Aging effects in the COMPASS hybrid Micromegas+GEM pixelized detectors

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The COMPASS experiment
The hybrid Micromegas
Beam conditions 2015-2022
Detector performances
Conclusions
Fixed target experiment for hadron structure studies

- Muon and hadron beams up to 200 GeV
- 2 spectrometers
- Taking data 2002-2022
- High statistic experiment (> 30 kHz trigger rate)
- High intensities in 2015-2018 (μ and π)
**First COMPASS Micromegas (2001-2014)**

- First Micromegas detectors installed in a particle physics experiment (installed 2001-2002)
- 40x40 cm² area on light board sandwich
- Good resolutions: 70-100 μm, 10 ns
- Light gas mixture Ne + 10% C₂H₆ + 10% CF₄, to keep discharge rate low
- Blind center to reduce electronics occupation
- Low noise electronics based on SFE16 (threshold ~ 4000 e⁻)
- 12 planes on X, Y, U, V (45°) orientations in 3 stations
- Lasted more than 10 years (2001-2012) with a few refurbishing: drift gap increased to 5mm, mesh from Ni to Cu
- Stable performance with up to $10^{13}$ p/cm² integrated
NEW PIXELIZED MICROMEGAS DETECTORS

Motivations
- Tracking at very small angle with same material budget as old Micromegas
- Reduction of discharge rate required for Drell-Yan program (high intensity pion beam)
- Improve robustness

Project
- Discharge reduction based on hybrid Micromegas, with an additional GEM foil
- Detector center readout with pixels, same active area 40x40 cm²
- Robustness with bulk Micromegas technology
- Highly integrated APV-25 readout electronics (1024 → 2560 channels / plane)
- Same gas mixture Ne + 10 C₂H₆ + 10% CF₄

3 layers of photosensitive coverlay tightening the mesh

stainless steel woven mesh

Cu strips

PCB board

bulk technology

APV chip

protection circuit
Hybrid MM with 1 GEM foil
- GEM foil for preamplification (gain 10-20)
- Micromegas stage at lower gain → fewer discharge

Studied with muon and pion beams
- Tests at PS (low energy pions) and SPS in association with Saclay CLAS12 group
- Spark rates decreased by factor 10 to >100

spark prob. per hadron

CERN PS ~1 GeV pion beam

Ar + 5% isobutane

M. Vandenbroucke, G. Charles
Too high flux for strips in center
- Expected particle flux $> 100$ kHz/mm²
- $> 500$ kHz/channel with strip read-out $\rightarrow$ would lead to 10% electronics inefficiency

Rectangular pixels + strips in periphery
- 400 μm pitch pixels, like strips $\rightarrow$ same spatial resolution
- 1280 pixels + 1280 strips
- 40x40 cm² total active area
- Material budget $\sim 0.38\%$ $X_0$ per plane
Drell-Yan runs 2014-2015 and 2018
- High flux 190 GeV pion beam
- \( \sim 3.5 \times 10^8 \) pions per 5s spill
- \( \sim 23 \times 10^{13} \) pions in total (9 in 2015, 14 in 2018)
- Several thick targets in beam
  - 110 cm polarized ammonia
  - 7 cm aluminum
  - 150 cm tungsten plug + absorber
- Beam stopped in tungsten plug but lot of secondaries and low energy particles
- Detectors just after absorber → large flux
- Additional Lithium shield before MM added in 2018

DVCS runs 2016-2017
- Medium intensity 160 GeV \( \mu^+ \) and \( \mu^- \) beam on 2.5m-long hydrogen target
- \( \sim 6 \times 10^7 \) muons per 5s spill
- \( 3 \times 10^{13} \) muons delivered in total

Transversity run 2021 and 2022
- High flux 160 GeV muon beam
- 1.2m-long polarized \( ^6 \)LiD target
- \( 2.5 \times 10^8 \) muons per 5s spill
- \( 1.3 \times 10^{13} \) muons in total

Flux estimations by N. d'Hose, C. Quintans and J. Matousek
Estimations based on simulations

- FLUKA MC with realistic absorber geometry
- Done by Angelo Maggiora (INFN Torino) 2011-2015
- Radiation at 1st MM station
- With and without additional Li layer before MM
- Total irradiation of first MM station in 2015 + 2018 estimated to
  - $3.4 \times 10^{14}$ neutrons
  - $5 \times 10^{14}$ photons
MM station 1

- High flux pion beam (2015 Drell-Yan run)
- Large current due to low momentum particles in detectors, spill structure very visible
- Discharges barely visible as amplification currents much larger

Standard MM with reduced gain, inactive centers

Low intensity pion beam

Discharges

Spill structure change
EFFICIENCY WITH LOW FLUX MUON BEAM

Station 1

Efficiencies corrected from pile-up contributions

Strips 1X: Eff = 99.1%
Strips 1Y: Eff = 99.3%
Strips 1U: Eff = 98.4%
Strips 1V: Eff = 99.0%

Pixels 1X: Eff = 99.1%
Pixels 1Y: Eff = 98.7%
Pixels 1U: Eff = 91.1%
Pixels 1V: Eff = 98.9%

Low intensity muon beam, Drell-Yan run 2015
Nominal efficiency
Station 1, close to absorber

High intensity pion beam, Drell-Yan run 2015

Lower efficiency due to large particle flux
Station 3, 1.5 m from absorber

- Strips 3X: Eff = 98.3%
- Strips 3Y: Eff = 98.8%
- Strips 3U: Eff = 97.7%
- Strips 3V: Eff = 98.2%

- Pixels 3X: Eff = 97.2%
- Pixels 3Y: Eff = 97.4%
- Pixels 3U: Eff = 84.1%
- Pixels 3V: Eff = 93.9%

High intensity pion beam, Drell-Yan run 2015

Lower efficiency due to high particle flux
Station 1, close to hydrogen target

Medium intensity muon beam, DVCS run 2016
High efficiency despite large particle flux
Station 1

Low intensity muon beam, Drell-Yan run 2015

Residuals 85-95 μm
Station 1, close to absorber

Strips 1X: \( \sigma_{\text{residual}} = 121 \, \mu m \)

Strips 1Y: \( \sigma_{\text{residual}} = 128 \, \mu m \)

Strips 1U: \( \sigma_{\text{residual}} = 120 \, \mu m \)

Strips 1V: \( \sigma_{\text{residual}} = 122 \, \mu m \)

Pixels 1X: \( \sigma_{\text{residual}} = 110 \, \mu m \)

Pixels 1Y: \( \sigma_{\text{residual}} = 134 \, \mu m \)

Pixels 1U: \( \sigma_{\text{residual}} = 137 \, \mu m \)

Pixels 1V: \( \sigma_{\text{residual}} = 121 \, \mu m \)

High intensity pion beam, Drell-Yan run 2015

Degraded resolutions due to high particle flux
Station 1

Medium intensity muon beam, DVCS run 2016

Residuals 70-85 μm
Station 1

Strips 1X

\( \sigma_{\text{residual}} = 13.49 \text{ ns} \)
\( \sigma_1 = 12.02 \text{ ns} \)

Strips 1Y

\( \sigma_{\text{residual}} = 12.43 \text{ ns} \)
\( \sigma_1 = 9.39 \text{ ns} \)

Strips 1U

\( \sigma_{\text{residual}} = 13.43 \text{ ns} \)
\( \sigma_1 = 11.99 \text{ ns} \)

Strips 1V

\( \sigma_{\text{residual}} = 13.39 \text{ ns} \)
\( \sigma_1 = 11.12 \text{ ns} \)

Pixels 1X

\( \sigma_{\text{residual}} = 11.86 \text{ ns} \)
\( \sigma_1 = 11.86 \text{ ns} \)

Pixels 1Y

\( \sigma_{\text{residual}} = 11.90 \text{ ns} \)
\( \sigma_1 = 10.52 \text{ ns} \)

Pixels 1U

\( \sigma_{\text{residual}} = 13.51 \text{ ns} \)
\( \sigma_1 = 10.47 \text{ ns} \)

Pixels 1V

\( \sigma_{\text{residual}} = 12.50 \text{ ns} \)
\( \sigma_1 = 12.59 \text{ ns} \)

Low intensity muon beam, Drell-Yan run 2015

Time resolution ~12-13 ns
Station 1, close to absorber

Strips 1X
\[ \sigma_{\text{residual}} = 13.98 \text{ ns} \]
\[ \sigma_{i} = 12.53 \text{ ns} \]

Strips 1Y
\[ \sigma_{\text{residual}} = 14.48 \text{ ns} \]
\[ \sigma_{i} = 10.77 \text{ ns} \]

Strips 1U
\[ \sigma_{\text{residual}} = 15.49 \text{ ns} \]
\[ \sigma_{i} = 11.69 \text{ ns} \]

Strips 1V
\[ \sigma_{\text{residual}} = 14.32 \text{ ns} \]
\[ \sigma_{i} = 10.94 \text{ ns} \]

Pixels 1X
\[ \sigma_{\text{residual}} = 14.46 \text{ ns} \]
\[ \sigma_{i} = 10.66 \text{ ns} \]

Pixels 1Y
\[ \sigma_{\text{residual}} = 14.22 \text{ ns} \]
\[ \sigma_{i} = 9.65 \text{ ns} \]

Pixels 1U
\[ \sigma_{\text{residual}} = 16.34 \text{ ns} \]
\[ \sigma_{i} = 10.80 \text{ ns} \]

Pixels 1V
\[ \sigma_{\text{residual}} = 14.60 \text{ ns} \]
\[ \sigma_{i} = 10.92 \text{ ns} \]

High intensity pion beam, Drell-Yan run 2015

Time resolution 14-16 ns
Station 1

Medium intensity muon beam, DVCS 2016

Time resolution ~11-13 ns
Station 1, close to target

Strips 1X
Eff = 97.7 %

Strips 1Y
Eff = 97.6 %

Strips 1U
Eff = 86.8 %
APV card in error

Strips 1V
Eff = 97.0 %
APV card in error

Pixels 1X
Eff = 96.1 %

Pixels 1Y
Eff = 95.7 %

Pixels 1U
Eff = 95.4 %

Pixels 1V
Eff = 96.4 %

High intensity muon beam, transversity run 2022
Almost nominal efficiencies but in pixel centers
Occupy of pixel channels, station 1

High intensity muon beam, transversity run 2022

Almost nominal efficiencies
Station 1, close to target

Without correction from pile-up contributions

Strips 1X
Raw eff = 97.8%

Strips 1Y
Raw eff = 97.7%

Strips 1U
Raw eff = 87.4%

Strips 1V
Raw eff = 97.1%

Pixels 1X
Raw eff = 97.7%

Pixels 1Y
Raw eff = 97.6%

Pixels 1U
Raw eff = 97.2%

Pixels 1V
Raw eff = 97.9%

High intensity muon beam, transversity run 2022
Efficiencies 97-98%
Station 1, close to target

High intensity muon beam, transversity run 2022

Residuals 85-90 µm
Station 1, close to target

High intensity muon beam, transversity run 2022

Time resolution 13-18 ns
**CONCLUSIONS**

- **Pixelized hybrid Micromegas detectors**
  - Discharge rates reduced by factor $>100$ with hybrid GEM + Micromegas structure
  - Pixel readout in center with same spatial resolution
  - Used since 2023 in AMBER experiment in same beam line, with different phases foreseen, including Drell-Yan measurements

- **Irradiation impact**
  - Muon beams in 2016-2017 and 2021-2022, significant irradiation only around detector centers
  - Pion beams on very thick target in 2014-2015 and 2018, low energy photons and neutrons on whole detector surface
  - Detector performance sensitive to beam conditions, impact of channel occupancies
  - But almost no degradation with the time
  - Best performances: efficiencies around 98%, spatial resolutions around 80 μm, time resolutions around 12 ns

Hybrid Micromegas structure with 1 GEM foil interesting to get MM-like performance in high muon and hadron flux conditions