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
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
Multi-Wire Proportional Chamber - MWPC

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

Properties:
- Flexible geometry and large area (~m²)
- Many well developed position encoding methods
- Works in magnetic field
- Rate capability ≈ 10⁴ Hz/mm²
- Electron avalanche multiplication (Gain) ≈ 10⁴-10⁵
- Position resolution → down to 100 μm for 1 mm wire spacing (limited in size)

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

Cathode

Anode

primary electron
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


Wire spacing → 1-2 mm

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

Anode spacing → 200 μm
MSGC: Performances and Limits

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

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

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


Anode

Cathode

Cathode

polyimide

EDGE PASSIVATION

MICRODISCHARGES

BREAKDOWN

AGING

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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

GAS ELECTRON MULTIPLIER
Sauli
NIMA 386 (1907) 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
Micro-Pattern Gas Detectors

GEM : Gas Electron Multiplier

Sauli (1997)

High Spatial Resolution (≈40 μm)

Giomataris (1996)

Counts

Iguaz et al. 2009 J. Phys. 179

55Fe X-ray (5.9 keV)

11.2% (FWHM)

μ-megas

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

- Effective single-electron detection
- High gas gain \( \sim 10^5 \) (>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: 1 mbar - few bar

Introduced in // by different groups:
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

- $\text{H}_2$ (alternatively $\text{iC}_4\text{H}_{10}$) as proton target
  - 1 neutron pickup ($p,d$)
  - 2 neutron pickup ($p,t$)
  - p-scattering
- $\text{D}_2$ as deuteron target
  - 1 neutron transfer ($d,p$)
  - 1 proton pickup ($d,^3\text{He}$)
  - Inelastic scattering ($d,d'$)
- $^3\text{He}$
  - 1 proton transfer ($^3\text{He},d$)
- $^4\text{He}$ as alpha target
  - Inelastic scattering ($^4\text{He},^4\text{He'}$),
  - Isoscalar Giant Resonances excitations …
  - Alpha-induced reactions for astrophysical p-process

- Purity (no quencher) $\Rightarrow$ High Reaction Yield
- Low-Pressure Operation $\Rightarrow$ Large Dynamic Range

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

Miyamoto et al. 2010 JINST 5 P05008
Multi-layer THGEM (M-THGEM)
Manufactured by multi-layer PCB techniques out of FR4/G-10/ceramic substrate

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

2-Layer M-THGEM

3-Layer M-THGEM

Cortesi et al., arXiv:1606.07314

Single 2-layer M-THGEM

Gain vs. Reduced Bias (V/torr)

Pure He
UV-Light

600 torr
450 torr
300 torr
150 torr

760 torr
450 torr
300 torr
150 torr
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

Hybrid MM + M-THGEM

Energy (MeV)

FWHM_{MM} = 4.5%
FWHM = 5%

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Complex geometries needed with extra electrodes to trap the ions:

**MHSP**


**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

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

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

~ 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)

Costa et al. Nature 441 (2001) 662

Colas, RD51 Meet. 2009 kolimpary (Greece)
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.

<table>
<thead>
<tr>
<th>Name (Lab)</th>
<th>MPGD Technology</th>
<th>Volume Area</th>
<th>Pressure (atm)</th>
<th>Operation Performance</th>
<th>Status</th>
</tr>
</thead>
<tbody>
<tr>
<td>ACTAR (GANIL)</td>
<td>μ-megas</td>
<td>8000 cm³</td>
<td>0.01-3</td>
<td>Counting rate &lt; $10^4$ nuclei but higher if some beam masks are used</td>
<td>Under Construction</td>
</tr>
<tr>
<td>MAIKo (RNCP)</td>
<td>μ-PIC</td>
<td>2750 cm³</td>
<td>0.4-1</td>
<td>FADC electronics 2*256 channels</td>
<td>Test</td>
</tr>
<tr>
<td>PANDA (FAIR)</td>
<td>μ-megas/GEM</td>
<td>22500 cm²</td>
<td>1</td>
<td>Continuous-wave operation: $10^{11}$ interaction/s</td>
<td>Under Construction</td>
</tr>
<tr>
<td>CAT (CNS)</td>
<td>GEM</td>
<td>2000 cm³</td>
<td>0.2-1</td>
<td>FADC electronics 400 channels</td>
<td>Test</td>
</tr>
<tr>
<td>pAT-TPC (NSCL)</td>
<td>μ-megas (+THGEM)</td>
<td>2000 cm³</td>
<td>0.01-1</td>
<td>GET electronics 256 channels</td>
<td>Operational</td>
</tr>
<tr>
<td>AT-TPC (NSCL)</td>
<td>μ-megas (+THGEM)</td>
<td>8000 cm³</td>
<td>0.01-1</td>
<td>GET electronics &gt;10'000 channels</td>
<td>Operational</td>
</tr>
<tr>
<td>TACTIC (CNS)</td>
<td>GEM</td>
<td>8000 cm³</td>
<td>0.25-1</td>
<td>Low beam energy (&lt;2 MeV/u)</td>
<td>Test</td>
</tr>
<tr>
<td>MINOS (CNS)</td>
<td>μ-megas</td>
<td>6000 cm³</td>
<td>1</td>
<td># of Channel= 600</td>
<td>Operational</td>
</tr>
<tr>
<td>SuperFRS (FAIR)</td>
<td>GEM</td>
<td>Few m²</td>
<td>1</td>
<td>High dynamic range Particle detection from p to Uranium</td>
<td>Under Construction</td>
</tr>
</tbody>
</table>

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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

**ACTAR**

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

- Telescopes
- Protons
- Beam counter

**MAIKo**

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

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**46Ar(4.5MeV/n)**

- Proton
- GET electronics: >10'000 channels

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

**T. Furuno et al., J. of Phys. 569 (2014) 012042**
# MPGD: Neutrino Physics

from M. Titov MPGD2017

<table>
<thead>
<tr>
<th>Experiment / Timescale</th>
<th>Application Domain</th>
<th>MPGD Technology</th>
<th>Total detector size / Single module size</th>
<th>Operation Characteristics / Performance</th>
<th>Special Requirements / Remarks</th>
</tr>
</thead>
</table>
| T2K @ Japan            | Neutrino physics (Tracking) | TPC w/ Micromegas | Total area: ~ 9 m²  
Single unit detect: 0.36x0.34 m² - 0.1m² | Spatial res.: 0.6 mm  
Max. rate: < low  
Rad. Hard.: no  
Moment. res.: 9% at 1 GeV | The first large TPC using MPGD |
| SHiP @ CERN            | Tau Neutrino Physics (Tracking) | Micromegas, GEM, mRWEFL | Total area: ~ 26 m²  
Single unit detect: 2 x 1 m² - 2m² | Max. rate: < 150 μm  
Spatial res.: no  
Rad. Hard.: no | Provide time stamp of the neutrino interaction in brick |
| LBN-DEMO (WA105 @ CERN): | 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  
Max. rate: 4x10⁻⁷ Hz/m²  
Spatial res.: 1 mm  
Rad. Hard.: no | Detector is above ground (max. rate is determined by muon flux for calibration) |
| DUNE Dual Phase Far Detector | Neutrino physics (Tracking-Calorimetry) | LAr TPC w/ THGEM double phase readout | Total area: 720 m²  
Single unit detect. (0.5x0.5 m²) ~ 0.25 m² | Max. rate: 4x10⁻⁷ Hz/m²  
Spatial res.: 1 mm  
Rad. Hard.: no | Detector is underground (rate is neutrino flux) |
## MPDG: Rare Event search

**from M. Titov MPGD2017**

<table>
<thead>
<tr>
<th>Experiment / Timescale</th>
<th>Application Domain</th>
<th>MPGD Technology</th>
<th>Total detector size / Single module size</th>
<th>Operation Characteristics / Performance</th>
<th>Special Requirements / Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>DARWIN (multi-ton dual-phase LXe TPC)</td>
<td>Dark Matter Detection</td>
<td>THGEM-based GPMT</td>
<td>Total area: ~30m² Single unit detect. ~20 x 20 cm²</td>
<td>Max. rate: 100 Hz/cm² Spatial res.: ~1 cm Time res.: ~few ns Rad. Hard.: no</td>
<td>Operation at ~180K, radiopure materials, dark count rate ~1 Hz/cm²</td>
</tr>
<tr>
<td>PANDAX III @ China</td>
<td>Astroparticle physics Neutrinoless double beta decay</td>
<td>TPC w/ Micromegas µbulk</td>
<td>Total area: 1.5 m² Energy Res.: ~1-3% @ 2 MeV Spatial res.: ~1 mm</td>
<td>High radiopurity High-pressure (10b Xe)</td>
<td></td>
</tr>
<tr>
<td>NEWAGE® Kamioka</td>
<td>Dark Matter Detection</td>
<td>TPC w/ GEM-µPIC</td>
<td>Single unit det. ~30x30x41 (cm³) Angular resolution: 40° @ 50keV</td>
<td></td>
<td></td>
</tr>
<tr>
<td>CAST @ CERN:</td>
<td>AstroParticle Physics: Axions, Dark Energy/Matter, Chameleons detection</td>
<td>Micromegas µbulk and InGrid (coupled to X-ray focusing device)</td>
<td>Total area: 3 MM µbulks of 7x7 cm² Total area: 1 InGrid of 2 cm² Spatial res.: ~100µm Energy Res: 14% (FWHM) @ 6 keV Low bkg. levels (2-7 keV): µMM: 10-6 cts s-1 keV-1 cm-2 InGrid: 10-5 cts s-1 keV-1 cm-2</td>
<td>High radiopurity, good separation of tracklike bkg. from X-rays</td>
<td></td>
</tr>
<tr>
<td>IAXO</td>
<td>AstroParticle Physics: Axions, Dark Energy/Matter, Chameleons detection</td>
<td>Micromegas µbulk, CCD, InGrid (+ X-ray focusing device)</td>
<td>Total area: 8 µbulks of 7 x 7 cm² Energy Res: 12% (FWHM) @ 6 keV Low bkg. Levels (1-7 keV): µbulk: 10-7 cts s-1 keV-1 cm-2</td>
<td>High radiopurity, good separation of tracklike bkg. from X-rays</td>
<td></td>
</tr>
</tbody>
</table>

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### T2K Neutrino Oscillations: **FIRST** and the **LARGEST** TPCs equipped with MM

- \( \sim 9 \text{ m}^2 \) 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
- \( \text{Xe} + \text{TMA} \rightarrow \sim 10\% \text{ FWHM} \rightarrow \text{extrapolated to 1\% @ 2.5 MeV} \)
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

Windowless (2-phases)

Operated in Cryogenic Liquid

Bubble-assisted Liquid Hole-Multipliers

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

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

Erdal et al. arXiv:1509.02354
MPGD: cryogenic R&D (Concept Gallery)


- A. Buzulutskov, A. Bondar, JINST 1 (2006) P08006
- Y. L. Ju et al, Cryogenics 47 (2007) 81


- D. Akimov, NIMA 628 (2011) 50
- A. Buzulutskov et al, EPL 94 (2011) 52001
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

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

$\text{Gain} \times \text{Primaries} = Q_{\text{max}} < 10^8$

Simulation of Steamers in Micromegas

gap: 100 $\mu$m, $N_0=100$ e$^-$

Kline and Siambis J. Phys. Rev. A5 794

Fonte, MPGD workshop 2010 Freiburg (Germany)
Gain Limit at High Counting Rate


Breakdown statistics via superimposition & Raether limit $\Rightarrow$ slow ions left in the avalanche volume

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

Mere statistics seems to qualitatively reproduced the experimental data

Peskov et al., 2010 JINST 5 P11004

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Gain Limit: Cathode excitation Effect & Electron Jet Emission

a) Cathode excitation

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)

b) Jet Emission

Explosive emission of electrons (Jet) from the film

Resistive MPGD

Micromegas: Resistive Anodes

Traditional Micromegas  Resistive Micromegas

beam: $\pi$, $\mu$
120 GeV/c

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

Bianco et al. RD51 Meeting 2014 CERN

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

Gain = 5000

peak value (arb. units)

Rate (Hz/cm$^2$)

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NSCL

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

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

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

Cortesi et al., 2015 JINST P02012
Cortesi et al., 2015 JINST P09020
Cortesi et al., arXiv:1512.07102

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

Cortesi et al., 2015 JINST P02012
Cortesi et al., 2015 JINST P09020
Cortesi et al., arXiv:1512.07102
Pin/Dot Type Avalanche Structures

Alternative Structures, various successful applications
But:
- Small area & expensive
- Single-stage → low gain

μ-PIC; Ochi et al. 2001

2D simulation

Cathode
Anode

Standard PCB

MicroDot Biagi et al. et al. 1995
MOS Technology

Gain

10^4

450 600 850 650
Anode voltage [V]

Drift plane

Cathode
Anode

MIP A, Rehak et al. 1999
MOS Technology

>10^4

Cathode
Anode

MOS Technology

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