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Novel triple-GEM mechanical design for CMS-ME0 detector and preliminary performance

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on behalf of the CMS Muon Group

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1. ME0 Project

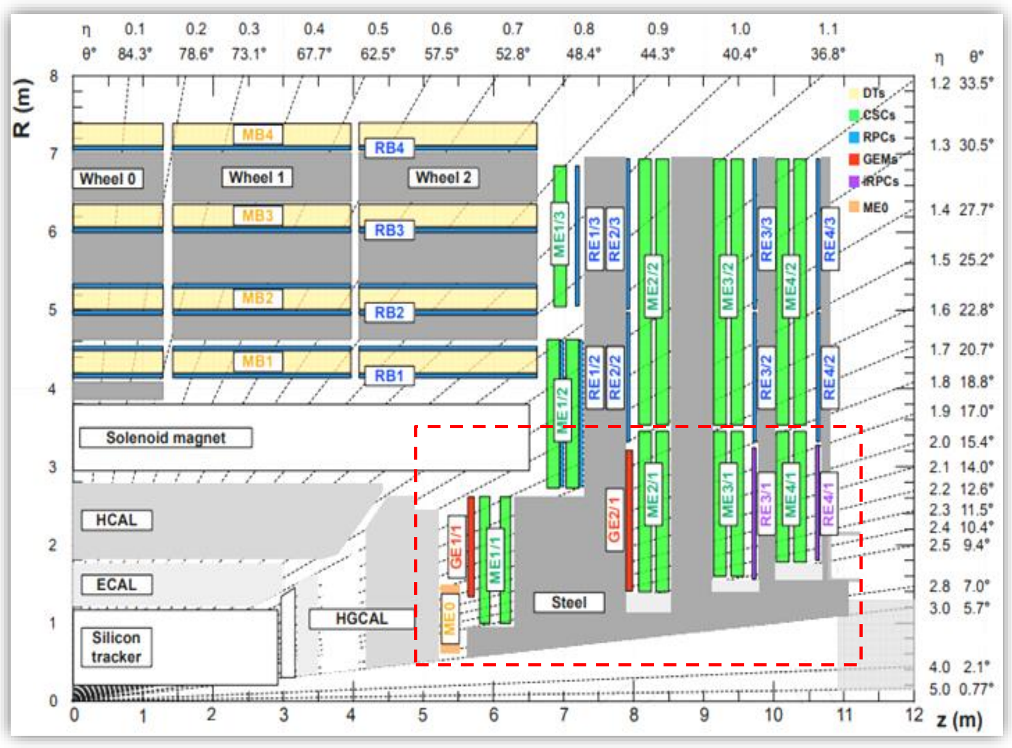

Figure 1. An $R-z$ cross section of a quadrant of the CMS detector, including the Phase-2 upgrades ($RE3/1, RE4/1, GE1/1, GE2/1, ME0$).

The high-luminosity LHC (HL-LHC) upgrade is setting now a new challenge for particle detector technologies. In the CMS muon system gas detectors, the increase in luminosity will produce a particle background ten times higher than under conditions at the LHC.

To cope with the high rate environment and maintain the actual performance, the new triple-Gas Electron Multiplier detectors will be installed in the innermost region of the forward muon spectrometer of the CMS experiment.

The ME0 system will cover $2.03 < \eta < 2.80$ using six layers of triple-GEM detectors. The six layers provide good pattern recognition and background rejection. The ME0 system provides unique coverage in the range $2.40 < \eta < 2.80$ and strengthens the coverage provided by the CSCs, RPCs and GE2/1 in the range $2.03 < \eta < 2.40$.

The main motivation for the new ME0 detectors is the increase of the geometrical acceptance for muons, which is most relevant for multi-muon final states such as $H \to 4\mu$, and for forward particle production.

2. ME0 Detector Mechanical Design

The CMS Muon Group has developed a novel construction design of large-area, trapezoidal-shaped triple-GEM detectors for the GE1/1, GE2/1 and ME0 projects.

ME0 Detector Module Construction

- a new *self-stretching technique* has been introduced to mechanically stretch the GEM foils without using spacer grids or glue inside the gas volume in order to avoid dead regions (several %) or possibly outgassing contaminants which could trigger premature aging processes.
- Drift and Readout electrode are made by standard single layer PCB. Electrical signal is extracted by "vias" on PCB through new Hirose connectors.
- The moveable internal glass-epoxy frames are controlled by "stretching screws".
- The tightness of the chambers is assured by an external glass-epoxy frame sealed with rubber O-rings.
- Chamber assembly is performed in clean room (at least class 1000) to avoid the GEM foils contamination.

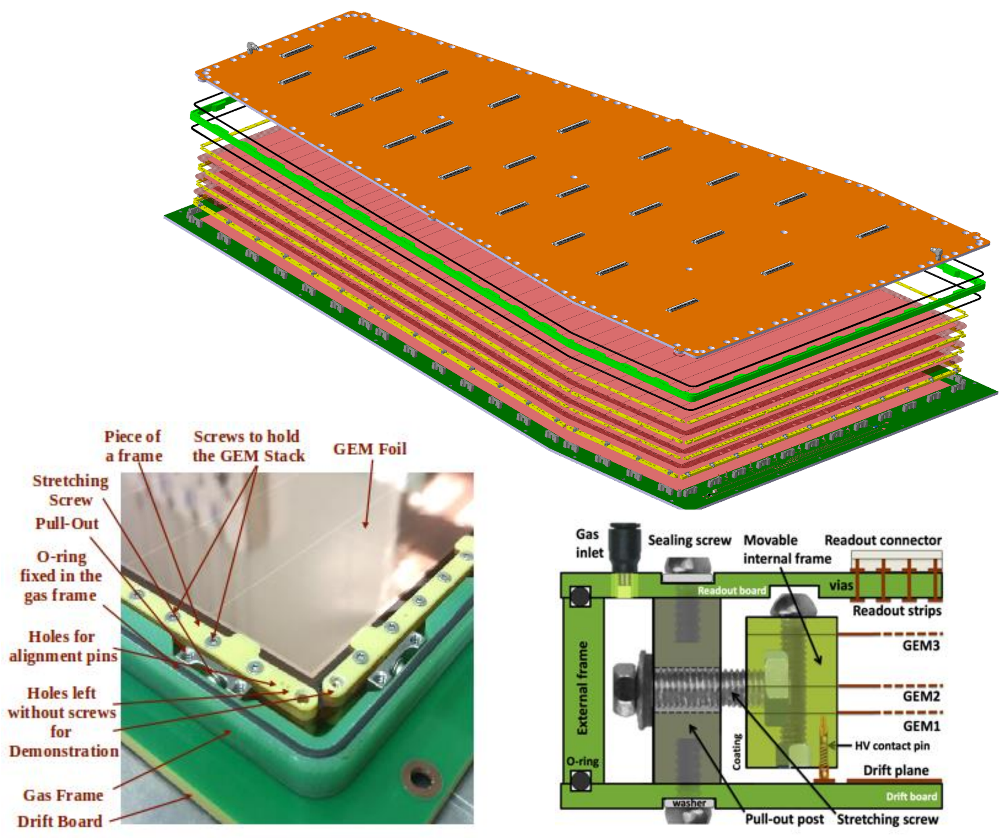

Figure 2. Top: Exploded view of the mechanical design of a ME0 triple-GEM detector module and its main assembly components. Bottom: Magnified view of the section of the ME0 module with GEM foils stack tensioned against the pull-outs mounted onto the drift board and surrounded by outer frame having O-ring on its grooves (left). Concept and mechanism employed to stretch the GEM foils (right).

Internal Distance Holders

During the GE1/1 detectors mass-production, it has been observed that the PCB boards, which define the gas enclosure of the detector, get deformed (inflate) under the internal gas overpressure, introducing irregularities in the planarity of the GE1/1 detector, which could potentially affect the uniformity of the detector performance.

A new solutions and design upgrades based on the PCB *internal distance holders* (pillars) have been implemented to prevent such effects in the future ME0 upgrade projects.

The distance between the readout and the drift board is maintained by $7.2^{\pm 0.05}\,mm$ thick precisely machined pull-out posts and four internal distance holders. The stainless steel pillars are circular with $5.02^{\pm 0.05}\,mm$ diameter and a height of $7.2^{\pm 0.05}\,mm$, and insulated by a $2.0^{\pm 0.05}\,mm$ thick glass-epoxy collar.

The pull-out posts and the internal distance holders define not only the detector active volume but, more importantly, they assure the co-planarity of the readout and drift board.

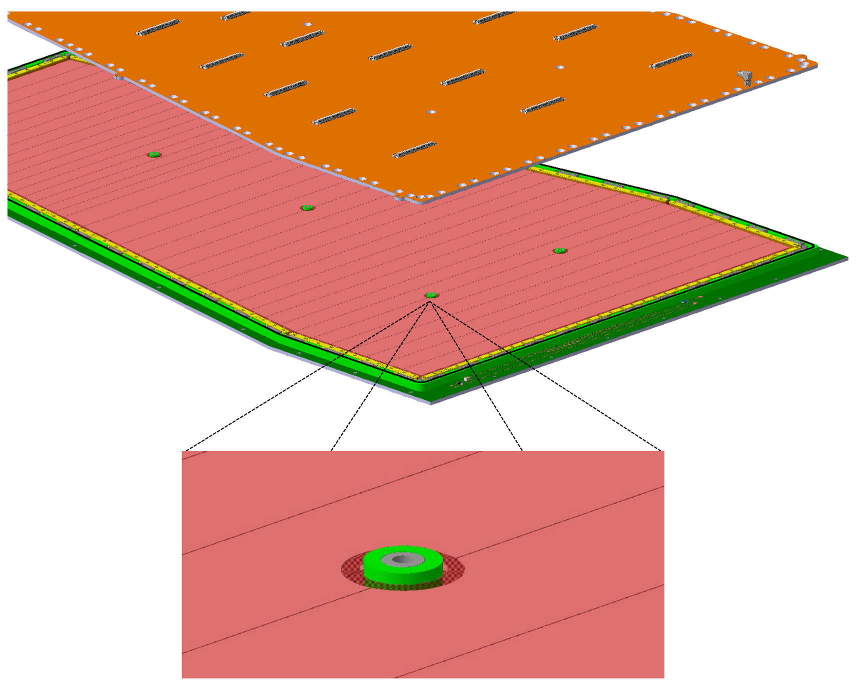

Figure 3. Top: Exploded view of the mechanical design of a ME0 triple-GEM detector module showing the internal distance holders (pillars) and their insulating glass-epoxy collar. Bottom: Magnified view of the pillars (in grey) and its glass-epoxy collar (in green)

Double-Sides Segmented GEM-foils

To reduce the *propagation probability* and the *damage probability* of the front-end electronics, to improve the high voltage stability of the GEM-foil in case of discharges and allow efficient de-coupling of the bottom foil through a protection resistor, a dedicated additional R&D on the GEM foils have been carried out which reverted to the decision to segment also the GEM foil surfaces oriented towards the readout board with segmentation identical to the one adopted for the surfaces oriented towards the drift board.

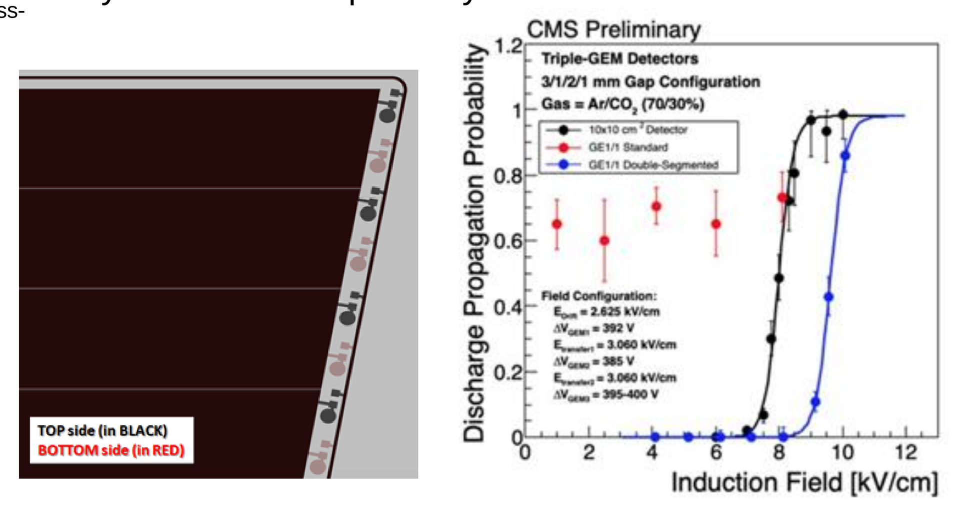

Figure 4. Schematic view of the double side segmented GEM-foil (left) and discharge propagation probability as a function of the induction field for $10 \times 10\ cm^2$ chamber compared with GE1/1 chamber assembled with and without double segmented GEM foils.

Measurements confirmed the hypothesis: no spark propagation towards the RO board has been observed in the HV range where the triple-GEM chambers will be operated, about $4\ kV/cm$.

Six ME0-module stack design

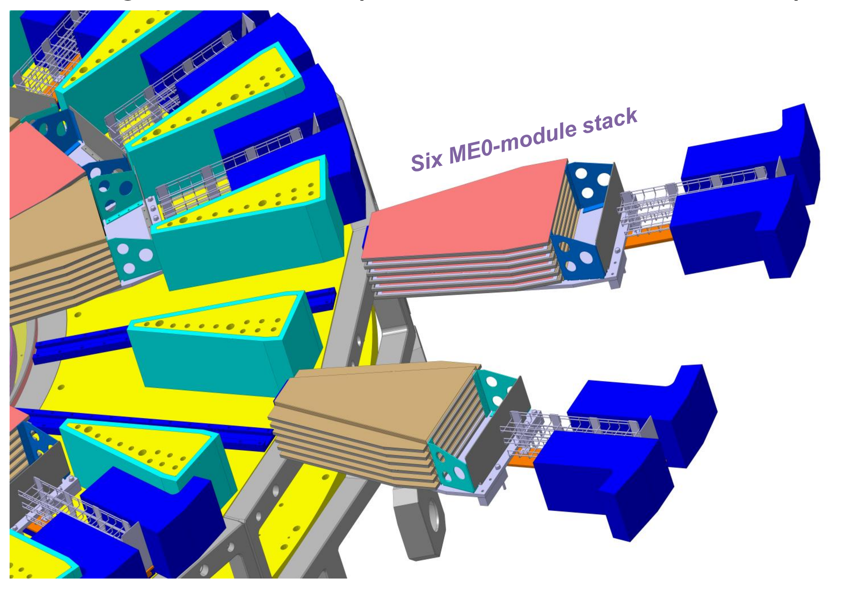

Figure 5. 3D drawing of the insertion of two adjacent stacks of six ME0 modules (pink/brown) into the endcap nose. The rails for sliding the stacks into the endcap are visible both on the nose (blue) and on the stack (orange). Note the alternating orientation of modules in the stacks.

The ME0 detector station comprises 36 module stacks (18 per end-cap), each composed of six ME0 modules, compared to the two-layer design of GE1/1 and GE2/1.

Each trapezoidal ME0 detector covers an azimuthal angular window of $20°$. Thus altogether $18 \times 6 \times 2 = 216$ triple-GEM chambers are needed. The chambers are $3.34\ cm$ thick and in total a space of about $30\ cm$ is occupied by a six-layer stack, including shielding.

Each stack is mounted on a $15\ mm$ thick aluminum plate which supports the stack mechanically. This creates an independently working complete unit, which will allow testing and qualifying of individual ME0 stacks before their installation in the CMS end-cap nose.

3. ME0 Detector Prototype Characterization

Two ME0 prototype module, with double side segmented GEM-foils, have been fully assembled, tested and qualified at the CMS-GEM QA/QC Lab. in CERN by following the well-established techniques used for the GE1/1 module qualification.

Measurement of the gas detector tightness

The test aims to identify a possible gas leak and eventually measuring the *gas leak rate* by monitoring the drop of the internal over-pressure as a function of time.

The chamber is filled with CO_2 until an over-pressure $P_0 \approx 25\ mBar$ is reached. The test consists in the monitoring of the detector over-pressure in 1 hour. The pressure drop is modeled by the function $P_m(t) = P_0 \times e^{(-t/\tau)}$. The parameter τ qualifies how fast the overpressure inside the detector decreases as a function of the time.

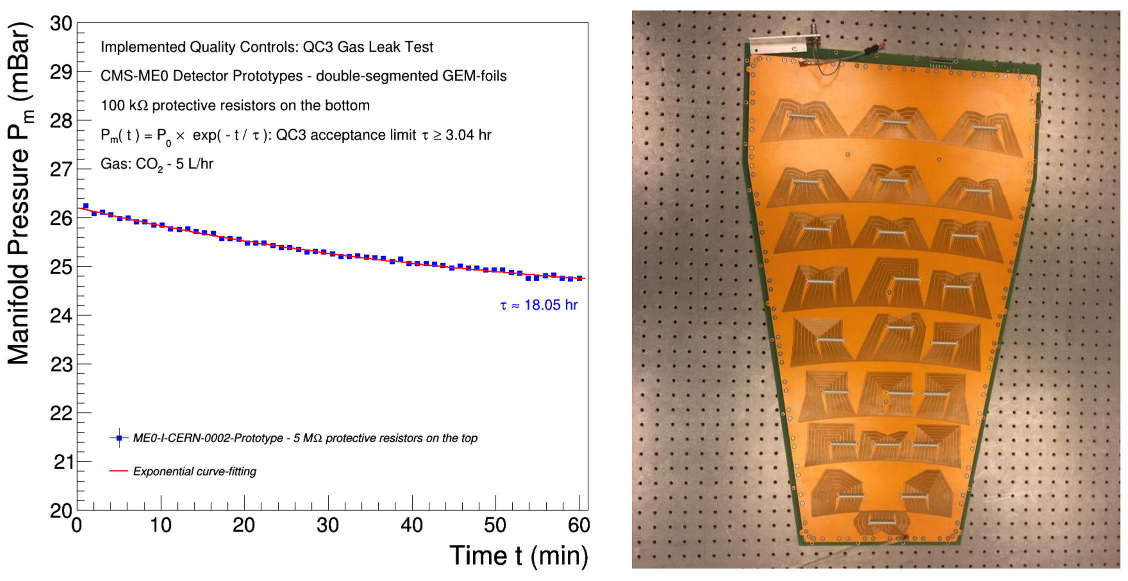

Figure 6. Results from the Gas Leak Test on the ME0 detector prototype. Left: The pressure drop is modeled by the function $P_m(t) = P_0 \times e^{(-t/\tau)}$, which provides a gas leak time constant $\tau \sim 18\ hr$. Right: picture of the first ME0 module assembled at CMS-GEM Clean Room in CERN.

High Voltage and Linearity Test

The HV and Linearity Test aims to determine the *current-voltage curve*, in order to identify possible malfunctions, defects in the HV circuit and *intrinsic noise rate* (i.e. pulses not produced by ionizing particle). The detector is ramped up to $3.0\ kV$ in steps of $200\ V$ and up to $4.9\ kV$ in steps of $100\ V$ in pure CO_2. For each step, the current through the HV circuit and the intrinsic noise rate of the detector, read by the bottom of the third GEM-foils, are recorded.

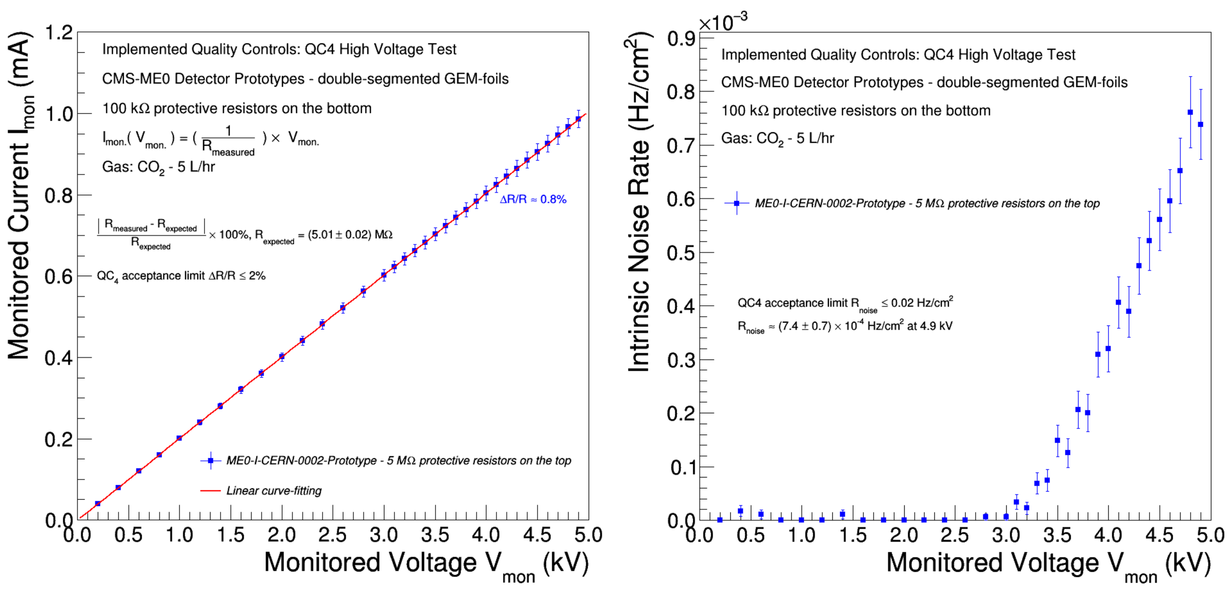

Figure 7. Results from the HV and Linearity Test on the ME0 detector prototype. Left: current through the HV divider as a function of the applied voltage. The linear fit to the experimental data provides an equivalent resistance $R_{equiv.} \sim 4.97\ M\Omega$, resulting in a deviation of about 0.8% with respect to the expected value ($R = 5.01 \pm 0.02\ M\Omega$). Right: intrinsic noise rate N_{noise} as a function of the applied voltage: $N_{noise} \sim 0.73 \times 10^{-3}\ Hz/cm^2$ at $4.9\ kV$, a negligible value with respect to the background rate expected in CMS ME0 region in standard operating conditions.

Measurement of the Effective Gas Gain and Energy Spectrum

The *effective gas gain* and the *energy spectrum* are measured in the standard Ar/CO_2 $(70/30)$ gas mixture on a reference readout sector located at the geometrical center of the detector as a function of the current through the divider with an X-ray tube with silver target and beam energy which peaks at $22.5\ keV$ and $25\ keV$.

The results for the ME0 module assembled with double segmented GEM-foils are fully consistent with the gas gain and energy resolution of the GE1/1 detectors assembled with standard GEM-foils.

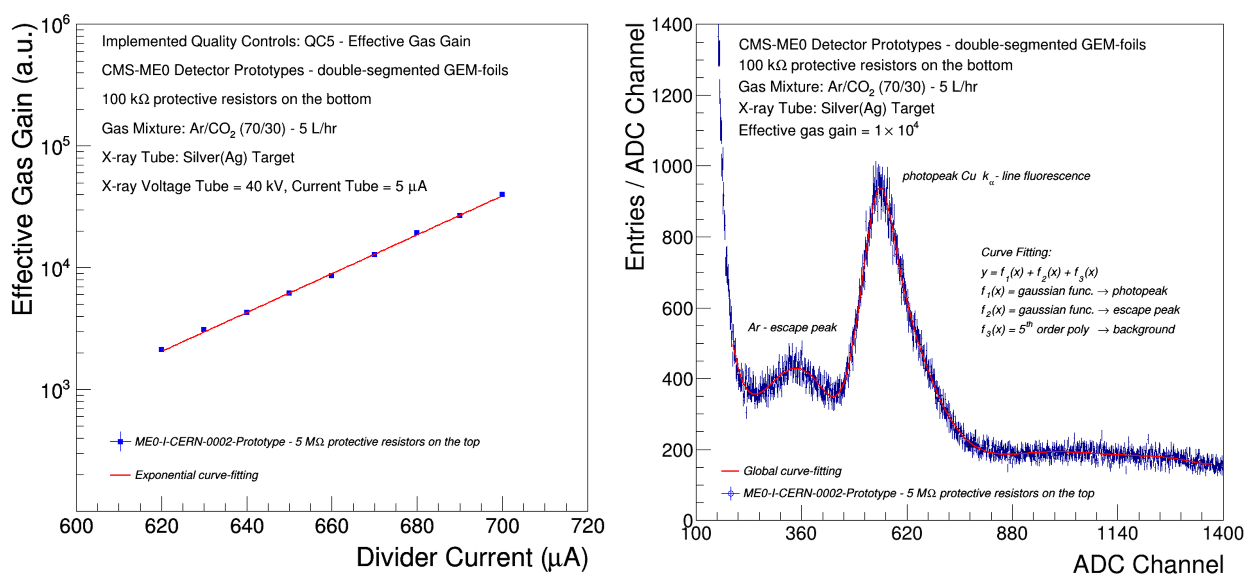

Figure 8. Results from the effective gas gain (left) and typical energy spectrum (right) of the ME0 detector prototype operating in Ar/CO_2 $(70/30)$ at an initial gas gain of 1×10^4. A clear separation of the main photopeak and the Ar - escape peak is achieved.

4. Gas Gain Uniformity Studies

New generation high energy physics experiments require large-area gas detectors. The overall performance of these detectors depends on gas gain uniformity, energy resolution and efficiency over the entire active region. Several factors, like variations in hole diameter, variations in gas gap due to inaccurate stretching or bending in the PCB readout and drift board under the internal gas overpressure, etc., could lead to non-uniformity in the triple-GEM detector. Thus it is essential to measure the *gas gain uniformity* over the entire surface area.

The effective gas gain has been measured in the 24 readout sectors in order to create a map of the detection performance.

The detector under test was operated at an average gas gain of 2×10^4 with Ar/CO_2 $(70/30)$ and fully illuminated by the X-ray tube.

The distribution of effective gas gain values is fit to extract the mean (μ) and the standard deviation (σ) of the distribution. The *response uniformity* of the detector is defined as $\sigma/\mu \times 100\%$ and it's proportional to the gain variation across the whole detector surface.

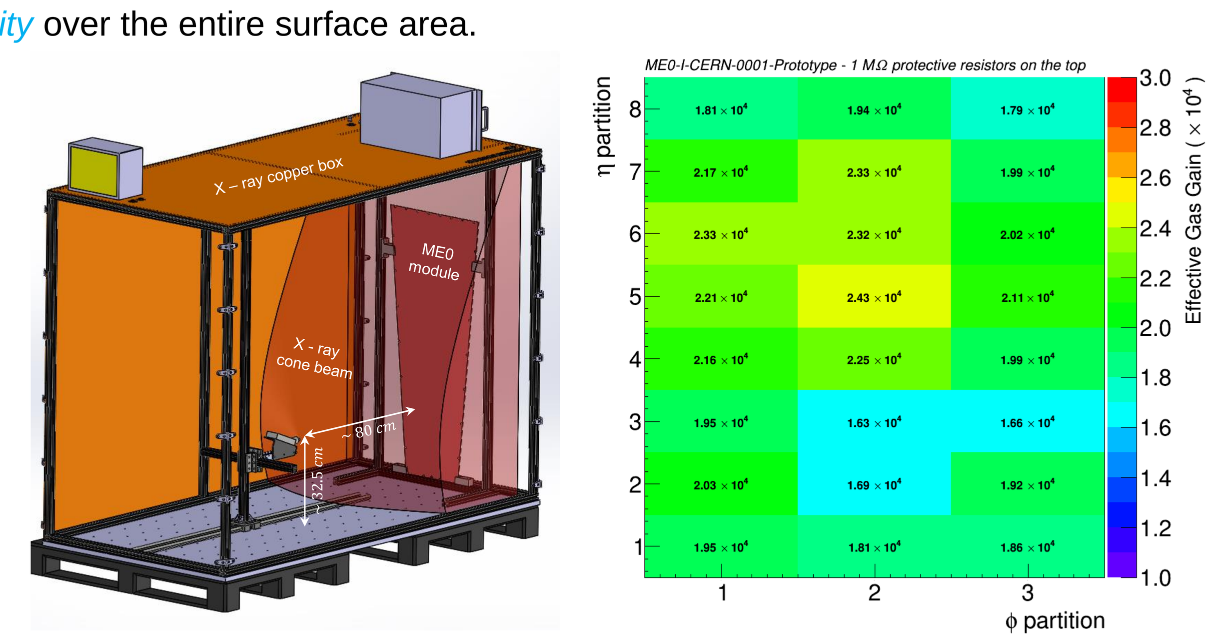

Figure 9. Left: Schematic overview of the X-ray copper box showing the detector under test operated at an average gas gain of about 2×10^4 with Ar/CO_2 $(70/30)$ and fully illuminated by a $22\ keV$ $X\text{-}ray$ generator. Right: 2D mapping of the effective gas gain measurement of the ME0 module prototype as a function of spatial location. The detectors under test are

The response uniformity for the ME0 module prototype with $1\ M\Omega$ (left) protective resistors is 11.2% and for the ME0 module prototype with $5\ M\Omega$ (right) on the top is 12.5%, indicating a good uniformity of the two detector prototypes.

GE1/1 Detector Response Uniformity

The bending of drift and readout electrodes could affect the drift and induction electric fields, modifying the transparency of the GEM-foils.

In the GE1/1 detector for the LS2 mass-production, the maximum variation of the induction gap caused by the maximum flatness deviation of the readout board could reach $(1 + 0.4)\ mm$ and leading to a non-uniformity of about 40% in the electric induction field, i.e. an intrinsic variation of gas gain of about 25%.

A great effort has been made by the CMS Muon Group on the ME0 detector design and assembly procedure in order to mitigate the drift and readout board bending effect, by introducing the internal distance holders (pillars) to assure the co-planarity of the drift and readout board.

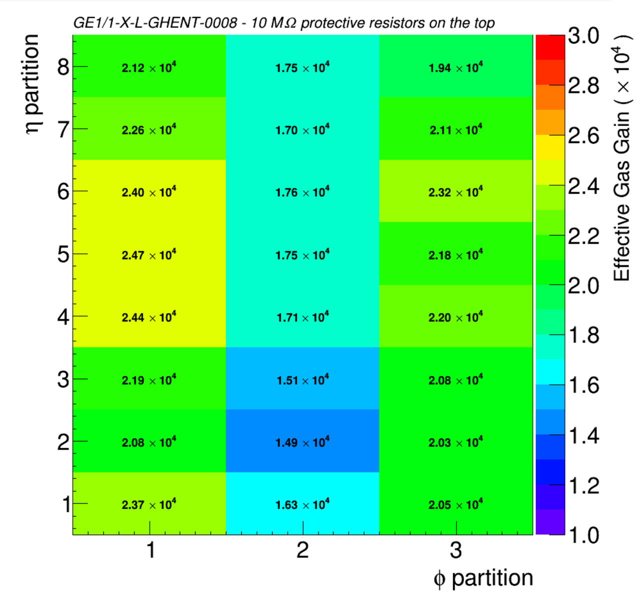

Figure 10. 2D mapping of the effective gas gain measurement of a GE1/1 detector for LS2 mass production as a function of spatial location.

5. Future Plans

Due to the harsh background environment expected in the innermost ME0 region, it is fundamental to:

- study the impact of the protective resistors on the rate capability of the ME0 module detector and at the same time ensure a proper protection against the effects of accidental discharges.
- study the long-term operation of the ME0 module detector, in particular the study of the aging phenomena.

[1] Fallavollita F, 2018, *Triple-Gas Electron Multiplier technology for future upgrades of the CMS experiment: construction and certification of the CMS GE1/1 detector and longevity studies*, CERN Ph.D. thesis, CERN-THESIS-2018-349.
[2] A. Colaleo et al., *CERN-LHCC-2017-012, CMS-TDR-016*, 12 September 2017.