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Production and quality control of the GEM GE2/1 detector for the upgrade of the CMS endcap muon system

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1. Introduction

The CMS muon system will be supplemented with 3 additional triple-GEM based muon stations for the HL-LHC era or Phase 2. GEM detectors are scheduled to be installed in front of existing CSC chambers to allow reducing the L1-trigger rates to tenfold for a pT threshold ~ 20 GeV with respect to the present configuration. GE1/1 was already installed during the 2nd long shut-down period while the GE2/1 mass production was initiated in 2021 at the GEM laboratory at CERN. The GE2/1 system, two wide planer-ring-shape layers with an inner radius ~1.5 m and an outer radius ~3.2m, is comprised of 18 chambers per layer, 36 chambers per endcap. One chamber is composed 4 different sized modules optimizing the η coverage. GE2/1 will cover the forward range 1.6 < $|\eta|$ < 2.4 and is scheduled to be installed during the year end technical stop (YETS) of 2023/2024.

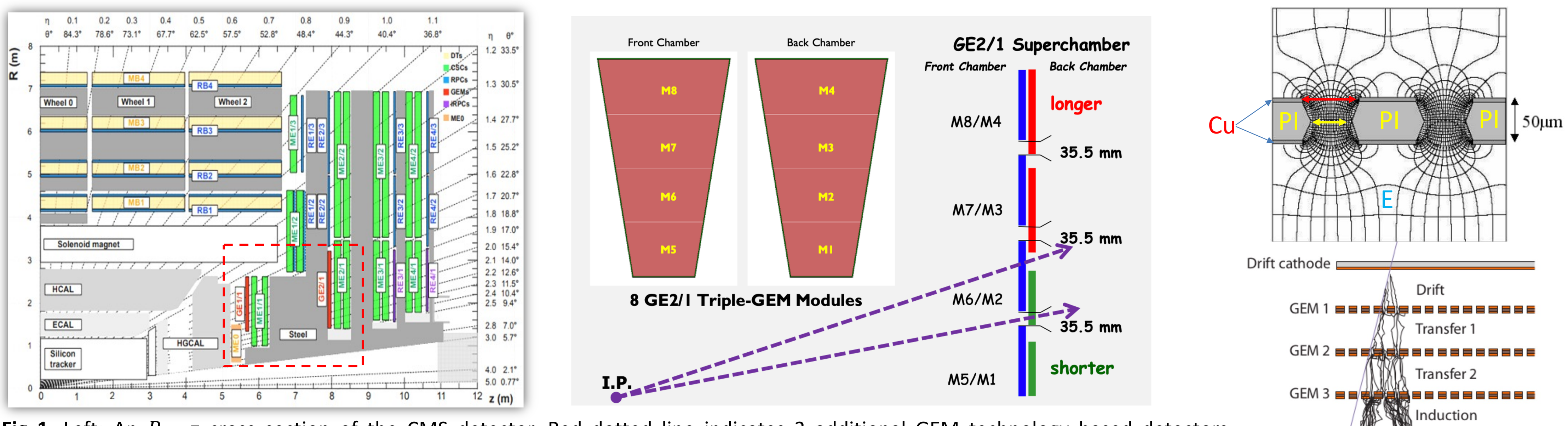


Fig 1. Left: An $R-z$ cross section of the CMS detector. Red dotted line indicates 3 additional GEM technology based detectors (GE1/1, GE2/1, ME0) Middle: GE2/1 chamber schematic layout. Right: The electric filed configuration inside GEM foil hole and GEM detector working mechanism.

2. GE2/1 Quality control (QC) process

The GE2/1 mass production is distributed over various collaboration Institutes. Industrial partners supply components to the GEM laboratory at CERN from where they are distributed to the production sites. All assembled modules undergo the predefined standard quality control (QC) procedure. All assembled module are collected again at the CERN GEM lab where they will be assembled to trapezoidal-shaped GE2/1 chambers and send to P5 for installation. Well defined advanced quality controls are very important to guarantee the successful performance of modules assembled at the different production sites.

The Standard QC steps are ten in total, from QC1 to QC10. It can be splitted in 4 steps based on the chamber manufacturing process:
1. QC1 to QC2 for GEM foils, 2. QC3 to QC5 for modules, 3. QC6 to QC8 for the electronics and chamber tests wit cosmics , 4. QC9 to QC10 after transportation at P5.

CERN Foil supplier	QC1	Material visual inspection
	QC2	GEM foil leakage current test in HV
	GE21 Assembly	GE2/1 Assembly @CERN and different sites
CERN Production sites	QC3	Module gas leak test
	QC4	Module Intrinsic noise and VI linearity
	QC5	Module gas gain and uniformity test
CERN	QC6	HV stability test with multi channel HV
	QC7	Chamber electronics connectivity test
	QC8	Chamber cosmic test

3. QC1: Visual inspections at production sites

The foils quality is inspected by using an optical microscope
- HV lines and SMD resistors check
- foil surface conditions and suspicious defects check
- drift, readout-side PI(polyimide), Cu(cupper) layers hole size measurement in 5 different foil areas

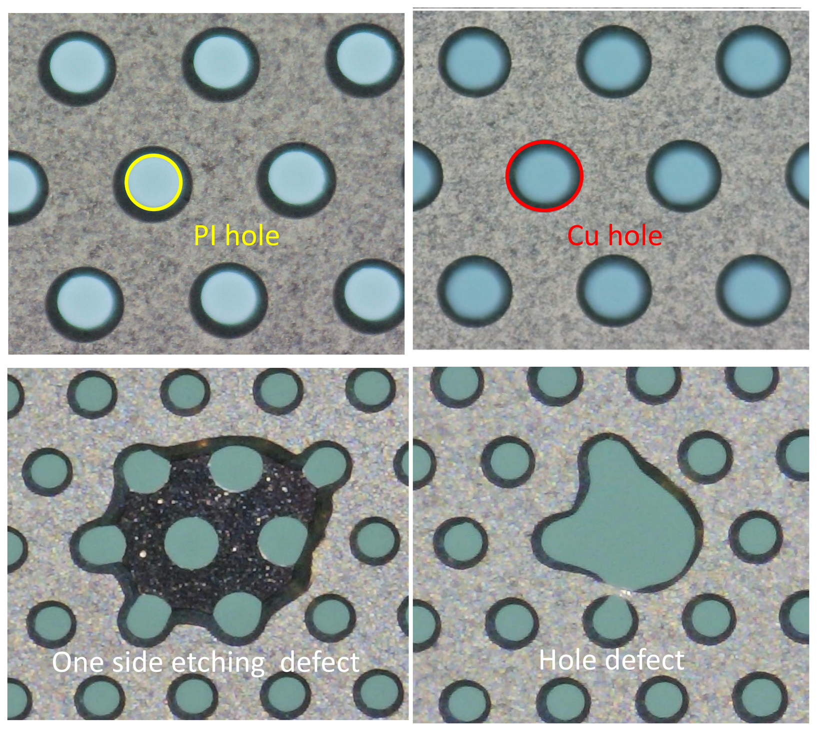
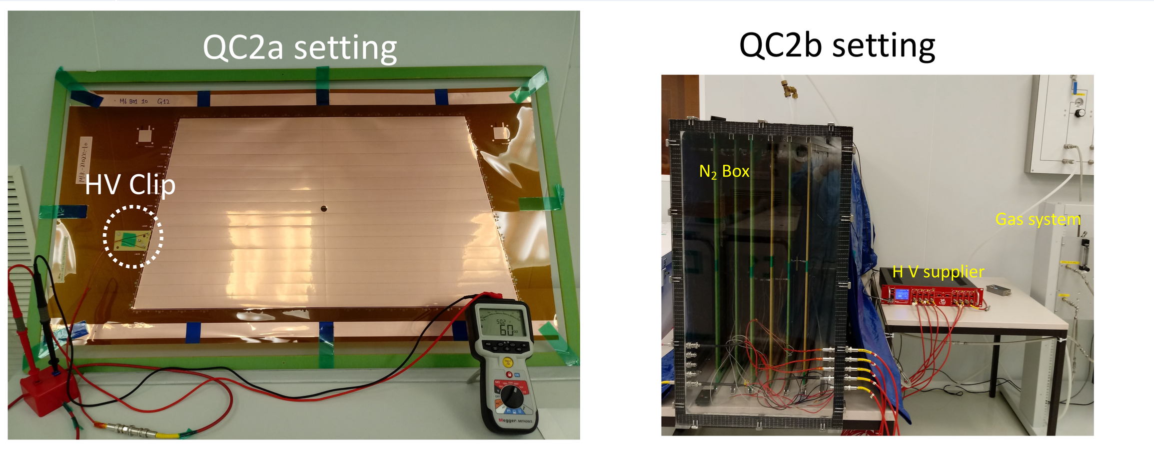


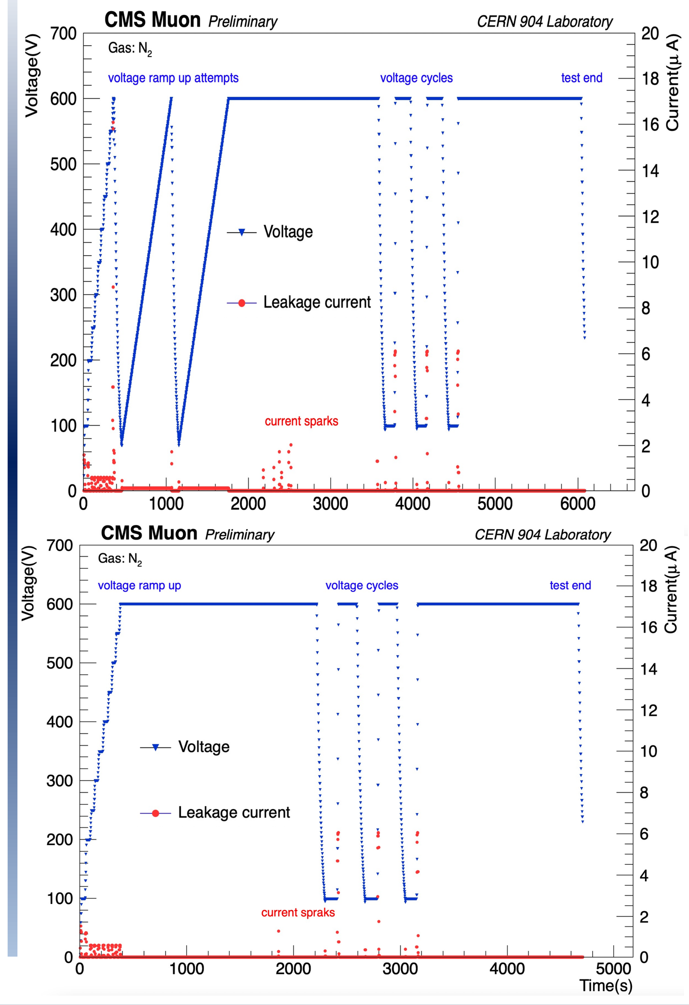
Fig 2. Microscopic view of GEM Foil. The PI and Cu-hole sizes are important for the gain since the amplification occurs inside of hole. Upper images: Changing the light intensity on the optical table permits the measurement of PI, Cu holes in the Fig 1. Lower images show typical foil defects. Left: one side etching defect. Right: missing holes. a size covering less than 10 holes is acceptable.

4. QC2: HV stability and Leakage Current check

QC2	Test condition in Detail
QC2a	**HV 500V apply**, **Impedance >10GΩ**, Sparks and Impedance check for 30s two consecutively, after counting every 1mins until 5 mins If sparks sustained, counting will be continued up to 10 min.
QC2b	**Nitrogen gas fusions with 100L/h** until reaches the relative **humidity** < 7% , **Part1**: 600V for 90 minutes. **- leakage current range < 20 μA** **Part2**: 600 V for 14 hours, monitoring the current and the number of sparks. **N of current sparks $\leq$ 3, leakage current range < 2 μA**



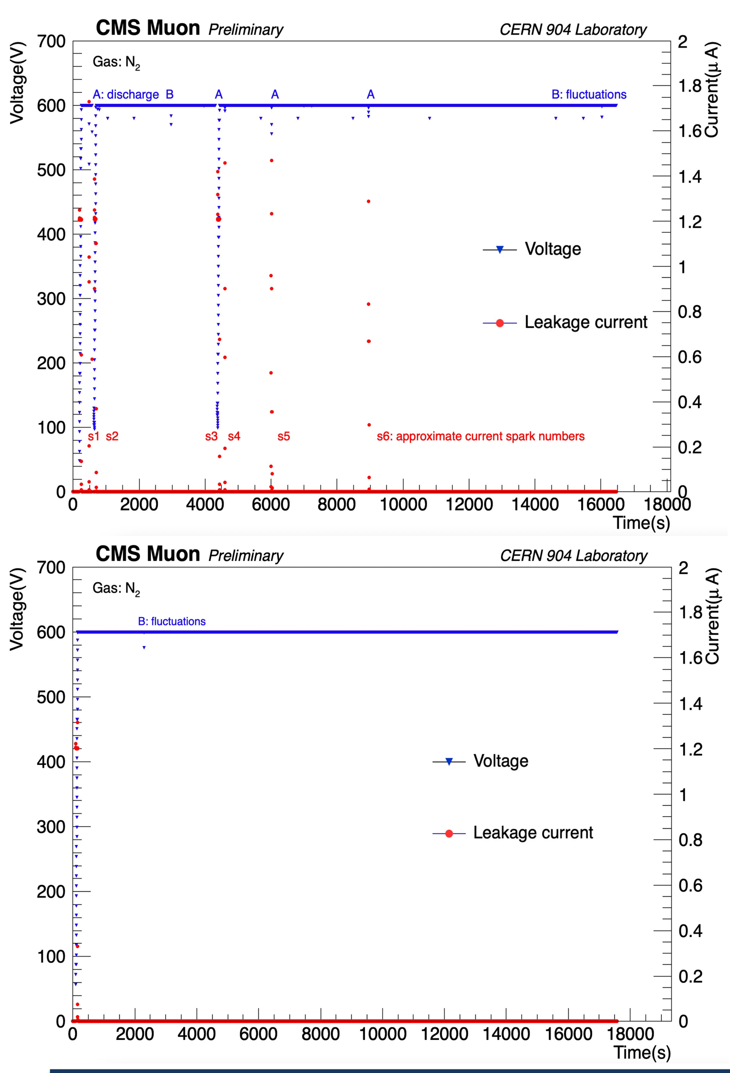
4-1. QC2b part1 example result



An example of a GE2/1 foil after the "QC2b part1" step. Abnormal (upper plot) and passed (lower plot).

Foils which passed the step QC2a are stored in a N_2 box. After reaching the nominal humidity (< 7%), high voltage is applied on the foils top – down and ramped up until 600V and maintained for 90 mins.
The example result reached the 600V only on the third ramp-up attempt.
Dust, deposit, defects on the foil are the cause of sudden current sparks.
This spark rate is reduced (lower plot) during the repeated tests.
The GE2/1 foils were produced in Korea and at the CERN lab. They have a 10 MΩ protection resistor on the foil's drift side, 100 kΩ on the foil's readout side for GEM1, GEM2 and 0 Ω for GEM3. The resistor configuration is optimized for discharges and its propagation.

4-2. QC2b part2 example result

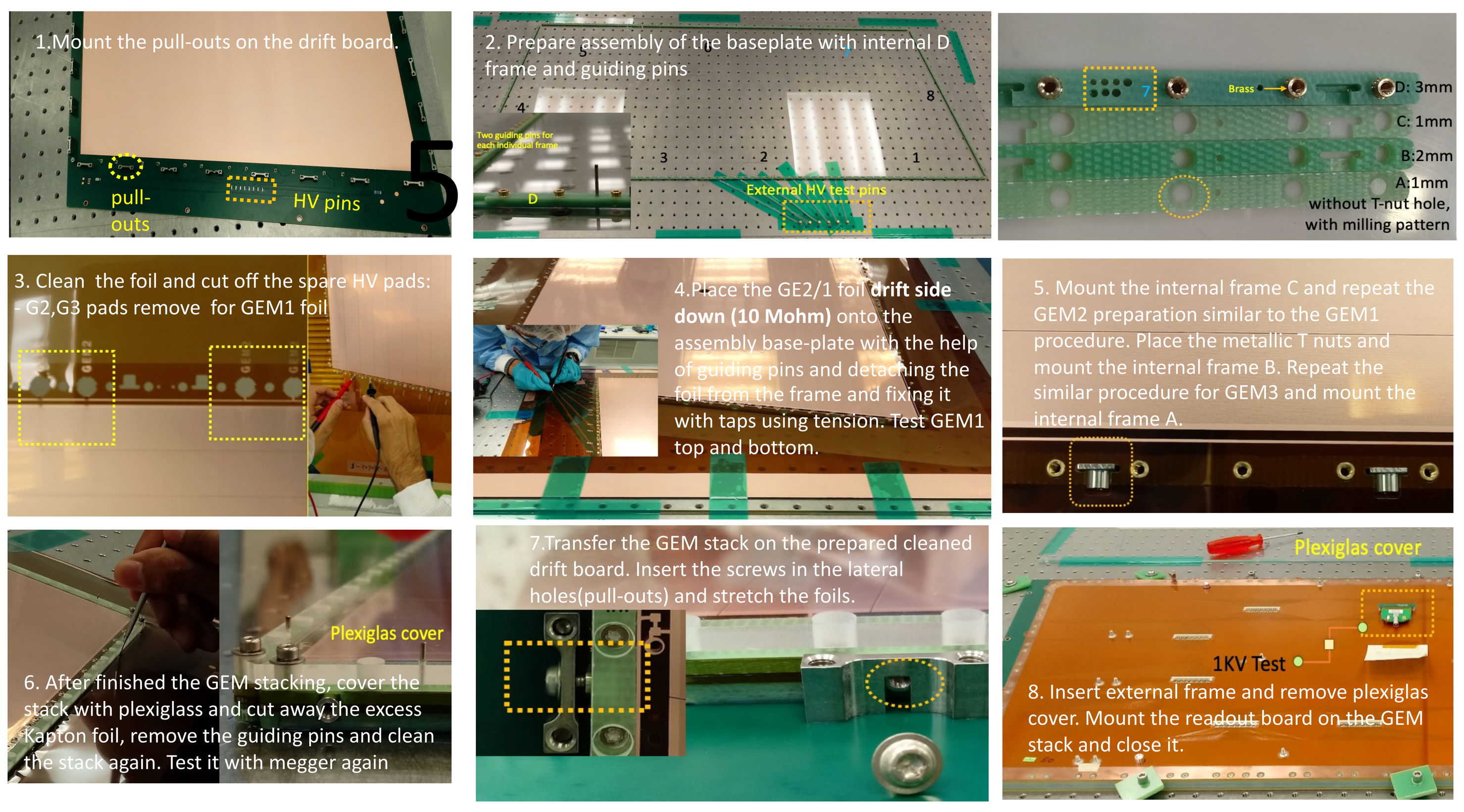


An example of a GE2/1 foil after the "QC2b part2". Failed (upper plot) and passed (lower plot).

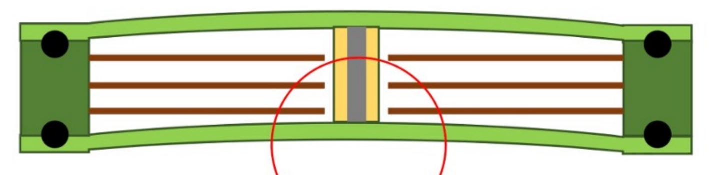
Foils which passed "QC2b part1" undergo a 600 V test for 14h in a N_2 box with <7% humidity.
The observed leakage current should be less than 2 uA and the limit on current sparks is three.
Simultaneous and sustained discharges (upper plot) indicate the instability of foil and discharge events can damage the GEM foil itself. Discharges also prevent the stable operation of the detector. When the foil's condition reaches stability during the test, current sparks and voltage fluctuations are also reduced (lower plot). For the resolution of problematic zones, only the initial part of test is reported in the plot.

5. Overview of GE2/1 assembly process

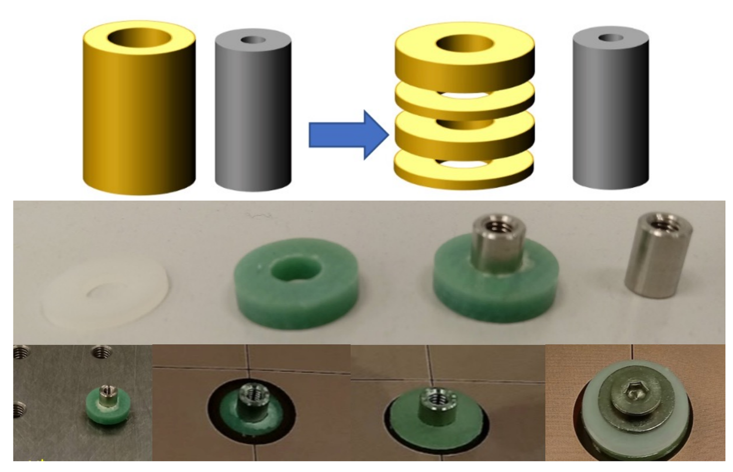
After having passed the QC2 tests, foils are available for module assembly which proceeds in the following 3 steps:
A. Mount 3 layer of GEM foils as stack (2~6)
B. Moved the GEM stack to drift board, stretch to have uniform gaps between foils.(1,7)
C. Close with the readout board(8)

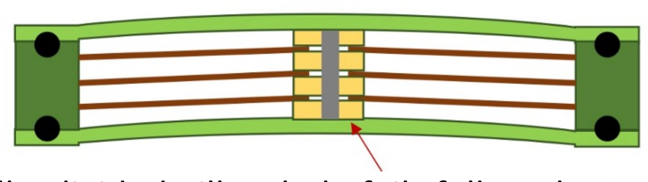


5-1. New method for GE2/1 assembly



Critical zone with lower gap when PCB is bent

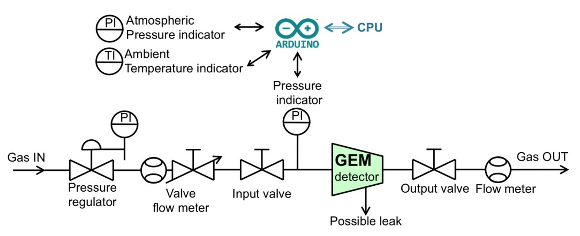


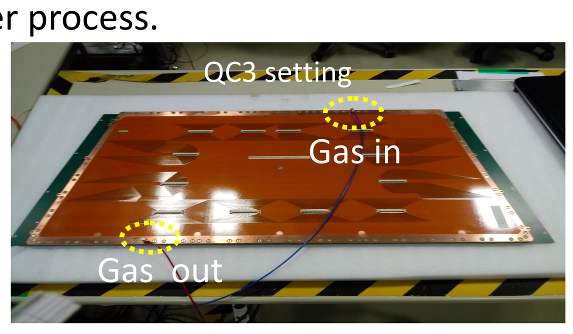


Partially divided pillars help foils follow the PCB structure. The impact of new method will be fully verified by QC5 uniformity test.

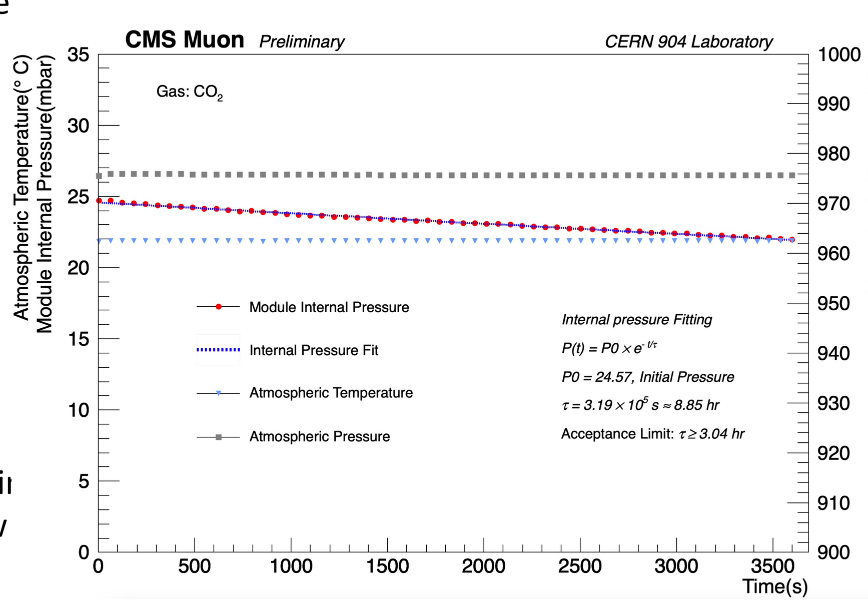
6. QC3: Module gas leak test

QC3 is a gas tightness test after the module is assembled. Besides checking for a gas leak, it also prevents the possibility of contamination from an external source. Gas contamination can affect the detector performance through deterioration of the charge amplification and electron transfer process.

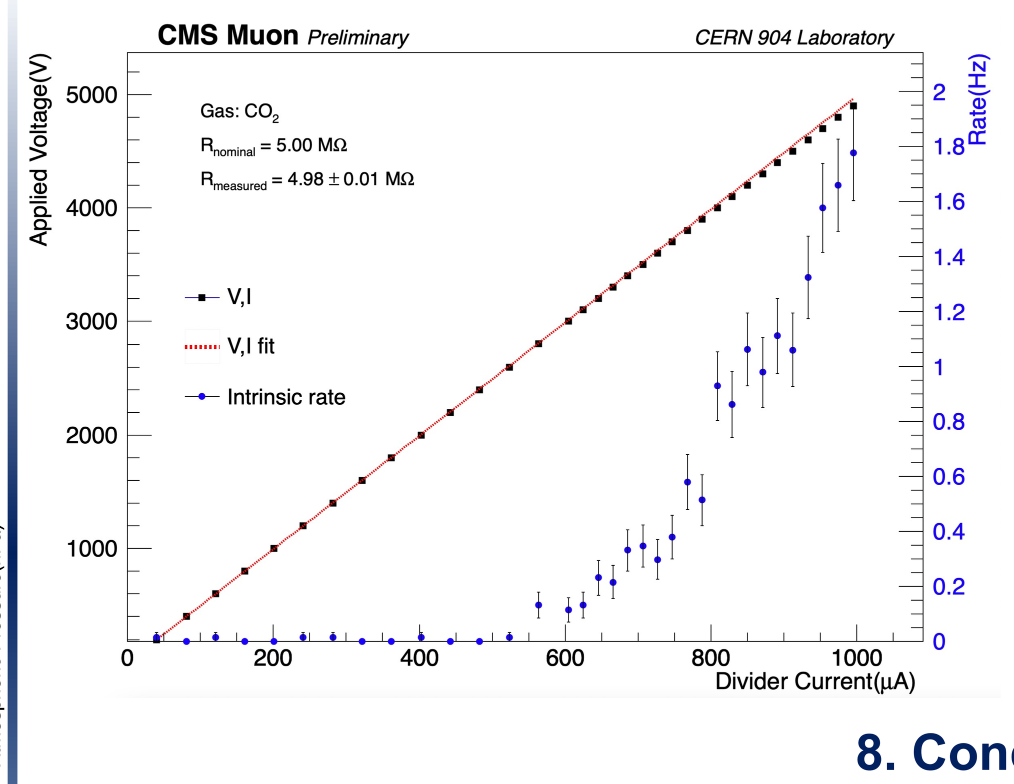


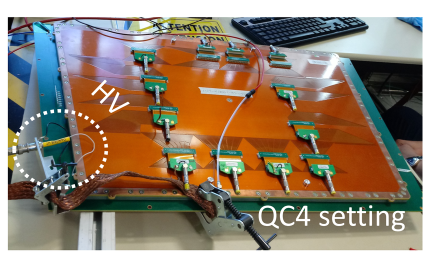


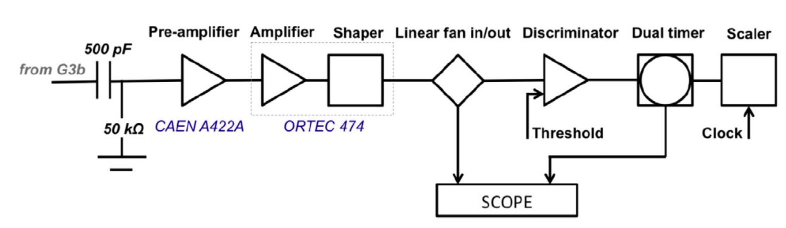
The Example shows a GE2/1 module which passed QC3. The module is flushed with CO_2 for an hour. After an hour, the gas output is closed. when the internal pressure reaches around ~25 mbar, the input inlet is also closed. The internal pressure changing rate should be less than 7 mbar/h corresponding to a time constant τ > 3.04 h.
Time constant τ > 3.04 h condition ensures that the leak rate will remain below 1% of the total incoming flow rate.



7. QC4: V,I linearity & Intrinsic noise test







QC4 measures the module's intrinsic noise and the linearity of high voltage (HV) versus divider current. A non-linearity would indicate the presence of instable parasitic impedance, which can be caused by a defect on the HV circuit or a GEM foil problem. Intrinsic detector noise is caused by detector design defects and imperfection of the electrodes. After flushing the module with CO_2 for an hour, the module's intrinsic noise rate is measured during a HV scan between 200 V and 4900 V. The acceptable limit for the Intrinsic noise rate is below 100 Hz. To measure the linearity of the HV and divider current, HV, I data are fitted with a first order polynomial . The slope value of the fit corresponds to the measured resistor value, R_measured, the register sum of the HV filter and the HV divider corresponds to R_nominal. To pass the test, the resistor deviation has to be less than 3%

8. Conclusion

- GE2/1 mass production started successfully since 2021 with the collaboration of different production sites.
- To ensure comparable performance of modules produced at different productions sites, a number of advanced quality control steps are defined. Steps QC1 to QC4 are critical for module' performance and example results are presented.

[1] A. Colaleo *et al.*, CERN-LHCC-2017-012, CMS-TDR-016, 12 September 2017.
[2] *M. Abbas, M. Abbrescia, H. Abdalla et al.,* Quality control of mass-produced GEM detectors for the CMS GE1/1 muon upgrade , *Nuclear Inst. and Methods in Physics Research, A 1034 (2022) 166716*