GEM DETECTORS
20 YEARS OF DEVELOPMENTS AND APPLICATIONS
Fabio Sauli
TERA Foundation
CERN
1988: MICRO-STRIP GAS COUNTER (MSGC)

THIN METAL STRIPS ON GLASS SUBSTRATE

LIGHT AND COMPACT DETECTOR CONSTRUCTION

A. Oed,
*Nucl. Instr. and Meth.* A263(1988)351

RATE CAPABILITY ~ 1 MHz/mm²
POSITION ACCURACY ~ 40 µm
2-TRACK RESOLUTION ~ 500 µm

HERA-B MSGC INNER TRACKER ~ 200 MSGC 20x20 mm²
CMS CENTRAL TRACKER ~ 5500 MSGC

MSGC: DISCHARGE PROBLEMS

MILD OR SERIOUS DISCHARGE PROBLEMS!

HERA-B MSGC INNER TRACKER

50 sparks/min

~ 1990 TO PRESENT: NEW DEVELOPMENTS

MICRO-GROOVE

MICRO-GAP

MICRO-WIRE

MICRO-PIN ARRAY

MICROMEGAS

Y. Giomataris, 
Nucl. Instr. and Meth. A419(1998)239
UV PHOTONS DETECTION (RICH): MWPC WITH PHOTOSENSITIVE GAS (TEA)

MULTISTEP CHAMBER

1978: THE MULTISTEP CHAMBER (MSC)

G. Charpak and F. Sauli, Phys. Lett. 78B(1978)723

SINGLE ELECTRON DETECTION
SIMULATED CHERENKOV RING
(COLLIMATED UV SOURCE)

E605 RICH
POLYIMIDE ETCHING:
CONTACTS THROUGH FLEXIBLE PRINTED CIRCUITS
Angelo Gandi and Rui De Oliveira
CERN’s Printed Circuit Workshop (EST-DEM)
1996: MSC+µVIAS => GEM

THE GAS ELECTRON MULTIPLIER (GEM):
100 µm PITCH HOLES ON COPPER-CLAD POLYIMIDE FOIL

PRESENTED AT:
IEEE Nuclear Science Symposium & Medical Imaging Conference
Anaheim, CA November 3-9, 1996

F. Sauli, Nucl. Instr. and Meth. A386(1997)531
**GEM MANUFACTURING**

**DOUBLE MASK PHOTOLITHOGRAPHY**

- 50 µm Kapton
- 5 µm Cu Photoresist coating, masking and exposure to UV light
- Metal etching
- Kapton etching
- Second masking
- Metal etching and cleaning

**“STANDARD” GEM**

- DOUBLE CONICAL “HOURGLASS”

- 140 µm
- 70 µm
MSGC WITH GEM PREAMPLIFIER

COMBINED GAIN CURVES

R. Bouclier et al, Nucl. Instr. and Meth. A396(1997)50
HERA-B MSGC+GEM

CERN’s Printed Circuit Workshop (EST-DEM)

~ 200 GEM FOILS, 20x20 cm²

Bagaturia et al,
GASEOUS $\alpha$ SOURCE: $^{232}\text{Th} \rightarrow ^{232}\text{Rn+}$ (6.4 MeV) \hspace{1em} $\Delta E \sim 500$ keV \hspace{1em} $\sim 10^4 e^+$

THORIUM

GEM:

MICROMEGAS:

Q $\sim 10^4 \cdot 10^3 = 10^7 e^+$

RAETHER LIMIT

MULTI-GEM STRUCTURES

DOUBLE GEM

\[ V_D \quad E_D \quad \text{Drift } D \]

\[ \Delta V_{\text{GEM1}} \quad V_{1D} \quad E_T \quad \text{Transfer } T \]

\[ \Delta V_{\text{GEM2}} \quad V_{2D} \quad E_I \quad \text{Induction } I \]

TRIPLE GEM

\[ \text{HV} \quad \text{DRIFT} \]

\[ E_D \quad \text{DRIFT} \]

\[ E_T \quad \text{TRANSFER 1} \quad \text{GEM 1} \]

\[ E_B \quad \text{TRANSFER 2} \quad \text{GEM 2} \]

\[ E_I \quad \text{INDUCTION} \quad \text{GEM 3} \]

\[ \text{READOUT BOARD} \]

- HIGHER GAINS
- REDUCED ION BACKFLOW
- LOWER DISCHARGE PROBABILITY

$^{220}$Rn INTERNAL $\alpha$ SOURCE  

TRIPLE GEM

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P. Gasik RD51Coll. Meeting (CERN 2016)
WHAT ABOUT THE RAETHER LIMIT?

VERY LARGE GAINS OBSERVED IN PURE NOBLE GASES
CHARGE CONFINEMENT: HOLES ARE (QUASI) INDEPENDENT


P. Bhattacharya, MPGD Workshop (Trieste 2015)
HYBRID DETECTORS

GEM + MICROMEGAS

1 GeV π BEAM

VGEM=280 V

DISCHARGE PROBABILITY

GAIN

10^{-4}

10^{-5}

S. Procureur et al, Nucl. Instr. and Meth. A659(2011)91

M. Vandenbroucke, JINST 7(2012)C05014
DISCHARGE STUDIES - ALICE GEM TPC

DISCHARGE PROPAGATION: LAST GEM TO ANODE

SECTORS POWERING: STANDARD

DISCHARGE PROPAGATION PROBABILITY:

![Diagram showing discharge propagation probability with standard and flipped sectors.]

DISCHARGE PROPAGATION DELAY:

![Diagram showing discharge propagation delay with standard and flipped sectors.]

P. Gasik RD51Coll. Meeting (CERN 2016)
SINGLE GEM X-RAY DETECTOR

2-DIMENSIONAL CARTESIAN STRIPS READOUT

- HIGH PROPORTIONAL GAINS
- FAST ELECTRON SIGNAL
- READOUT PLANE AT GROUND POTENTIAL
- PATTERNED AT WILL

A. Bressan et al,

6 keV RADIOGRAPHY
LOCALIZATION ACCURACY

DOUBLE GEM  \( \text{Ar-CO}_2 \)

\( \sigma \approx 40 \mu m \)

A. Bressan et al., Nucl. Instr. and Meth. A425(1999)262

TIME RESOLUTION: LHCB MUON TRIGGER

TRIPLE GEM  \( \text{A-CO}_2-\text{CF}_4 \)

\( \sigma \approx 4.5 \text{ ns} \)

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

SINGLE GEM RATE CAPABILITY

\( 1 \text{ MHz} \text{ mm}^2 \)

\[ \begin{align*}
\Delta V_{\text{GEM}} &= -467 \text{ V} \\
V_{\text{DRIFT}} &= -2000 \text{ V} \\
\text{Ar-CO}_2 &\text{ (70-30)}
\end{align*} \]


RADIATION RESISTANCE

\( 20 \text{ C/cm}^2 \)

\( \sim 4 \times 10^{14} \text{ MIPS cm}^{-2} \)

\[ \begin{align*}
\text{Ar}/\text{CO}_2/\text{CF}_4 &= 60/20/20 \\
\end{align*} \]

TRIPLE GEMs FOR COMPASS TRACKER

~30 TRIPLE GEM 30x30 cm² - 2D CARTESIAN READOUT

HV TESTING DURING ASSEMBLY

C. Altumbas et al,
Nucl. Instr. and Meth. A490(2002)177

L. Ropelewski
GEM SECTORS AND READOUT PATTERNS

GEM SECTORS SEPARATION (200 µm)

1x1 mm² PIXELS AND STRIPS

CENTRAL BEAM KILLER

MEASURED FLUX IN HADRON BEAM:

SEM I-CIRCULAR MODULES

TEN-GEM TOTEM FORWARD SECTOR

TRIPLE-GEM PROTOTYPE

GAS DETECTORS DEVELOPMENT
CERN
L. Ropelewski....M. Van Stenis.....
KLOE-2 INNER TRACKER

A. Balla et al, Nucl. Instr. and Meth. A732(2013)221

BES III DETECTOR at IHEP (Beijing)

R. Farinelli, RD51 Coll. Meeting (Aveiro 2016)
“SPHERICAL” MULTIGEM AND READOUT BOARD

Sketch of a spherical triple GEM detector

S. Duarte Pinto arXiv:1011.5528v1
LARGE SIZE GEM PRODUCTION

SINGLE MASK PHOTOLITOGRAPHY
R. De Oliveira, CERN EP-DT-EF

Cu-clad Kapton

Single mask Photoresist

Cu etching

Kapton etching

Second Cu etching

“CYLINDRICAL” HOLES

DISMOUNTABLE MECHANICAL ASSEMBLY
EDGE STRETCHED GEM FOILS
CERN-INFN-BONN

GEM MODULES: 100-120 cm x 22-45 cm
36 SUPERCHAMBERS IN EACH ENDCAP


B. Dorney, MPGD WORKSHOP (Trieste 2015)
LARGE PROTOTYPE IN TET BEAM

B. Dorney, MPGD Workshop (Trieste 2015)
ALICE GEM-TPC UPGRADE

Chilo Garabatos, Deputy Project Leader

QUAD-GEM WITH STAGGERED HOLES

A. Deisting, MPGD Workshop (Trieste 2015)
ALTERNATIVE GEM STRUCTURES

GLASS GEM

- GOOD GAIN UNIFORMITY
- GOOD ENERGY RESOLUTION
- NON-OUTGASSING MATERIALS

H, Takahashi et al, Nucl. Instr. and Meth. A724(2013)1
THICK ELECTRON MULTIPLIER (THGEM)

ALSO CALLED LARGE ELECTRON MULTIPLIER (LEM)

MECHANICAL DRILLING OF METAL-CLAD PC BOARD
- SELF-SUPPORTING
- HIGH GAIN (?)

DEVELOPMENTS FOR THE COMPASS RICH-1 UPGRADE

LARGE RIM:
- HIGH GAIN
- CHARGING UP

RIMLESS:
- LOW GAIN
- STABLE

GAIN VS TIME (CHARGING UP EFFECT):

GAIN VS X-RAY RATE: TRIPLE GEM (2006)

MULTIGEM GAIN AT VERY HIGH RATES

NEW MEASUREMENTS (2015)

SINGLE GEM

TRIPLE GEM

GDD

P. Thuiner, PhD TU Vienna (2016)

SIMULATION: CHARGE DENSITIES VS RATE

POSITIVE IONS BACKFLOW (OR FEEDBACK):

\[ IBF = \frac{I_{\text{DRIFT}}}{I_{\text{ANODE}}} \]

THE WISH:
ONE IBF ION PER PRIMARY

\[ IBF \frac{1}{GAIN} 10^{-4} \]

MULTIGEMS: THE IBF VALUE DEPENDS ON GEOMETRY, FIELDS AND DIFFUSION:

\[ \Delta V_{\text{GEM}} = 300 \text{ V} \]

\[ \Delta V_{\text{GEM}} = 400 \text{ V} \]

\[ \Delta V_{\text{GEM}} = 500 \text{ V} \]

\[ \Delta V_{\text{GEM}} = 550 \text{ V} \]

\[ E_D/E_i = 25\% \]

\[ \sim 30\% \]

\[ S. \text{ Backmann et al., Nucl. Instr. Meth. A438(1999)376} \]

\[ A. \text{ Bondar et al, Nucl. Instr. and Meth. A496(2003)325} \]
EXPLOIT THE DIFFERENCE BETWEEN IONS’ AND ELECTRONS’ DIFFUSION IN AN OFFSET DOUBLE GEM

FOUR GEMS WITH STAGGERED HOLES

GEM 1 & 4: STANDARD PITCH 140 µm
GEM 2 & 3: LARGE PITCH 280 µm

ENERGY RESOLUTION VS IBF:

A.Deisting, MPGD Workshop (Trieste 20125)
TRIPLE GEM OPERATED IN Ne-CO$_2$ 90-10
$2 \times 10^7$ p-p ANNIHILATIONS   GAIN M=2000  IBF $2.5 \times 10^{-3}$

SPACE CHARGE DENSITY:

ELECTRIC FIELD DISTORTIONS:

F.W. Bohmer et al., Nucl. Instr. and Meth. A719 (2013) 101
GAS DETECTORS SIMULATION TOOLS

MAGBOLTZ (Steve Biagi)
GARFIELD (Rob Veenhof)
+ ELECTRIC FIELD, ENERGY LOSS,...

P. Bhattacharya, RD51 Collaboration
GAS DETECTORS SIMULATION TOOLS

ALICE GEM TPC SIMULATION

Ion Backflow
Electron Avalanche

P. Bhattacharya, MPGD Workshop (Trieste 2015)
CASCADE: $^{10}\text{B}$-COATED GEM ELECTRODES

THERMAL NEUTRON RADIOGRAPHY

M. Klein and Ch. Schmidt, Nucl. Instr. and Meth. A628(2011)9
b-GEM:
TRIPLE GEM WITH ALUMINUM FOIL CATHODE COATED WITH 1 μm OF BORON CARBIDE
READOUT: 144 PADS, 8x8 mm²

2-D THERMAL NEUTRON BEAM PROFILE

SENSITIVITY TO GAMMA BACKGROUND:

NEUTRON DETECTORS

BORON ARRAY NEUTRON DETECTOR (BAND-GEM)

Alumina Lamellas coated on both sides with $^{10}$B$_4$C

G. Croci et al, MPGD Workshop (Trieste 2015)
REFLECTIVE CsI PHOTOCATHODE ON UPPER GEM ELECTRODE
• NO PHOTON FEEDBACK
• INSENSITIVE TO DIRECT IONIZATION

TRIPLE GEM
COLLIMATED SINGLE UV PHOTON SOURCE
POSITION ACCURACY

“INVERSE FIELD” TPC


THICK GEM CsI-COATED 30x30 cm²


TRIPLE THGEM PROTOTYPE

SINGLE EVENT (6 GeV π BEAM)
CHERENKOV RING IMAGING

COMPASS RICH-1 MPGD UPGRADE
DOUBLE STAGGERED THGEMS+MICROMEGAS

M. Alexeev et al, MPGD Workshop (Trieste 2015)
SOFT X-RAY POLARIMETRY

5.9 keV PHOTOELECTRON (80 µm pixels pitch):

MEASURED ANGULAR MODULATION:

GEM POLARIMETER IN SPACE

GEMS MISSION CANCELLED BY NASA (2012)

NEW MISSION (2017):
POLARIMETRY FOR RELATIVISTIC ASTROPHYSICAL X-RAY SOURCES (PRAxYS)


Toru Tamagawa, MPGD Workshop (Saragoza 2013)
TRIPLE-GEM WITH MEDIPIX READOUT
256x256 pixels, 55x55 μm²

COMPTON ELECTRON:

RECORDED EVENTS:

**X-RAY FLUORESCENCE ANALYSIS**

28x28 mm² MICRO-HOLE AND STRIP PLATE (MHSP) WITH RESISTIVE LINES 2-D READOUT

**X-RAY TRANSMISSION IMAGE:**

**ELEMENTAL ANALYSIS:**

ENERGY-RESOLVED X-RAY FLUORESCENCE

J. Veloso, RD51 Special Workshop on Photon detection (CERN, 2015)
IMAGING CHAMBER (1987)

TRIETHYLAMINE (TEA): INTERNAL WAVELENGTH SHIFTER

CARBON TETRAFLUORIDE SCINTILLATION:

**Graph:**
- **X-axis:** Wavelength (nm)
- **Y-axis:** Light intensity (a.u.)
- Data points show a peak around 600 nm.

**Text:**
- "OPTICAL IMAGING (2002)"
- "He-CF₄ GAS FILLING"
DOSE MONITORING IN HADROTHERAPY

DOUBLE GEM WITH OPTICAL DETECTION

![Diagram of double GEM with optical detection](image)

BEAM PROFILE:

![Beam profile graph](image)

α PARTICLES FROM $^{220}$Rn and $^{216}$Po

$^{55}$Fe 5.9 keV X-RAYS

$^{55}$Fe source

Full energy

Escape

Pileup

F. Resnati, EP Detector Seminar (CERN, April 29, 2016)
ENERGY RESOLVED FLUORESCENCE ANALYSIS

- X-ray tube
- GEMs
- Pin-hole
- Shielding
- Camera and lens

Graph showing counts/bin vs. collected light (a.u.).

Images of different colors:
- Red
- Green
- Blue

F. Resnati, MPGD Workshop (Aveiro, 2016)
SMALL DRONE-IN-THE BOX

JUMPING DRONE RADIOGRAPHY (30 keV)

F. Resnati, MPGD Workshop (Aveiro, 2016)
X-RAY TOMOGRAPHY

IMAGE -> SINOGRAMS -> FILTERED BACK PROJECTION -> 3D IMAGE

F. Resnati, MPGD Workshop (Aveiro, 2016)
CORRECTION OF THE PARALLAX ERROR

PINHOLE CAMERA:
PARALLAX ERROR

PLANISPHERICAL GEM
CONCENTRIC GRADED POTENTIAL RINGS
ON CATHODE AND GEM ELECTRODES

RADIAL CONVERSION AND DRIFT:

Computed with COMSOL Multiphysics

F. Sauli, PCT Patent WO99/21211
PLANISPHERICAL GEM WITH OPTICAL READOUT

CAD-CAM DESIGN
3-D PRINTING OF MOST PARTS
SEGMENTED GEMS MANUFACTURED AT CERN (R. De Oliveira)

10 cm Ø  10 cm FOCUS (ADJUSTABLE)

Segmented cathode
Field shaper
Main frame
Two segmented GEMs

Active detector volume
Voltage divider
Light shielding housing camera

... F. Brunbauer.....M. Van Stenis.....
PLANISPHERICAL GEM

MASK WITH 1 mm Ø HOLES PATTERN

55Fe 5.9 keV

MASK

UNIFORM DRIFT FIELD

RADIAL DRIFT FIELD

F. Sauli, MPGD Workshop (Aveiro 2016)
FLUORESCENCE IMAGE OF A COPPER MESH 1mm STRIPS AT 5 mm PITCH

X-RAY TUBE
20 keV

Florian Brunbauer, October 20
The gas electron multiplier (GEM): Operating principles and applications

Fabio Sauli
CERN, Geneva, Switzerland

ABSTRACT

Introduced by the author in 1987, the Gas Electron Multiplier (GEM) constitutes a powerful addition to the family of fast radiation detectors, originally developed for particle physics experiments. The device has spawned a large number of developments and applications; a web search yields more than 400 articles on the subject. This note is an attempt to summarize the status of the design, developments, and applications of the new detector. © 2016 CERN for the benefit of the Authors. Published by Elsevier B.V. This is an open access article under the CC BY license (http://creativecommons.org/licenses/by/4.0/).

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