15th *Vienna Conference on Instrumentation*
18th - 22th February 2019

Upgrade of the CMS Muon System with GEM Detectors

VCI2019
Gaseous Detectors Section

Francesco Fallavollita (CERN)
on behalf of the CMS Muon Group

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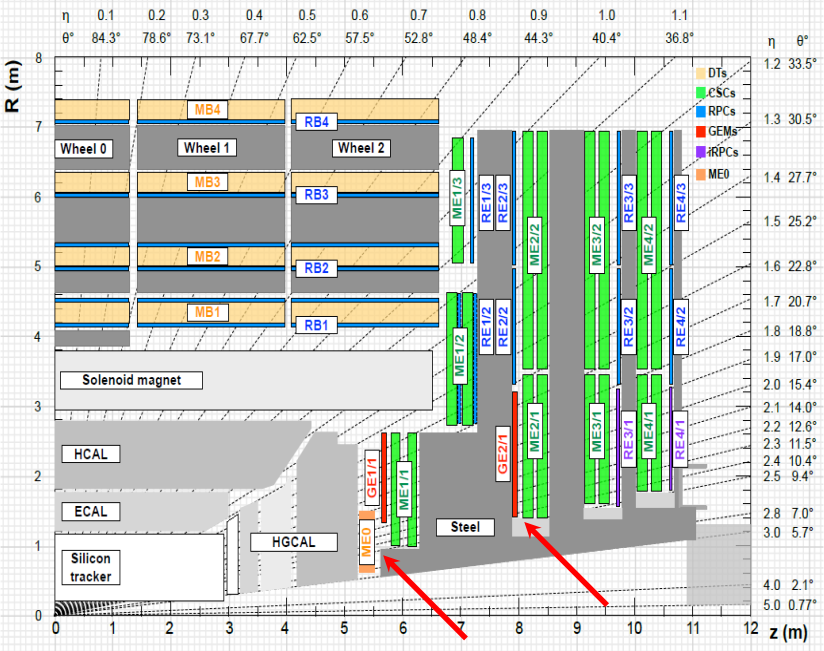
CMS Forward Muon System Upgrade

Present CMS endcap muon detectors:

- CSC + RPC covering $0.9 < |\eta| < 1.6$
- Only CSC covering $1.6 < |\eta| < 2.4$

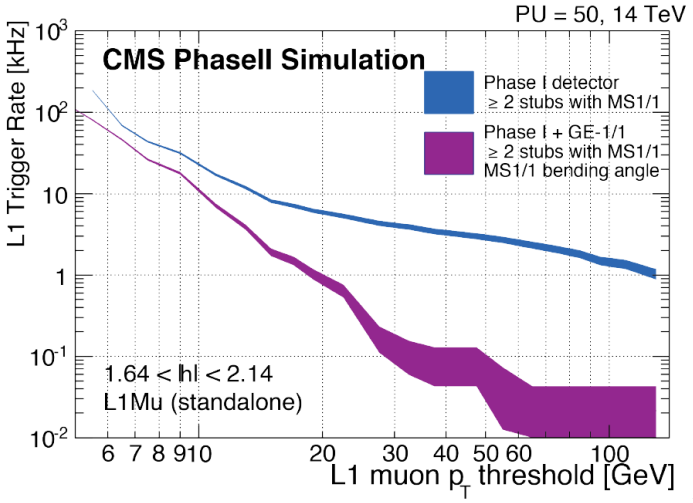


From 2026: High - Luminosity LHC

→ Increase luminosity to $5 \times 10^{34}\ s^{-1} cm^{-2}$ $(5 \times \text{nominal value})$

→ Upgrade current Muon Forward System:

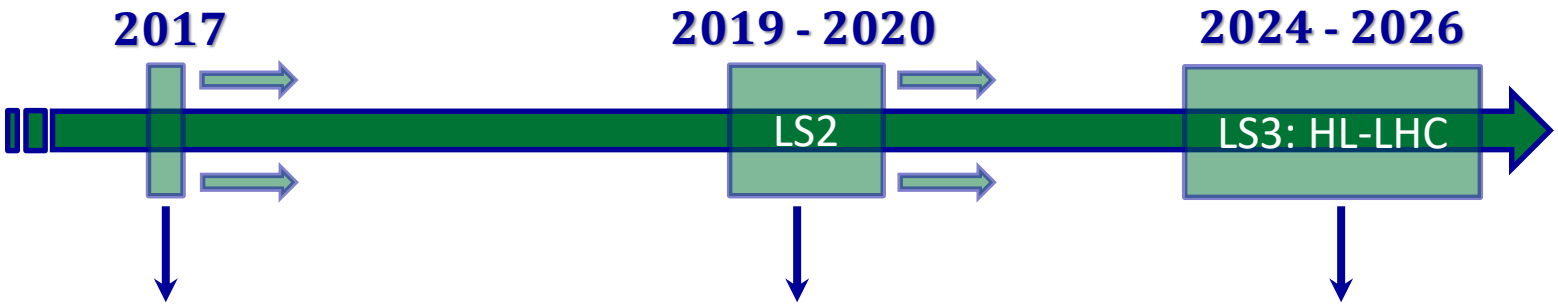
- Increase redundancy in endcaps
- Improve p_T measurements in low B field (solenoid)
- Reduce the trigger rates



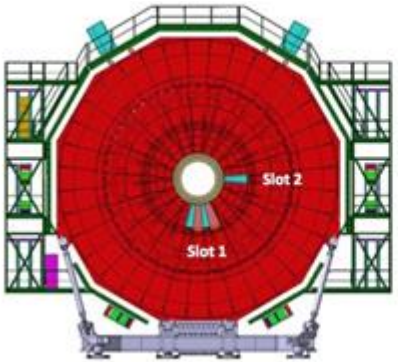
Future GEM installation $1.5 < |\eta| < 2.8$

- GE1/1 project and GE2/1 project
- ME0 project

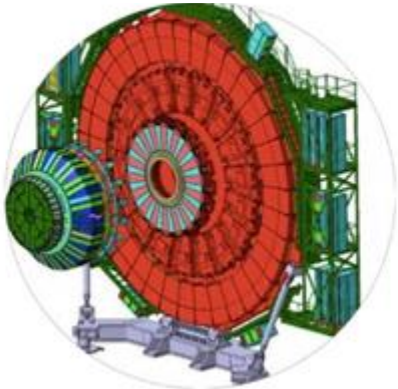
GEM in CMS: integration plans



Slice Test



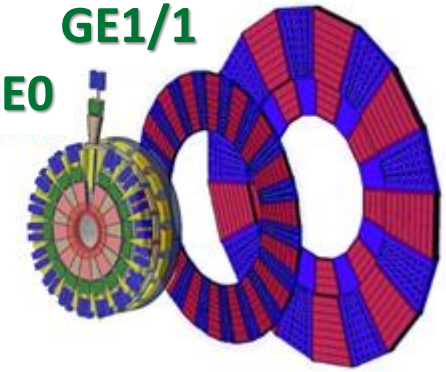
GE1/1



GE2/1

GE1/1

ME0



Slice Test = commissioning of 5 GE1/1 detectors in CMS

1 out of 5 with final readout electronics and HV

Installation of GE1/1 during Long Shutdown 2

144 chambers in two endcaps
GE1/1: $1.5 < |\eta| < 2.2$

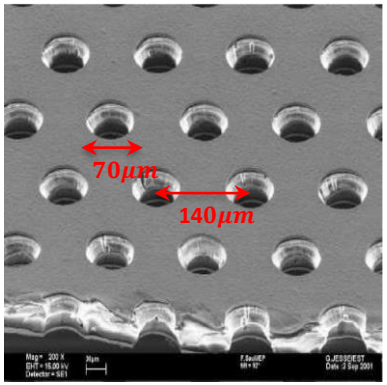
GE2/1 and ME0 installed by the end of Long Shutdown 3

GE2/1: $1.5 < |\eta| < 2.2$
ME0: $2.0 < |\eta| < 2.8$

Gas Electron Multiplier Technology

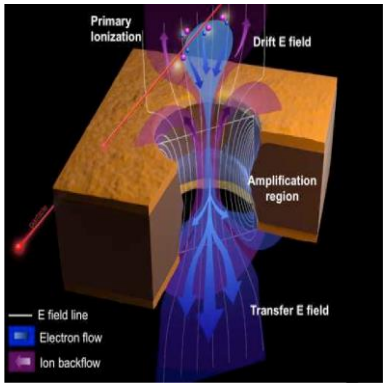
GEM foils:

- $50\ \mu m$ thick copper/cladded polyimide foils
- Holes $(\text{diameter} = 70\ \mu\text{m})$ in hexagonal pattern $(\text{pitch} = 140\ \mu\text{m})$



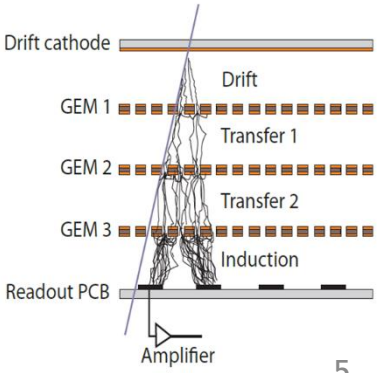
GEM chamber:

- Gas detectors: charged particles ionize gas
- One or multiple GEM- foils $(\text{e.g. triple} - \text{GEM} = 3\ \text{foils})$
- HV applied: amplification process inside holes $(\text{E} \sim 60\ \text{kV/cm})$



Performance:

- Rate capability: up to $\text{O}(\text{MHz/cm}^2)$
- Triple-GEM chamber efficiency $> 97\%$ for MIPs
- No aging effects after $3000\ fb^{-1}$ $(\text{and even up to } 875\ \text{mC/cm}^2)$



CMS GEM GE1/1 Project

The 1st project of the CMS GEM Collaboration

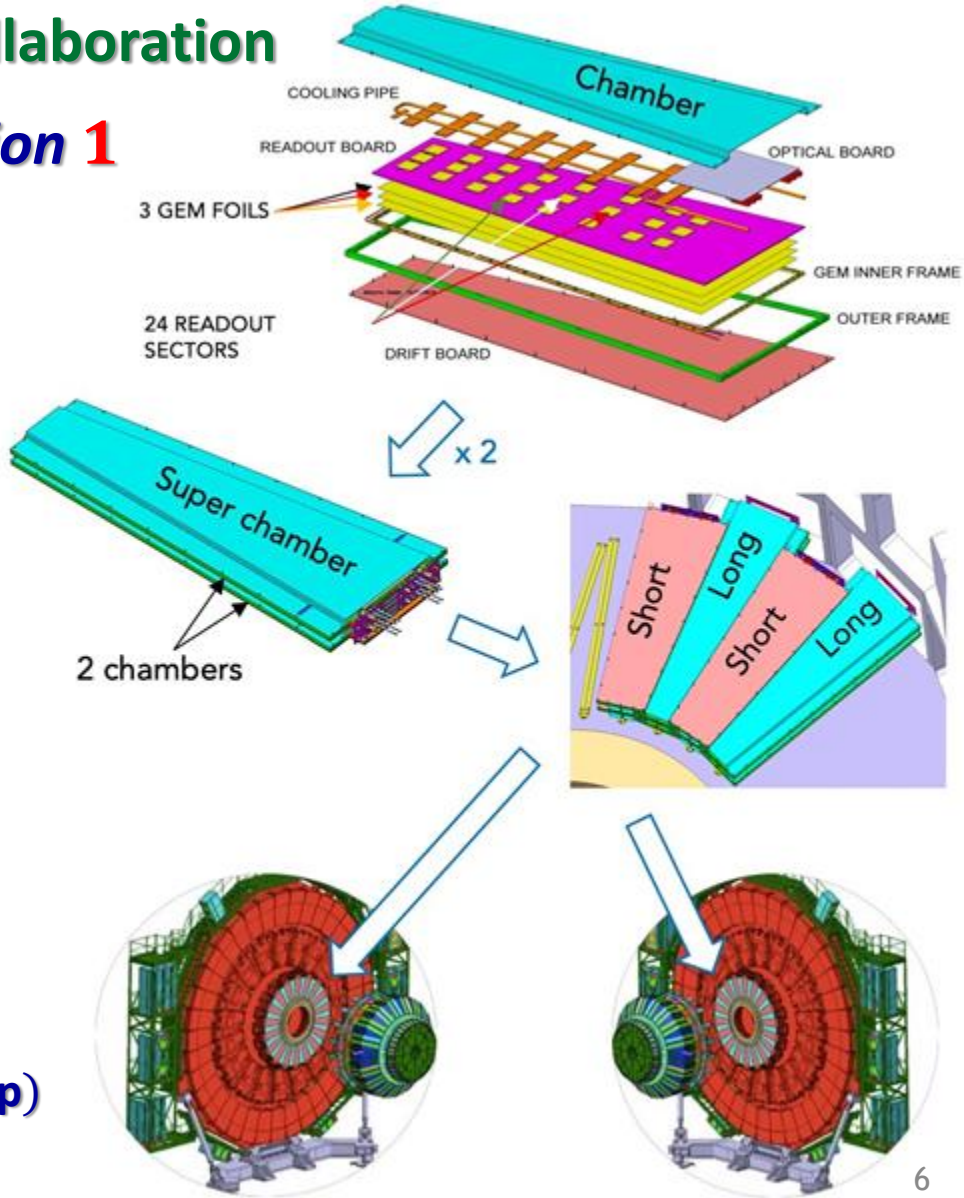
GEM Endcap Ring 1 Station 1

GE1/1 chamber

- **Triple-GEM chambers**
- **Gas mixture Ar/CO_2 $(70/30\%)$**
- **Large area $O(m^2)$**
- **Covering $1.5 < |\eta| < 2.2$**

- **144 trapezoidal Long and Short chambers**
- **24 readout sectors per chamber**
- **128 radial strips for each sector**
- **Digital readout**

- **72 Super Chambers (2 coupled chambers)**
- **Each Super Chamber covers $10.15°$ (overlap)**



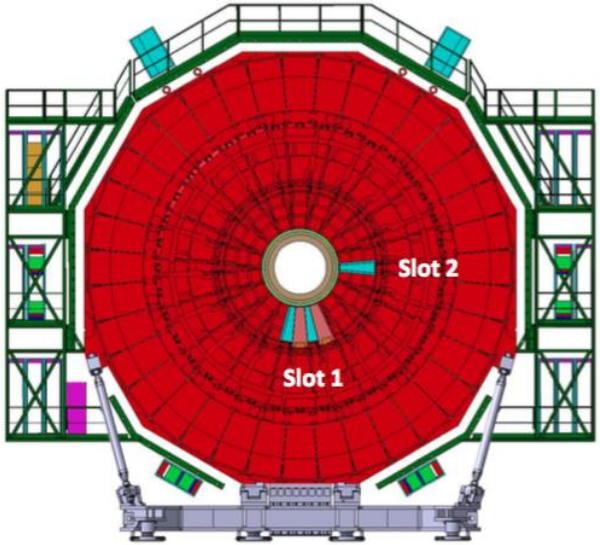
CMS GE1/1 triple-GEM Detectors Slice Test

Co-authors
Martina Ressegotti and Ilaria Vai

GE1/1 Slice Test Overview

A demonstrator with 5 SuperChambers (or *GEMINI*) took place in 2017-18 with the goals to:

- **Proving the system's operational conditions**
- **Developing the integration into the CMS online system**
- **Start acquiring installation and commissioning expertise**



SLOT - 1 → *4 GEMINI*:

- **High Voltage supplied with a single HV channel per detector (8 HV channels in total)**
- **The HV is distributed to the detector's electrodes through a voltage divider**
- **Readout system based on VFAT2 ASICs**

SLOT - 2 → 1 *GEMINI*:

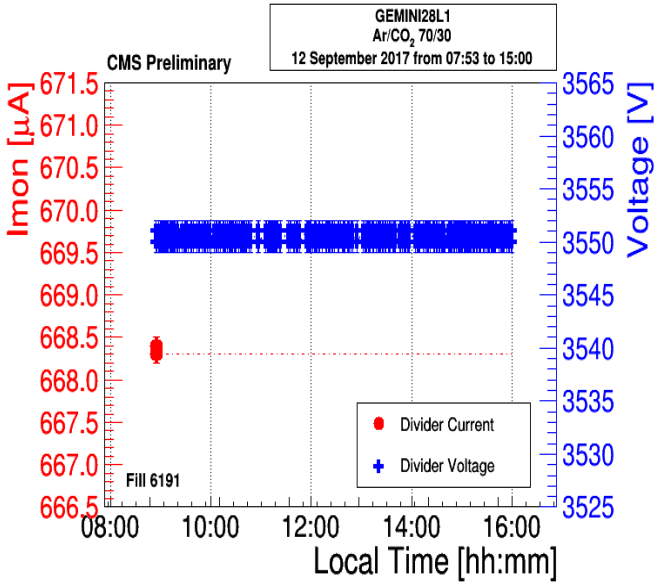
- **High Voltage supplied with a multi-channel power supply realized specifically for triple-GEM detectors (CAEN A1515TG)**
- **The HV module provides 7×2 voltage channels to power independently all detector's electrodes**
- **Readout system based on VFAT2 ASICs in 2017, moved to VFAT3 ASICs in 2018**

GE1/1 Slice Test - System Stability

The activity of 2017 included a study of stability of triple-GEM detectors into the CMS environment

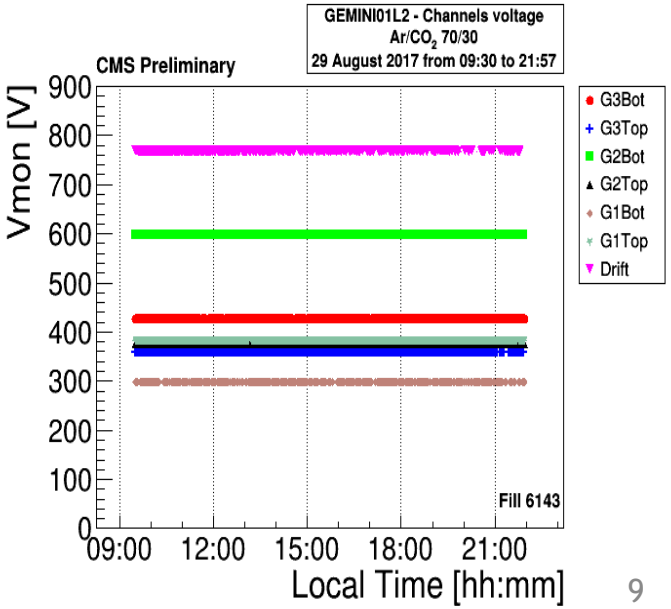
- **Single HV channel**

  → **high voltage fluctuations $< 1\%$ observed in a period of 7 hours during LHC collisions** $(L_{max} \approx 1.1 \times 10^{34} cm^{-2} s^{-1})$



- **Multichannel HV**

  → **high voltage fluctuations $< 1\%$ observed for all 7 HV channels in a period of 12 hours during LHC collisions** $(L_{max} \approx 9.3 \times 10^{33} cm^{-2} s^{-1})$



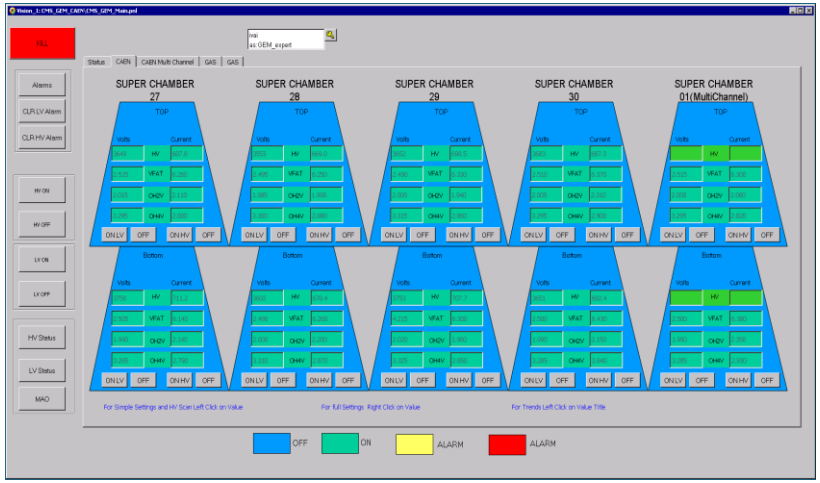
- **LV channels**

  → **LV channels showed the same stability both with and without beam**

GE1/1 Slice Test - Integration into CMS

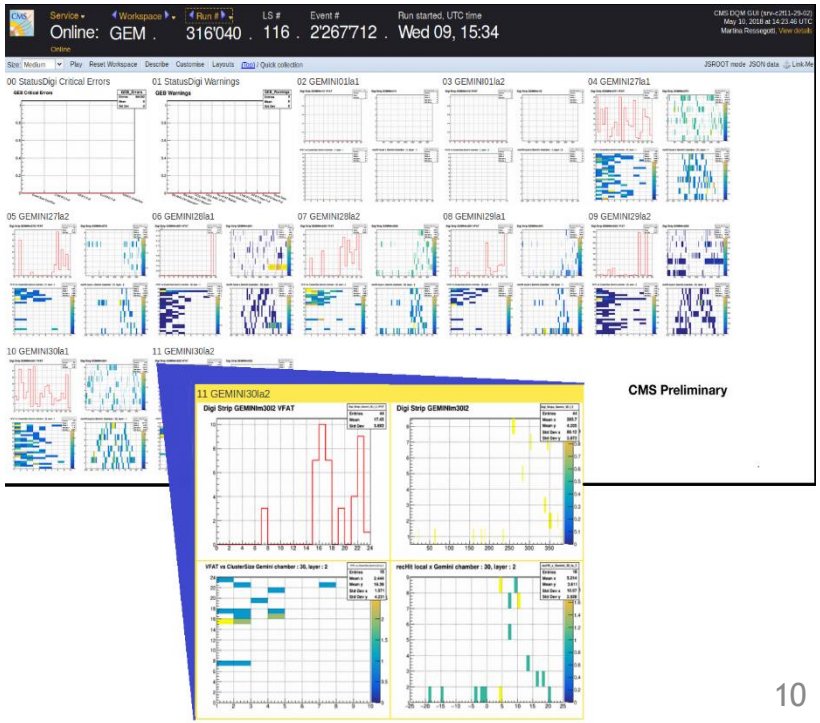
Detector Control System (DCS)

- The Detector Control System (DCS) was locally developed to control the HV and LV system and to monitor the gas system and environmental parameters.
- A Finite State Machine (FSM) was then added in order to prepare the system for the operation in central DCS.
- The final integration of the GEM DCS in CMS was reached at the end of 2017.



Data Quality Monitoring (DQM)

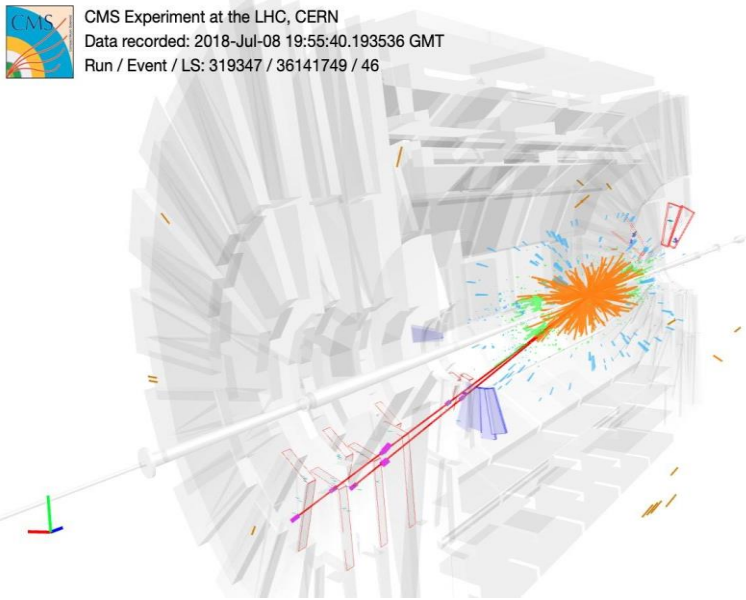
- The inclusion of GEMs into the global runs entails also the need of monitoring the quality of data collected as well as the performance of the detectors.



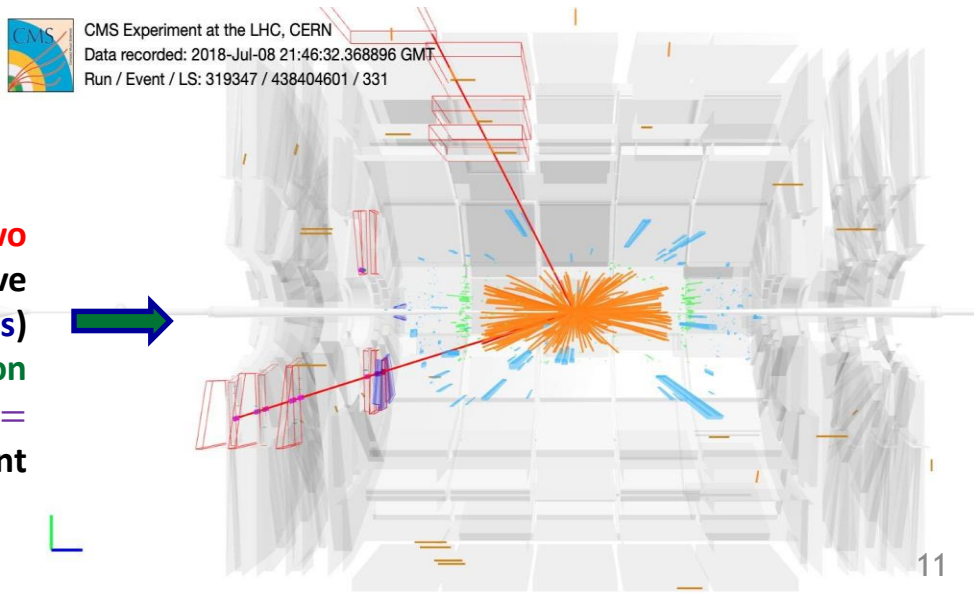
GE1/1 Slice Test - First Results

GE1/1 Slice Test: Success!

First results of reconstructing collision data with GEMs in muon reconstruction 2017/2018



LHC run2 2018C p-p collision event display showing two muons (red lines), associated with hits on one of the five GE1/1 slice test super-chambers (blue trapezoidal boxes) at station 1 of the endcap muon system. The antimuon ($p_T = 30.11\ GeV/c^2, \eta = -1.956$) and muon ($p_T = 53.597\ GeV/c^2, \eta = -1.993$) has a combined invariant mass of $3.011\ GeV/c^2$ (*J/Ψ meson particle*).



LHC run2 2018C p-p collision event display showing two muons (red lines), associated with hits on one of the five GE1/1 slice test super-chambers (blue trapezoidal boxes) at station 1 of the endcap muon system. The antimuon ($p_T = 34.01\ GeV/c^2, \eta = -0.540$) and muon ($p_T = 37.63\ GeV/c^2, \eta = -1.985$) has a combined invariant mass of $91.141\ GeV/c^2$ (*Z^0 boson particle*).

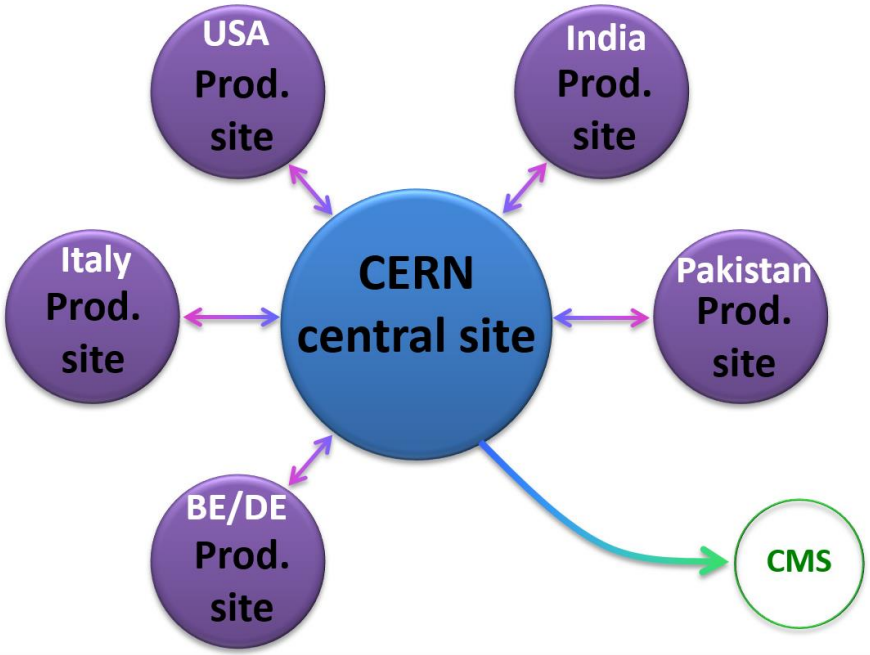
CMS GE1/1 triple-GEM Detectors Construction and Certification

Co-authors
Mohsin Abbas, Michele Bianco,
Jeremie Merlin and Archana Sharma

GE1/1 Production Sites

→ **Distribution of the production in various sites:**

- Share the effort with CMS - GEM institutes
- Generate a large community of GEM experts
- Equip production sites with infrastructure, tooling and knowledge for GE2/1 and ME0 productions



→ **2-years training program**

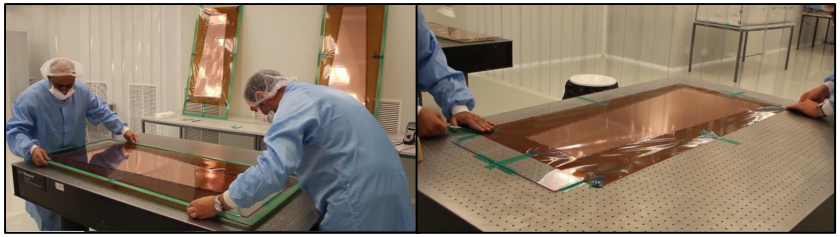
- Using same procedure
- Using same infrastructure
- All Quality Control deliverables validated by the production community

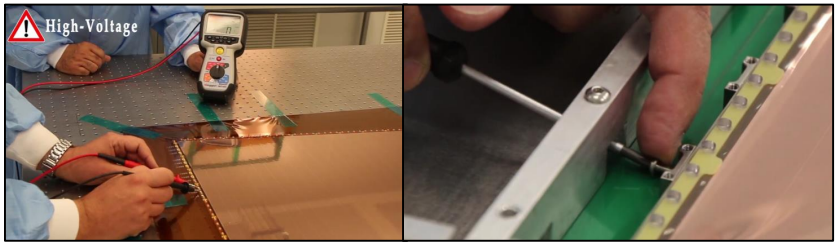
GE1/1 Detector Assembly Procedure

Preparation of the components (in laboratory)

~1/2 d

- *Cleaning of the components*
- *Preparation of the HV circuit*
- *Mounting of the pull-outs*
- *Selection of the O-ring*

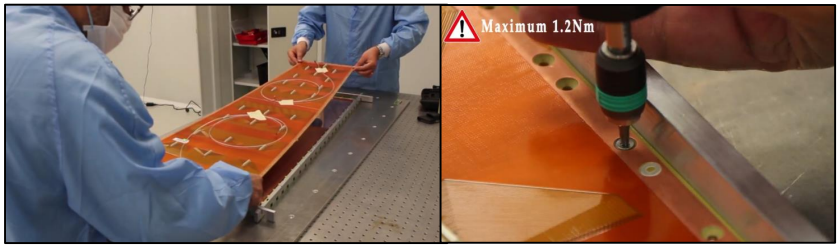




Assembly (in clean room)

~2 hr

- *Fast test of the GEM-foils*
- *Mounting of the stack*
- *Closing of the chamber*



1 day is sufficient to fully assemble a GE1/1 detector

D. Abbaneo et al., *Layout and assembly technique of the GEM chambers for the upgrade of the CMS first muon endcap station*, Nucl. Instrum. Methods Phys. Res., A 918 (2019) 67 - 75

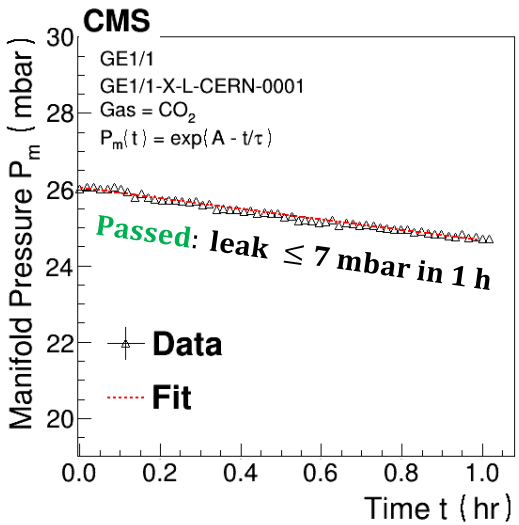
GE1/1 QC Overview

CERN
- **QC1** — Material Inspection
- **QC2** — GEM-foils Test

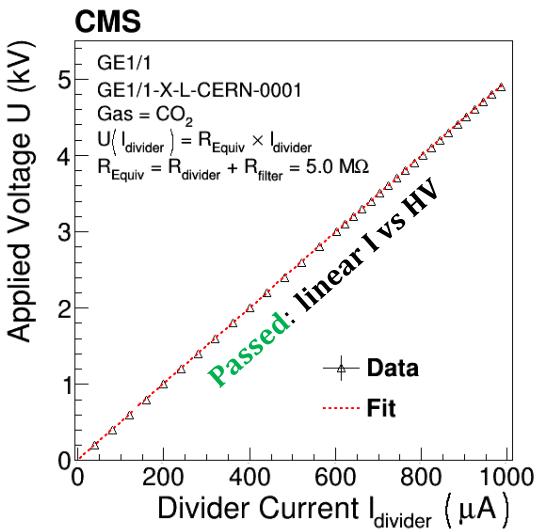
Production sites
- Assembly
- **QC2** — GEM-foils Test (fast)
- **QC3** — Gas Leak Test
- **QC4** — HV Test
- **QC5** — Gas Gain Calibration

CERN
- **QC6** — HV Stability Test
- **QC7** — Electronics Connectivity Test
- **QC8** — Cosmic Test

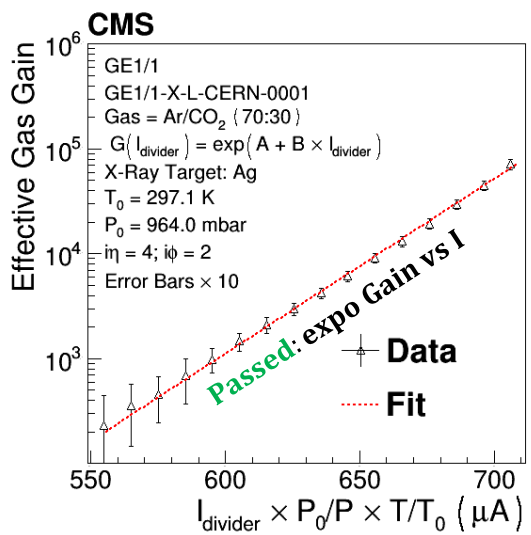
QC3 - Gas Leak Test



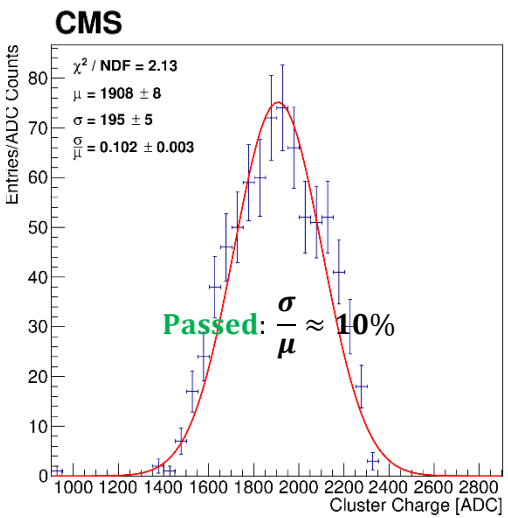
QC4 - HV Integrity



QC5.1 - Effective Gas Gain



QC5.1 – Gas Gain Uniformity



GE1/1 Detector Production Status

Super Chamber Assembly:

On-time production:

(last update 9th Feb. 2019)

- **160 detectors already assembled**
- **151 detectors fully validated up to QC5**
- **6 Quality Control on-going**
- **3 chamber need to be repaired**
- **13 detectors fully equipped with electronics and services (6 Super Chamber + 1 chamber)**

CMS GE1/1 triple-GEM Detectors Electronics

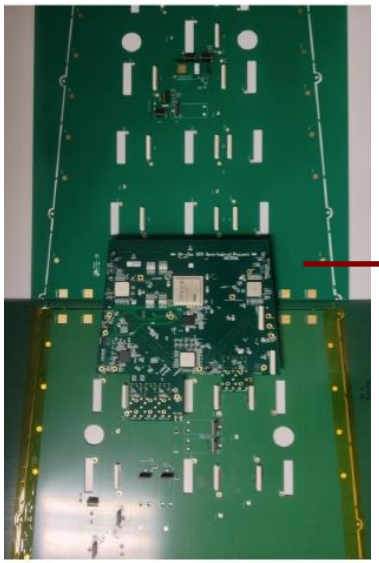
Co-authors
Brian Dorney, Francesco Ivone, Gilles de Lentdecker and Federica Simone

GE1/1 Electronics: Overview

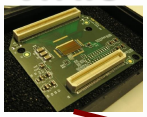
ON - DETECTOR

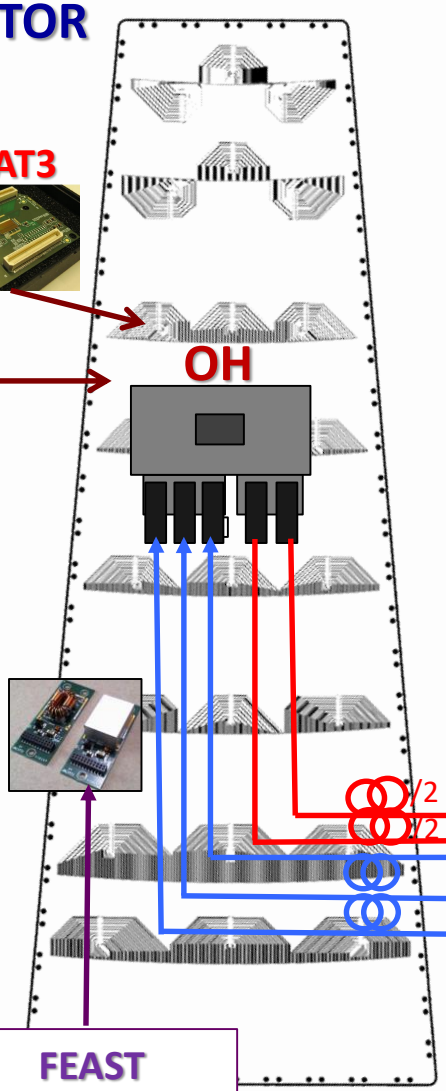
OFF - DETECTOR

2 - pieces GEB v3 $(1.0 - 1.2m)$



VFAT3

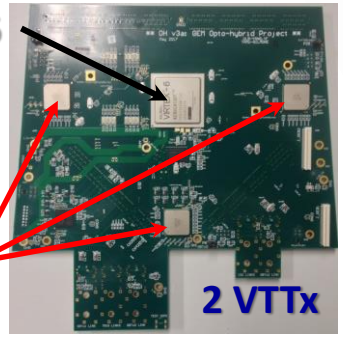




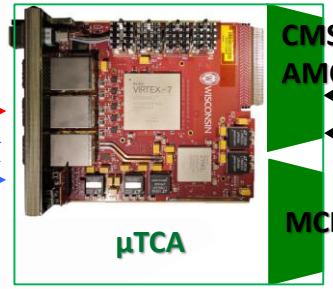
CSC
Trigger
Mother Board
(TMB)

Trigger data
(3.2 Gbps – 10b/8b)

Opto - Hybrid v3 (OH)



Tracking data
3 x GBT – 4.8
Gbps

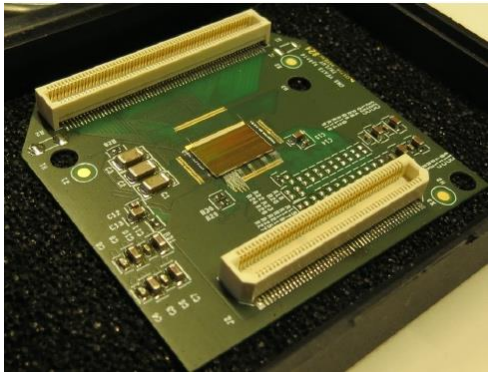


AMC = CTP7 from
CMS Trigger upgrade

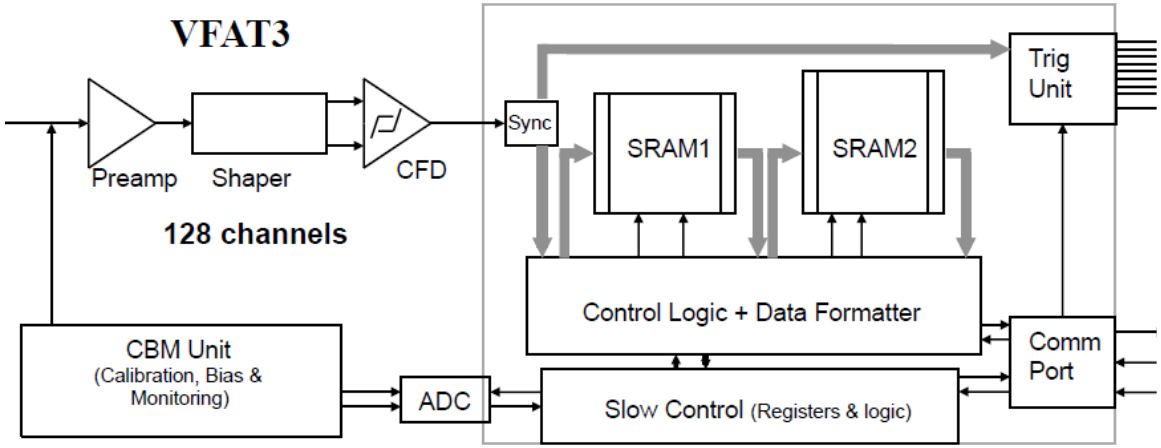
GE1/1 Electronics: VFAT3 Front-end

VFAT3 chip on hybrid:

- Binary output, CFD
- 320 MHz
- L1 latency: up to 25.6 µs
- Slow control: ePort, GBT compatible
- Trigger data:
  → 1bit = OR of 2 strips (+DDR option)



VFAT3 chip on hybrid



- Trigger path: 8 sLVDS pairs @ 320Mbps 64b/bx (128b/bx DDR)
- Fast OR: Each pair of channels, lossless
- SPZS: Full granularity, up yo 6 partitions /bx
- DDR: Full granularity, lossless.
- Data path: Full granularity after LV1 + time tag LV1 latency extended to 25us LV1 rate extended to 1MHz.
- Communication interface to GBT: Comm-Port allows bi-directional communication of control commands, CMB (calibration, bias and monitoring) and data readout through a single port to the GBT.

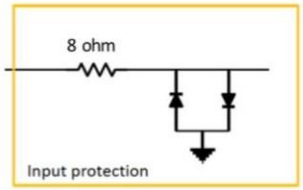
VFAT hybrid for GE1/1: input protection circuit studies

The GEM collaboration is carrying out an R&D campaign to improve the input protection and robustness of front-end electronics preventing possible discharge damage

HV3b - V2

Initial baseline

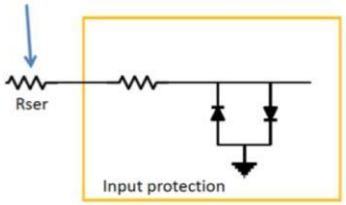
Internal input protection only (diode). Channels burnt with $E > 28\ \mu J/disc$

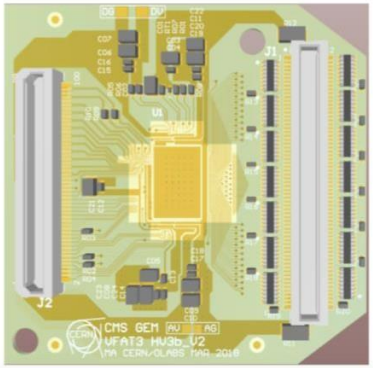


HV3b - V3

Ext. input protection ($R = 330\ \Omega$)

OK after 500 ESD $470\ \mu J/disc$
X-talk $+15\%$; Noise $+20\%$
No radiation issues expected

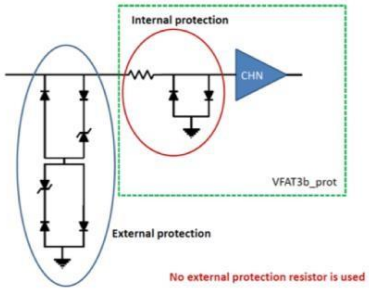


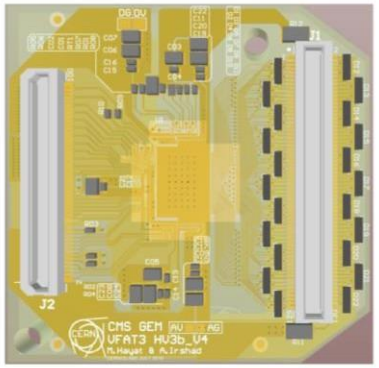


HV3b - V4

Ext. Input protection (diodes)

OK after 540 ESD $470\mu J/disc$
No increase of noise observed
Rad Hard studies OK (10 Mrad)





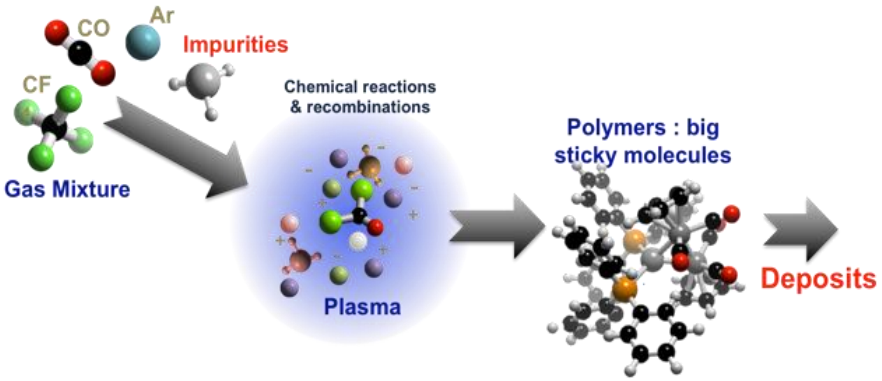
CMS ME0 triple-GEM Detectors Long-term Operation

Co-authors
Davide Fiorina and Jeremie Merlin

Aging of Gaseous Detectors

Classica Aging:

- Chemical processes occurring in the plasma avalanches release free radicals chemically active
- Radicals → Monomers → Polymers
- Polymers deposit on sensible surfaces (anode, cathode, insulations, etc.)



→ **Detector performances loss!**

CMS needs to validate triple-GEM technology for the ME0 project

- Expected hit flux in the ME0 muon detectors: $\sim 50\ kHz/cm^2$
- Constraints on the technology for the upgrade:
  - Longevity $>$ 10 HL-LHC years $(\times\ safety\ factor\ 3!)$
  - Accumulated charge (10 HL–LHC years):
    $\rightarrow Q_{tot} = Rate \times Primaries \times Gain \times Time \times q_e \sim 283\ mC/cm^2\ (at\ Gain = 2 \times 10^4)$
- $850\ mC/cm^2$ of integrated charge $(safety\ factor\ 3!)$ needed to fully validate the triple-GEM technology for the new ME0 project

Longevity Studies at GIF++ facility

GIF++ facility:

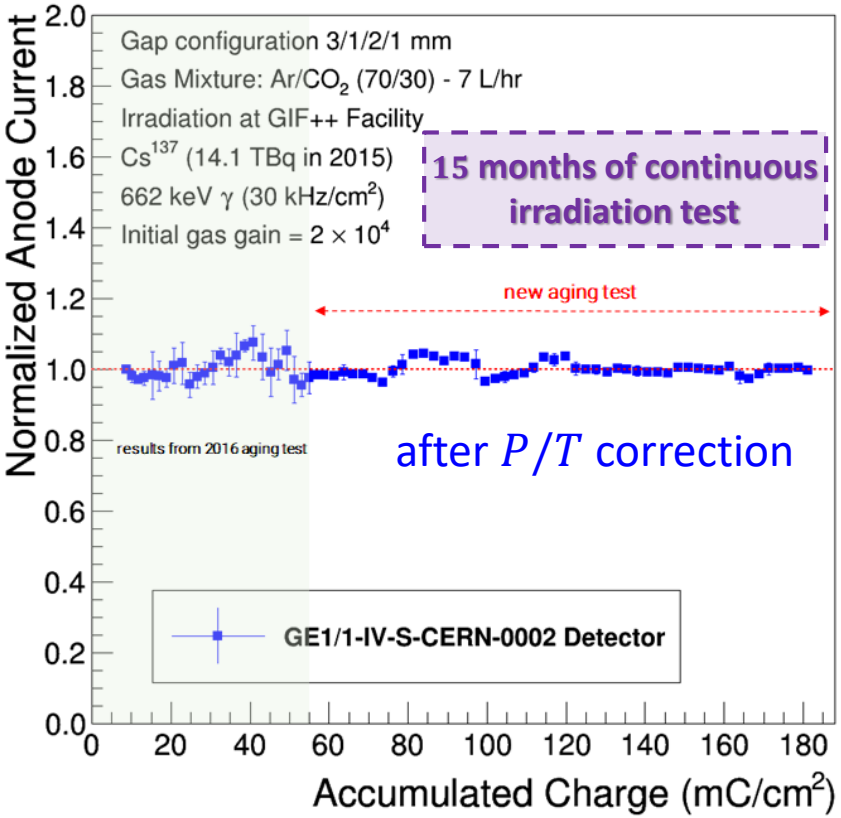
- The facility consists of an intense $14\ TBq$ (in 2015) ^{137}Cs source emitting $662\ keV$ photons and lower energetic scattered photons
- Particle flux: $\sim 10^8$ Hz/cm^2

Detector under test:

- CMS GE1/1 triple-GEM detector (similar to the final design)
- Effective Gas Gain: 2×10^4
- Gas Mixture: $Ar/CO_2\ (70/30)$

Measured parameter:

- Monitoring of the anode current (representative of the detector gas gain)



NO aging observed up to $\sim 182\ mC/cm^2$

($\sim 64\%$ of ME0 operation at the HL-LHC)

Additional 5 - 5.5 years are needed in order to validate the ME0 project with the safety factor 3

Longevity Studies at CMS-GEM Production Lab.

Source:

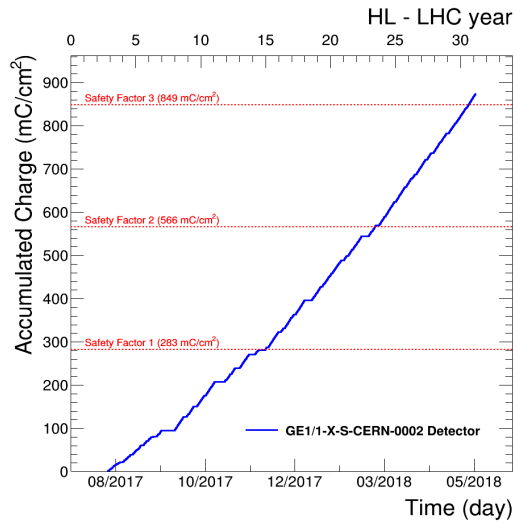
- 22 keV X-ray photons from X-rays generator

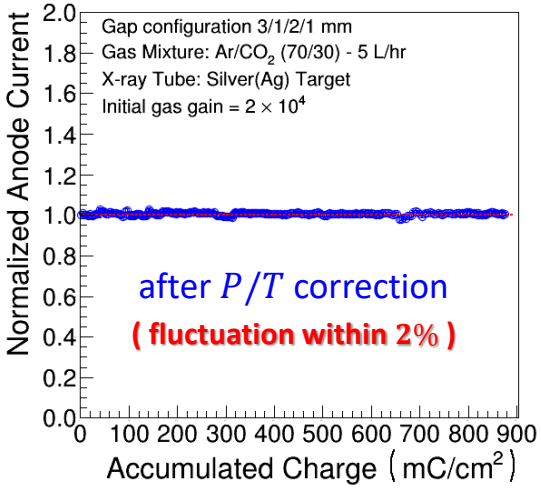
Detector under test:

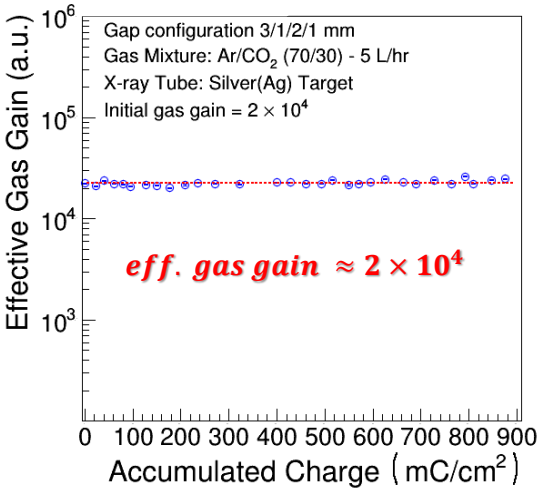
- CMS GE1/1 triple - GEM detector (final design and material)
- Effective Gas Gain: 2×10^4
- Gas Mixture: Ar/CO_2 (70/30)

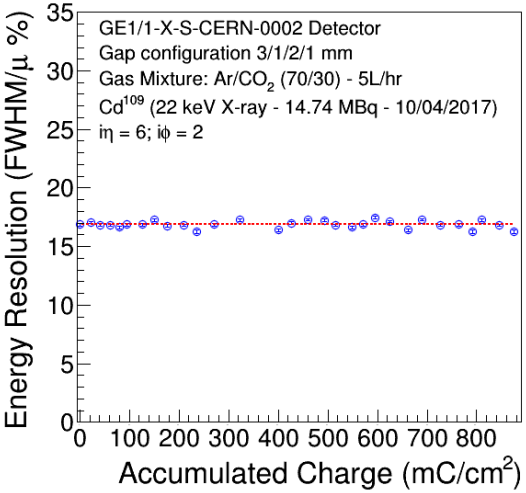
Measured parameter:

- Monitoring of the anode current during the irradiation test
- Weekly effective gas gain meas.
- Weekly energy resolution meas.









X-ray Aging Test at CMS-GEM Lab. (4000 hours of continuous tests) → **NO aging observed up to ~ 875 mC/cm^2** (~ 31 years of ME0 operation at the HL-LHC)

Longevity Studies at CMS-GEM Production Lab.

Source:

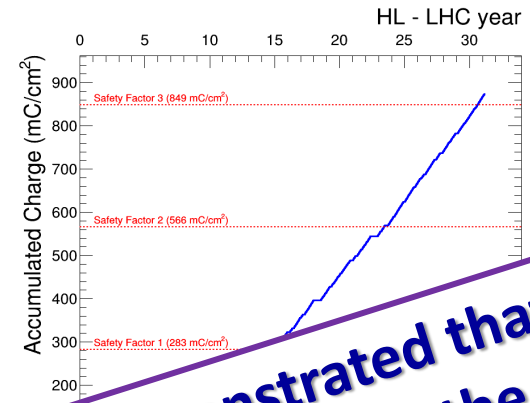
- 22 keV X-ray photons from X-rays generator

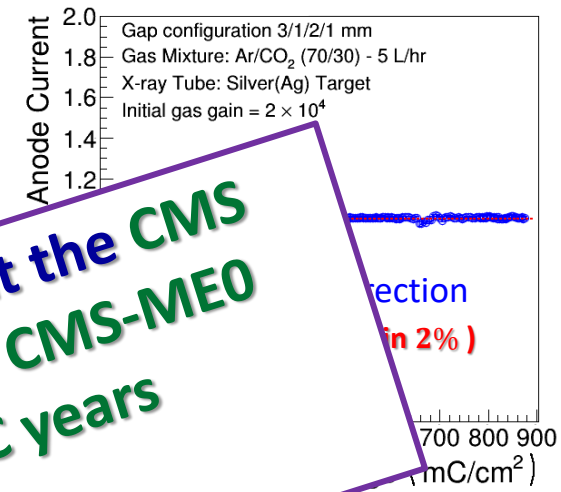
Detector under test:

- CMS GE1/1 triple - GEM detector (final design and material)
- Effective Gas Gain: 2
- Gas Mix

Measure

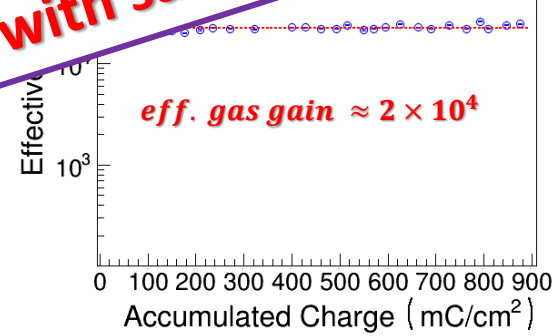
- Monit during
- Weekly gain meas.
- Weekly energy resolution meas.

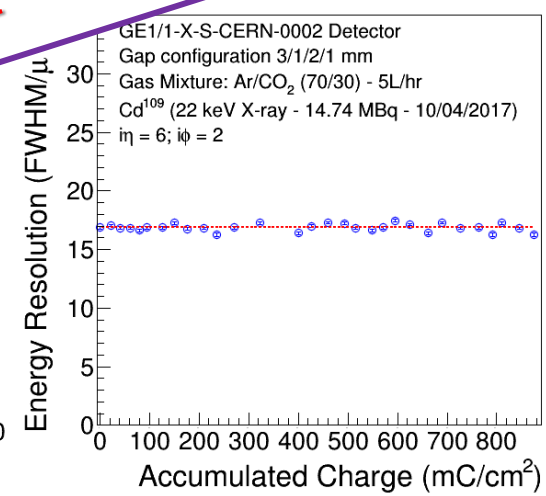




The Longevity Studies demonstrated that the CMS triple-GEM detector can operate in the CMS-ME0 environmental for over 10 HL-LHC years

→ with safety factor 3 ←





X-ray Aging Test at CMS-GEM Lab.

(4000 hours of continuous tests)

→ **NO aging observed up to $\sim 875\ mC/cm^2$**

($\sim$ 31 years of ME0 operation at the HL-LHC)

Conclusions (1/2)

1. *CMS GE1/1 triple-GEM Detectors Slice Test*

- **A Slice Test composed of 5 Super-Chambers installed at beginning of 2017**
  - **High Voltage and Low Voltage systems: functional and stable**
  - **DCS and DAQ system: functional and successfully calibrated**
  - **Operation: successfully detected cosmic muons and muons from p-p collisions**
  - **Other aspects not covered here: gas system, cooling system, cable routing and other necessary services have been installed/performed and worked properly**
- **Slice Test removed at the end of January 2019 in preparation for the final installation of the GE1/1 station**

2. *CMS GE1/1 triple-GEM Detectors Construction and Certification*

- **Successful production of 144/144 (100%) detectors in 10 production sites**
  - **All tested detectors are within specifications (with uniform performances)**
  - **Full production has been completed in December 2018**
- **Production of Super-Chambers and final certification are in a full swing**

Conclusions (2/2)

3. CMS GE1/1 triple-GEM Detectors Electronics

- GE1/1 Slice Test has observed irreversible channel loss in the VFAT-V2
- R&D campaign launched this summer to understand:
  - The origin of the channel loss: discharges propagating to the anode plane
  - The weakness in GE1/1 front-end protection: new hybrids have been designed with diode protection

4. CMS ME0 triple-GEM Longevity Studies

- Longevity test ongoing at GIF++ facility (γ - *ray exposure*)
  - NO aging observed up to $\sim 182\ mC/cm^2$
  - $\sim 64\%$ of *ME0* operation at the HL-LHC
- Longevity test ongoing at CMS-GEM QA/QC facility (X - *ray exposure*)
  - NO aging observed up to $\sim 875\ mC/cm^2$
  - 10 years of *ME0* operation at the HL-LHC (safety factor 3.1)
- Advanced Longevity Studies (preliminary results)
  - Aging issues originated by particles with different ionization powers
  - Clear correlation between specific ionization power and polymer creation rate

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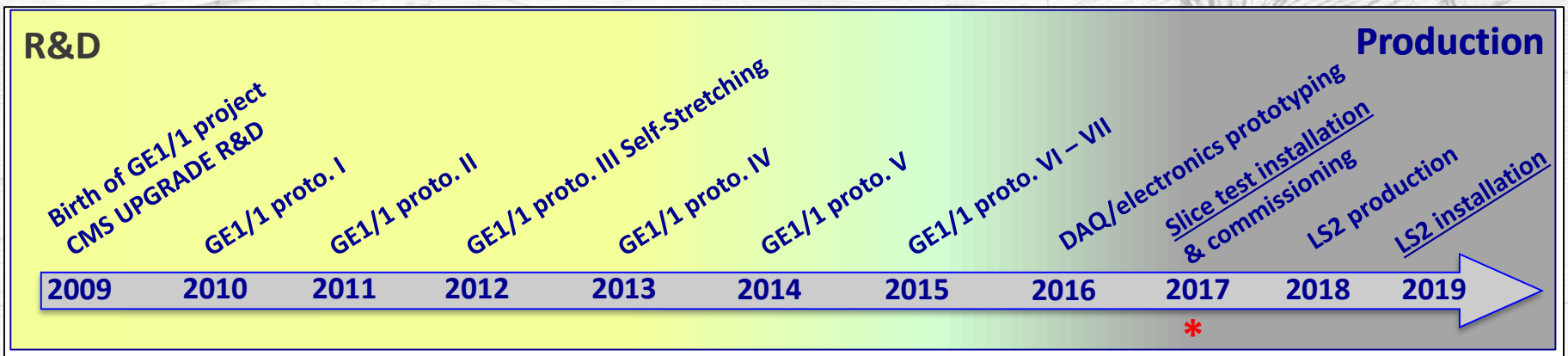
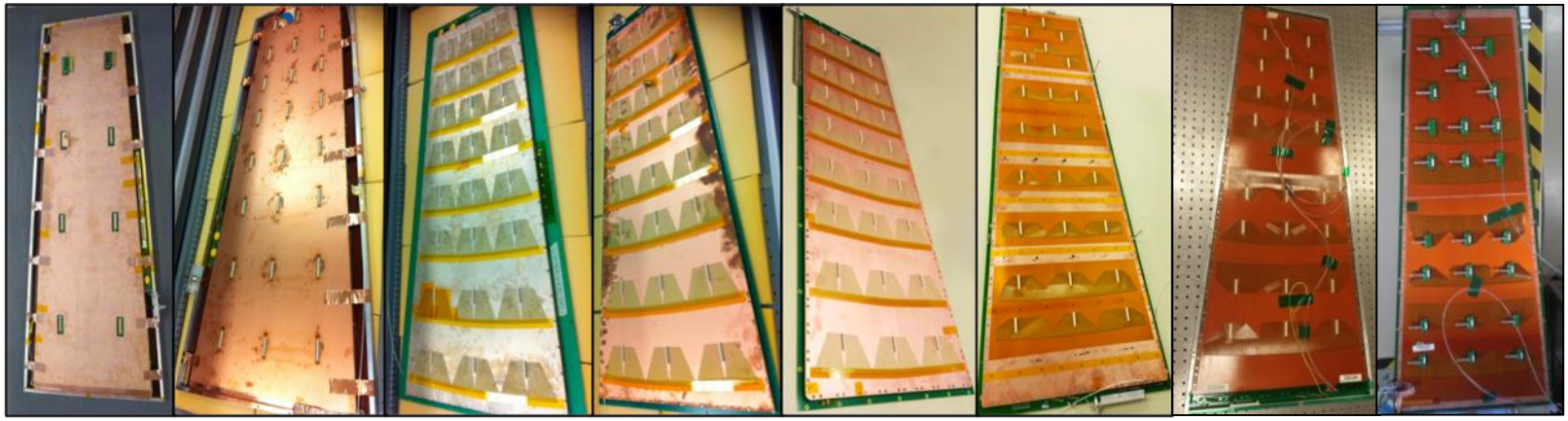
- **Federica Simone**, University of Bari and Bari INFN, Italy
- **Ilaria Vai**, University of Pavia and Pavia INFN, Italy

BACKUP SLIDES

GE1/1 Historical Development





GE1/1-I (2010)	GE1/1-II (2011)	GE1/1-III (2012)	GE1/1-IV (2013)	GE1/1-V (2014)	GE1/1-VI (2015)	GE1/1-VII (2016)	GE1/1-X (2017)

Comments:

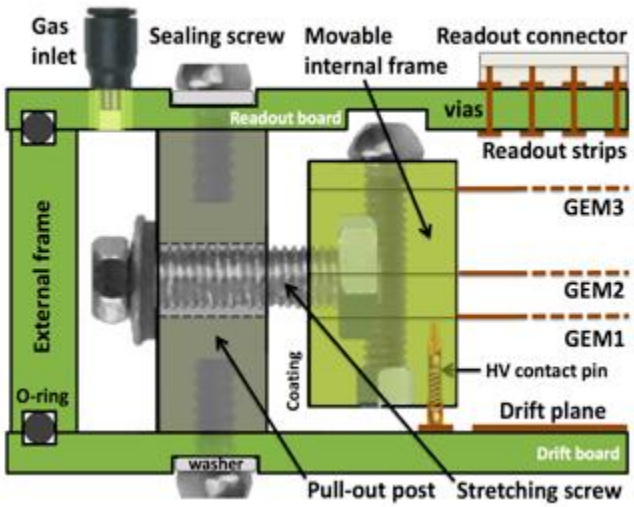
- More than 5 years of $R\&D$ to optimize the performance, reliability and construction
- Production of 10 Slice Test chambers → installed in CMS in January 2017

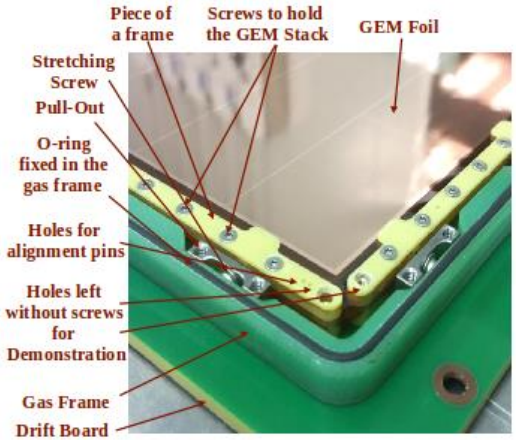
(*) Installation of a new GEM production facility at CERN (904 Lab.)

GE1/1 Detector Design

GE1/1 Detector Construction

- GE1/1 detectors introduced a novel technique of GEM chambers construction, which avoid the usage of glue
- GE1/1 detectors are realizing using GEM foils stretched by means of moveable FR4 frame (internal). Cathode and Readout electrode made by standard single layer PCB. Electrical signal extracted by "vias" on PCB trough 130 pins Panasonic connectors
- The internal frames are controlled by "stretching screws"
- The tightness of the chambers is assured by an external FR4 frame sealed with O-ring
- Chamber assembly have to be performed in clean room (at least class 1000) to avoid GEM foils contamination
- GE1/1 chamber production distributed in several production sites
- GE1/1 Mass production started in April 2017

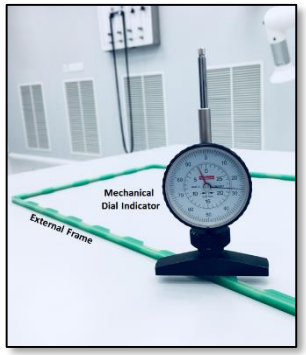


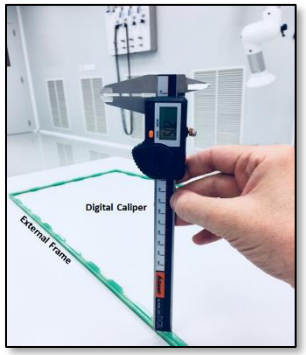


GE1/1 QC Overview

QC1 - Detectors Components Inspection and Qualification

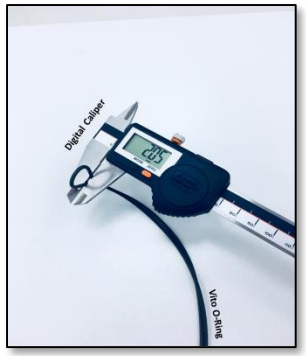
All the GE1/1 detector components produced by industrial companies are delivered to CERN where they are immediately verified for defects and tested





→ *Internal / external frames*

- Optical inspection to identify possible cracks, mechanical unconformities and manufacturing defects on the epoxy glass structure
- Measurements of the width and depth of the grooves along periphery of the external frame that will accommodate the Viton O-ring in order to ensure greater degree of the gas-tightness of the detector



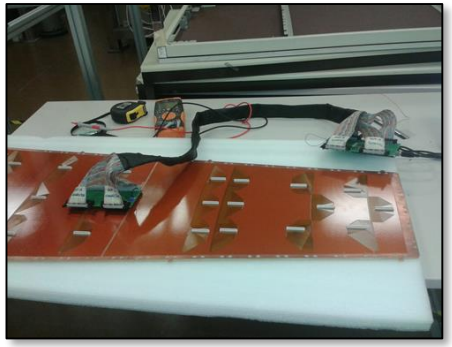
→ *Viton O-ring*

- Measurements of the external diameter in order to ensure a correct coupling between the O-ring and the external frame and ensure a correct gas-tightness

QC1 - Detectors Components Inspection and Qualification

→ *Drift Board*

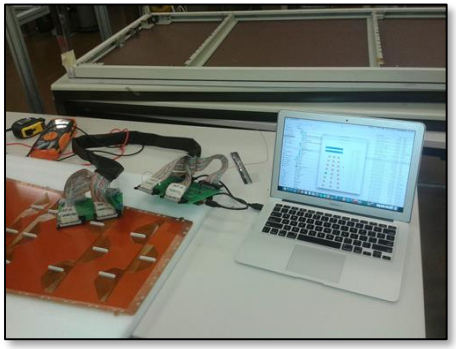
- Optical inspection to identify possible mechanical damage and surface anomalies on the drift electrode and its planarity



Connectivity Test

→ *Readout Board*

- Optical inspection to check the planarity of the readout board and possible macroscopic scratches and defects on the readout strips or Panasonic adopters for signal readout
- Connectivity test in order to inspect the readout board for possible shorts between strips or open strip-readout connections



Connectivity Test

- The readout board under test is rejected if:
  - $\boldsymbol{short\ circuit \geq 4}$
    (in the whole readout board)
  - $\boldsymbol{faulty\ channels \geq 3}$
    (inside the same Panasonic adapter)

Microscopy photos of the readout strips showing some examples of defects and short circuits between the readout strips.

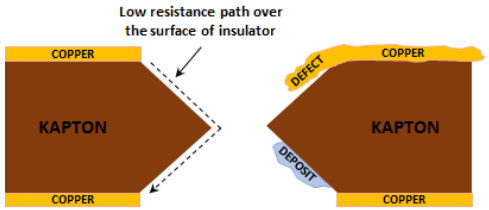
QC2 - Leakage Current Test

The QC2 - leakage current test aims to determine the quality of a GEM-foil by measuring the maximum leakage current flowing on the surface of the GEM-holes.

GEM-foils produced in the CERN PCB workshop are delivered to CMS GEM clean room, where they undergo to dedicated QA/QC test:

1. Optical inspection to identify macroscopic defects on the copper or Kapton layers, which could increase the probability of electrical breakdown and/or short circuit
2. Dedicated quality control test (QC2 - Leakage Current test) to measure the **leakage current** and possible **discharge**

When a voltage is applied across the GEM-foil, a current flows from its top to bottom due to the surface conductivity of the Kapton which is known as **leakage current**



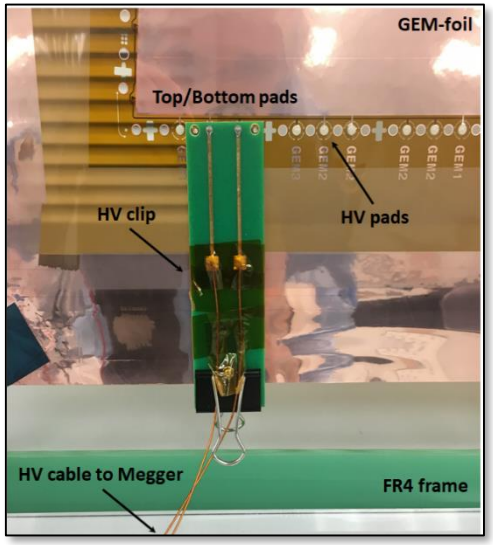
Presence of dust, pollution or defects could provoke an increase the leakage current flowing through the polyimide surface

It is possible determinate the integrity of the GEM-foils by measuring this leakage current and/or possible discharge

QC2 - Leakage Current Test

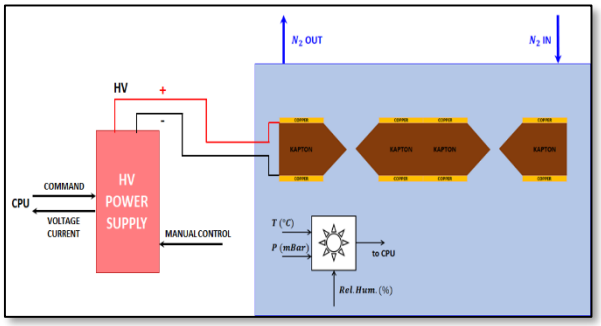
→ QC2 Fast Term Stability

- The first step consists of applying $550\ V$ to the GEM-foil and measure the leakage current between the top and the bottom electrodes and the number of possible discharge
- QC2 Fast Term Stability is performed both in CERN PCB workshop before the foils delivered and as soon as the foils arrive in the CMS - GEM QA/QC lab.
- The QC2 Fast Term Stability is performed with a Multi Mega-ohmmeter (Megger) over a period of $10\ \mathrm{min.}$ in air
- The GEM-foil is accepted if:
  - $\boldsymbol{impedance \geq 10\ G\Omega}$
  - $\boldsymbol{number\ of\ discharge\ \leq 2}$
    (during the last two/three minutes of test)
- If the number of discharges exceed the limit, the GEM-foils have to be re-cleaned with antistatic roll or, in the worst case, with $DI\ water$ in ultrasonic baths

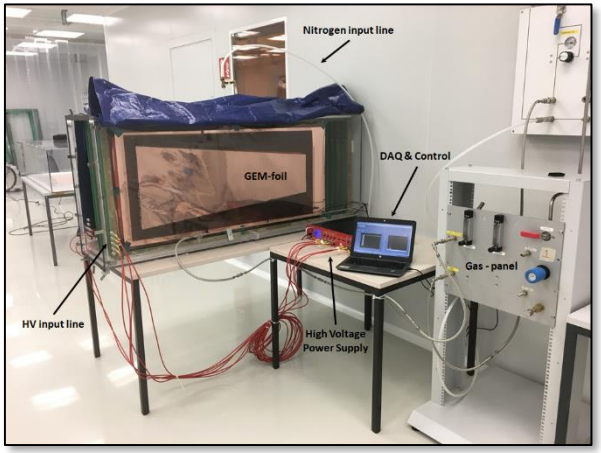


QC2 - Leakage Current Test

→ QC2 Long Term Stability



Schematic view of the QC2 long term stability setup



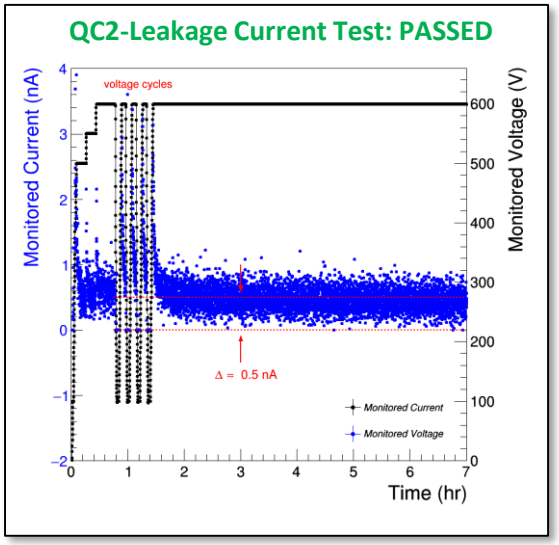
- Goal of the QC2 Long Term Stability test is the ultimate certification of the GEM-foils before the installation in the GE1/1 detectors
- QC2 Long Term Stability test is conducted using CAEN HV module with $50\ pA$ of current resolution acquired through *LabView* based software
- The GEM-foils are kept at low humidity level ($\sim 7\ \%$) in a dedicated box by flushing in pure dry Nitrogen ($N_2\ flow\ rate\ \approx\ 50\ L/hr$)
- GEM-foils are rejected if the test is failed more than three times (see next slide)
- GEM-foils fails the test are promptly sent back to the CERN-PCB workshop for cleaning

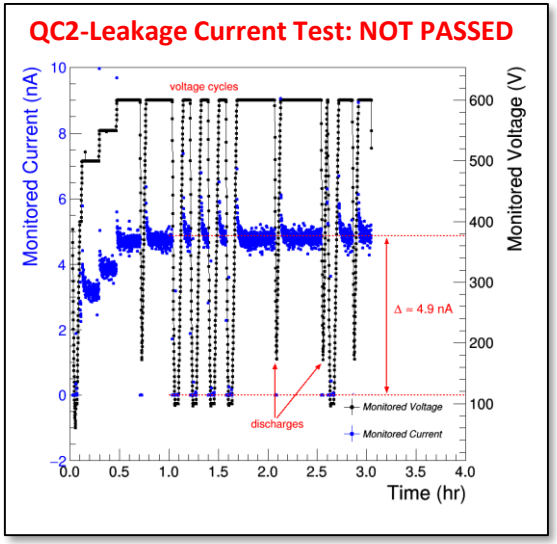
QC2 - Leakage Current Test

→ QC2 Long Term Stability

The Long test is divided into preliminary characterization phase and 3 steps with data monitoring:

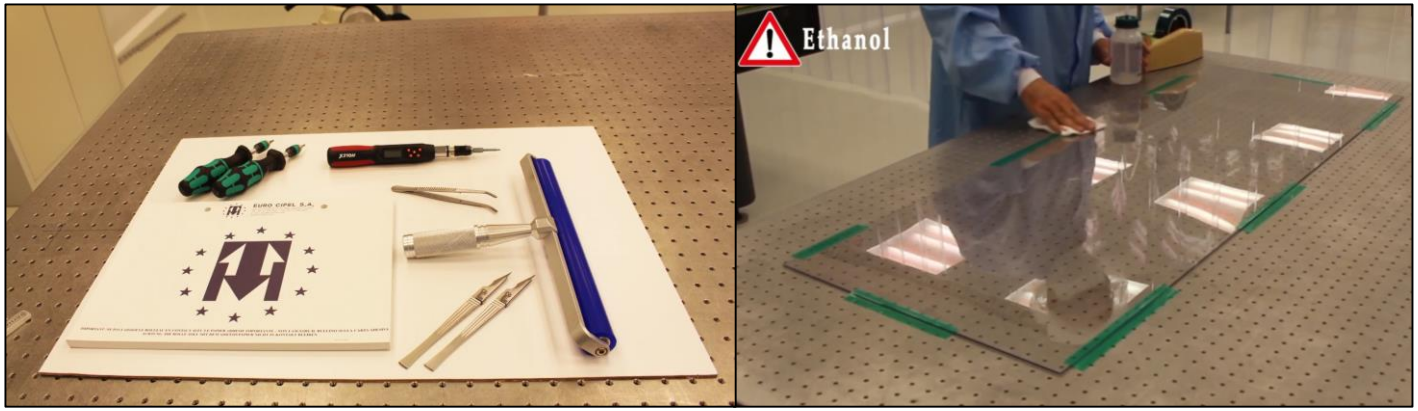
- During the "first gas flushing period" $\sim 36/48\ hr$, needed to reduce the relative humidity up to $\sim 7\%$, the GEM-foils are kept at $500/550\ Volts$, (Current limit $100\ nA$, trip time 1 sec)
- **Step 1**: Slow rump up to $500\ V$, plateau monitor at 500 and $550\ Volts$; step is passed if no discharges occurred for 10 min. for each HV value
- **Step 2**: HV fixed at $600\ Volts$, current and discharges are monitored; step is passed if no discharges occurred for 15 min. or no more than two discharges during the last $6\ hr$ (Current limit $50\ nA$, Trip Time 0 sec)
- **Step 3**: Voltage switches between $100\ Volts$ and $600\ Volts$, to evaluate a possible off-set in the current measurement



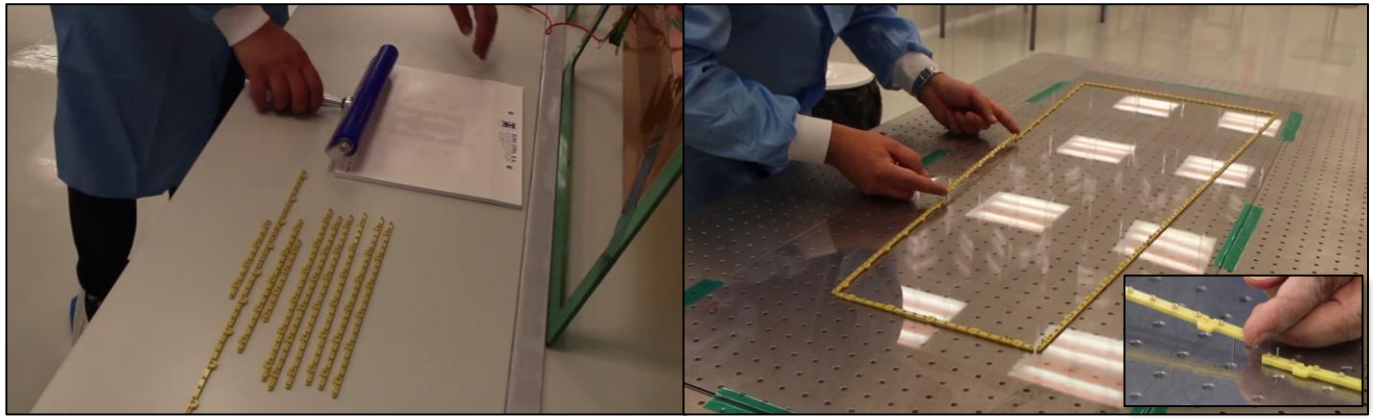


GE1/1 Detector Assembly

Step 1: all the tools are prepared and carefully organized for the assembly (left). The working table, made of PolyMethyl MethAcrylate (PMMA), is cleaned with an anti-static paper and ethanol (right).

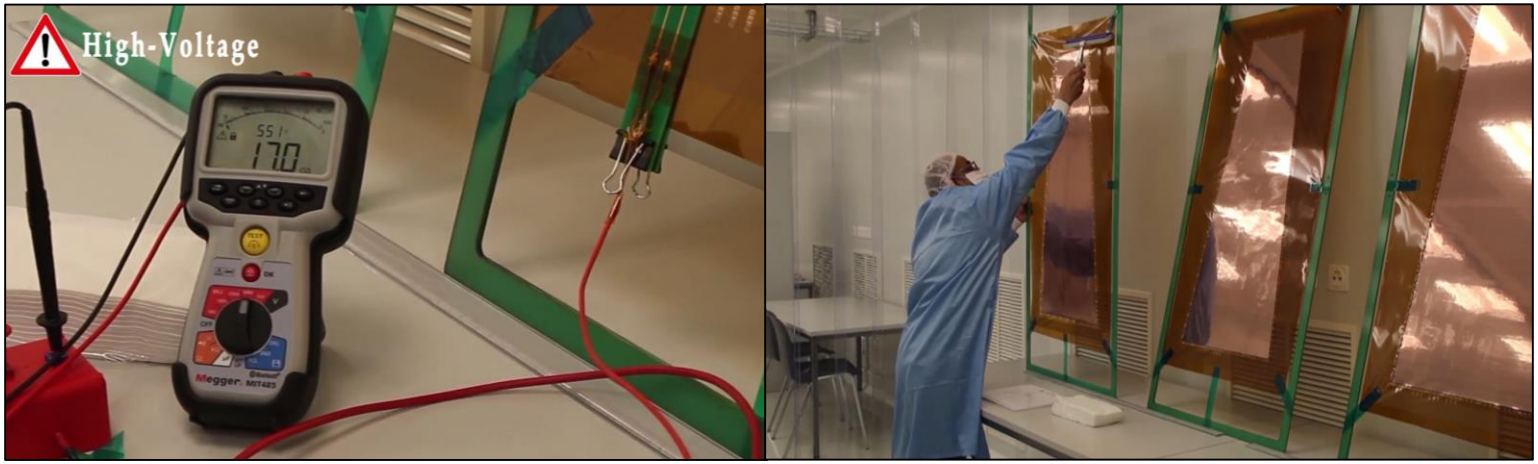


Step 2: the internal frames, responsible of holding the GEM stack, are cleaned with an anti-static roll (left) and placed on working table thanks to guiding pins (right).

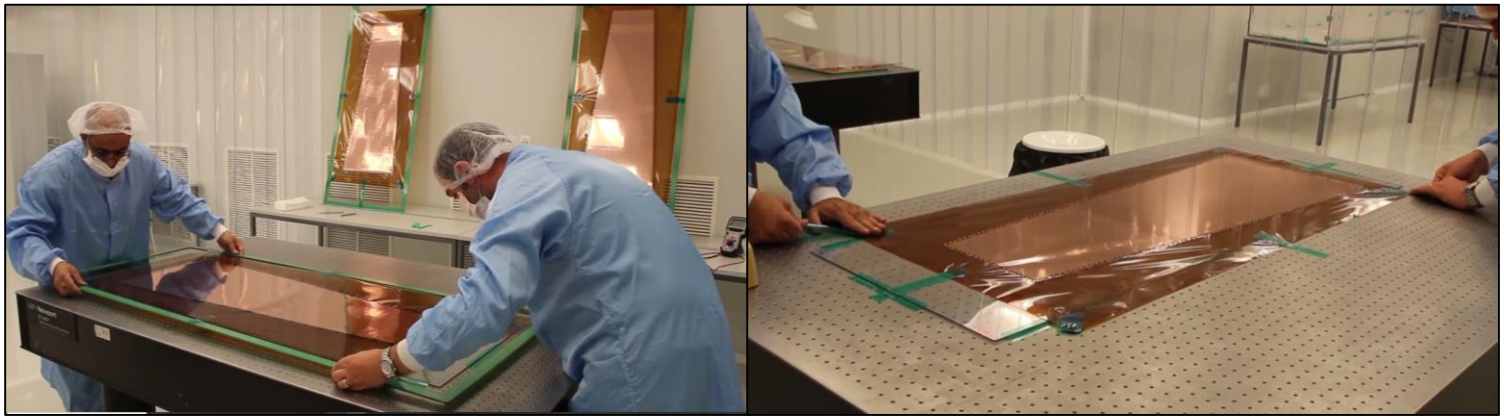


GE1/1 Detector Assembly

Step 3: the first GEM foil is tested at $550\ V$ and cleaned again with the adhesive roll.

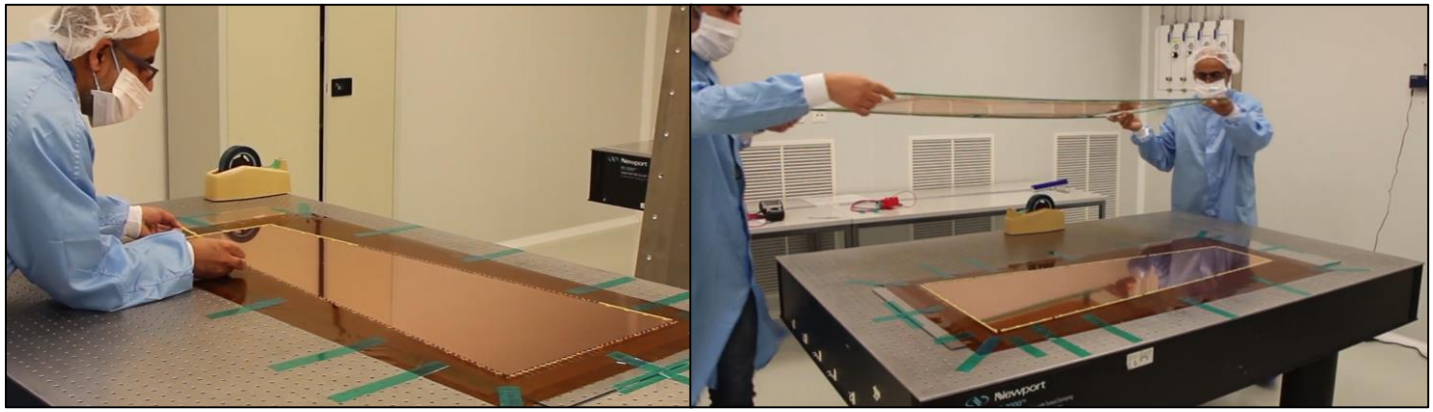


Step 4: the first GEM is placed on the first layer of internal frames (left). The foils is stretched by hand and attached to the working table to ensure the flatness and stability of the structure (right).

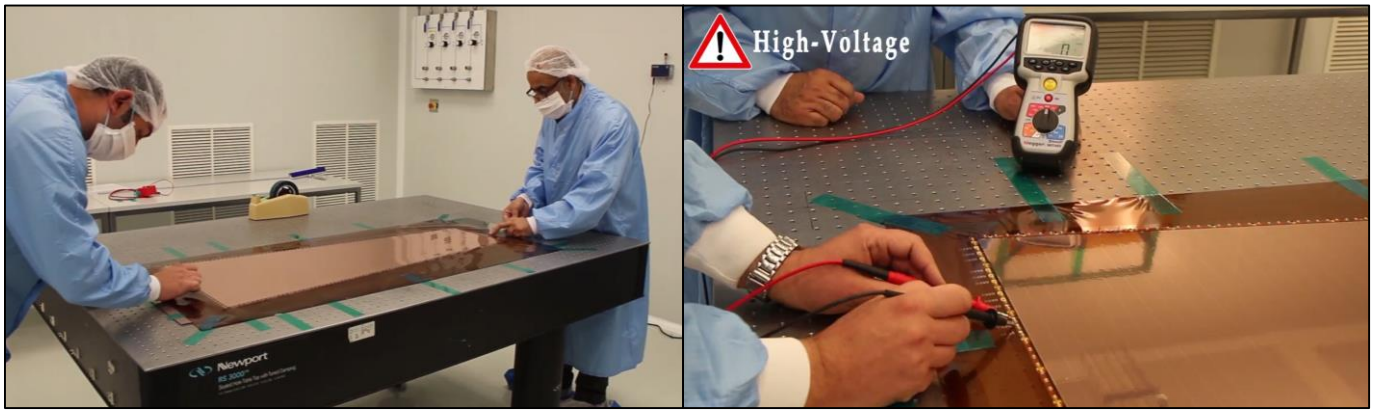


GE1/1 Detector Assembly

Step 5: the second layer of internal frames is placed on top of the first GEM (left). After testing and cleaning, the second GEM is added to the stack (right).

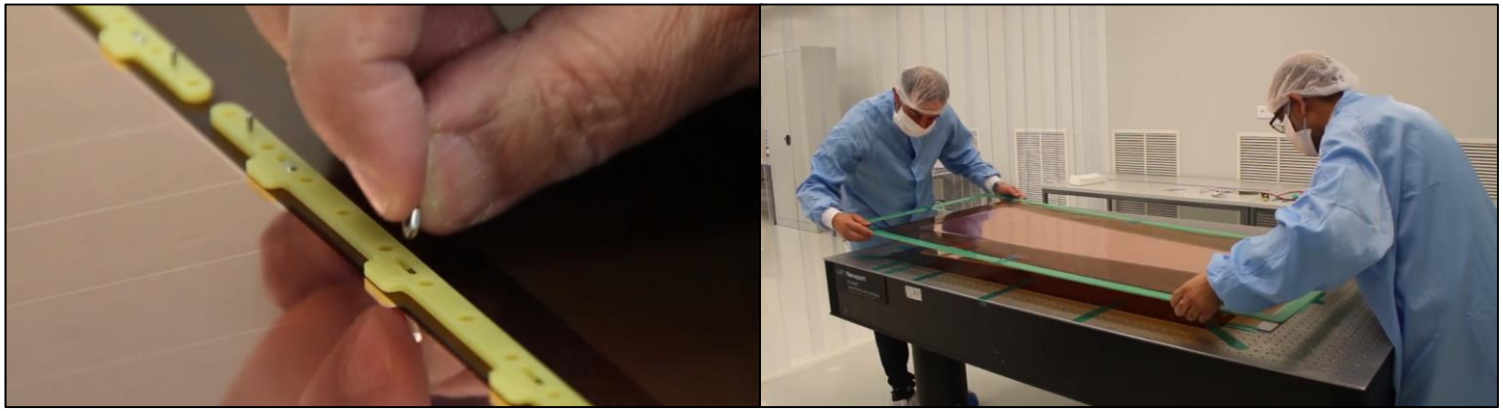


Step 6: same operation as before, the second GEM is stretched manually (left) and tested at $550\ V$ (right).



GE1/1 Detector Assembly

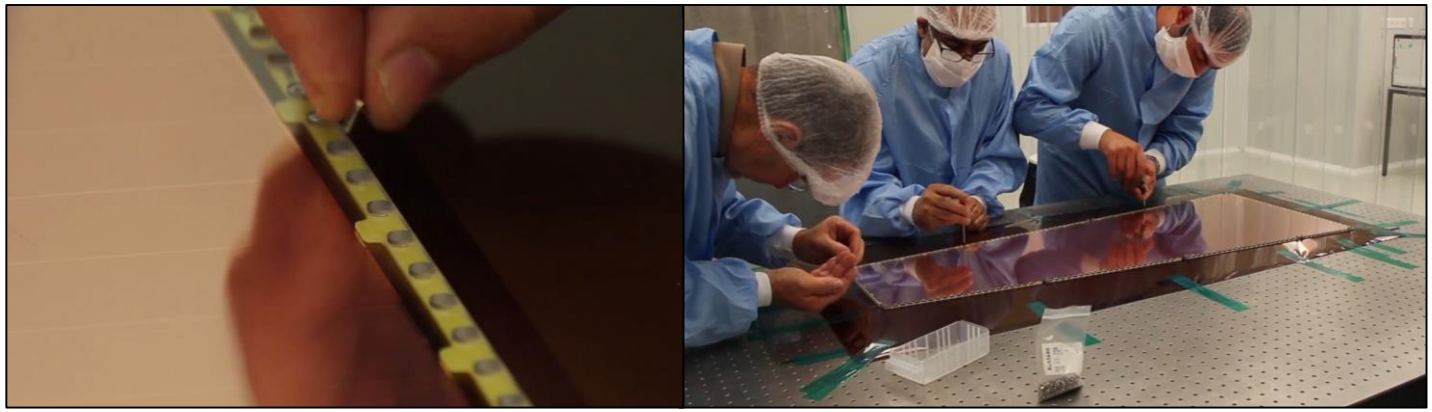
Step 7: after the third layer of internal frames is in position, metallic nuts are inserted in the dedicated housing of the frames. Then, the last GEM foils is added to the structure.



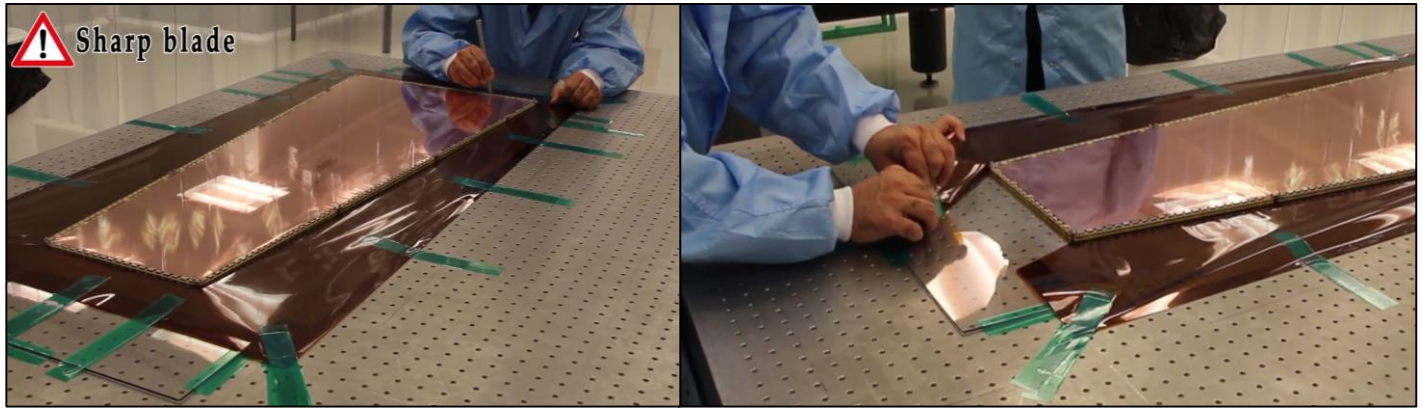
Step 8: the last layer of internal frames is added to close the stack (left), the GEM stack is protected by a PMMA cover placed fixed to the top of the internal frames.

GE1/1 Detector Assembly

Step 9: vertical screws are inserted into the frames in order to attach all the frame layers and GEM together.

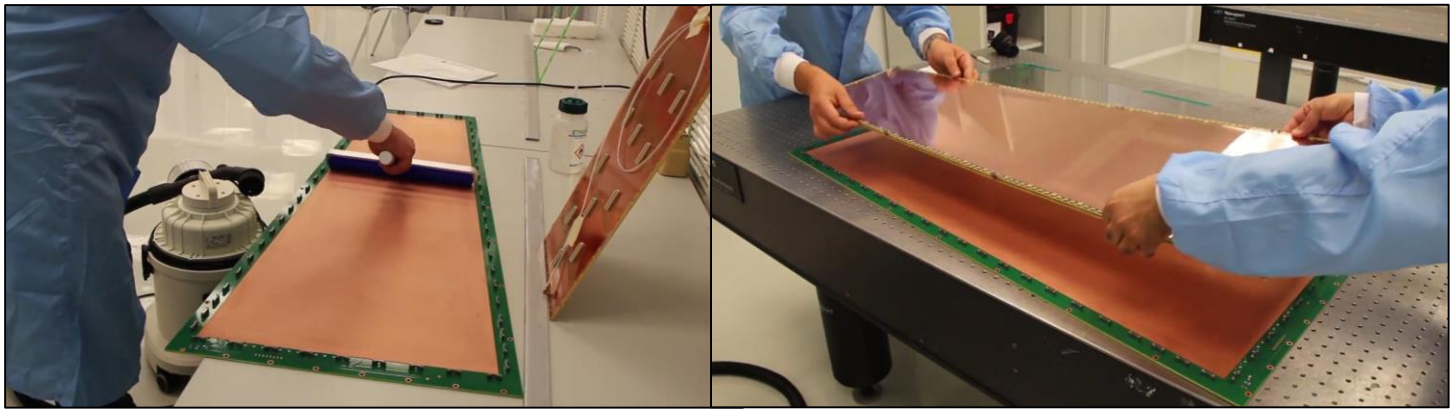


Step 10: the excess of polyimide foil is cut and detached from the GEM stack.

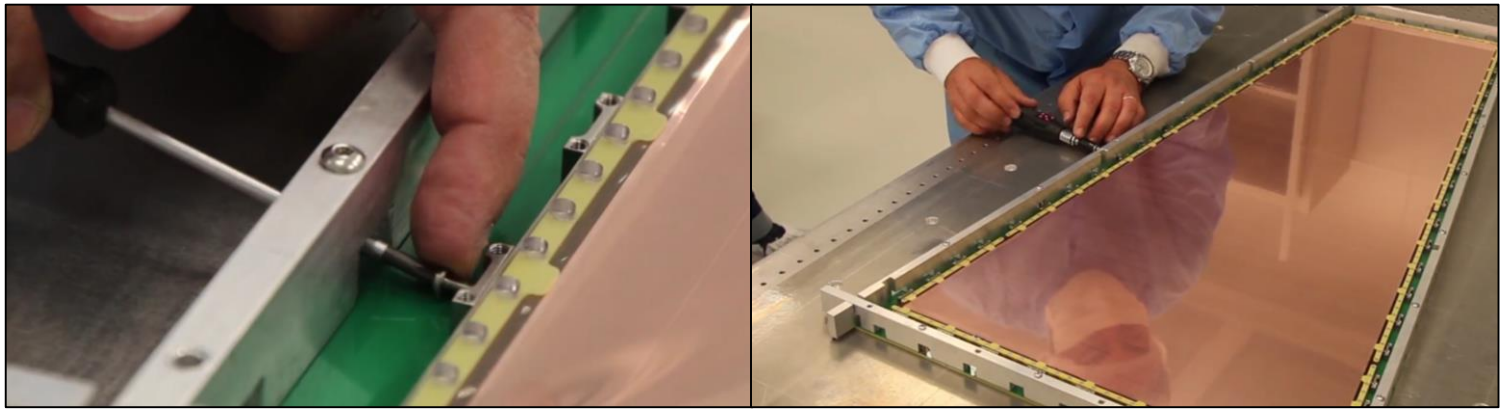


GE1/1 Detector Assembly

Step 11: after being cleaned with the anti-static roll (left), the drift plane is positioned below the GEM stack (right).

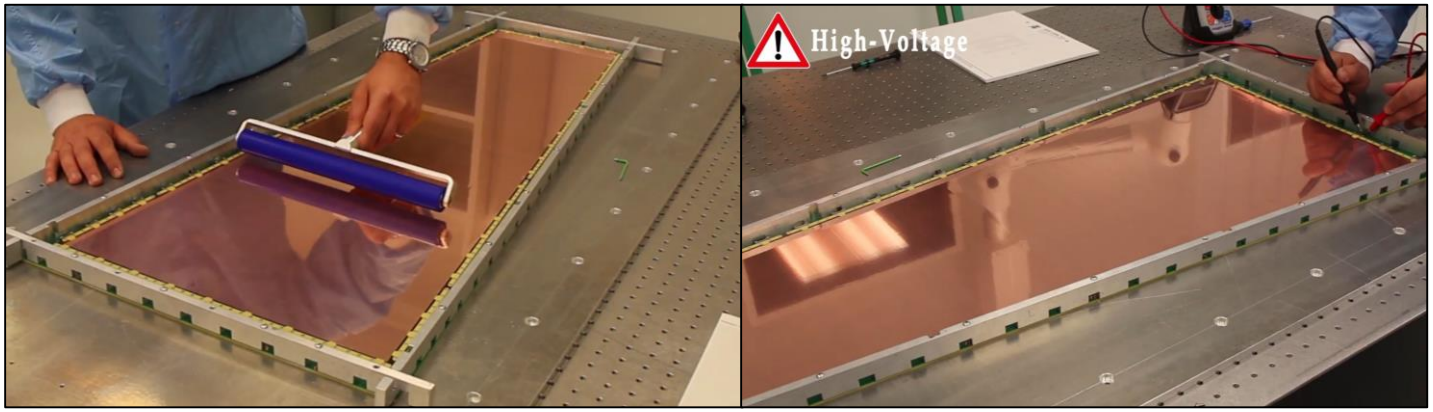


Step 12: lateral screws are inserted in the stainless steel pull-outs attached to the drift board until it reaches the embedded nuts (left). Then, torque control tools are used to stretch the foils, for a tension about 8 - $10\ cN \cdot cm$.

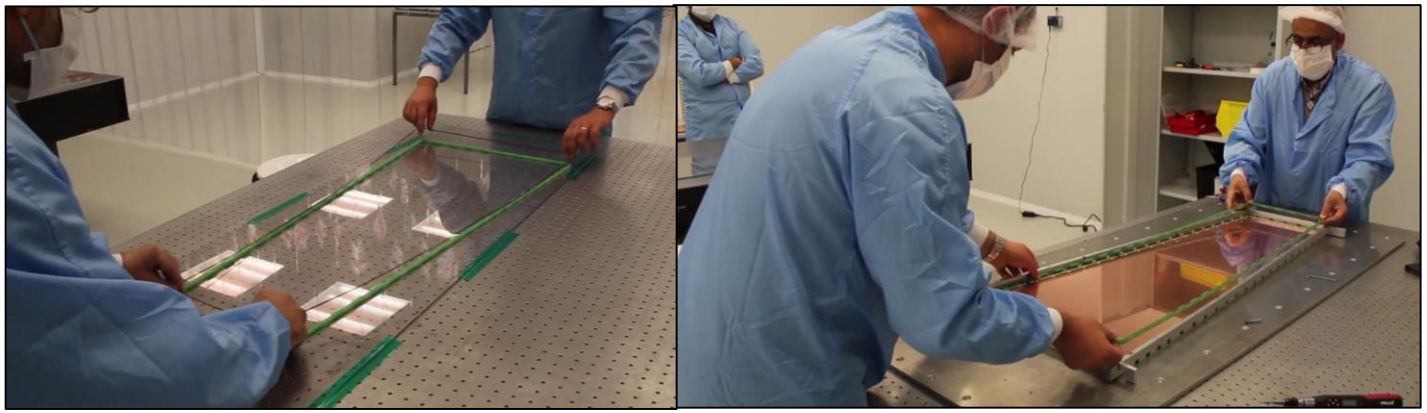


GE1/1 Detector Assembly

Step 13: the possible dust produced during the stretching step is removed with an anti-static roller (left) and the three GEM foils are tested once again at $550\ V$.



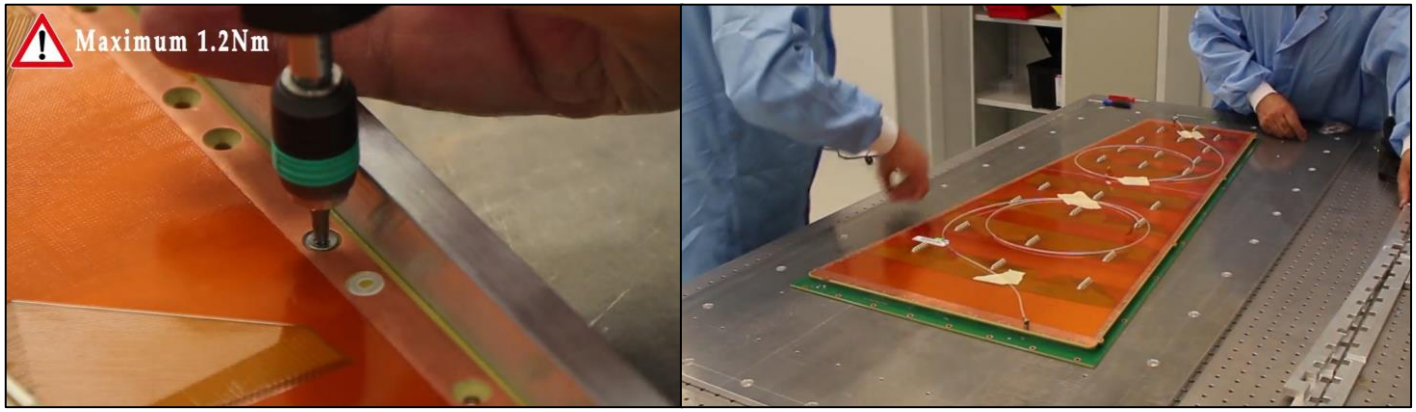
Step 14: The external frames is equipped with the O-rings (left) and it is placed around the GEM stack (right).



GE1/1 Detector Assembly

Step 15: after being cleaned (left), the readout board is placed on top of the external frame to close the chamber.

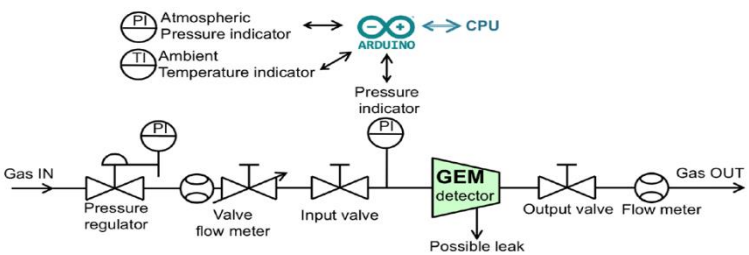
Step 16: finally, washers are inserted in the dedicated housings of the readout board before the last screws are used to attach all the elements together and close the gas volume (left). Picture of a last generation GE1/1 detector just after the assembly (right).



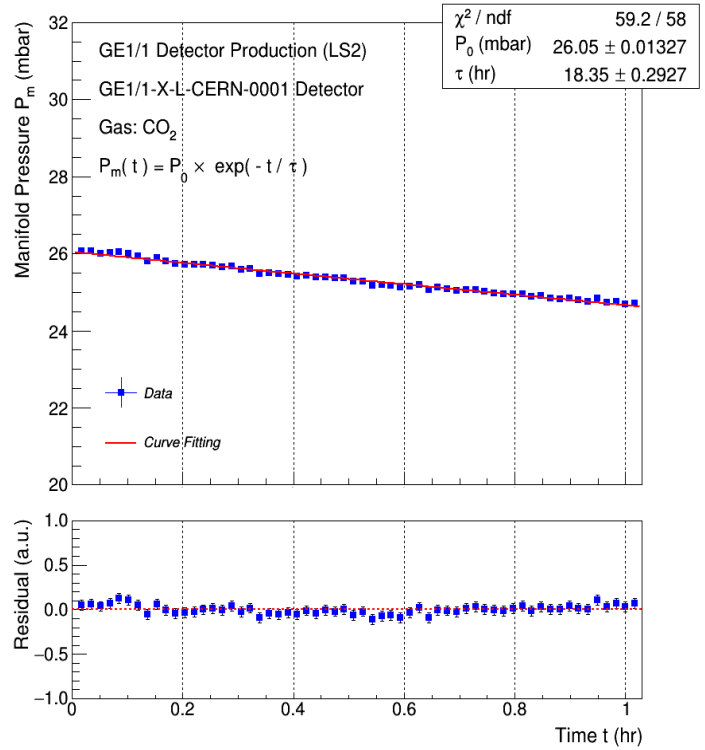
QC3 - Gas Leak Test

Identify the Gas Leak Rate of the detector by monitoring the drop of the internal over-pressure as a function of time and check the gas tightness

- **The detector is pressurized at 25 - $30\ mbar$ in pure CO_2**



- **The pressure drop is measured during one hour after closing the gas volume**
- **The experimental data are modeled by the function: $P_m = P_0 \times e^{-t/\tau}$ to extract the gas leak time constant τ**



Typical $Pressure$ vs $Time$ curve obtained during the QC3 gas leak test. The parameter τ obtained by fitting is the Gas Leak Time Constant.

QC3 - Gas Leak Test

→ ***Acceptance criteria***

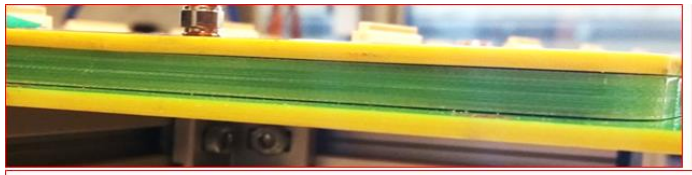
The detector under test is validated if the pressure drop in the detector + gas system does not exceed:

$$\Delta P \leq 7\ mbar/hr$$

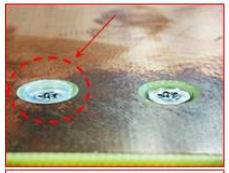
at initial over-pressure of $25\ mbar$, which corresponds to a gas leak time constant:

$$\tau \geq 3.04\ hr$$

Examples of damage assembly components identified as potential gas leak sources in the GE1/1 detectors



GAPS AT THE INTERFACE BETWEEN THE EXTERNAL FRAME AND PCBs

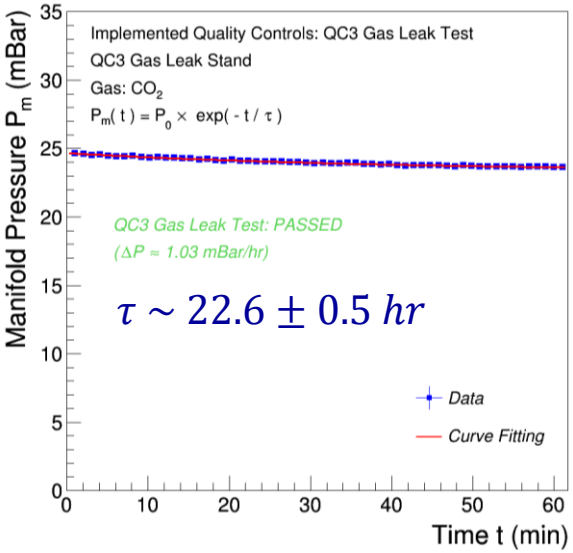


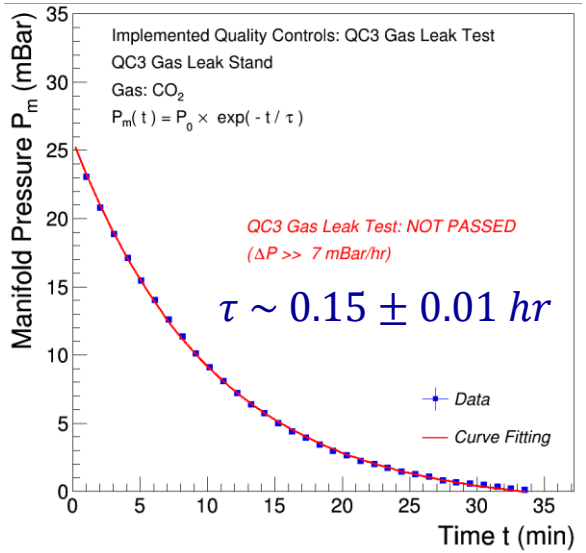
FAULTY WASHERS

BENDED PULLOUTS

CLOGGED GAS CONNECTORS

FAULTY SCREWS





GE1/1 QC Overview

CERN
- QC1 — Material Inspection
- QC2 — GEM-foils Test

Production sites
- Assembly
- QC2 — GEM-foils Test (fast)
- QC3 — Gas Leak Test
- QC4
- QC5

CERN
- QC6
- QC7
- QC8

QC3 - Gas Leak Test

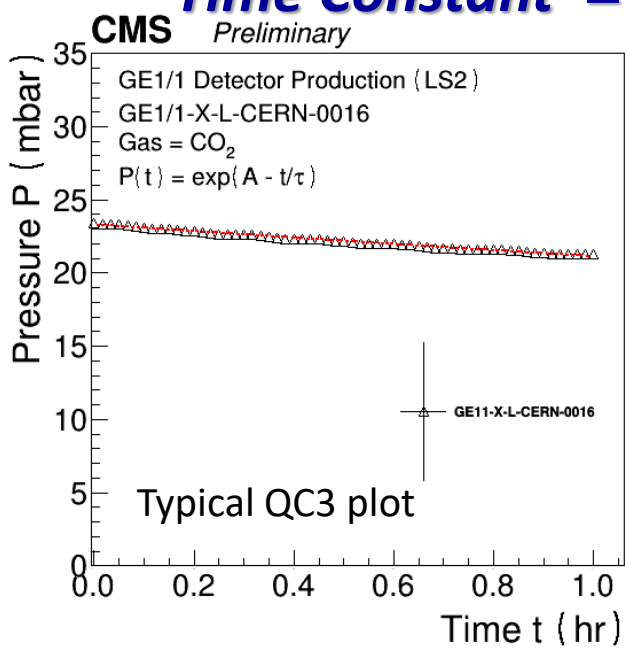
→ Pressurize the detectors at 25 $mbar$

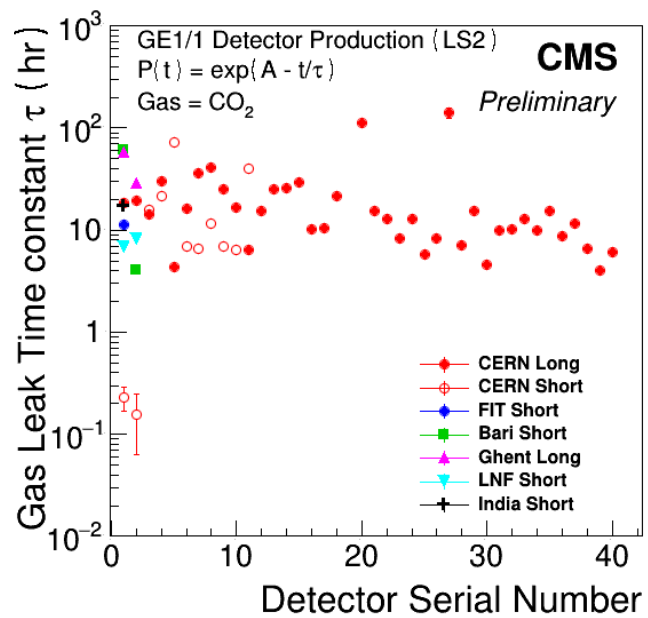
→ Measure the pressure drop during one hour after closing the gas volume

→ Fit the results to extract the time constant of the system

Statistics: $(mean \pm std.)$

Time Constant $= 16.2 \pm 11.8\ hr$





QC4 - High Voltage Test

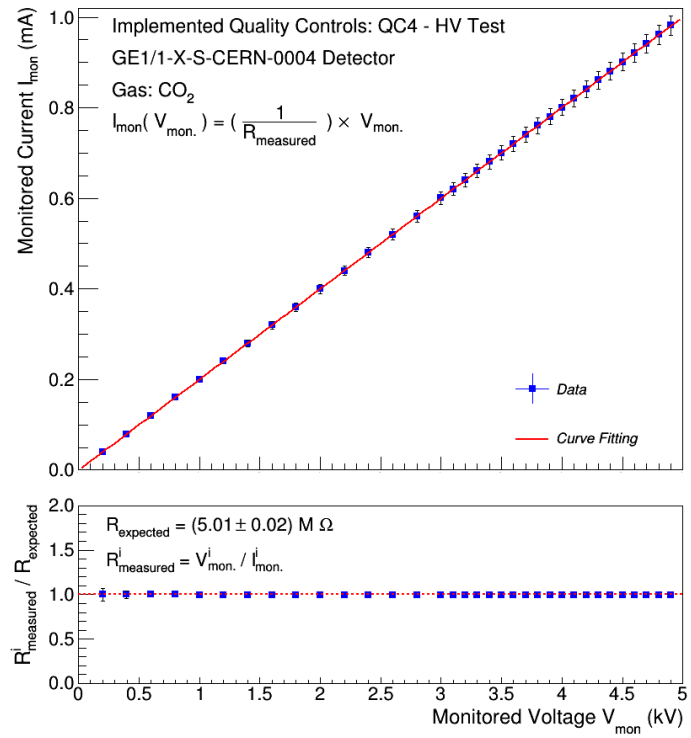
Determine Current vs Voltage curve of the detector and identify possible malfunctions, defects in the HV circuit

- The detector is ramped up to $3.0\ kV$ in step of $200\ V$ and up to $4.9\ kV$ in step of $100\ V$ in pure CO_2 using a resistive HV divider
- For each step, the current through the HV circuit of the detector is recorded
- The experimental data are modeled by the function: $I_{mon.} = \left(\frac{1}{R_{equiv.}}\right) \times V_{mon.}$

→ *Acceptance criteria*

$$\frac{|R_{measured} - R_{expected}|}{R_{expected}} \times 100\% \leq 2\%$$

(The percentage variation of resistance reflects the goodness of the linearity of the experimental Current-Voltage curve)

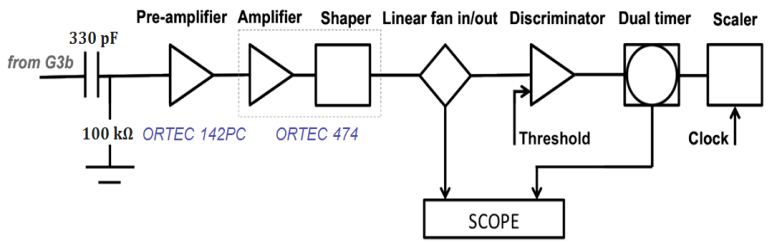


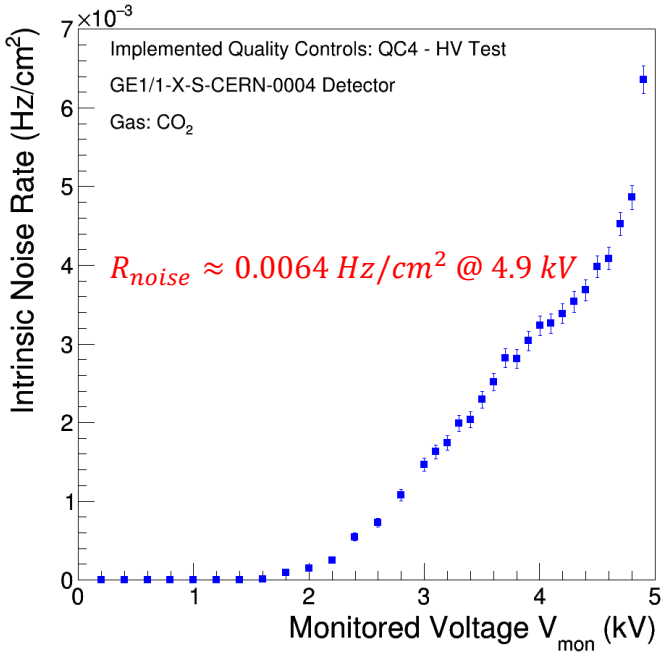
Typical I vs V curve obtained during the QC4 HV test. $I_{mon.}$ represents the current flowing through the HV divider to provide power to the detector electrodes.

QC4 - High Voltage Test

Determine Intrinsic Noise Rate (i.e. pulses not produced by ionizing particle) over the entire detector surface

- The detector is ramped up to $3.0\ kV$ in step of $200\ V$ and up to $4.9\ kV$ in step of $100\ V$ in pure CO_2 using a resistive HV divider
- For each step, the intrinsic noise rate R_{noise} of the detector is recorded from the bottom of the third GEM-foil





Typical *Intrinsic Noise Rate* as a function of the applied voltage obtained during the QC4 HV test: $R_{noise} \approx 6.4 \times 10^{-3}\ Hz/cm^2$ at $4.9\ kV$.

→ ***Acceptance criteria***

$$R_{noise} \leq 0.02\ Hz/cm^2\ (at\ 4.9\ kV)$$

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QC4 - High Voltage Test

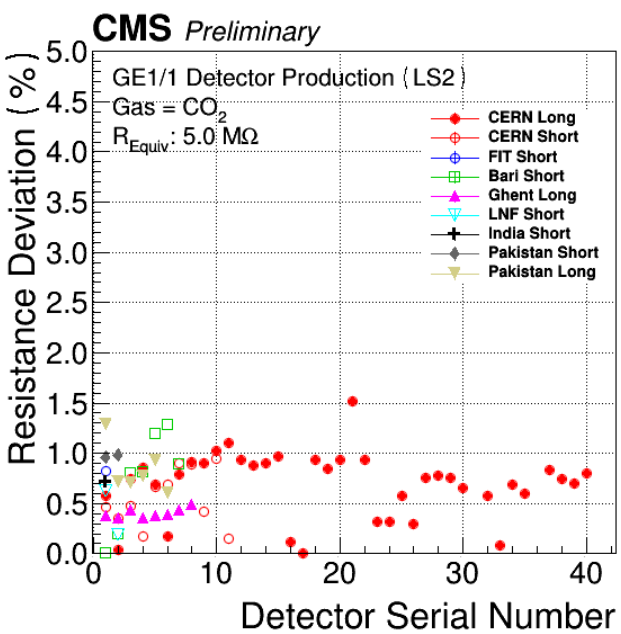
→ Measure the I vs. V characteristics

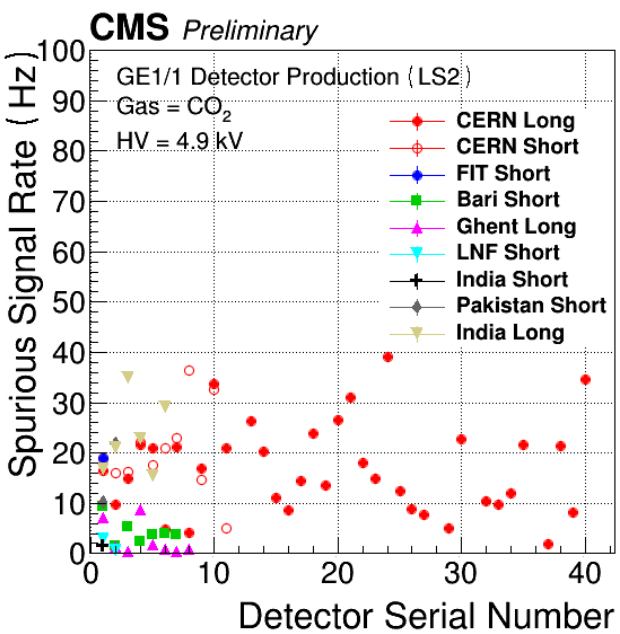
→ Measure the spurious signal rate over the entire detector surface

Statistics: (mean ± std.)

$R/R_{expected} = 0.65 \pm 0.23\ \%$

Spurious Signal Rate $= 19.5 \pm 11.2$ Hz





QC5 - Gas Gain Measurement

A 2-steps procedure to measure the Effective Gas Gain

STEP 1
Effective Gas Gain Measurement

→ *First operation in Ar/CO_2 $(70/30)$ at high particle flux*

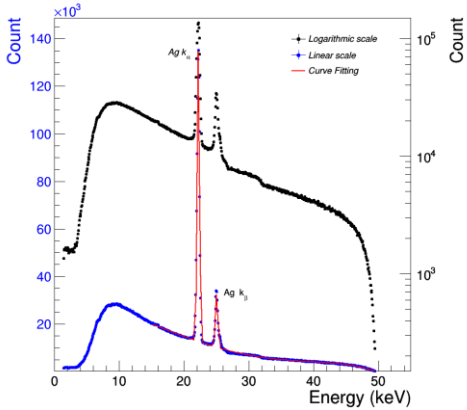
→ *Get the effective gas gain versus HV in one readout sector*

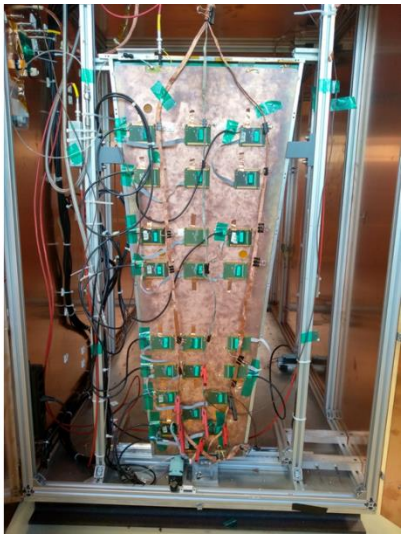
STEP 2
Response Uniformity Measurement

→ *Get "internal" gas gain variations map*

→ *Get average gas gain and std. deviation after compiling with eff. gas gain meas.*

Target	*Silver*
Voltage Tube	*10 kV min. / 50 kV max*
Current Tube	*5 μA min. / 200 μA max*
Output Cone Angle	*120°*





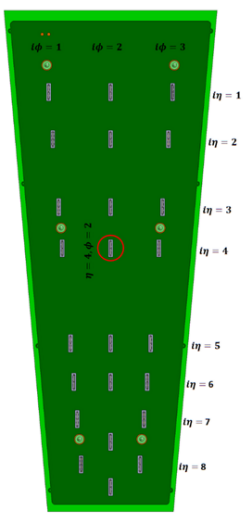
Both tests performed inside a copper box using an X-ray generator $(\sim 22\ keV\ X-rays)$

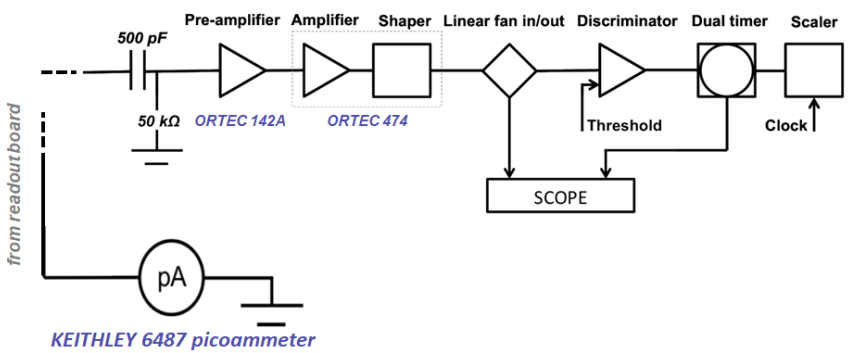
QC5 - Effective Gas Gain Meas.

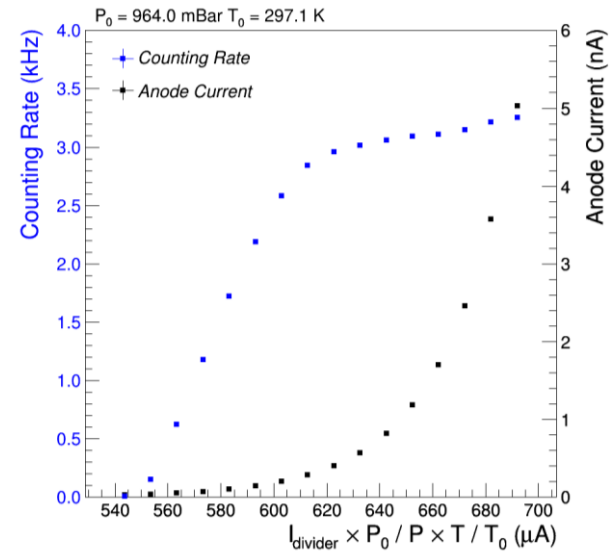
Measure the Effective Gas Gain as a function of the voltage applied on the resistive high voltage divider

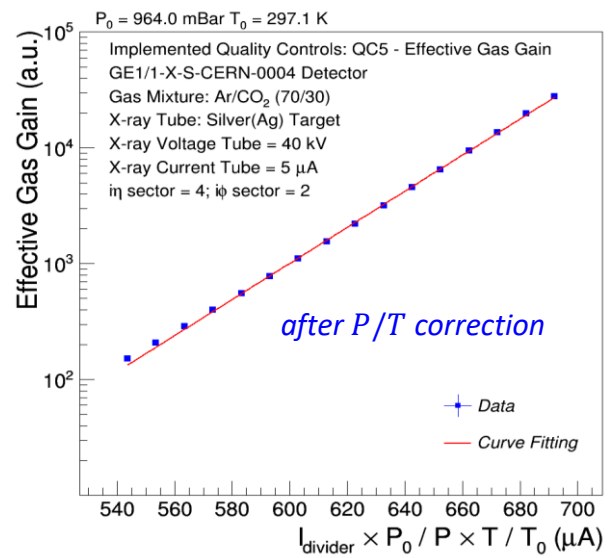
- Effective gas gain of GE1/1 detector is measured in a single readout sector $(\eta = 4, \phi = 2)$
- The Effective gas gain is defined as:

$$G_{eff} = \frac{I_{RO}}{(n_p \times q_e \times R_s)}$$





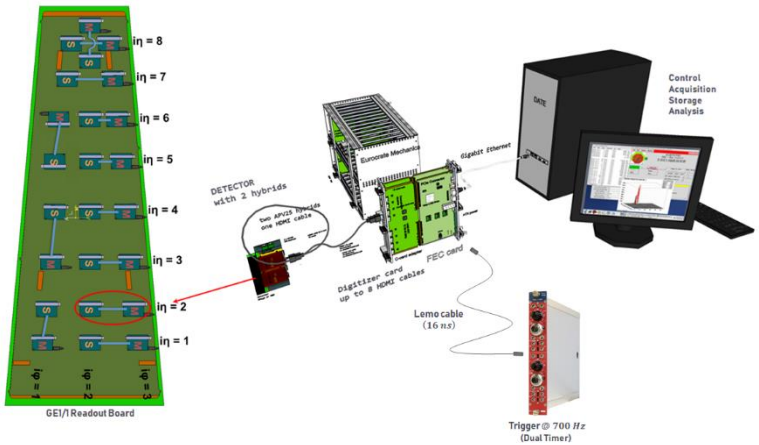


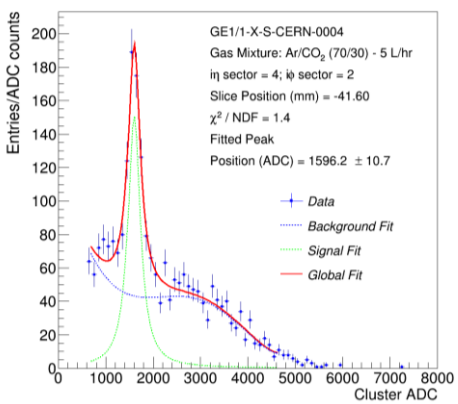


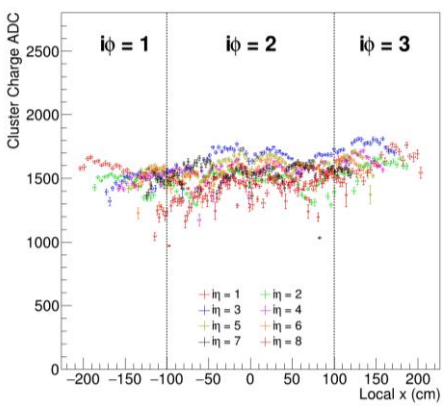
QC5 - Response Uniformity Meas.

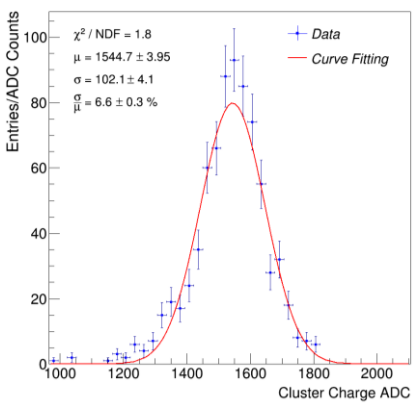
Measure the internal gas gain variations maps for each detector

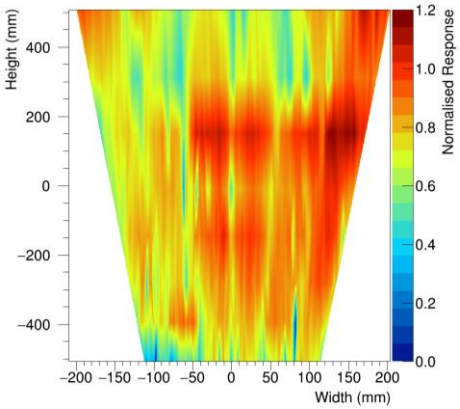
- Detector fully irradiated with X-rays
- RO based on analog electronics (APV25)
- Measure the copper fluorescence for every readout channels
- Compare ionization peak position (2D map)
- The uniformity map is used to calculate the average effective gas gain and the standard deviation for each detector











GE1/1 QC Overview

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- QC5 — Gas Gain Calibration

CERN
- QC6
- QC7
- QC8

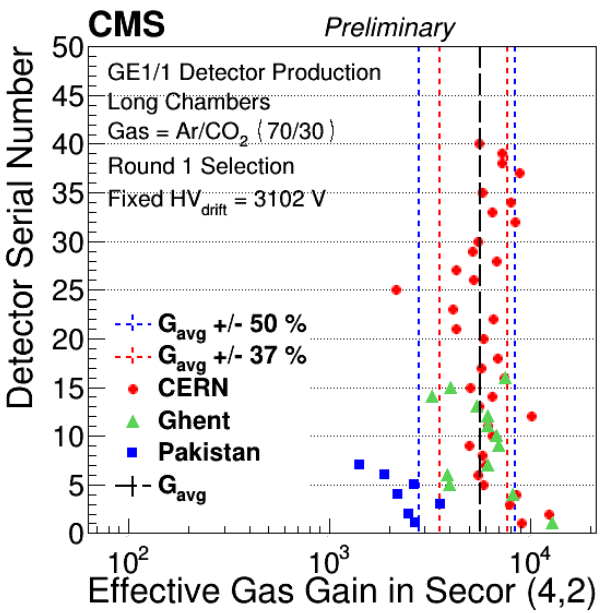
QC5 – Step 1
Effective Gain Test

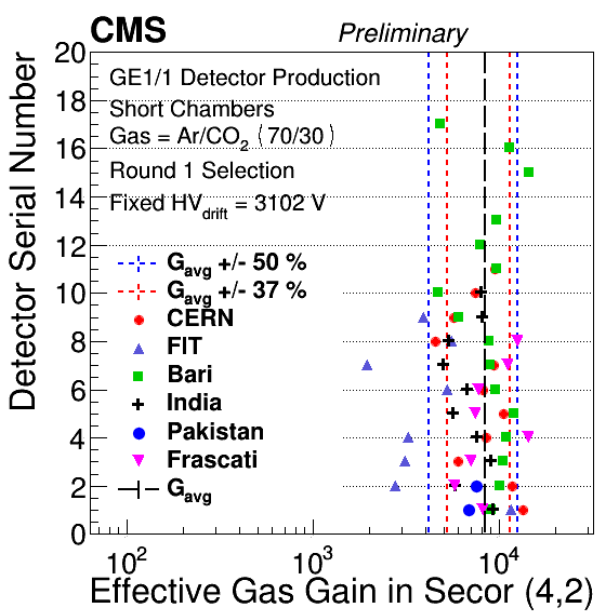
→ Measure the absolute gas gain in one readout sector

Statistics: (mean ± std.)

Long → $G_{eff} = 5786.9 \pm 2108.8\ (36.4\%)$

Short → $G_{eff} = 7980.0 \pm 2893.3\ (36.2\%)$





Gain Variation in 3-GEM Structures

Electron Multiplication

Variations of GEM thickness

- *Producers claims* $50 \pm 0.1\ \mu m$
- *i.e. Gain variations:*

$\pm 2.4\%$ *for single-GEM* $(\sigma_{total}/G_{total} = \sqrt{3} \times \sigma_{single}/G_{single})$

$\pm 4.2\%$ *for triple-GEM*

+ Second order variations

- **Thickness of GEM copper layers** $(\pm 0.5\%)$

Variations of GEM hole diameter

- *Outer diameter:* $70 \pm 5\ \mu m$
- *i.e. Gain variations:*

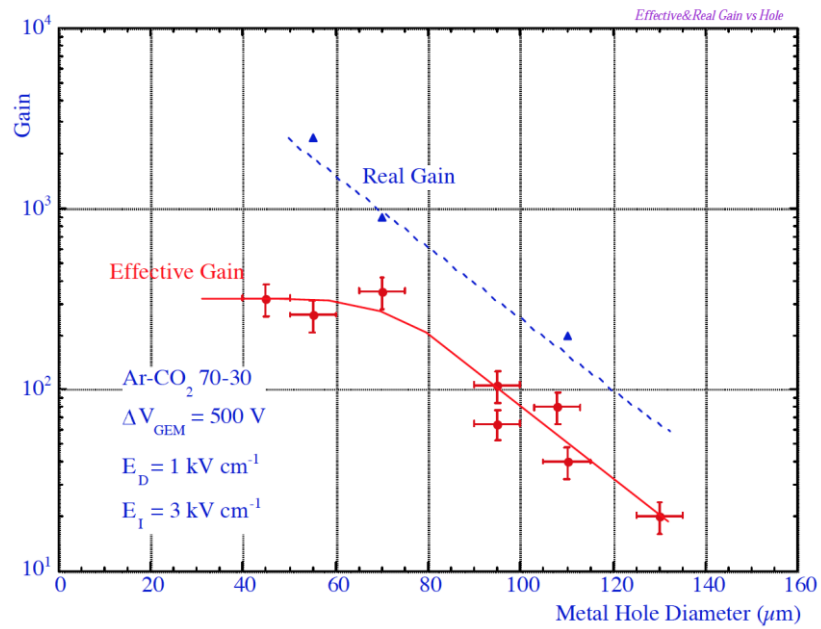
$\pm 15\%$ *for single-GEM*

$\pm 26\%$ *for triple-GEM*

+ Second order variations

- **Variations of the inner hole diameter**
- **Variations of the hole asymmetry**

S. Bachmann et al., ERN-EP/99-48, 1999

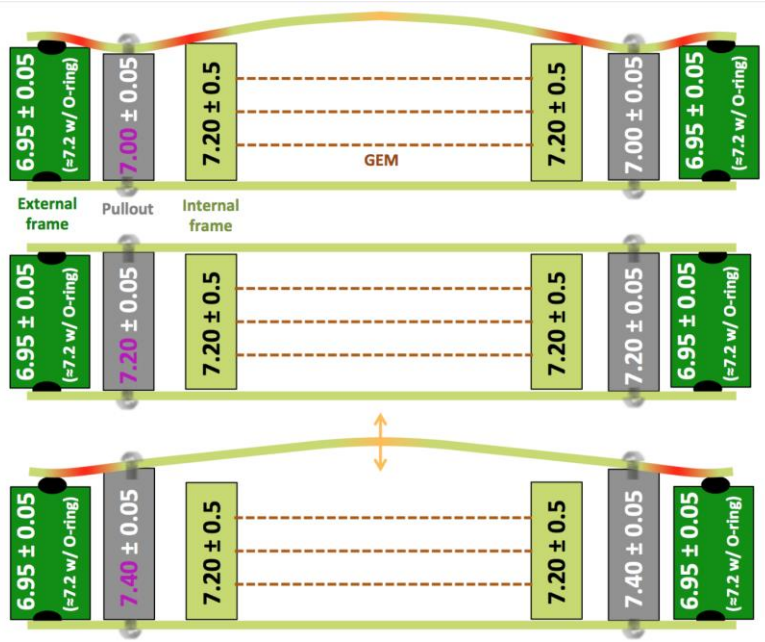


Gain Variation in 3-GEM Structures

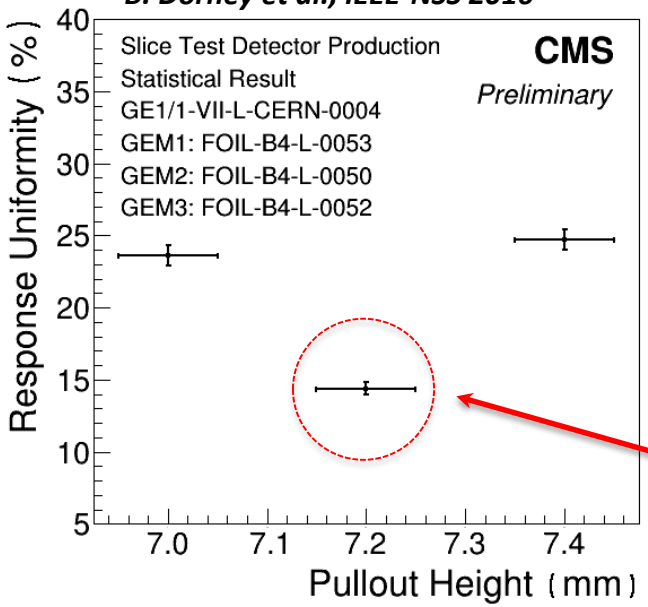
Bending of Drift and RO PCBs

GEM Transparency

- *Initial bending from fabrication process*
- *Induced by GEM stretching*
- *Induced by mechanical stress on O-ring and internal frames*
- *Bending due to gas over-pressure*
- *Slice test production team worked a lot on chamber design and assembly procedures to mitigate the bending effect*



B. Dorney et al., IEEE-NSS 2016



Best configuration

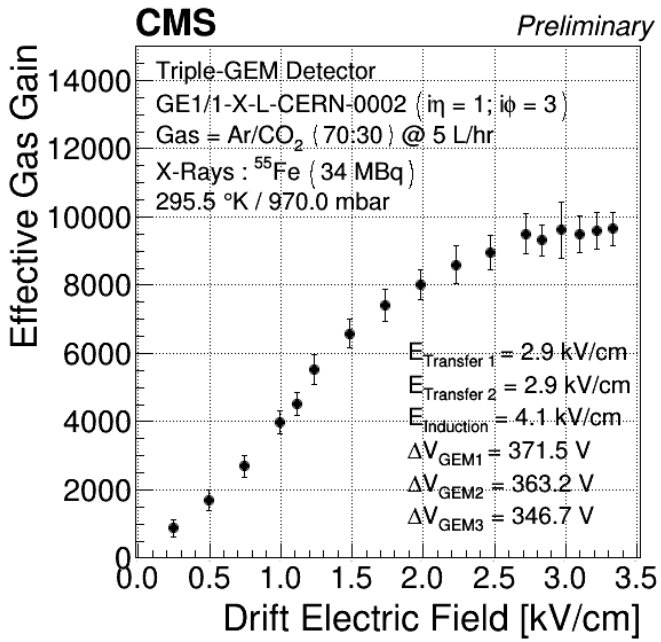
Gain Variation in 3-GEM Structures

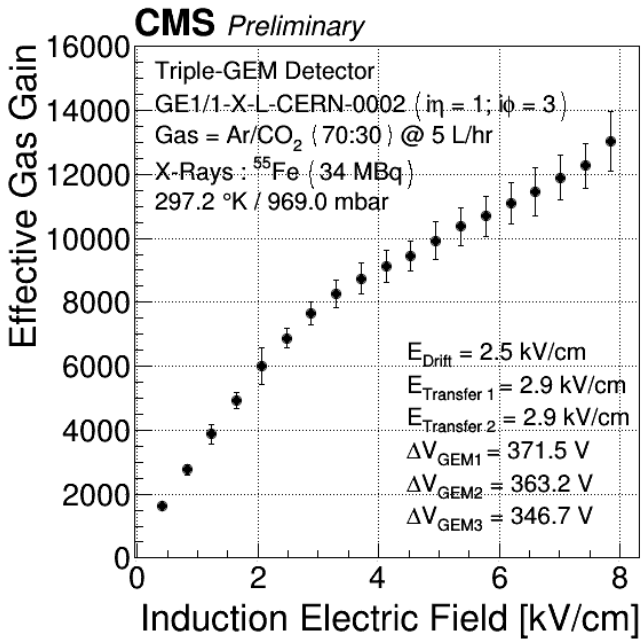
Bending of Drift and RO PCBs

GEM Transparency

- $Gap_{Drift} = 3 + 0.6\ mm$ / $Gap_{induction} = 1 + 0.4\ mm$
- $i.e.\ Electric\ fields\ +\ 20\%\ (drift)\ and\ +\ 40\%\ (RO)$
- $i.e.\ Gain\ variations:\ +\ 7.5\%\ (drift)\ and\ +\ 25\%\ (RO)$

(May also change by few % depending on the internal pressure)





+ Second order variations

- **Thickness of the internal frame PU coating ($\pm\ 0.5\ \%$)**
- **Height of the pull-outs ($\pm\ 0.7\ \%$)**

Gain Variation in 3-GEM Structures

Gas temperature and pressure

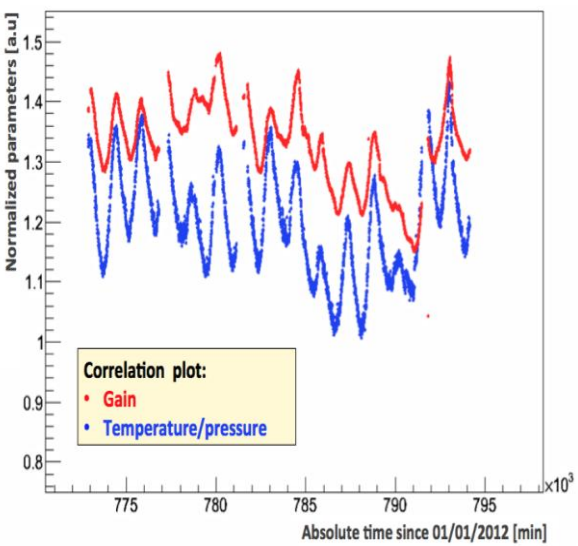
Environmental Parameters

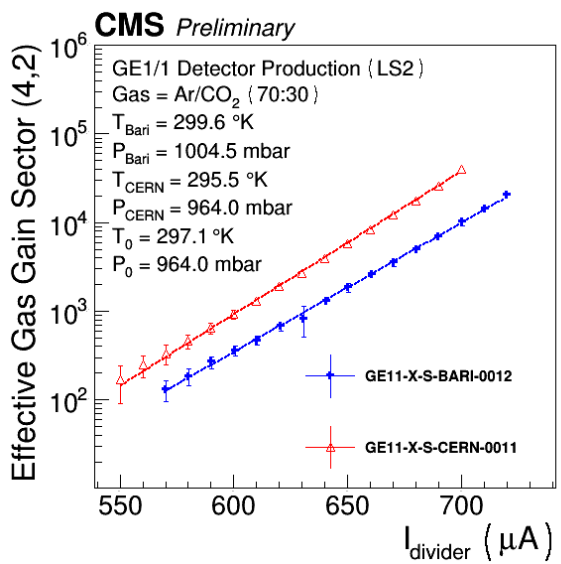
- ***Known effect in gaseous detectors***

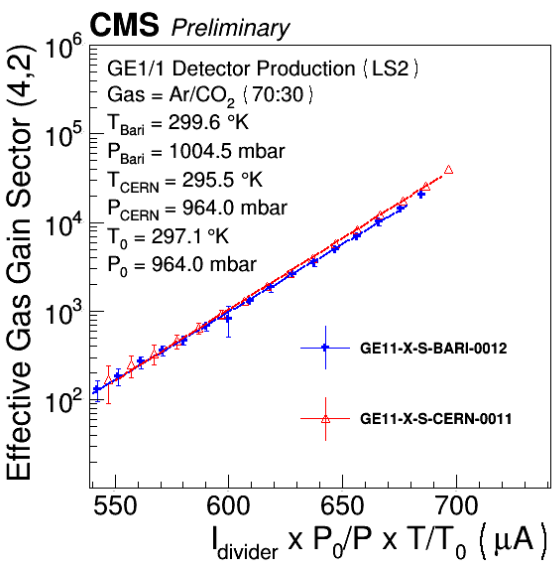
$$Gain \sim Exp(\alpha_{Townsend}) \sim Exp\left({}^{E}/_{\rho_{gas}}\right) \sim Exp\left(E \times {}^{T}/_{P}\right)$$

- ***Corrections on Detector HV***

$$Gain_{measured} \sim Exp(HV) \rightarrow Exp\left(HV \times {}^{T}/_{P} \times {}^{P_0}/_{T_0}\right)$$







+ Second order variations

- **Variations of the internal pressure (i.e. gas flow rate)**
- **Variations of the gas composition ("second order" because under control in GEM QC setups)**

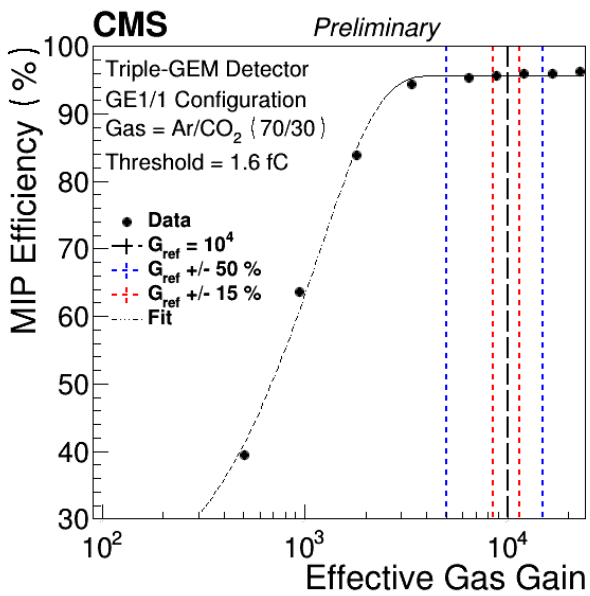
Gain Variation in 3-GEM Structures

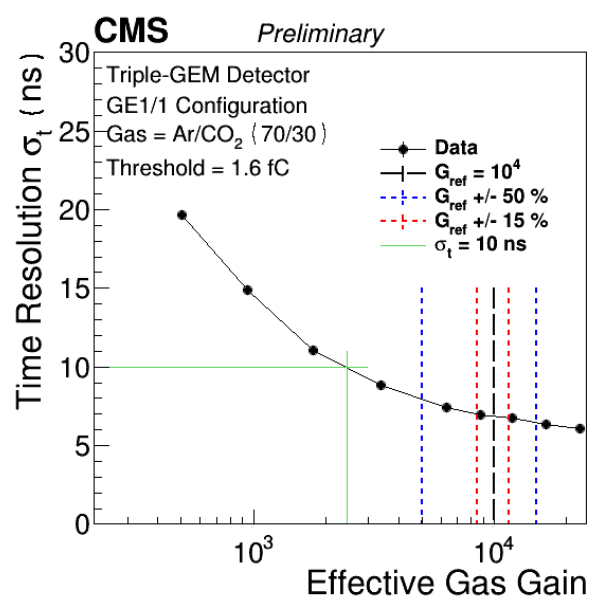
Total gain variations

$$\sigma_{total} = \sqrt{\sigma_{GEM\ thickness}^2 + \sigma_{hole\ diameter}^2 + \sigma_{bending\ drift}^2 + \sigma_{bending\ RO}^2}$$

$\sigma_{total} = 37.1\ \%$ *(relative error – first order approximation)*

From B2B test beam (data provided by I. Vai and M. Ressegotti - Jan 2017)





Binary electronics (VFAT3) == large operating range at best performance

Individual chamber average gain can be within 50% of the other chamber without affecting the global performances

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- QC5 — Gas Gain Calibration

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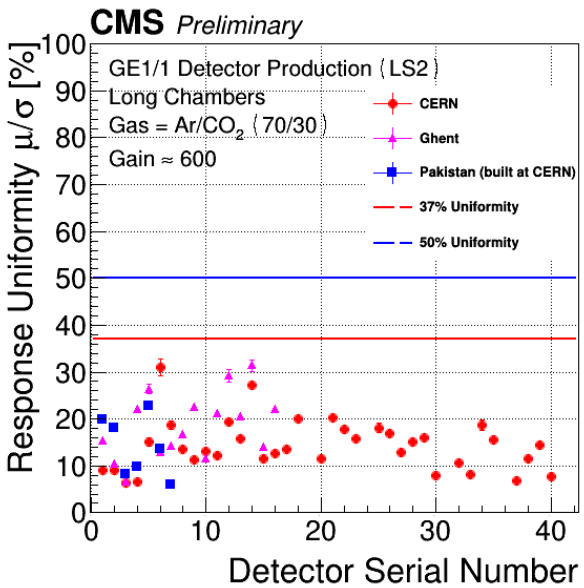
QC5 – Step 2
Response Uniformity Test

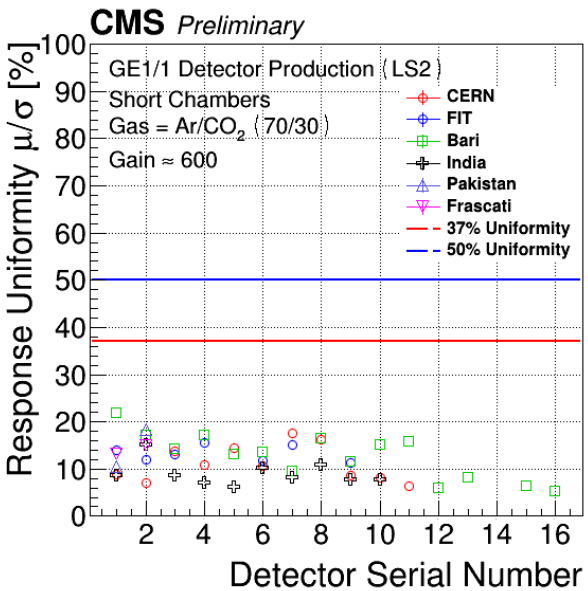
→ Detector fully irradiated with X-rays
→ RO based on analog electronics (APV25)
→ Measure the internal gain variations map

Statistics: (mean ± std.)

Long → $\sigma/\mu = 15.35 \pm 6.17\,\%$

Short → $\sigma/\mu = 11.77 \pm 3.89\,\%$

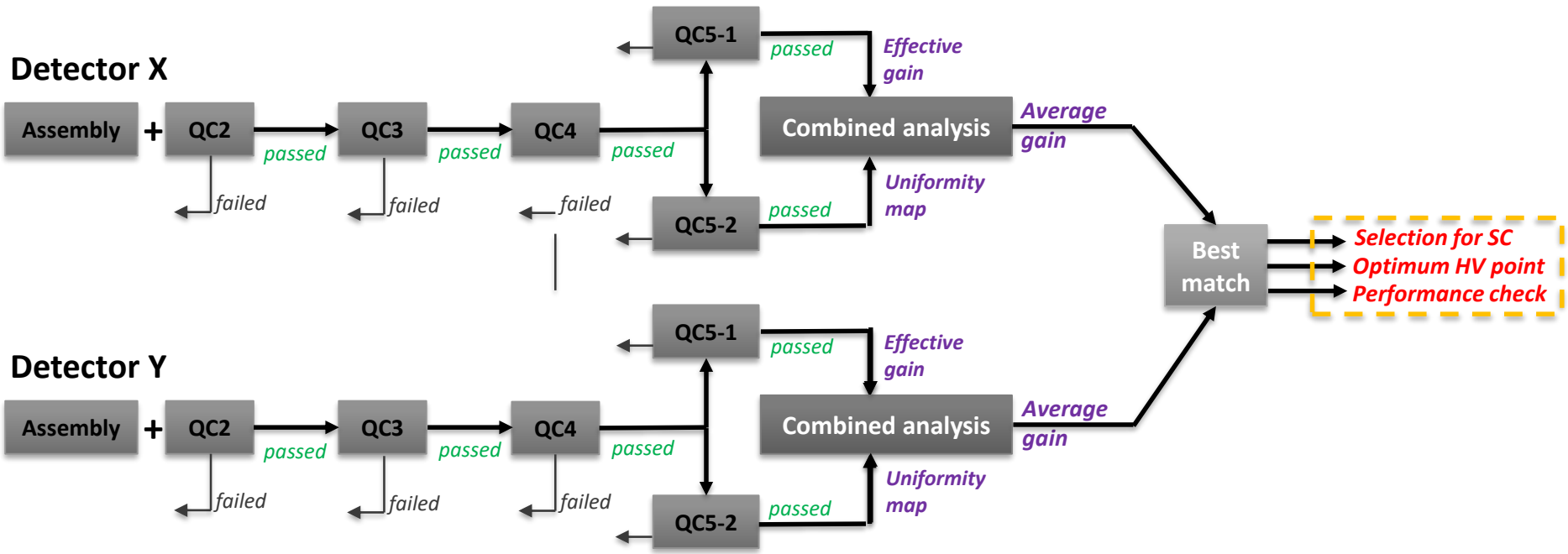




GE1/1 QC Overview

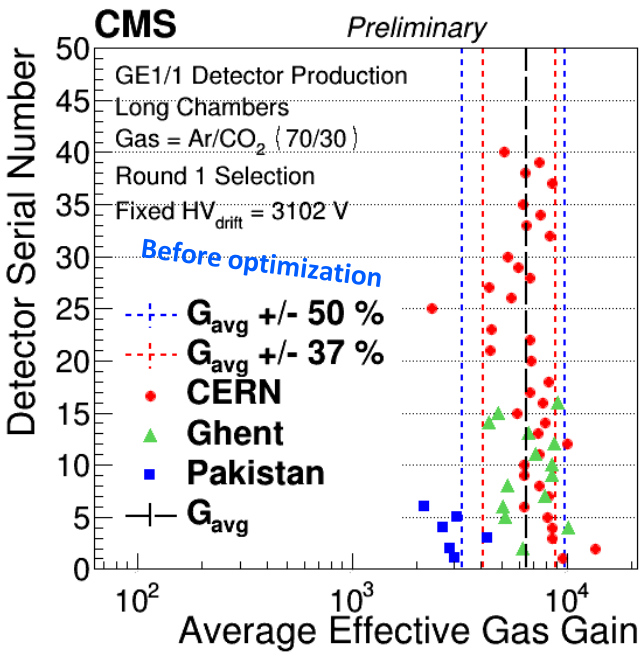
Chamber selection for SC assembly

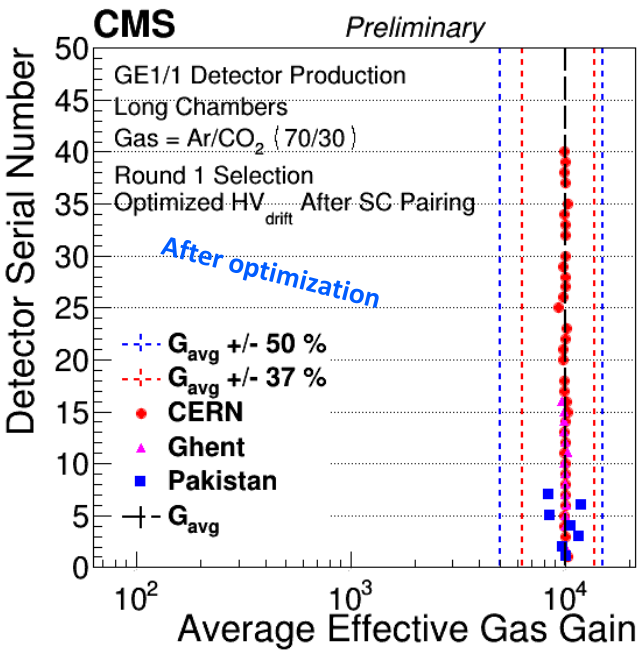
- **Define the detector pool (not already paired, QCs passed and validated, physically present at CERN)**
- **Compile the QC data to select the chambers with the most <u>similar characteristics</u>**



GE1/1 QC Overview

Chamber selection (Long) for SC assembly





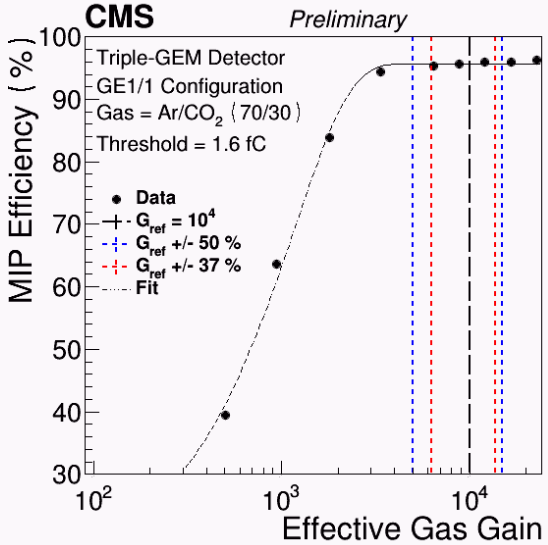
Statistics before/after HV optimization:

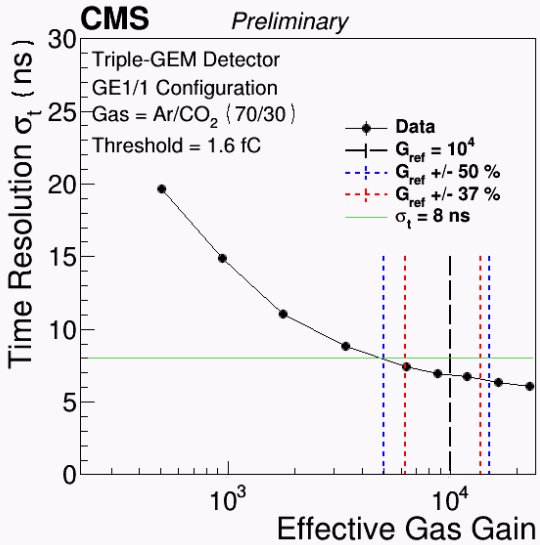
Before $\rightarrow G_{eff} = 6492.1 \pm 2246.0\ (34.6\%)$

After $\rightarrow G_{eff} = 10011.2 \pm 376.2\ (4.8\%)$

Round 1 : 56 selected chambers (28 SCL)

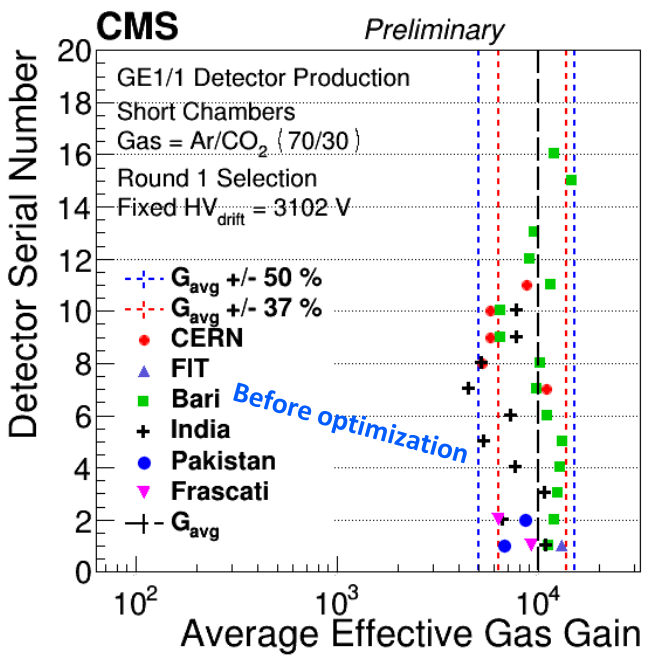
GE1/1 performances

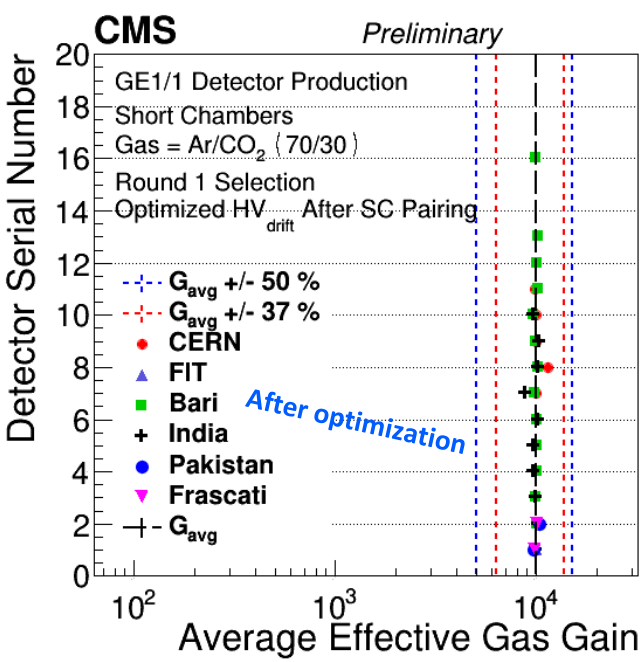




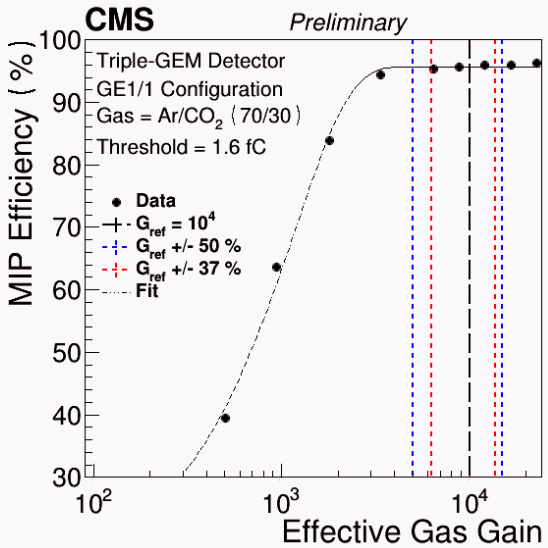
GE1/1 QC Overview

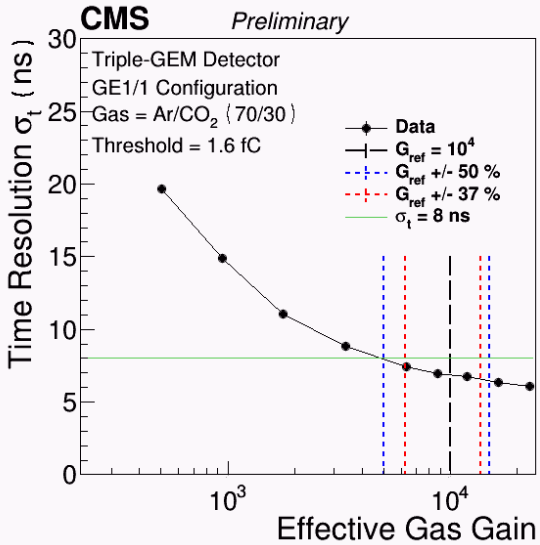
Chamber selection (Short) for SC assembly





GE1/1 performances





Statistics before/after HV optimization:

Before $\rightarrow G_{eff} = 8705.0 \pm 3246.2\ (37.3\%)$

After $\rightarrow G_{eff} = 10006.6 \pm 364.9\ (3.6\%)$

Round 1 : 34 selected chambers (17 SCL)

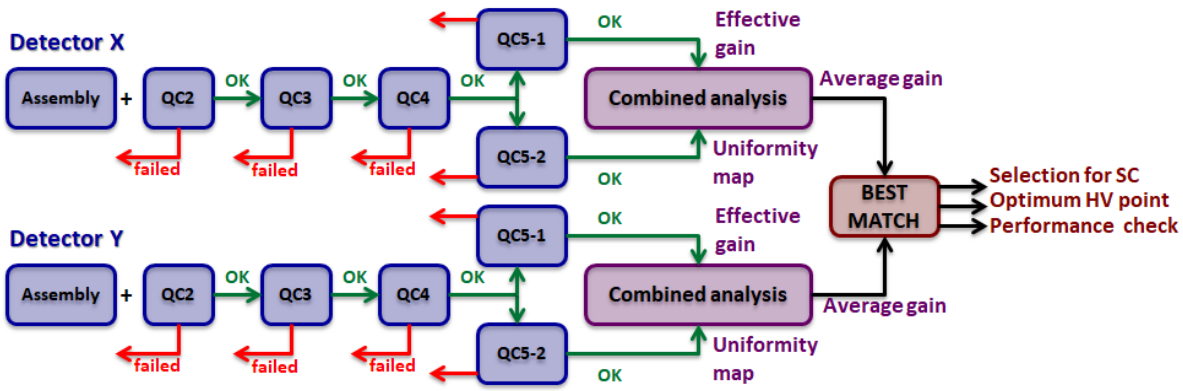
GE1/1 Super Chamber Matching

CERN
- **QC1** — Material Inspection
- **QC2** — GEM-foils Test

Production sites
- **Assembly**
- **QC2** — GEM-foils Test (fast)
- **QC3** — Gas Leak Test
- **QC4** — HV Test
- **QC5** — Gas Gain Calibration

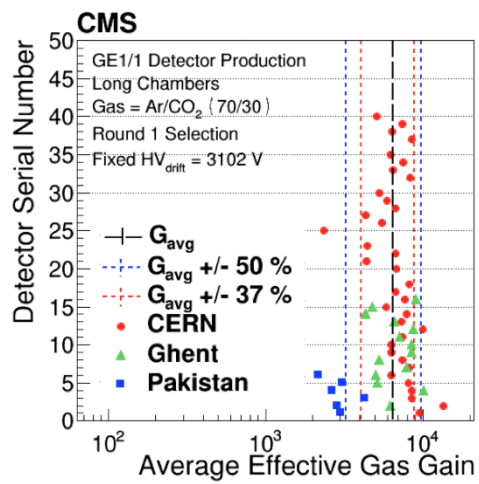
CERN
- **QC6** — HV Stability Test
- **QC7** — Electronics Connectivity Test
- **QC8** — Cosmic Test

Compile the QC data to select the chambers with the most similar characteristics



GE1/1 Long Chamber

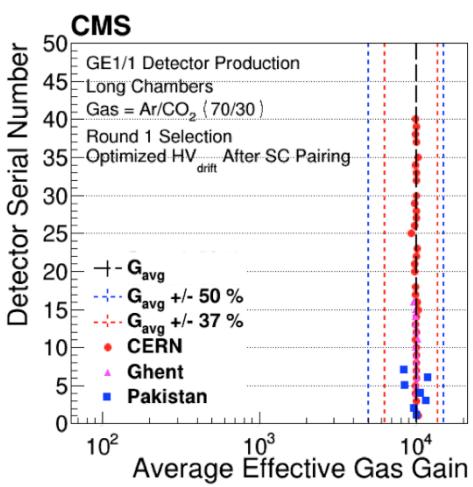
Before Optimization



$\langle G \rangle_{eff} \sim 5786.9 \pm 2108.8$

$\sigma / \langle G \rangle_{eff} \sim 36.4\%$

After Optimization



$\langle G \rangle_{eff} \sim 10011.2 \pm 376.2$

$\sigma / \langle G \rangle_{eff} \sim 4.8\%$

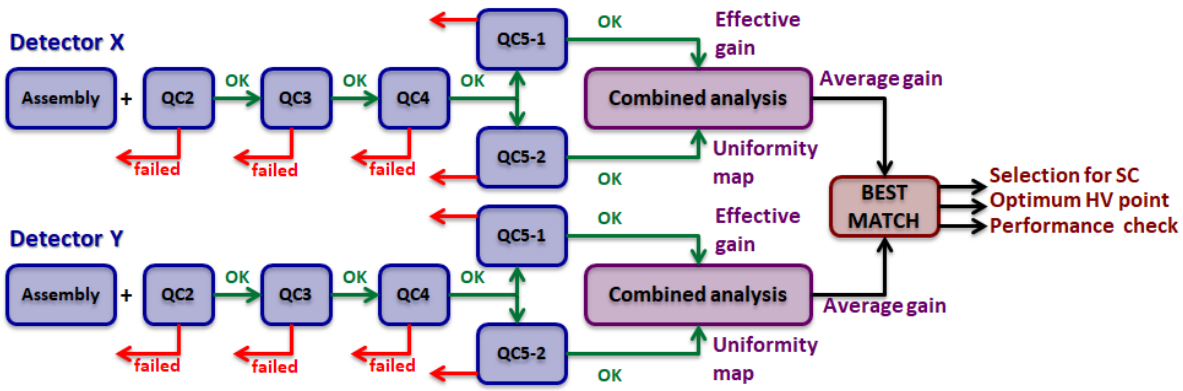
GE1/1 Super Chamber Matching

CERN
- QC1 — Material Inspection
- QC2 — GEM-foils Test

Production sites
- Assembly
- QC2 — GEM-foils Test (fast)
- QC3 — Gas Leak Test
- QC4 — HV Test
- QC5 — Gas Gain Calibration

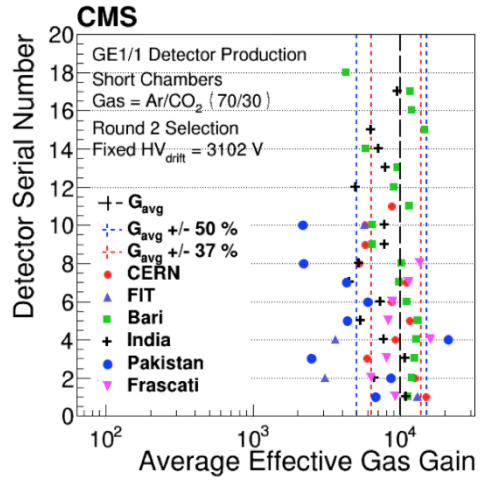
CERN
- QC6 — HV Stability Test
- QC7 — Electronics Connectivity Test
- QC8 — Cosmic Test

Compile the QC data to select the chambers with the most similar characteristics



GE1/1 Short Chamber

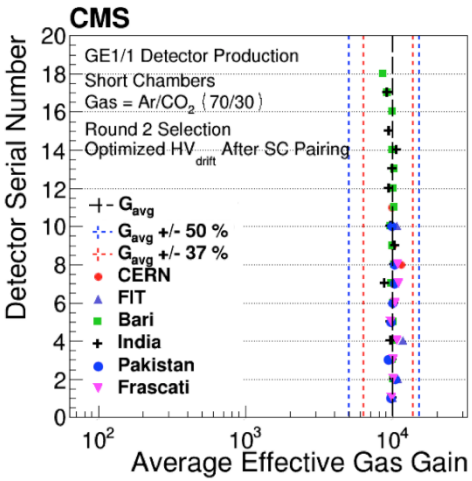
Before Optimization



$\langle G \rangle_{eff} \sim 5786.9 \pm 2108.8$

$\sigma/\langle G \rangle_{eff} \sim 36.4\%$

After Optimization



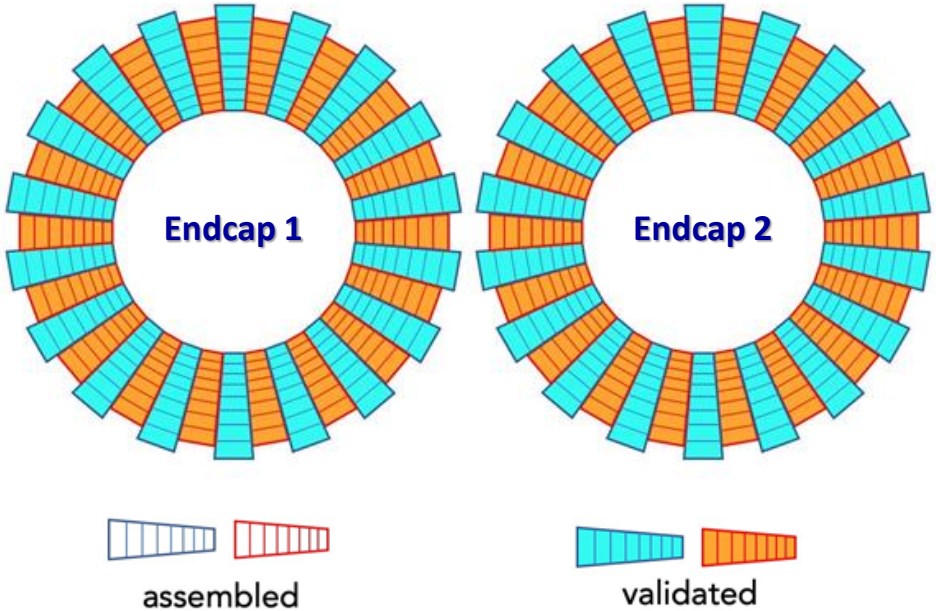
$\langle G \rangle_{eff} \sim 10011.2 \pm 376.2$

$\sigma/\langle G \rangle_{eff} \sim 4.8\%$

GE1/1 Detector Production Status

On-time production

- 160 detectors already assembled
- 148 detectors fully validated up to QC5
- 7 validation on-going
- 5 QC on-going
- 3 chamber rejected (need intervention)



- Successful production of 160 detectors in 10 Production Sites
- All tested chambers within specifications

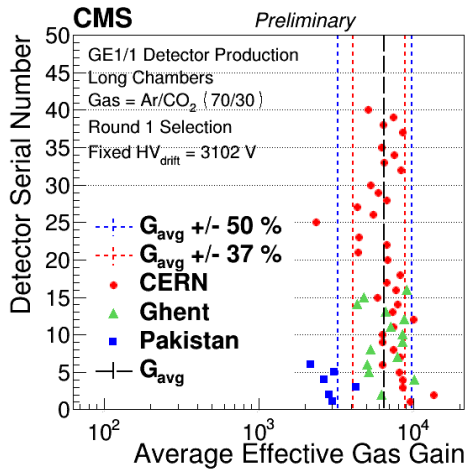
Full production of 144 detectors (2 full endcaps) completed in December 2018

GE1/1 Super Chamber Matching

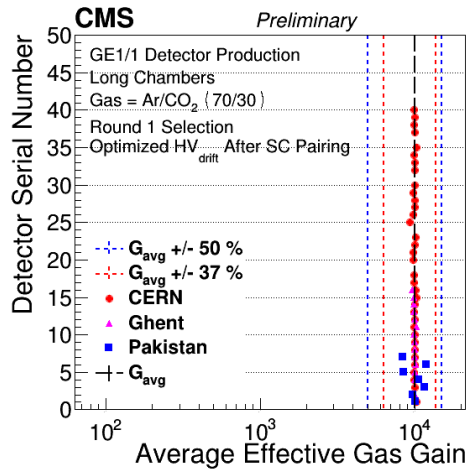
Before Optimization

After Optimization

GE1/1 Long Chamber

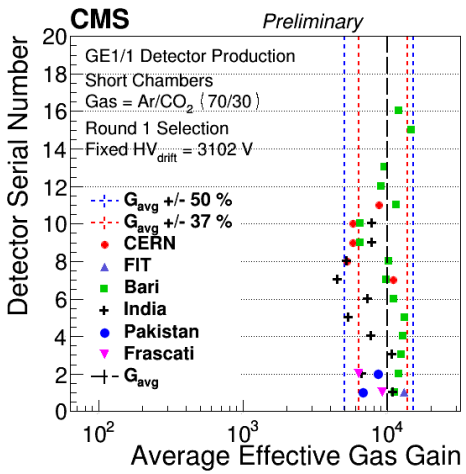


$\langle G \rangle_{eff} \sim 5786.9 \pm 2108.8 \rightarrow \sigma/\langle G \rangle_{eff} \sim 36.4\%$

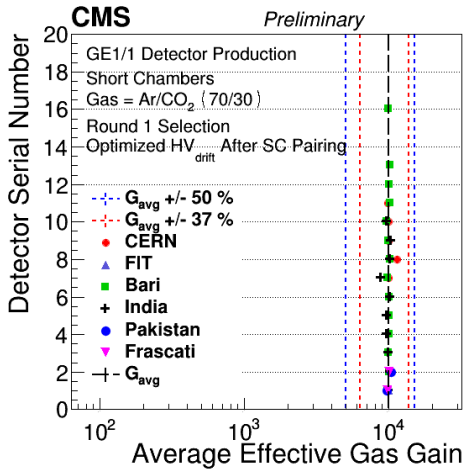


$\langle G \rangle_{eff} \sim 10011.2 \pm 376.2 \rightarrow \sigma/\langle G \rangle_{eff} \sim 4.8\%$

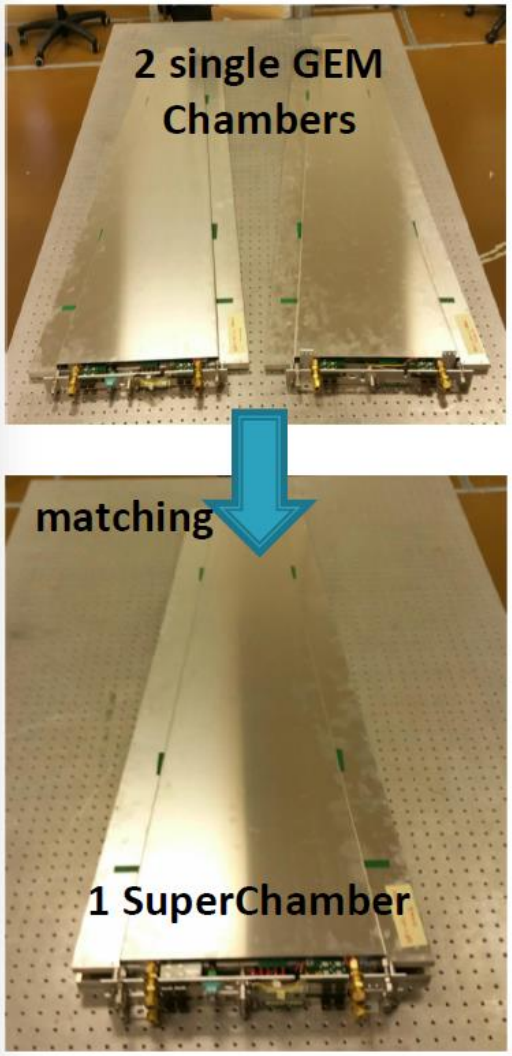
GE1/1 Short Chamber



$\langle G \rangle_{eff} \sim 7980.0 \pm 2893.0 \rightarrow \sigma/\langle G \rangle_{eff} \sim 36.2\%$



$\langle G \rangle_{eff} \sim 10006.0 \pm 364.9 \rightarrow \sigma/\langle G \rangle_{eff} \sim 3.6\%$



Longevity Studies

Aging of Gaseous Detectors:

Radiation hardness

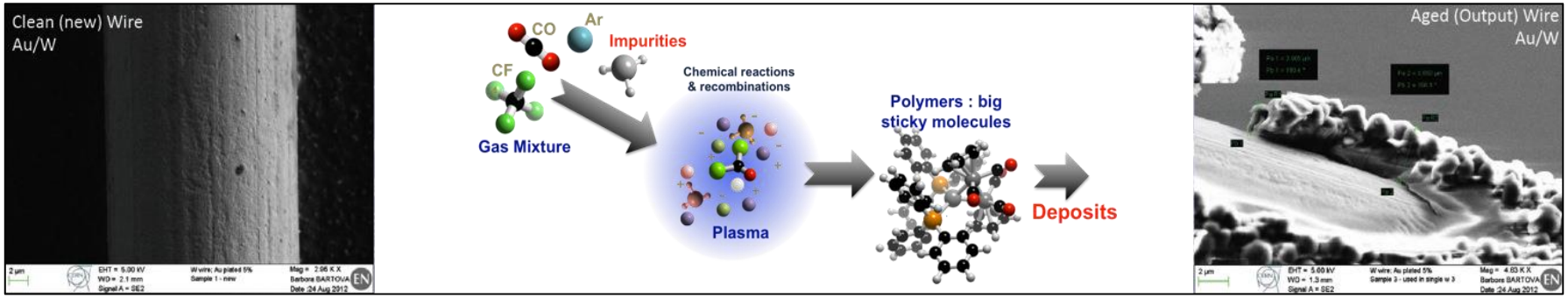
- modifications of the physical, chemical and electrical properties of the detector materials

Long-term damages/variation of the structure

- modifications of the stretching strength with time inducing non-uniformity
- discharges-induced damages

Classical Aging

- production of polymers in the plasmas during the amplification (gain losses, non-uniformity, self-sustained discharges, increase of the dark current, degradation of the space/time/energy resolutions, lower rate capability, etc.)



Complex phenomenon

- Many input parameters (technology, geometry, mode of operation, charge, gas mixture, etc.)
- Several possible processes (plasma conditions)
- Various results (type of polymers, physical state, electrical properties, etc.)

Aging of Gaseous Detectors:

How to measure longevity of gaseous detectors?

→ **Measure various properties of the detector at different accumulated doses**

→ **Monitor gas gain fluctuations during the irradiation**

Requirements:

→ **Accelerate aging with strong radiation**

→ **High acceleration factors reduce polymer production rate (so aging effects)**

→ **Recommendations:**

- $Acceleration\ factor \ll 100 \times real\ operation\ (realistic\ conditions)$
- $Accumulate\ expected\ dose\ with\ safety\ factor$

→ **Monitor the environmental parameters:**

- $Temperature$
- $Pressure$
- $Gas\ purity\ /\ gas\ flow\ rate$

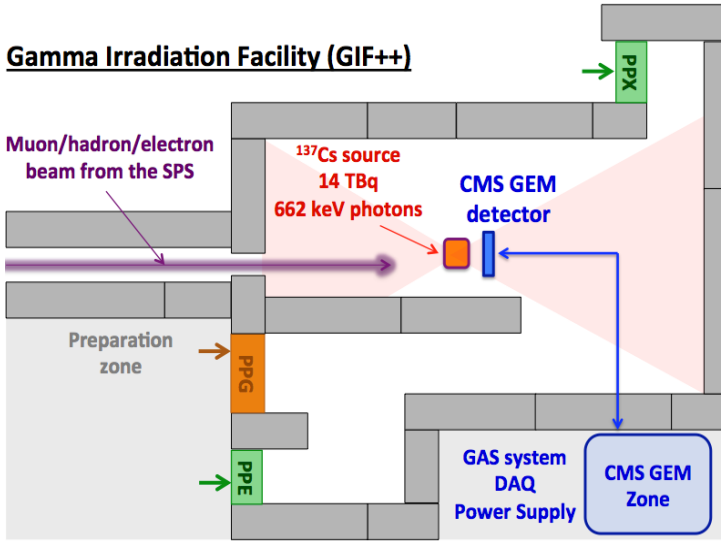
→ **High Purity Systems:**

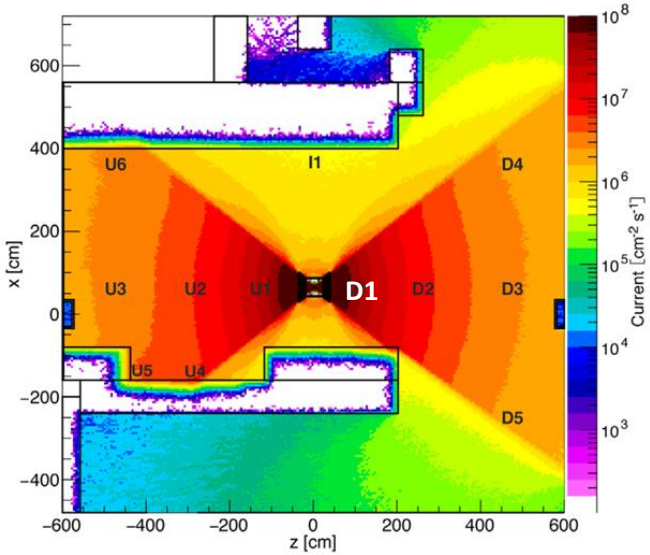
- $Aging\ mostly\ enhanced\ by\ pollution\ in\ the\ gas\ mixture$

Gamma Irradiation Facility (GIF++)

How to reproduce the aging effects?

- The facility consists of an intense $14\ TBq$ (in 2015) ^{137}Cs source emitting $662\ keV$ photons and lower energetic scattered photons
- The GIF++ photons have an energy fairly representative of the energy of LHC/HL-LHC photons seen by the muon detectors





The GE1/1 detector under test is placed at $\sim 1m$ from the source point (D_1 position):

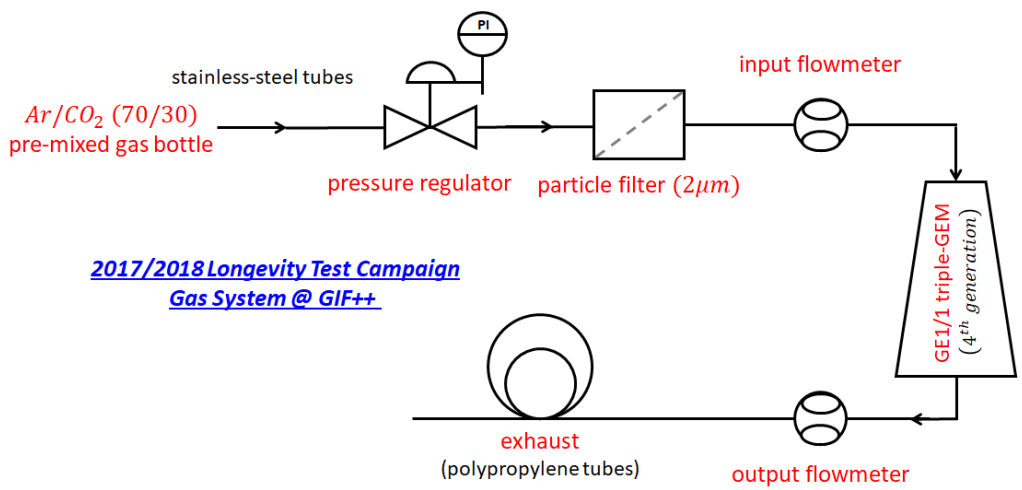
- upper half of the detector is operating under a particle flux just below $10^8\ Hz/cm^2$
- lower half receive a flux lower by four orders of magnitude ($10^4\ Hz/cm^2$)

Experimental Setup at GIF++ facility

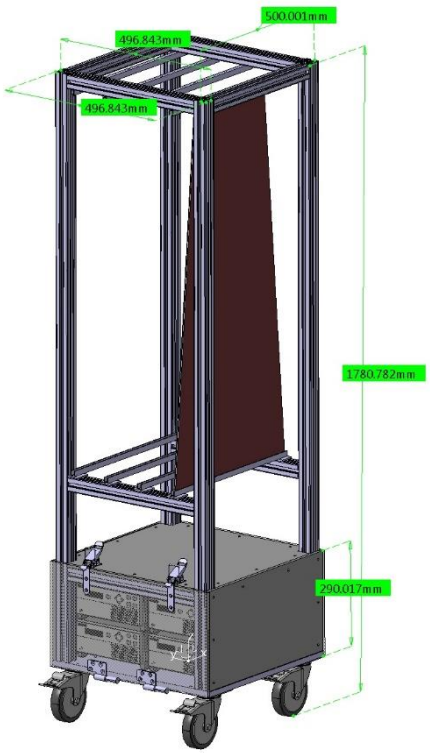
Detector Under Test and Conditions of Operation:

- **CMS GE1/1 triple-GEM detector 4th generation**
  (representative of the detectors that will be installed in the CMS Muon end-caps)
- **Effective Gas Gain: 2×10^4**
- **Gas Mixture: Ar/CO_2 (70/30) - Gas Flow Rate: $5.0\ L/h$**

Irradiated chamber @ GIF++ during the aging studies 2015/2016: $\sim 55\ mC/cm^2$ collected in about 6 months of continuous tests.

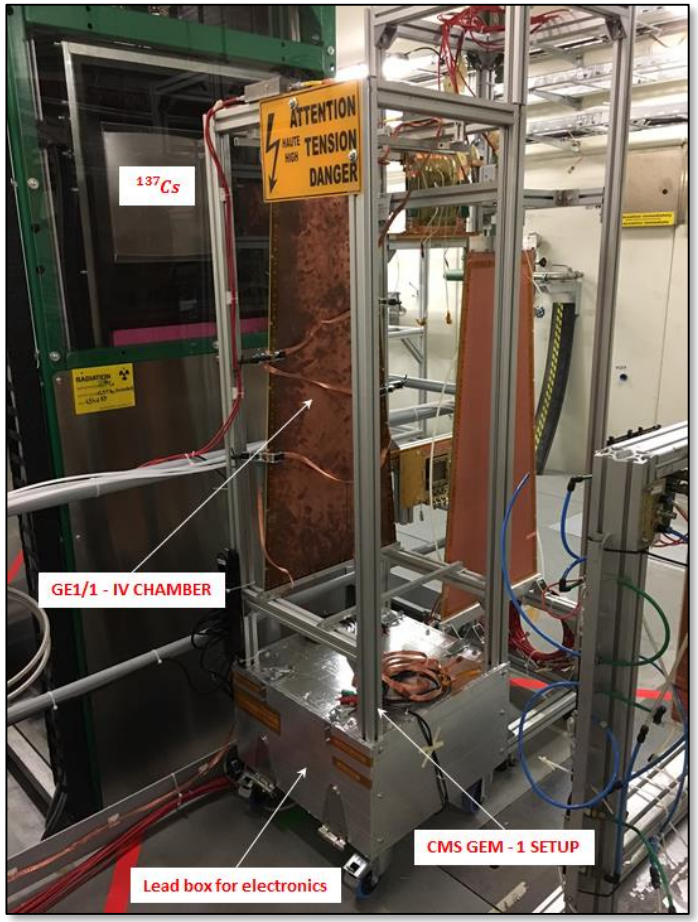


2017/2018 Longevity Test Campaign
Gas System @ GIF++



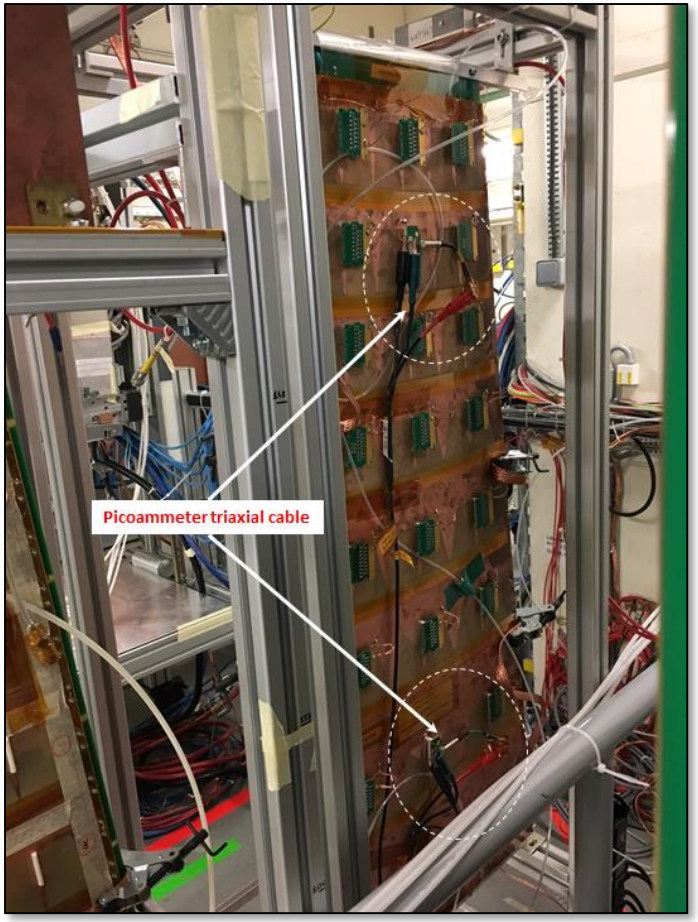
- **New setup designed in aluminium bosh-profiles and assembled to host the triple-GEM chambers**
- **The DAQ electronics placed below the detector structure and protected inside the lead shielding box**

Installation inside the GIF++ facility



CMS-GEM1 setup inside the GIF++ bunker (back view)

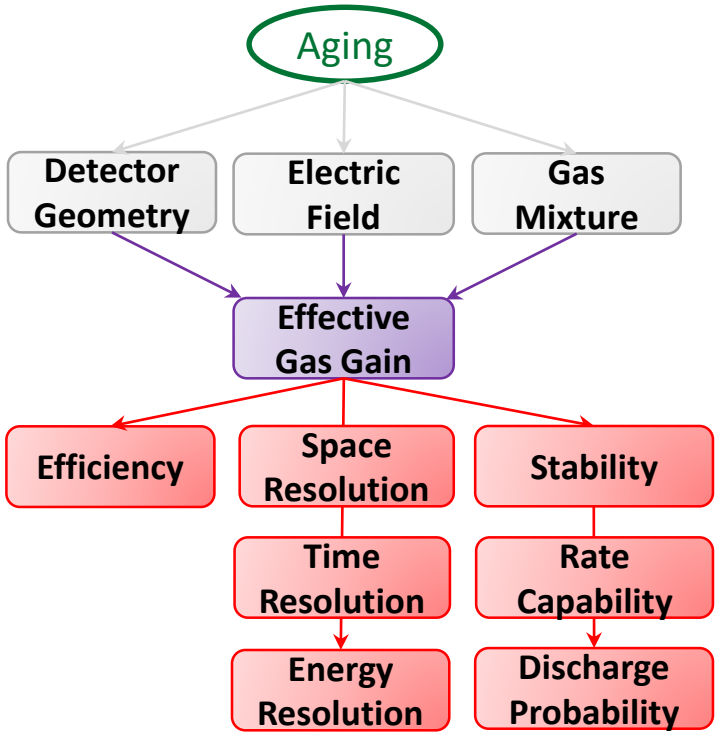
CMS-GEM1 setup inside the GIF++ bunker (front view)

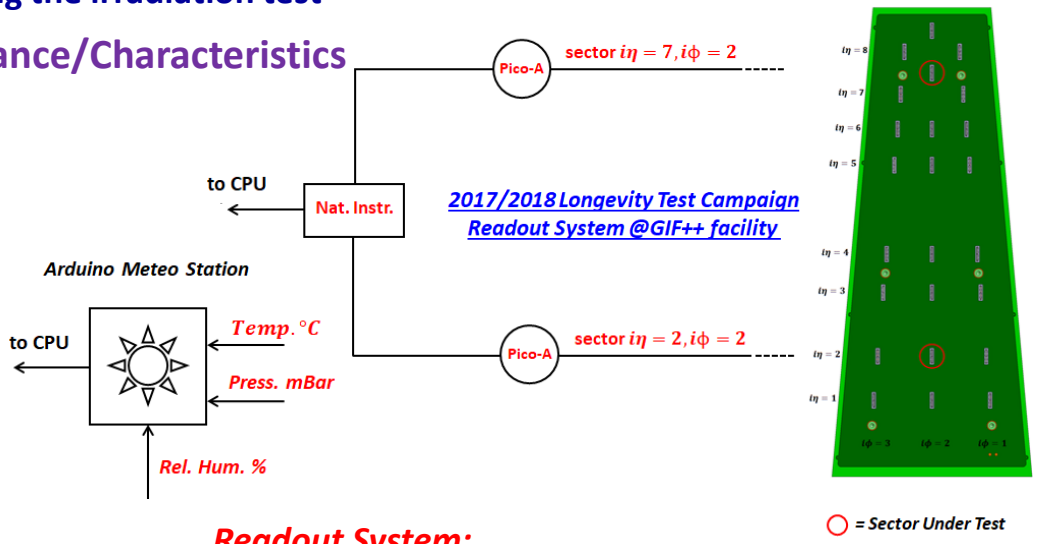


Data Acquisition System at GIF++ facility

How to identify the aging effect?

- Impossible to measure all performance and characteristics during the irradiation test.
  - → Requires specific experimental condition (beam, low energy X-ray, etc.)
  - → Probability to disturb the system during the irradiation test
- Aging → Effective Gas Gain → Perfomance/Characteristics





Readout System:

2 pico-ammeters to monitor the anode current during the irradiation test.

Meteo Station:

Meteo Station inside the GIF++ bunker to monitor environmental parameters.

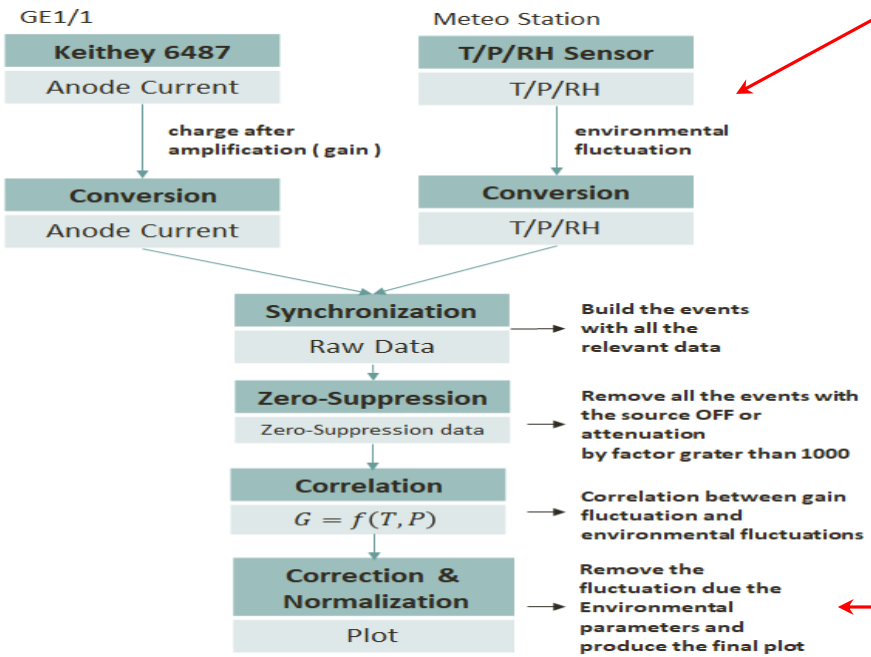
Analysis Procedure at GIF++ facility

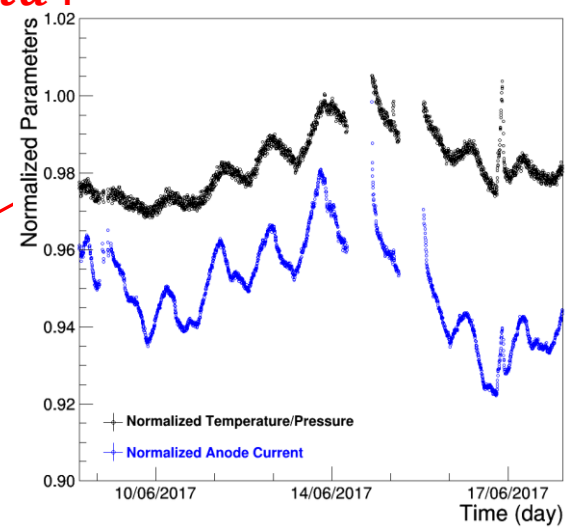
How to extract the aging effect from the raw data?

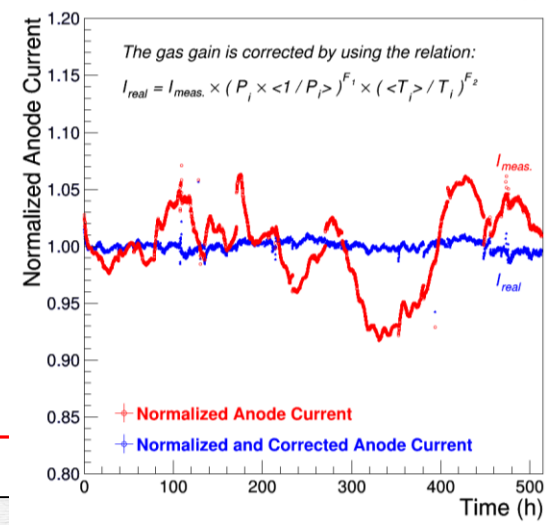
- The anode current, which reflects the effective gas gain of the detector, depends on the gas density, function itself of the temperature and pressure:

$$I_{real} = I_{measured} \times \left(P_i \times \left\langle \frac{1}{P_i} \right\rangle\right)^{F_1} \times \left(\frac{\langle T_i \rangle}{T_i}\right)^{F_2}$$

- Environmental fluctuations can *hide* the aging effect

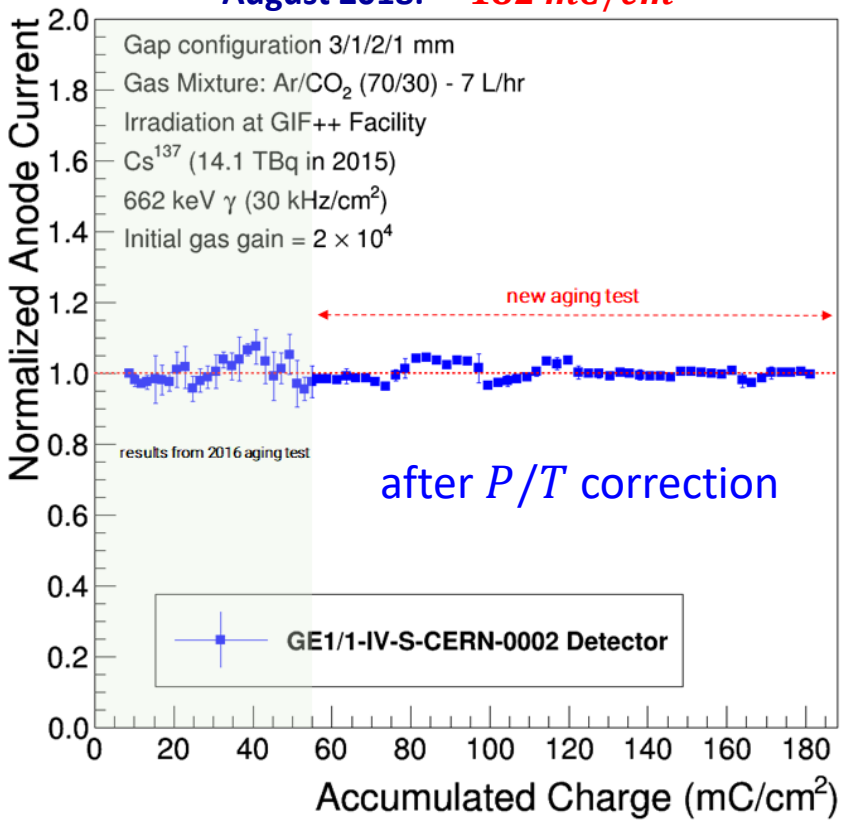






Accumulated Charge and Anode Current Measurement

Total Integrated Charge @ GIF++ up to August 2018: $\sim 182\ mC/cm^2$



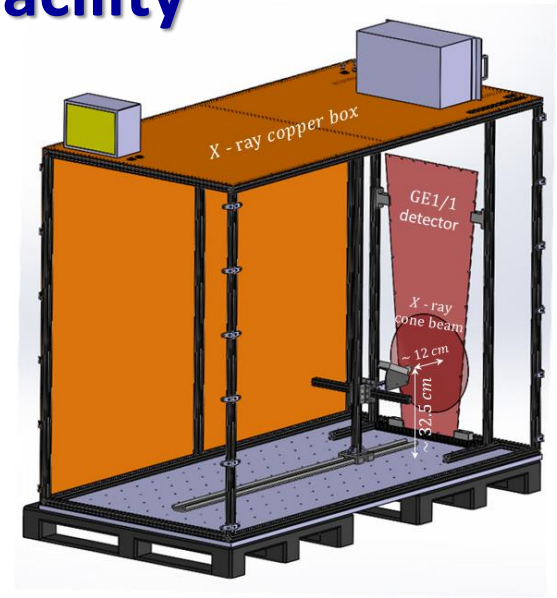
NO aging observed up to $\sim 182\ mC/cm^2$

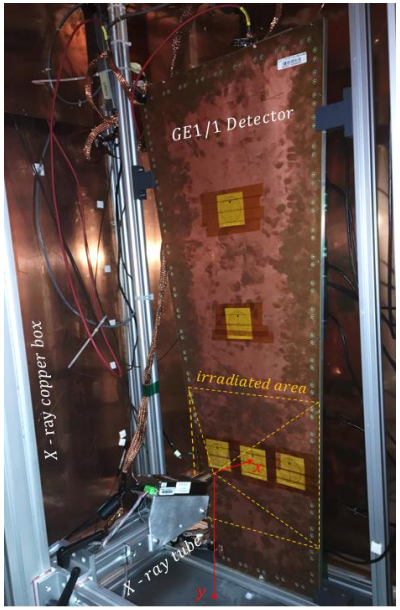
($\sim 64\%$ of ME0 operation at the HL-LHC)

- **The longevity studies will continue at the GIF++ until the detector accumulates a total charge of about $\sim 850\ mC/cm^2$**
- **This will take additional $5-5.5$ years of exposure due to the duty factor of the GIF++**
- **To overcome this extremely long time, an additional longevity test has been setup in summer 2017 exposing a GE1/1 triple-GEM detector to $\sim 22\ keV$ X-rays photons at CMS-GEM QA/QC facility (904 Lab.)**

Experimental Setup at CMS-GEM facility

- *QA/QC X-ray station adapted for longevity studies*
- *Source: $22\ keV\ X\text{-}ray$ photons from $X\text{-}rays$ generator*
- *Detector: $LS2\text{-}GE1/1$ detector with the final geometry and materials*





$X\text{-}ray$ configuration:

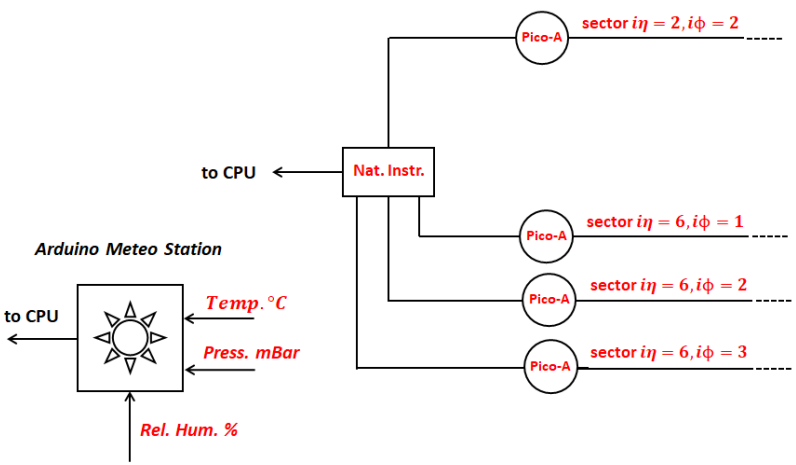
The X-Ray gun has been placed at $12cm$ from the detector in order to:

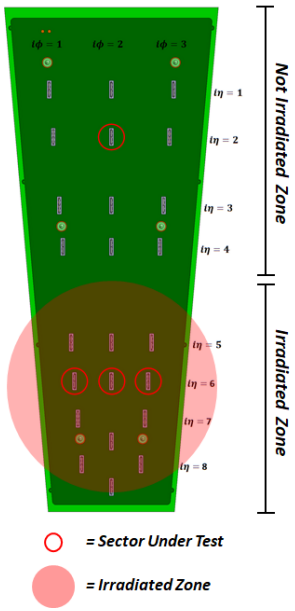
- **Maximize anode current and accelerate aging studies (5 months instead 5.5 years at GIF++ facility)**
- **Irradiate the GEM-foils, external / internal frame, O-ring, etc.**

ME0 Longevity Studies
CMS-GEM QA/QC facility

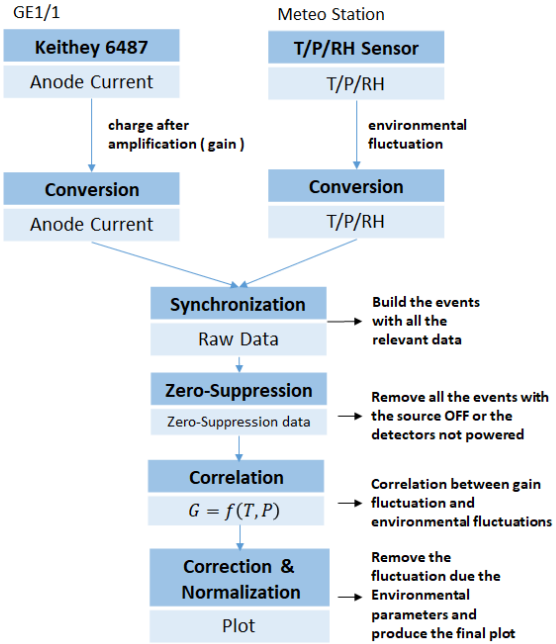
Data Acquisition and Analysis Procedure

2017/2018 Longevity Test Campaign
Readout System @ CMS-GEM QA/QC Lab.





2017/2018 Longevity Test Campaign
Analysis Procedure



Readout System:

3 pico-ammeters on the irradiated zone to monitor the anode current during the irradiation test

1 pico-ammeter on the non-irradiated zone as a reference during the irradiation test

Meteo Station:

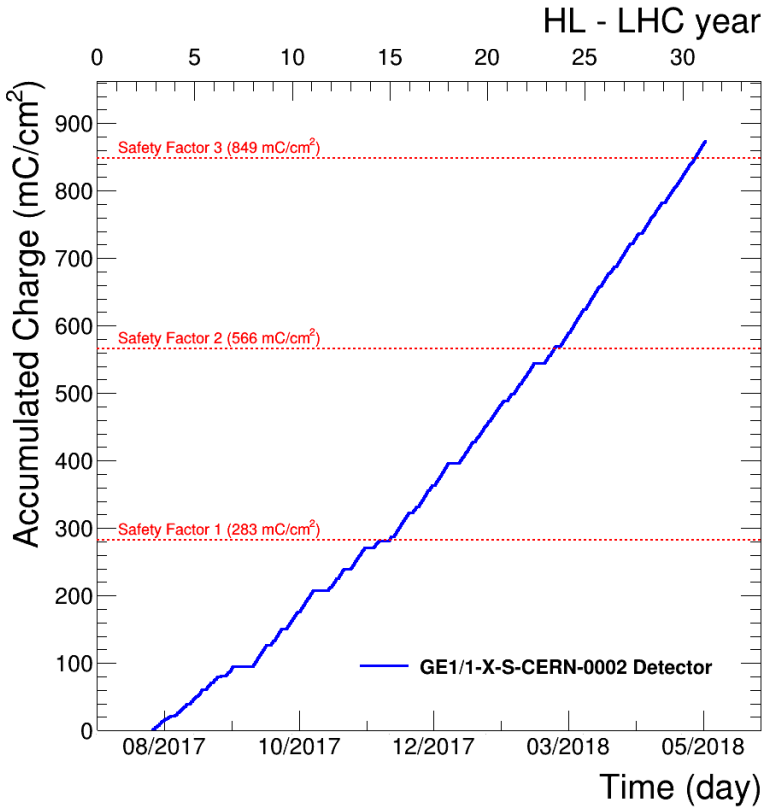
Arduino Meteo Station inside the X-ray copper box to monitor environmental parameters.

During the irradiation test, in addition to the monitoring of the anode current:

- **The *effective gas gain* and the *energy resolution* have been continuously measured every week on the readout sectors under test.**
- **The *gas gain map uniformity* measurements have been performed every month to check for the gas gain variation between the irradiated and non irradiated detector active area.**

ME0 Longevity Studies
CMS-GEM QA/QC facility

Accumulated Charge and Anode Current Measurement



X-ray Aging Test @ 904-Lab

(4000 hours of continuous tests)

NO aging observed up to $\sim 875\ mC/cm^2$

($\sim$ 31 years of ME0 operation at the HL-LHC)

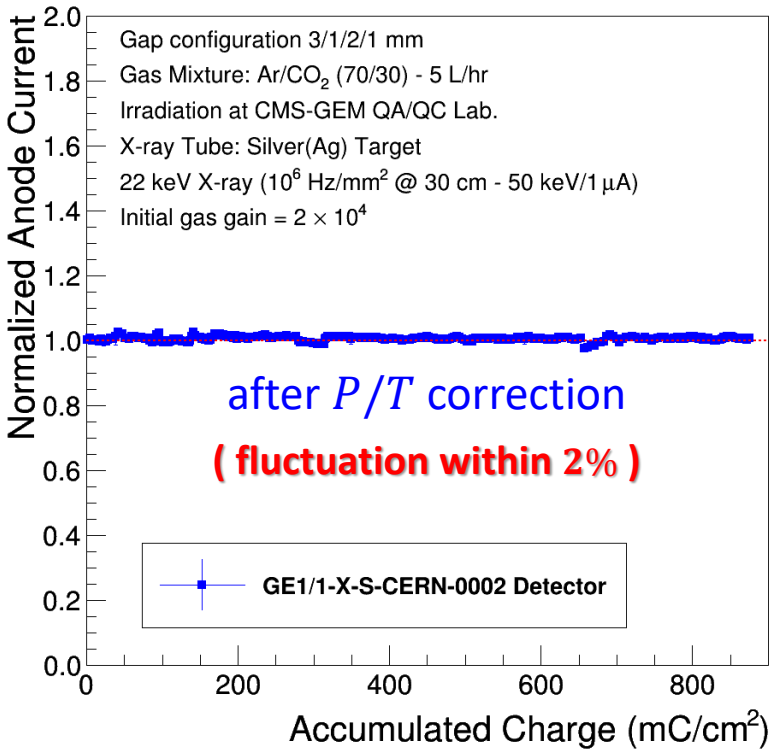
$$\varepsilon_{904Lab} = \frac{exposure\ time}{total\ time} \sim 83\ \%$$

Efficiency @ 904-Lab.

$$R(Q_{int})_{83\%} \sim 5.6\ mC/cm^2 \cdot day$$

Integrated Charge Rate

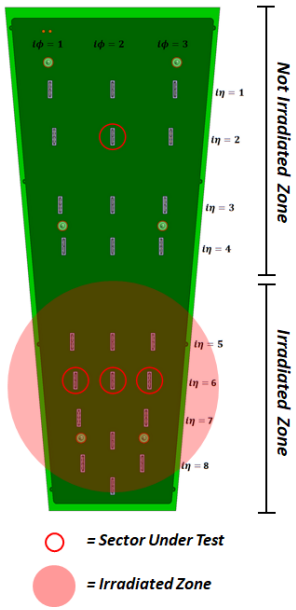
$\sim 20\ hr$ of continuous irradiation per day

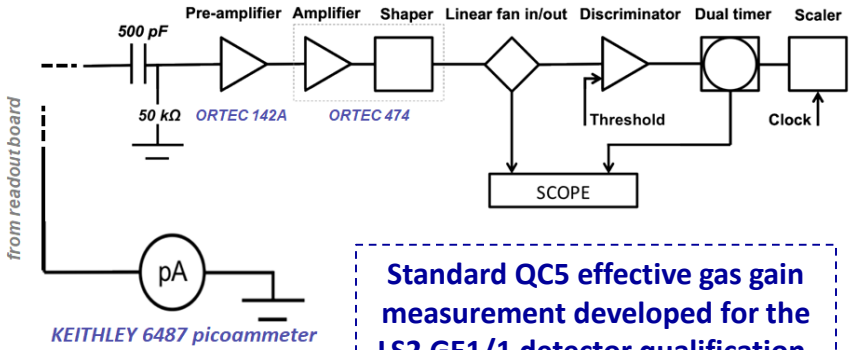


ME0 Longevity Studies
CMS-GEM QA/QC facility

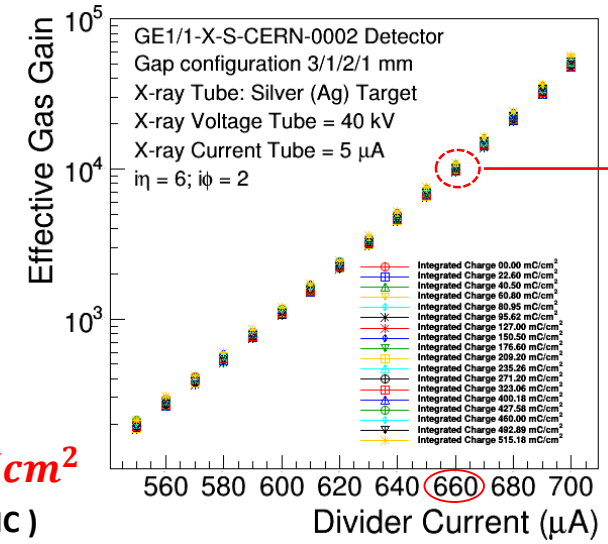
Weekly Effective Gas Gain Measurement

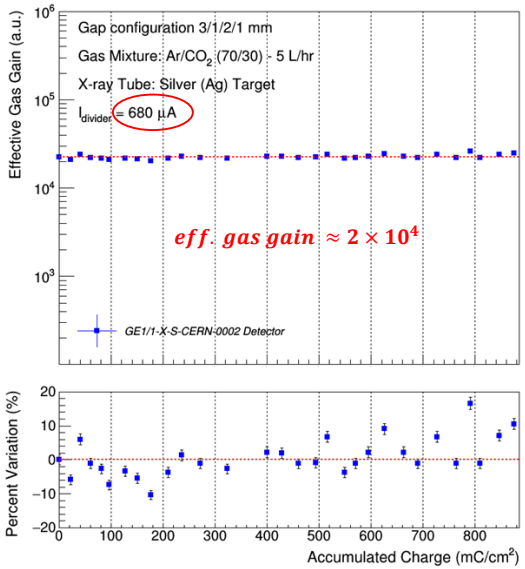
(i. e. every ~ 30 mC/cm²)

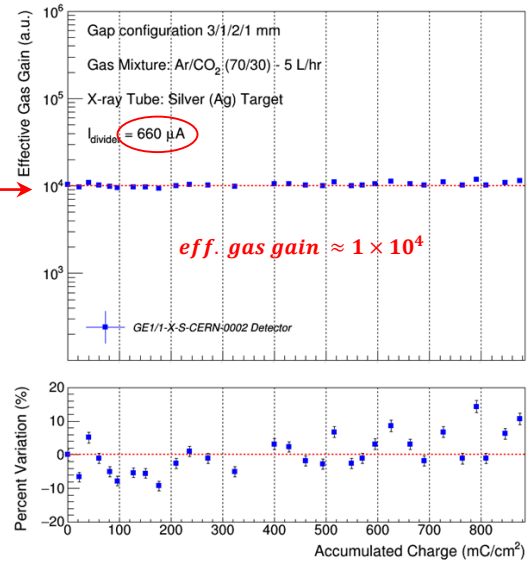




Standard QC5 effective gas gain measurement developed for the LS2 GE1/1 detector qualification.







- Effective gas gain stable during the entire irradiation test and only fluctuates within 10% of its initial value.
- Gas gain fluctuations include also the variations induced by the environmental conditions.

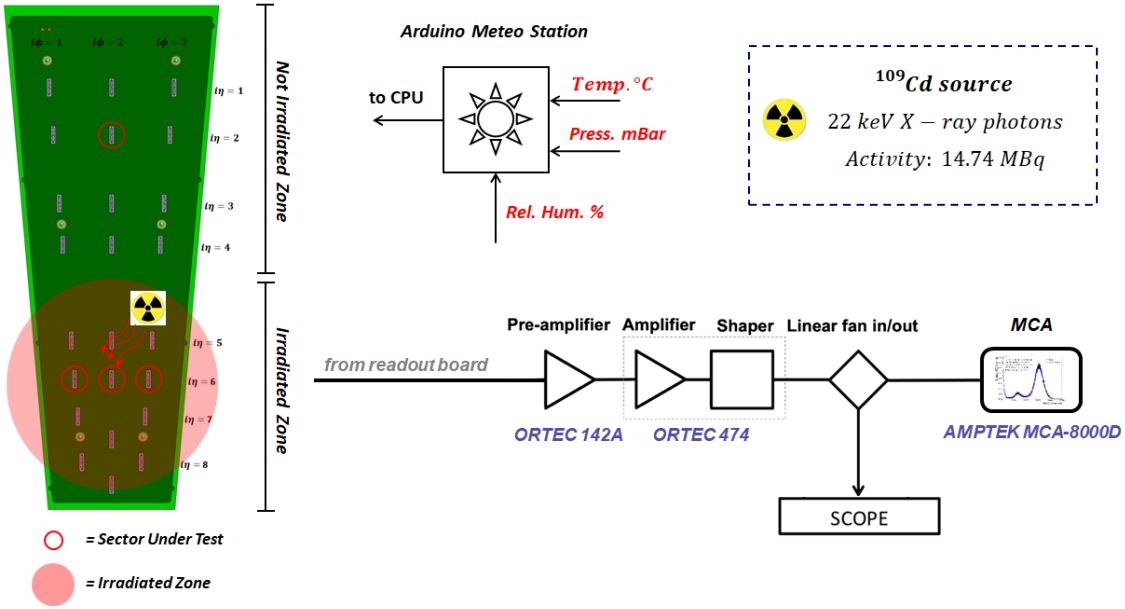
NO aging observed up to ~ 875 mC/cm^2

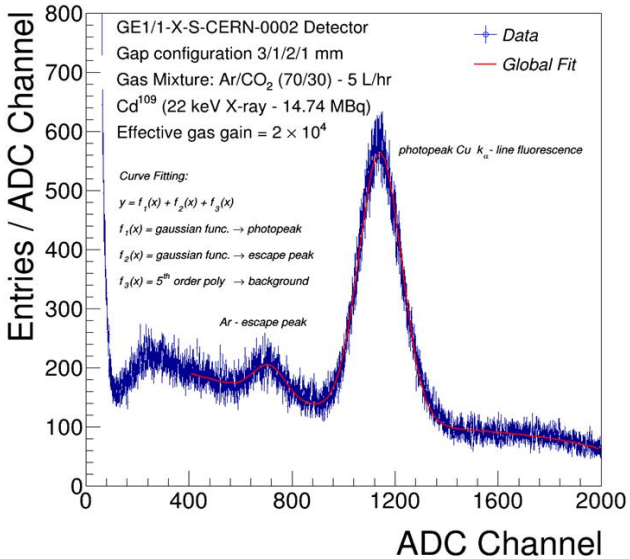
(~ 31 years of ME0 operation at the HL-LHC)

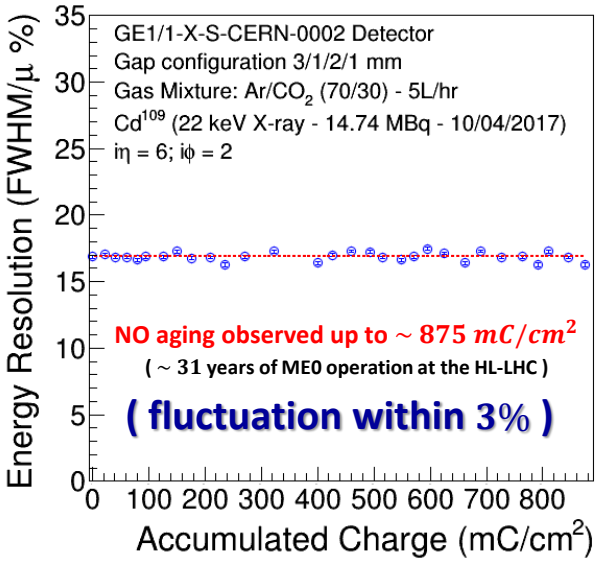
ME0 Longevity Studies
CMS-GEM QA/QC facility

Weekly Energy Resolution Measurement

$(\text{i.e. every} \sim 30\ \text{mC/cm}^2)$







The experimental data are modeled by the function:

$$y = f_1(x) + f_2(x) + f_3(x)$$

$f_1(x) = gaussian\ func. \rightarrow photopeak \rightarrow \rightarrow$ { *photopeak sigma value* σ ; *photopeak mean value* μ }

$f_2(x) = gaussian\ func. \rightarrow escape\ peak$

$f_3(x) = 5^{th}\ order\ poly \rightarrow background$

Energy Resolution

$$\frac{FWHM}{\mu}\% = \frac{2\sqrt{2ln(2)}\,\sigma}{\mu}\%$$

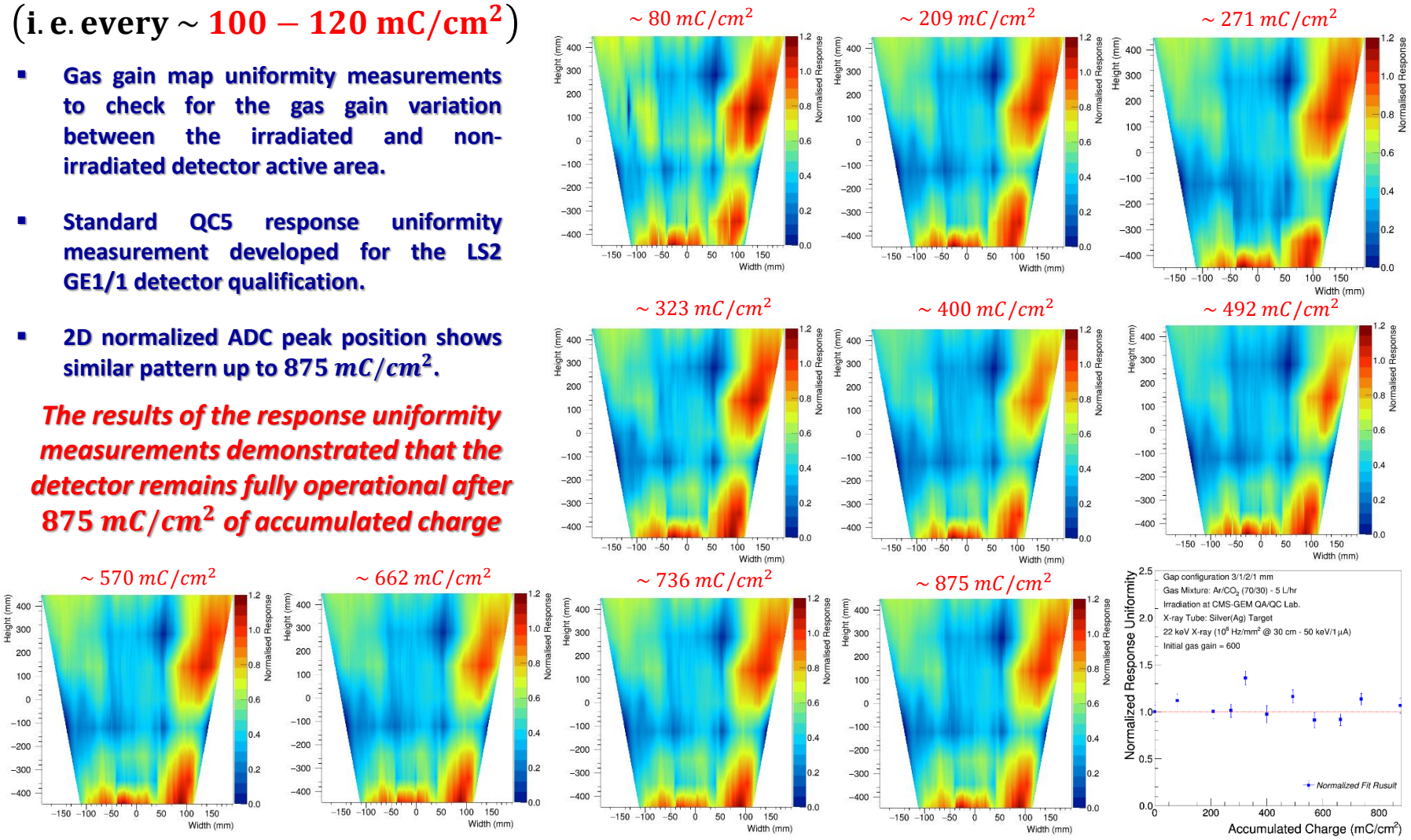
ME0 Longevity Studies
CMS-GEM QA/QC facility

Monthly Response Uniformity Measurement

$(\text{i.e. every} \sim 100 - 120\ \text{mC/cm}^2)$

- Gas gain map uniformity measurements to check for the gas gain variation between the irradiated and non-irradiated detector active area.
- Standard QC5 response uniformity measurement developed for the LS2 GE1/1 detector qualification.
- 2D normalized ADC peak position shows similar pattern up to 875 mC/cm^2.

The results of the response uniformity measurements demonstrated that the detector remains fully operational after 875 mC/cm^2 of accumulated charge

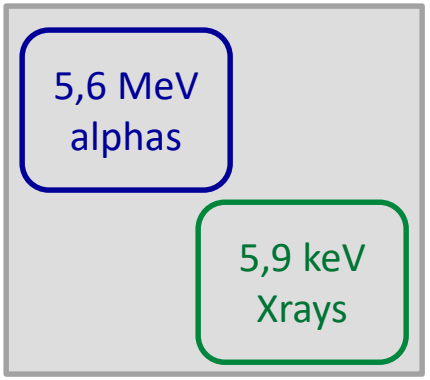


Advanced Longevity Studies

Advanced Longevity Studies:

- **Investigate aging issues originated by particles with different ionization powers to properly represent the long-term gaseous detector behavior in real experiments:**

  ^{241}Am: $5.6\ MeV$ α - particle and ^{55}Fe: $5.9\ keV$ X-rays



GEM 10x10 prototype

Detector under test:

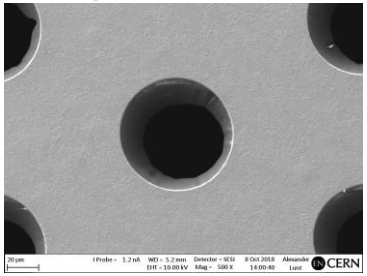
- **GEM $10 \times 10\ cm^2$ prototype irradiated in two different sectors**

Method to accelerate the aging:

- **Contaminate the gas mixture with pollutants (hydrocarbons and Si - based molecules)**

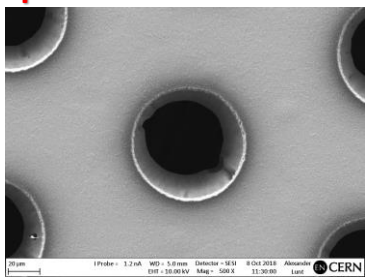
SEM and EDS analysis to study polymer density around GEM holes

X - rays irradiated hole



- **Light Si deposits on the top layer around the holes (2 - 3 μm)**
- **Perfectly clean surface on the bottom side**

α - particles irradiated hole



- **Si deposits on the entire top and bottom surface with larger structure in a strip of 10 - 15 μm around the holes**

NO degradation of the effective gas gain and energy resolution