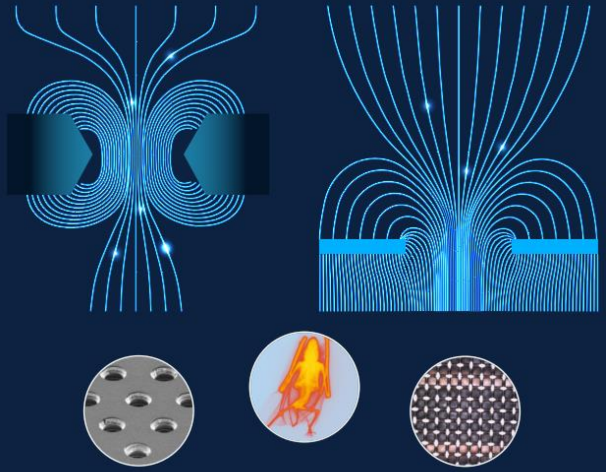
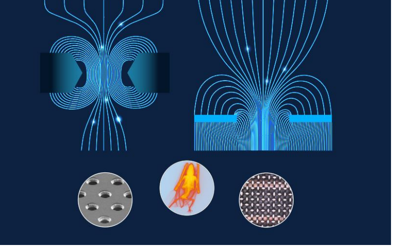


RD51
Micro Pattern Gaseous Detectors
School

CERN
27 November - 1 December 2023

Micro Pattern Gaseous Detectors 1

Esther Ferrer Ribas
IRFU/CEA



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

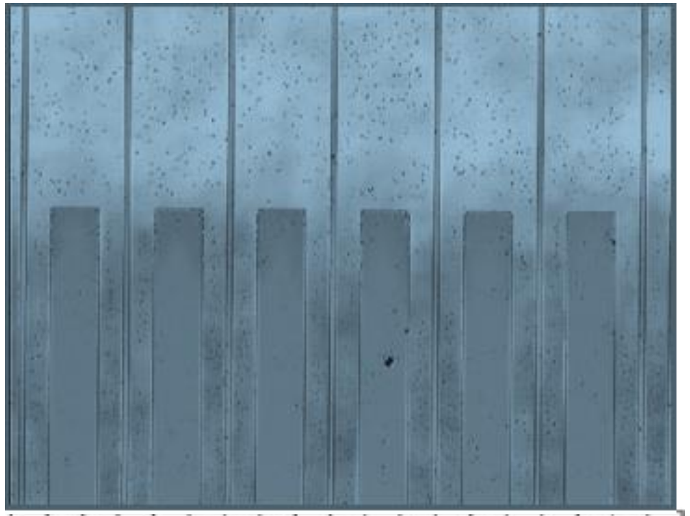
MSGC

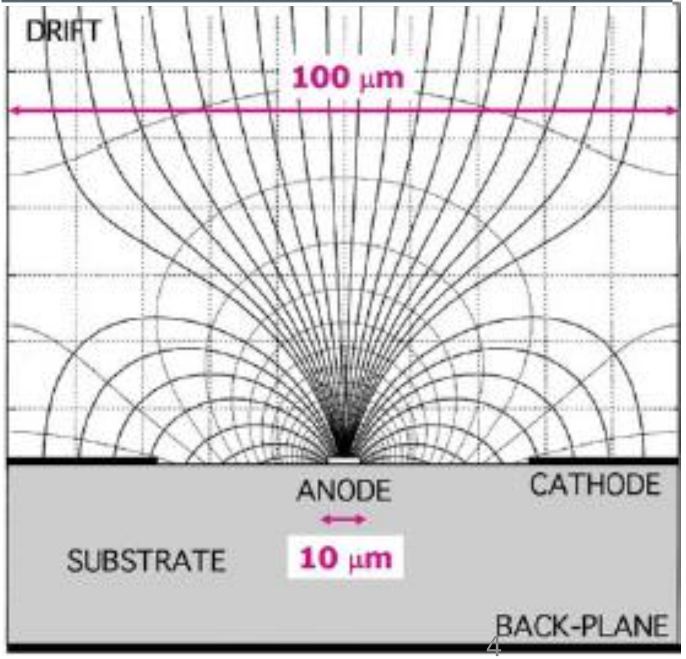
Performance

- 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.

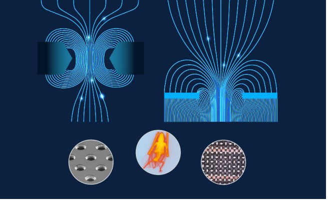
Limitations:

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

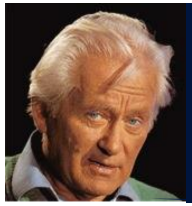




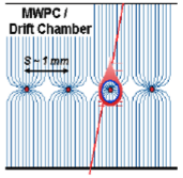
Credit: Sauli « Gaseous Radiation Detectors »



Birth of MPGD

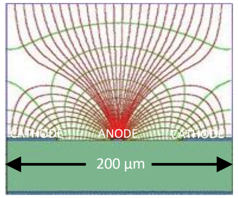


MWPC
Multi-Wire Proportional Chamber
G. Charpak et al., 1968

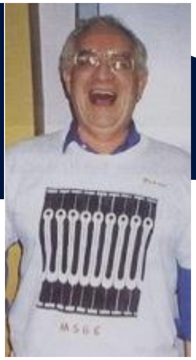


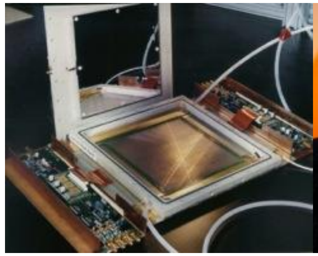
TPC
Time Projection Chamber
D. R. Nygren et al., 1974

MPGD



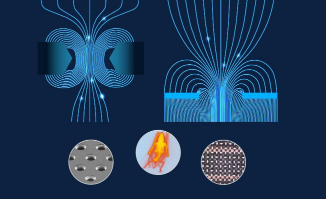
MSGC
Micro-Strip Gas Chamber
A. Oed, 1988





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

GEM
Gas Electron Multiplier
F. Sauli, 1997



Gas Electron Multiplier (GEM)

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

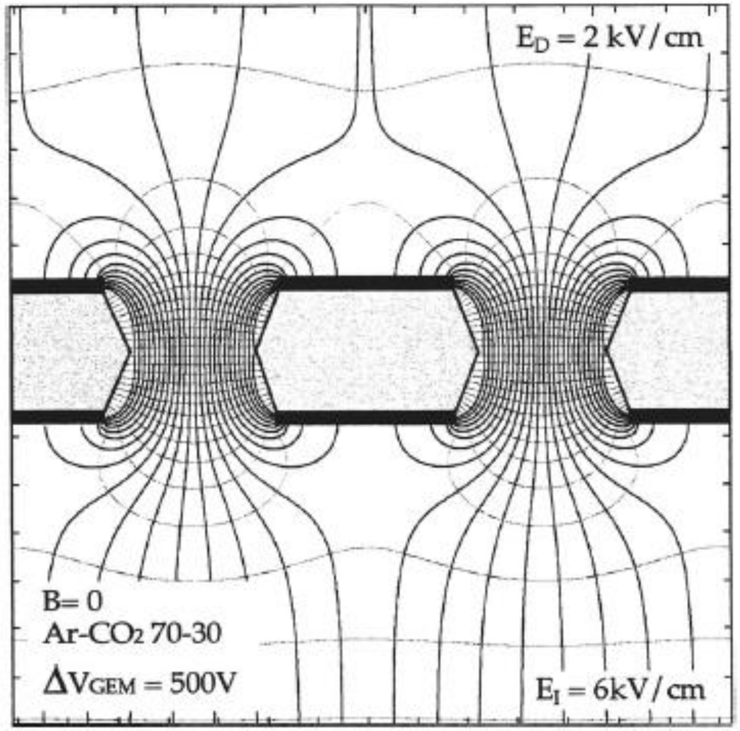
Received 6 November 1996

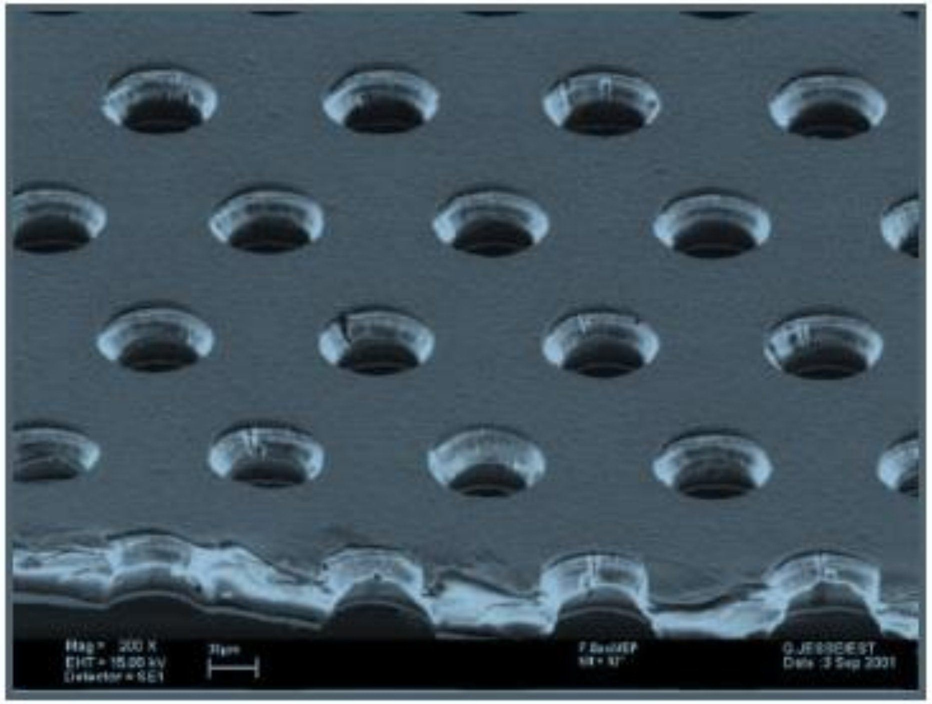
Abstract

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

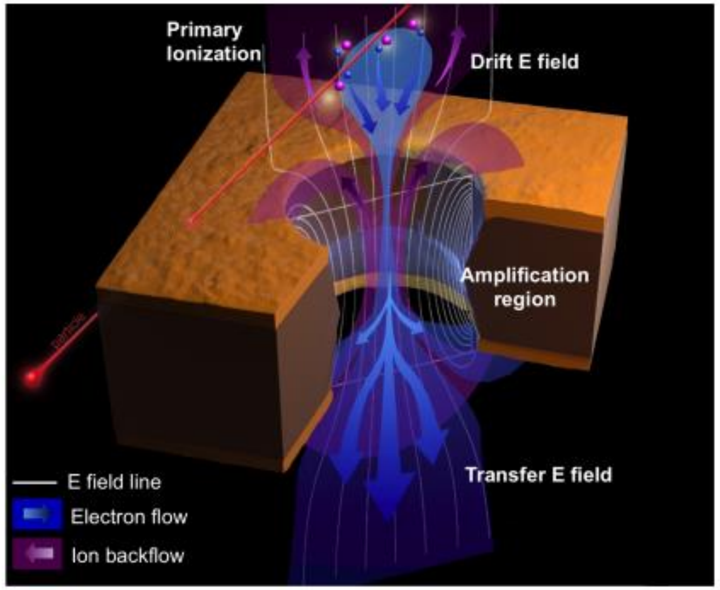


FIGURE 4.24: Schematic representation of a GEM hole in operation.

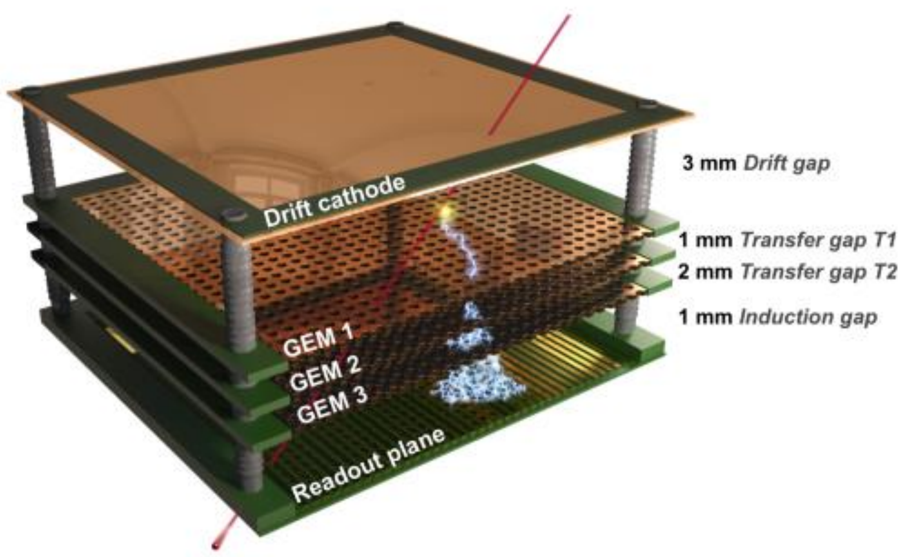


FIGURE 4.27: Schematic view of a triple-GEM detector.

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

Manufacturing of GEM

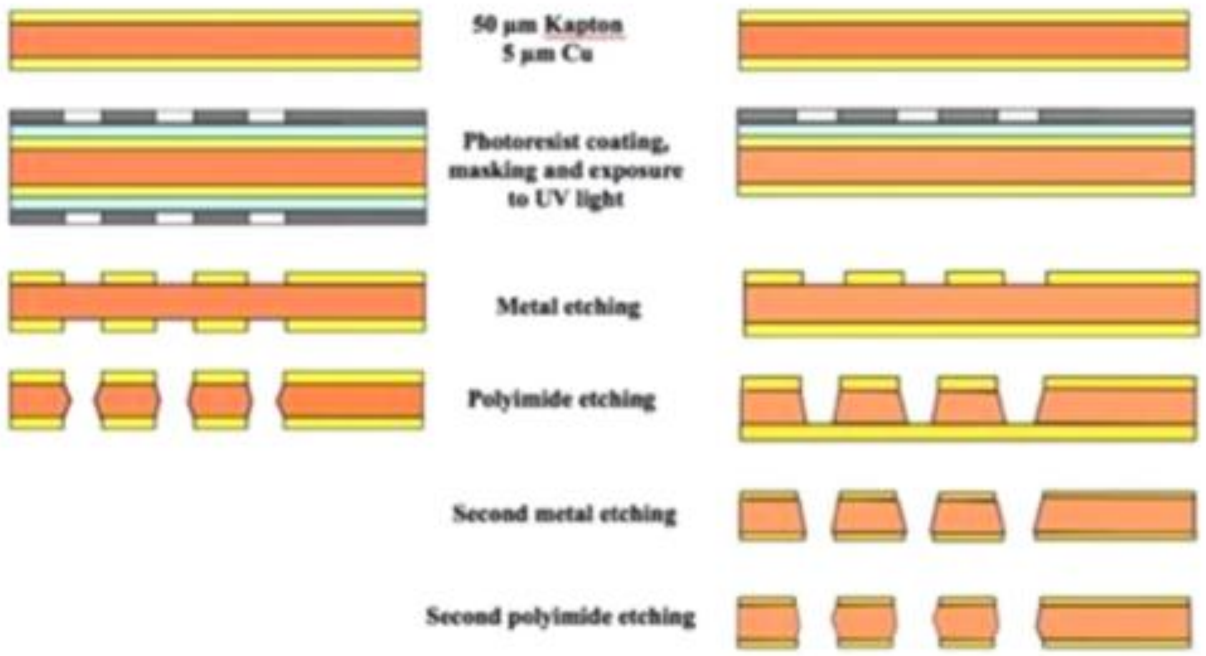
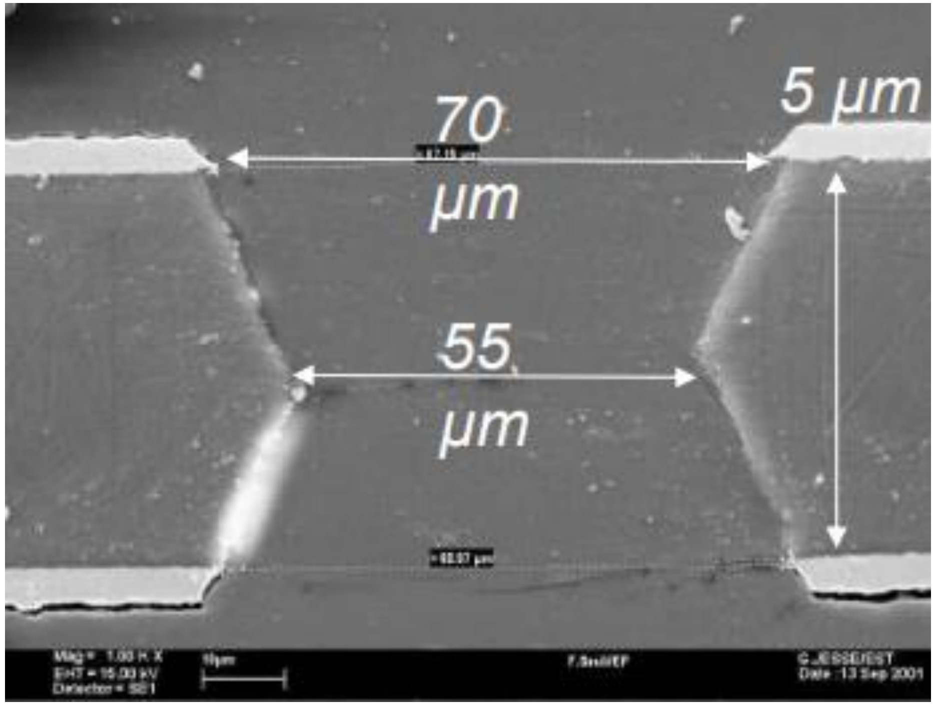


Fig.17. Double- (left) and single-mask GEM manufacturing.



Details tomorrow « **Manufacturing techniques » by Rui de Oliveira**

Performance in single GEM

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

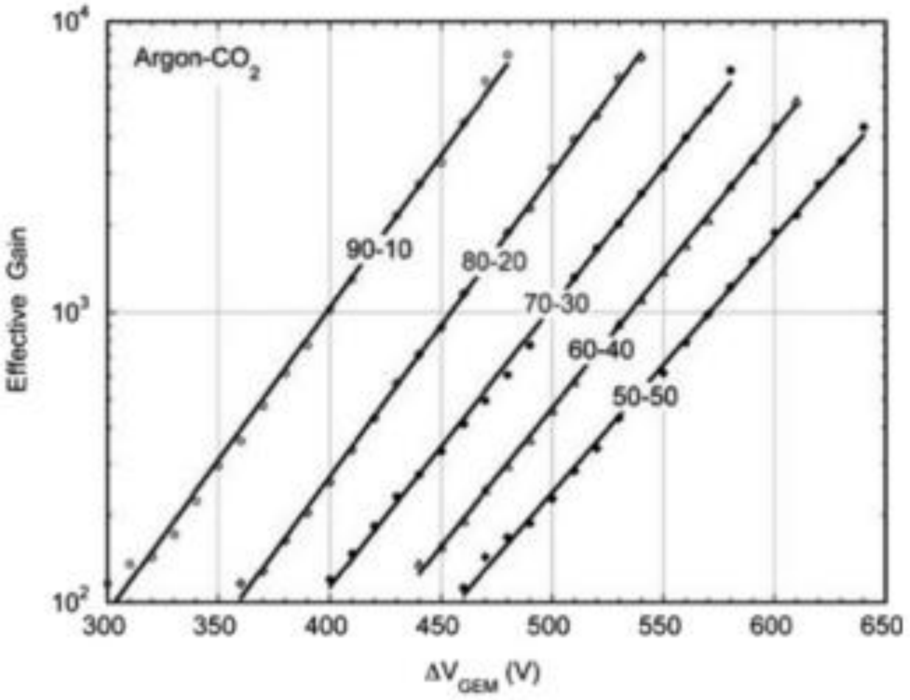


Fig. 8. Single GEM effective gain as a function of voltage in Ar–CO_2 mixtures at atmospheric pressure.

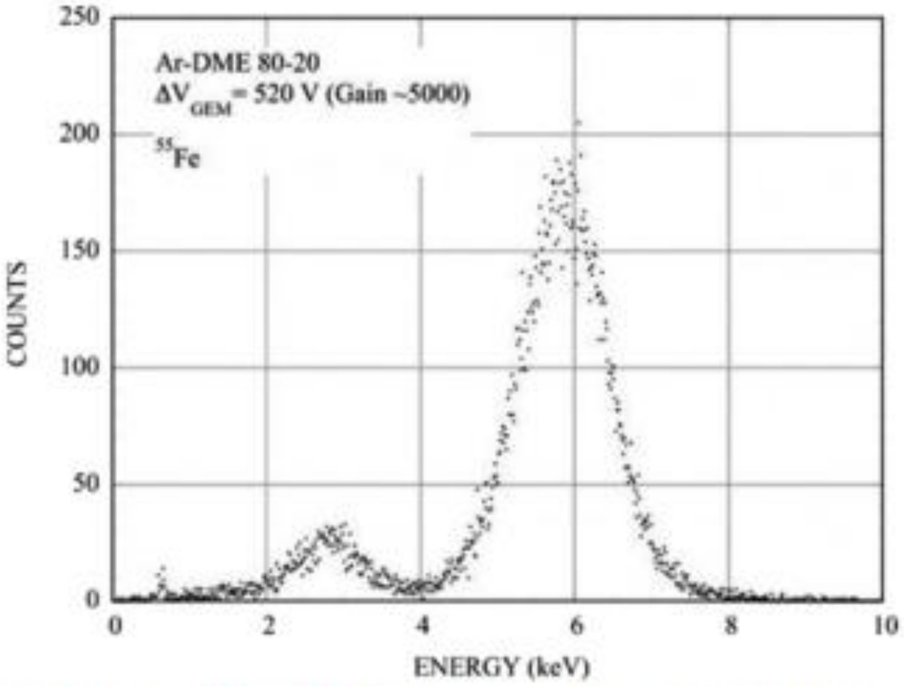


Fig. 9. Pulse height spectrum on 5.9 keV for a single GEM. The relative energy resolution is ~17% FWHM.

Influence of the holes geometry

Optimum hole diameter ~ foil thickness
Narrower holes larger fields for a fixed V but losses on the wall compensante for the higher gain

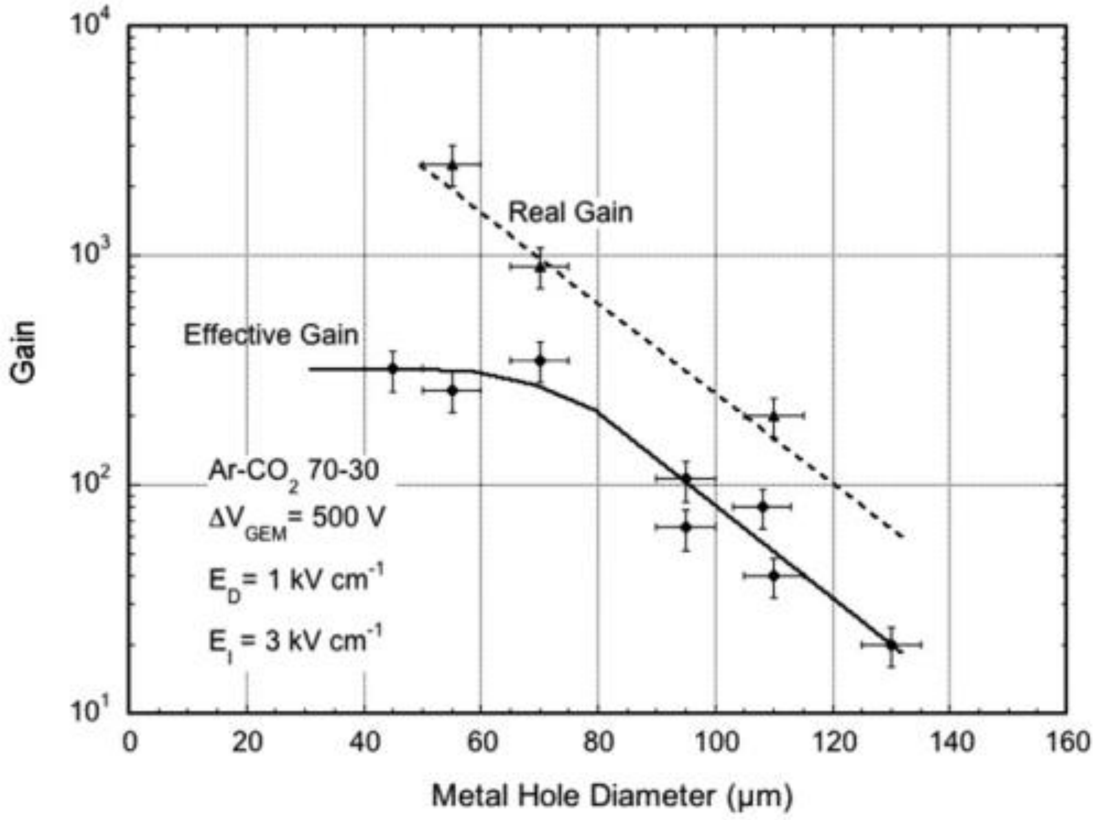


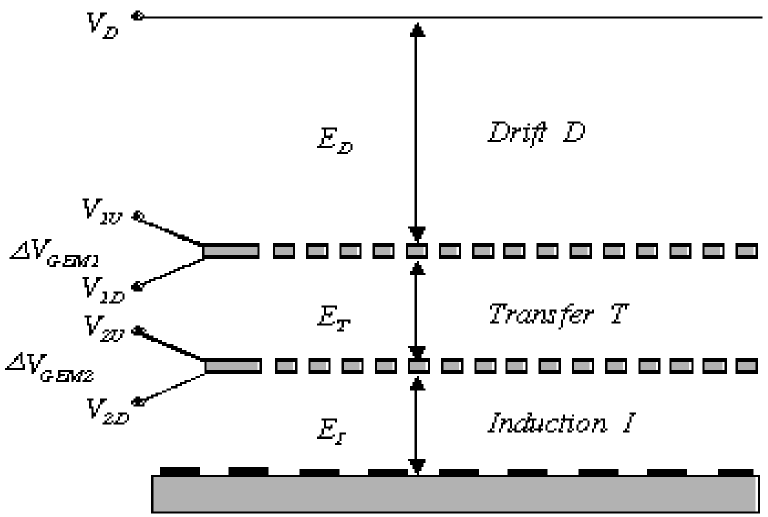
Fig. 4. Effective and real gain at fixed GEM voltage as a function of hole's diameter.

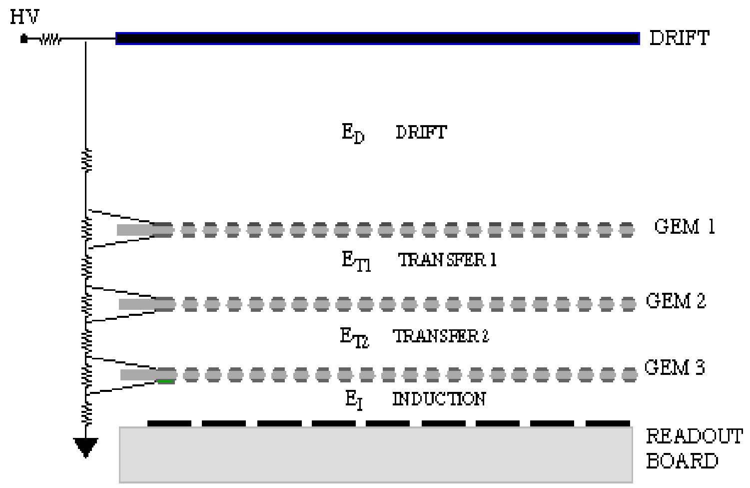
Effective gain= Detected electrons/Primary electrons

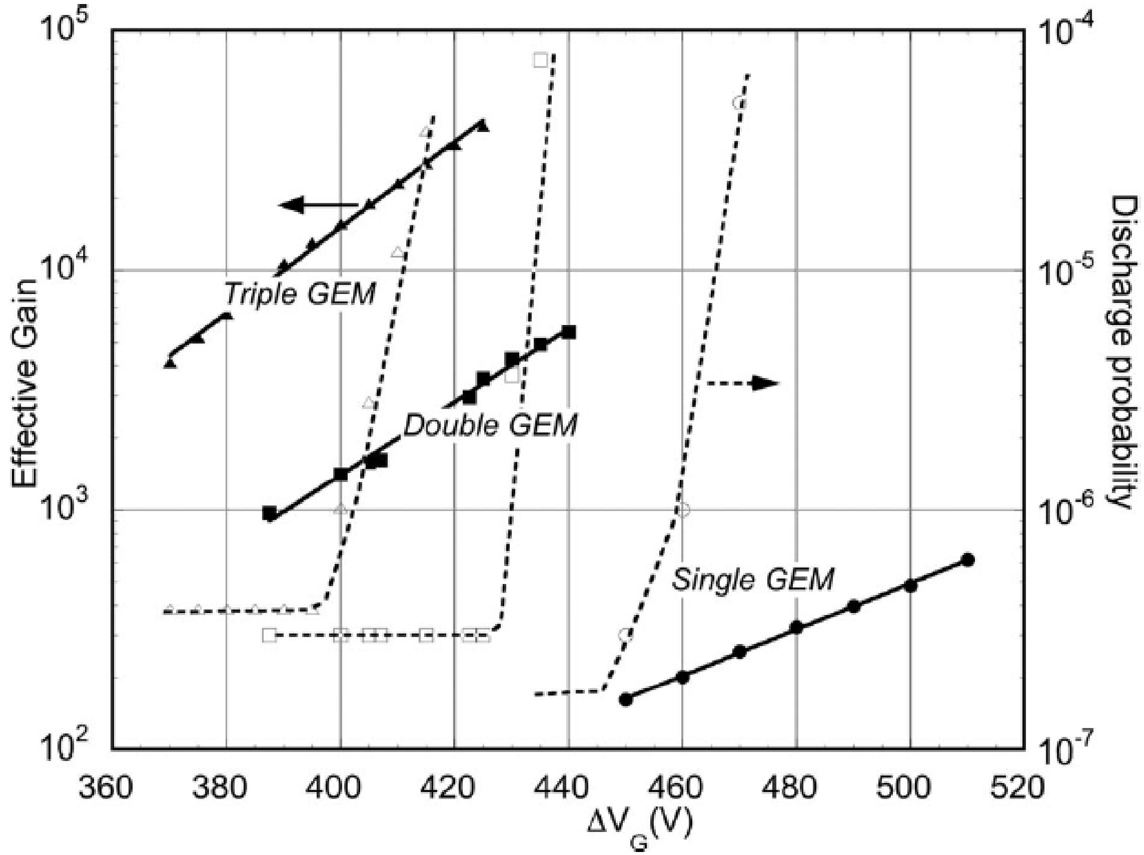
F. Sauli, NIM A 805 (2016) 2-24

Multi-GEM

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

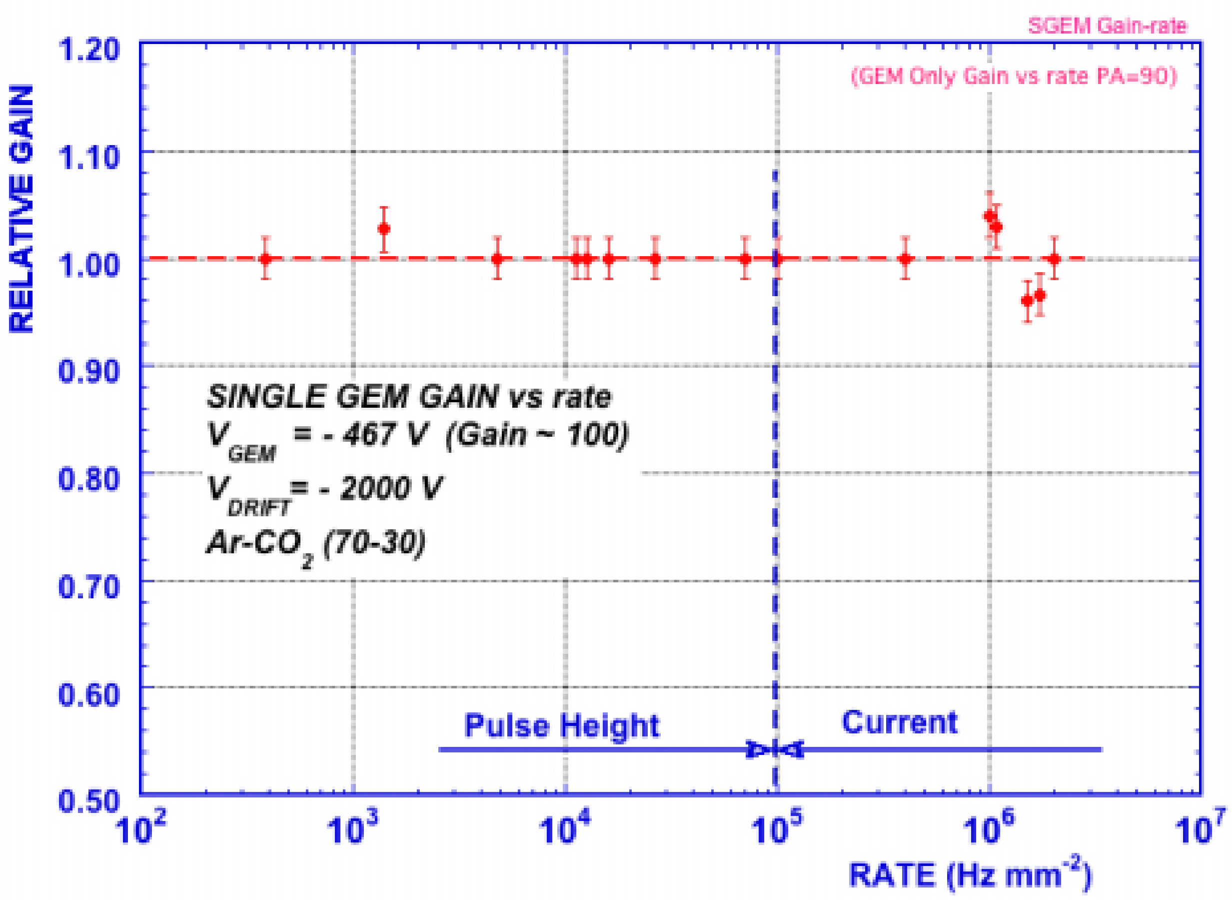






S. Bachmann et al,
Nucl. Instr. and Meth. A479(2002)294

GEM Rate capability



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

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

GEM spatial resolution

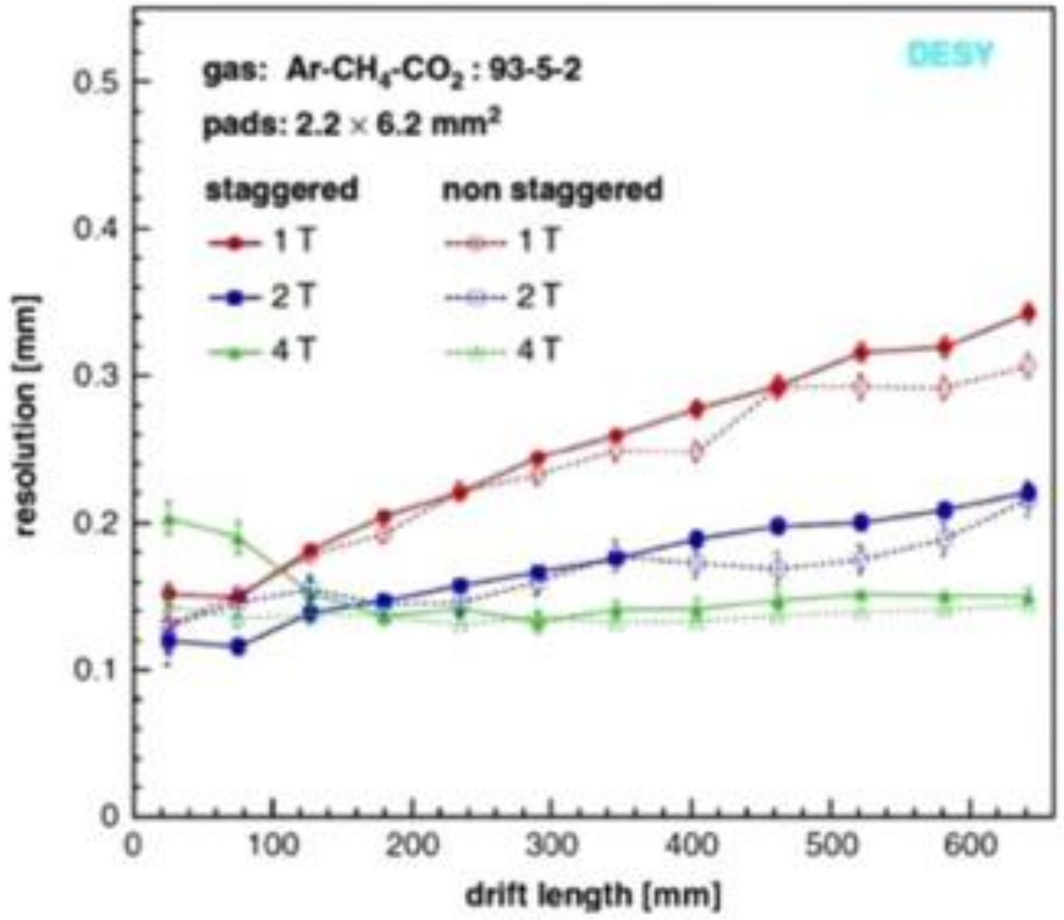
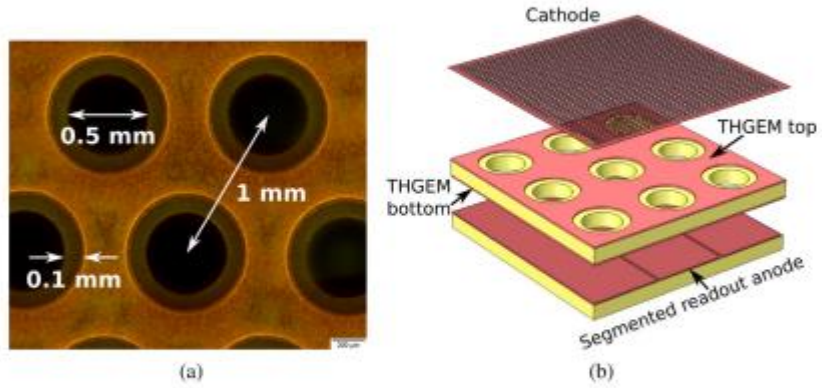


Fig. 46. GEM-TPC longitudinal resolution as a function of drift length and magnetic field.

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

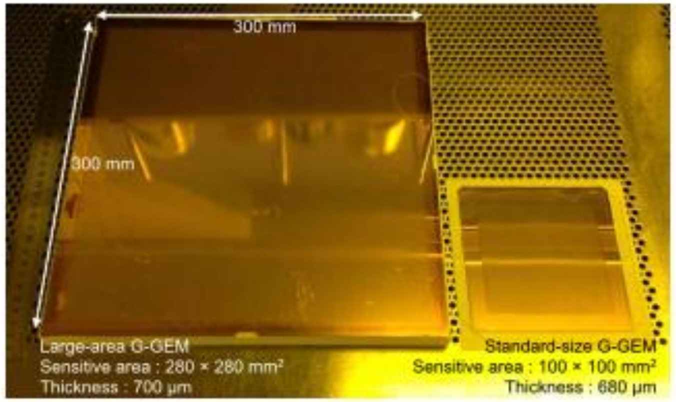
GEM family

THICKGEM/LEM



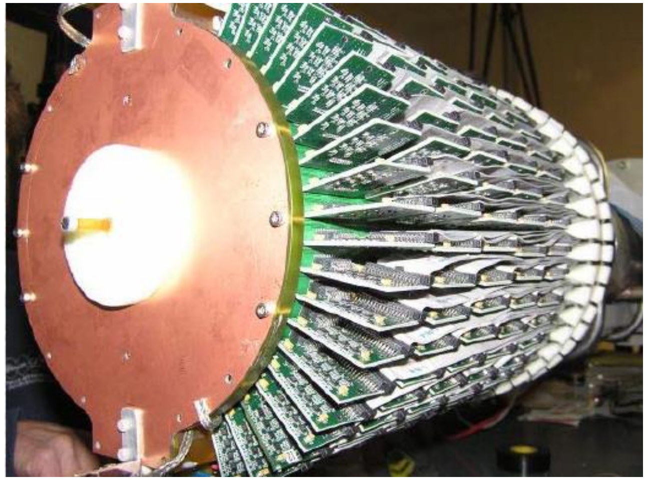
S. Bressler et al. , Progress Particle and Nuclear Physics 130 (2023) 104029

GLASSGEM

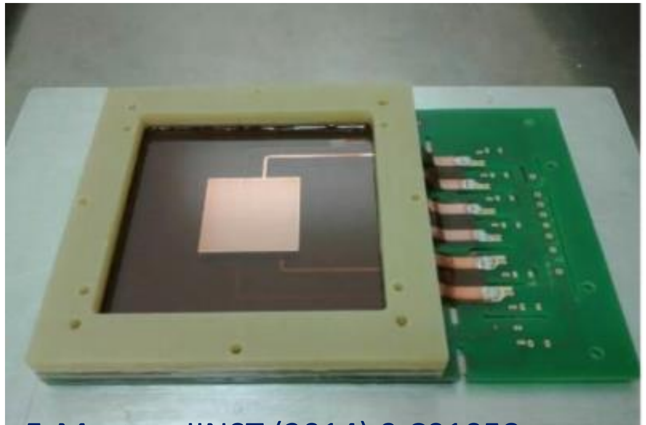


Y. Mitsuya et al., NIM A 795 (2015) 156-159

Cylindrical GEM



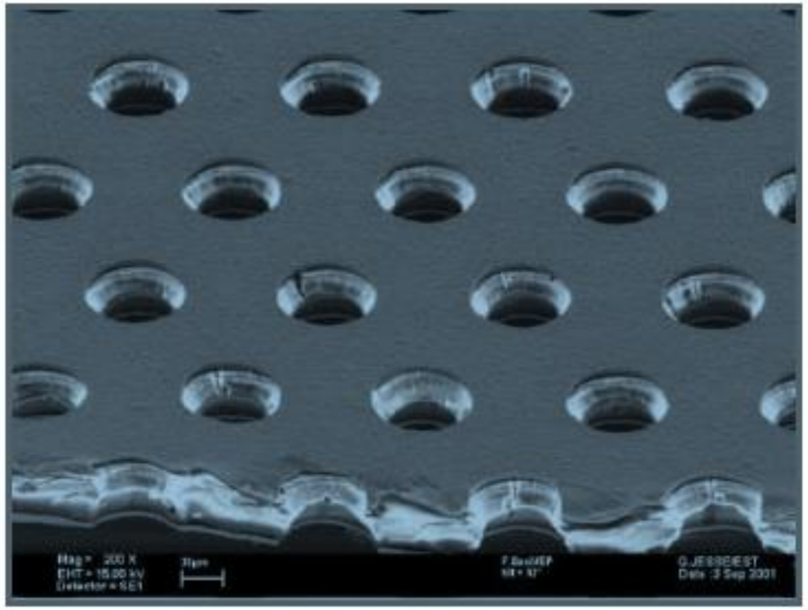
GEMPix: a triple GEM structure read by 50 micron pixels

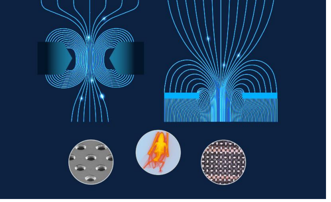


F. Murtas, JINST (2014) 9 C01058

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

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*

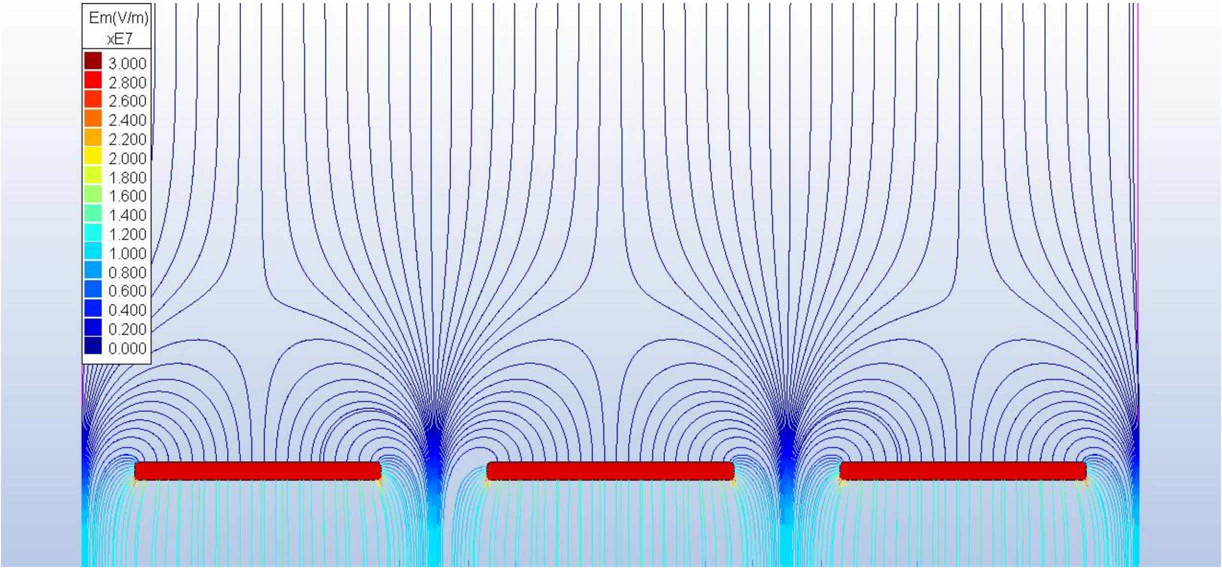
[b] *Ecole Superieure de Physique et Chimie Industrielle de la ville de Paris, ESPECI, Paris, ESPCI, Paris, France* and *CERN/AT, Geneva, Switzerland*

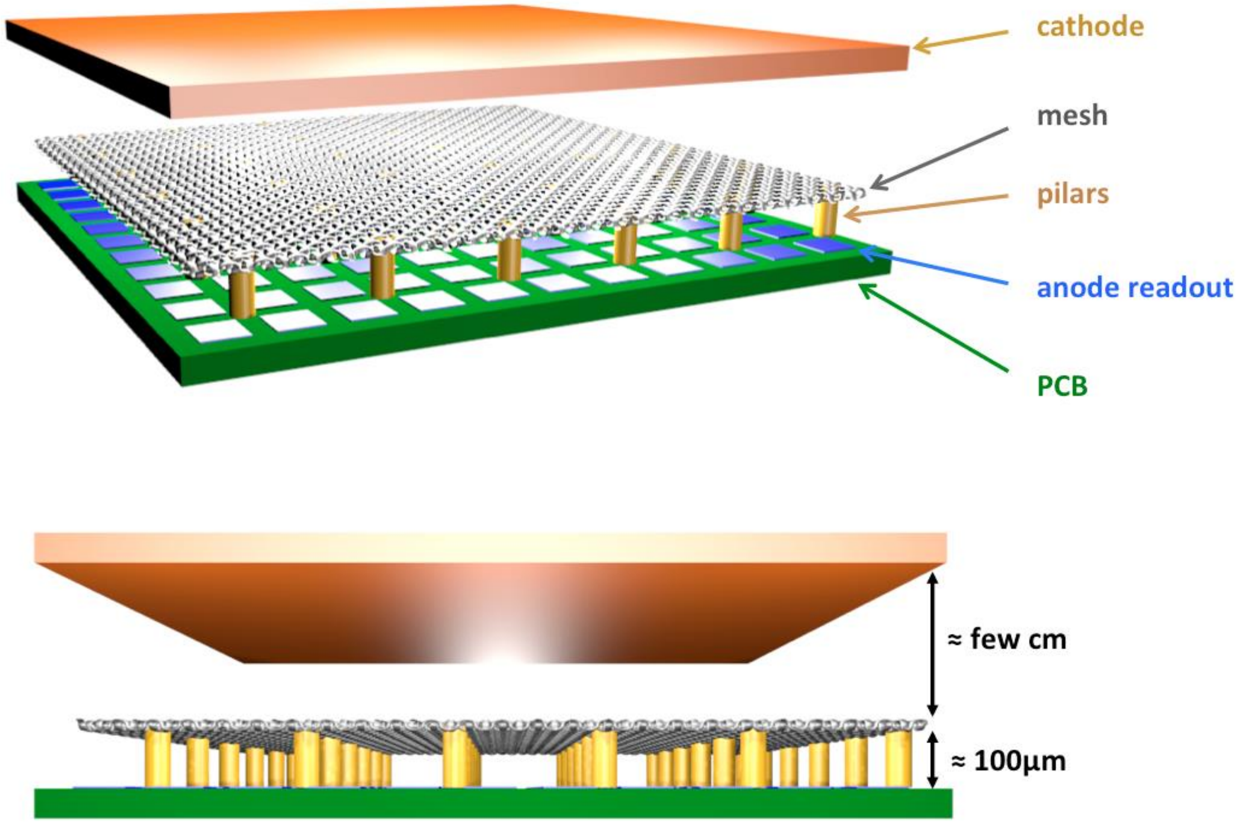
Received 24 January 1996

Abstract

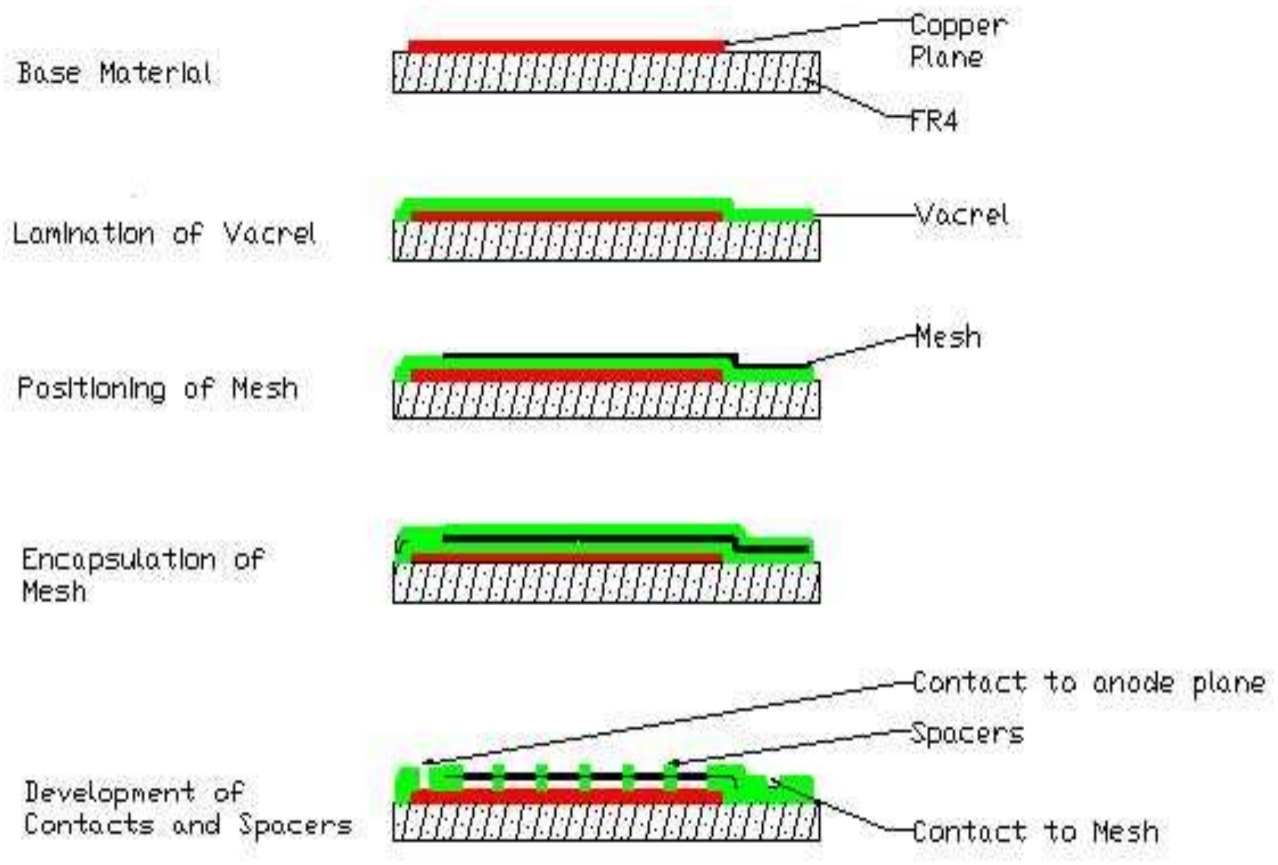
We describe a novel structure for a gaseous detector that is under development at Saclay. It consists of a two-stage parallel-plate avalanche chamber of small amplification gap (100 μm) combined with a conversion-drift space. It follows a fast removal of positive ions produced during the avalanche development. 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.

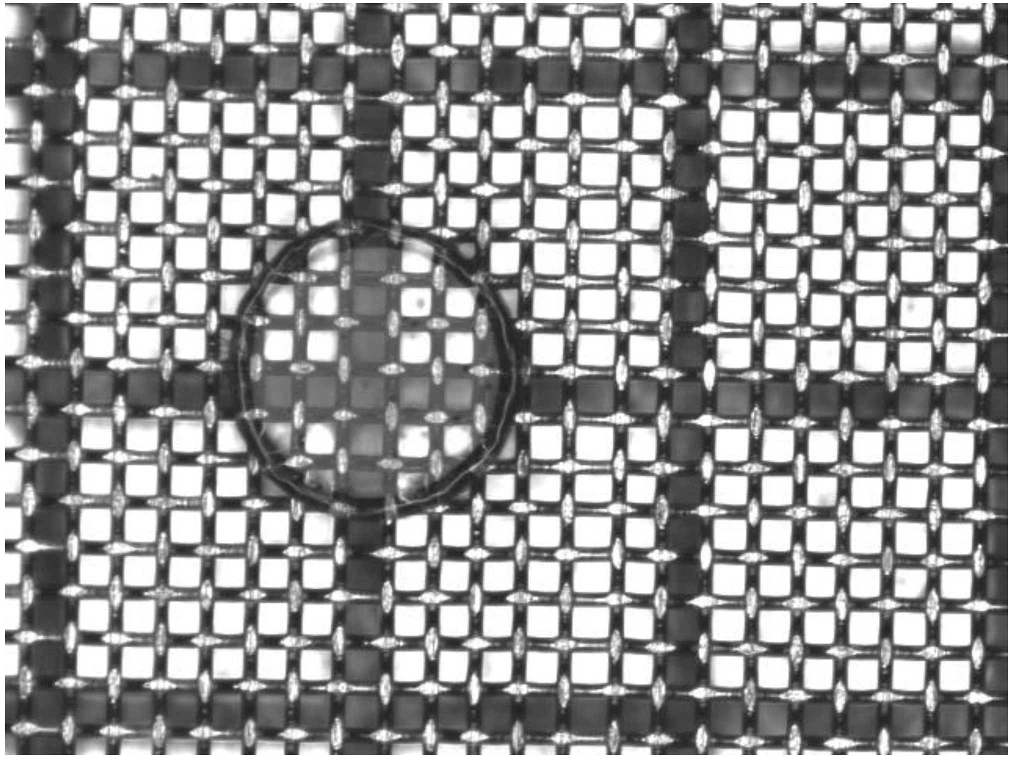
Micromegas


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

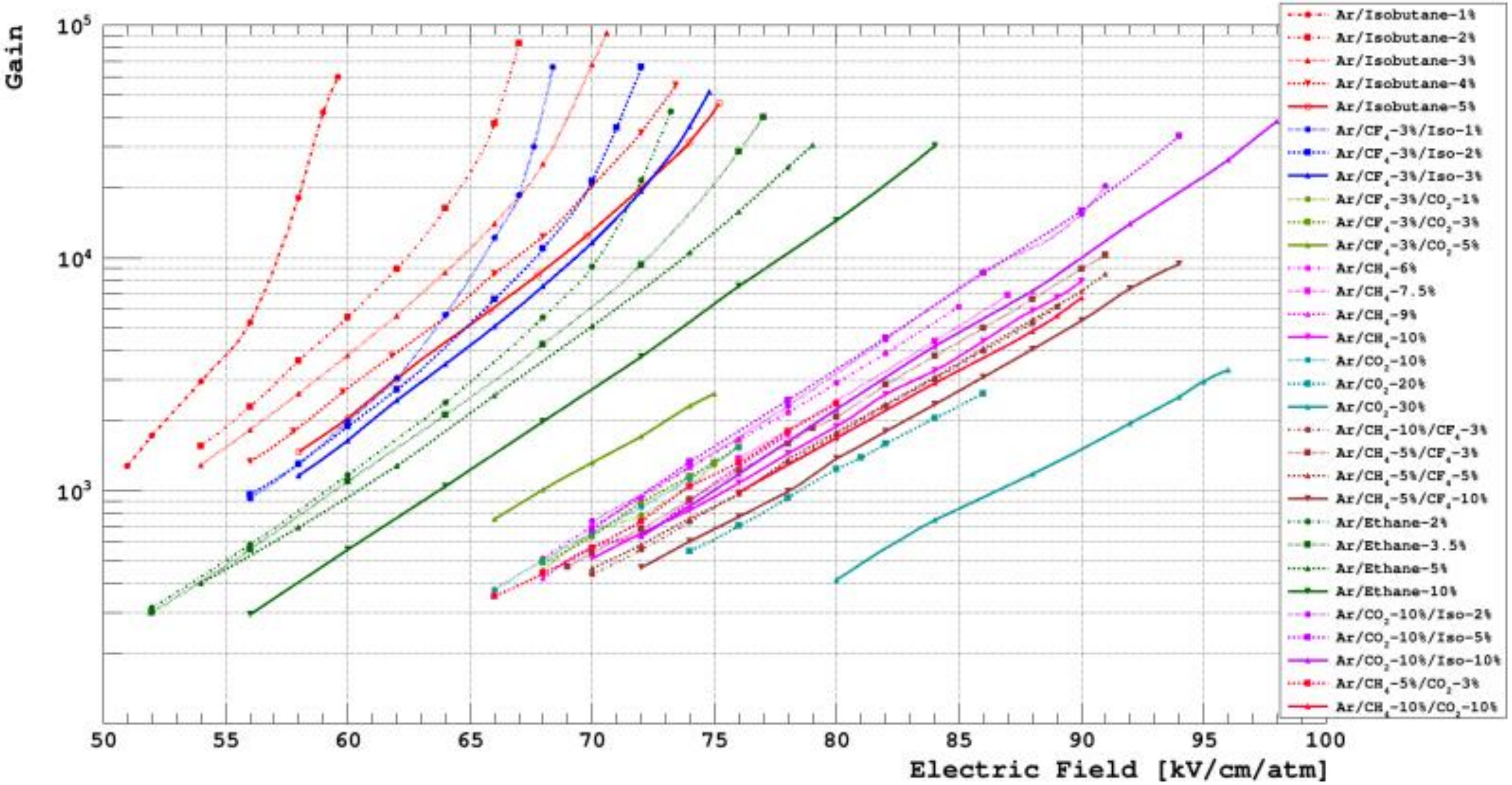
Manufacturing of Micromegas





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, Octobre 2022

Micromegas spatial resolution

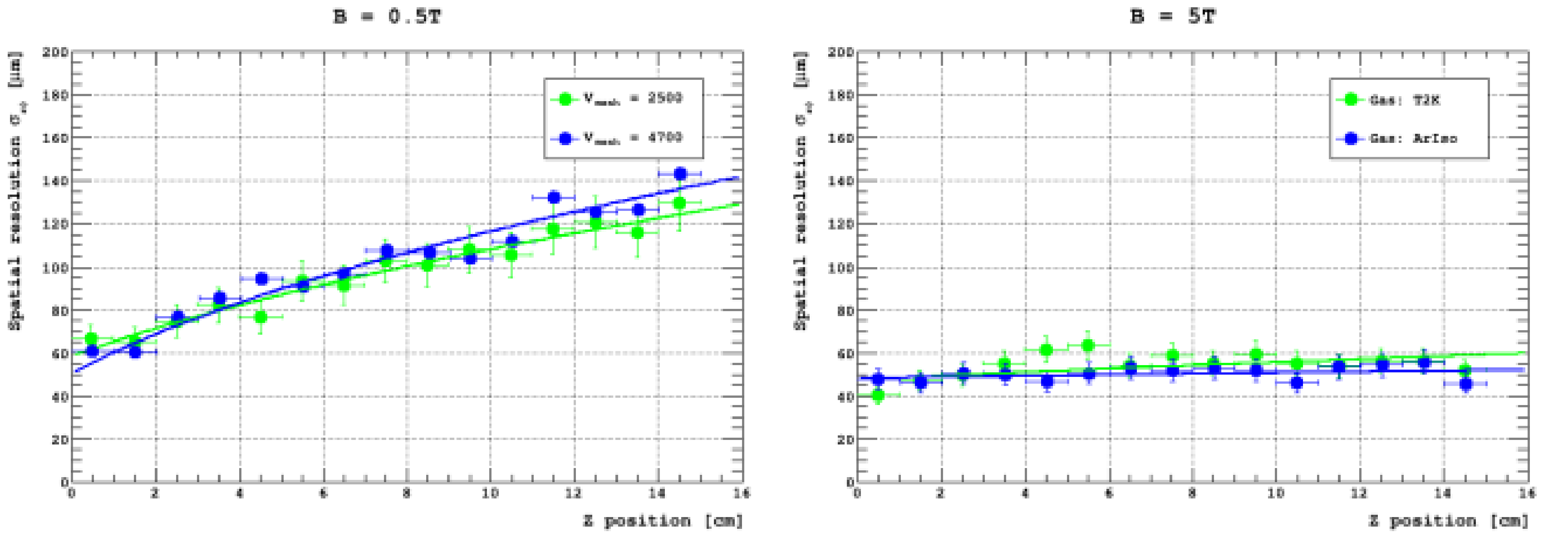
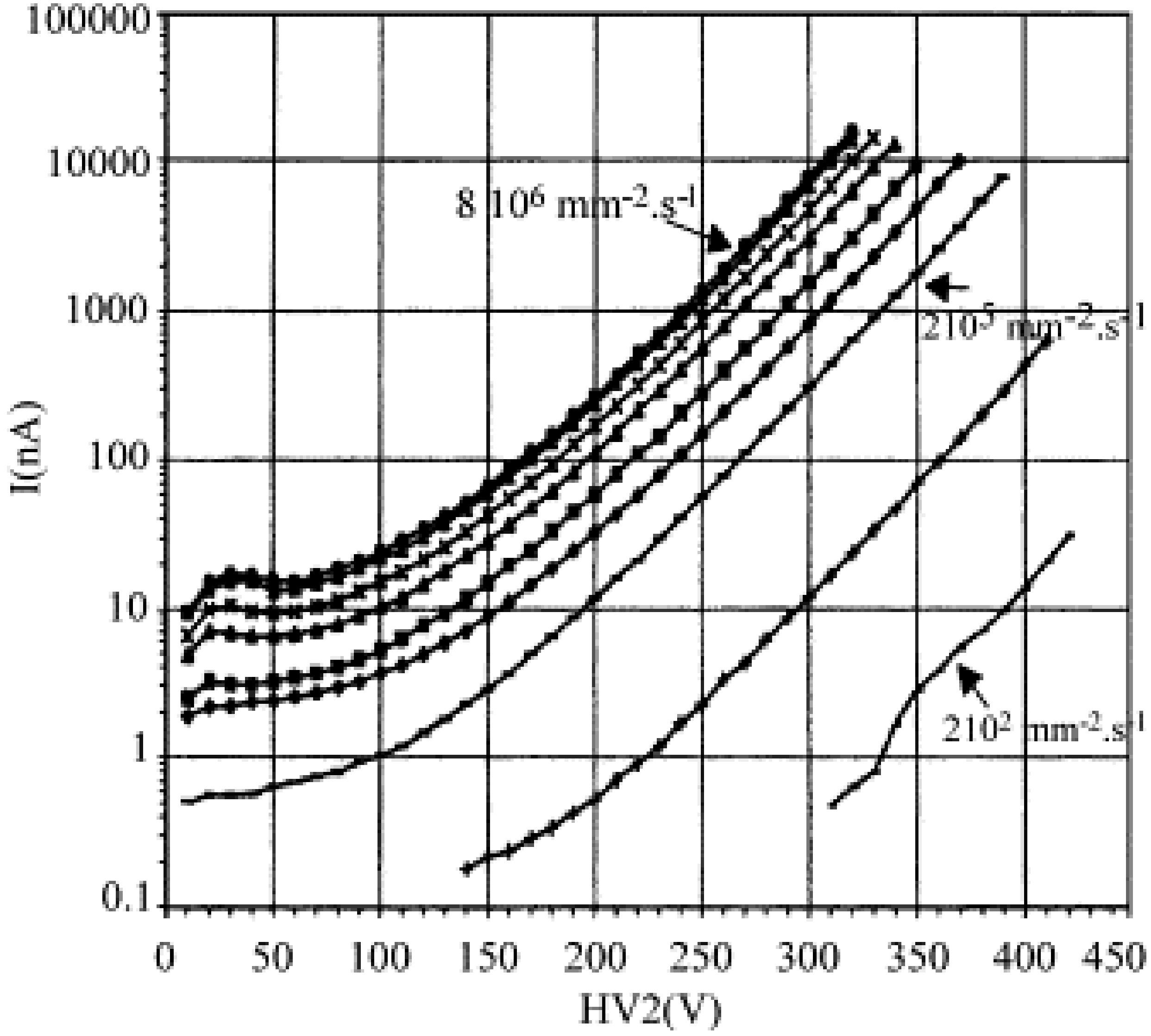


Figure 5.5: Spatial resolution $\sigma_{r\phi}$ using the Carleton TPC: [left] at 0.5 T in T2K gas mixture with two Micromegas gain 2500 and 4700 ; [right] at 5 T in Ar:Isobutane/95:5 and T2K gas mixtures

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

Micromegas rate capability

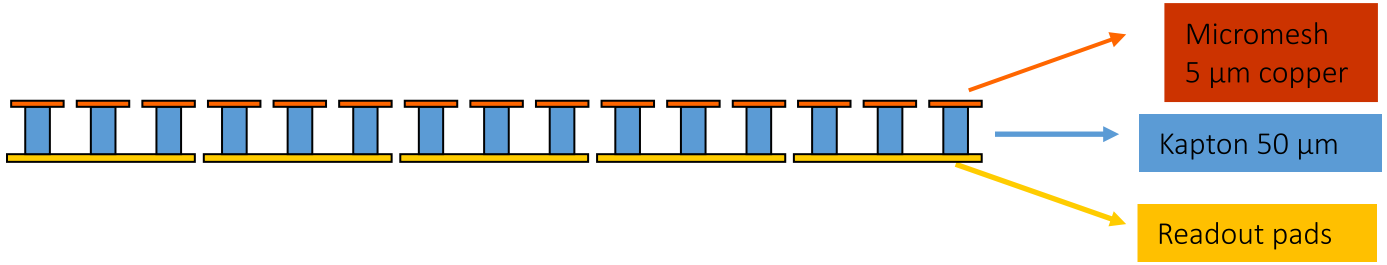


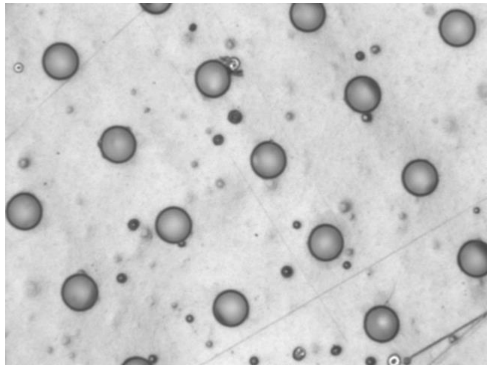
Current increases with the flux
All curves parallel
Gain independent of the rate
No saturation is observed

G. Puill et al., IEEE Trans Nuclear Science, 46 (1999) 6

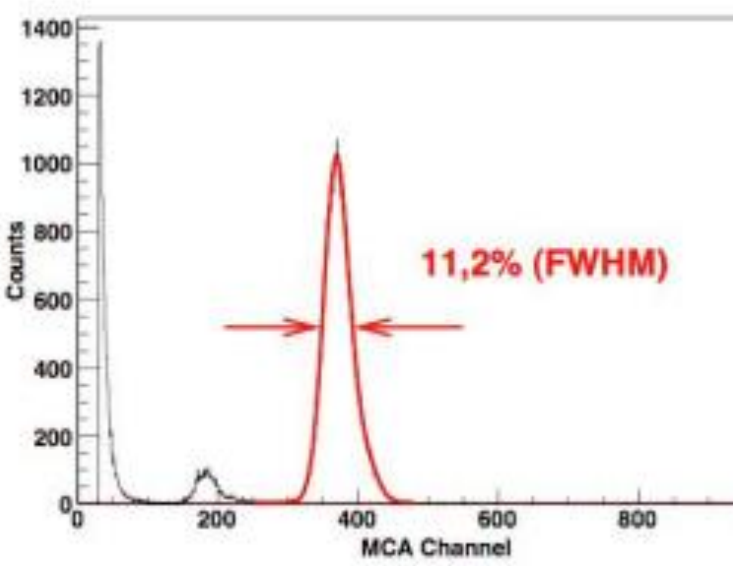
Microbulk

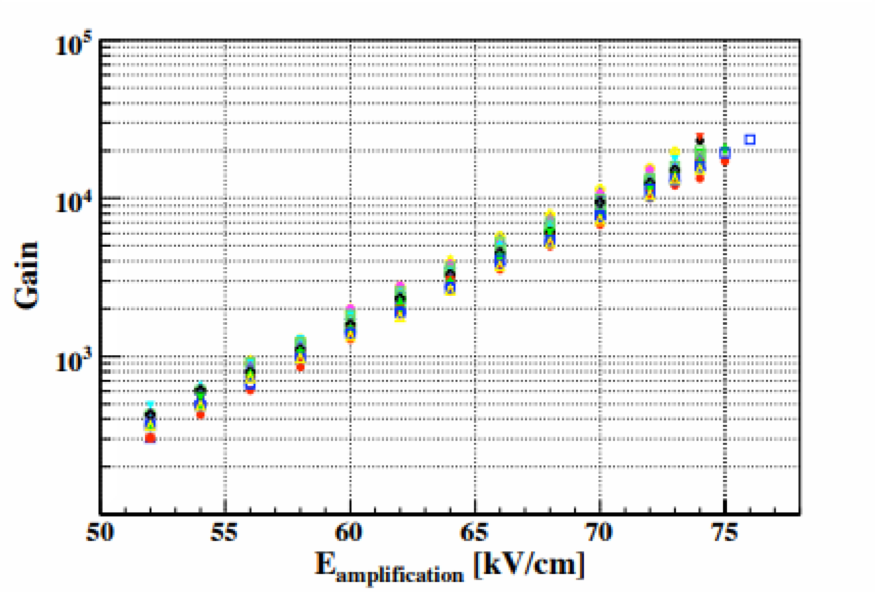
Pitch 100 µm,
Holes 30 µm

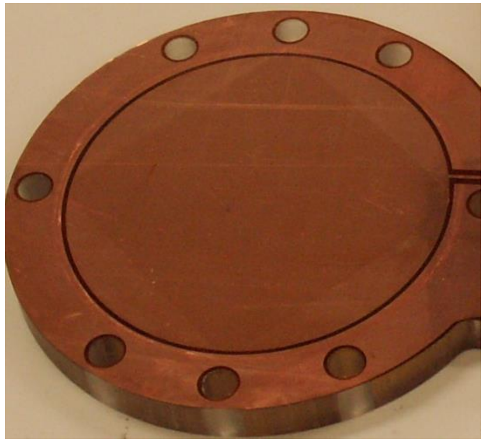




S. Andriamonje et al. JINST 2010 5 P02001







Resistive Micromegas

- Resistive coating:
  - Charge dispersion
  - Spark protection

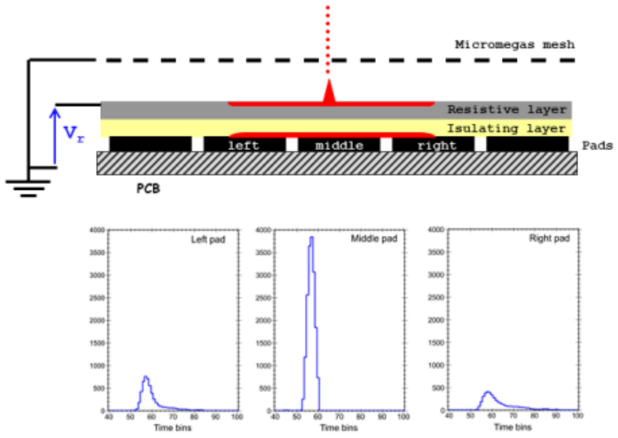
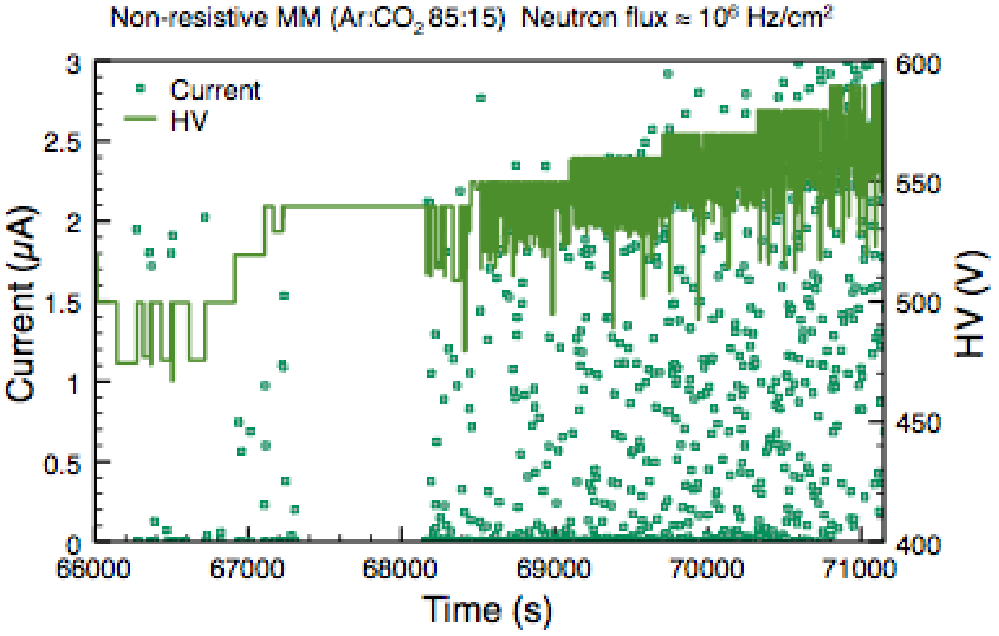
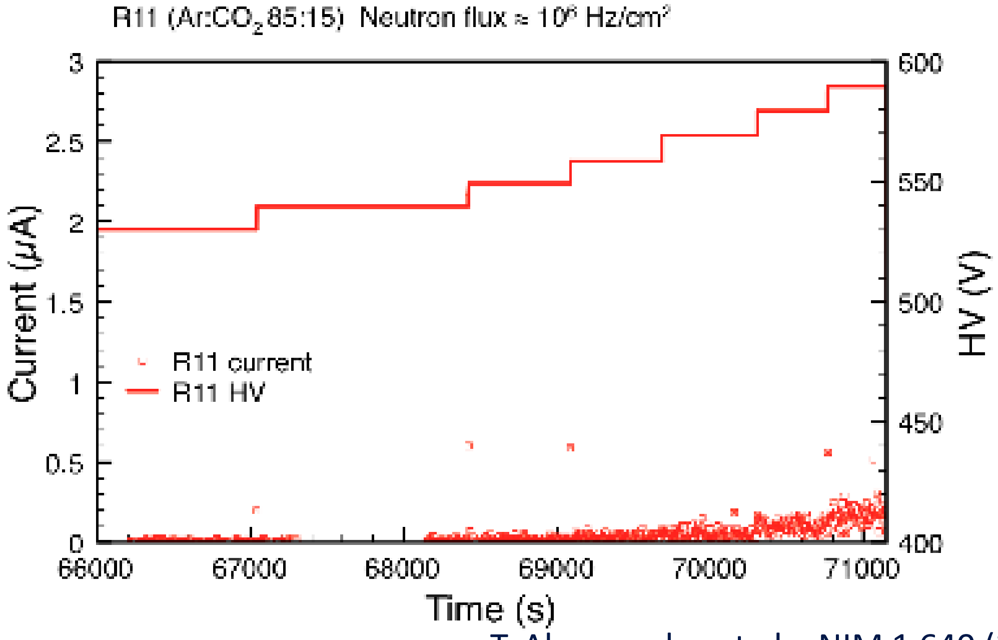


Figure 1.11: [Top] Resistive Micromegas principle. [Bottom] Pad signals recorded by an electronics after shaping.

David Attié, HDR, October 2022

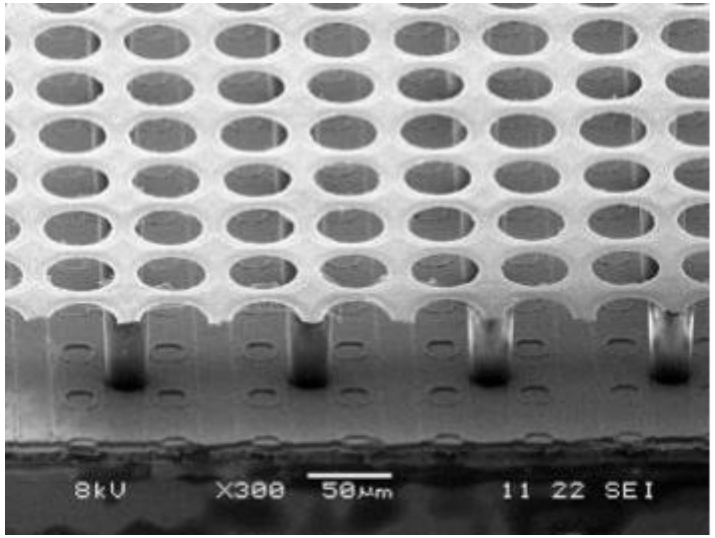


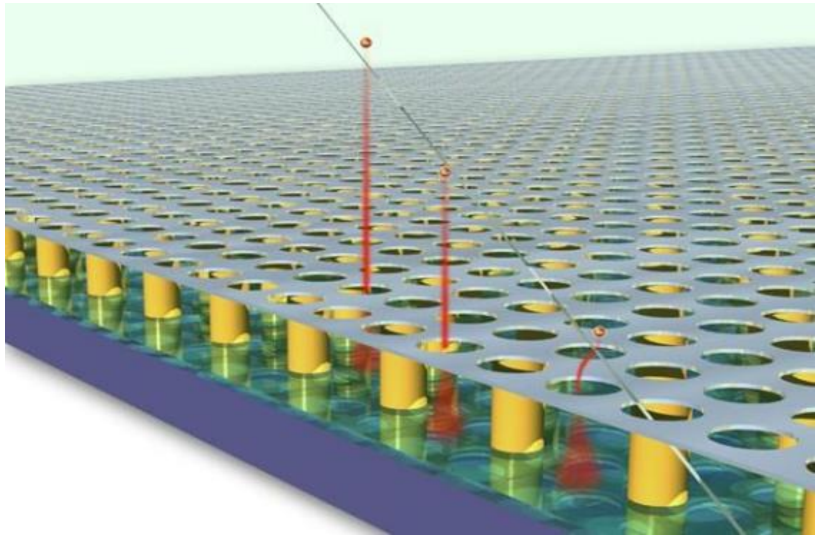


T. Alexopoulos et al., NIM 1 640 (2011) 110-118

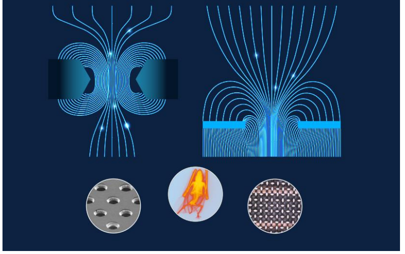
Ingrid

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)



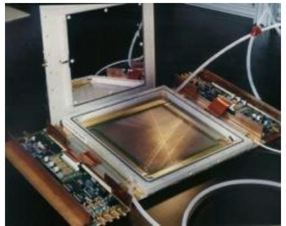
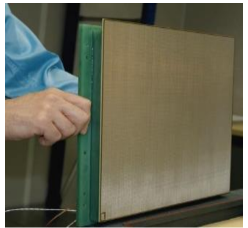
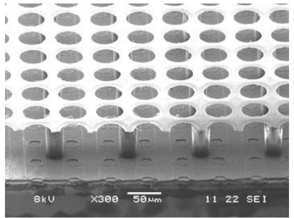


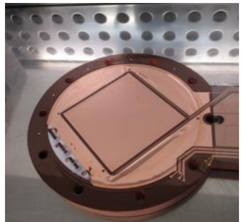
- Mesh is directly built on the silicon pixel readout chip
- High gain and small pixel size allow single electron detection
- High resitive silicon oxide layer protection against discharges



Micromegas family

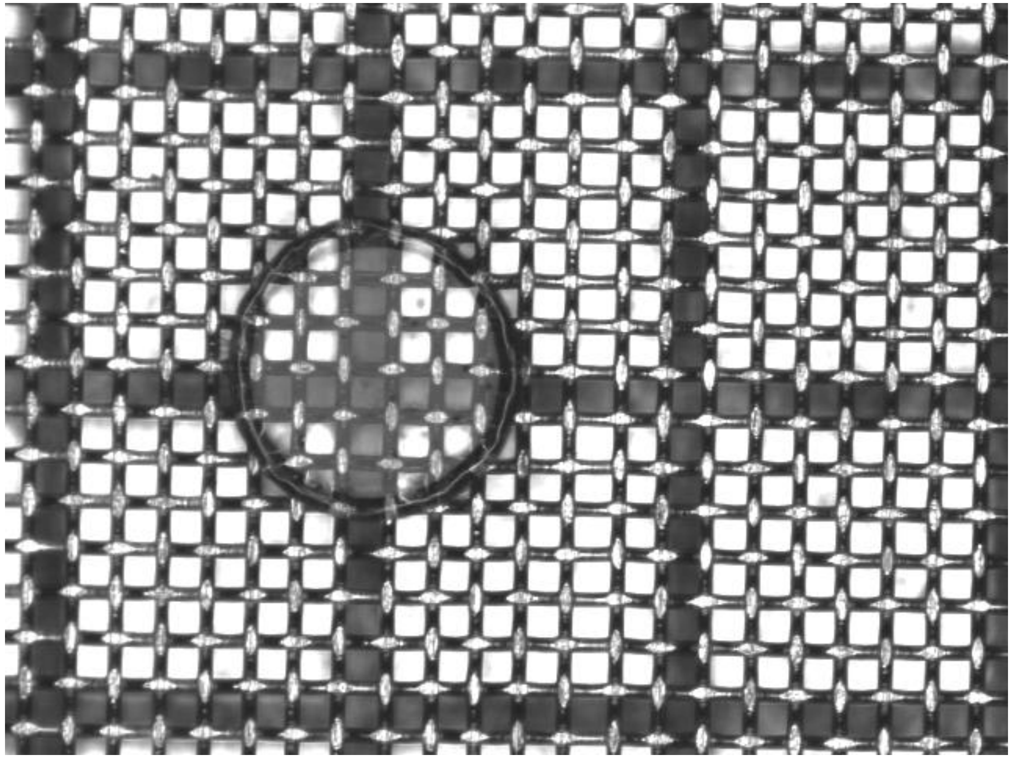
	Classical 1996	Bulk 2003	Ingrid 2005	Microbulk 2006
Mesh Readout plane	TWO mechanical entities	INTEGRATED: ONE single entity		
Type of mesh	Any type	30 µm Stainless steel	1 µm Aluminium	5 µm Copper
Advantages	Demontability Large Surface	Robust Industrial manufacturing process (PCB)	Excellent energy resolution Single electron efficiency	Intrinsically Flexible Low mass Radiopure

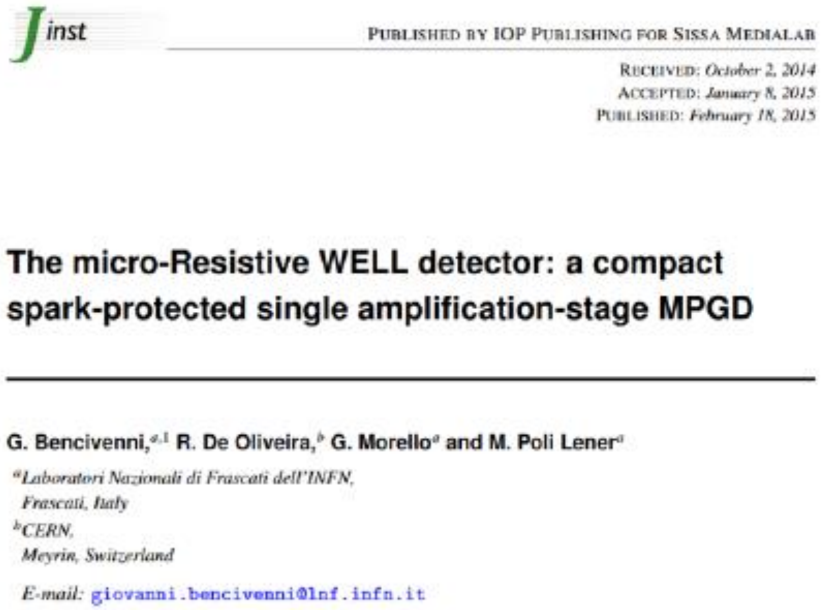


Micromegas properties

- 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^{16} 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



μ-Rwell



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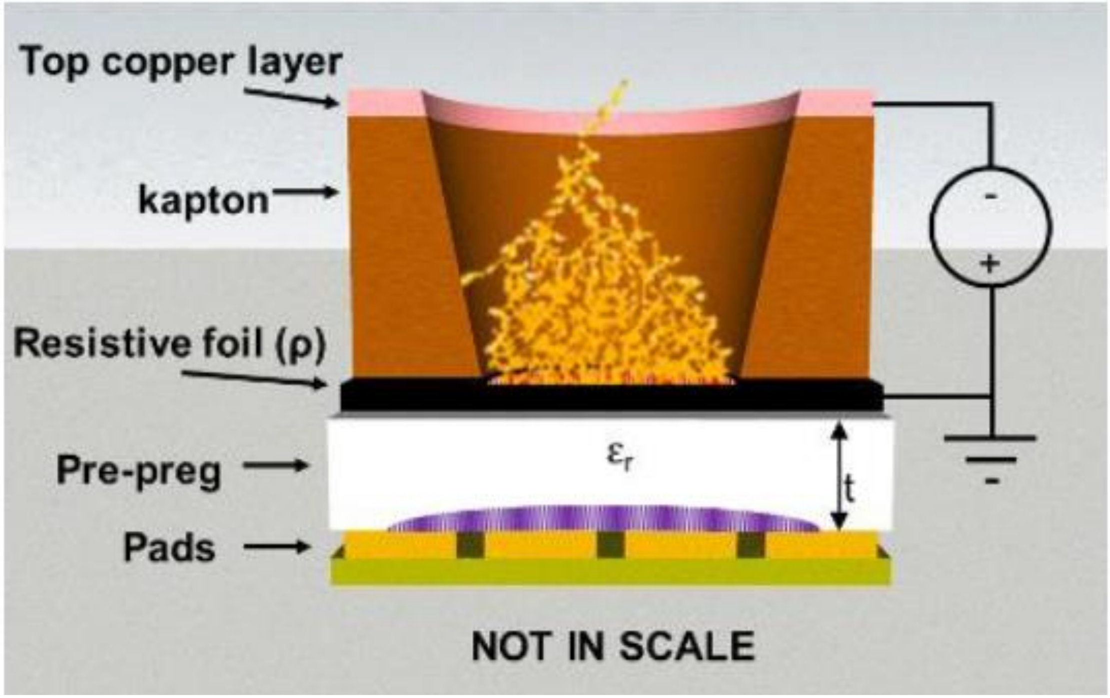
The micro-Resistive WELL detector: a compact spark-protected single amplification-stage MPGD

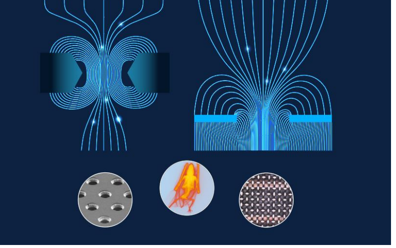
G. Bencivenni,[a,1] R. De Oliveira,[b] G. Morello[a] and M. Poli Lener[a]

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

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

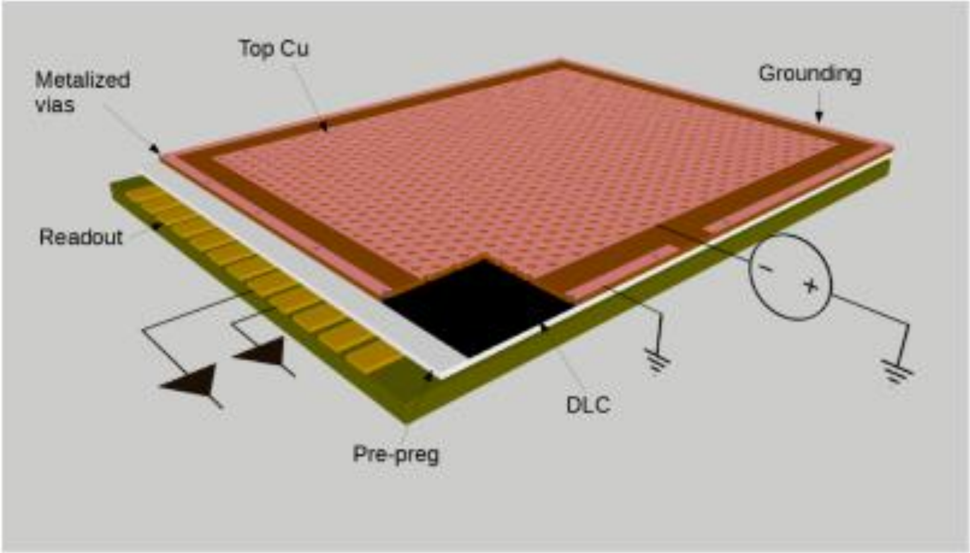


- The μRWELL is composed of a μ-RWELL PCB + Cathode
- μRWELL PCB : amplification stage coupled to the readout PCB through a resistive layer
- Resistive layer: Diamond-Like-Carbon with a resistivity 20-100 MOhm/square



µ-Rwell Low rate: Single resistive layer

Single resistive layer



2D current evacuation based on a single resistive layer

Grounding around the active area

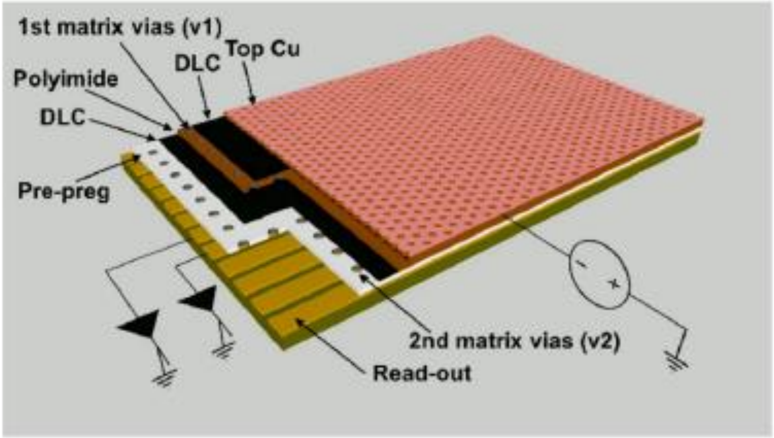
For large area: problem the path of the current depends on position=> detectot inhomogeneity

Limited rate capability < 100 kHz/cm^2

μ-Rwell high rate

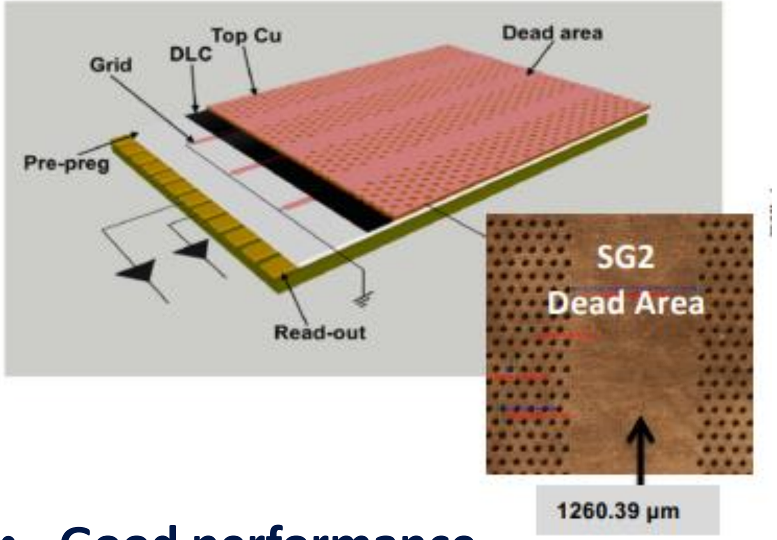
M. Poli Lener, MPGD 2022

Double resistive layer



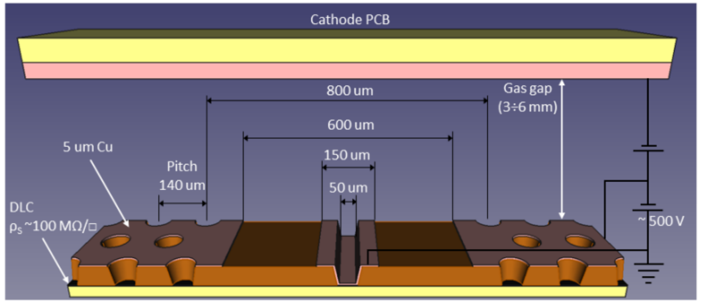
- Very good performance
- Complex manufacturing due to the double matrix of vias

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

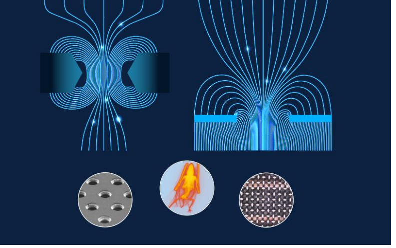
PEP (Patterning-Etching-Plating)



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

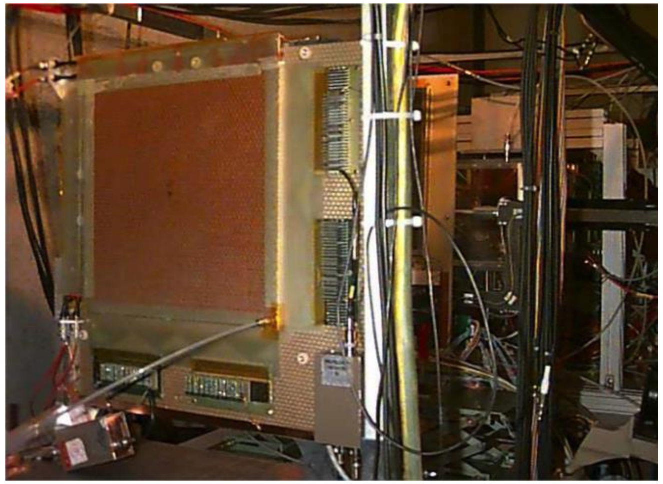
MPGD Applications*

*Obviously Not exhaustive

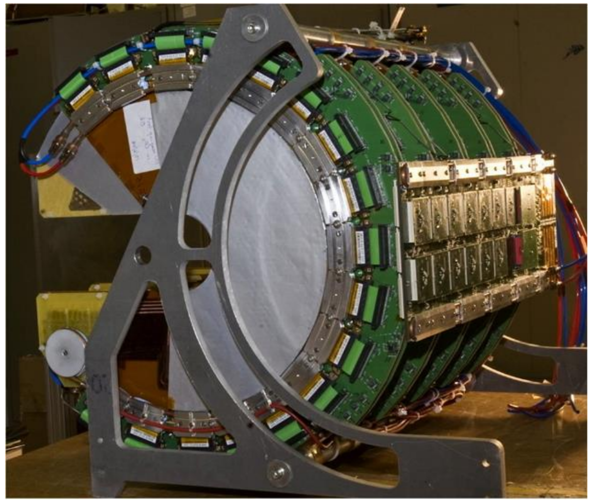


GEM Implementations

COMPASS

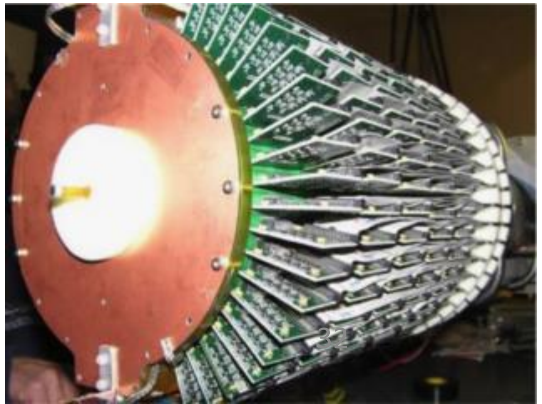


TOTEM

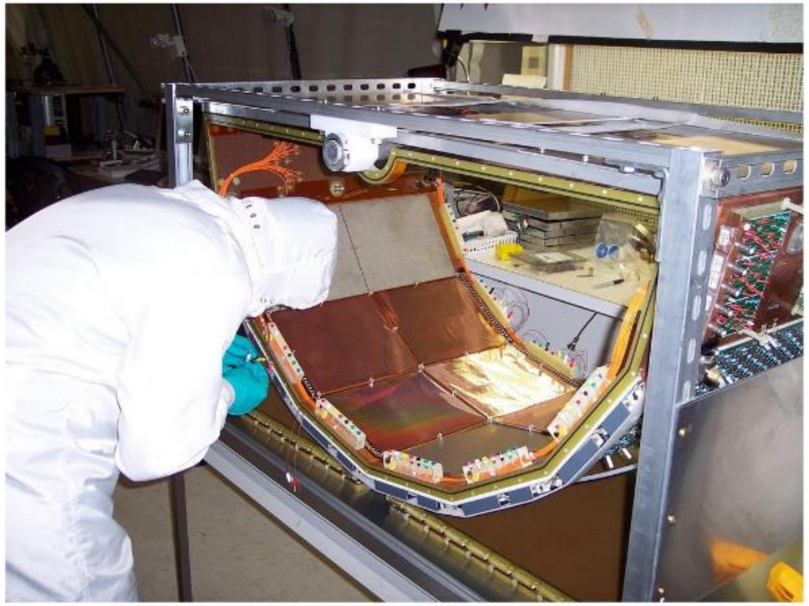


KLOE-2

BONUS RADIAL TPC



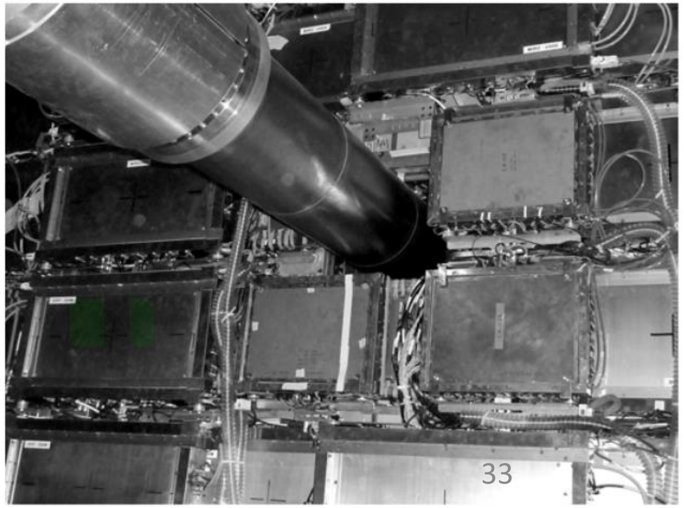
GEM Implementations



HBD for PHENIX

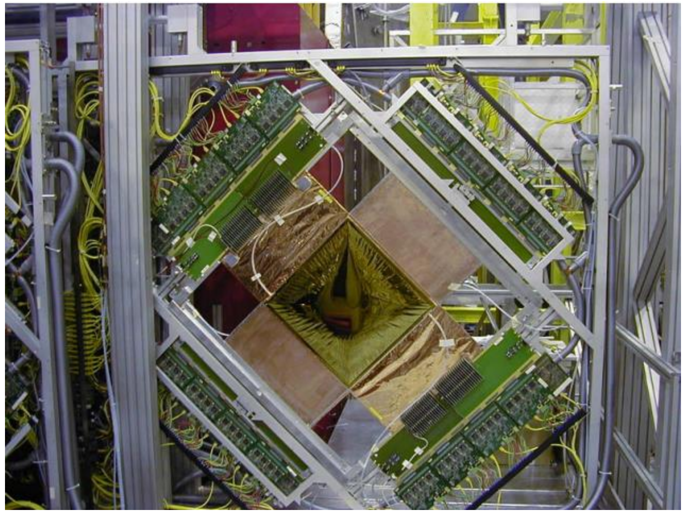
ALICE TPC UPGRADE

LHCB

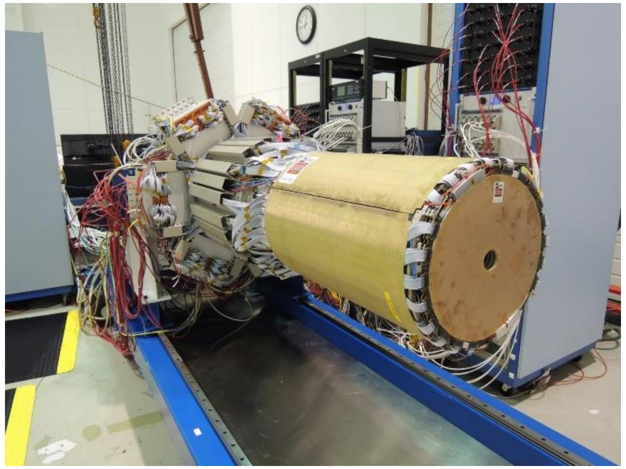


Micromegas Implementations

COMPASS

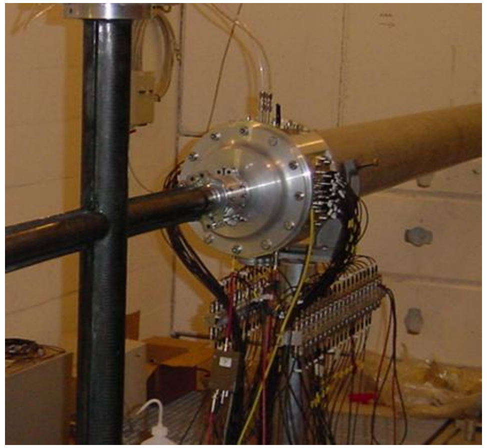


CLAS12



T2K

NTOF



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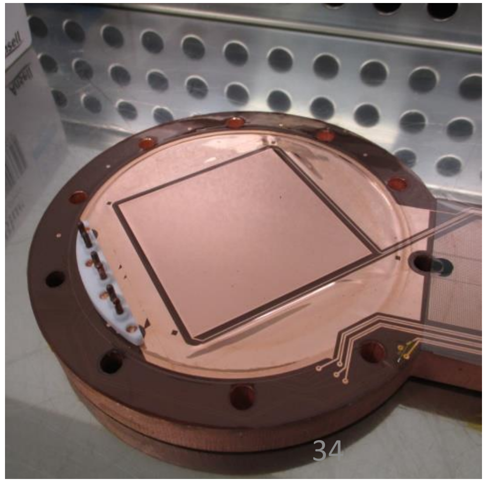
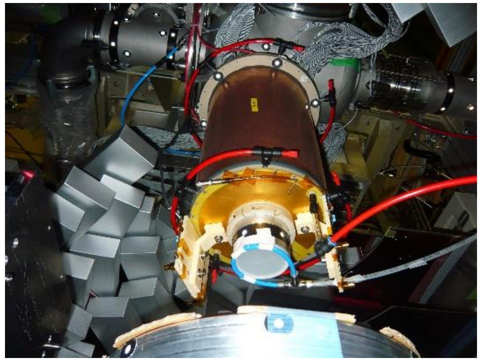


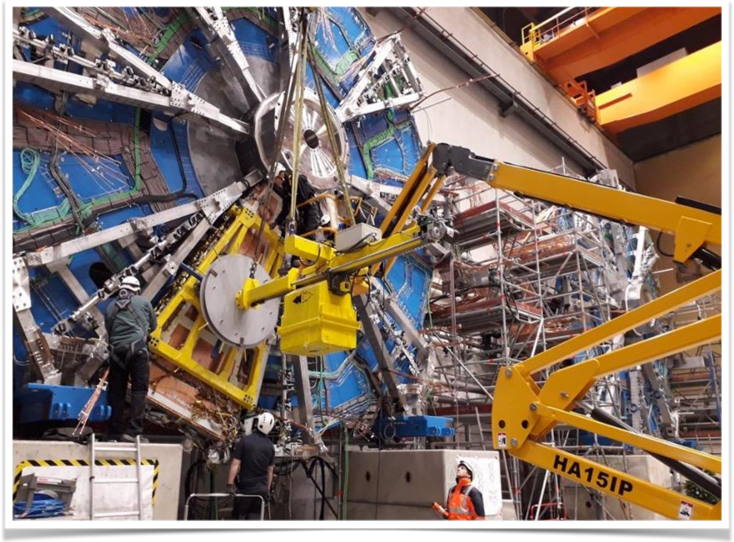
Micromegas implementations

MINOS

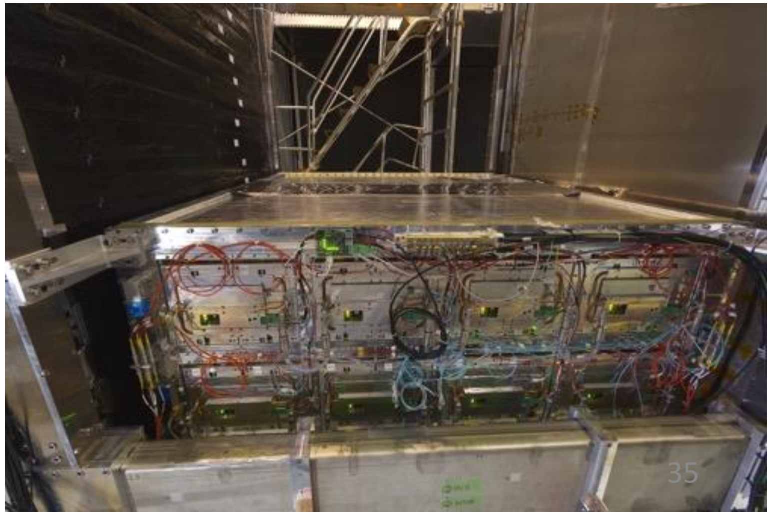


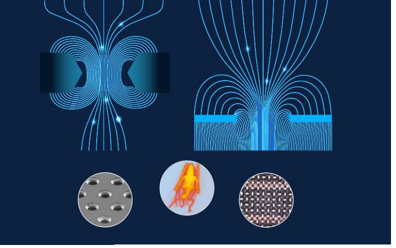
ACTAR-TPC

ATLAS-NSW



ND280 upgrade High-Angle TPCs





Hybrid Implementation: GEM + Micromegas

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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]

[a] INFN, Sezione di Trieste, Trieste, Italy
[b] INFN, Sezione di Torino and University of Torino, Torino, Italy
[c] I3N - Physics Department, University of Aveiro, Aveiro, Portugal
[d] INFN, Sezione di Trieste and University of Trieste, Trieste, Italy
[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

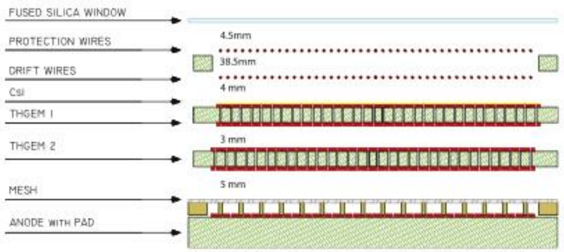


Fig. 2. Sketch of the hybrid single photon detector: two THGEM layers are coupled to a MM. Drift and protection wire planes are shown. Image is not to scale.

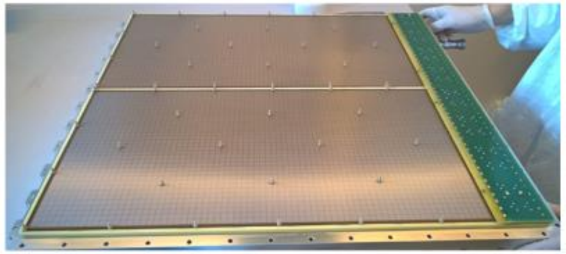


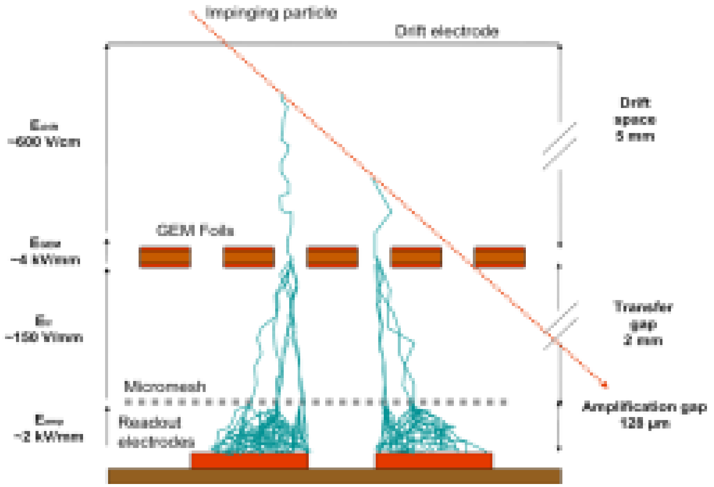
Fig. 3. Two Micromegas mounted side by side in a PD. The pillars that preserve the distance between the micromesh and the THGEM above it are also visible.

Performance of large pixelised Micromegas detectors in the COMPASS environment

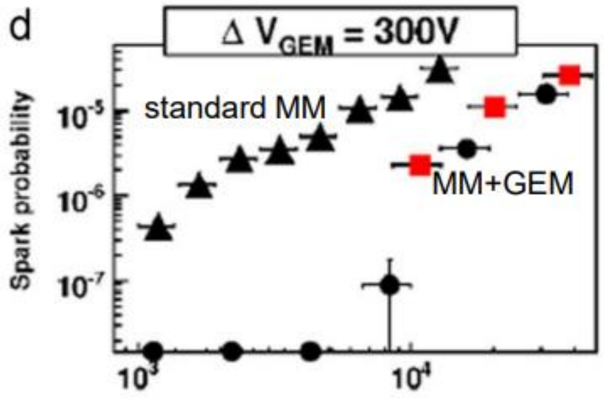
2014 JINST

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

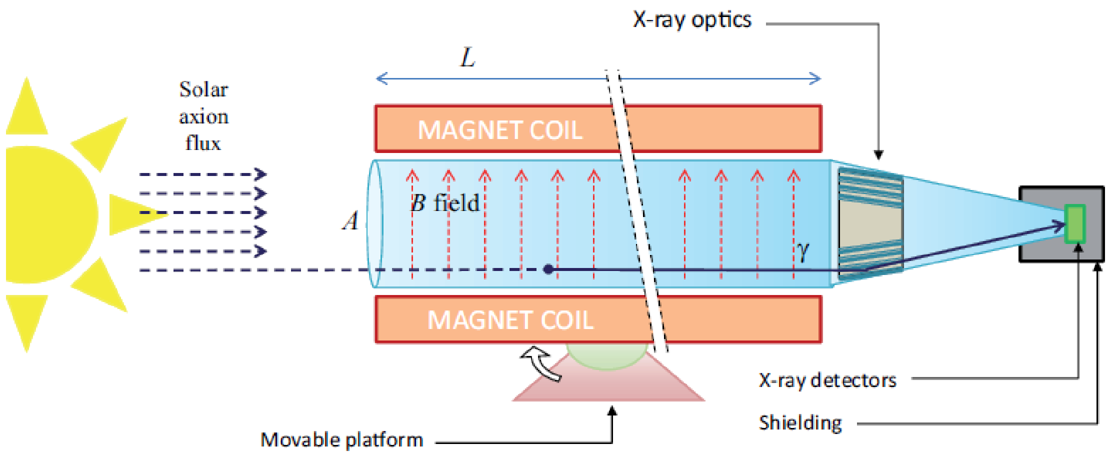
CEA Saclay DSM Irfu,
91191 Gif sur Yvette Cedex, France



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



Micromegas for axion solar search: CAST and BabyIAXO



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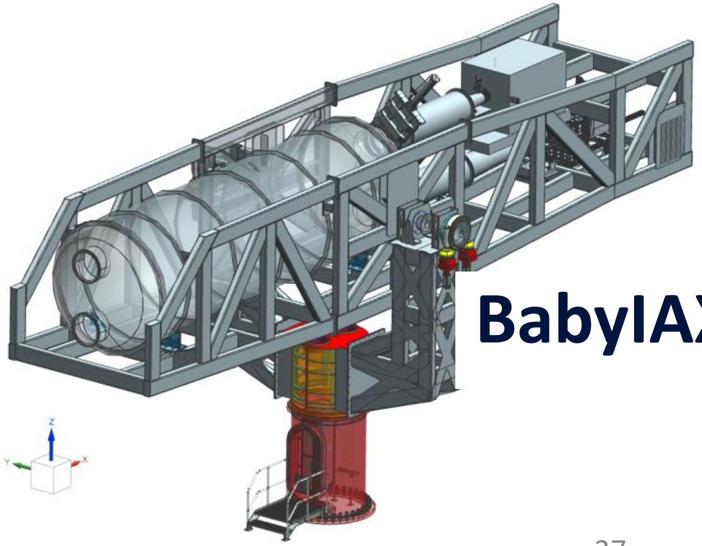


BabyIAXO

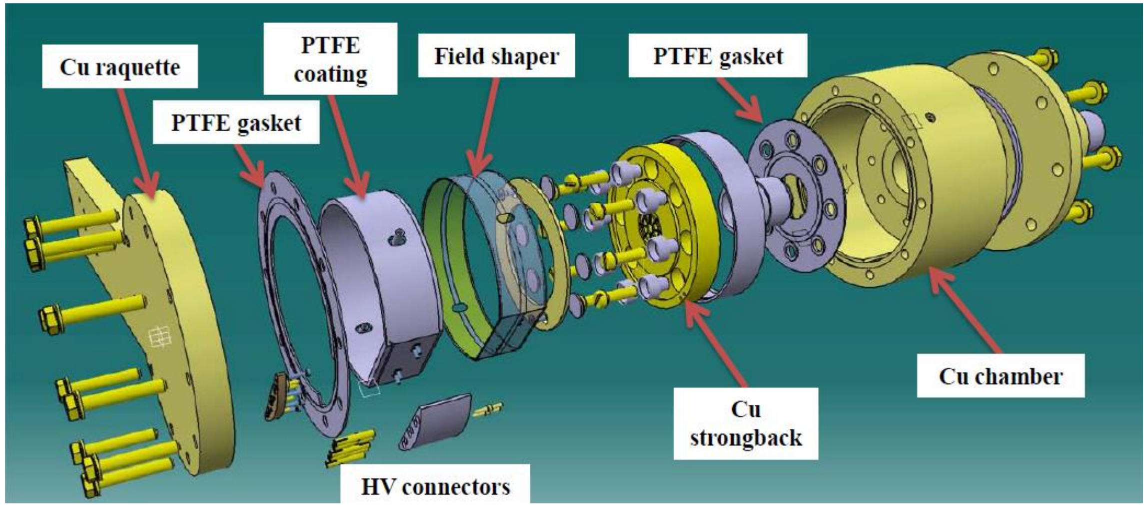
Specifications for the detectors:
High detection efficiency in the RoI (0-10 keV)

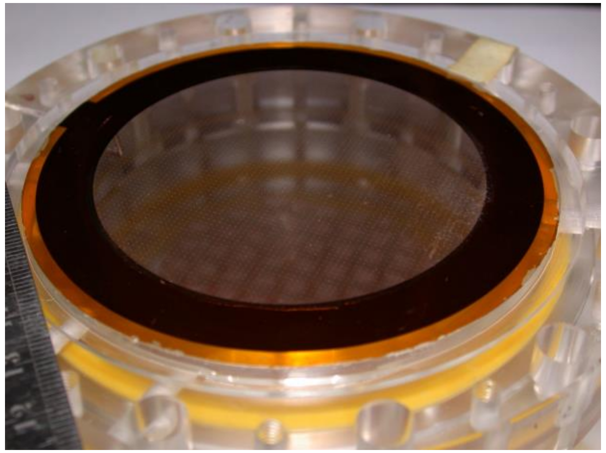
Very low background < 10 keV: 10^{-7} c/keV/cm^2/s : less than 1 event per 6 months of data taking!

- ➔ use of shielding
- ➔ radiopurity
- ➔ advanced event discrimination strategies

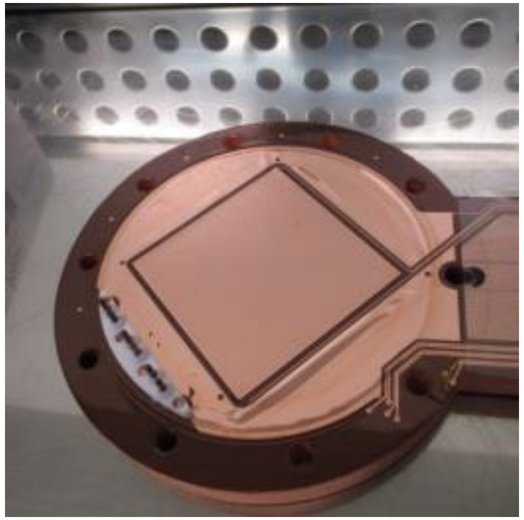
Abeln et al. JHEP 05 (2021) 137

Micromegas for axion solar search: CAST and BabyIAXO



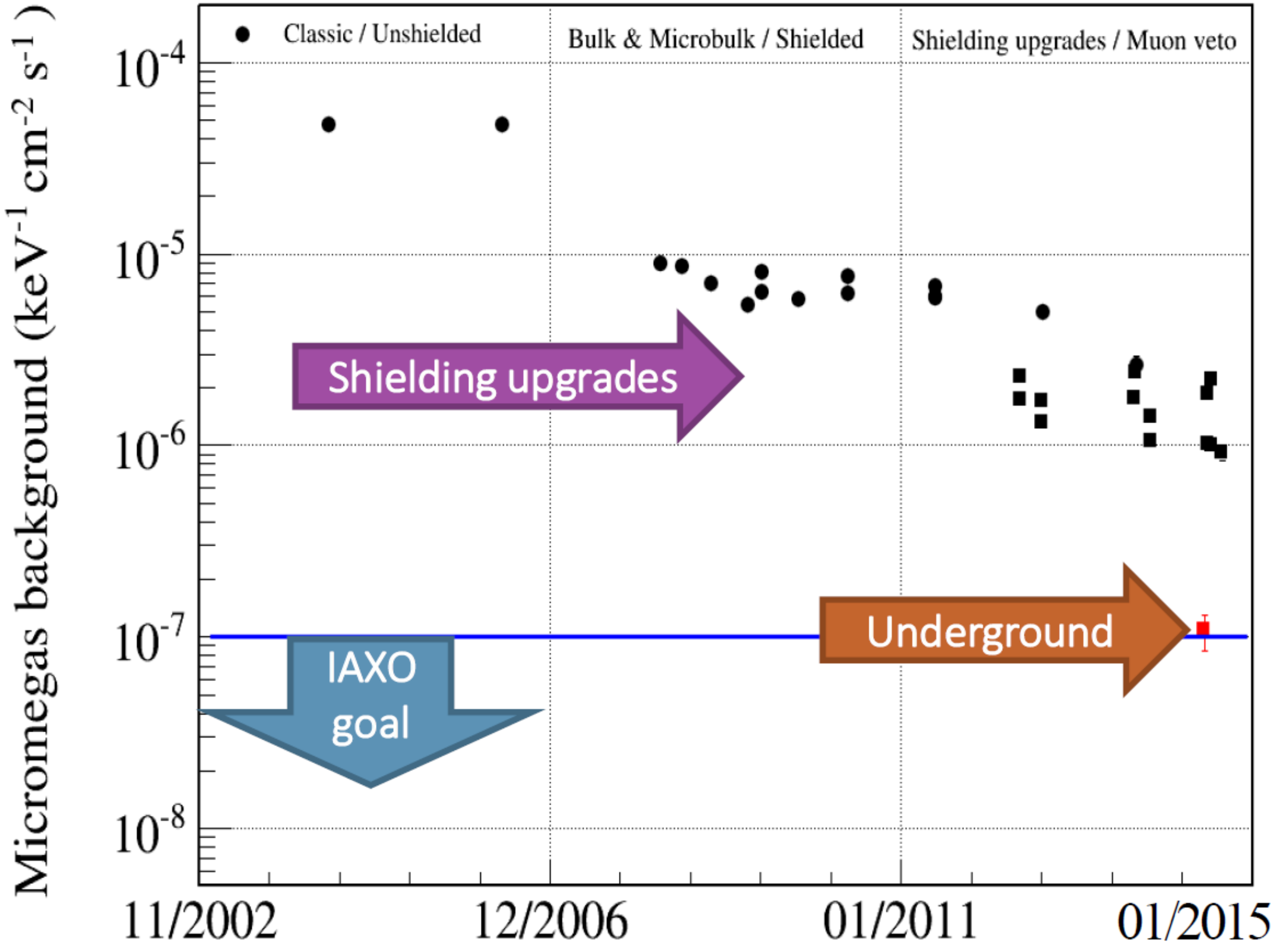


Standard Micromegas/Floating Mesh



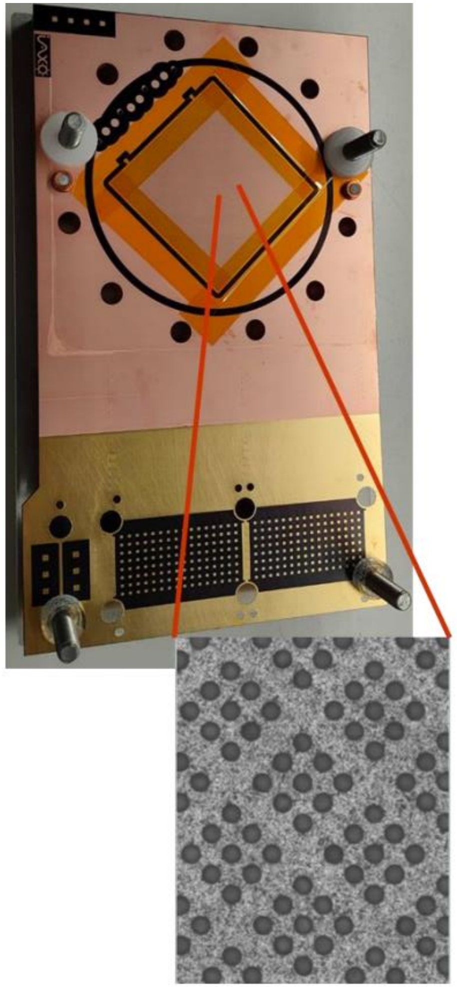
Microbulk

Micromegas for axion solar search: CAST and BabyIAXO

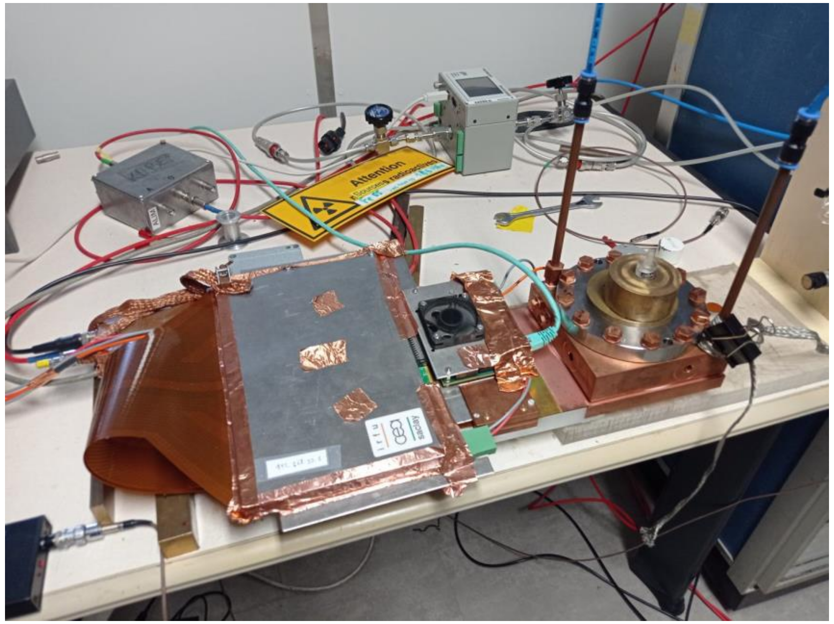


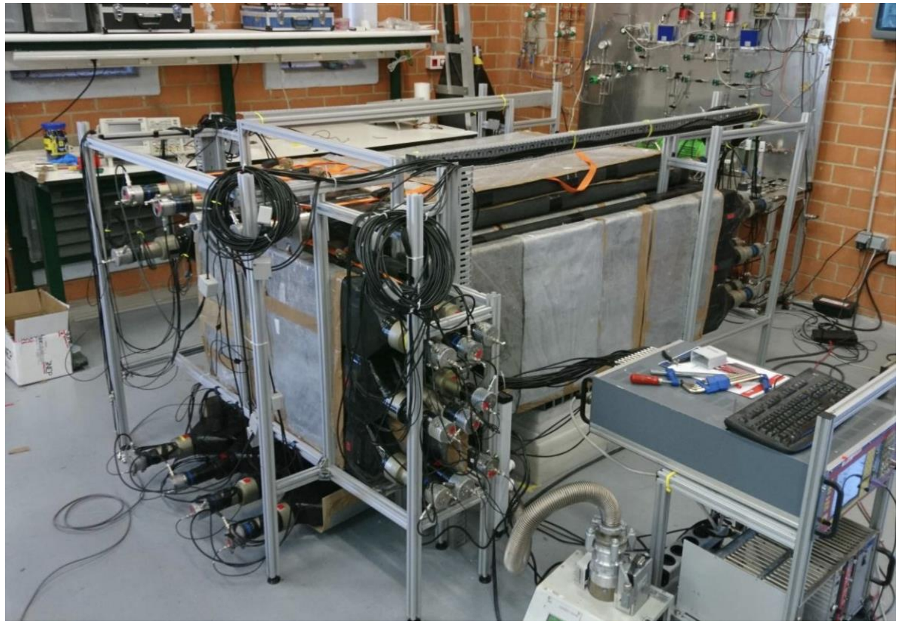
S. Aune et al., JINST 9 (2014) 9 P01001
F. Aznar et al., JCAP 12 (2015) 9 008

BabyIAXO Microbulk prototype



Micromegas for axion solar search: CAST and BabyIAXO



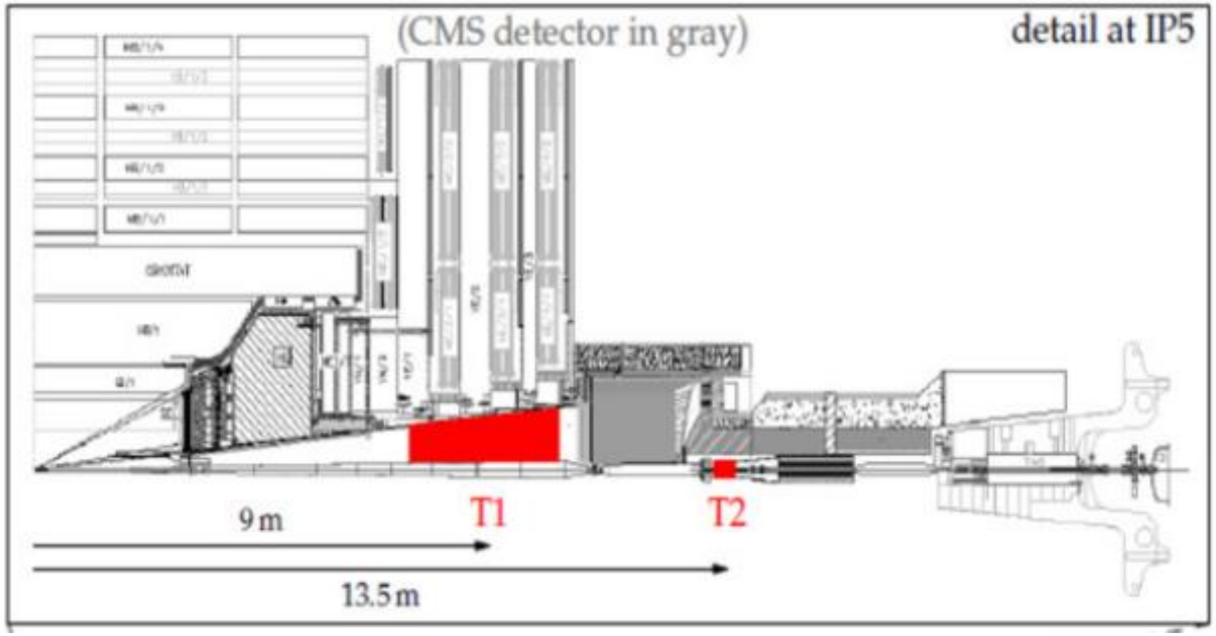


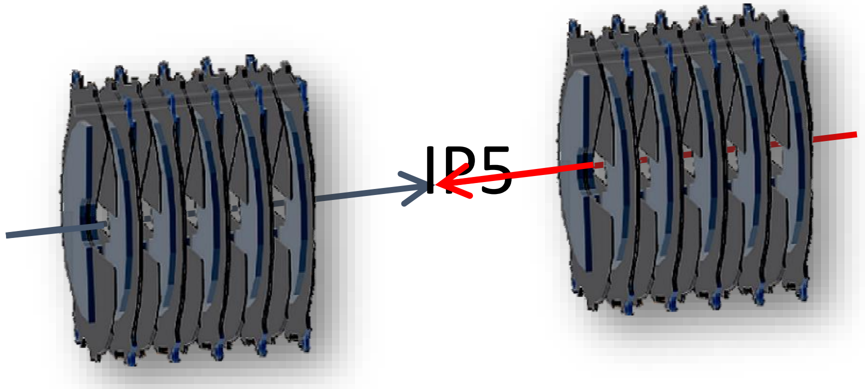
GEM TOTEM T2 Tracker (LHC)

Dedicated to diffractive and forward physics

Measurement of inelastically produced charge particles in Interaction Point 5

Each arm of the telescope 20 triple GEM
Tracking and trigger capabilities





GEM TOTEM T2 Tracker (LHC)

Detector requirements

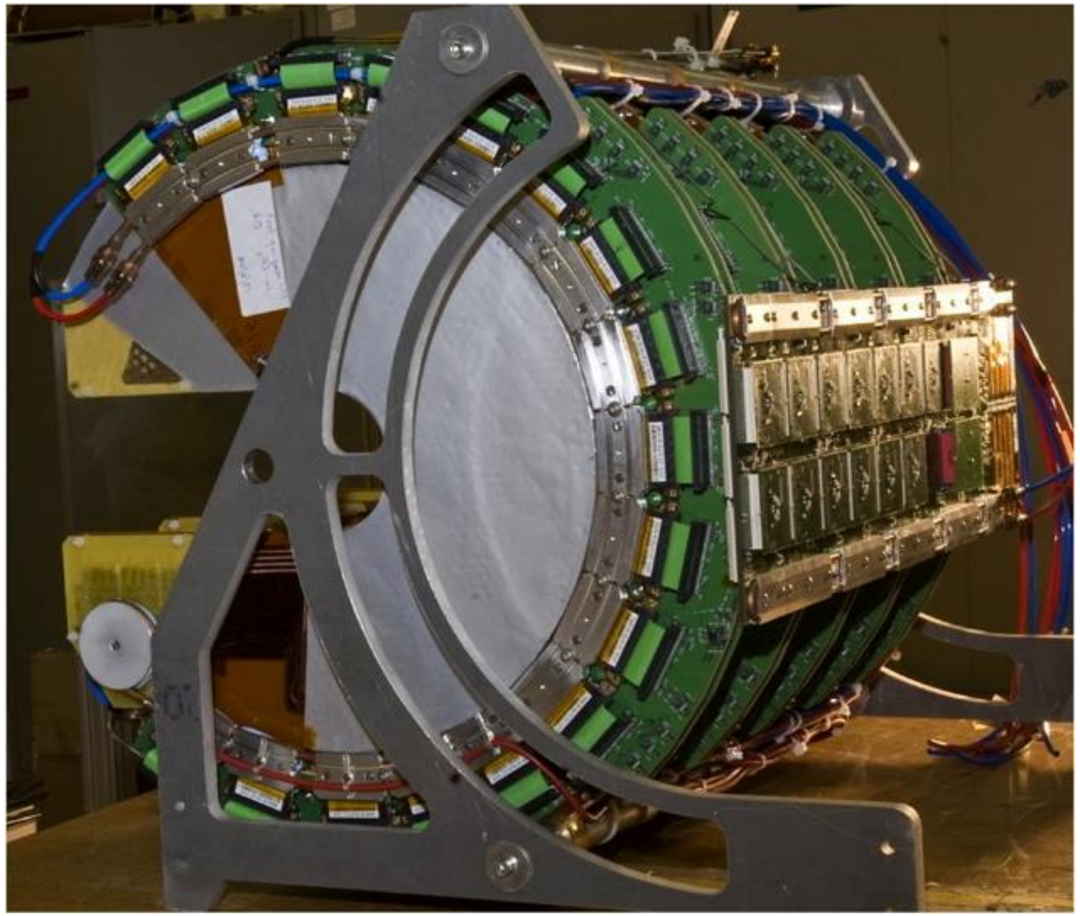
Rate capability: charge particle rates 10^4 p/mm^2/s^1
Ageing: 1 year of continuous operation 10^{11} p/mm^2
Discharges : 10 discharges/cm^2/year
Time resolution < 10 ns
Spatial resolution < 100 µm
Efficiency > 97%

Half Moon Triple GEM chamber: 40 detectors
Inner diameter 80 mm and outer diameter 300 mm.

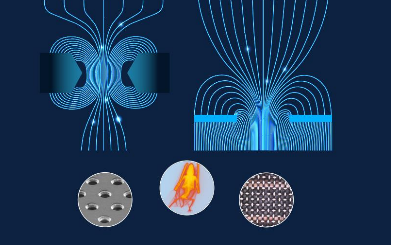
Readout: tracking and triggering

- Radial strips (accurate track's anle): 512 strips, 400 µm pitch, 80 µm width
- Pad matrix (fast trigger): 1560 pads

GEM TOTEM T2 Tracker (LHC)

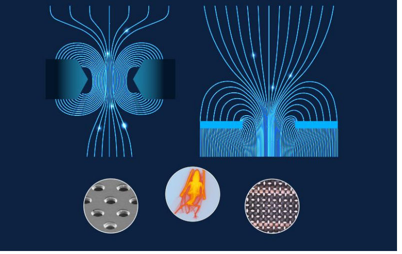


M.G. Bagliesi et al, Nucl. Instr. Meth. A617(2010)134



Summary

- MPGDs are mature technologies
- MPGDs today: GEM, Micromegas and µRWell
- Versatile, adaptable → wide range of applications
  « MPGD 2 » Eraldo Oliveri
  « MPGD in HEP » Paulo Iengo
  « Applications beyond HEP » Marco Cortesi
  « Applications beyond fundamental research » Jona Bortfeld
- Challenging R&D
  - Optical readout
  - High rates/Aging
  - Large areas



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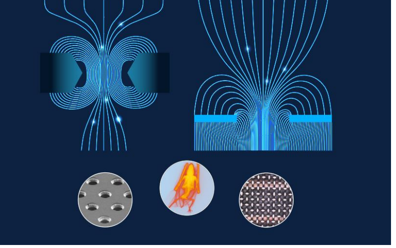
Acknowledgements

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



Further reading

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

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

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