GEM single-mask characterization and influence of the GEM foil orientation

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On behalf of the CMS muon group

Upgrade of the CMS muon spectrometer in the forward region with the GEM technology (Poster by M.Gruchala)

Results of the longevity study with triple-GEM technology for the upgrade of the CMS muon end-cap (Poster by J. Merlin)

Numerical predictions of GEM sheet nonlinear mechanical properties under large deformations (Talk by O. Bouhali)

https://indico.cern.ch/event/581417/contributions/2556708/
Historical development

**GE1/1 prototyping:**

- **Generations I and II**
  - First experience with large-size detectors

- **Generation III**
  - New configuration to fulfil CMS requirements
  - New stretching technique

- **Generation IV - VII**
  - Improvement of the stretching technique
  - Improvement of the mechanics

- **Generation X**
  - Final version for LS2 production

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Inverted GEM foils

<table>
<thead>
<tr>
<th>GE1/1-I</th>
<th>GE1/1-II</th>
<th>GE1/1-III</th>
<th>GE1/1-IV</th>
<th>GE1/1-V</th>
<th>GE1/1-VI</th>
<th>GE1/1-VII</th>
<th>GE1/1-X</th>
</tr>
</thead>
</table>
### GEM foils geometries

#### Double-mask technique:
- **“Standard” for small areas** \( (\leq 40\times40 \text{ cm}^2) \)
- **Gives a perfect bi-conical shape**

<table>
<thead>
<tr>
<th>Hole location</th>
<th>Diam. ([\mu\text{m}])</th>
<th>Err. ([\mu\text{m}])</th>
</tr>
</thead>
<tbody>
<tr>
<td>Top</td>
<td>70.1</td>
<td>± 0.2</td>
</tr>
<tr>
<td>Middle</td>
<td>49.1</td>
<td>± 1.2</td>
</tr>
<tr>
<td>Bottom</td>
<td>69.4</td>
<td>± 0.8</td>
</tr>
</tbody>
</table>

#### Single-mask technique:
- **Suitable for large areas**
- **Gives a “asymmetric” bi-conical shape**

<table>
<thead>
<tr>
<th>Hole location</th>
<th>Diam. ([\mu\text{m}])</th>
<th>Err. ([\mu\text{m}])</th>
<th>Diam. ([\mu\text{m}])</th>
<th>Err. ([\mu\text{m}])</th>
</tr>
</thead>
<tbody>
<tr>
<td>Top</td>
<td>73.8</td>
<td>± 3.3</td>
<td>71.0</td>
<td>± 2.1</td>
</tr>
<tr>
<td>Middle</td>
<td>51.3</td>
<td>± 2.7</td>
<td>52.8</td>
<td>± 5.4</td>
</tr>
<tr>
<td>Bottom</td>
<td>85.5</td>
<td>± 4.1</td>
<td>86.1</td>
<td>± 4.9</td>
</tr>
</tbody>
</table>

- **How does this asymmetry affect the operation of the detectors?**
Special R&D prototype

10x10 detector with two orientations:
- Gap configuration
  - 2/2/2/2 mm
  (using the common 3/2/2/2 electric field configuration)
- RO board replaced by a single copper pad
- Using a second Kapton widow on the bottom side

Testing the two orientations without opening the chamber:
- Save time
- Reduce the risk of damaging foils during assembly
- Keep the same gap uniformity for all the tests.

Two sets of measurements:
- 3 “standard” double-mask 10x10 GEM foils
- 3 single-mask 10x10 GEM foils

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Effective gain: test setup

Primary goal of the study:

- Compare the effective gain for the 2 sets of foils in both possible orientations
- HV powering through a HV divider
- Operation in Ar/CO₂ (70:30)
- Count rate measurement from G3 bottom
- Anode current from the RO electrode
Effective gain: results and discussion

Looking at the effective gain ratios:

**Comments:**
- Double-mask orientation A = double-mask orientation B \(\rightarrow\) confirms the symmetry of the config./holes
- Single-mask orientation A = double-mask \(\rightarrow\) enlarging entrance hole does not affect transparency/multiplication
- Single-mask orientation B = 3.6 x single-mask orientation A \(\rightarrow\) exit hole diameter strongly affect the extraction efficiency or the multiplication.
Effective gain: results and discussion

We reproduced with 10x10 cm² single-mask foils the effect observed with GE1/1 detectors.
Rate capability: test setup

Rate capability strongly correlated with GEM transparency:

- At fluxes of $10^4$-$10^5$ Hz/mm$^2$
- increase of the GEM transparency
- At fluxes above $10^6$ Hz/mm$^2$
- accumulation of ions near the holes
- Typical “gain bump” at high flux

Effects of High Charge Densities in Multi-GEM detectors – P. Thuiner et al. – MPGD2015
https://agenda.infn.it/getFile.py/access?contribId=106&sessionId=2&resId=0&materialId=slides&confId=8839

Test setup:

- Irradiation with AMPTEK mini-X
- Silver target, mostly converts in the copper drift
- Use sets of attenuators to scan different flux ranges
  - from $10^2$ – $10^6$ Hz/mm$^2$
- Use 1mm collimator to define the size of the beam spot

Measuring:
- Count rate at high attenuation
- Anode current
Double-mask configuration results match the expectations at high interaction fluxes, showing a gain bump between $10^4$ and $10^6$ Hz/mm$^2$.

- Single-mask orientation A = double-mask → confirms the collection efficiency is not affected.
- Single-mask orientation B results show a smaller increase of the GEM transparency → the extraction efficiency is already close to the maximum before the space charge affect the chamber’s operation.
Another characteristics strongly related to the GEM geometry:

- Also depending on the initial environmental conditions
  - Temp. / Atm. Pressure / humidity
  - Gas mixture
  - Initial gain
  - Properties of the source
    (interaction rate/ primaries)

Test setup:

- Fe$^{55}$ source
  - Interaction rate = 1.1 kHz/cm$^2$
- Monitoring continuously anode current and peak position from G3 during 5 hours
- Monitoring continuously environmental parameters
- Thermal insulation of the detector and All the pipes (SS and copper – no plastic)

Comment:

- Initial and final gain scans along the chamber were performed to disentangle global gain fluctuations and local variations due to charging up

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Charging up: results and discussion

Comment:
- Initial and final scans show gain variation only in the irradiated position


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Charging up: results and discussion

Comment:
- Initial and final scans show gain variation only in the irradiated position
- Single-mask orientation A = double-mask \( \rightarrow \) confirms the previous observations
- Single-mask orientation B has a lower gain variation and become stable before the other configuration

Summary and plans

**From the CMS GEM point of view:**
- **Confirmed the single-mask hypothesis concerning the low gain in GE1/1-IV**
- Reproducing the initial observation
- Testing the basic characteristics that involve the GEM transparency
- **Identified the best orientation (B) for the CMS chambers**
  - Higher gain (performance) at lower voltage
  - Better gain stability vs. time and vs. interaction rate
- **Plans to finalize this study**
  - Measure directly the GEM transparency vs. configuration/orientation
  - Support the experimental data with simulation

**From the GEM community point of view:**
- **Better understanding of the single-mask technology**
- New comparison study
- Effect of the hole geometry on GEM transparency
- **Another parameter that can be tuned to improve GEM performance**
  - Clues on how the hole asymmetry can affect the detector’s operation
  - Trigger interest for further development
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Thank you
Mechanical self-stretching:

- No glue – No spacers
- Assembly time reduced to few hours instead of days
- Introduced for the first time in GE1/1 generation III
Spare: GEM foil production techniques

**Double-mask**

- Raw material → *Vacuum deposited copper*
- Photo-resist and Masking → *UV exposure and development*
- Copper electro-etching →
- Chemical polyimide etching →

**Single-mask**

- Bottom copper etching →
- Photo-resist stripping →
- Bottom polyimide etching → *Hole geometry transformation*
### Specification/parameter

<table>
<thead>
<tr>
<th>Specification/parameter</th>
<th>GE1/1 detector</th>
</tr>
</thead>
<tbody>
<tr>
<td>Detector technology</td>
<td>Gaseous detector / MPGD</td>
</tr>
<tr>
<td>Charge Amplification element</td>
<td>triple-GEM structure (tensioned at ~ 5N/m)</td>
</tr>
<tr>
<td>Number of chambers in overall system</td>
<td>144 (72 in each end-cap)</td>
</tr>
<tr>
<td>Chamber shape (active readout area)</td>
<td>Trapezoidal / opening angle 10.15° 2.6 mrad</td>
</tr>
<tr>
<td>Active area overlap between chambers</td>
<td></td>
</tr>
<tr>
<td>Short chamber dimensions</td>
<td>L: 106.1 cm, W: (23.1 – 42.0) cm, D: 0.7 cm</td>
</tr>
<tr>
<td>Long chamber dimensions</td>
<td>L: 120.9 cm, W: (23.1 – 44.6) cm, D: 0.7 cm</td>
</tr>
<tr>
<td>Total chamber thickness</td>
<td>D: 3.5 cm</td>
</tr>
<tr>
<td>Active readout area</td>
<td>0.345 m² (short ch.) / 0.409 m² (long ch.)</td>
</tr>
<tr>
<td>Active chamber volume</td>
<td>2.6 liters (short ch.) / 3 liters (long ch.)</td>
</tr>
<tr>
<td>Radial distance from beam line</td>
<td>130.2 cm (at inner edge of active area)</td>
</tr>
<tr>
<td>Geometric acceptance in $\eta$</td>
<td>1.61 – 2.18 (short ch.) / 1.55 – 2.18 (long ch.)</td>
</tr>
<tr>
<td>Signal readout structure</td>
<td>Truly radial copper strips</td>
</tr>
<tr>
<td>Readout strip angular dimensions</td>
<td>230 $\mu$rad width / 436 $\mu$rad pitch</td>
</tr>
<tr>
<td>Number of $\eta$-segments in readout</td>
<td>8</td>
</tr>
<tr>
<td>Number of readout strips per $\eta$-segment</td>
<td>384</td>
</tr>
<tr>
<td>Number of readout strips per chamber</td>
<td>3,072</td>
</tr>
<tr>
<td>Counting gas mixture</td>
<td>$Ar/CO_2$ 70 : 30 or $Ar/CO_2/CF_4$ 45 : 15 : 40</td>
</tr>
<tr>
<td>Nominal operational gas flow</td>
<td>1 chamber volume per hour</td>
</tr>
<tr>
<td>Number of gas inlets / outlets</td>
<td>1 / 1</td>
</tr>
<tr>
<td>Nominal HV applied to drift electrode</td>
<td>3200 V ($Ar/CO_2$) / 4000 V ($Ar/CO_2/CF_4$)</td>
</tr>
<tr>
<td>Nominal operational gas gain</td>
<td>$1 – 2 \times 10^4$</td>
</tr>
<tr>
<td>Demonstrated rate capability</td>
<td>$100 \text{ MHz/cm}^2$</td>
</tr>
</tbody>
</table>
## Spare : HV configurations

<table>
<thead>
<tr>
<th>Region</th>
<th>Gap [mm]</th>
<th>Electric field [kV/cm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Drift</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>Transfer 1</td>
<td>1</td>
<td>3.5</td>
</tr>
<tr>
<td>Transfer 2</td>
<td>2</td>
<td>3.5</td>
</tr>
<tr>
<td>Induction</td>
<td>1</td>
<td>5</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Region</th>
<th>Voltage [V]</th>
<th>Average Electric field [kV/cm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\Delta_{GEM1})</td>
<td>450</td>
<td>89</td>
</tr>
<tr>
<td>(\Delta_{GEM2})</td>
<td>440</td>
<td>88</td>
</tr>
<tr>
<td>(\Delta_{GEM3})</td>
<td>420</td>
<td>84</td>
</tr>
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<tbody>
<tr>
<td>Drift</td>
<td>3</td>
<td>2.4</td>
</tr>
<tr>
<td>Transfer 1</td>
<td>2</td>
<td>3.6</td>
</tr>
<tr>
<td>Transfer 2</td>
<td>2</td>
<td>3.6</td>
</tr>
<tr>
<td>Induction</td>
<td>2</td>
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</thead>
<tbody>
<tr>
<td>(\Delta_{GEM1})</td>
<td>400</td>
<td>80</td>
</tr>
<tr>
<td>(\Delta_{GEM2})</td>
<td>360</td>
<td>72</td>
</tr>
<tr>
<td>(\Delta_{GEM3})</td>
<td>325</td>
<td>65</td>
</tr>
</tbody>
</table>
Use of attenuation filter to properly measure the interaction flux: