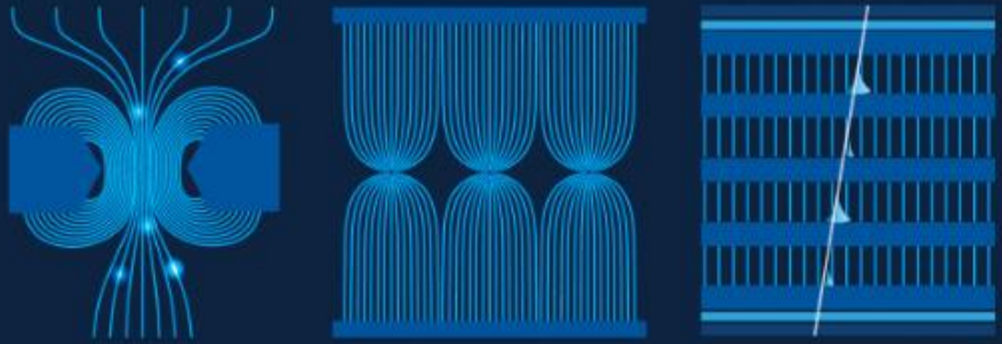


DRD1
Gaseous Detectors
School
CERN
November 27 - December 6, 2024

Micro Pattern Gaseous Detectors

Esther Ferrer Ribas
CEA/IRFU

Outline

Birth of Micro Pattern Gaseous Detectors (MPGD)

Gas Electron Multipliers

Micromegas

Micro Resistive Well

Applications

Birth of Micro Pattern Gaseous Detectors

In the 90's advances in microelectronics and photolithographic technology on flexible and standard PCB substrates favored the invention

Pitch size of a few hundred microns, an order of magnitude improvement in granularity over wire chambers

First Micro Pattern Gaseous Detector (MPGD): Micro-strip Gas Counter (MSGC) Oed, 1988

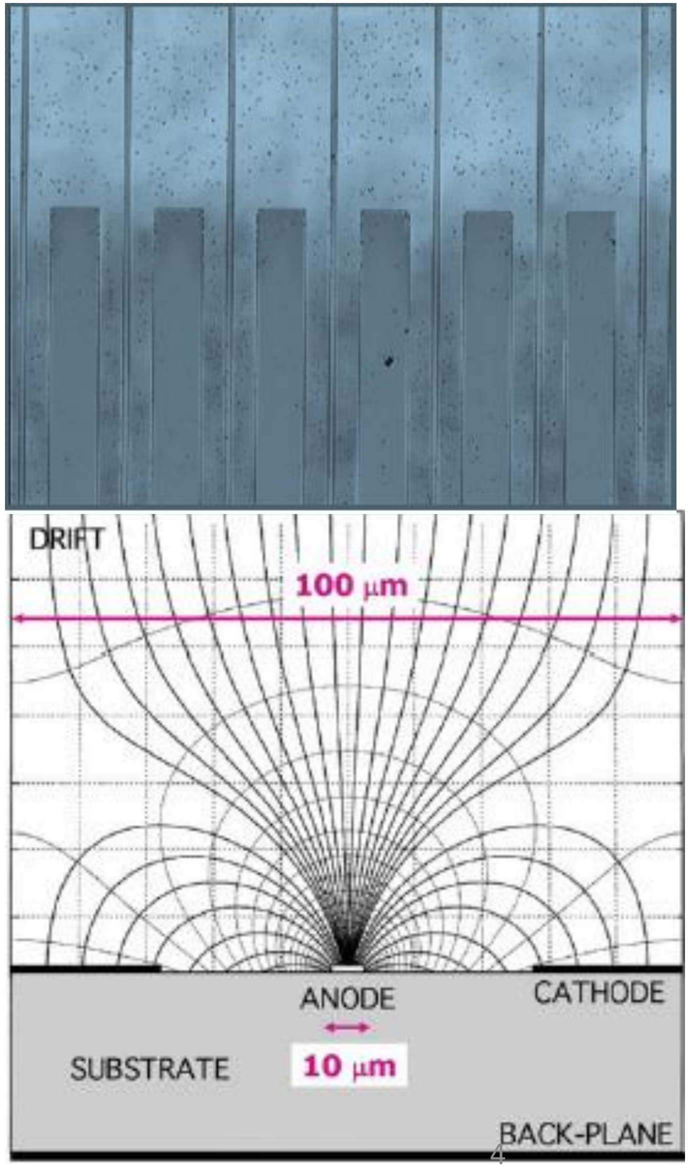
MSGC

Performance

- Intrinsic high-rate capability (>10^6 Hz/mm^2),
- excellent spatial resolution (down to 30 µm),
- multiparticle resolution (~500 µm),
- single photo-electron time resolution in the ns-range,
- large sensitive area and dynamic range.

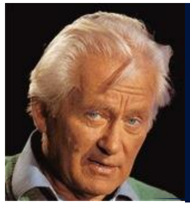
Limitations:

- Destructive sparks,
- time-dependent gain shifts (substrate polarization and charging up),
- deterioration during sustained irradiation (“aging”).

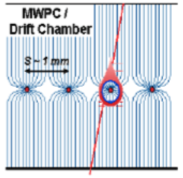


Credit: Sauli « Gaseous Radiation Detectors »

Birth of MPGD

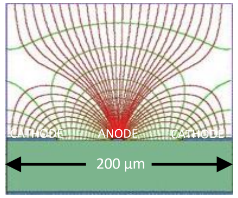


MWPC
Multi-Wire Proportional Chamber
G. Charpak et al., 1968

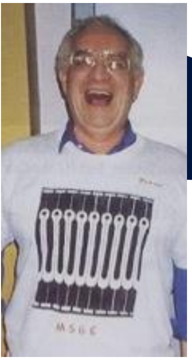


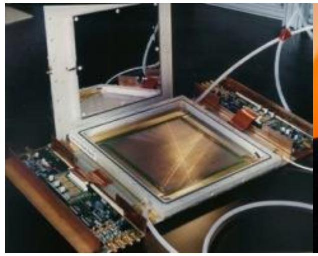
TPC
Time Projection Chamber
D. R. Nygren et al., 1974

MPGD



MSGC
Micro-Strip Gas Chamber
A. Oed, 1988

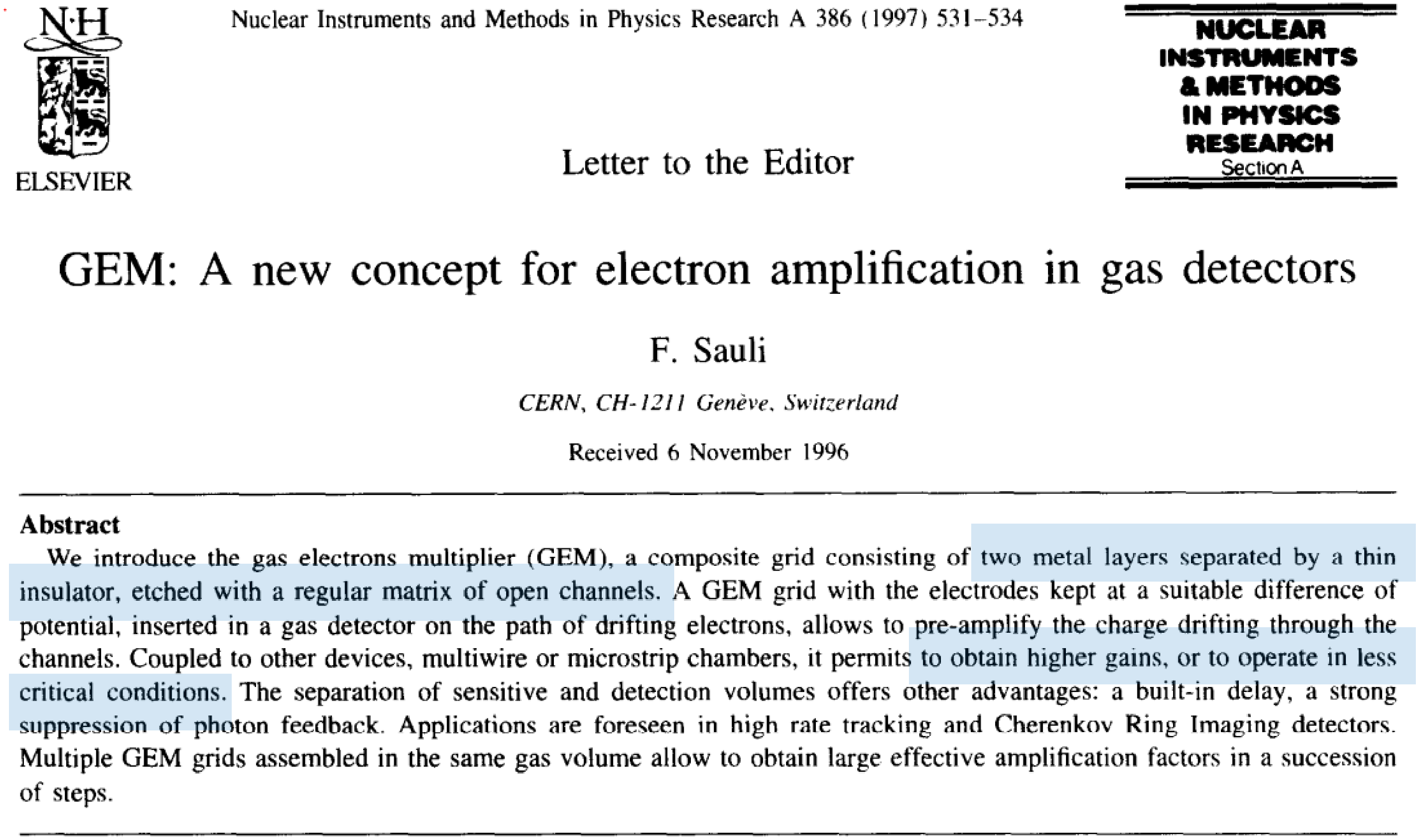




MICROMEGAS
MICRO-MEsh GAseous Structure
I. Giomataris et al., 1996

GEM
Gas Electron Multiplier
F. Sauli, 1997

Gas Electron Multiplier (GEM)



N·H
ELSEVIER

Nuclear Instruments and Methods in Physics Research A 386 (1997) 531–534

NUCLEAR
INSTRUMENTS
& METHODS
IN PHYSICS
RESEARCH
Section A

Letter to the Editor

GEM: A new concept for electron amplification in gas detectors

F. Sauli

CERN, CH-1211 Genève, Switzerland

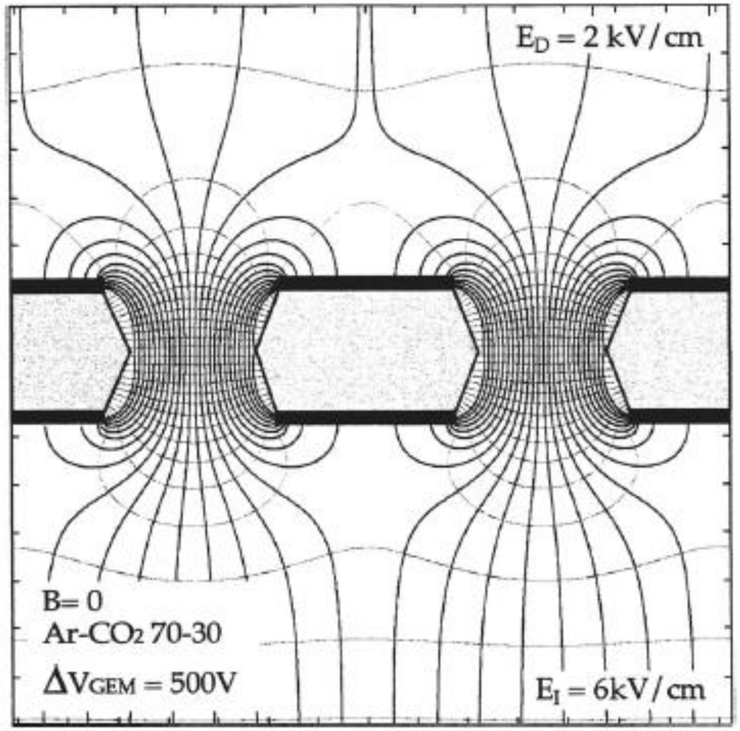
Received 6 November 1996

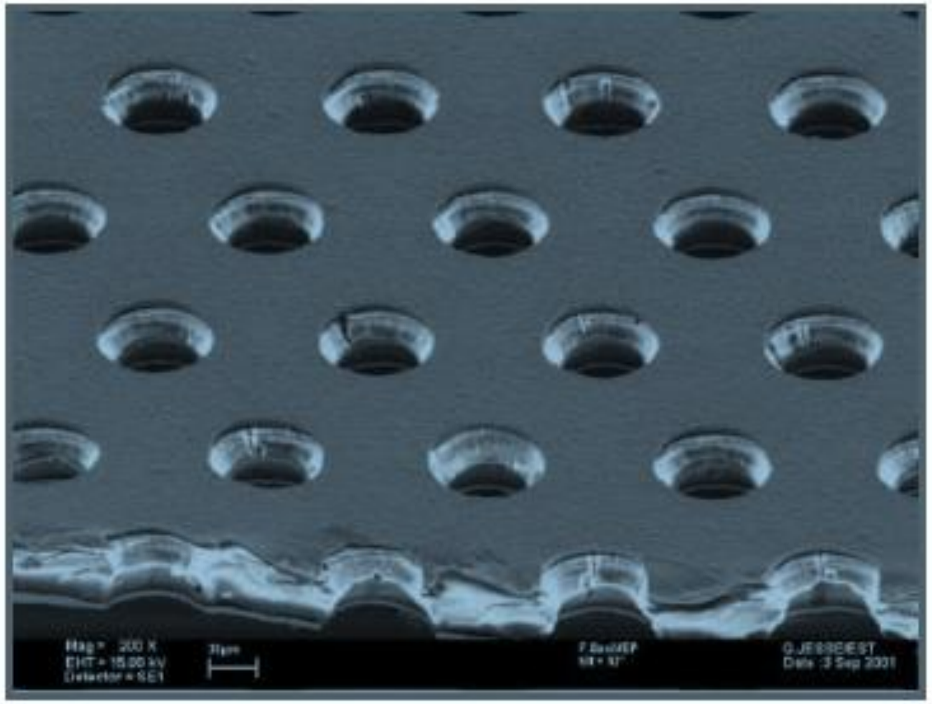
Abstract

We introduce the gas electrons multiplier (GEM), a composite grid consisting of two metal layers separated by a thin insulator, etched with a regular matrix of open channels. A GEM grid with the electrodes kept at a suitable difference of potential, inserted in a gas detector on the path of drifting electrons, allows to pre-amplify the charge drifting through the channels. Coupled to other devices, multiwire or microstrip chambers, it permits to obtain higher gains, or to operate in less critical conditions. The separation of sensitive and detection volumes offers other advantages: a built-in delay, a strong suppression of photon feedback. Applications are foreseen in high rate tracking and Cherenkov Ring Imaging detectors. Multiple GEM grids assembled in the same gas volume allow to obtain large effective amplification factors in a succession of steps.

GEM

A thin, metal-clad polymer foil chemically perforated by a high density of holes, typically 100/mm^2





Large ΔV between the two sides of the foil creates a high field
Electrons released in the upper region, drift towards the holes acquiring enough energy to provoke ionisations
Large fraction of electrons are transferred into the lower section

GEM

Full decoupling of amplification stage (GEM) and readout stage (PCB, anode)

Amplification and readout structures can be optimized independently

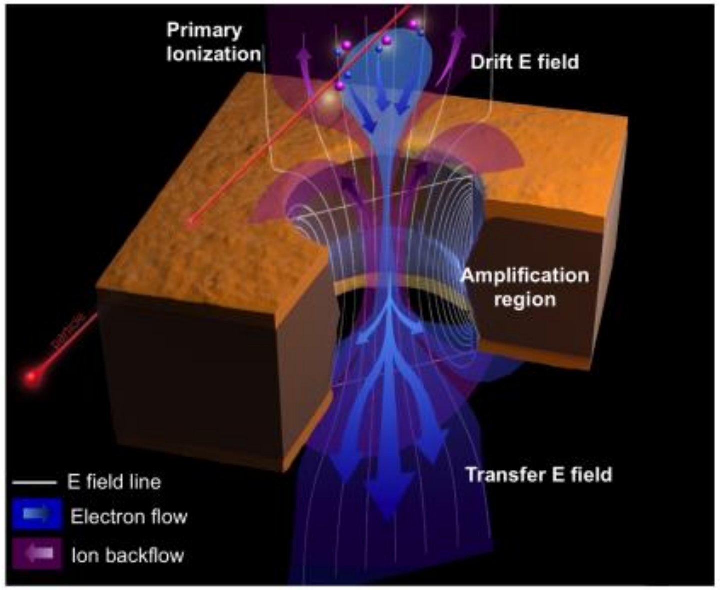


FIGURE 4.24: Schematic representation of a GEM hole in operation.

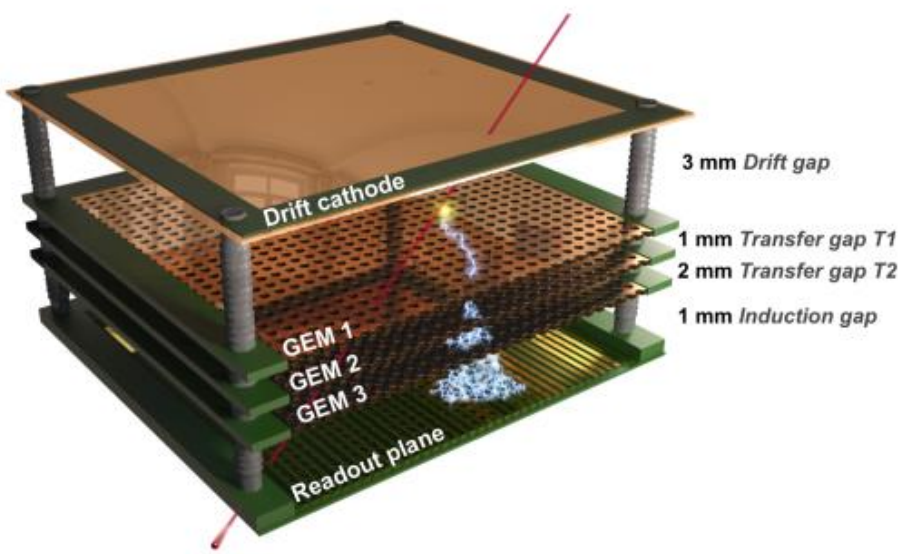
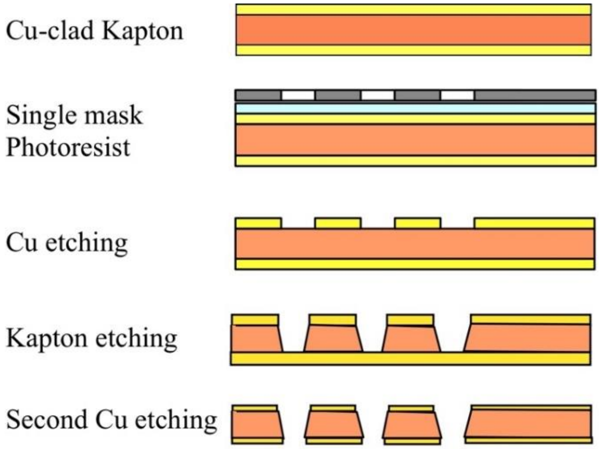


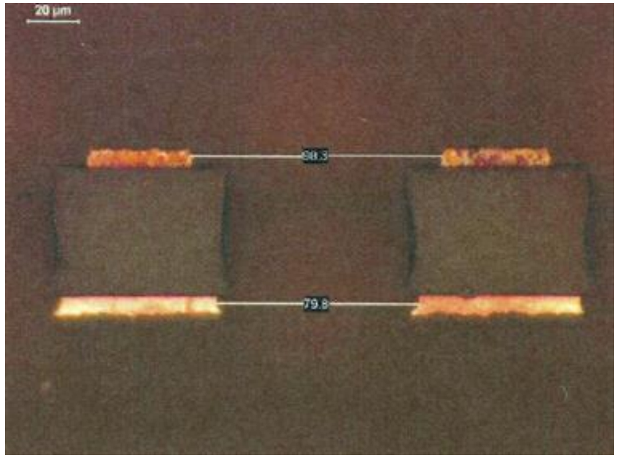
FIGURE 4.27: Schematic view of a triple-GEM detector.

"Study of long-term sustained operation of gaseous detectors for the high rate environment in CMS", J. Merlin, CERN PHD theses, https://cds.cern.ch/record/2155685/files/CERN-THESIS-2016-041.pdf

Manufacturing of GEM: single mask

Large size detectors



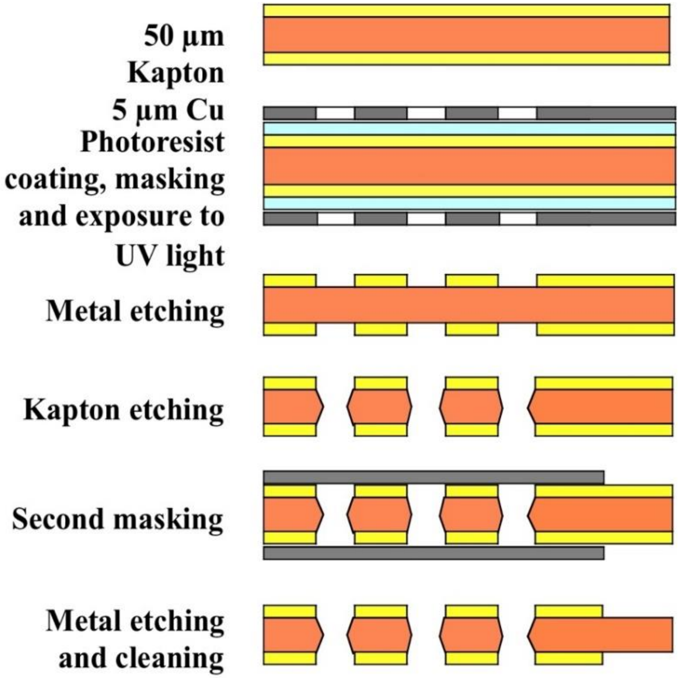


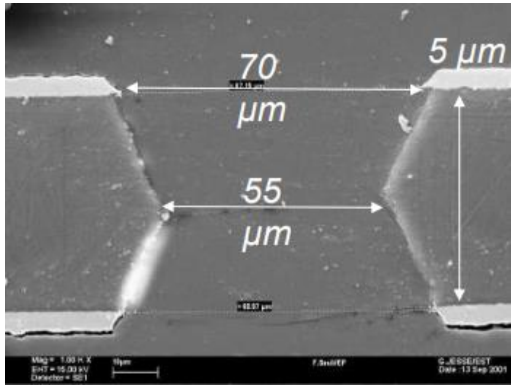
« MPGD manufacturing » by Rui de Oliveira on 3/12

From F. Sauli RD51 school 2023

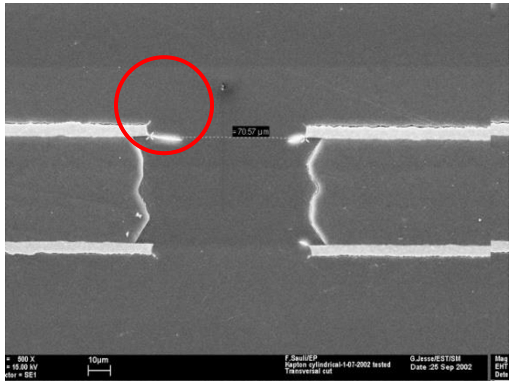
Manufacturing of GEM: double mask

From F. Sauli RD51 school 2023

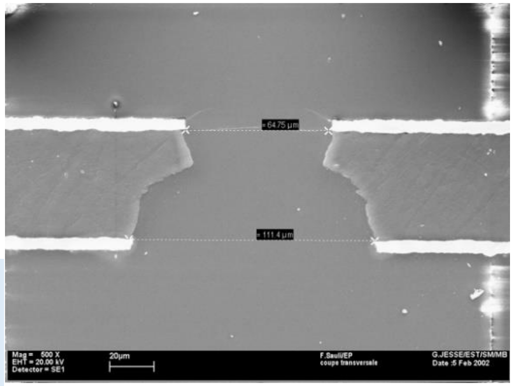




STANDARD
Double-Conical
Hourglass



CYLINDRICAL

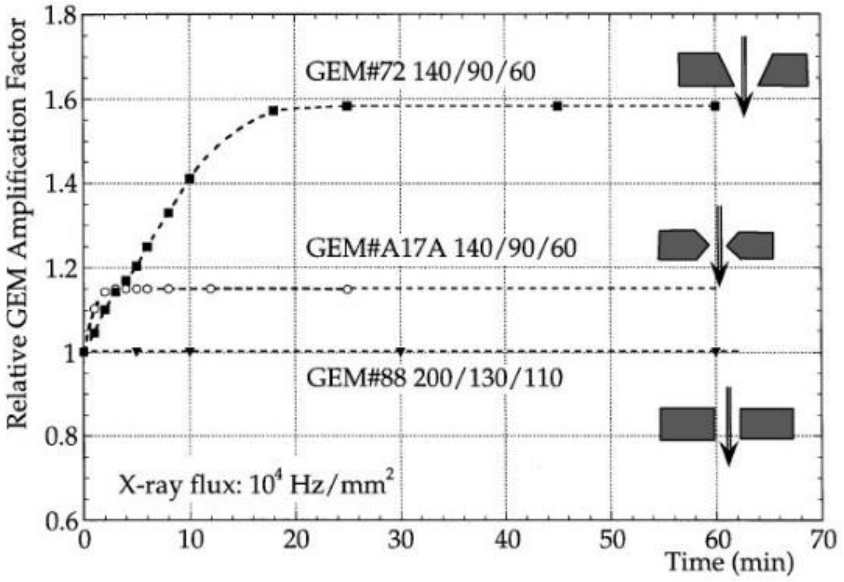


CONICAL

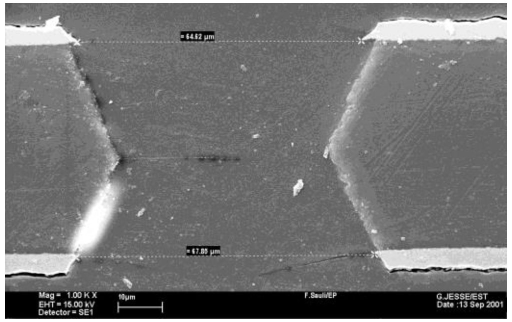
« MPGD manufacturing » by Rui de Oliveira on 3/12

Manufacturing of GEM: double mask

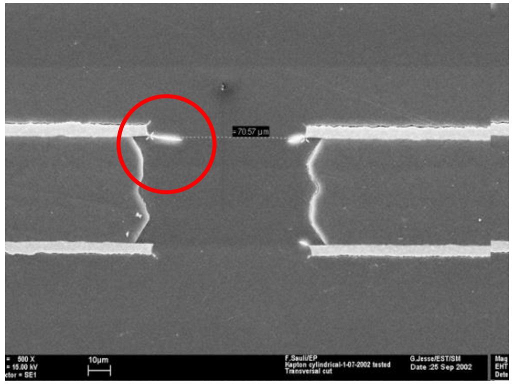
- **Shape of the holes influence performance**
- **Trade off: high gains/charging up effects**
- Standard: patch for discharge longer/reaching higher gains but more insulator so more charging up



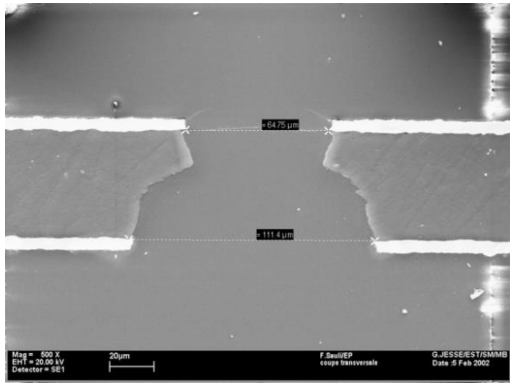
From F. Sauli RD51 school 2023



STANDARD
Double-Conical
Hourglass

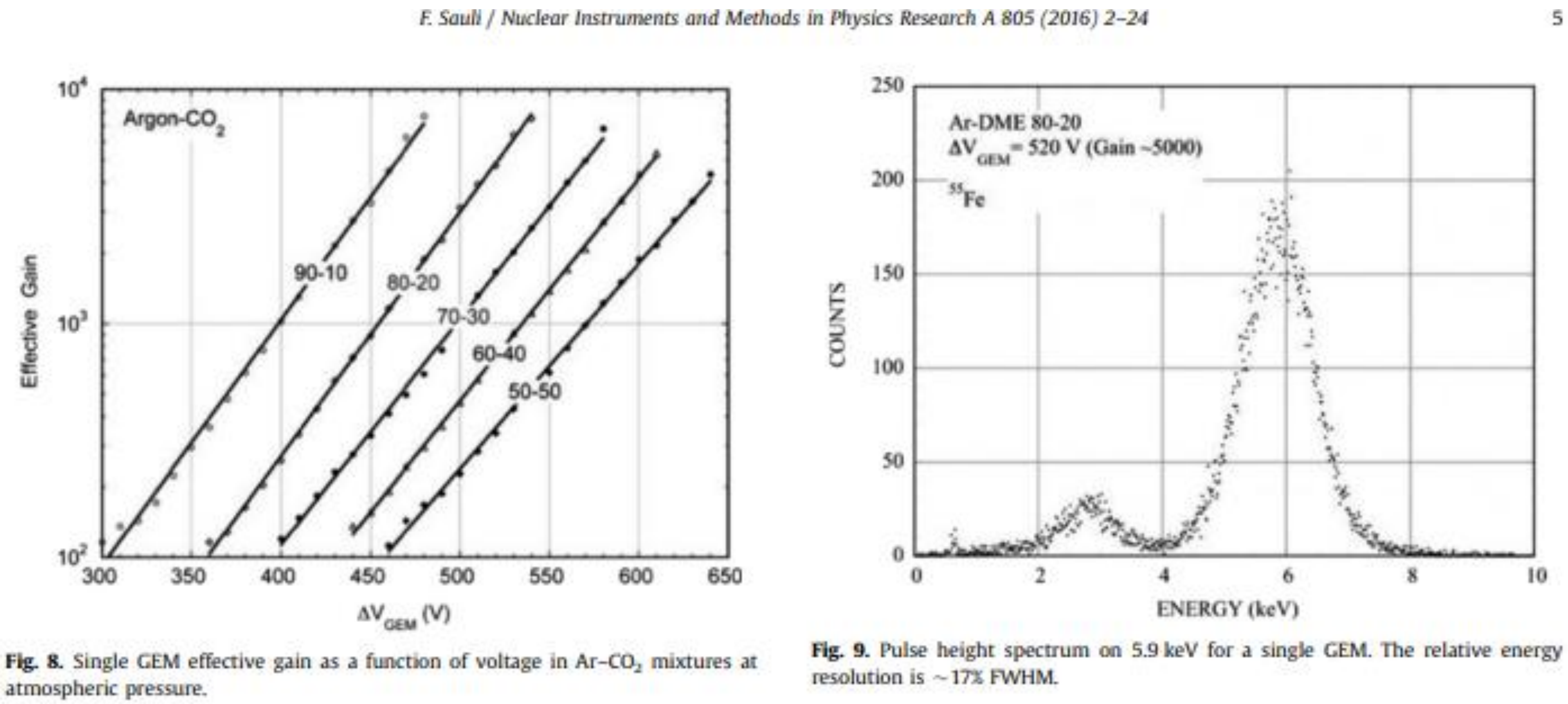


CYLINDRICAL



CONICAL

Performance in single GEM



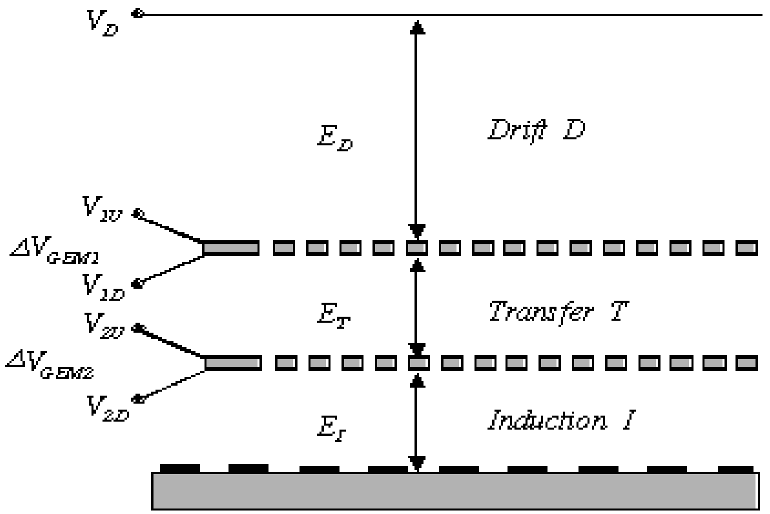
F. Sauli / Nuclear Instruments and Methods in Physics Research A 805 (2016) 2–24 5

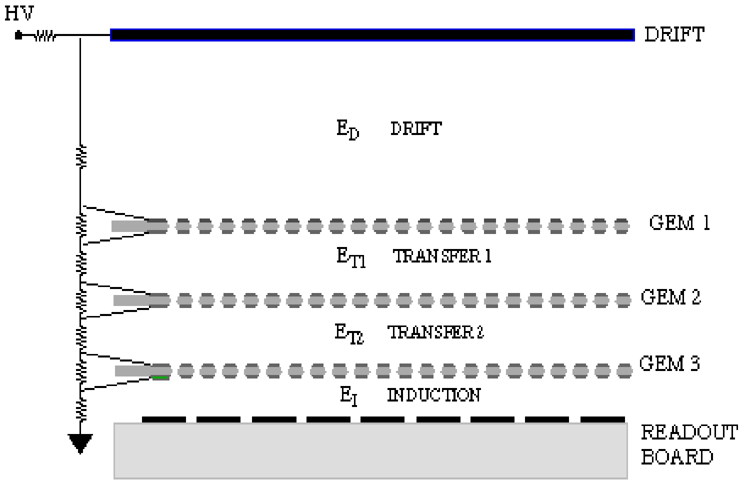
Fig. 8. Single GEM effective gain as a function of voltage in Ar–CO$_2$ mixtures at atmospheric pressure.

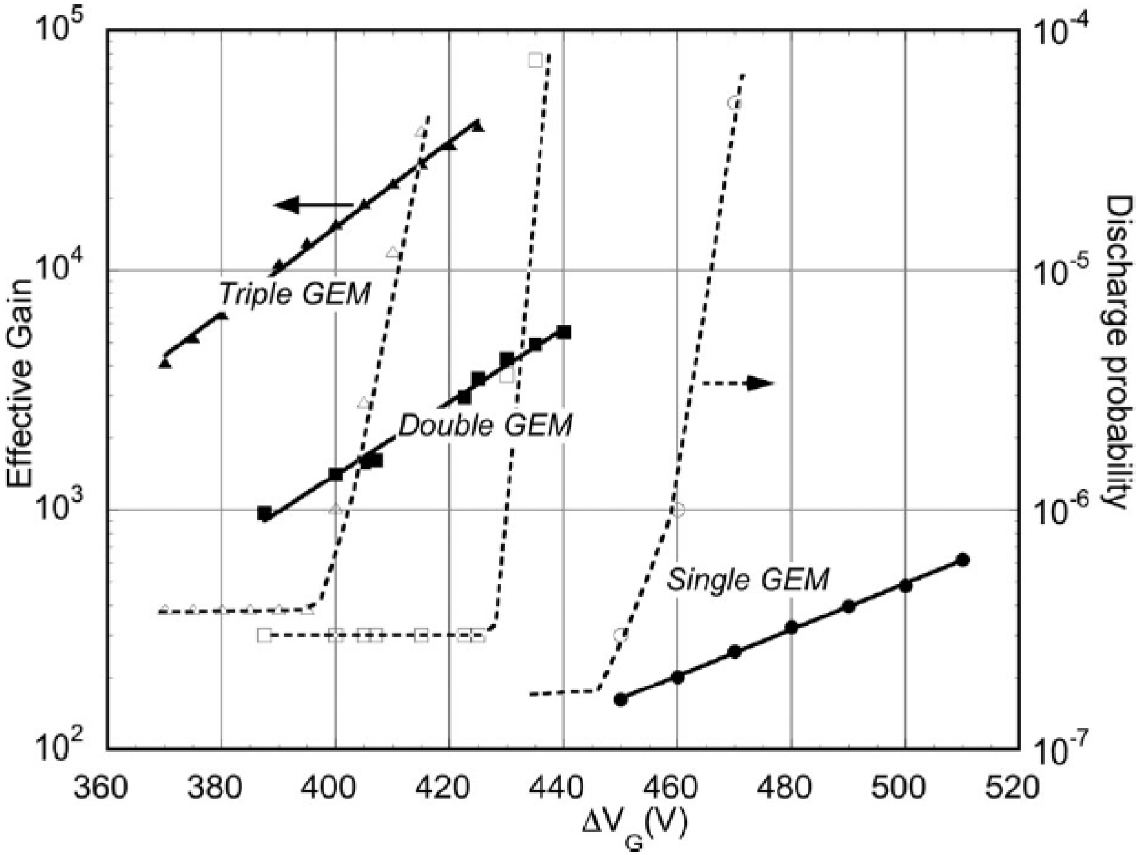
Fig. 9. Pulse height spectrum on 5.9 keV for a single GEM. The relative energy resolution is ~17% FWHM.

Multi-GEM

Cascade of GEM electrodes
Allows attaining higher gain with each GEM at lower voltage
Discharges disfavoured

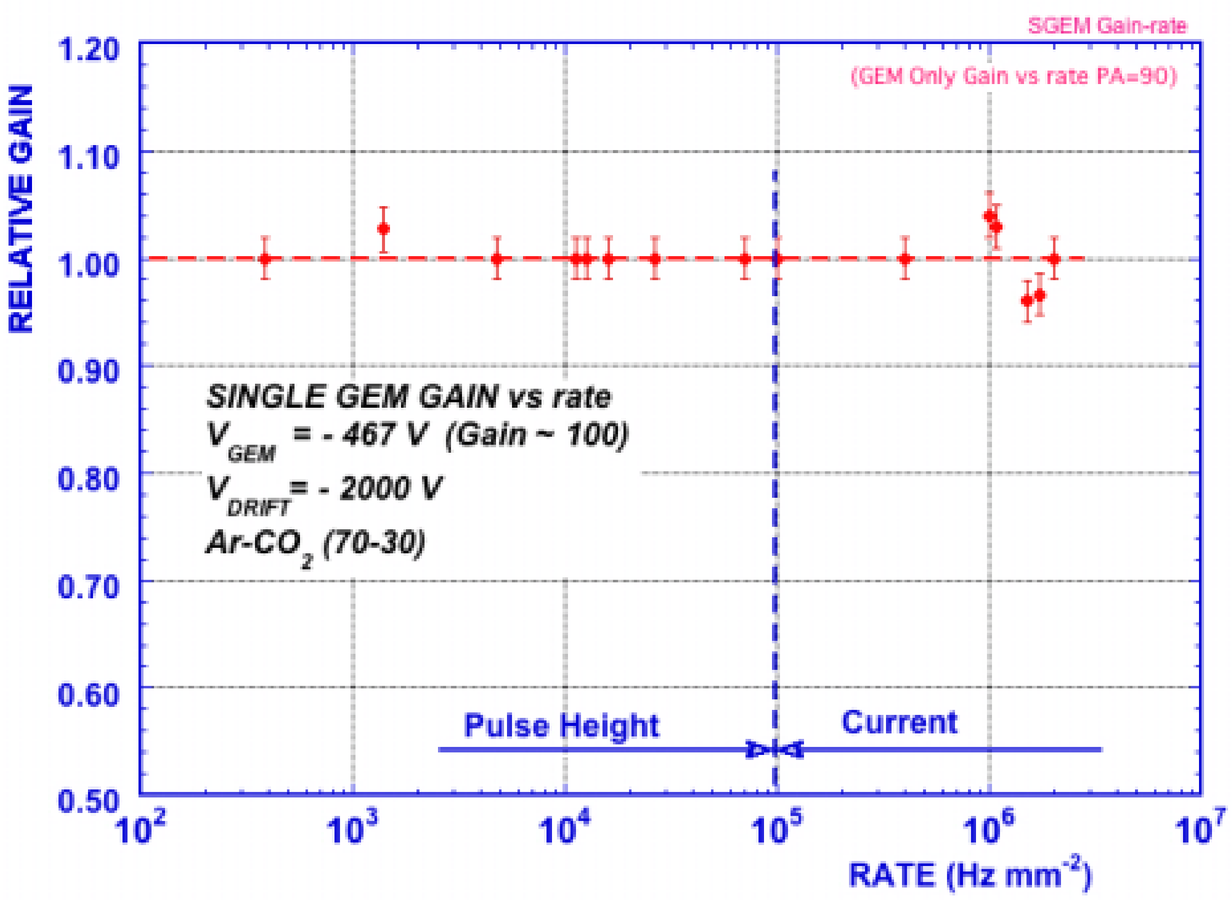






S. Bachmann et al, Nucl. Instr. and Meth. A479 (2002)294

GEM Rate capability



5.9 keV X-rays:
> 2.10^6 mm^{-2}

J. Benlloch et al, IEEE NS-45(1998)234

GEM spatial resolution

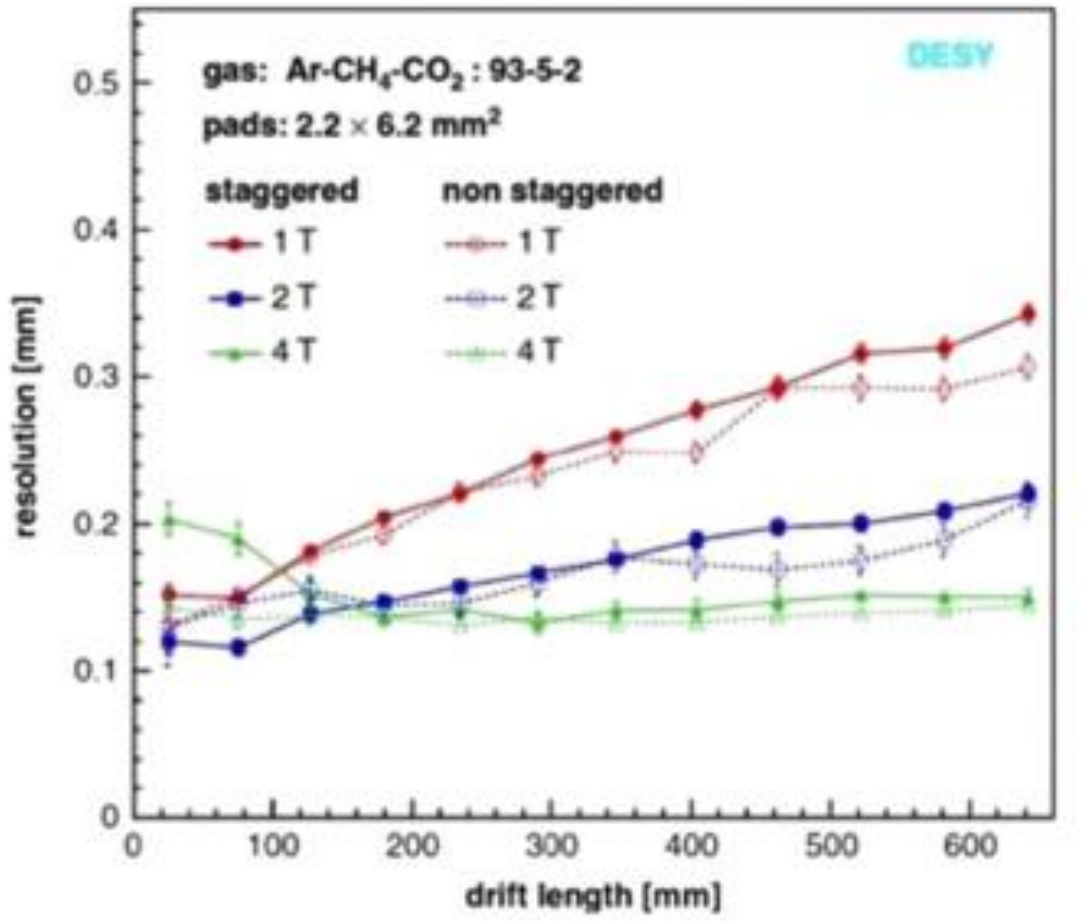
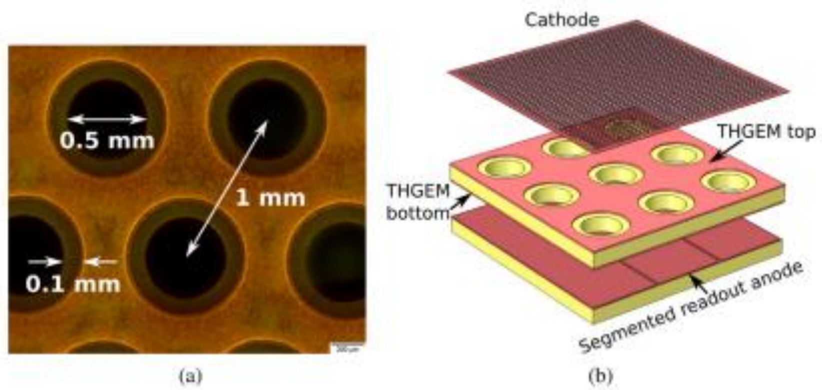


Fig. 46. GEM-TPC longitudinal resolution as a function of drift length and magnetic field.

F. Sauli, NIM A 805 (2016) 2-24

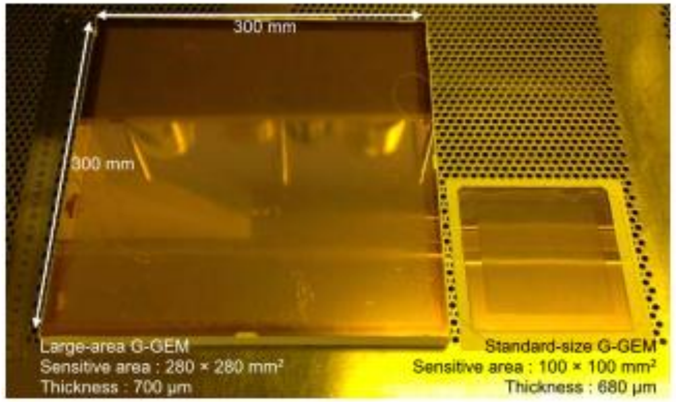
GEM family

THICKGEM/LEM



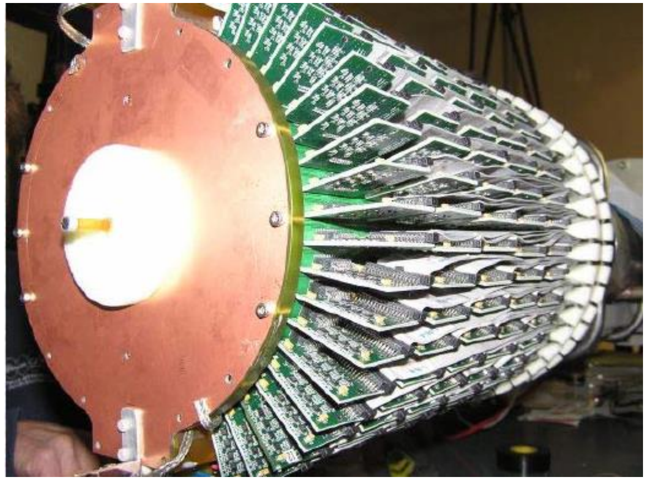
S. Bressler et al. , Progress Particle and Nuclear Physics 130 (2023) 104029

GLASSGEM

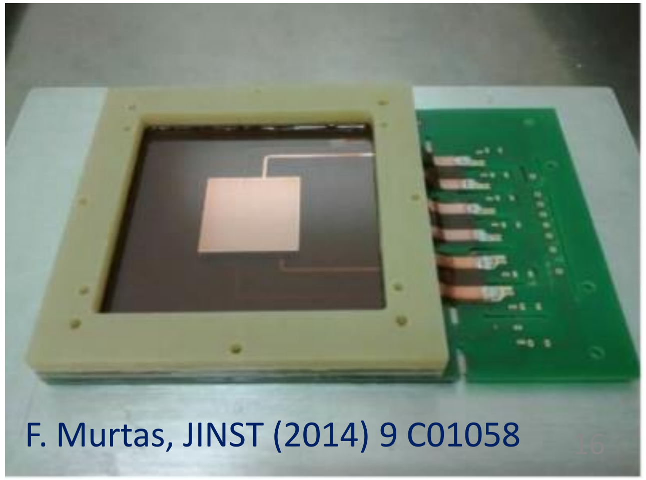


Y. Mitsuya et al., NIM A 795 (2015) 156-159

Cylindrical GEM

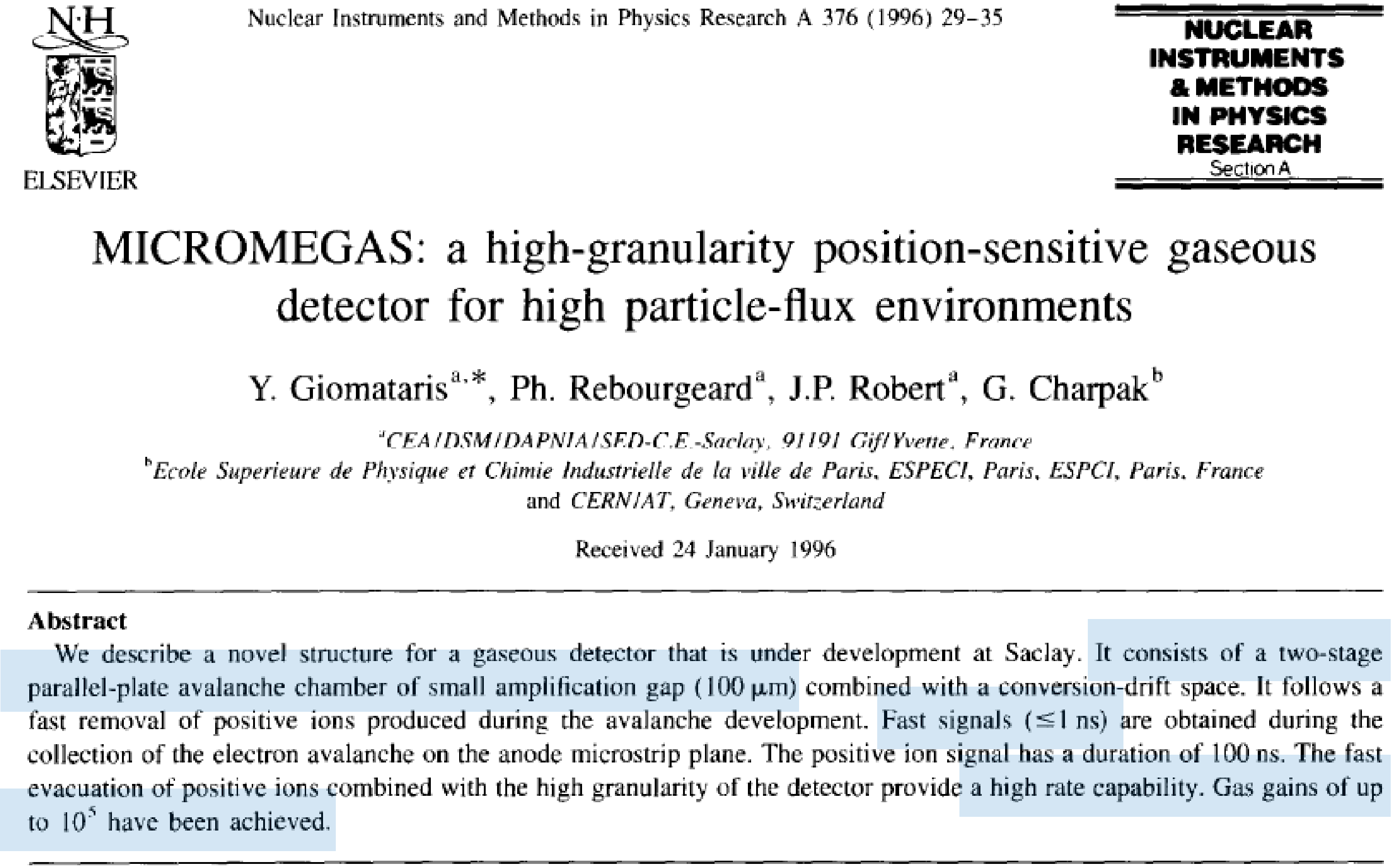


GEMPix: a triple GEM structure read by 50 micron pixels



F. Murtas, JINST (2014) 9 C01058

Micromegas



ELSEVIER

Nuclear Instruments and Methods in Physics Research A 376 (1996) 29–35

NUCLEAR INSTRUMENTS & METHODS IN PHYSICS RESEARCH
Section A

MICROMEGAS: a high-granularity position-sensitive gaseous detector for high particle-flux environments

Y. Giomataris[a,*], Ph. Rebourgeard[a], J.P. Robert[a], G. Charpak[b]

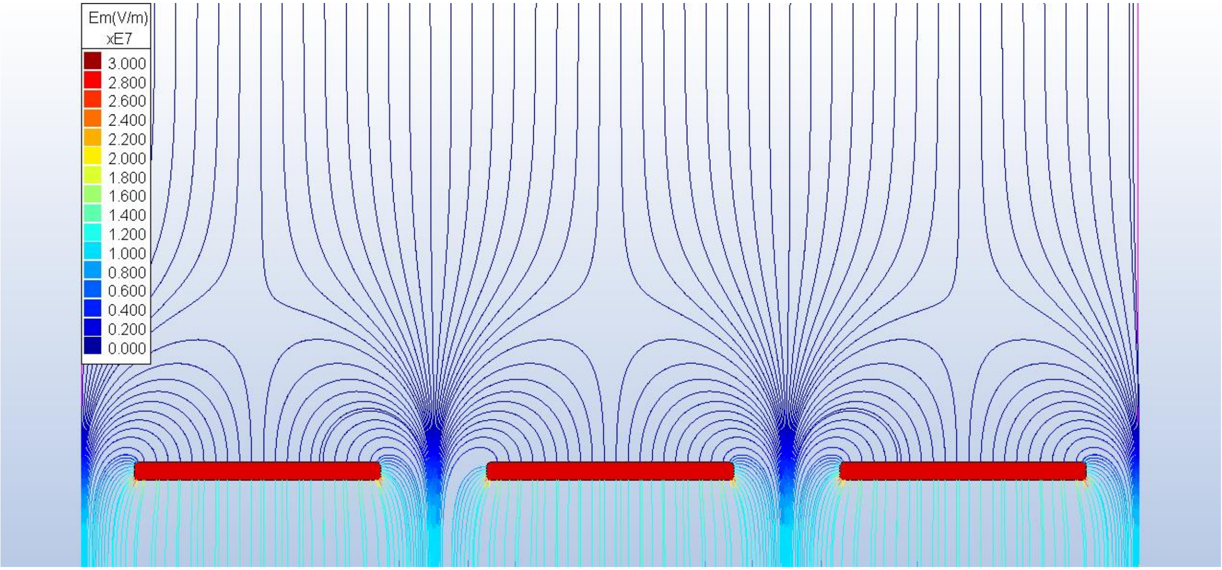
[a] *CEA/DSM/DAPNIA/SED-C.E.-Saclay, 91191 Gif/Yvette, France*
[b] *Ecole Superieure de Physique et Chimie Industrielle de la ville de Paris, ESPECI, Paris, ESPCI, Paris, France*
and *CERN/AT, Geneva, Switzerland*

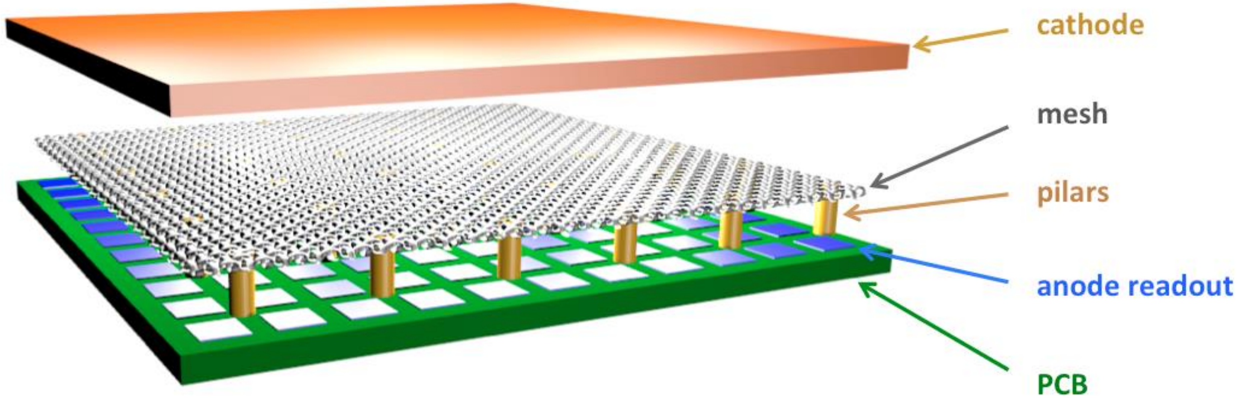
Received 24 January 1996

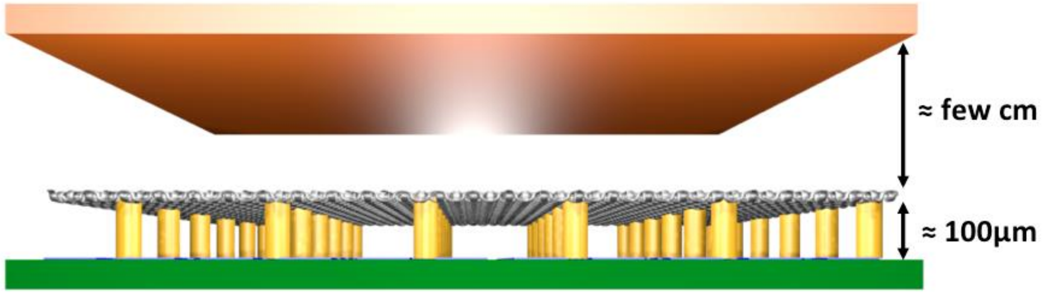
Abstract

We describe a novel structure for a gaseous detector that is under development at Saclay. It consists of a two-stage parallel-plate avalanche chamber of small amplification gap (100 µm) combined with a conversion-drift space. It follows a fast removal of positive ions produced during the avalanche development. Fast signals (≤ 1 ns) are obtained during the collection of the electron avalanche on the anode microstrip plane. The positive ion signal has a duration of 100 ns. The fast evacuation of positive ions combined with the high granularity of the detector provide a high rate capability. Gas gains of up to 10^5 have been achieved.

Micromegas


Em(V/m)
xE7
3.000
2.800
2.600
2.400
2.200
2.000
1.800
1.600
1.400
1.200
1.000
0.800
0.600
0.400
0.200
0.000


cathode
mesh
pilars
anode readout
PCB


≈ few cm
≈ 100µm

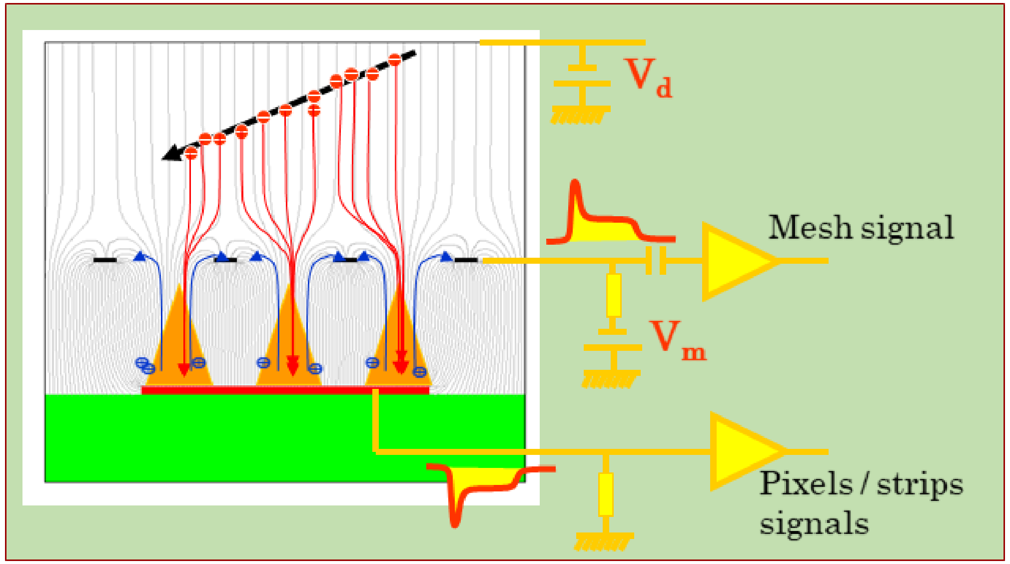
Micromegas

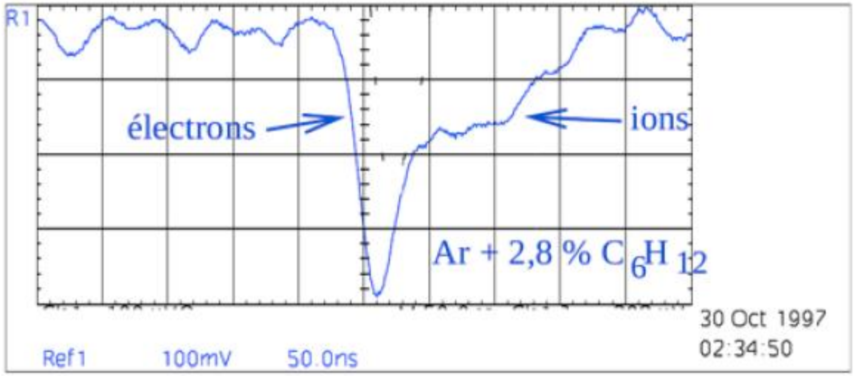
- Multiplication takes place in high E field (~ 40 kV/cm) between the anode and the mesh
  - High gain (up to 10^5 or more)
  - Single stage of amplification
    - Fast signals (< 1 ns)
    - Fast & natural ion collection
    - Low ion backflow to the drift region
    - Short recovery time (~150 ns)

      → High-rate capability (>MHz)

➔ Signal is induced by both electron & ion movement towards the anode / micromesh

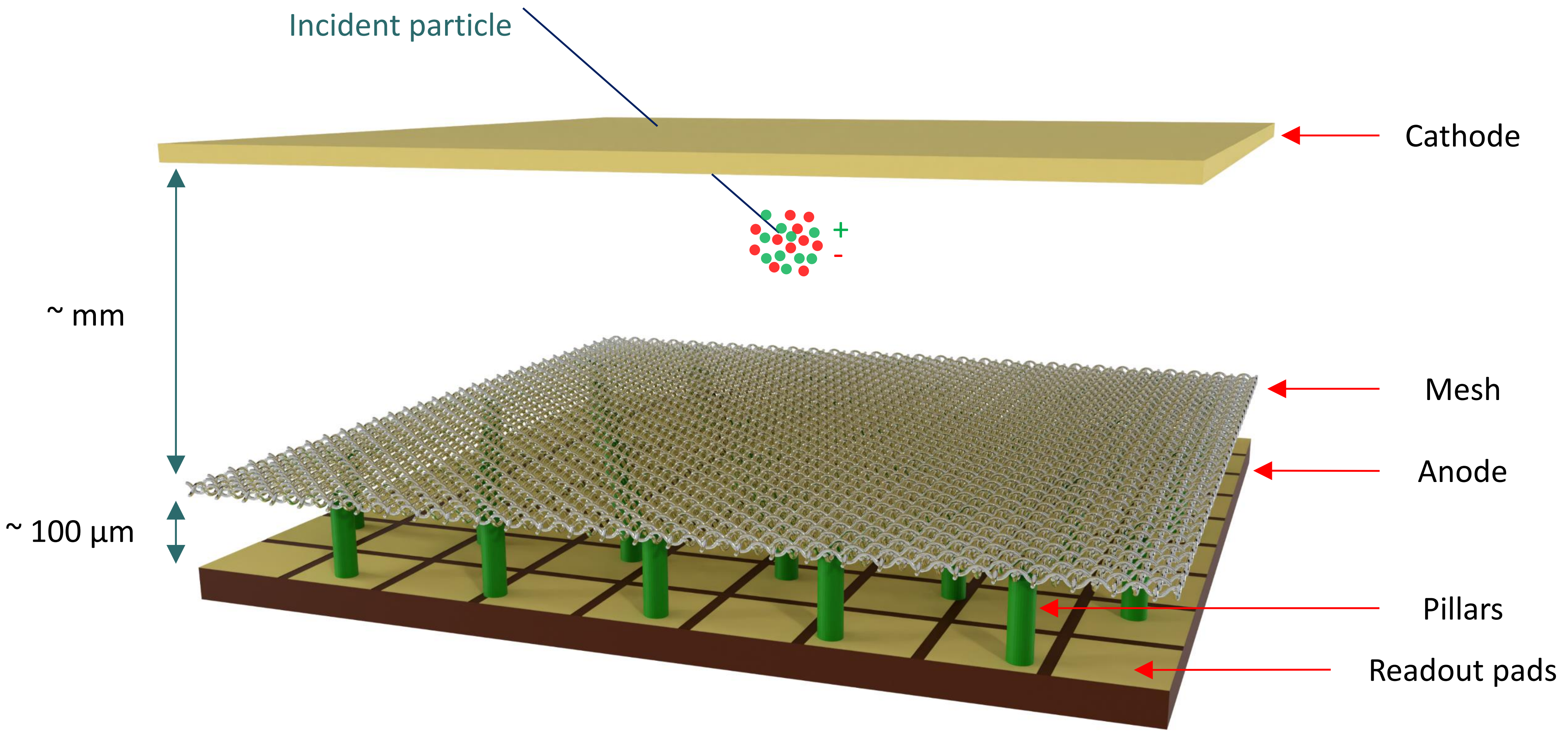
  - Thin amplification gap (50-150 µm) →
    - Small imperfections → no gain variations





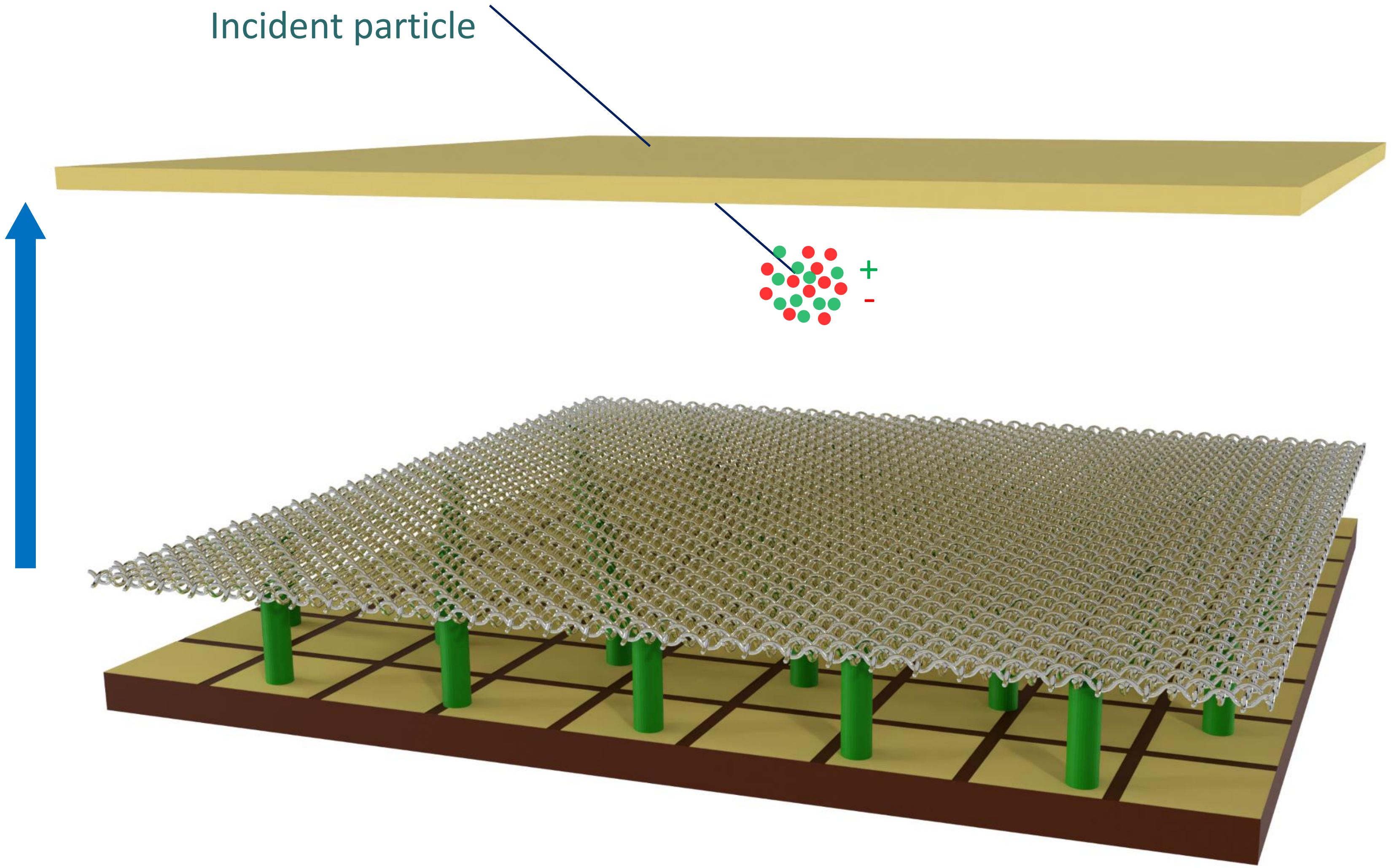
Micromegas

A. Cools PhD animation



Micromegas

A. Cools PhD animation

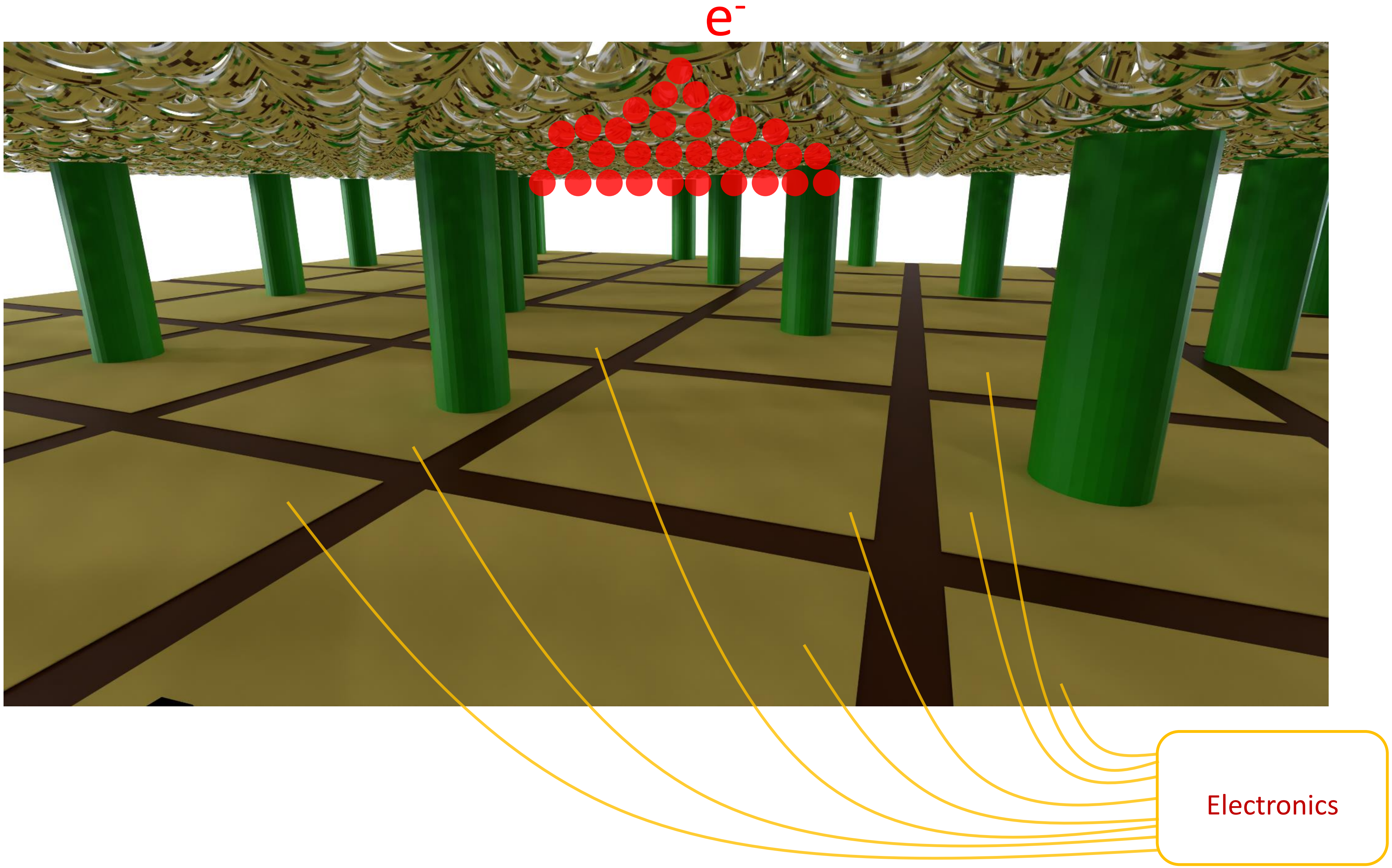


E ≈ 70 V/cm

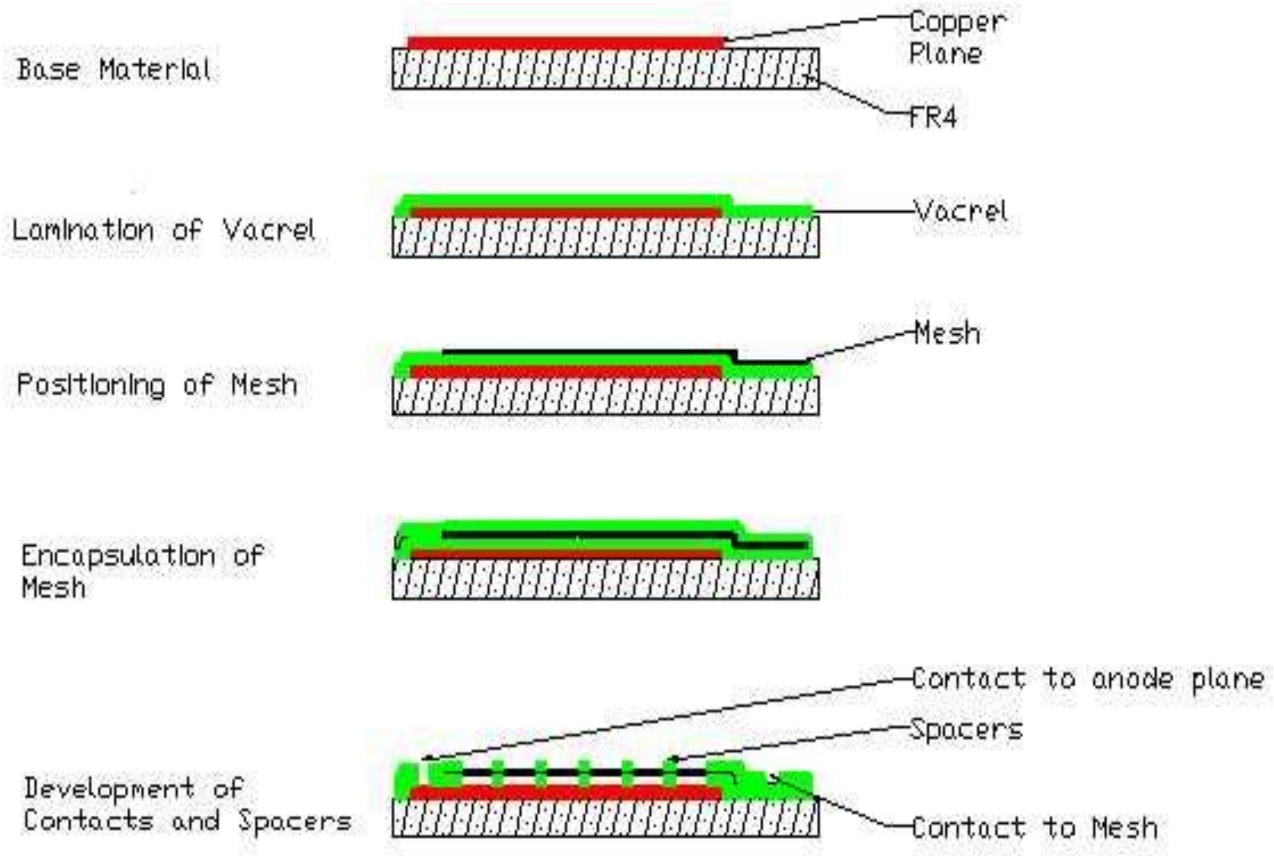
Micromegas

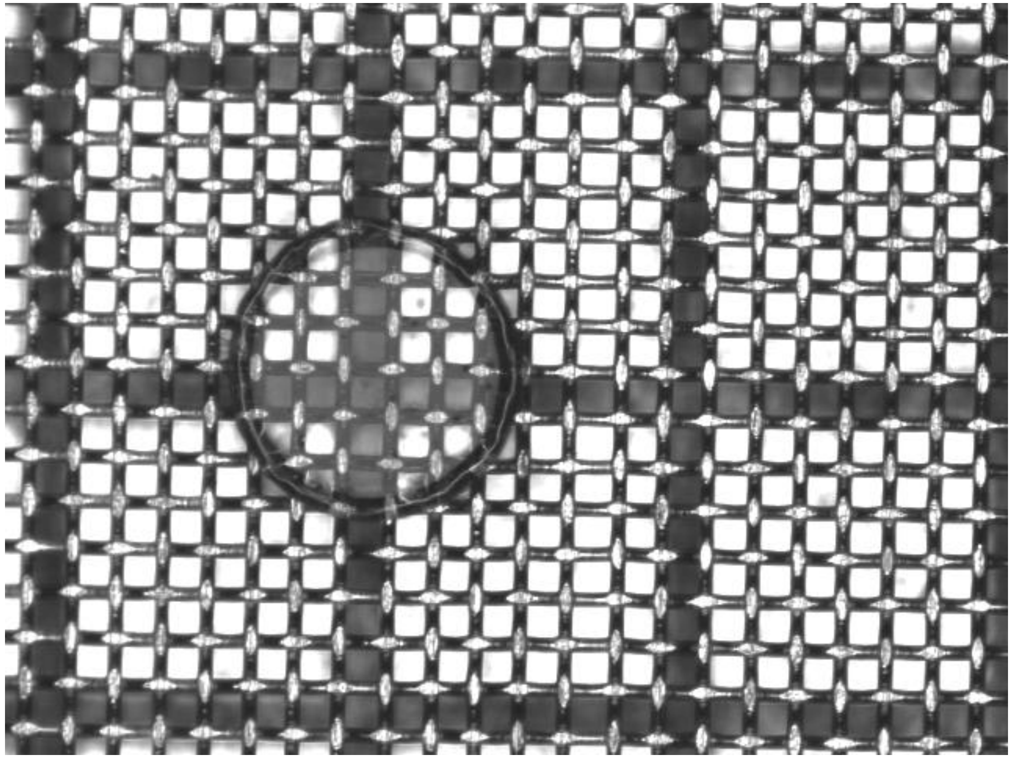
A. Cools PhD animation

E ≈ 50 kV/cm



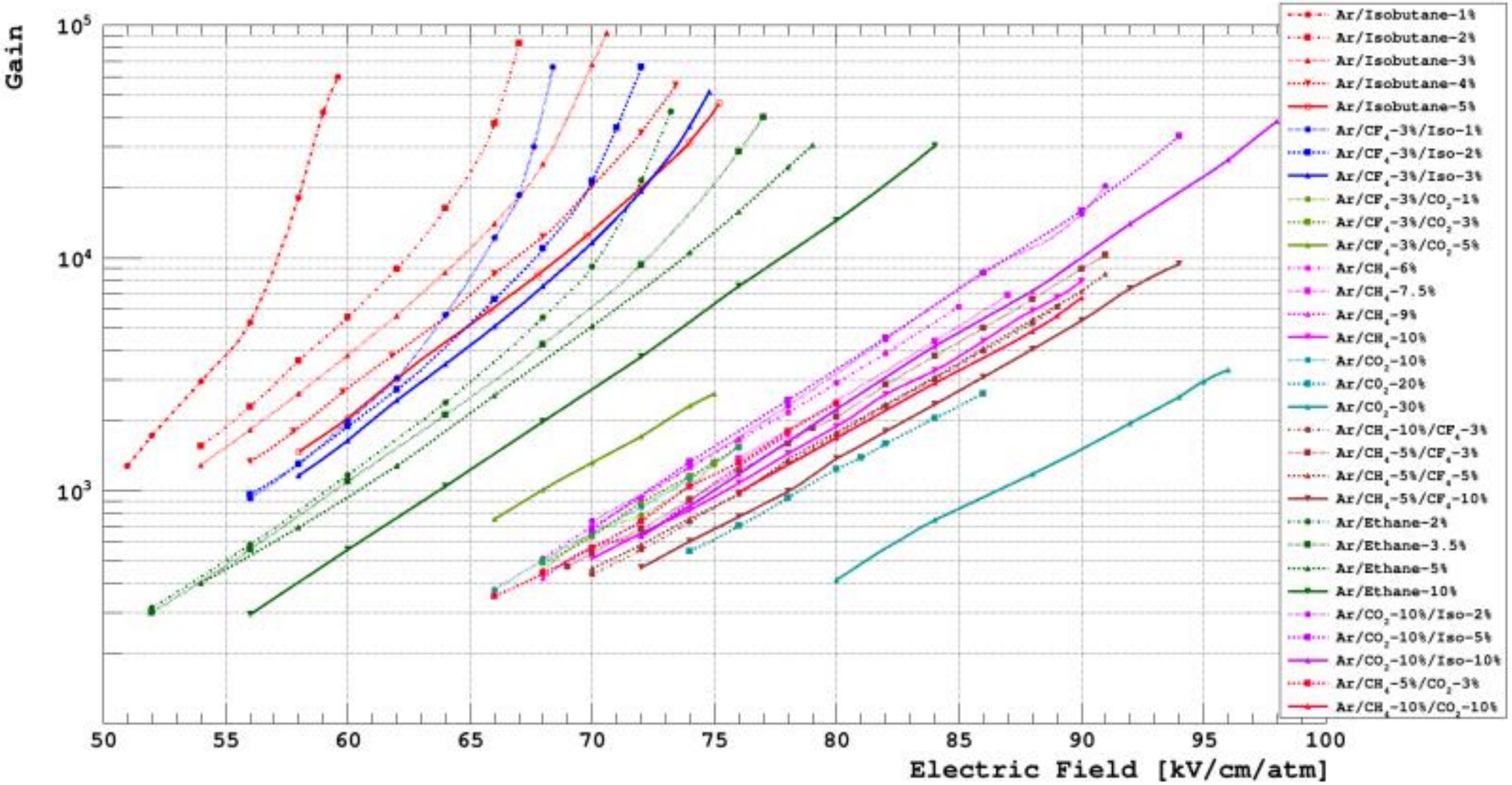
Manufacturing of Micromegas





I. Giomataris et al., NIM. A 560 (2006) 405-40

Micromegas Gain



David Attié, “Gaseous tracking detectors for academic and societal applications”, Habilitation à diriger des recherches, October 2022

Micromegas spatial resolution

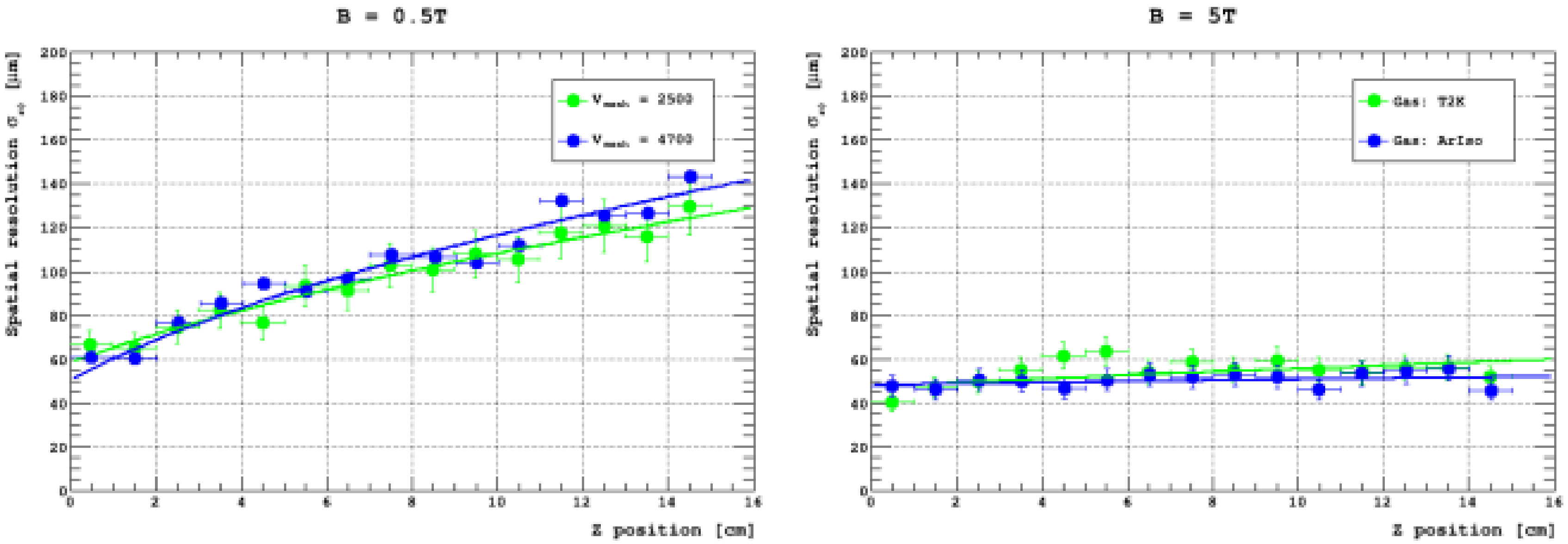
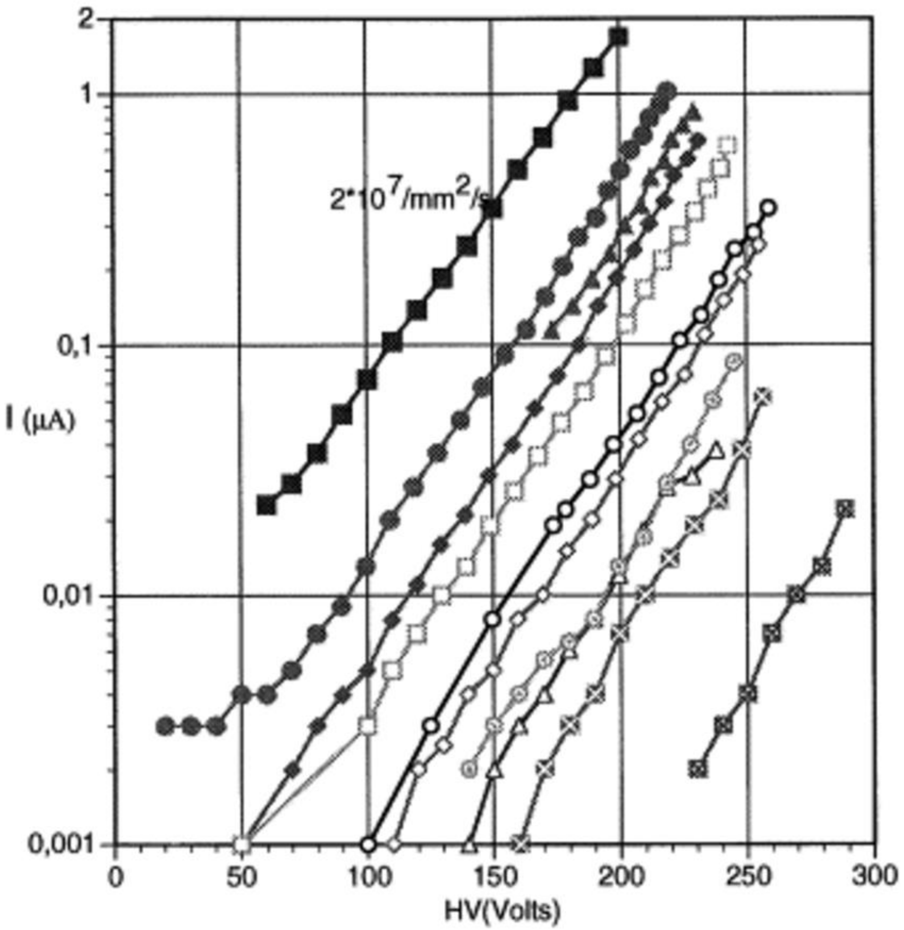


Figure 5.5: Spatial resolution $\sigma_{r\phi}$ using the Carleton TPC: [left] at 0.5 T in T2K gas mixture with two Micromegas gain 2500 and 4700 ; [right] at 5 T in Ar:Isobutane/95:5 and T2K gas mixtures

David Attié, “Gaseous tracking detectors for academic and societal applications”, Habilitation à diriger des recherches, Octobre 2022

Micromegas rate capability

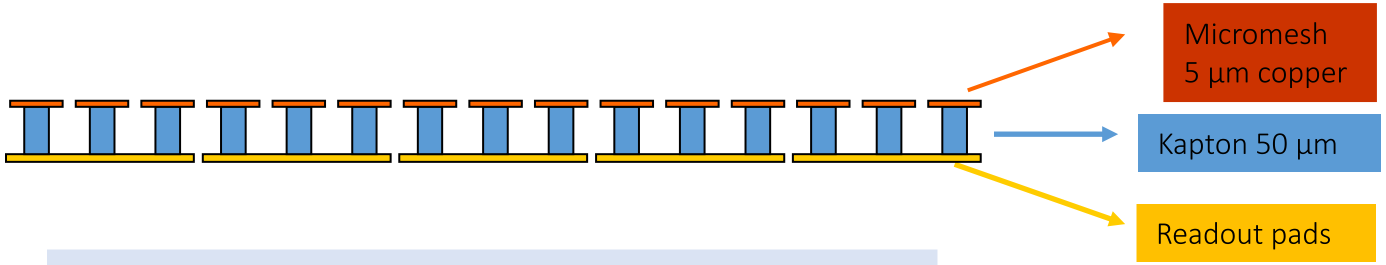


Current increases with the flux
All curves parallel
Gain independent of the rate
No saturation is observed

G. Charpak et al. NIMA 1998 412 47-60

10 MeV protons
Particle fluxes from 4×10^2 up to 2×10^7particles $mm^{-2}s^{-1}$
Ar + 5% isobutane

Microbulk

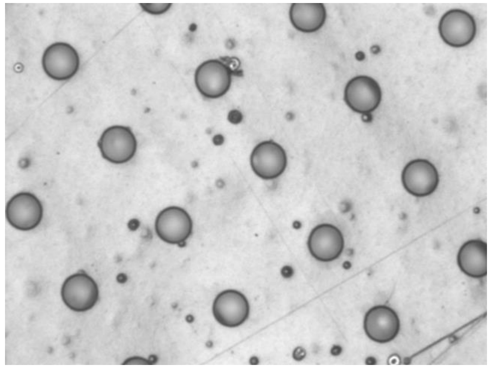

Micromesh
5 µm copper

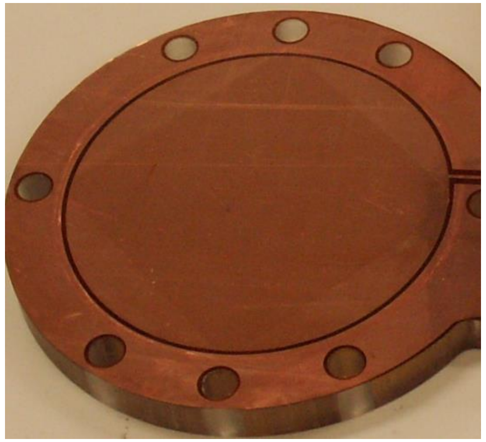
Kapton 50 µm

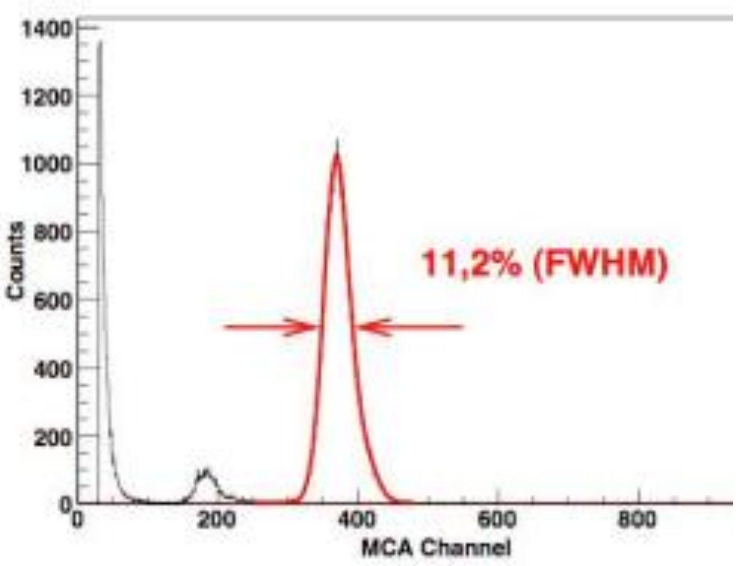
Readout pads

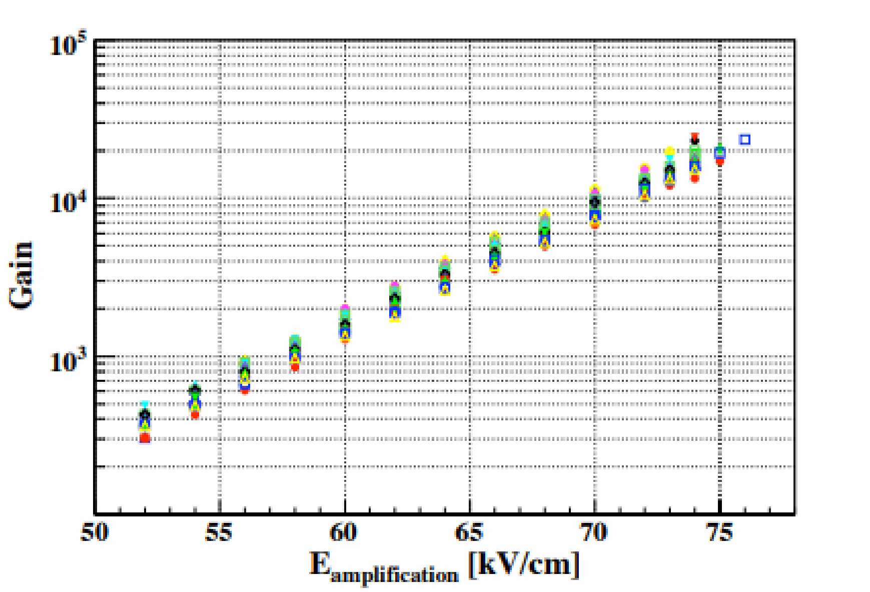
S. Andriamonje et al. JINST 2010 5 P02001

Pitch 100 µm,
Holes 30 µm









Resistive Micromegas

- Resistive coating:
  - Charge dispersion
  - Spark protection

A. Bellerive et al., eConf C050318 (2005) 0829

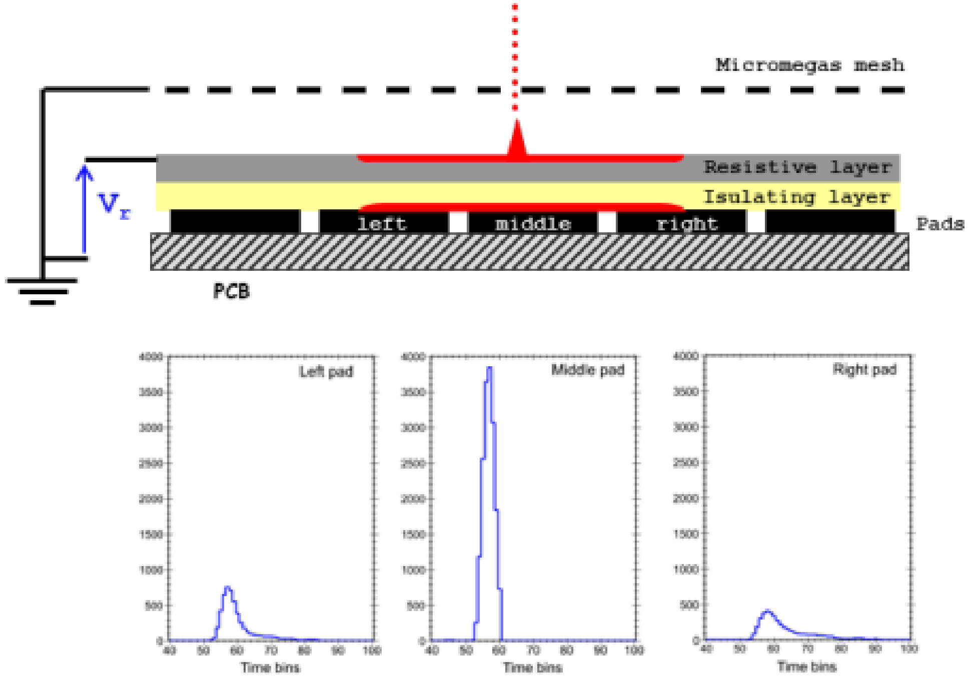
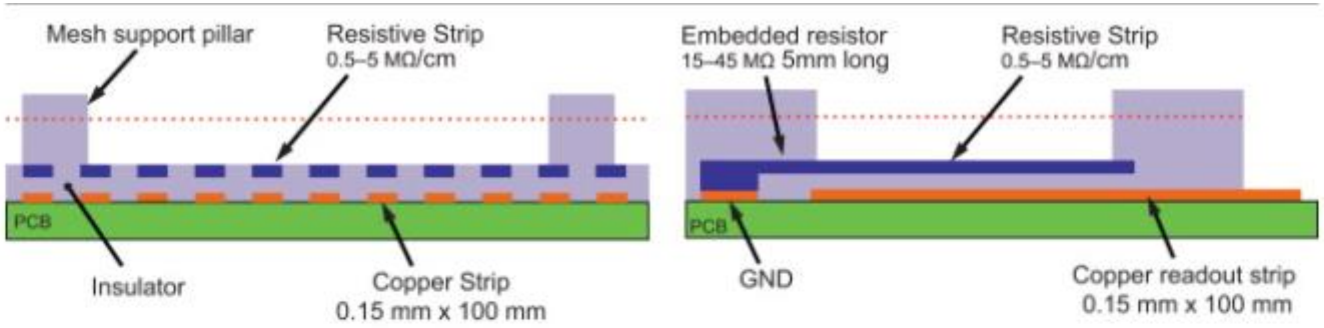
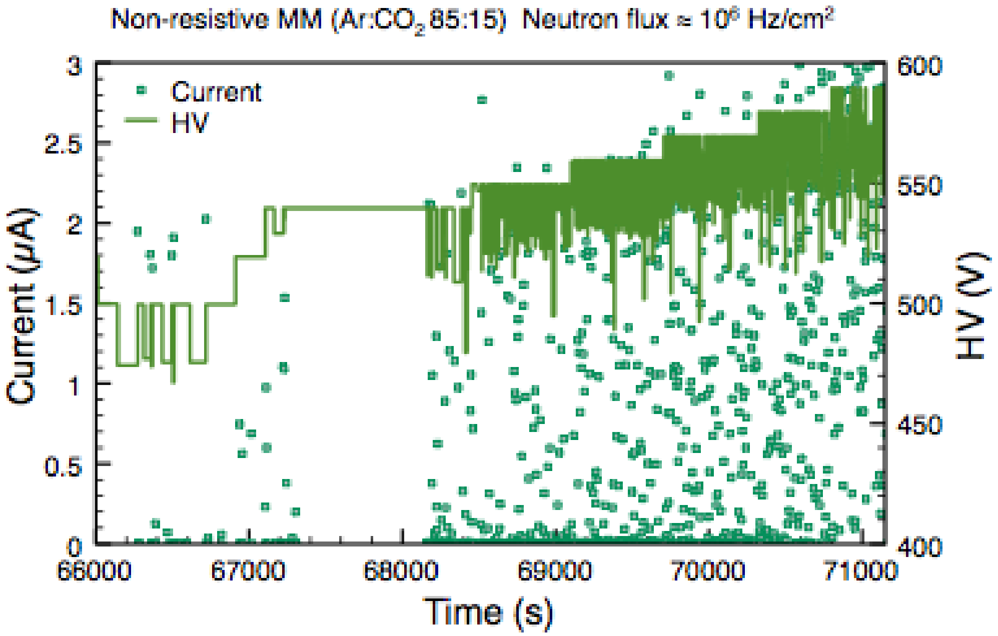


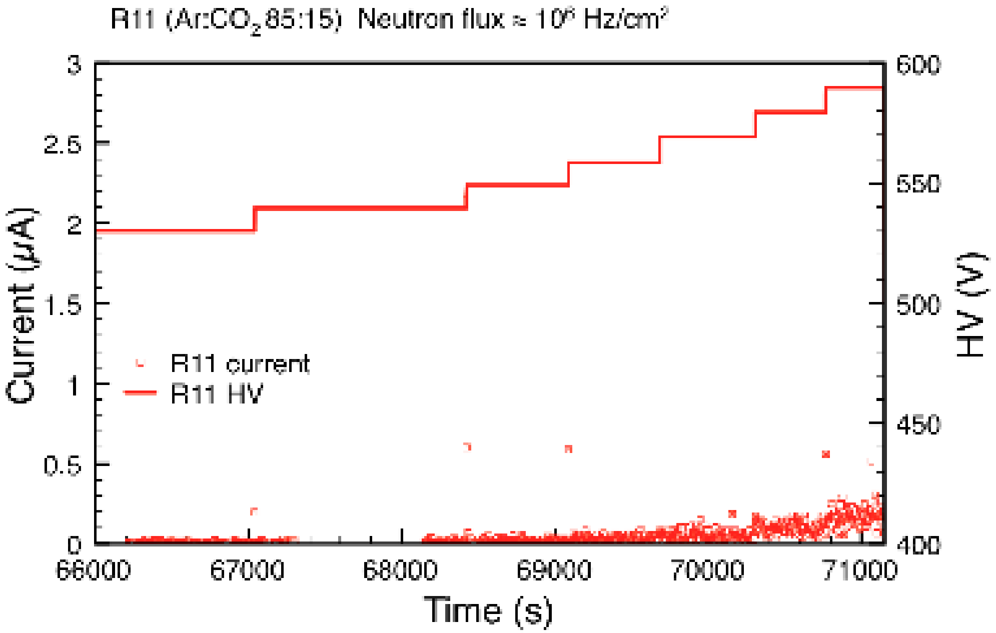
Figure 1.11: [Top] Resistive Micromegas principle. [Bottom] Pad signals recorded by an electronics after shaping.

David Attié, HDR, October 2022

Resistive strips Micromegas




Non-resistive MM (Ar:CO$_2$ 85:15) Neutron flux ≈ 10^6 Hz/cm^2


R11 (Ar:CO$_2$ 85:15) Neutron flux ≈ 10^6 Hz/cm^2

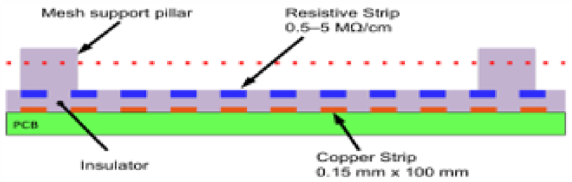
T. Alexopoulos et al., NIM 1 640 (2011) 110-118

Resistive Micromegas

From R. De Oliveira
RD51 MPGD School 2023

All Resistive MM structures

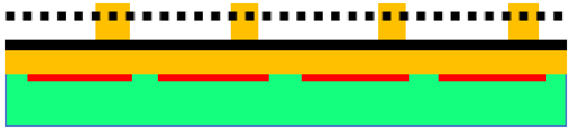
Medium-rate detectors 100kHz/cm2
Side evacuation of the charges



Screen printed resistive strips (ATLAS NSW)

2013

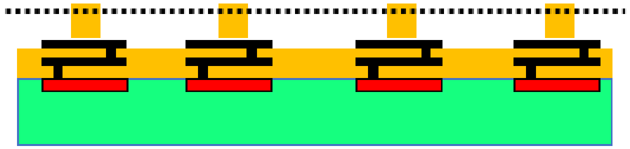
or



1 full DLC layer

2015

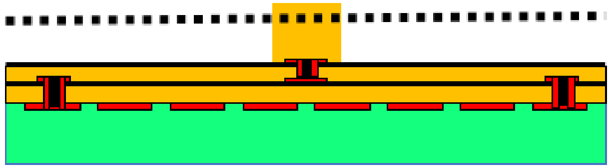
High-rate detectors 10Mhz/cm2
Charge evacuation inside active area



2 layers with screen printed pads

2015

or

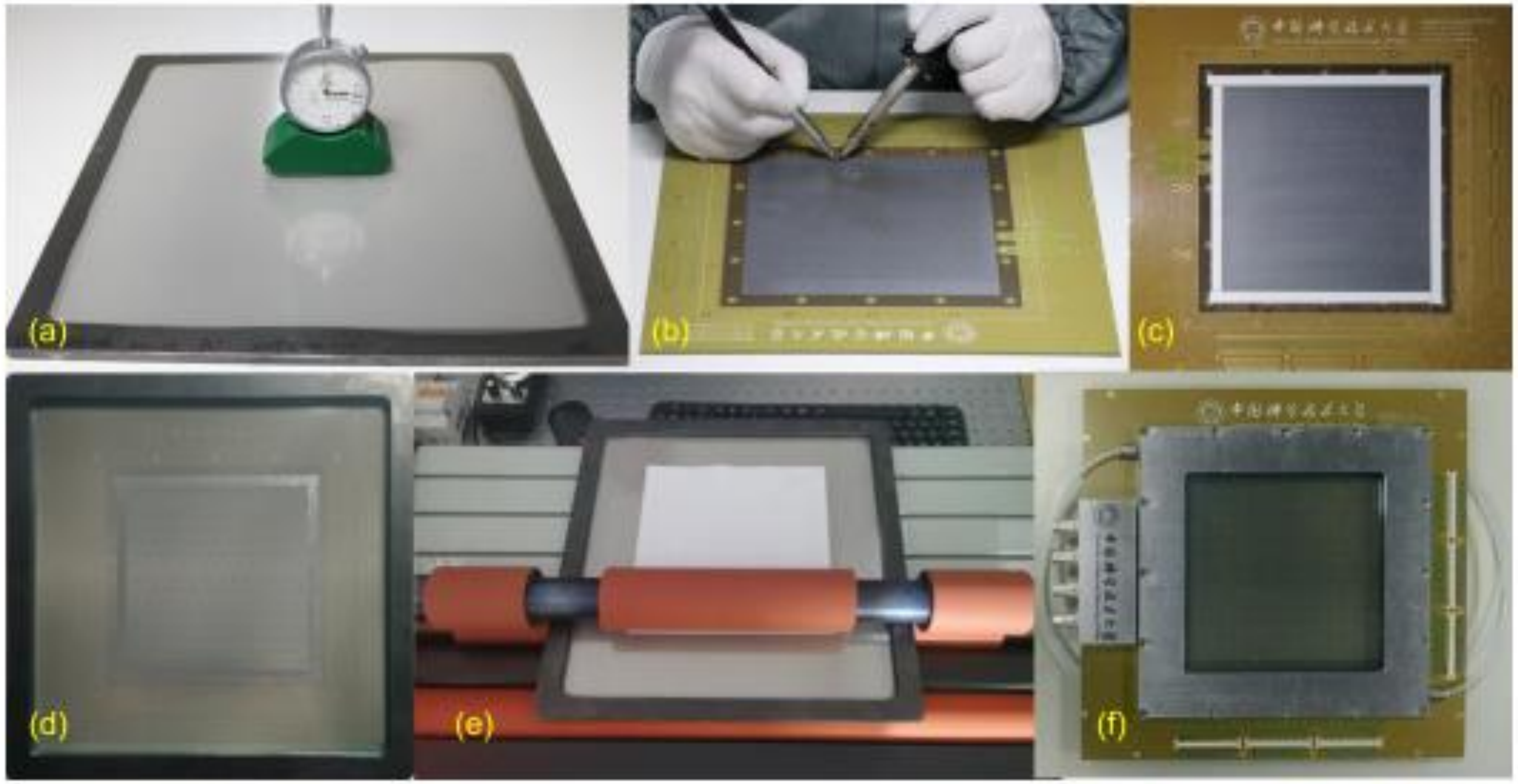


2 DLC layers without patterns

2020

M. Alviggi et al., e-print:2411.1702

Thermal Bonded Micromegas

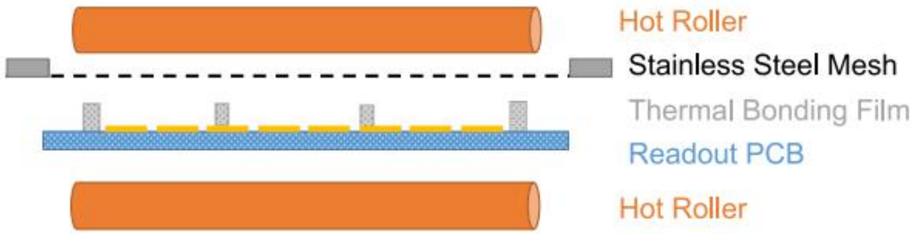


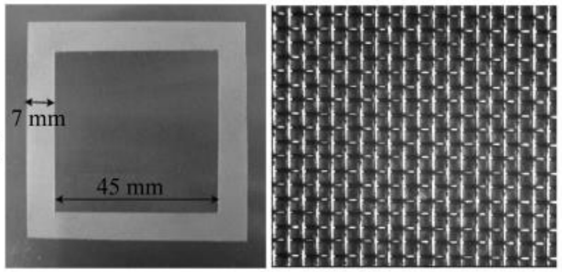
(a) Stretching of the mesh
(b) Pre-setting the spacers on the anode
(c) Setting the borders for the mesh fixation
(d) Stacking the mesh
(e) Thermal bonding using a hot roller
(f) Complete view after full assembly

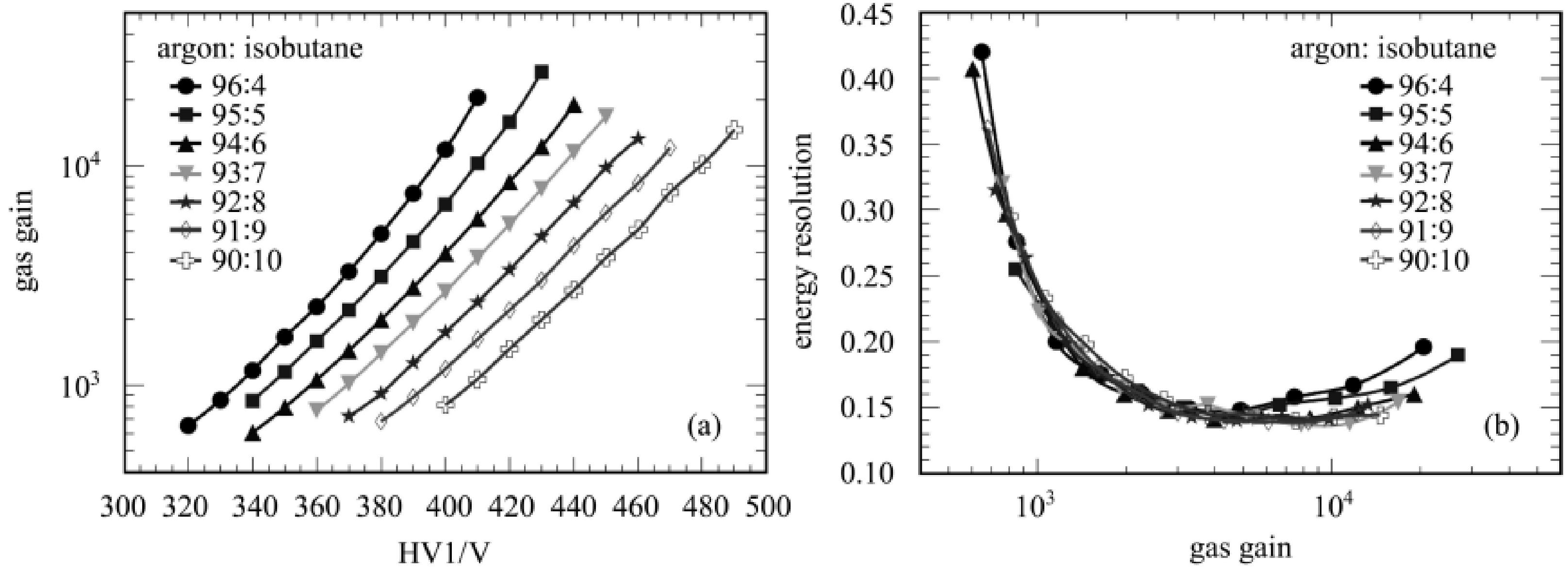
J. Feng et al 2021 NIM A 989 (2021) 16958

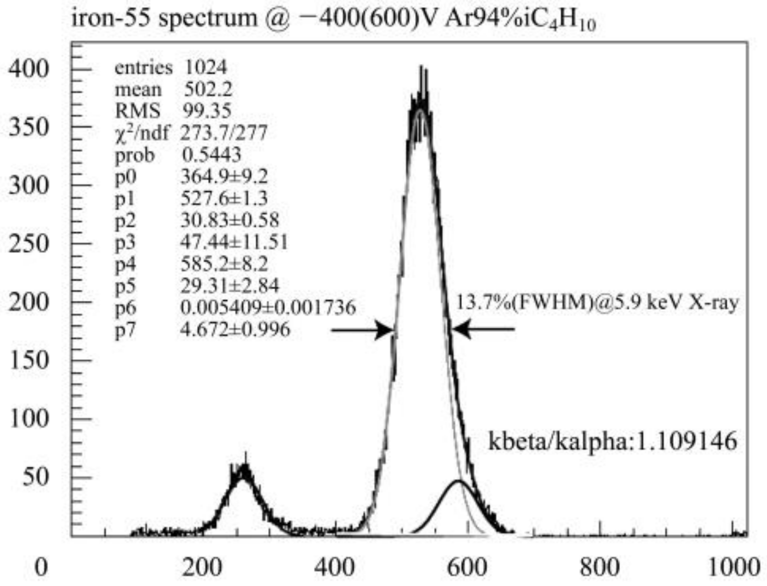
Thermal Bonded Micromegas

G. Liang et al 2011 Chinese Phys. C 35 163
Z. Zhang et al 2014 JINST 9 C10028


Hot Roller
Stainless Steel Mesh
Thermal Bonding Film
Readout PCB
Hot Roller







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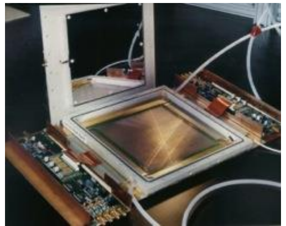
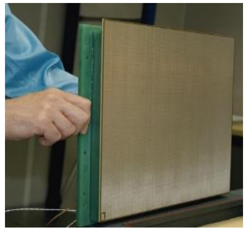
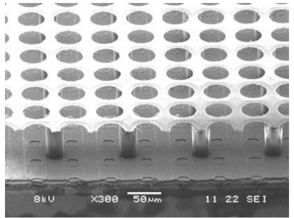
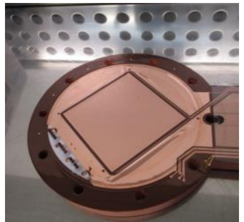
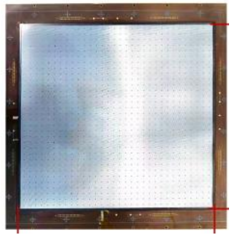
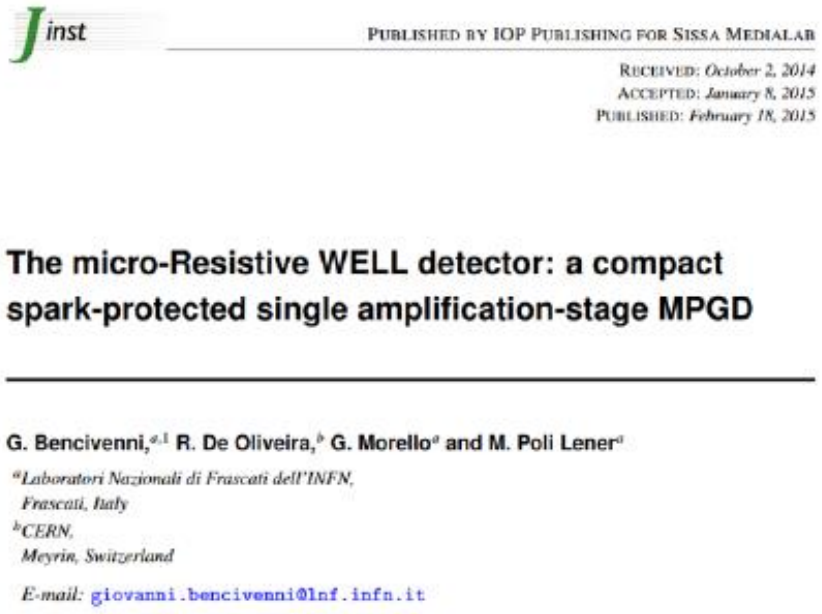
Micromegas family

XY Microbulk (2012)
Piggyback (20213)

	Standard **1996**	**Bulk** **2003**	**Ingrid** **2005**	**Microbulk** **2006**	**Thermal Bonded** **2011**
Mesh Readout plane	TWO mechanical entities	INTEGRATED: ONE single entity			
Type of mesh	Any type	30 µm Stainless steel	1 µm Aluminium	5 µm Copper	30 µm Stainless steel
Advantages	Demontability Large Surface	Robust Industrial manufacturing process (PCB)	Excellent energy resolution Single electron efficiency	Intrinsically Flexible Low mass Radiopure	Easy mass production without the need for etching High gains
					

µ-Rwell


PUBLISHED BY IOP PUBLISHING FOR SISSA MEDIALAB

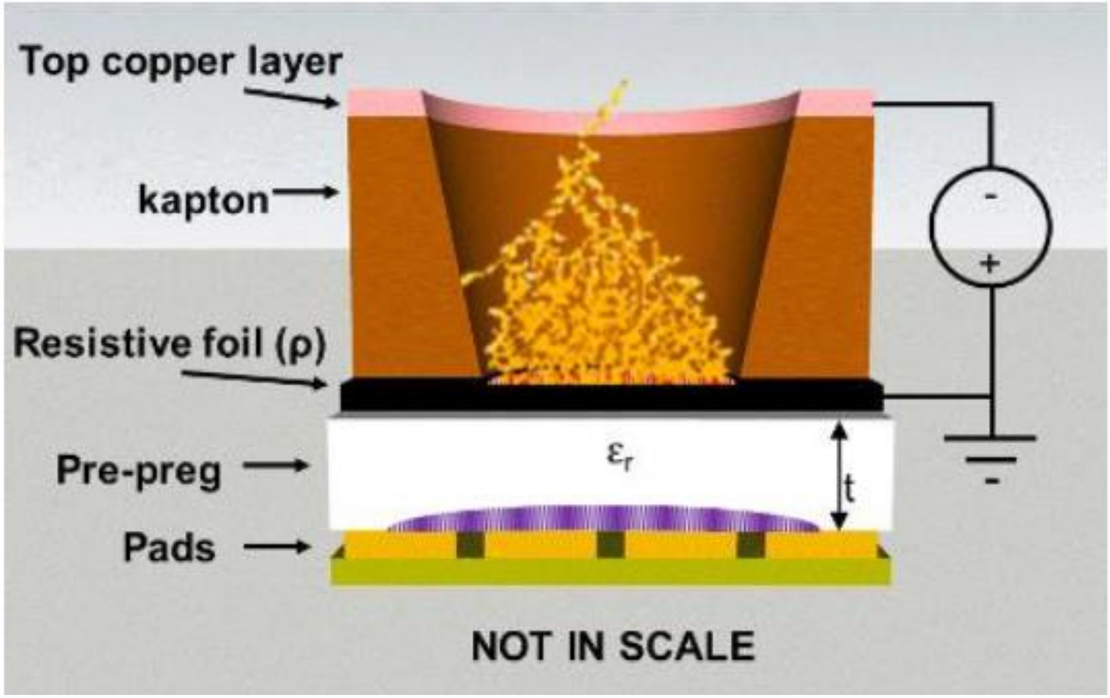
RECEIVED: *October 2, 2014*
ACCEPTED: *January 8, 2015*
PUBLISHED: *February 18, 2015*

The micro-Resistive WELL detector: a compact spark-protected single amplification-stage MPGD

G. Bencivenni,[a,1] R. De Oliveira,[b] G. Morello[a] and M. Poli Lener[a]

[a] *Laboratori Nazionali di Frascati dell'INFN, Frascati, Italy*
[b] *CERN, Meyrin, Switzerland*

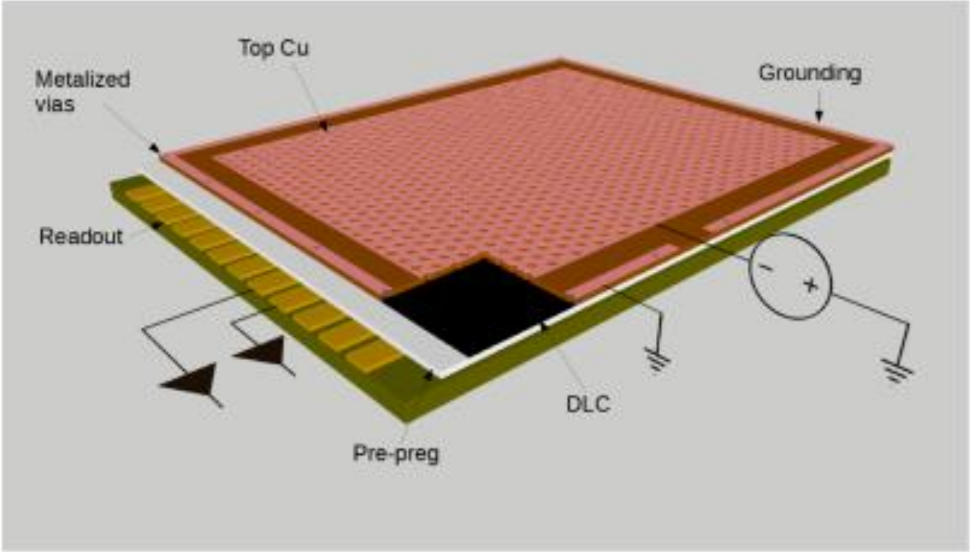
E-mail: giovanni.bencivenni@lnf.infn.it



- The µRWELL is composed of a µ-RWELL PCB + Cathode
- µRWELL PCB : amplification stage coupled to the readout PCB through a resistive layer
- Resistive layer: Diamond-Like-Carbon with a resistivity 20-100 MOhm/square

µ-Rwell Low rate: Single resistive layer

Single resistive layer (2014-1017)

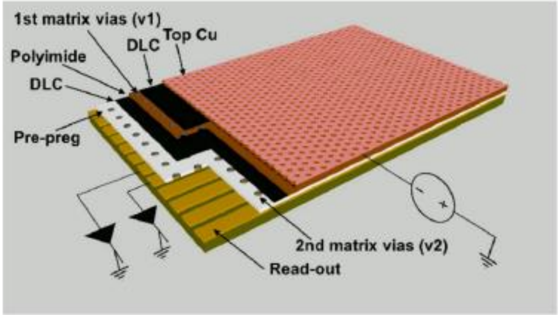


- Based on GEM fabrication techniques. Micromegas like amplification and signal formation
- 2D current evacuation based on a single resistive layer
- Grounding around the active area
- For large area: problem the path of the current depends on position=> detector inhomogeneity
- Limited rate capability < 100 kHz/cm^2

G. Bencivenni et al, 2019 *JINST* 14 P05014

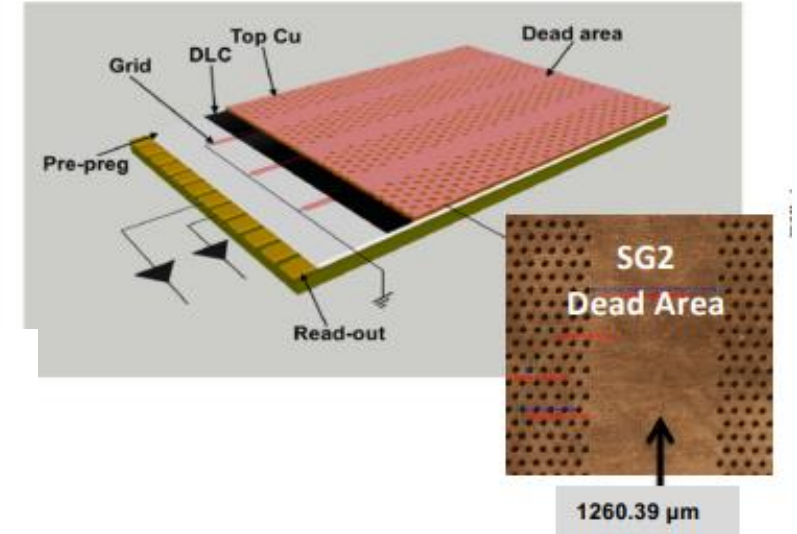
µ-Rwell high rate

Double resistive layer



- Very good performance
- Complex manufacturing due to the double matrix of vias

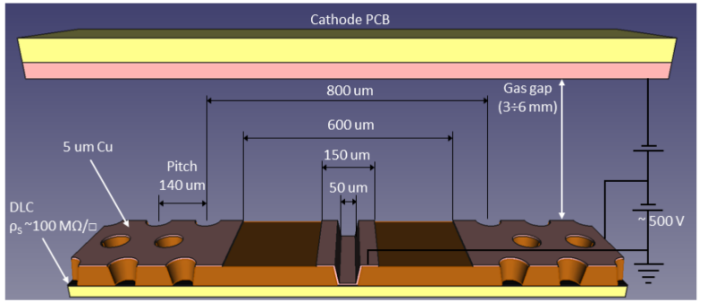
Silver grid



- Good performance
- 2D evacuation scheme by a conductive grid (screen printed or etched)
- Alignment of the conductive grid pattern with the amplification pattern difficult

M. Poli Lener, MPGD 2022

PEP (Patterning-Etching-Plating)

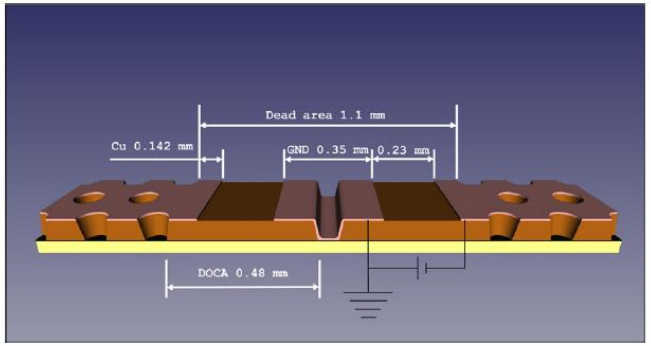


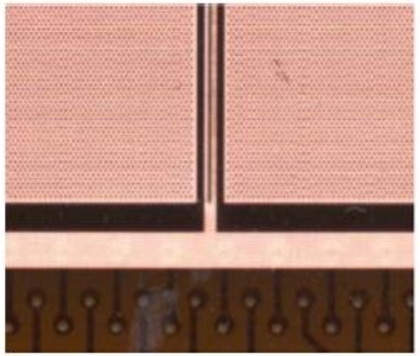
- Single DLC layer
- DLC grounding from top by kapton etching and plating
- No alignment problems
- Scalable to large sizes

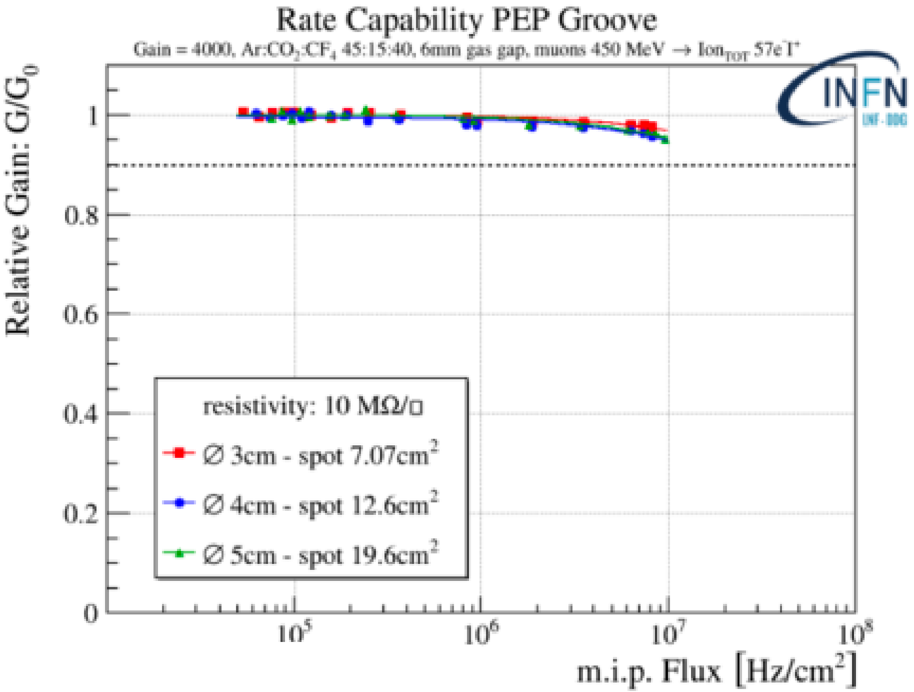
μ-Rwell high rate

G. Bencivenni et al, NIM A 1069 (2024) *169725*

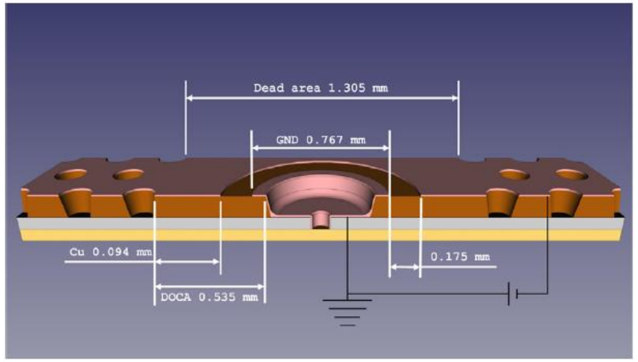
PEP Groove

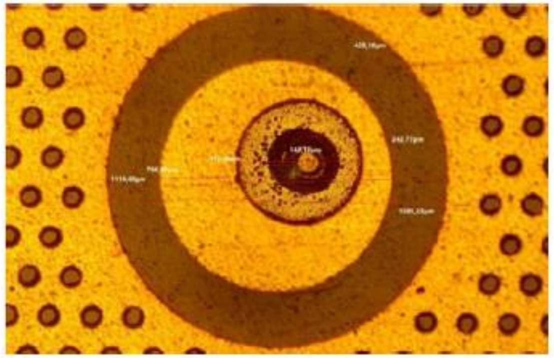


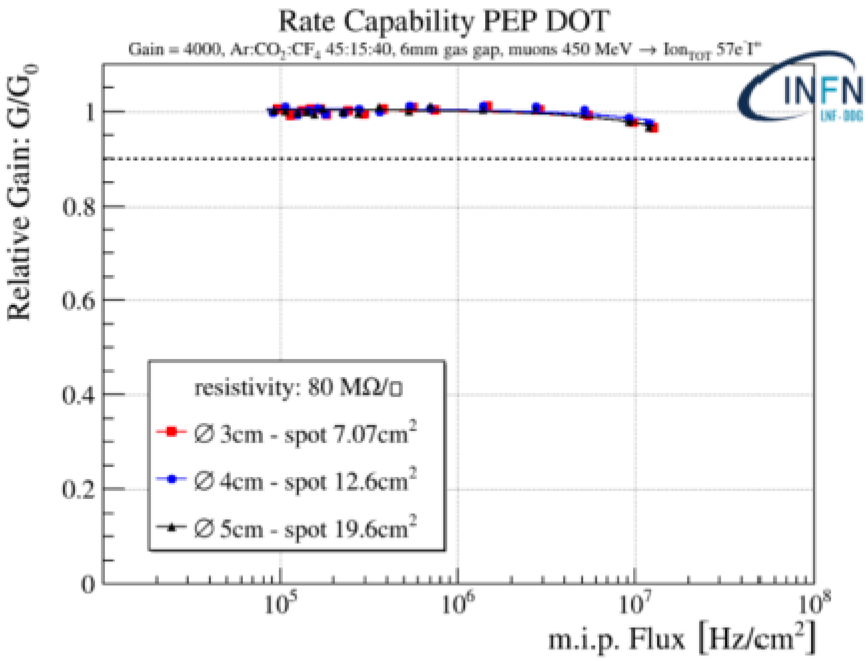




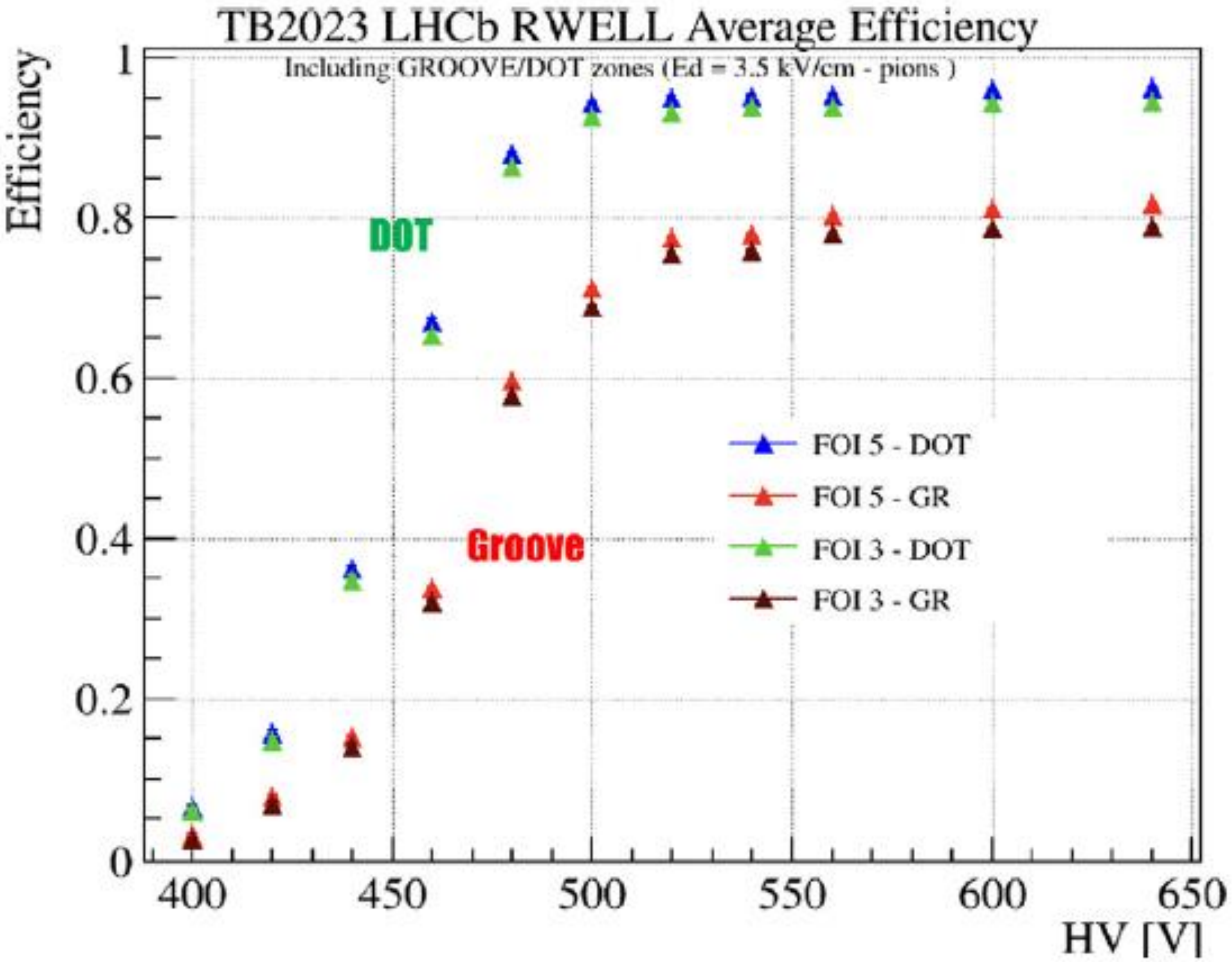
PEP Dot







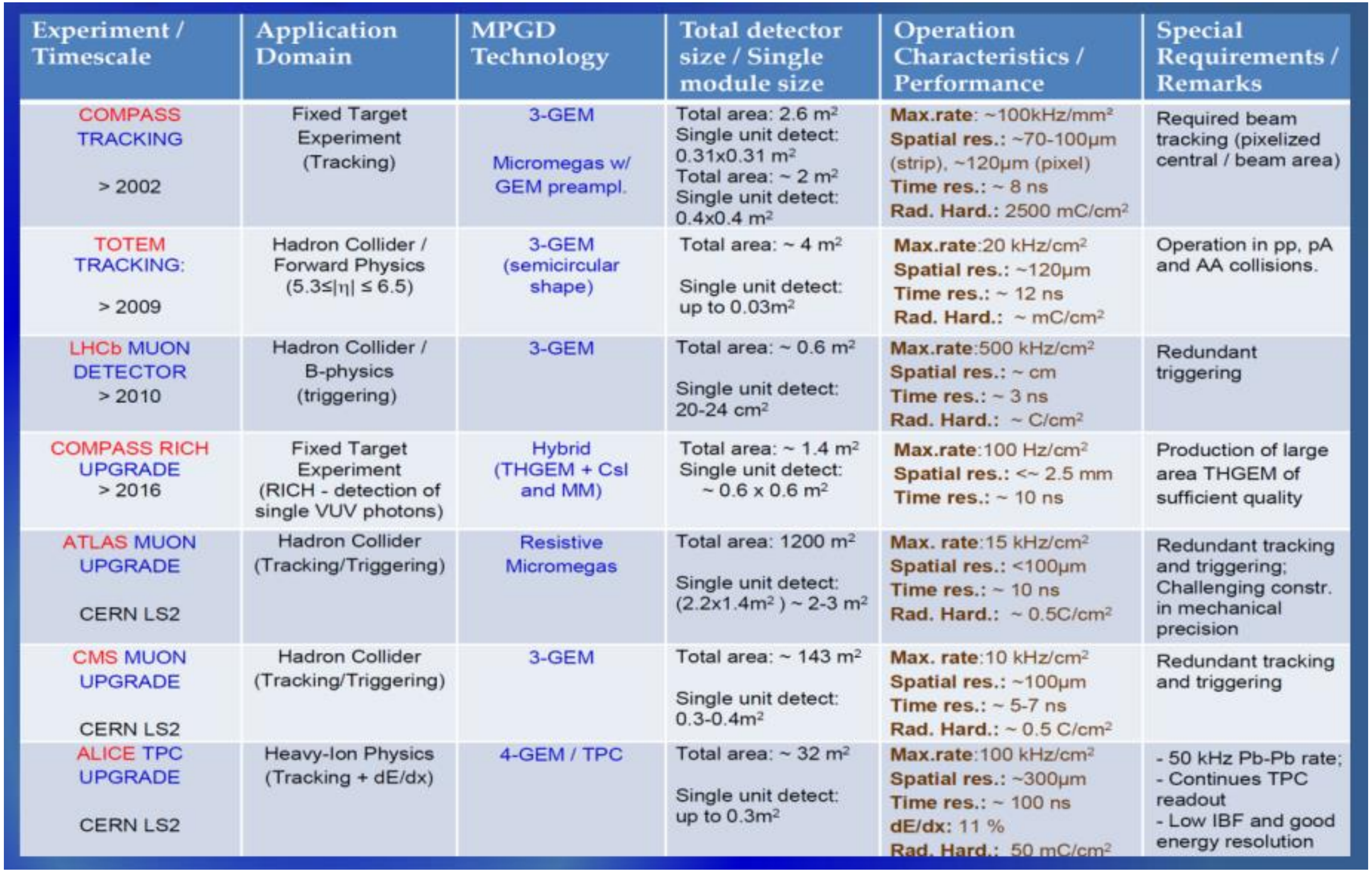
µ-Rwell high rate



G. Bencivenni et al,
NIM A 1069 (2024) *169725*

MPGD Applications

MPGD @ CERN experiments



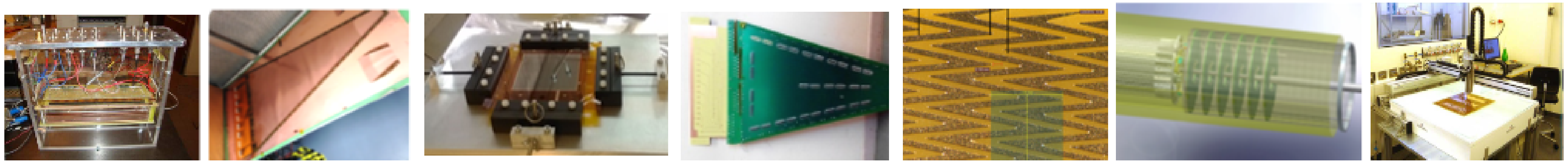
Experiment / Timescale	Application Domain	MPGD Technology	Total detector size / Single module size	Operation Characteristics / Performance	Special Requirements / Remarks
COMPASS TRACKING > 2002	Fixed Target Experiment (Tracking)	3-GEM Micromegas w/ GEM preampl.	Total area: 2.6 m^2 Single unit detect: 0.31x0.31 m^2 Total area: ~ 2 m^2 Single unit detect: 0.4x0.4 m^2	**Max.rate**: ~100kHz/mm^2 **Spatial res.**: ~70-100μm (strip), ~120μm (pixel) **Time res.**: ~ 8 ns **Rad. Hard.**: 2500 mC/cm^2	Required beam tracking (pixelized central / beam area)
TOTEM TRACKING: > 2009	Hadron Collider / Forward Physics ($5.3 \leq \lvert\eta\rvert \leq 6.5$)	3-GEM (semicircular shape)	Total area: ~ 4 m^2 Single unit detect: up to 0.03m^2	**Max.rate**:20 kHz/cm^2 **Spatial res.**: ~120μm **Time res.**: ~ 12 ns **Rad. Hard.**: ~ mC/cm^2	Operation in pp, pA and AA collisions.
LHCb MUON DETECTOR > 2010	Hadron Collider / B-physics (triggering)	3-GEM	Total area: ~ 0.6 m^2 Single unit detect: 20-24 cm^2	**Max.rate**:500 kHz/cm^2 **Spatial res.**: ~ cm **Time res.**: ~ 3 ns **Rad. Hard.**: ~ C/cm^2	Redundant triggering
COMPASS RICH UPGRADE > 2016	Fixed Target Experiment (RICH - detection of single VUV photons)	Hybrid (THGEM + CsI and MM)	Total area: ~ 1.4 m^2 Single unit detect: ~ 0.6 x 0.6 m^2	**Max.rate**:100 Hz/cm^2 **Spatial res.**: <~ 2.5 mm **Time res.**: ~ 10 ns	Production of large area THGEM of sufficient quality
ATLAS MUON UPGRADE CERN LS2	Hadron Collider (Tracking/Triggering)	Resistive Micromegas	Total area: 1200 m^2 Single unit detect: (2.2x1.4m^2) ~ 2-3 m^2	**Max. rate**:15 kHz/cm^2 **Spatial res.**: <100μm **Time res.**: ~ 10 ns **Rad. Hard.**: ~ 0.5C/cm^2	Redundant tracking and triggering; Challenging constr. in mechanical precision
CMS MUON UPGRADE CERN LS2	Hadron Collider (Tracking/Triggering)	3-GEM	Total area: ~ 143 m^2 Single unit detect: 0.3-0.4m^2	**Max. rate**:10 kHz/cm^2 **Spatial res.**: ~100μm **Time res.**: ~ 5-7 ns **Rad. Hard.**: ~ 0.5 C/cm^2	Redundant tracking and triggering
ALICE TPC UPGRADE CERN LS2	Heavy-Ion Physics (Tracking + dE/dx)	4-GEM / TPC	Total area: ~ 32 m^2 Single unit detect: up to 0.3m^2	**Max.rate**:100 kHz/cm^2 **Spatial res.**: ~300μm **Time res.**: ~ 100 ns **dE/dx**: 11 % **Rad. Hard.**: 50 mC/cm^2	- 50 kHz Pb-Pb rate; - Continues TPC readout - Low IBF and good energy resolution

M. Titov
Gaseous detector lecture at the ICFA school 2023

(Not up-to-date)

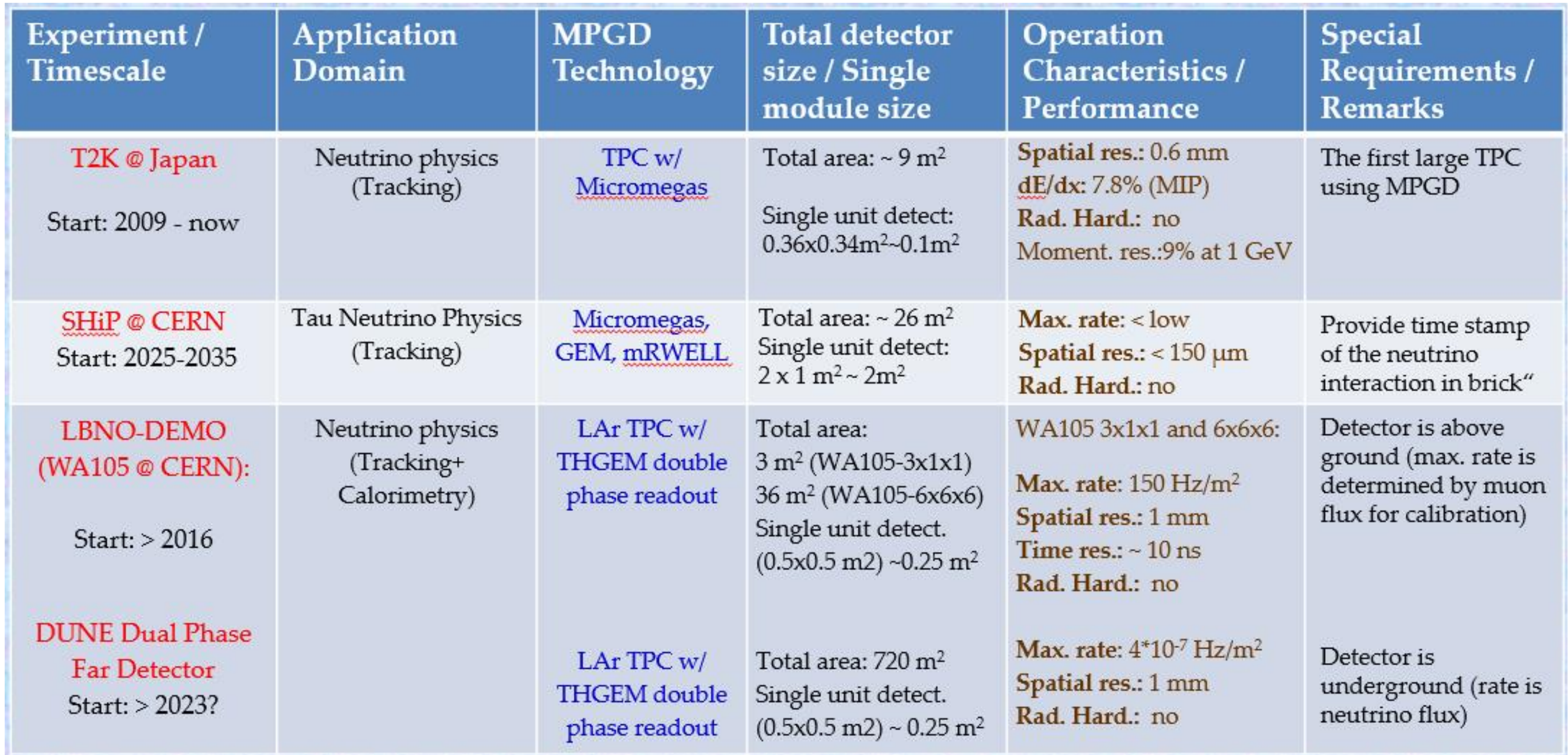
MPGD @ nuclear physics

Name (Lab)	MPGD Technology	Volume Area	Pressure (atm)	Operation Performance	Status
ACTAR (GANIL)	μ-megas	8000 cm^3	0.01-3	Counting rate < 10^4 nuclei but higher if some beam masks are used	Under Construction
MAIKo (RNCP)	μ-PIC	2750 cm^3	0.4-1	FADC electronics 2*256 channles	Test
PANDA (FAIR)	μ-megas/GEM	22500 cm^2	1	Continuous-wave operation: 10^{11} interaction/s	Under Construction
CAT (CNS)	GEM	2000 cm^3	0.2-1	FADC electronics 400 channels	Test
pAT-ATP (NSCL)	μ-megas (+THGEM)	2000 cm^3	0.01-1	GET electronics 256 channels	Operational
AT-TPC (NSCL)	μ-megas (+THGEMs)	8000 cm^3	0.01-1	GET electronics >10'000 channels	Operational
TACTIC (CNS)	GEM	8000 cm^3	0.25-1	Low beam energy (<2 MeV/u)	Test
MINOS (CNS)	μ-megas	6000 cm^3	1	# of Channel= 600	Operational
SuperFRS (FAIR)	GEM	Few m^2	1	High dynamic range Particle detection from p to Uranium	Under Construction Run: 2018-2022
...	...	...	...	...	...

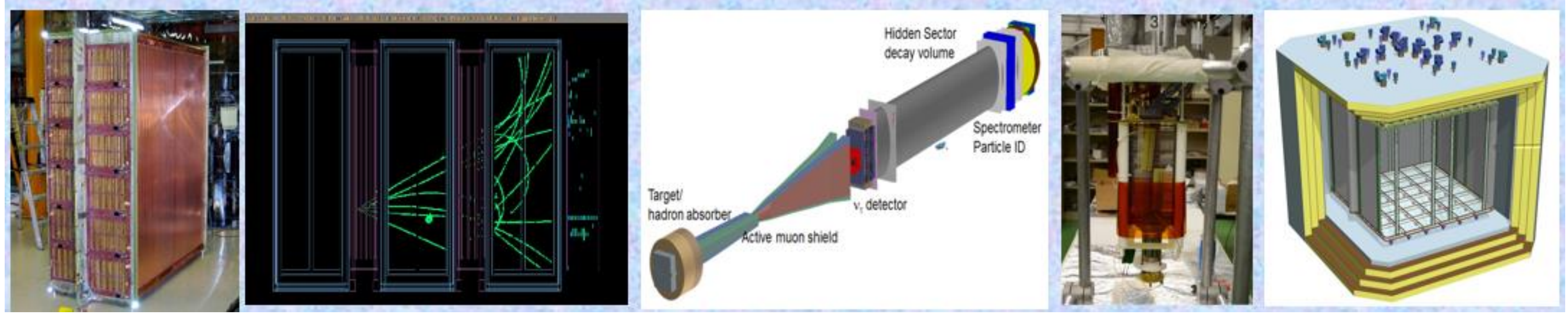


RD51 MPGD School 2023
M. Cortesi

MPGD neutrino physics



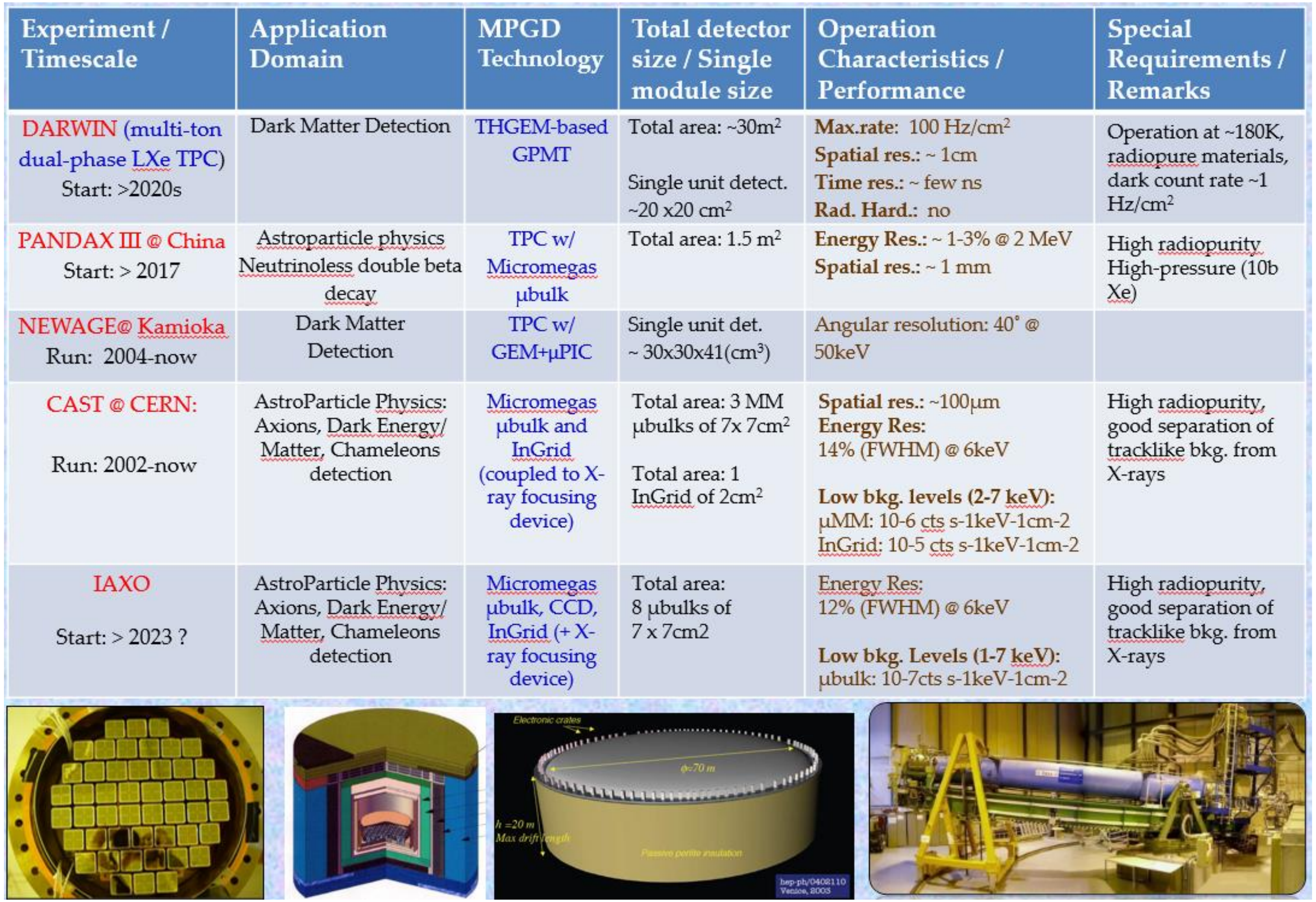
Experiment / Timescale	Application Domain	MPGD Technology	Total detector size / Single module size	Operation Characteristics / Performance	Special Requirements / Remarks
T2K @ Japan Start: 2009 - now	Neutrino physics (Tracking)	TPC w/ Micromegas	Total area: ~ 9 m^2 Single unit detect: 0.36x0.34m^2~0.1m^2	**Spatial res.:** 0.6 mm **dE/dx:** 7.8% (MIP) **Rad. Hard.:** no Moment. res.:9% at 1 GeV	The first large TPC using MPGD
SHiP @ CERN Start: 2025-2035	Tau Neutrino Physics (Tracking)	Micromegas, GEM, mRWELL	Total area: ~ 26 m^2 Single unit detect: 2 x 1 m^2 ~ 2m^2	**Max. rate:** < low **Spatial res.:** < 150 μm **Rad. Hard.:** no	Provide time stamp of the neutrino interaction in brick“
LBNO-DEMO (WA105 @ CERN): Start: > 2016	Neutrino physics (Tracking+ Calorimetry)	LAr TPC w/ THGEM double phase readout	Total area: 3 m^2 (WA105-3x1x1) 36 m^2 (WA105-6x6x6) Single unit detect. (0.5x0.5 m2) ~0.25 m^2	WA105 3x1x1 and 6x6x6: **Max. rate:** 150 Hz/m^2 **Spatial res.:** 1 mm **Time res.:** ~ 10 ns **Rad. Hard.:** no	Detector is above ground (max. rate is determined by muon flux for calibration)
DUNE Dual Phase Far Detector Start: > 2023?		LAr TPC w/ THGEM double phase readout	Total area: 720 m^2 Single unit detect. (0.5x0.5 m2) ~ 0.25 m^2	**Max. rate:** $4*10^{-7}$ Hz/m^2 **Spatial res.:** 1 mm **Rad. Hard.:** no	Detector is underground (rate is neutrino flux)



M. Titov
[Gaseous detector lecture at the ICFA school 2023]

(Not up-to-date)

MPGD @ rare event detection



Experiment / Timescale	Application Domain	MPGD Technology	Total detector size / Single module size	Operation Characteristics / Performance	Special Requirements / Remarks
DARWIN (multi-ton dual-phase LXe TPC) Start: >2020s	Dark Matter Detection	THGEM-based GPMT	Total area: ~30m^2 Single unit detect. ~20 x20 cm^2	**Max.rate:** 100 Hz/cm^2 **Spatial res.:** ~ 1cm **Time res.:** ~ few ns **Rad. Hard.:** no	Operation at ~180K, radiopure materials, dark count rate ~1 Hz/cm^2
PANDAX III @ China Start: > 2017	Astroparticle physics Neutrinoless double beta decay	TPC w/ Micromegas µbulk	Total area: 1.5 m^2	**Energy Res.:** ~ 1-3% @ 2 MeV **Spatial res.:** ~ 1 mm	High radiopurity High-pressure (10b Xe)
NEWAGE@ Kamioka Run: 2004-now	Dark Matter Detection	TPC w/ GEM+µPIC	Single unit det. ~ 30x30x41(cm^3)	Angular resolution: 40˚ @ 50keV	
CAST @ CERN: Run: 2002-now	AstroParticle Physics: Axions, Dark Energy/ Matter, Chameleons detection	Micromegas µbulk and InGrid (coupled to X-ray focusing device)	Total area: 3 MM µbulks of 7x 7cm^2 Total area: 1 InGrid of 2cm^2	**Spatial res.:** ~100µm **Energy Res:** 14% (FWHM) @ 6keV **Low bkg. levels (2-7 keV):** µMM: 10-6 cts s-1keV-1cm-2 InGrid: 10-5 cts s-1keV-1cm-2	High radiopurity, good separation of tracklike bkg. from X-rays
IAXO Start: > 2023 ?	AstroParticle Physics: Axions, Dark Energy/ Matter, Chameleons detection	Micromegas µbulk, CCD, InGrid (+ X-ray focusing device)	Total area: 8 µbulks of 7 x 7cm2	Energy Res: 12% (FWHM) @ 6keV **Low bkg. Levels (1-7 keV):** µbulk: 10-7cts s-1keV-1cm-2	High radiopurity, good separation of tracklike bkg. from X-rays

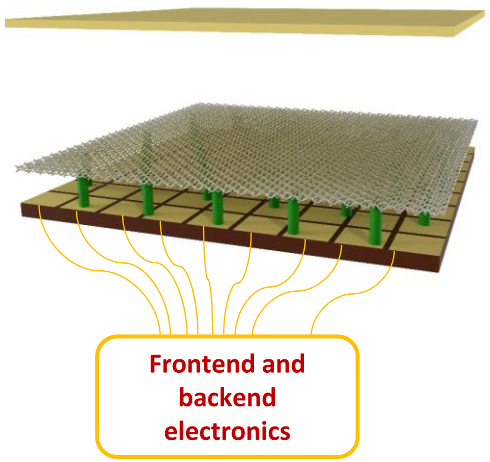
M. Titov
[Gaseous detector lecture at the ICFA school 2023]

(Not up-to-date)

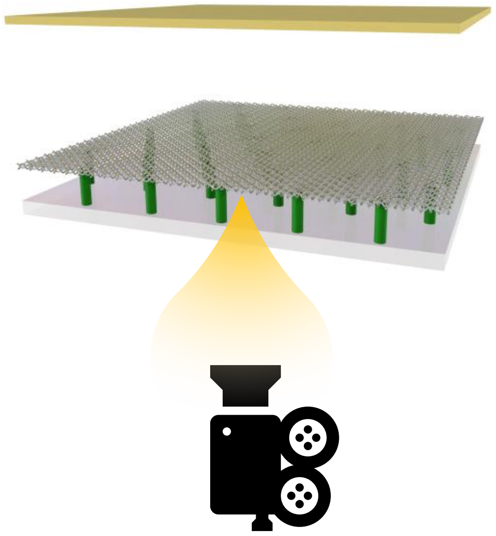
Two chosen applications

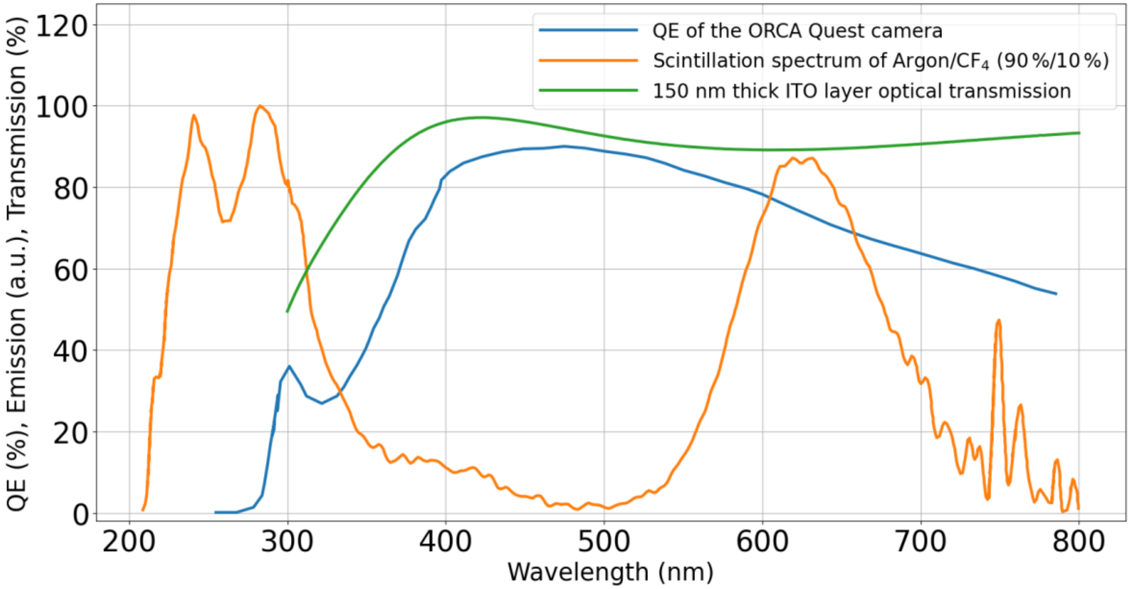
Charge and optical readout

Charge readout



Optical readout





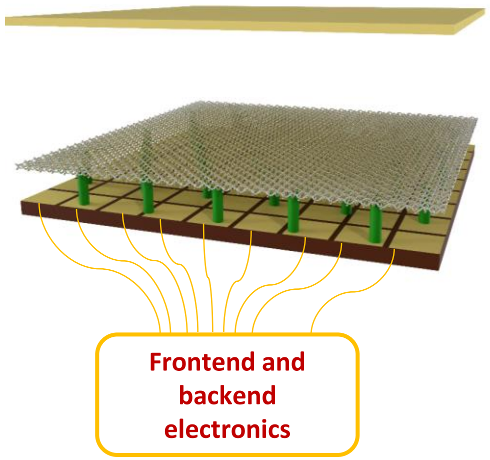
Optical readout of MicroPattern Gaseous detectors (MPGDs) relies on recording scintillation light emitted during electron avalanche multiplication

Scintillation spectrum of gas mixtures with CF$_4$ is well suited for readout with CCD or CMOS imaging sensors

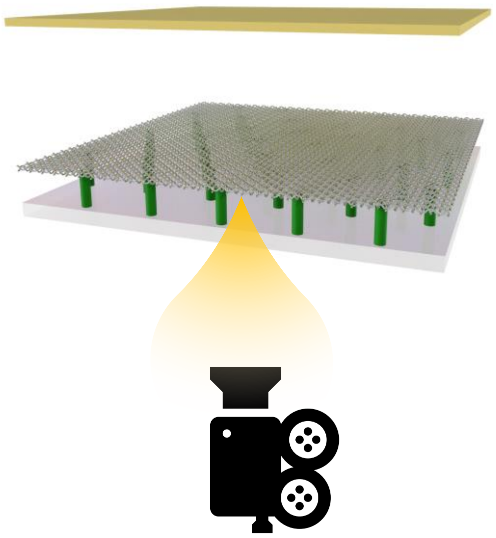
High spatial resolution can be obtained

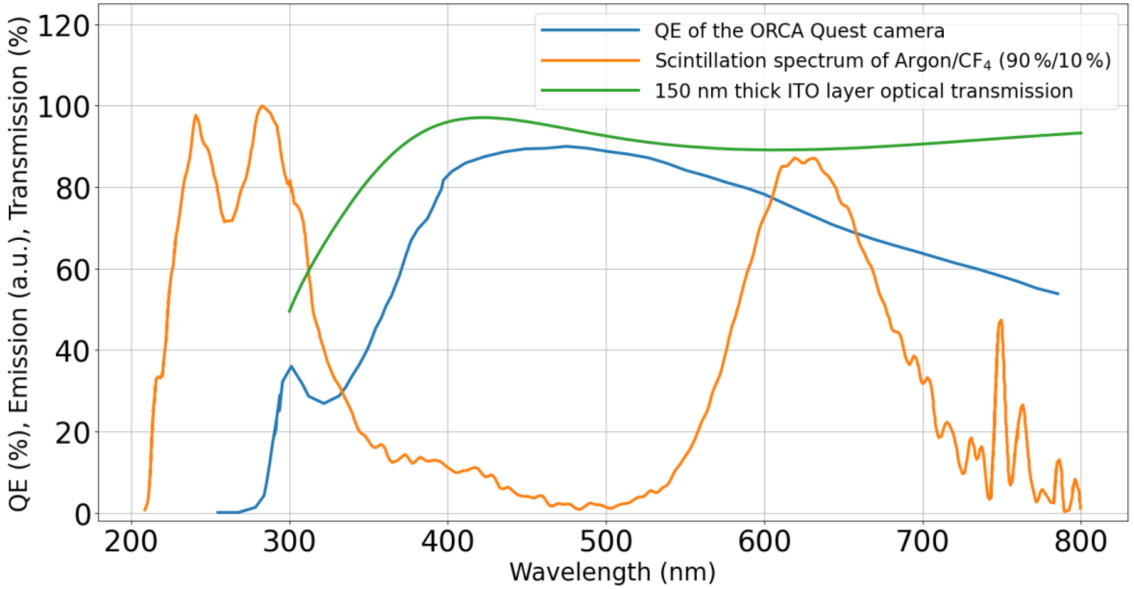
Charge and optical readout

Charge readout



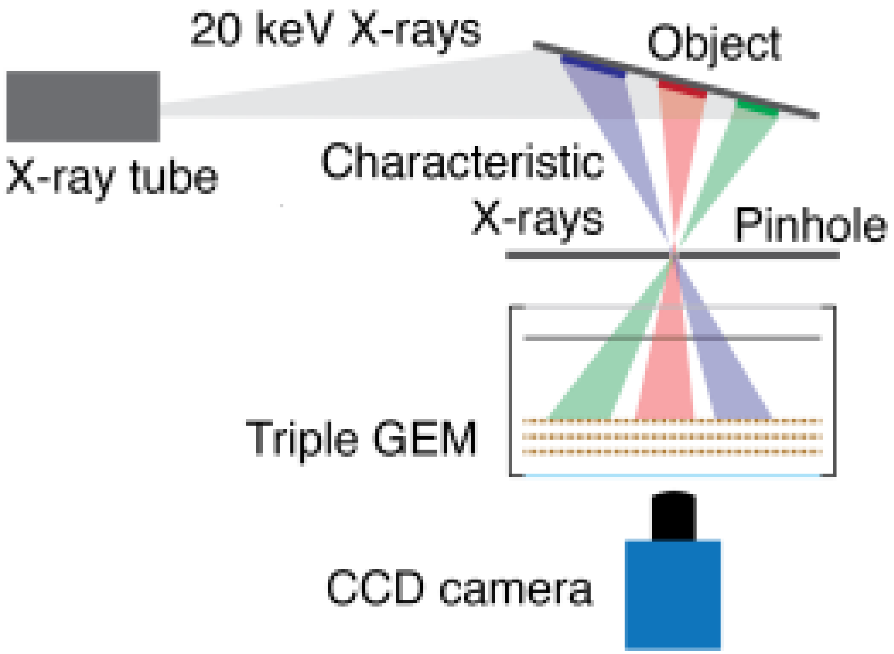
Optical readout





- Use of camera (**large number of pixels**, use of lens for **large field of view**)
- **Easy handling of the data** (light intensity matrix)
- **Online imaging** thanks to very low data processing and light **integration approach**

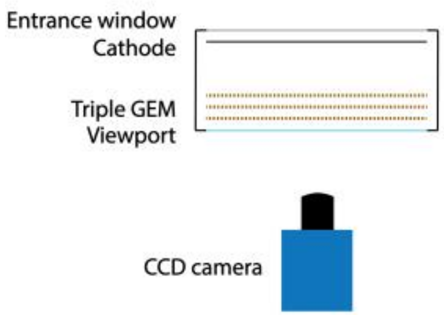
X-ray fluorescence with optically read-out GEM

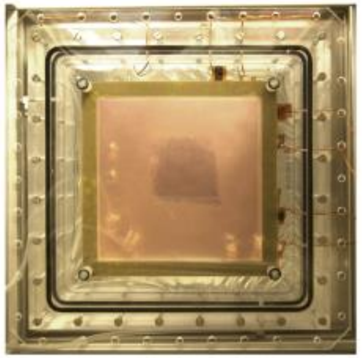


- Materials are excited by X-rays
- Characteristic X-ray emisson is produced
- X-ray fluorescence ➔identification of different materials in an image
- Recorded light proportional to the energy of the incident particle

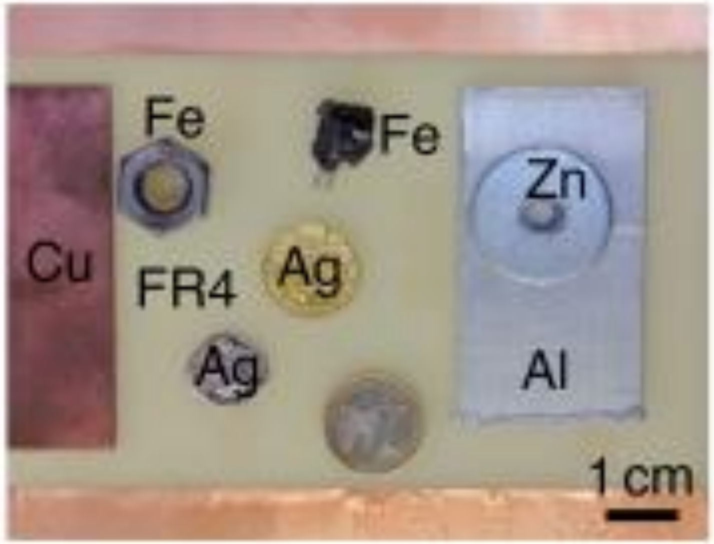
F.M. Brunbauer et al 2018 JINST 13 T02006

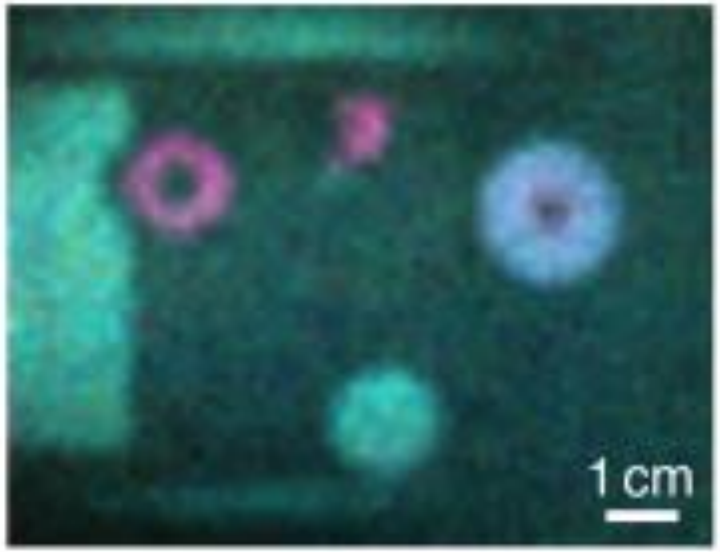
X-ray fluorecence with optically read-out GEM





F.M. Brunbauer et al. 2018 JINST 13 T02006



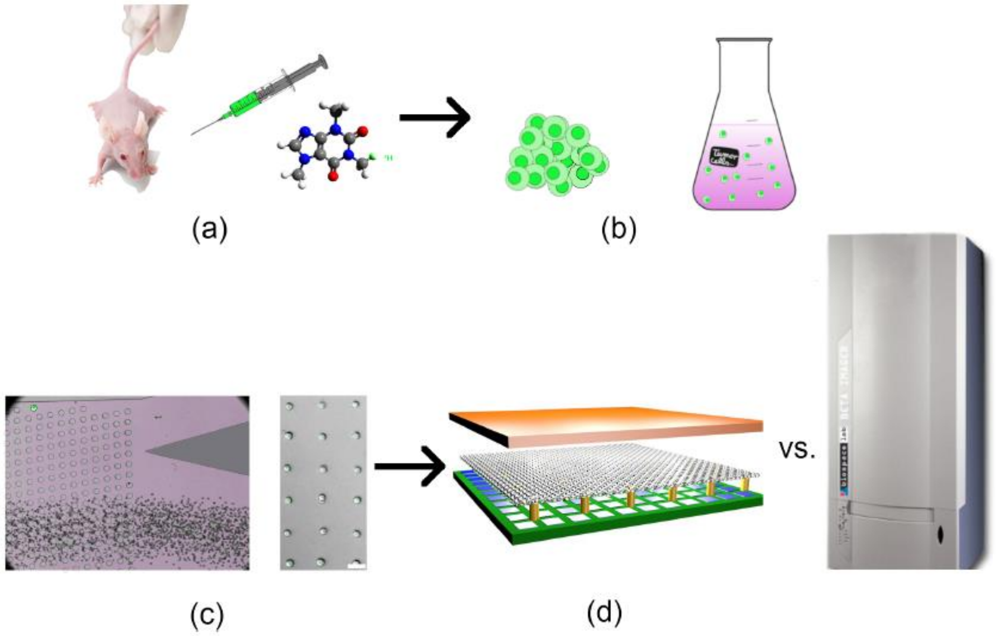


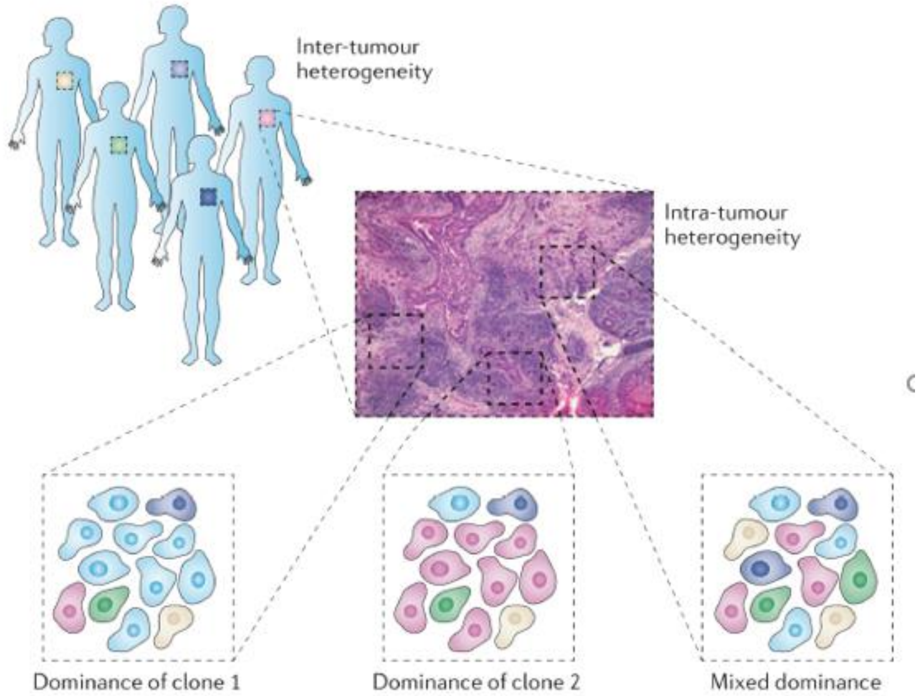
Beta imaging with Glass Micromegas

Context: oncological research

Drugs labelled with tritium 3H

Drug efficiency➔measurement of 3H activity

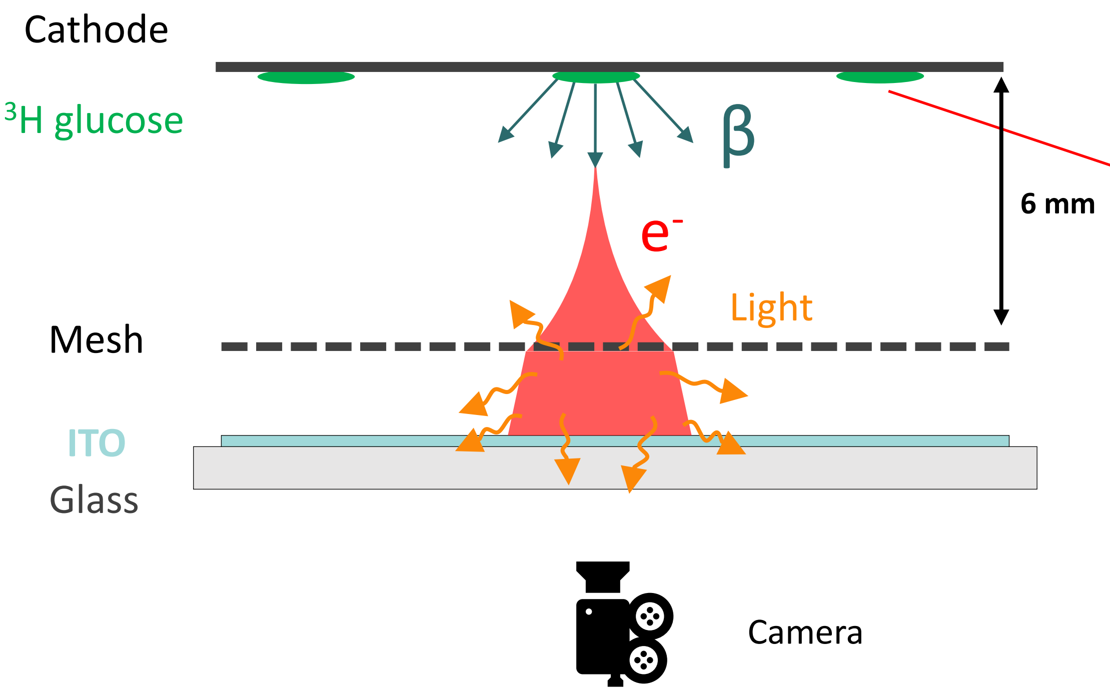


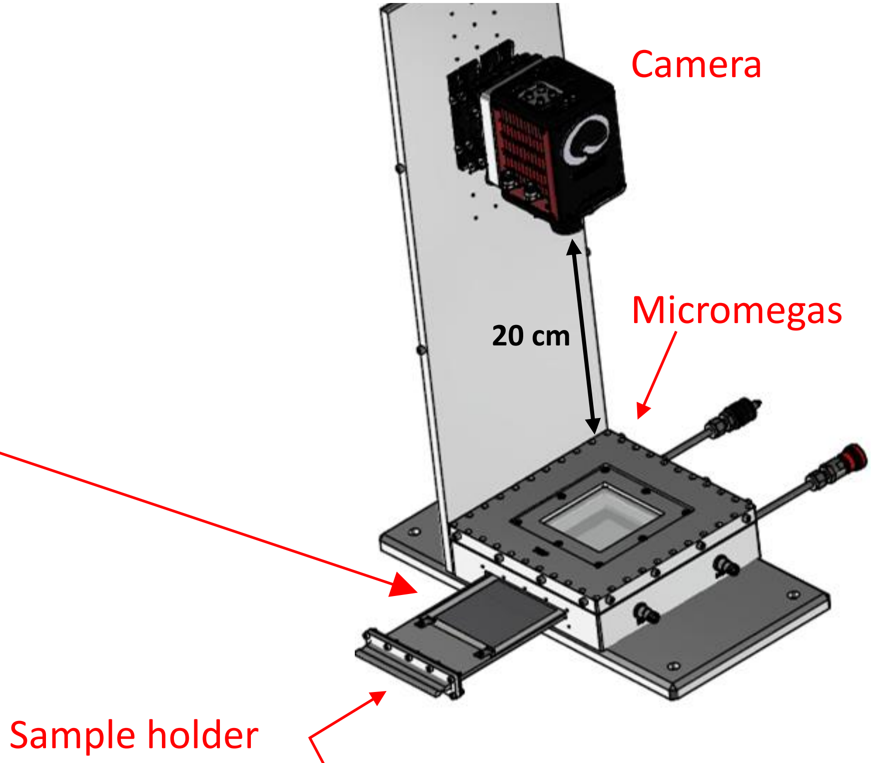


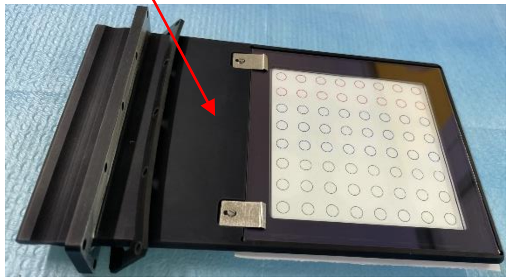
Marusyk, Nature Reviews Cancer 12(5) (2012) 323-34

Beta imaging with Glass Micromegas

A. Cools PhD 2024 Université Paris-Saclay



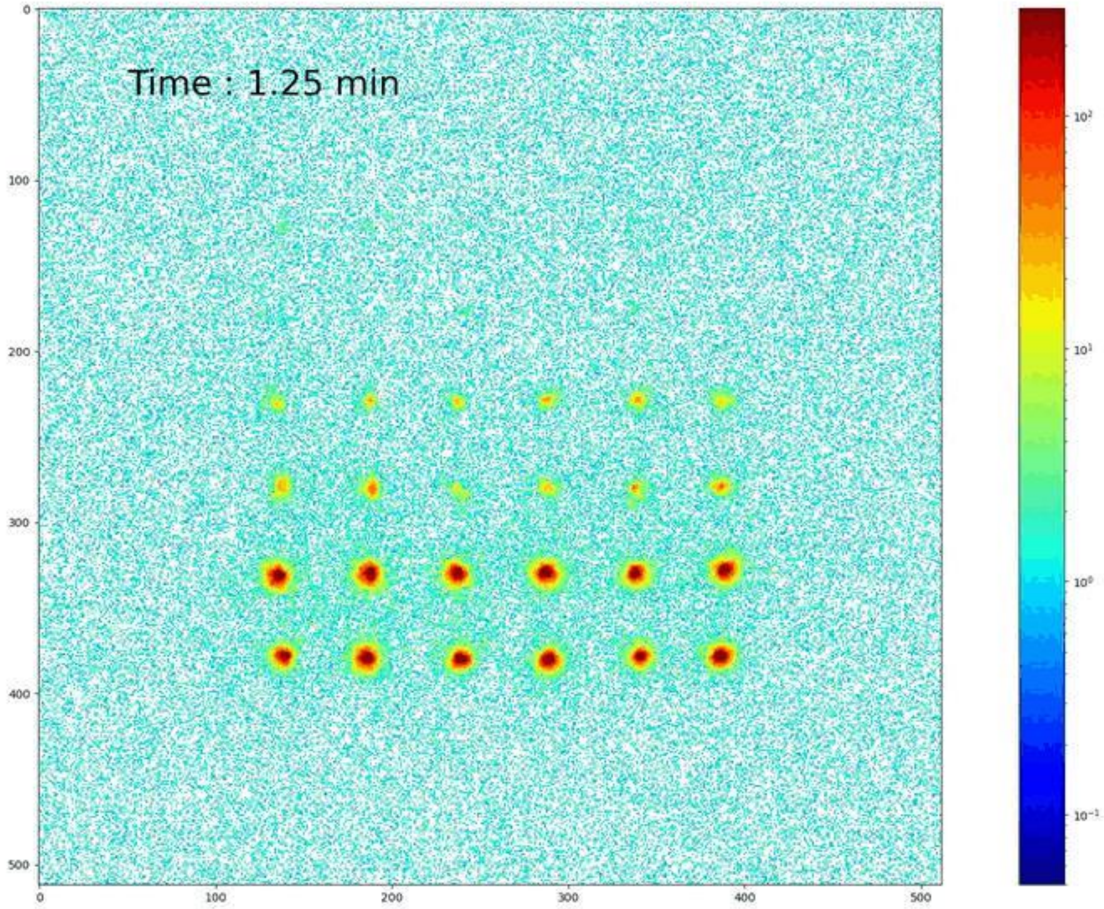




- ^{3}H concentration ↔ Sample activity (Bq)
- Assess the activity measurement sensitivity and dynamic range → Activities: 0.1 Bq, 1 Bq and 10 Bq

50

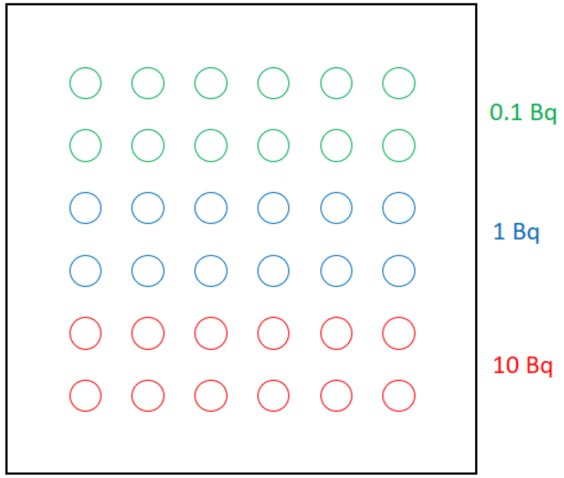
Beta imaging with Micromegas

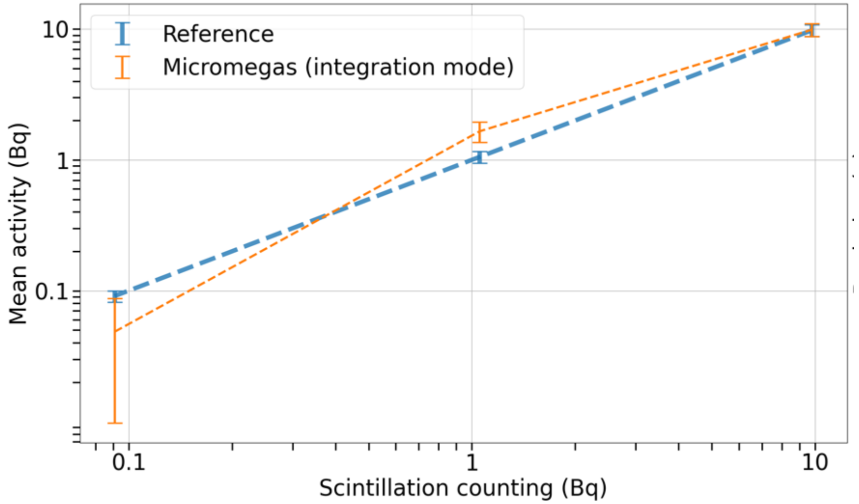


Light intensity profile over time

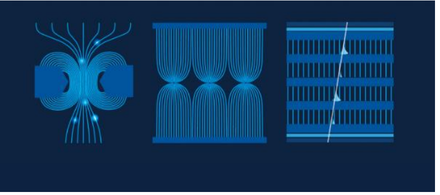
5 s exposure time frames for 1h acquisition

Gain ~ 10^4





A. Cools et al NIMA (2023)1048 167910



Summary

MPGDs, GEM and Micromegas, are mature technologies

Thin amplification region (~100 µm), well separated from conversion / drift region

- Fast collection of positive ions (~100 ns)
- Fast signals (~ ns)
- High gain (~10^5)
- High spatial resolution (~30 µm)
- High rate capability (~MHz/mm^2)
- Low ion backflow (~ 1%)
- More robust than wires
- Better ageing / radiation hardness
- Large area scalability
- Fabrication simplicity / lower cost
- Versatility (tracking, TPC, imaging)

Summary

- MPGDs today: GEM, Micromegas and µRWell

- Versatile, adaptable ➔ wide range of applications

High Energy Physics
Nuclear Physics
Rare event detection
Neutrino physics
Polarimetry
Applications beyond fundamental research: Muon tommography, Medical Physics, Neutron detection

Talks by **P. Iengo, M. Cortesi, J. Bortfeld**

Perspectives

- Challenging R&D
  - Optical readout
  - High rates/Ageing
  - Large areas

RD51 MPGD School 2023 E. Oliveri

- R&D for future colliders: Future Cicular collider (FCC),Cicular electron positron collider (CEPC), Electron Ion Collider (EIC)…
  - Trackers
  - Muon detectors

Talk D. Gonzalez

Thanks!

Acknowledgements

D. Attié, F. Jeanneau, Y. Giomataris, E. Oliveri,
T .Papaevangelou, F. Sauli, M. Titov, M. Vandenbroucke

Further reading

F. Sauli and A. Sharma, «Micro-patern Gaseous Detectors», *Ann.Rev.Nucl.Part.Sci.* 49 (1999) 341-388

Y. Giomataris, “Development and prospects of the new gaseous detector Micromegas”, NIM A 419 (1998) 239-250

F. Sauli, “The gas electron multiplier (GEM): Operating principles and applications”, NIM A 805 (2016) 2-24

S. Bressler, «The Thick Gas Electron Multiplier and its derivatives: Physics, technologies and applications, Progress Particle and Nuclear Physics 130 (2023) 104029

D. Attié et al., « Current Status and Future Developments of Micromegas Detectors for Physics and Applications”, Appl.Sciences 11 (2021) 12, 5362

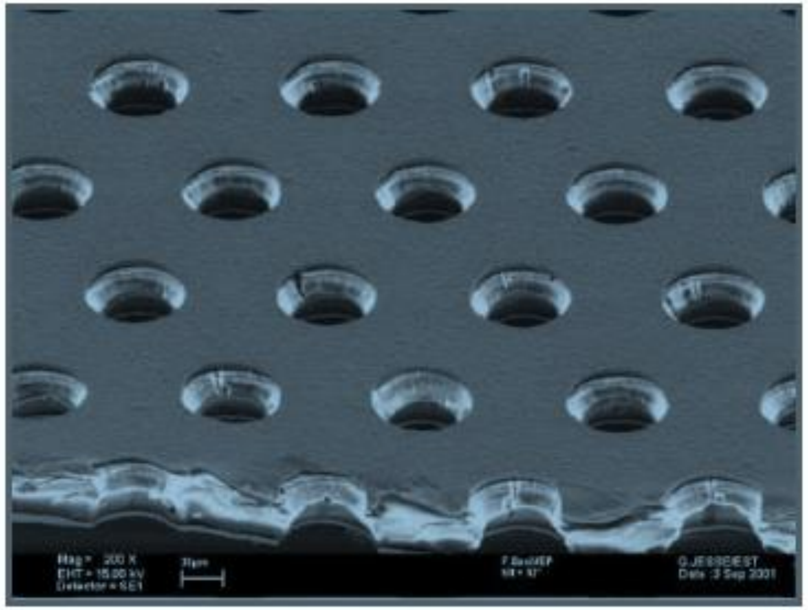
Gaseous Radiation Detectors, Fundamental and Applications, Fabio Sauli, Cambridge Monographs on Particle Physics, Nuclear Physics and Cosmology, Cambridge University Press

Micro-Pattern Gaseous Detectors: Principles of Operation and Applications, Fabio Sauli, World Scientific

Spare

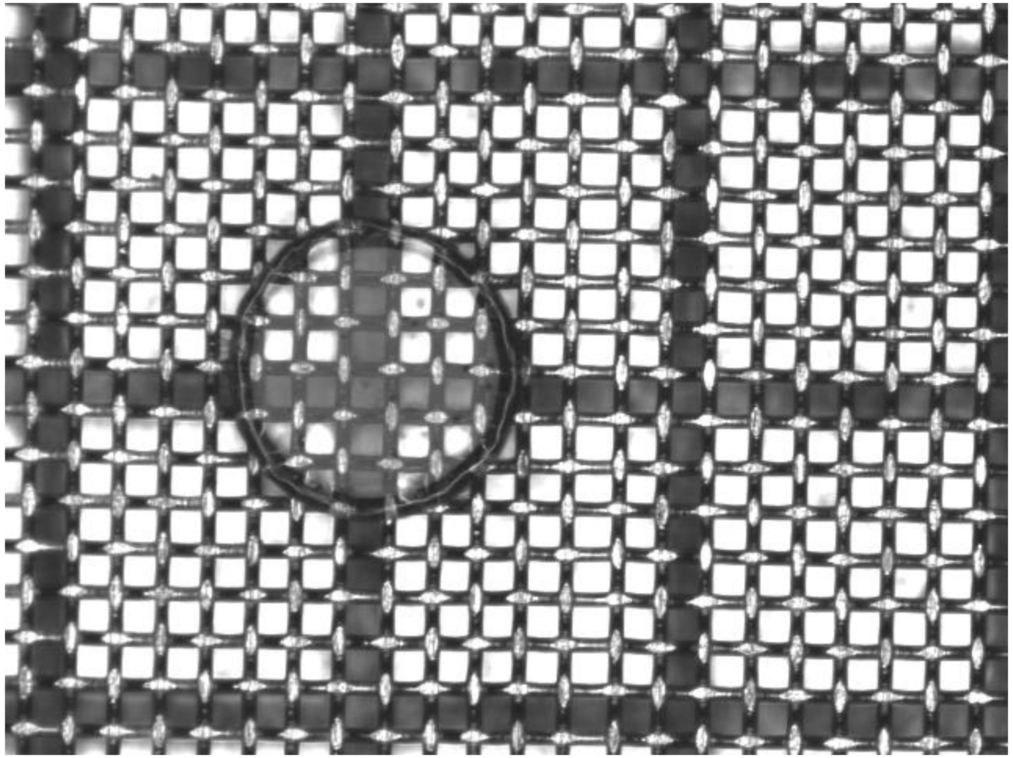
GEM Properties

- **High Rate Capability** → MHz/mm^2 (MIP - Minimum Ionizing Particles, 2MeV cm^2 /g)
- **High Gain** →Up to 10^5 -10^6
- **High Space Resolution**→ <100 μm
- **Good Time Resolution** →In general few ns , sub-ns in specific configuration
- **Good Energy Resolution**→10-20% FWHM @ soft X-Ray (6 KeV)
- **Excellent Radiation Hardness**
- **Good Ageing Properties**
- **Ion Backflow Reduction** → ~% level, below % in particular configurations
- **Large size**
- **Low material budget**
- **Low cost**



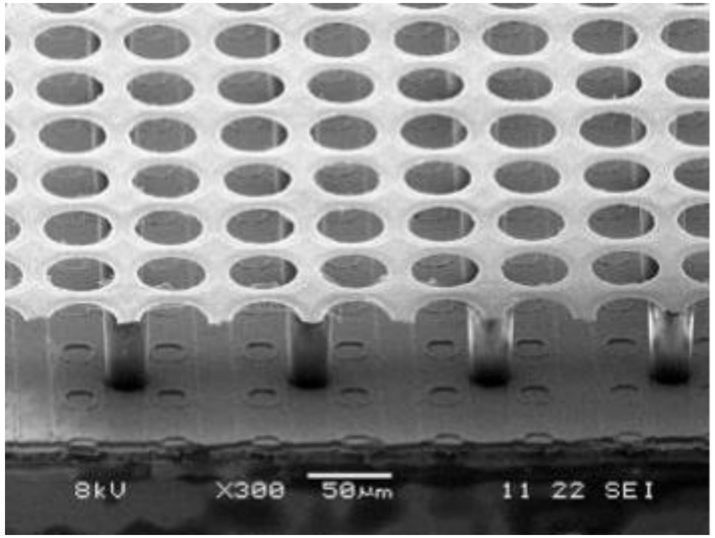
Micromegas properties

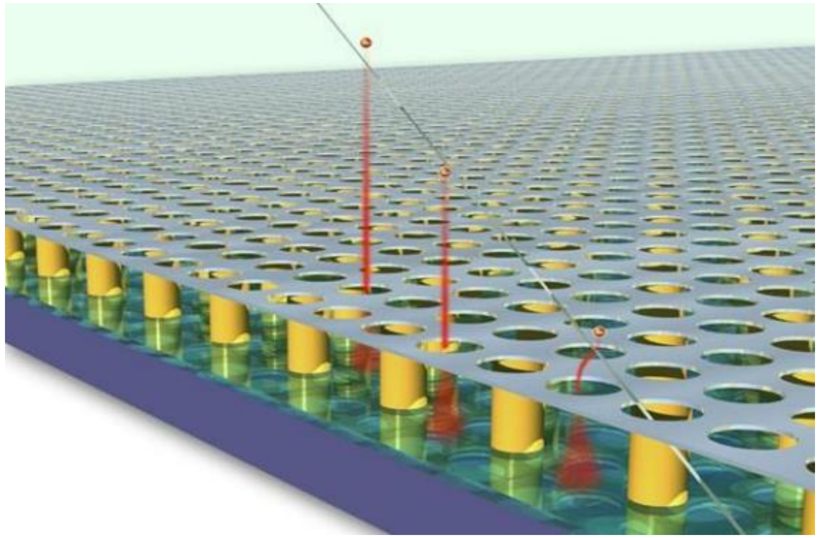
- High gain (>10^4)
- Good energy (11% @ 6 keV) and time resolution (< 1 ns)
- Good spatial resolution (~100 µm)
- Reduced ion feedback < 1%
- Radiation hardness (10^6 p/cm^2)
- Fast ion collection→ operation at high flux
- Good Ageing Properties
- Large size
- Low material budget
- Low cost
- Cope with sparks: resistive coating



Ingrid

M. Chefdeville et al., Nucl. Instr. Meth. Phys. Res. A 556, 490 (2006)
H. van der Graaf, Nucl. Instr. Meth. Phys. Res. A 580, 1023 (2007)





- Mesh is directly built on the silicon pixel readout chip
- High gain and small pixel size allow single electron detection
- High resitive silicon oxide layer protection against discharges

Hybrid Implementation: GEM + Micromegas

Contents lists available at ScienceDirect

Nuclear Inst. and Methods in Physics Research, A

journal homepage: www.elsevier.com/locate/nima

The hybrid MPGD-based photon detectors of COMPASS RICH-1

J. Agarwala[a,j], M. Alexeev[b], C.D.R. Azevedo[c], F. Bradamante[d], A. Bressan[d], M. Büchele[e], C. Chatterjee[d], M. Chiosso[b], A. Cicuttin[a,j], P. Ciliberti[d], M.L. Crespo[a,j], S. Dalla Torre[a], S. Dasgupta[a], O. Denisov[f], M. Finger[g], M. Finger Jr.[g], H. Fischer[e], M. Gregori[a], G. Hamar[a], F. Herrmann[e], S. Levorato[a], A. Martin[d], G. Menon[a], D. Panzieri[h], G. Sbrizzai[d], S. Schopferer[e], M. Slunecka[g], M. Sulc[i], F. Tessarotto[a,*], J.F.C.A. Veloso[c], Y. Zhao[a]

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[b] *INFN, Sezione di Torino and University of Torino, Torino, Italy*
[c] *I3N - Physics Department, University of Aveiro, Aveiro, Portugal*
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[e] *Universität Freiburg, Physikalisches Institut, Freiburg, Germany*
[f] *INFN, Sezione di Torino, Torino, Italy*
[g] *Charles University, Prague, Czech Republic and JINR, Dubna, Russia*
[h] *INFN, Sezione di Torino and University of East Piemonte, Alessandria, Italy*
[i] *Technical University of Liberec, Liberec, Czech Republic*
[j] *Abdus Salam ICTP, 34151 Trieste, Italy*

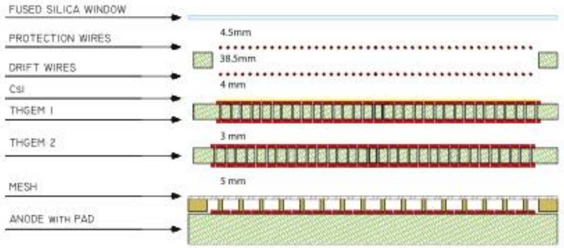

Fig. 2. Sketch of the hybrid single photon detector: two THGEM layers are coupled to a MM. Drift and protection wire planes are shown. Image is not to scale.

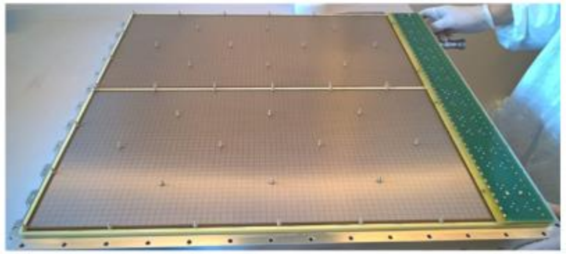

Fig. 3. Two Micromegas mounted side by side in a PD. The pillars that preserve the distance between the micromesh and the THGEM above it are also visible.

Performance of large pixelised Micromegas detectors in the COMPASS environment

F. Thibaud,[1] P. Abbon, V. Andrieux, M. Anfreville, Y. Bedfer, E. Burtin, L. Capozza, C. Coquelet, Q. Curiel, N. d'Hose, D. Desforge, K. Dupraz, R. Durand, A. Ferrero, A. Giganon, D. Jourde, F. Kunne, A. Magnon, N. Makke, C. Marchand, D. Neyret, B. Paul, S. Platchkov, M. Usseglio and M. Vandenbroucke

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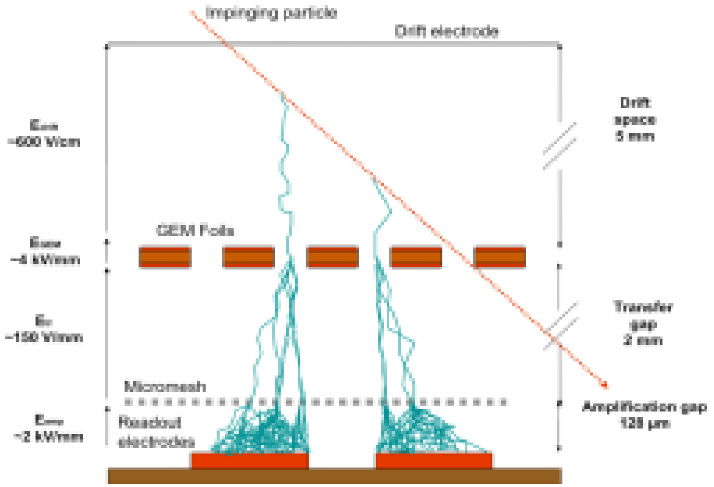
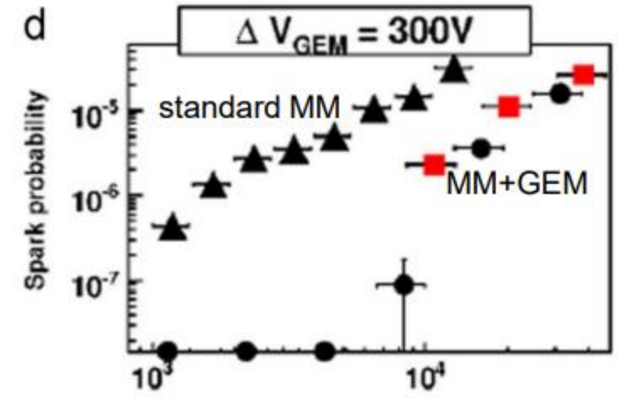
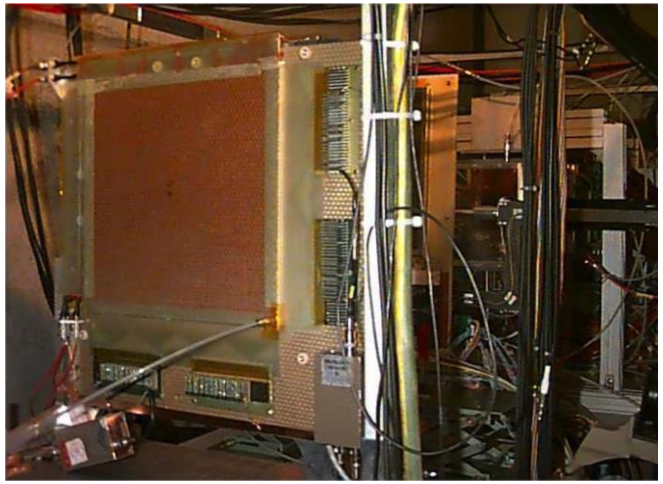


(a) Hybrid detector: insertion of a GEM foil above the micromesh.

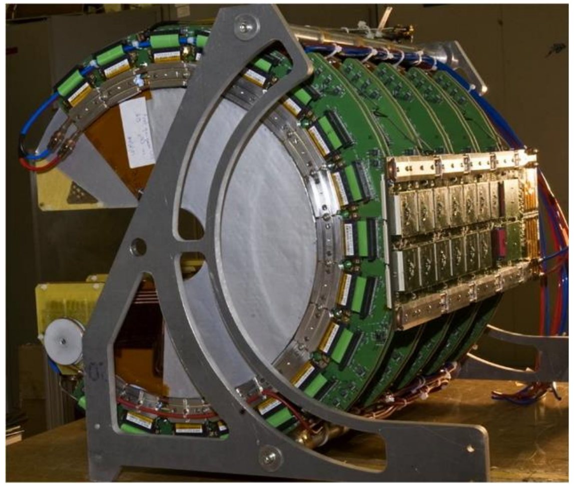


GEM Implementations

COMPASS

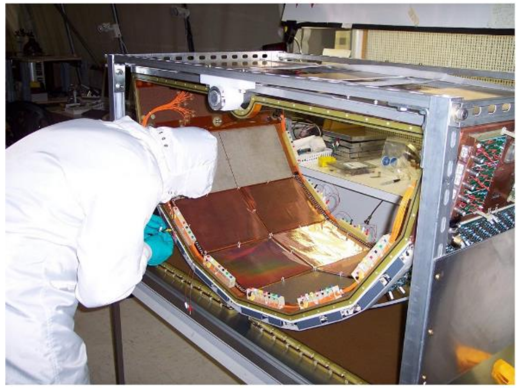


TOTEM

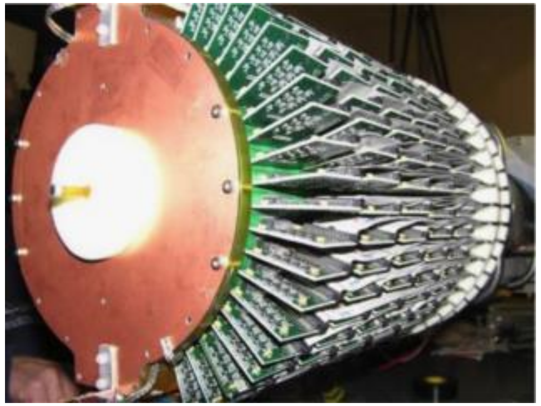


KLOE-2

HBD for PHENIX

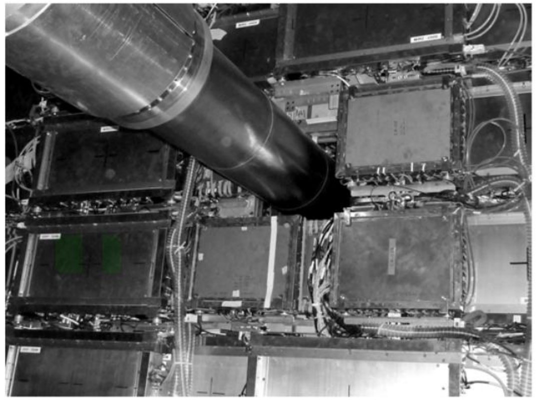


BONUS RADIAL TPC



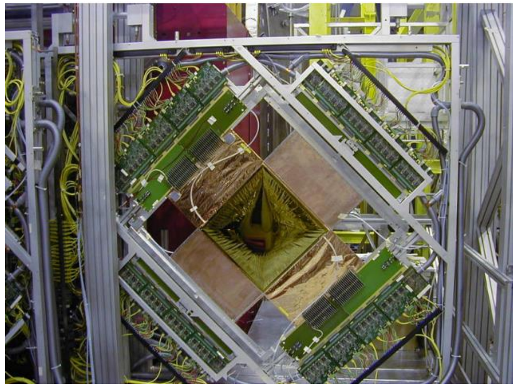
ALICE TPC UPGRADE

LHCB



Micromegas Implementations

COMPASS

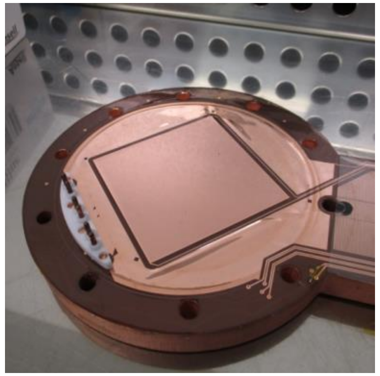


CLAS12

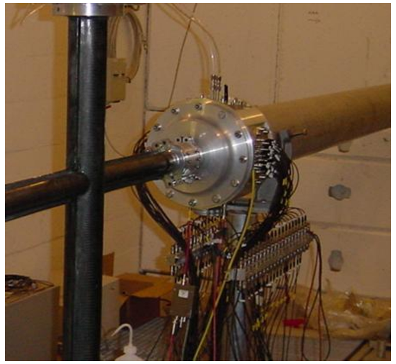
ATLAS-NSW

T2K

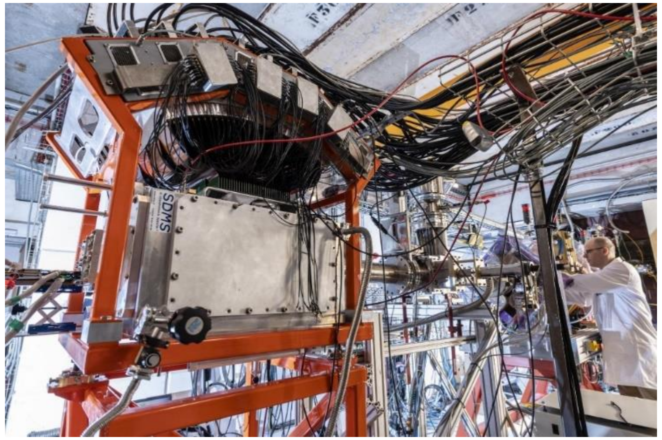
CAST



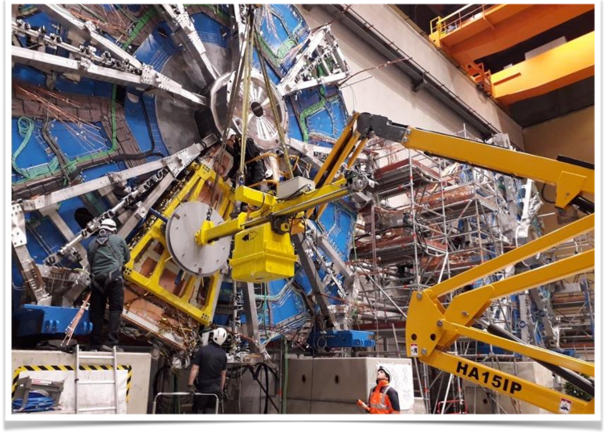
NTOF



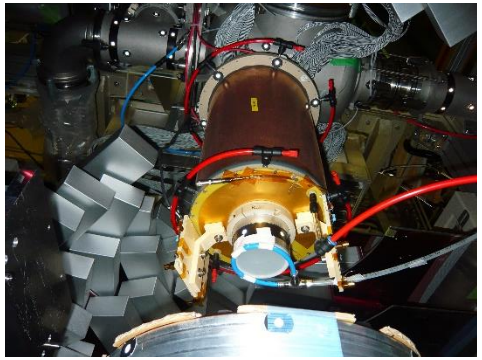
ACTAR-TPC



ATLAS-NSW



MINOS



ND280 upgrade High-Angle TPCs