Beam test of the GEM detectors for the Phase-II upgrade of CMS

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For the HL phase at the LHC, the CMS Muon System will be upgraded by adding new stations of GEM detectors:

- **GE2/1** in the region $1.6 < |\eta| < 2.4$ to enhance redundancy
- **ME0** in the region $2.4 < |\eta| < 2.8$ to extend the acceptance
GEM 2021 Test Beam

Main goals
- First operation and performance measurement with beam of final-design CMS Phase-2 GEM detectors with their full front-end electronics and DAQ.
- First beam operation of ME0 prototype with new GEM foil design.
- Measure the space resolution of tracker (LEMM Test Beam*)

Detectors under test
- 4 high-resolution 10x10 cm² triple-GEM chambers for beam telescope
- CMS Phase II GEM detectors (GE2/1 and ME0)
- 20x10 cm² random hole segmented prototype

*LEMM Test Beam will use the 10x10 cm² GEM for beam telescope and GE2/1 modules in the muon arms.
R&D for ME0 design

ME0 station: first CMS muon endcap station from beam line
Hostile background environment (up to 150 kHz/cm²) → new GEM foil segmentation studied to minimize the average gain drop

More on arXiv:2201.09021v1
Experimental setup: CMS Phase II GEMs

**GE2/1** Production detector (M1 module)

- 348 radial strips, pitch 1.3 – 1.7 mm
- (expected space resolution 380 – 500 μm)

**ME0** second generation with azimuthal segmentation

Additionally: R&D 20×10 prototype with random hole segmentation that offers a simpler masking and the possibility to recover inefficiency areas due to sectorization in GEM foils (possible R&D for ME0)

More on [this presentation](#)

Later added in the setup
Experimental setup: Beam telescope

- **Four** 8.9x8.9 cm² **high-resolution** triple-GEMs
  358 strips, 250 µm pitch
  (expected space resolution 75 µm)
- **Trigger: three-scintillator coincidence** (2 front + 1 back)

Tracker chamber readout strips

Efficiencies measured with cosmics before test beam

- **Four**
- **2mV/fC**
- **8x**
- **Total Gain: 16mV/fC**

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**Front-end ASIC: VFAT3**
- 128 channels
- High sensitivity (45 mV/fC)
- 0.5 MHz/strip rate capability

**Plugin cards** for VFAT connection to GEB

**Fire-Fly cables 1.5 m long** for VFAT connection to tracking chambers to GEB

**For GE2/1 and Tracking chambers**
- On-detector FPGA: OptoHybrid (Xilinx ARTIX-7) [CMS-TDR-013]
- 3x (one per GEB)
  - VFAT e-links to GBTx
  - VTRx + fibers to back-end
  - VTTx to trigger lines (unused)

**For ME0**
- On-detector FPGA-less: OptoHybrid ASIAGO
  - Readout interface for 6 VFATs on the ME0 GEB
  - 2 lpGBT chips and 1 VTRx+ transceiver on each OH board
  - Sends data to backend without compression (no FPGA)
• All data sent to BE over optical links
• Custom PCIe back-end based on commercial FPGA
• 1 Gb/s Ethernet-based local readout on DAQ machine through additional network card

CVP-13 inside DAQ machine + network card (local DAQ) + water cooling

Local DAQ NIC: NVIDIA Mellanox MCX4121A-XCAT

SFP+ limit 10 Gb/s
Reconstruction and analysis – Track building

1st step: **Unpack data** converting raw binary data to readable objects (Digi)

2nd step: Clusterize the digi information to construct RecHits (Local reconstruction)

3rd step: **Build tracks** from the RecHits of each tracking chamber

4th step: **Analyze tracks** to extract efficiency, residuals, etc.
1. Choose the chamber under test

2. Build track using the remaining chambers

3. Extrapolate residual distribution on test chamber

4. Use the mean value of the distribution as correction parameter of the test chamber

5. Repeat for next chamber

6. Repeat for all chambers until converging
Reconstruction and analysis – Angular alignment

Iterative method similar to transversal alignment

Method: determining chamber misalignment from residuals vs propagated hit position.
Assuming $x_{\text{prop}}$ is the correct value and $x_{\text{rec}}$ is misaligned by $\theta$,

$$
\begin{align*}
x_{\text{rec}} &= x_{\text{prop}} \cos \theta - y_{\text{prop}} \sin \theta \\
y_{\text{rec}} &= x_{\text{prop}} \sin \theta + y_{\text{prop}} \cos \theta
\end{align*}
$$

so

$$
\begin{align*}
\delta x &= x_{\text{rec}} - x_{\text{prop}} = x_{\text{prop}} (\cos \theta - 1) - y_{\text{prop}} \sin \theta \\
\delta y &= y_{\text{rec}} - y_{\text{prop}} = x_{\text{prop}} \sin \theta + y_{\text{prop}} (\cos \theta - 1)
\end{align*}
$$

Considering that

$$
\cos \theta - 1 \sim O(\theta^2) \quad \text{while} \quad \sin \theta \sim O(\theta),
$$

it is most sensitive to extract $\theta$ from the correlation of $\delta x$ vs $y_{\text{prop}}$ (or from $\delta y$ vs $x_{\text{prop}}$).
GE2/1 performances

Efficiency map
Excellent local efficiency to 150 GeV muons reachable thanks to lower electronic noise at a gain of $2 \times 10^4$. Average efficiency limited to 98% by sectorization dead areas.

Noise level of front-end electronics attached to GE2/1 detector: the shielding provided by the GEB and the several grounding pins of the VFAT3 plugin cards allow to keep the noise below 0.5 fC

346 ± 5.9 µrad space resolution in angular coordinate
ME0 Efficiency

Comparison of efficiency profiles for ME0 second generation detector and 20x10 random-hole segmented prototype:

• The profile is obtained by slicing the two-dimensional efficiency map along the y direction. The efficiency profile is fitted with a Gaussian function comb, shown in the red line. The labels indicate the sigma of each efficiency dip extracted from the gaussian fit.

• The inefficiency areas due to the sectorization in ME0 can be recovered by the random-hole sectorization that limits the inefficiency dips to 5%.
Triple GEM tracker performances – Space resolution

- Average space resolution of 81 \( \mu m \) extracted from residual distribution

- Space resolution depends on cluster size:
  - At low cluster size: low-charge clusters reconstructed with wrong number of strips due to high threshold
  - At high cluster size: asymmetric signal spreading due to delta rays in single cluster

Residual distribution for tracking chamber 2 in y-direction for cluster size < 10

Space resolution of tracking chamber 2 vs cluster size
Triple GEM tracker performances – Efficiency

**HV efficiency scan** obtained by requiring that
- The extrapolated hit of the track on the test chamber falls in the active area of the chamber
- The extrapolated hit matches a 2D reconstructed hit

Efficiency to muons between 90% and 100% for BARI-01 and BARI-02 operated at effective gas gain of $10^5$

Lower efficiency for BARI-03 and BARI-04 operated at a lower effective gain

Main limitation due to **low signal to noise ratio**
Conclusions and future plans

• The performance of final CMS Phase-2 GEM detectors was demonstrated in particle beam with good tracking performance provided by 10x10 cm$^2$ triple-GEMs.

• An excellent efficiency was observed in the CMS Phase-2 detectors.

• A random-hole segmented triple-GEM has shown the possibility to recover the inefficiency induced by the segmentation dead area.

In the 2022 CMS GEM test beam a full ME0 detector with random hole segmentation will be tested and a time resolution measurement on the CMS GEM detectors with final electronics will be performed.
Backup
GEM Detector – Working principle

GEM foil

Single-GEM detector
HV GEM foil sectorization

Microscopic view of the separation area of two HV sectors

Microscopic view of random hole sectorization

For more details see this paper
**Data taking summary**

**Official data-taking window (oct 20 – nov 2)**
- 1-2 days: detector commissioning, touching up DAQ and local readout, first latency scan
- Days 3-5: tracker data taking with muons
- 7 days: HV training on GE2/1 detector finished, data taking with all GE2/1 setup
  - long overnight runs + shorter daily runs and debugging
- Pion runs:
  - 2 long runs at max beam intensity (~2MHz/cm²)
  - L1A rate limited from 800 kHz to 100 kHz by introducing dead time
  - 2 rate scans (10⁵-10⁶ pions per spill)

**1 week break (nov 3 – nov 10)**

**Parasitic run (nov 10 – nov 15)**
- Main activities: more statistics and rate scans with GE2/1
- Introduced R&D GEM prototypes
Tracker noise level

Trk detectors (10x10) have still same basic design as 10-15 years ago ...
Improvements made for GE21 and ME0 with shielding in ROB and GEB are very clear)

Frontend ASICs on 10x10 connected to “hanging” GEB by Firefly cables (2 trackers/GEB)