Micromegas Detectors for the Muon Spectrometer Upgrade of the ATLAS Experiment

PSD10: 10th International Conference on Position Sensitive Detectors
University of Surrey, 7-12 September, 2014
OUTLINE

- LHC and ATLAS Upgrade program
- Detectors in the present Small Wheel and Motivations for the New Small Wheel
- NSW chamber technology and challenges

- Micromegas
  - History and detector breakthroughs
  - ATLAS Micromegas Design
  - Construction
  - Prototypes, tests
  - Test-beam and Performance Studies

- Conclusions
ATLAS:
- Phase-0 Upgrade: Consolidation + Insertable B-Layer (IBL) in LS1
- Phase-1 Upgrade: New Small Wheels, LAR Calo + TDAQ upgrade, Fast Track Trig.
- Phase-2 Upgrade: New Inner Tracker
**The ATLAS Detector**

**Muon spectrometer**

**µ Tracking Toroid Magnet**

*Precision Tracking:*
- MDT (Monitored drift tubes)
- CSC (Cathode Strip Chambers)

*Trigger:*
- RPC (Resistive Plate Chamber)
- TGC (Thin Gas Chamber)

**Inner Detector (ID)**

**Tracking 2T Solenoid Magnet**

- Silicon Pixels 50 x 400 µm²
- Silicon Strips (SCT)
  - 80 µm stereo
- Transition Radiation Tracker (TRT) up to 36 points/track

**Calorimeter system**

**EM and Hadronic energy**

- Liquid Ar (LAr) EM barrel and end-cap
- LAr Hadronic end-cap
- Tile Calo (Fe–scintillator) hadronic barrel

**3 Level Trigger system**

- L1 – hardware – 100 kHz  2.5 µs latency
- L2 – software – 3-4 kHz  10 ms latency
- EF – software – 100 Hz  1-2 s latency

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• The Small Wheel (Innermost Endcap Muon Station) is the region with highest background rates in the present ATLAS Muon Spectrometer.
• The present system is based on Cathode Strip Chambers (CSCs), Monitored Drift Tubes (MDTs) and TGC for particle tracking.
• Located between endcap calorimeter and endcap toroid.

Pseudorapidity coverage: $1.3 < |\eta| < 2.7$
Consequences of luminosity rising beyond design values for forward muon wheels

- Present Muon L1 trigger in the EndCap relies on the Big Wheel station only: Calculating a track angle/vector and extrapolating to IP
- The Level1 Trigger rate in the EC is dominated by fake triggers
- At a $3 \times 10^{34}$ cm$^{-2}$s$^{-1}$ L1MU20 ($p_T > 20$ GeV) rate is estimated ~60 kHz, exceeding the available bandwidth (~15kHz for muons)

Replace the Muon Small Wheels with the **New Small Wheels**

- Can filter out fake tracks by being able to reconstruct track vector/direction also in the endcap inner (EI) station
- Extend L1 trigger coverage to $\eta = 2.6$ with angular resolution of 1 mrad
Cavern Background

- Measured hit rates in the Endcap Inner (Small Wheel) and extrapolated to $3 \times 10^{34} \text{ cm}^{-2} \text{s}^{-1}$
- At $5 \times 10^{34} \text{ cm}^{-2} \text{s}^{-1}$ (luminosity of HL-LHC) the maximum expected rate in the NSW is about $15 \text{ kHz/cm}^2$ ($>5 \text{ MHz/MDT}_\text{tube}$) (incl. Safety factor of 1.5)

Efficiencies and resolutions

- Above 300 kHz/tube the MDT efficiency drops significantly due to dead time from background hits
- Limit for CSCs is reached even earlier, due to only 4 detection layers (instead of 6 for MDT)
- MDT Resolution degradation due to gain loss caused by space charge
Combination of sTGC and MicroMegas (MM) multiplets: 4+4+4+4 detector planes

**sTGC** *(small strip TGC)* primary trigger detector
- Bunch iD with good timing resolution
- Good online space resolution for NSW track vector with <1 mrad angle resolution

**MicroMegas (MM)** primary precision tracker
- Good Space resolution ~100 µm, independent of angle
- Good track separation (0.4 mm readout granularity)
- Provide also online segments for trigger

- Common front-end ASIC: VMM under development at BNL. First prototype tested on detector at beam test in 2012; new version soon available for tests
- Work together to make a robust detector for the high rate region of very limited access
- The NSW will operate from 2019 until 2032 → ROBUSTNESS and REDUNDANCY
**Micromegas (MICRO-MEsh GASeous Structure)**

Belongs to the family of Micro-Pattern Gas Detector (MPGD), the gaseous detector family born in the 1988 with the Micro-Strip Gas Chamber (A. Oed).

MM are parallel-plate chambers where the amplification (up to $10^5$) takes place in a thin gap, separated from the conversion region by a fine metallic micro-mesh, supported by ~100 µm high insulating pillars.

Charge is collected on the anode readout board, generally realized with suitable segmented standard PCB.

“….our detector combines most of the qualities required for a high-rate position-sensitive particle detector: excellent resolution can be obtained with fine strips printed on a thin G10 substrate or a thin kapton foil.”


Funnel field lines $\rightarrow$ electron transparency very close to 1

Small gap $\rightarrow$ fast evacuation of the positive ions (~100 ns)

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The first use of MMs in a large scale HEP experiment was in COMPASS in 2001:
twelve 40x40 cm$^2$ MMs, developed by the CEA-Saclay group were installed in the tracking system of COMPASS.

- The greatest “enemy” of MMs was the discharges with high flux of high ionizing particles (hadrons) → sparks between mesh and strips → inefficiency + aging

→ The main limitation for very large diffusion of Micromegas
Mesh at very small distance from the cathode (~100 µm)

- Issue of very small variation in distance → Gain uniformity
- Very stringent mechanical requirements


- A simple process based on the Printed Circuit Board (PCB) technology.
- could be extended to “large” area detectors made by the industry.
- The low cost fabrication and robustness

 Limitation of bulk MM:
PCB Industries → limited to 60 cm wide manufacturing
## Micromegas: Requirements for ATLAS

<table>
<thead>
<tr>
<th>ATLAS Needs</th>
<th>Requirements for the Micromegas. NEEDS for IMPROVEMENTS</th>
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<tbody>
<tr>
<td>Size: several m²</td>
<td>- New construction/assembly concept starting from the 40x40 cm² size to 2-3 m²</td>
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<td></td>
<td>- Overcome the limit of 60cm wide PCB manufacturing (abandon bulk MM)</td>
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<tr>
<td>Environment: particle fluence dominated by n, γ, hadrons (few real muon tracks)</td>
<td>Ageing</td>
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<td>Rates: up to 15 kHz/cm² in the hottest region in HL-LHC</td>
<td>High Rate capability</td>
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<tr>
<td>Precision Tracking independent from the angle of the track</td>
<td>Position resolution &lt; 100 μm (and mechanical precision – see slide 19)</td>
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<tr>
<td>Trigger capability</td>
<td>Angular resolution (~1 mrad in a multilayer system)</td>
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→ Several years of developments and tests at CERN in the context of the ATLAS Upgrade
The discharge problem has been overcome with the implementation of a layer of resistive strips facing the amplification gap. In case of spark, the electric field locally drops down damping the discharge.

In MMs the resistive layer is realized as resistive strips capacitively coupled with the copper readout strips.

Voltage drop due to sparking

T. Alexopoulos et al. “A spark-resistant bulk-micromegas chamber for high-rate applications” NIM A 640 (2011) 110
Decoupling of the mesh from the readout plane (no bulk micromegas) → essential for reliable construction for large-dimension detectors

- In the ATLAS MMs the mesh is integrated in the Drift electrode, while pillars are realized on the anode readout PCB.
- Closing the detector the mesh is “pushed” on the pillars that guarantee its distance (128 µm high) from the anode, thus defining the amplification gap.
- The conversion/drift gap is 5 mm wide. The gas tightness is ensured by an O-ring.
**High Voltage Configuration:**

*First resistive MM had the cathode at ~ -800 V, mesh at ~ -500 V, Strips at ground*

**MESH AT GROUND ("Inverted HV scheme")**

- Allows the segmentation of the HV on the anode plane
- Easier from construction point of view (no insulation needed between the mesh and the supporting metallic frames)
- More stable operation of the detector (good ground, better electrostatic configuration between mesh and resistive strips)
**THE LAYOUT OF THE NEW SMALL WHEEL**

**16 Sectors:**
- 8 Small
- 8 Large

**Non-IP side:**
Large sectors, covering area from \( r = 92 \) cm to 465 cm

**IP side:**
Small sectors, covering area from \( r = 90 \) cm to 445 cm

**Sectors:**
Package of sTGC and MicroMegas “wedges” + central spacer frame

- 2 Multilayers per sector
- Each ML: 4 MM and 4 sTGC planes

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Micromegas Wedge Segmentation

Small sector modules

1821.5
1321.1
1319.2

SM2

1350
2210

Large sector modules

2220
2022.8
2008.5

LM2

1410
2310

LM1

2210

Construction Sites:
- SM1: Italy/INFN (Pavia, Rome1, Rome3, Frascati, Lecce, Cosenza, Napoli)
- SM2: Germany – Munich, Freiburg, Wurzburg, Mainz
- LM1: Saclay
- LM2: Thessaloniki + Dubna (+ CERN)

Radial segmentation of R/O PCB per plane
- SM1 and LM1: 5 PCBs
- SM2 and LM2: 3 PCBs

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MM QUADRUPLE CONFIGURATION – A SIMPLIFIED SKETCH

1 - Drift panel
2 - Read-out panel x2
3 - Drift panel x2
4 - Read-out panel x2
5 - Drift panel

Cathode
Pillars
Resistive strips
R/O Strips

Mesh

eta strips
stereo strips

not to scale

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Requirements for the precision in the construction of any NSW chamber in order to reach a momentum resolution of 15% at 1 TeV in ATLAS:

- “For every detector plane, the position along the precision coordinate should be known with an RMS error of less than 30 $\mu$m”.
- “The position of any chamber element on the coordinate perpendicular to the above precision coordinate should be known with an RMS error of less than 80 $\mu$m”

…THE MECHANICAL PRECISION IS A VERY BIG CHALLENGE !

Chamber Construction: Prototypes, Experience, Status

- Mechanical Prototypes
- Operational Prototypes
- First Micromegas Quadruplet with ATLAS Configuration
MICROMEGAS CONSTRUCTION – MECHANICAL PROTOTYPES

M1 by LMU

M2 by INFN Roma

M3 by INFN Pavia under measurement in Freiburg

M4 by Saclay
The effect of Gas over pressure has been tested using a Single Gap with Mesh.
Deformation mitigation with INTERCONNECTION SCREWS (3 screws used)
Mechanical deformations due to Gas over pressure (3 mbar) have been studied using, Laser and Optical Fibers (Fiber Bragg Grating)

Simulation
3 interconnections 3 mbar
Max deviation ~120 µm

Deformation map (3mbar – 0 mbar)

Observed deformations due to Gas overpressure
AverageDeformation = 140 µm ; MaxDef <300 µm
Several large area single gap chambers built at CERN in the past year: L1, L2, L3

New multi-gap operational prototypes are currently being built at ~all construction Labs

New multi-gap prototypes with ATLAS MM Configuration recently built at CERN. Considered as a Module -1 of ATLAS MM
The Micromegas Small Wheel Project (MSW)

Two identical detectors are being built

- One for the 2014 test beam campaign
- One will be installed in ATLAS, (initially in the outer wheel) at a later stage moved on the Small Wheel, to operate during Run2 in real conditions

- Dimensions 1.2 x 0.5 m² (to fit upper half of CSC)
- Configuration very close to final module
- Four layers (quadruplet) 2 eta 2 stereo (x and u,v planes)
- Strip pitch 0.425 mm, 1024 strips/layer
- PCB Production as close as possible to final production

Small deformation of a drift panel visible

Overall flatness of the single panel $\sigma < 100 \ \mu m$

Flatness improves after detector assembly
Resistive strips on 50 μm kapton foil are glued on the PCB with readout strip pattern.

Two technique for resistive strips currently being evaluated:
- Sputtering
- Screen Printing

Typical resistivity:
- ~10-20 MΩ/cm (~300-600 kΩ/☐)

Resistive strips interconnection
- Homogeneous resistivity (independent from distance)
- Insensitivity to broken lines

Readout strips (512 channels per side) for Zebra interconnection (no connector mounted on the boards)

Central hole for panels interconnection
**Test-Beam and Performance Studies**

- Initiate a process of MM Performance Review, implying test-beam re-analysis, simulation, software development, algorithms improvements
EARLY EXPERIENCE AND CHOICES FOR ATLAS MM

Test Beam Summer 2008
CERN SPS 120 GeV Pions

Mean = 0.3 µm
σ = 65.7 µm

After subtraction of track extrapolation error and Multiple Scattering
→ σ ~ 30 µm

Strip pitch: 250 µm

VERY GOOD RESOLUTION (perpendicular tracks) can be reached with:
• Small size strip pitch
  → Issue with number of channels in ATLAS
• Ar-iso-butane-Freon gas mixtures
  → Ageing issues for operation in ATLAS

The CHOICE FOR ATLAS Micromegas:
• Pitch size ~ 0.4 mm → ~2M total number of channels
• Gas mixture Ar-CO₂ (93/7 subject to further optimization)

Fulfills ATLAS requirements

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June 2012 → CERN H2 First Test-beam with Magnetic Field (validation of MC)

July-September 2012 → CERN H6 (120 GeV pions)
- Tests and validation of µTPC mode with APV25
- First test of VMM1 chip.
- First tests on large size MM 1x1m²

June 2013 DESY (5 GeV electrons) Test-Beam with Magnetic Field

Doublets arranged “back-to-back”
**Test-Beam Setup 2012-2013 – Typical Setup**

**Typical setup**

- Up to 8 MM Test chambers aligned along the beam line (plus reference chambers)
- Test Chambers: Resistive strips, Active area of 10x10 cm$^2$
- Oriented in back-to-back configuration forming doublets
- **Strip pitch of 0.4 mm**, drift gap of 5 mm, Amplif. Gap 128 mm
- operated with Ar:CO$_2$ gas mixture (93:7).
- Our “nominal” HV configuration (mesh at ground):
  - $E_{\text{drift}} = 600$ V/cm; $v_{\text{drift}} = 47\,\mu$m/ns
  - Amplification Voltage 450 -- 550 V (Gain $\sim 10^4$)

**FE and DAQ**

- APV25 operated at 40 MHz – 27 samples
  - tot time window of 675 ns
- SRS (RD51-CERN) Read-Out system adopted
- Preliminary tests of new FE chip, first version of VMM

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Distribution of local inefficiencies as measured from the missing hits on one chamber corresponding to a reconstructed track from the other chambers.

Cluster inefficiencies in the range 1 to 2% consistent with the partially dead area due to the presence of 300µm diameter pillars separated by 2.5 mm.

Position resolution for perpendicular tracks estimated by difference of cluster charge centroid measurements of pairs of MM chambers.

About 73 µm with an average cluster size of 3.2
Similar results obtained with a full track reconstruction method.
**The micro-TPC method for Inclined Tracks**

- Sub 100 µm spatial resolution easy to achieve for perpendicular tracks.
- For inclined tracks need to exploit time information to operate in “micro-TPC” mode.

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**Diagram Description:**

- **x(mm)** vs. **Time(ns)** for different angles: θ = 10°, 20°, 30°, 40°.
- **µTPC Angle = 30.3 deg**
- **µTPC Track Angle = 30.3 deg**

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The μTPC method has been successfully applied in many test-beam data. However, a sizeable angular bias is observed due to capacitive induction of the signal on neighbouring strips. The effect is well reproduced by simulations (LTSpice, ANSOFT Maxwell).

A new procedure was developed to take into account this effect to reduce the angular bias and to improve the spatial resolution.
The optimized correction only applied to the first and last strips:

- Do not use first/last strip if its charge is more than 6 times smaller than its neighbour.
- Otherwise correct the charge position for the edge strips of the cluster in proportion to the ratio of charges with their neighbours.

After correction, a significant reduction of the angle bias and an improvement in the \( \mu \)TPC angle resolution is obtained.
Spatial resolution is measured from the difference of the reconstructed position in two chambers.
In case of the micro-TPC between tracklets extrapolated to half gap of the chambers (“y-half”).

![Graph showing single plane spatial resolution vs incident angle.]
August 7-14 (and August 15-27 parasitically) at PS/T9 – beam: 10 GeV/c $\pi^+/p$

**SETUP**

Reference Micromegas Test Chambers

Test of the MSW prototype
First test of an assembled quadruplet with the same configuration as the ATLAS quadruplets

**MSW Operation Conditions**

- Ar:CO$_2$ gas mixture (93:7)
- HV configuration (mesh at ground):
  - $E_{\text{drift}} = 600 \text{ V/cm}; \quad v_{\text{drift}} = 47 \mu \text{m/ns}$
  - Amplification Voltage $\sim 550 \text{ V}$ (Gain $\sim 10^4$)
- Strip pitch $\sim 0.4 \text{ mm}$
Preliminary result of Spatial Resolution on the precision coordinate (corrections for beam angular spread not included)

MSW0-MSW1

Preliminary result of Spatial Resolution on the second coordinate.
In very good agreement with expectations

Tmm2y-MSW23y

2nd coordinate from the stereo planes, compared with reference chamber Tmm2
R17a detector is exposed to different radiation sources
R17b detector is kept unexposed as reference

Gain control measurements are performed before and after each exposure.

After the ageing both detectors are taken to the H6 CERN-SPS pion beam line.

The goal was to accumulate an integrated operation charge equivalent to the one
would be obtained at the HL-LHC for 10 years for each type of radiation.
## Overview of Micromegas Ageing Tests - Exposure

<table>
<thead>
<tr>
<th>Irradiation with</th>
<th>Charge Deposit (mC/cm²)</th>
<th>HL-LHC Equivalent</th>
</tr>
</thead>
<tbody>
<tr>
<td>X-Ray</td>
<td>225</td>
<td>5 HL–LHC yrs equivalent</td>
</tr>
<tr>
<td>Neutron</td>
<td>0.5</td>
<td>10 HL–LHC yrs equivalent</td>
</tr>
<tr>
<td>Gamma</td>
<td>14.84</td>
<td>10 HL–LHC yrs equivalent</td>
</tr>
<tr>
<td>Alpha</td>
<td>2.4</td>
<td>$5 \times 10^8$ sparks equivalent</td>
</tr>
</tbody>
</table>

The two R17 prototypes were taken to the H6 SPS CERN pion beam to perform a **comparative study between both prototypes, irradiated and non-irradiated** one.

Both detectors reach efficiencies of about 99.5%, proving that there is no visible degradation effect in these measurements.
VMM ASIC Main Features

- Highly programmable ASIC provides both precision measurement and trigger primitives
- Low noise charge amplification, shaping with baseline stabilization
- 64 channels digital output
- Digital zero-suppressed readout of the address, amplitude, and time
- Peak detector provides signal amplitude
- Peak Timing with negligible time walk and ~2ns resolution
- Neighbor enable logic allows processing below threshold signals
- The address of the channel with the earliest time with respect to the trigger, the Address in Real Time (ART) → used for triggering with the micromegas
Mesh stretching tests in INFN Roma Tre

INFN test panel

INFN Pavia precision templates for RO board alignment

Panel assembly

Final preparations to start module-0 construction after the summer ...

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CONCLUSIONS

• The ATLAS NSW Upgrade will enable the Muon Spectrometer to retain its excellent performance also beyond design luminosity and for the HL-LHC phase
• Deployment of a new detector technology, Micromegas, for the first time for a very large scale detector and with large area chambers
• Test-Beam and performance studies show that the Micromegas fulfil the ATLAS requirements

And …there is much more not covered in this presentation: Electronics, Alignment, …

• Detector construction is not the only challenge: Alignment, Mechanics, Electronics are equally crucial and highly complex areas needed for a success
• End of this year and 2015 will be crucial:
  – Module-0 production
  – Transition to series production
  – First prototypes for many of the electronics components
BACKUP SLIDES
**The Detectors in the Present Small Wheels**

**Monitored Drift Tubes:**
- 3 cm diameter tubes filled with Ar:CO₂ @ 3 bar abs
- Tube resolution $\leq 80 \mu$m, track resolution/station $\leq 50 \mu$m
- Rate capability limited by 1 dimensional readout
- Optical rays for monitoring deformation and displacement

**Cathode Strip Chambers:**
- Innermost part of the inner endcap station
- Multi-wire proportional chambers, operated at 1 bar (Ar:CO₂)
- Segmented cathode, strips perpendicular to wires
- Resolution/plane: 60µm from *strip charge distribution*

**Thin Gap Chambers:**
- Multi-Wire proportional chambers with very small gap size
- Cathode – wire distance smaller than distance between wires
- Operated in quasi saturated mode with n-pentane + CO₂
- Fast readout, small intrinsic time jitter ($\leq 1.5$ ns), high efficiency
- Provide also 2nd coordinate measurements for MDTs, main purpose in the present Small Wheel!
• TGC already used in OPAL, DELPHI @ LEP and also present in the ATLAS Endcap Muon region
• From the ~2 cm strip pitch of the TGC already in ATLAS → to 3.2 mm strips (small-strips TGCs)

- 50µm gold-plates tungsten wires, spaced 1.8mm apart,
- Wires sandwiched between 2 cathode planes 1.4 mm from the wires
- Cathode surface resistivity 100 kΩ/m² reached by graphite coating

• Trigger: Coincidence of pad signals define Region of Interests (RoI), selected strip information sent to trigger processor for precision position calculation
• Track position reconstruction from strip charge centroid, 2nd coordinate from wire readout

• Resistive cathodes (i.e. the graphite layer) set a limit to the rate capability
• To increase rate capability (> 10 kHz/cm²) necessary to pass from present TGC cathode resistivity (1 MΩ/cm²) to 100 kΩ/cm²
• Construction of 4 modules Mechanical Prototypes is CONCLUDED (according to old segmentation):
  INFN PV, RM (IT), Saclay (FR), LMU (DE)

Ongoing measurements:
• Mesh tension and gas overpressure induced deformations
• Thermo-mechanical deformations – Validation of simulations
  ▪ Crucial input for in-plane alignment needs
  ▪ Assess and define method to attach modules to sector structure

Construction of single wedge full size mechanical prototype CONCLUDED: CERN

-heating of one side of the chamber via voltage regulated electric heating tapes

\[ M2 \Delta T=1.9^\circ \rightarrow \text{Deformation} \sim 42 \text{ } \mu\text{m RMS} \]
Performance Studies with the APV25 Readout Chip

Timings and Amplitudes measured for each hit-strip applying a fit function to the sampled shaper output values

\[ FD(t) = K \frac{1}{1 + e^{-(t-t_{FD})/\sigma_{FD}}} + B \]

- Intrinsic Time Resolution \( \sim 5 \text{ns} \) (primary ionization spread)
- Temporal resolution estimated from earliest strip differences between two MM back-to-back for inclined tracks (30°)
- Measured \( \sigma_T \sim 10 \text{ ns} \). Dominated by APV25 response and precision of the fit

\[ \sigma_T = 10.1 \pm 0.2 \text{ ns} \]

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