Micropattern Gaseous Detectors Technologies

Michele Bianco, CERN EP-CMX-SCI

EURIZON Detector School, Wuppertal, 17th-28th July 2023

Gaseous Detector lecture #4

Micropattern Gaseous Detectors Technologies

- Current Trends in Micro-Pattern Gaseous Detectors (Technologies): Photolithography, Etching, Coating, Doping, …
- Micromegas: operation and performance, ageing, discharge and breakdown, resistive MM; The ATLAS NSW MM
- GEM: operation and performance, ageing, discharge and breakdown, applications - CMS, ALICE TPC, LHCb, Totem, Compass
- 2nd generation MPGD: micro-RWELL, RPWELL, Large Size Pixelized Micromegas for high-rate application, PICOSEC detector
- MPGD: Manufacturing and relations with industries

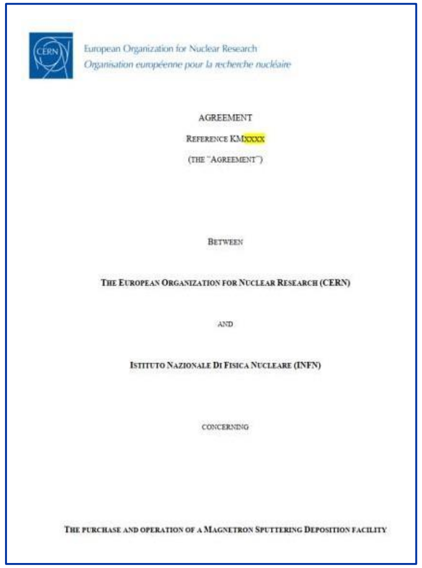
Current Trends in Micro-Pattern Gaseous Detectors (Technologies)

Micro Pattern Technology (MPT) workshop
Research/Development/Production of MPGD

- **Key role played by CERN EP-DT MPT workshop**
- **Aspects covered by MPT:**
  A. New developments (MPGD structures and architectures)
  B. Production for R&D
  C. Production for experiments and large (large for us large but not for industry) volumes
- **C → TT toward industry explored/done/ongoing…**

Dedicated slides at the end of this lecture

- **A & B (& C) → consolidating cooperation and sharing with MPT workshop** ⟶
  - sharing between CERN & INFN of a DLC sputtering machine (costs and use sharing / personnel training)
- **A & B → TT towards/between institutes & national laboratories workshops… (MPT/Saclay/LNF/ LNGS/FTD Bonn/… ? …)**



European Organization for Nuclear Research
Organisation européenne pour la recherche nucléaire

AGREEMENT
REFERENCE KMxxxx
(THE "AGREEMENT")

BETWEEN

THE EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH (CERN)

AND

ISTITUTO NAZIONALE DI FISICA NUCLEARE (INFN)

CONCERNING

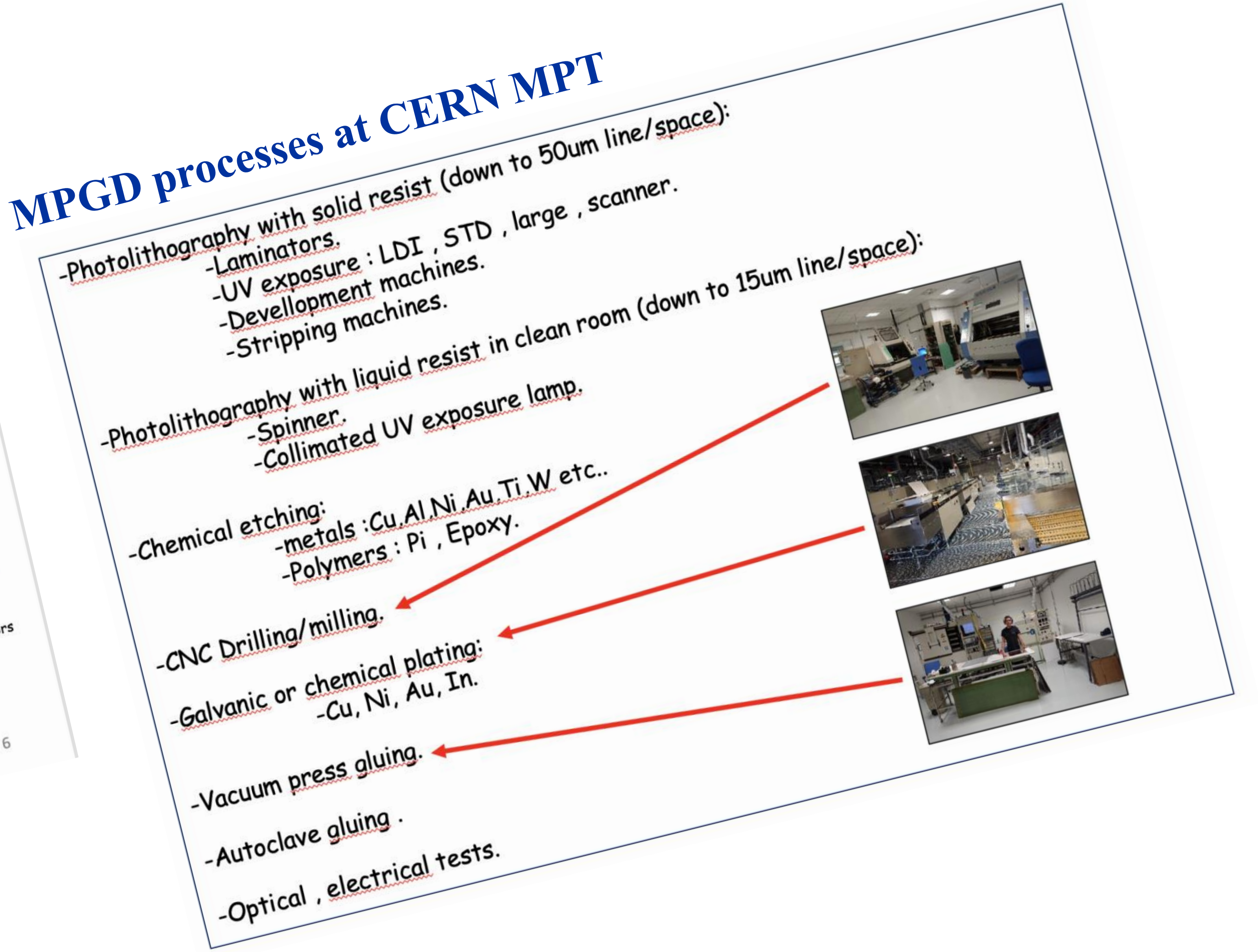
THE PURCHASE AND OPERATION OF A MAGNETRON SPUTTERING DEPOSITION FACILITY

C.I.D: the joint CERN-INFN DLC facility

Current Trends in Micro-Pattern Gaseous Detectors (Technologies)

Examples of MPT activities

MPGD processes at CERN MPT



https://indico.cern.ch/event/999799/contributions/4204334/attachments/2236247/3790326/infrastructures.pdf

Current Trends in Micro-Pattern Gaseous Detectors

Pulsed DC magnetron reactive PVD
New fundamental tool for substrate deposition

- Resistive layers:
  -DLC, semiconductors.
- Photocathodes:
  -Metallic, DLC, B4C, GaN, mix?
- Metals:
  -AL, Cu, Ni, etc..

- Budget (CERN INFN Project):
  -25% INFN
  -25% CERN EP/DT group
  -50% CERN MPT workshop self financing

- Max foil size:
  -1.7m x 0.6m.
- Useful size:
  -1.7m x 0.5m.

5 targets.
3 simultaneous deposition.
3 gas inputs:
H2,N2,CH4,C4H10,Ne,Ar etc..
300deg heater.

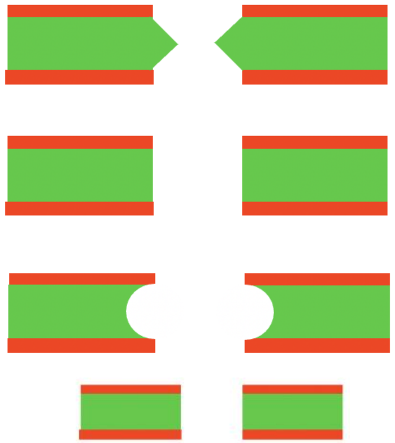
Current Trends in Micro-Pattern Gaseous Detectors

Development topics at MPT workshop

GEM hole example

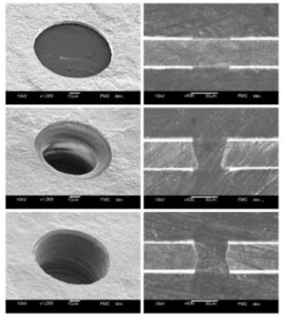
Subtractive micro-structuring

- Chemical
- Laser
- Plasma

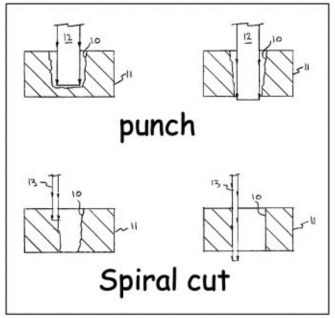


Laser micro-structuring

C02 laser

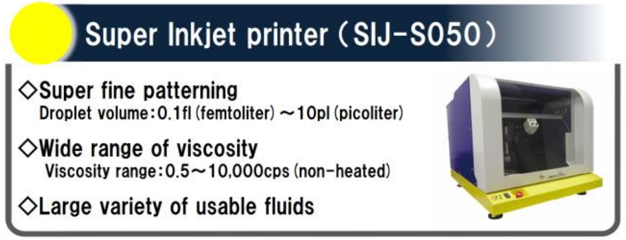


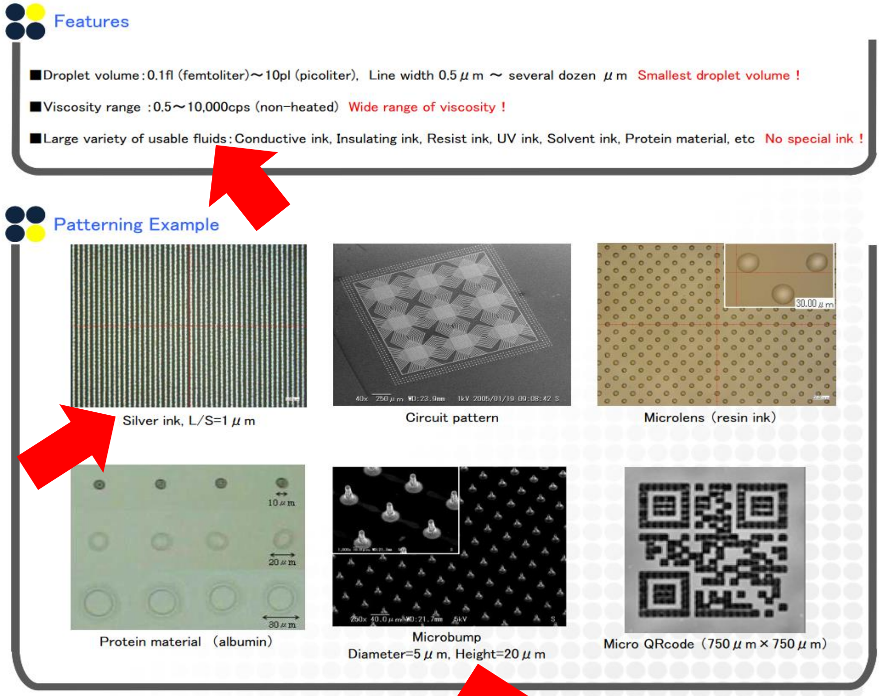
UV laser



Laser machine on the market are still too slow and too small to compete with chemical etching

Additive Micro-structuring





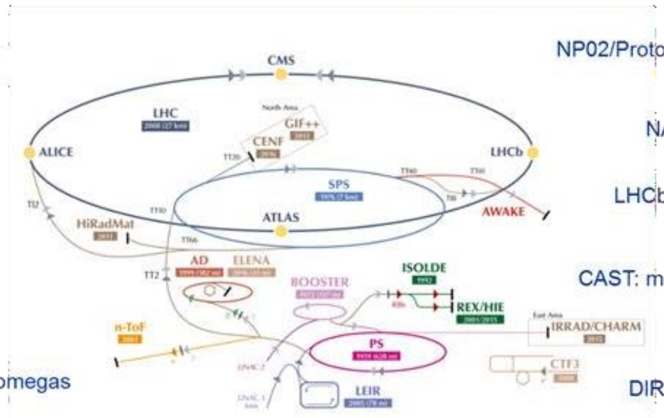
MPGD concepts/ideas compatible with micro printing are welcome!!!!!

The R&D51 Collaboration: The Place!!!

Technological developments often need large infrastructures

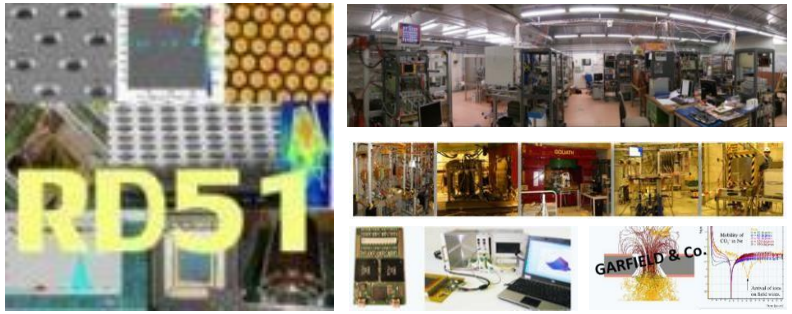
EP-DT
Detector Technologies

TOTEM: GEM
CMS: GEM
ALICE: GEM
ATLAS: micromegas



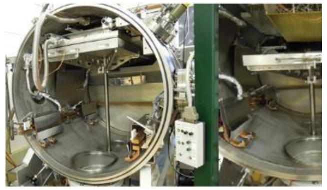
COMPASS: 2TGEM+mm, micromegas, GEM
NP02/Proto DUNE-DP: LEM
NA48: micromegas
LHCb: GEM, µRWELL
CAST: micromegas, Ingrid
DIRAC: MSGC-GEM

MPGD technologies spread over LHC experiments (existing or planned)



International collaboration on MPGD
Started in 2008 (white paper/CERN)
Common facilities (lab/GDD, test beam/SPS)
developments (simulation/electronics) and
workshop (MPT) @ CERN

Micro Pattern Technology (MPT) workshop
Research/Development/Production of MPGD



Thin Film and
Glass lab

Irradiation Facilities

EP-DT-FS
Gas
Group

Gas
Group

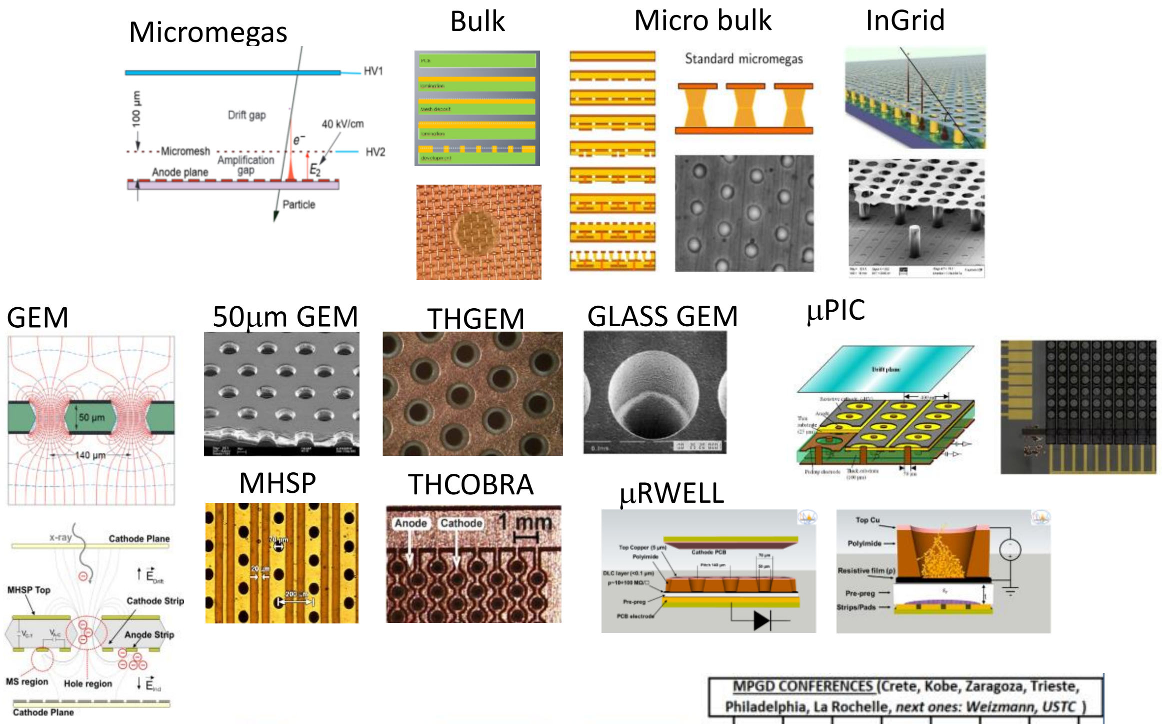
GDD Gas Detector
Development team
R&D on MPGD,
RD51 Support

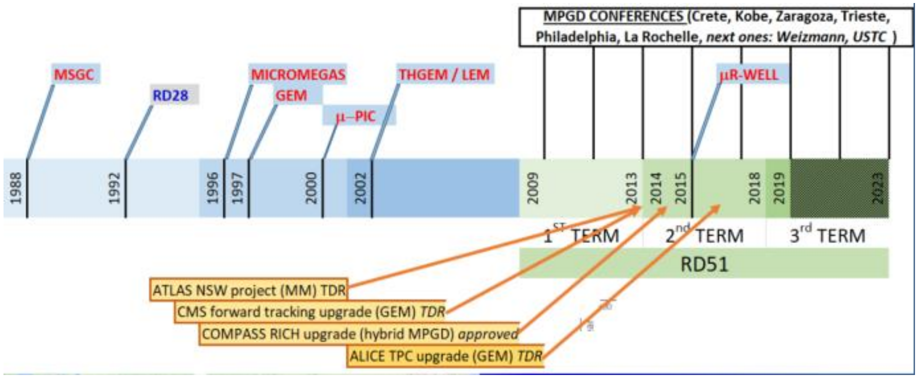
EP R&D

Strategic R&D on
MPGD (large systems,
novel solution,
framework and tools)

https://indico.cern.ch/event/999799/contributions/4204424/attachments/2236130/3790095/Networking.pdf

Micro Pattern Gas Detector Family





• High Rate Capability	• Up to MHz/mm^2 (MIP)
• High Gain	• Up to 10^5 -10^6
• High Space Resolution	• <100µm
• Good Time Resolution	• In general few ns , sub-ns in specific configuration
• Good Energy Resolution	• 10-20% FWHM @ soft X-Ray (6KeV)
• Excellent Radiation Hardness	
• Good Ageing Properties	
• Ion Backflow Reduction	• % level sort of easy, below % in particular configuration
• Photon Feedback Reduction	
• Large size	• m^2
• Low material budget	
• Low cost	
• …	

All subjects illustrated by examples:
A fully comprehensive review is impossible!
Technology share-point R&D51

The MPGD family and their applications

MPGD-based Neutron Detectors

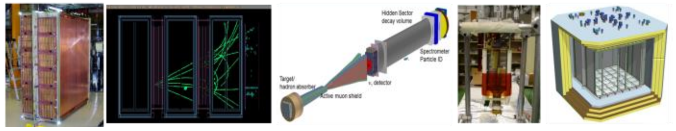
MPGD coupled to n-converters:

- ITER / Spallation Sources
- Neutron-beam diagnostics

Experiment / Timescale	Application Domain	MPGD Technology	Total detector size / Single module size)	Operation Characteristics / Performance	Special Requirements / Remarks
ESS NMX: Neutron Macromolecular Crystallography Start: > 2020(for 10 y.)	Neutron scattering Macromolecular Crystallography	GEM w/ Gd converter	Total area: ~ 1 m² Single unit detect: 60x60 cm²	**Max.rate**: 100 kHz/mm² **Spatial res.**: ~500μm **Time res.**: ~ 10 us n.-eff: ~ 20% efficient - γ rejection of 100	Localise the secondary particle from neutron conversion in Gd with < 500um precision
ESS LOKI- SANS: Small Angle Neutron Scattering (Low Q) Start: > 2020(for 10 y.)	Neutron scattering: Small Angle	GEM w/ borated cathode	Total area: ~ 1 m² Single unit detect: 33x40 cm² trapezoid	**Max.rate**: 40 kHz/mm² **Spatial res.**: ~4 mm **Time res.**: ~ 100 us n. –eff. >60% (at λ= 4 Å) - γ rejection of 10^-7	Measure TOF of neutron interaction in a 3D borated cathode
SPIDER: ITER NBI PROTOTYPE Start: ~ 2017(for 10 y.)	CNESM diagnostic: Characterization of neutral deuterium beam for ITER plasma heating using neutron emission	GEMs w/ Al-converter (Directionality - angular) capability)	Single unit detect: 20x35 cm²	**Max.rate**: 100 kHz/mm² **Spatial res.**: ~ 10 mm **Time res.**: ~ 10 ms n.-eff: >10^-5 γ rejection of 10^-7	Measurement of the n-emission intensity and composition to correct deuterium beam parameters
n_TOF beam monitoring/ beam profiler Run: 2008-now	Neutron Beam Monitors	MicroMegas μbulk and GEM w/ converters	Total area: ~ 100cm²	**Max.rate**:10 kHz **Spatial res.**: .: ~300μm **Time res.**: ~ 5 ns **Rad. Hard.**: no	

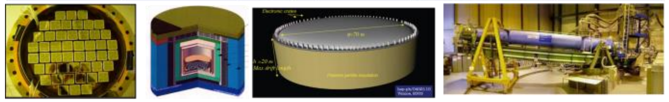
MPGD Technologies for Neutrino Physics

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 m² Single unit detect: 0.36x0.34m²~0.1m²	**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 m² Single unit detect: 2 x 1 m² ~ 2m²	**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 DUNE Dual Phase Far Detector Start: > 2023?	Neutrino physics (Tracking+ Calorimetry)	LAr TPC w/ THGEM double phase readout LAr TPC w/ THGEM double phase readout	Total area: 3 m² (WA105-3x1x1) 36 m² (WA105-6x6x6) Single unit detect. (0.5x0.5 m2) ~0.25 m² Total area: 720 m² Single unit detect. (0.5x0.5 m2) ~ 0.25 m²	WA105 3x1x1 and 6x6x6: **Max. rate**: 150 Hz/m² **Spatial res.**: 1 mm **Time res.**: ~ 10 ns **Rad. Hard.**: no **Max. rate**: 4*10⁻⁷ Hz/m² **Spatial res.**: 1 mm **Rad. Hard.**: no	Detector is above ground (max. rate is determined by muon flux for calibration) Detector is underground (rate is neutrino flux)



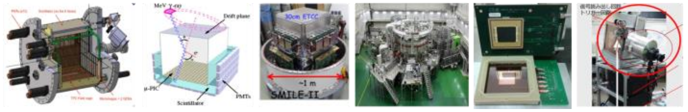
MPGD Technologies for Dark Matter Detection

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: ~30m² Single unit detect. ~20 x20 cm²	**Max.rate**: 100 Hz/cm² **Spatial res.**: ~ 1cm **Time res.**: ~ few ns **Rad. Hard.**: no	Operation at ~180K, radiopure materials, dark count rate ~1 Hz/cm²
PANDAX III @ China Start: > 2017	Astroparticle physics Neutrinoless double beta decay	TPC w/ Micromegas μbulk	Total area: 1.5 m²	**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(cm³)	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 7cm² Total area: 1 InGrid of 2cm²	**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



MPGD Technologies for X-Ray Detection and γ-Ray Polarimetry

Experiment/ Timescale	Application Domain	MPGD Technology	Total detector size / Single module size	Operation characteristics / Performance	Special Requirements/ Remarks
KSTAR @ Korea Start: 2013	Xray Plasma Monitor for Tokamak	GEM GEMPIX	Total area: 100 cm² Total area: 10-20 cm²	**Spat. res.**: ~ 8x8 mm^2 2 ms frames; 500 frames/sec Spat. res.: ~50x50 μm^2 1 ms frames;5 frames/sec	
PRAXyS Future Satellite Mission (US-Japan): Start 2020 - for 2years	Astrophysics (X-ray polarimeter for relativistic astrophysical X-rays	TPC w/ GEM	Total area: 400 cm³ Single unit detect. (8 x 50cm³) ~400cm³	**Max.rate**: ~ 1 lcps **Spatial res.**: ~ 100 um **Time res.**: ~ few ns **Rad. Hard.**: 1000 krad	Reliability for space mission under severe thermal and vibration conditions
HARPO Balloon start >2017?	Astroparticle physics Gamma-ray polarimetry (Tracking/Triggering)	Micromegas + GEM	Total area: 30x30cm2 (1 cubic TPC module) Future: 4x4x4 = 64 HARPO size mod.	**Max.rate**: ~ 20 kHz **Spatial res.**: < 500 um **Time res.**: ~ 30 ns samp.	AGET development for balloon & self triggered
SMILE-II: Run: 2013-now	Astro Physics (Gamma-ray imaging)	GEM+μPIC (TPC+ Scintillators)	Total area: 30 x 30 x 30 cm³	Point Spread Function for gamma-ray: 1°	
ETCC camera Run: 2012-2014	Environmental gamma-ray monitoring (Gamma-ray imaging)	GEM+μPIC (TPC+ Scintillators)	Total area: 10x10x10 cm³	Point Spread Function for gamma-ray: 1°	



Maksym Titov, Conference Summary, 5th International Conference on Micro-Pattern Gas Detectors (MPGD2017), Temple University, Philadelphia

This list is now almost 6 years old, is time to update it ☺

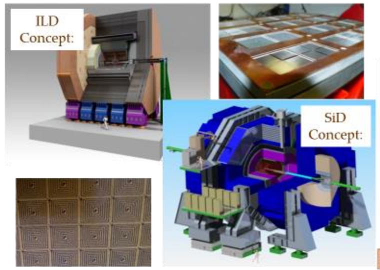
https://indico.cern.ch/event/581417/contributions/2558346/attachments/1465881/2266161/2017_05_Philadelphia_MPGD2017ConferenceSummary_25052017_MS.pdf

The MPGD family and their applications

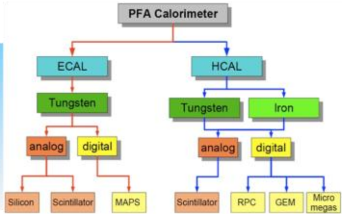
Experiment / Timescale	Application Domain	MPGD Technology	Total detector size / Single module size	Operation Characteristics / Performance	Special Requirements / Remarks
ATLAS Muon System Upgrade: Start: 2019 (for 15 y.)	High Energy Physics (Tracking/Triggering)	Micromegas	Total area: 1200 m^2 Single 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:
ATLAS Muon Tagger Upgrade: Start: > 2023	High Energy Physics (Tracking/triggering)	µ-PIC	Total area: ~ 2m^2	**Max.rate**:100kHz/cm^2 **Spatial res.**: < 100µm	
CMS Muon System Upgrade: Start: > 2020	High Energy Physics (Tracking/Triggering)	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
CMS Calorimetry (BE) Upgrade Start > 2023	High energy Physics (Calorimetry)	Micromegas, GEM	Total area: ~ 100 m^2 Single unit detect: 0.5m^2	**Max. rate**: 100 MHz/cm^2 **Spatial res.**: ~ mm	Not main option; could be used with HGCAL (BE part)
ALICE Time Projection Chamber: Start: > 2020	Heavy-Ion Physics (Tracking + dE/dx)	GEM w/ 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**: 12 % (Fe55) **Rad. Hard.**: 50 mC/cm^2	- 50 kHz Pb-Pb rate; - Continues TPC readout - Low IBF and good energy resolution
TOTEM: Run: 2009-now	High Energy/ Forward Physics (5.3≤|eta|≤6.5)	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 System Run: 2010 - now	High Energy / B-flavor physics (muon triggering)	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
FCC Collider Start: > 2035	High Energy Physics (Tracking/Triggering/ Calorimetry/Muon)	GEM,THGEM Micromegas, µ-PIC, InGrid	Total area: 10.000 m^2 (for MPGDs around 1.000 m^2)	**Max.rate**:100 kHz/cm^2 **Spatial res.**: <100µm **Time res.**: ~ 1 ns	Maintenance free for decades

MPGD Technologies for the International Linear Collider

Experiment / Timescale	Application Domain	MPGD Technology	Total detector size / Single module size	Operation Characteristics / Performance	Special Requirements/ Remarks
ILC Time Projection Chamber for ILD: Start: > 2030	High Energy Physics (tracking)	Micromegas GEM (pads) InGrid (pixels)	Total area: ~ 20 m^2 Single unit detect: ~ 400 cm^2 (pads) ~ 130 cm^2 (pixels)	**Max. rate**: < 1 kHz **Spatial res.**: <150µm **Time res.**: ~ 15 ns **dE/dx**: 5 % (Fe55) **Rad. Hard.**: no	Si + TPC Momentum resolution : $dp/p < 9*10^{-5}$ 1/GeV Power-pulsing
ILC Hadronic (DHCAL) Calorimetry for ILD/SiD Start > 2030	High Energy Physics (calorimetry)	GEM, THGEM RPWELL, Micromegas	Total area: ~ 4000 m^2 Single unit detect: 0.5 - 1 m^2	**Max.rate**:1 kHz/cm^2 **Spatial res.**: ~ 1cm **Time res.**: ~ 300 ns **Rad. Hard.**: no	Jet Energy resolution: 3-4 % Power-pulsing, self-triggering readout



Particle Flow Calorimetry (ILD/SiD):



MPGD Tracking Concepts for Hadron / Nuclear Physics

Experiment/ Timescale	Application Domain	MPGD Technology	Total detector size / Single module size	Operation Characteristics/ Performance	Special Requirements/ Remarks
COMPASS @ CERN Run: 2002 - now	Hadron Physics (Tracking)	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**:10^7 Hz (~100kHz/mm^2) **Spatial res.**: ~70-100 µm (strip), ~120µm (pixel) **Time res.**: ~ 8 ns **Rad. Hard.**: 2500 mC/cm^2	Required beam tracking (pixelized central / beam area)
KEDR @ BINP Run: 2010-now	Particle Physics (Tracking)	GEM	Toral area: ~0.1 m^2	**Max. rate**:1 MHz/mm^2 **Spatial res.**: ~70µm	
SBS in Hall A @ JLAB Start: > 2017	Nuclear Physics (Tracking) nucleon form factors / struct.	GEM	Total area: 14 m^2 Single unit detect. 0.6x0.5m^2	**Max. rate**:400 kHz/cm^2 **Spatial res.**: ~70µm **Time res.**: ~ 15 ns **Rad. Hard.**: 0.1-1 kGy/y.	
pRad in Hall B @ JLAB Start: 2017	Nuclear Physics (Tracking) precision meas. of proton radius	GEM	Total area: 1.5m^2 Single unit detect. 1.2x0.6 m2	**Max. rate**:5 kHz/cm^2 **Spatial res.**: ~70µm **Time res.**: ~ 15 ns **Rad. Hard.**: 10 kGy/y.	
SoLID in Hall A@ JLAB Start: ~ > 2020	Nuclear Physics (Tracking)	GEM	Total area: 40m^2 Single unit detect. 1.2x0.6 m2	**Max. rate**:600 kHz/cm^2 **Spatial res.**: ~100µm **Time res.**: ~ 15 ns **Rad. Hard.**: 0.8-1 kGy/y.	
E42 and E45 @JPARC Start: ~2020	Hadron Physics (Tracking)	TPC w/ GEM, gating grid	Total area: 0.26m^2 0.52m(diameter) x0.5m(drift length)	**Max. rate**:10^6 kHz/cm^2 **Spatial res.**: 0.2-0.4 mm	Gating grid operation ~ 1kHz
ACTAR TPC Start: ~2020 for 10 y.	Nuclear physics Nuclear structure Reaction processes	TPC w/ Micromegas (amp. gap -220 µm)	2 detectors: 25*25 cm2 and 12.5*50cm2	Counting rate < 10^4 nuclei but higher if some beam masks are used.	Work with various gas (He mixture, iC4H10, D2…)

Cylindrical MPGDs as Inner Trackers for Particle / Nuclear Physics

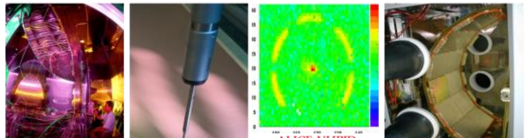
Experiment/ Timescale	Application Domain	MPGD Technology	Total detector size / Single module size	Operation Characteristics/ Performance	Special Requirements/ Remarks
KLOE-2 @ DAFNE Run: 2014-2017	Particle Physics/ K-flavor physics (Tracking)	Cylindrical GEM	Total area: 3.5m^2 4 cylindrical layers L(length) = 700mm R (radius) = 130, 155, 180, 205 mm	**Spatial res**:(r phi) = 250um **Spat. res.(z)** = 350um	- Mat. budget 2% X0 - Operation in 0.5 T
BESIII Upgrade @ Beijing Run: 2018-2022	Partcile Physics/ e+e- collider (Tracking)	Cylindrical GEM	3 cylindrical layers R ~ 20 cm	**Max. rate**: 10 kHz/cm^2 **Spatial res**:(xy) = 130um **Spat. res.(z)** = 1 mm	- Material ≤ 1.5% of X_0 for all layers - Operation in 1T
CLAS12 @ JLAB Start: > 2017	Nuclear Physics/ Nucleon structure (tracking)	Planar (forward) & Cylindrical (barrel) Micromegas	Total area: Forward ~ 0.6 m^2 Barrel ~ 3.7 m^2 2 cylindrical layers R ~ 20 cm	**Max. rate**: ~ 30 MHz **Spatial res.**: < 200µm **Time res.**: ~ 20 ns	- Low material budget : 0.4 % X0 - Remote electronics
ASACUSA @ CERN Run: 2014 - now	Nuclear Physics (Tracking and vertexing of pions resulting from the p-antip annihilation	Cylindrical Micromegas 2D	2 cylindrical layers L = 60 cm R = 85, 95 mm	**Max. trigger rate**: kHz **Spatial res.**: ~200µm **Time res.**: ~ 10 ns **Rad. Hard.**: 1 C/cm^2	- Large magnetic field that varies from -3 to 4T in the active area
MINOS Run: 2014-2016	Nuclear structure	TPC w/ cylindrical Micromegas	1 cylindrical layer L=30 cm, R = 10cm	**Spatial res.**: <5 mm FWHM Trigger rate up to ~1 KHz	- Low material budget
CMD-3 Upgrade @ BINP Start: > ~2019 ?	Particle physics (z-chamber, tracking)	Cylindrical GEM	Total arear: ~ 3m^2 2 cylindrical layers	**Spatial res.**: ~100µm	

MPGD Tracking for Heavy Ion / Nuclear Physics

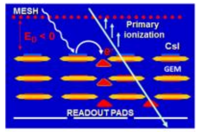
Experiment / Timescale	Application Domain	MPGD Technology	Total detector size / Single module size	Operation Characteristics / Performance	Special Requirements/ Remarks
STAR Forward GEM Tracker @ RHIC Run: 2012-present	Heavy Ion Physics (tracking)	GEM	Total area: ~ 3 m^2 Single unit detect: ~ 0.4 x 0.4 m^2	**Spatial res.**: 60-100 µm	Low material budget:: < 1% X0 per tracking layer
Nuclotron BM@N @ NICA/JINR Start: > 2017	Heavy Ions Physics (tracking)	GEM	Total area: ~ 12 m^2 Single unit detect: ~ 0.9 m^2	**Max. rate**: ~ 300 MHz **Spatial res.**: ~ 200µm	Magnetic field 0.5T orthogonal to electric field
SuperFRS @ FAIR Run: 2018-2022	Heavy Ion Physics (tracking/diagnostics at the In-Fly Super Fragment Separator)	TPC w/ GEMs	Total area:~ few m^2 Single unit detect: Type I : 50 x 9 cm^2 Type II: 50 x 16 cm^2	**Max. rate**:~ 10^7 Hz/spill **Spatial res.**: < 1 mm	High dynamic range Particle detection from p to Uranium
PANDA @FAIR Start > 2020	Nuclear physics p - anti-p (tracking)	Micromegas/ GEMs	Total area: ~ 50 m^2 Single unit detect: ~ 1.5 m^2	**Max. rate**: < 140kHz/cm^2 **Spatial res.**: ~ 150µm	Continuous-wave operation: 10^{11} interaction/s
CBM @ FAIR: Start: > 2020	Nuclear Physics (Muon System)	GEM	Total area: 9m^2 Single unit detect: 0.8x0.5m^2-0.4m^2	**Spatial res.**: < 1 mm **Max. rate**: 0.4 MHz/cm^2 **Time res.**: ~ 15ns **Rad hard.**: 10^{13} n.eq./cm^2/year	Self-triggered electronics
Electron-Ion Collider (EIC) Start: > 2025	Hadron Physics (tracking, RICH)	TPC w/GEM readout Large area GEM planar tracking detectors	Total area: ~ 3 m^2 Total area: ~ 25 m^2	**Spatial res.**: ~ 100 um (rϕ) Luminosity (e-p): 10^{33} **Spatial res.**: ~ 50- 100 um **Max. rate**: ~ MHz/cm^2	Low material budget Low material budget

MPGD Technologies for Photon Detection

Experiment / Timescale	Application Domain	MPGD Technology	Total detector size / Single module size	Operation Characteristics / Performance	Special Requirements / Remarks
COMPASS RICH UPGRADE Start > 2016	Hadron Physics (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
PHENIX HBD Run: 2009-2010	Nuclear Physics (RICH – e/h separation)	GEM+CsI detectors	Total area: ~ 1.2 m^2 Single unit detect: ~ 0.3 x 0.3 m^2	**Max. rate**: low **Spatial res.**: ~ 5 mm (rϕ) **Single el. eff.**: ~ 90 %	Single el. eff. depends from hadron rejection factor
SPHENIX Run: 2021-2023	Heavy Ions Physics (tracking)	TPC w/GEM readout	Total area: ~ 3 m^2	**Multiplicity**: dNch/dy ~ 600 **Spatial res.**: ~ 100 um (rϕ)	Runs with Heavy Ions and comparison to pp operation
Electron-Ion Collider (EIC) Start: > 2025	Hadron Physics (tracking, RICH)	TPC w/GEM readout + Cherenkov RICH with GEM readout	Total area: ~ 3 m^2 Total area: ~ 10 m^2	**Spatial res.**: ~ 100 um (rϕ) Luminosity (e-p): 10^{33} **Spatial res.**: ~ few mm	Low material budget High single electron efficiency



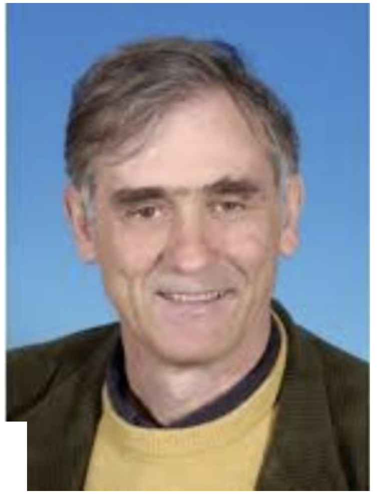
ALICE VHPID THGEM

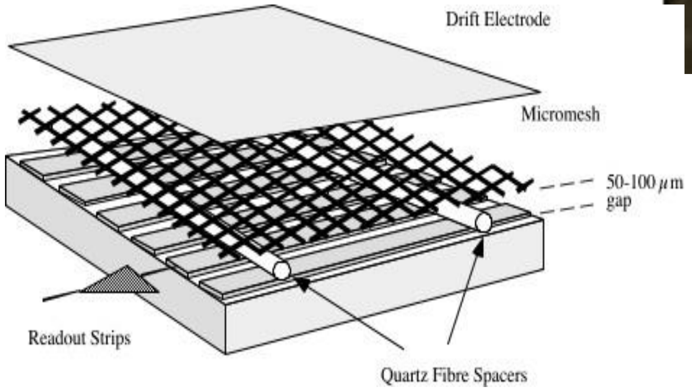


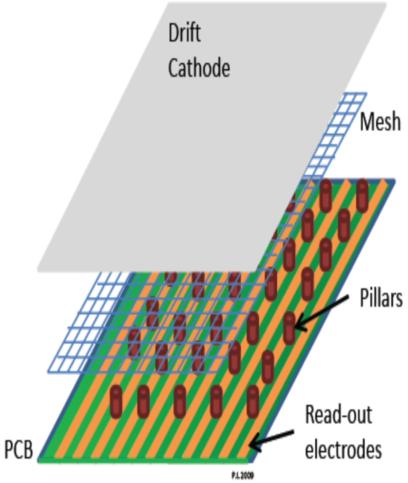
HBD Concept:

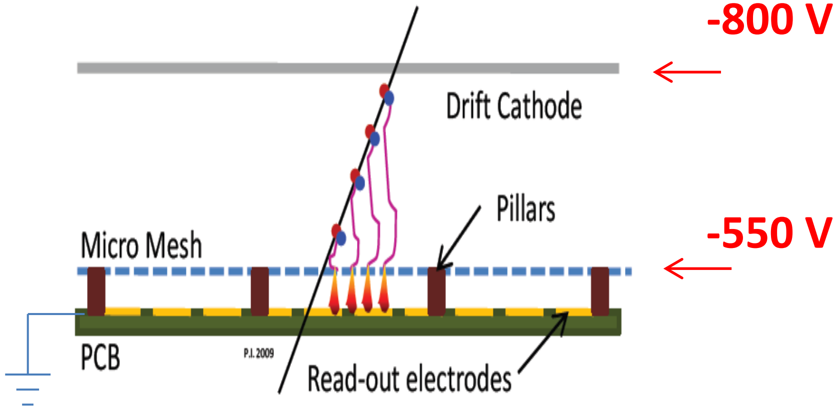
Micromegas: Detector Principles

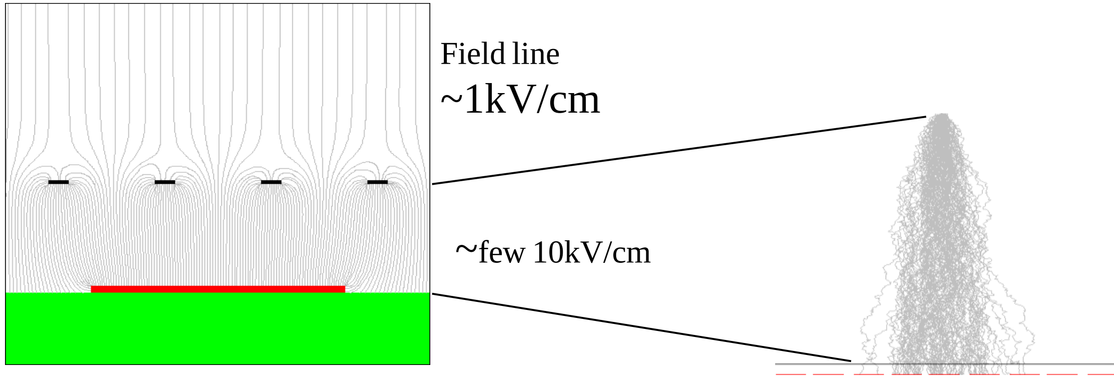
- Micromegas are parallel-plate chambers where the amplification takes place in a thin gap, separated from the conversion region by a fine metallic mesh
- The thin amplification gap (short drift times and fast absorption of the positive ions) makes it particularly suited for high-rate applications







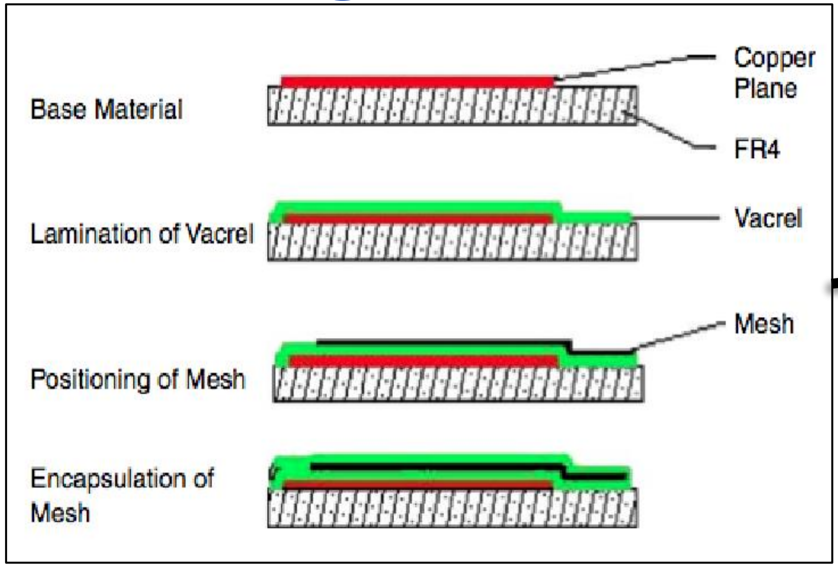


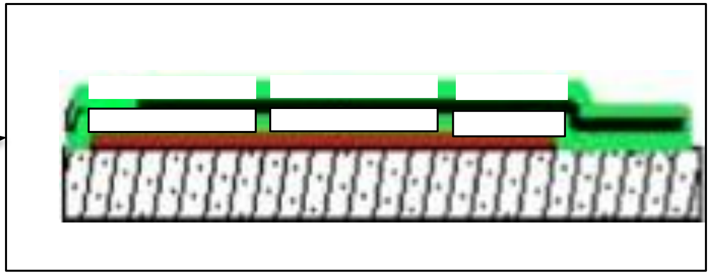


Micromegas: Detector Principles

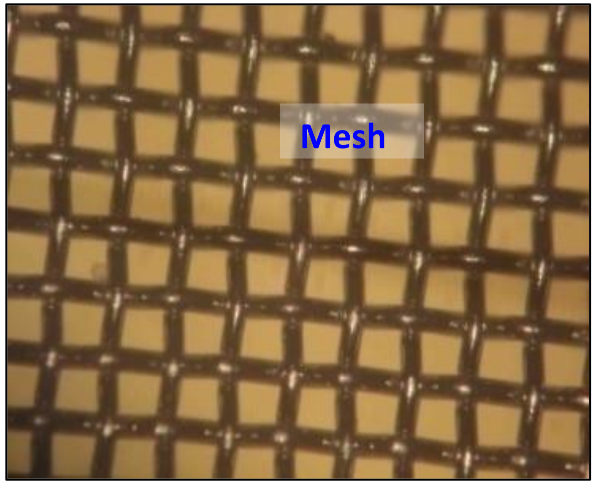
MM Evolution: Bulk Technology

NIM A560 (2006) 405



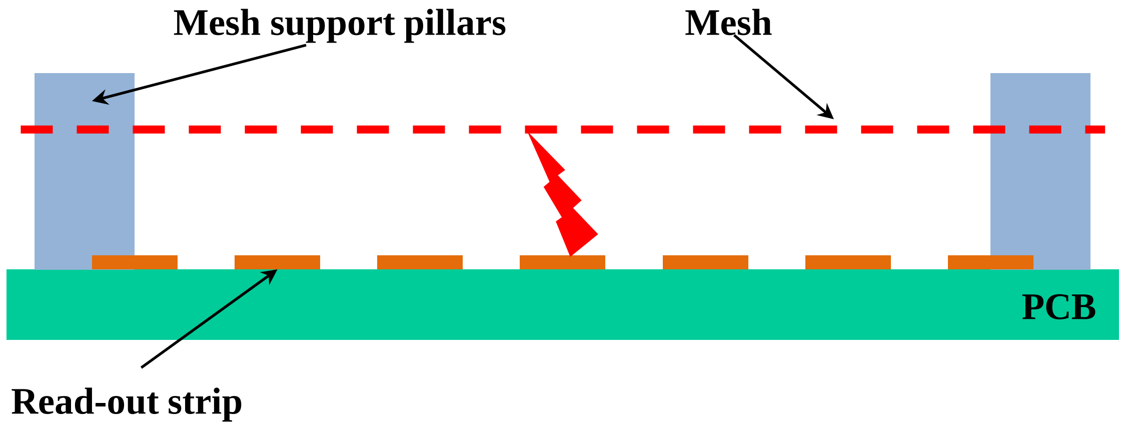


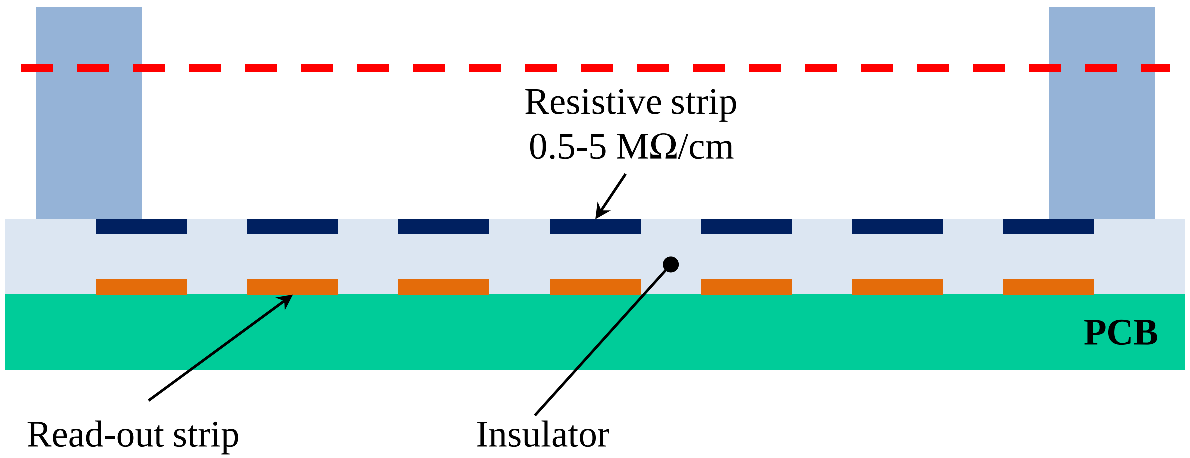
The Insulator (Vacrel 8100 in this case) is photosensitive and can be removed by etching, creating the pillars.



- New mesh used for bulk MM.
- Woven wire mesh, wire diameter about 20–30 μm and about 80% transparency.
- Largely produced for serigraphic application.
- Electroformed micromesh was normally used before.

Micromegas: Resistive MM (spark resistant)





- Sparks between mesh and readout strips may damage the detector and readout electronics and/or lead to large dead times as a result of HV breakdown
- Several protection/suppression schemes tested
  - A large variety of resistive coatings of anode
  - Double/triple amplification stages to disperse charge, as used in GEMs (MM+MM, GEM+MM)
- Finally settled on a protection layer with resistive strips
- To avoid spark effect the readout strips were covered with the 64 µm thick insulator layer with resistive strips on top of it connected to the +HV via discharge resistor and mesh is connected to GND

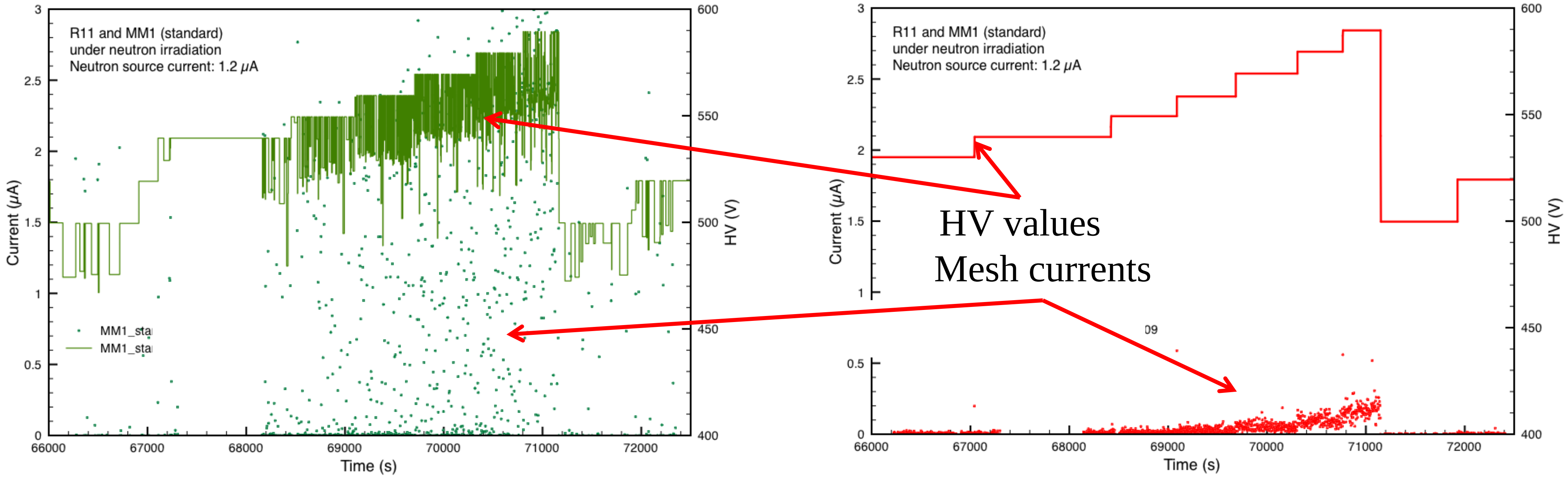
Micromegas: resistive MM

MicroMegas mesh currents and HV drop in neutron beam

Gas: Ar:CO_2 (85:15) Neutron flux: ≈ 10^6 n/cm^2/sec

Standard MM:
Large currents
Large HV drops, recovery time O(1s)
Chamber could not be operated stably

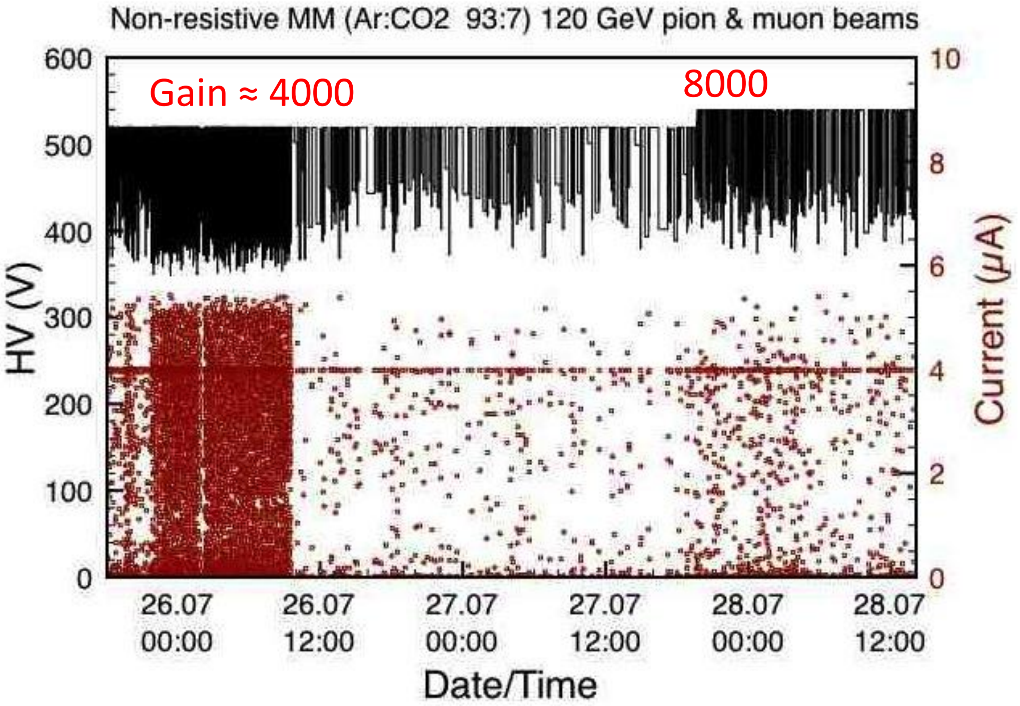
Resistive MM:
Low currents
Despite discharges, but no HV drop
Chamber operated stably up to max HV



Micromegas: resistive MM

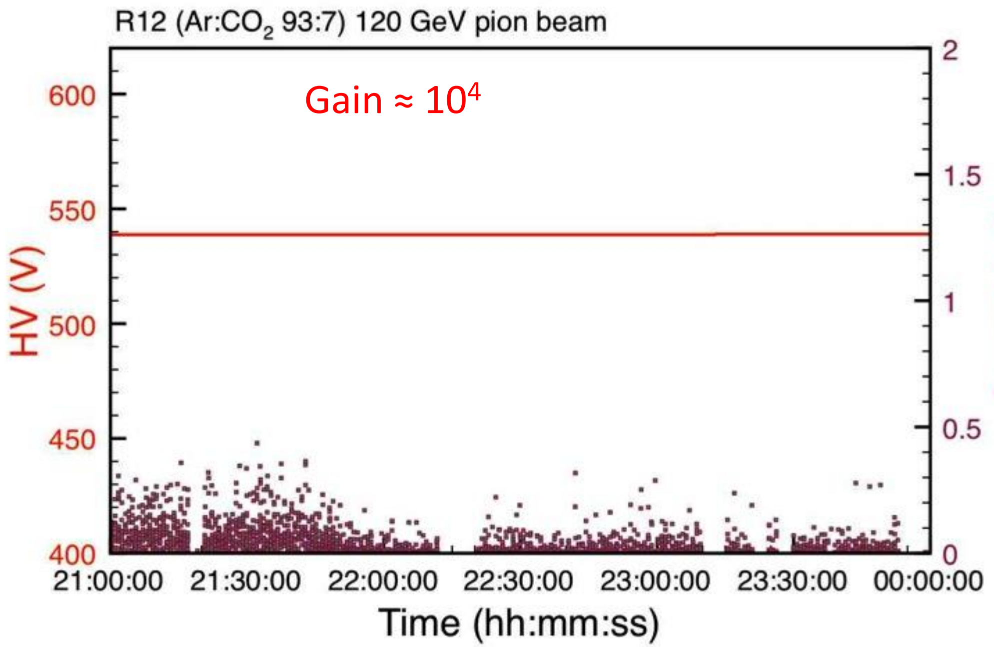
Sparks in 120 GeV pion & muon beams

Standard MM



- Pions, no beam, muons
- Chamber inefficient for O(1s) when sparks occur

Resistive MM

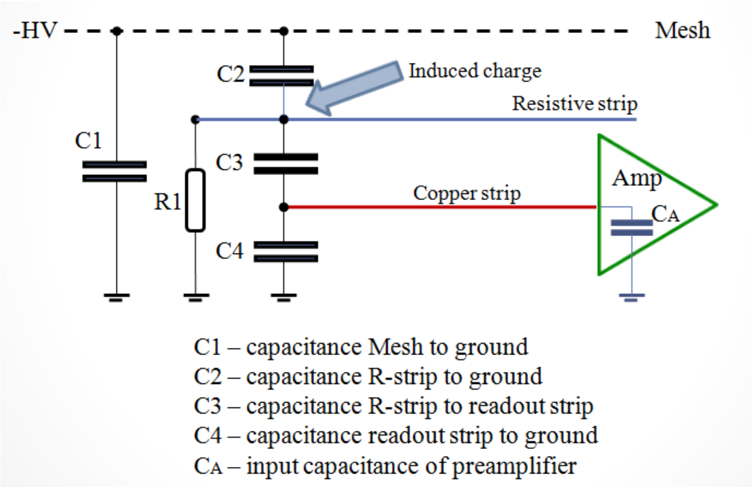


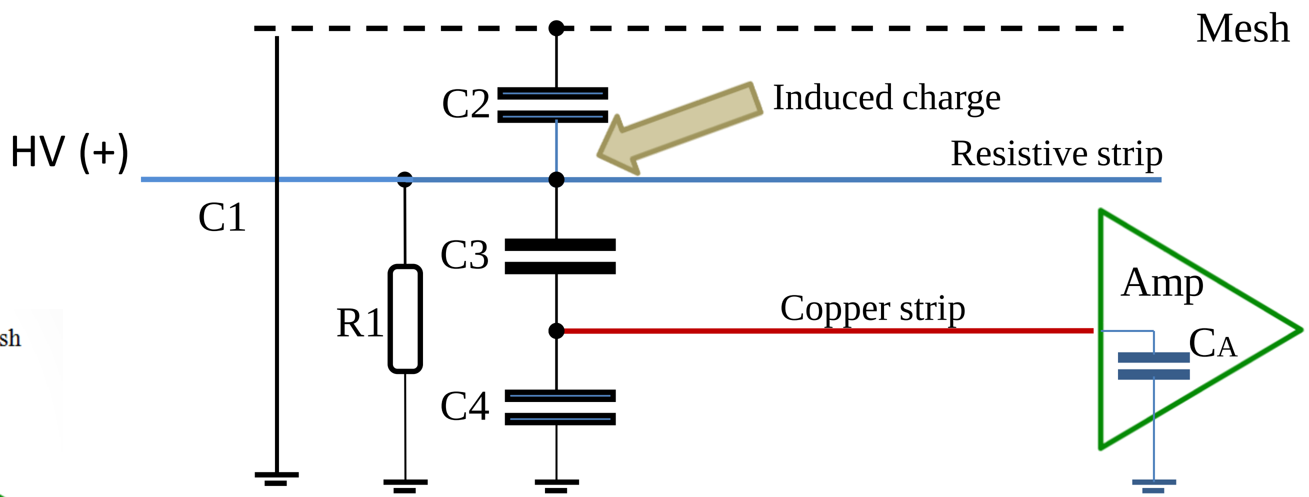
- Stable, no HV drops, low currents for resistive MM
- Same behavior up to gas gains of > 10^4

Micromegas: spark resistant

Equivalent scheme of resistive Micromegas chambers

(Reversed HV schema, more stable during the operation)



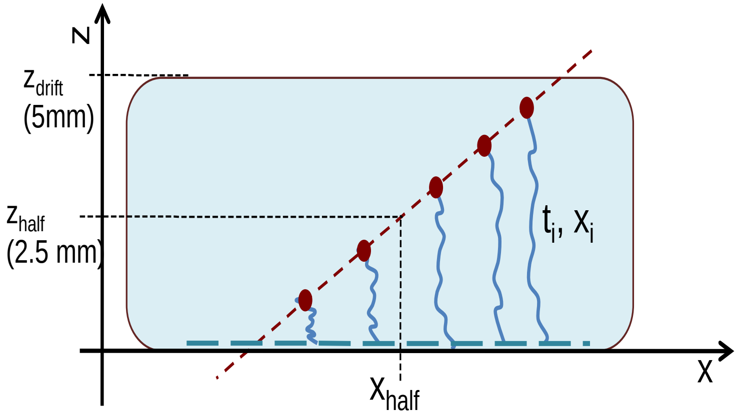


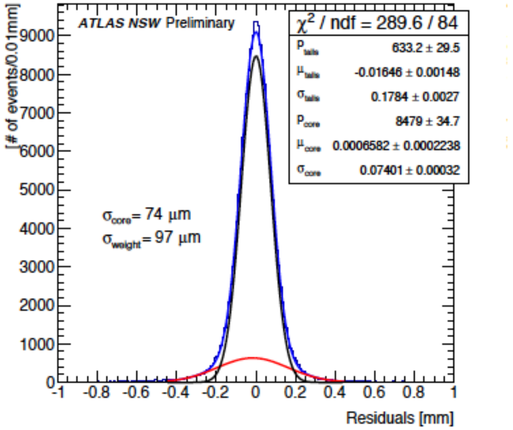
C1 – capacitance Mesh to ground
C2 – capacitance R-strip to ground
C3 – capacitance R-strip to readout strip
C4 – capacitance readout strip to ground
C_A – input capacitance of preamplifier

Micromegas: Performance and MicroTPC

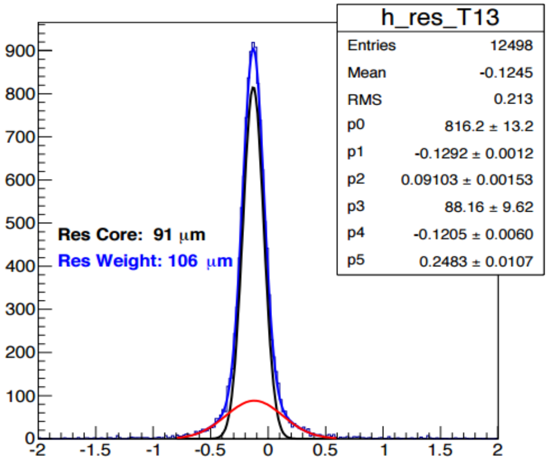
Working with analog FE, two different methods are used in order to extract the correct spatial information:

- Using charge amplitude (Centroid hit)
    - Accuracy rapidly decreasing for larger track angles.
- Using time information (μTPC segment).
    - Performance improving with increasing cluster size

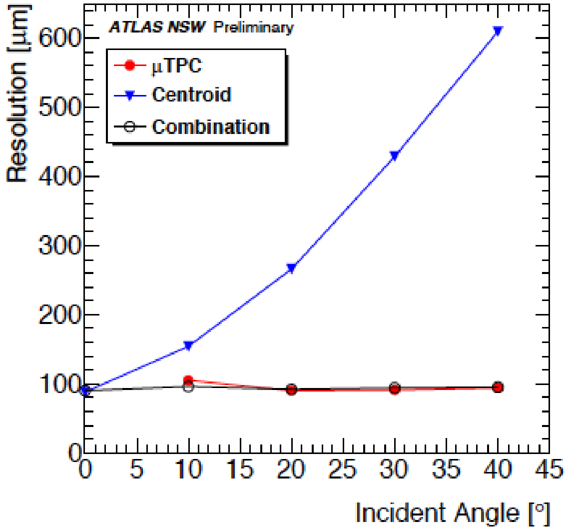




Resolution achieved with centroid method for perpendicular track using chamber with 400 μm strip pitch



Resolution achieved with μTPC method for 30 ⁰ inclined track using chamber with 400 μm strip pitch



Micromegas Aging studies

- A resistive-strip MM has been exposed at CEA Saclay to 5.28 keV X-rays for 12 and 21 days. In parallel, an 'identical' chamber was measured without being irradiated continuously
- Accumulated charge: 765 + 918 mC/4 cm^2 (>20 years of ATLAS MM at HL-LHC)

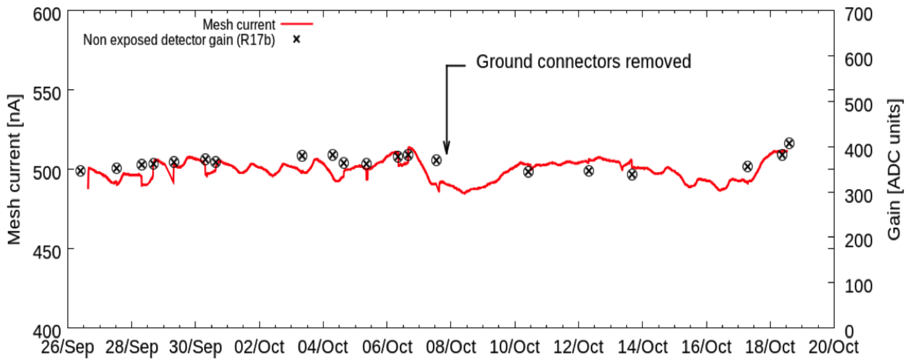
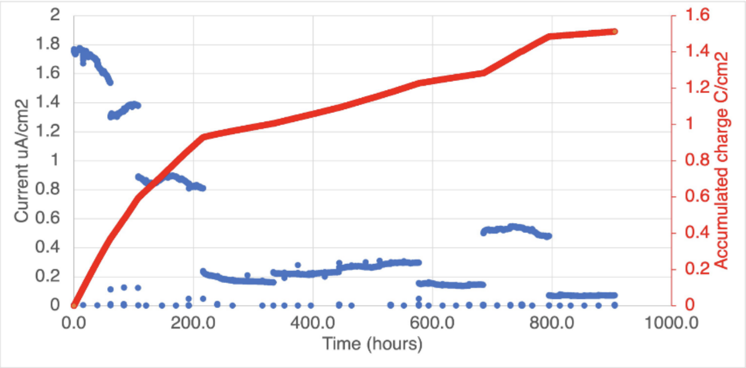
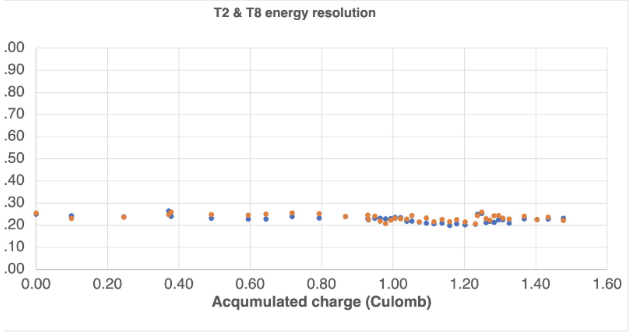


Figure 9. Mesh current evolution provided by the high voltage power supply (red line) and the R17b gain control measurements with R17b detector (black circles).

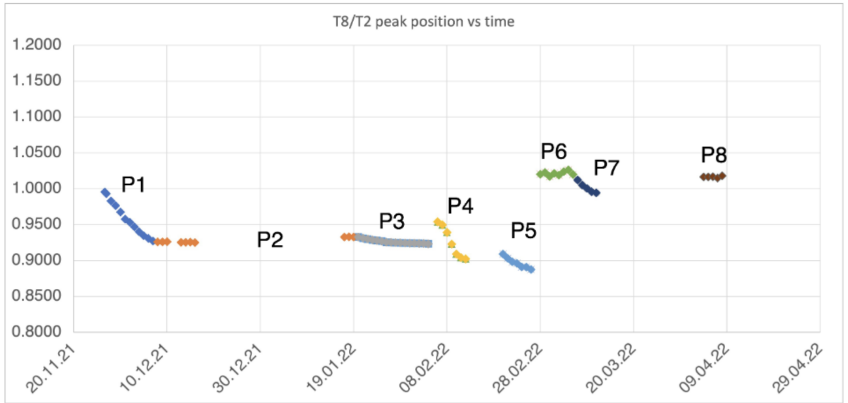
- Aging test for MM chambers using ATLAS gas mixture $Ar:CO_2:iC_4H_{10}$ 93:5:2



Integrated charge Vs time



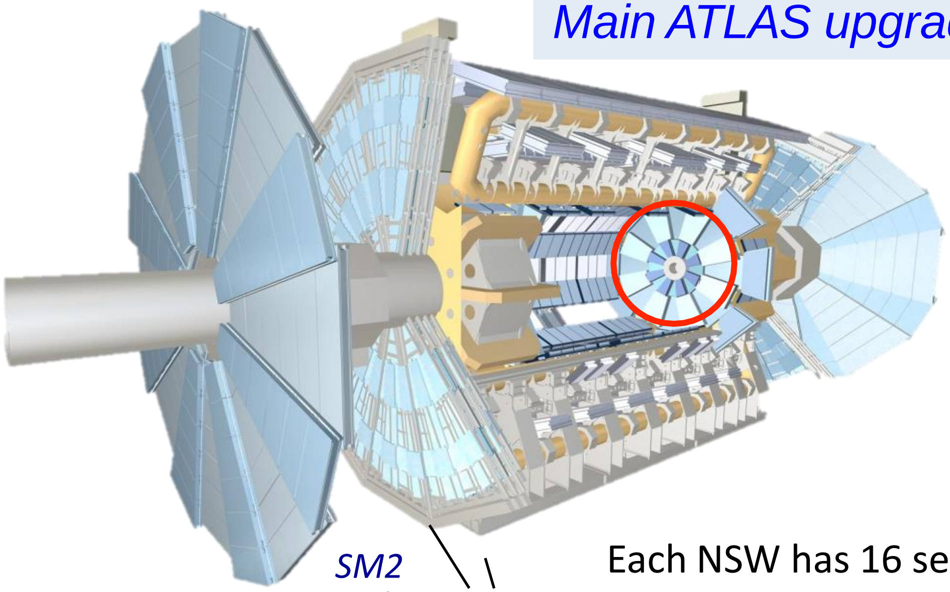
Energy resolution

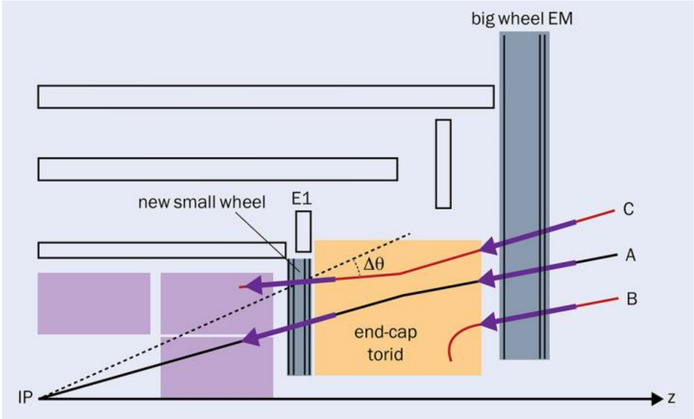


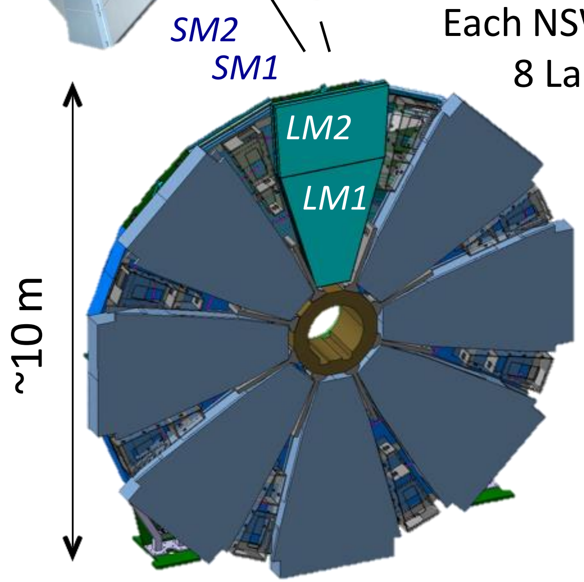
Effective gain for irradiated chamber (T8) versus reference not integrated chamber (T2), the drop of gain during the first part of the irradiation test is attributed a large charge-up effect due to the very high (MHz/cm^2) irradiation flux

Micromegas for the ATLAS NSW

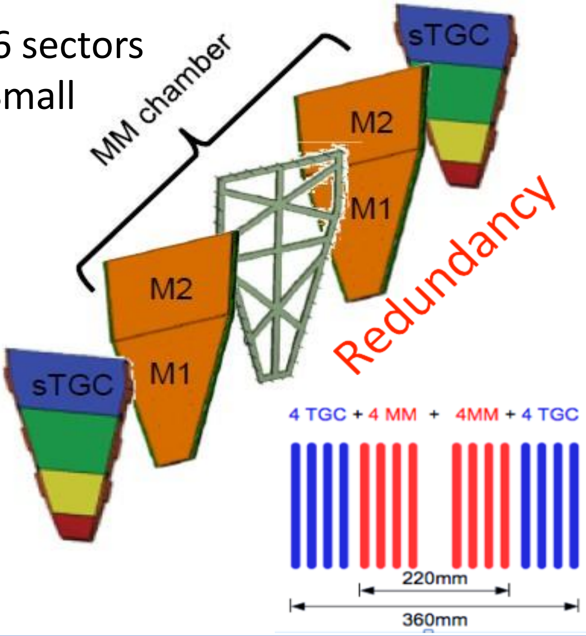
Main ATLAS upgrade during the Long Shutdown 2 (2019/20) (Phase-1)







Each NSW has 16 sectors
8 Large + 8 Small



Two different technology:

- MM (main role tracking)
- sTGC (main role trigger)

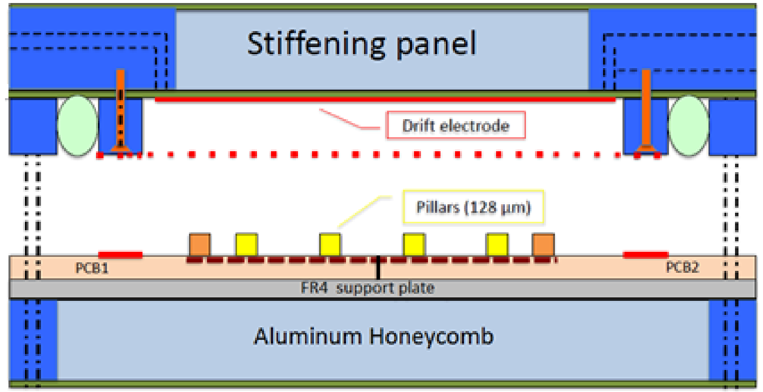
NSW Requirements

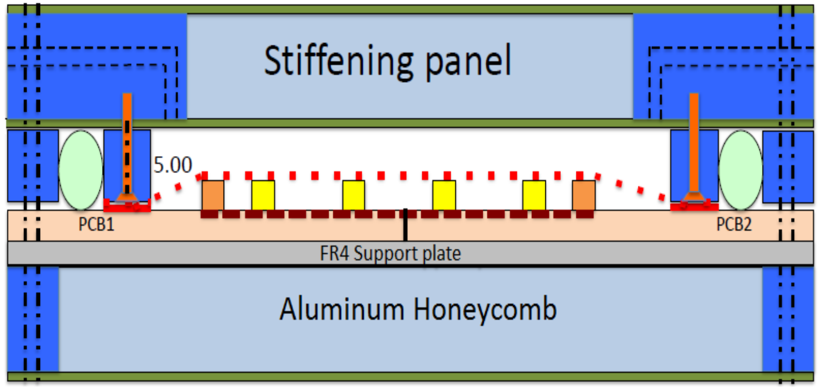
- 15% P_T resolution at 1 TeV
- → ~100 μm resolution per plane
- Keep single muon trigger under control
- → 1 mrad online angular resolution

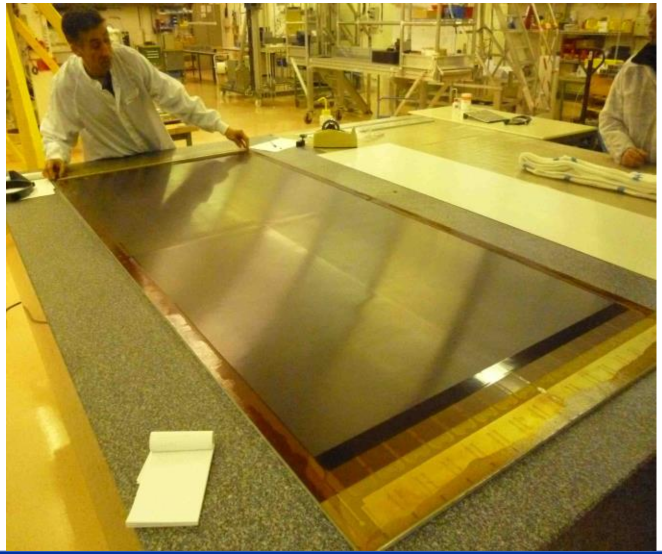
About 15kHz / cm^2 at $L \approx 5 \times 10^{34}\ cm^{-2}s^{-1}$

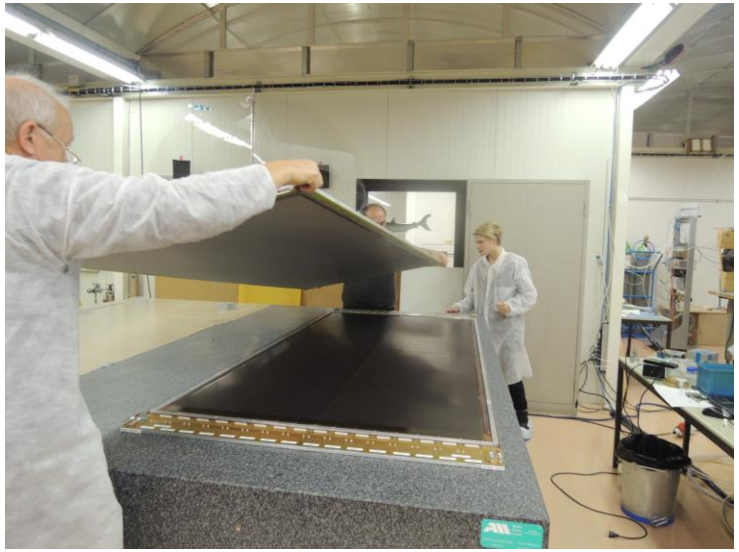
Building large Micromegas: Non-bulk technique

Non-bulk technique (**floating mesh**) that uses also pillars to keep the mesh at a defined distance from the board, the mesh is integrated with the drift-electrode panel and placed on the pillars when the chamber is closed. This allows us to build very large chambers using standard printed circuit boards (PCB)



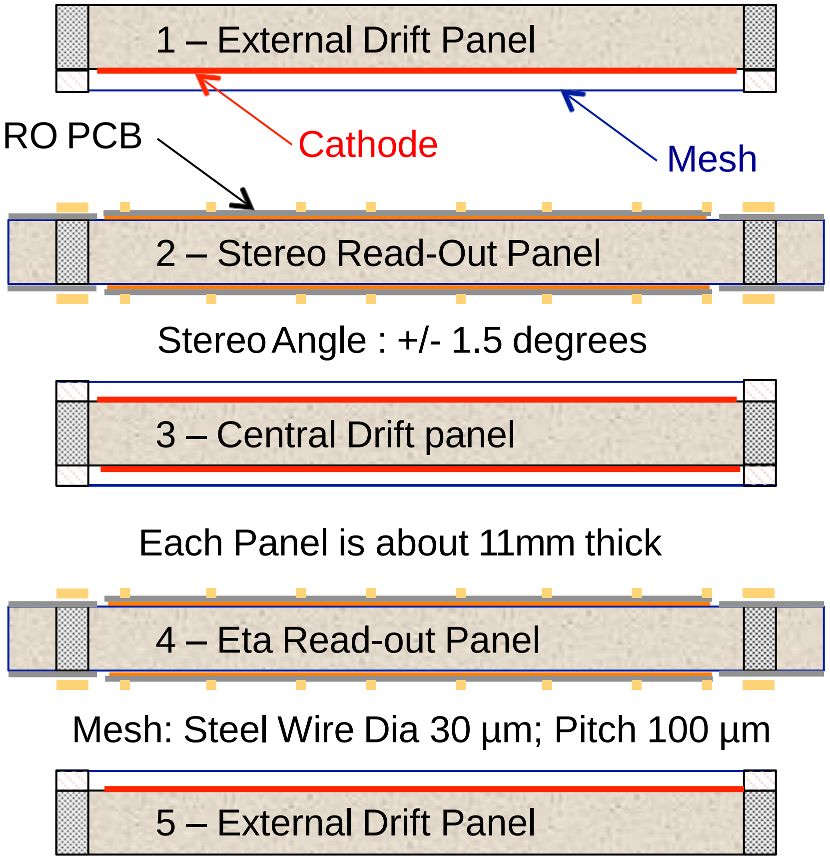






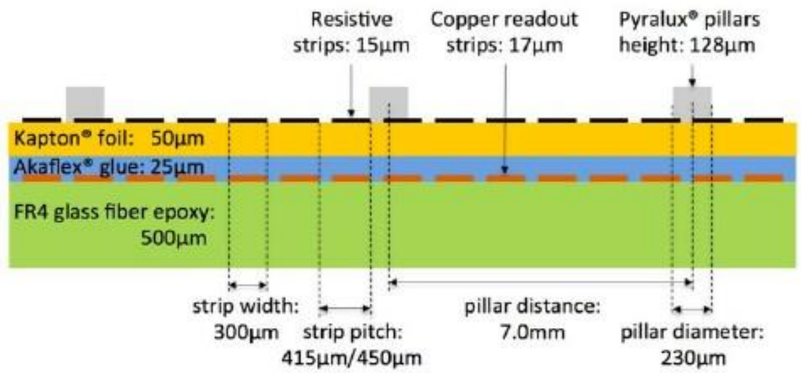
Micromegas for the ATLAS NSW

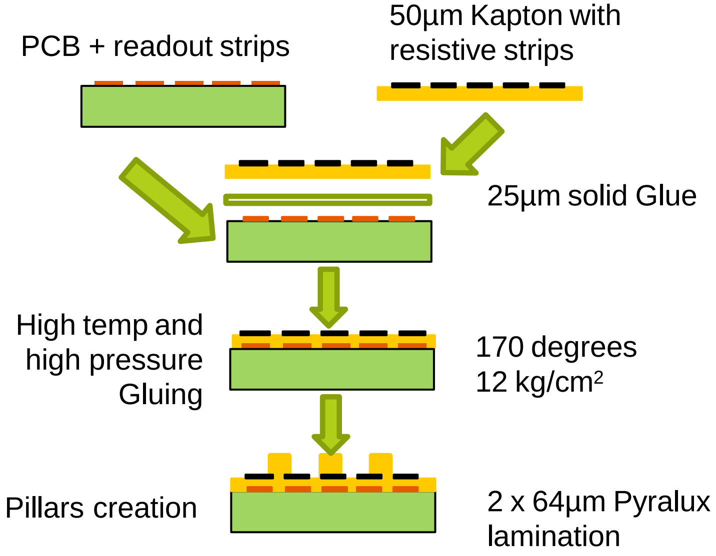
MM Quadruplet Exploded View

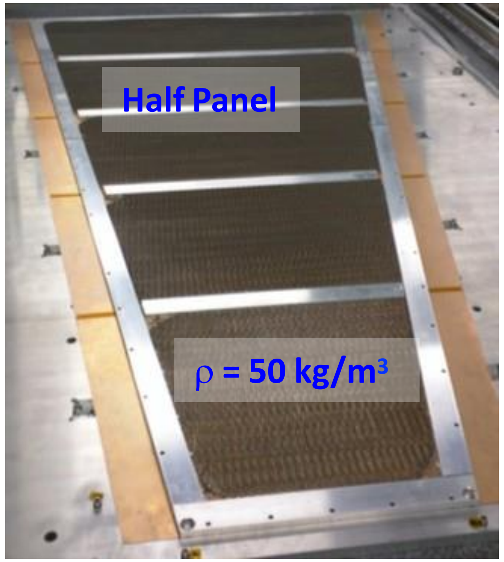


Five panels joined to make a detector unit (Quadruplet) with 4 gas layers.

Building Large Area MM

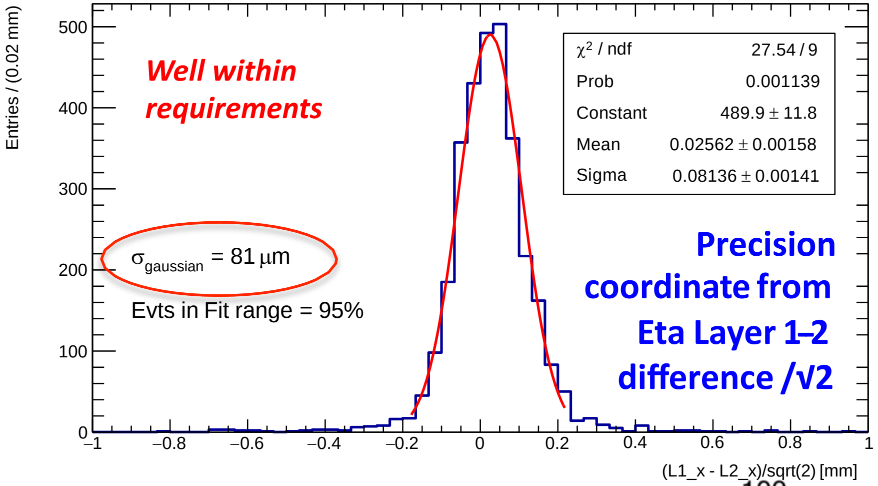


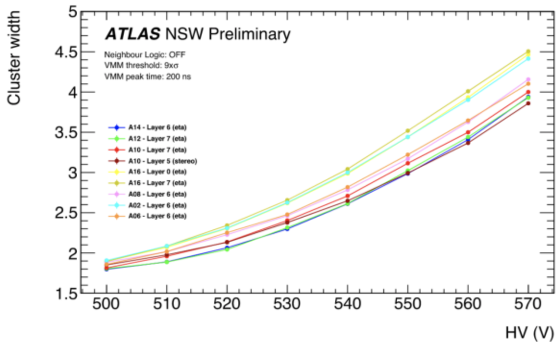


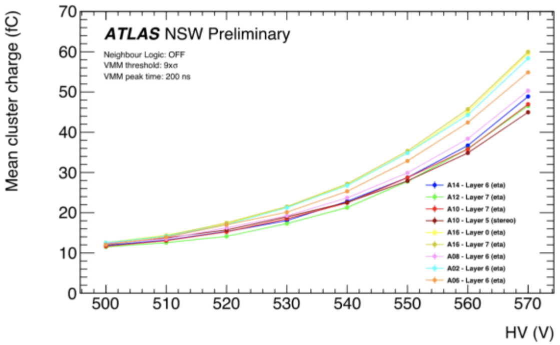


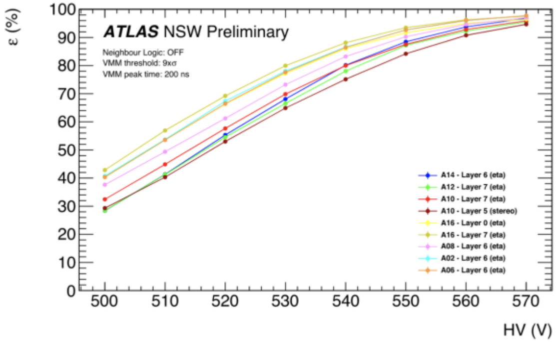
Micromegas for the ATLAS NSW

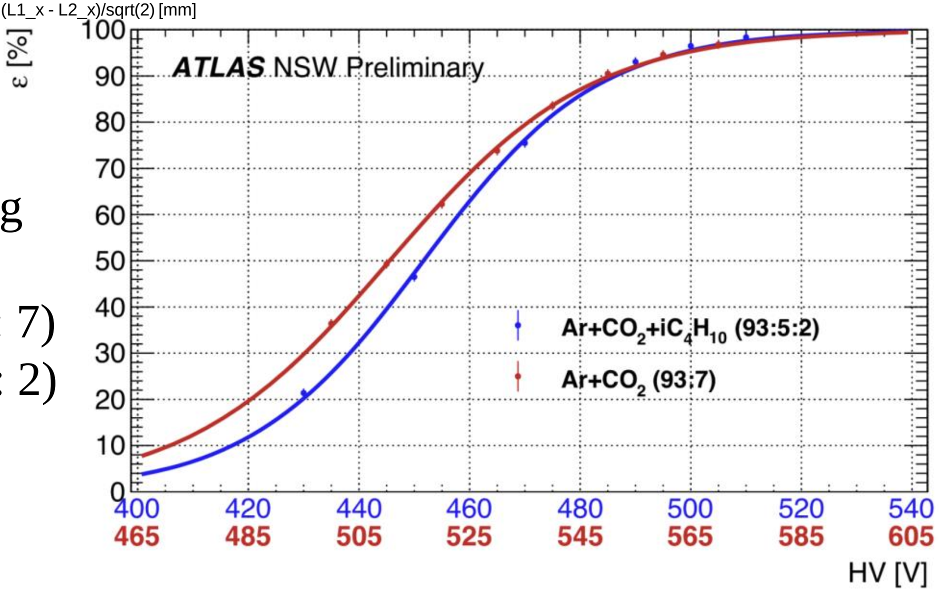
Spatial Resolution of the precision coordinate







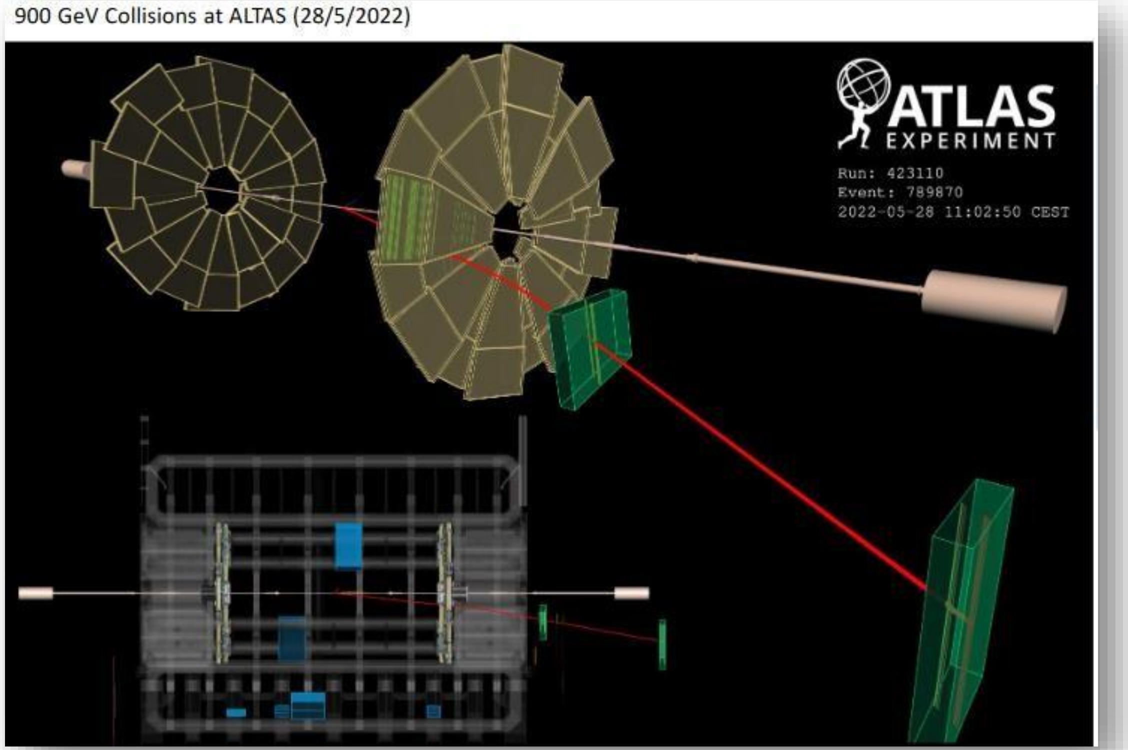




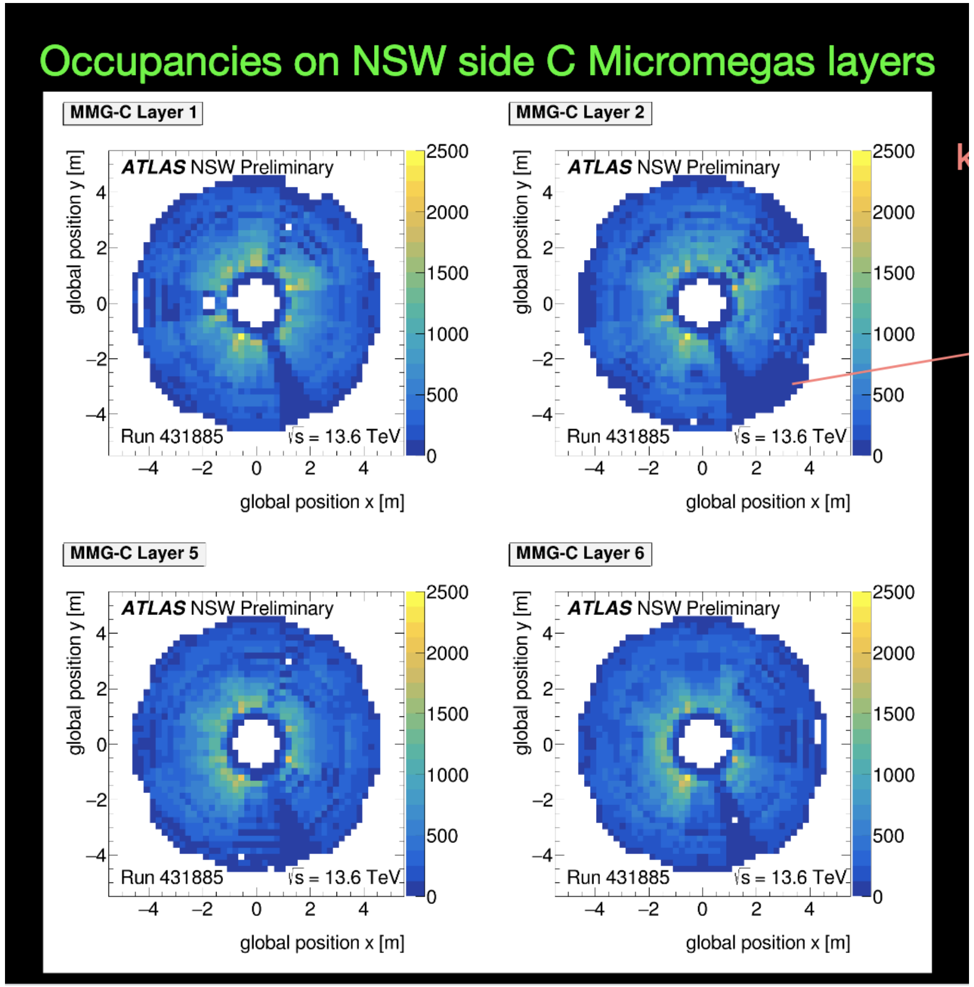
Efficiency turn on curve comparing the performances of the 2 gas mixture under study: Ar: CO2 (93: 7) (red) and Ar: CO2: iC4H10 (93: 5: 2)

Cluster width (top left), mean cluster charge (top right) and efficiency (bottom) of different layers of the NSW as a function of the amplification voltage

Data from ATLAS NSW

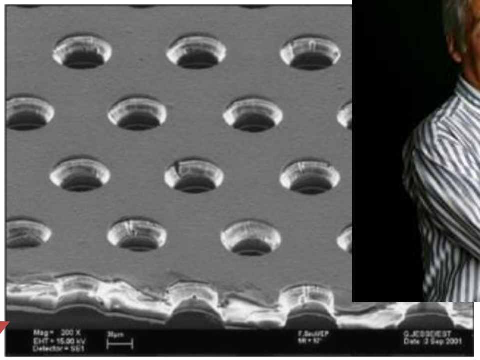


T. Vafeiadis, The New Small Wheel project of ATLAS, CERN EP Detector Seminar 17/6/2022, https://indico.cern.ch/event/1168778/attachments/2464624/4227403/_2022_06_17-TV-DetSeminar.pdf

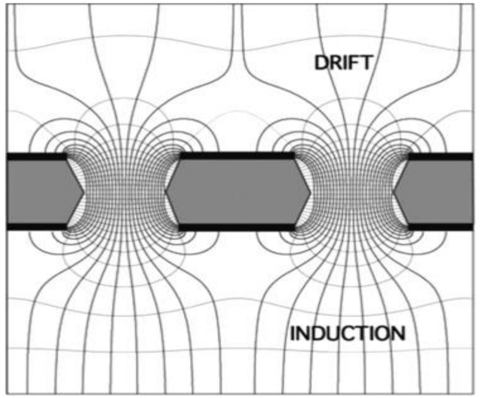


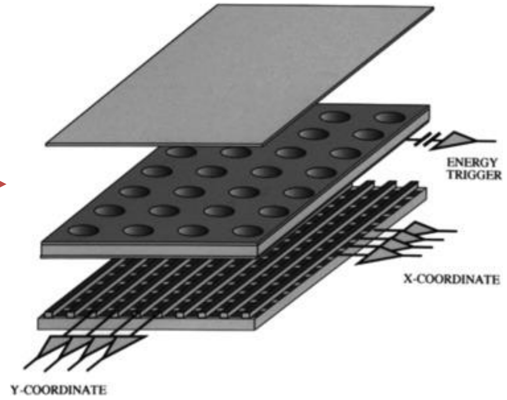
151st LHCC Meeting - OPEN Session, ATLAS Status Report by T. J. Khoo, https://indico.cern.ch/event/1192325/contributions/5012980/attachments/2507852/4309670/LHCC_ 20220914.pdf

What are the GEM: Principles



- Concept of **G**as **E**lectron **M**ultipliers
  - **G**as **E**lectron **M**ultipliers (**GEM**) was introduced by **Fabio Sauli** in 1996-97
  - Gas Electron Multiplier electrode is a thin polymer foil, metal-coated on both sides and pierced with a high density of holes, typically 50–100 mm^{-2}
  - Inserted between a drift and a charge collection electrode, and with the application of appropriate potentials, the GEM electrode develops near the holes equipotential field lines
  - The large difference of potential applied between the two sides of the foil creates a high field in the holes; electrons released in the upper region drift towards the holes and acquire sufficient energy to cause ionizing collisions with the molecules of the gas filling the structure
  - A sizeable fraction of the electrons produced in the avalanche′s front leave the multiplication region and transfer into the lower section of the structure, where they can be collected by an electrode, or injected into a second multiplying region, schematically a single GEM detector, with a two-dimensional patterned charge detection anode

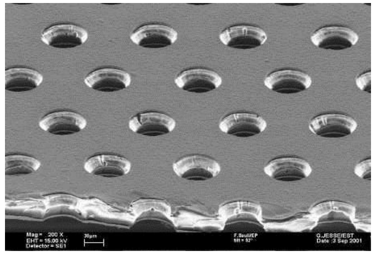


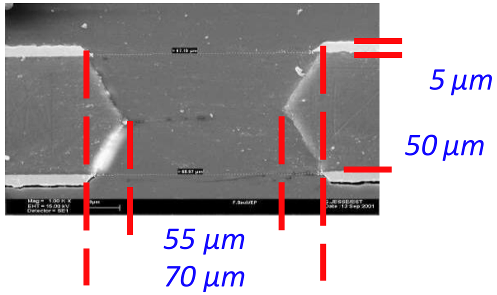


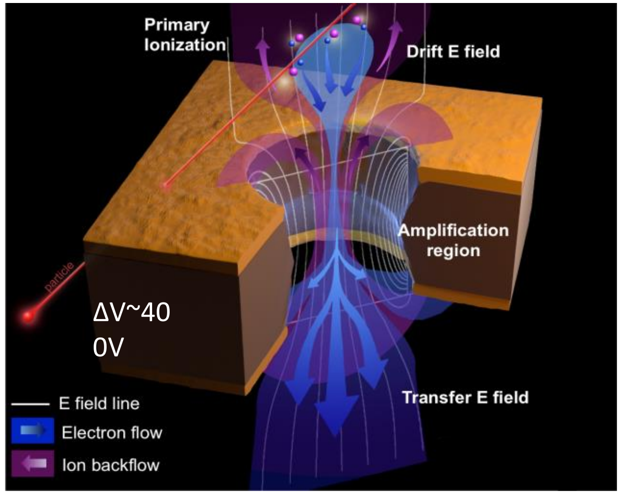
What are the GEM

Gas Electron Multipliers

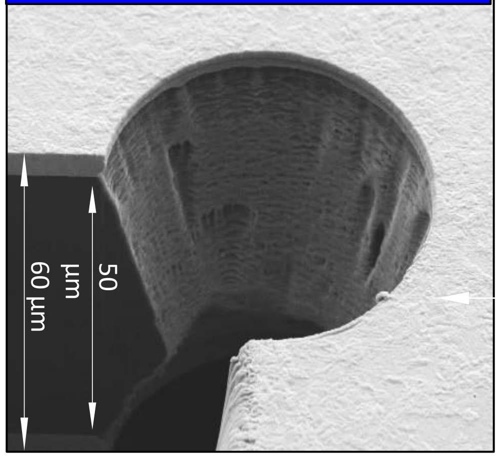
SEM picture of a GEM





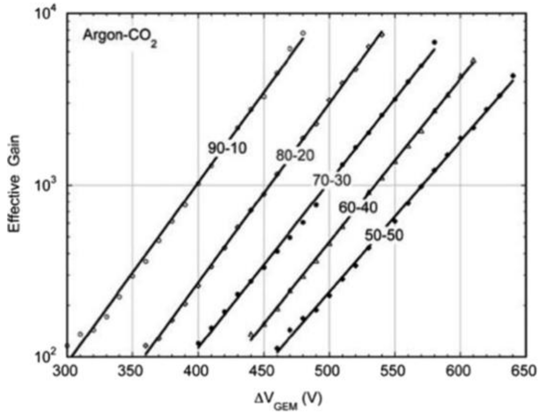


SEM picture of a GEM hole



Electrons entering the GEM holes will accelerate in the intense electric field (~80 kV/cm) and provoke the ionization of gas molecules, giving rise to an electron avalanche

Multiplication: 1 e^- input to > 1000 e^- output (as a function of gas and HV)



Master of GEM

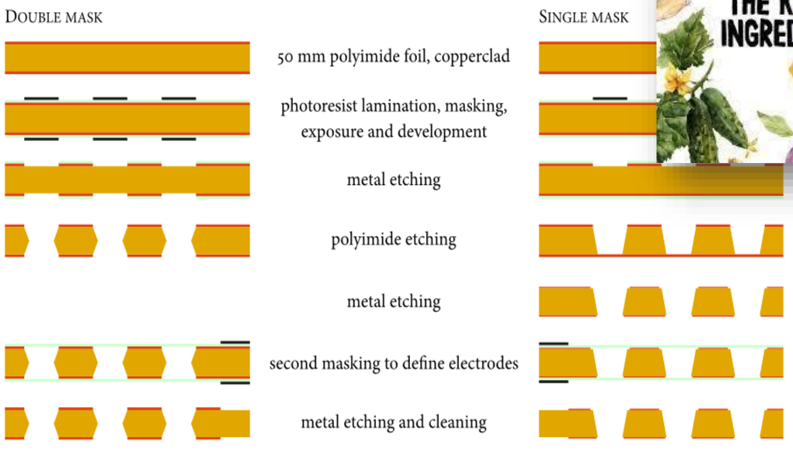
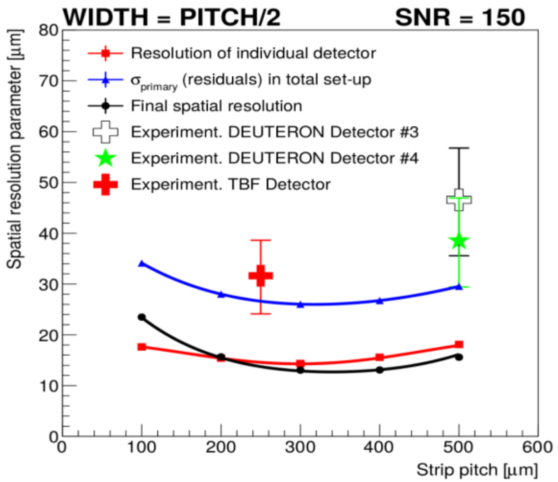


Figure 1. Schematic comparison of procedures for fabrication of a double-mask GEM (left) and a single-mask GEM (right).

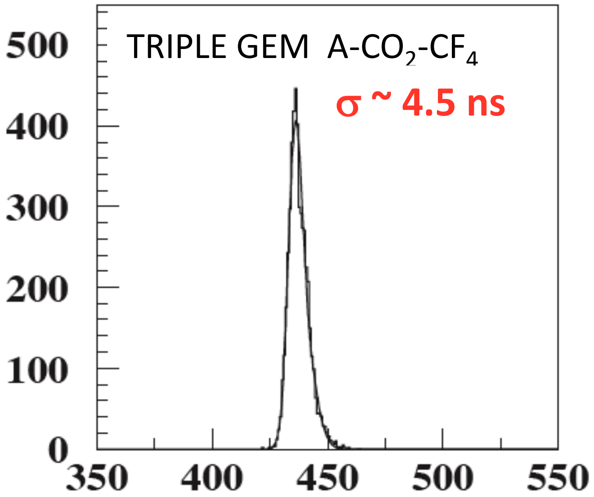
CERN's Printed Circuit Workshop

https://indico.cern.ch/event/1175363/attachments/2477073/4252122/MBianco_CMS_GEM.pdf

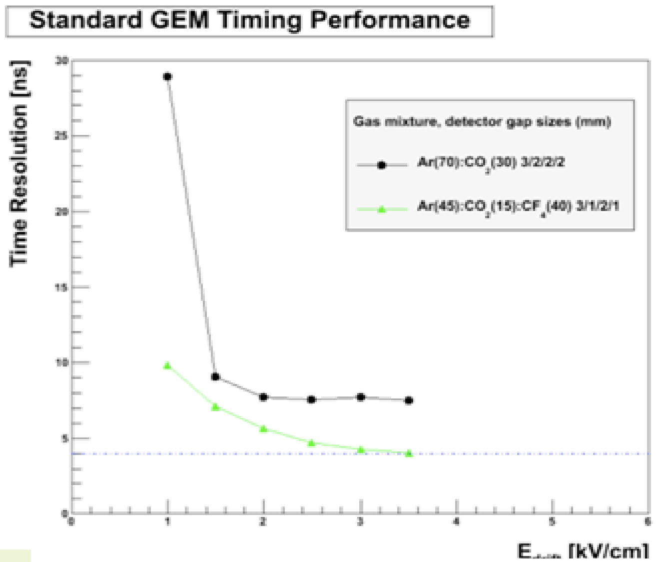
GEM: Operation and Performance



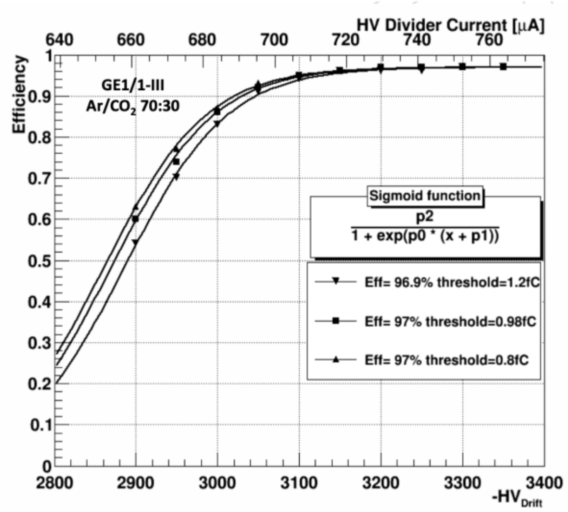
V.N. Kudryavtsev et al 2020 JINST15 C05018



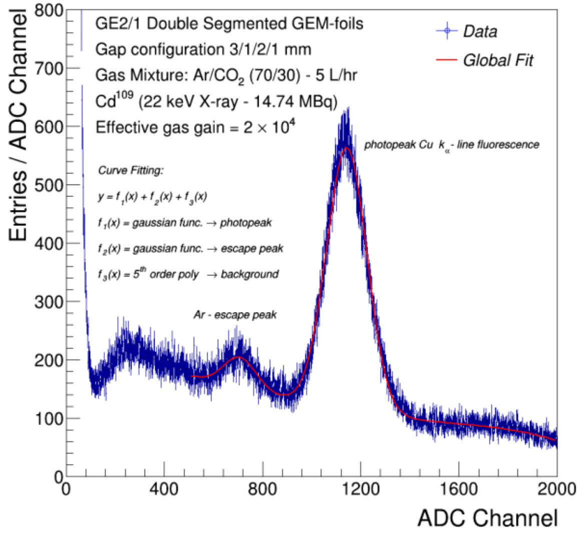
M. Alfonsi et al, Nucl. Instr. and Meth. A535(2004)319



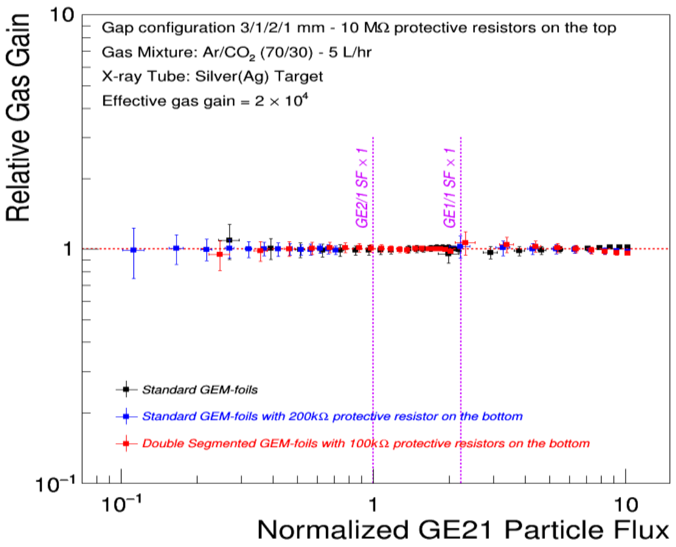
CMS TECHNICAL DESIGN REPORT FOR THE MUON ENDCAP GEM UPGRADE
CMS-TDR-013



CMS-TDR-013



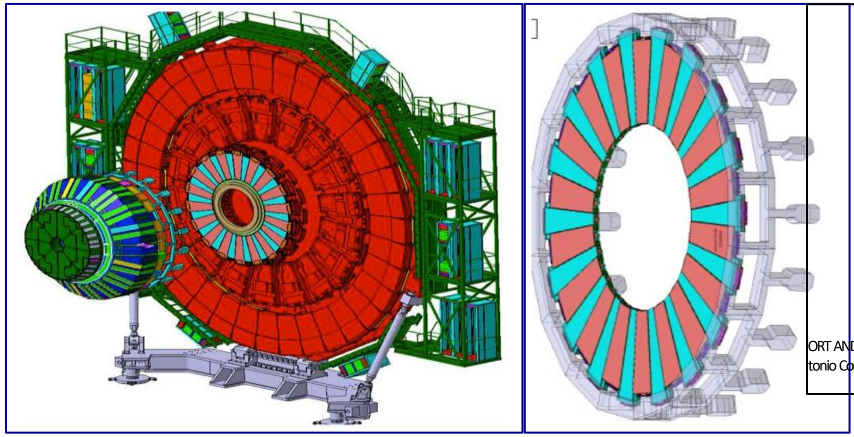
M. Bianco 2020 *JINST* **15** C09045

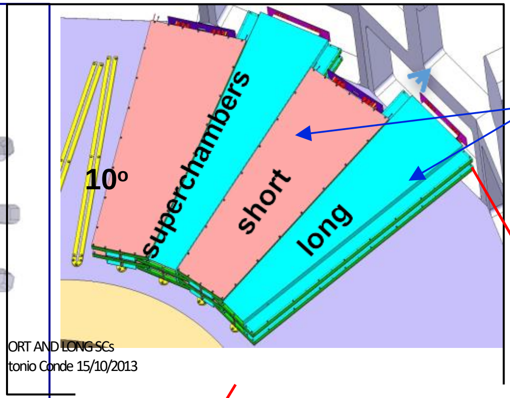


M. Bianco 2020 *JINST* **15** C09045

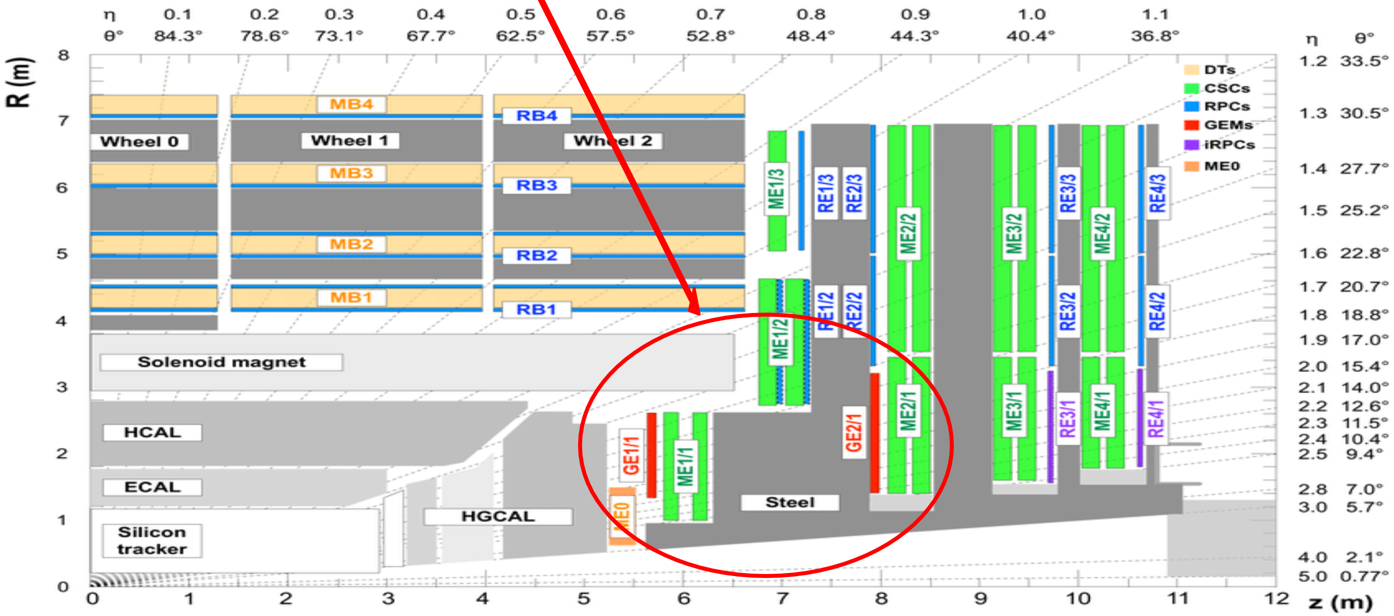
GEM for CMS Experiment

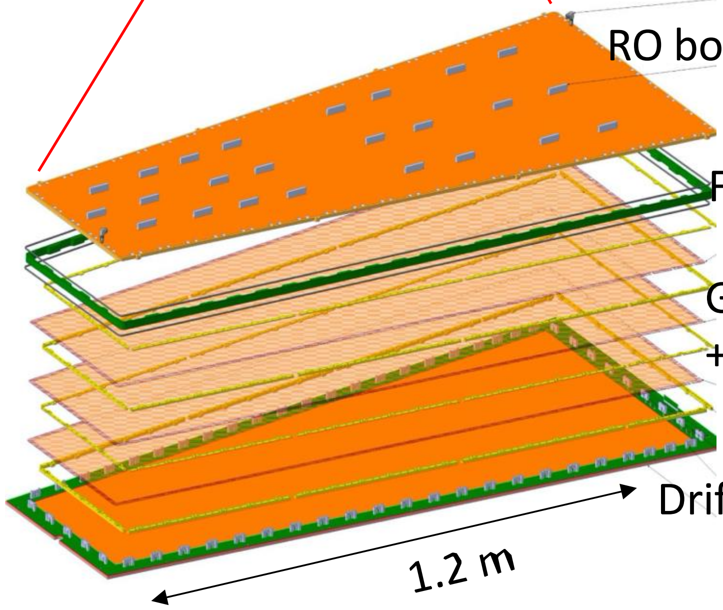
The GEM upgrade: three new stations GE1/1, GE2/1 and ME0 based on the triple-GEM technology



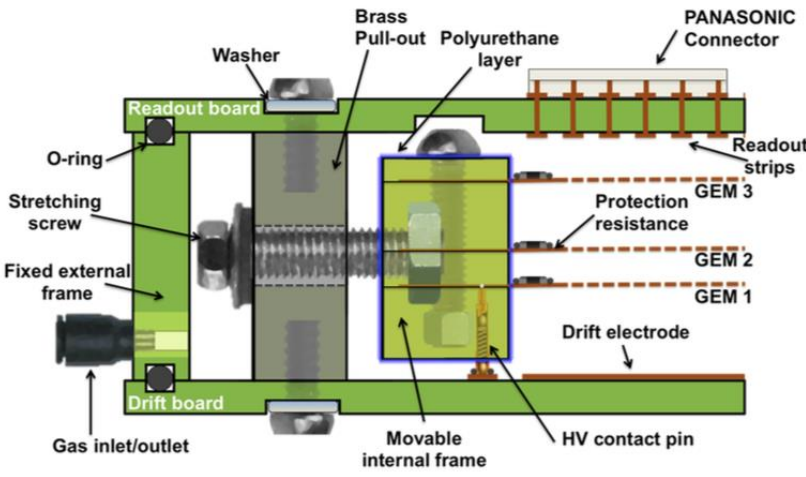


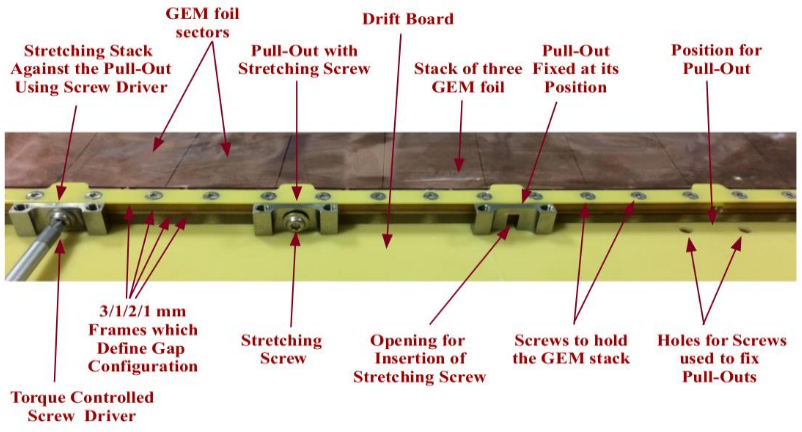
Two different shapes (long and short) to fit the CMS mechanical structure

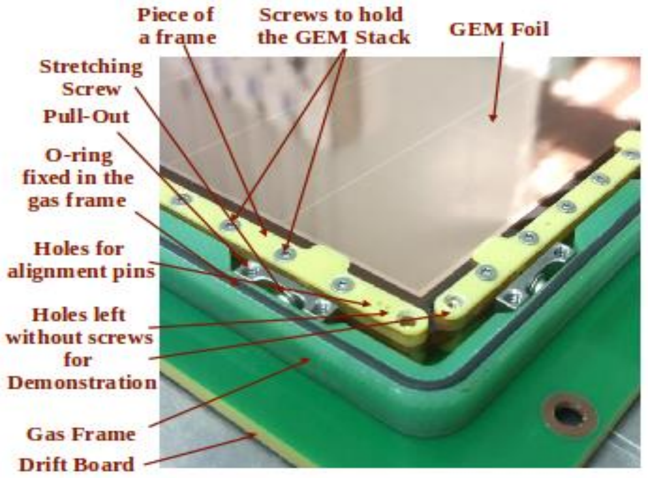


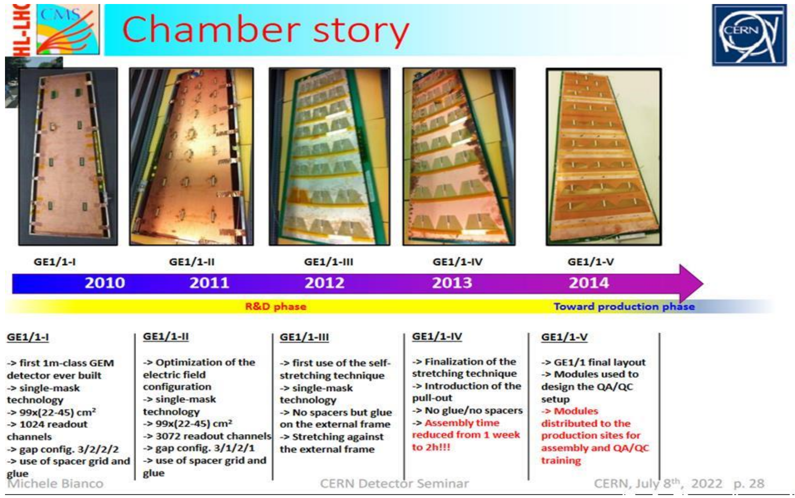


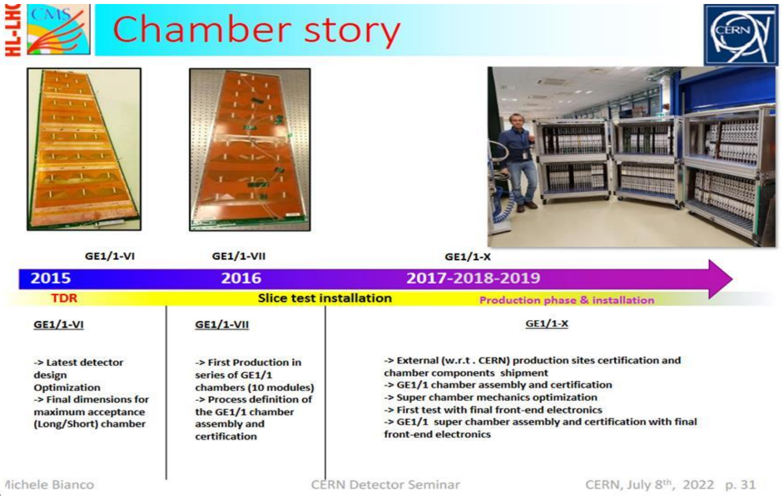
GEM for CMS Experiment

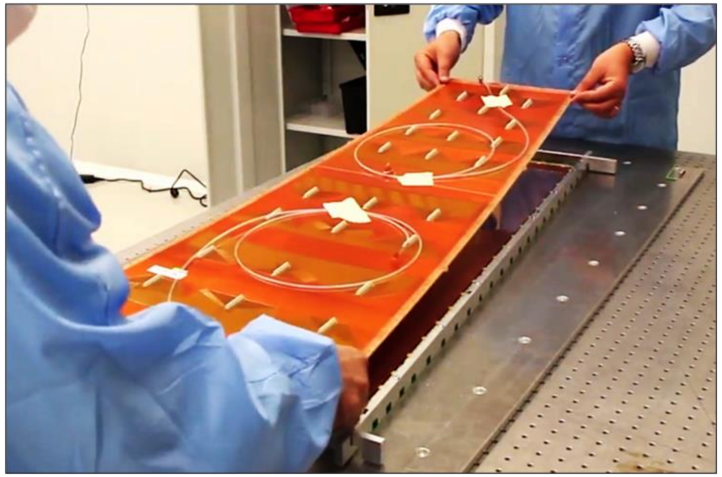






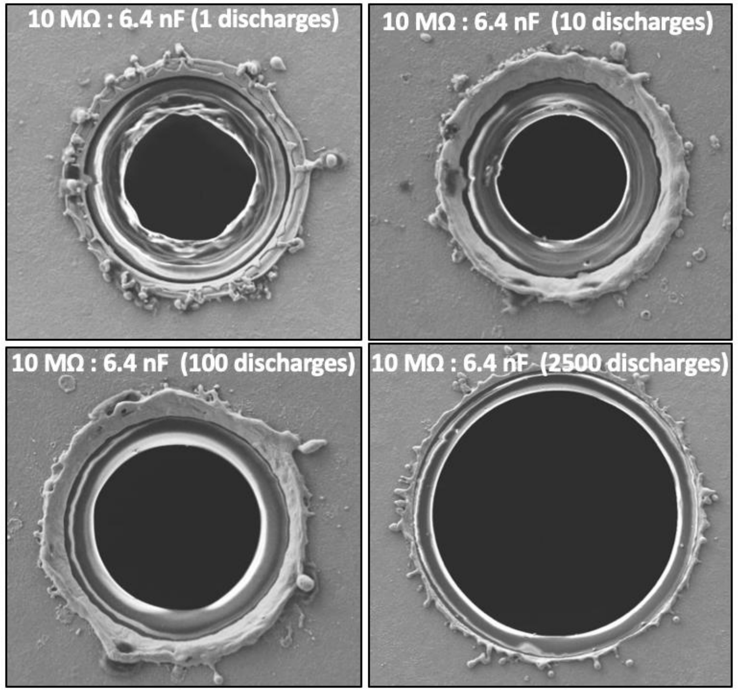


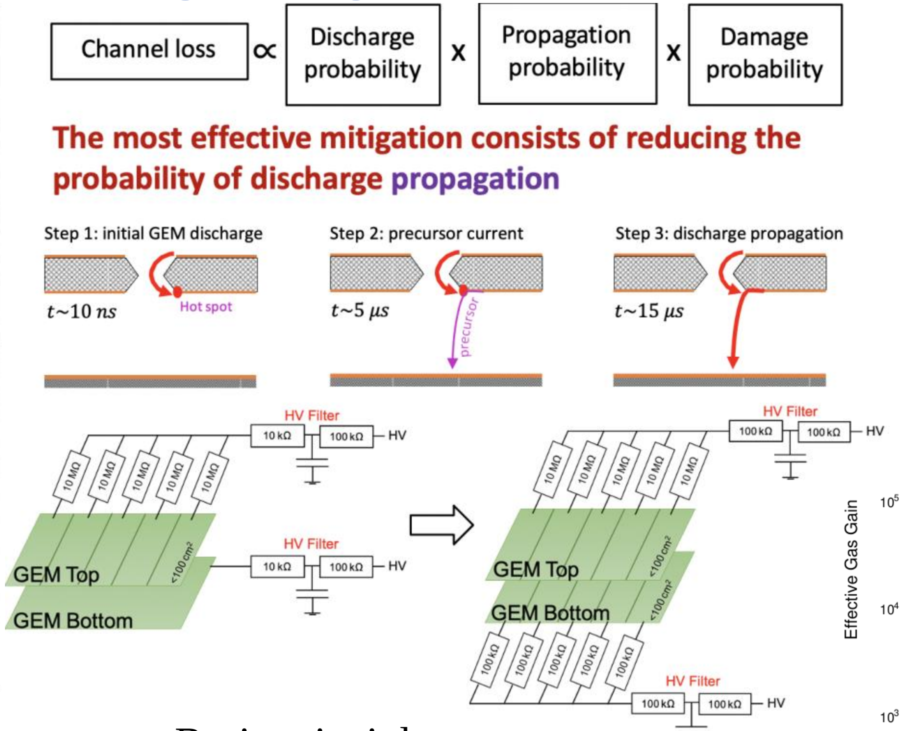


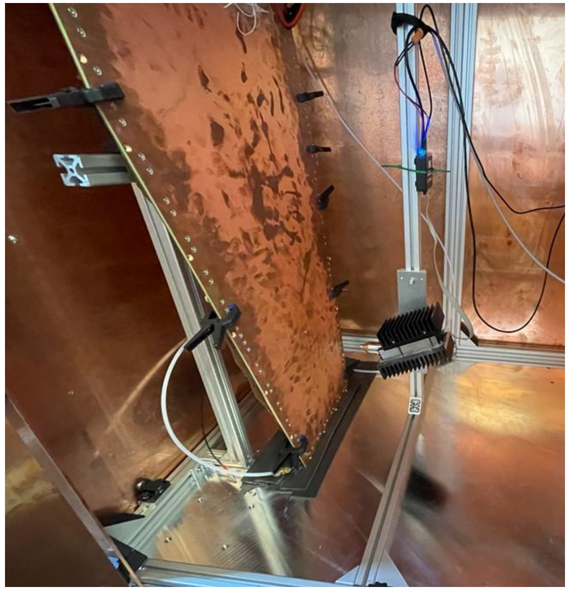


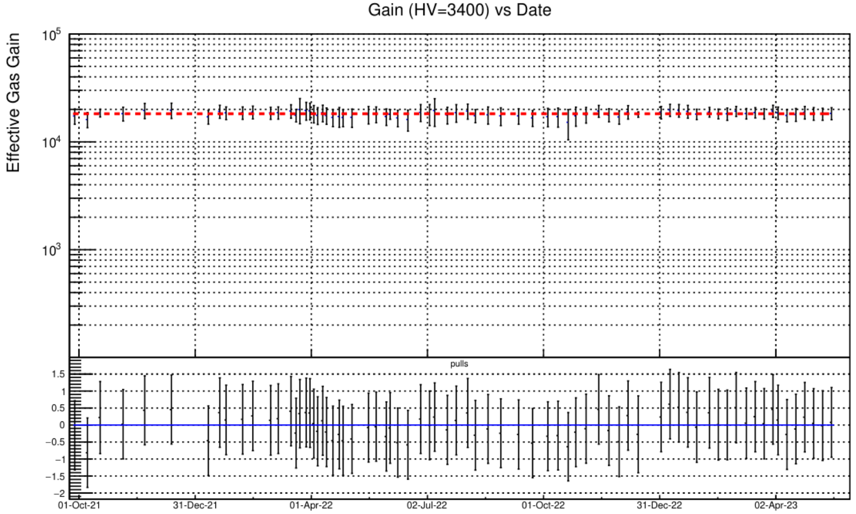
https://indico.cern.ch/event/1175363/attachments/2477073/4252122/MBianco_CMS_GEM.pdf

GEM: Discharge & Ageing









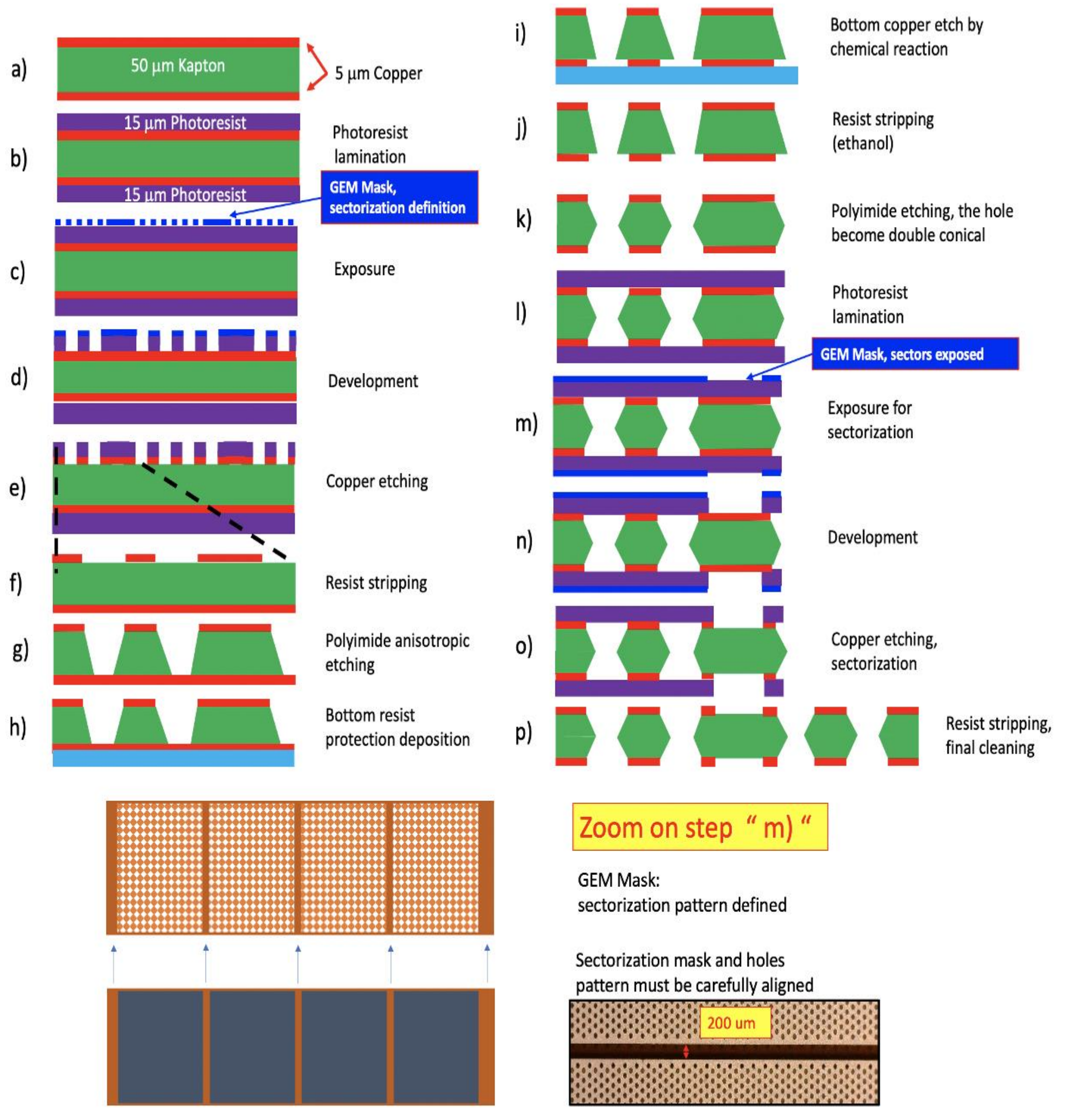
Defects (or rarely very high charge density), can generate discharges at the level of GEM holes.
If we exclude the possible FE damages, if not correctly protected, the effect of the discharges is to modify the hole shape, making it larger (after hundreds of discharges) and leading to gain reduction. Problems can come from the sputtering of copper and polyamide around (and inside the hole) which could generate shorts.

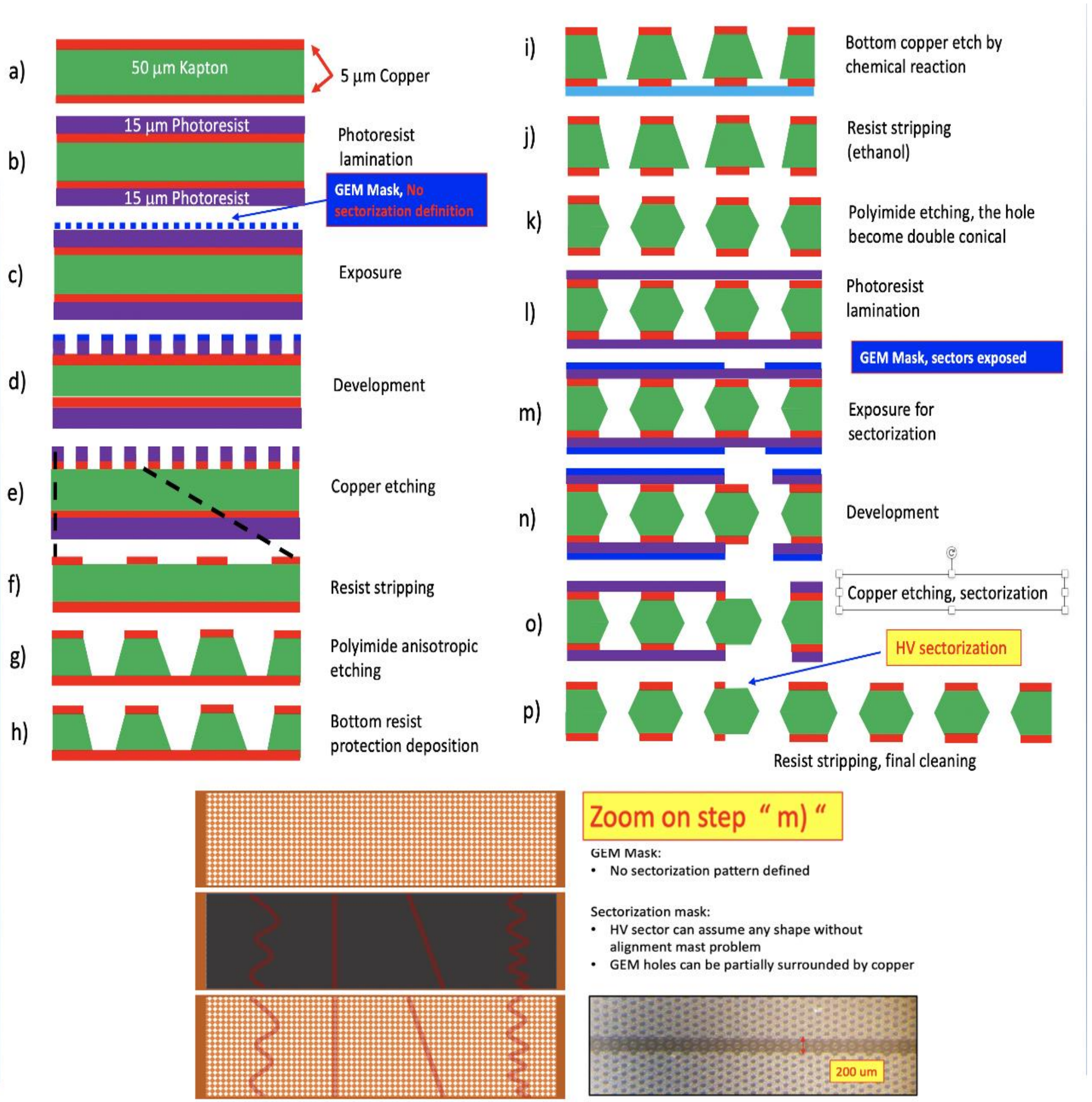
Basic principle:

- HV segments on the top: GEM protection against regular discharges
- HV segments on the bottom: protection against discharge propagation

In Aachen irradiation/ageing tests, collected up to 8 C/cm^2 on the **ME0-CERN-0001** prototype.
The chamber effective gain, has not been affected

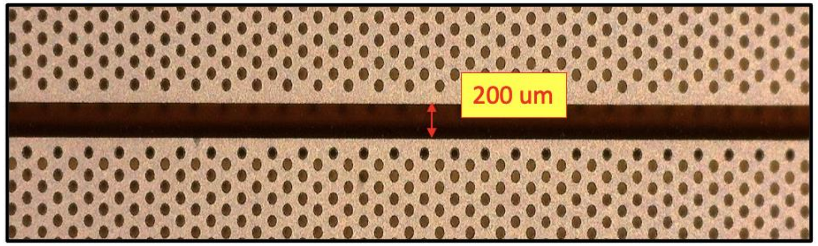
GEM: Improving segmentation technique



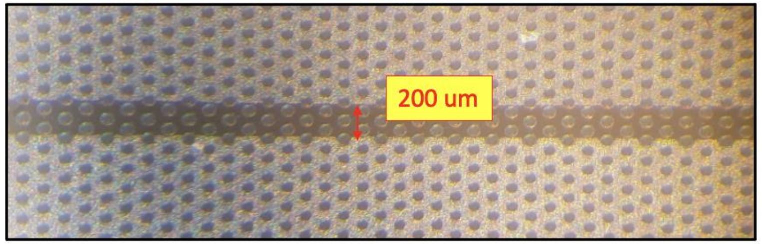


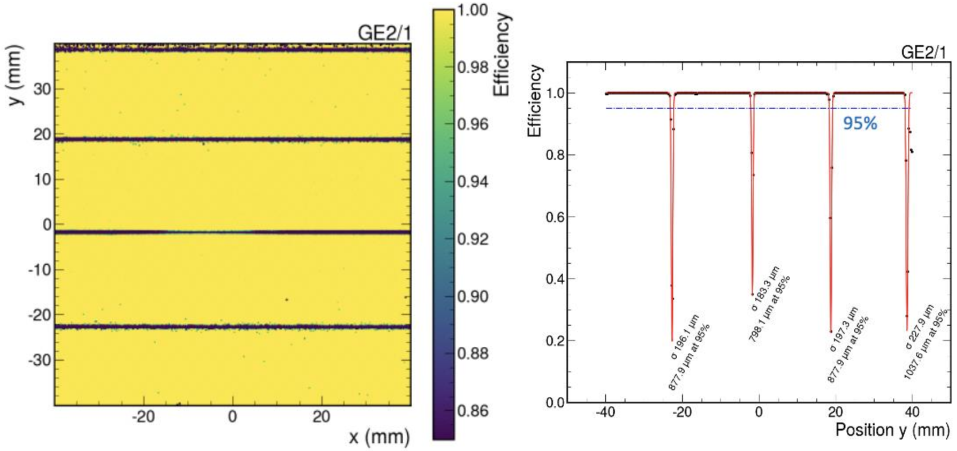
GEM: Operation and Performance

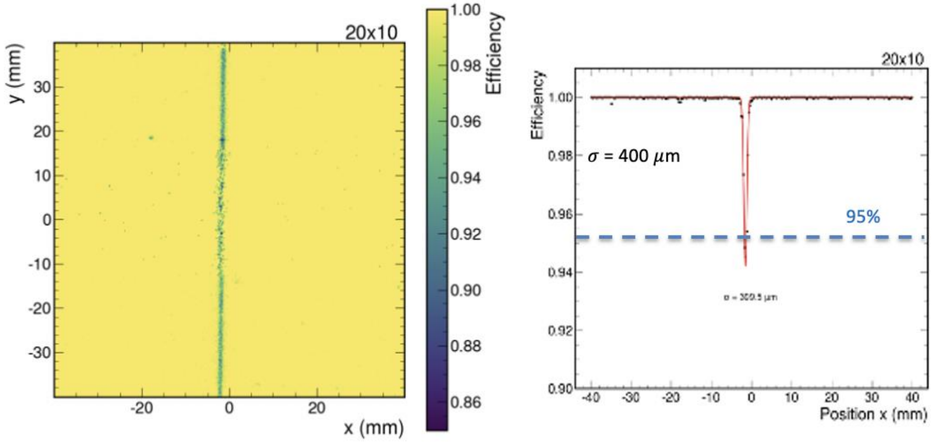
Zoom on "Standard Segmentation"



Zoom on "Random Segmentation"





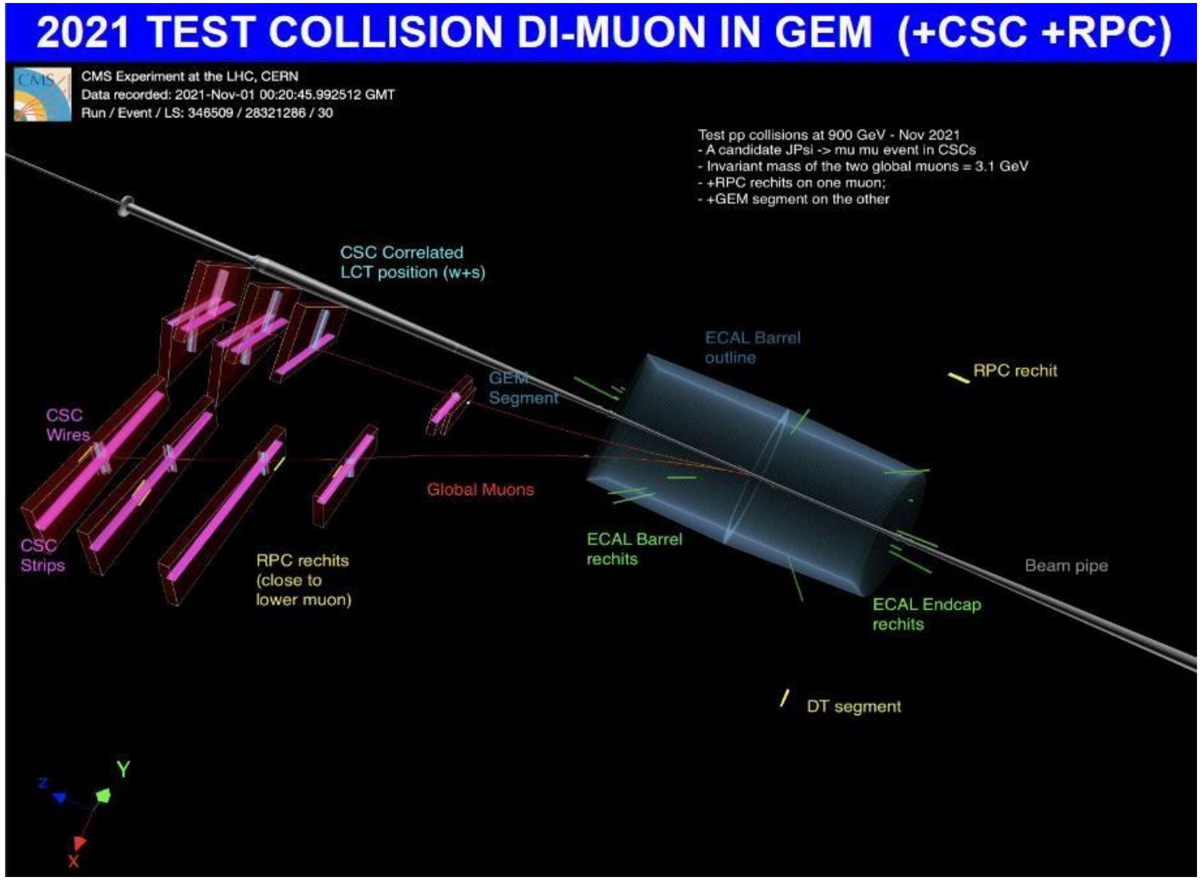


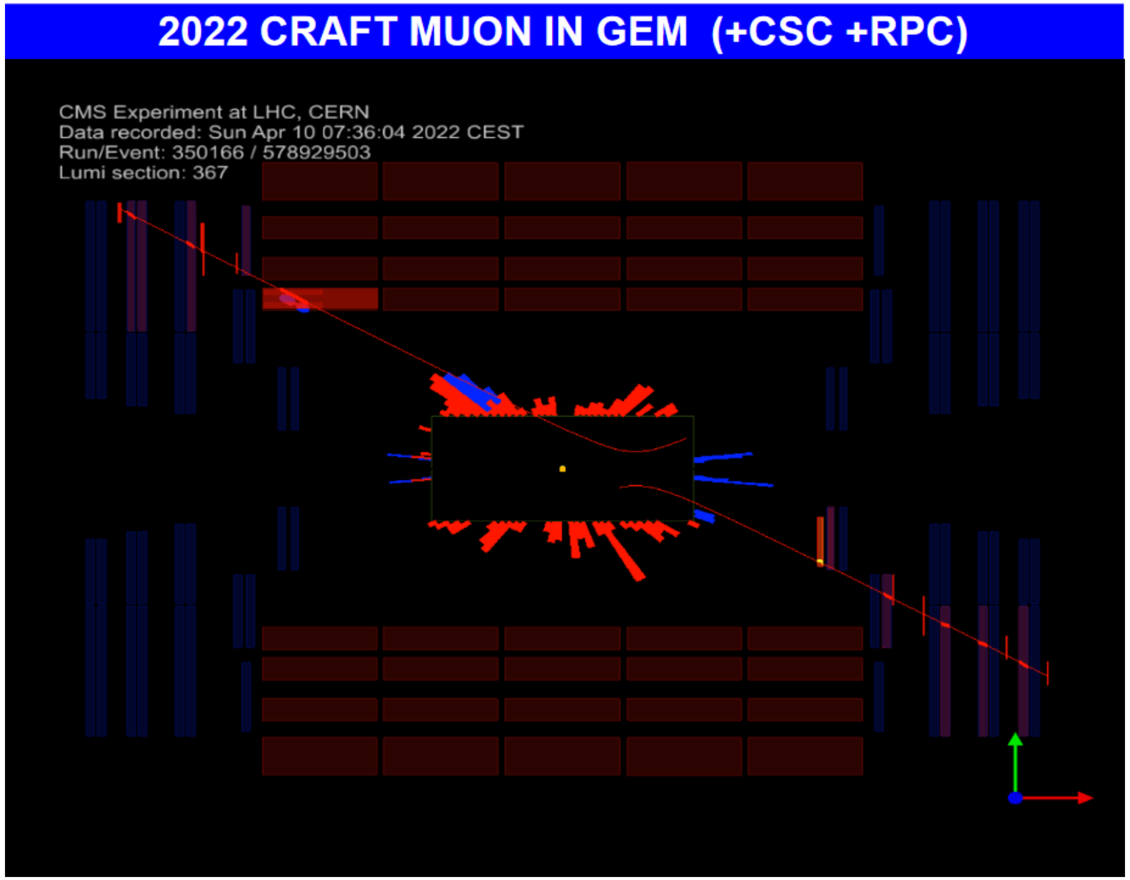
- Efficiency measured in CMS - GE2/1 chamber operated at GAIN: 2E4, instrumented with Standard Segmented GEM foils
- Sigma Efficiency dip due to the HV segmentation is 200 μm (Dip @ 95%: $w = 900 \pm 100$ μm)
- Efficiency drop also up to ~20%

- Window of 9cm x 9cm, in 10x20 chamber with Random Segmented foils defined by the Tracker coverage
- Sigma Efficiency dip due to the HV segmentation is 400 μm ($\ll$ width 95% efficiency)
- Efficiency drop very limited ~94%

https://indico.cern.ch/event/1120714/contributions/4867134/attachments/2469534/4236245/MBianco_Poster_for_iWorid2022_V2.pdf

Data from CMS GEM GE1/1

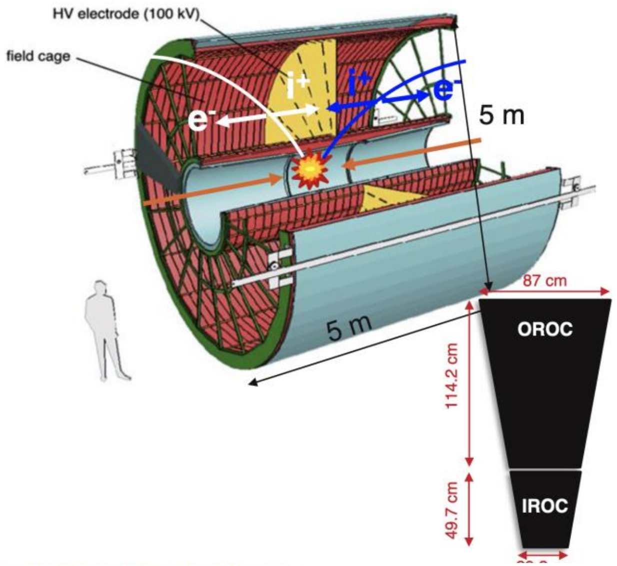




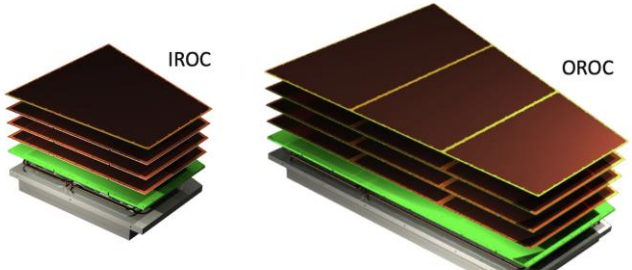
M. Bianco, The GEM detectors within the CMS Experiment, CERN EP Detector Seminar, 8/7/2022, https://indico.cern.ch/event/1175363/

GEM in ALICE Experiment

THE ALICE TPC



GEMS FOR ALICE UPGRADE



- Large-size single-mask foils from CERN PCB workshop
- 1 stack in IROC, 3 stacks in OROC

Requirements:

- Operate at the gain of 2000 in Ne-CO_2-N_2 (90-10-5)
- IBF < 1% at gain = 2000 □ ε = 20
- Local energy resolution σ/E < 12% for ^{55}Fe
- Stable operation under LHC conditions

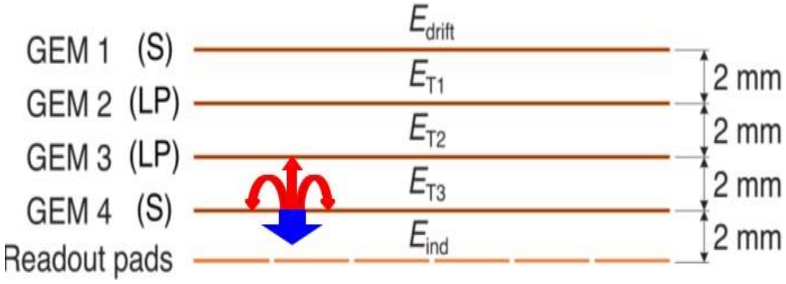
For TPC fundamental the IBF suppression!!!

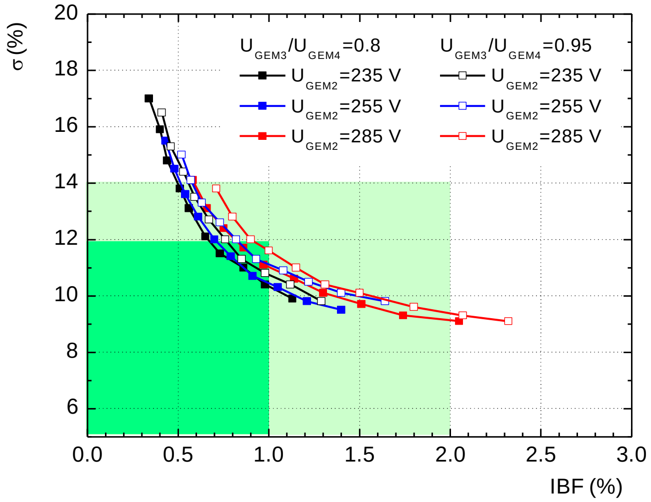
Three measures to suppress the ion back flow into drift region:

– Low gain in GEM 1, highest in GEM 4

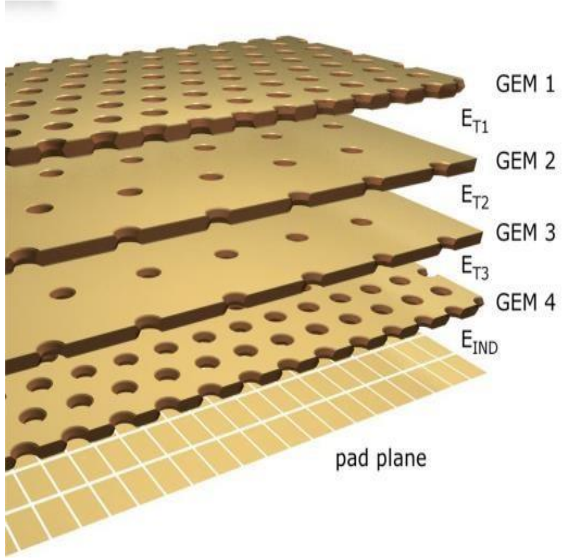
– Two layers of large pitch (LP) foils (GEM2 and GEM 3) block ions from GEM 4

– Very low transfer filed E_{T3} (100 V/cm) between GEM3 and GEM4

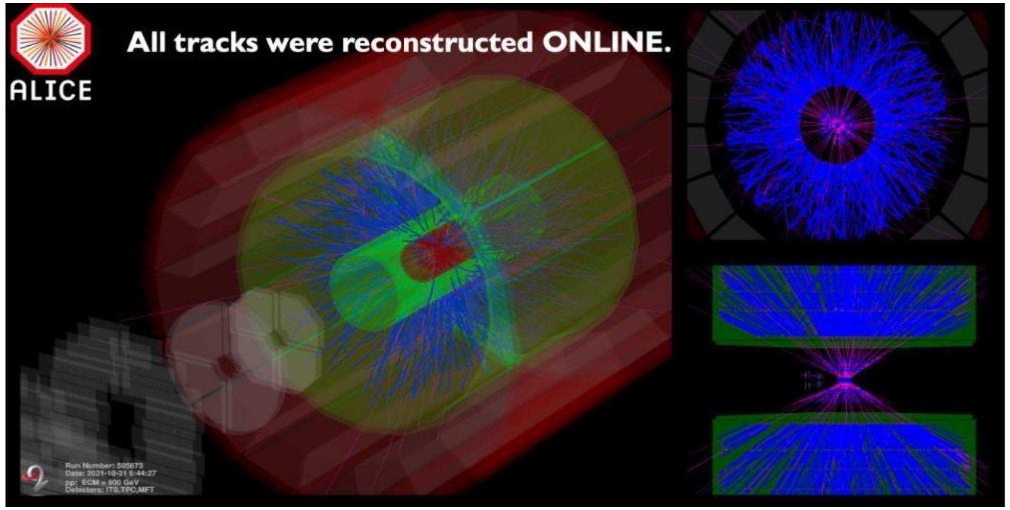


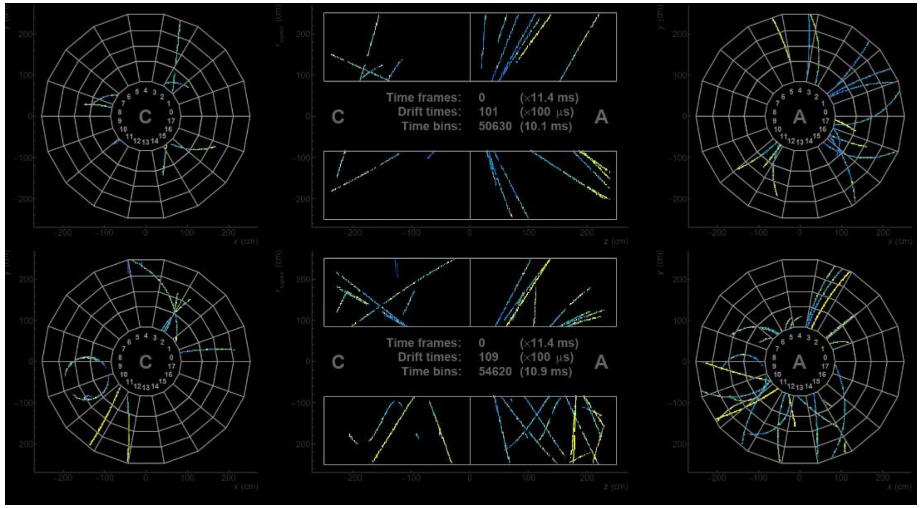


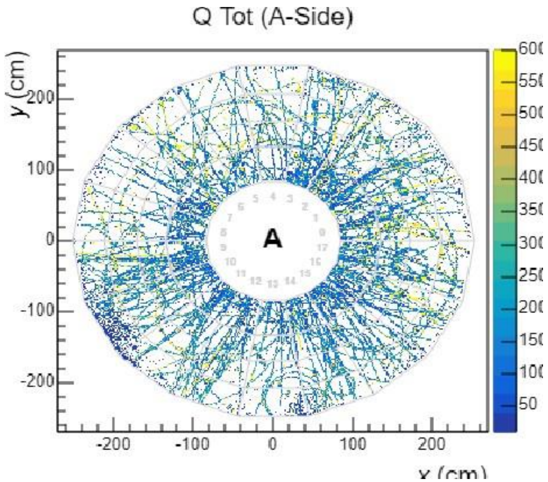
Performance with optimized HV configuration
IBF = Ion BackFlow, σ= energy resolution for ^{55}Fe

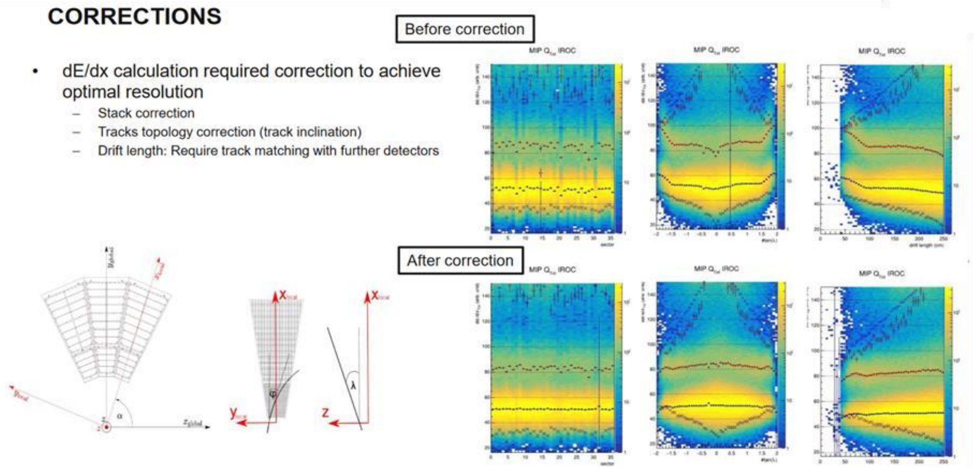


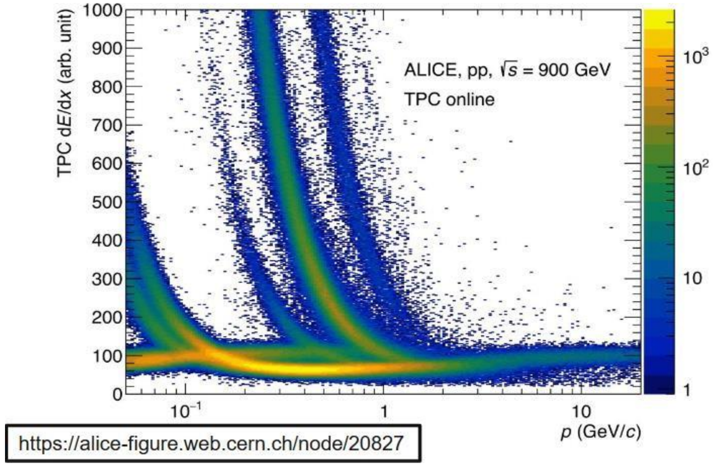
GEM in ALICE: Pilot Run





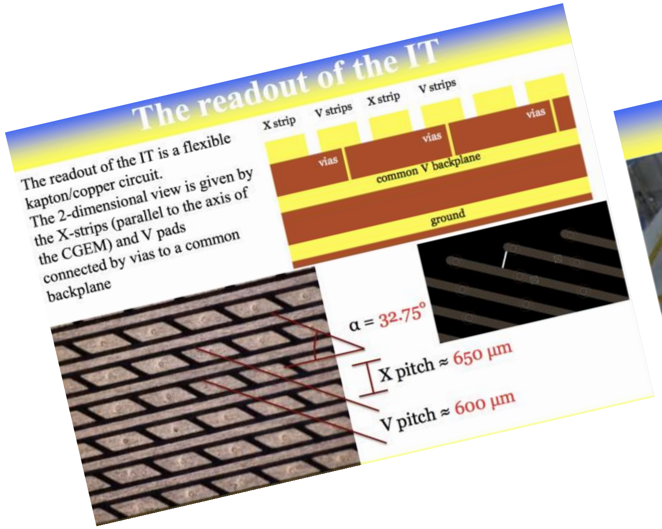




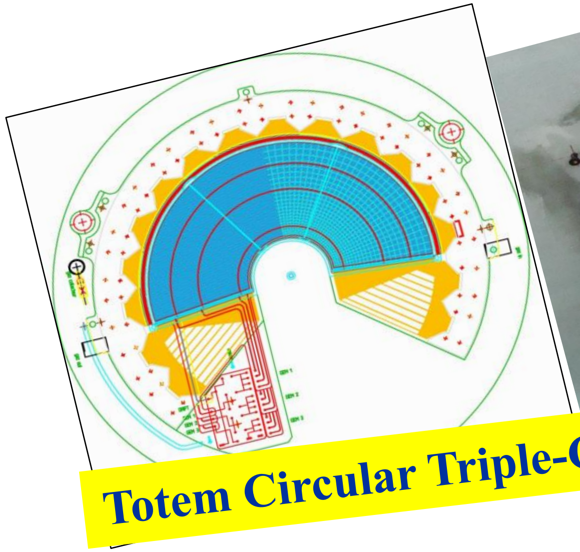


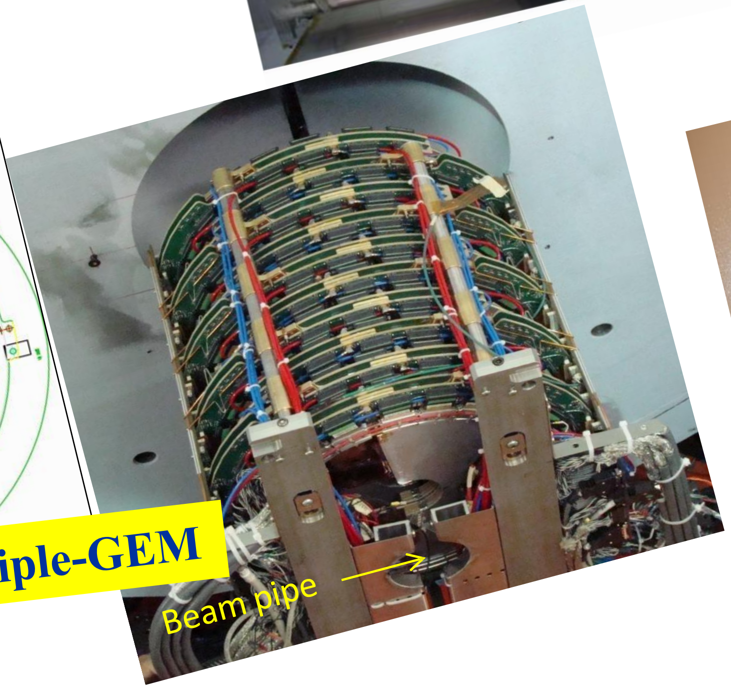
https://indico.cern.ch/event/1172978/attachments/2468524/4234156/2022_06_24_CERN_Seminar_rmunzer_v4.pdf

GEM: KLOE, Totem, LHCb, …..

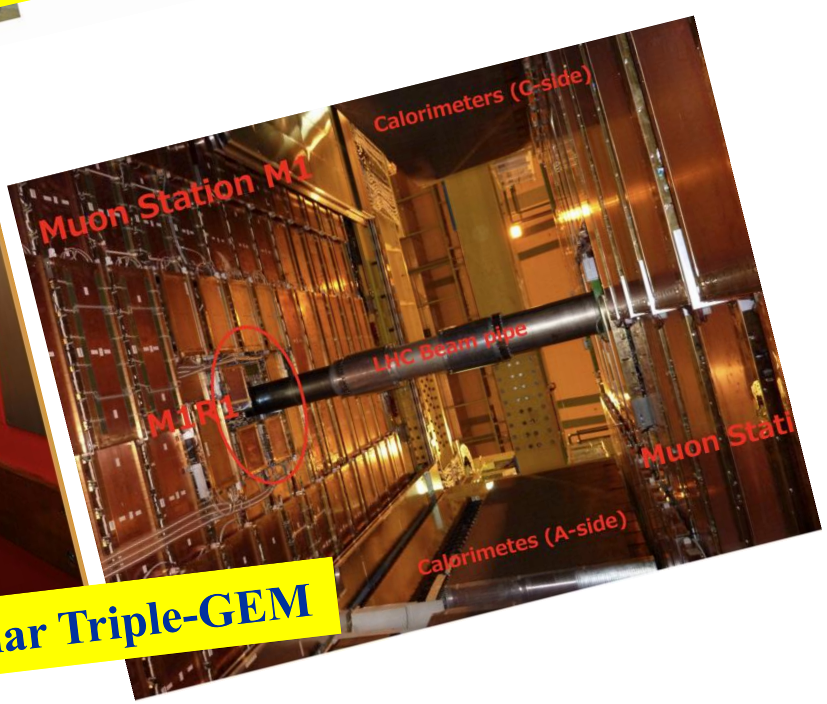


KLOE Cylindrical Triple-GEM





Totem Circular Triple-GEM



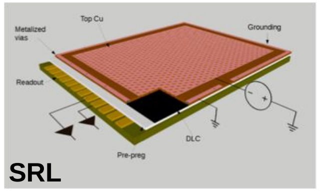
LHCb Rectangular Triple-GEM

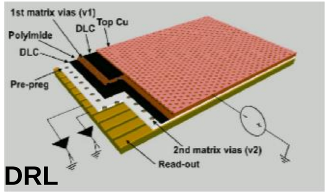
μ-RWELL story

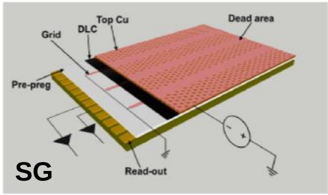
R&D on low-rate layout

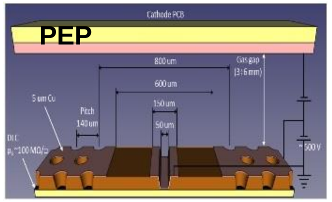
R&D on high-rate layout

New MPGD idea in collaboration with GDD





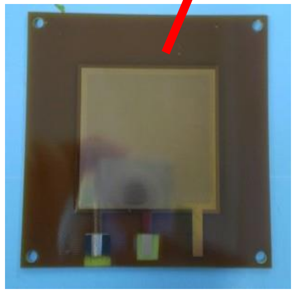




R&D start

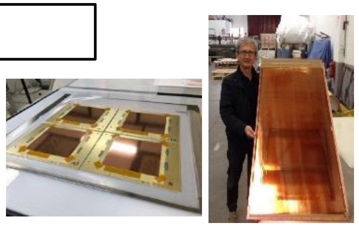
TT @ ELTOS

2009 2014 2015 2016 2017 2018 2019 2020 2021 2022 2023



TB @ high rate @ PSI

TB @ CERN



TT @ ELTOS

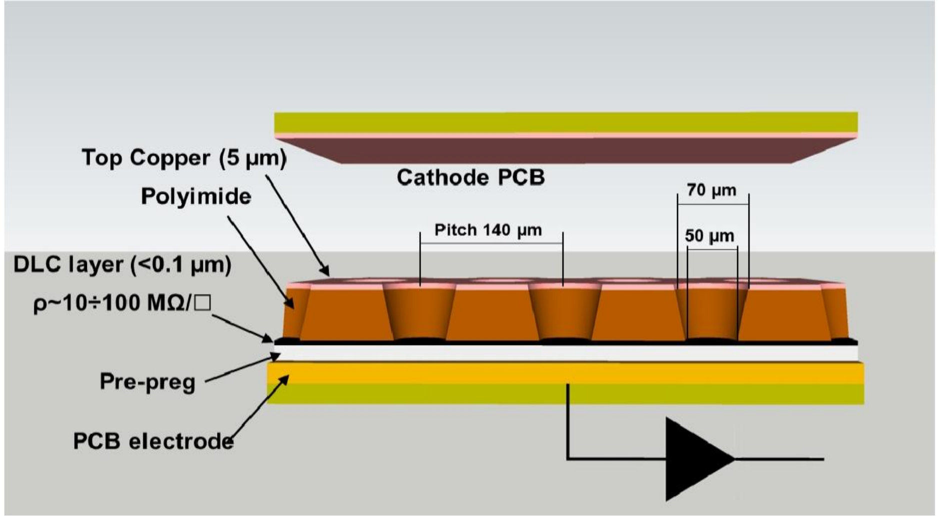
The µ-RWELL technology

The device is composed of two elements:

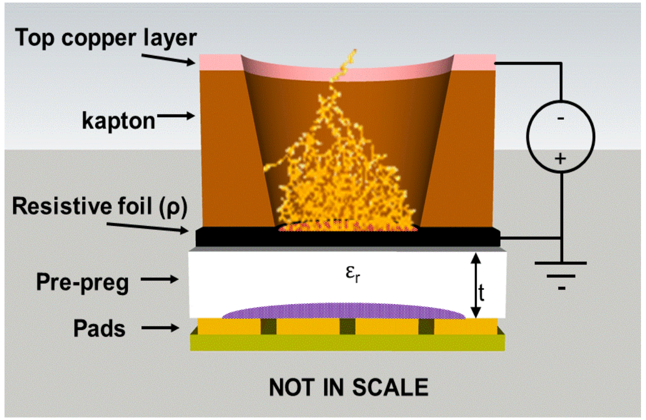
- µ-RWELL_PCB
- drift/cathode PCB defining the gas gap

µ-RWELL_PCB = amplification-stage ⊕ resistive stage ⊕ readout PCB

large area & flexible geometry



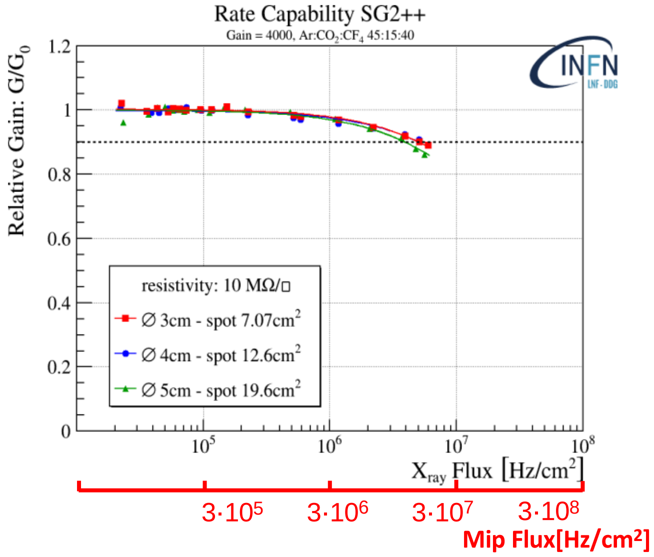
- The "WELL" acts as a multiplication channel for the ionization produced in the gas of the drift gap
- The charge induced on the resistive layer is spread with a time constant, $\tau \sim \rho \times C$



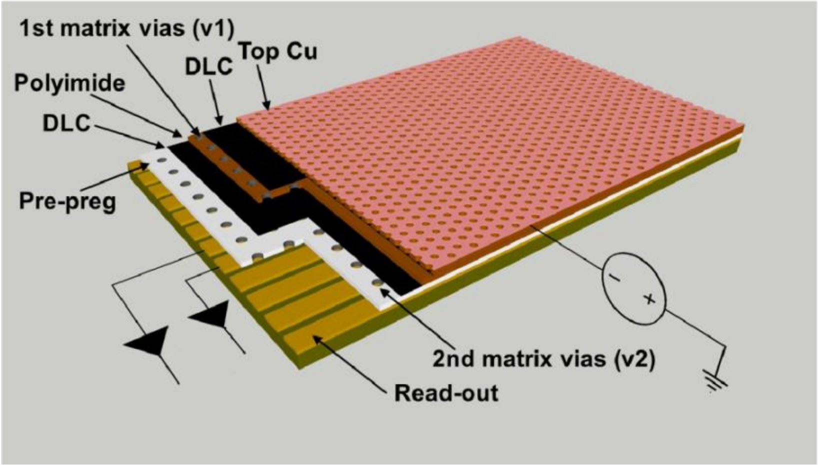
$$C = \varepsilon_0 \times \varepsilon_r \times \frac{S}{t} = 35\, pF \times S(cm^2)$$

μ-RWELL High-Rate Layout

The purpose of these HR versions is to reduce the distance to be "travelled" by the charge towards the ground

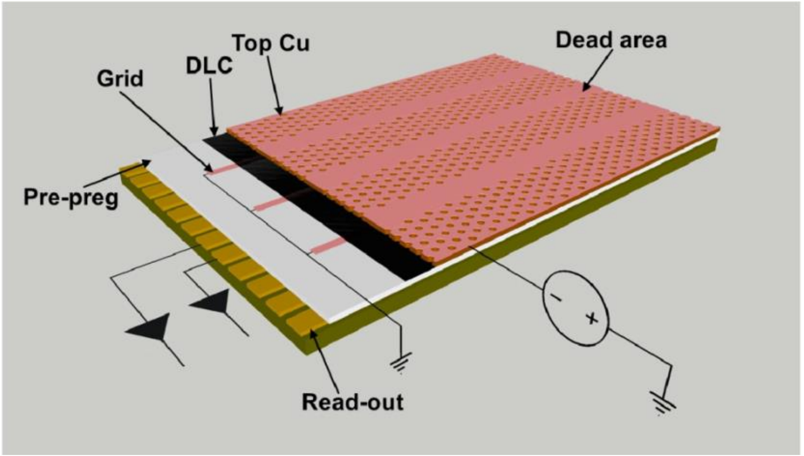


Double Resistive layer (DRL)

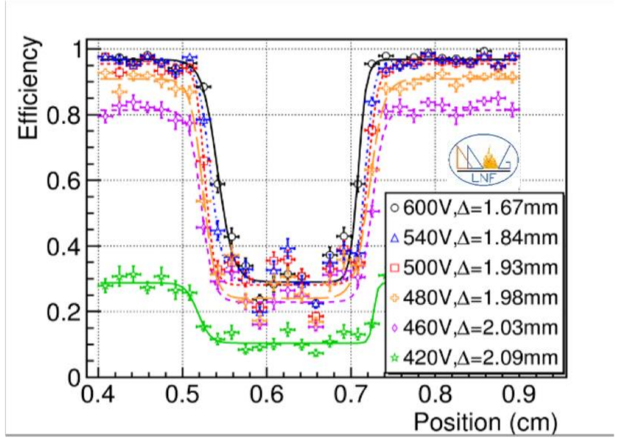


- 3-D grounding
- Double DLC layers connected through matrices of conductive vias to the readout electrodes (density 1/cm2)

Silver Grid (SG)



- 2-D grounding
- Single DLC layer grounded by means conductive strip lines realized on the DLC layer (density 1/cm)

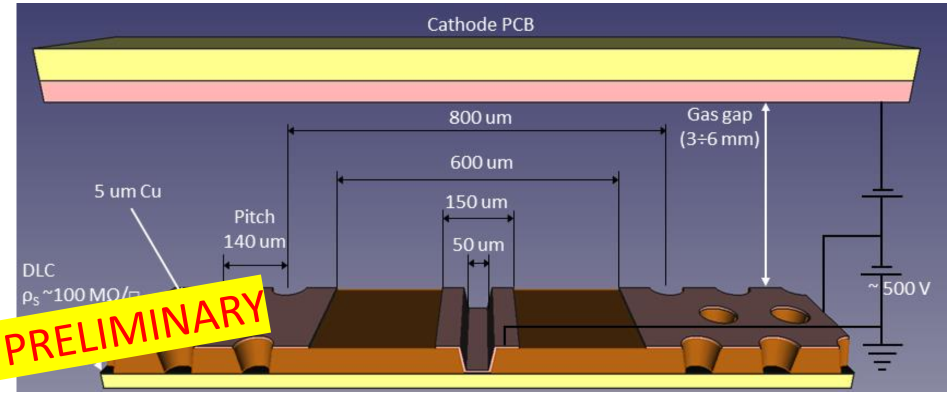


Silver Grid design introduced to simplify the e technology transfer, since the TT of the DRL industrial production is difficult, The new design, is based on the simple single-resistive layout with a suitable surface current evacuation scheme, the Grid layout (to avoid sparks) introduce dead area which reduce the geometrical acceptance

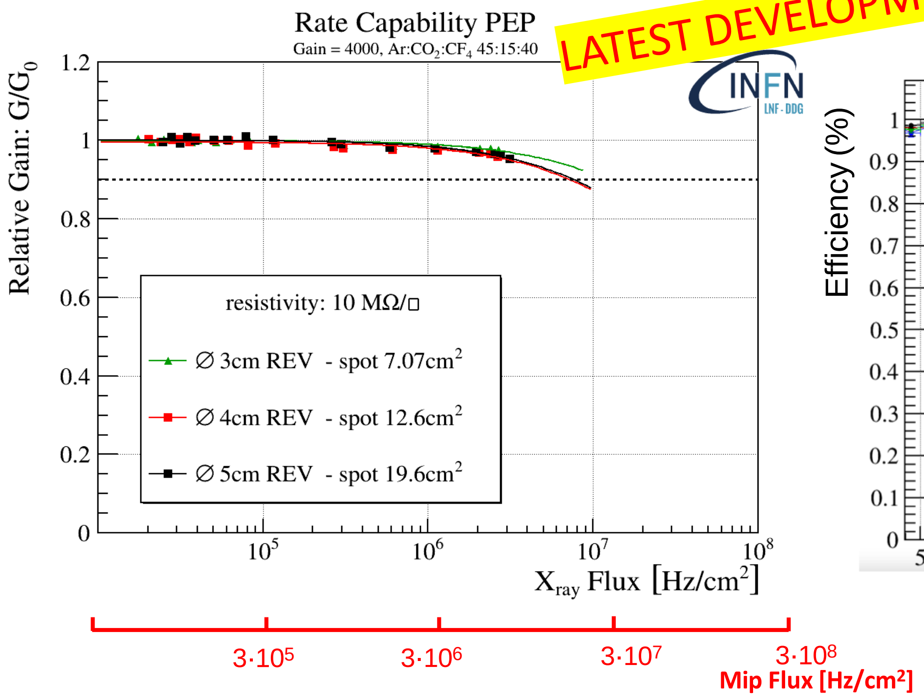
The µ-RWELL technology

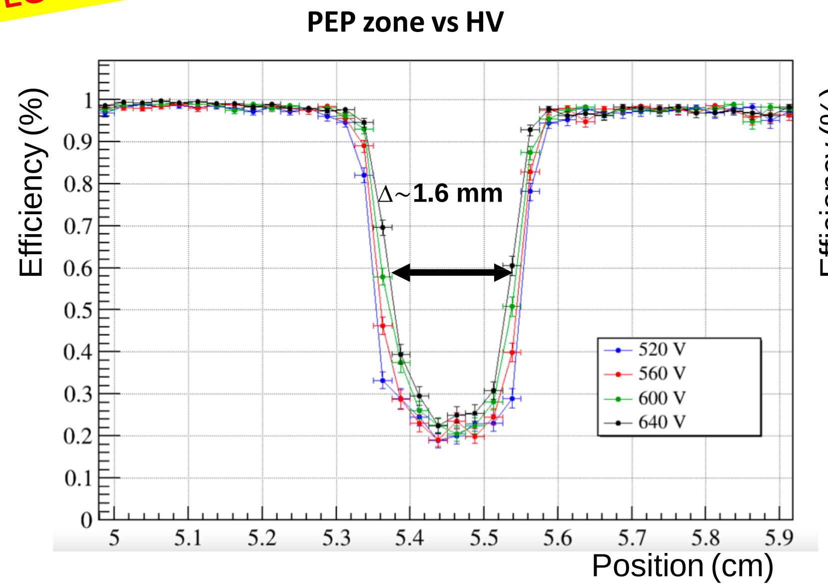
The PEP (Patterning – Etching – Plating[h])

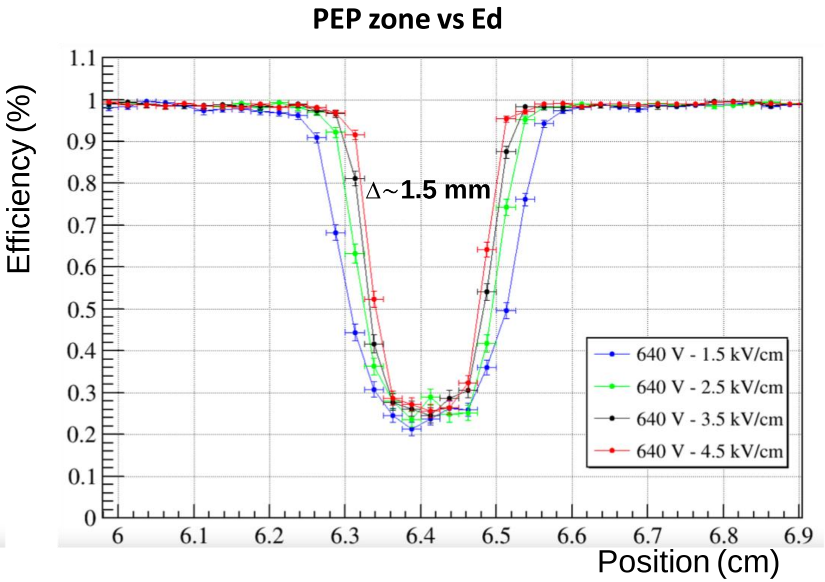
- Single DLC layer
- Grounding from top by kapton etching and plating
- No alignment problems
- **Scalable to large size**
- **Measured dead zone > 1.6 mm wrt 0.8 mm (by design)**



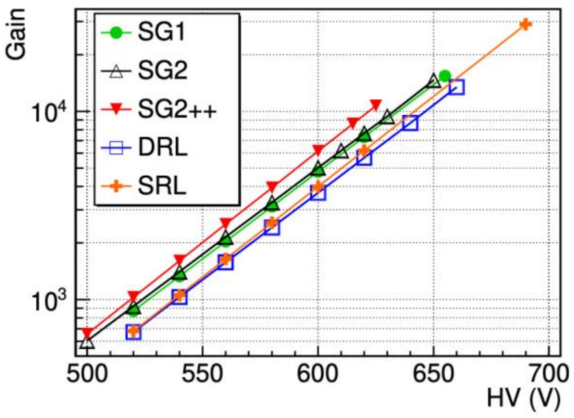
LATEST DEVELOPMENT, RESULTS STILL PRELIMINARY



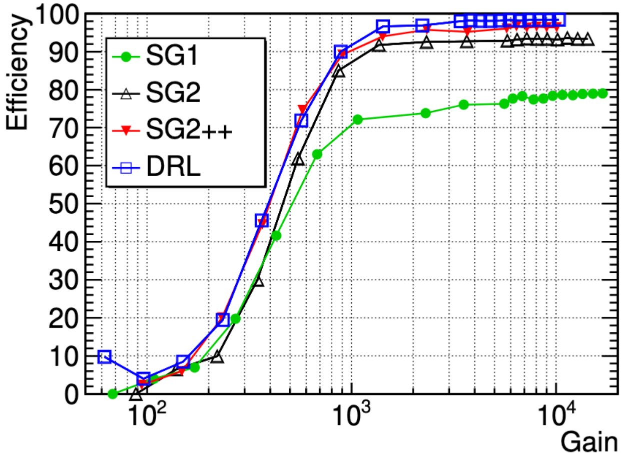




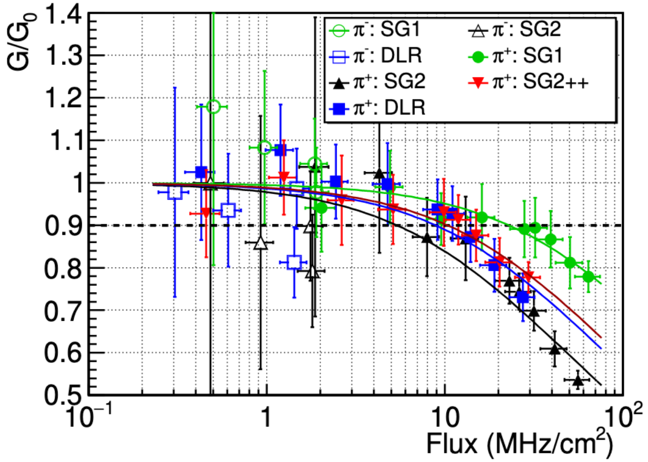
μ-RWELL Performances

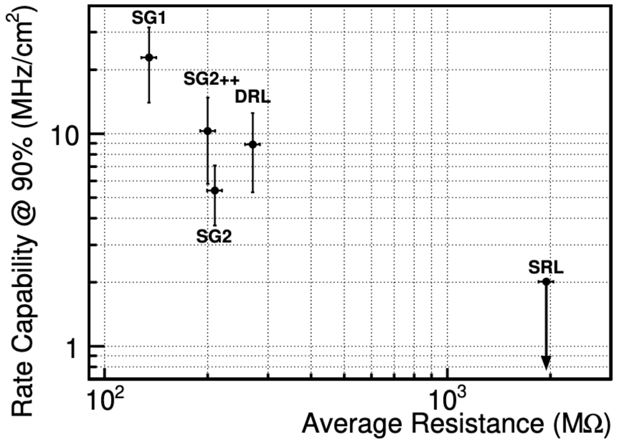


Gas gain of the uRwell (different HR layout) characterized at PSI



Efficiency as a function of the gas gain for the HR layouts (SG1 affected by geometrical acceptance)





Thanks to the resistive plane:

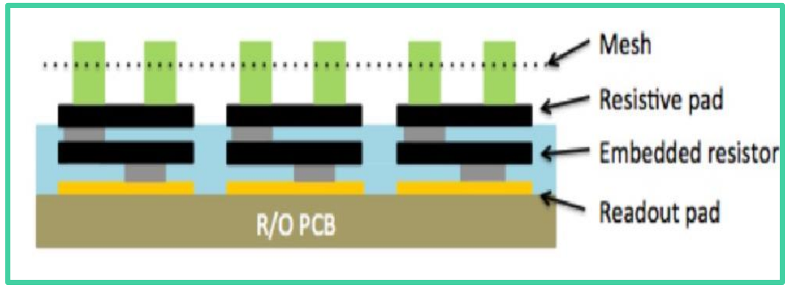
- **very reliable**
- **very low discharge rate**
- **adequate for high particle rates O(1MHz/cm2)**

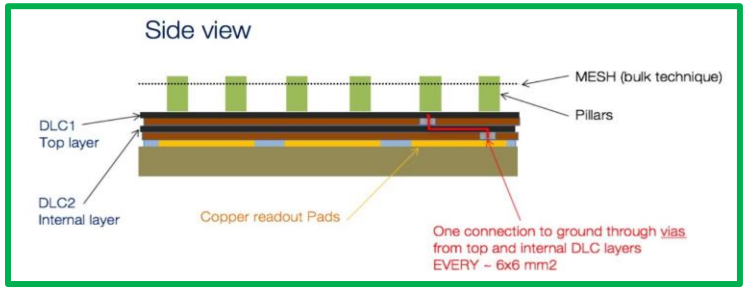
- **gain ≥10^4**
- **space resolution < 60 μm**
- **time resolution < 6 ns**

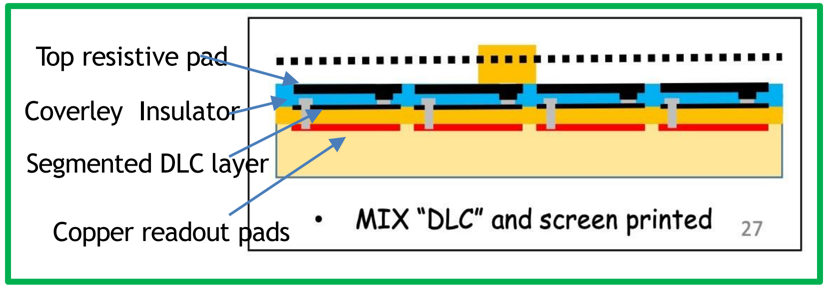
Small-PAD Resistive MM

MPGD for very high-rate application

Scheme 1: PAD-Patterned embedded resistor	Scheme 2: Double DLC uniform resistive layer	Scheme32: Mixed solution (PAD-P-Mix





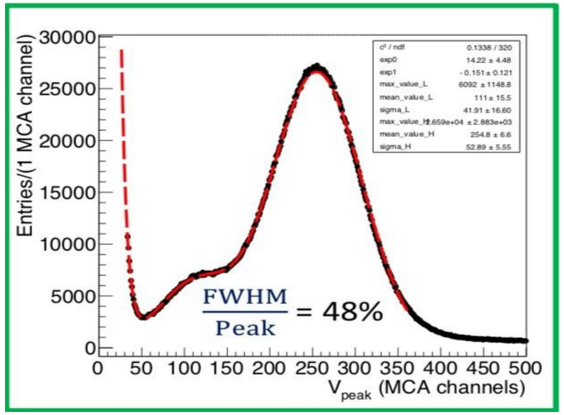


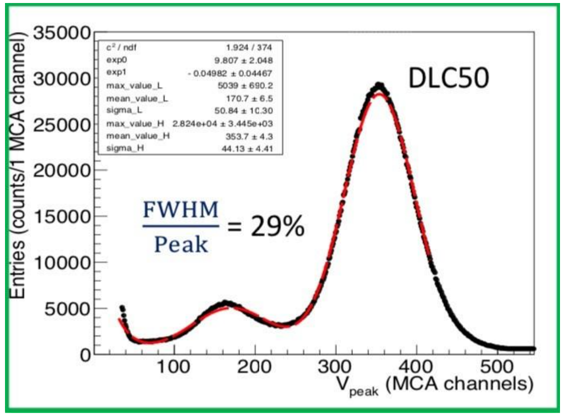
Two planes of independent screen printed carbon resistive pads with the same geometry of copper readout pads;

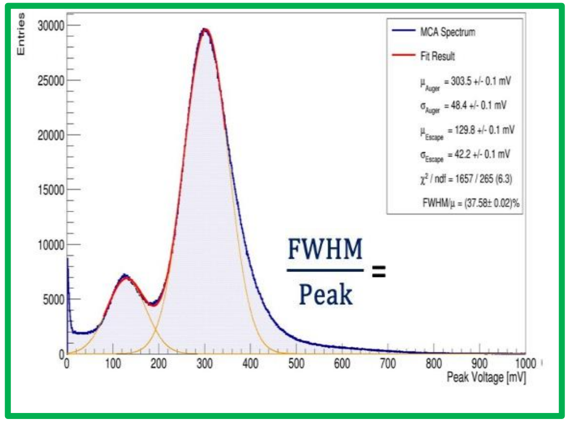
Two continuous resistive DLC layers (5 - 50 MΩ/□) interconnected between them and to the readout pads with network of conducting links with the pitch of few mm, to evacuate the charge;

The resistive pad facing the amplification gap is always screen printed. The intermediate resistor is done by DLC layer

Much more similar to scheme 1



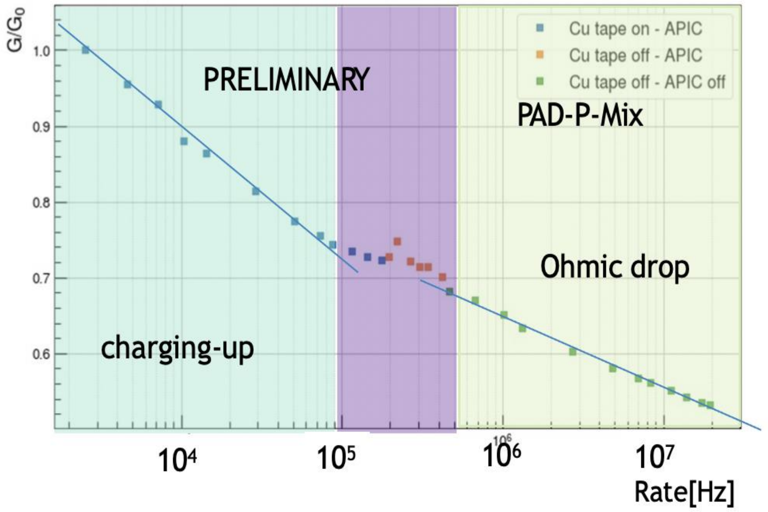




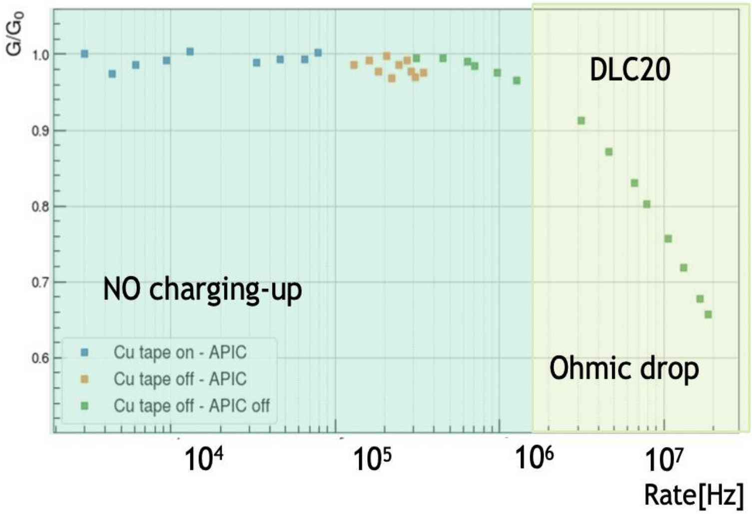
Small-PAD Resistive MM

Rate capability performances

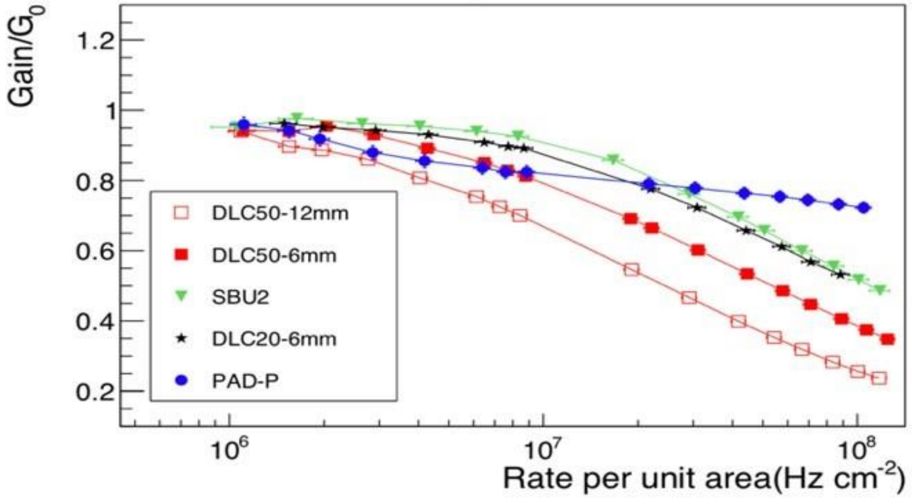
X-rays exposure area 0.79 cm² (shielding with 1cm diameter hole)



- Significant gain drop at “low” rates dominated by charging-up effects as for PAD-P schema
- Negligible ohmic voltage drop for the individual pads for rates between 0,1 and ~2 MHz/cm2



- Almost constant gain at “low” rates (up to few MHz/cm².
- Significant ohmic voltage drop at higher rates



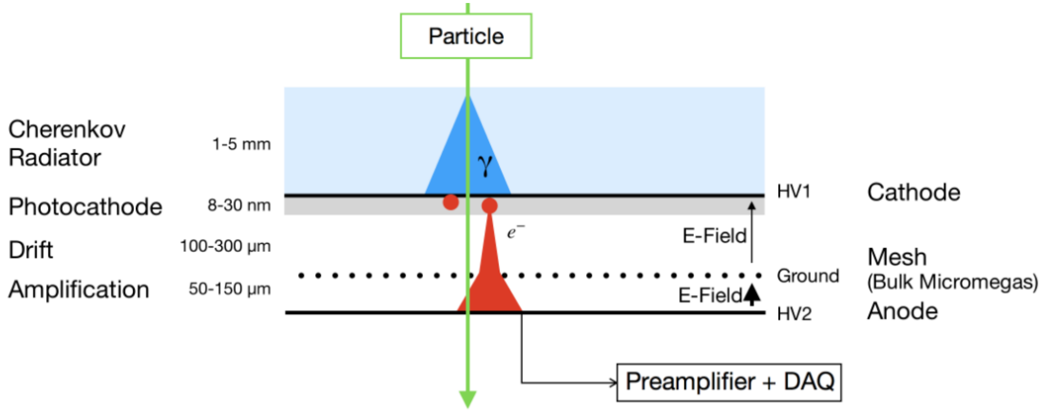
PAD-P shows a sizeable gain drop due to the charging-up at lower rates (up to few MHz/cm²) but a lower ohmic drop due to the fact that each pads behaves as an independent resistor to ground.

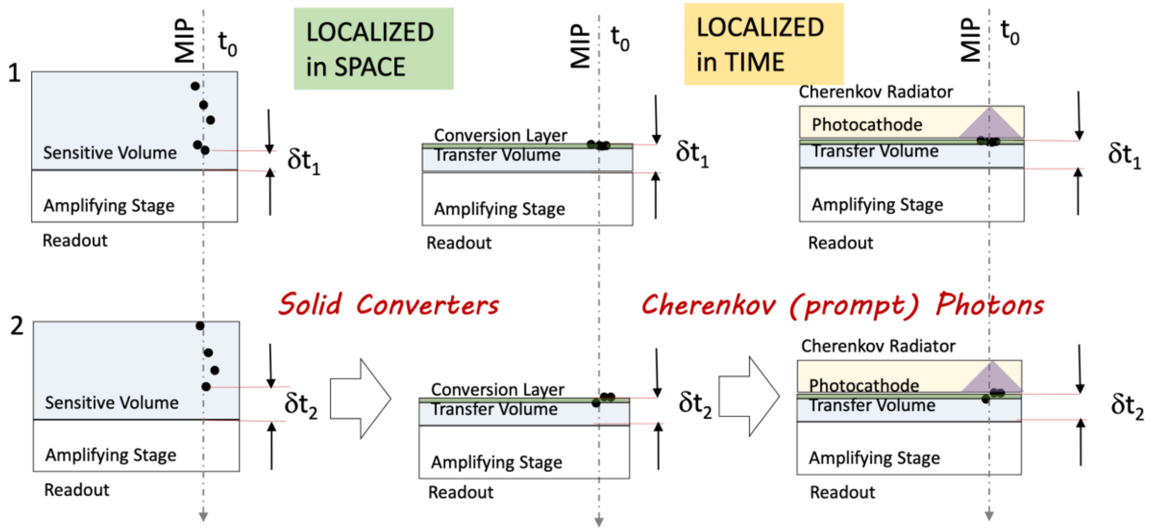
DLC20, SBU (Sequential Build Up process) have a comparable behaviour in the explored region (up to ~100 MHz/cm²):

Mean values of the resistance between first and second DLC protection foils are almost the same

For rates greater than 20-30 MHz/cm² they shown a higher gain drop w.r.t. PAD-P

PicoSec

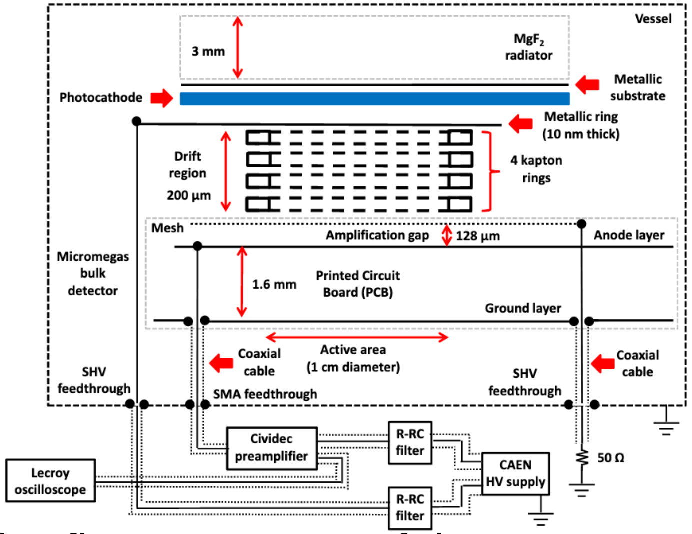




Primary electrons at the same time in the same place

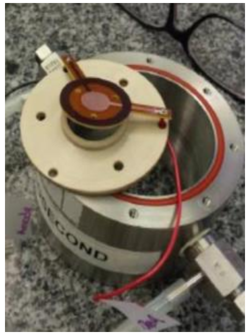
The PICOSEC detection concept

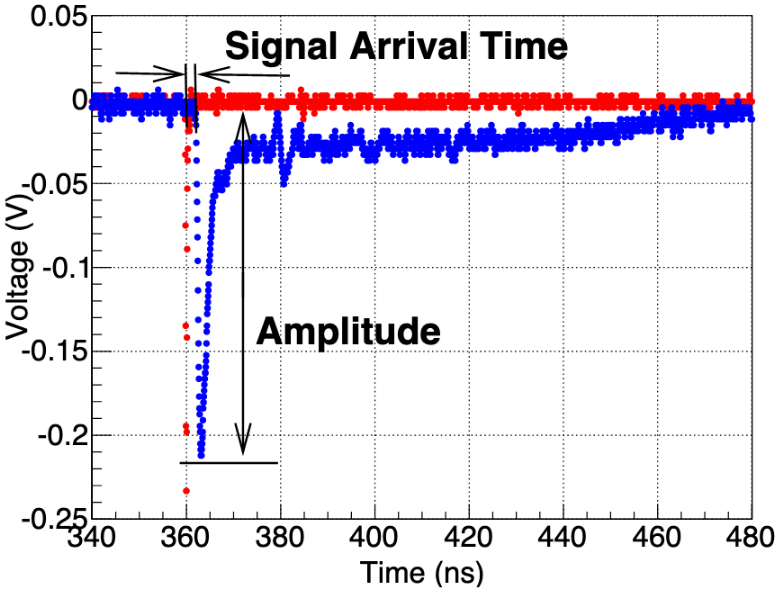
The passage of a charged particle through the Cherenkov radiator produces UV photons, which are then absorbed at the photocathode and partially converted into electrons. These electrons are subsequently preamplified and then amplified in the two high-field drift stages and induce a signal which is measured between the anode and the mesh.



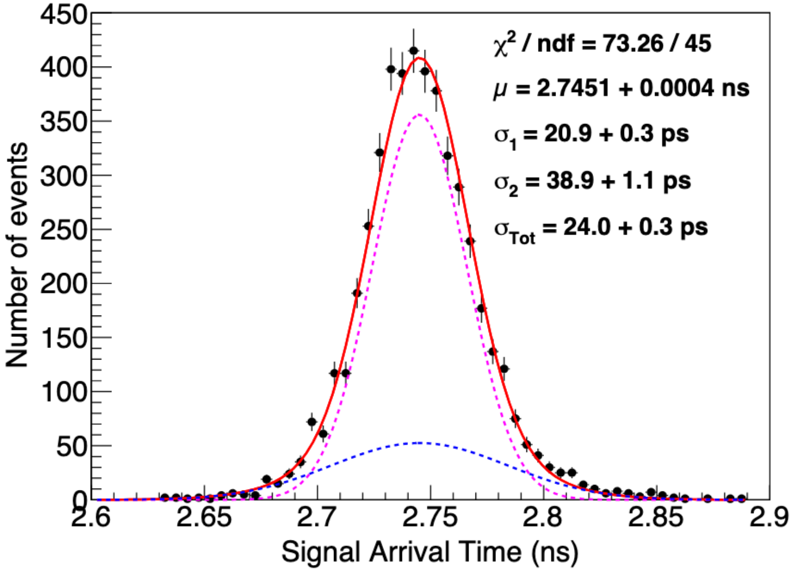
Sketch of the first prototype of the PICOSEC detector,

PICOSEC

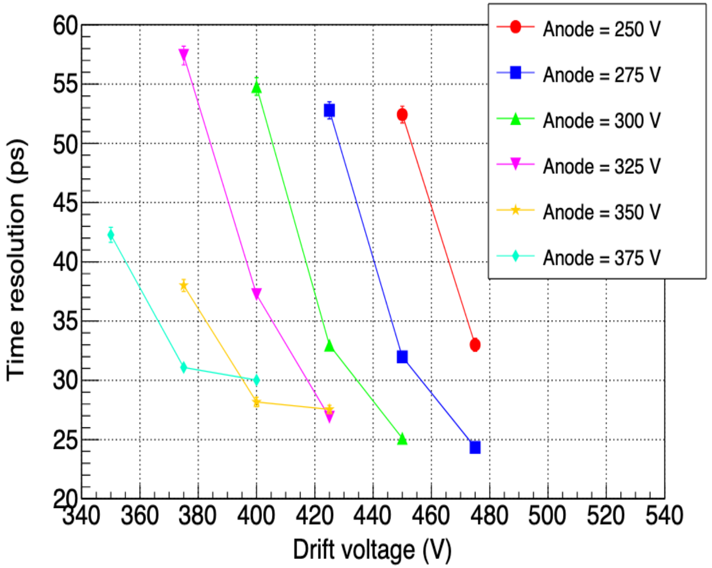




An example of an induced signal from the PICOSEC detector generated by 150 GeV muons (blue points), recorded together with the timing reference of the microchannel plate MCP signal (red points)

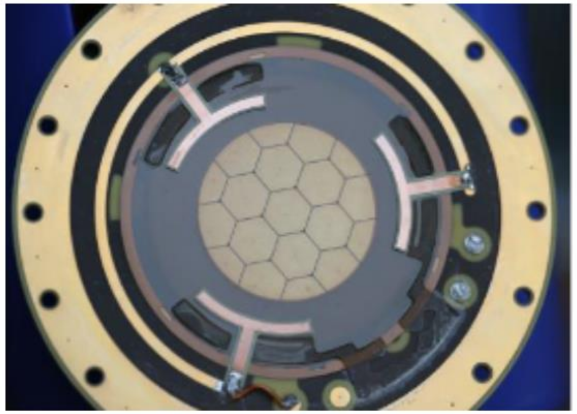


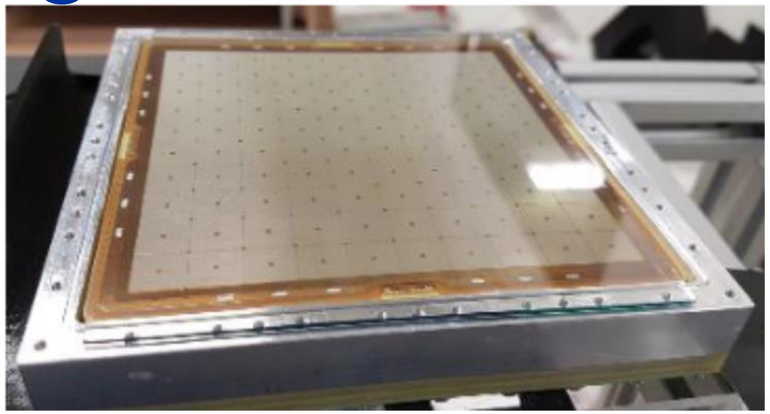
An example of the signal arrival time distribution for 150 GeV muons, and the superimposed fit with a two Gaussian function, for an anode and drift voltage of275 V and 475 V, respectively.

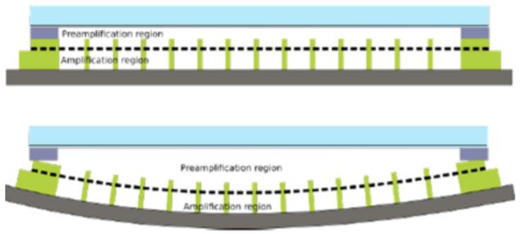


Dependence of the time resolution on the drift and anode voltage fora PICOSEC detector irradiated by 150 GeV muons.

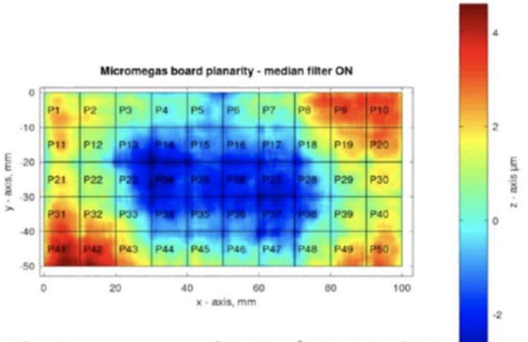
PICOSEC Large Area







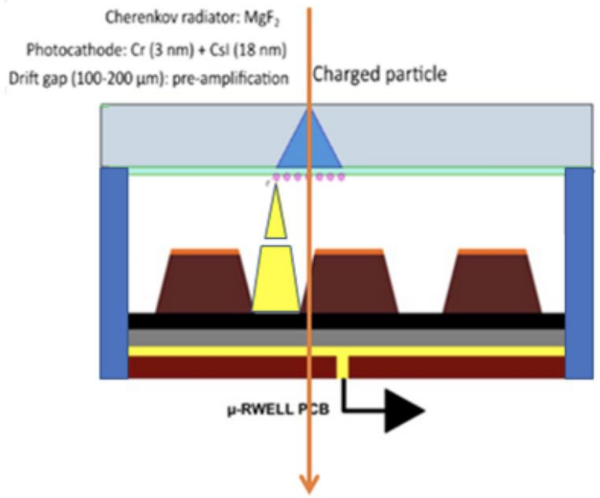
Problem of non-uniform preamplification gap



Planarity measurements of 10x10 cm^2 MM, A. Utrobičić

Planarity is one of the most challenging parameters for large surface PICOSEC detectors. PICOSEC based on uRWell instead of MM to improve reduce planarity issue has been proposed

- Aiming at large area detectors, multi-pad PICOSEC prototypes were developed, which comprise segmented anodes divided into either hexagonal or square pads
- Extensive tests in particle beams revealed that a detector with 19 hexagonal pads, each with 1 cm diameter, offers similar time resolution to the single-pad PICOSEC prototype
- Also true in the case that the incoming MIP induces signals in more than one of the neighboring pads
- Particle-beam tests of an improved, larger prototype (comprising 100 1cm×1cm pads) demonstrated even better timing capabilities



Technology Transfer and Relations with Industries

Preamble

- Academic physics researchers usually do not have dedicated training (or in theory are not supposed to have) for interaction with industries, this could lead to multiple unexpected problems when R&D or Mass Production process, which require interaction with company, need to be launched.

- While the technical/bureaucratic aspects could be effectively improved by appropriate training, knowledge of the market which could support development and production of Gas Detectors is often the result of previous experiences and interaction with collaborators

The following slides do not want to make a list of good/bad companies (the assessment could be the results of particular lucky or not well-prepared collaboration) rather examples, hints and tips for process preparation and interactions with the companies

Technology Transfer and Relations with Industries

… before and during the engineering process

- ***Do something similar have been already designed produced?***
  - When? By whom? For which project?
    - Inquire the involved people for feedback and detailed summary of lesson learnt
- ***Are the technical solutions adopted affordable by standard company*?**
  - Often engineers and technicians in our Institute, with similar tools regularly available in the market are able to achieve much better results
- ***Do you have already in mind possible company for the production?***
  - Yes: Involve them in the engineering process
  - No: Too bad, looks asap on the market
- ***Are the technical/manufacturing specifications in line with the documentations/specs adopted by the company ?***
  - Compatibility of design and production tools is a key point

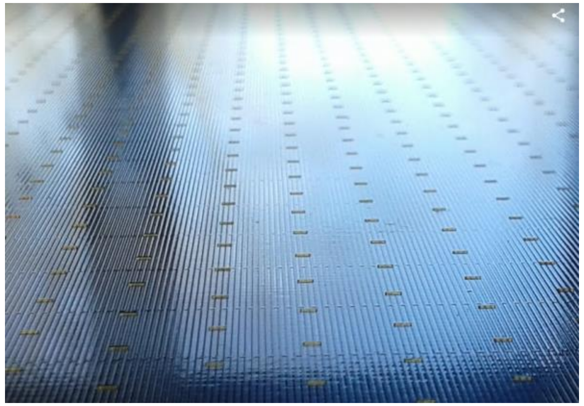
Technology Transfer and Relations with Industries

…before to start a production process

- ***Do the production will require a dedicated Technological Transfer?***
  - The process should start asap, possibly with a pre-series production as qualification step for a possible call for tender
- ***Single supplier or splits order?***
  - Both solutions have pro and cons, correct risk analysis should be carried out before adopting one or the other strategy
- ***Production in batches, per components types, mixed, …***
  - Projects needs could not match the "modus operandi" of the company, for large production of several different components, companies use to work in series completing the production of each single type before to move to the next one; This could not fit with the general project plan. Switching continuously production between different type of similar but not identical components could easily lead to production mistake and cost increase. Production planning, with adequate float, should be steered and submitted to the company at the time of the contract
- ***Logistic and communication matter!!!***

ATLAS NSW MM anode boards production

- **Largest industrial production of MPGD ever: 1300 m2 detector surface**
  - Resistive Micromegas fully produced in industries (first time)
  - Mass production: 2112 boards of unprecedented size: up to 45 x 220 cm^2
  - Technology developed at CERN and transferred to industries



- Two companies selected: ELVIA (F), ELTOS (IT)
- Choice to split production in 2 sites
  - Pros:
    - Helped in keeping the schedule. None of the firms could stand the full production in the required time
    - Each firm knew about the other → helped in promoting a good competition
    - Allows to find a quick fallback solution in case of failure of one company (saving the time for the technology transfer to a new company, still slowing down the total production)
    - Experimenting different technical solutions to adapt production to the specific firm → knowledge improvement
    - Allowed to quickly disentangle issues coming from components (common) wrt firm production specific issues
  - Cons:
    - Double efforts to follow up production at the two firm's premises
    - Develop firm-specific adaptation of production (facing different problems)
    - Establish two communication lines
- Final comment: was the right choice

I. photolithographic creation of copper pattern
standard process.
complex due to: size of board, required precision & board elongation (humidity).

II. cutting of Kapton foil with resistive pattern
non-standard but simple & required accuracy only ±1mm

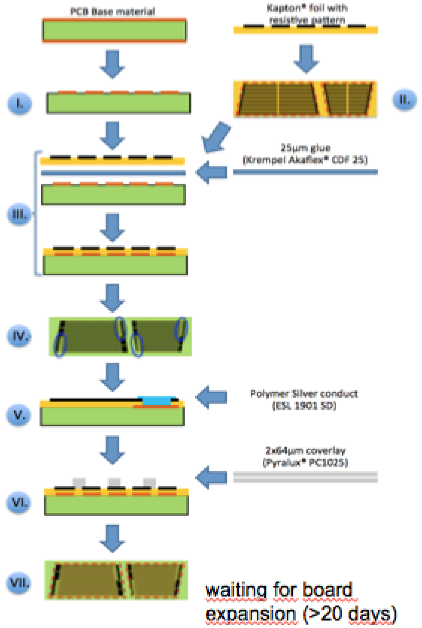
III. stacking and high-pressure & temperature gluing of Kapton foil, glue foil and board
standard process for small boards
complex due to: size of board & required cleanliness.

IV. chemical silver plating of copper pads
standard process

V. screen-printing of silver paste
non-standard but rather simple & required accuracy only ± 1mm

VI. lamination of coverlay & pillar creation
standard process for small boards.
complex due to: size of boards, highly non-standard pattern, required flatness

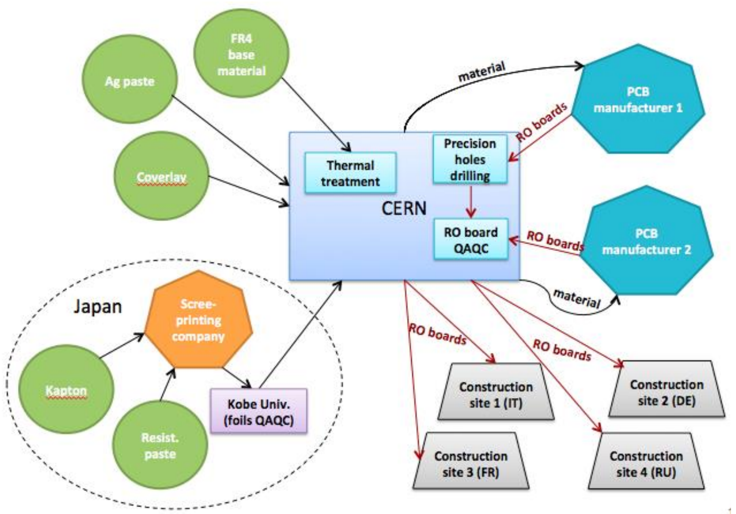
VII. cutting of boards and drilling of non-precision holes
standard process on CNC machine.
complex due to size of boards, required cutting precision & board elongation (humidity).



ATLAS NSW MM anode boards production

Main problems:

- Schedule!
- Production steps were new/unusual for the companies.
- Complex logistics
- Problems with subcontractor
- The technical responsible of production frequently change
- Two companies -> Two had different styles and policy. Need to adapt to them.



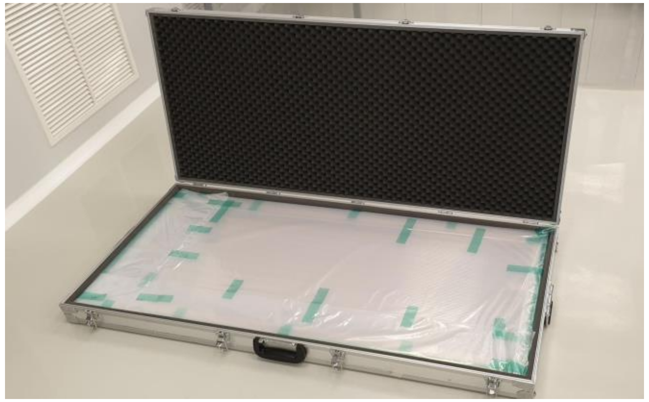
- **A constant follow-up at the companies during the whole production (>3 years) from experts was needed**
- **Huge follow-up and QC effort (manpower and cost)**

- **Final remarks: both companies considered the ATLAS production as an R&D, not a series production.**
- **Their main goad was to acquire ('for free') new expertise and potentially open up new market. Another advantage was to get credit from known research institutes (CERN & others)**
- **Both reached a yield >80%, larger than expected by both at the start of production. They are potentially interested in other similar commitments, based on the acquired knowledge.**

GEM Production in Industry (CMS Experience)

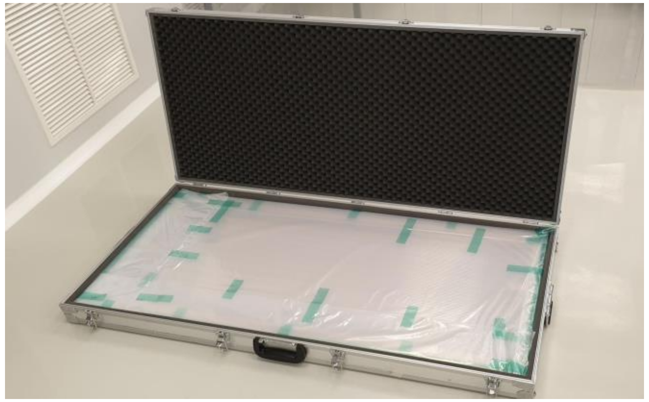
- Technological Transfer process very long, the company tried to master the single mask etching technique as at CERN but than moved to the double mask technique, this extended quite a lot the R&D and startup time
- GEM foils production expected for GE1/1 project didn’t arrive on time
  - The CMS-GEM collaboration didn’t push too much the company because backup solution was in place (full production at CERN)
- Facility refurbishment during the R&D process required long interruption of the tests
- Modification of local environmental protection rules imposed additional stop and delay
- *GEM foils size limited by machine/infrastructure and glass masks (~ 1 m long)*
- Company extremely collaborative along all the time of the process
- Several Internship with the SEUL University
- At the end production rate quite high > 30 large GEM foils/month

MECARO was qualified for GE2/1 and ME0 projects project



GEM Production in Industry (CMS Experience)

- GE2/1 Production started in 2020/21, regularly running for about one year and half
- Suddenly in Aug 2022 the company changed ownership and the new management didn't want to continue production of GEM foils, considered not profitable and out of the core project
- Collaboration interrupted; production relocated at CERN!!!
- Currently SEUL University is trying to setup new collaboration partially insourcing the production in his institute



Long path and big investment with, so far, limited results

Relations with Industries

- Extremely challenging requirements of future HEP experiments call for close collaboration between academia and industry. This collaboration should start as early as possible and address prototyping at the R&D stage, through to qualification testing and later tendering and purchasing.
- Good knowledge of the possible industrial applications are required to increase the chances of successful collaborations with industry.
- **To motivate industrial partners** to invest in sophisticated production lines for building detectors, scientific collaboration **must convince (ideally prove) industry that such detectors have a real market potential beyond particle physics**

some time the goal with industry seem to be the outsourcing of complete detector production …But

- ***Are (or can be) HEP detectors (Gas detector in our case) a real Industrial Product?***
- ***Academia attitude is to push over the limits / Industrial attitude is to produce standardized & very well qualified products; may non-convergent views ?***
- ***Could an "exaggerated industrialization" revert in reduction of our community attitude to detectors innovation?***

To the students

during these days, attending to the class **"Making engaging scientific presentations",** I learned that I should not thank you for the attention, but at let me **THANK YOU** for the interested post-lecture questions and discussions

To the organizers

THANKS FOR THE INVITATION

Reference (Talks/Workshops)

- CERN EP Department - R&D on experimental technologies 1st WG2 Meeting https://indico.cern.ch/event/702148
- CERN EP Department - R&D on experimental technologies https://indico.cern.ch/event/696066/contributions/2927894/attachments/1618327/2573211/RDonGaseousDetectorTechnologies.pdf
- ECFA Detector R&D Roadmap Symposium of Task Force 1 Gaseous Detectors https://indico.cern.ch/event/999799/
- Mini-Workshop on gas transport parameters for present and future generation of experiments https://indico.cern.ch/event/1022051/timetable/?view=standard
- https://indico.desy.de/event/22513/contributions/46788/attachments/30337/38104/20200224-EDIT-GaseousDetectors.pdf
- https://indico.cern.ch/event/1120714/contributions/4867134/attachments/2469534/4236245/MBianco_Poster_for_iWorid2022_V2.pdf
- https://indico.cern.ch/event/999799/contributions/4204334/attachments/2236247/3790326/infrastructures.pdf
- CERN Detector Seminar: https://indico.cern.ch/event/1175363/attachments/2477073/4252122/MBianco_CMS_GEM.pdf
- CERN Detector Seminar: https://indico.cern.ch/event/1168778/attachments/2464624/4227403/_2022_06_17-TV-DetSeminar.pdf
- CERN Detector Seminar: https://indico.cern.ch/event/1172978/attachments/2468524/4234156/2022_06_24_CERN_Seminar_rmunzer_v4.pdf
- Workshop on Resistive Coatings for Gaseous Detectors : https://agenda.infn.it/event/18156/timetable/?view=standard

References:

-) G. Macini, et al,. "*Validation of the New Small Wheel Micromegas sectors for the phase1 upgrade of the muon forward spectrometer of the ATLAS experiment at CERN*" Phys. Scr. 98 (2023) 044007

-) Bencivenni, R. De Oliveira, G. Morello and M.P. Lener, "*The micro-Resistive WELL detector: a compact spark-protected single amplification-stage MPGD*", 2015 JINST 10 P02008

-) G. Bencivenni et al, "*The μ-RWELL layouts for high particle rate*", 2019 JINST14 P05014

-) K. Dehmelt, et. al,"*Snowmass 2021 White Paper Instrumentation Frontier 05 White Paper 1: MPGDs: Recent advances and current R&D*", arXiv.2203.06562v3

-) S Duarte Pinto *et al* 2009 *JINST* 4 P12009

-) Paolo Iengo, Givi Sekhniaidze "*Irradiation and longevity test of Resistive Micromegas detectors*", PoS (ICHEP2022)351

-) E. Farina, et. al,. "*Resistive Micromegas high-rate and long-term ageing studies at the CERN Gamma Irradiation Facility*", NIM A 1042 (2022) 167423

-) F. Sauli, "*The gas electron multiplier (GEM): Operating principles and applications*", NIM A, 386 (1997), p. 531

-) S. Bachmann, *et al.* "Charge amplification and transfer processes in the gas electron multiplier"' NIM A, 438 (1999), p. 376

-) A. Bressan, *et al.* "*Two-dimensional readout of GEM detectors*", NIM A, 425 (1999), p. 254

-) A. Bondar, *et al.* "*Study of ion feedback in multi-GEM structures*"', NIM A, 496 (2003), p. 325

References:

-) M. Villa, *et al.* *"Progress on large area GEMs* ", NIM A, 628 (2011), p. 182

-) H. Fenker, *et al.* *"BoNus: Development and use of a radial TPC using cylindrical GEMs*", NIM A, 592 (2008), p. 273

-) A. Balla, *et al.* *"Construction and test of the cylindrical-GEM detectors for the KLOE-2 Inner Tracker*", NIM A, 732 (2013), p. 221

-) P. Everaerts, "*Rate capability and ion feedback in GEM detectors",* (Thesis at Gent University 2006)

-) F. Sauli, "*GEM readout of the time projection chamber*", CERN-EP-TA1 Internal Report (1999)

-) ALICE_Collaboration, "*Technical Design Report for the Alice Time Projection Chamber*", 2014.

-) Va'vra, A. Sharma "*Single electron detection in quadruple-GEM detector with pad readout*", NIM A, 478 (2002), p. 235

-) R. Bellazzini, *et al.* *"Imaging with the invisible light*", NIM, 581 (2007), p. 246

-) Murtas, F. "*The GEMPix Detector*", https://doi.org/10.1016/j.radmeas.2020.106421

-) Leidner, J., Murtas, F., Silari, M., "*Medical Applications of the GEMPix*", Appl. Sci. 2021,11, 440. https://doi.org/10.3390/app11010440

-) Leidner, J., Ciocca, M., Mairani, A., Murtas, F. and Silari, M., "*A GEMPix-based integrated system for measurements of 3D dose distributions in water for carbon ion scanning beam radiotherapy*", (2020) Med. Phys., 47: 2516-2525. https://doi.org/10.1002/mp.14119

References:

-) F.Sauli, Yellow Report, CERN-77-09 (1977)

-) F. Fallavollita, “*Novel triple-GEM mechanical design for the CMS-ME0 detector and its preliminary performance*”, 2020 *JINST* 15 C08002

-) M. Bianco, et. al.,”*Rate capability of large-area triple-GEM detectors and new foil design for the innermost station, ME0, of the CMS endcap muon system*”, arXiv:2201.09021v1

-) F. Fallavollita, “*Aging phenomena and discharge probability studies of the triple-GEM detectors for future upgrades of the CMS muon high rate region at the HL-LHC*”, NIM , A 936 (2019) 427–42

-) A. Colaleo, P.Verwilligen, *et al, “Diamond-Like Carbon for the Fast Timing MPGD”* 2020 *J. Phys.: Conf. Ser.* **1498** 012015

-) M. Iodice *et. al., “Small-Pad Resistive Micromegas: rate capability for different spark protection resistive schemes”,* 2020 *JINST* **15** C09043

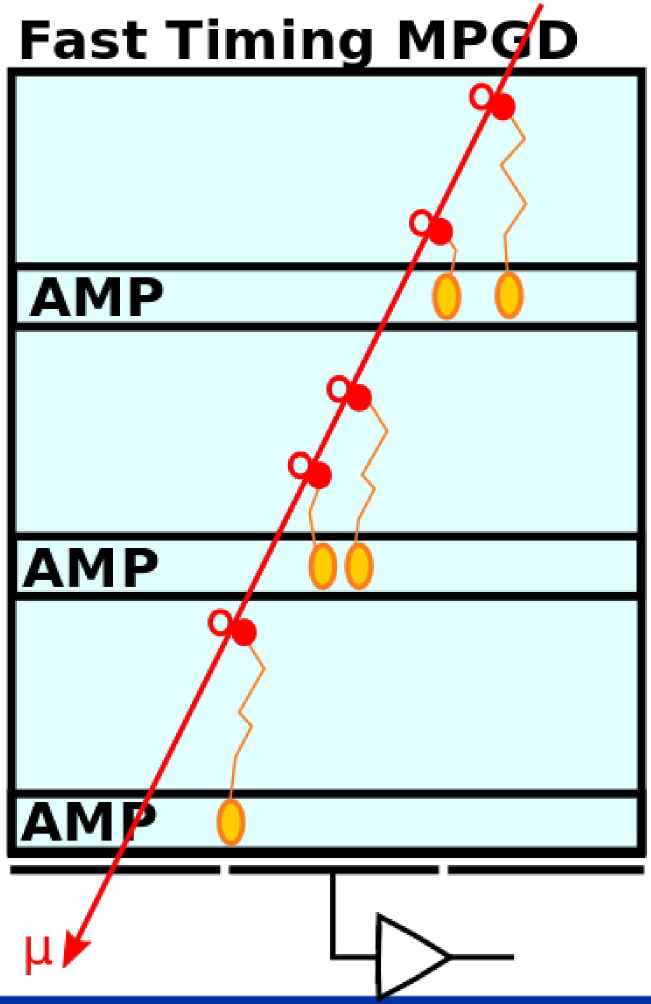
-) R. De Oliveira, M.Maggi, A. Sharma, “*A novel fast timing micropattern gaseous detector: FTM*”. arXiv:1503.05330 (2015)

-) J. Bortfeldt, et. al., “*PICOSEC: Charged particle timing at sub-25 picosecond precision with a Micromegas based detector*”, arXiv:1712.05256v

Backup

Fast Timing MPGD (FTM)

- **Time resolution of <u>all</u> proportional gas detectors (GEM,MM,uRWELL,…) is limited to 5-10ns [1]**
- Typical <u>fluctuation of closest primary electron</u> to amplification structure:
  λ~ 2.8mm^{-1} → $\langle d \rangle$ = 350μm @ v_{drift} = 50-70μm/ns → σ_t = 5-7 ns time resolution [2]



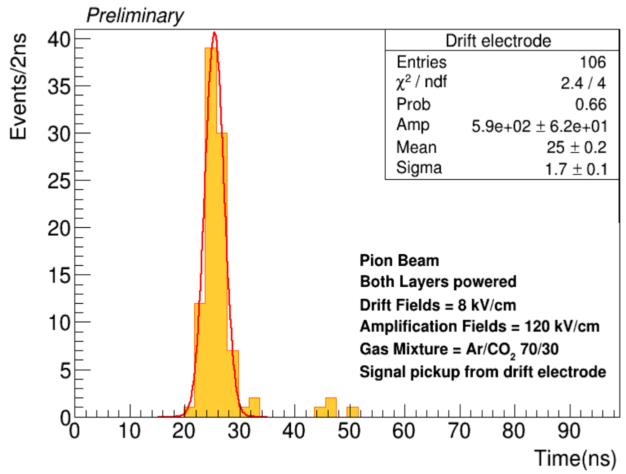
Fast Timing MPGD: Working Principle

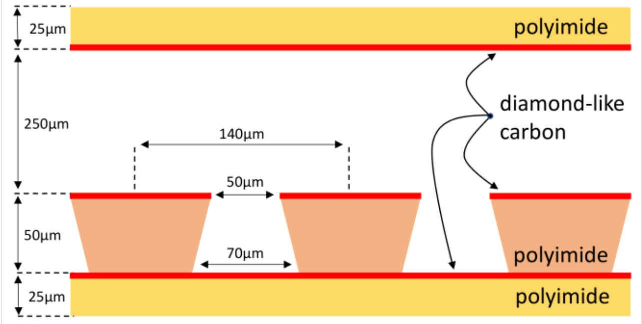
- Divide drift in multiple layers, each with Amplification
- Resistive electrodes => Electrode Transparency
- Closest primary electron => Fastest Signal
- Time Resolution $\sigma_t = 1/(\lambda \cdot v_{drift} \cdot N)$, where N = layers
- Observed: 2ns with 2 layer-detector [4] (→ OK)

Fast Timing MPGD: Challenges

- Fully Resistive MPGD (no Copper, only DLC, resist. kapton)
- Detect single-electron (or single cluster) instead of many primary+secondary electrons created in drift gap
- **Requires High Gain Structures: G = 10^4 - 10^5**
- **Requires sensitive front-end** (< 1fC, few ns rise-time)

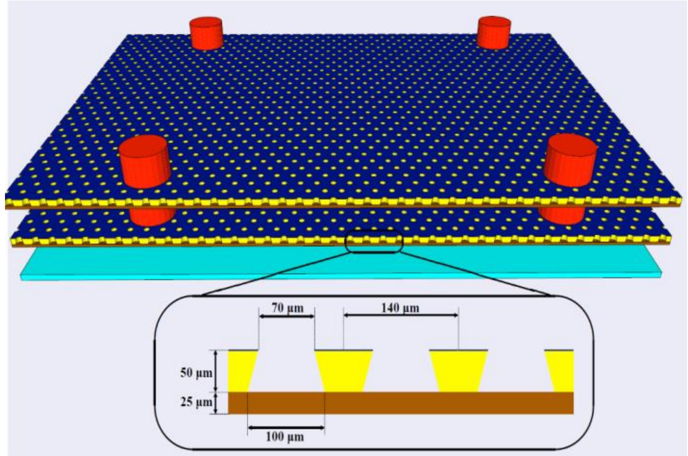
Test Beam Results (2 layers)





Design of single Layer:
Perforated GEM foil with DLC electrode

Fast Timing MPGD (FTM): Design



Single layer specifications:

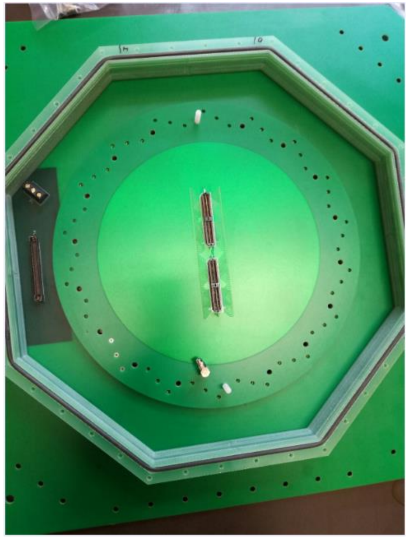
- Drift layer: 250µm drift layer *(Red: Dupont Coverlay spacers)*
- Gain layer: 50µm Kapton *(Yellow: GEM foil: 70µm hole, 140µm pitch)*
- Support Layer: 200µm *(Brown: Pre-Preg (glue) + FR4 PCB)*
- Resistive coating: 10–100 nm,~100 MΩ/ □ *(Blue: DLC)*

FTM requirements:

detection of single photo-e⁻(closest) instead of alle⁻in drift (i.e. factor 10 reduction in charge)
detection with single amplification layer(Triple GEM has amplification divided in three stages)

Therefore:

⇒need high gain structure, with low spark/discharge rate
⇒need low noise detector and low noise electronics
⇒need electronics that can process pulse with low charge ($10^4 e^- = 1.6$ fC)
⇒need electronics that can process and preserve a fast pulse



home.cern