Validation and performance results of the first CMS GE2/1 muon production chambers

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Introduction

The Large Hadron Collider (LHC) is set to undergo upgrades to prepare for the high- luminosity phase. To manage the increased background rates and trigger requirements, the CMS muon system will be enhanced by adding additional muon detectors based on Gas Electron Multiplier (GEM) technology. The GE2/1 station will feature 72 GEM chambers, composed of 288 modules, covering the pseudorapidity range of 1.62 to 2.43 [1]. Out of the required 288 modules, 96 have been already produced, but later rejected due to the discovery of the copper dust contamination. Currently, the GE2/1 chambers are being retrofitted, and the first two production-grade chambers (1 new + 1 refurbished) have been installed earlier this year after successful validation in a GEM cosmic-ray stand.

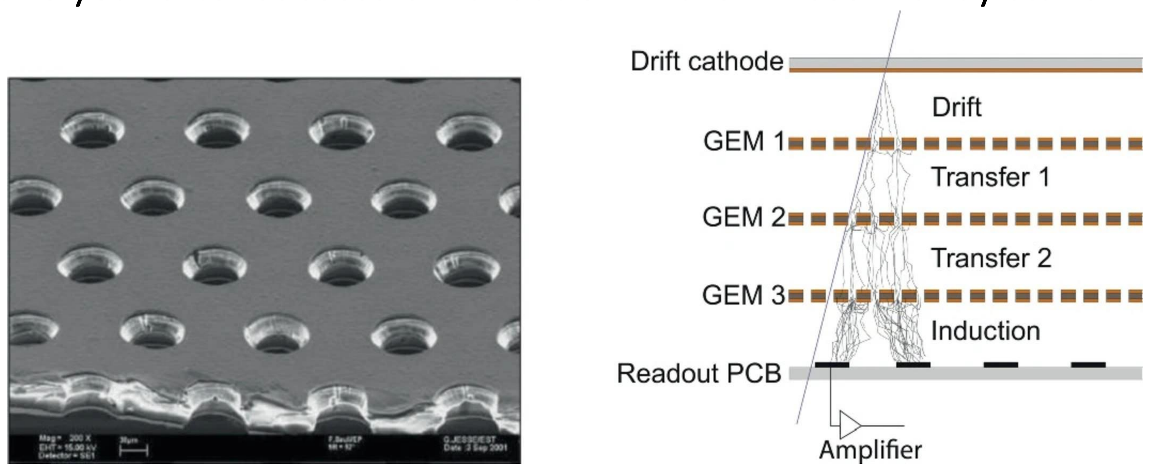

Fig. 1: (Left) Scanning Electron Microscope (SEM) picture of a GEM foil. (Right) GEM Technology : comprising of three foils separated by 3/1/2/1 mm gaps. Electrons passing through will ionize the gas and create an electron avalanche which is readout by analog signal [2].

GE2/1 Design and Insertion in CMS

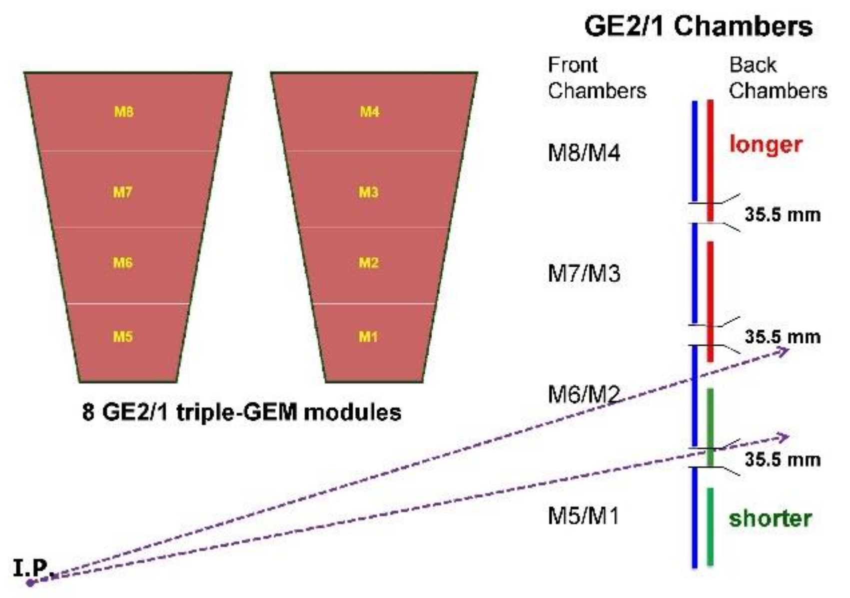

Fig. 2: Geometrical design of GE2/1 front and back chambers.

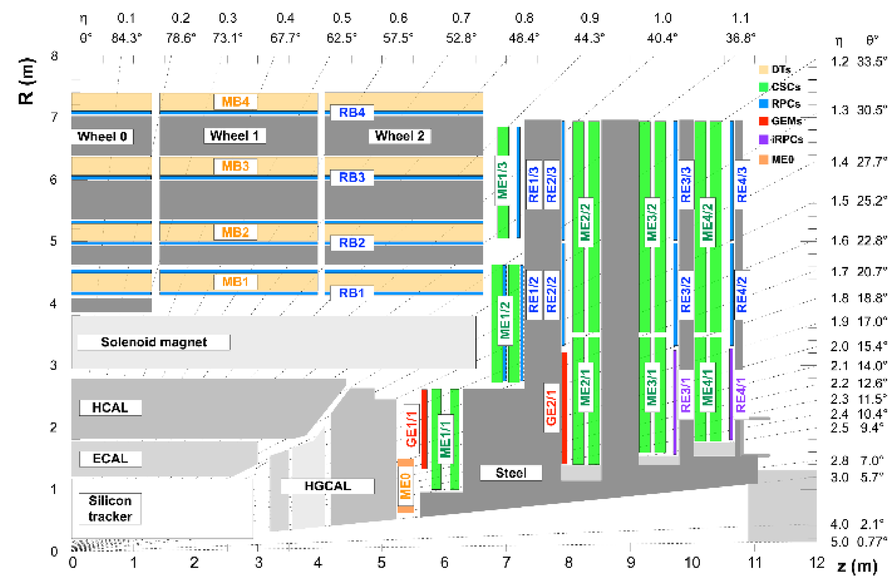

Fig. 3: A cross-sectional view of CMS, highlighting the high-eta region in which the GEM detectors have been/will be installed.

GE2/1 Production Workflow

Requirement: All GE2/1 detectors must pass 8 stages of quality control (QC) before they can be installed at P5, which is verified for the front-type chambers for installation during EYETS23-24.

QC of individual components → Module assembly → Module QC → Chamber Assembly → Chamber QC → Storage

At CERN | At production sites including CERN | At CERN

- QC1 Component acceptance test
- QC2 Foil leakage current test
- GE21 Assembly
- QC3 Module gas leak test
- QC4 Module HV Test
- QC5 Module gas gain and uniformity test
- QC6 Module HV stability test
- QC7 Front-end electronics test/validation
- QC8 Chamber cosmic-stand test

QC2: Foil Test

Procedure: Put the foils in N_2 box for 16 hours so that the humidity is below 7%.

Part 1

- Starting at 100 V, increase the voltage across each GEM foil in 100 V step until 600 V is reached.
- Check the current (nA) in each step.
- Lower the voltage to 100 V and repeat the last two steps three times.

Part 2

- Set the voltage at 600 V and check the current (μA) over 14 hours.
- Number of trips has to be ≤ 3 for a module to pass this test.

QC3: Module Gas Leak Test

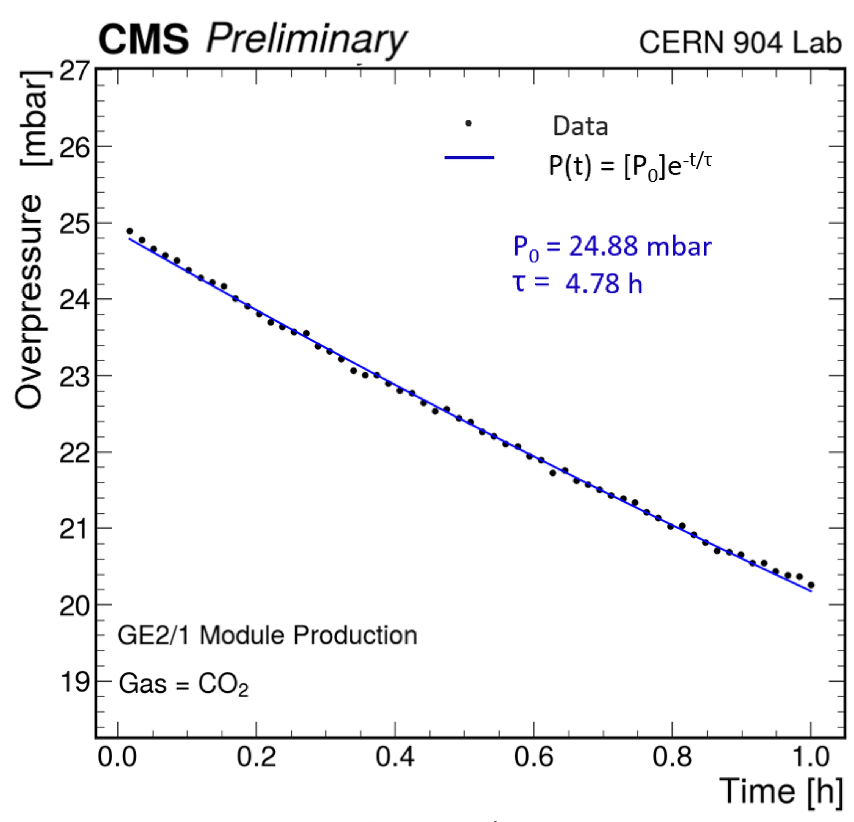

Fig. 4: Gas leak rate for a GE2/1 module currently installed in CMS as measured in pure CO_2 over one hour. The module meets the acceptance criterion for a gas-tight module of τ > 3.04 hours [3].

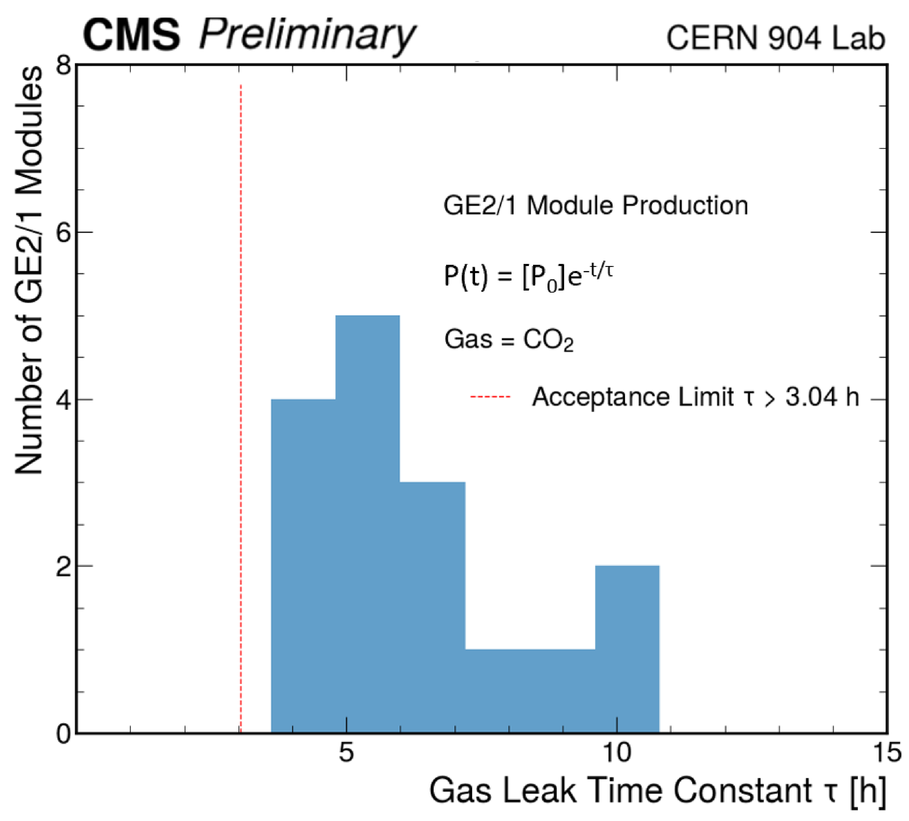

Fig. 5: Gas leak time constants of 16 GE2/1 modules currently installed in CMS as measured in pure CO_2. All modules meet the acceptance criterion for a gas-tight module of τ > 3.04 hours [3].

QC4: Module HV Test

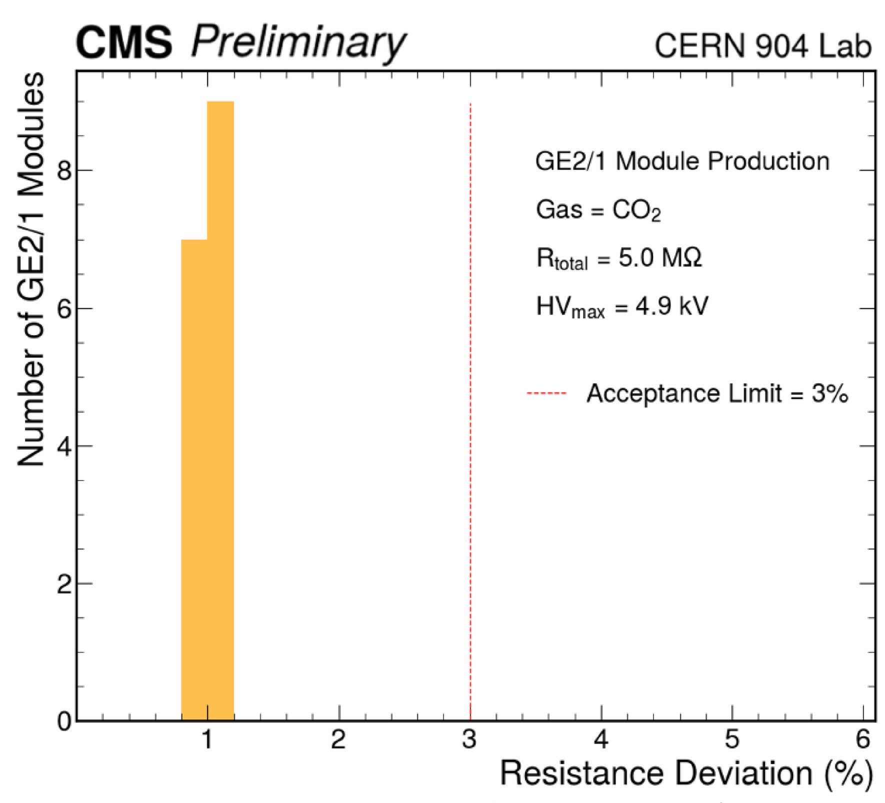

Fig. 6: Resistance deviation D_R (%) for 16 GE2/1 modules currently installed in CMS as measured in pure CO_2. The test is passed if D_R < 3% as the threshold for accepting a detector [3]. D_R (%) = 100 x (|$R_{measured}$ - $R_{nominal}$|) / $R_{nominal}$.

QC5: Module Gas Gain and Uniformity Test

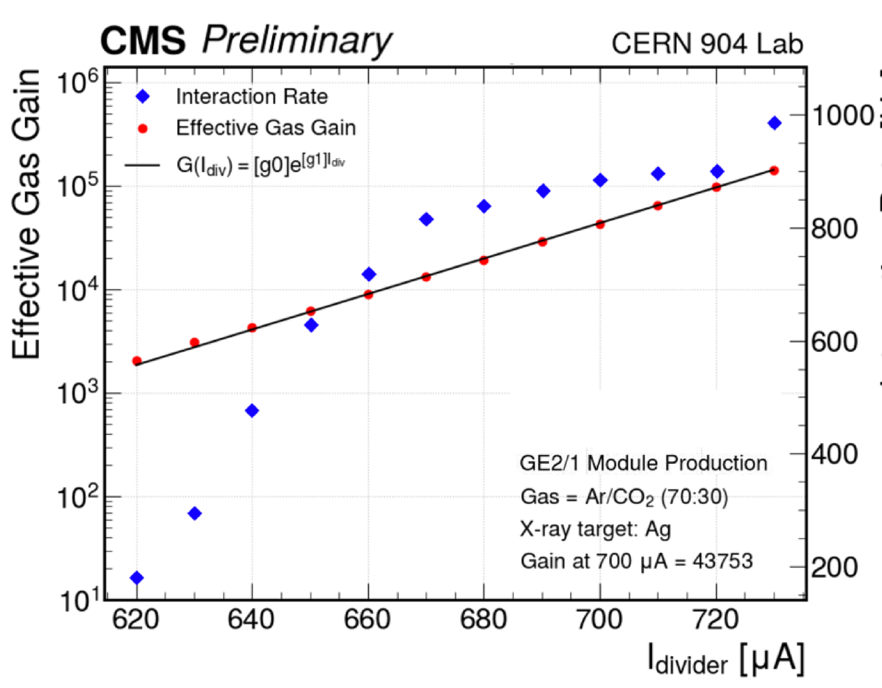

Fig. 7: Gas effective gain test for a GE2/1 module currently installed in CMS. The detector is configured to achieve an effective gain above 1.5 × 10⁴ [3], with an actual effective gain of 4.4 × 10^4 at a divider current of ≈700 μA.

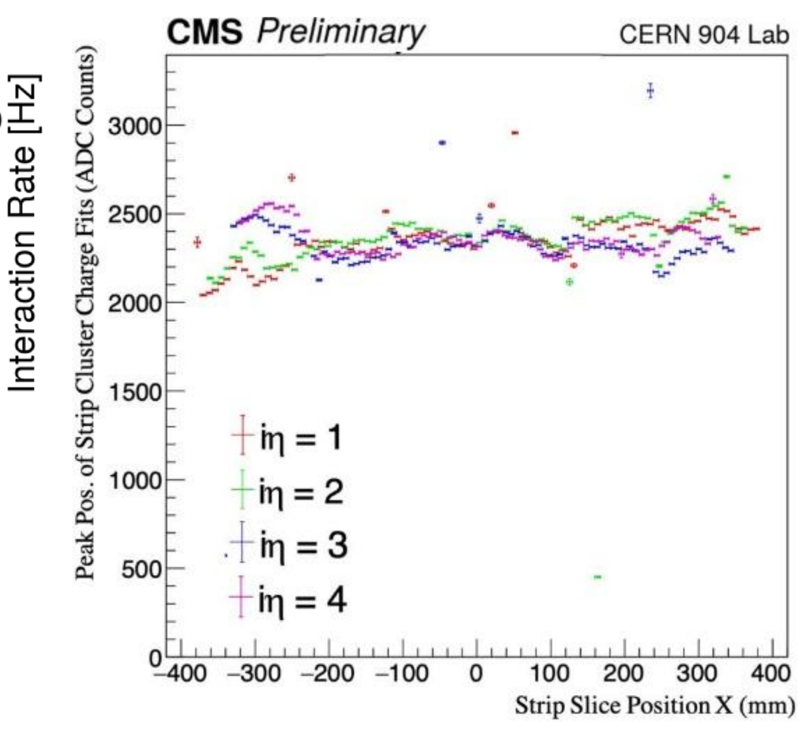

Fig. 8: Gain uniformity test for a GE2/1 module currently installed in CMS. Effective gain response is measured for each of the four η partitions (iη = 1, 2, 3, 4) using an X-ray source.

QC6: Module Gas Gain and Uniformity Test

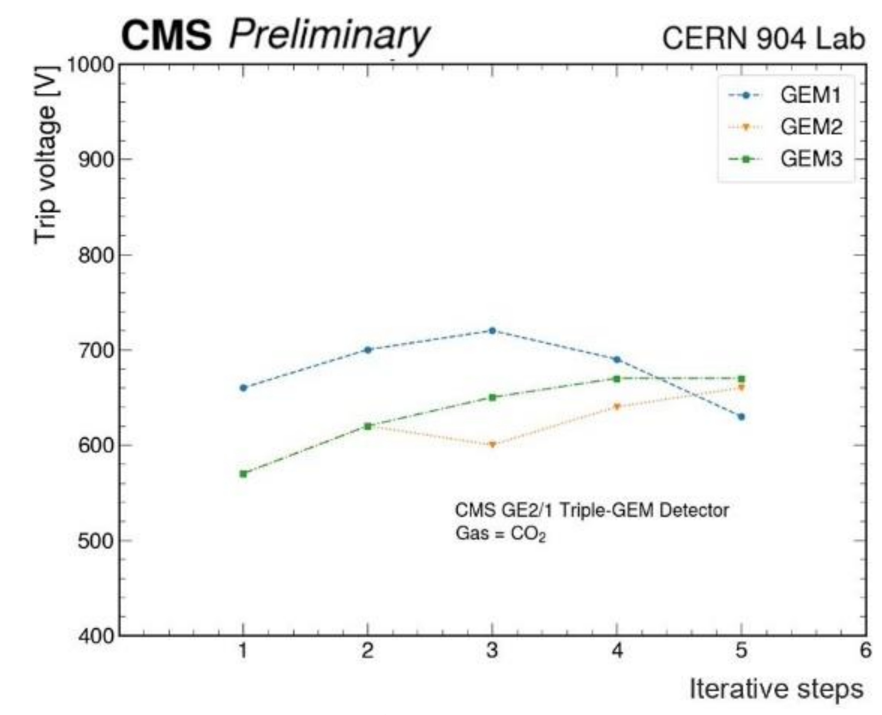

Fig. 9: HV stress test for a GE2/1 module currently installed in CMS, aiming to characterizing the three GEM foils (GEM1, GEM2, GEM3) in pure CO_2 by gradually increasing the high voltage (HV). During each of five iterations, the maximum voltage each foil can sustain without tripping is recorded. The module passes if the maximum voltage exceeds 550 V in the final iteration.

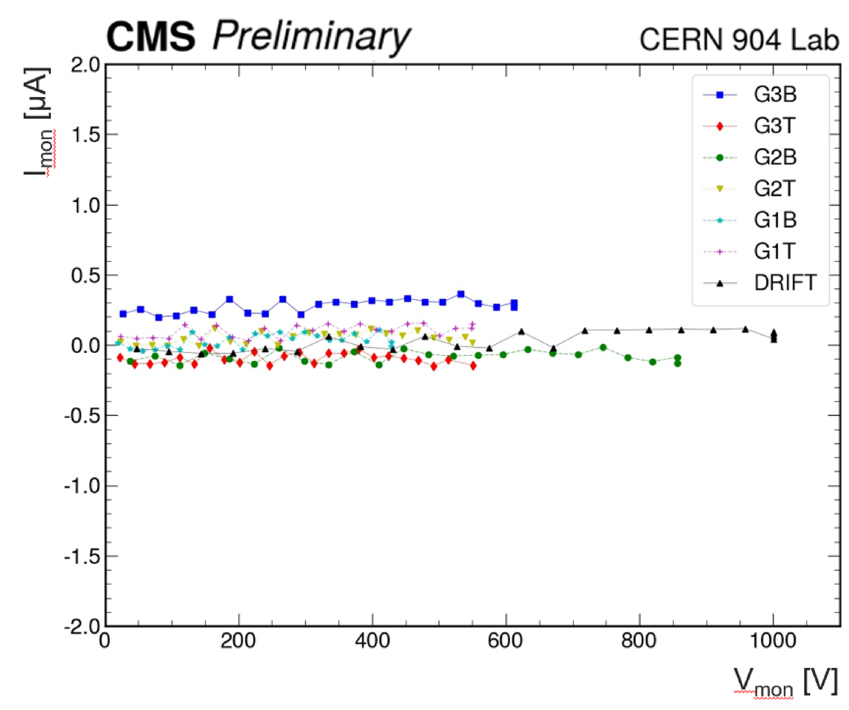

Fig. 10: I-V stability test for a GE2/1 module currently installed in CMS where the current is monitored over 2 hours across seven detector electrodes using a multi-channel power supply.

QC7: Front-end Electronics Test

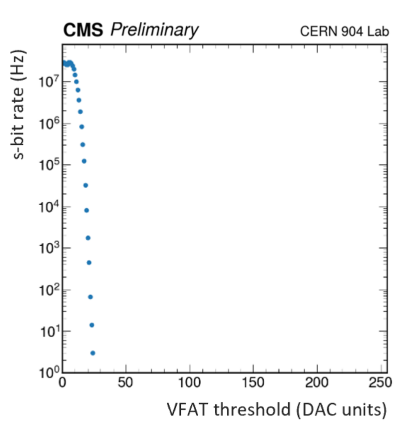

Fig. 11: S-bit rate scan used in electronics quality control tests to detect potential issues in the trigger path. The plot shows a typical good response, with the curve used to determine the operational threshold based on the accepted noise rate.

QC8: Chamber Efficiency Test

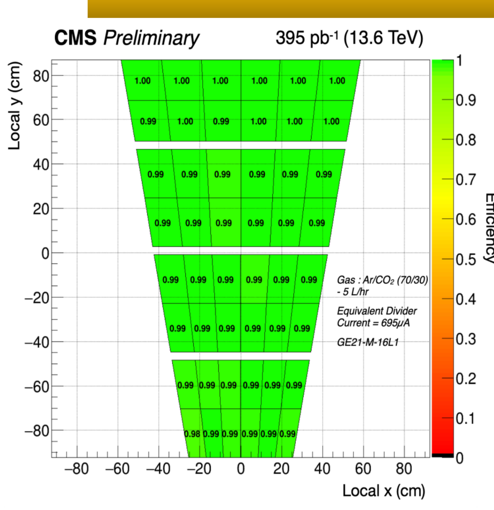

Fig. 12: Efficiency map for a GE2/1 chamber recorded while installed in CMS.

It is the final validation of the assembled GE2/1 chambers, determining their detection efficiency, HV stability, and the HV working point at which the detectors are fully efficient.

$$\text{Efficiency} = \frac{n_{matched\ hits}}{n_{expected\ hits}}$$

Performance in CMS

- Four GE2/1 production chambers have been fully validated and two of which have been installed in CMS during the Extended Year End Technical Stop (EYETS) of 2023-24. They are currently fully operational in P5, located in the negative endcap (Sectors 16 and 18).
- We continue to evaluate the HV stability and discharge rate of these new chambers. We have seen good front-end electronics stability.
- Latest efficiencies using p-p collision data are on average 99% when using standalone muon tracks formed from other muon chambers.

Conclusions

- Two GE2/1 chambers were tested and fully validated using cosmic muon data with high efficiency and operational stability.
- Their optimal working point was determined to be at an equivalent divider current of 680 μA.
- After being inserted into CMS during EYETS 2023-24, these two chambers were commissioned and have been participating in data-taking for 2024.

[1] A. Colaleo et al., CMS Technical Design Report for the Muon Endcap GEM Upgrade, CMS-TDR-013.
[2] F. Sauli, GEM: a new concept for electron amplification in gas detectors, 384 Nucl. Instrum. Methods Phys. Res. A, 386 (1997) 531 – 534.
[3] M. Abbas et al., Nuclear Inst. and Methods in Physics Research, A 1034 (2022) 166716.