Status Report on the Upgrade of the CMS muon system with triple-GEM detectors

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Overview

• Triple-GEM detectors
• The CMS GEM project
  – System design
  – Impact on CMS muon trigger performance
• CMS triple-GEM detector performance
• Preliminary results on ageing
• CMS triple-GEM Electronics
  – VFAT3 front-end chip
  – Readout chain
• Up-coming activities
• Summary
CMS requirements

- Maximum geometric acceptance within the given CMS envelope
- Rate capability of 1-2 kHz/cm²
- Single-chamber efficiency > 98 % for MIP
- Angular pitch of 460 mrad.
- Timing resolution of 10 ns or better for a single chamber.
- Gain uniformity of 10% or better across a chamber and between chambers.
- No gain loss due to aging effects after 200 mC/cm² of integrated charge
The CMS GEM project

1.55 < |\(\eta| < 2.18

**GE1/1:**
- baseline detector for GEM project
- 36 staggered super-chambers per endcap, each super-chamber spans 10°
- One super-chamber is made of 2 back-to-back triple-GEM detectors
- Will guarantee high trigger performance during late Phase I and throughout Phase II
- Installation: LS2 (2018-19)

**ME0:**
- Muon tagger at highest |\(\eta| |
- 2.0 < |\(\eta| < 3.5
- 6 layers of Triple-GEM
- each chamber spans 20°
- Installation: LS3 (2022-24)

**GE2/1:**
- 1.55 < |\(\eta| < 2.45
- 18 staggered super-chambers per endcap, each chamber spans 20°
- Installation: LS3 (2022-24)
Muon Trigger performance

- L1 trigger rate “flattening”
  - Low-\(p_T\) muons scattering can occasionally have stubs aligned like for a high-\(p_T\) muon (rare, but lots of low-\(p_T\) muons);
  - L1 muon-trigger momentum resolution can be improved by measuring the bending angle with CSC+GEM

- Low thresholds have a large impact on physics that relies on a of low-\(p_T\) muon:
  - Higgs, SUSY gaugino or stop pair production
R&D: 6 generations of triple-GEMs

- **Generation I**
  The first 1m-class detector ever built but still with spacer ribs and only 8 sectors total. Ref.: 2010 IEEE (also RD51-Note-2010-005)

- **Generation II**
  First large detector with 24 readout sectors (3x8) and 3/1/2/1 gaps but still with spacers and all glued. Ref.: 2011 IEEE. Also RD51-Note-2011-013.

- **Generation III**
  The first sans-spacer detector, but with the outer frame still glued to the drift. Ref.: 2012 IEEE N14-137.

- **Generation IV**
  First detector with complete mechanical assembly; no more gluing parts together! Upcoming papers from MPG D 2013; And IEEE2013.

- **Generation V**
  Very close to what we will install in CMS. Features re-designed stretching apparatus that is now totally inside gas volume. Fall 2014 test beam campaign for final performance measurements. Publication pending.

- **Generation VI**
  Latest detector design; what we will install in CMS. Optimized final dimensions for maximum acceptance and final eta segmentation. Upcoming test beam campaign for DAQ chain stress test!

- **GEM foil production** uses single mask technology for wet etching
  - Dramatically reduces foil production costs and large sizes to be manufactured
  - Performance same as that of double mask

- **Mechanical foil stretching procedure**
  - Construction time reduced from week(s) to two hours per chamber
Performances

Over the years numerous tests, also with beam (CERN/FNAL), have been performed

![Graph showing gas gain vs rate](image)

- Effective gas gain
- Rate (kHz/cm²)
- Effective gas gain vs -V_drift [V]
- Hit rate vs -V_drift [V]
- Time resolution vs E_drift [kV/cm]

**Ag X-ray 22 keV**
- GE1/1-IV
- Ar-CO₂-CF₄ 45:15:40

**Rate (kHz/cm²)**
- 1.0E-01
- 1.0E+00
- 1.0E+01
- 1.0E+02
- 1.0E+03

**Effective Gas Gain**
- 10 kHz/cm² equivalent MIP

**Over the years numerous tests, also with beam (CERN/FNAL), have been performed**

**GE1/1-IV Spatial Resolution**

- Entries: 10120
- χ² / ndf: 724.7 / 97
- Constant: 1193 ± 17.1
- Mean: 0.002537 ± 0.000397
- Sigma: 0.2678 ± 0.0025

**Gas mixture, detector gap sizes (mm)**
- Ar(70):CO₂(30) 3/2/2/2
- Ar(45):CO₂(15):CF₄(40) 3/1/2/1

**4 ns**
Aging studies

Test with GE1/1-IV at the CERN Gamma Irradiation Facility (GIF):

- $^{137}\text{Cs}$ source of 566 GBq
- Incident γ rate ~ 100 kHz/cm$^2$ → few kHz/cm$^2$
- $\text{Ar}/\text{CO}_2/\text{CF}_4$:45/15/40 (0.5L/h), gas gain: 2 x 10$^4$
- No gain drop after 10 mC/cm$^2$ (over 12 months)
- Next steps:
  - Move to GIF++ to reach >100 mC/cm$^2$ (16.7 TBq $^{137}\text{Cs}$)

Outgassing studies:

- At room T° and at 50°C
- Being performed on all materials in contact with gas
- Outgassing box-SWPC-10x10 cm$^2$ triple-GEM
- Chromatograph to identify impurities
- Viton O-ring: Ok
- Polyurethane Cellpack: Ok
- Polyurethane Nuvoverne: Ok
GE1/1 readout system

VFAT3 (front-end ASIC)

GEM Electronic Board (GEB)

Opto-Hybrid (OH)

GBT

On Detector

Optical links @ 3.2Gbps

Links to CSCs

Off Detector

micro-TCA

AMCs MP7

AMC13

μTCA AMC13, MCH

MP7

Power Supplies

LV

HV

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VFAT3 design

- Evolution of TOTEM VFAT2 chip
- 128 channel chip,
- Both polarity
- Provide tracking and trigger data
- LV1A latency up to 20µs
- Interface to and from GBT @ 320 Mbps
- Rad. tolerant up to 100 Mrad (radiation hardness of up to 1MRad is sufficient for the GE1/1 application through Phase-II)
- First submission : end of 2015 (TSMC 130)

A lot of simulations have been done to study the expected time resolution:

![CMS triple-GEM signal simulations with GARFIELD](image)

### Simulated VFAT3 Transfer Function

### Expected Time resolution

![Graph showing time resolutions](image)
On-detector electronics

- GEB board:
  - GEM Electronics Board: large PCB to avoid cables along GEM
  - Plugged on the GEM readout board

At CERN:
- GE1/1 electronics integration tests on-going with CSC detector and electronics
- Building a large (15 super-chambers) Quality Control cosmic test bench

160 MHz LVDS signal over longest GEB line, within spec. for VFAT2 (40 MHz)
Towards LS2 and beyond

- Full installation in LS2 (2018-2019)
  - 144 super-chambers equipped with VFAT3

- Slice test (YETS 2016)
  - 4 super-chambers will be installed during 2016 LHC End of Year Technical Stop
  - GE1/1 equipped with VFAT2 + OH + uTCA
  - GE1/1 data integrated to CMS DAQ
  - Goals: reduce commissioning period at the full installation, gain experience in integration
  - All components will be thoroughly qualified in the large Quality Control test bench

- LHC Phase II (LS3, 2022)
  - 2nd GE station (GE2/1) and forward tagger ME0

R&D ongoing: geometry, background rates, radiation hardness…
Summary

• CMS GEM project well on track
  – Technical Design Report (TDR) submitted to LHCC in March 2015

• Detector R&D:
  – 5 years of R&D has given us 6 generations of prototypes; each an improvement of the last!!!
  – GE1/1-V, test beam in fall 2014 for final performance measurements
  – GE1/1-VI, geometry changes to optimize detector acceptance in CMS

• Ageing measurements on-going (next at GIF++)

• Large Quality Control test bench being built (not shown in this presentation)

• 6 production sites ready (not shown in this presentation)

• Electronics and DAQ developments ongoing as well
  – VFAT3 analog part (incl. CFD) currently tested
  – 1st version of the new electronics (GEB, OH, uTCA, GLIB, …) tested with beam
  – 2nd version (longer GEB, OH with new FPGA, …) available and under test
  – Integration tests with CSC electronics started

• CMS GEM Community entering in production mode!

27/5/2015

G. De Lentdecker, 13th Pisa Meeting on Advanced Detectors
BACK-UP
De Lentdecker, 13th Pisa Meeting on Advanced Detectors
Aging studies

Test at the CERN Gamma Irradiation Facility (GIF):

- Expected rate: few kHz/cm² $\rightarrow$ few 10s kHz/cm²
- Expected charge after 10 years: 100 mC/cm²

- Test with GE1/1-IV (no spacer, no glue, final set of material)
- $^{137}$Cs source
- $^{55}$Fe sources for reference chambers
- $^{109}$Cd source for outgassing study
Performances
Next steps

• Integration facility:
  – 1 CMS ME1/1CSC & 1 GE1/1 detector
  – Integration of the new GE1/1 electronics
    • Get trigger signal from CSC detector and clock through the CMS TTC system
    • Use uTCA crate + GLIB + CMS AMC13

• Large Quality Control test bench:
  – 15 super-chambers at the same time
  – Efficiency & spatial resolution VS. HV
  – Results logged in performance database
  – Data taking will start in April 2016

• Test beams:
  – First version of new GE1/1 electronics tested in Dec ’14
  – 2\textsuperscript{nd} version will be tested in Fall 2015
GE1/1 physics

- **Redundancy** in $1.5 < |\eta| < 2.2$ region with additional GEMs
  - $\sim 20\%$ of interesting physics channels ($H \rightarrow 4\mu$, $Z \rightarrow 2\mu$, $H \rightarrow \tau\tau$) in GE1/1 region

- **Lowering the trigger threshold**
  - in $H \rightarrow \tau\tau$ yields gain in sensitivity:
    - $H \rightarrow \tau (\mu\nu\nu)\tau$ (had)
    - $H \rightarrow \tau (\mu\nu\nu)\tau (\mu\nu\nu)$
    - Lowering trigger $p_T$ from $\sim 20$ GeV (post-LS1 plan) to $\sim 15$ GeV = $\sim 20\%$ gain

- Challenge of **the forward region**. Impact of PU on muon reconstruction. Fraction of non-prompt muons in forward region increases dramatically with 140 PU.
The GE1/1 system

- $1.55 < |\eta| < 2.18$
  - Short and long chambers for maximum coverage
- 36 superchambers (SC) per side of CMS
  - Each chamber spans $10^\circ$ in $\phi$
  - 2 chambers/SC
  - 144 chambers total
- Total foil area ~140m$^2$

Five years of R&D has given us six generations of prototypes; each an improvement of the last!!!
The GE2/1 system

- $1.55 < |\eta| < 2.45$
  - Short and long chambers
  - Each chamber spans $20^\circ$ in $\phi$
  - 2 chambers/SC
  - 144 chambers total
- Targeting 2 rings of double-layered triple-GEM
  - one ring with 8 and one ring with 12 $\eta$ partitions
- Total foil area $\sim 145m^2$
The ME0 system

- $2.0 < |\eta| < 3.5$
  - $20^\circ$ wedges affixed to back of upgraded CMS HCAL endcap

- Six layers of triple-GEM detectors
  - Design ongoing

- Significantly increases muon acceptance for high profile analyses
  - e.g. $H \rightarrow ZZ \rightarrow 4\mu$

- Total foil area $\sim 144m^2$

Thicknesses cm:
- 2.5 Borated Poly
- 1.2 Pb
- 3.2 Single Chamber 1
- 3.2 Single Chamber 2
- 3.2 Single Chamber 3
- 3.2 Single Chamber 4
- 3.2 Single Chamber 5
- 3.2 Single Chamber 6
- 3.2 Sliding Rail
- 1.2 Pb
- 2.5 Borated Poly

28.8cm
GE2/1 & ME0 system considerations

- GE2/1 Long= 1816mm > manufacturer capability
  - Investigating segmentation of GEB board:

- ME0 will be exposed to rates > 10 x GE1/1 rates
  - Investigating data rates and bandwidth requirements
ME0 mean trigger & tracking rates

• Probability to hit the optical link bandwidth limit (3.2 Gbps / link):

<table>
<thead>
<tr>
<th>Trigger</th>
<th>Data rate (Gbps)</th>
<th>Prob with 2 links</th>
<th>Prob with 3 links</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fast OR ZS</td>
<td>2.68</td>
<td>1.34%</td>
<td>0.02%</td>
</tr>
</tbody>
</table>

- Still investigating other data format
- Note: optical link bandwidth based on GBT. For LS3, higher speed GBT probably available

<table>
<thead>
<tr>
<th>Tracking (L1A @ 1MHz)</th>
<th>Data rate (Gbps)</th>
<th>Prob with 1 links</th>
<th>Prob with 3 links</th>
</tr>
</thead>
<tbody>
<tr>
<td>SPZS*</td>
<td>2.15</td>
<td>&lt;10^{-7}</td>
<td>&lt;10^{-7}</td>
</tr>
</tbody>
</table>

*SPZS: Sequential Zero Suppression a variant of the CMS RPC data format

• GE1/1 Probability to hit the optical link bandwidth limit (3.2 Gbps / link):

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<th>Prob with 1 links</th>
<th>Prob with 2 links</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fast OR ZS</td>
<td>0.05</td>
<td>6 10^{-5} %</td>
<td>&lt;10^{-7}</td>
</tr>
</tbody>
</table>