Development of Micro Pattern Gas Detectors for HEP and Nuclear Physics

OUTLINE

• RD51/MPGD history
• Organization/Infrastructures
• Technological achievements
• Applications

ICNFP2017 Conference, 17 – 29 Aug 2017, Kolymbari, Crete, Greece
From Multi-Wire Proportional Chambers to Micro Pattern Gaseous Detectors

**MSGC: Oed 1988**

- Rates: $\sim 10^6$ Hz/mm$^2$
- But: Sparks, irreversible damages

**GEM: Sauli 1997**

- Rates: $> 10^6$ Hz/mm$^2$
- $\sigma_{\text{Spatial}} \sim 30 \mu m$

**MWPC: Charpak 1968**

- $S = 1 \text{ mm}$

**Micromegas: Giomataris 1996**

- Rates: $> 10^6$ Hz/mm$^2$
- $\sigma_{\text{Spatial}} \sim 30 \mu m$

**RD51 Collaboration**

- 86 Institutions
- 500 Scientists

**μ-PIC**

- Ingrid
Main objectives:
- MPGD technological development
- Provide the collaboration framework
- Develop common simulation packages
- Develop common read out electronics
- Access to “MPGD know-how”
- Foster Industrial production

→ huge growth in interest in the MPGD technologies

Collaboration Spotting Software: http://collspotting.web.cern.ch/
RD51 Collaboration

Technological Aspects
New Detector Structures

MPGD Electronics

Detector Physics and Performance
RD51 Common Projects

Modeling of Physics Processes
Software Tools

RD51 Common Projects

Applications, Training and Dissemination

Production and Industrialization

Common Test Facilities

WG1:

WG2:

WG3:

WG4:

WG5:

WG6:

WG7:
**RD51 related infrastructures:**

1) **EP DT MPT Workshop (Head: Rui De Oliveira)**

The heart of the MPGD Globe: Design, prototyping, production
New infrastructure (building, MPGD production machines, clean room etc) will be soon ready

2) **GDD Laboratory (RD51)**

The Detector R&D laboratory:
- Permanent users (ALICE, ATLAS, ESS)
- Temporary Users stations
- Cosmic stands, X-ray and radioactive sources
- Clean room, Workshop
- Vacuum and Gas System
- MPGD Electronics support
- 15 visiting groups, synergies with companies

3) **Test Beam Area (SPS/H4 semi permanent RD51 area)**

GOLIATH
(1.5T Max, 1mt gap)

Organize test beam
3 times (2 weeks)/year
RD51 Technological achievements (I)

- **Large MPGDs production/industrialization of GEM, THGEM, Micromegas:**
  - Single mask GEM
  - Bulk Micromegas

- **High rates and spark mitigation:**
  - Staged Gain: multiple layers
  - GEM, THGEM, MHSP
  - Resistive coating, buried resistors
  - Micromegas, RETGEM, RPWELL
**RD51 Technological achievements (II)**

- **Ion Back Flow (IBF)**, Application in TPCs (field distortion) and photon detection (photocathode protection): Multiple Layers

Hybrid: THGEM+ CsI and MM

- Staggered THGEMs

Multi layer GEM stack MHSP/GEM/F-R-MSHP

- **Radiation hardness**
  LHC MPGD Upgrades (ATLAS NSW project - Resistive Micromegas and CMS GEM muon chambers) proven to withstand the equivalent of 10 years of operation at the HL-LHC. Irradiation with: neutrons, X-rays, $\alpha$ and $\beta$.

- **IBF** ~ $5 \cdot 10^{-2}$
- **IBF** ~ $(5 - 25) \cdot 10^{-3}$
- **IBF** ~ $(1-3) \cdot 10^{-4}$
RD51 Technological achievements (III)

- **Sealed detectors** (purity) for space and non-laboratory applications

- **Physics simulations and tools**

  **Software tools:** Magboltz (transport equations), Degrad (cluster size), Garfield++ (speeding up), optimization of charging up simulation

  **Modeling of Physics processes:** Penning in Ne mixtures, CO2 impact, GEM gas gain dependence on hole diameter, impact of mesh geometry to micromegas

- **Read-out electronics**

  **Scalable Readout System:** Development of the readout system for MPGDs adaptable to various FE ASIC chips (APV25, VMM2, GEMRoc)

  Development of generic electronic devices for MPGDs:
**MPGD Technologies for Present and Future:**

- Hadron / Nuclear Physics Experiments-Heavy Ion Facilities
- High Energy Physics
- Hadron / Lepton Colliders
- Photon / Neutron Detection
- Neutrino Physics / Dark Matters Detection
- X-Ray Detection and γ-Ray Polarimetry
MPGD Technologies: LHC experiments Upgrades
Challenges: Ultra high rates, radiation harsh environment, longevity, large area detectors

Present:
- TOTEM (GEM), LHCb (GEM)

Future:
- ATLAS Muon System NSW ($\mu$ M), Muon tagger $\mu$-PIC, CMS Muon System (GEM), ALICE (GEM TPC), FCC Collider (GEM, THGEM, Micromegas, $\mu$-PIC, InGrid)

ATLAS NSW (mm)

CMS (GEM)

ALICE (GEM)
GEM / Micromegas: Technology Developments Highlights

MM for the ATLAS Muon System Upgrade:
Standard Bulk MM suffers from limited efficiency at high rates due to discharges induced dead time.
Solution: Resistive Micromegas technology:
- Add a layer of resistive strips above the readout strips
- Spark neutralization/suppression (sparks still occur, but become inoffensive)

2.4 x 1m² MM resistive chamber constructed and characterized at CERN RD51 lab

GEMs for the CMS Muon System Upgrade:
Single-mask GEM technology (instead of double-mask)
- Reduces cost / allows production of large-area GEMs
- R&D: 6 generations of triple-GEM detectors

Assembly optimization: self-stretching technique:
assembly time reduction from 3 days → 2 hours
Ion Back Flow in a GEM system reduced from > 5% (3 GEM) to < 1% (4 GEM) → discovered enhanced ion trapping at high rates

ALICE TPC Upgrade → replace MWPC with 4-GEM (to limit space charge effects)

- Continuous TPC readout for 50 kHz Pb-Pb readout
- Maintain physics requirements: IBF < 1%, energy; σ(E)E < 12% achieved

Preproduction:
Single-mask GEM allows for production of ~1 m foils
MPGD Technologies: Hadron and Nuclear and Heavy Ion Physics experiments

Challenges: Ultra High rates, IBF

Present:
COMPASS (GEM, μ Megas, THGEM RICH), rates: 100kHz/mm²
First experiment to use MPGDs (GEM, Micromegas and recently THGEM)
KEDR (GEM), Rates: 1MHz/mm²
CLAS12: Cylindrical MM

Future: JLAB: SBS, pRad, SoLID (GEM, NP, tracking), JPARC: E42, E45 (Hadron Physics, ACTAR TPC)

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The ACTAR TPC Project
(gas is used as a secondary target for nuclear reactions):

Goal: Nuclear structure with rare-isotope beams

Cylindrical GEM for BESIII
Experiment @ e+e- collider Beijing

Rohacell technique for mechanical structure

J. Pancin

MM-based readout
MPGD Technologies: Photon detection
Challenges: IBF photocathode protection

Present:
COMPASS (THGEM RICH)

Future: JLAB: SBS, pRad, SoLID (GEM, NP, tracking), JPARC: E42, E45 (Hadron Physics, ACTAR TPC)

After a long-term fight for increasing electrical stability at high rates: MWPC robust operation is not possible at gain~$10^5$ because of photon feedback, space charge & sparks.

PMTs not adequate → only small demagnification factor allowed; 5 m² of PMTs not affordable.
MPGD Technologies: Neutron detectors (ITER spallation sources, Beam diagnostics)

Challenges: Low mass detectors
Present:
nTOF
Future:
ESS (macromolecular chrystallography, neutron scattering)

**nTOF at CERN**

- **Installation on NTOF**
- **Beam profile at detector**
- **4 pad detector**
- **μMegas detector:**
  - 2D reconstructed image
  - T. Papaevangelou
- **μM Neutron Monitor applied to fission reactor**

**GEM detector**

- **2D image of thermal neutron**
  - F. Murtas
- **2D image of fast neutron**

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22/08/2017

Theo Geralis
**MPGD Technologies: Neutrino Physics**

**Challenges: Large area TPCs**

**Present:**
T2K (Japan), first large scale neutrino experiment with MPGD (9 m² TPC with micromegas)

**Future:**
LBNO-DEMO (LAr TPC THGEM), DUNE 720 m² (LAr TPC THGEM), Ship (26 m² micromegas, GEM, mRWELL)

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**T2K experiment**

- 72 Micromegas, 120k channels (since 2009)
- Charge, momentum and dE/dx PID)
- Spatial resolution : 0.6 mm
- Momentum res.: 9% at 1 GeV
- dE/dx: 7.8 % (distinguish μ/e, identify ν_e)
MPGD Technologies: Dark Matter detection
Challenges: Ultra low background detectors < $10^{-7}$ cts/keV/cm$^2$

Present:
CAST (Micromegas $\mu$ bulk and Ingrid), NEWAGE (Kamioka, TPC GEM, $\mu$ PIC)

Future:
PANDA-X (TPC $\mu$ bulk micromegas, DARWIN (THGEM GMPT), IAXO ($\mu$ bulk micromegas)

NEWAGE
$\mu$-PIC based TPC with electronics
Only DM experiment with 3-D tracks

K. Miuchi, A. Ochi

NEWAGE-0.3b'

$\mu$-PIC
- $31 \times 31$ cm$^2$
- made by DNP, Japan

$\mu$-PIC
- $31 \times 32$ cm$^2$
- 70$\mu$m/140$\mu$m
- LCP 100$\mu$m
- made by Scienergy, Japan

GEM

IAXO: Axion searches

- Large toroidal 8-coil magnet L = ~20 m
- 8 bores: 600 nm diameter each
- 8 x-ray telescopes = 8 detection systems
- Rotating platform with services

$10^5$ better SNR than CAST

Very low background x-ray detectors needed

$\mu$bulk background

Underground data
With optimised shielding

IAXO goals

10/2002 06/2006
02/2010 10/2013

date

10^{-7}
MPGD Technologies: X and $\gamma$ ray detection and polarimetry
Astrophysics and fusion plasma monitor
Challenges: Track photoelectrons and low energy e
Present:
KSTAR Korea (Plasma monitor), SMILE II ($\gamma$-ray imaging, GEM and $\mu$ PIC), ETCC camera (GEM and $\mu$ PIC) environmental $\gamma$ ray monitoring
Future:
PRAXyS (TPC GEM x-ray polarimetry), CALISTE (piggy back micromegas, X-ray polarimetry)

KSTAR Tokamak
GEMPIX (GEM + Timepix) for fusion

PRAXyS X-ray polarimetry
GEM + Readout
GEMs

- The first dedicated mission for X-ray polarimetry in astrophysics
- US-Japan joint mission (NASA lead)
- The space craft carries two identical GEM-TPC
<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>ILC Time Projection Chamber for ILD:</td>
<td>High Energy Physics (tracking)</td>
<td>Micromegas GEM (pads)</td>
<td>Total area: ~ 20 m²</td>
<td>Max. rate: &lt; 1 kHz</td>
<td>Si + TPC Momentum resolution: dp/p &lt; 9*10^{-5} 1/GeV</td>
</tr>
<tr>
<td>Start: &gt;2030</td>
<td></td>
<td>InGrid (pixels)</td>
<td>Single unit detect: ~ 400 cm² (pads)</td>
<td>Spatial res.: &lt;150µm</td>
<td>Power-pulsing</td>
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<td></td>
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<td>~ 130 cm² (pixels)</td>
<td>Time res.: ~ 15 ns</td>
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<td>dE/dx: 5 % (Fe55)</td>
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<td>Rad. Hard.: no</td>
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<td>Max. rate:1 kHz/cm²</td>
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<td>Spatial res.: ~ 1cm</td>
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<td>Time res.: ~ 300 ns</td>
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<td></td>
<td></td>
<td>Rad. Hard.: no</td>
<td></td>
</tr>
<tr>
<td>ILC Hadronic (DHCAL) Calorimetry for ILD/SiD</td>
<td>High Energy Physics (calorimetry)</td>
<td>GEM, THGEM RPWELL, Micromegas</td>
<td>Total area: ~ 4000 m²</td>
<td>Jet Energy resolution: 3-4 %</td>
<td></td>
</tr>
<tr>
<td>Start &gt;2030</td>
<td></td>
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<td>Single unit detect: 0.5 - 1 m²</td>
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<td>Max. rate:1 kHz/cm²</td>
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<td>Rad. Hard.: no</td>
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</tbody>
</table>

**Particle Flow Calorimetry (ILD/SiD):**

**SiD Concept:**

**ILD Concept:**
Generic Detector R&D

Fast timing with MM

Aim at < 50ps resolution
- Cherenkov radiator
- Photocathode
- 200um drift
- MicroMeGas

R&D on:
- photocathode protection
- photocathode alternatives
- secondary emitter materials

Graphene

Membrane opaque to ions and transparent to electrons
- solution of the ion back-flow in gaseous detectors
- protective layer on photocathodes
- enhancement of electron emission

GEM optical readout and OTPC

Study:
- Visible (near UV and near IR) scintillation of gases
- Event topology study
- Imaging

Glass GEM

Photo Etchable Glass 3 (PEG3):
Rigid (self sustained structure)
‘Laser assisted etching’ opens new possibilities
Slightly conductive (milder charge-up)
Clean and low outgassing (sealed operation)

Imaging with electronic readout
Scintillating Readout of Glass GEM:
Glass GEM × scintillation gas × mirror × optical camera:

- Convert radiation into visible light
- Optical mirror to prevent the CCD from irradiated directly with X-rays

Radiography with various radiation sources:

<table>
<thead>
<tr>
<th>Scintillator</th>
<th>Photons</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>CsI(Tl)</td>
<td>59,000 ph/MeV</td>
<td>Ultra high yield (orders of three)</td>
</tr>
<tr>
<td>NaI(Tl)</td>
<td>38,000 ph/MeV</td>
<td>High photon yield with low energy depositing radiation</td>
</tr>
<tr>
<td>SrI</td>
<td>115,000 ph/MeV</td>
<td></td>
</tr>
<tr>
<td>Glass GEM + Ar/CF$_4$</td>
<td>85,000 ph/keV</td>
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</tr>
</tbody>
</table>

3D CT of Medicine Tablet:

Micro-sphere medicine tablet

- Micro-spheres medicine inside the medtab
Coating GEM with GRAPHENE: need to increase e- Energy > 10kV/cm. Did not succeed to transmit e- via 3-layer Graphene. Literature: yet unclear (to our community) “directions”

⇒ consult with surface chemists!

GRAPHENE:
2-GASES MM detector
Gaseous Detector Timing, the “Picosecond Detector Concept”

Small Drift: low diffusion, low primary ionization in gas

Pre-amplification: longitudinal diffusion reduced, effects of primary ionization in gas reduced

2016 Test-Beam @ CERN:

- Detector scaling (towards applications):
  - Diamond as photocathode or secondary emitter...
  - On the way of understanding what we need

S. White

E. Oliveri
**MPGD Conferences since 2009:**
1\textsuperscript{st} MPGD2009, Kolymbari, Greece
2\textsuperscript{nd} MPGD2011, Kobe, Japan
3\textsuperscript{rd} MPGD2013, Zaragoza, Spain
4\textsuperscript{th} MPGD2015, Trieste, Italy
5\textsuperscript{th} MPGD2017, Temple University, USA

**Special focus MPGD events. Most recent:**
- Academia-Industry Matching event:
  Second special workshop on \textbf{neutron detection} with MPGDs, CERN, March 2015
- Rd51 Academia-Industry Matching event:
  Special workshop on \textbf{photon detection} with MPGDs, CERN, June 2015
- Topical workshop on \textbf{resistive electrodes}, CERN, Dec. 2015
- Topical workshop on \textbf{discharges} in MPGDs, CERN, March 2016
- MPGD \textbf{Applications Beyond Fundamental Science} Workshop, Aveiro, Portugal, Sept. 2016

- Schools, visits, events
CONCLUSIONS

MPGD technologies have received enormous boost over the last decade

MPGDs are used in many scientific domains

MPGDs are used in many applications beyond Particle Physics

Exciting field for creative new ideas, attractive for young scientists!
BACKUP
Building a Microbulk with x–y readout (Regular way): Lengthy and very delicate process

- Kapton foil (50 μm), double Cu-coated (5 μm)
- Construction of readout strips/pads (Photolithography)
- Attachment of a single-side Cu-coated foil
- Construction of readout lines
- Etching of kapton
- Vias construction
- 2nd Layer of Cu-coated kapton
- Photochemical processing of mesh holes
- Kapton etching
- Cleaning

13/05/2016  Theo Geralis
Microbulk Micromegas with segmented mesh

1) Real x-y structure
2) Mass minimization
3) Production Simplification
4) Large surface detectors

Thinnest neutron detector ever:
Thickness: 2 x 5 μm

ΔE/E = 11.5% !!!

FWHM @ 5.9 keV
ILC DHCAL Particle Flow Calorimetry: Resistive Micromegas

Optimisation:
- reduce resistivity and evacuation time but still suppress sparking

- "Vertical" evacuation of charge using buried resistors, proposed by Rui de Oliveira

Use at future LC or the HL-LHC:
- Operation at high rates
- Suppress discharges, preserve linearity
- High granularity for PF calorimetry,
- Small pads \( \sim 1 \times 1 \text{ cm}^2 \)
- Large dynamic range (1 – 100s of MIPs)

Tests with X-rays, Cu 8 keV, at high rates:
(intermediate RC, Gain=4000):
- Excellent linearity up to 1 MHz/mm\(^2\)
- 25% lower Gain at 10 MHz/mm\(^2\)