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The Compact Muon Solenoid Experiment

CMS Performance Note

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ME0 Quality Control Results from Initial Productions

CMS Collaboration

Abstract

As the High-Luminosity upgrade of the Large Hadron Collider (HL-LHC) is scheduled to begin in 2026, the CMS muon system is being upgraded. One of its main upgrades is the installation of Gas Electron Multiplier (GEM) detectors, ME0, in the very forward region of the CMS endcap ($2.0 < \eta < 2.8$).

Mass production of the ME0 modules started in April 2024 and is progressing smoothly. This report summarizes the quality control (QC) results of ME0 modules from initial production phase, including the results of gas leakage rates measurement, high voltage (HV) linearity tests, effective gas gain measurement, and response uniformity measurement.

ME0 Quality Control Results from Initial Productions

https://cms-results.web.cern.ch/cms-results/public-results/detector-performance/

CMS Collaboration

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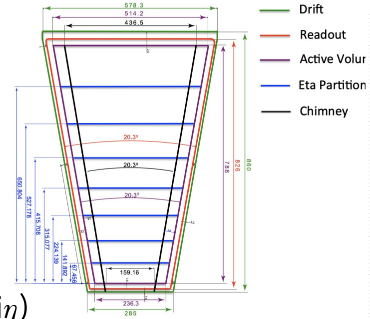
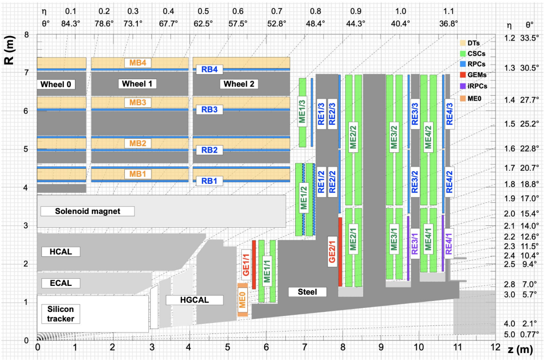
Introduction

The ME0 system

- ❑ Triple-GEM technology
- ❑ Coverage: $2.0 < |\eta| < 2.8$
- ❑ The full system: 216 ME0 Modules (108 modules per endcap)
  - 1 ME0 stack consists of 6 ME0 modules (18 stacks per endcap; coverage of 20°)
- ❑ Readout sector of a single ME0: 8 sectors along the η coordinate (iη)
  - Each iη sector consisting of 384 strips (only the first iη sector consisting of 374 strips)
  - Each iη sector is divided into 3 partitions (iϕ)

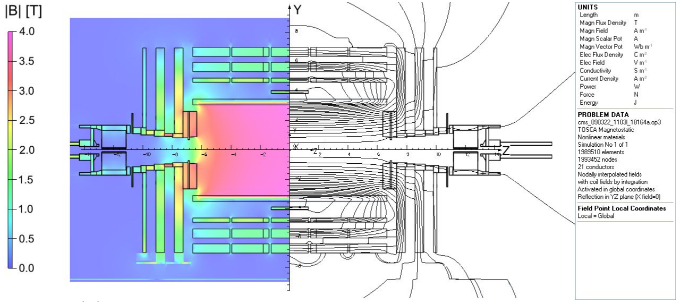


Design and dimensions of the ME0 module. Plot from [1].


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). Plot from [1].

TDR requirement on ME0 [1]

- Maximum geometric acceptance
- Single-chamber efficiency of 97% or better for detecting MIPs.
- Rate capability of at least 150 kHz/cm^2.
- Gain uniformity of 15% or better across a module and between modules.
- No gain loss due to aging effects after 840 mC/cm^2 of integrated charge for ME0.
- Angular resolution of 500 μrad or better.
- A discharge rate that does not impede performance or operation.


Value of |B| (left) and field lines (right) predicted on a longitudinal section of the CMS detector. Plot from [2].

[1] CMS Collaboration, *The Phase-2 Upgrade of the CMS Muon Detectors*, CERN- LHCC-2017-012 ; CMS-TDR-016, 2017.
[2] CMS Collaboration 2010 *JINST* **5** T03021.

Overview of Quality Control (QC)

QC procedures

QC steps		
QC1	Initial inspection of the module components	
QC2	GEM Foil Validation	
QC3	Gas Leakage Measurement	
QC4	High Voltage Linearity Test	
QC5	Part 1	Effective Gas Gain Measurement
	Part 2	Gain Uniformity Measurement
QC6	High Voltage Stability Test	

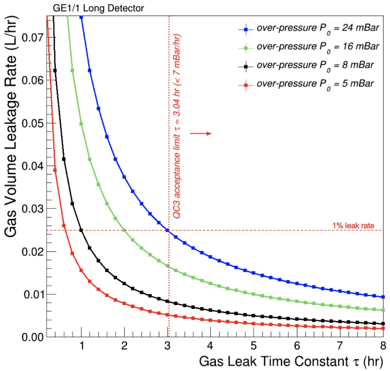
not the efficiency plot exactly but plots for the tests which can affect the efficiency

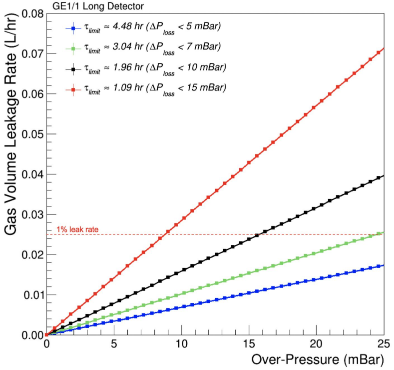
- Single-chamber efficiency of 97% or better for detecting MIPs.
- Gain uniformity of 15% or better across a module and between modules.

→ QC results here are to show detector matching the requirements.

QC3 – Gas Leak Measurement

- ❑ The QC3 aims to quantify the gas leak rate of a detector by monitoring the internal over-pressure as a function of time
- ❑ The pressure drop is modeled by the function $P(t) = P_0 e^{-t/\tau}$
  - P_0 : a constant representing the initial over-pressure of the detector
  - τ : the time constant which quantifies how fast the over-pressure inside the detector decreases as a function of time





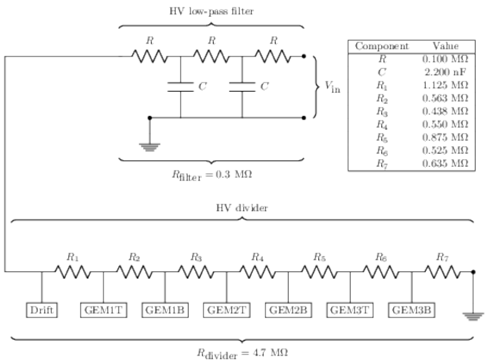
Plot & threshold information are from GE1/1 QC result paper [3].

[3] M. Abbas et al., *Quality control of mass-produced GEM detectors for the CMS GE1/1 muon upgrade*, Nucl. Instrum. Methods Phys. Res., A 1034 (2022) 166716.

Overview of Quality Control (QC)

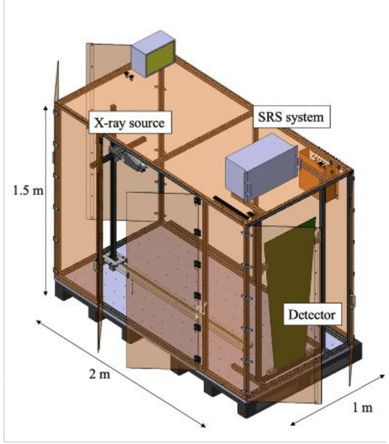
QC4 –High Voltage Linearity Test

- This test aims to check the on-detector circuitry distributing HV to the electrodes
- $R_n = R_{divider} + R_{low\text{-}pass\ filter}$ = 4.7 MΩ + 0.3 MΩ (depending on the site, lab 904 case) = 5.0 M Ω
- The deviation of the resistance of the powering circuit: $D_R = 100 * |R_n - R_m| / R_n$
- Acceptance criterion: $D_R < 3\%$ [3]
  - R_n: The nominal resistance of the powering circuit
  - R_m: The measured resistance of the powering circuit

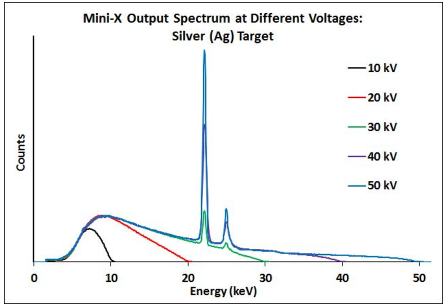


The circuit diagram for the HV filter and the ceramic HV divider (bottom) [3].

QC5 Part 1 – Effective Gain Measurement



- The effective gas gain $G = I_{RO} / I_{primary+secondary} = I_{RO} / (R \cdot e \cdot N_{p+s})$
  - R : rate of electrons converted from the photoelectric effect
  - e : electron charge
  - N_{p+s} : primary and secondary electrons produced by the photoelectron in the gas
  - I_{RO} : the read-out current
- Amptek mini-X (X-ray gun) with a silver target; 40 kV, 5 μA
  - Emitted photons (~ 22 keV) by X-ray excite the copper electrons, which leads to emitting fluorescence photons
- Temperature & Pressure correction applied.



Energy spectrum of Amptek Mini-X X-ray with silver (Ag) target [4].

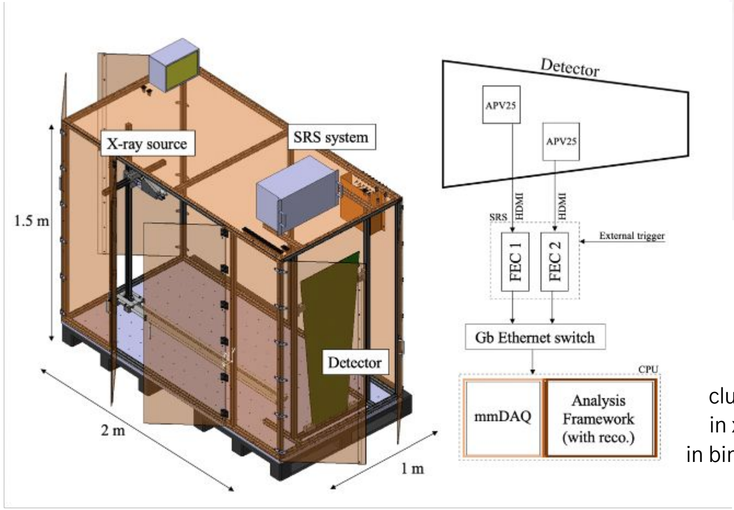
[4] Amptek Mini-X manual

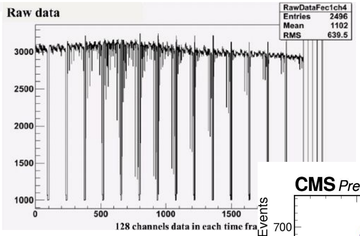
Overview of Quality Control (QC)

QC5 Part 2 – Gain Uniformity Measurement

Process: Signal induced on RO strips → APV25 → ADC → FEC → DAQ

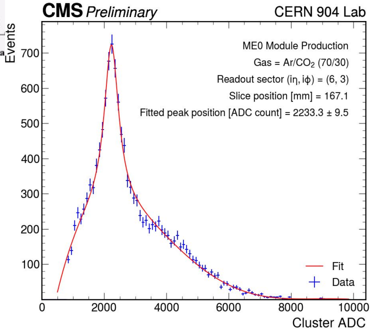
Analog Pipeline Voltage mode (APV) Front-end concentrator cardsr(FEC)
Analog-to-Digital Converter (ADC) Data Acquisition (DAQ)



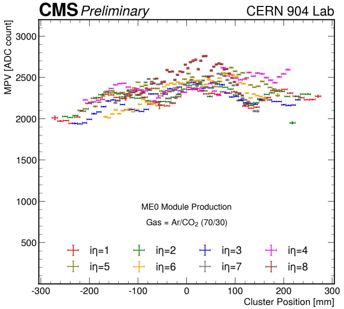


Plot from [5].

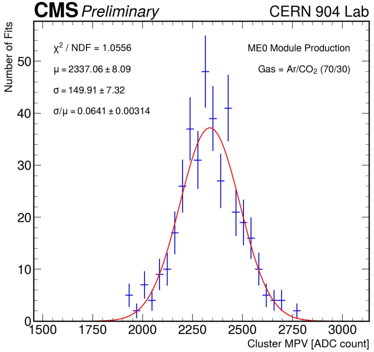
clusterization and binning
in x position of the cluster
in bins which are 8-strips wide



Peak position of
clusterADC over the
entire ME0 detector



Make a histogram
using the data points
from this distribution

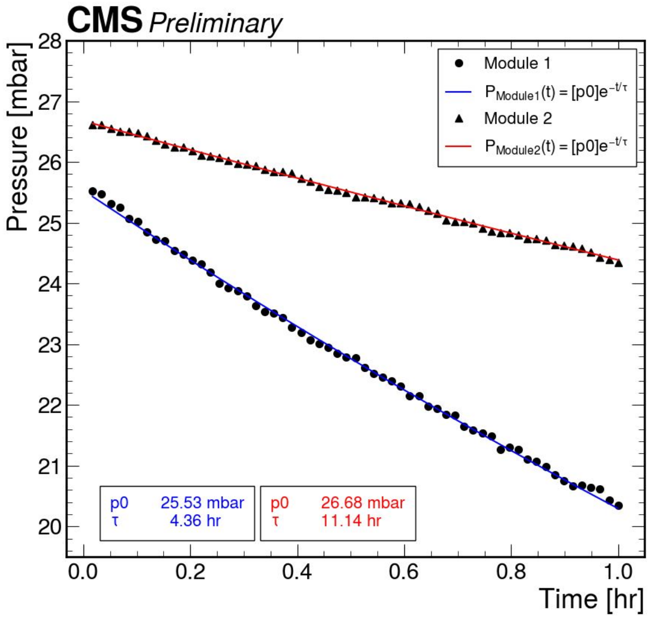


Response Uniformity = 100* σ/μ (%)
→ Acceptance limit: R.U. < 15%

[5] DOI:10.1109/NSSMIC.2010.5873822

Gas leak measurement

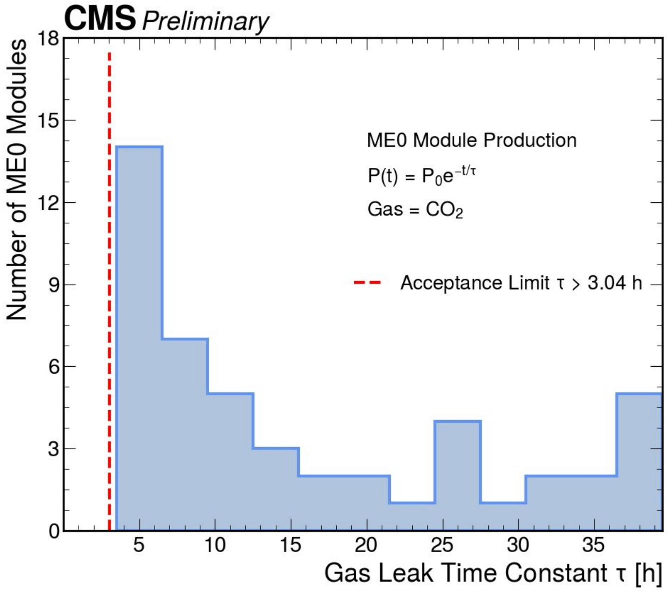
An example of gas leak measurement



Examples of the gas leak rate measurement on two ME0 detectors. The measurement was conducted in two different sites. This plot shows the change of the over-pressure of the modules over one hour. The pressure drop is modelled by the function $P(t) = P_0 e^{-t/\tau}$, where τ quantifies how fast the over-pressure inside the detector decreases over time. Modules with τ higher than 3.04 hour are accepted [3]. ME0 modules shown in the plot have passed the gas leak measurement with τ of 4.36 and 11.14 hour respectively.

Gas leak measurement

Result of gas leak measurement on 50 ME0

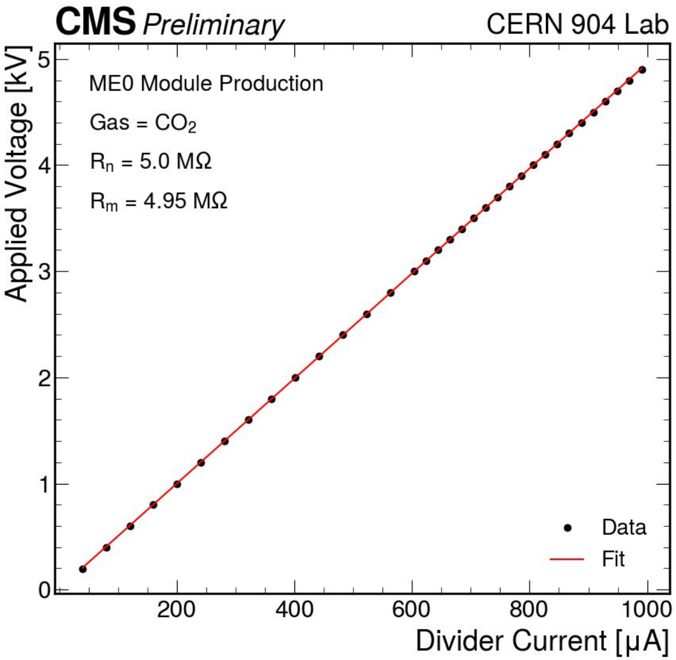


Result of the gas leak rate measurement on 50 ME0 detectors. The detectors are filled with pure CO_2 until the inside pressure reaches 25 mBar. The inside over−pressure is monitored every minute over one hour. The pressure drop is modelled by the function $P(t) = P_0 e^{-t/\tau}$, where τ quantifies how fast the over−pressure inside the detector decreases over time. The threshold for acceptance of this test is $\tau > 3.04$ h which is represented by a dashed red line in the plot. All the tested 50 ME0 modules passed the test.

The last bin includes 5 ME0 modules with τ higher than 40 hours. The mean τ of 50 ME0 modules is 15.82 h.

High Voltage Linearity Test

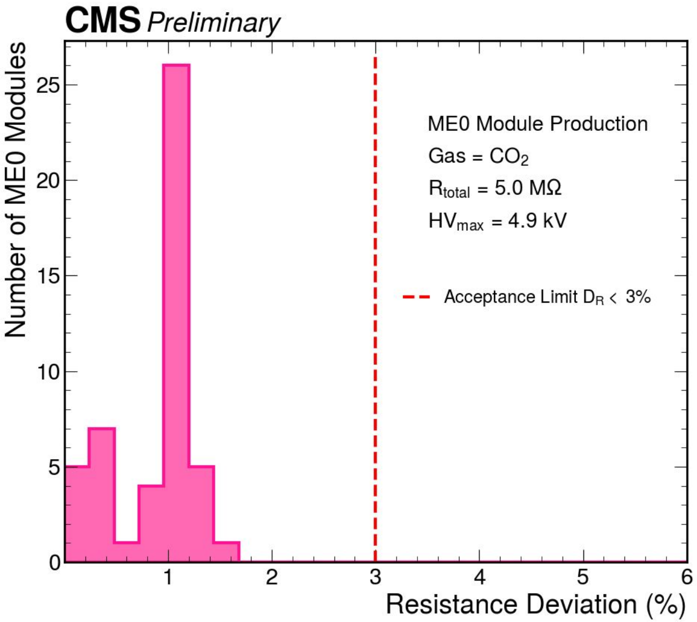
An example of HV linearity test



Applied voltage as a function of divider current for one ME0 module. A linear fit of the measured data points is shown. The slope of the fit is taken as the measured resistance R_m. The nominal resistance R_n represents the total resistance of the High Voltage (HV) divider together with a custom low–pass protection filter. The deviation of the resistance of the powering circuit is defined as $D_R = 100*|R_n - R_m| / R_n$ and only modules with a deviation smaller than 3% are accepted. In the plot, the result of an example ME0 module shows a deviation of ~1%, well below the acceptance limit.

High Voltage Linearity Test

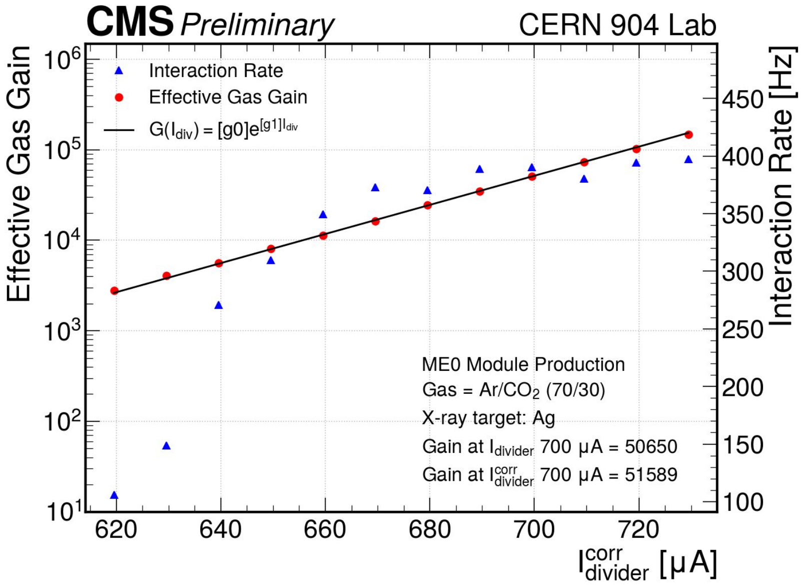
Result of HV Linearity Test on 50 ME0



Resistance deviation distribution of the High Voltage (HV) linearity test on 50 ME0 modules. A simple ceramic voltage divider consisting of a small network of ohmic resistors is soldered on the drift board to divide the voltage. The current through the powering circuit is recorded for each HV point up to 4.9 kV in steps of 100–200 V in pure CO_2 in this measurement. Once the measurement is performed, the measured resistance R_m is estimated by means of a linear fit. The nominal value R_n corresponds to the total equivalent resistance of the ceramic divider and low-pass filter, 5 $M\Omega$. The deviation of the measured resistance D_R, is calculated with respect to R_n: $D_R = 100^* |R_n - R_m| / R_n$. The acceptance criterion is $D_R < 3\%$.

Effective Gas Gain Measurement

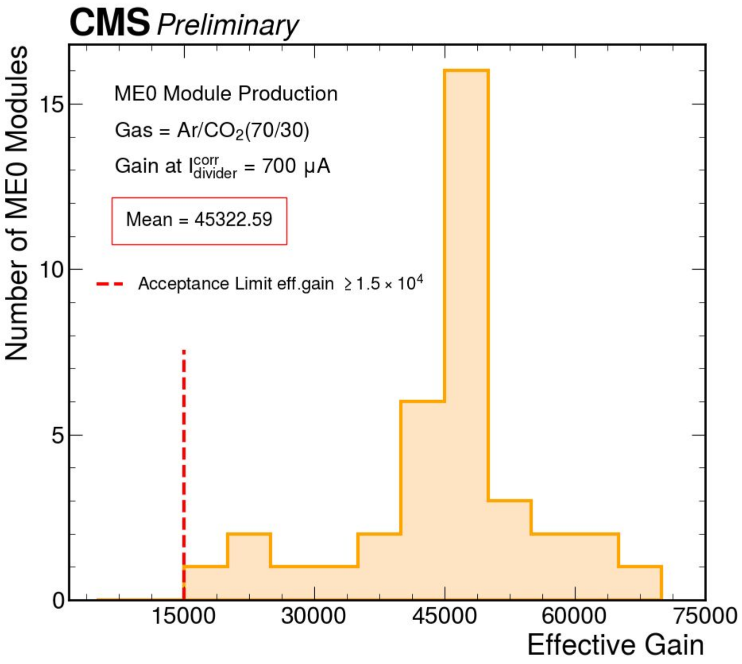
An example of effective gas gain measurement



An example of effective gas gain measurement on ME0 production module. The measurement is performed in Ar/CO_2 (70/30) gas mixture utilizing a silver (Ag) target Amptek Mini-X operated at 40 kV and 5 μA. The energy spectrum of the emitted photons from the X-ray has peak at 22.5 keV. These photons are absorbed by the copper atoms of the drift printed circuit board (PCB) of the ME0 module, emitting 8.05 keV photons by fluorescence.
The effective gas gain G is given by $G = I_{RO} / R \cdot e \cdot n_T$ where I_{RO}, R, and n_T are the readout current, the rate of the incoming photons, and the total number of electrons in the gas, respectively. Then, effective gas gain distribution is fitted with an exponential function: $G = [g0]e^{[g1]I}$. Only modules with the effective gas gain higher than 15000 at 700 μA are accepted.
Since the gas gain is affected by temperature (T) and pressure (P), T/P correction is applied on $I_{divider}$ to overcome this interference as following: $I_{divider}^{corr} = I_{divider}\ [(P_0/P)(T/T_0)]^{0.43}$ where P_0 = 964.4 mBar and T_0 = 297.1 K. The gas gains at 700 μA before and after T/P correction are 50650 and 51589, respectively.

Effective Gas Gain Measurement

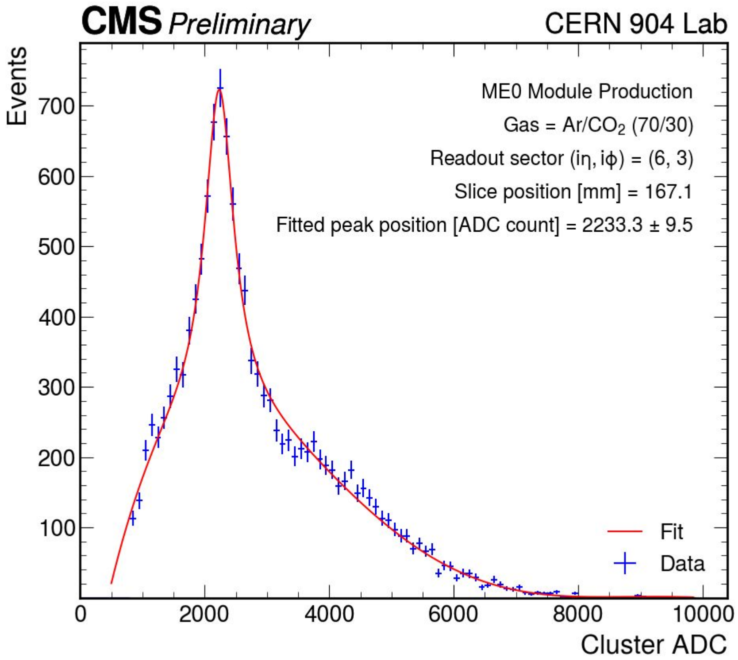
Effective gas gain at 700 uA



Distribution of effective gas gain of 37 ME0 modules at 700 μA after temperature (T) and pressure (P) correction. The effective gas gain is determined by comparing the primary current induced in the drift gap with the induced current on the readout electrode, and it's given by $G = I_{RO} / (R \cdot e \cdot n_T)$, where I_{RO}, R, and n_T are the readout current, the rate of the incoming photons, and the total number of electrons in the gas, respectively. The gas mixture for operating this measurement is Ar/CO_2 (70/30). The following T/P correction is applied on $I_{divider}$: $I_{divider}^{corr} = I_{divider}\,[(P_0/P)(T/T_0)]^{0.43}$ where P_0 = 964.4 mBar and T_0 = 297.1 K. Only modules with the effective gas gain higher than 15000 at 700 μA are accepted.

Gain Uniformity Measurement

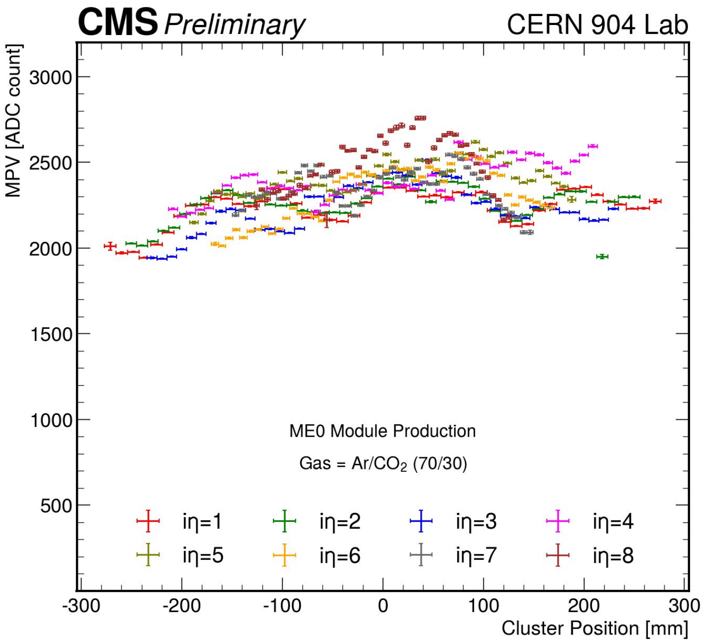
An example of gain uniformity measurement



An example of a cluster ADC distribution for one ME0 module. The measurement is performed in Ar/CO_2 (70/30) gas mixture utilizing a silver (Ag) target Amptek Mini-X. For each η sector (iη), the strips are clusterized and then ADC distributions are produced separated by the x position of the cluster, with each distribution representing a section of the detector 8 strips wide. The peak of the distribution is fitted with a Cauchy function over a 5th order polynominal for the background. The cluster most probable values (MPVs) of the charge spectrum over the entire module are used to calculate the gain uniformity later.

Gain Uniformity Measurement

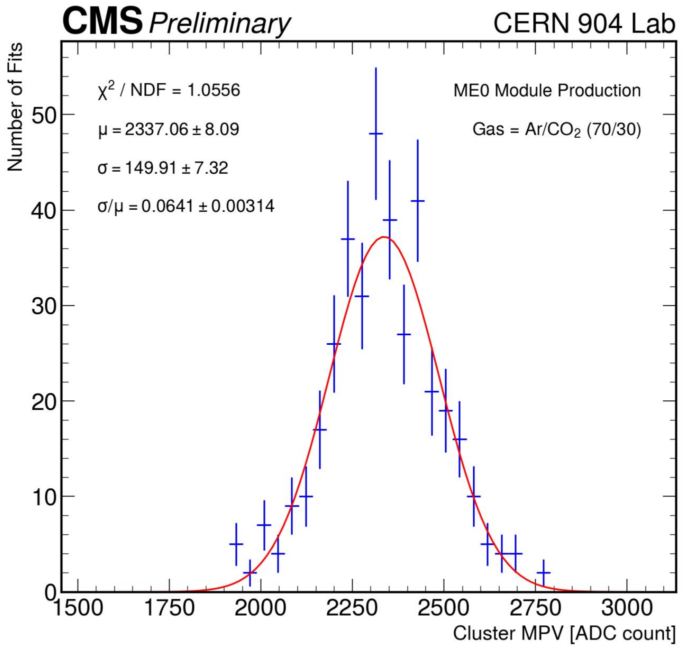
An example of gain uniformity measurement



An example of gain variation across a ME0 Module. For each η sector (iη), the strips are clusterized and then ADC distributions are produced separated by the x position of the cluster, with each distribution representing a section of the detector 8 strips wide. The cluster most probable value (MPV) of the charge spectrum, in ADC unit, is shown as a function of the cluster position and of iη. The outlier data point for iη = 2 is due to misfit.

Gain Uniformity Measurement

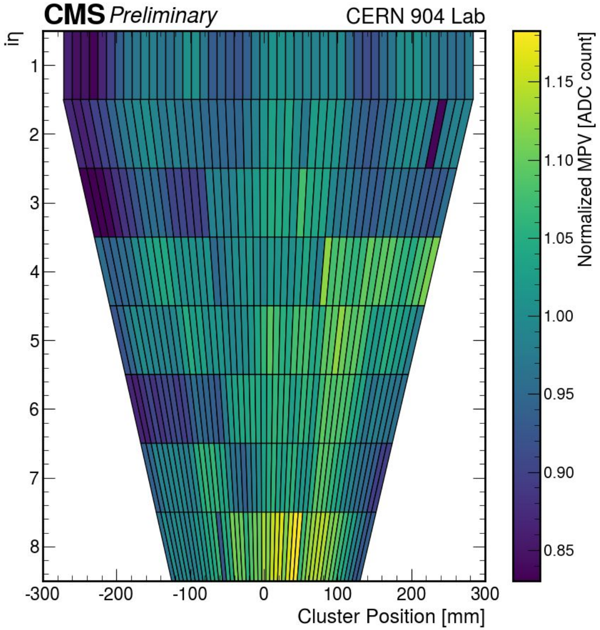
An example of gain uniformity measurement



The cluster most probable value (MPV) charge distribution of 8 strips aggregated cluster for an example ME0 module. The response uniformity (R.U.) is defined as 100 * σ/μ (%), where μ and σ are the mean and the standard deviation of a gaussian fit on the distribution, respectively. Only modules with R.U. smaller than 15% are accepted, the tested module here was accepted with the R.U. of 6.41%.

Gain Uniformity Measurement

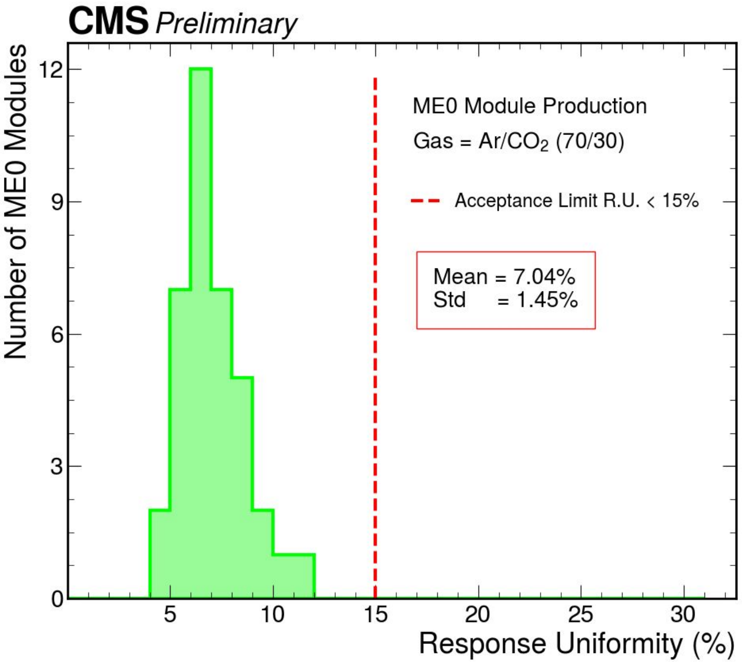
An example of gain uniformity measurement



An example of the gain variation across a ME0 module in 2D. For each η sector (iη), strips are aggregated in cluster and the clusters are binned with a size of 8 strips wide. The cluster most probable values (MPVs) are normalized to the mean cluster MPV. The normalized cluster MPVs in ADC unit as a function of the cluster position and of iη are shown in the plot. The outlier data points for iη = 2 and 8 are due to misfit.

Gain Uniformity Measurement

Result of gain uniformity measurement on 37 ME0



Distribution of response uniformity of 37 ME0 detectors is shown in the plot.
Relative response uniformity measurement is performed in order to check the gain across the entire detector and to quantify its variation.
The measurement is performed with silver (Ag) target X-ray in Ar/CO_2 (70/30) gas mixture. The ADC spectrum is recorded with analogue electronics on all the ME0 strips. We compare the cluster most probable value (MPV) in 8-strips wide bins in ADC unit across one entire ME0 Module. Then the distribution of cluster MPV is fit to extract mean μ and sigma σ in order to define response uniformity as $100 * \sigma/\mu$. A maximum gain variation of 15% is taken as the upper threshold on the allowed response variation across a ME0 detector. The tested 37 ME0 modules passed the gain uniformity measurement with the mean response uniformity of 7.04%.