A Muon detector based on the \( \mu \)-RWELL technology

Overview

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For evident reasons of price, gas detectors are the obvious choice for equipping these extremely large surfaces.
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Muon detectors for FCC-ee
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r>1m rate<500 kHz/cm²
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FCC-hh detector

ATLAS muon system HL-LHC rates (kHz/cm\(^2\)):
MDTs barrel: 0.28
MDTs endcap: 0.42
RPCs: 0.35
TGCs: 2
Micromegas and sTGCs: 9-10

Table 4.5: Expected rates on the muon detector when operating at an instantaneous luminosity of \(2 \times 10^{33} \text{ cm}^{-2} \text{s}^{-1}\) at a collision energy of 14 TeV. The values are averages, in kHz/cm\(^2\), 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.

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<td>M2R3</td>
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HL-LHC muon system gas detector technologies, and especially MPGDs, would work for most of the FCC-hh detector area.
Muon detectors for CepC
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In the baseline option, inspired from ILD, the muon detection system is composed of two layers of RPC stations.

An upgrade of the muon detector by using MPGDs could provide a much finer space resolution with a similar time resolution at a relatively modest increase in price.

The fine space resolution of the detectors could allow to obtain a standalone muon momentum measurement and to trace back the muon stabs to the tracker tracks.
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Principle of operation of MPGDs
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Improve gas detectors
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Slow ion motion
Limited multi-track separation

Reduce multiplication region size
Faster ion evacuation
Higher spatial resolution

S. Franchino, 2016
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S. Franchino, 2016
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**Improving gas detectors**

- Slow ion motion
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*First MPGD: Micro Strip Gas Chamber (MSGC) OED, 1988*

Reduce the size of the detecting cell (~100 µm) using chemical etching techniques
Use PCB technology to obtain very fine electrodes O(10 µm)
Same working principle as proportional wire chambers
- Conversion region (low E field)
- High E field in well localised regions where multiplication happens

S. Franchino, 2016
Evolution of MPGDs

Micro Gap Chambers

Micro Gap Wire Chamber

Micro Wire Chamber


MicroWELL

MicroGroove

MicroPin

R. Bellazziniet al Nucl. Instr. and Meth. A423(1999)125


P. Rehak et al., IEEE Nucl. Sci. Symposium seattle 1999


μPIC

DT Training Seminar

Ochi et al NIMA471(2001)264

S. Franchino, 2016
More recent MPGDs
More recent MPGDs

F. Sauli, NIM. A386(1997)531

GEM (std, Thick, glass, ...)

Gain
~20
~20
~20
~8000

S. Franchino, 2016
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I. Giomataris et al., NIM A 376 (1996)

Micromegas
(bulk, micro bulk, resistive, ..)

S. Franchino, 2016
More recent MPGDs

- **GEM (std, Thick, glass, ...)**
  - F. Sauli, NIM. A386(1997)531
  - Drift cathode, Gain: ~20 for GEM 1, GEM 2, GEM 3, ~8000 for readout PCB

- **Micromegas (bulk, micro bulk, resistive, ..)**
  - I. Giomataris et al., NIM A 376 (1996)

- Ageing: OK (no thin wires)
- Spark protection: multiple amplification stages, resistive electrodes

S. Franchino, 2016
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- Fine patterning realized with PCB photolithography techniques
  - Fine position resolution (< 100 microns)
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Properties of MPGDs

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- Fine patterning realized with PCB photolithography techniques
  - Fine position resolution ( < 100 microns )
  - Good timing resolution ( < 10 nsec )
  - High rate capability ( > 10^7 counts/mm )
- Excellent radiation hardness
- Use components that can be mass produced by industry
The $\mu$-RWELL technology
The $\mu$-RWELL technology

The $\mu$-RWELL detector is composed of two elements: the cathode and the $\mu$-RWELL_PCB.
The \( \mu \)-RWELL technology

The \( \mu \)-RWELL detector is composed of two elements: the **cathode** and the \( \mu \)-RWELL\_PCB .

![Diagram of the \( \mu \)-RWELL detector with specifications](image)

- **Drift/cathode PCB**
  - Well pitch: 140 \( \mu \)m
  - Well diameter: 70-50 \( \mu \)m
  - Kapton thickness: 50 \( \mu \)m

- **Copper top layer (5\( \mu \)m)**
- **DLC layer (0.1-0.2 \( \mu \)m)**
- **R rigid PCB readout electrode**
- **Well diameter**: 70-50 \( \mu \)m

G. Bencivenni et al., 2015\_JINST\_10\_P02008
The µ-RWELL technology

The µ-RWELL detector is composed of two elements: the cathode and the µ-RWELL_PCB.

The µ-RWELL_PCB is realized by coupling:

- Drift/cathode PCB
- Copper top layer (5µm)
- DLC layer (0.1-0.2 µm)
- R ~10 - 200 Ω/□
- Well pitch: 140 µm
- Well diameter: 70-50 µm
- Kapton thickness: 50 µm
- Gas gap 4-7 mm

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1. a “suitable WELL patterned kapton foil” as “amplification stage”

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Drift/cathode PCB

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The $\mu$-RWELL\_PCB is composed of:

1. Copper top layer (5µm)
2. DLC layer (0.1-0.2 µm)
3. Rigid PCB readout electrode

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Rigid PCB readout electrode

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2. a “resistive stage” for the discharge suppression & current evacuation

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   i. “Low particle rate” (LR) $\sim 100$ kHz/cm$^2$:
      - single resistive layer $\rightarrow$ surface resistivity $\sim 100$ M$\Omega$/☐ (CMS-phase2 upgrade - SHIP)

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3. a standard readout PCB

Drift/cathode PCB

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- DLC layer (0.1-0.2 µm)
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3. a standard readout PCB

Collaboration of INFN, CERN, Eltos
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3. a standard readout PCB

Collaboration of INFN, CERN, Eltos

Major advantages wrt. GEM
- 1 kapton foil instead of 3
- No stretching
- Spark safe
μ-RWELL References

Low rate version:

High rate version:
- G. Bencivenni et al., “Recent results of μ-RWELL detector”, PoS(MPGD2017)019
- G. Bencivenni et al., “The μ-RWELL technology: status and perspective”, to be submitted to PoS

For more informations on the μ-RWELL technology please follow M. Poli Lener’s poster “The Micro-Resistive-WELL (μ-RWELL) detector for large area Muon systems at future circular colliders”
μ-RWELL features
µ-RWELL features

• µ-RWELL guiding principles
  • Retain the same excellent performances of GEM and MM
  • Improve the resistance to sparks
  • Simplify the components construction and final assembly
**μ-RWELL features**

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• More robust
  • Resistive DLC layer makes the detector very spark safe
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FCC 2018 week - A Muon detector based on the $\mu$-RWELL technology - Paolo Giacomelli

$\mu$-RWELL features

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- More robust
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- Simpler final assembly
  - Kapton foil glued to PCB: no stretching needed

- Less components, simpler construction $\rightarrow$ significant cost reduction
The High Rate scheme (LHCb)

1. Copper layer 5 µm
   Kapton layer 50 µm
   DLC layer: 0.1 – 0.2 µm
   (10-200 MΩ/□)

2. 2nd resistive kapton layer with ~ 1/cm²
   “through vias” density
   DLC-coated kapton base material

3. 2nd resistive kapton layer
   pad/strips readout on standard PCB

4. DLC-coated base material after copper and kapton chemical etching
   (WELL amplification stage)

This resistive scheme allows to reach a detector rate capability > 1 MHz/cm² with a negligible gain drop (see M. Poli Lener’s poster: «The micro-Resistive-WELL (µ-RWELL) detector for large area Muon system at Future Circular Colliders»

- G.Bencivenni et al., PoS(MPGD2017)019
- G.Bencivenni et al., to be submitted to Pos
CMS GE1/1 \(\mu\)-RWELL prototype at H8 test beam
CMS GE1/1 $\mu$-RWELL prototype at H8 test beam

Ar/CO$_2$/CF$_4$
45/15/40

VFAT FEE
CMS GE1/1 $\mu$-RWELL prototype at H8 test beam

**Efficiency**

- **Ar/CO$_2$/CF$_4$**
  - 45/15/40

- VFAT FEE

---

FCC 2018 week - A Muon detector based on the $\mu$-RWELL technology - Paolo Giacomelli
CMS GE1/1 $\mu$-RWELL prototype at H8 test beam

**Efficiency**

- $\varepsilon$ (%)
- $97\%$

**Time resolution**

- $\sigma_t$ (ns)
- $\sim 6$ ns

limited by VFAT saturation

Ar/CO$_2$/CF$_4$

VFAT FEE

45/15/40
CMS GE1/1 $\mu$-RWELL: GIF++ ageing test

1) GE1/1 $\mu$-RWELL (ArCO$_2$)

2) “high rate” $\mu$-RWELL (ArCO$_2$CF$_4$) 10cmx10cm

3) reference $\mu$-RWELL (ArCO$_2$) 10cmx10cm

$\mu$RWELL prototypes exposed inside the GIF++
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\( \mu \)RWELL prototypes exposed inside the GIF++

GE1/1 has accumulated a dose of \(~32\) mC/cm\(^2\) (more than 10 times the dose after 10 years of HL-LHC)
CMS GE2/1 sector $\mu$-RWELL prototype
CMS GE2/1 sector $\mu$-RWELL prototype

M4 $\mu$-RWELL
CMS GE2/1 sector $\mu$-RWELL prototype

M4 $\mu$-RWELL prototype is a trapezoid of ~55-60x50 cm$^2$

Largest $\mu$-RWELL ever built and operated!
CMS GE2/1 sector $\mu$-RWELL prototype

GE2/1 20° sector with 2 M4 $\mu$RWells
(2 m height, 1.2 m base)

M4 $\mu$-RWELL prototype is a trapezoid of ~55-60x50 cm²
Largest $\mu$-RWELL ever built and operated!

M4 $\mu$-RWELL
H4 test beam with 150 GeV muons:
- Voltage scan (amplification scan)
- Uniformity scan across the surface of the detector at 530 V (~12000 gain, still to be conditioned)

The excellent results obtained demonstrate the great collaboration between INFN-Eltos and Rui de Oliveira’s lab.

GE2/1 20° sector with 2 M4 µRWells
(2 m height, 1.2 m base)

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Largest µ-RWELL ever built and operated!
CMS GE2/1 sector $\mu$-RWELL: HV scan

M4 right side:
- Drift Field = 3.0 kV/cm
- $V_{\mu\text{-RWELL}}$ = scan

Efficiency = \[ \frac{\# \text{ hits (Tracker 1 & Tracker 2 & M4 right)}}{\# \text{ hits (Tracker 1 & Tracker 2)}} \]

![Graph showing efficiency vs. $V_{\mu\text{-RWELL}}$](image)

- Muon beam
- Ar/CO$_2$ 70/30
CMS M4 \(\mu\)-RWELL: homogeneity

Efficiency = \(\frac{\# \text{ hits (Tracker 1 & Tracker 2 & M4 right)}}{\# \text{ hits (Tracker 1 & Tracker 2)}}\)

M4 right side:
- Drift Field = 3.0 kV/cm
- \(V_{\mu\text{-RWELL}} = 530\) V

Homogeneity at \(HV=530\) V, TOP RIGHT M4
- Efficiency = \(\varepsilon \approx 98\%\)

Homogeneity at \(HV=530\) V, BOTTOM RIGHT M4
- Efficiency = \(\varepsilon \approx 98\%\)

Beam on the edge of the detector
NOT inefficiency!!
CMS GE2/1 sector $\mu$-RWELL prototype

M4 right side:
- Drift Field = 3.0 kV/cm
- $V_{\mu}$-RWELL = 530 V

Efficiency = \frac{\# \text{ hits (Tracker 1 & Tracker 2 & M4 right)}}{\# \text{ hits (Tracker 1 & Tracker 2)}}

Muon beam

![Graph showing the efficiency distribution across M4 chamber.

Distance from the bottom of M4 (cm)
Distance from the center of M4 (cm)
μ-RWELL High Rate version

When: 5 - 19 July 2017

2 GEM Trackers (10x10 cm$^2$) RD51 setup

2 μ-RWELLs (10x10 cm$^2$) HR scheme

1 μ-RWELL (CMS-GE2/1 M4 shape) LR scheme
**μ-RWELL High Rate version**

**Tracker GEMs**
- Gas mixture: Ar/CO$_2$ 70/30

**2 GEM Trackers**
- 10x10 cm$^2$
- 400 μm strip-pitch
- X-Y strip readout

**HR μ-RWELLs**
- Gas mixture: Ar/CO$_2$/CF$_4$ 45/15/40

**HR μ-RWELL prototypes**
- 10x10 cm$^2$
- 6x8 mm$^2$ pad readout

**All detectors readout:**
- APV 25
- (Charge Centroid analysis)
\(\mu\)-RWELL High Rate version

- Drift Field = 2.5 kV/cm
- \(V_{\mu\text{-RWELL}} = \text{scan}\)

\[
\text{Efficiency} = \frac{\# \text{ hits (Tracker 1 & Tracker 2 & HR proto)}}{\# \text{ hits (Tracker 1 & Tracker 2)}}
\]

Ar/CO\(_2\)/CF\(_4\) 45/15/40

Courtesy of LNF-DDG
μ-RWELL High Rate: rate capability

Pion beam

Rate = beam scint. counts/4.2 s/(σxσy*2.53^2)

Beam profile: GEM trackers

Ar/CO\textsubscript{2}/CF\textsubscript{4} 45/15/40

Courtesy of LNF-DDG
Summary of results with $\mu$-RWELLs
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- GE1/1 prototype at H8 test beam in 2016
  - Very good time resolution, $\sigma_t < 6$ ns (about 4.5 ns obtained)
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  - Gain stability up to 20000
  - No dark current, no discharges
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- HR $\mu$-RWELL tested up to rates $> 1$ MHz/cm$^2$
Conclusions
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- MPGDs, and in particular the $\mu$-RWELL technology, are an excellent option for realising future large Muon detection systems.
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- MPGDs, and in particular the $\mu$-RWELL technology, are an excellent option for realising future large Muon detection systems
- A large mosaic of $\sim$50x50 cm$^2$ $\mu$-RWELL detectors is probably the best solution from the industrial point of view
Conclusions

• MPGDs, and in particular the $\mu$-RWELL technology, are an excellent option for realising future large Muon detection systems.

• A large mosaic of $\sim$50x50 cm$^2$ $\mu$-RWELL detectors is probably the best solution from the industrial point of view.

• An upgrade of the muon system for the CLD detector of FCC-ee, substituting the RPCs with $\mu$-RWELL detectors is an attractive opportunity.
Conclusions

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- The IDEA detector concept for FCC-ee implements $\mu$-RWELL.
  - This system can provide a time resolution of the order of 5 ns and a space resolution of $<200$ $\mu$m.
Conclusions

• MPGDs, and in particular the \( \mu \)-RWELL technology, are an excellent option for realising future large Muon detection systems.

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  - Trace back the muon stubs to the tracker tracks
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  - Stadalone muon reconstruction.
  - Trace back the muon stubs to the tracker tracks.
  - Provide excellent momentum resolution and a robust muon trigger.
- $\mu$-RWELL technology is also suitable for the muon systems of detectors at future hadron colliders, like FCC-hh.
Backup
Muon detectors for FCC-ee
Muon detectors for FCC-ee

There are two detector concepts for FCC-ee: the CLD (CLIC-inspired detector) model and the IDEA concept.
Muon detectors for FCC-ee

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In the CLD (CLIC-inspired detector) the muon system is made of 6 muon stations interleaved in the iron return yoke, and every muon station is made of RPCs.
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Also this muon detector could be improved by adopting finer space resolution MPGDs.
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In the CLD (CLIC-inspired detector) the muon system is made of 6 muon stations interleaved in the iron return yoke, and every muon station is made of RPCs.

Also this muon detector could be improved by adopting finer space resolution MPGDs.

There is also the IDEA concept, discussed in the previous slide.


- Proposed for Phase II upgrade (~2023)
- Need high granularity ~ 0.1mm
- BG rate > 100kHz/cm² (HIP, gamma)
- Rate tolerant, Pixel type detector needed

\( \mu \)-PIC with resistive Diamond-LC electrodes:

\( \mu \)-PIC with resistive Diamond-LC electrodes:

Spark rate reduction using resistive \( \mu \)-PIC for fast neutron

\( \mu \)-RWell Detector:

- Very reliable
- Almost completely discharge-free
- Adequate for high particle rates \( O(1\text{MHz/cm}^2) \) thanks to the segmented-resistive-layer
- Suitable for large area applications (1.8 x 1.2 m² proto was tested in 2017)
Muon detector for FCC-ee

CLIC Detector requirements from physics

- **momentum resolution**
  - Higgs recoil mass, Higgs coupling to muons, BSM (smuon and neutralino masses)
  - for high $p_T$ tracks

\[ \sigma_{p_T}/p_T^2 \simeq 2 \times 10^{-5} \text{GeV}^{-1} \]

Example: $H \rightarrow \mu\mu$ @ 3 TeV

- **jet energy resolution**
  - W/Z di-jet mass separation
  - jet energy up to 1 TeV

\[ \sigma_E/E \simeq 3.5\% \]

- **impact parameter resolution**
  - c/b tagging, Higgs BR

\[ \sigma_{d_0} = a^2 + \frac{b^2}{p^2 \sin^3 \theta} \]
\[ a \lesssim 5\mu m \quad b \lesssim 15\mu m \text{GeV} \]

- **lepton ID efficiency** > 95%
  - over full energy range

- **forward coverage**
  - electron and photon tagging (e.g. dark matter studies)
GEM Phase 2 Forward muon system

- **Muon tagger** at highest $\eta$ ($\eta<2.8$)
- 36 20° super-module wedge each consists 6 layers of chambers.
- Numb. of chambers: 216
- Installation: July 2024

- **ME0**
- $1.6<|\eta|<2.4$
- 36 20° super-chambers
- Total number of chambers: 72
- Installation: YETS 2022

- **GE2/1**
- L1 trigger rate reduction, enhance via redundancy, reconstruction
- ME0 detector extends coverage and performance of muon Id and trigger beyond $\eta=2.4$ up to $\eta<2.8$
GE1/1 $\mu$-RWELL: test at H8 (nov. 2016)

1. Construction & test of the first 1.2x0.5m$^2$ (GE1/1) $\mu$-RWELL 2016
2. Mechanical study and mock-up of 1.8x1.2 m$^2$ (GE2/1) $\mu$-RWELL 2016-2017
3. Construction of the first 1.8x1.2m$^2$ (GE2/1) $\mu$-RWELL (only M4 active) 01-09/2017

GE1/1 $\mu$-RWELL prototype

H8 Beam Area (18th Oct. 9th Nov 2016)
Muon/Pion beam: 150 GeV/c

N° 2 LHCb $\mu$-RWELL protos
10x10 cm$^2$
40-35 MΩ/□
400 μm pitch strips

N° 1 CMS $\mu$-RWELL proto
100x50 cm$^2$
70 MΩ/□
800 μm pitch strips
GE2/1 $\mu$-RWELL: GIF++ ageing test

**Context:**
CMS Muon System, R&D Phase II Upgrade with MPGD: $\mu$-RWELL

**Motivations:**
Need to qualify the behaviour and performance of $\mu$-RWELL detectors in a harsh radiation environment.

**Duration of the test:**
will stay at least 6 months. GE2/1 HL-LHC dose achievable in a short time (few weeks)

1) GE1/1 $\mu$-RWELL (ArCO$_2$)
2) “high rate” $\mu$-RWELL (ArCO$_2$CF$_4$) 10cmx10cm
3) reference $\mu$-RWELL (ArCO$_2$) 5cmx5cm
Highest spikes are of the order of 1-2 μA. This further demonstrates the intrinsic robustness of μ-RWELL.
GE2/1 alternative option: $\mu$RWELL

We have built a full scale GE2/1 sector with 2 M4 $\mu$-RWELL operating detectors.

1) M4 left and right are mirrored.
2) Size: 606.5 x 498.5 x 1 mm
3) Strip layout inspired to the GE2/1 GEM option
4) Final drawing finished (Gatta-LNF)
5) DLCed foils ready (Ochi-Kobe)
6) Preliminary tests at ELTOS done
7) PCB production at Eltos done, then glueing with kapton foil

Modules fit within 74 mm splicing → dead space less than 0.01%
GE2/1 sector equipped with two active M4 $\mu$RWELL

Brought to H4 test beam on July 12th