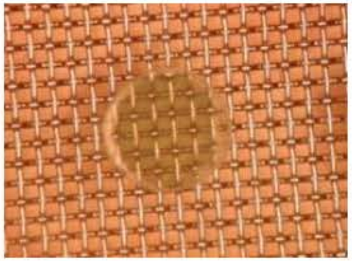
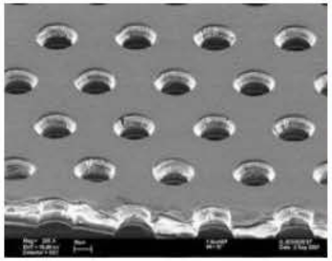
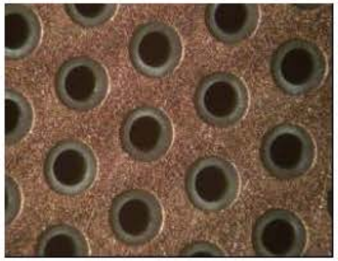
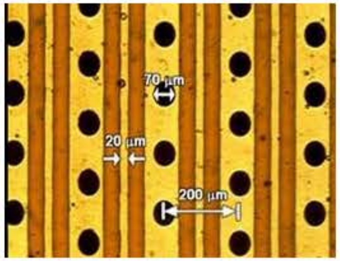
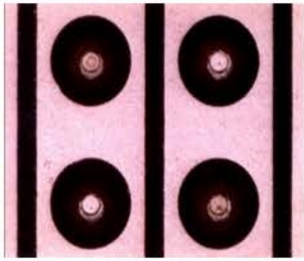

MicroMegas

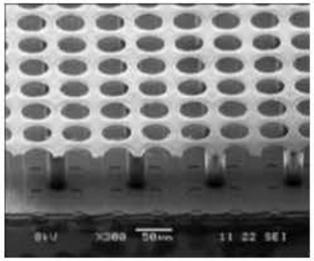

GEM


THGEM



MHSP


microPIC


Ingrid

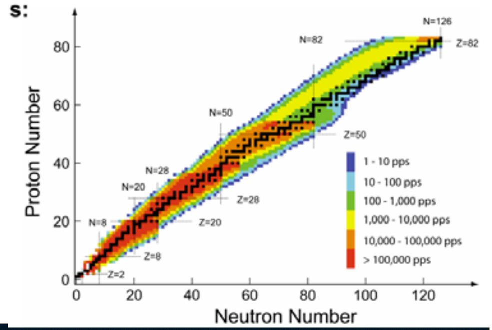
Developments and applications of Micro-Pattern Gaseous Detectors (MPGD): a concise review.

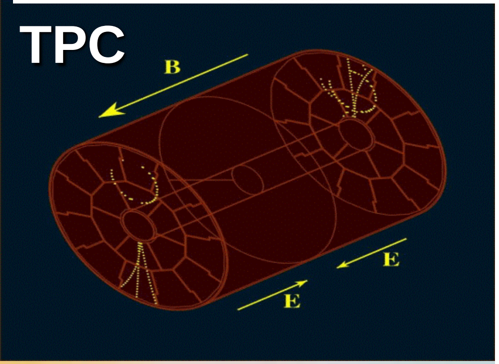
New gaseous detectors technologies for neutrino and nuclear physics

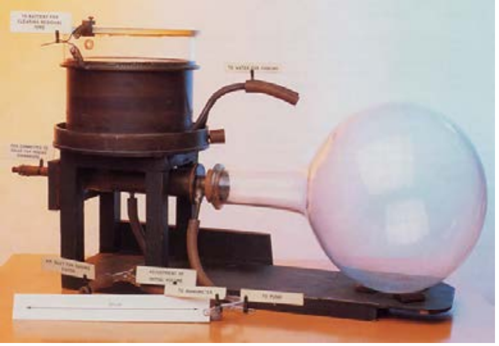
Marco Cortesi (Michigan State University)

Outline:

- History
- Overview of MPGD Technology
- Performances and Limitations
- Applications (NP and Cryogenic)
- Summary & Prospective





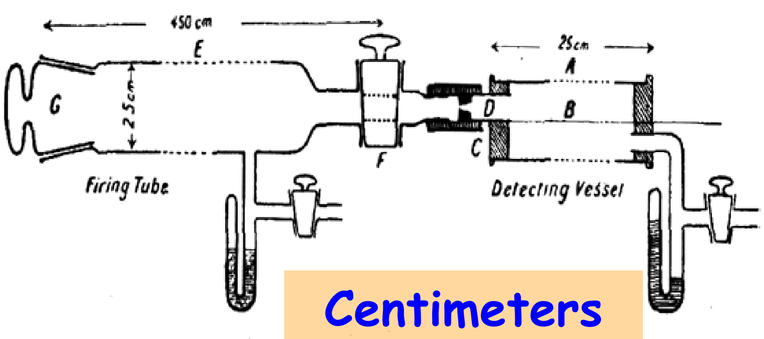


NSCL
National Science Foundation
Michigan State University

MICHIGAN STATE UNIVERSITY

GAS DETECTORS & FUNDAMENTAL RESEARCH

1906 Rutherford & Geiger

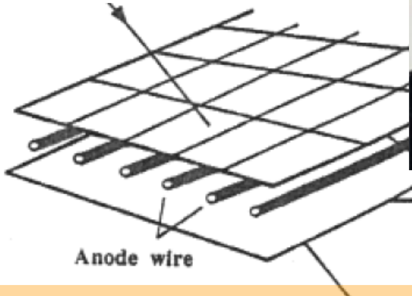


Centimeters

Gaseous detectors: why ?

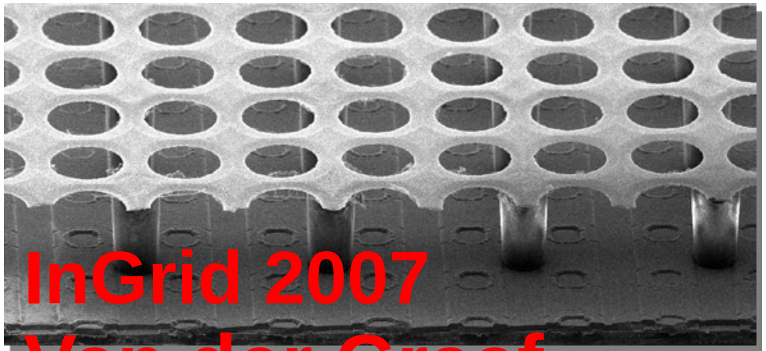
- good stability, robustness and aging compared to solid/liquid detectors
- low radiation length
- good space and moderate energy resolution
- three dimensional readout/flexible geometry
- still today the only choice whenever large-area coverage with low material budget is required

MWPC 1968
G. Charpak
Nobel Prize in 1992



Tens-Hundred Microns

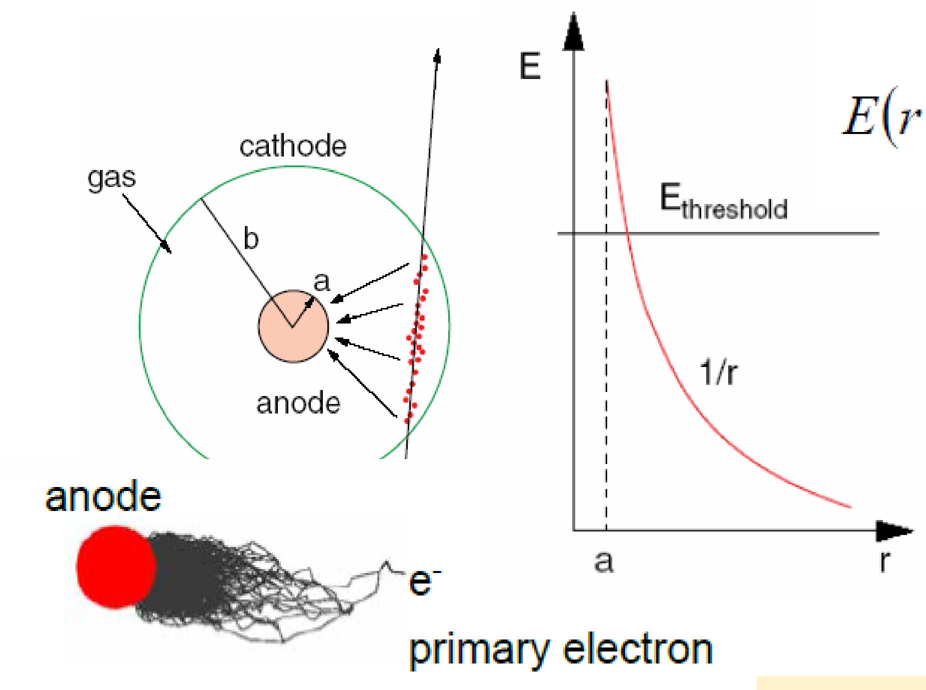
Microns



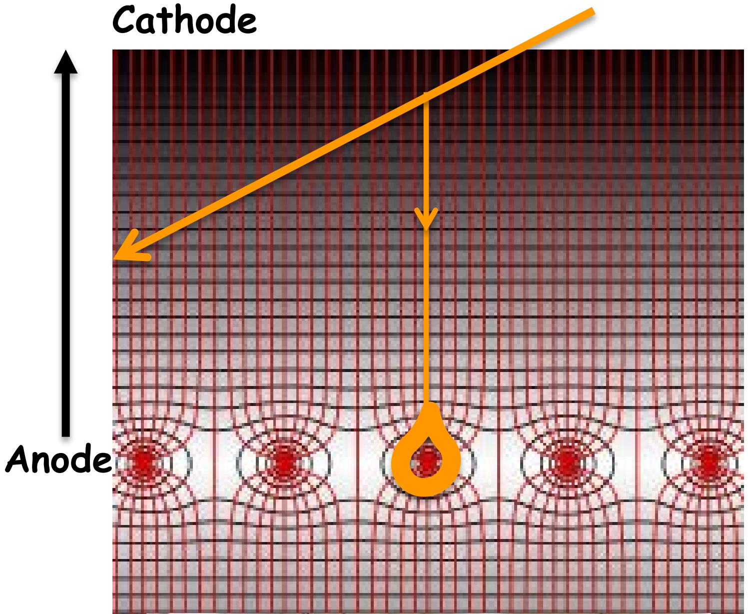
InGrid 2007
Van der Graaf

Multi-Wire Proportional Chamber -MWPC

G. Charpak et al, *NIM A* 62 (1968), 262.



$$E(r) = \frac{CV_0}{2\pi\varepsilon_0} \cdot \frac{1}{r}$$



<u>Properties</u>:

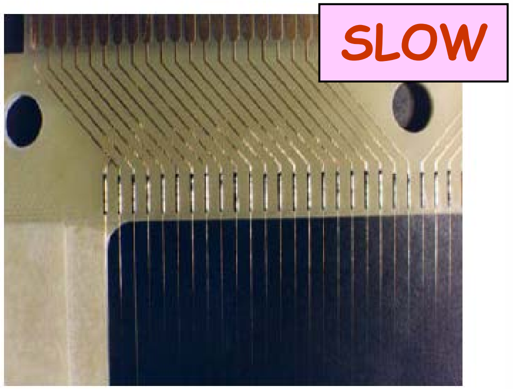
- Flexible geometry and large area (~m^2)
- Many well developed position encoding methods
- Works in magnetic field
- Rate capability ≈ 10^4 Hz/mm^2
- Electron avalanche multiplication (Gain) ≈ 10^4-10^5
- Position resolution ➔ down to 100 μm for 1 mm wire spacing (limited in size)

Micro-Strip Gas Chamber:
The Beginning of a New Era!

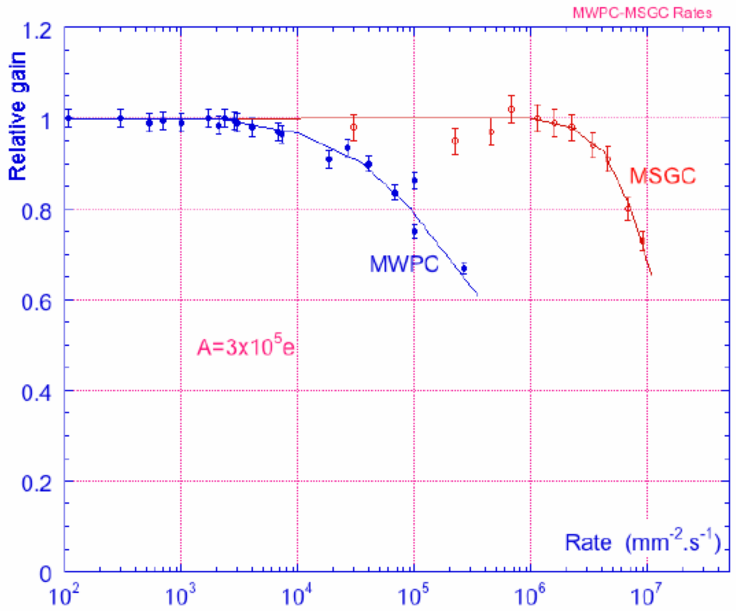
Wire-Based Detector:
"Mechanics", Economic but
Secondary effects ➔ Gain limits
Space charge ➔ Counting-rate limits
Aging ➔ Damage after long-term operation

New Idea: move down in size & add cathodes very close to anodes to evacuate ions produced during the avalanche process

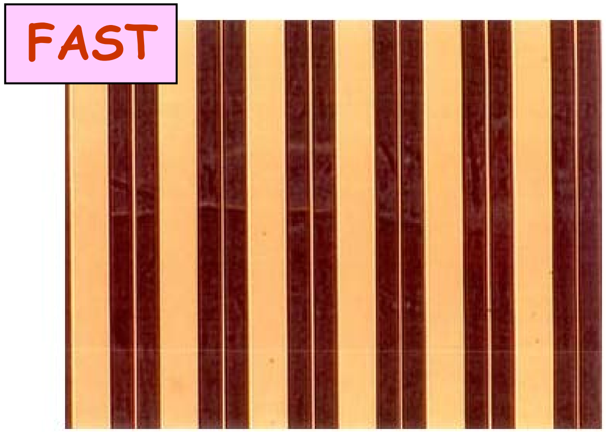
A. Oed, NIMA 263 (1988) 351



Wire spacing ➔ 1-2 mm



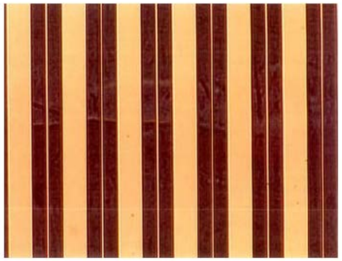
MSGC



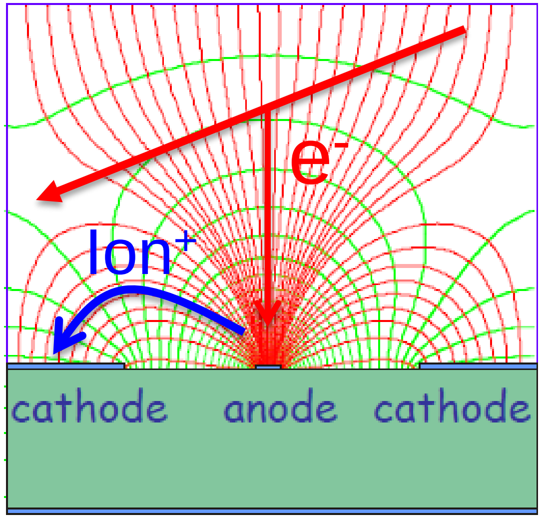
Anode spacing ➔ 200 µm

Rate Capability Limits due to space charge overcome by increasing the amplifying cell granularity

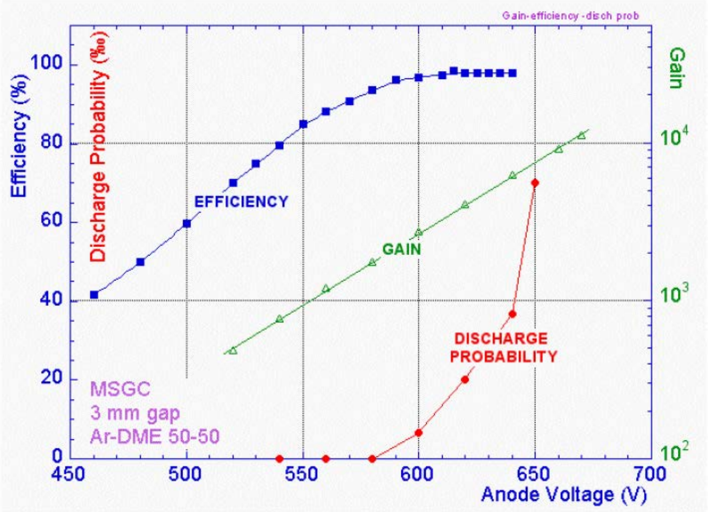
MSGC: Performances and Limits



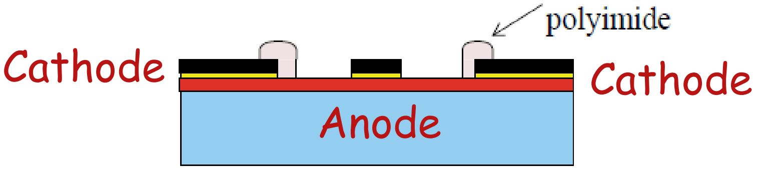
A. Oed, NIMA 263 (1988) 351



Production: Electrodes formed on insulating substrate by micro-lithographic technology



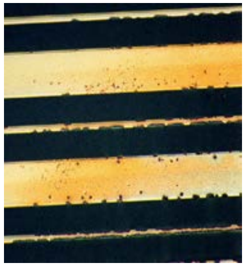
Limitations:
- High E-values at the edge between insulator and strips → discharges
- Charge accumulation at the insulator → gain evolution vs time



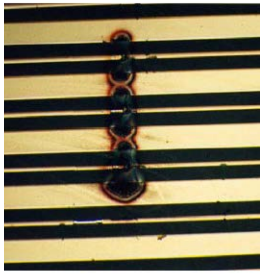
EDGE PASSIVATION

Later (~ 1999-2000):
Passivation of the cathode edges → MSGD operational!

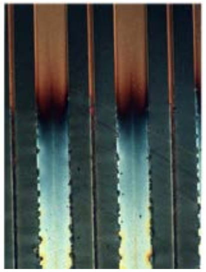
MICRODISCHARGES



BREAKDOWN

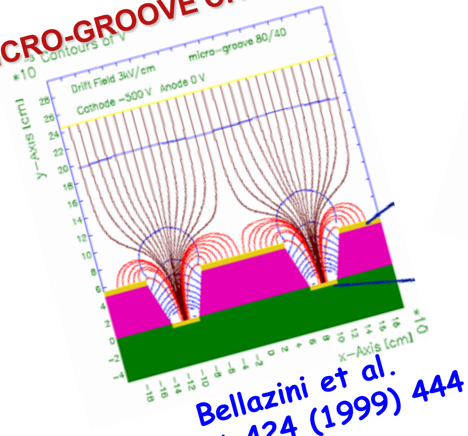


AGING



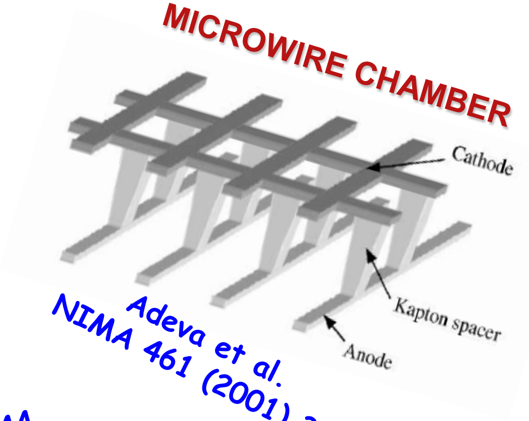
Micro-Pattern Gaseous Detector

MICRO-GROOVE CHAMBER



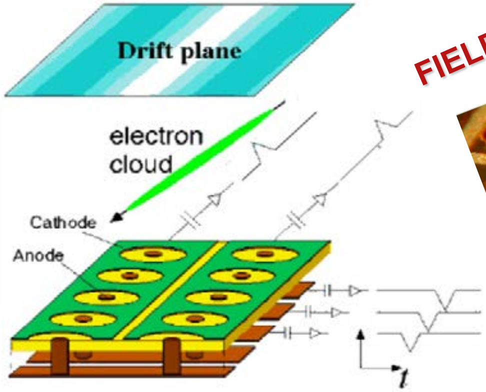
Bellazini et al.
NIMA 424 (1999) 444

MICROWIRE CHAMBER



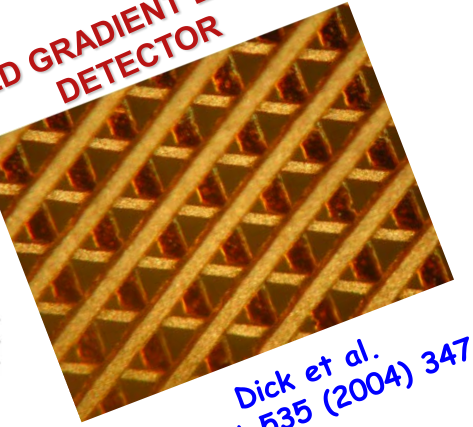
Adeva et al.
NIMA 461 (2001) 33

MICRO-PIXEL CHAMBER



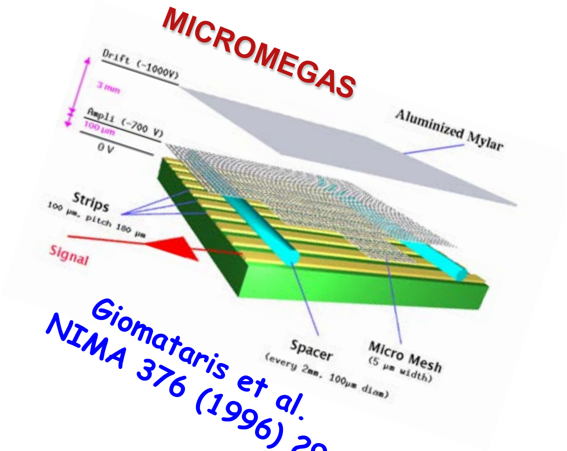
Ochi et al.
NIMA 471 (2001) 264

FIELD GRADIENT LATTICE DETECTOR



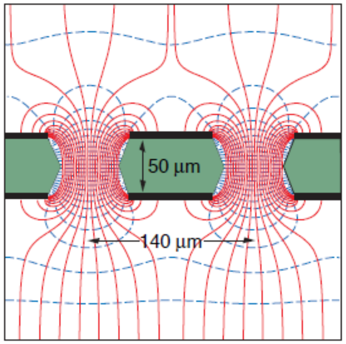
Dick et al.
NIMA 535 (2004) 347

MICROMEGAS



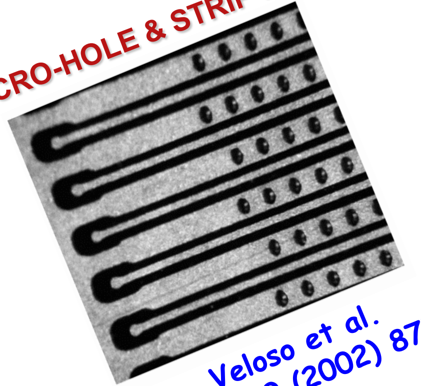
Giomataris et al.
NIMA 376 (1996) 29

GAS ELECTRON MULTIPLIER



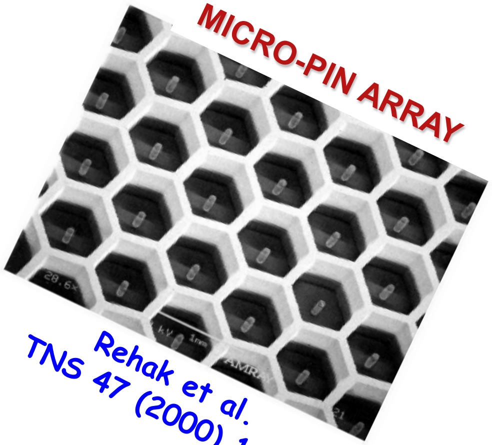
Sauli
NIMA 386 (1007) 531

MICRO-HOLE & STRIP PLATE



Veloso et al.
TNS 49 (2002) 875

MICRO-PIN ARRAY



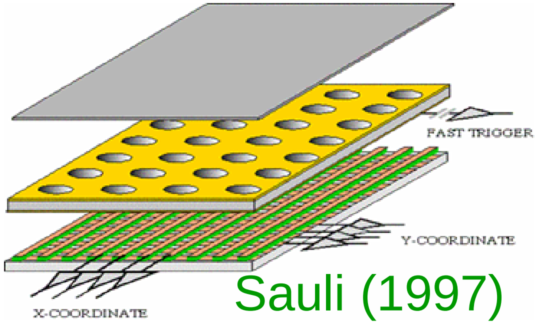
Rehak et al.
TNS 47 (2000) 1426

…. and many others

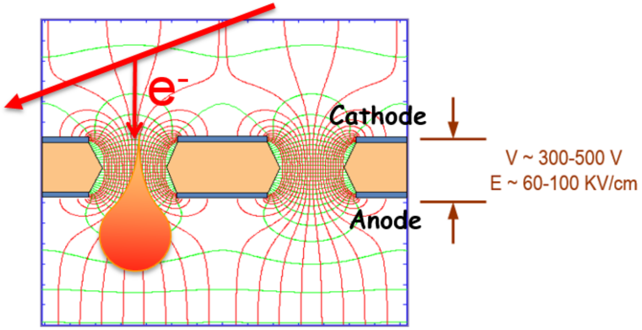
National Science Foundation
Michigan State University

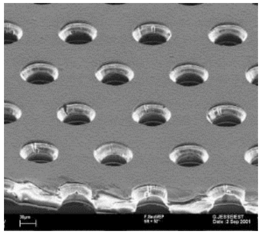
Micro-Pattern Gas Detectors

GEM : Gas Electron Multiplier

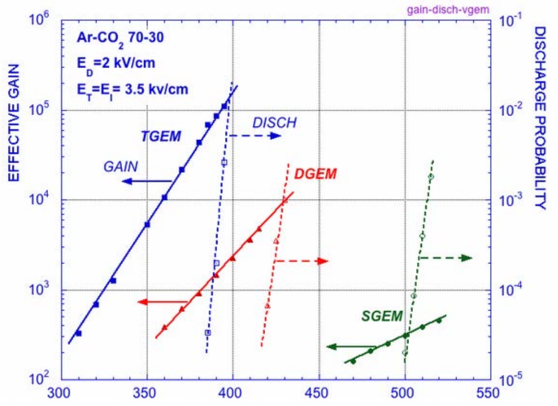


Sauli (1997)

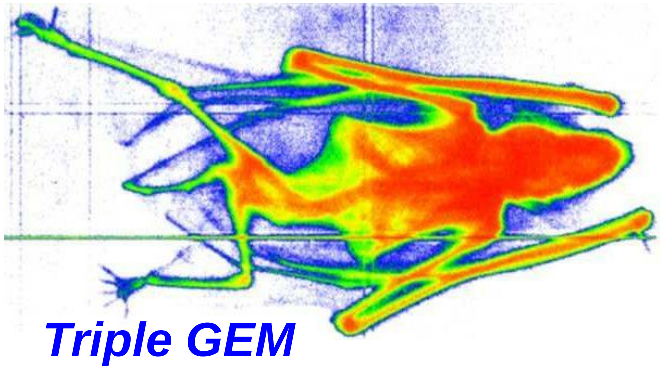




https://gdd.web.cern.ch/GDD/

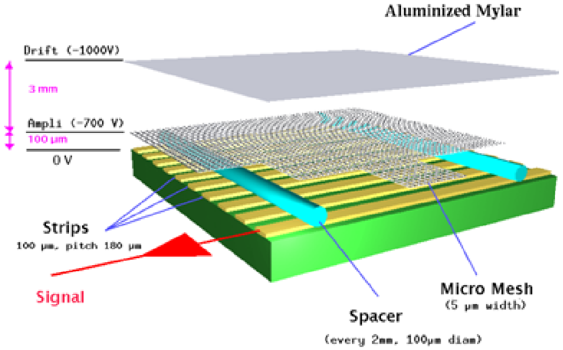


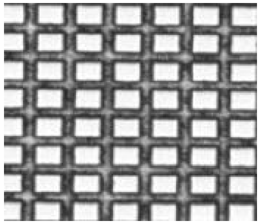
High Spatial Resolution (≈40 µm)

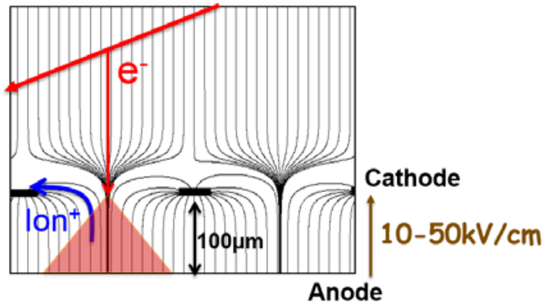


Triple GEM

Micromegas : Micro Mesh Gaseous Detector

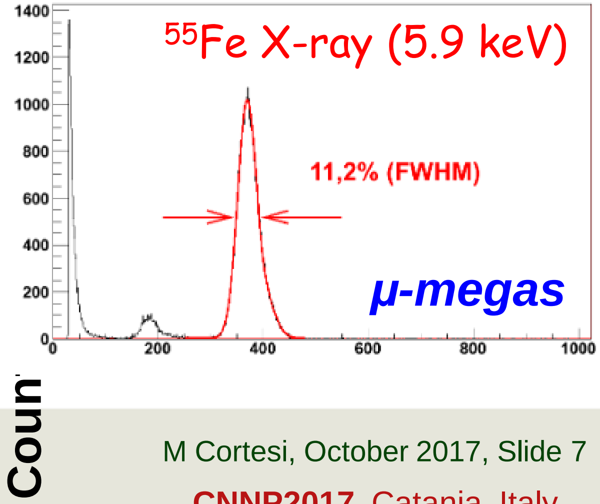






Giomataris (1996)

Iguaz et al. 2009 J. Phys. 179

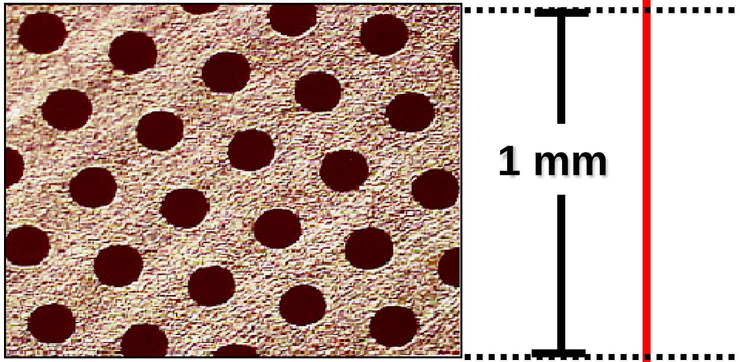


Thick-Gas Electron Multiplier (THGEM)

Simple & Robust → Manufactured by standard PCB techniques of precise drilling in G-10/FR-4 (and other materials) and Cu etching

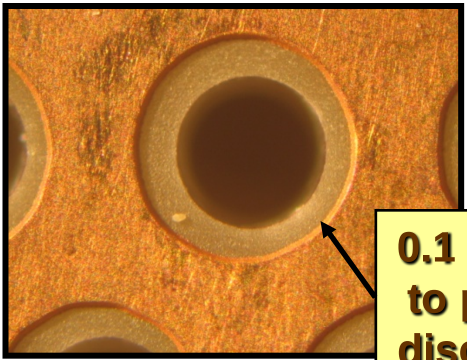
STANDARD GEM

10^3 GAIN IN SINGLE GEM



THGEM

10^5 gain in single-THGEM



0.1 mm rim to prevent discharges

- Effective single-electron detection
- High gas gain ~10^5 (>10^6) @ single (double) THGEM
- Few-ns RMS time resolution
- Sub-mm position resolution
- MHz/mm^2 rate capability
- Cryogenic operation: OK
- Gas: molecular and noble gases
- Pressure: 1mbar - few bar

Introduced in // by different groups:

L. Periale et al., NIM A478 (2002) 377.

P. Jeanneret, PhD thesis, Neuchatel U., 2001.

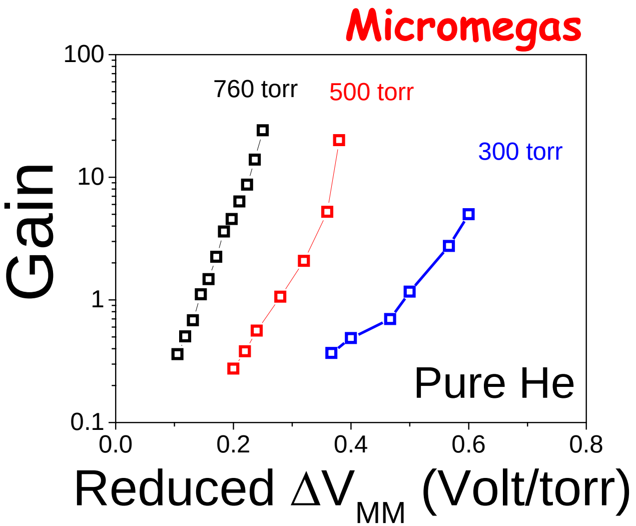
P.S. Barbeau et al, IEEE NS50 (2003) 1285

R. Chechik et al., NIMA 535 (2004) 303

"pure" elemental gas for low-energy nuclear physics applications

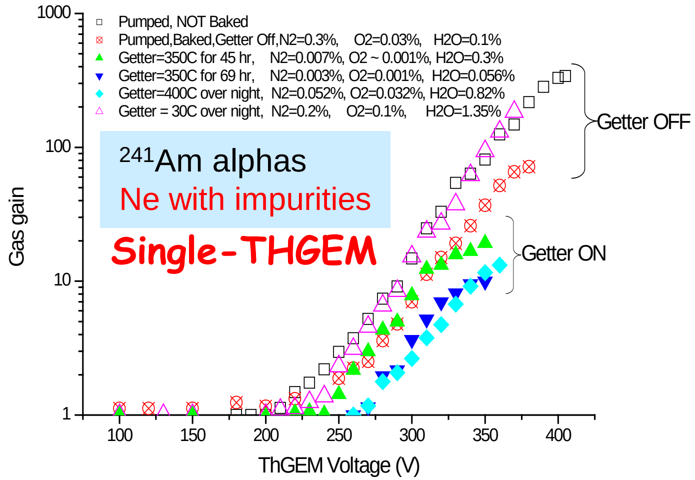
Active-Target Gases for Studying Inverse Kinematic Reactions

- H_2 (alternatively iC_4H_{10}) as proton target
  - 1 neutron pickup (p,d)
  - 2 neutron pickup (p,t)
  - p-scattering
- D_2 as deuteron target
  - 1 neutron transfer (d,p)
  - 1 proton pickup (d,^{3}He)
  - Inelastic scattering (d,d')
- ^{3}He
  - 1 proton transfer (^{3}He,d)
- ^{4}He as alpha target
  - Inelastic scattering (^{4}He, ^{4}He'),
  - Isoscalar Giant Resonances excitations …
  - Alpha-induced reactions for astrophysical p-process



-) Purity (no quencher) → High Reaction Yield
-) Low-Pressure Operation → Large Dynamic Range

Endcap Detector Performance:
Gas Gain, Energy Resolution, Spatial Resolution, Counting Rate Capability, Stability etc…

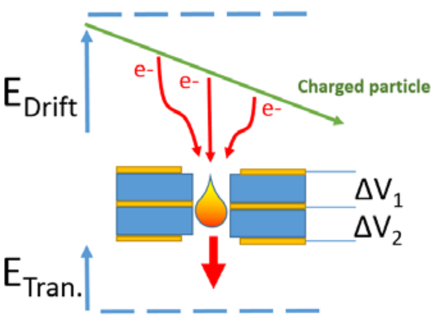


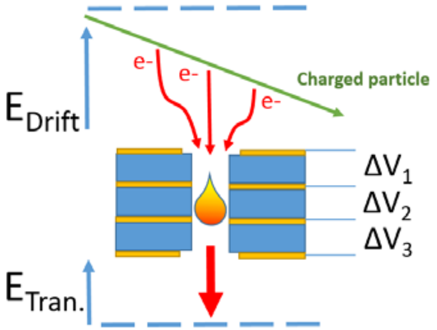
Miyamoto et al. 2010 JINST 5 P05008

National Science Foundation
Michigan State University

Multi-layer THGEM (M-THGEM)

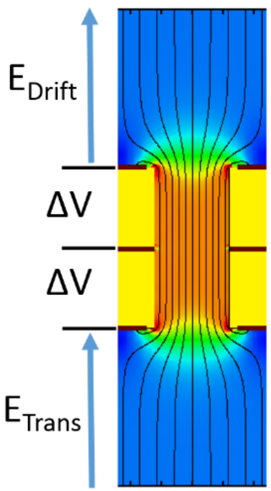
Manufactured by multi-layer PCB techniques out of FR4/G-10/ceramic substrate



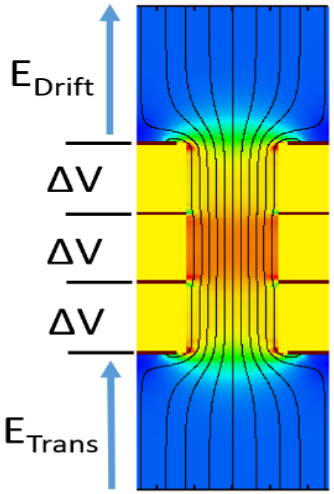


-) No loss of charge ➔ high gain @ low voltage
-) Robust avalanche confinement
➔ lower secondary effects
-) Long avalanche region
➔ high gain @ low pressure
-) Field geometry stabilized by inner electrodes
➔ reduced charging up

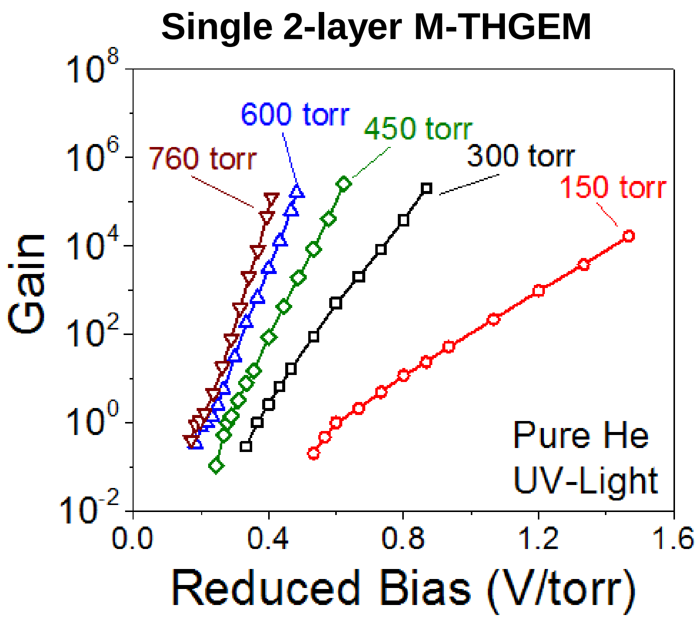
2-Layer M-THGEM



3-Layer M-THGEM



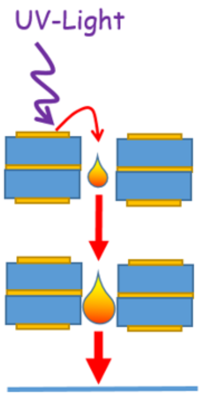
Cortesi et al., arXiv:1606.07314

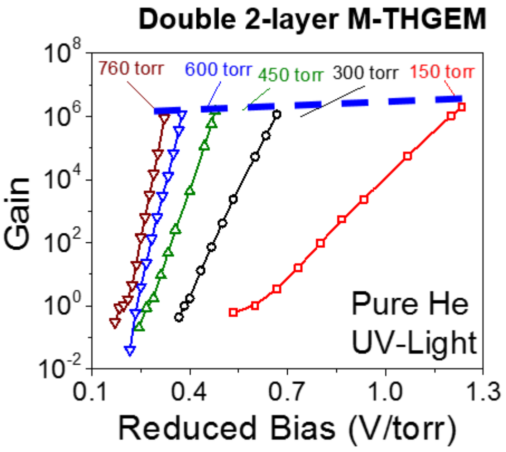


Multi-layer THGEM (M-THGEM): performance

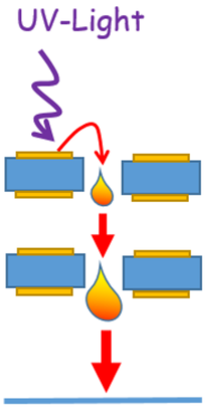
Cortesi et al., arXiv:1606.07314

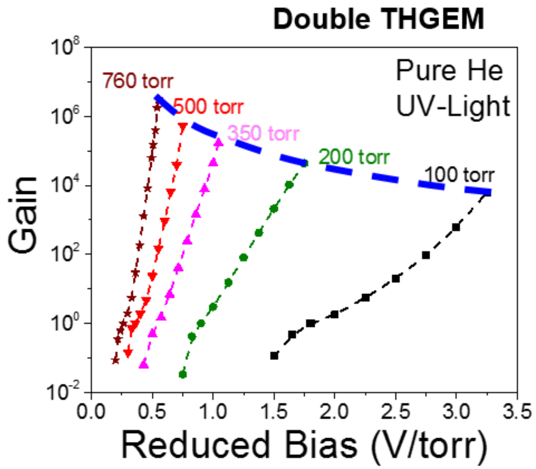
10x10cm² M-THGEM
(thickness = 1.2 mm, hole = 0.5 mm, pitch = 1 mm)



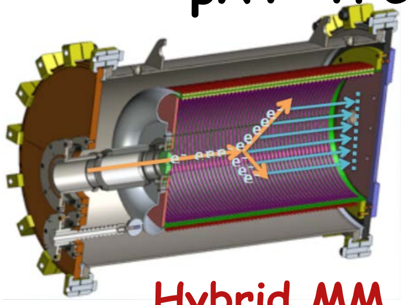


10x10cm² THGEM
(thickness = 0.6 mm, hole = 0.5 mm, pitch = 1 mm)

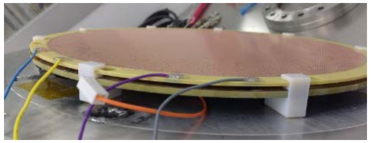


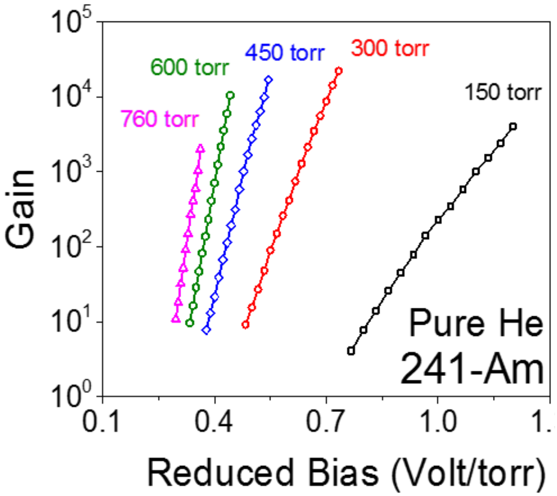


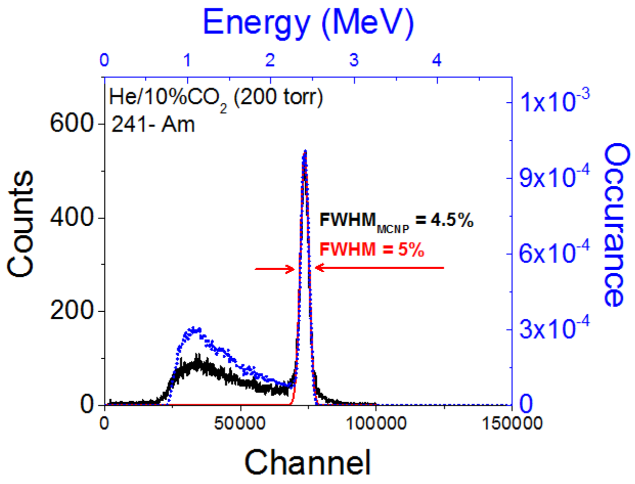
pAT-TPC (NSCL)



Hybrid MM + M-THGEM



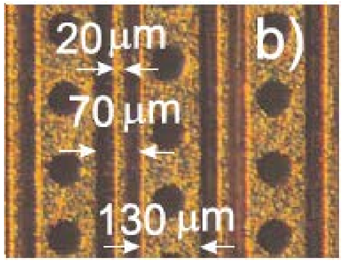




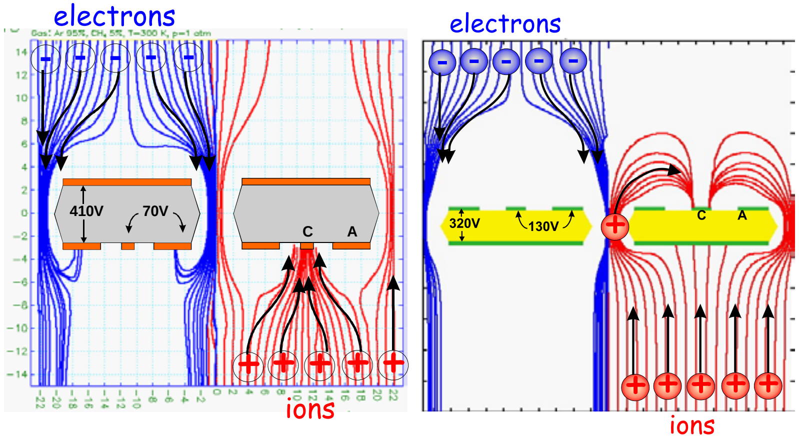
Micro-Hole Strip Plate & COBRA

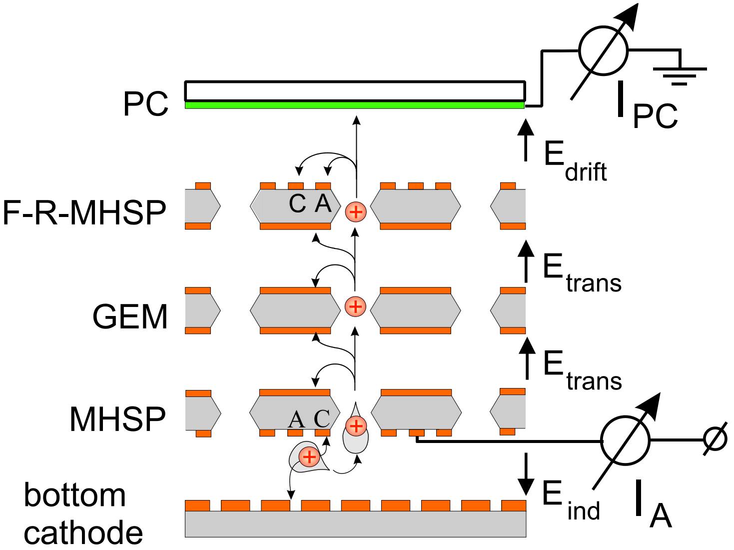
Complex geometries needed with extra electrodes to trap the ions:

MHSP

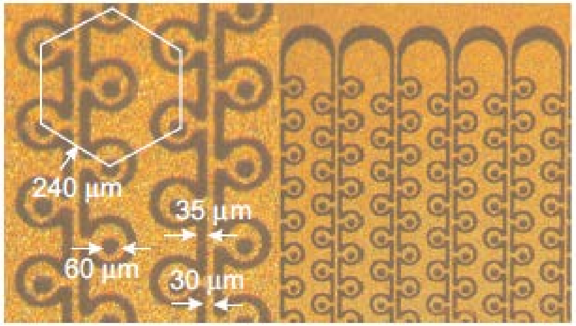


Veloso et al. Rev.Sc. Instr. 71 (2000) 2371

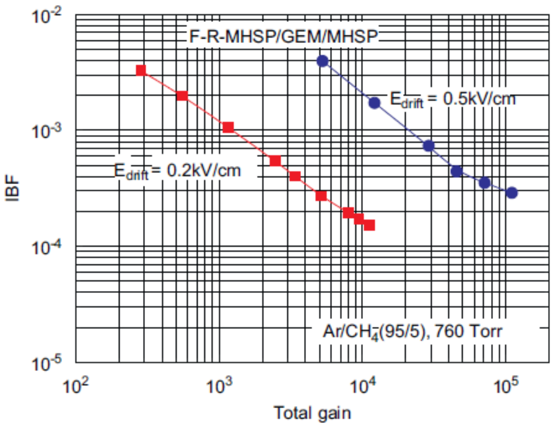


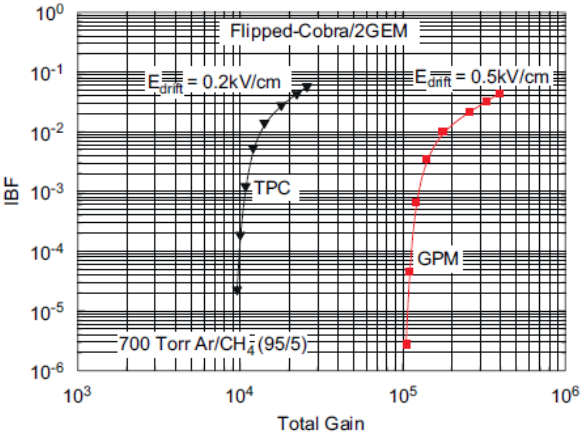


COBRA



Lyashenko et al. NIMA 598 (2009) 116



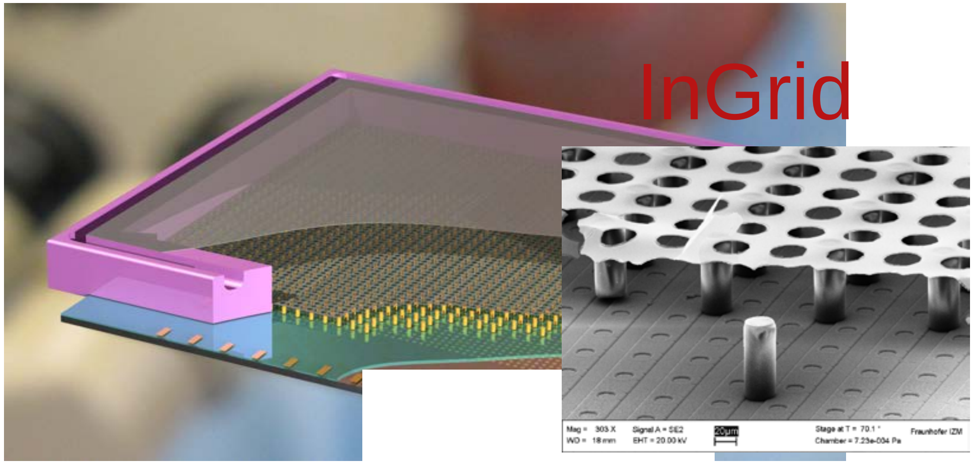


With MHSP/GEM cascade
BEST ION TRAPPING : 10^{-4}
100 X better than 3-GEM
20 X better than Micromegas

The Ultimate detector?

INTEGRATED MICROMEGAS AND PIXEL SENSOR

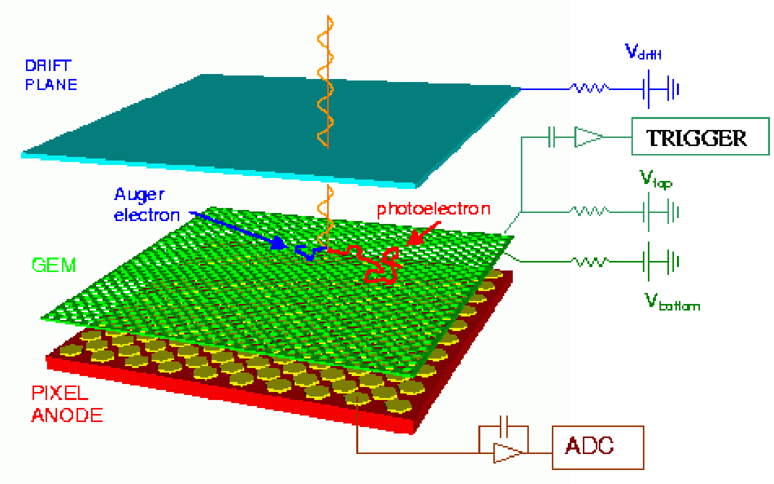
Post processing of TIMEPIX chip to form metal mesh on insulating pillars



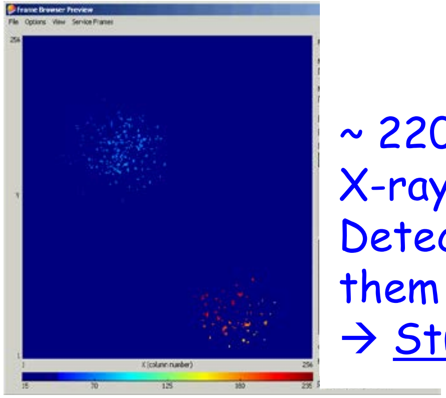
M. Chefdeville et al, NIMA 556 (2006) 490

GEM + ASIC

Avalanche Charge transferred to a pixelated anode plane mounted on top of an ASIC chip



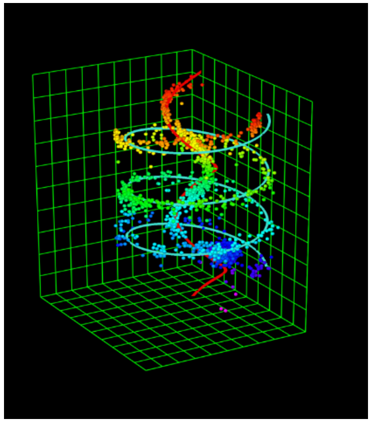
Costa et al. Nature 441 (2001) 662



~ 220 Electrons from a X-ray (5.9 keV) conversion ➔ Detected one by one and count them in μ-TPC (6 cm drift)

→ Study single electron response

Colas, RD51 Meet. 2009 kolimpary (Greece)



Electrons tracks from ^{90}Sr

In magnetic Field (0.2 Tesla)

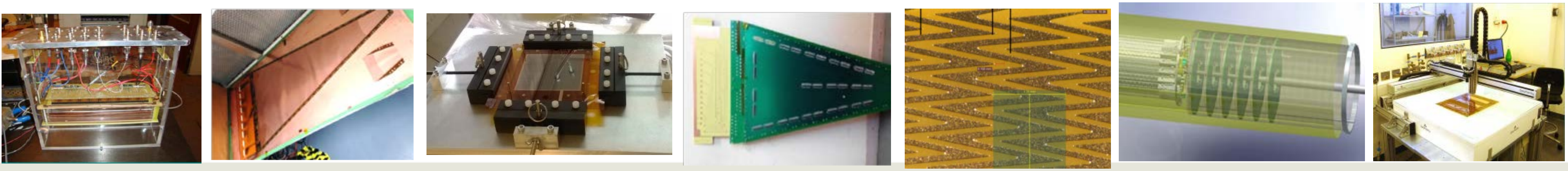
Applications

HEP, Astrophysics, Nuclear Physics, Industry and Medical Diagnostic

- High Rate Particle Tracking and Triggering
- Time Projection Chamber Readout
- Photon Detection (UV-Visible Gaseous PhotoMultiplier, Cherekov Imaging)
- Calorimeter (DHCAL @ ILC)
- X-ray (X-rays Astronomy, Cosmic Ray)
- Neutron Detection (Fast/Thermal/Cold Neutron Radiography/Tomography, Spectroscopy, Special Nuclear Material Detection, Nuclear Waste)
- Medical/Biology Applications (Portal Imaging, Beam Monitor for Hadron therapy, PET)
- Homeland Security (Early Earthquake Warnings, Forest Fire Detection, Drugs & Explosive Detection, Cosmic Rays Muons Tomography)
- Industry (Non-destructive testing, Nuclear Power Plan Development)
- Cryogenic Applications (Dark Matter search, neutrino Physics, Double-Beta Decay, Digital Radiography)

MPGD: Tracking for Heavy-Ion/Nuclear Phys.

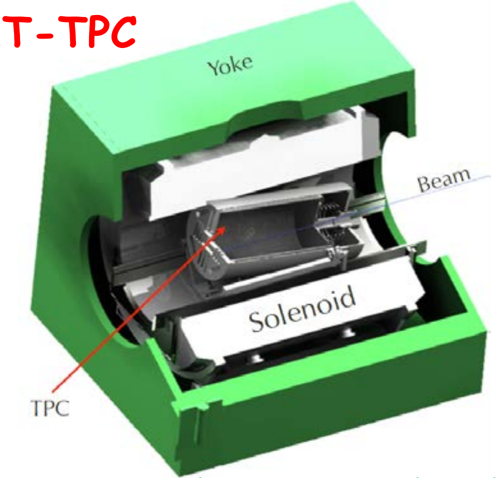
Name (Lab)	MPGD Technology	Volume Area	Pressure (atm)	Operation Performance	Status
ACTAR (GANIL)	μ-megas	8000 cm^3	0.01-3	Counting rate < 10^4 nuclei but higher if some beam masks are used	Under Construction
MAIKo (RNCP)	μ-PIC	2750 cm^3	0.4-1	FADC electronics 2*256 channles	Test
PANDA (FAIR)	μ-megas/GEM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

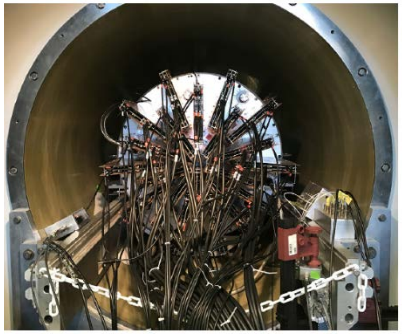


Active-Target TPC for low-energy NP

Goal: Study of inverse-kinematic nuclear reactions with resolutions equal to the one achieved in direct kinematics with high-resolution spectrometers + higher efficiency & thicker targets

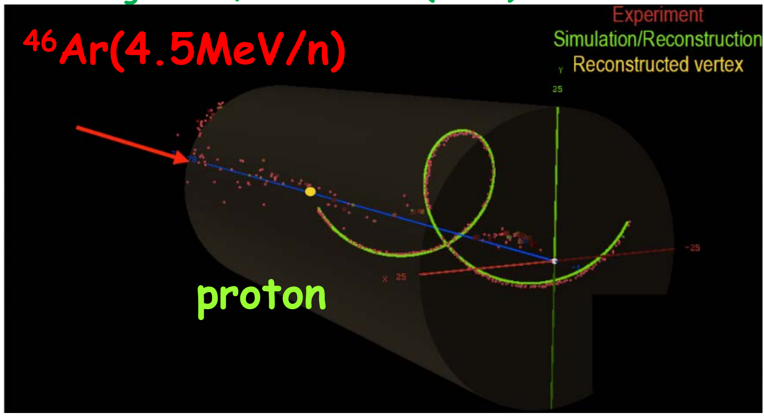
AT-TPC





Position-sensitive endcap detector µ-megas+THGEM

W. Mittig et al., NIMA 784 (2015) 498



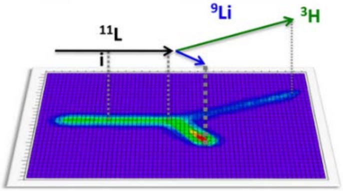
GET electronics: >10'000 channels

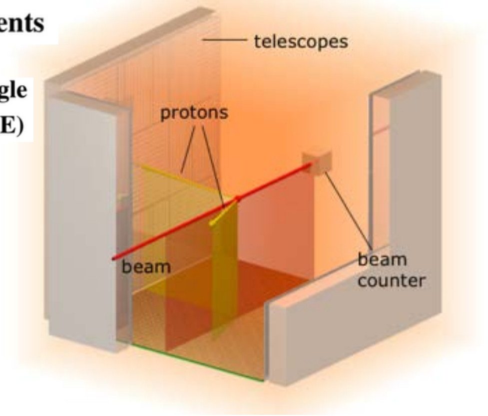
ACTAR

µ-megas+THGEM

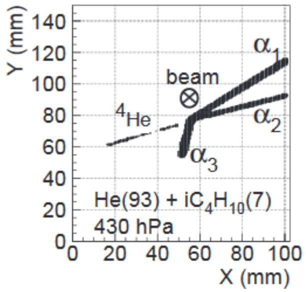
reaction *and* decay experiments

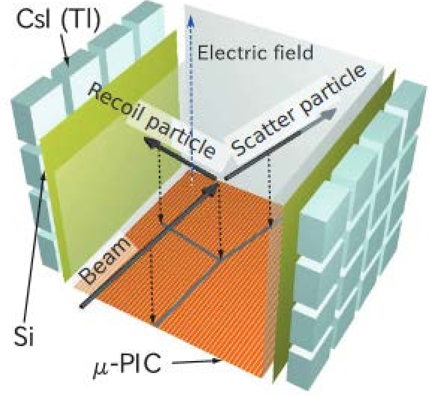
Cubic for reactions to increase solid angle
Cuboid for high-energy beams (i.e. LISE)





MAIKo





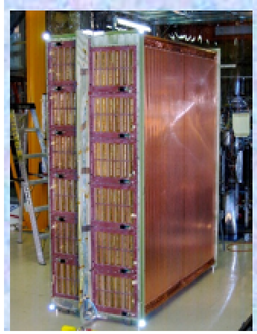
Ancillary Si-CsI(Tl) detectors used to generate trigger

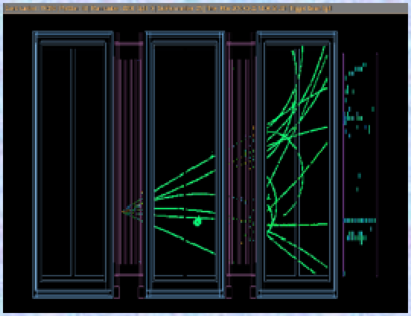
T. Furuno et al., J. of Phys. 569 (2014) 012042

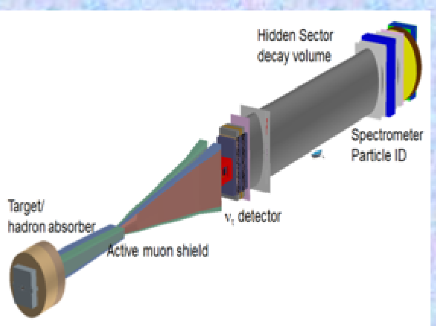
MPGD: Neutrino Physics

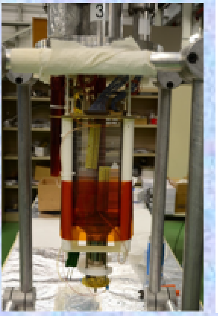
from M. Titov MPGD2017

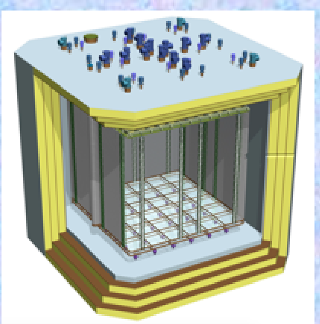
Experiment / Timescale	Application Domain	MPGD Technology	Total detector size / Single module size	Operation Characteristics / Performance	Special Requirements / Remarks
T2K @ Japan Start: 2009 - now	Neutrino physics (Tracking)	TPC w/ Micromegas	Total area: ~ 9 m² Single unit detect: 0.36x0.34m²~0.1m²	**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	Neutrino physics (Tracking+ Calorimetry)	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	WA105 3x1x1 and 6x6x6: **Max. rate:** 150 Hz/m² **Spatial res.:** 1 mm **Time res.:** ~ 10 ns **Rad. Hard.:** no	Detector is above ground (max. rate is determined by muon flux for calibration)
DUNE Dual Phase Far Detector Start: > 2023?		LAr TPC w/ THGEM double phase readout	Total area: 720 m² Single unit detect. (0.5x0.5 m2) ~ 0.25 m²	**Max. rate:** 4*10⁻⁷ Hz/m² **Spatial res.:** 1 mm **Rad. Hard.:** no	Detector is underground (rate is neutrino flux)







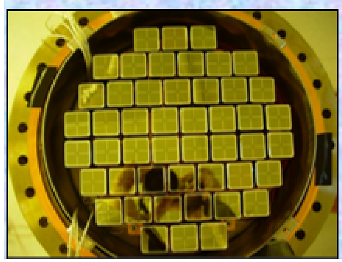


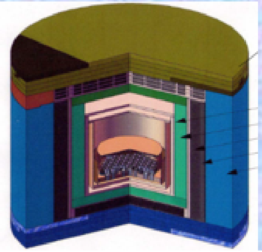


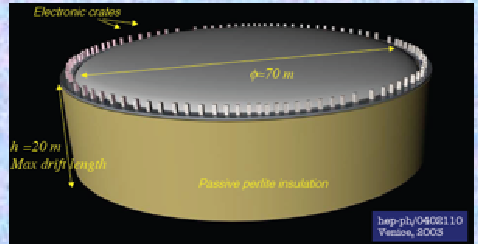
MPDG: Rare Event search

from M. Titov MPGD2017

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



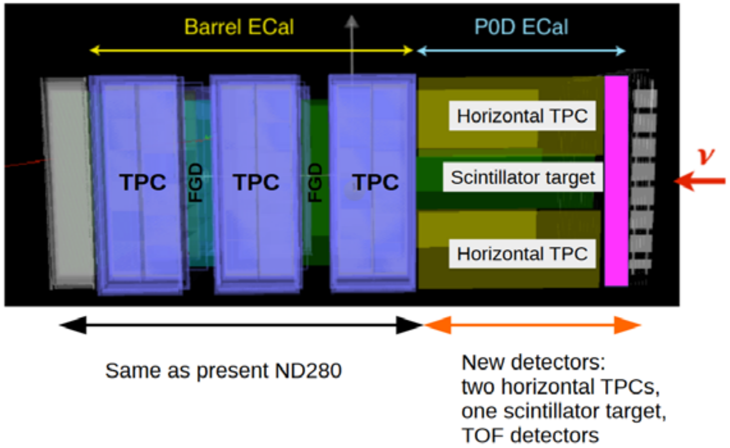


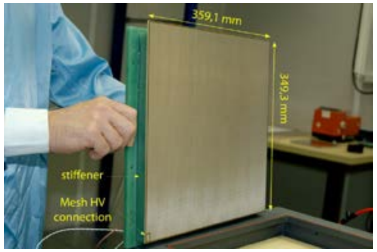


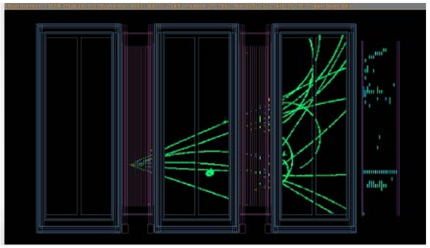
MPGD: Neutrino Physics & Neutrino-less DBD

T2K Neutrino Oscillations: <u>**FIRST**</u> and the <u>**LARGEST**</u> TPCs equipped with MM

~9 m^2 with 72 bulk MM (120k ch.) operated since 2009







T2K-II phase and TPC-based ND upgrade:

- T2K aims to continue data-taking from 2021 to 2025
- 400 new appearance events at the far detector
- Needs to reduce the systematic uncertainties to 3-4%
- Upgrade of the near detector to be installed in 2020

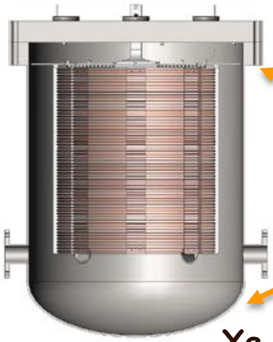
PANDAX-III: Xenon high pressure gaseous TPC for neutrino-less double-beta searches

Approach:

- ❑ high pressure gaseous Xe 136 TPC
- ❑ direct ionization read-out
- ❑ g-background rejection with event topology

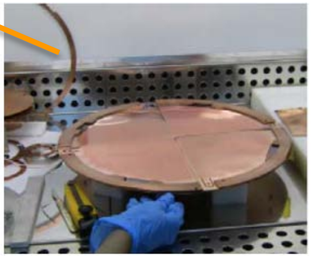
Important challenges

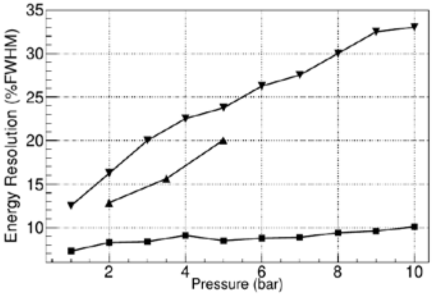
- ❑ Energy resolution <3% FWHM, up to 1%
- ❑ radiopurity < 10^{-3} c/keV/kg/year



TPC mBulk-MM prototype

Up to 50kg 10bar Xenon gas mixture





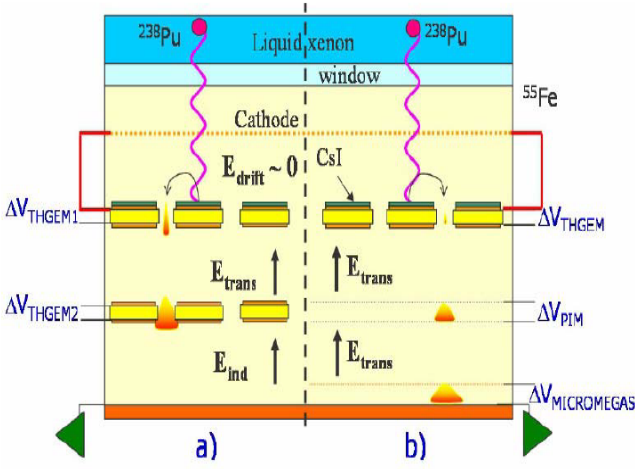
Xe + TMA → ~ 10% FWHM → extrapolated to 1% @ 2.5 MeV

THE CRYOGENIC FRONTIER

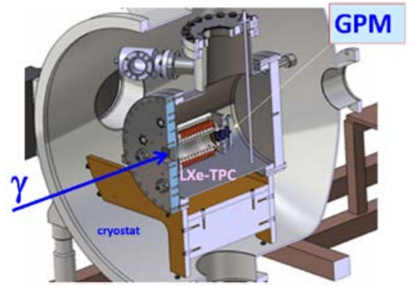
Read-out elements of cryogenic noble liquid detectors

- Rear event detectors (n, DM) & Medical Physics (PET)
- Detecting the scintillation light produced in the noble liquids
- Options of scintillator light and ionization charge detection by a same detector!

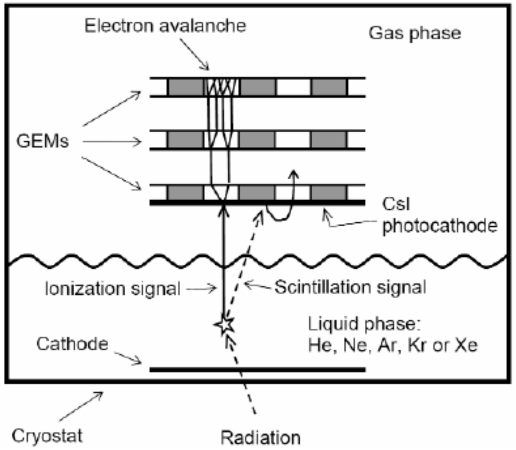
with windows



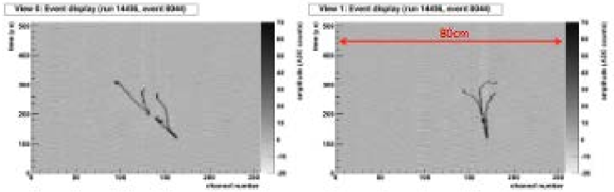
S.Duval et al., JINST 6 (2011) P04007



Windowless (2-phases)

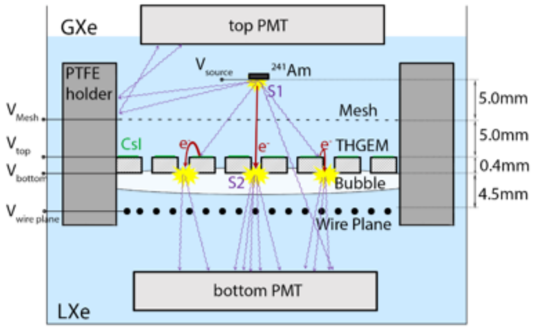


A. Bondar et al., NIMA 556 (2006) 273
B. & Rubbia group ETHz - LArTPC

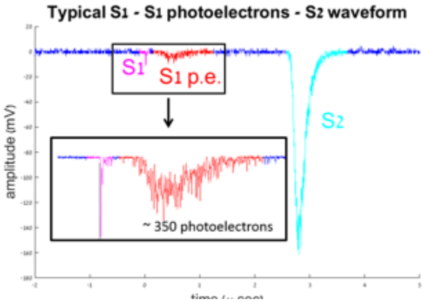


Operated in Cryogenic Liquid

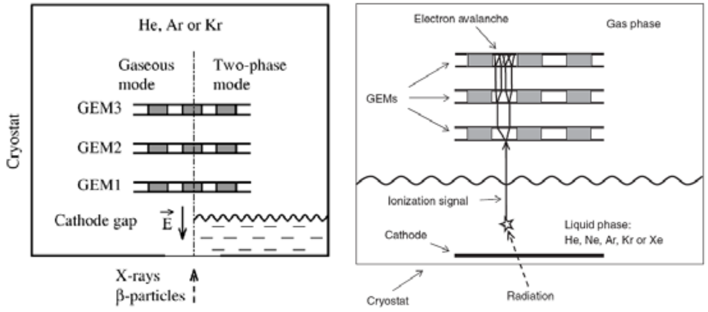
Bubble-assisted Liquid Hole-Multipliers



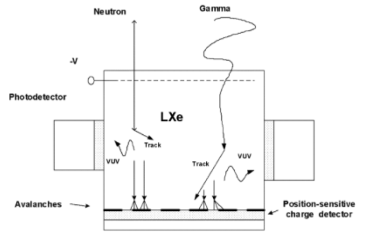
Erdal et al. arXiv:1509.02354



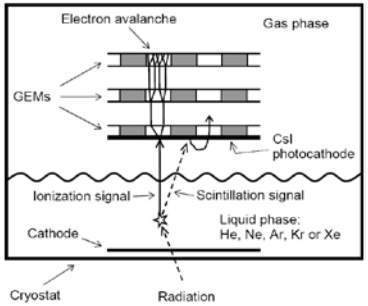
MPGD: cryogenic R&D (Concept Gallery)



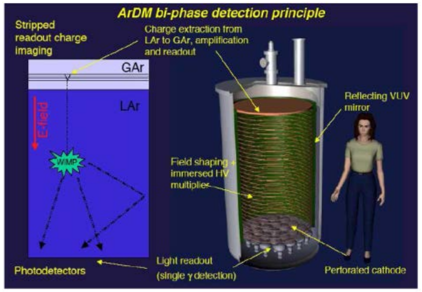
A.Buzulutskov et al, IEEE TNS 50 (2003) 2491; A.Bondar et al, NIMA 524 (2004) 130



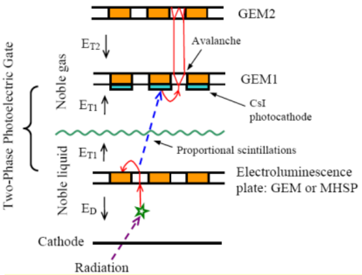
Periale et al, IEEE TNS 52 (2005) 927



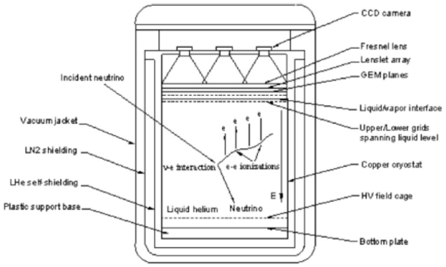
A.Bondar et al, NIMA 556 (2006) 273



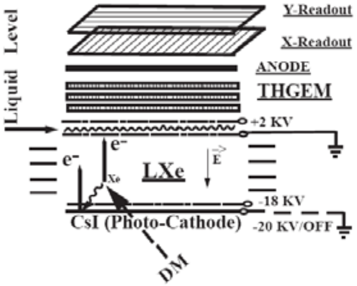
A.Rubbia, J. Phys. Conf. Ser. 39 (2006) 129



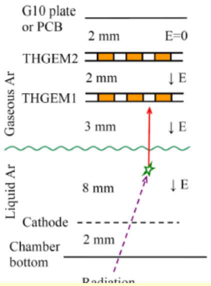
A.Buzulutskov, A.Bondar, JINST 1 (2006) P08006



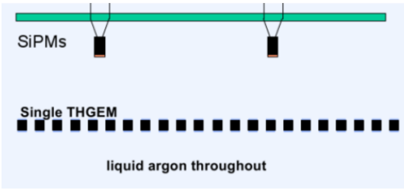
Y.L.Ju et al, Cryogenics 47 (2007) 81



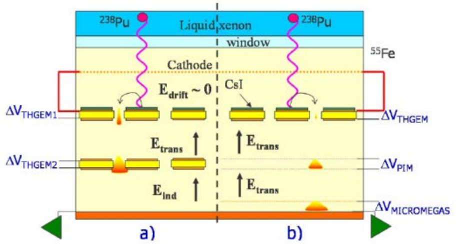
M.Gai et al, Eprint arxiv:0706.1106 (2007)



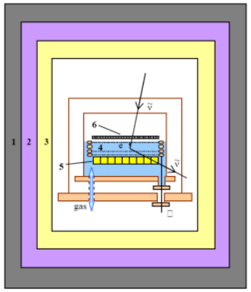
A.Bondar et al, JINST 3 (2008) P07001



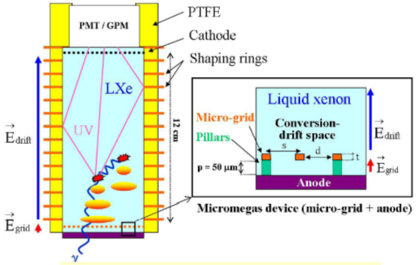
Lightfoot et al, JINST 4 (2009) P04002



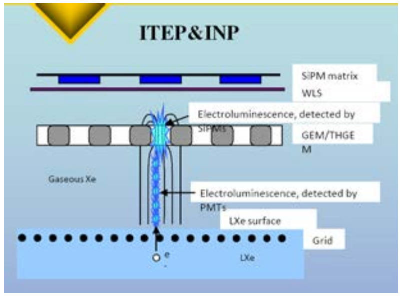
S. Duval et al, JINST 6 (2011) P04007



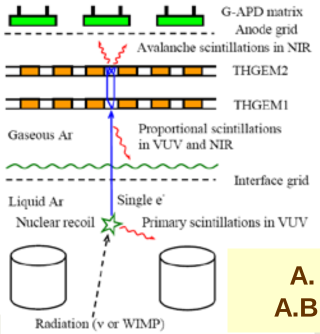
D.Akimov et al, JINST 4 (2009) P06010



S. Duval et al, JINST 4 (2009) P12008



D.Akimov, NIMA 628 (2011) 50



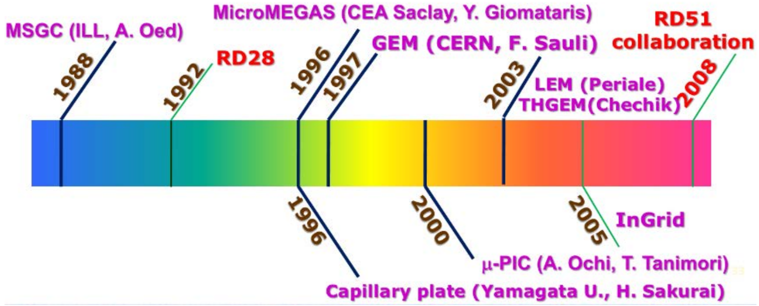
A. Bondar et al, JINST 5 (2010) P08002
A.Buzulutskov et al, EPL 94 (2011) 52001

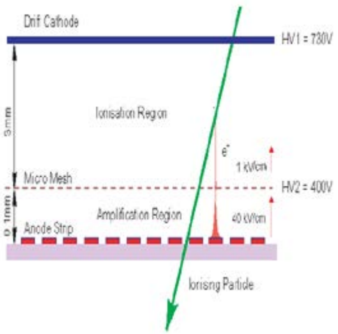
National Science Foundation
Michigan State University

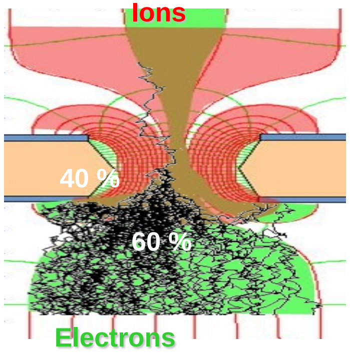
MICHIGAN STATE UNIVERSITY

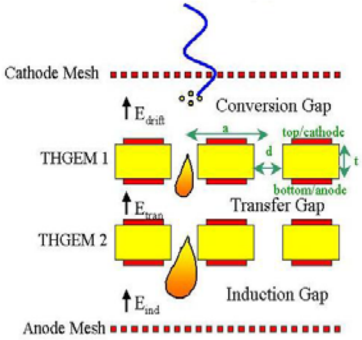
MPGD Performance Summary

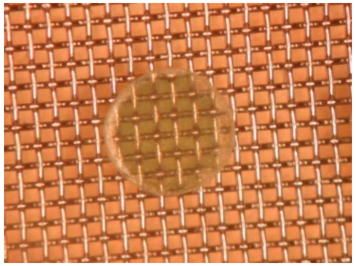
- High Rate Capability
- High Gain
- High Space Resolution
- Good Time Resolution
- Good Energy Resolution
- Excellent Radiation Hardness
- Reduced Ion Back-flow
- Reduced Photon-feedback

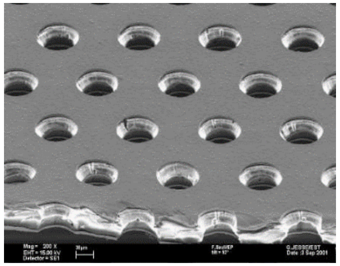


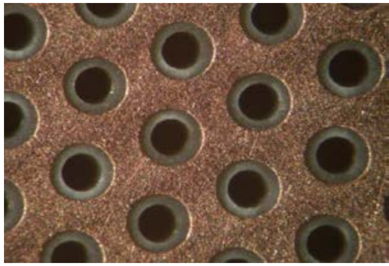


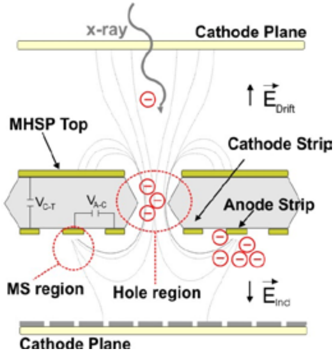


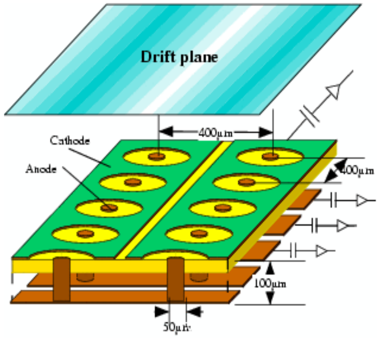


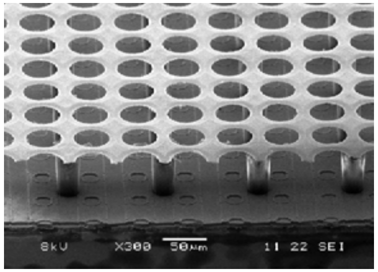












Gain Limit: Discharges

What are the causes of breakdowns?

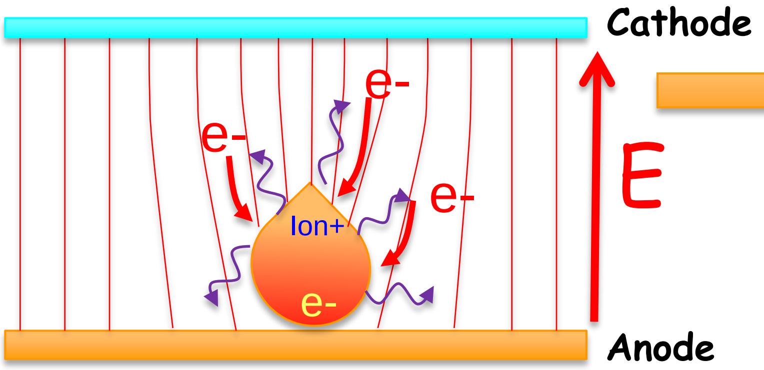
I) In bad quality detectors – imperfections

II) Highly Ionizing Background

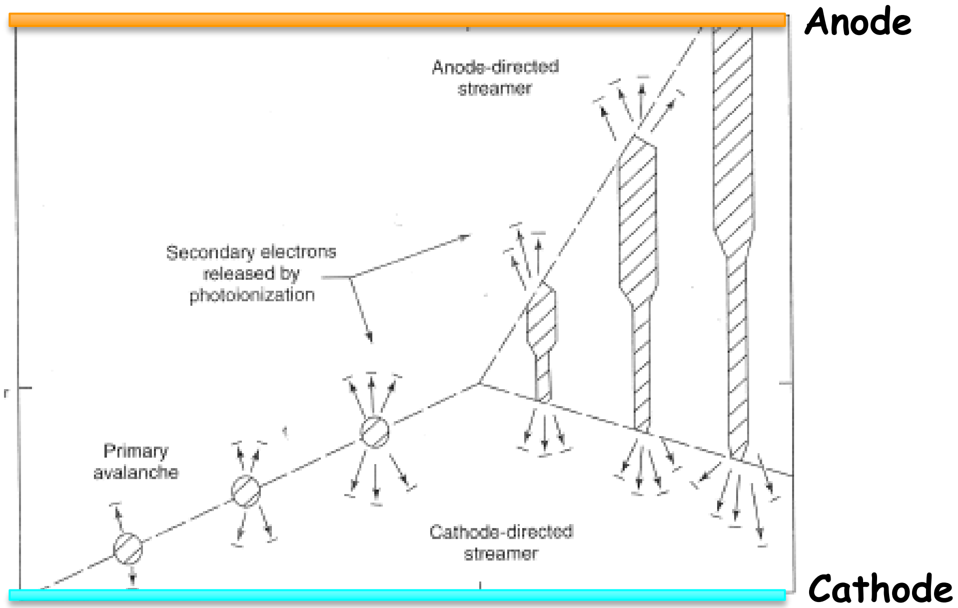
III) In good quality detectors - there are **several fundamental reasons**
- -) Reather Limit
- -) High Counting Rate effects
- -) Photons/Ions Feedback
- -) Cathode Excitation Effect and Jet Emissions
- -) Surface Streamer

Reather Limit

Photon-mediated local feedback in a strong space-charge field



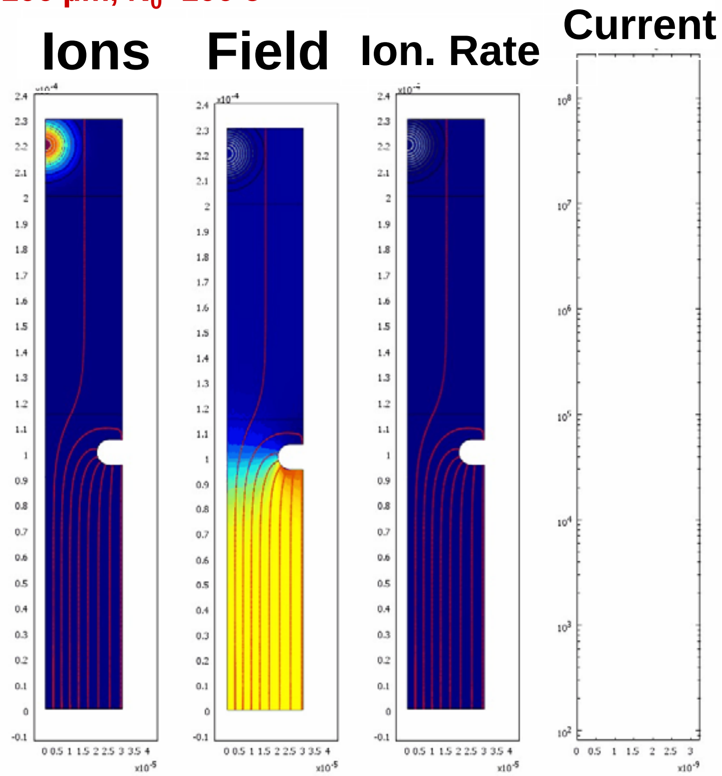
Gain × Primaries = $Q_{max} < 10^8$



Kline and Siambis J. Phys. Rev. A5 794

Simulation of Steamers in Micromegas

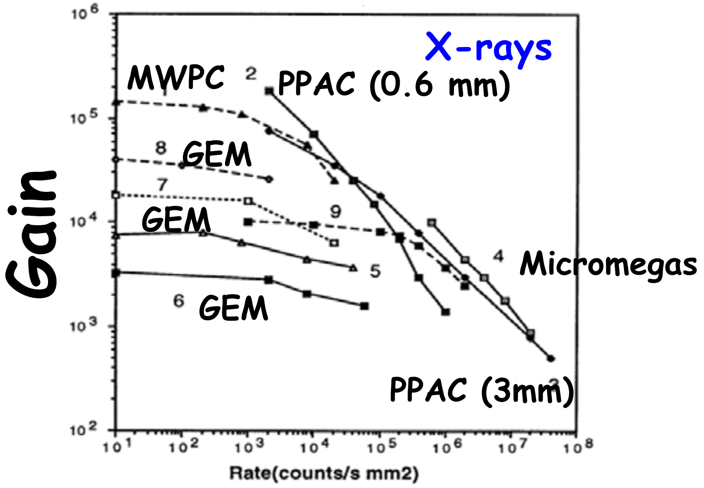
gap: 100 μm, N_0=100 e^-



Fonte, MPGD workshop 2010 Freiburg (Germany)

Gain Limit at High Counting Rate

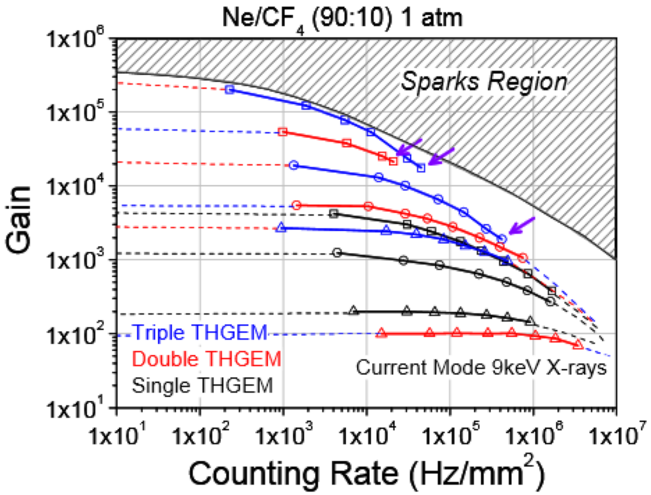
Ivaniouchenkov et al., IEEE Trans. Nucl. Sci. 45 (1998) 258



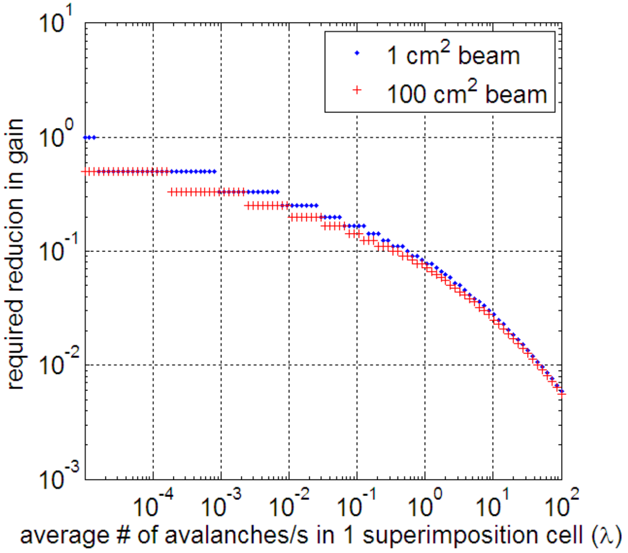
Breakdown statistics via superimposition & Raether limit ➔ slow ions left in the avalanche volume

Fonte et al. RD51 Meeting 2008, Paris (France)

Peskov et al., 2010 JINST 5 P11004

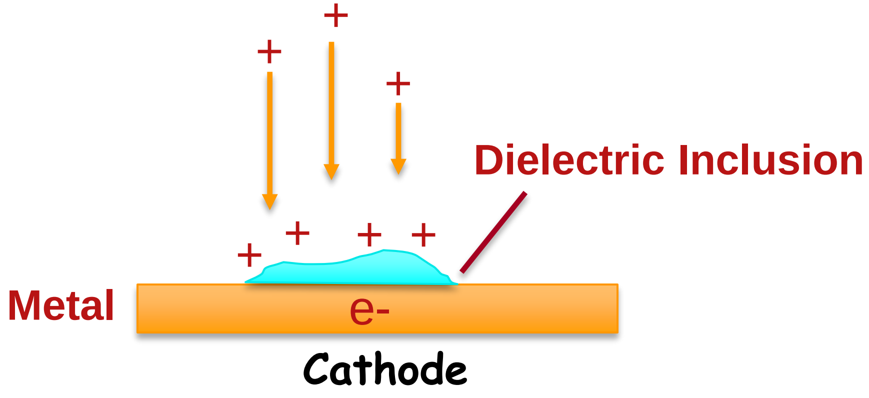


Mere statistics seems to qualitatively reproduced the experimental data

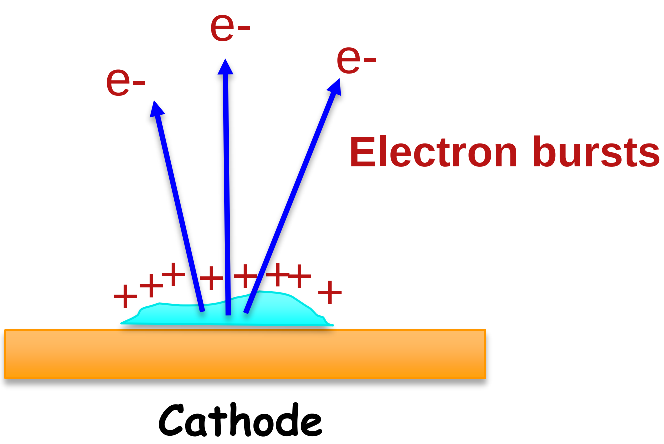


Gain Limit: Cathode excitation Effect & Electron Jet Emission

a) Cathode excitation



b) Jet Emission



Fonte et al. IEEE Nuc. Sci 46 (1999) 321

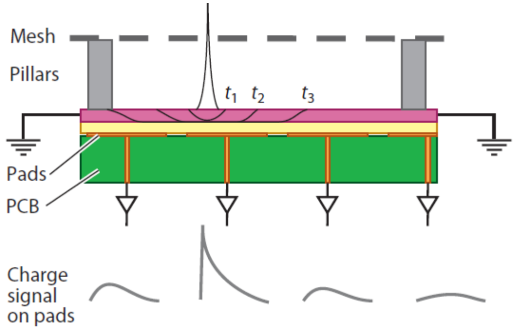
Strong localized electric field established by positive charges accumulated on the surface of a thin insulating layer.

Electrons migrate from the cathode towards the surface of the insulating layer (tunneling effect)

Explosive emission of electrons (Jet) from the film

Resistive MPGD

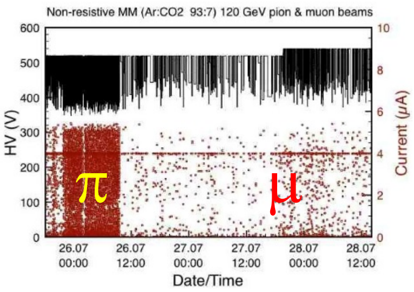
Micromegas: Resistive Anodes

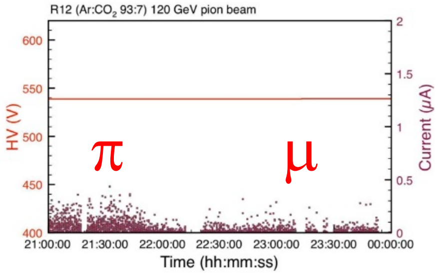


Traditional Micromegas

beam: π, μ
120 GeV/c

Resistive Micromegas



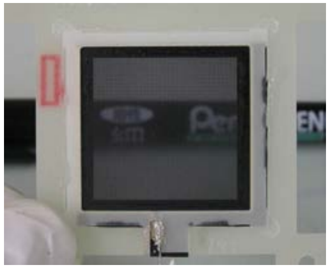


Wotschack CERN Det. seminar, 18/11/2011

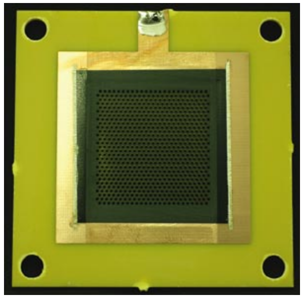
Resistive Hole-Type Multiplier

Olivera et al.
NIMA 576 (2007) 362

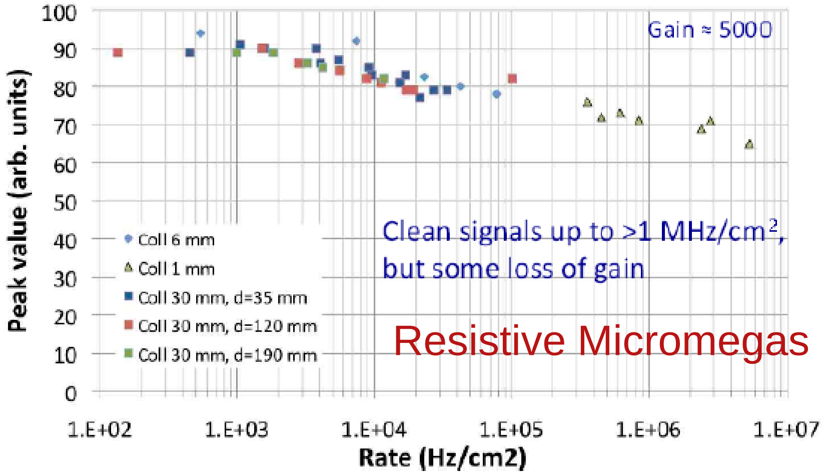
Di Mauro, et al.
NIMA 581 (2007) 225



Re-GEM: electrodes by resistive kapton



Re-THGEM: resistive electrode



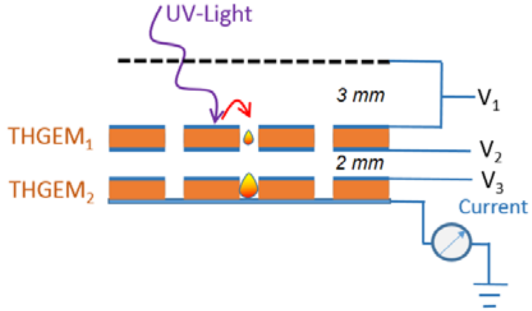
Clean signals up to >1 MHz/cm^2, but some loss of gain

Resistive Micromegas

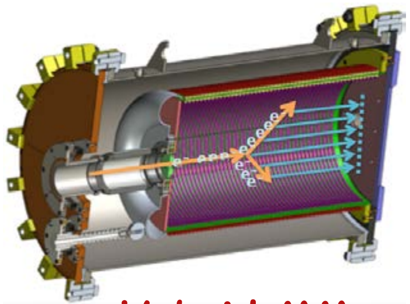
Bianco et al.RD51 Meeting 2014 CERN

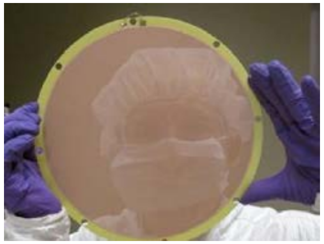
Operation of THGEM in low-pressure, “pure” elemental Gas

THGEM geometry:
-) Thickness = 0.6 mm
-) Hole Ø = 0.5 mm
-) Hole Pitch = 1 mm

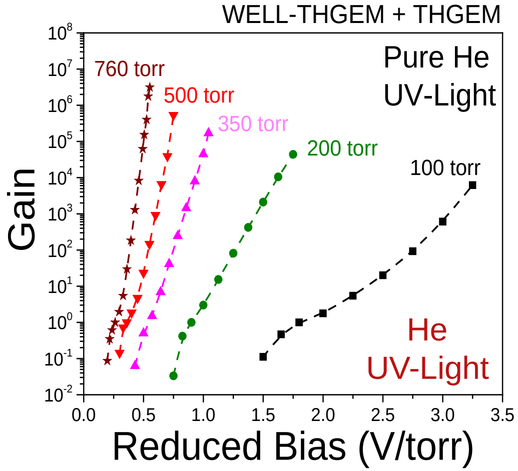


pAT-TPC (NSCL)

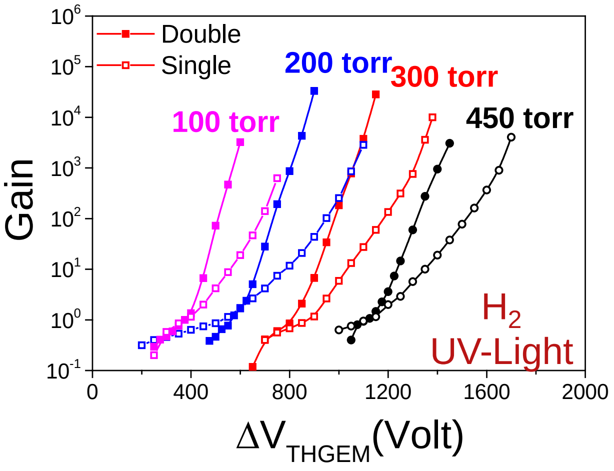




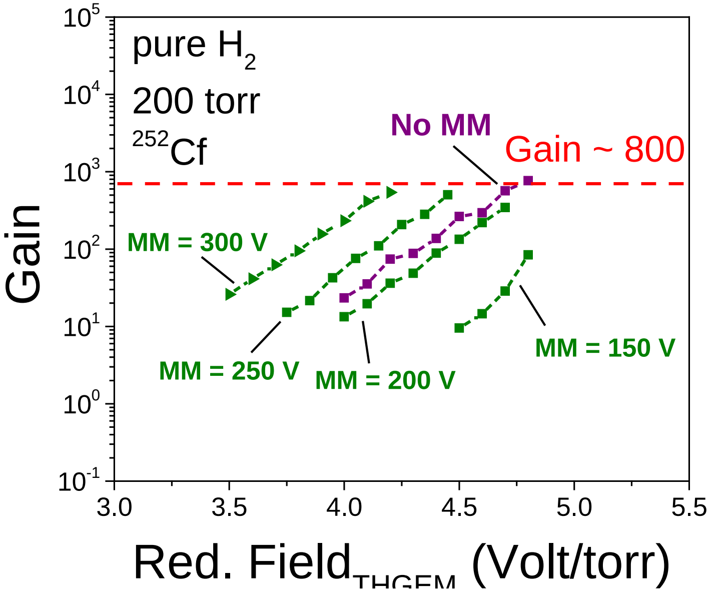
Cortesi et al., 2015 JINST P02012



Cortesi et al., 2015 JINST P09020



Hybrid MM + double THGEM



Cortesi et al., arXiv:1512.07102

Large maximum achievable gain at low pressure due to:

1) Extended avalanche volume (larger than the e^- mean free path)
   ➔ high e^- multiplication
2) Avalanche confinement within the hole
   ➔ Lesser photon-mediated secondary effects

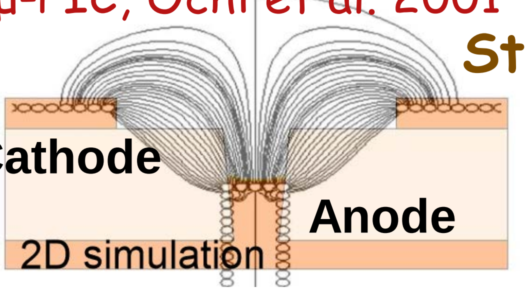
Pin/Dot Type Avalanche Structures

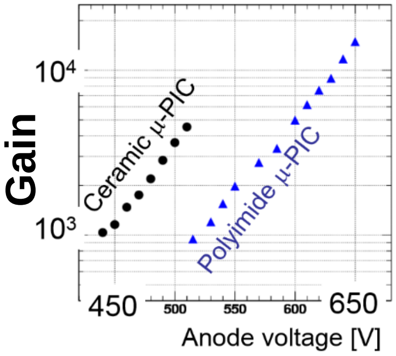
Alternative Structures,
various successful applications
But:

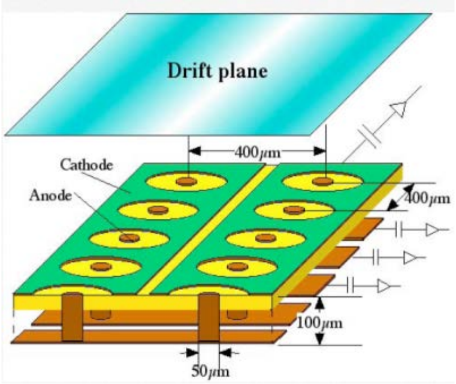
- Small area & expensive
- Single-stage ➔ low gain

μ-PIC; Ochi et al. 2001

Standard PCB

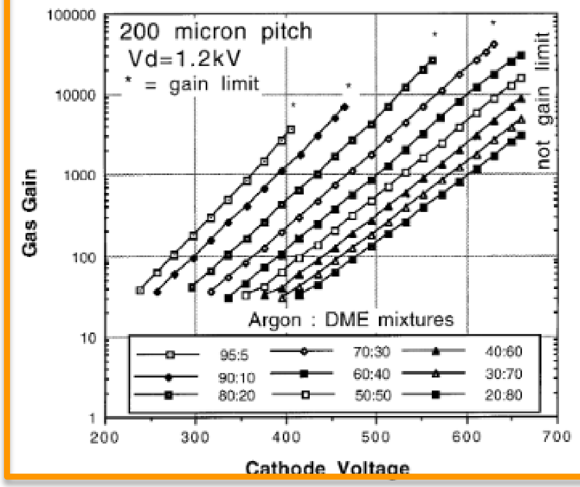


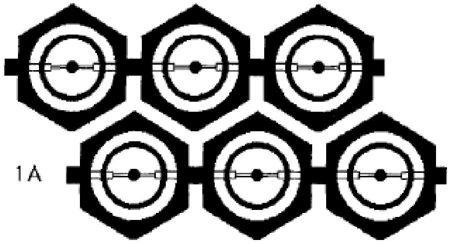




MicroDot Biagi et al. et al. 1995

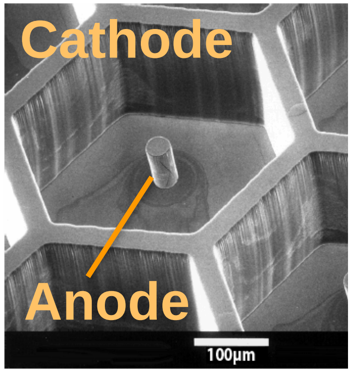
MOS Technology

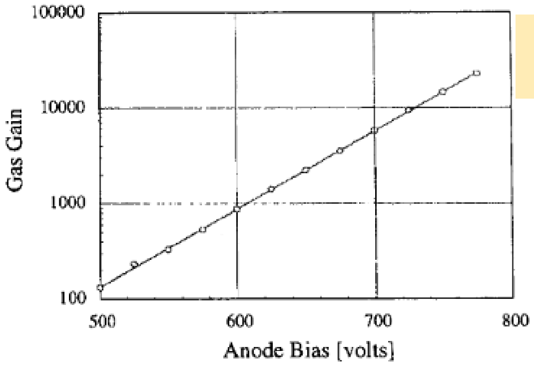




MIcro Pin Array (MIPA), Rehak et al. 1999

MOS Technology





>10^4