The upgrade of the forward Muon Spectrometer of the ATLAS Experiment: the New Small Wheel project

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Motivation

- Main ATLAS upgrade during the LHC Long Shutdown 2 (2019/20)
- Will replace the present Small Wheel, not designed to exceed $10^{34}$ cm$^{-2}$s$^{-1}$
- Expected rates up to 15 kHz/cm$^2$

- Maintain momentum resolution: 15% $p_T$ resolution at 1 TeV →
  ~100 μm resolution per plane on a multilayer station
- Keep single muon trigger rate under control → 1 mrad online angular resolution

Pseudorapidity coverage: $1.3 < |\eta| < 2.7$
NSW Layout

- Small-strip Thin Gap Chambers (sTGC) and Micromegas (MM)
  - sTGC: primary trigger detectors
  - MM: primary tracking detector
- Arranged in units (quadruplets) with 4 detector layers \(\rightarrow 1\) quad = 1 detector unit
- 8 sTGC and 8 MM detector layers
  \(\rightarrow\) high redundancy (limited accessibility, long lifetime)
- \(~1200\ m^2\) active area for each technology
- \(~2.4M\) readout channels
Detector layout

- Au plated W wires between two resistive cathode planes (2.8 mm apart) → measurement of transverse (phi) coordinate
- Precision cathode plane: 3.2 mm pitch strips for Level-1 trigger and precision coordinate measurement
- Cathode pads for Level-0 trigger → define which strips to read for trigger

- Gas: n-pentane:CO2 45:55
- Operating HV=2.9 kV
- Graphite cathode resistivity ~ 100/200 kΩ/☐

- Trapezoidal shape quads, up to 2 m² surface
- 6 quad types; 32 detectors per type
- Institutes from 5 Countries

06/07/17

The ATLAS NSW Upgrade
Cathode boards

- Cathode boards: very challenging precision
  - Thickness ±25 µm on periphery, ±37.5 µm elsewhere
  - Precise positioning of the strips
  - Production in industries: USA and IT/IL ongoing
  - Recent results encouraging

- Constant follow-up at companies
- All boards undergo detailed QAQC

- Alignment of readout planes is crucial for trigger capability
- Brass insert manufactured together with the strip boards → 40 um precision
- Precise pin used to align planes using the brass insert
Construction steps

- Cathode boards production
- Graphite spraying, polishing
- Precision frame gluing
- Wire winding & soldering
- Detector assembly, closing
Test results

- **Test-beam of sTGC full-size prototype at Fermilab**
  - 32 GeV pion beam; Rate ~1kHz/cm²
  - VMM1 ASIC as FE elx
  - Scintillator trigger
  - External tracking with Si detector

- **Bunch-crossing identification capability (triggering)**
  - 95% of total hits contained in a 25 ns windows (after window time offset adjustment)

- **Spatial resolution for perpendicular tracks**
  - $\sigma < 50 \mu m$ after differential non-linearity correction

- **Aging test: 10x20 cm² prototype**
  - No aging effect after 150y HL-LHC equivalent dose → details in back-up

NSW TDR: LHCC-2013-006

**arxiv:1509.06329**
Production status

- Cathode boards production started at industries
- All but one construction sites* have built a full scale prototype (Module-0) and are ready to commence production
  *PNPI waiting for late delivery of components
- Testing procedure and tooling for QA ready

Gain uniformity map

X-ray scanner

Russia

Cosmic ray test - China

Chile
Micromegas
Detector layout

- Resistive micromegas; 128 \( \mu \text{m} \) amplification gap, 5 mm drift gap
- 415/450 \( \mu \text{m} \) strip pitch for precise position measurement
- Exploiting uTPC technique for inclined tracks
- Two layers with stereo strips (\( \pm 1.5^\circ \)) for coarse tracking in the transverse coordinate

- Gas: Ar:CO2 97:3
- Operating HV = 560V ampl; 300V drift
- Resistivity of resistive patterns \( \sim 1 \, \Omega/\square \)

- Trapezoidal shape quads, up to 3 m\(^2\) surface
- 4 quad types; 32 detectors per type
- Each quad has 2 anode and 3 cathode panels
- Institutes from 5 Countries + CERN
Anode boards

- Stringent technical requirements on production
  - Non-standard operations, cleanliness, etc.
- Resistive kapton foils produced by screen printing in industry (JP)
- Long technology transfer process from CERN to industries
- Many quality issues during prototyping, now solved
- Production ongoing in industries (IT, FR)
- >10% boards completed; good quality, production rate OK

- Constant follow-up at companies
- All boards undergo detailed QAQC at CERN
Construction

- **Construction steps**
  - Boards production
  - Gluing of boards into panels
    - Vacuum
    - Al-honeycomb and Al frames
  - Mesh stretching and gluing on cathode panels
  - Detector assembly, closing

- **PCB alignment with contact-CCD cameras**
  - Precision <10 μm

- **Mesh stretching - IT**

- **Detector assembly**

- **Readout (anode) panel**

- **Panel assembly - DE**

- **Flatness rms = 21 μm**
Two full-size prototypes tested with particle beam at CERN
- 120 GeV pion beam
- APV25 front-end hybrid; dedicated DAQ system (MMDAQ)
- Scintillator trigger

Preliminary: results (no sw alignment nor correction):
- Efficiency ~99%
- Spatial resolution for perpendicular tracks: σ~50 μm w/o tails

- Aging test: 10x10 cm² prototype @ GIF++ at CERN
  - No aging effect after 10y HL-LHC equivalent dose
  - details in talk by B. Alvarez Gonzalez tomorrow
Production status

- Production and test of anode boards ongoing
- Three (/4) full scale prototype (Module-0) built. Test ongoing.
- Module-0 from France almost completed
- Panel construction for final detectors started in IT, DE, GR; after summer for RU and FR
- Testing procedure and tooling for QA ready

Mesh washing - IT

Panel gluing - RU

Planarity measurement - DE

Quad manipulation - IT

Gas tightness test - DE

σ=15 μm

D.I. water at high pressure (>80 bar)

Cosmic stand - DE
Electronics

- 2.4 M readout and trigger channels
- 4096 FE boards for MM (MMFE8)
- 1536 FE boards for sTGC (sFE & pFE)
- Custom FE ASICs (VMM)
  - drives trigger and tracking primitives with high speed serializers
  - drives trigger candidates to the backend trigger processor system
  - Same for sTGC and MM
- Total power consumption ~75 kW

NSW trigger and data acquisition architecture

- Radiation tolerant ASIC
- 130 um Global Foundries 8RF-DM process
- 64 channels low noise charge amplifier
- Shaper w/ baseline stabilizer
- Discriminator with trimmer
- Peak and time detector
- ToT and TtP measurements
- Low power ADCs (6-, 10-, 8-bit)
VMM Test Results

- Version 3 of VMM ASIC produced in 2016 and tested on bench and real detectors

- ASIC working ~OK; noise higher than desired
  - Pick-up from DC-DC converter on the board
  - Efforts for mitigate the problem ongoing

- Plan: submit a new version (VMM-3a) to fix small issues
  - Pre-production on time by Jan. '18
Engineering & Mechanics

- NSW will be assembled in surface, moved to LHC Point1 (ATLAS) and lowered into the shaft
- Related activities on engineering and mechanics for detector integration and installation started and progressing well

Sector support structure under production in industry

New shielding disk under assembly in industry

Detector assembly on support structure

Wheel storage, transport and manipulation tools

Wheel integration on surface (CERN)
Summary

- The New Small Wheel is the largest ATLAS upgrade project for LHC Long Shutdown 2
- Challenging project:
  - Unprecedented use of Micromegas detector
  - sTGC pushed to the frontier
  - Custom FE ASIC and trigger/DAQ chain
  - Complex mechanics
- Tight schedule, delays accumulated
- ATLAS fully committed to bring it to success
Additional Material
sTGC Aging

- Aging test conducted on a small (10x20 cm²) prototype
- 90Sr source irradiating ~5 anode wires
- Three gas flow rates tested: 10/5/2.5 cc/min
- Total accumulated charge: 11 C/cm equivalent to 150y at HL-LHC

- No sign of aging found looking at the detector current
- Chemical analysis of the irradiated wires showed deposits of carbon and oxygen enriched molecules not affecting the detector performance
Spatial resolution for inclined tracks

- **Micromegas**

- **sTGC**
Micromegas Board Production

I. Copper pattern creation by photolithography
II. Cutting of Kapton foils with resistive pattern
III. High pressure Gluing of Kapton foil on the PCB
IV. Connection between HV input line and resistive strips (screen printed: silver conductive paste)
V. Selective plating on connector pads
VI. Pillar creation (2x 64μm Pyralux coverlay)
VII. Cutting of the boards and drilling of the non-precision holes (holes for mechanical assembly and alignment)
MM progress on quality: pillars

- Long pillars (1.2 mm x 0.2 mm) running parallel to the readout strips do not affect the detector performance, while insuring larger attachment surface
- Tested on 10x10 cm² bulk-MM built at CERN
MM progress on quality

- Enclosures and bubbles
  
  Great improvement:
  - Technological transfer
  - Procedure and work-flow optimization
  - Cleanliness during gluing

- Resistive vs readout strip alignment
  
  Not critical; improved with design changes allowing for an easier alignment during staking and check after gluing
MM progress on quality

- **Edge cutting**
  - Module0 boards: 2015
  - Pre-series board: 2016
  - Great improvement:
    - Procedure and work-flow optimization
    - Design improvement: removed 1 strip to allow for larger safety margin

- **Silver line HV connection**
  - First step improvement
  - Second step improvement
  - Third step improvement