Gaseous Detectors R&D for FCC

Maxim Titov
CEA Saclay IRFU / CERN

Future Circular Collider Week (FCC), London, June 5-9, 2023
Gaseous Tracking / Muon Detection @ Future Colliders:
Drift Chamber → TPC → RPC → Micro-Pattern Gas Detectors

Primary choice for large-area coverage with low material-budget (+ dE/dx measurement)

1990’s: Industrial advances in photolithography has favoured the invention of novel micro-structured gas amplification devices (MSGC, GEM, Micromegas, …)

- Scaling up MPGD detectors, while preserving the typical properties of small prototypes, allowed their use in the LHC upgrades
  - Many emerged from the R&D studies within the CERN-RD51 Collaboration

- Successful accomplishment of LHC upgrades will help to disseminate MPGD technologies even wider


HL-LHC Upgrades: Tracking (ALICE TPC/GEM); Muon Systems: RPC, CSC, MDT, TGC, GEM, Micromegas;

Future Hadron Colliders: FCC-hh Muon System (MPGD - OK, particle rates are comparable with HL-LHC)
Future Lepton Colliders: Tracking (FCC-ee / CepC - Drift Chambers; ILC / CePC - TPC with MPGD readout)
Calorimetry (ILC, CepC – RPC or MPGD), Muon Systems (many gas det. are OK)

Future Election-Ion Collider: Tracking (GEM, µWELL; TPC/MPGD), RICH (THGEM), TRD (GEM)
CERN Detector Seminars in 2022: LS2 Upgrades

Major MPGDs developments for ATLAS, CMS, ALICE upgrades, towards establishing technology goals and technical requirements, and addressing engineering and integration challenges … and first results from Run 3 !!!

"The New Small Wheel project of ATLAS"
by Theodoros Vafeiadis (17 Jun 2022)
https://indico.cern.ch/event/1168778/

"Continuous data taking with the upgraded ALICE GEM-TPC"
by Robert Helmut Munzer (24 Jun 2022),
https://indico.cern.ch/event/1172978/

"The GEM detectors within the CMS Experiment"
Michele Bianco (08 Jul 2022)
https://indico.cern.ch/event/1175363/

All three major LHC upgrades, incorporating MPGDs, started their R&D in close contact with RD51, using dedicated setups at GDD-RD51 Laboratory
Large-Area MM / GEM Detectors for ATLAS / CMS Upgrade

Resistive MM for ATLAS NSW Muon 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)

Still, main issue encountered: HV unstability
=> found to be correlated to low resistance of resistive strip anode
=> applied solutions + passivation in order to deactivate the region where R<0.8 MΩ

Production, sector integration (~1200m² resistive MM):

GEMs for CMS Muon System Upgrade:
- Single-mask GEM technology (instead of double-mask) → Reduces cost / allows production of large-area GEM
- Assembly optimization: self-stretching technique: → assembly time reduction to 1 day

September 2020: 144 GEM chambers installed

Breaking news: GEM (GE1/1) installation completed last week. First phase2 detector installed!
<table>
<thead>
<tr>
<th>Experiment / Timescale</th>
<th>Application Domain</th>
<th>Gas Detector 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><strong>ALICE TPC UPGRADE</strong></td>
<td>Heavy-Ion Physics</td>
<td>4-GEM / TPC</td>
<td>Total area: ~ 32 m²</td>
<td>Max. rate: 100 kHz/cm²</td>
<td>- 50 kHz Pb-Pb rate;</td>
</tr>
<tr>
<td>CERN LS2</td>
<td>(Tracking + dE/dx)</td>
<td></td>
<td>Single unit detect: up to 0.3m²</td>
<td>Spatial res.: ~300µm</td>
<td>- Continues TPC readout</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Time res.: ~ 100 ns</td>
<td>- Low IBF and good energy resolution</td>
</tr>
<tr>
<td><strong>CMS MUON UPGRADE</strong></td>
<td>Hadron Collider</td>
<td>3-GEM</td>
<td>Total area: ~ 50 m²</td>
<td>Max. rate: 5 kHz/cm²</td>
<td>Redundant tracking and triggering</td>
</tr>
<tr>
<td>GE11 CERN LS2</td>
<td>(Tracking/Triggering)</td>
<td></td>
<td>Single unit detect: 0.3-0.4m²</td>
<td>Spatial res.: 0.6 – 1.2mm</td>
<td>Improved pt resolution in trigger</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Time res.: ~ 7 ns</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Rad. Hard.: ~ 0.18 C/cm²</td>
<td></td>
</tr>
<tr>
<td><strong>CMS MUON UPGRADE</strong></td>
<td>Hadron Collider</td>
<td>3-GEM</td>
<td>Total area: ~ 65 m²</td>
<td>Max. rate: 1.5 kHz/cm²</td>
<td>Extension of the Muon System in</td>
</tr>
<tr>
<td>GE21 CERN L3</td>
<td>(Tracking/Triggering)</td>
<td></td>
<td>Single unit detect: 0.3m²</td>
<td>Spatial res.: 0.6 – 1.3mm</td>
<td>pseudorapidity, installation behind</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Time res.: ~ 7 ns</td>
<td>HGCAL</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Rad. Hard.: ~ 0.09 C/cm²</td>
<td></td>
</tr>
<tr>
<td><strong>CMS MUON UPGRADE</strong></td>
<td>Hadron Collider</td>
<td>iRPC</td>
<td>Total area: ~ 140 m²</td>
<td>Max. rate: 2kHz/cm²</td>
<td>Redundant tracking and triggering</td>
</tr>
<tr>
<td>RE3.1, RE 4.1 2023-24 (CERN L3)</td>
<td>(Tracking/Triggering)</td>
<td></td>
<td>Single unit detect: 2m²</td>
<td>Spatial res.: ~1-2cm</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Time res.: ~ 1 ns</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Rad. Hard.: ~ 1 C/cm²</td>
<td></td>
</tr>
<tr>
<td><strong>LHCb MUON UPGRADE</strong></td>
<td>Hadron Collider</td>
<td>µ-RWELL</td>
<td>Total area: ~ 90 m²</td>
<td>Max. rate: 900 kHz/cm²</td>
<td>About 600 detectors</td>
</tr>
<tr>
<td>CERN LS4</td>
<td>(triggering)</td>
<td></td>
<td>Single unit detector: From 0.4x0.3 m²</td>
<td>Spatial res.: ~ cm</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>To 0.8x0.3 m²</td>
<td>Time res.: ~ 3 ns</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Rad. Hard.: ~ 2 C/cm²</td>
<td></td>
</tr>
</tbody>
</table>
September 2020: 144 GEM GE1/1 chambers installed

Additional station GE2/1 and ME0 → same technical solution successfully adopted for the GE1/1

High granularity and spatial segmentation for efficient matching of muon stubs to the offline pixel tracks.

Multi-layered structure to discriminate muon against neutrons (uncorr hits).

Detector requirements
- Rate-Capability: up to 150kHz/cm²
- Ageing: 7.9 C/cm² integrated charge in 10 yrs

Discharge and x-talk mitigation strategy
- GEM1 & GEM2 double segmented for discharge mitigation
- GEM3 single side (toward the Drift) segmented to reduce "cross-talk" effects

Aging test tests
- No aging observed anywhere in Ar:CO₂ up to 1.5 C/cm² => 7.9 C/cm² expected by 2023

R&D needed to optimize the technology for operation of large area detector in very high rate environment

CMS Large-Area GEMs (GE2/1, ME0) for HL-LHC Upgrade

GE21 Detector System
- 72 chambers arranged in 2 layers installed
- On-chamber and off-chamber
  - 4 triple GEM modules per chamber
- 20° Chambers, layout similar to GE1/1, but covering much larger surface. (1.62<h<2.43)
  - hit rate < 2 kHz/cm² (GE1/1 was up to 5 kHz/cm²)

ME0 Detector System
- 36 Stacks 6 layers each
- 20° Stacks, Module Size comparable with GE1/1 chamber but covering high eta region (2<h<2.8)
- Background ~ 10² higher that GE2/1, very demanding from performance point of view

A. Colaleo
CMS RPC Upgrade Project for HL-LHC

Effect of the improved time resolution of the RPC system in Phase 2:

Barrel Muon Track Finder (BMTF): it uses DT and RPC trigger primitives (TP) to reconstruct segments merged to obtain a muon candidate. RPC improves TP time resolution by ~15(30)% without(with) DT aging.

Endcap Muon Track Finder (BMTF): RPC is the only muon detector providing timing with more granularity than a bunch-crossing.
<table>
<thead>
<tr>
<th>Experiment / Timescale</th>
<th>Application Domain</th>
<th>Gas Detector 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>ATLAS MUON UPGRADE</td>
<td>Hadron Collider (Tracking/Triggering)</td>
<td>Endcap: Res. Micromegas &amp; sTGC</td>
<td>Endcap area: 1200 m² Single unit detect: (2.2x1.4m²) ~ 2-3 m²</td>
<td>Max. rate:20 kHz/cm² Spatial res.: &lt;100 µm Time res.: ~ 10 ns Rad. Hard.: ~ 0.5 C/cm²</td>
<td>Redundant tracking and triggering; Challenging constr. in mechanical precision</td>
</tr>
<tr>
<td>ATLAS MUON UPGRADE (BIS78 PILOT)</td>
<td>Hadron Collider (Tracking/Triggering)</td>
<td>Part of Inner Barrel: RPC + sMDT</td>
<td>Barrel area (3 layers): 140 m² Single unit det.: ~ m²</td>
<td>Max. rate:1 kHz/cm² Spatial res.: ~ 7 mm Time res.: ~ 1 ns Rad. Hard.: 300 fb</td>
<td>Redundant tracking and triggering; 9 layers with 2D hit position + time</td>
</tr>
<tr>
<td>CERN LS3</td>
<td>Hadron Collider (Tracking/Triggering)</td>
<td>Inner Barrel: RPC</td>
<td>Barrel area: 1400 m² Single unit det.: ~ m²</td>
<td>Max. rate:10 kHz/cm² Spatial res.: ~ (0.1 x 1) cm in (η, ϕ) Time res.: ~ 0.5 ns Rad. Hard.: 3000 fb</td>
<td>Redundant tracking and triggering; 9 layers with 2D hit position + time</td>
</tr>
<tr>
<td>ATLAS MUON UPGRADE (BI PROJECT)</td>
<td>Hadron Collider (Tracking/Triggering)</td>
<td>Forward region: Res MM, µWELL, µPIC</td>
<td>Total area: ~ 5 layers x1 m² Single unit detect: 0.1 m²</td>
<td>Max. rate: 10 MHz/cm² Spatial res.: ~200 µm Time res.: ~ 5 ns Rad. Hard.: ~ 10 C/cm²</td>
<td>Hit rates falls rapidly with the distance from the beam axis. Given parameters are for extreme conditions at 25 cm from the beam. Miniaturization of readout elements needed there to keep occupancy low</td>
</tr>
<tr>
<td>CERN AFTER LS3</td>
<td>Hadron Collider (Tracking/Triggering)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
ATLAS RPC Upgrade Project for HL-LHC Upgrade

BIS78 Upgrade – Pilot Project (LS2):

- The existing 32 BIS7 and BIS8 MDT will be replaced by 16 new muon stations made of:
  - one sMDT BIS7+8 chamber
  - two RPC triplets (BIS7 and BIS8)
- Selectivity in transition region improved by adding a new trigger layer
- 8 stations for one end cap (side A) to be installed in 2020
- BIS78 can be considered as a pilot project for the Phase II BI upgrade.

BI RPC Upgrade (LS3):

<table>
<thead>
<tr>
<th></th>
<th>Standard RPC</th>
<th>BIS78 RPC</th>
<th>BI RPC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Effective threshold</td>
<td>1mV</td>
<td>0.5mV</td>
<td>0.3mV</td>
</tr>
<tr>
<td>Power consumption</td>
<td>30 mW</td>
<td>6 mW</td>
<td>10 mW</td>
</tr>
<tr>
<td>Technology</td>
<td>GaAs</td>
<td>BJT Si + SiGe</td>
<td>Bi-CMOS SiGe</td>
</tr>
<tr>
<td>Discriminator</td>
<td>Embedded</td>
<td>Separated</td>
<td>Embedded</td>
</tr>
<tr>
<td>TDC embedded</td>
<td>No</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>Gap Width</td>
<td>2 mm</td>
<td>1 mm</td>
<td>1 mm</td>
</tr>
<tr>
<td>Operating Voltage</td>
<td>9600 V</td>
<td>5800 V</td>
<td>5400V</td>
</tr>
<tr>
<td>Electrode thickness</td>
<td>1.8 mm</td>
<td>1.2 mm</td>
<td>1.2 mm</td>
</tr>
<tr>
<td>Time resolution</td>
<td>1 ns</td>
<td>0.4 ns</td>
<td>0.4 ns</td>
</tr>
</tbody>
</table>

New generation of RPC for BI:

- Higher rate capability: \( \rightarrow \) kHz/cm²
- Longer longevity: \( \rightarrow \) 10 years @ HL-LHC
- Higher spatial resolution: \( \rightarrow \) 1 cm
- Higher time resolution: \( \rightarrow \) 0.5 ns

- Reduced bakelite thickness:
  - Less voltage loss in bakelite \( \rightarrow \) improve the rate capability, larger induced signals
- Reduced gap size:
  - Less charge produced per event \( \rightarrow \) improve longevity, rate capability
  - Less high voltage applied but higher field \( \rightarrow \) better time resolution

- New generation FE electronic:
  - Higher amplification factor and high S/N ratio to compensate the lost gas amplification.
- Improved readout panel and method
  - Better mechanics structure, better signal transmission and better spatial resolution.
<table>
<thead>
<tr>
<th>Experiment / Timescale</th>
<th>Application Domain</th>
<th>Gas Detector 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>LHeC COLLIDER</td>
<td>Electron – Proton</td>
<td>RPC / MDT</td>
<td>Total area ~ 400 m²</td>
<td>Max. rate: 3 kHz/cm²</td>
<td></td>
</tr>
<tr>
<td>MUON SYSTEM</td>
<td>Collider Tracking/Triggering</td>
<td></td>
<td>Single unit detect: 2-5 m²</td>
<td>Time res.: ~0.4 ns</td>
<td></td>
</tr>
<tr>
<td>at HL-LHC</td>
<td></td>
<td></td>
<td></td>
<td>Rad. Hard.: 0.3 C/cm²</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Spatial res.: 1mm (RPC) 80 µm (MDT single tube)</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>FCC-ee and/or CEPC</td>
<td>Lepton Collider</td>
<td>µ-RWELL</td>
<td>Total area: 225 m²</td>
<td>Max. rate: 10 kHz/cm²</td>
<td></td>
</tr>
<tr>
<td>IDEA PRESHOWER DETECTOR</td>
<td>Tracking</td>
<td></td>
<td>Single unit detect: (0.5x0.5 m²) ~0.25 m²</td>
<td>Spatial res.: ~60-80 µm</td>
<td></td>
</tr>
<tr>
<td>SYSTEM START: &gt;2030</td>
<td></td>
<td></td>
<td></td>
<td>Time res.: 5-7 ns</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Rad. Hard.: &lt;100 mC/cm²</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>RPC</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>FCC-ee and/or CEPC</td>
<td>Lepton Collider</td>
<td>All HL-LHC technologies</td>
<td>Total area: 3000 m²</td>
<td>Max. rate: &lt; 500 kHz/cm²</td>
<td></td>
</tr>
<tr>
<td>IDEA MUON SYSTEM</td>
<td>Tracking</td>
<td>(MDT, RPC, MPGD, CSC)</td>
<td>Single unit detect: ~0.25 m²</td>
<td>Spatial res.: &lt;100 µm</td>
<td></td>
</tr>
<tr>
<td>START: &gt;2050</td>
<td></td>
<td></td>
<td></td>
<td>Time res.: ~ 3 ns</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Rad. Hard.: ~ C/cm²</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Redundant tracking and triggering;</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>FCC-hh COLLIDER</td>
<td>Hadron Collider</td>
<td>RPC or new generation</td>
<td>Total area: ~ 3500 m²</td>
<td>Max. rate: &lt;100 kHz/cm²</td>
<td></td>
</tr>
<tr>
<td>MUON SYSTEM</td>
<td>Tracking/Triggering</td>
<td>fast Timing MPGD</td>
<td>Single unit detect: 0.3-0.4 m²</td>
<td>Spatial res.: ~100µm</td>
<td></td>
</tr>
<tr>
<td>START: &gt; 2050</td>
<td></td>
<td></td>
<td></td>
<td>Time res.: &lt;10 ns</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Rad. Hard.: &lt; C/cm²</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Redundant tracking and triggering</td>
</tr>
</tbody>
</table>

- **Muon System at ILC**: no challenges, same technology as for HCAL (RPC, MPGD)
- **Muon System at LHeC**: CDR update uses design similar to Phase 2 in ATLAS, and in particular, Barrel Muon - second generation RPC and small Monitored Drift Tubes: 1 layer composed of a triplet of RPC 1mm gas-gaps and ~8 layers of MDT tubes assembled in station of ~ 2 m²
Muon System for the FCC-hh Collider

Barrel Muon system (2 layers): 2000 m² total
Endcap Muon System (2 layers): 500 m² total
Forward Muon System: (4 layers): 320 m² total

HL-LHC muon system gas detector technology will work for most of the FCC detector area

Forward region (r < 1 m) → more R&D would be needed

ATLAS Muon System HL-LHC: (kHz/cm²):
- MDTs barrel: 0.28
- MDTs endcap: 0.42
- RPCs: 0.35
- TGCs: 2
- Micromegas und sTGCs: 9-10

LHCb Muon System (MWPC):

<table>
<thead>
<tr>
<th>Region</th>
<th>Minimum</th>
<th>Average</th>
<th>Maximum</th>
</tr>
</thead>
<tbody>
<tr>
<td>M2R1</td>
<td>0.096 ± 0.0014</td>
<td>0.11 ± 0.02</td>
<td>0.15 ± 0.05</td>
</tr>
<tr>
<td>M2R2</td>
<td>0.17 ± 0.02</td>
<td>0.20 ± 0.02</td>
<td>0.23 ± 0.03</td>
</tr>
<tr>
<td>M3R1</td>
<td>0.017 ± 0.002</td>
<td>0.10 ± 0.03</td>
<td>0.13 ± 0.04</td>
</tr>
<tr>
<td>M3R2</td>
<td>0.33 ± 0.05</td>
<td>0.41 ± 0.06</td>
<td>0.48 ± 0.08</td>
</tr>
<tr>
<td>M3R3</td>
<td>0.11 ± 0.012</td>
<td>0.12 ± 0.02</td>
<td>0.15 ± 0.04</td>
</tr>
<tr>
<td>M4R1</td>
<td>1.75 ± 0.25</td>
<td>2.05 ± 0.01</td>
<td>2.10 ± 0.02</td>
</tr>
<tr>
<td>M4R2</td>
<td>1.58 ± 0.032</td>
<td>1.77 ± 0.04</td>
<td>1.82 ± 0.05</td>
</tr>
<tr>
<td>M4R3</td>
<td>1.97 ± 0.29</td>
<td>2.15 ± 0.42</td>
<td>2.22 ± 0.51</td>
</tr>
</tbody>
</table>

Table 4.5: Expected rates on the muon detector when operating at an instantaneous luminosity of $2 \times 10^{33}$ cm⁻²s⁻¹ at a collision energy of 14 TeV. The values are averages, in kHz/cm², over the chamber with the minimum illumination, the whole region and the chamber with maximum illumination. The values are extrapolated from measured rates at 8 TeV.
μ-RWELL for Preshower / Muon System @ FCC - ee

μ-RWELL Performance:

\[ \varepsilon = 98\% \]

\[ \sigma_\theta \sim 60\div80 \, \mu m \]

Rate ≥ 10 MHz/cm²

\[ \alpha_t \sim 5\div6 \, \text{ns} \]

μ-RWELL High-Rate Layout for LHCb Upgrade: μ-RWELL Low-Rate Layout for FCC-ee / CePC:

- Double Resistive layer (DRL)
- Silver Grid (SG)
- 3-D grounding
- Double DLC layers connected through matrices of conductive vias to the readout electrodes (density 1/cm²)
- 2-D grounding
- Single DLC layer grounded by means of conductive strip lines realized on the DLC layer (density 1/cm)

μ-RWELL Performance:

- 2-D current evacuation scheme based on a single resistive layer
- Conductive grounding line all around the perimeter of the active area
- Limitation for large area: the signal amplitude depends on the particle incident point → limited rate capability - O(10kHz/cm²)

Technology transfer with ELTOS:

Step 1: producing μ-RWELL PCB
- with top patterned (pad/strip)
- without bottom patterned

Step 2: DLC patterning
- in ELTOS with BRUSHING machine

Step 3: DLC foil gluing on PCB
- double 106-prepreg (~2x60 μm thick) (already used in ELTOS)
- pre-smoothing + 106-prepreg (~50 μm thick)
- single 1000-prepreg (~75 μm thick)

Step 4: top copper patterning

Step 5: Kapton etching on small PCB

Finalization
Detector @ CERN for final preparation

G. Bencivenni
Towards Large Area in Fast Timing GASEOUS DETECTORS

**Multi-Gap Resistive Plate Chambers (MRPC):**

- ALICE TOF detector (160m²) achieved time res. ~ 60 ps
- New studies with MRPC with 20 gas gaps using a low-resistivity 400 μm-thick glass → down to 20 ps time resolution

![Cross section of the double stack 20-gap MRPC](image)

### Gaseous Detectors: Micromegas with Timing (RD51 Picosec Collaboration)

- **σ ~ 25 ps timing resolution (per track)**

![Micromegas detector setup](image)

**Tested in RD51 testbeam July 2021**

<table>
<thead>
<tr>
<th>Experiment / Timescale</th>
<th>Application Domain</th>
<th>Gas Detector Technology</th>
<th>Total detector size / Single module size</th>
<th>Operation Characteristics / Performance</th>
<th>Special Requirements/ Remarks</th>
</tr>
</thead>
</table>
| ILC TPC DETECTOR      | e+e- Collider Tracking + dE/dx | MM, GEM (pads), InGrid (pixels) | Total area: ~ 20 m²  
Single unit detect: ~ 400 cm² (pads)  
~ 130 cm² (pixels) | Max. rate: < 1 kHz  
Spatial res.: <150µm  
Time res.: ~ 15 ns  
dE/dx: 5 % | Si + TPC Momentum resolution: dp/p < 9*10⁻⁵ 1/GeV  
Power-pulsing |
| CEPC TPC DETECTOR     | e+e- Collider Tracking + dE/dx | MM, GEM (pads), InGrid (pixels) | Total area: ~ 2x10 m²  
Single unit detect: up to 0.04 m² | Max. rate: >100 kHz/cm²  
Spatial res.: <100 µm  
Time res.: ~ 100 ns  
dE/dx: <5% | - Higgs run  
- Z pole run  
- Continues readout  
- Low IBF and dE/dx |
| IDEA CENTRAL TRACKER  | e+e- Collider Tracking/ Triggering | He based Drift Chamber | Total volume: ~ 50 m³  
Single unit detect: (12 m² X 4 m) | Max. rate: < 25 kHz/cm²  
Spatial res.: <100 µm  
Time res.: 1 ns  
Rad. Hard.: NA | Particle separation with cluster counting at 2% level |
| SUPER-CHARM TAU FACTORY | e+e- Collider Main Tracker | Drift Chamber | Total volume: ~ 3.6 m³ | Max. rate: 1 kHz/cm²  
Spatial res.: ~100 µm  
Time res.: ~ 100 ns  
Rad. Hard.: ~ 1 C/cm | - Challenging mechanics & mat. budget < 1% X0 |
| SUPER-CHARM TAU FACTORY | e+e- Collider Inner Tracker | Inner Tracker (cylindrical µR WELL, or TPC / MPDG read.) | Total area: ~ 2 - 4 m²  
Single unit detect: 0.5 m² | Max. rate: 50-100 kHz/cm²  
Spatial res.: ~<100 µm  
Time res.: ~ 5 -10 ns  
Rad. Hard.: ~ 0.1-1 C/cm² | - Challenging technical challenges: low mass, large area  
Endcap: moderate technical challenges |
| ELECTRON-ION COLLIDER (EIC) | Electron-Ion Collider Tracking | Barrel: cylindrical MM, µR WELL  
Endcap: GEM, MM, µR WELL | Total area: ~ 25 m² | Luminosity (e-p): 10³³  
Spatial res.: ~ 50- 100 um  
Max. rate: ~ kHz/cm² |

Gaseous Tracking Systems @ Future Colliders
TPC with MPGD Readout for ALICE Upgrade and ILC

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

- Upgrade for continuous TPC readout @ 50 kHz Pb-Pb collisions
- Phys. requirements:
  - IBF < 1%
  - Energy res. $\sigma(E)/E < 12\%$

TPC reinstallation in the ALICE cavern (August 2020)

ILC – TPC with MPGD-based Readout

Target requirement of a spatial resolution of 100 um in transverse plane and dE/dx resolution < 5% have been reached with all technologies (GEM, MM and GridPix)

If dE/dx combined with ToF using SiECAL, P < 10GeV region for pion-K separation covered

ILC: gating scheme, based on large-aperture GEM
- Machine-induced background and ions from gas amplific.
- Exploit ILC bunch structure (gate opens 50 us before the first bunch and closes 50 us after the last bunch)

Electron transparancy > 80% for $\Delta V \sim 5V$


M. Ruan
ILC TPC Performance: Technology Comparison

Target requirement of a spatial resolution of 100 µm in transverse plane and dE/dx resolution < 5% have been reached with all technologies (GEM, MM and GridPix)

- **GEM**: ~ 4-6 mm² pads & sufficient diffusion in multi-GEM structure
- **MM**: 20 mm² pads & charge spreading using resistive-anode readout
- **Gridpix**: 55x55 µm² pixels with digital readout

Micromegas + GEM studies for CEPC / FCC-ee to minimize ion backflow (gating is not possible)

ArXiv: 2003.01116

M. Ruan

Added value of TIME information for ILC: dE/dx combined with ToF (SiW-ECAL) for K-PID

H. Qi
Towards Large-Scale Pixel “GridPix” TPC

Testbeams with GridPixes:
160 GridPixes (Timepix) & 32 GridPixes (Timepix3)

Physics properties of pixel TPC:
• Improved dE/dx by cluster counting
• Improved meas. of low angle tracks
• Excellent double track separation
• Lower occupancy @ high rates
• Fully digital read out (TOT)

Quad board (Timepix3) as a building block → 8-quad detector (32 GridpPixs) with a field cage at test-beam @DESY in June 2021:

IEEE TNS 64 (2017) 5, 1159-1167

Testbeams with GridPixes:
160 GridPixes (Timepix) & 32 GridPixes (Timepix3)

3 modules for LP TPC @ DESY: 160 (1 x 96 & 2 x 32) GridPixs
320 cm² active area, 10.5 M. channels, new SRS Readout system

A PIXEL TPC IS REALISTIC!

P. Kluit @ IAS HEP Hong Kong (2022)

NIM A956 (2020) 163331

Module with 96 InGrids on 12 „octoboards“

LP Endplate with 3 modules

Testbeams with GridPixes: 160 GridPixes (Timepix) & 32 GridPixes (Timepix3)

- ion back flow can be further reduced by applying a double grid.
- Protection layer resistivity to be reduced
- New Timepix4 developments

IEEE TNS 64 (2017) 5, 1159-1167
**Pixel TPC for Z-Pole Running at CEPC and FCC-ee**

**Track Distortions in ILC TPC @ 250 GeV (L~10^{34} cm^{-2}):
**
- At ILC beam-beam effects are dominant: primary ion density 1-5 ions/cm³ → track distortions < 5 µm
- Gas amplification 10^3 → ILC without gating leads to track distortions of 60 µm → gating device is needed

**Track distortions @ CePC / FCC-ee:**
- HZ-pole running → γγ-background is very small → pad / pixels are OK – ion bkg. comparable to ILC @ 250 GeV
- Z-pole running (@10^{36})→ primary ion density 1000 ions/cm³ → serious tracks distortions O(mm); space charge effects could be calibrated (e.g. ALICE) ???
- Study pixel - TPC to replace pad - TPC for Z-pole running @ CEPC

**Crucial considerations for FCC-ee / CEPC @ Z pole running:**
- primary ionization of the gas;
- ions from the gas amplification stage;
- power consumption (no power pulsing possible);
- operation at 2 T during the Z-peak running;

- ✔ Ion backflow (IBF) can give a lot of additional charge → so IBF must be controlled (IBF = 5/1.5 → 80 / 14 um)
- ✔ Measuring IBF for Gridpix is a priority, expected 𝒪𝒪(1‰)

**Future R&D needed:**
- Optimal pad size to improve track resolution;
- Pixel size > 200 um or large → cost reduction
Cluster Counting / Charge Summation / Granularity

Simulation of PID with gaseous tracking and timing in ILD Prototype

Cluster Counting promises a few times better dE/dx resolution & separation power:

→ in time (small drift cells): requires very fast electronics
→ in space (TPC + pixelated endplates): requires good cluster finding algorithm

Cluster Counting ia an attractive option and is complementary to classical dE/dx by the spread charge

Some groups focus on it and ongoing for CEPC, FCC-ee…

Current full ILD reconstruction:

✓ 6 mm pads → 4.6 % dE/dx resolution
✓ 6 mm → 1 mm: 15% improved resolution via charge summing (dE/dx)
✓ 6 mm → 0.1 mm: 30% improved res. via cluster counting (dN/dx)
An ultra-light drift chamber (IDEA concept) targeted for FCC-ee and CePC was inspired by DAFNE KLOE Wire Chamber and by more recent version of it for MEG2 experiment.
IDEA Drift Chamber Concept

1st CHALLENGE: wire types – Carbon wires

2nd CHALLENGE: 350,000 wires!: wiring strategy

2nd CHALLENGE: mechanics and materials

3rd CHALLENGE: simulation – experimental tests

4th CHALLENGE: peak finding algorithms

Evolution of the MEG2 drift chamber wiring

Pre-stressed stays

GEANT4 with HEED clusterization model

Simulation package (IHEP-Beijing contribution)

Alternative algorithms

4th CHALLENGE: data reduction

The excellent performance of the cluster finding algorithms in offline analysis, relies on the assumption of being able to transfer the full spectrum of the digitized drift signals. However ...

- according to the IDEA drift chamber operating conditions:
  - 55-44 drift cells in 112 layers (≈130 hits/track)
  - maximum drift time of 500 ns
  - cluster density of 20 clusters/cm
  - signal digitization 12 bits at 2 G/s

... and to the FCC-ee running conditions at the 2-pole
- 100 KHz of 2 decays with 20 charged tracks/event multiplicity
- 30 KHz of 20 hadrons with 10 charged tracks/event multiplicity
- 2.5% occupancy due to beam noise
- 2.5% occupancy due to hits with isolated peaks

Reading both ends of the wires, \(\Rightarrow \text{data rate} \geq 1 \text{ TB/s}!\)

Solution consists in transferring, for each hit drift cell, instead of the full signal spectrum, only the minimal information relevant to the application of the cluster timing/counting techniques, i.e., the amplitude and the arrival time of each peak associated with each individual ionisation electron.

improvement needed regards the construction technique and the electronics needed for the cluster counting.

This can be accomplished by using a FPGA for the real time analysis of the data generated by the drift chamber and successively digitized by an ADC.

Single channel solution has been successfully verified.

G. Cianfrani et al., The Use of FPGA in Drift Chambers for High Energy Physics Experiments: May 31, 2017
DOI: 10.2741/2847

With this procedure data transfer rate is reduced to ~ 25 GB/s

Extension to 4-channel board is in progress. Ultimate goal is a multi-ch.
board (128 or 256 channels) to reduce cost and complexity of the system and to gain flexibility in determining the proximity correlations between hit cells for track segment finding and for triggering purposes.

Implementing ML algorithms on FPGA for peak finding
## Vertex & Tracking Challenges @ Future Lepton Colliders

### All-Silicon vs Silicon + Gaseous Tracking: some open technology questions to be addressed:

- **All-Silicon tracker (ILC / SiD, CLICdp, FCC / CLD, CEPC / FST concepts):**
  - ILC: number of layers; thin detectors, time-stamping capability, minimize material budget (2D/stitching); power savings / engineering;
  - Circular colliders: continuous operation → power-pulsing is not possible (aim less power consumption & active (increased) cooling) → increased material budget;

- **Silicon + TPC (ILC / ILD, CEPC baseline concepts):**
  - ILC: use of GEM-grid gating; dE/dx performance looks OK;
  - CC: can TPC stand for (extremely) high readout rate; ion feedback – can it cope @ Z-pole;
  - Calibration and detector alignment;
  - Low power consumption FEE ASIC;
  - Mechanical (field cage rigidity) and distortion (field cage quality, module flatness) challenges;

- **Silicon + Wire/Drift Chamber (FCC / IDEA, CEPC / IDEA):**
  - Can it cope with high rates @ Z-pole;
  - Half as many hits as in TPC → more Si-layers → momentum resolution sufficient ?;
  - Aging effects: hydrocarbon-based mixtures are not trustable for long-term operation in DC → search for different gas mixtures;
  - Very long wires (~4m), study/modify wires material;
  - dE/dx by cluster counting (depends on N_{hits} in DC);
MPGD Technologies @ Future R&D Trends

**RESISTIVE MATERIALS** and related detector architectures for single-stage designs (μPIC, μ-RWELL, RPWELL, resistive MM)

→ improves detector stability; single-stage is advantage for assembly, mass production & cost.

- **Diamond-like carbon (DLC) resistive layers**
  → Solutions to improve high-rate capability (≥ MHz)

- New manufacturing techniques & structures:
  - Solid-state photon and neutron converters, **INNOVATIVE NANOTECHNOLOGY COMPONENTS** (graphene layers);
  - Emerging technologies related to novel PCs, MicroElectroMechanical Systems (MEMS), sputtering, 3-D printing of amplifying structures and cooling circuits.

![Diagram of different resistive protection approaches with Micro-Megas](image-url)

- Resistive **DLC Collaboration**

![Diagram of DLC cathode, anode, cathode pickup, and anode readout](image-url)
Graphene-based Functional Structures and Nanostructures for novel MPGD Concepts

Graphene layers for: ion-backflow suppression, protection of photocathodes, solid conversion layers

The unique properties of two-dimensional materials such as graphene as well as carbon-based nanostructures offer new perspectives for novel gaseous radiation detectors. This may include performance improvements for detectors for HEP experiments as well as new application fields combining wideband sensitivity of advanced materials with high gain factors and granularity offered by Micro Pattern Gaseous Detectors.

PhD project of Giorgio Orlandini (FAU Erlangen-Nürnberg) in EP-DT-DD Gaseous Detector Development lab

Application 1: Suspended graphene for ion backflow suppression and gas separation

Suppressing ion backflow can significantly improve high-rate capabilities and reduced electric field distortions in Time Projection Chambers.

Application 2: Protection of photocathodes with graphene layers

Atomically thin coating layers could protect sensitive photocathodes such as CsI against environmental factors and ion bombardment, which is important for preserving specifications of precise timing detector in harsh ion-back flow conditions. Additionally, modifications of the work functions of converter layers can be used to increase QE.

Application 3: Graphene and nanostructures for photon conversion and as solid converters

Graphene quantum dots (GQD), carbon nanotubes and graphene have been shown to exhibit broadband sensitivity and could be used as versatile conversion layers. Utilising solid conversion layers enables high detection efficiencies and can be used for precise timing with gaseous radiation detectors.

First work on GEM & graphene layers: NIMA824 (2016) 571
Structure in **WG2**, alignment with the scientific program of the ECFA roadmap through the applications, related to future facilities challenges outlined by R&D Themes (DRDT), but also to the GSRs.

**DRD1 Scientific Organization: Working Groups**

<table>
<thead>
<tr>
<th>DRDT</th>
<th>Applications</th>
<th>Tools and infrastructures</th>
</tr>
</thead>
<tbody>
<tr>
<td>DRDT1.1</td>
<td>Inner and central tracking with PID capability</td>
<td>WG1 Gas and material studies</td>
</tr>
<tr>
<td>DRDT1.2</td>
<td>Photon detection (PID)</td>
<td>WG3 Detector physics, simulations and software tools</td>
</tr>
<tr>
<td>DRDT1.3</td>
<td>Timing detectors</td>
<td>WG4 Electronics for gaseous detectors</td>
</tr>
<tr>
<td>DRDT1.4</td>
<td>Muon system</td>
<td>WG5 Detector production</td>
</tr>
<tr>
<td>DRDT1.4</td>
<td>Calorimetry</td>
<td>WG6 Common test facilities</td>
</tr>
<tr>
<td>DRDT1.4</td>
<td>TPC for rare event searches</td>
<td>WG7 Training and dissemination</td>
</tr>
</tbody>
</table>

**DRDT1.3**

**DRDT1.4**

**WG2**

**WG3**

**WG4**

**WG5**

**WG6**

**WG7**

**WG8**
Structure of the DRD1 document:

- Executive summary
- Research topics and Work plan
- WorkPackages (strategic R&D in ECFA Roadmap described in 3.2)
- Scientific organization
- Resource and infrastructures

The draft document already sent to the contact persons

DRD1 Community proposal discussion (Jun. 22-23):
https://indico.cern.ch/event/1273991/
### Challenges for the future muon systems

- Extend state-of-the-art rate capability and longevity by minimum one order of magnitude or more in the highest eta region (up to an order of MHz/cm²)
- Enable detectors efficiently working with suitable low GWP mixtures
- Two objectives above can be favored in 3 ways:
  - low noise electronics integrated in a highly stable and noise immune Faraday cage
  - detector geometries increasing the signal collection
  - use of innovative resistive material for suppressing discharges on the electrodes.
- Time resolution $O(10-100\text{ps})$ for timing applications in a very high rate collider, (e.g., for identifying bunch-crossing, pile-up mitigation, and improved determination of the particle velocity)
- Large-scale serial production.
- Large series industrializes production

### Applications
Future electron colliders (ILC, FCC-ee, CepC), Muon collider, Hadron Physics, FCC-hh. Technologies: RPC, Micromegas and GEM, mRWELL, gridsPix, m-PIC, FTM…

### Example of DRD1 Work Package: Muon Systems

<table>
<thead>
<tr>
<th>Task</th>
<th>Performance Goal</th>
<th>DRD1 WG#</th>
<th>ECPA DRD7</th>
<th>Comments</th>
<th>Delta new 3 y</th>
<th>Interested Institutes</th>
</tr>
</thead>
<tbody>
<tr>
<td>New resistive materials (RPC) and production techniques for resistive layers</td>
<td>- Develop low-cost resistive layers (technology dependent) - Increase rate capability</td>
<td>W0G3 (3.1C, 3.2D), W0G7 (7.1, 7.5)</td>
<td>1.1, 1.2</td>
<td>HPL, low resistivity glass, Semiconductors, Printed resistive patterns</td>
<td>Design, construction, and test of prototypes with new production techniques</td>
<td>INFN-RMN, INFN-PD, KOBEL, Pavia</td>
</tr>
<tr>
<td>New resistive materials (MPGD)</td>
<td>- Stable up to gains of $O(10^4)$ - High gain in a single multiplication stage</td>
<td>W0G3 (3.1C, 3.2D), W0G4, W0G7 (7.1, 7.9)</td>
<td>1.2</td>
<td>Conceptual electronics design based on gas detector simulation and experimental measurements</td>
<td>Development and test of a complete prototype</td>
<td>USTC, INFN-PD, INFN-RMN, INFN-LNF, INFN-FE</td>
</tr>
<tr>
<td>New front-end electronics</td>
<td>- J1 threshold - High-sensitivity electronics (together with new detector structures) to achieve stable and efficient operation up to $O(10^4)$</td>
<td>W0G5, W0G7 (7.1, 7.2)</td>
<td>1.1</td>
<td>- Integration of the FEE in the detector Faraday cage - Integration of electronics and readout PCB</td>
<td>First prototype by end of 2024 for commissioning at test beam</td>
<td>INFN-Bologna</td>
</tr>
<tr>
<td>Scalable multichannel readout system</td>
<td>- Front-end link concentrates to a powerful FPGA with possibilities of triggering and $O(20$GB/s) to DAQ</td>
<td>W0G3 (3.1A, 3.1B, 3.3C), W0G4, W0G7 (7.1, 7.4)</td>
<td>1.1, 1.2</td>
<td>- FPGA-based interface - FPGA with embedded processors for triggering and readout - Customized firmware and software can be bootstrapped from existing readout system</td>
<td>CERN, WURZBURG, INFN-BA, INFN-TIFFIN</td>
<td></td>
</tr>
<tr>
<td>Eco-friendly gases</td>
<td>- Guarantee long-term operation - Explore compatibility and optimized operation with high-GWP gases</td>
<td>W0G3 (3.1B, 3.2D), W0G5, W0G7 (7.1, 7.2)</td>
<td>1.1</td>
<td>- Ageing studies - Leak mitigation and maintenance of existing systems</td>
<td>- Test and characterization of gas-detection technologies with high-GWP gases (broadly)</td>
<td>INFN-MILANO-BOSCO</td>
</tr>
<tr>
<td>Manufacturing</td>
<td>- Construction of large area detectors at low cost - Modular design - Technology transfer scheme and training center for production</td>
<td>W0G3 (3.2D), W0G5, W0G7 (7.1, 7.2)</td>
<td>1.3</td>
<td>- Optimization of the manufacturing procedures to minimize time consuming or costly steps</td>
<td>- Design and manufacturing of large area detector - Large area DLC production</td>
<td>INFN-Bologna, INFN-RMN, INFN-TIFFIN</td>
</tr>
<tr>
<td>Thinner layers and increased mechanical precision over large areas</td>
<td>- Test to experience the ultimate limits to thinning down the detector</td>
<td>W0G3 (3.1B, 3.1D, 3.2B), W0G4, W0G7 (7.1, 7.3)</td>
<td>1.1</td>
<td>- Discharge probability - Aging</td>
<td>- Test and characterization of gas-detection technologies with high-GWP gases (broadly)</td>
<td>INFN-Bologna, INFN-RMN, INFN-TIFFIN</td>
</tr>
<tr>
<td>Longevity on large detector areas</td>
<td>- Study discharge rate and the impact of irradiation and transported charge (C/cm²)</td>
<td>W0G3 (3.1B, 3.1D, 3.2B), W0G4, W0G7 (7.1, 7.3)</td>
<td>1.1</td>
<td>- Discharge probability - Aging</td>
<td>- Test and characterization of gas-detection technologies with high-GWP gases (broadly)</td>
<td>INFN-Bologna, INFN-RMN, INFN-TIFFIN</td>
</tr>
</tbody>
</table>
Example of DRD1 Work Package: Inner/Central Tracking

Challenges for the TPC

- Good dE/dx resolution, partly driven by a good gain uniformity;
- very low (gain x Ion Back Flow) to drastically reduce space charge distortions;
- high readout granularity to cope with the particle multiplicity;
- electronics with low power dissipation to meet the increased density of readout channels.
- large area coverage at reduced low cost, relying on lightweight mechanical structures based on composite materials.

Area of application: future electron colliders (ILC, FCC-ee, CEPC). Timeline: 2035-2040, most of the R&D goals should be reached by 2030 to allow for timely construction.