with DLC
Next step: GEM

FTM – R&D on GEM resistive foils

From P. Verwilligen

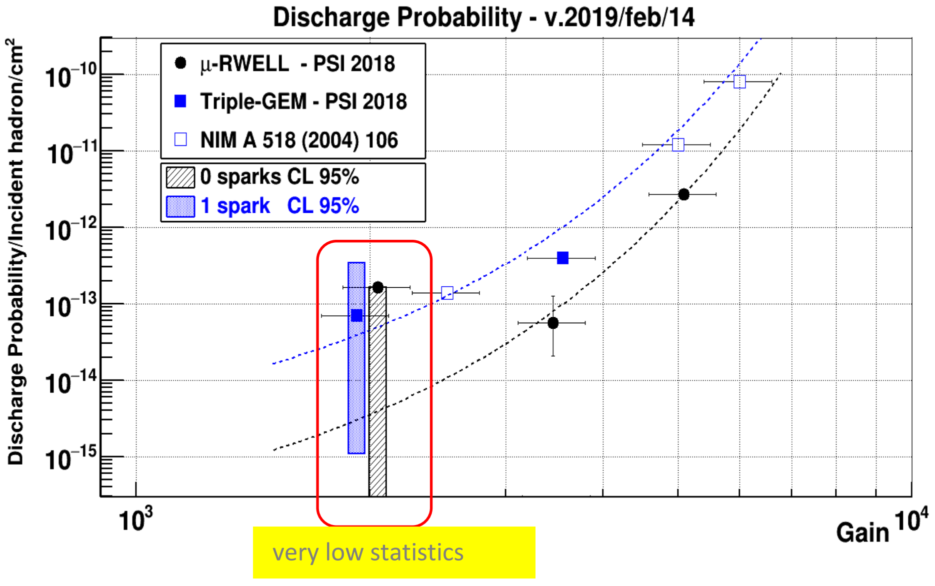


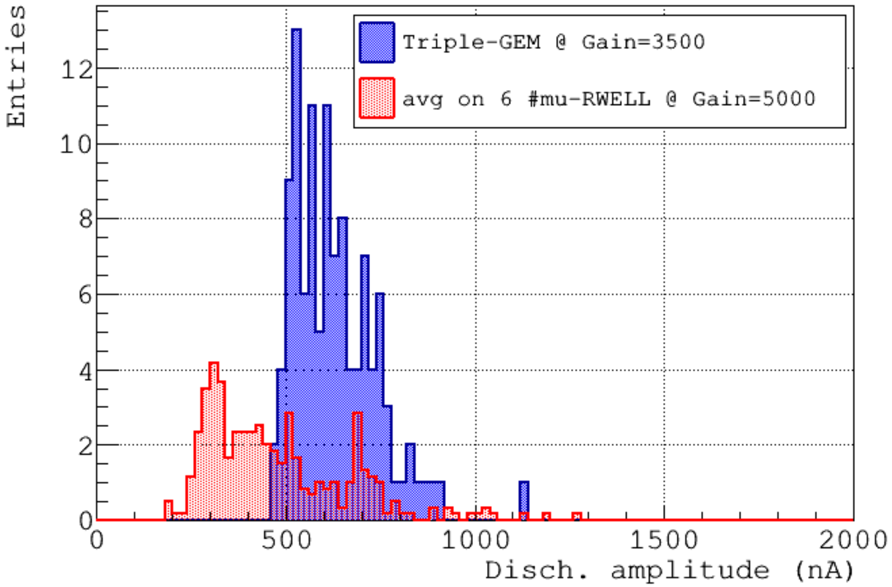
Discharge studies – uRWELL Vs Triple-GEM

The discharge probability measured @ PSI and compared with the measurement done with GEM at the same time and in the 2004 (*same gas mixture - $Ar:CO_2:CF_4$ = 45:15:40*).

Measurement conditions:

- current mode
- $p_{\pi+}$=270 MeV/c π^+ beam ⊕ 3.5% proton





A "discharge" defined as the current spike exceeding the steady current level correlated to the particle flux (~90 MHz on a ~5 cm^2 beam spot size).

The discharge probability for μ-RWELL comes out to be slightly lower than the one measured for GEM. While its discharge amplitude seems to be lower than the one measured for GEM.