Micropattern Gas Detectors

Recent Developments and Perspectives

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Outline

- Introduction – MSGCs and its descendants
- Tracking in Particle Physics with MPGDs
- Readout of TPCs with MPGDs
- Photon Detection with MPGDs
- Neutron Detection with MPGDs
- Conclusions
Microstrip Gas Chamber

**MSGC** [A. Oed, NIM A263, 351 (1988)]

- Pattern of thin anode and cathode strips on high-resistivity substrate
- Higher spatial resolution
- Higher rate capability than MWPCs

**HERA-B**

Drift plane

Cathode (136 μm)

Anode (10 μm)

3 mm

250 μm

300 μm glass substrate (DESAG D263)

**CMS prototype**

geometry and typical dimensions (former CMS standard)

Gold strips + Cr underlayer

Glass DESAG AF45 + S8900 semiconducting glass coating, $p=10^{16} \, \Omega/\square$
MSGC Electric Field

\[ U_B \sim U_C \]

\[ U_B \sim U_A \]
**Photolithography**

**Direct etching**
- Metallization (Ni/Cr-Al)
- UV-sens. varnish
- Positive mask
- Exposure
- Development
- Chem. removal of exposed areas
- Removal of metal
  - wet etching
  - plasma etching
- Removal of varnish
- Cleaning

**Lift-off**
- Metallization (only adhesion layer)
- UV-sens. varnish
- negative mask
- Exposure
- Chem. removal of exposed areas
- Deposition of desired metal
- Removal of polym. varnish
- Removal of adhesion layer (short etching)
MSGC Defects

- Damaged or cut strips due to gas discharges when exposed to highly ionizing radiation
- Polymer deposits after long-time operation
- Cathode edges damaged due to micro discharges
Breakdown of gas rigidity when avalanche size
> $10^7 - 10^8$ electron/ion pairs (Raether limit)
- Due to manufacturing defects ➔ Quality control / assurance
- Due to heavily ionizing particles

Second generation MPGDs:
- Prevent discharges ➔ Optimize design
  - Field configuration
  - Gas mixture / purity
  - Separation of amplification / readout stage
  - Multi-stage amplification
- Minimize impact of discharges on detector operation
  - Reduce dead time after discharge
  - Reduce available energy
  - Protection of front-end electronics
The MPGD Zoo

Microgap Chamber (MGC)  
[F. Angelini et al., NIM A335, 69 (1993)]

Microdot Chamber  
[S.F. Biagi et al., NIM A361, 72 (1995)]

Compteur à Trous (CAT)  
[F. Bartol et al., J. Phys. III 6, 337 (1996)]

Micro Groove Counter  
[Bellazzini et al., NIM A424, 444 (1999)]

Micro Wire Detector  
[B. Adeva et al., NIM A435, 402 (1999)]

WELL Detector (μCAT)  
[R. Bellazzini et al., NIM A423, 125 (1999)]

and many more...

Here:

Micromegas
GEM
MHSP

Micropattern Gas Detectors  
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Gas Electron Multiplier

GEM [F. Sauli, NIM A386, 531 (1997)]

- Thin polyimide foil, typ. 50 µm
- Cu-clad on both sides, typ. 5 µm
- Photolithography: ~ $10^4$ holes/cm²

- $\Delta U = 300-500$ V
  - high E-field inside holes: ~ 50 kV/cm
  - avalanche multiplication
GEM-based Detector

- Standalone amplification stage
- Gain is mainly a property of GEM foil
  - relaxed mechanical tolerances
- Fast electron signal (no slow ion tail)
- Possibility to detect energy signal on lower GEM electrode
  - self-triggering
- Separation of amplification and readout
- High flexibility for readout electrode
Multi-GEM Detector

Possibility to cascade several GEM foils

- **higher gain at lower GEM voltages**
  [S. Bachmann, B. Ketzer et al., NIM A479, 294 (2001)]

- **discharge prevention**

- **no aging up to 7 mC/mm²**
  [C. Altunbas, B. Ketzer et al., NIM A515, 249 (2003)]
Micromegas Detector

Micromesh Gaseous Structure
[I. Giomataris et al., NIM A376, 29 (1996)]

- Thin gap parallel plate structure
- Fine metal grid (Ni) separates conversion (~3 mm) and amplification gap (50-100 µm)
- Very asymmetric field configuration: 1 kV/cm vs. 50 kV/cm

Fast collection of ions (~100 ns)
Saturation of Townsend coefficient (mechanical tolerances)
Good energy resolution
Tracking in HEP

**Vertex Detector:**
- Very high resolution, moderate area
  - Silicon microstrip / pixel detector

**Outer Tracker:**
- Very large area, moderate resolution
  - Drift chambers, MWPC, RPC

**Central Tracker:**
- Spatial resolution 50-100 μm
- Time resolution 10 ns
- Rate capability $10^4$-$10^5$ Hz/mm$^2$
- Fairly large active area
- Small material budget
- Affordable
  
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  MPGD
  
  Micropattern Gas Detectors
  B. Ketzer
The COMPASS Spectrometer

Fixed target experiment at SPS / CERN

Double magnetic spectrometer
- Tracking: VSAT+SAT+LAT
- Particle Id: RICH, $\mu$
- Calorimetry: ECAL, HCAL

Very high particle rates:
- $\mu$ beam: $2 \times 10^8$ / spill
- $h$ beam: $10^8$ / spill
<table>
<thead>
<tr>
<th>Structure</th>
<th>Spectroscopy</th>
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| **Muon beam** | Gluon polarization \( \Delta G/G \)  
Spin distributions \( \Delta q(x), \Delta_T q(x) \)  
Polarization of \( \Lambda \) | Muoproduction of hadrons |
| **Hadron beam** | Polarizability of \( \pi \) and \( K \) | Charmed baryons  
Gluonic systems  
Exotic hadrons |
**COMPASS Micromegas Tracker**

**SAT** in front of first dipole:
- 12 projections (12 detectors)

**Active area**: 40 x 40 cm²

**Gas**: Ne/C₂H₆/CF₄ (80/10/10)

**Drift, Micromesh**: 4 µm thick,
- 200/500 lines/inch

**Gaps**: 3.2 mm / 100 µm

**Beam Killer**: 5 cm diam.

**Anode strips**: 1-D
- Pitch 360 µm (center)
- 420 µm (periphery)

**Thickness** of detector (1 proj.):
- 0.35% X₀

**Readout**: TOT (digital)
- SFE16 ampl/disc. + F1 TDC

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Micromegas Efficiency

- Plateau ($\varepsilon >98\%$) reached for all detectors
- Gain $\sim 6000$
- High intensity: $\langle \varepsilon_{1D} \rangle = 97\%$
- Efficiency loss in central region due to pile-up: $\sim 2\%$

[C. Bernet et al., NIM A536, 61 (2005)]
Micromegas Resolution

**Time resolution**

- **Time:**
  \[ T_{\text{mean}} = 0.6t_{\text{lead}} + 0.4t_{\text{trail}} \]

- **Standard physics run:** 4•10^7 μ+/s:
  \[ \langle \sigma_{T_{\text{mean}}} \rangle \approx 9.3\text{ns} \]

**Spatial resolution**

- **Amplitude:**
  \[ Q(1000e^-) = 6.24e^{(\text{TOT}/134)^2} \]

- **Standard physics run:** 4•10^7 μ+/s:
  \[ \langle \sigma_x \rangle \approx 92\mu\text{m} \]

[C. Bernet et al., NIM A536, 61 (2005)]

Micropattern Gas Detectors  

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**COMPASS Triple GEM Tracker**

- **SAT** behind first dipole: 44 projections (22 detectors)
- **Active area**: 31 x 31 cm²
- **Gas**: Ar/CO₂ (70/30)
- **Discharge prevention**:
  - Triple GEM
  - Asymmetric gain sharing
  - Segmented foils: 13 sectors
- **Beam Killer**: 5 cm diam., activatable
- **Spacer grid of 3 x 3 strips, 400 µm**
- **Anode strips**: 2-D, pitch 400 µm
- **Thickness** of detector (2 proj.):
  - 0.4% X₀
- **Readout**: analog pipeline
  - APV25 + 10-bit ADC

[C. Altunbas, B. Ketzer et al., NIM A490, 177 (2002)]
COMPASS GEM – 2D Readout

- 2 orthogonal sets of 768 parallel strips
- Insulated by 50 µm Kapton
- Pitch 400 µm
- Charge sharing adjusted to ~ 1:1
COMPASS GEM Efficiency

Low intensity beam: $5 \times 10^6 \mu^+$/s
- All detectors reach plateau ($\varepsilon > 98\%$)
- Gain $\sim 8000$
- SNR $\sim 18$
- Losses due to spacer grid: 1.2-1.5%

Standard physics beam: $4 \times 10^7 \mu^+$/s
- Background correction
  \[ \varepsilon_{\text{app}} = \varepsilon + (1 - \varepsilon) \cdot b \]
- Single plane: $\left< \varepsilon_{1D} \right> = 97.2\%$
- 2D (space point): $\left< \varepsilon_{2D} \right> = 95.6\%$
- Rates up to 25 kHz/mm²

[B. Ketzer et al., Nucl. Phys. B 125C, 368 (2003)]
[B. Ketzer et al., NIM A535, 314 (2004)]
COMPASS GEM Resolution

Spatial resolution

- Test beam/low intensity: $\langle \sigma_x \rangle \approx 50 \mu m$
- Standard physics run: $4 \times 10^7 \mu^+ / s$: $\langle \sigma_x \rangle \approx 70 \mu m$

Time resolution

- 3 analog samples per trigger
- Good timing: rising edge of signal
- Reconstruct $t_0$ from known pulse shape $\langle \sigma_t \rangle \approx 12 \text{ns}$

[B. Ketzer et al., NIM A535, 314 (2004)]
The LHCb Experiment

A dedicated B physics experiment at LHC

- Study of CP violation in B-sector:
  - Measurement of $\alpha$, $\beta$, $\gamma$ of CKM matrix
  - Measurement of $\Delta m$, $\Delta \Gamma$
- Rare decays
- Spectroscopy in B-sector

Fixed target detector layout
LHCb Muon Trigger

Goal:
• Trigger on high-$p_T$ muons from B-decays $B \rightarrow \mu X$
• Identify muon tracks offline

Requirements:
• $\delta p_T/p_T \sim 20\%$
• Time resolution <3 ns to identify bunch crossings
• 99% efficiency in 20 ns window

Layout:
• 5 muon stations: M1 in front of calorimeters, M2-5 behind
• M1 (outer regions) & M2-5: MWPC (rate < 100kHz/cm²)
• M1 (inner region): 24 triple GEM detectors (rate ~ 500 kHz/cm²)
  2 chambers digitally OR-ed
LHCb Triple GEM

Goal: Trigger on electron cluster closest to 1st GEM

\[ \sigma(t) = \frac{1}{(n\nu_d)} \]

Gas: Ar/CO\(_2\)/CF\(_4\) (45/15/40)
Active area: 20 x 24 cm\(^2\)
Pad size: 10 x 25 mm\(^2\)
Gaps: 3/1/2/1 mm

PAD Cluster Size limit

2.9 ns r.m.s.

[G. Bencivenni et al., IEEE NSS 2005, Puerto Rico]
The TOTEM Experiment

Total Cross Section, Elastic Scattering and Diffraction Dissociation at LHC / CERN

T1: $3.1 < \eta < 4.7$
T2: $5.3 < \eta < 6.5$

T1: 5 CSC (3 coord. / chamber)
T2: 8 triple GEM planes (pads + strips)
## TOTEM GEM Detectors

**Pads:**
- 1536 (~2x2 mm² - ~7x7 mm²)
- digital readout for trigger

**Strips:**
- 256 (pitch 400 µm)
- analog readout

[F. Sauli et al., priv. comm.]
KABES at NA48

Kaon Beam Spectrometer at NA48/2
Direct CP violation in $K^\pm \rightarrow \pi^+\pi^-\pi^\pm$ decays

- Measurement of time and vertical position of each beam particle
  - $K$ tagging with TOF, $K$ momentum and charge (splitting in achromat)
  - $\sigma_t=0.7\text{ns}$, $\sigma_x=50\mu\text{m}$ (drift)
  - $\sigma_y=80\mu\text{m}$ (strips),
  - $\delta p/p<1\%$
  - Mistagging probability $<2\%$

[B. Peyaud, NIM A535, 247 (2004)]
TPC with MPGD

**Time Projection Chamber** [D.R. Nygren et al., Phys. Today 31, 46(1978)]

- 3-D tracking device
- Large solid angle
- Low mass
- PID by \( dE/dx \) measurement
- Standard: MWPC + gate

**MPGD readout**: ILC, PANDA, ...
- Fast signal
- Multi-track resolution 10 x better
- Reduced \( E \times B \) effect
- Ion feedback suppressed → no gating?
Ion Backflow in MPGD

Intrinsically suppressed due to asymmetric field configuration

Triple GEM

- $E_{\text{drift}} = 200 \text{ V/cm}$
- $U_{\text{GEM1,2}} = 310 \text{ V}$
- $U_{\text{GEM3}} = 350 \text{ V}$
- $E_{\text{trans1}} = 6 \text{ kV/cm}$
- $E_{\text{trans2}} = 60 \text{ V/cm}$
- $E_{\text{ind}} = 8 \text{ kV/cm}$

Micromegas

- $E_{\text{drift}} = 200 \text{ V/cm}$
- $U_{\text{GEM1,2}} = 310 \text{ V}$
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- $E_{\text{trans1}} = 6 \text{ kV/cm}$
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- electron extraction from holes improved at higher B-field
- ion backflow follows $1/\alpha = (E_d/E_a)^{-1}$

[M. Killenberg et al., NIM A530, 251 (2004)]

[1/P. Colas et al., NIM A535, 226 (2004)]
The PANDA Detector

Antiproton Annihilations at Darmstadt

HESR at FAIR: Studies of hadron structure with $p\bar{p}$ annihilations:

- $c\bar{c}$ spectroscopy
- gluonic systems (hybrids, glueballs)
- modifications of hadron properties in nuclear medium
- hypernuclei

- Luminosity $2 \times 10^{32}$ cm$^{-2}$s$^{-1}$
- $2 \times 10^7$ annihilations/s

Central tracker: TPC or Straws
- $\delta p/p \sim \%$
- very low mass (photon conversion!)

Micropattern Gas Detectors

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The TPC for PANDA

- 2 half cylinders
- $L=150$ cm, $R=15$-42 cm
- Gas: Ne/CO$_2$/CH$_4$
- Multi-GEM stack for amplification and ion backflow suppression
- Pad size $\sim 2 \times 2$ mm$^2$
- Simulations:
  - $\delta p/p \sim 1\%$
  - $dE/dx$ resolution $\sim 6\%$
- Challenges:
  - space charge build-up
  - continuous sampling
Photon Detection with MPGD

Why?

- High spatial resolution
- Adaptable dynamic range
- Single photon detection
- Energy selection
- Large areas
- Flexible geometry
- Affordable

Example:
Soft X-ray image with double GEM

How?

- Photoionization of gas
- Photoelectron extraction from solid photocathodes

[S. Bachmann, B. Ketzer et al., NIM A471, 115 (2001)]
X-Ray Plasma Diagnostics

Unambiguous 2-D time-resolved imaging of soft X-rays (1-10 keV)

Diagnostics of magnetic fusion plasma:
• High contrast due to energy selection
• Count rate up to 10 MHz/pixel
• Frame rate up to 100 kHz
• Tested at FTU & NSTX

Setup:
• Pinhole camera
• Single GEM amplification
• Ne/DME (80/20)
• 12 x 12 pixels, 2 x 2 mm²

[D. Pacella et al., Rev. Sci. Instr. 72, 1372 (2001)]
[D. Pacella et al., NIM A508, 414 (2003)]
**X-Ray Polarimetry**

**Astrophysical models:**
- polarization of X-rays from NS, BH, AGN
- Photoelectron emission pref. in direction of photon polarization
- Reconstruction of photoelectron tracks -> photon polarization

**Setup:**
- Single GEM, Ne/DME (80/20)
- Pixel readout: 200 µm pitch
- Analog readout
- Sensitive energy: 2-10 keV

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[E. Costa et al., Nature 411, 662 (2001)]

[R. Bellazzini et al., NIM A510, 176 (2003)]

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Micropattern Gas Detectors

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Axions:
• postulated to solve strong CP problem
• candidates for dark matter
• very light, neutral, weakly interacting with matter
• produced in the sun via the Primakoff effect

Detection: inverse Primakoff reaction
• 9T, 10m long LHC dipole magnet
• platform: ±8º (vert.), ±40º (horiz.)
• Detectors:
  • X-ray telescope with CCD
  • TPC
  • Micromegas: low bgr, 2-D

[S. Andramonje et al., NIM A535, 309 (2004)]
Detection of UV Photons

Gaseous Photomultipliers:

- Multi-GEM amplification
  \( G \geq 10^6 \): single photons!
- Semitransparent or reflective photocathodes
- Large active area
- High 2-D position resolution
- Fast: ns time resolution
- Operation in high magnetic fields

[A. Breskin et al., NIM A513, 250 (2003)]
GEM Cerenkov Detector

Setup:
- 3/4-GEM detector
- CsI refl. PC
- CH₄ gas
- Quartz window
- Hexaboard readout for multi-hit resolution

[S. Bachmann, B.Ketzer et al., NIM A478, 104 (2002)]

- Position resolution 100µm
- Double-hit resolution ~ 1mm
- Multi-photon reconstruction

[F. Sauli, NIM A553, 18 (2005)]
Detection of Visible Light

- Bialkali-photocathodes
  - very reactive → sealed detector!
- Noble gas mixtures, high pressure
- Problem:
  - Ion backflow to PC
    - Aging
    - Secondary electron emission
      - Limited gain
  - Especially severe for visible-range PC
- R&D on novel structures:
  - Micro Hole & Strip Plate
  - Thick GEM
    [R. Chechik et al., NIM A535, 303 (2004)]

MHSP
[J.M. Maia et al., NIM A504, 364 (2003)]
MPGD readout by VLSI Pixel Chips

**Ultimate resolution:**
- only diffusion-limited
- readout pixel size < 100µm

**VLSI ASIC (CMOS):**
- charge collecting pad
- preamplifier, shaper
- discriminator / sample&hold
- data readout (MUX)

Resolve individual clusters!
- pattern recognition & track fitting in dense environment
- dE/dx resolution for TPC

**CMOS ASIC:** 2100 pixels, 80µm
[R. Bellazzini et al., NIM A535, 477 (2004)]

**MediPix2:** 65k pixels, 55µm
[X. Llopart et al., IEEE TNS 49, 2279 (2002)]

GEM: photoelectron track
TPC+Micromegas: cosmic track + δ-electron
Conclusion

• **MPGD** have matured to **reliable detectors** in many different fields

• **Tracking detectors in HEP:**
  - DIRAC (GEM)
  - COMPASS (GEM+Micromegas)
  - NA48 (Micromegas)
  - LHCb (GEM)
  - TOTEM (GEM)

• **High-rate Time Projection Chamber:**
  - ILC, PANDA
  - Minimize ion-backflow
  - Maximize resolution ➔ digital TPC?
  - Optimization of gas, electric field configuration necessary

• **Photon detectors:**
  - Soft X-ray detection
  - Gaseous photomultiplier: UV/visible light detection ➔ fast RICH?

• **Neutron detection**

Stay tuned for many new applications & ideas...