GEM Detectors for CMS Experiment

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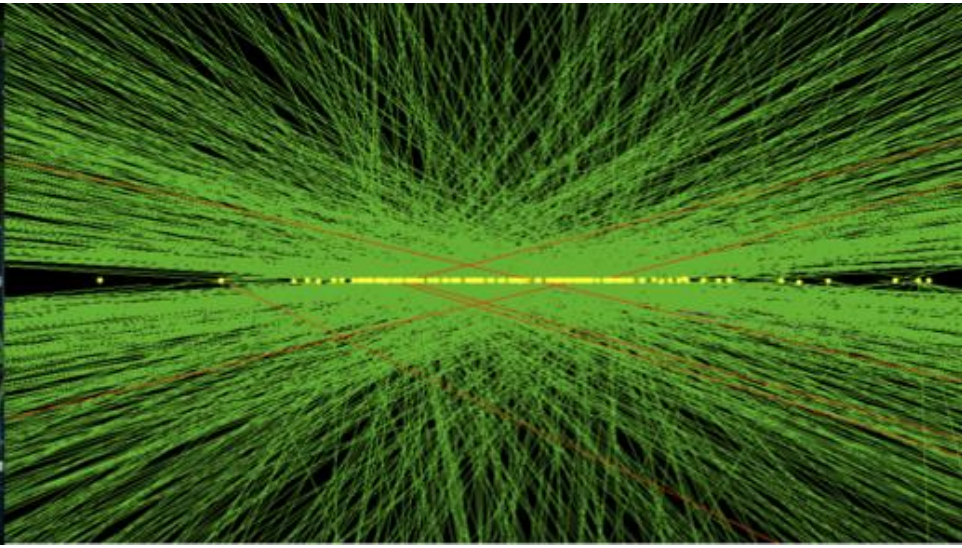
(CERN Geneva, Switzerland)

Detector Seminar

July 8th, 2022

Acknowledgements

Thanks to CMS GEM group!!!

Special mention to:

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Thanks to the organizers for the invitation!!!

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- GE2/1 project
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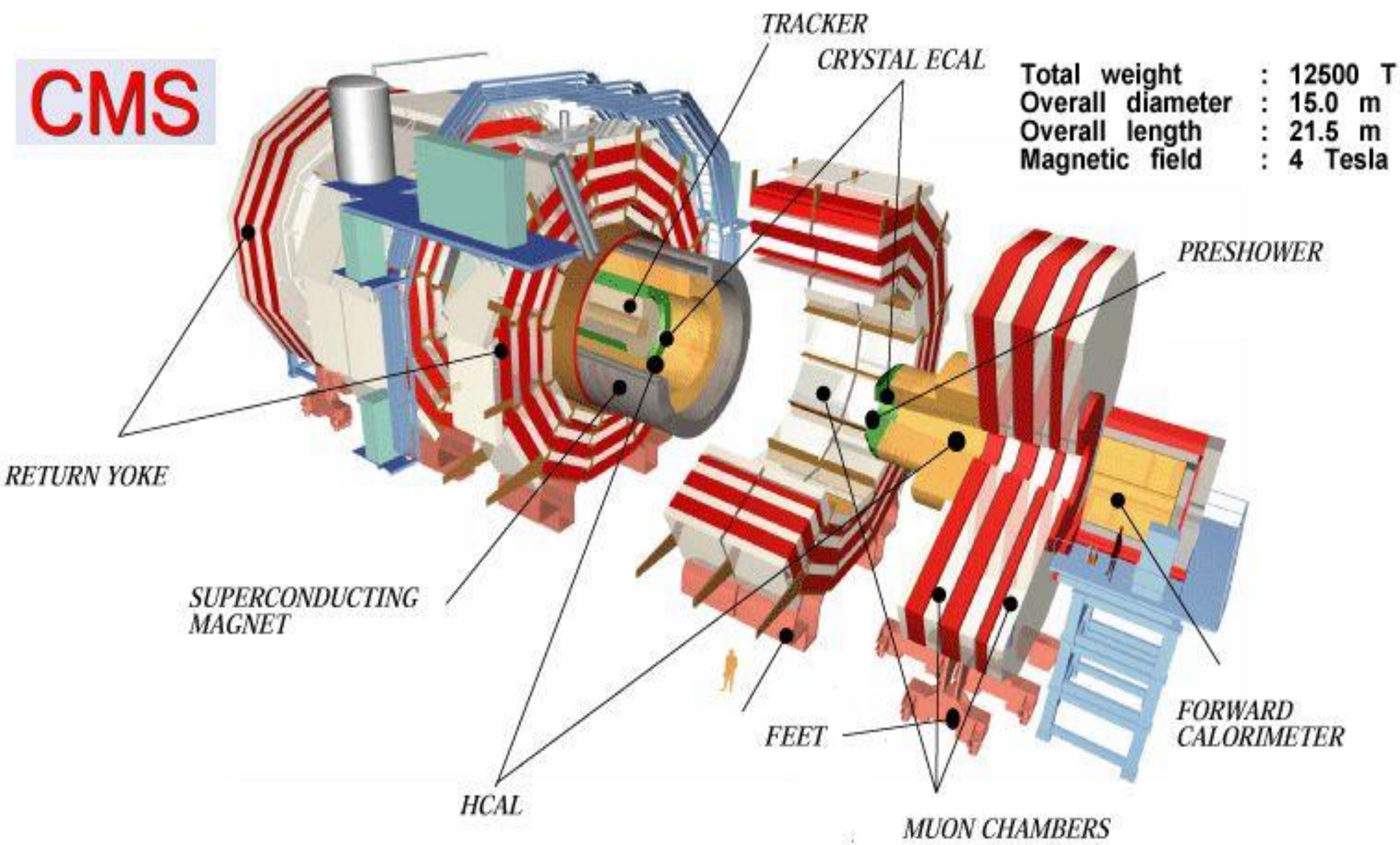
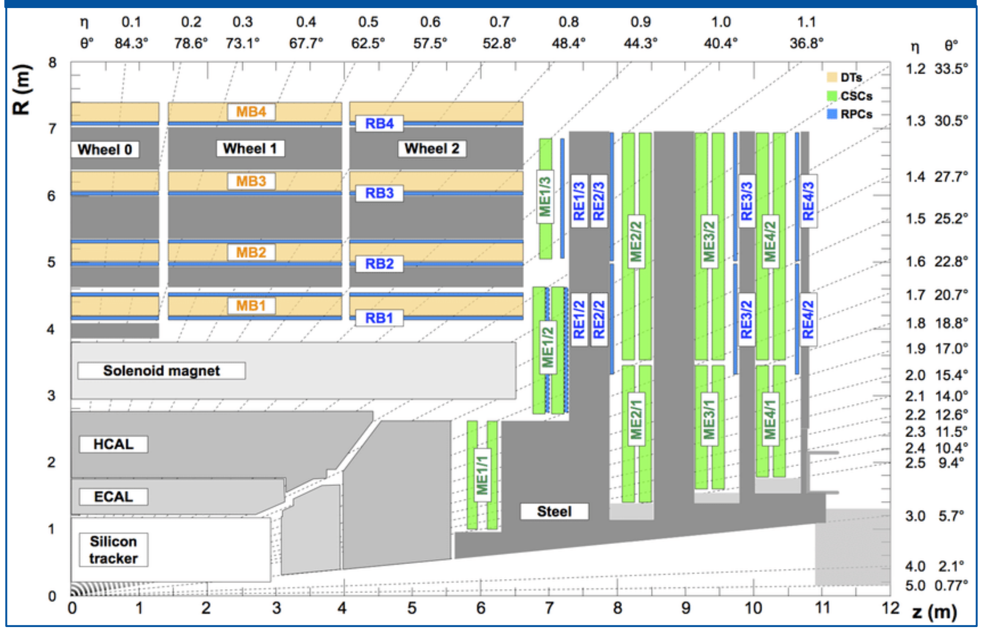
Compact Muon Solenoid



CMS Muon Spectrometer before LS2

Highly hermetic and redundant muon system, at least four stations on a muon path in all directions

A cross-section of the CMS experiment before the LS2 upgrade



3 technologies:

- **Drift Tubes** and **Cathode Strip Chambers** (for tracking and triggering);
- **Resistive Plate Chambers** (for triggering).

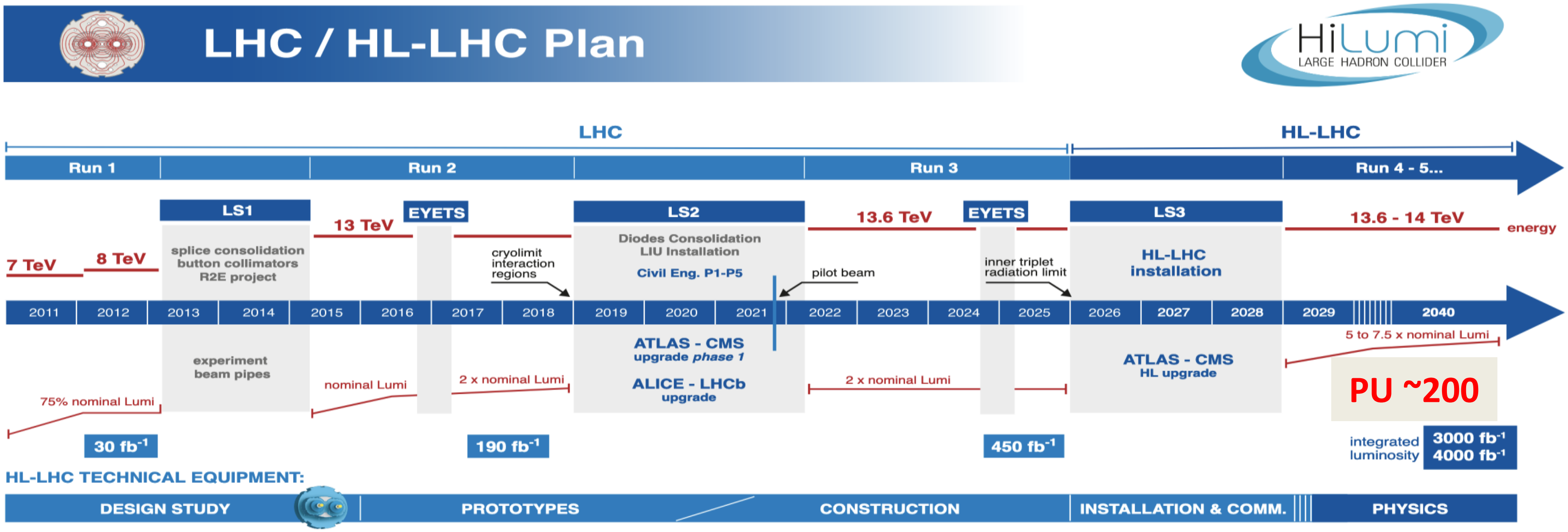
Eta coverage:

- |η|<1.6: 4 layers of CSCs and RPCs, DTs
- the |η|≥1.6: CSCs only;

GOALS:

- **robust**, **redundant** and **fast** identification of the muons
- **Level-1 trigger** has access to muon information only
- **Momentum measurement**: the muon system is relevant for high pt muon (>100 GeV) and in the high η region (large lever arm of the muon system)

Challenges from HL-LHC



Goal: keep the same performance as in Phase-1

CMS Upgrades

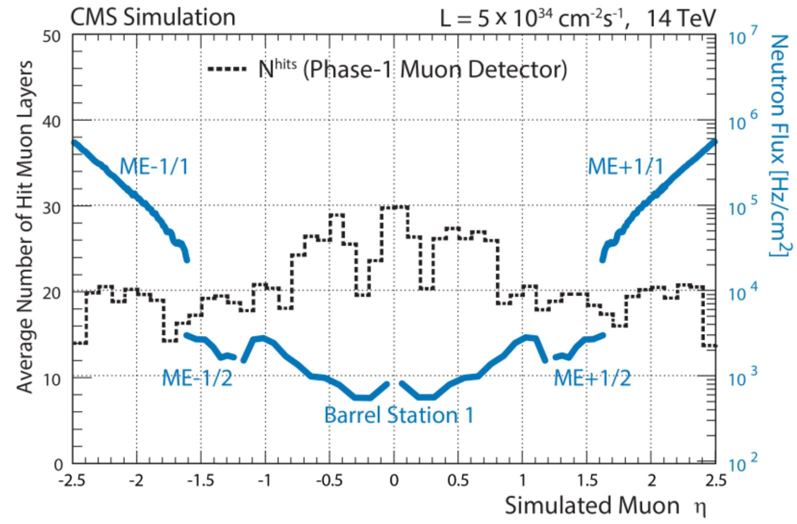
- New tracker (4 pixel layers +3 disks)
- New trigger/DAQ:
  - Track information at L1 with extended trigger latency (total of 12.5 μs)
  - Increased L1 bandwidth to 750 kHz
- Calorimeters with higher granularity
- **Upgrade of Muon system**

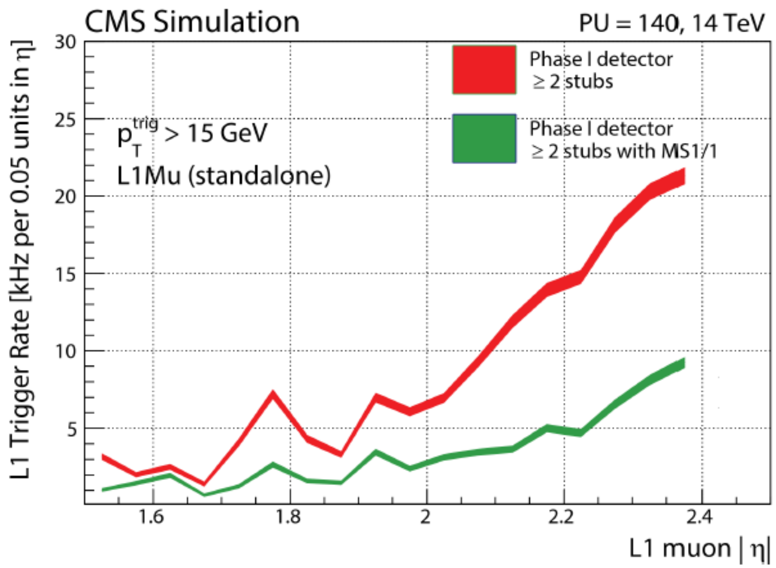
} $|\eta| < 3$

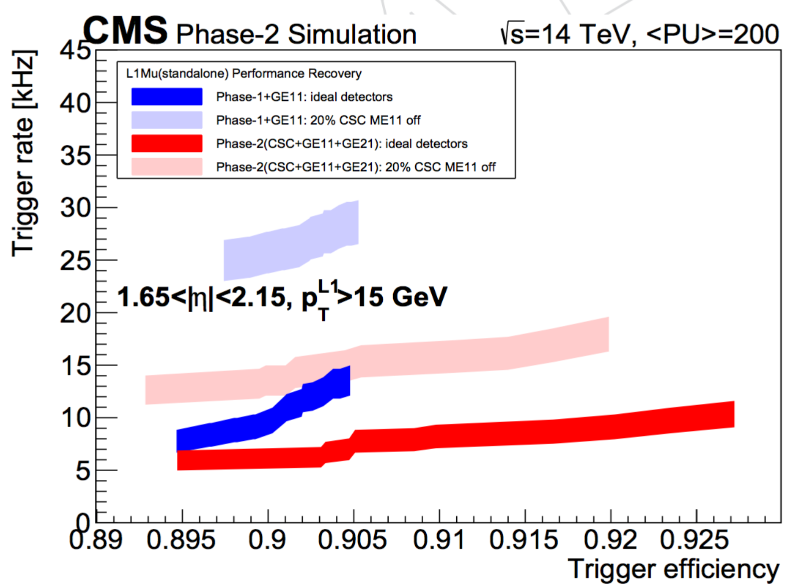
Challenges from HL-LHC

Maintain standalone trigger and reconstruction, mitigation of efficiency loss due to aging of the current detectors can be met if:

- the number of hits recorded is sufficiently large
- spatial accuracy and the time resolution are very good.
- good momentum measurement for the rejection of unwanted soft muons, mis-measured as high p_t muons → prevent increase in p_t threshold

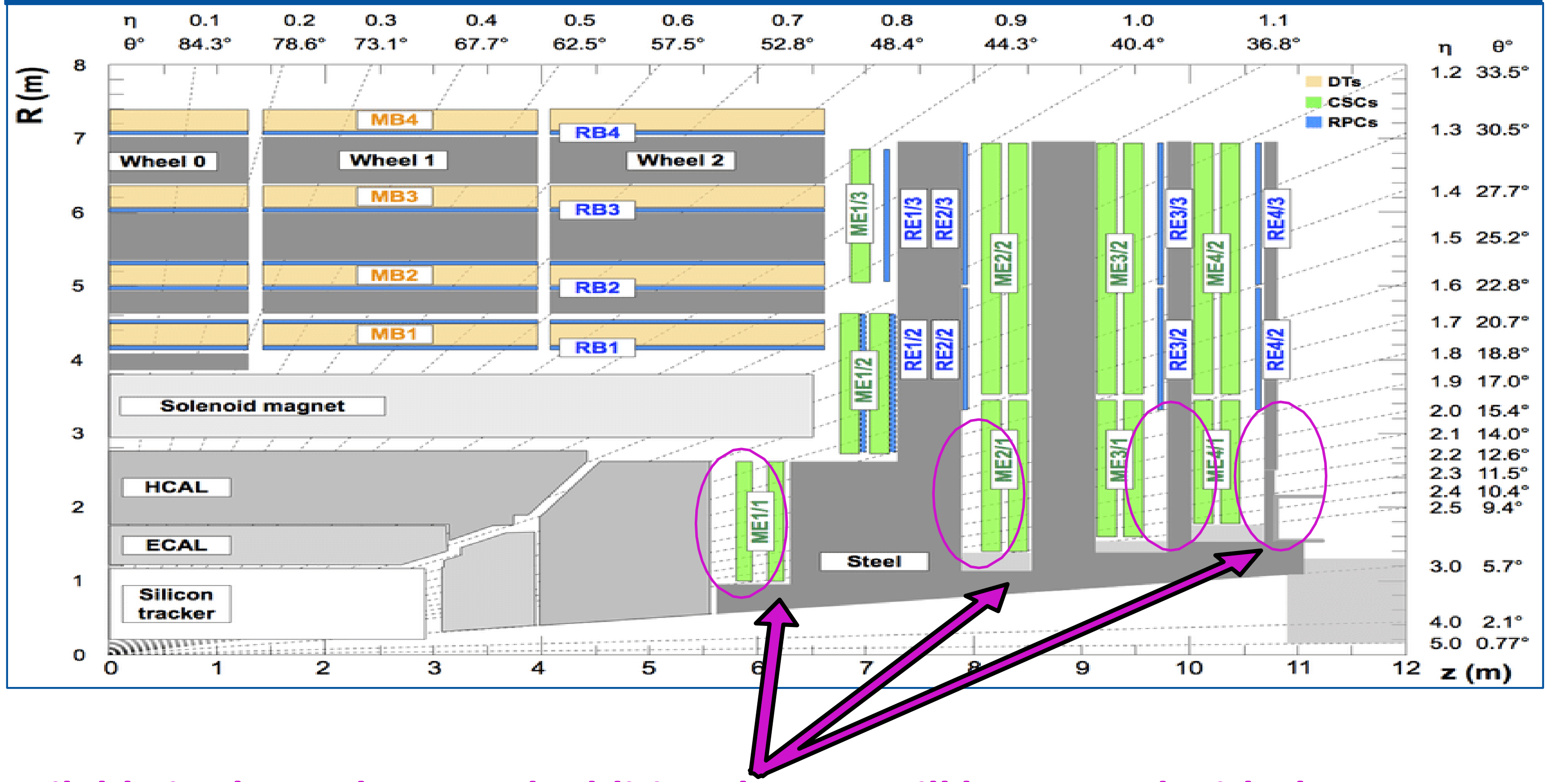






CMS Muon Spectrometer after LS3

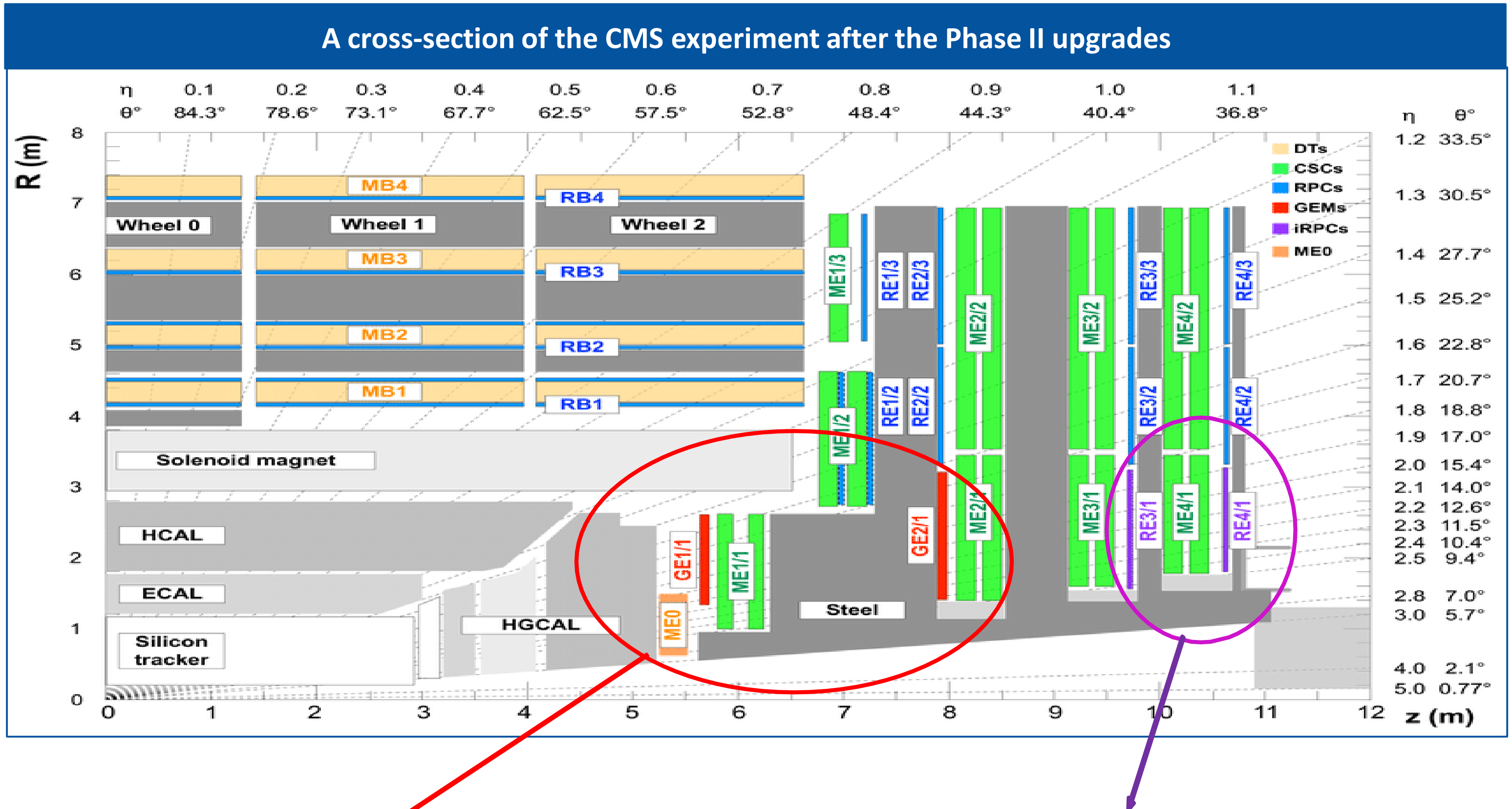
A cross-section of the CMS experiment before the LS2 upgrade



Space is available in the endcaps and additional space will be created with the new CMS Nose!

➔ **Possibility to insert additional detection layers in order to provide a better selection/measurement of the muons and to add redundancy to maintain the CMS performance in case of failure**

CMS Muon Spectrometer after LS3



The GEM upgrade: three new stations GE1/1, GE2/1 and ME0 based on the triple-GEM technology

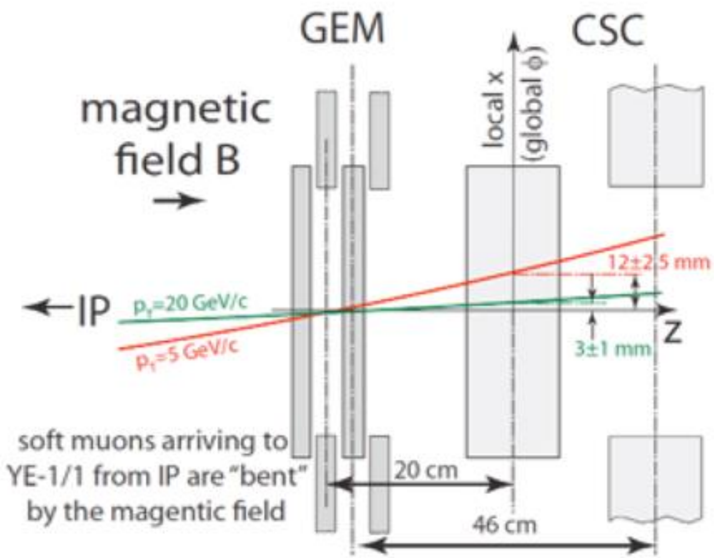
The RPC upgrade: two new stations RE3/1 and RE4/1 based on the improved-RPC technology

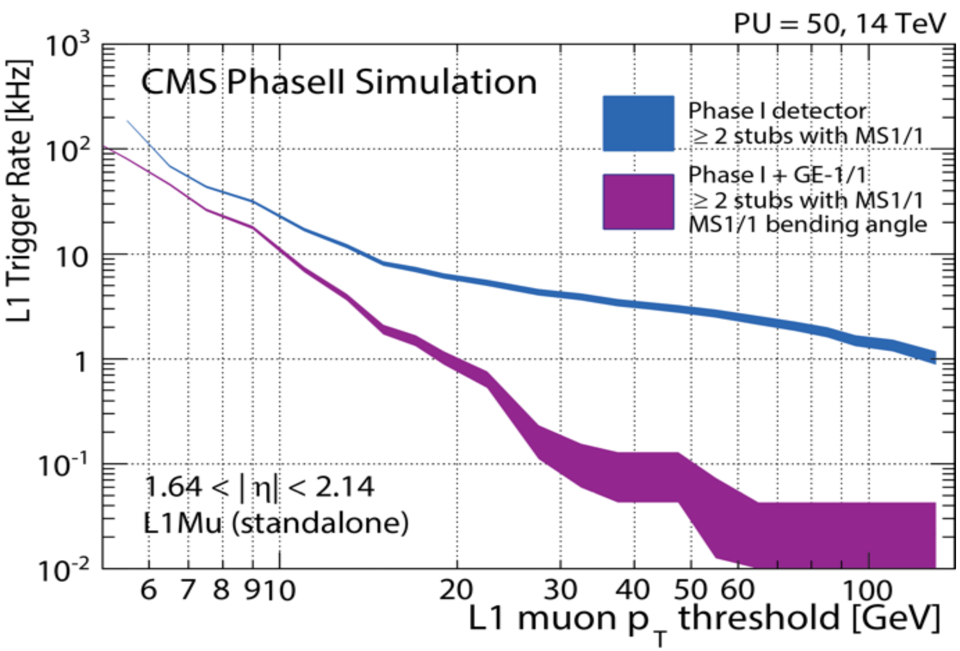
How GEMs will help

GE1/1

Till LS2, forward trigger for |η|>1.6 relies entirely on the CSC system (ME1/1) strong B field

GEM detector in front of CSC can measure muon bending angle in magnetic field and add redundancy



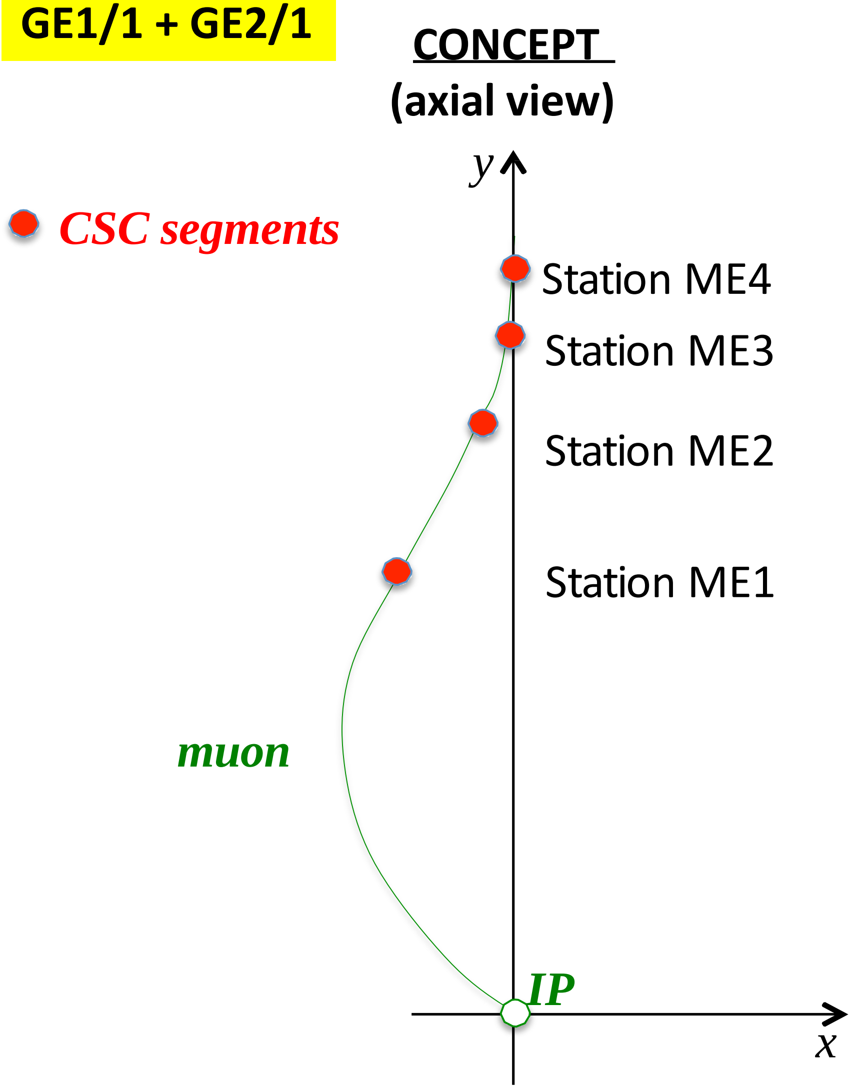


maintain 15 GeV online threshold, keep < 5 kHz rate, high efficiency

How GEMs will help

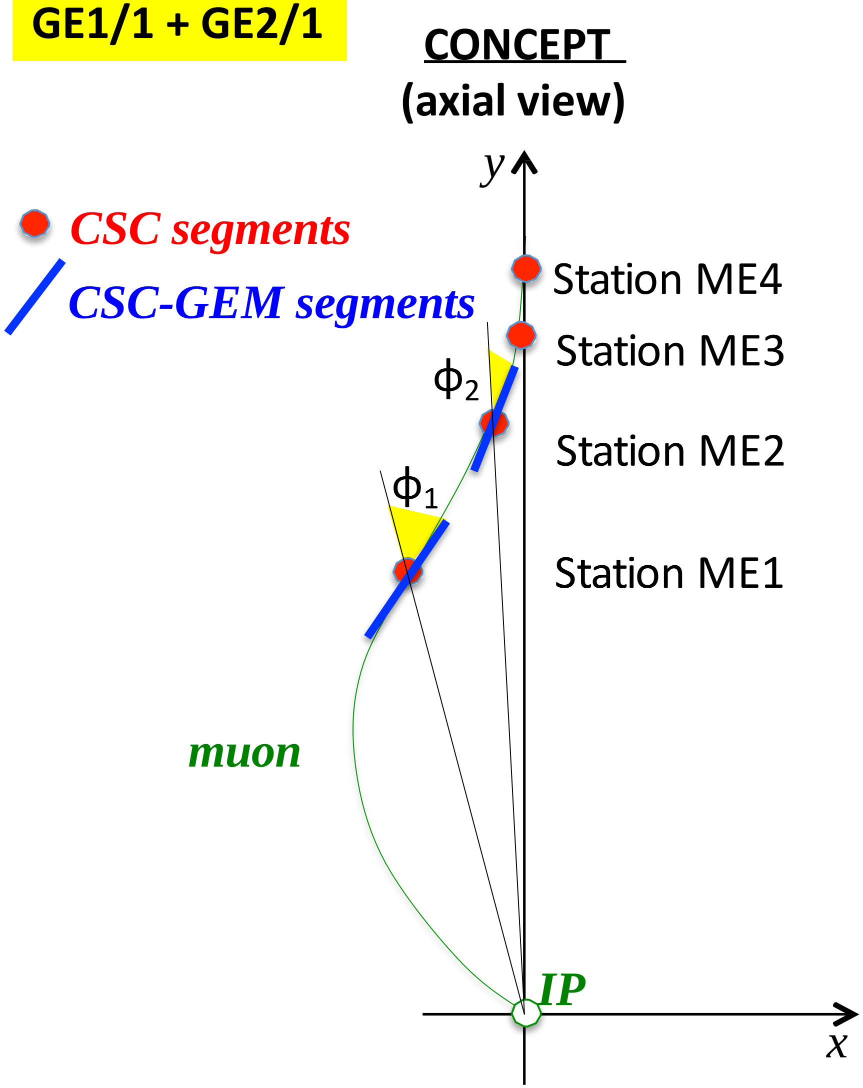
GE1/1 + GE2/1

CSCs alone provide short segments with low-precision info on segment direction



How GEMs will help

GE1/1 + GE2/1



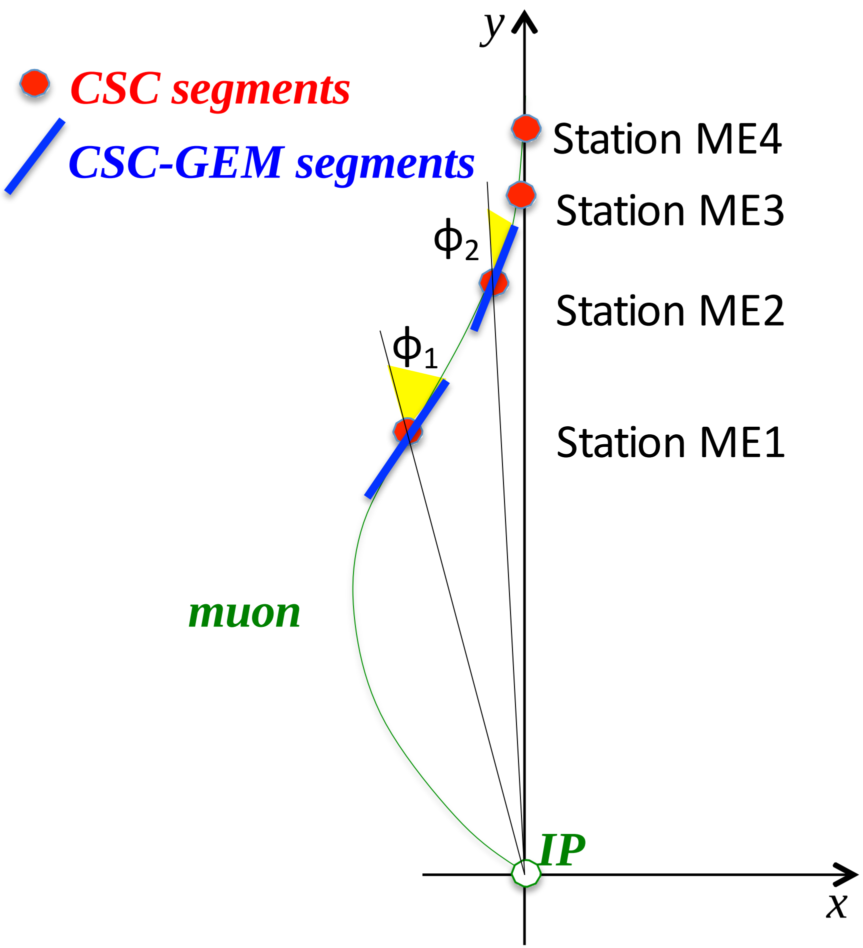
CSCs alone provide short segments with low-precision info on segment direction

GEM-CSC tandems in ME1 and ME2 stations give accurate measurement of muon "local" direction sensitive to muon p_T

How GEMs will help

GE1/1 + GE2/1

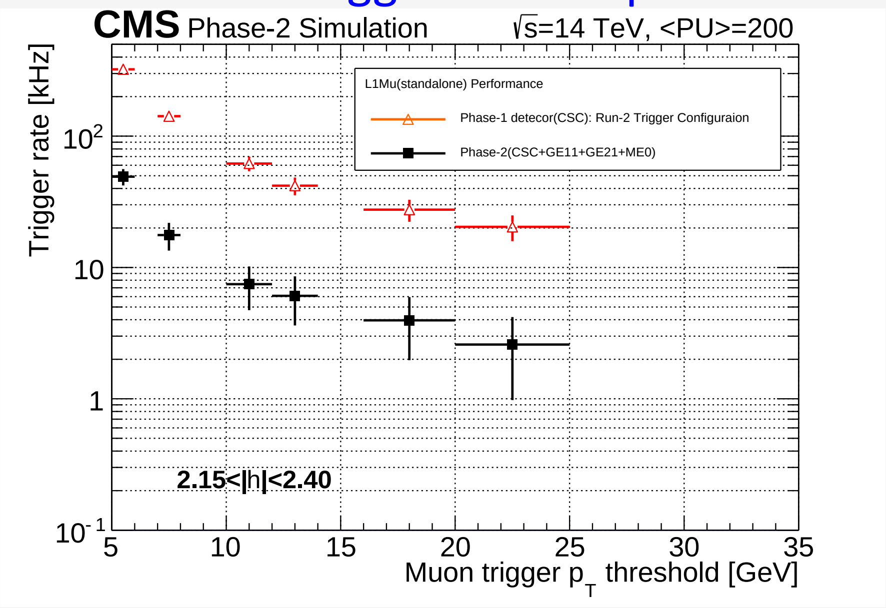
CONCEPT (axial view)



CSCs alone provide short segments with low-precision info on segment direction

GEM-CSC tandems in ME1 and ME2 station give accurate measurement of muon "local" direction sensitive to muon p_T

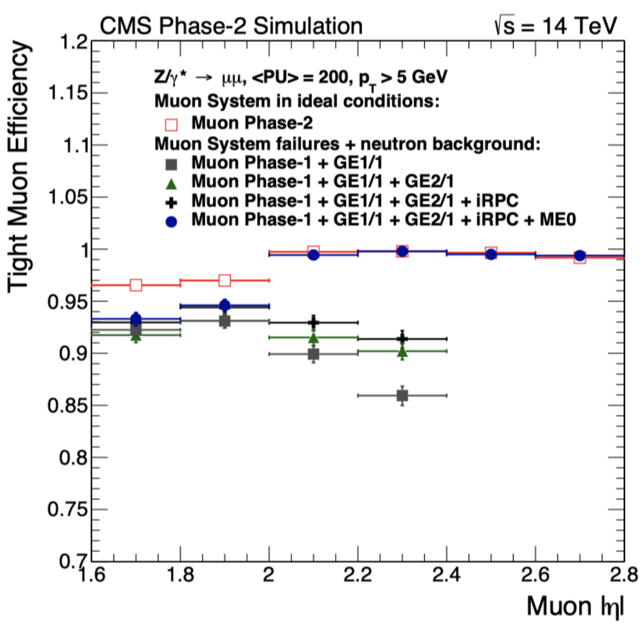
p_T measurement improves and, hence, the standalone L1-trigger rate drops

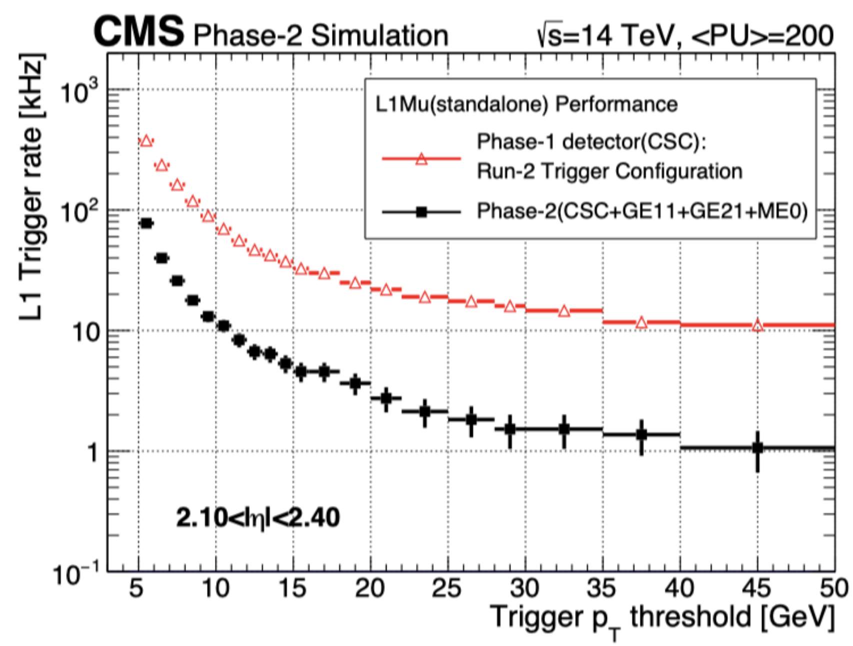


How GEMs will help

ME0

- ME0 will increase the acceptance of CMS Muon System up to |η| = 2.8, will provide a muon trigger signal in the very forward region, and the ME0 hits will be used in the offline muon reconstruction
- The ME0 chambers partially overlap (up to |η| = 2.4) with the existing CSC endcap muon chambers
- The ME0 detector extends the muon acceptance into the pseudorapidity range 2.4 < |η| < 2.8, which is beyond the reach of any other CMS muon detector. The increased muon acceptance is fully covered by the new Phase-2 inner silicon tracker
- Each ME0 detector consists of six layers of triple-GEM chambers, compared to the two-layer design of GE1/1 and GE2/1

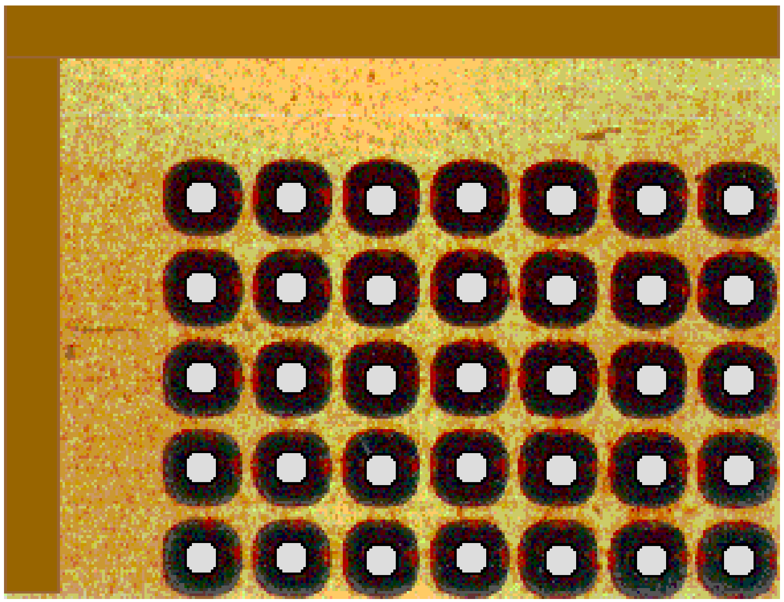


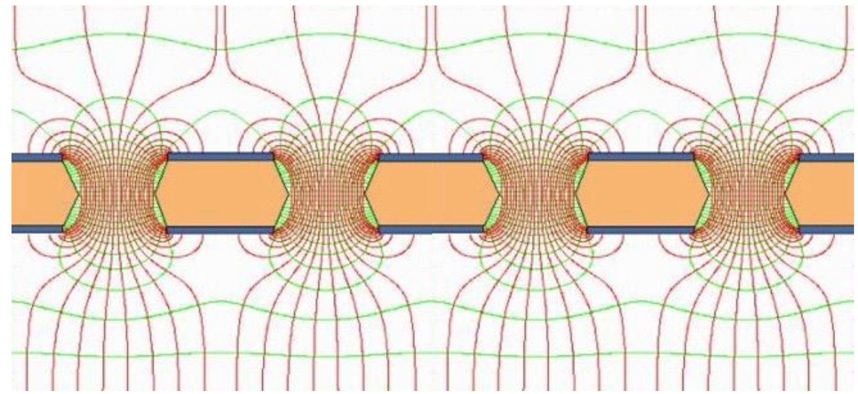


What are the GEM

THE GAS ELECTRON MULTIPLIER (GEM):

100 µm PITCH HOLES ON COPPER-CLAD POLYIMIDE FOIL





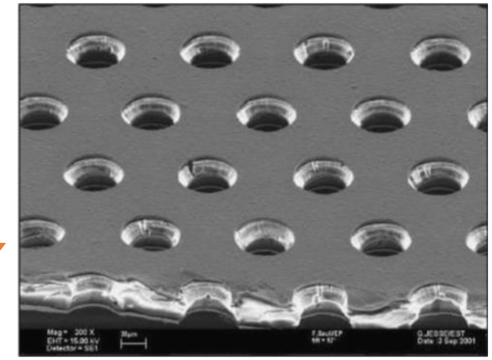
F. Sauli, Nucl. Instr. and Meth. A386(1997)531

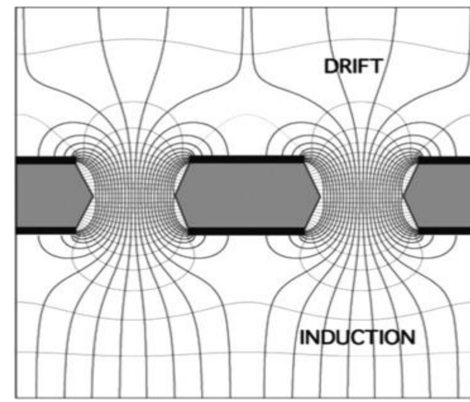
PRESENTED AT:
IEEE Nuclear Science Symposium & Medical Imaging Conference
Anaheim, CA November 3-9, 1996

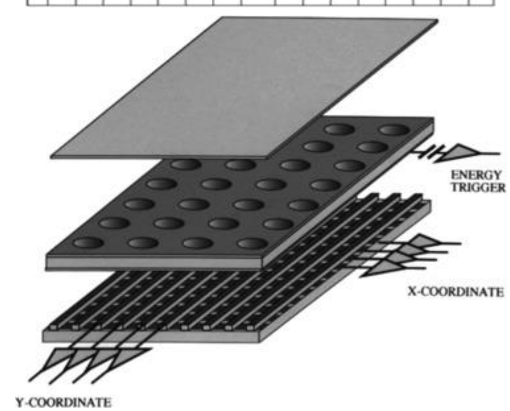
What are the GEM

- Concept of Gas Electron Multipliers

  - Gas Electron Multipliers (GEM) was introduced by Fabio Sauli in 1996-97
  - Gas Electron Multiplier electrode is a thin polymer foil, metal-coated on both sides and pierced with a high density of holes, typically 50–100 mm^{-2}
  - Inserted between a drift and a charge collection electrode, and with the application of appropriate potentials, the GEM electrode develops near the holes equipotential field lines
  - The large difference of potential applied between the two sides of the foil creates a high field in the holes; electrons released in the upper region drift towards the holes and acquire sufficient energy to cause ionizing collisions with the molecules of the gas filling the structure
  - A sizeable fraction of the electrons produced in the avalanche's front leave the multiplication region and transfer into the lower section of the structure, where they can be collected by an electrode, or injected into a second multiplying region, schematically a single GEM detector, with a two-dimensional patterned charge detection anode



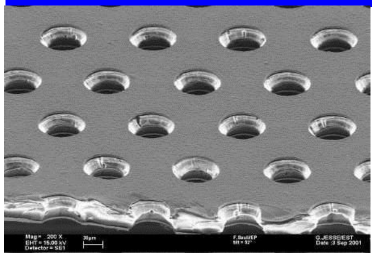


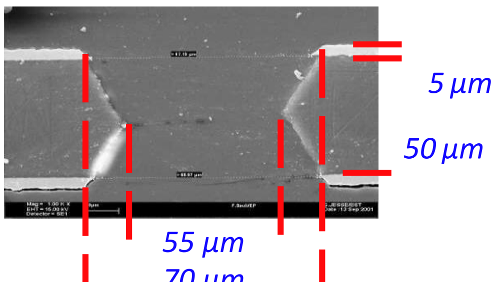


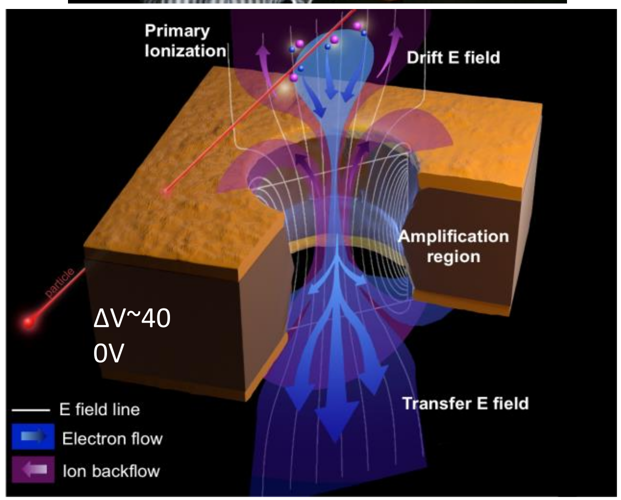
What are the GEM

Gas Electron Multipliers

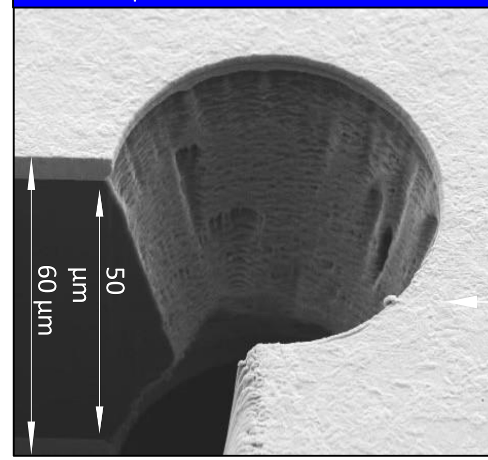
SEM picture of a GEM





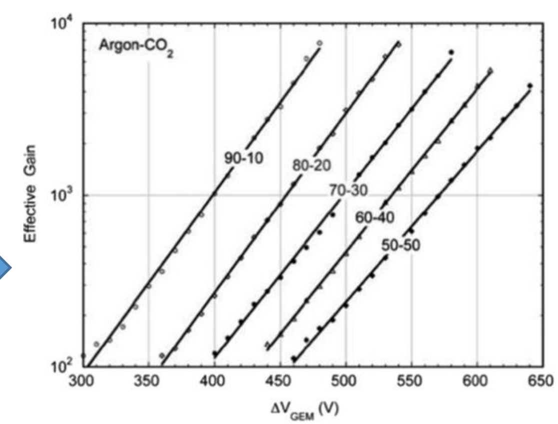


SEM picture of a GEM hole



Electrons entering the GEM holes will accelerate in the intense electric field (~80 kV/cm) and provoke the ionization of gas molecules, giving rise to an electron avalanche

Multiplication: 1 e^- input to > 1000 e^- output (as a function of gas and HV)



Master of GEM

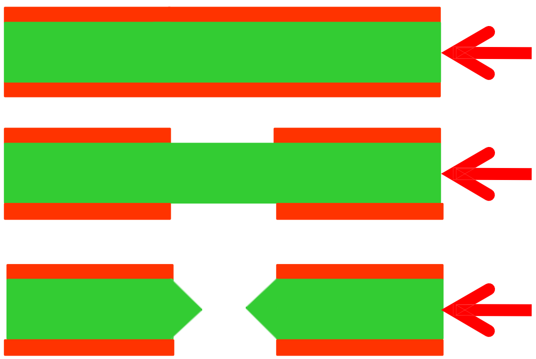
CERN's Printed Circuit Workshop

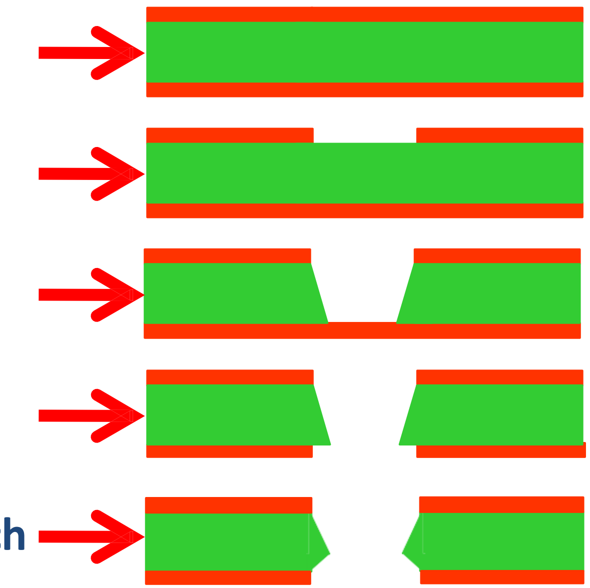
Mastering GEM

GEM production technique evolved along the time from double to single mask technique

- Double mask

- Single mask





- Same base material
- Hole patterning in Cu
- Polyimide etch
- Bottom electro etch
- Second Polyimide Etch

- Limited to ~ 100cm x 40cm due to
  - Mask precision and alignment
  - Lithography/Production machine

Pro

Fast Production (automatization, reduced manpower)

Cons

Very expensive setup (tools and glass mask)

- Limited to 2m x 60cm due to
  - Base material
  - Equipment (size bath for photolithography process)

Pro

Cheap mask (fundamental for R&D)

Cons

High intensity human labour

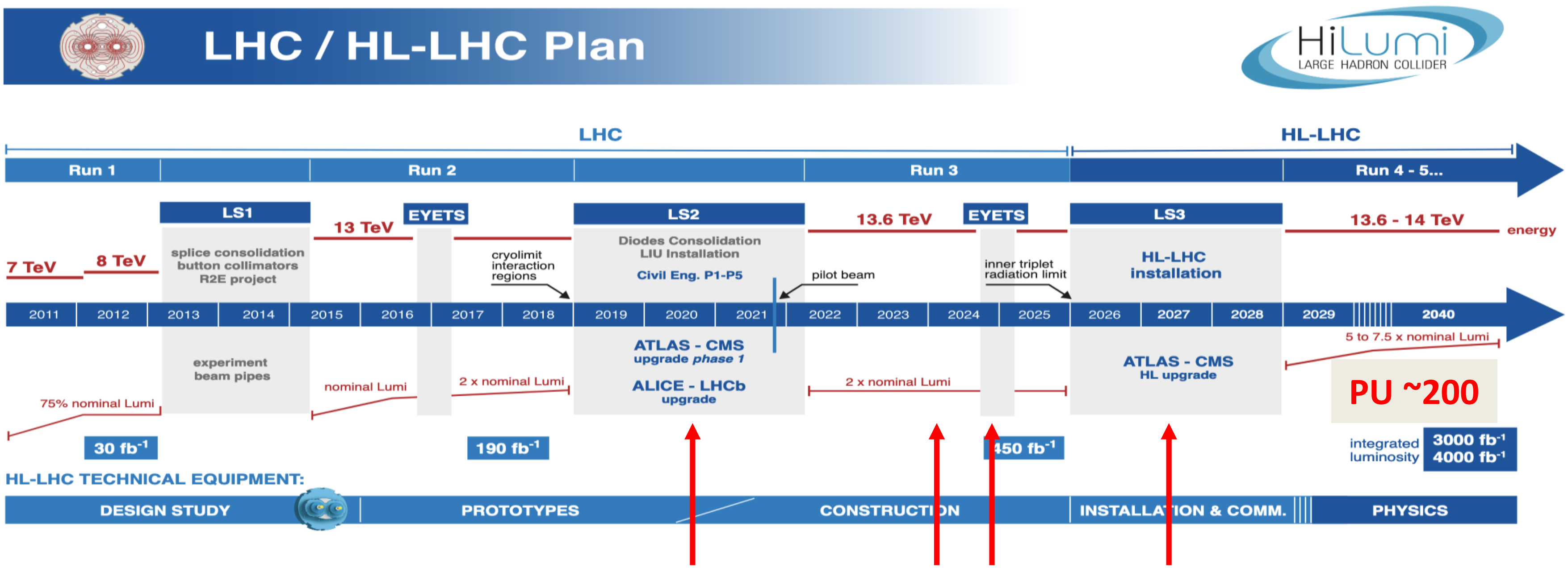
Interlude/Disclaimer

I'll not discuss the genesis of the GEM as technology for particle identification and their possible multiple applications, only the GEM for CMS Experiment

Some interesting references for those who want to broaden the horizon:

- F. Sauli, ***The gas electron multiplier (GEM): Operating principles and applications,*** NIM A, 386 (1997), p. 531
- S. Bachmann, *et al.* **Charge amplification and transfer processes in the gas electron multiplier** NIM A, 438 (1999), p. 376
- A. Bressan, *et al.* **Two-dimensional readout of GEM detectors** NIM A, 425 (1999), p. 254
- A. Bondar, *et al.* **Study of ion feedback in multi-GEM structures**, NIM A, 496 (2003), p. 325
- M. Villa, *et al.* **Progress on large area GEMs** NIM A, 628 (2011), p. 182
- H. Fenker, *et al.* **BoNus: Development and use of a radial TPC using cylindrical GEMs** NIM A, 592 (2008), p. 273
- A. Balla, *et al.* **Construction and test of the cylindrical-GEM detectors for the KLOE-2 Inner Tracker** NIM A, 732 (2013), p. 221
- P. Everaerts, **Rate capability and ion feedback in GEM detectors (Thesis at Gent University)** (2006)
- F. Sauli, **GEM readout of the time projaction chamber** CERN-EP-TA1 Internal Report (1999)
- L. Fabbietti, *et al.* **The PANDA GEM-based TPC prototype** NIM A, 628 (2011), p. 204
- ALICE_Collaboration, **Technical Design Report for the Alice Time Projection Chamber**, 2014.
- Va'vra, A. Sharma **Single electron detection in quadruple-GEM detector with pad readout** NIM A, 478 (2002), p. 235
- R. Bellazzini, *et al.* **Imaging with the invisible light** NIM, 581 (2007), p. 246
- J.A. Mir, *et al.* **Further studies on the gain properties of a Gas Electron Multiplier with a Micro-Induction Gap Amplifying Structure (GEM-MIGAS) aimed at low-energy X-ray detection** NIM A, 580 (2007), p. 1372
- A. Bondar, *et al.* **Two-phase argon and xenon avalanche detectors based on Gas Electron Multipliers** NIM A, 556 (2006), p. 273
- Murtas, F. **The GEMPix Detector**, https://doi.org/10.1016/j.radmeas.2020.106421
- Leidner, J.; Murtas, F.; Silari, M. **Medical Applications of the GEMPix**. Appl. Sci. 2021,11, 440. https://doi.org/10.3390/app11010440
- Leidner, J., Ciocca, M., Mairani, A., Murtas, F. and Silari, M. **A GEMPix-based integrated system for measurements of 3D dose distributions in water for carbon ion scanning beam radiotherapy**. (2020) Med. Phys., 47: 2516-2525. https://doi.org/10.1002/mp.14119
- …..

Timescale of GEM in CMS



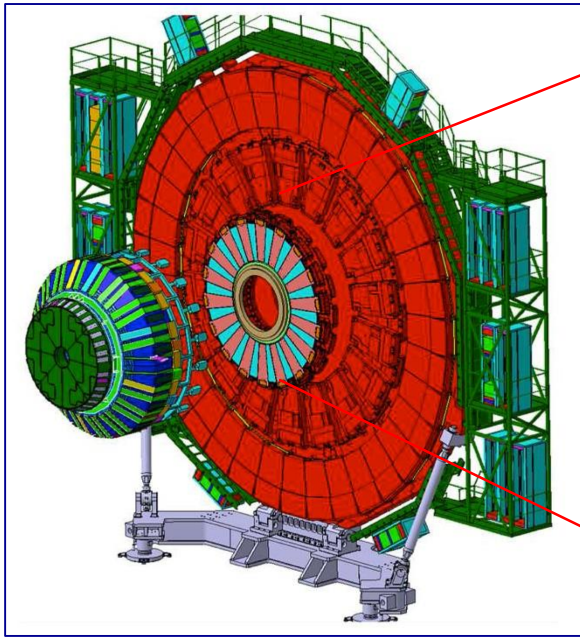
GE1/1

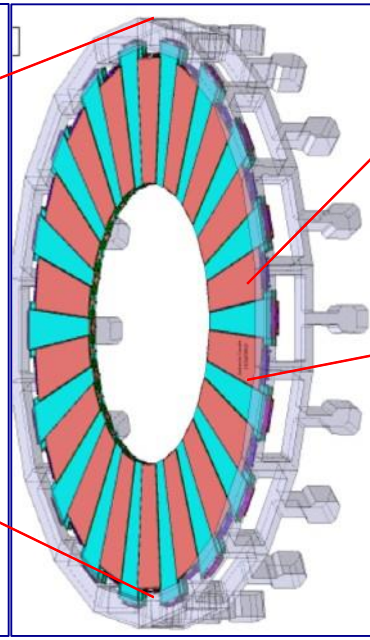
GE2/1

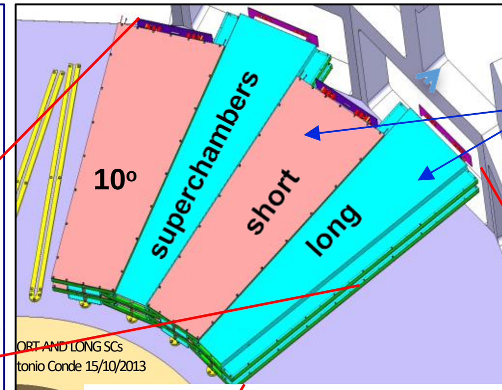
ME0


Apple Records
THE BEATLES
THE LONG AND WINDING ROAD
The long and winding road
toward the GEMs for CMS
ME0
GE2/1
GE1/1
30x30 cm
10x10 cm
CMS DT MUON contact
Di Vincenzo 164055

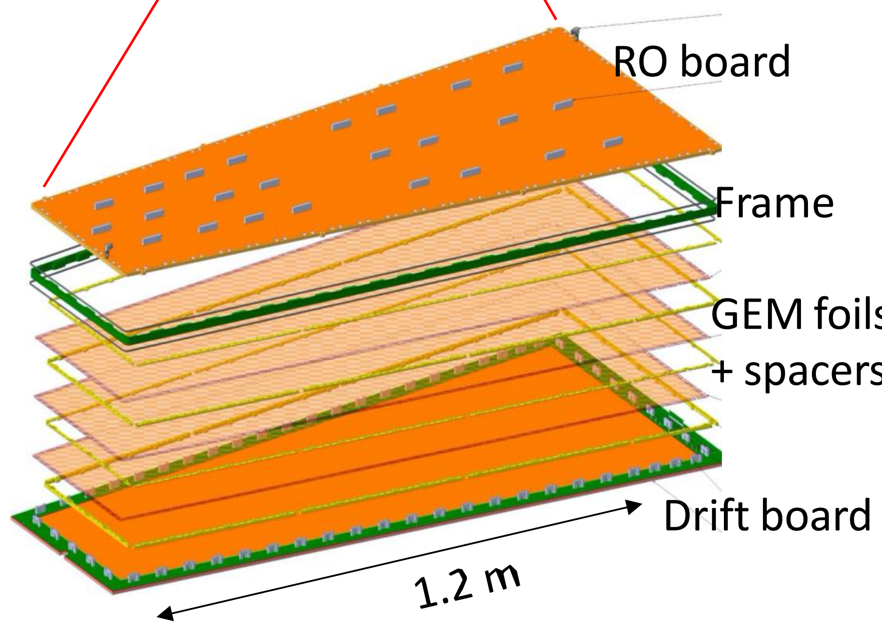
The GE1/1 Project





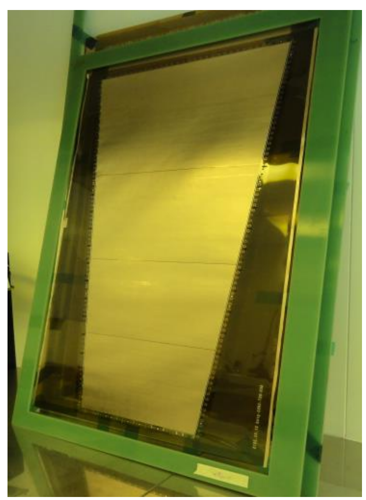


Two different shapes (long and short) to fit the CMS mechanical structure

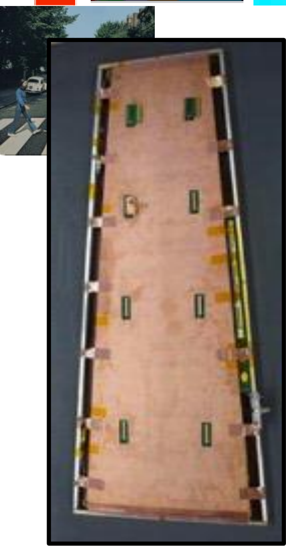


Triple-GEM detectors for the CMS upgrade:

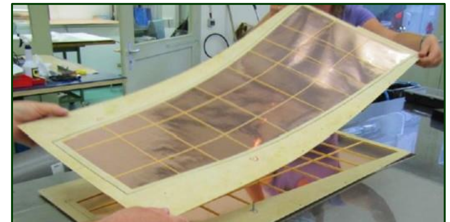
- Trapezoidal chambers up to 1.2 m long
- 144 chambers associated in pairs (super-chambers) to form two disks, one per end-cap



Chamber story



GE1/1-I



GEM foils on their frames

Thermo-stretching

Museum

2010 | 2011 | 2012 | 2013 | 2014

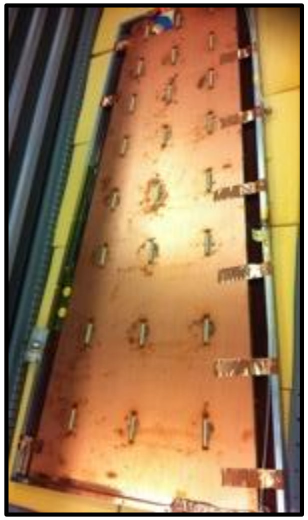
R&D phase | Toward production phase

GE1/1-I

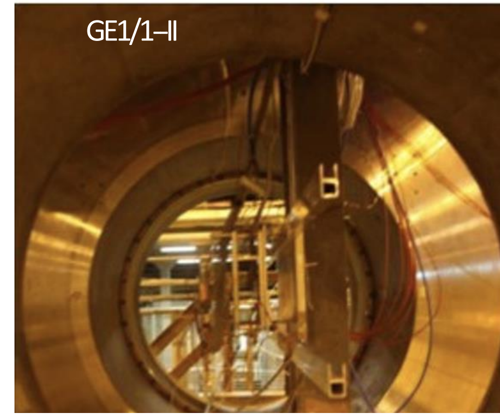
-> first 1m-class GEM detector ever built
-> single-mask technology
-> 99x(22-45) cm^2
-> 1024 readout channels
-> gap config. 3/2/2/2
-> use of spacer grid and glue

Chamber story

GE1/1-I



GE1/1-II



CMS M1 magnet: 3 T with a current around 4000 A GE1/1 region reaches 1.5 T

2010 | 2011 | 2012 | 2013 | 2014

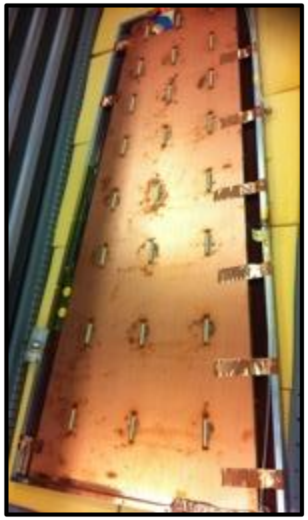
R&D phase | Toward production phase

GE1/1-I
-> first 1m-class GEM detector ever built
-> single-mask technology
-> 99x(22-45) cm^2
-> 1024 readout channels
-> gap config. 3/2/2/2
-> use of spacer grid and glue

GE1/1-II
-> Optimization of the electric field configuration
-> single-mask technology
-> 99x(22-45) cm^2
-> 3072 readout channels
-> gap config. 3/1/2/1
-> use of spacer grid and glue

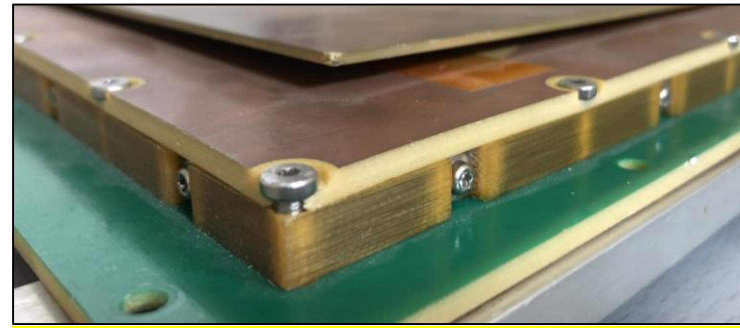
Chamber story

GE1/1-I



GE1/1-II

GE1/1-III



Pictures of the GE1/1 generation III external frame

2010 2011 2012 2013 2014

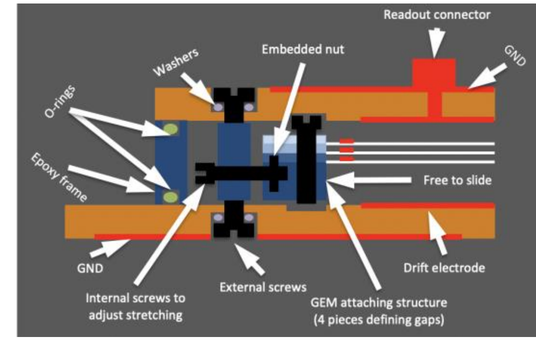
R&D phase — Toward production phase

GE1/1-I
-> first 1m-class GEM detector ever built
-> single-mask technology
-> 99x(22-45) cm^2
-> 1024 readout channels
-> gap config. 3/2/2/2
-> use of spacer grid and glue

GE1/1-II
-> Optimization of the electric field configuration
-> single-mask technology
-> 99x(22-45) cm^2
-> 3072 readout channels
-> gap config. 3/1/2/1
-> use of spacer grid and glue

GE1/1-III
-> first use of the self-stretching technique
-> single-mask technology
-> 99x(22-45) cm^2
-> 3072 readout channels
-> gap config. 3/1/2/1
-> No spacers but glue on the external frame

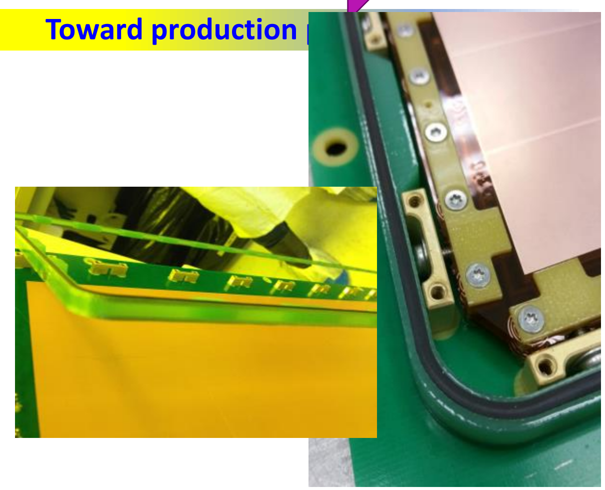
Chamber story



GE1/1-I GE1/1-II GE1/1-III GE1/1-IV

2010 2011 2012 2013 2014

R&D phase Toward production



GE1/1-I

-> first 1m-class GEM detector ever built
-> single-mask technology
-> 99x(22-45) cm^2
-> 1024 readout channels
-> gap config. 3/2/2/2
-> use of spacer grid and glue

GE1/1-II

-> Optimization of the electric field configuration
-> single-mask technology
-> 99x(22-45) cm^2
-> 3072 readout channels
-> gap config. 3/1/2/1
-> use of spacer grid and glue

GE1/1-III

-> first use of the self-stretching technique
-> single-mask technology
-> No spacers but glue on the external frame
-> Stretching against the external frame

GE1/1-IV

-> Finalization of the stretching technique
-> Introduction of the pull-out
-> No glue/no spacers
-> Assembly time reduced from 1 week to 2h!!!

Chamber story

GE1/1-I | GE1/1-II | GE1/1-III | GE1/1-IV | GE1/1-V

2010 | 2011 | 2012 | 2013 | 2014

R&D phase | Toward production phase

GE1/1-I

-> first 1m-class GEM detector ever built
-> single-mask technology
-> $99x(22\text{-}45)\ cm^2$
-> 1024 readout channels
-> gap config. 3/2/2/2
-> use of spacer grid and glue

GE1/1-II

-> Optimization of the electric field configuration
-> single-mask technology
-> $99x(22\text{-}45)\ cm^2$
-> 3072 readout channels
-> gap config. 3/1/2/1
-> use of spacer grid and glue

GE1/1-III

-> first use of the self-stretching technique
-> single-mask technology
-> No spacers but glue on the external frame
-> Stretching against the external frame

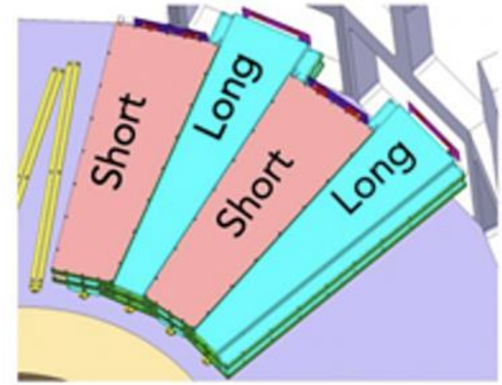
GE1/1-IV

-> Finalization of the stretching technique
-> Introduction of the pull-out
-> No glue/no spacers
-> Assembly time reduced from 1 week to 2h!!!

GE1/1-V

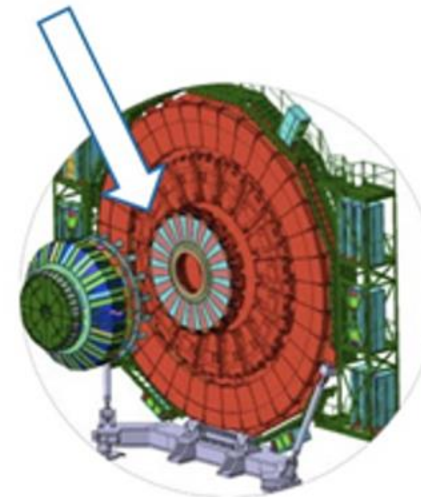
-> GE1/1 final layout
-> Modules used to design the QA/QC setup
-> Modules distributed to the production sites for assembly and QA/QC training

Chamber story



GE1/1-VI

2015	2016	2017-2018-2019
TDR	Slice test installation	Production phas



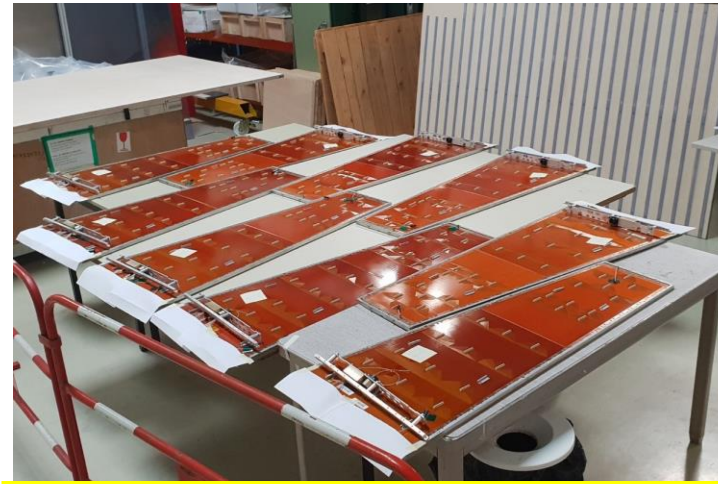
GE1/1-VI

-> Latest detector design Optimization
-> Final dimensions for maximum acceptance (Long/Short) chamber

Chamber story

GE1/1-VI

GE1/1-VII



GE1/1 Slice Test Production

2015 | 2016 | 2017-2018-2019

TDR | Slice test installation | Production phase & installation

<u>GE1/1-VI</u>

-> Latest detector design Optimization
-> Final dimensions for maximum acceptance (Long/Short) chamber

<u>GE1/1-VII</u>

-> First Production in series of GE1/1 chambers (10 modules)
-> Process definition of the GE1/1 chamber assembly and certification

Chamber story

GE1/1-VI

GE1/1-VII

GE1/1-X

2015 | **2016** | **2017-2018-2019**

TDR | **Slice test installation** | **Production phase & installation**

GE1/1-VI

-> Latest detector design Optimization
-> Final dimensions for maximum acceptance (Long/Short) chamber

GE1/1-VII

-> First Production in series of GE1/1 chambers (10 modules)
-> Process definition of the GE1/1 chamber assembly and certification

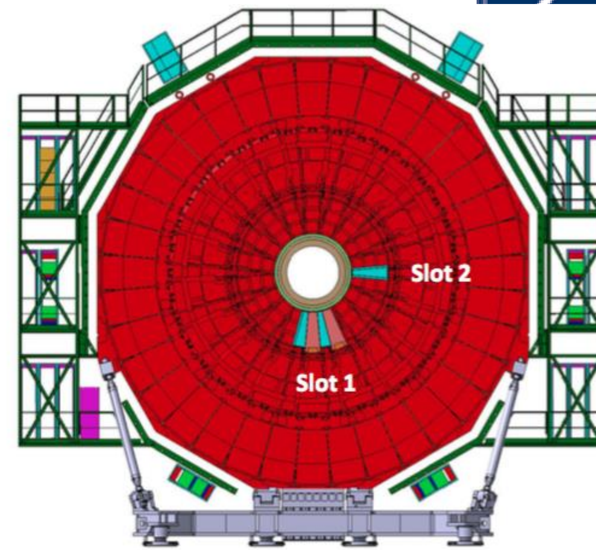
GE1/1-X

-> External (w.r.t . CERN) production sites certification and chamber components shipment
-> GE1/1 chamber assembly and certification
-> Super chamber mechanics optimization
-> First test with final front-end electronics
-> GE1/1 super chamber assembly and certification with final front-end electronics

The GE1/1 Slice Test

Demonstrator with 5 SuperChambers (SC) 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 SCs*:

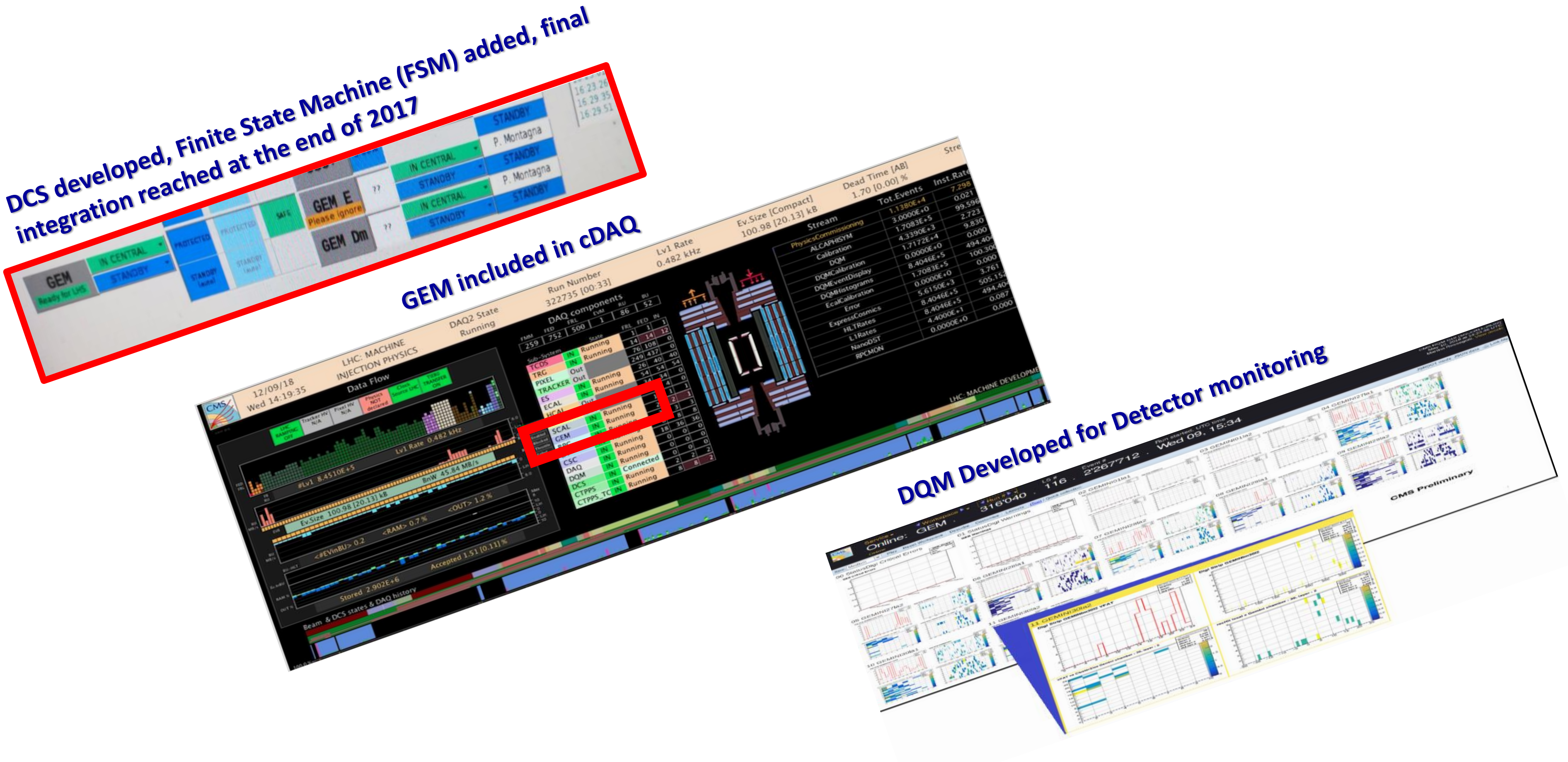
- High Voltage supplied with a **single HV channel** per detector (8 HV channels in total)
- The HV is distributed to the detector's electrodes through a voltage divider
- Readout system based on **VFAT2 ASICs**

SLOT - 2 → 1 *SC:*

- HV 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**

The GE1/1 Slice Test

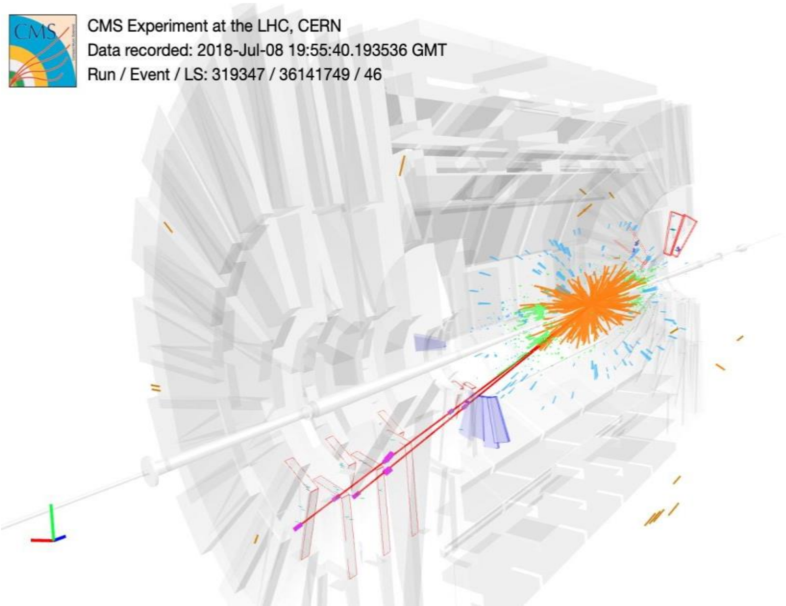
Slice Test exercise has been a fundamental opportunity to develop and test in situ the whole GE1/1 system (DAQ, DCS, DQM), and train a new generation of young expert



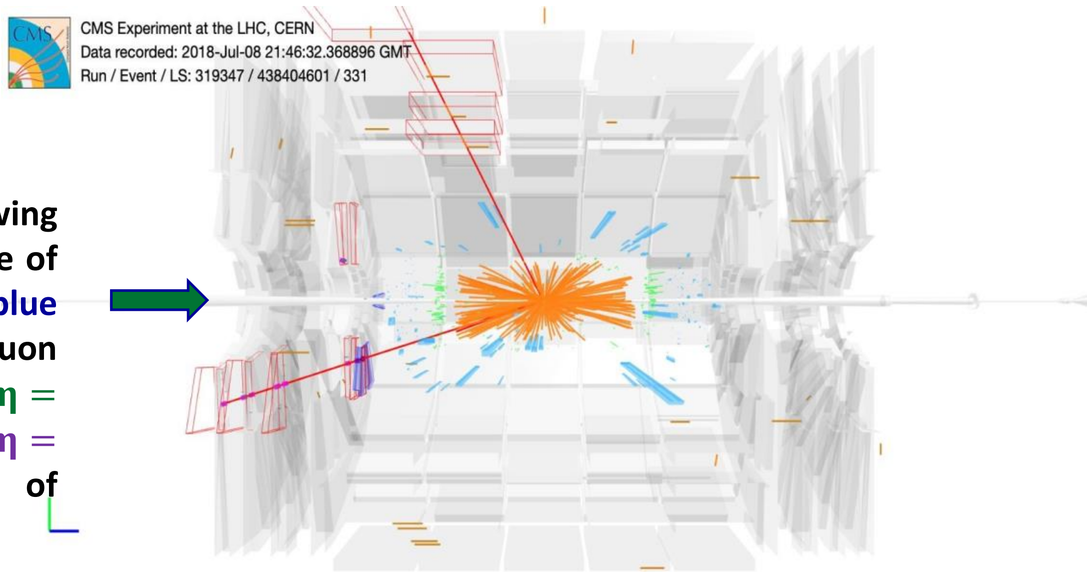
The GE1/1 Slice Test

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*).

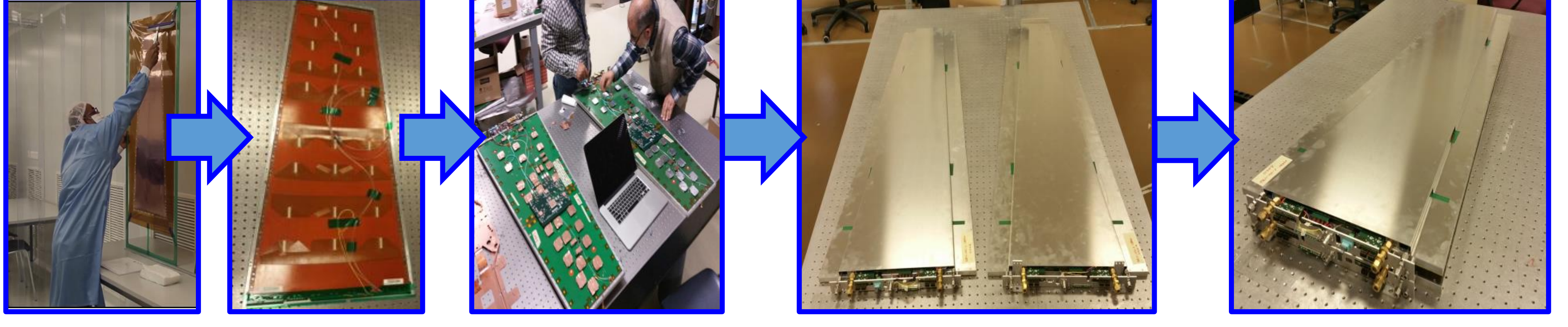


LHC run2 2018C p-p collision event display showing two muons (red lines), associated with hits on one of the five GE1/1 slice test super-chambers (blue trapezoidal boxes) at station 1 of the endcap muon system. The antimuon ($p_T = 34.01\ GeV/c^2, \eta = -0.540$) and muon ($p_T = 37.63\ GeV/c^2, \eta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

Mass Production & QA/QC

You want to arrive here

How to do?



Mass Production & QA/QC

What do you need?

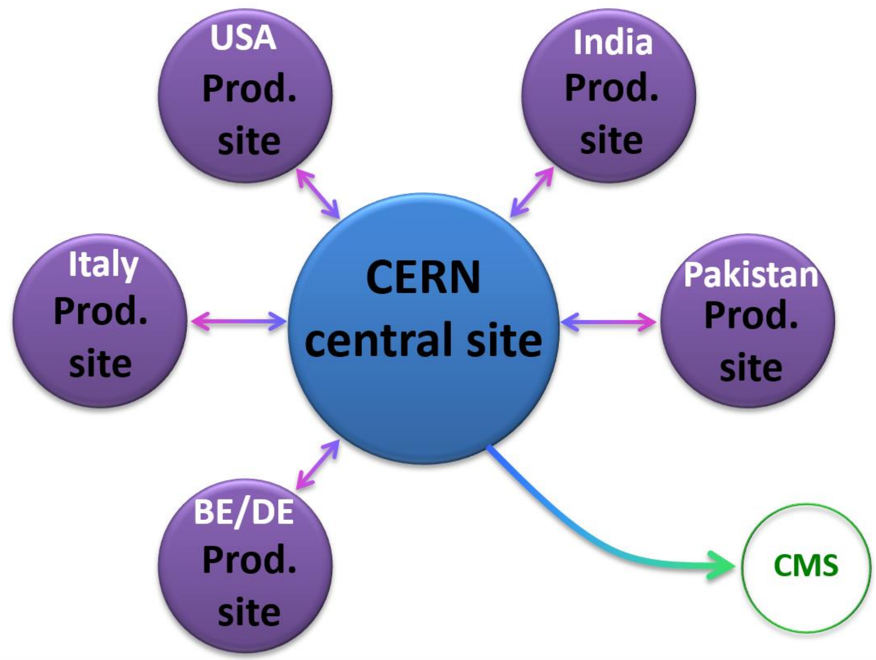
- A plan
- Infrastructures & Tools
- Validated process and certified manuals
- Time
- A Strong TEAM!!!

J.A. Merlin
GEM Production Manager

The Plan: General Organization

→ Distribution of the production in various sites:

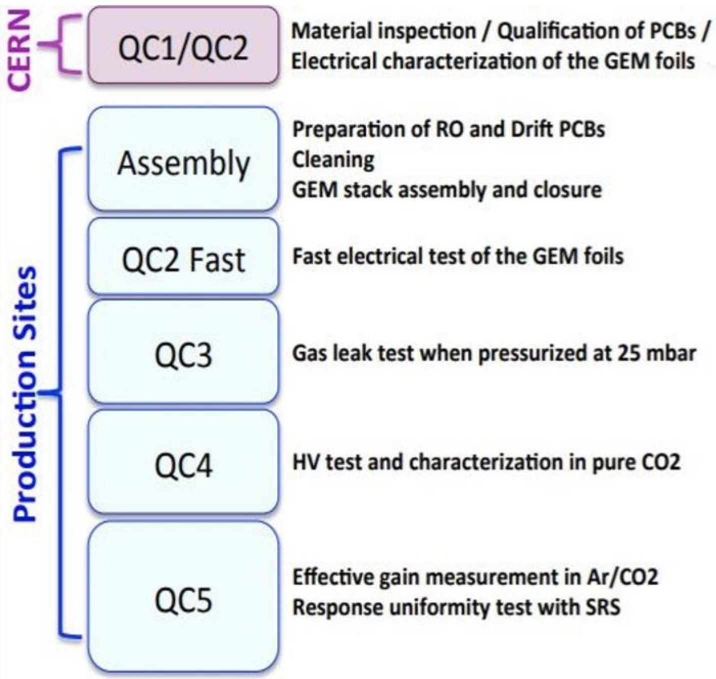
- **Share the effort with CMS - GEM institutes**
- **Generate a large community of GEM experts**
- Equip production sites with infrastructure, tooling and knowledge for GE2/1 and ME0 productions



→ 2-years training program

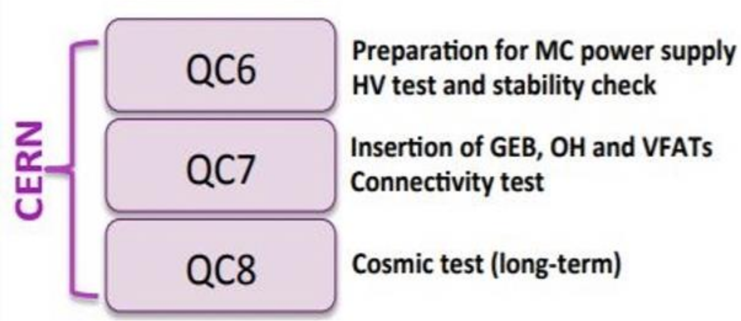
- **Using same procedure**
- **Using equivalent infrastructu**
- All Quality Control deliverables validated by the production community

The Plan: Production and QA/QC

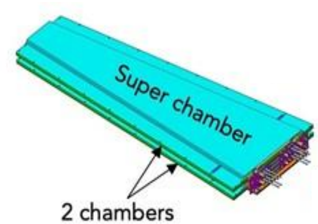


"Single-chamber" production summary:

- ✓ Successful and on-time production of both endcaps from Sept. 2017 to Dec. 2018
- ✓ In total 161/144 GE1/1 detectors:
  - 2 used for R&D activities (aging and discharge studies)
  - 3 required in-depth investigation (discarded)
  - 156 fully validated up to QC5 (yield > 97%)



"Super-chamber" production summary:



- ✓ 100% completed (76/72 needed in CMS)

Infrastructures & Tools

<u>New production facility in B904:</u>

- Clean room class 1000 and better - 102 m^2 + 18 m^2 (SAS) -
  - → Zone with improved class quality for detector assembly
  - → Can accommodate two production lines in parallel
- Test laboratory in 904/R-D09 (previously RPC) - 284 m^2 + storage space -
  - → Can accommodate two testing lines in parallel
  - → Can handle the last steps of the SC assembly and commissioning

Infrastructures & Tools

The Clean Room in 904 building

X-Ray Boxes & RP Area

The GEM QA/QC Lab (*T*he cosmic stand)

The process and the manuals

Manual for production site inspection and validation

GE1/1 Production Site Checkout Document

M. Bianco[1], B. Dorney[2], J. Merlin[3] on behalf of the *CMS Muon Group*

Manual for chamber assembly (+ dedicated papers)

Technical Assembly Manual for GE1/1 Chambers

M. Abbas[2, 3], M. Bianco*[2], M. Gola†[1], J. A. Merlin‡[2], R. De Oliveira[2], and A. Shah[1]

GE1/1 Quality Control : instructions

Michele Bianco*, Brian Dorney†, Jeremie A. Merlin‡

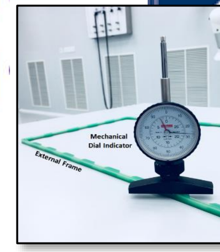
Manual for chamber qualification and certification

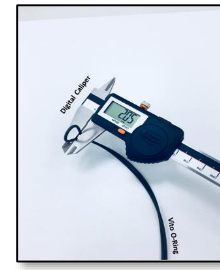
Assembly video tutorial illustrates the preparation and the assembly (1,5 h video)

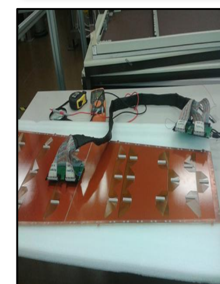
Assembly training at CERN, 10 sessions, components of all production sites

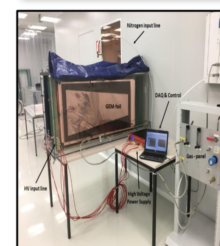
The GE1/1 QA/QC (Chamber components)

CERN { QC1, QC2









→ *Internal / external frames*

- Optical inspection to identify possible cracks,
- Measurements of the width and depth of the grooves that will accommodate the Viton O-ring

→ *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

→ *Drift/RO PCBs*

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

→ *GEM Foils (Fast & Long Test)*

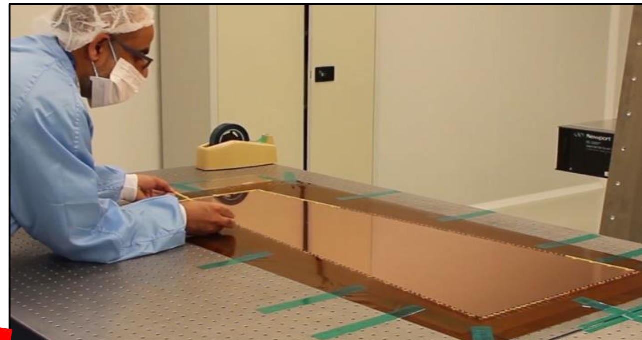
- Fast: Inspection for major defects, test with manual Insulator/Continuity tester (10 minutes, counting for eventual sparks)
- Long: Ultimate certification of the GEM-foils before the installation in the GE1/1 detectors, conducted using HV module with 50 pA of current resolution, GEM foils exercised in different steps between 100 and 600V in pure N2.

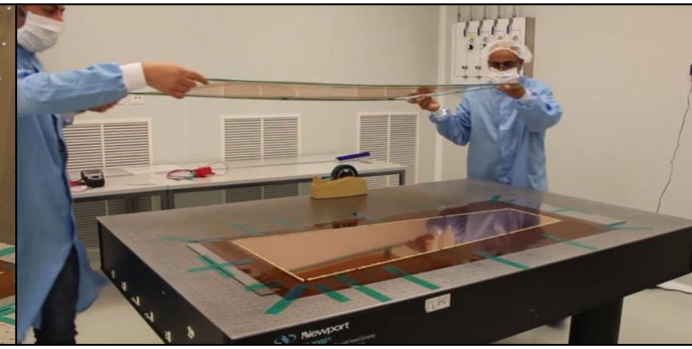
Full Process of GE1/1 Components QA/QC in Backup (Annex A)

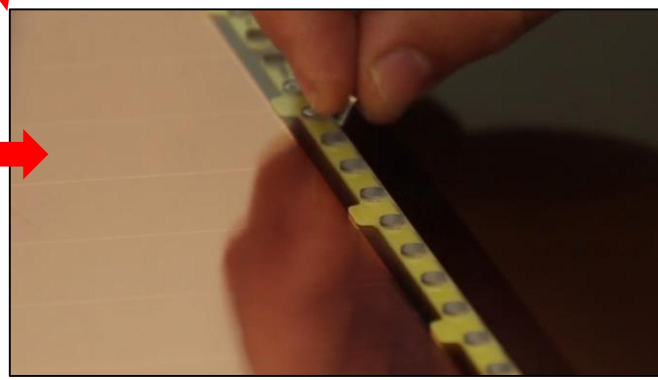
Assembly of GE1/1 chamber

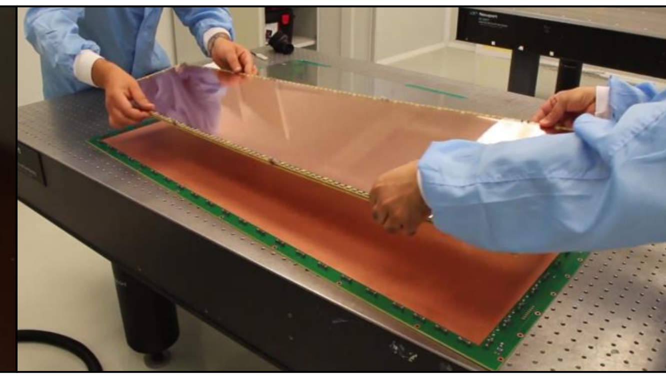
Production sites
- Assembly
- QC2 GEM-foils Test (fast)
- QC3 Gas Leak Test
- QC4 HV Test
- QC5 Gas Gain Calibration

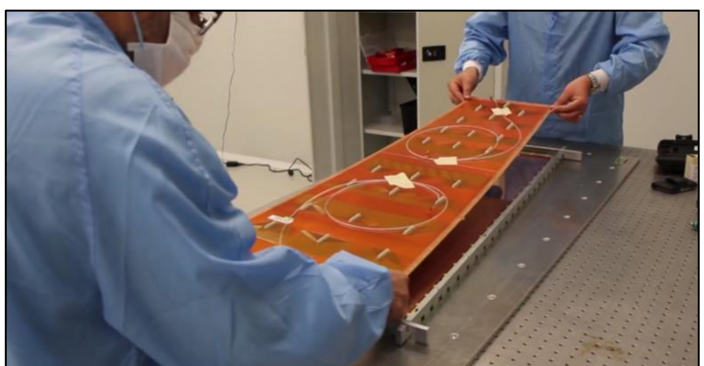
Foils stretched by hand, attached to the working table, the stack is assembled and fixed by means of FR4 frames than moved inside the Drift PCB Board







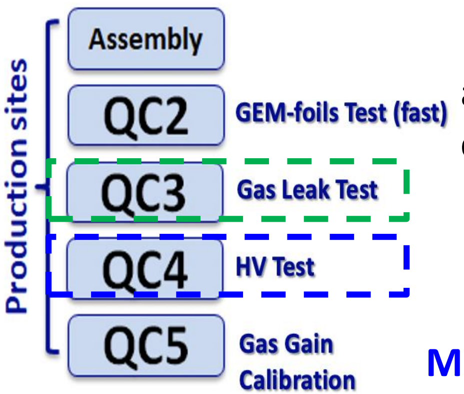




Foils stretched against the "pull out" and chamber closed placing the Readout Board

Full Assembly Process in Backup (**Annex B**)

The GE1/1 QA/QC (assembled chamber)



Motivation:

To check gas-tightness and avoid gas leaks

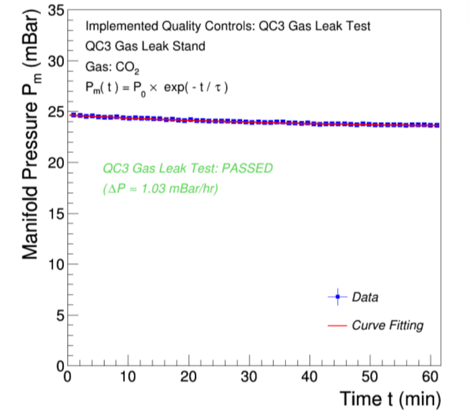
Acceptance criteria:

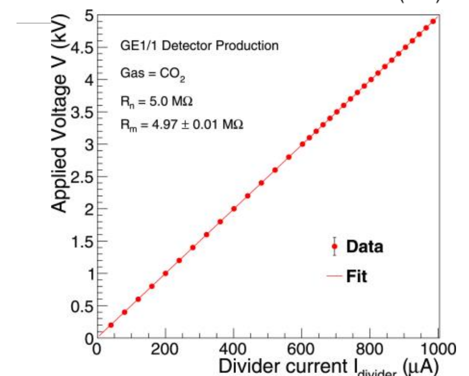
The detector under test is validated if the pressure drop in the detector + gas system does not exceed:

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

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

$$\tau \geq 3.04\ hr$$





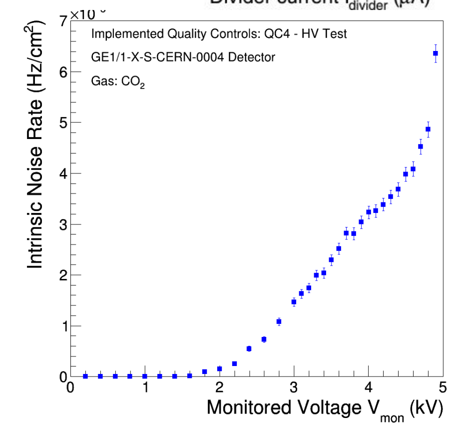
Motivation:

To check the on-detector circuitry & Intrinsic Noise

Acceptance criteria

$$\frac{|R_{measured} - R_{expected}|}{R_{expected}} \times 100\% \leq 3\%$$

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



Full Process of GE1/1 Chamber QA/QC in Backup (Annex C)

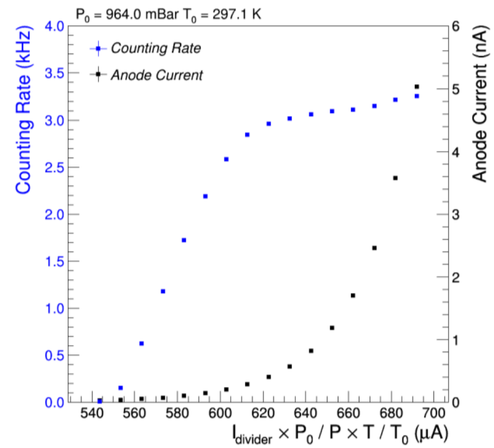
The GE1/1 QA/QC (assembled chamber)

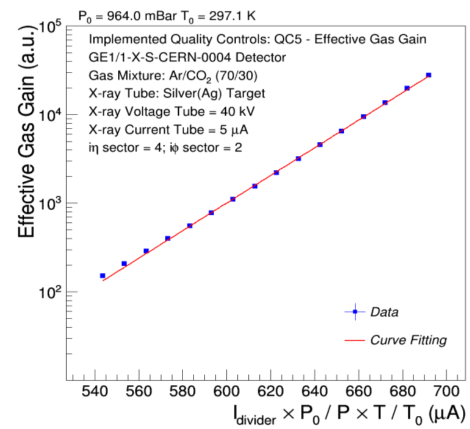
Production sites:
- Assembly
- QC2 — GEM-foils Test (fast)
- QC3 — Gas Leak Test
- QC4 — HV Test
- QC5 — Gas Gain Calibration

- Measurement taken in Ar/CO2 70/30
- Both tests performed inside a copper box using an X-ray generator (~ 22 keV X − rays)

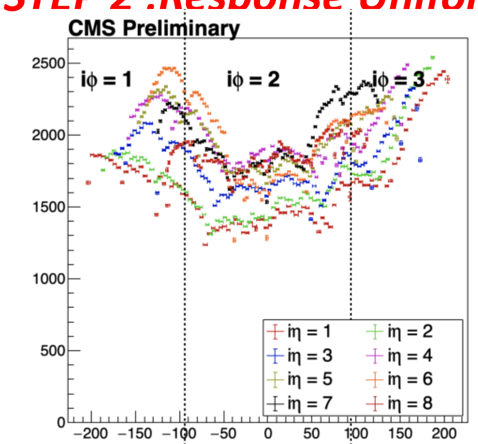
STEP 1: Effective Gas Gain Measurement

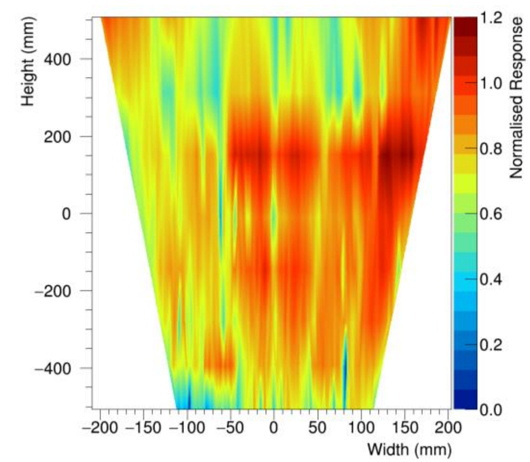
Effective gas gain versus HV in one readout sector, the Effective gas gain is defined as: $G_{eff} = \frac{I_{RO}}{(n_p \times q_e \times R_s)}$





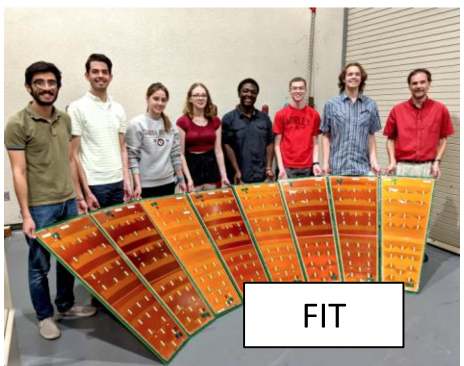
STEP 2 :Response Uniformity Measurement gas gain variations map

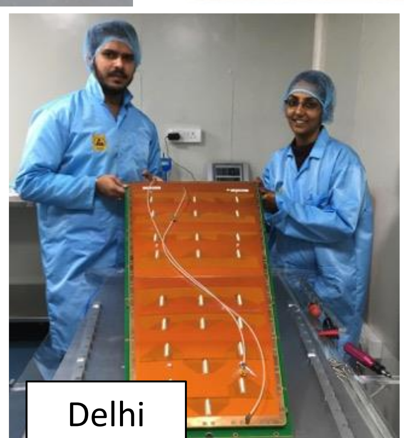




Full Process of GE1/1 Chamber QA/QC in Backup (**Annex C**)

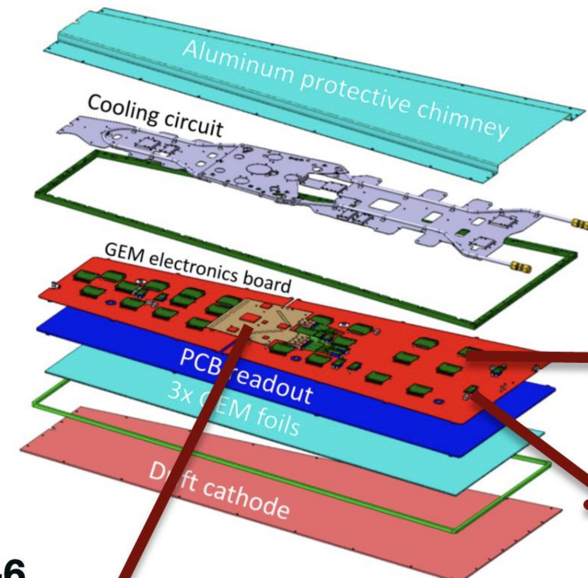
The Team!!!



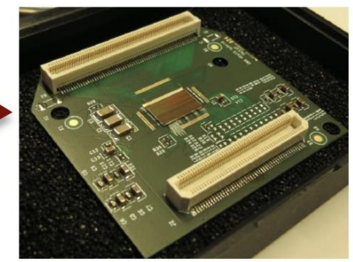


The Production Manager!!!

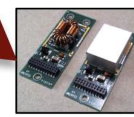
The GE1/1 electronics

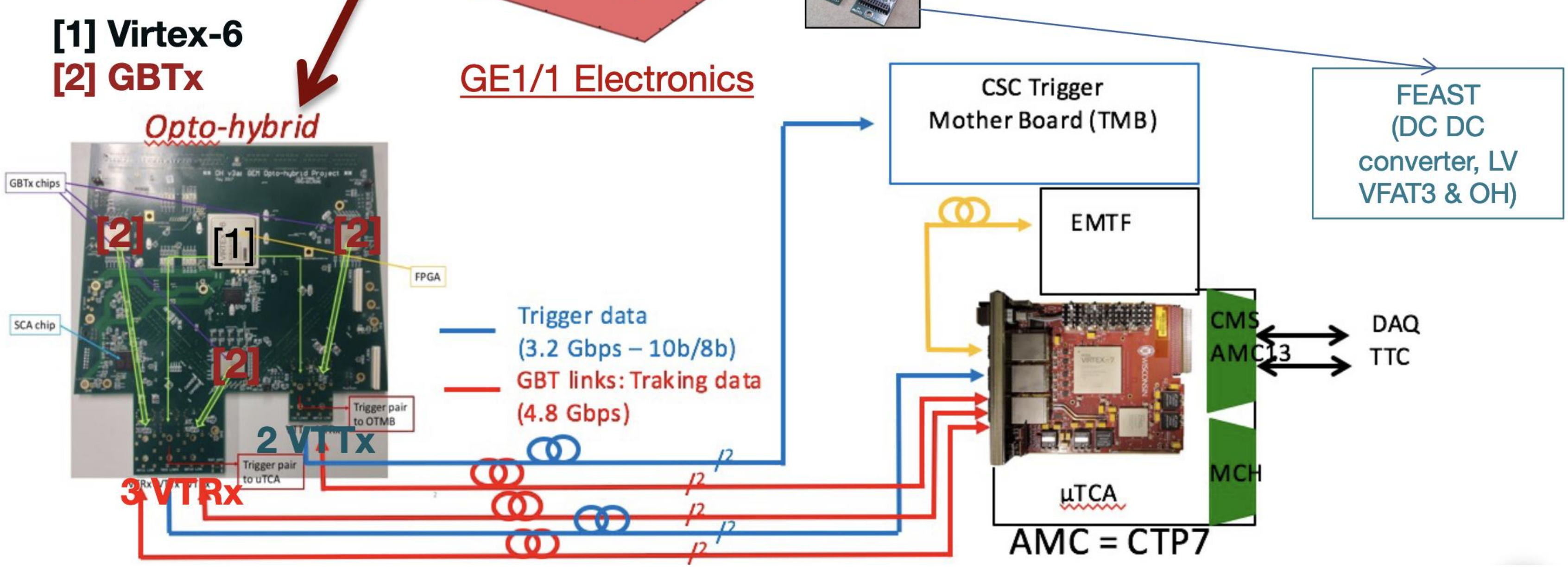


GE1/1 system:
- 72 Super-Chambers (SC)
- 3456 VFAT3 chips
- 432 GBT + VTRx optical link (DAQ path)



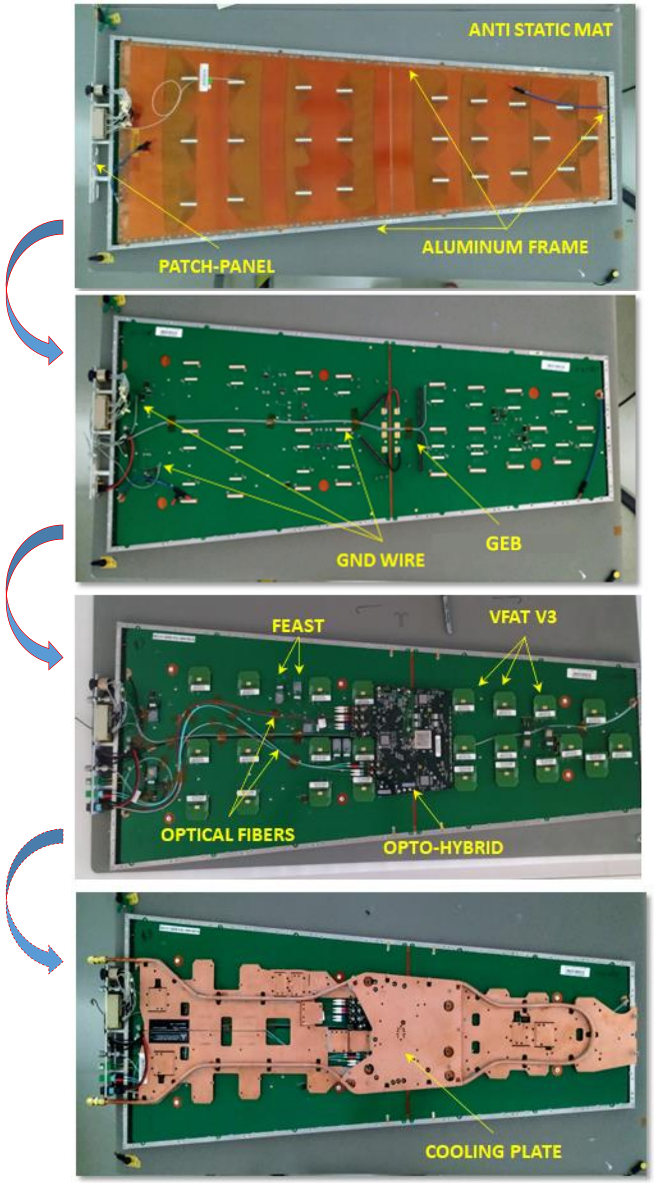
FE chip: VFAT3
- 24 VFAT3 / chamber
- 128 channels / chip
- Binary readout
- Tracking + Trigger data





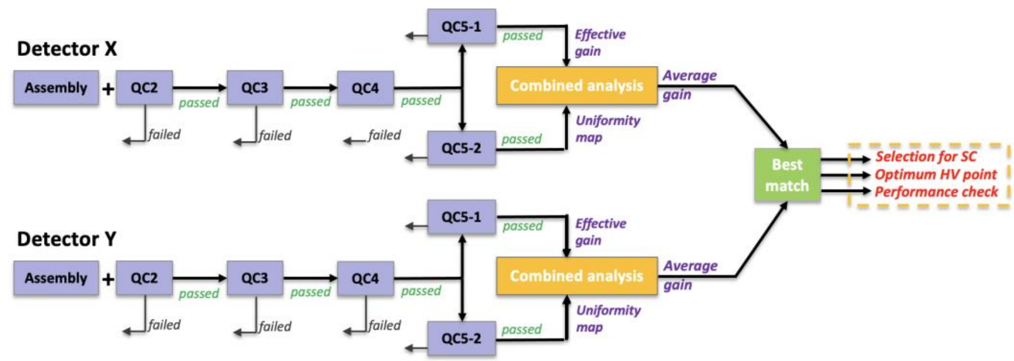
The electronics integration on the GE1/1 chambers

- Mounting of the GEB and on-chamber services (LV, gas pipes, grounding)
- Mounting of the OH and optical fibers
- Mechanical fixation of all components
- Verification of the voltages at the OH and FEAST levels
- First round of electronic connectivity test & noise measurement
- Cooling installation
- Second round of electronic connectivity test & noise measurement



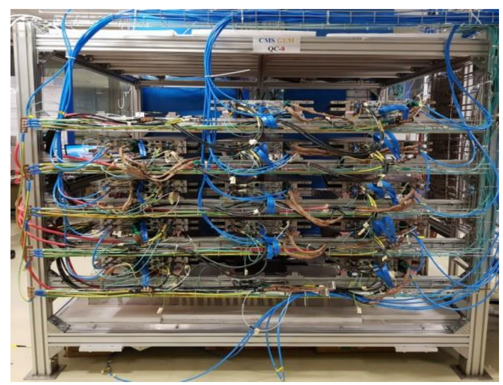
Super Chamber coupling & QA/QC

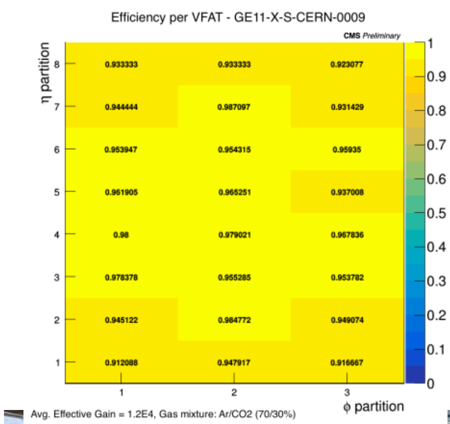
- **Chamber selection for SC assembly**
  - Define the detector pool (not already paired, QCs passed and validated)
  - Compile the QC data to select the chambers with the most <u>similar characteristics</u>



Super-Chamber (SC) validation

- Test the SC at nominal HV (check for possible discharges or instabilities)
- Measure the SC performance using cosmic rays (2 weeks-long test)





Final tests

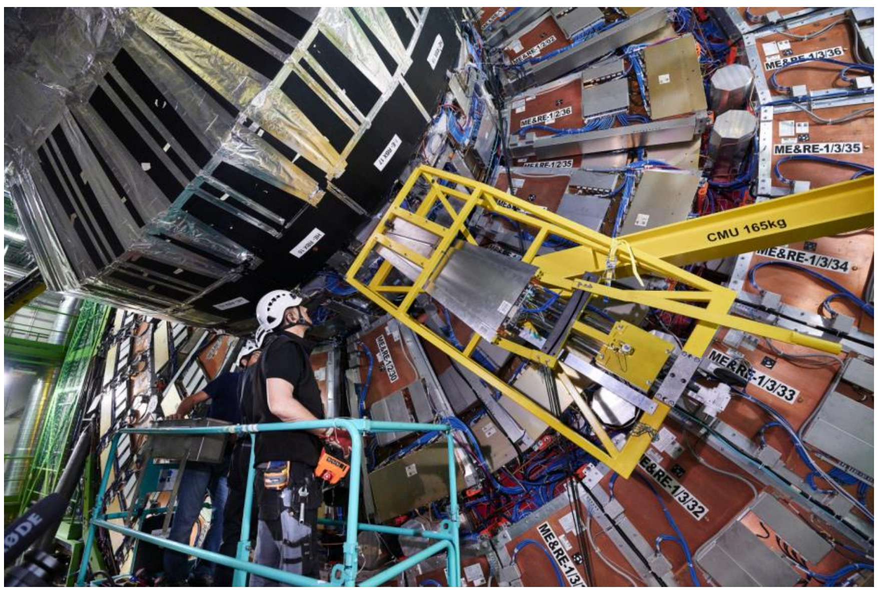
- Check for possible leaks on the cooling system
- Measure the relative position of the two layers in the SC (photogrammetry)
- Last verification of the patch panel connections

Ready! Move to P5

GE1/1 Super-Chamber Installation Overview

GE-1/1 SCs installation in the negative end-cap

- ✓ Installation of all 36 super-chambers for the first end-cap completed in Oct. 2019
- ▪ Multiple installation windows from July 2019 to October 2019



GE-1/1 SCs installation in the positive end-cap

- ✓ Installation of all 36 super-chambers for the second end-cap completed in Sept. 2020
- ▪ Installation and commissioning phase delayed to the COVID-19 lockdown

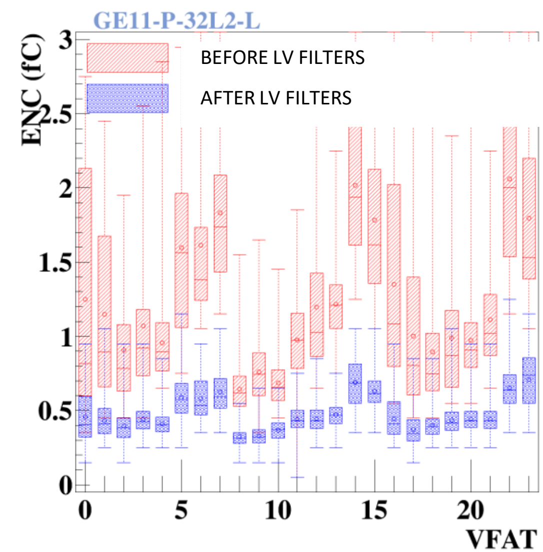
Nice pictures and movies of this story available at: http://cds.cern.ch/record/2684028 & https://www.youtube.com/watch?v=fU0ujGWbeQ0&feature=youtu.be

The early commissioning

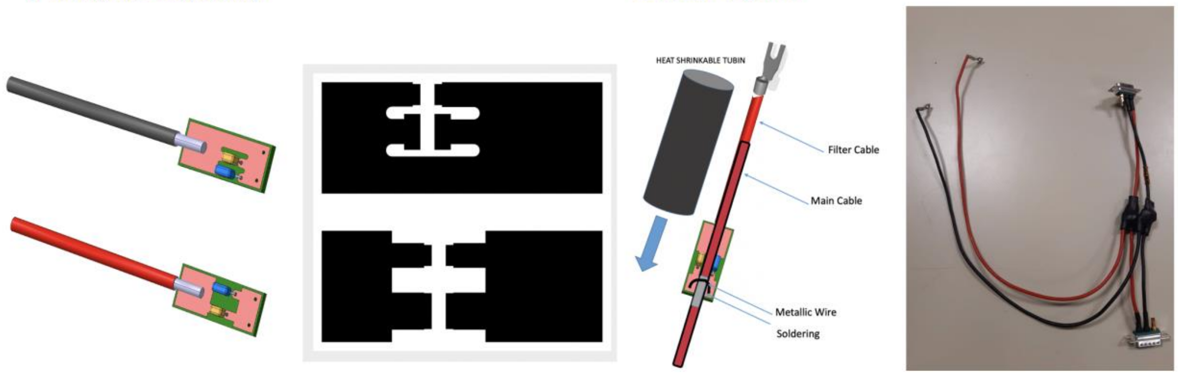
- Ritual HV/LV/Gas/RO Fiber … (in two words Detectors Services) maps checks
- HV training for GEM foils before applying regular HV settings

You’re ready to go for data taking but ..

- High levels of **noise** in the detector were measured already during early 2020 commissioning and confirmed at the end of the installation
  - Extensive campaign to investigate noise level in spring ’21
  - Due to conflicting schedule of operations and experts, the testing campaign was conducted at night after the end of the daily operations
- Effect was found to be linked to the GEM LV system
  - **LV filters** were developed to improve substantially the noise level in most of the problematic chambers
  - Installation of the filters conducted in May 2021



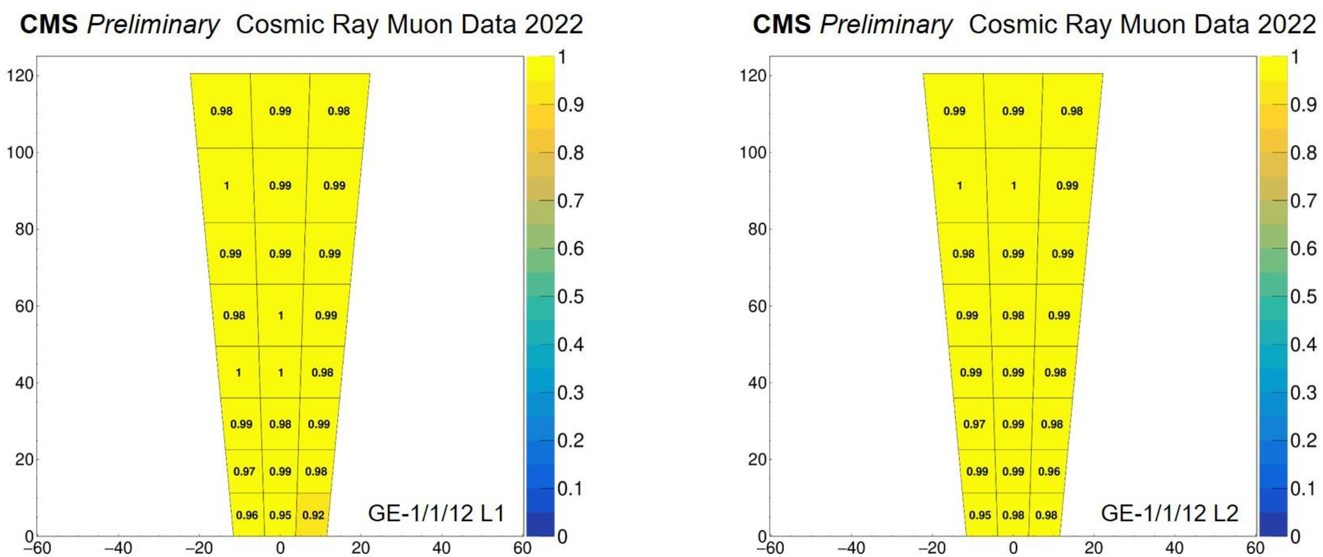
LV-/LV+ Filters (PCB with SMD components) | PCB layout (34 um of coppers) | Filter application and connection to ground | Adapter for P5



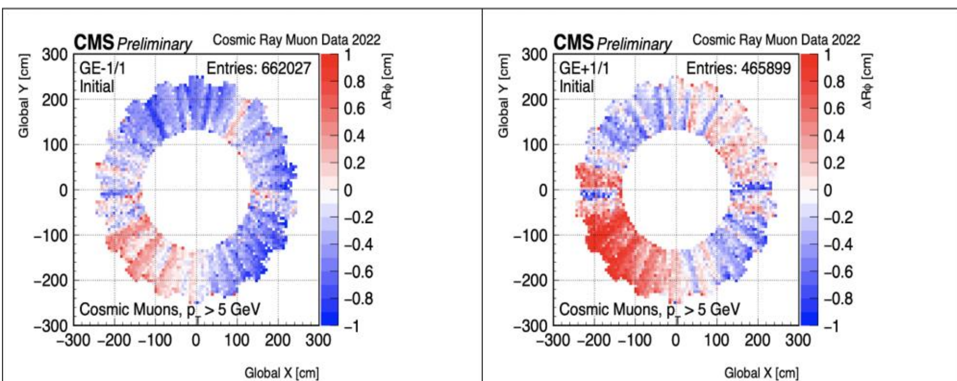
As ALICE number of trips at the first Magnet ramp up, summary of dedicated studies at the following link:

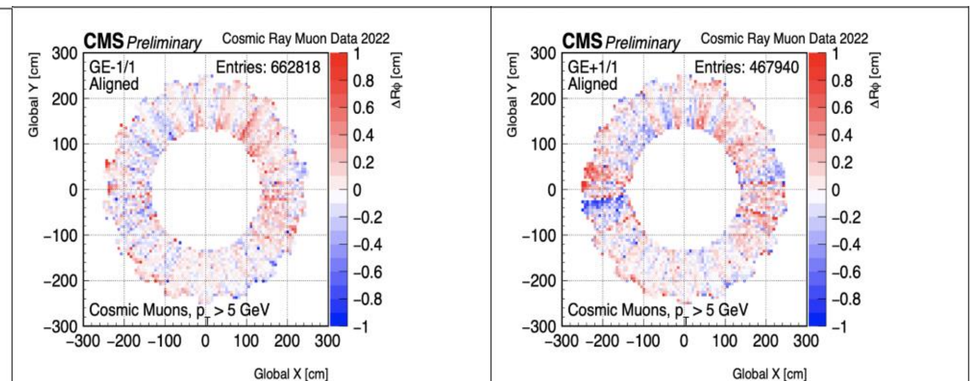
https://agenda.infn.it/event/22092/contributions/167812/attachments/91050/123179/Scalzafe_PisaPoster_Draft_5.pdf

Commissioning with Cosmics



Efficiency (per VFAT) on Layer 1 (left) and Layer 2 (right) of GE1/1 superchamber 12 in the minus endcap for cosmic ray muons taken in 2022.



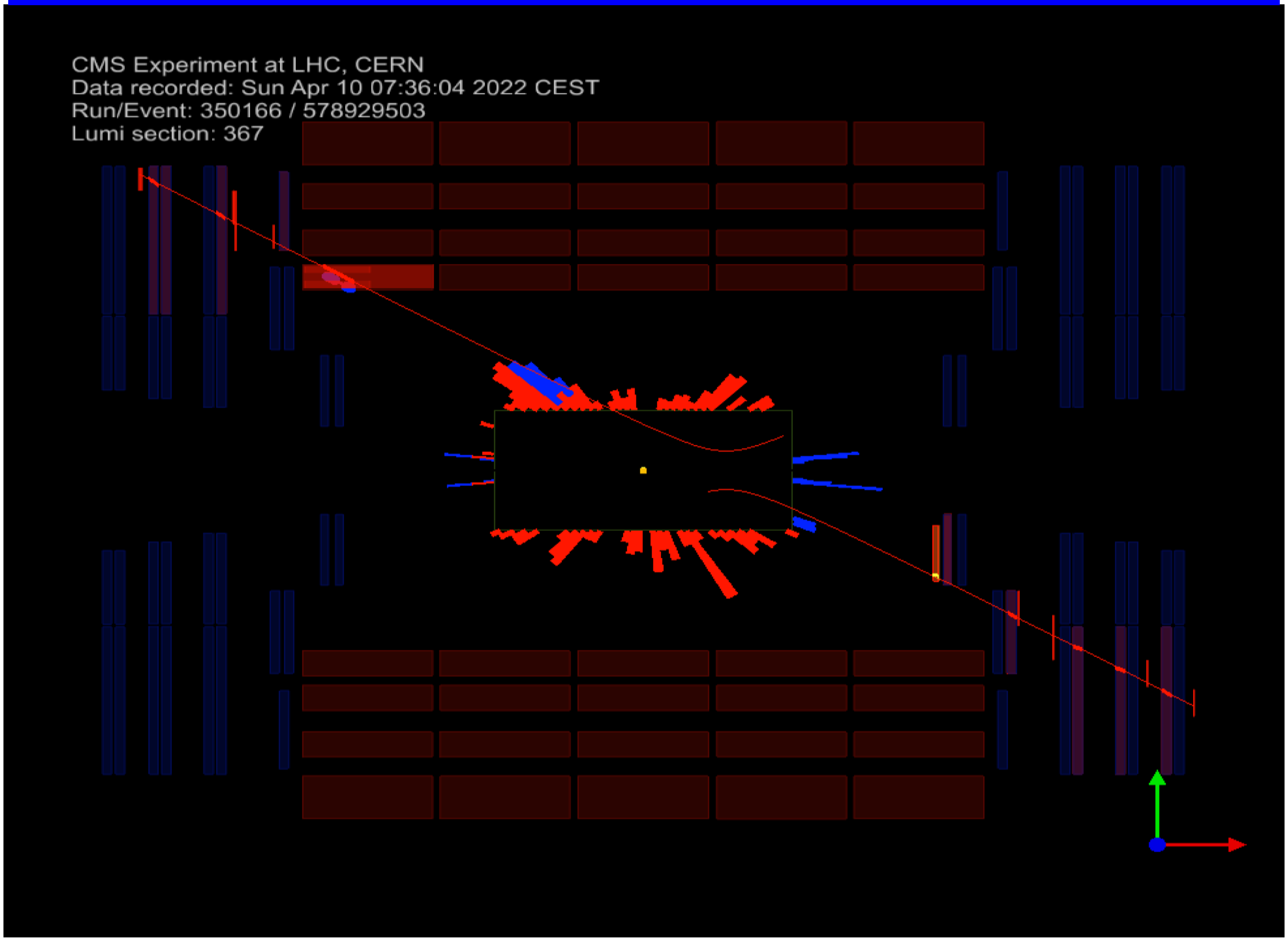


Residual map on GE1/1 superchambers (before its alignment) relative to the ME1/1 geometry

Residual map on GE1/1 superchambers (after its alignment) relative to the ME1/1 geometry

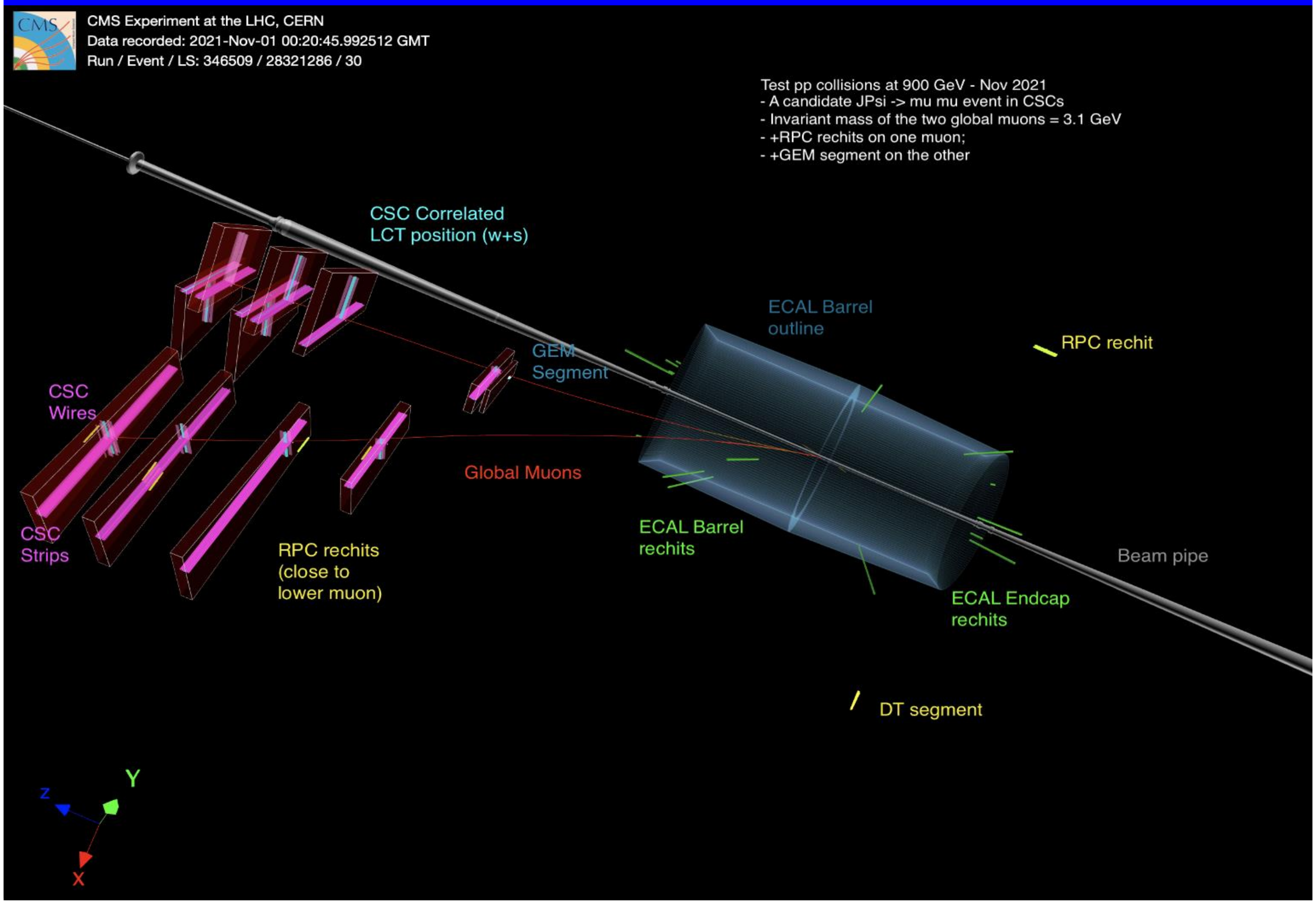
Commissioning with Cosmics

2022 CRAFT MUON IN GEM (+CSC +RPC)



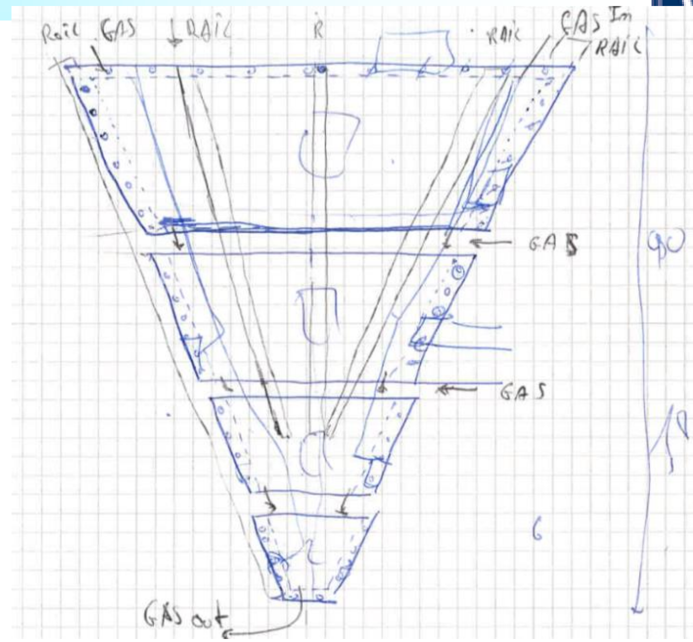
Commissioning with Beam

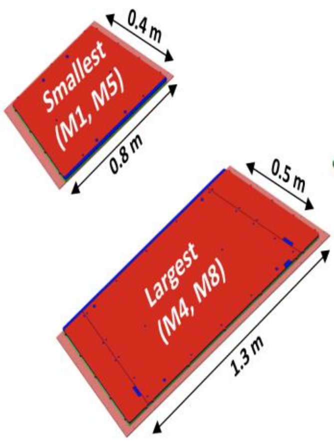
2021 TEST COLLISION DI-MUON IN GEM (+CSC +RPC)



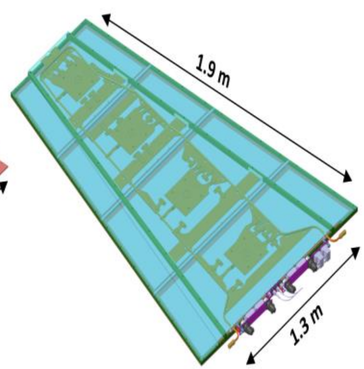
The GE2/1 Project

- Triple-GEM technology (same as GE1/1)
- 36 GE2/1 chambers per end-cap, organized in two layers of 18 chambers
- Each chamber consists of 4 GE2/1 modules
  - 288 modules in total
- Two different types of chambers to avoid the overlapping of dead areas
  - 8 different module designs called M1 to M8
- **Installation planned in YETS 2023/24 & 24/25**

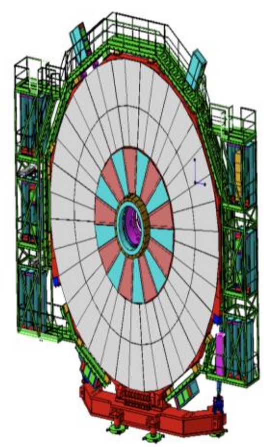




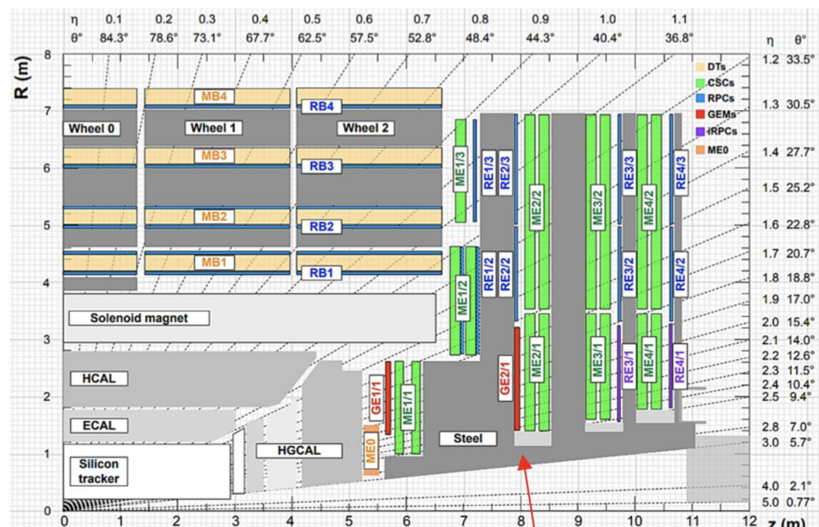
8 slightly different triple-GEM modules (M1 to M8)



BACK-type (M1 to M4) and FRONT-type (M5 to M8) chambers



Pseudo-rapidity coverage 1.62 < |η| < 2.43



Then, what new?

- Knowledge transfer: 50% of GE2/1 GEM Foils produced in Korea
- Long list of lesson learnt in GE1/1 applied to GE2/1:
  - Mechanics/Technology
    - Double segmented foils
    - Internal frames layout
    - Pillar
  - Electronics
    - Packaged Chips
    - Rigid-flex plugging cards
    - OHs not across GEBs + VTRx Cooling

GE2/1 Module production on-going, detector improvement will be also applied to ME0

Knowledge transfer

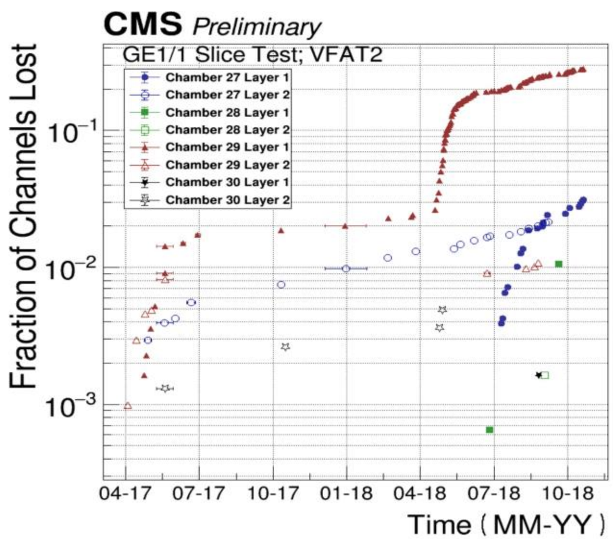
Two GEM Foils producers for GE2/1:

- **MPT workshop (CERN)** (same as GE1/1) → M1, M4, M5 and M8 types
- **Mecaro (KR)** (new producer investigated between 2017 and 2019 – approved in Jan. 2020) → M2, M3, M6 and M7 types
- Organized an in-depth internal review with KCMS representatives, Mecaro engineers, project management and Rui directly at the Korean factory

- Excellent experience with the Korean teams from Mecaro and Korea-CMS
  - Large team of experts, almost a constant presence at the factory for the foil validation
  - In-depth inspection and test of all foils in Korea before shipping to CERN for additional cross-check measurements
- In-depth report delivered with every single foil

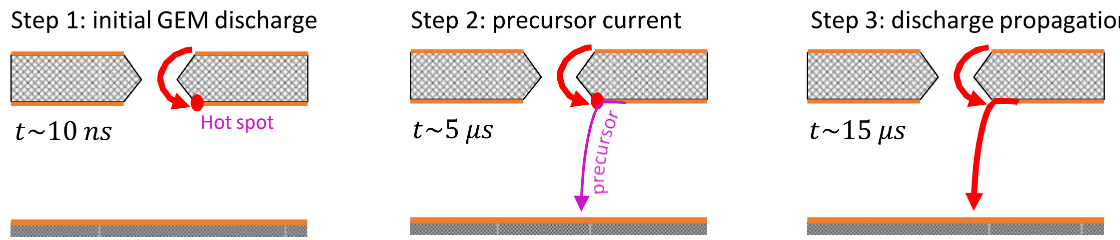
Lessons Learnt: Discharge Protection, GEM Foils double segmented

In GE1/1 Slice test observation of discharge propagation and experienced VFAT3 channel loss



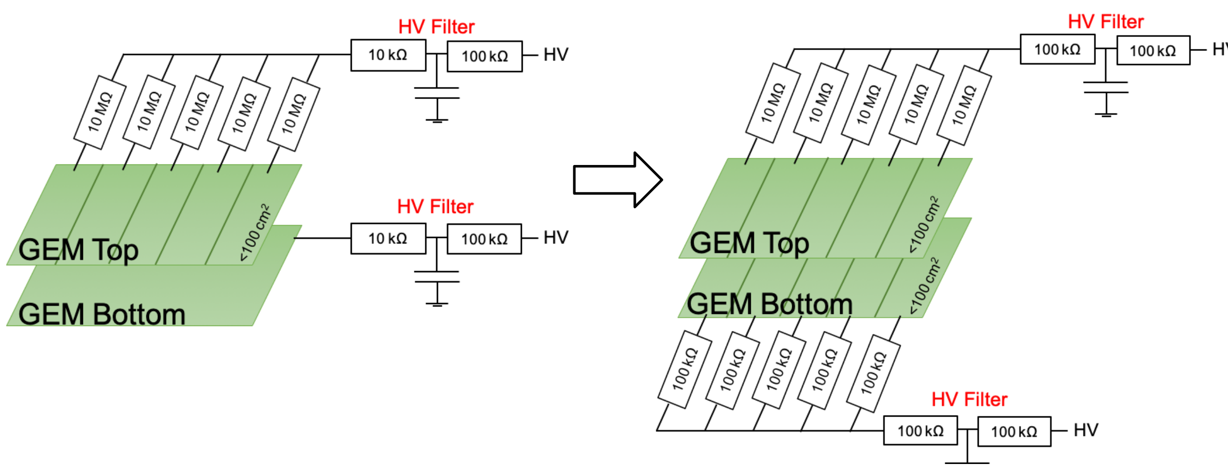
Channel loss ∝ Discharge probability x Propagation probability x Damage probability

The most effective mitigation consists of reducing the probability of discharge propagation



Basic principle:

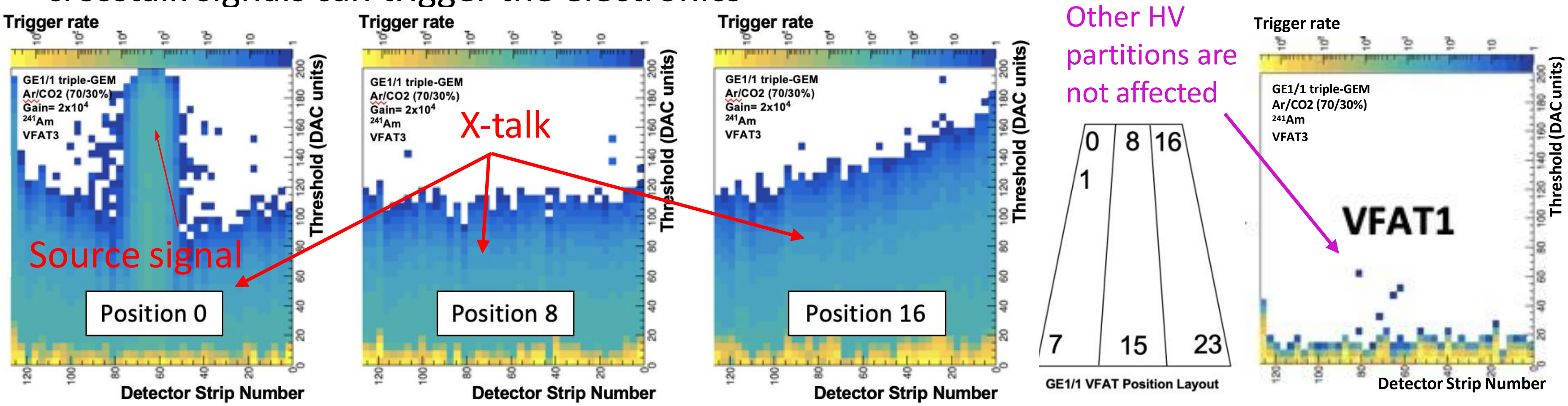
- HV segments on the top: GEM protection against regular discharges
- HV segments on the bottom: protection against discharge propagation



Lessons Learnt: Discharge Protection, GEM Foils double segmented

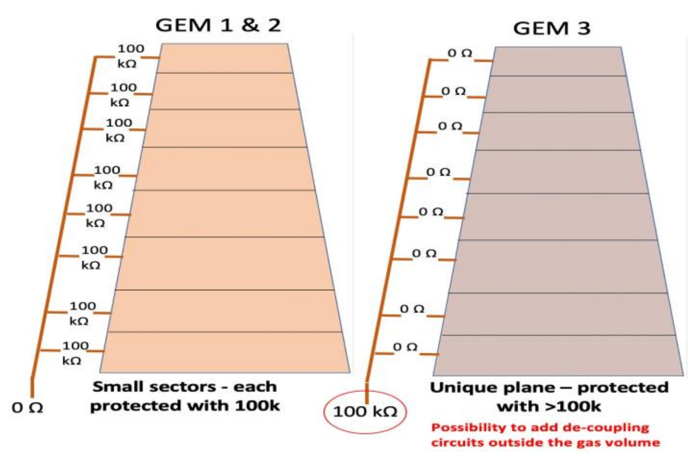
Side Effect - Crosstalk

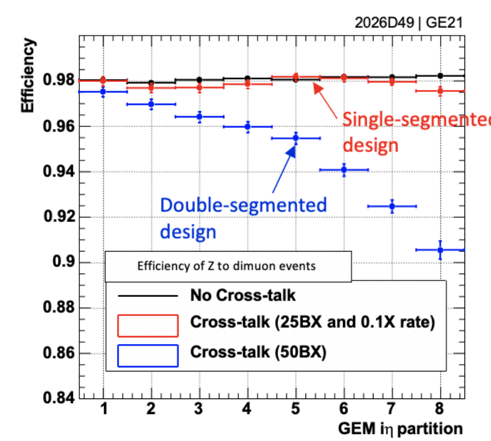
Reducing the size of the HV segments on the last GEM increases the HF impedance to ground → Induces cross-talk; In case of large signal amplitudes, the corresponding crosstalk signals can trigger the electronics



SOLUTION: the "mixed" design

- GEM1 and GEM2 are double-segmented to prevent the **discharge propagation**
- GEM3 is single-segmented to suppress the **crosstalk**

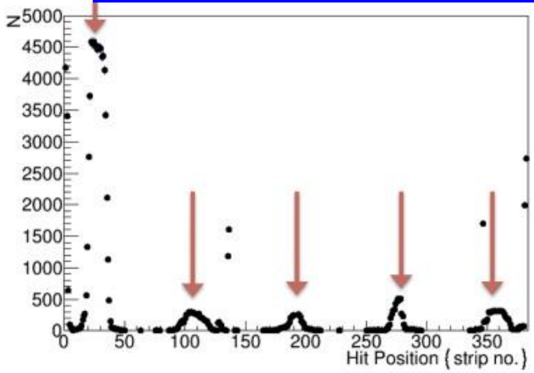


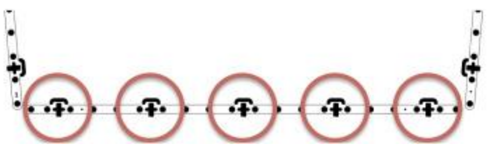


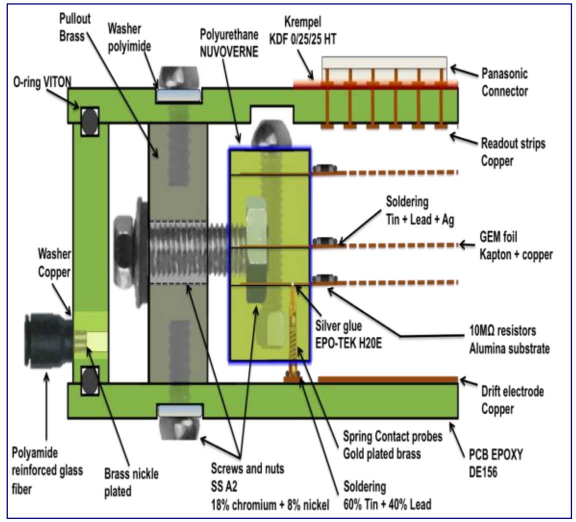
Full description @ https://indico.cern.ch/event/976526/ Summary of discharge studies in CMS GEM in (**Annex D**)

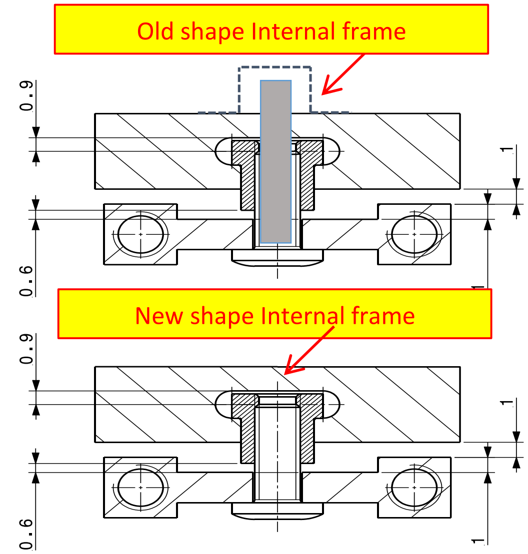
Lessons Learnt: Internal Frames

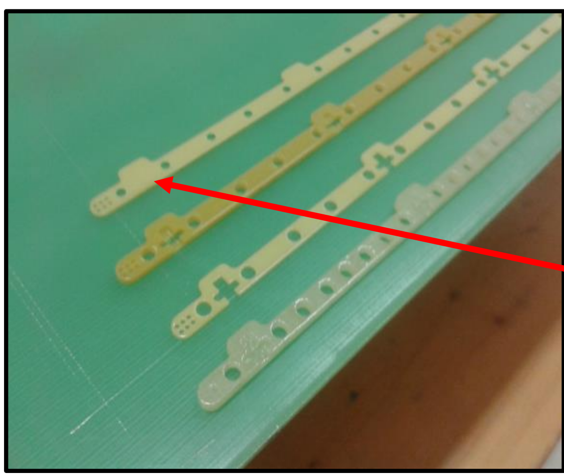
Fraction of Intrinsic Noise from the Internal Frames

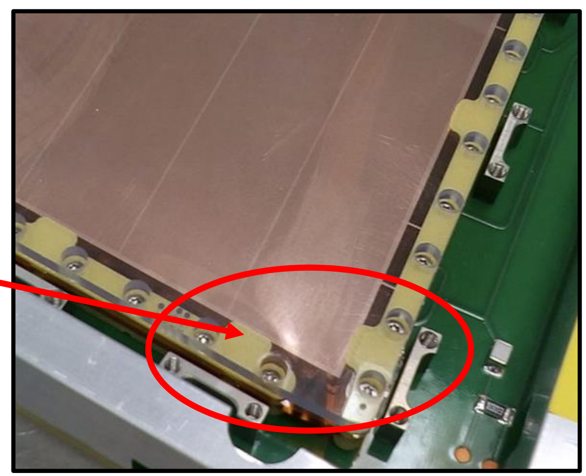










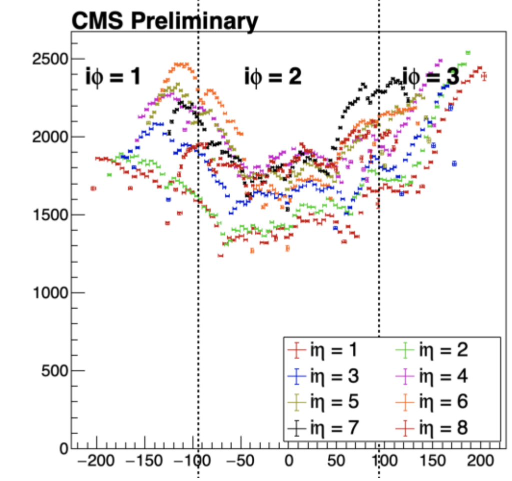


Lessons Learnt: Pillars

GE1/1 bending:

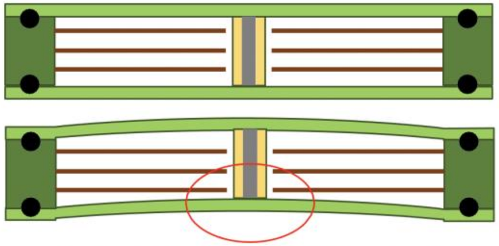
DRIFT and RO PCBs tend to bend when submitted to stretching forces, causing non-negligible variations of gain across the detector surface
(Different level of non uniformity)

Typical GE1/1 Uniformity



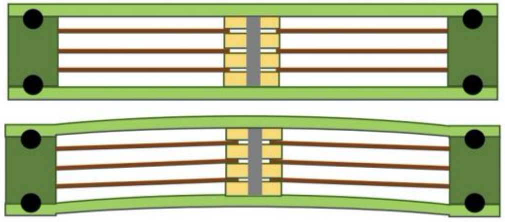
Pillar to constraint Drift Vs RO

FR4 pillar with SS cylinder

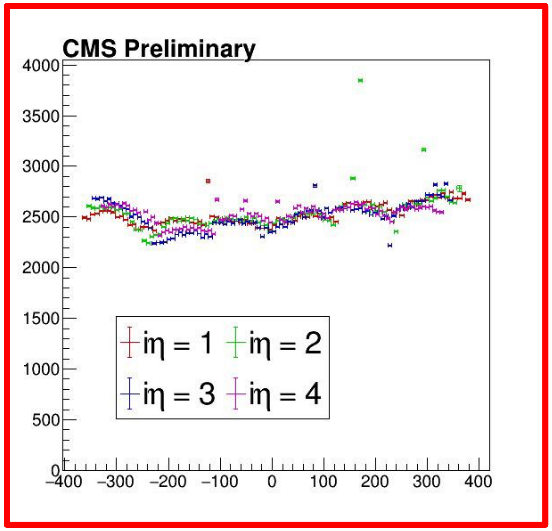


Bending inside – eventually deformation of Induction/Drift

Stratified FR4 pillar with SS cylinder

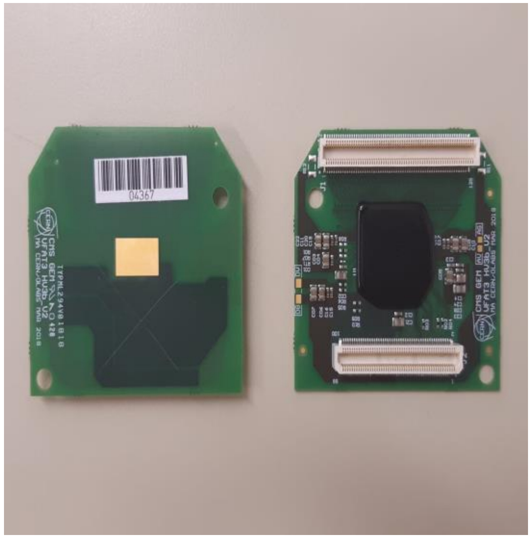


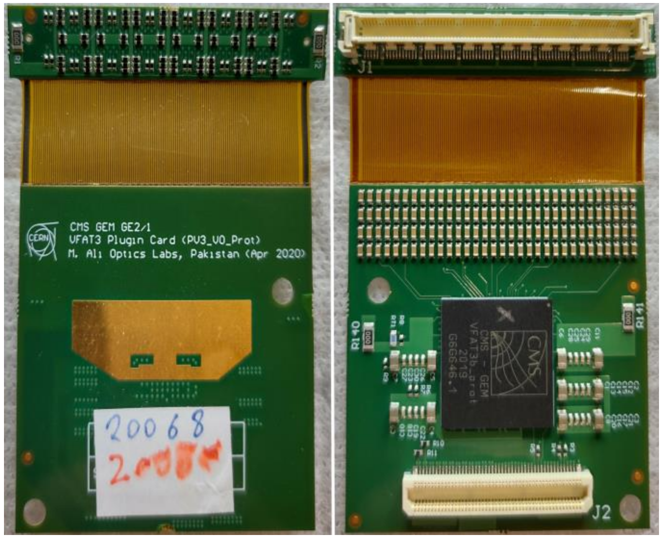
GE2/1 (M2)Uniformity



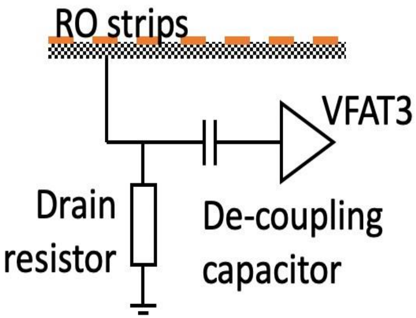
Lessons Learnt: FE Packaged Chip & Rigid-Flex PCB

- GEM FE Chips (VFAT3) has more than 500 I/O, extremely dense, makes the wire bonding high demanding in terms of quality of the Hybrids PCB
  - Production of GE1/1 PCB Hybrids painful
  - Moved to VFAT3 chip packaged for GE2/1 production
- Additional protection against discharges

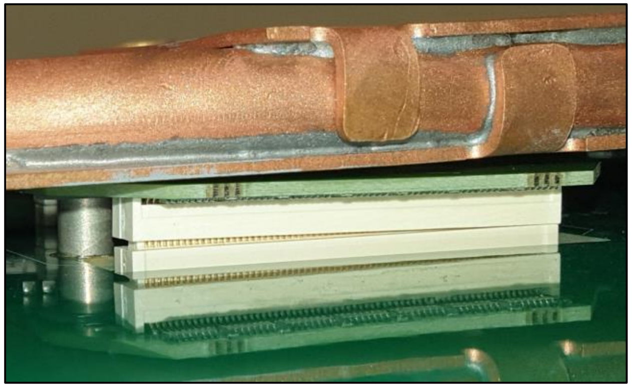




VFAT External protection and de-coupling



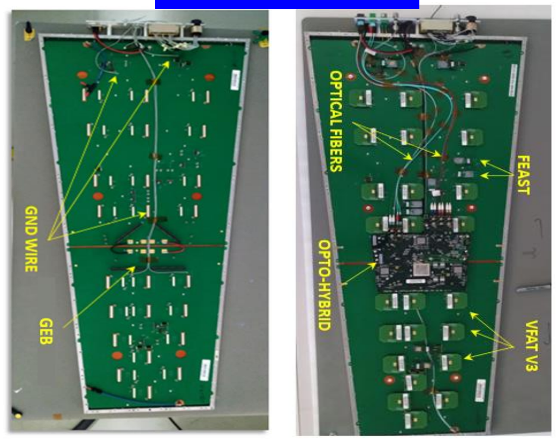
Flex PCB allow to absorb for misalignment between FE cards and GEBs



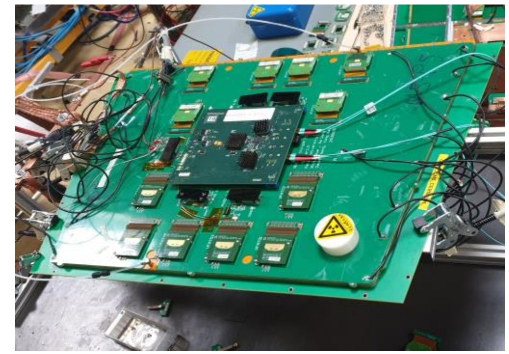
Lessons Learnt: OHs not across GEBs + VTRx Cooling

- In GE1/1 OHs sit across two different GEB pieces
  - Mounting connectors alignment not easy, stress is introduced on the electronics
- OH in the center of the GEB of each GE2/1 module

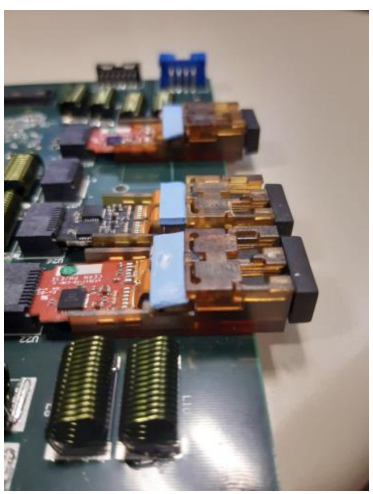
GE1/1 GEB & OH

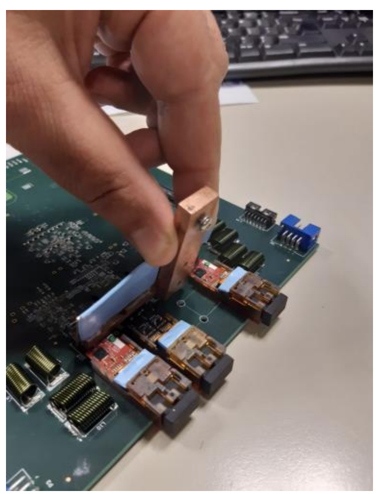


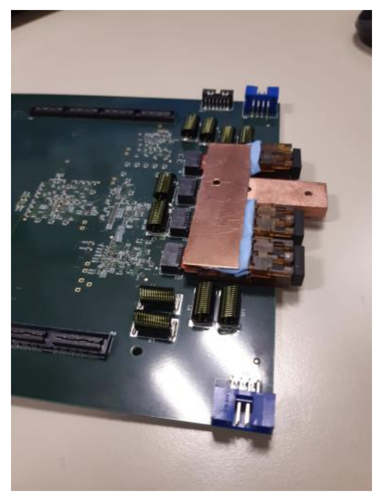
GE2/1 GEB & OH

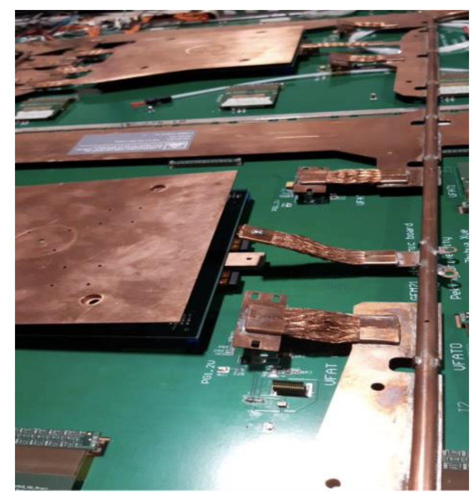


- VTRx's found to be "interesting" behavior, outgassing contaminate the surface of the ROSA ball lens, reducing (some time interrupting) the optical transmission, cooling of the ROSA can mitigate the outgassing







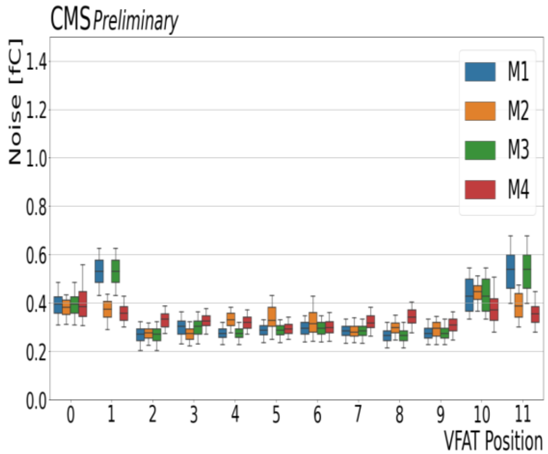


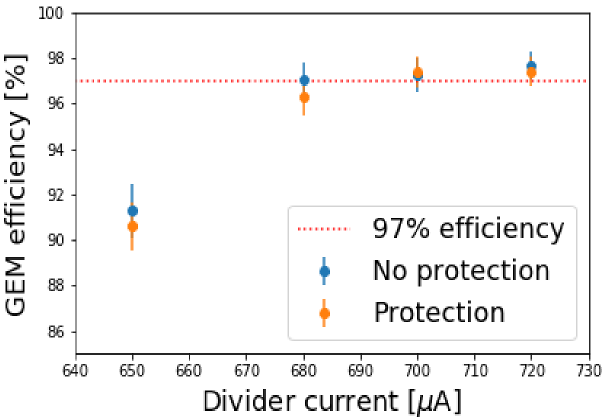
The Curious Case of VTRx Receiver Failures, *by Lauri Olantera (CERN)* https://indico.cern.ch/event/1099169/

GE2/1 Demonstrator

As for GE1/1, the GEM project is operating a nearly-final prototype in CMS before the full system in order to:

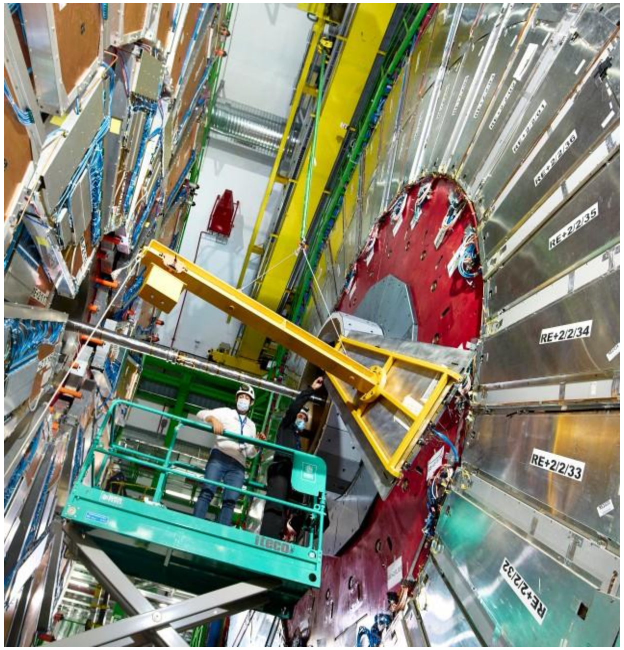
- → test the installation procedures
- → develop the DAQ/DCS/DSS tools
- → experience real operation

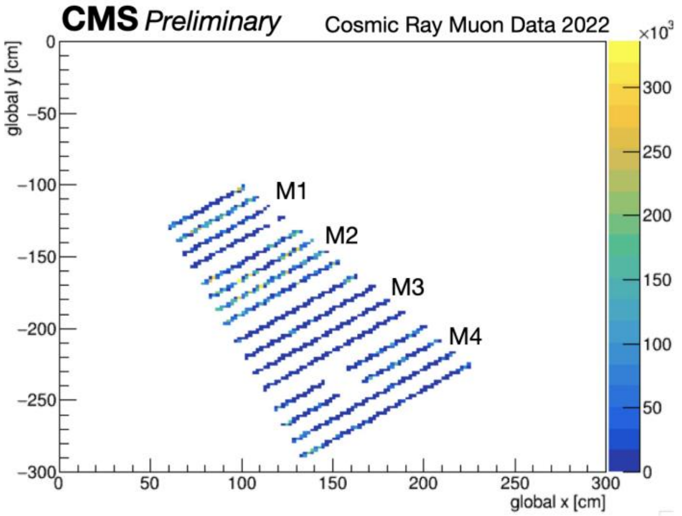




A demonstrator chamber was built, tested and installed in P5 in Nov

Using final electronics





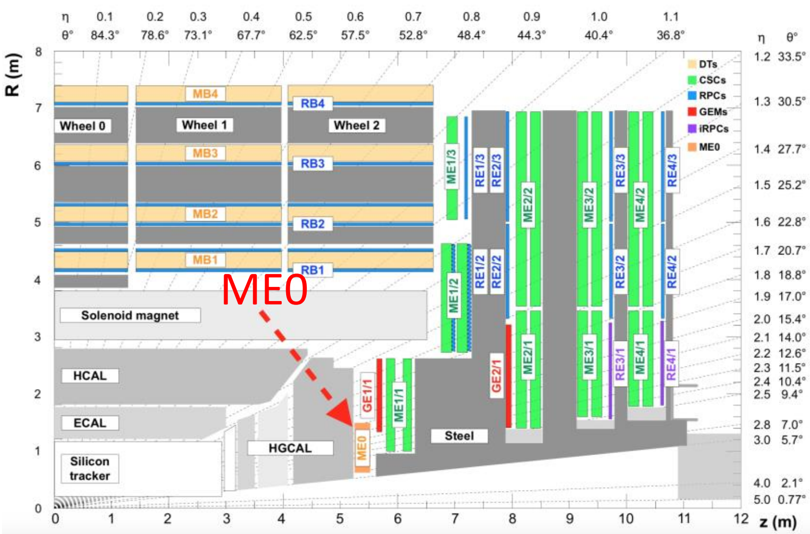
HL-LHC

The ME0 Project

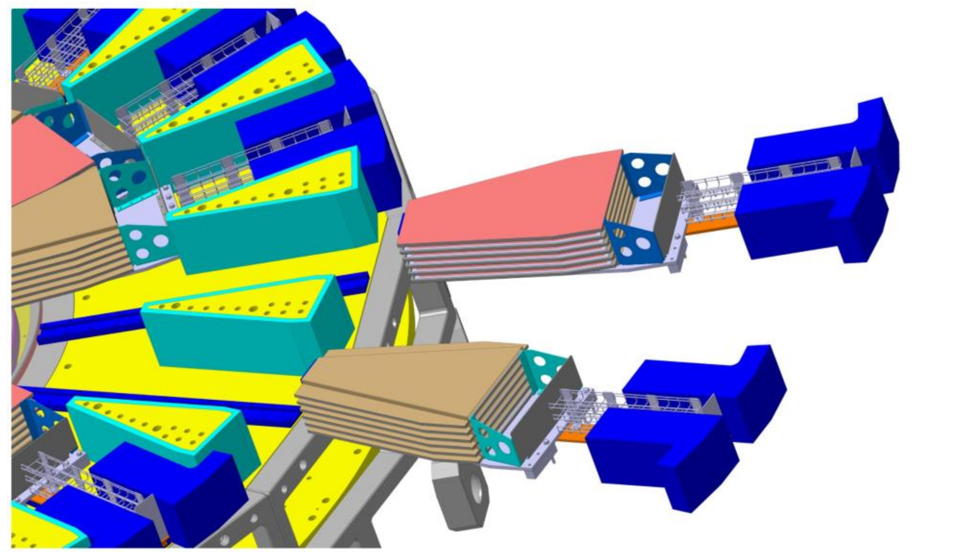
- The ME0 detector system is a layered stack of 6 triple-GEM detectors ($70{:}30\ Ar/CO_2$ fill gas)
- 18 stacks per endcap (36 total stacks; 216 modules total)
- ME0 detector system to increase coverage from $2.0 < |\eta| < 2.8$
- Module segmented into 8 readout partitions in η and 3 in φ (24 total RO sectors)

Requirements:

- 97% efficiency
- Rate capability of $\geq$ 150 $kHz \cdot cm^{-2}$
- Radiation hardness requirement $>7.9\ C \cdot cm^{-2}$
- Angular resolution $\leq$ 500 μrad
- Time resolution 8-10 ns for single layer
- Gain non-uniformity of $\leq$15% inter-/intra-module
- Sufficiently low discharge rate



Quadrant of the CMS experiment with ME0



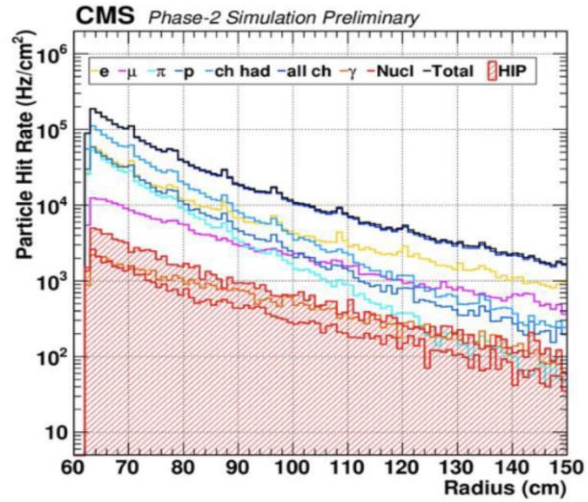
3D rendering of the insertion of two ME0 stacks into the new endcap nose

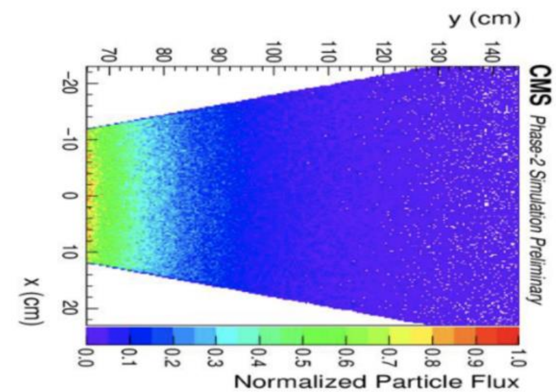
Rate challenge for the triple-GEM in ME0 station

- Expected Hit Rate → [2, **144**] **kHz/cm²**
- Average primary energy deposit **5.8 keV** i.e. **200 e-ion pairs**

- HIP: Heavily Ionizing Particle which deposits **>30 keV** in the detector
- HIP rate → [0.05, **4**] **kHz/cm²**

Need to evaluate the impact on detector operation





GEANT4 simulations
- Similar results with FLUKA

Linked, to the rate, challenges:

Discharge rate and propagation (**Annex D**)

Triple GEM Longevities (**Annex E**)

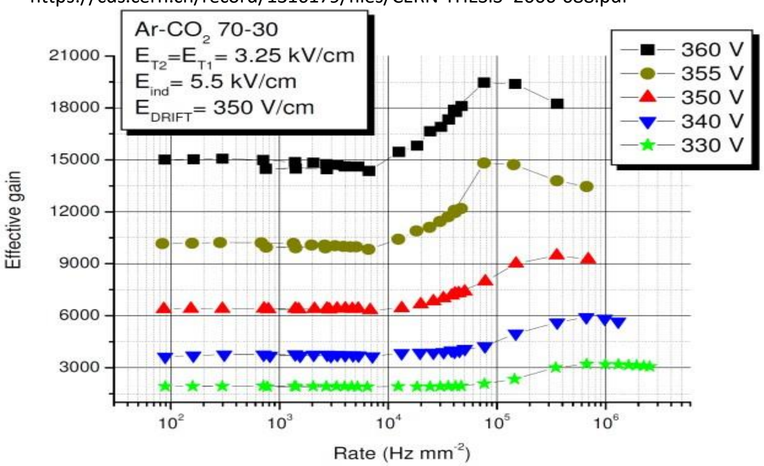
GEM Rate Capability

The ***rate capability*** of GEM-based detectors has been extensively studied in the last decade for different sizes, geometries, and configurations

$Ar/CO_2(70/30)$ – 3/2/2/2mm

P. Everaerts

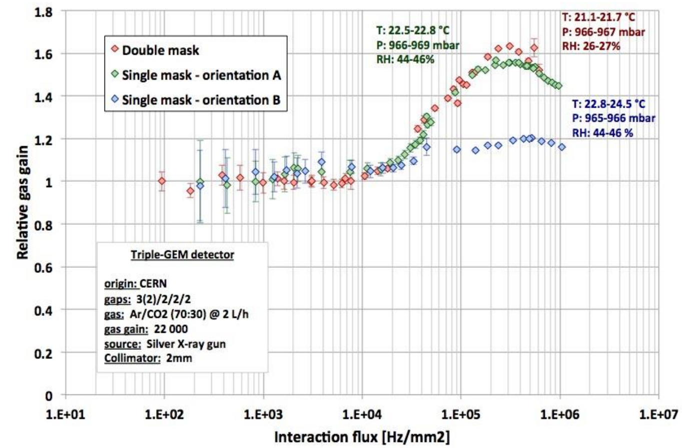
https://cds.cern.ch/record/1316179/files/CERN-THESIS- 2006-088.pdf

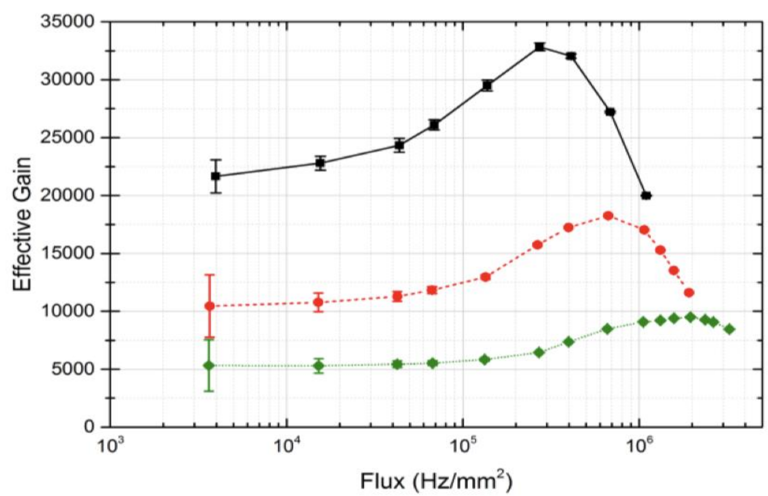


$Ar/CO_2(70/30)$ – 3/2/2/2mm

J.Merlin

https://cds.cern.ch/record/2155685/files/CERN- THESIS-2016-041.pdf





$Ar/CO_2(70/30)$ – 3/2/2/2mm

P. Thuiner

https://cds.cern.ch/record/2238855/files/CERN-THESIS-2016-199.pdf

GEM Rate Capability

The ***rate capability*** of GEM-based detectors has been extensively studied in the last decade for different sizes, geometries, and configurations … but:

Common experimental procedure:

1) source: ***X-ray generator*** *(soft X-ray photons)*
2) irradiated area: $\approx \boldsymbol{mm^2}$
   → reaching ***very high X-ray flux***
3) gain ramains stable up to a flux above $\boldsymbol{MHz/cm^2}$
   → demonstrating the absence of ***space charge phenomena!***

but one observes …

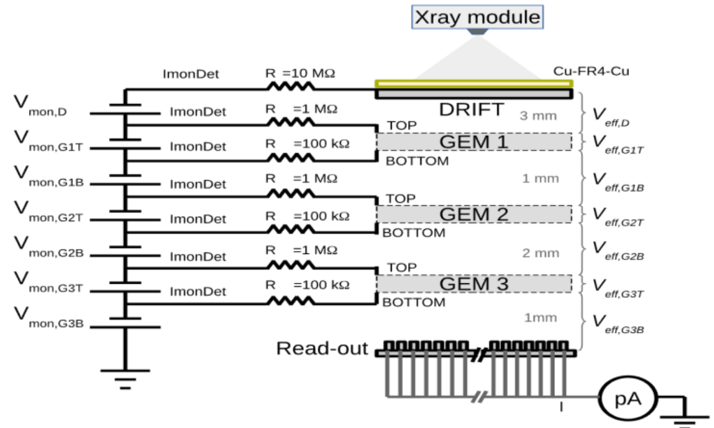
1) a ***low ion current*** flowing through the ***protection resistors*** due to the small irradiated area
   → inconsistent with a real experiment
2) a ***negligible voltage drop*** across the GEM-foils
   → as a result: high-rate capability up to tens or hundreds of MHz/cm^2

We need to stress the following points …

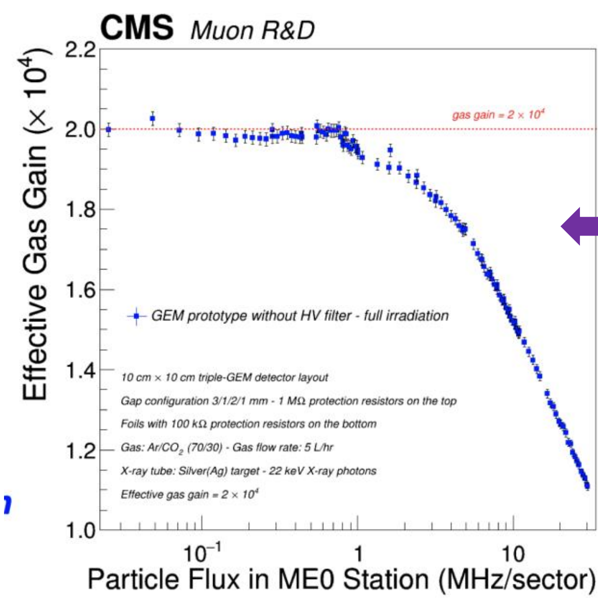
- rather than the space charge, the ion current, flowing through the protect. resistors, strongly affect the detector rate capability!
- a ***local irradiation*** $O(3\ mm^2)$ is drastically different to a ***global irradiation*** $O(3000\ cm^2)$!

GEM Rate Capability

- Re-evaluating rate capability of triple-GEM detectors by irradiating medium-to-large areas (~100 cm2)



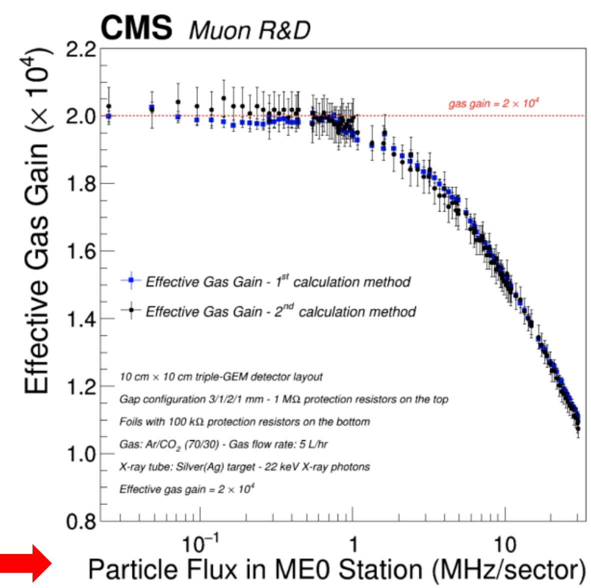
- Detector: **10×10 cm²triple-GEM** detector
  protection resistors **1 MΩ top,** 100 kΩ bottom
  per foil operated in Ar:CO_2 70:30
  powered by **multi-channel** CAEN A1515 (**400 pA res.**)
- Source: two silver-target Amptek **Mini-X tubes**
- Readout: Keithley 6487 **picoammeter, 10 fA resolution**



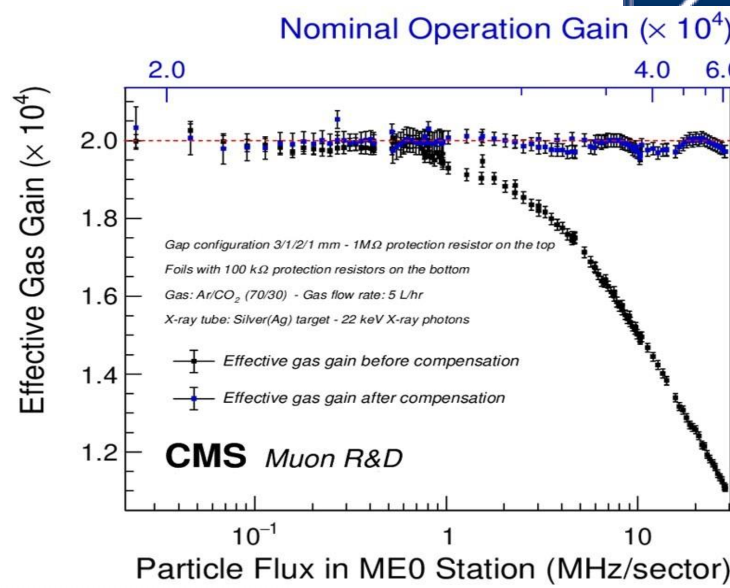
Gas gain drop estimated as:

$$g_{eff} = \frac{i_{anode}(W_{x-ray})}{q_e n_p R(W_{x-ray})}$$

Gas gain drop estimated evaluating the HV drop on the protection resistors due to the current flowing on the electrodes -> possibility to compensate for HV drop

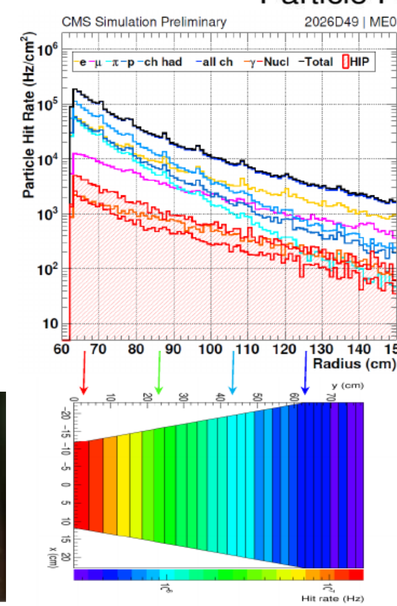


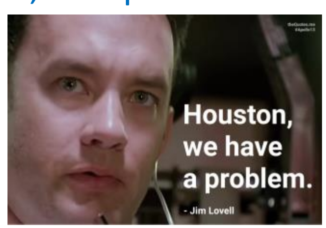
HV compensation on 10x10 cm GEM chamber



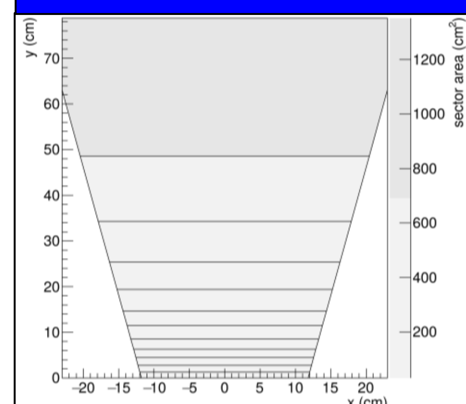
- Appling the correct HV value (correction for HV drop across the resistors) the Nominal Operation Gain is restored.
  - Dedicated software with iterative correction designed on purpose

- But in ME0 each HV sectors, as a function of the eta are expected to get different integrated flux, depending on the background shape
- How to compensate different drop with a unique HV channels?
  - A) Different HV sector area, to equalize the flux?
  - B) Different protection resistors, to equalize the HV drop across the sectors?
  - Combination of A) & B)?

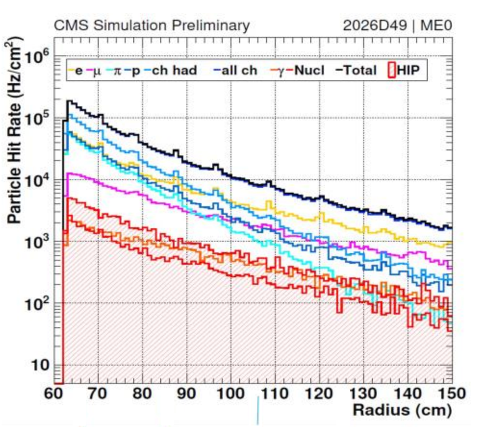


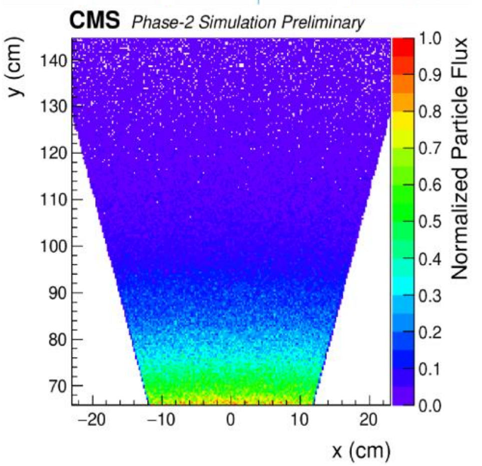


Possible HV drop equalization playing with the HV sectors area (case A)

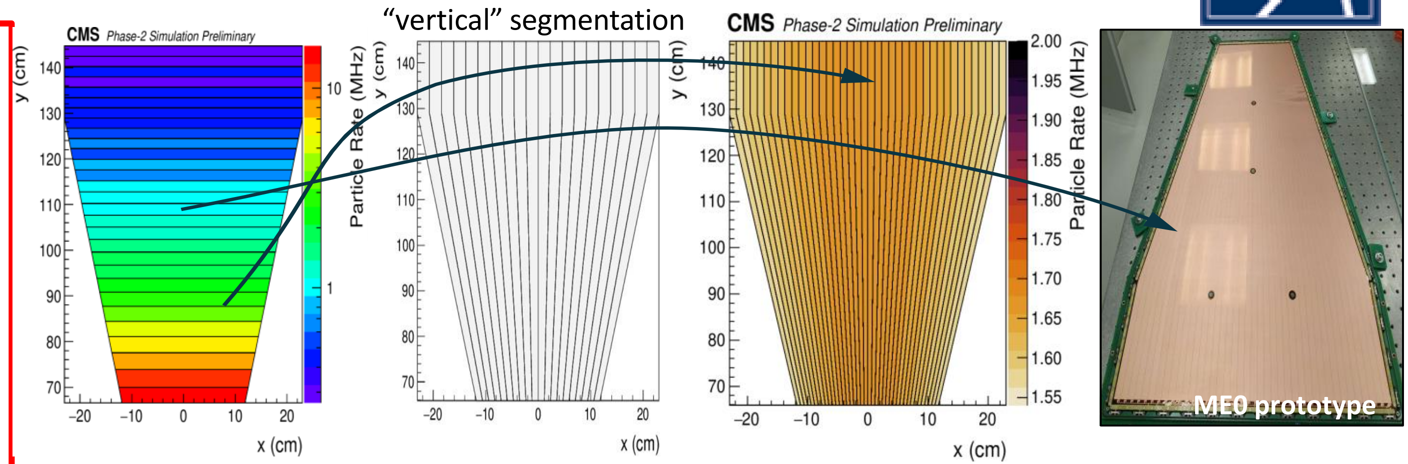


New HV segmentation for ME0 GEM Foils





ME0 environment:
- Large rate variation between the coolest and the hottest HV segments (about two orders of magnitude)



New segmentation introduced

→ Change the orientation of the HV segment → "vertical pattern"

→ Each segment will see the full BKG gradient i.e. collect the same current as the neighbor segments

→ **No dependency with the BKG shape**

→ **Uniform current across all segment**

→ **Uniform voltage drop that can be globally compensated**

→ A first prototype was assembled and tested in summer 2021

→ Reduced protection resistors based on past discharges studies (2 MΩ top, 100 kΩ bottom)

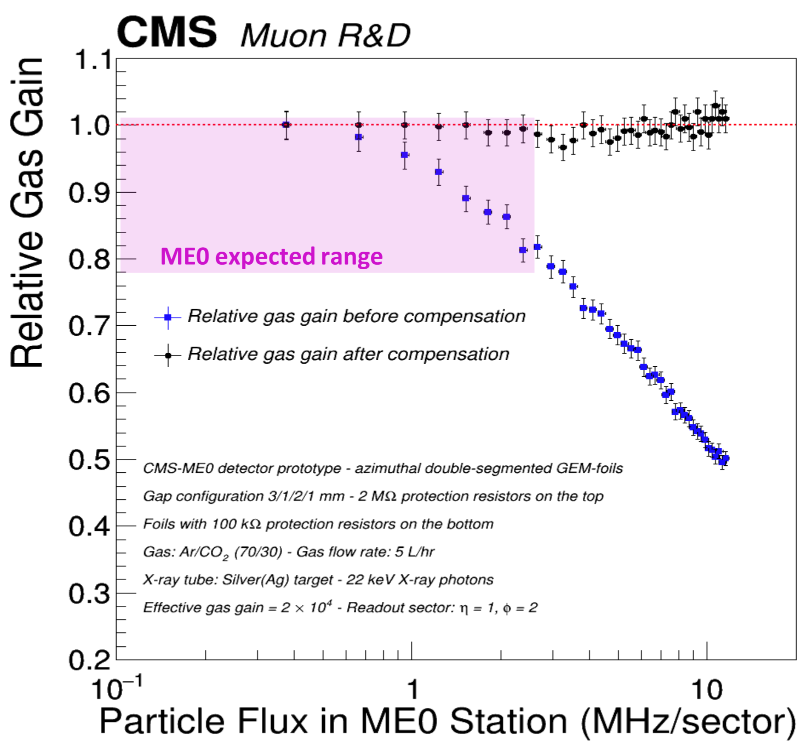
→ Both filter resistance and protection resistance are "merged" to minimize the overall HV resistance

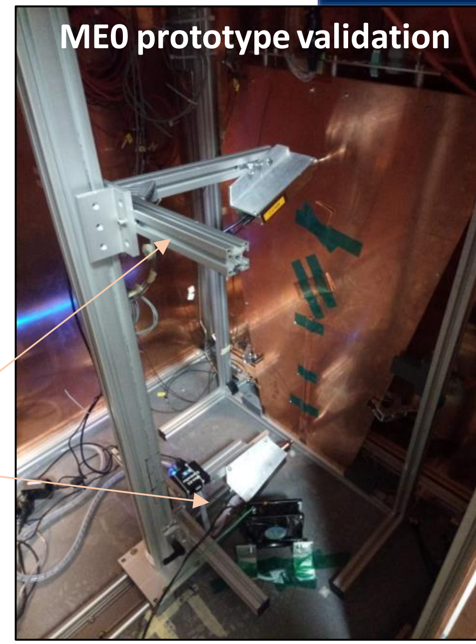
The egg of Columbus

Gain compensation studies with ME0 vertically segmented

On-going work in 904/GIF++:
- Rate capability comparison between different HV segments
- Gain compensation comparison
- Compensation validated along one HV segment

Next steps:
- Rate capability measurements and gain compensation @GIF++





CMS BKG emulation with multiple X-ray sources

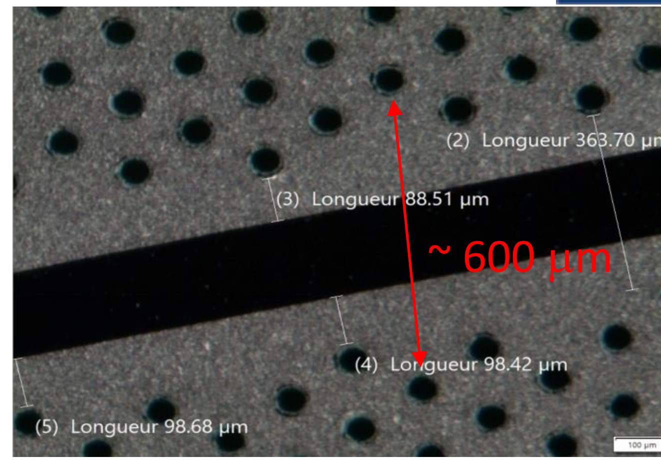
Measured effective gas gain as a function of the expected hit rate on the whole electrode area in the ME0 station. The detector under test was irradiated with an X-ray tube: Silver(Ag) target.

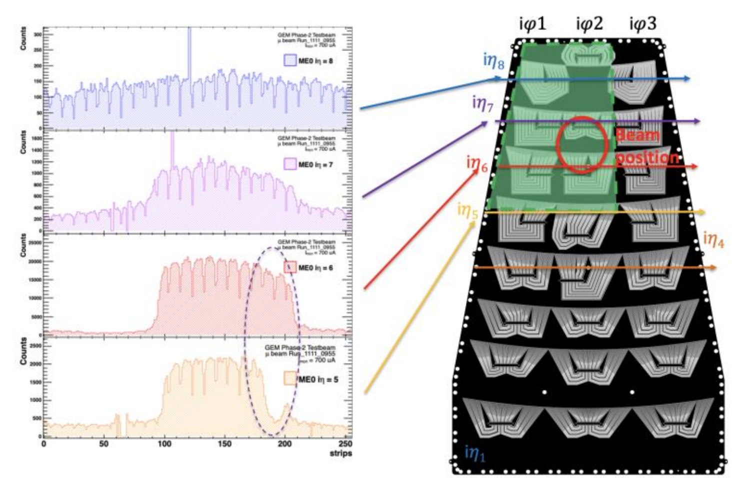
The compensation is obtained by applying overvoltages to each electrode separately to compensate the voltage drop induced by the moving charges in the gas.

- resistive HV filter installed: RC filter (2.5 kOhm + 2.2 nF)

R&D Random

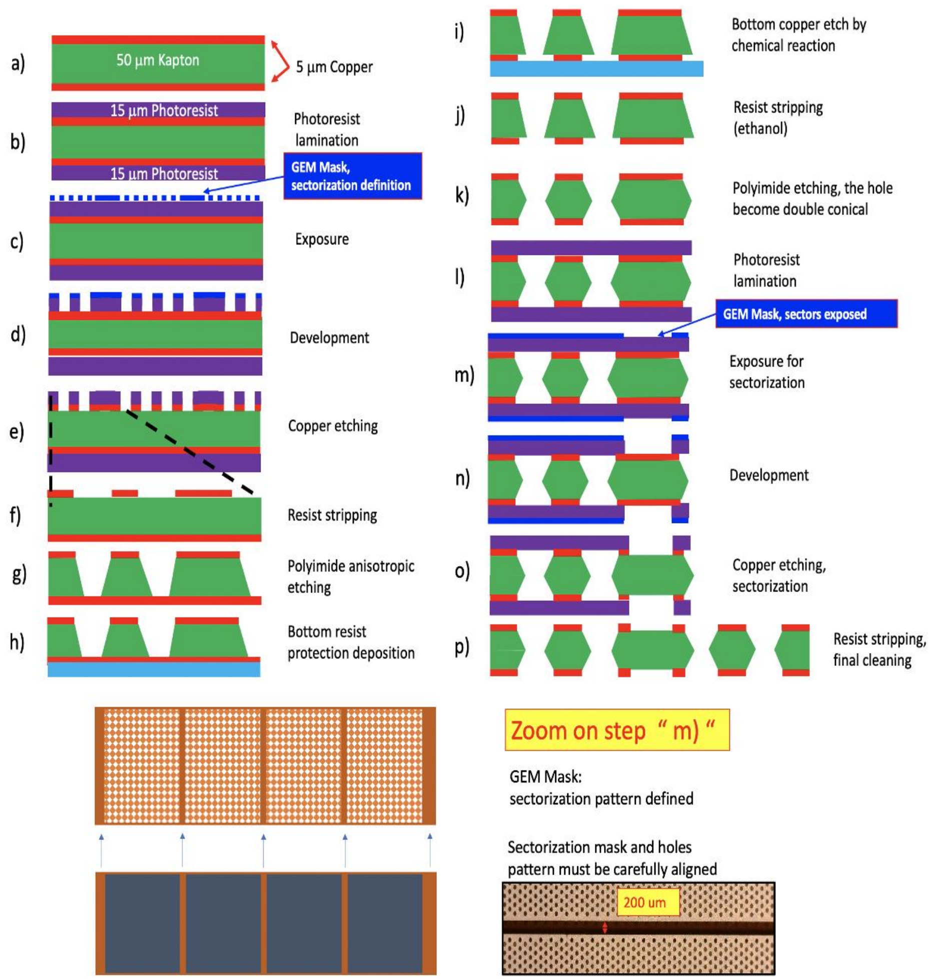
- Motivations
  - Simplification of large area GEM foils production
    - Removing GEM holes/Sectors alignment issue
  - Possibility to design HV sectors of any possible shape, with reduced dead area between HV sectors
  - Improve the GEM foils transparence
  - Remove possible overlap between HV sectorization and readout strips/pad in detectors realized with HV sectors and readout pattern overlapping along the same coordinate
  - Expect to improve efficiency and uniformity within the entire detector area covered by GEM foils
  - Prove that the single mask technique allow to master GEM foils without any issue against HV distribution stability
    - In the past similar R&D based on GEM foils produced were abandoned due the GEM foils instability against HV distribution (Sparks)

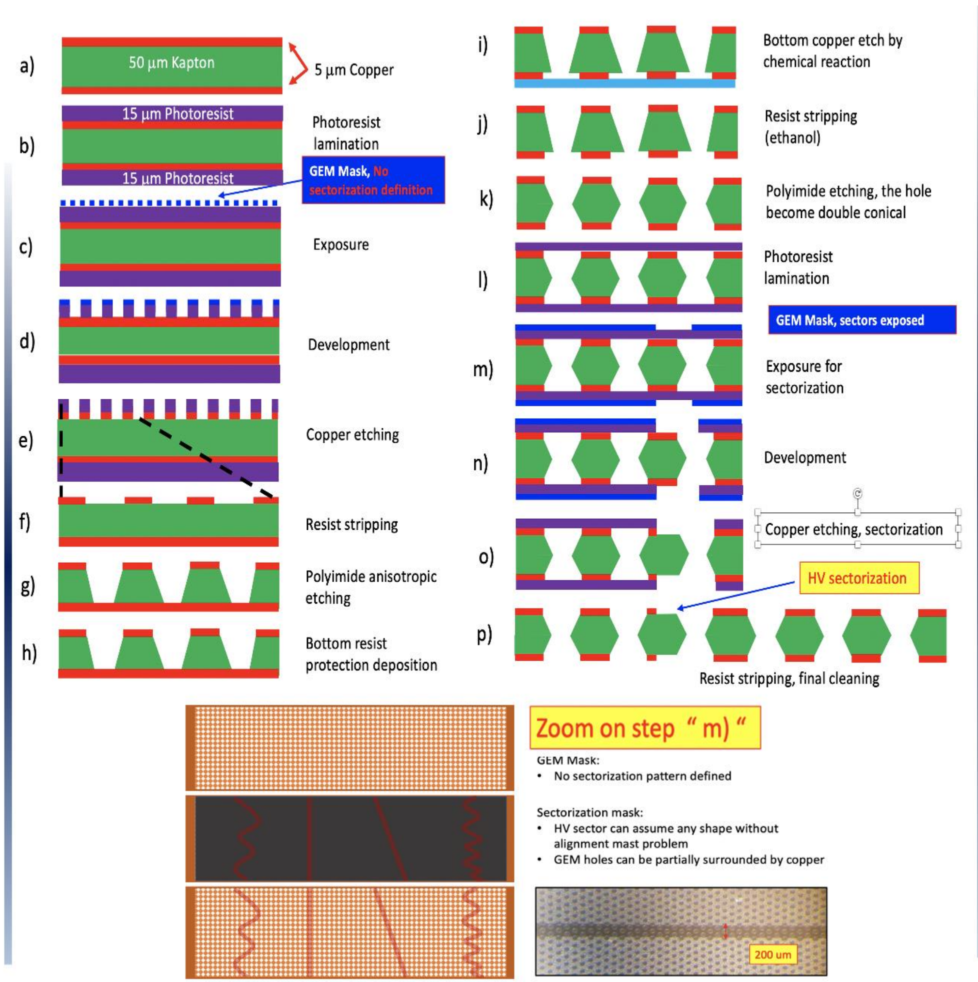




CMS-ME0 Module, equipped with GEM foils "Blank" sectorized along the RO Strips. Longitudinal HV segmentation clearly observed in occupancy plot

Improvements in GEM foils mastering technique





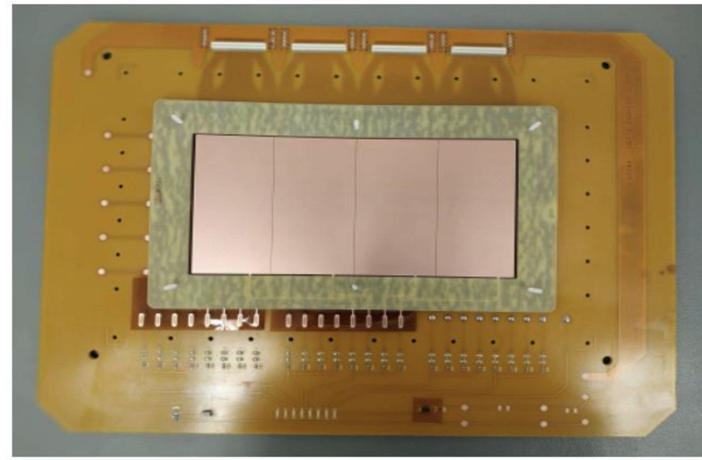
Random segmented 10x20 prototype

Characterization of the random electrode sectorization in the GEM-foils *by F. Fallavollita* https://indico.cern.ch/event/1071632/

Triple-GEM detector prototype

- ✓ active area: 10 cm × 20 cm
- ✓ gas configuration: 3/1/2/1 mm
- ✓ double-sided random segmented GEM-foils
- ✓ operating gas mixture: Ar/CO_2 (70/30) - 5 l/h
- → single-mask photolithography technique
- → 200 µm width copper free gaps produced at an angle of ~ 100 µm w.r.t. the hole pattern
- → 1MΩ prot. resist. on top, 100kΩ prot. resist. on bottom

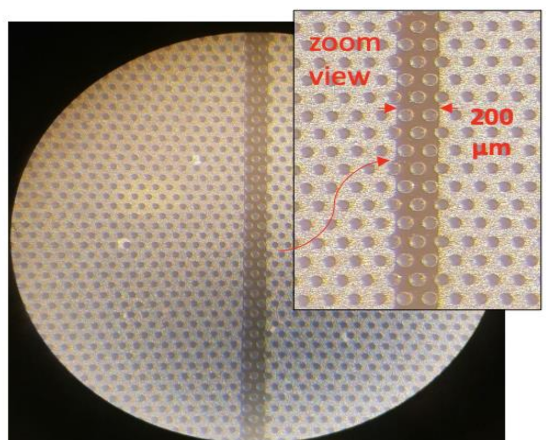
Double-sided random segmented GEM-foils



Optical inspection results:

- ✓optical inspection by backlight → good
- ✓holes uniformity → good
- ✓holes diameter → good

copper rings diameter: $\varnothing_{Cu}$ ~ 74 µm (required specs 70±5 µm)
polyimide rings diameter: $\varnothing_{PI}$ ~ 53 µm (required specs 50±5 µm)



Microscopie pictures of the random electrode sectorization

To be verified:

- ✓ Possible copper delamination risk in the vicinity of the insulating region between adjacent sectors
- ✓ Minimize the electric field distortion and recover the potential efficiency loss at the sector gaps

10x20 Chamber characterization

High Voltage and Linearity Test in pure N_2

- ✓ High voltage and linearity test aims to determine the current voltage curve in order to identify possible malfunctions, defects in the HV circuit and intrinsic noise rate
- ✓ High voltage test includes the operating of the chamber at HV values leading to electric current values exceeding 40% the nominal ones as required by a final experiment

NO trips of the power supply or disruptive events were recorded

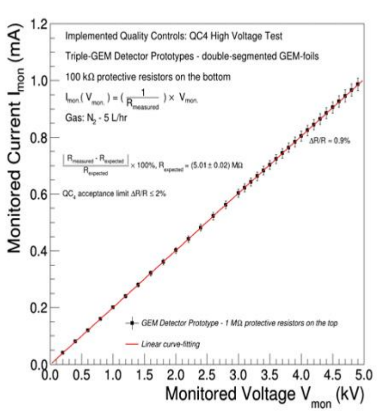
Measurement of the Effective Gas Gain in Ar/CO_2 (70/30)

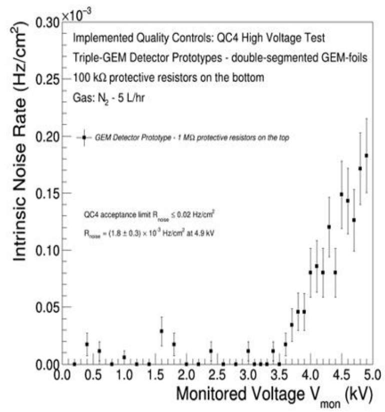
- ✓ Effective gas gain for the prototype with random electrode sectorization comparable to triple-GEM detector with standard sectorization

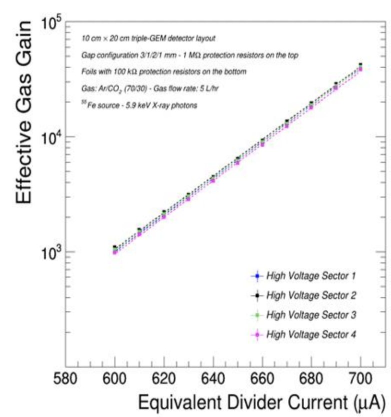
Effective gas gain in Ar/CO_2 (70/30) of about $2{\times}10^4$ at 680 μA of equivalent divider current (i.e. drift voltage 3.2 kV)

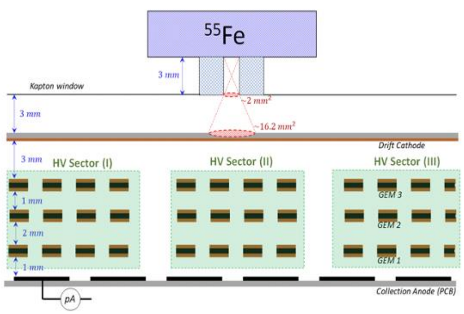
Gas Gain Uniformity

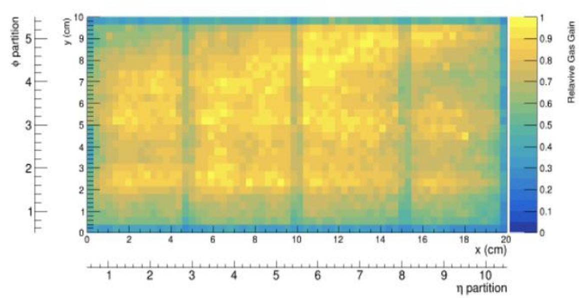
Gas gain map of the triple-GEM detector. Collimated 5.9 keV ^{55}Fe source (~ 2 mm^2) used to scan the 10 cm × 20 cm area at a 3 mm (x-coord.) × 4 mm (y-coord.) grid







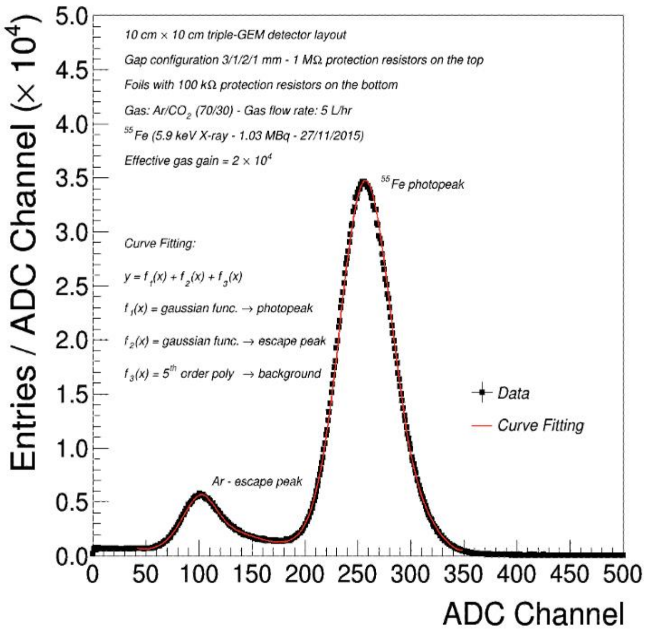




Stability tests

Energy Spectrum in Ar/CO_2 (70/30)

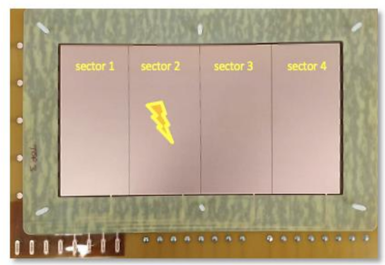
Typical energy spectrum of ^{55}Fe source: clean separation of the main photopeak and the Ar-escape peak is achieved



Energy resolution in Ar/CO_2 (70/30): $FWHM/_{\mu} \sim 15\%$

High Voltage Stability in Ar/CO_2 (70/30)

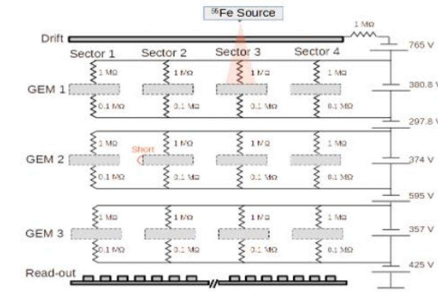
- ✓ If a sector of the GEM-foils is in short-circuit, the current flowing through the top and bottom side of the foil increases
- ✓ A short circuit is introduced in the sector 2 of GEM_1 (or GEM_2, or GEM_3)

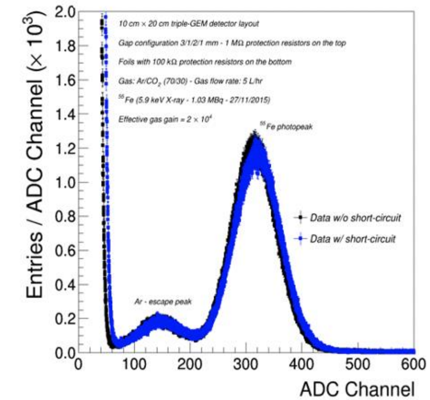


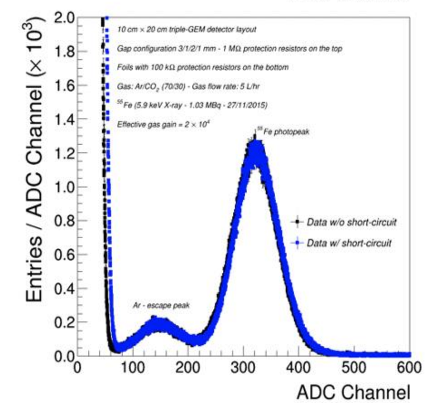
- ✓ The current flowing through the other sectors and foils is proved to be stable. No abnormal leakage current or discharges were detected during several hours of measurement

Energy Spectrum in Ar/CO_2 (70/30)

Energy spectra measured after positioning a ^{55}Fe source over a sectors adjacent to the short-circuited one are not affected by the presence of the short



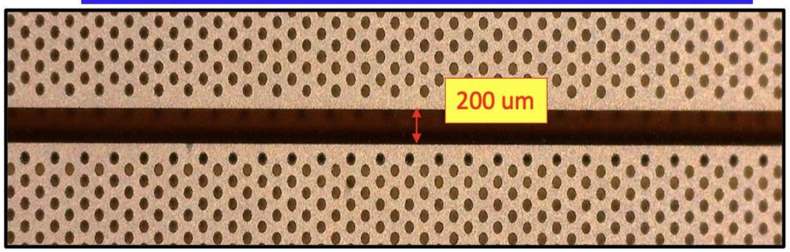


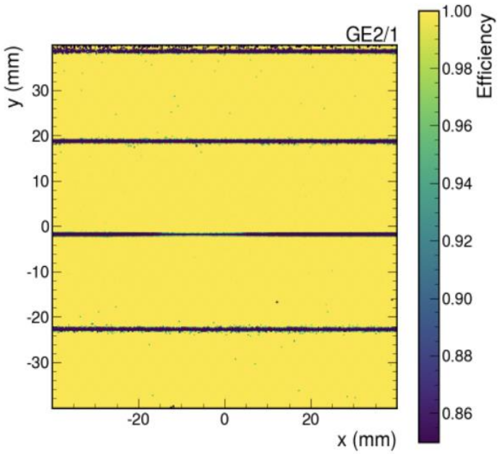


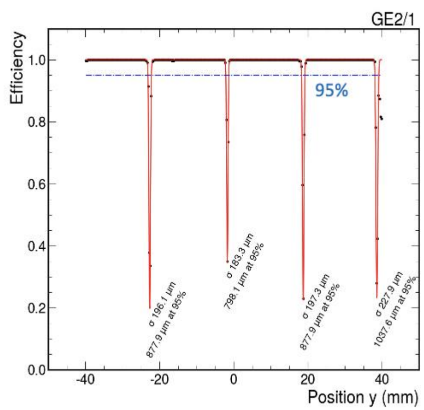
Results from CMS-GEM TB 2021

Efficiency measured in GE2/1 –M1 Module

Zoom on "Standard Segmentation"



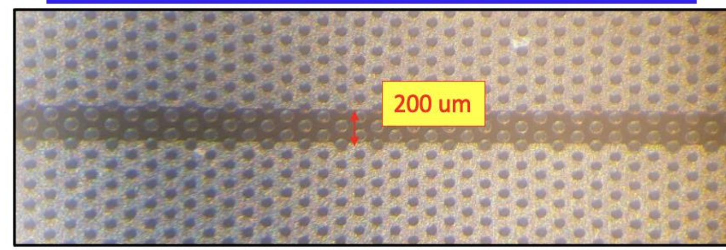


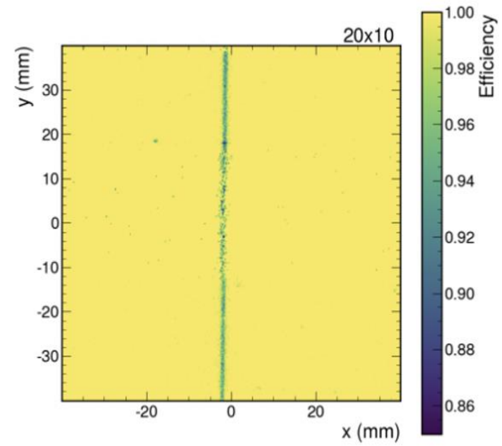


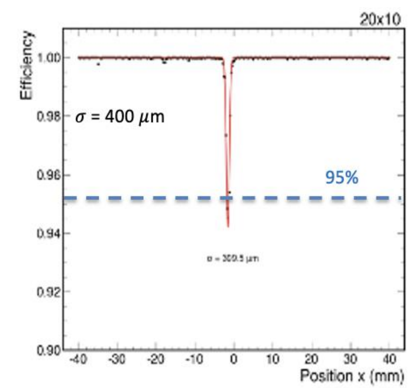
- Efficiency measured in CMS - GE2/1 chamber operated at GAIN: 2E4, instrumented with Standard Segmented GEM foils
- Sigma Efficiency dip due to the HV segmentation is 200 μm (Dip @ 95%: $w = 900 \pm 100\ \mu m$)
- Efficiency drop also up to ~20%

Efficiency in 10x20 prototype

Zoom on "Random Segmentation"







- Window of 9cm x 9cm, in 10x20 chamber with Random Segmented foils defined by the Tracker coverage
- Sigma Efficiency dip due to the HV segmentation is 400 μm ($\ll$ width 95% efficiency)
- Efficiency drop very limited ~94%

Summary

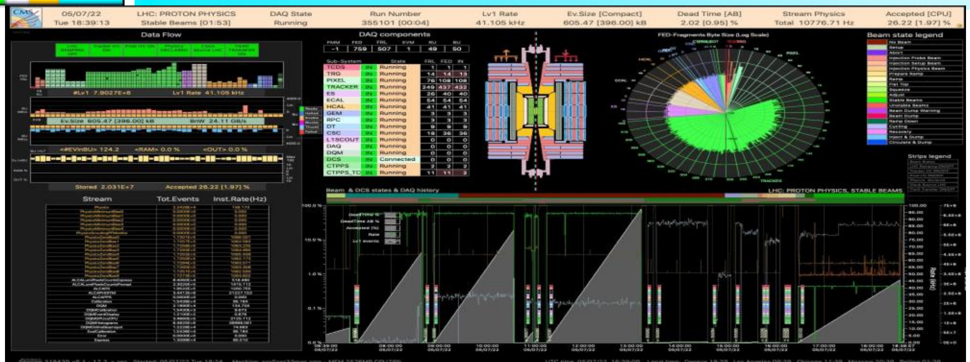
- A lot of work has been done in the last 15 years, but even more is still in front of the CMS-GEM collaboration
- The challenges posed by the CMS-GEM projects have been and excellent stimulus for the general development of the GEM technology
- GE1/1 project as been delivered during LS2 and now must be correctly operated in LHC Run3 to deliver good physics data
- Experiences acquired with GE1/1 projects fully reversed in GE2/1 and ME0
- GE2/1 is in full production, expected to be installed in the YETS 2023/24 & EYTES 2024/25
- ME0 design refinement in progress, the harsh environment in which the ME0 chambers will be operated pose new challenges for the triple GEM-GEM technology
  - Specific improvements in matter of rate capabilities, gain uniformity, discharge protection have been studied and introduced

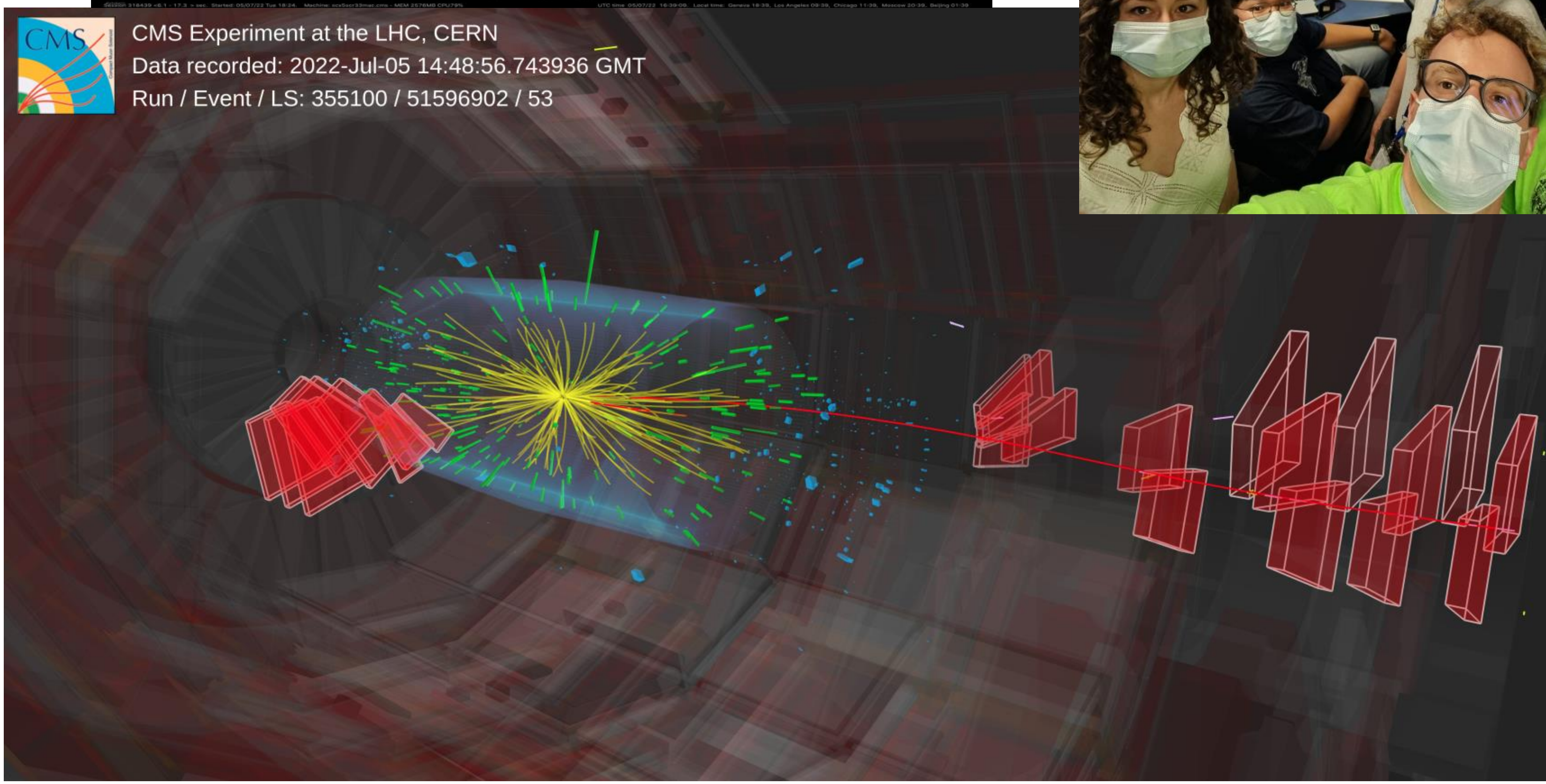
Thank you for your attention,

and very happy to be with you in person!

HL-LHC

GE1/1 Taking data @13.6 TeV



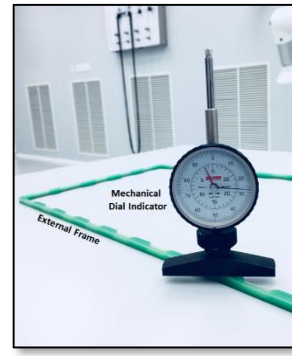


Bonus Tracks

- **Annex A : GE1/1 Components QA/QC**
- **Annex B : GE1/1 Chamber Assembly**
- **Annex C : GE1/1 Chamber QA/QC**
- **Annex D : Discharges studies with CMS-GEM Chambers**
- **Annex E : Aging studies with CMS-GEM Chambers**

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

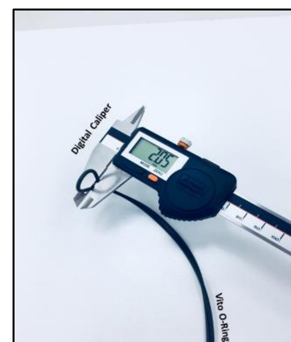


→ *Internal / external frames*

- 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

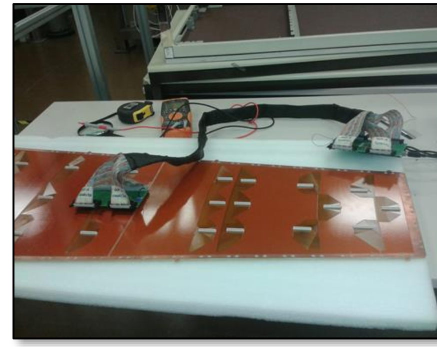


Annex A (GE1/1 Components QA/QC)

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

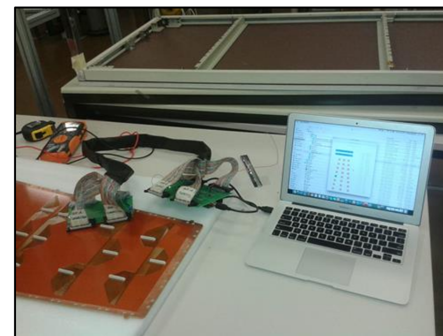


Connectivity Test

→ *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.

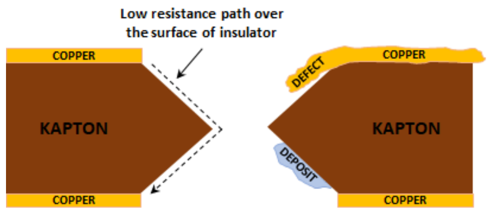
QC2 - Leakage Current Test

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**



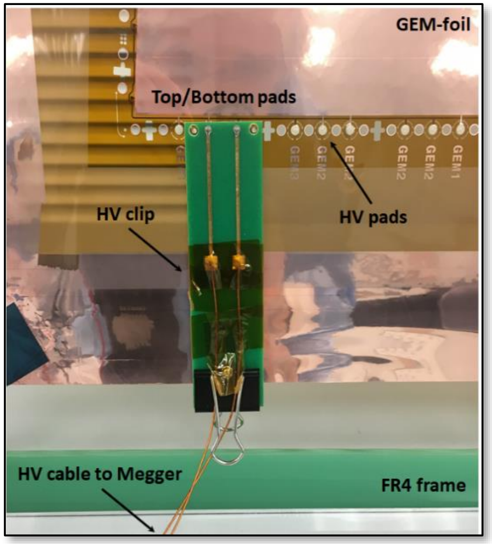
Presence of dust, pollution or defects could provoke an increase the leakage current flowing through the polyimide surface

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

QC2 - Leakage Current Test

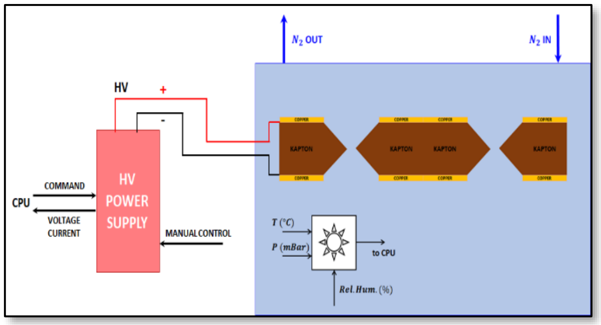
→ QC2 Fast Term Stability

- 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 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

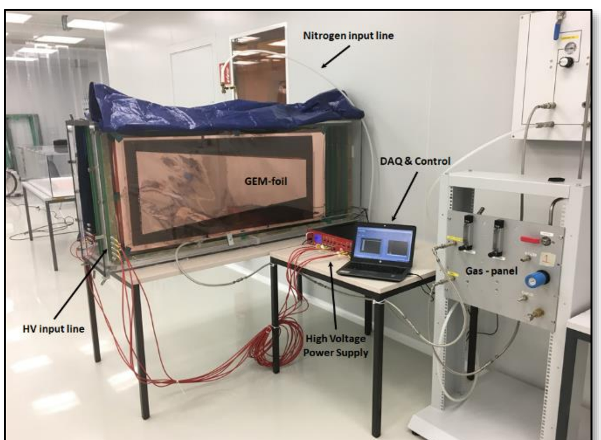


QC2 - Leakage Current Test

→ 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

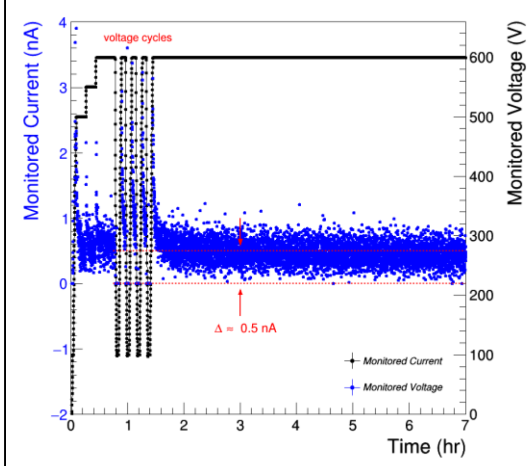
QC2 - Leakage Current Test

→ QC2 Long Term Stability

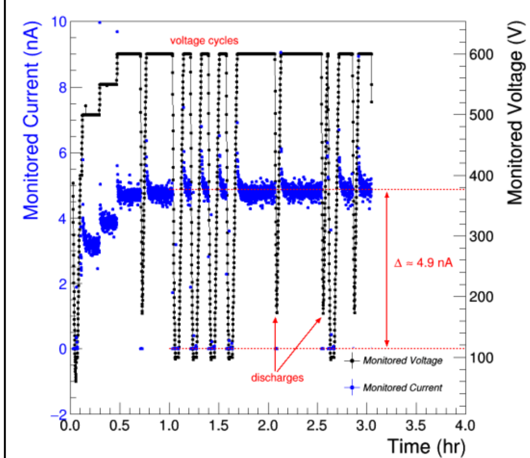
The Long test is divided into preliminary characterization phase and 3 steps with data monitoring:

- During the "first gas flushing period" $\sim 36/48\ hr$, needed to reduce the relative humidity up to ~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

QC2-Leakage Current Test: PASSED

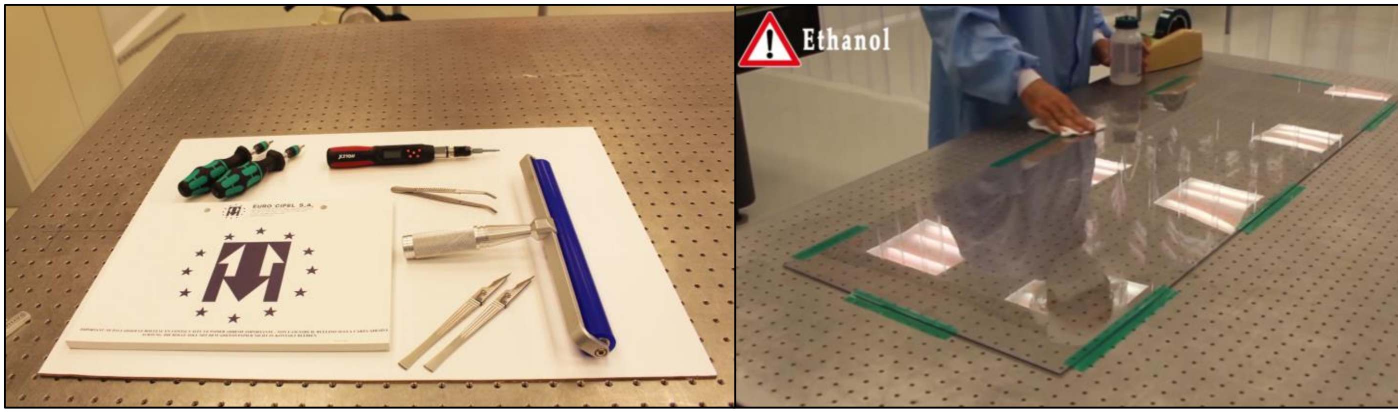


QC2-Leakage Current Test: NOT PASSED

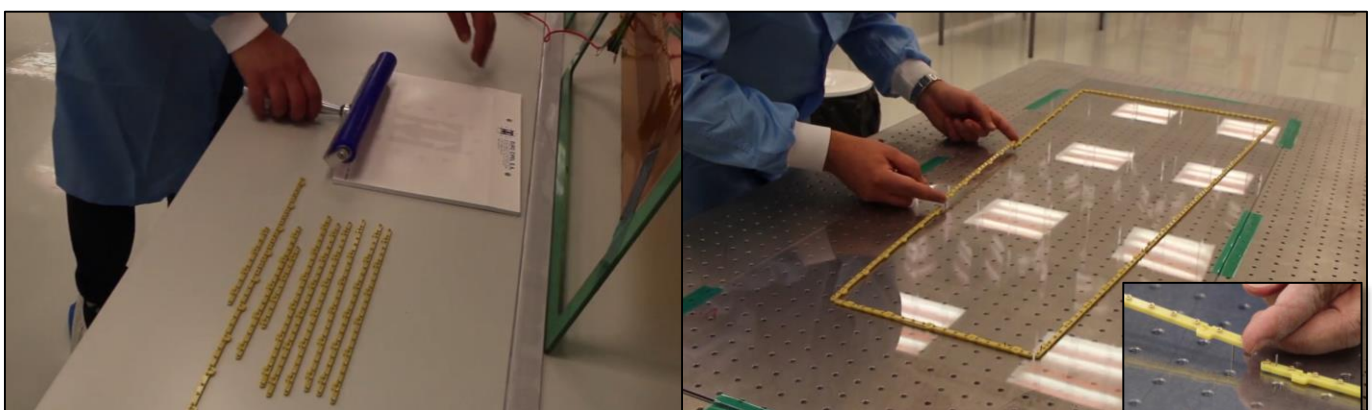


Annex B (GE1/1 Chamber Assembly)

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).

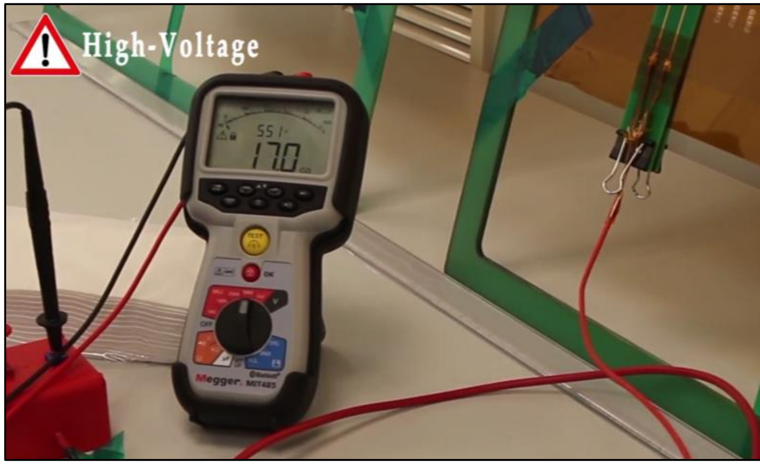


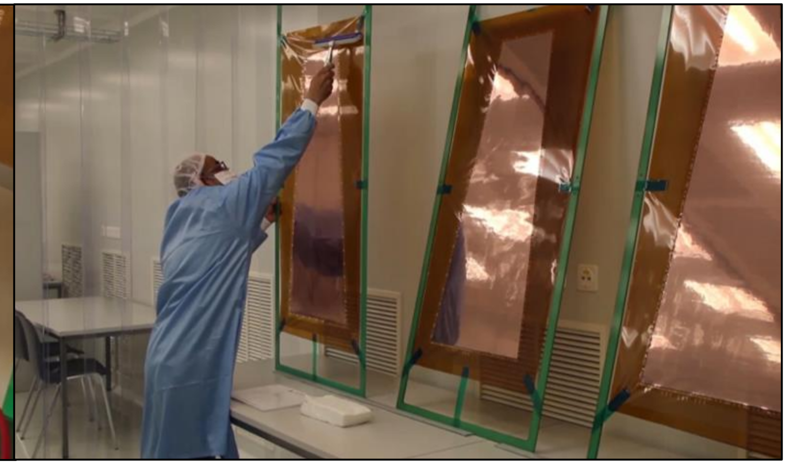
Step 2: the internal frames, responsible of holding the GEM stack, are cleaned with an anti-static roll (left) and placed on working table thanks to guiding pins (right).



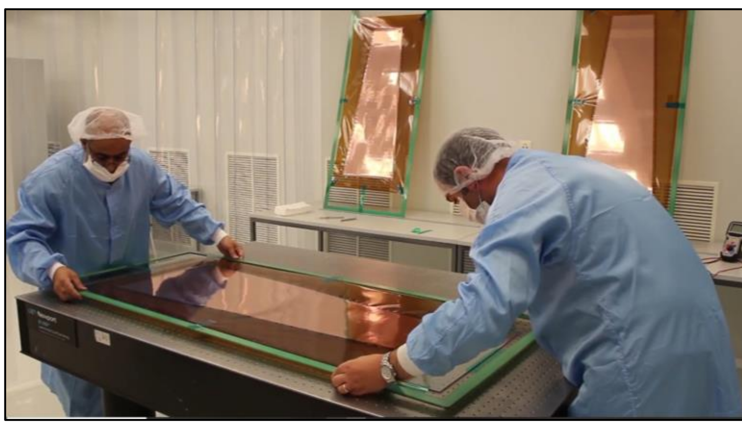
Annex B (GE1/1 Chamber Assembly)

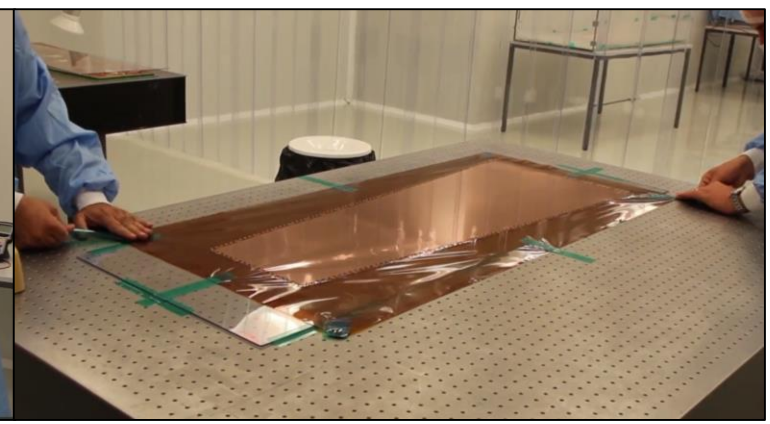
Step 3: **the first GEM foil is tested at $550\ V$ and cleaned again with the adhesive roll.**





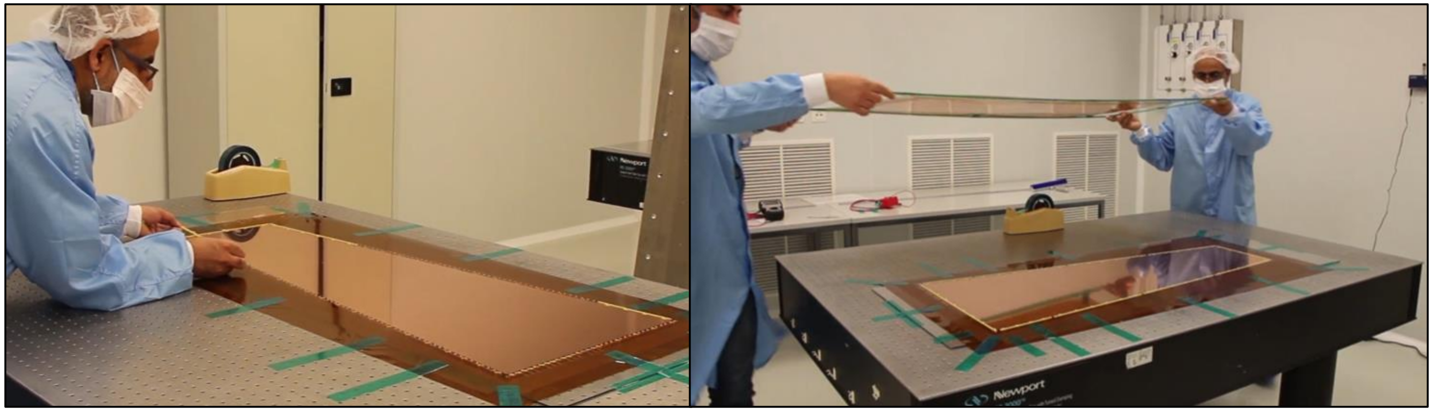
Step 4: **the first GEM is placed on the first layer of internal frames (left). The foils is stretched by hand and attached to the working table to ensure the flatness and stability of the structure (right).**





Annex B (GE1/1 Chamber Assembly)

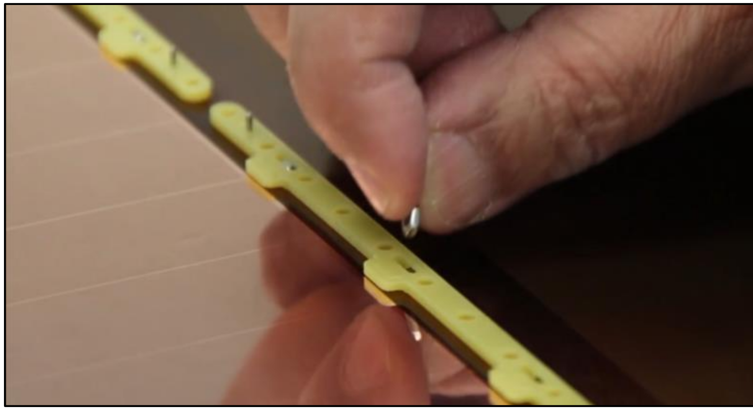
Step 5: the second layer of internal frames is placed on top of the first GEM (left). After testing and cleaning, the second GEM is added to the stack (right).



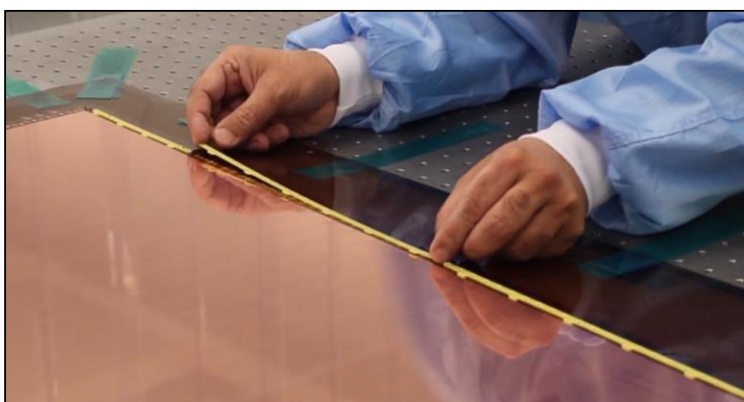
Step 6: same operation as before, the second GEM is stretched manually (left) and tested at $550\ V$ (right).

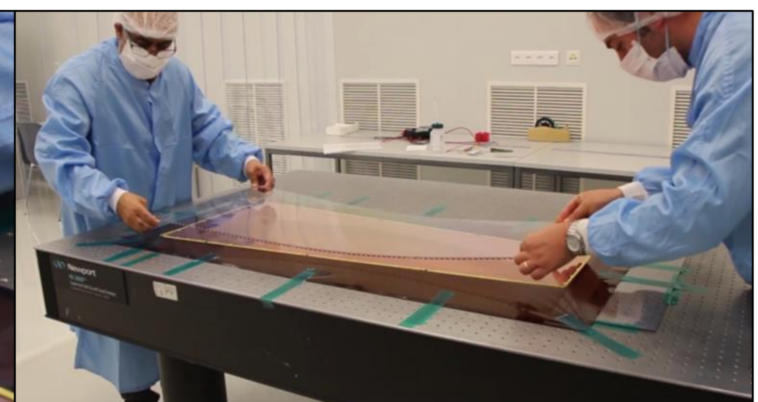
Annex B (GE1/1 Chamber Assembly)

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.



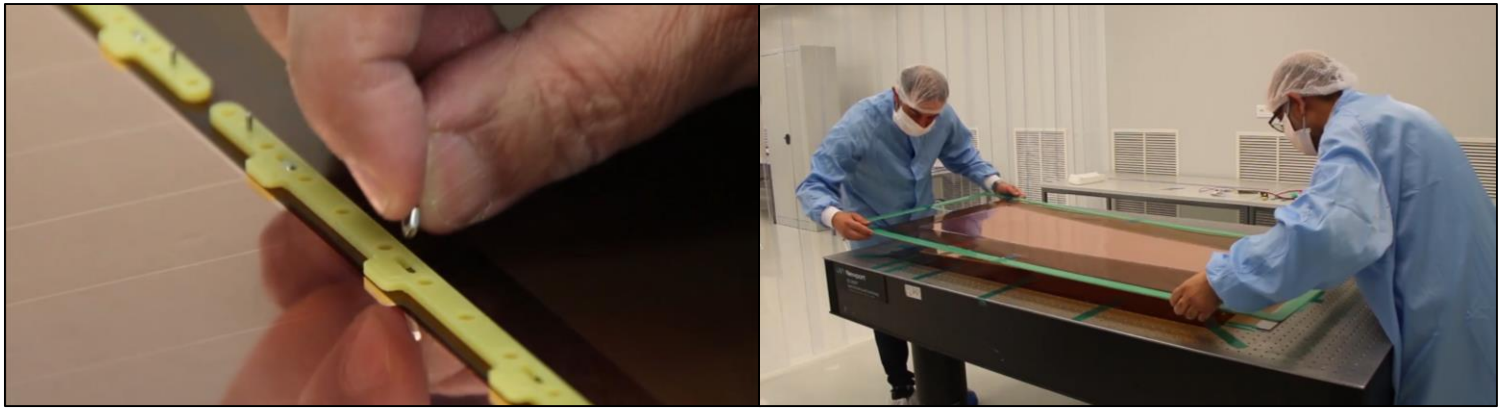
Step 8: the last layer of internal frames is added to close the stack (left), the GEM stack is protected by a PMMA cover placed fixed to the top of the internal frames.





Annex B (GE1/1 Chamber Assembly)

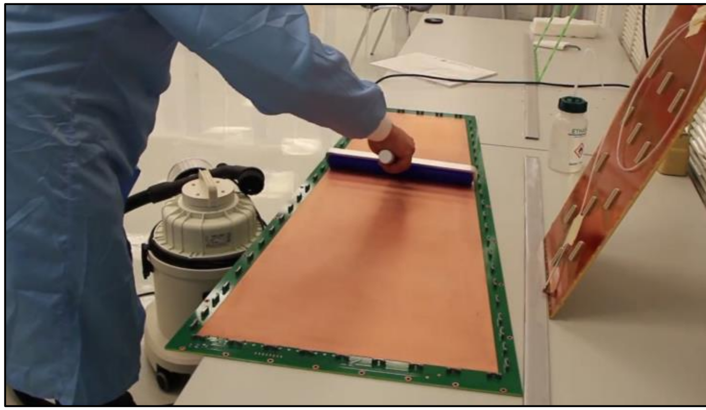
Step 7: **after the third layer of internal frames is in position, metallic nuts are inserted in the dedicated housing of the frames. Then, the last GEM foils is added to the structure.**

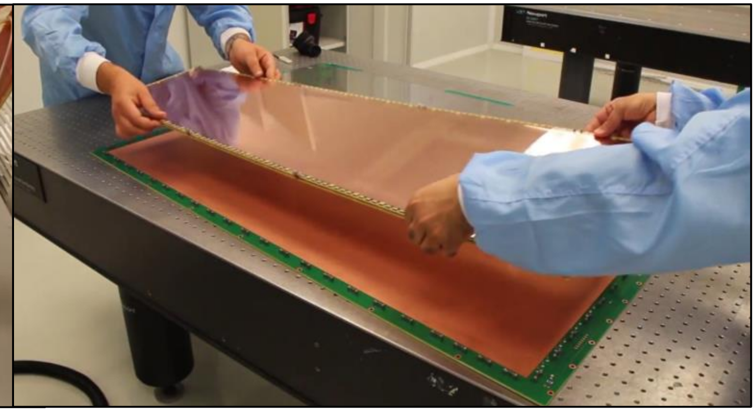


Step 8: **the last layer of internal frames is added to close the stack (left), the GEM stack is protected by a PMMA cover placed fixed to the top of the internal frames.**

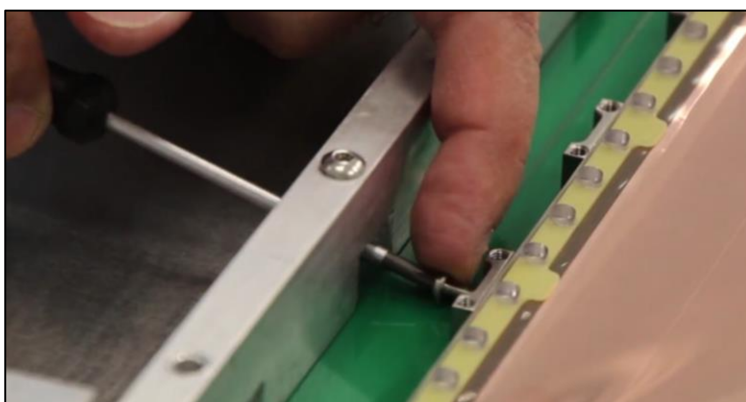
Annex B (GE1/1 Chamber Assembly)

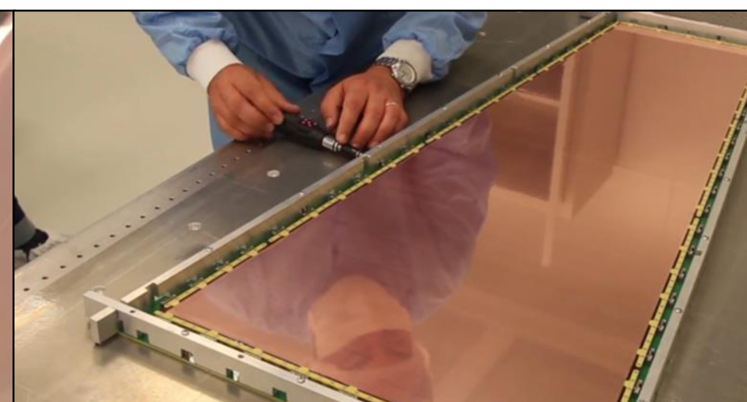
Step 11: after being cleaned with the anti-static roll (left), the drift plane is positioned below the GEM stack (right).





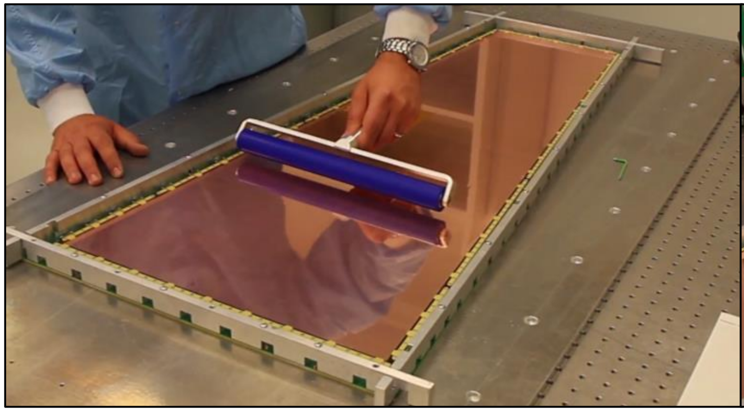
Step 12: lateral screws are inserted in the stainless steel pull-outs attached to the drift board until it reaches the embedded nuts (left). Then, torque control tools are used to stretch the foils, for a tension about 8 - 10 $cN \cdot cm$.

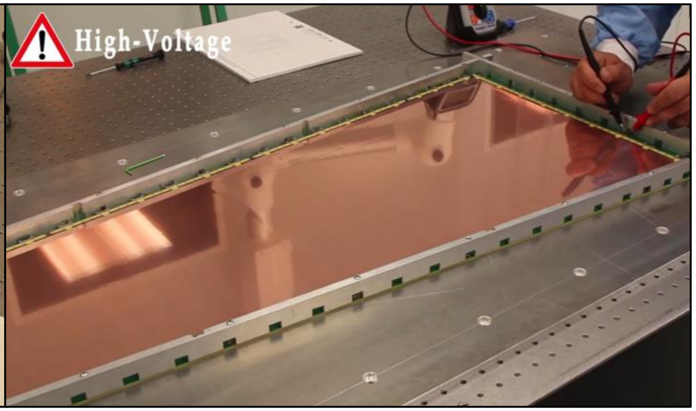




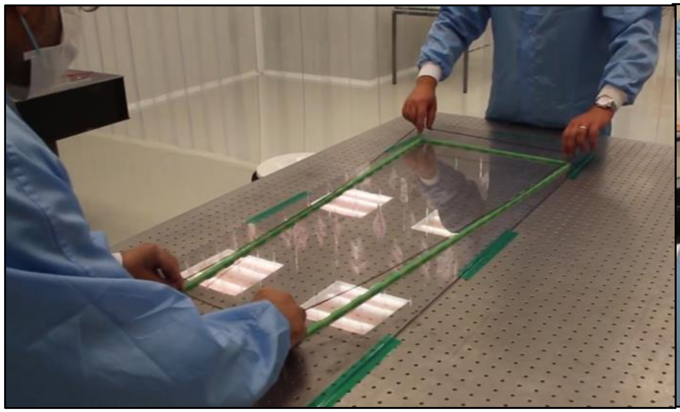
Annex B (GE1/1 Chamber Assembly)

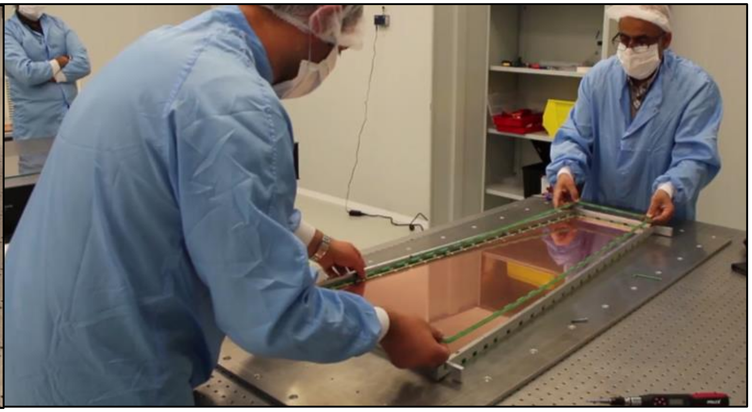
Step 13: the possible dust produced during the stretching step is removed with an anti-static roller (left) and the three GEM foils are tested once again at $550\ V$.





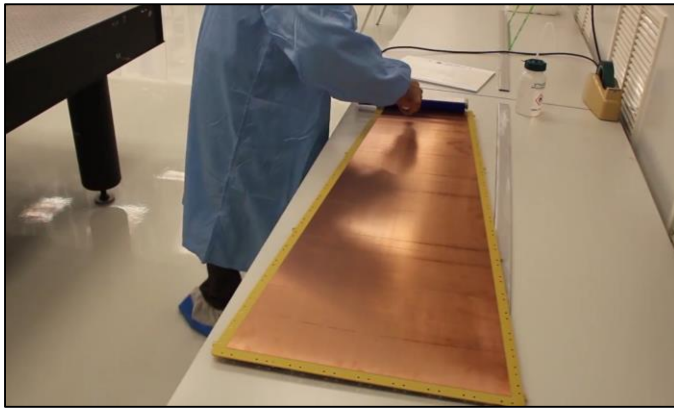
Step 14: The external frames is equipped with the O-rings (left) and it is placed around the GEM stack (right).

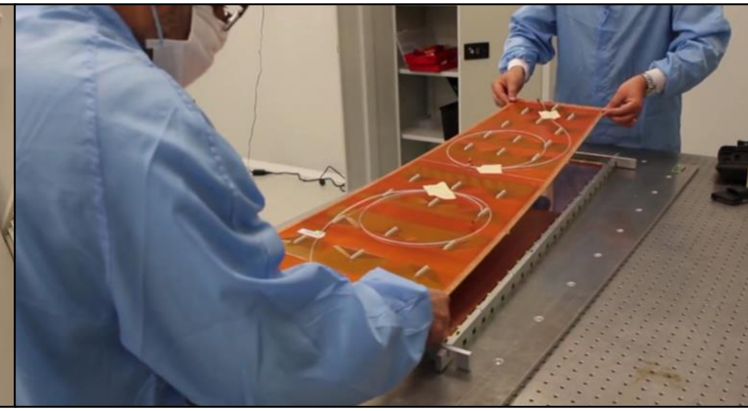




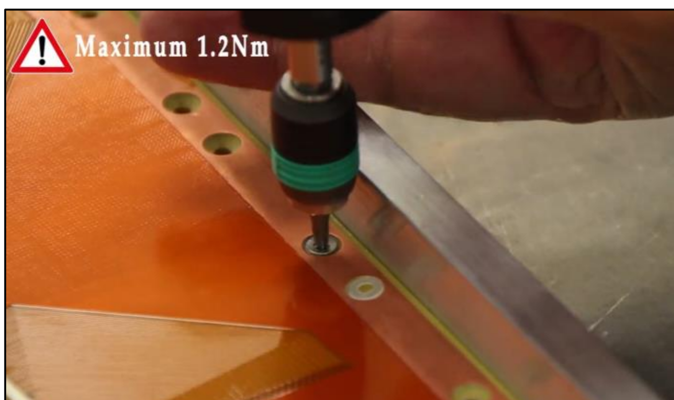
Annex B (GE1/1 Chamber Assembly)

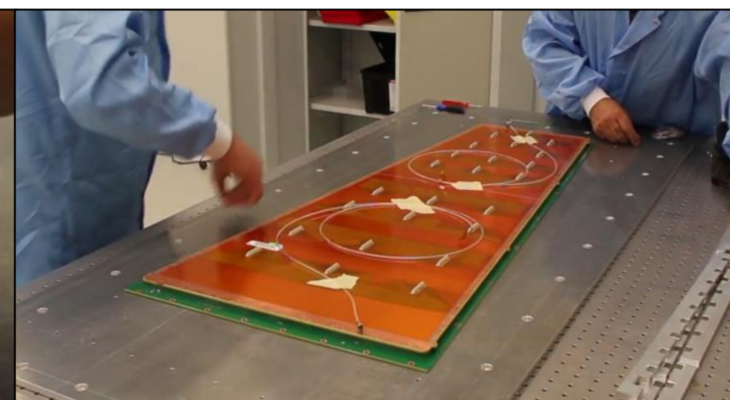
Step 15: after being cleaned (left), the readout board is placed on top of the external frame to close the chamber.





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).



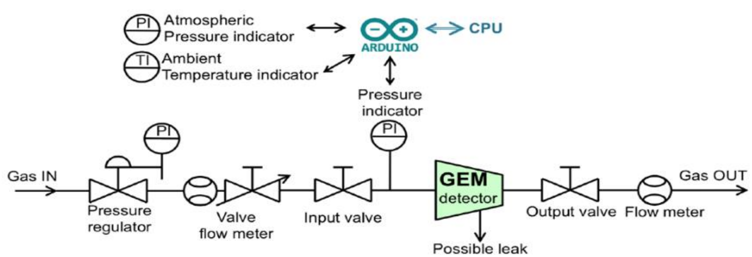


Annex C (GE1/1 Chamber QA/QC)

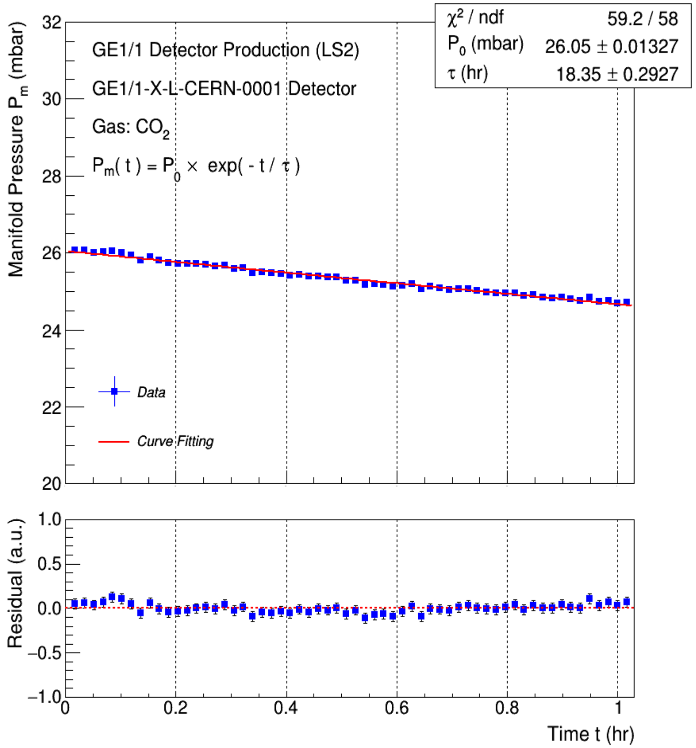
QC3 - Gas Leak Test

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.

Annex C (GE1/1 Chamber QA/QC)

QC3 - Gas Leak Test

→ ***Acceptance criteria***

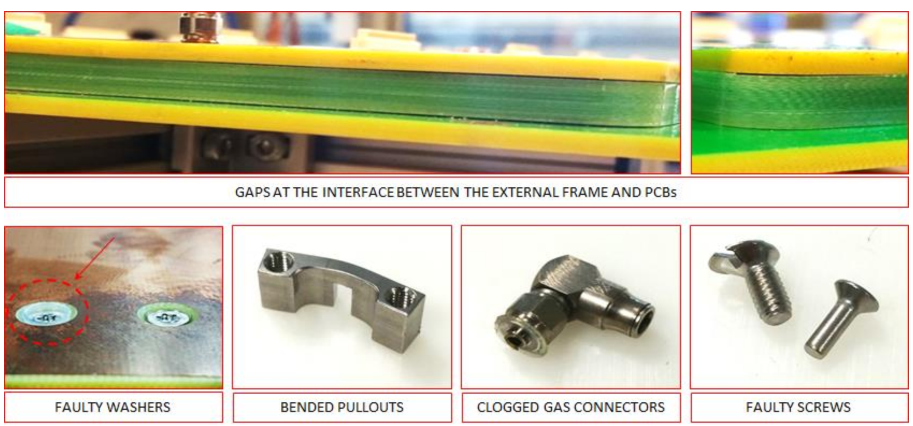
The detector under test is validated if the pressure drop in the detector + gas system does not exceed:

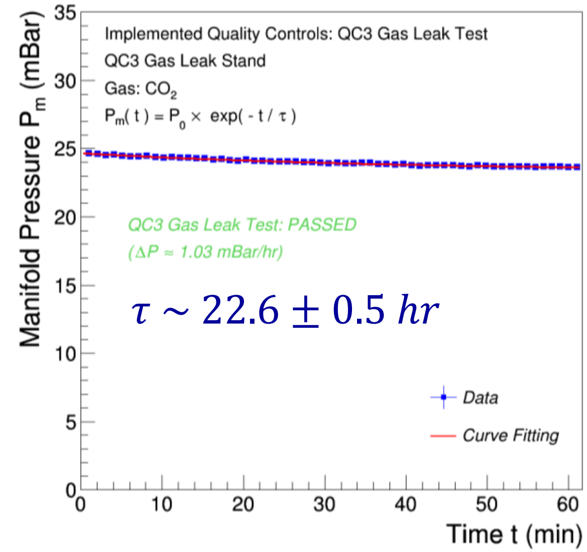
$$\Delta P \le 7\ mbar/hr$$

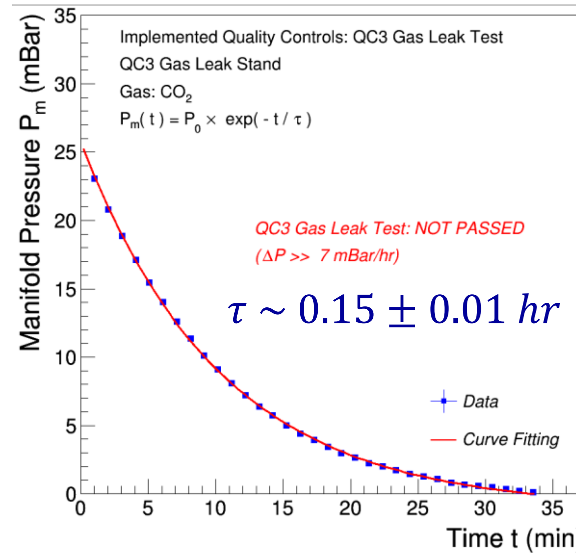
at initial over-pressure of $25\ mbar$, which corresponds to a gas leak time constant:

$$\tau \ge 3.04\ hr$$

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







Annex C (GE1/1 Chamber QA/QC)

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

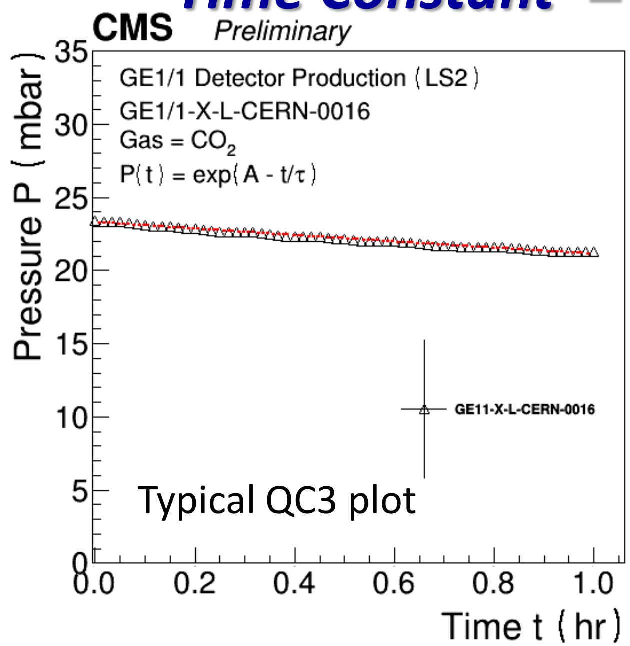
→ **Pressurize the detectors at $25\ mbar$**

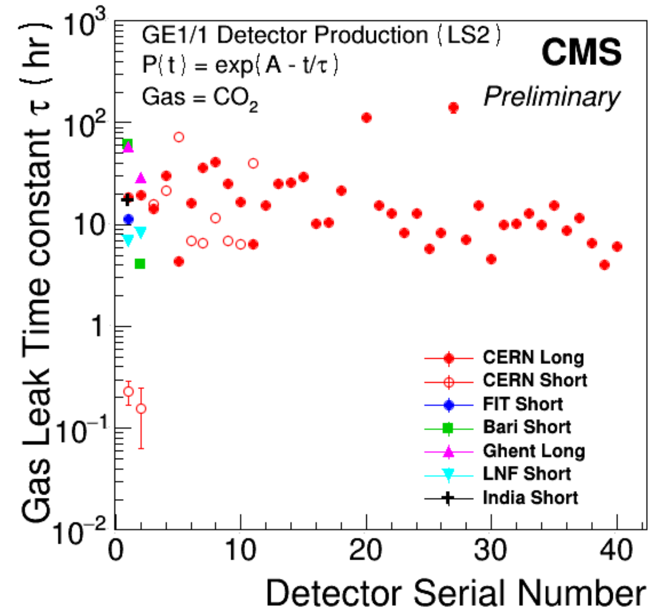
→ **Measure the pressure drop during one hour after closing the gas volume**

→ **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

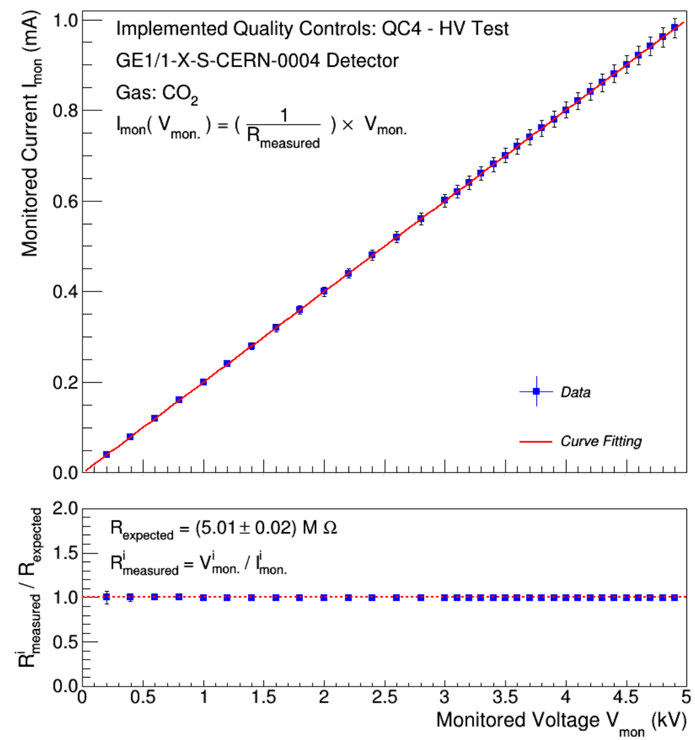
Determine Current vs Voltage curve of the detector and identify possible malfunctions, defects in the HV circuit

- 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)

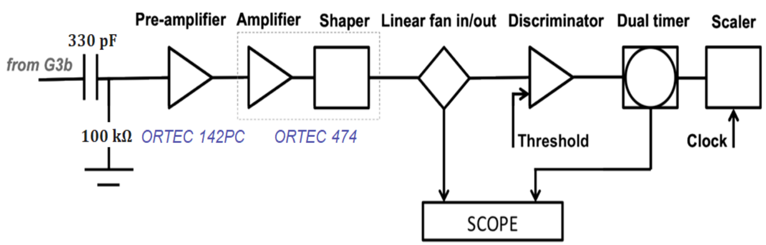


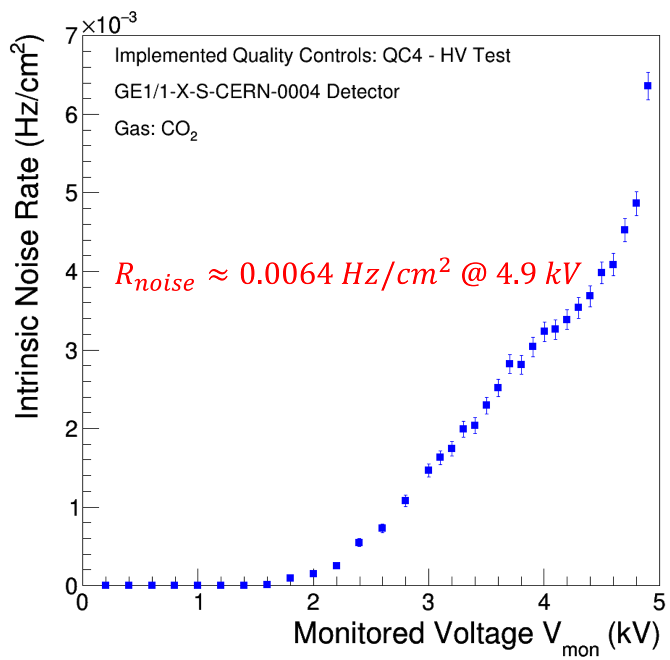
Typical I vs V curve obtained during the QC4 HV test. $I_{mon.}$ represents the current flowing through the HV divider to provide power to the detector electrodes.

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

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

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*

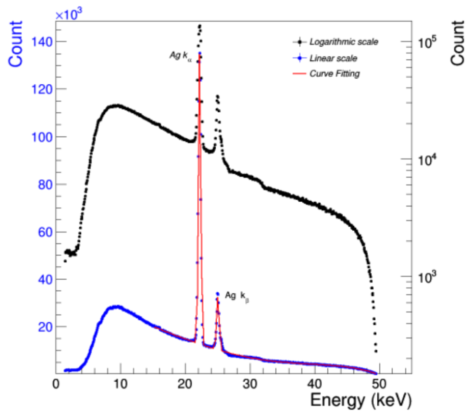
→ *Get the effective gas gain versus HV in one readout sector*

STEP 2

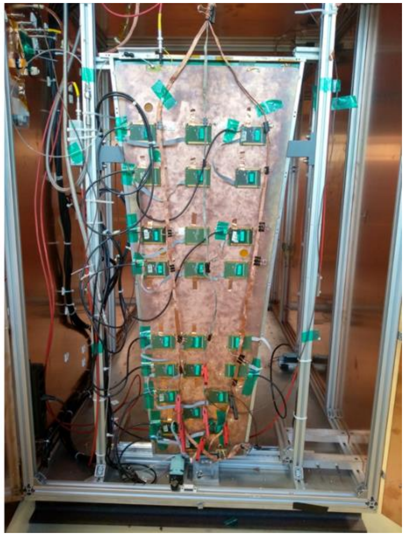
Response Uniformity Measurement

→ *Get "internal" gas gain variations map*

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



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

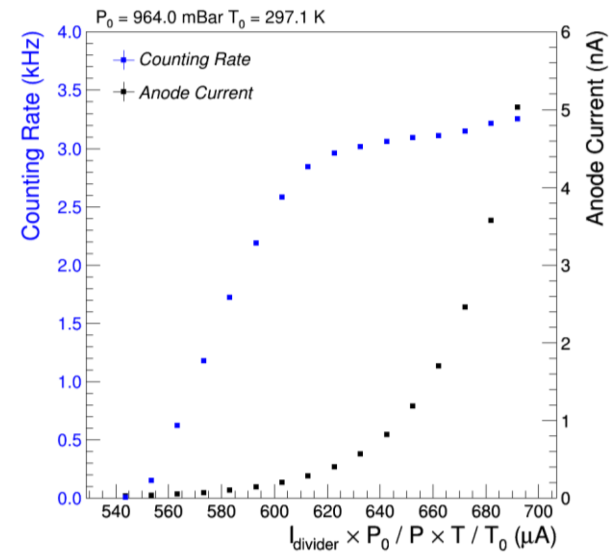


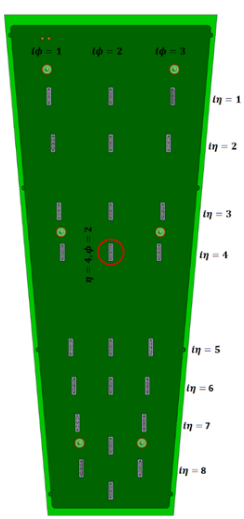
QC5 - Effective Gas Gain Meas.

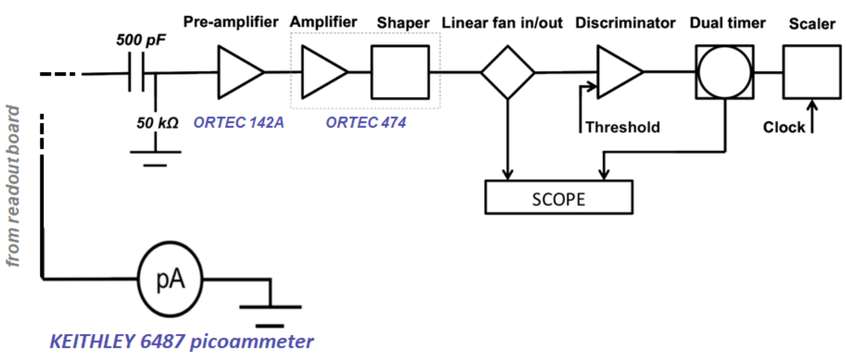
Measure the Effective Gas Gain as a function of the voltage applied on the resistive high voltage divider

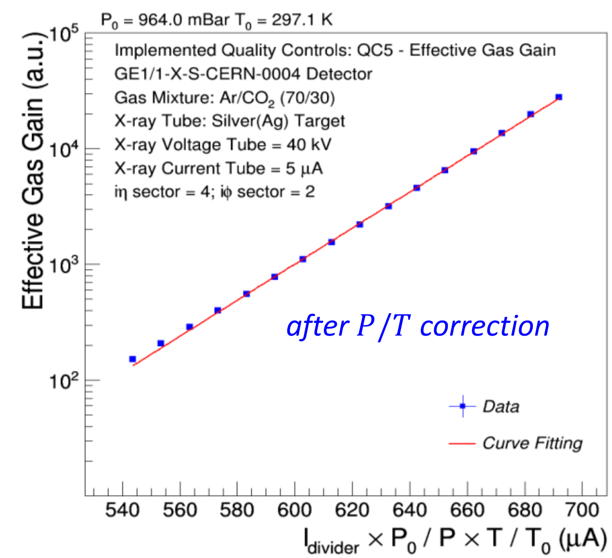
- Effective gas gain of GE1/1 detector is measured in a single readout sector $(\eta = 4, \phi = 2)$
- The Effective gas gain is defined as:

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





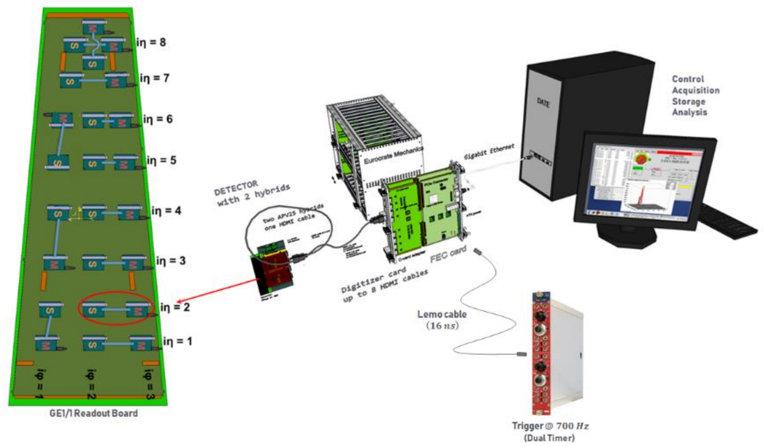


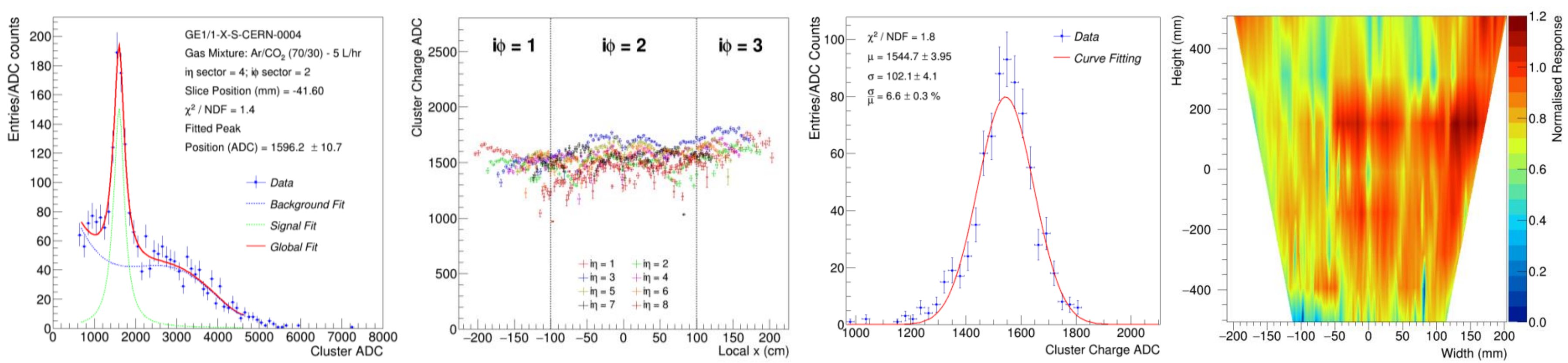


QC5 - Response Uniformity Meas.

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





Annex C (GE1/1 Chamber QA/QC)

HL-LHC

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
- QC7
- QC8

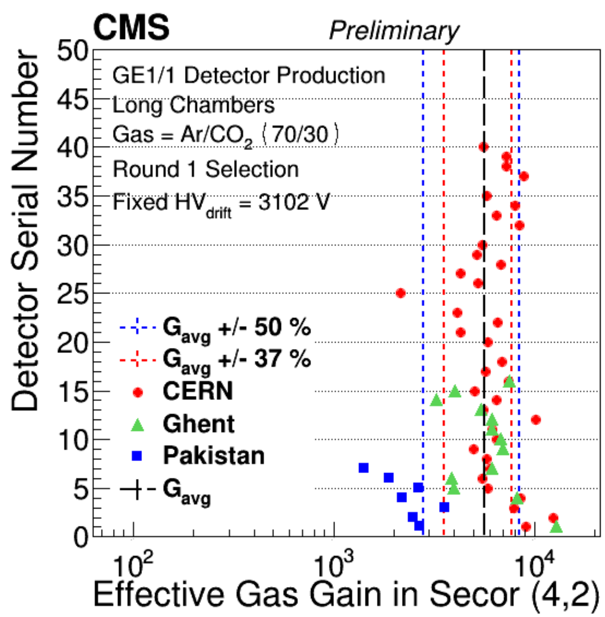
QC5 – Step 1
Effective Gain Test

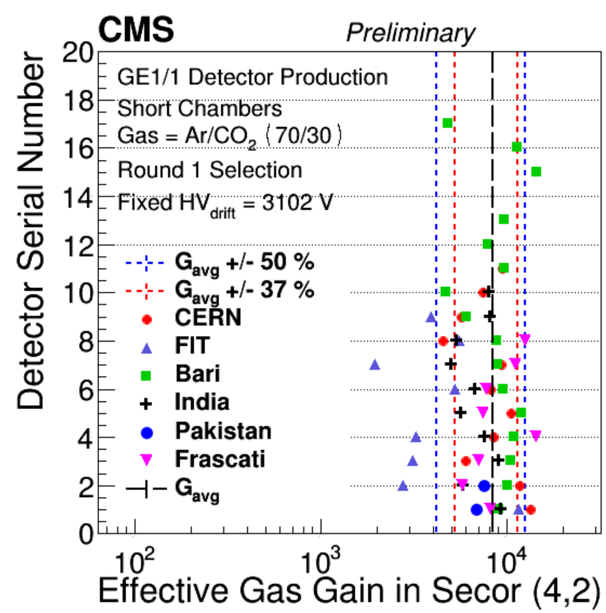
→ **Measure the absolute gas gain in one readout sector**

Statistics: (mean ± std.)

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

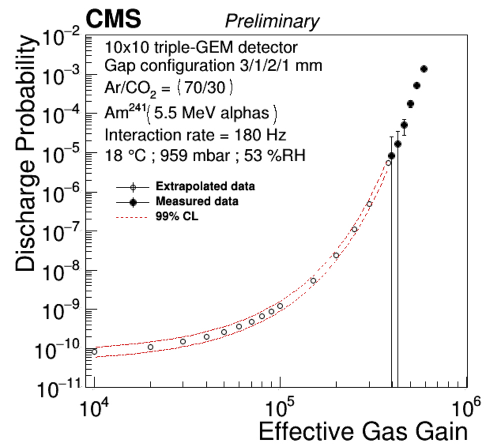
Short → $G_{eff} = 7980.0 \pm 2893.3\ (36.2\%)$

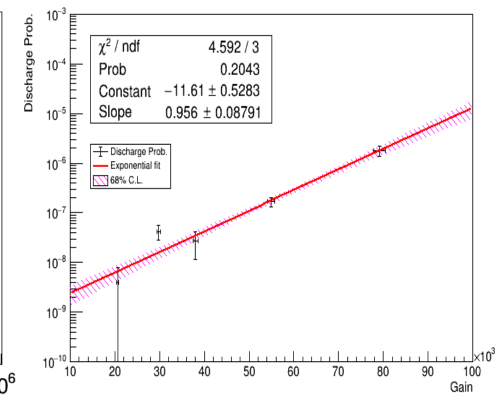


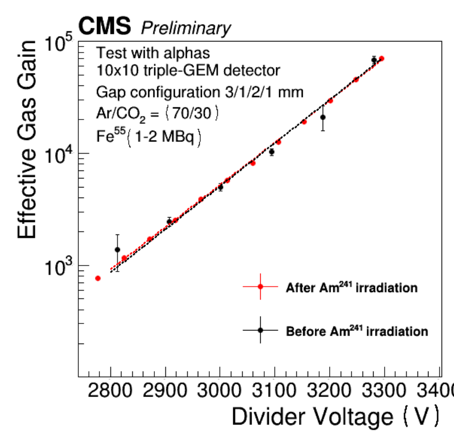


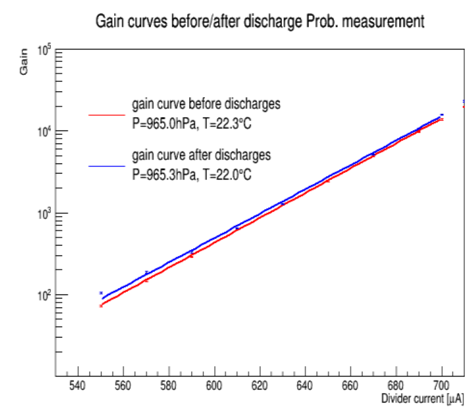
Annex D (GEM Discharges Studies)

- **Measuring the discharge probability:**
  - Tests in laboratory (alpha particles) with both small and large detectors
  - Tests in neutron facilities with CMS-like particle background
- **Test results:**
  - Determined lower and upper limits for discharge probability
  - Estimate total number of discharges per cm^2 in the hottest region
  - No temporary or permanent degradation of the detector performance could be measured after alpha irradiation, nor in neutron environment

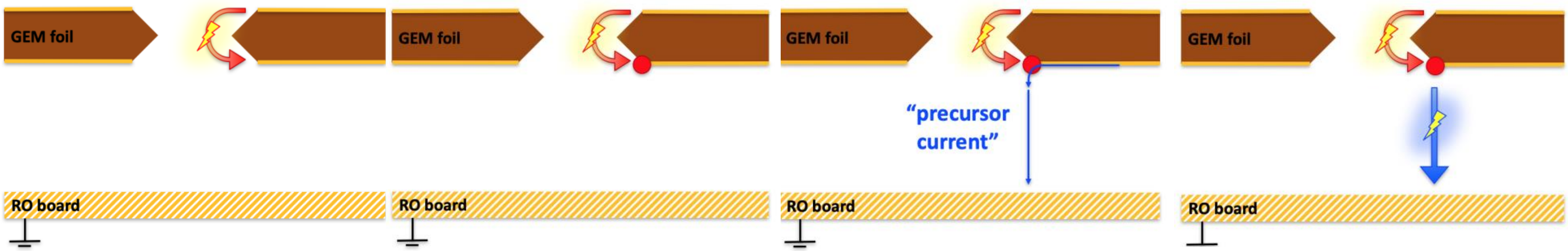


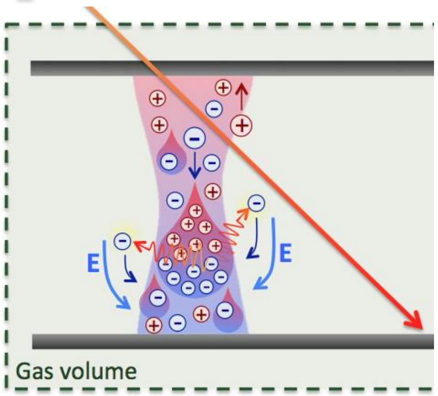




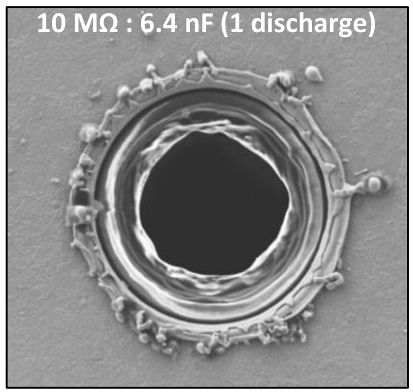


Annex D (GEM Discharges Studies)

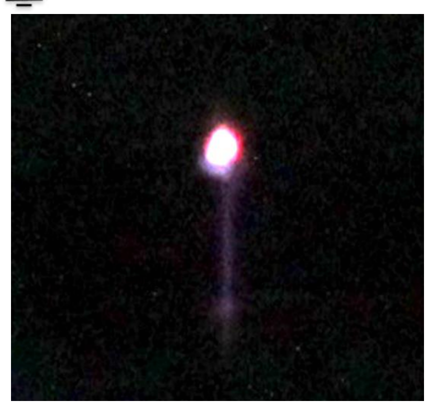




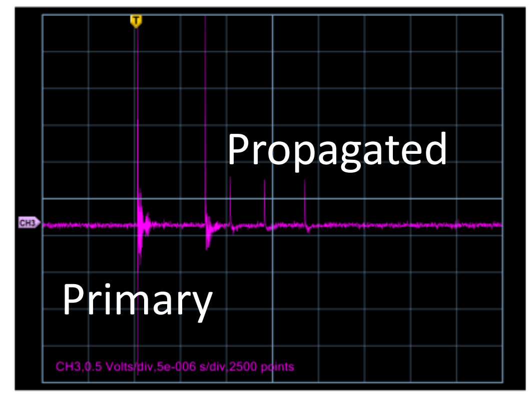
Typical development of avalanche into a streamer



SEM picture of a GEM hole (bottom) after one discharge with an energy of 2.0 mJ



A. Utrobičić et al. (University of Zagreb), MPGD Stability Workshop June 2018



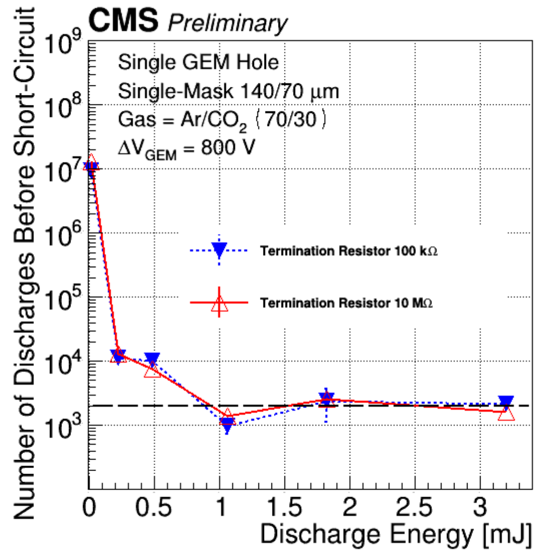
Typical EM interferences caused by propagating discharges in GEM detectors

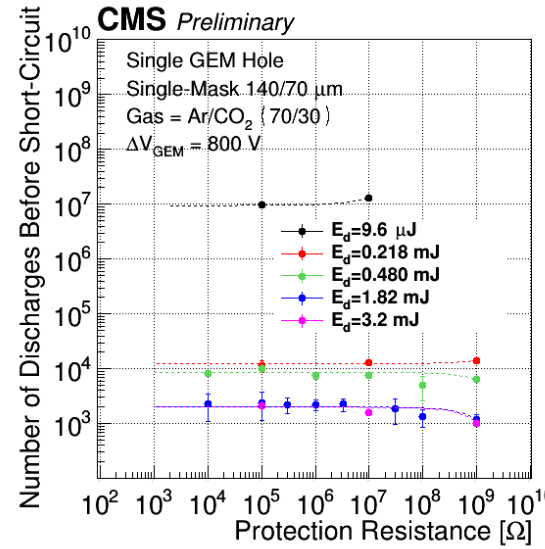
- **Step 1:**
  Primary discharged caused by the increase of the space charge density in the avalanche
- **Step 2:**
  Creation of a hot spot on the copper near the hole rim >2500 °C
- **Step 3:**
  Thermionic emission of electrons in the gas, enhanced by local electric field (Schottky effect)
- **Step 4:**
  Development of the precursor current into a streamer causing a second discharge

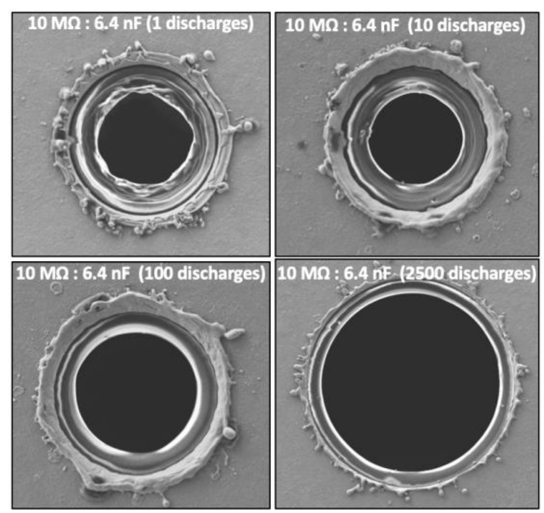
https://indico.cern.ch/event/757322/contributions/3396501/attachments/1839468/3015160/JMerlin_MPGD2019_Discharge_Study_V1_23042019.pdf

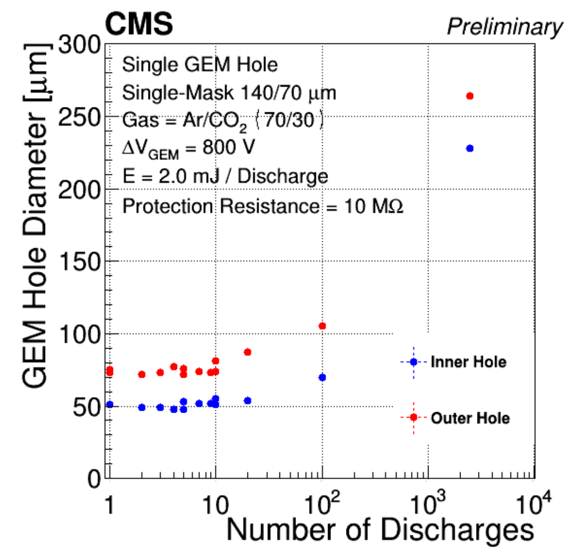
Annex D (GEM Discharges Studies)

- **Specific study on single GEM hole systems:**
  - Special GEM foil design with single hole to control the conditions of discharges and isolate the elements that play a role
- **Test results:**
  - Measurements reveal high resistance to discharges, even at high energy (>10^3)
  - Slight increase of the hole diameter after 10-20 discharges
  - No effect on detector gain since sharing of amplification over several layers and several holes



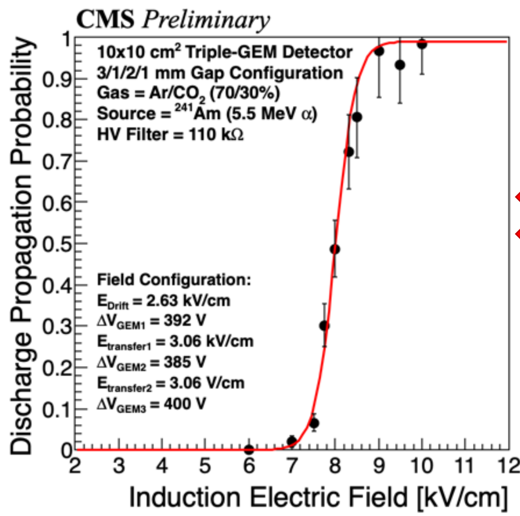


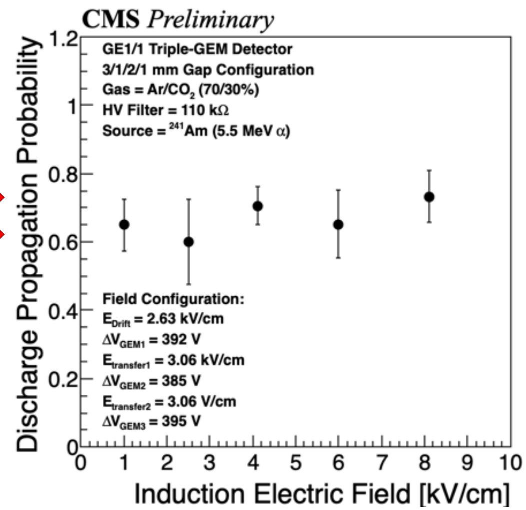


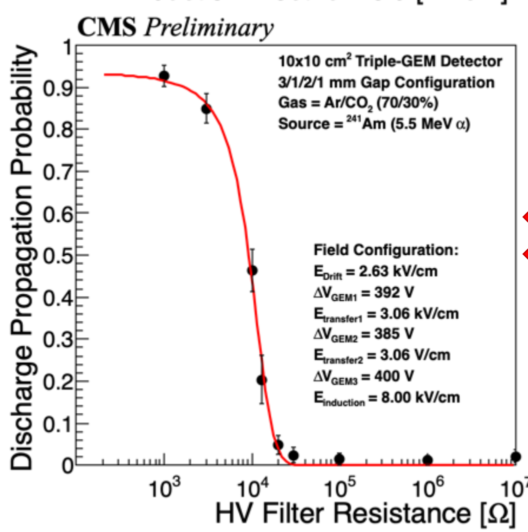


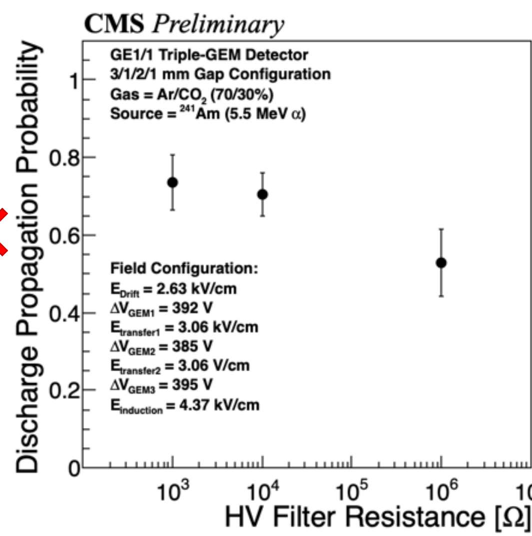
Annex D (GEM Discharges Studies)

GE1/1 Discharges









Tests with small 10x10 detectors:

- Influence of the induction field and filter resistor

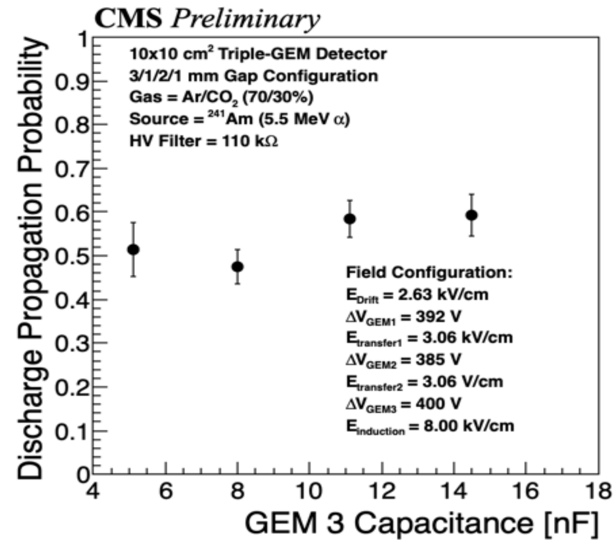
Tests with large detectors:

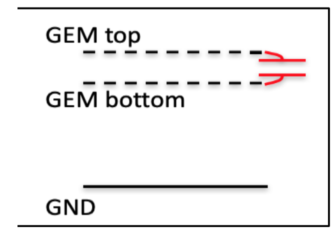
- No dependency on the induction field
- No effect from the filter resistor
- Clear inconsistency between small and large chambers
- Clear increase of the propagation probability with the induction capacitance → i.e. sufficient amount of energy on the foil to feed the precursor current and trigger discharge propagation

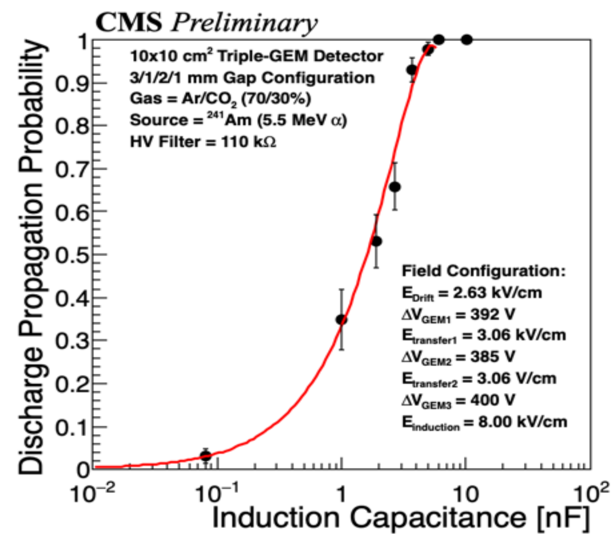
Annex D (GEM Discharges Studies)

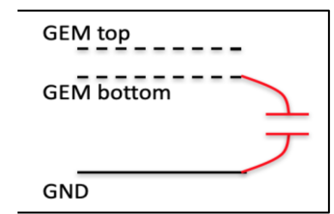
GE1/1 Discharges

- **Further studies to understand the differences between small and large chambers:**
  - No dependency with the GEM foil capacitance → no influence of the primary discharge energy
  - Clear increase of the propagation probability with the induction capacitance → i.e. sufficient amount of energy on the foil to feed the precursor current and trigger discharge propagation
  - All measurements indicate that the discharge propagation is more likely to happen in large foils due to the availability of energy directly stored in the foil

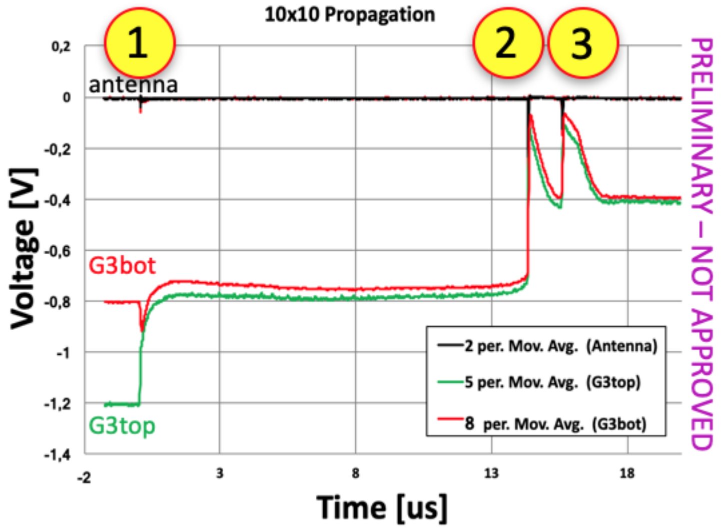








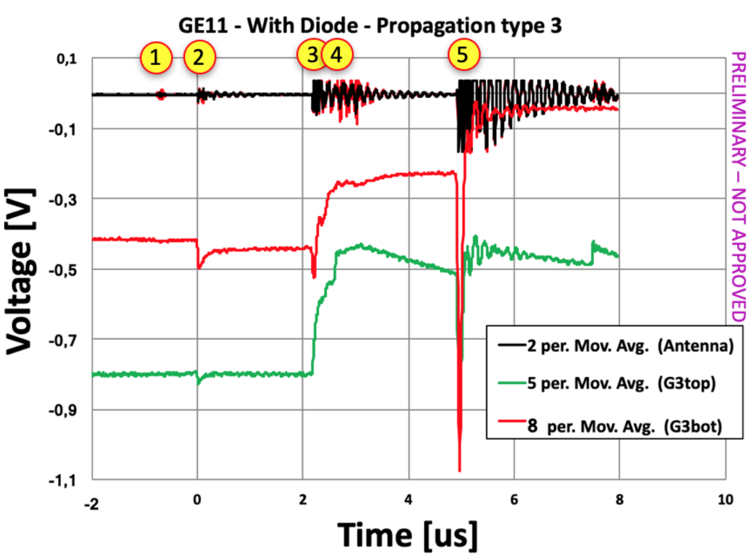
Annex D (GEM Discharges Studies)



1. Primary discharge in GEM3
2. Propagation from GEM3 to Readout
3. Re-ignition of the propagation

Propagation process in small detectors is simple and localized

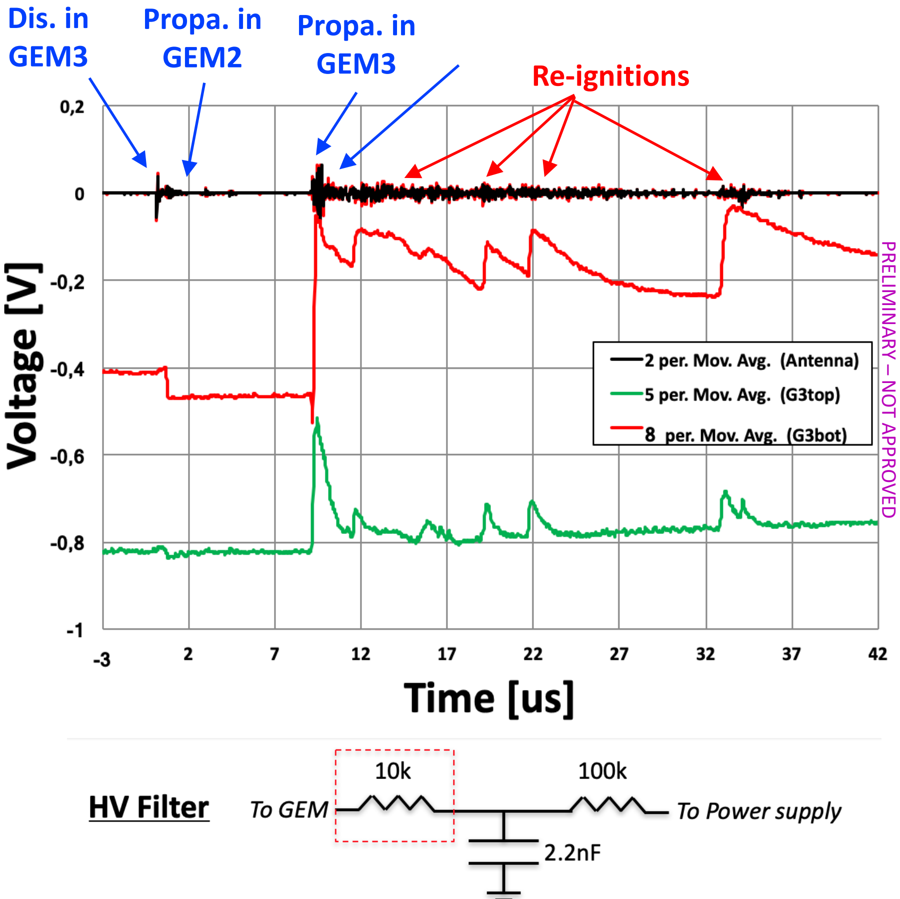
Large Detector

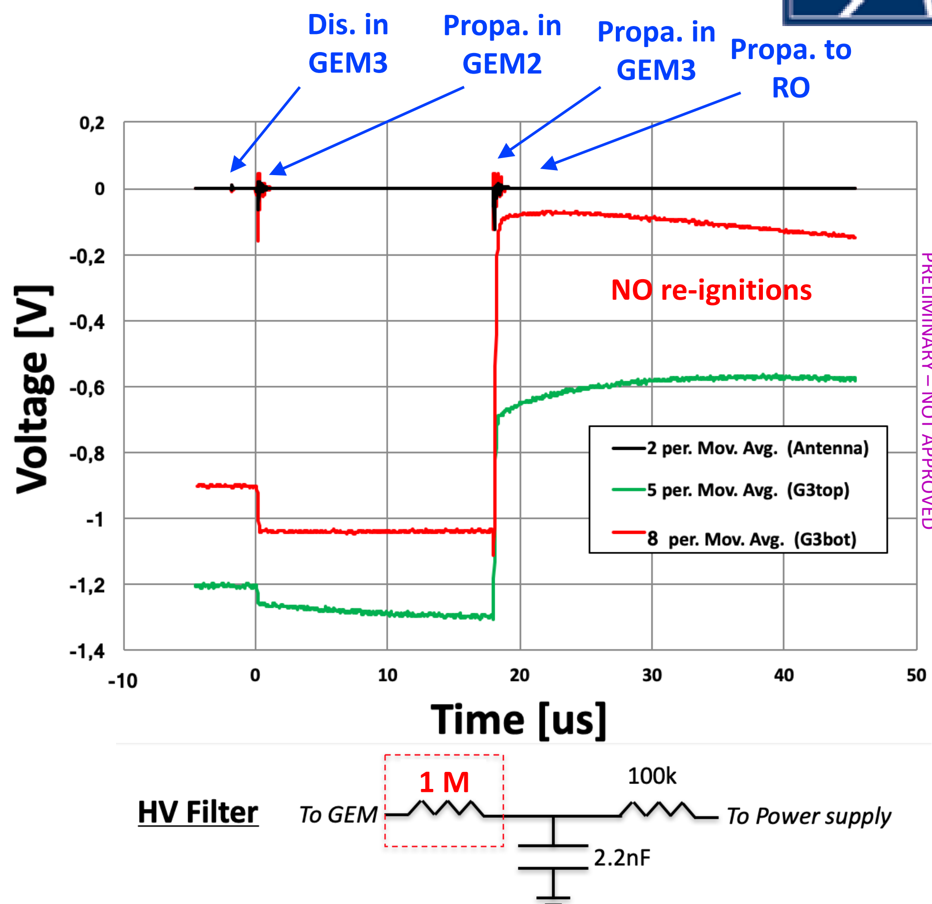


1. Primary discharge in GEM3
2. Propagation backward in GEM2
3. Propagation forward in GEM3
4. Propagation from GEM3 to Readout
5. Re-ignition of the propagation

Propagation process in large detectors is more complex (discharges "travel" backward and forward, accumulating more energy)

Annex D (GEM Discharges Studies)





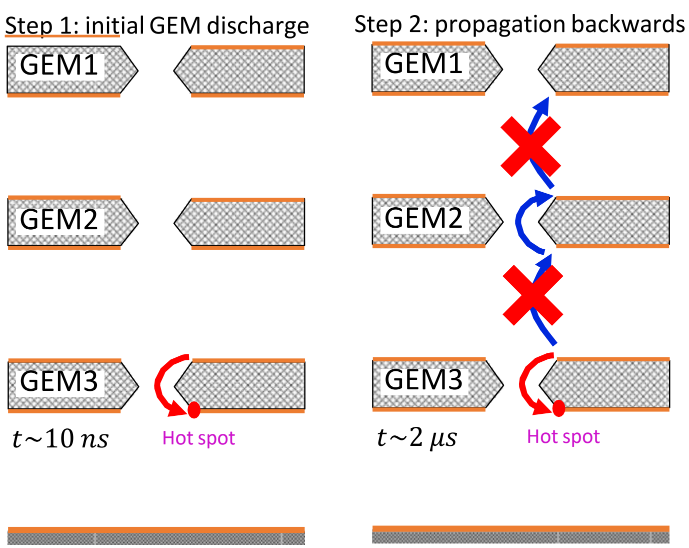
- **In-depth investigations with large detectors:**
  - Further studies indicates that the damage probability in large detectors is mainly due to propagation re-ignitions
  - Re-ignitions are fed by the energy stored in the filter capacitance → can be mitigated by tuning the filter capacitance → can reduce by a factor 10 the damage probability

Annex D (GEM Discharges Studies)

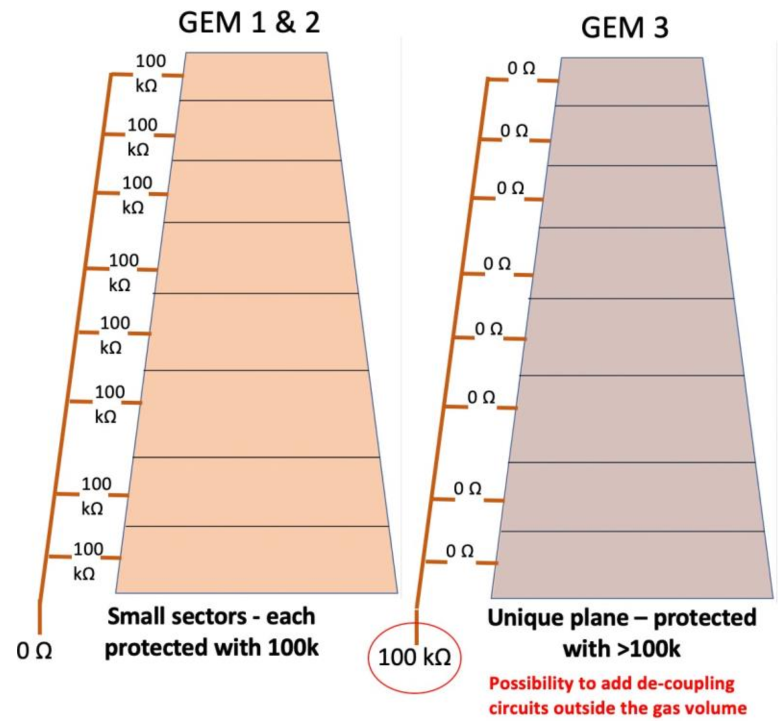
GE2/1 Discharges

Introducing the final configuration based on the "mixed" design:

- GEM1 and GEM2 are **double-segmented** to prevent the **discharge propagation**
- GEM3 is **single-segmented** to suppress the **crosstalk**
- The foil is actually double-segmented but the bottom segments are merged together using **0 Ω jumpers**



The propagation at low induction field can be stopped in the **transfer gaps** thanks to the double segmentation on the first GEMs → Propagation stopped before it can reach the RO



Merging the HV segments on the bottom of GEM3 allows to reproduce the single-segmented behavior while having the **same layout** for all the GEMs

Annex D (GEM Discharges Studies)

ME0 Discharges

HIP with $E_{deposited} > 30keV$

$P_d = 1.24x10^{-9} \pm 1.16x10^{-9}$
(average of the two sets of tests we performed)
Measured with $E_{deposited}$ ~ 350 keV

Assuming a LHC duty cycle = 0.33

Factor based on the GEM foil design

Factor based on the RO circuitry

Factor based on the electronics protection circuit

Factor based on the optimization of the internal electric fields

System	Max HIP rate R_{HIp}^{max}	Disch. probability P_d	Max discharge rate R_d^{max}	Number of disch. per year	Transfer propagation probability	Induction propagation probability	Damage probability	Improvement factor (E_field optimization)	Number of damaged RO channels per 10 year	Fraction of damaged RO channels per 10 year
(Unit)	Hz/sector	-	Hz/sector	y^{-1}/sector	-	-	-	-	$(10y)^{-1}$	$(10y)^{-1}$ (%)
Slice test*	$3.15x10^3$	$1.24x10^{-9}$	$3.90x10^{-6}$	39	0.5	1	0.95	1	185 per VFAT(128 ch)	**100**
GE11	$3.15x10^3$	$1.24x10^{-9}$	$3.90x10^{-6}$	39	0.5	1	0.03	1	6 per VFAT	**4.79**
GE21	$1.92x10^3$	$1.24x10^{-9}$	$2.38x10^{-6}$	24	$< 3x10^{-4}$	$< 10^{-3}$	0.03	1	$7x10^{-7}$ per VFAT	**~ 0**
ME0	$2.36x10^5$	$1.24x10^{-9}$	$2.93x10^{-4}$	2927	$< 3x10^{-4}$	$< 10^{-3}$	0.03	1	$9x10^{-5}$ per VFAT	**~ 0**

*** Obsolete design – for comparison purpose**

Improved by the double-segmentation on GEM1 and GEM2

Improved by the de-coupling circuit on the plugin cards

Improved by VFAT protection resistor and the new HV filter config.

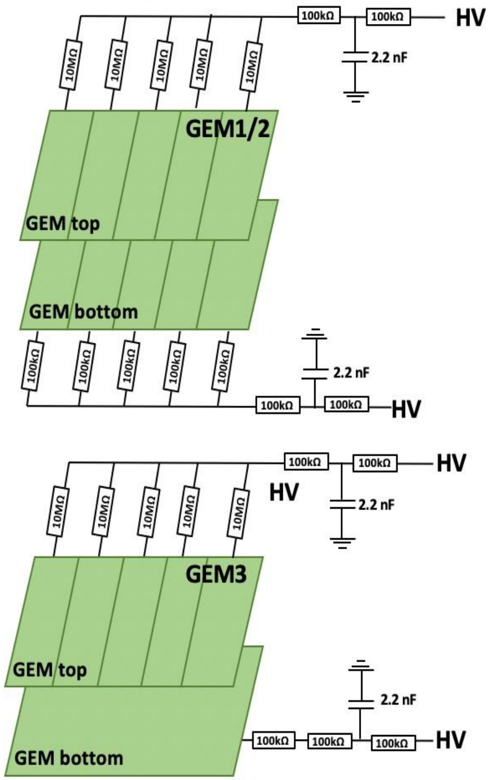
Studies are on-going: the improvement is not yet quantified

Annex D (GEM Discharges Studies)

ME0 Discharges

What is the impact of the new rate capability mitigation on the discharge behavior ?

GE2/1 Baseline (validated)



29 sectors $A \approx 100 cm^2$ → 40 sectors $A \approx 75 cm^2$

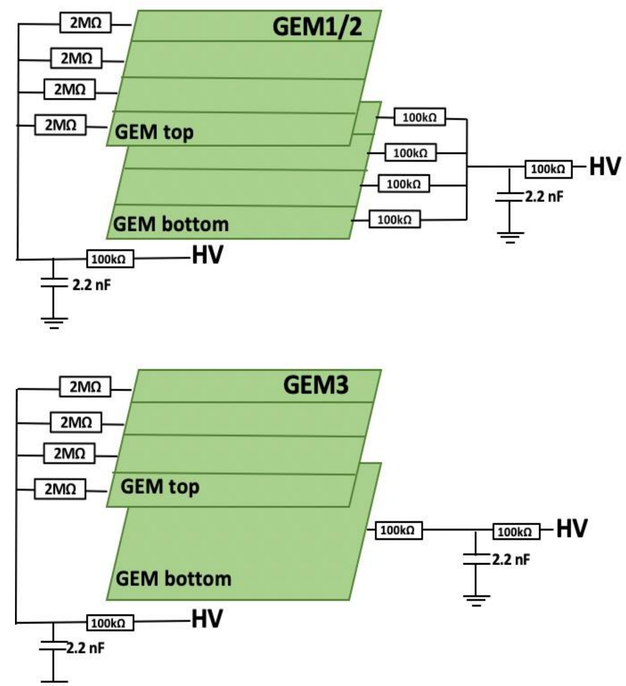
→Reduced area = reduced gap capacitance
→Expected reduction of the discharge propagation probability

10MΩ top protection → 2MΩ top protection

→Reduced protection resistance
→Expected no impact on the discharge propagation probability (as long as R> 30kΩ)

100kΩ + 100kΩ Filter resistors → 100kΩFilter resistors

ME0 Baseline



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:**

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

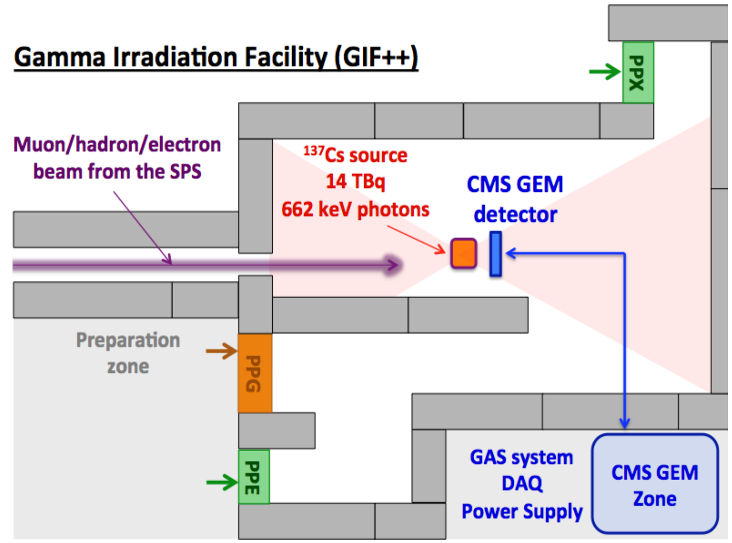
→ **High Purity Systems:**

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

GEM @ Gamma Irradiation Facility (GIF++)

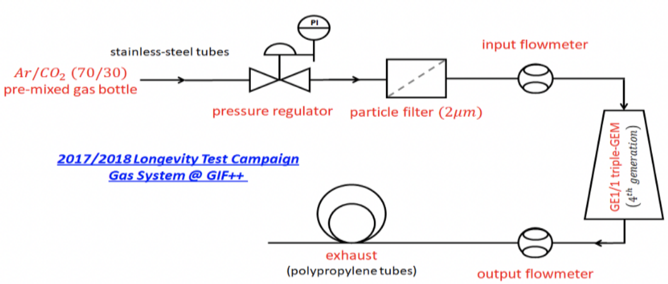
How to reproduce the aging effects?

- 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



- CMS GE1/1 triple-GEM detector 4^{th} 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.



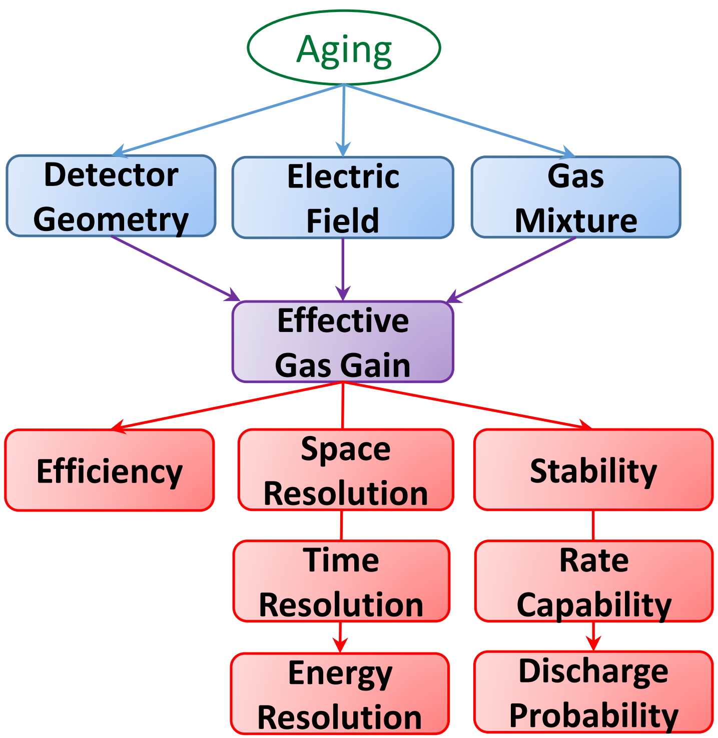
The GE1/1 detector under test is placed at $\sim 1m$ from the source point (D_1 position):

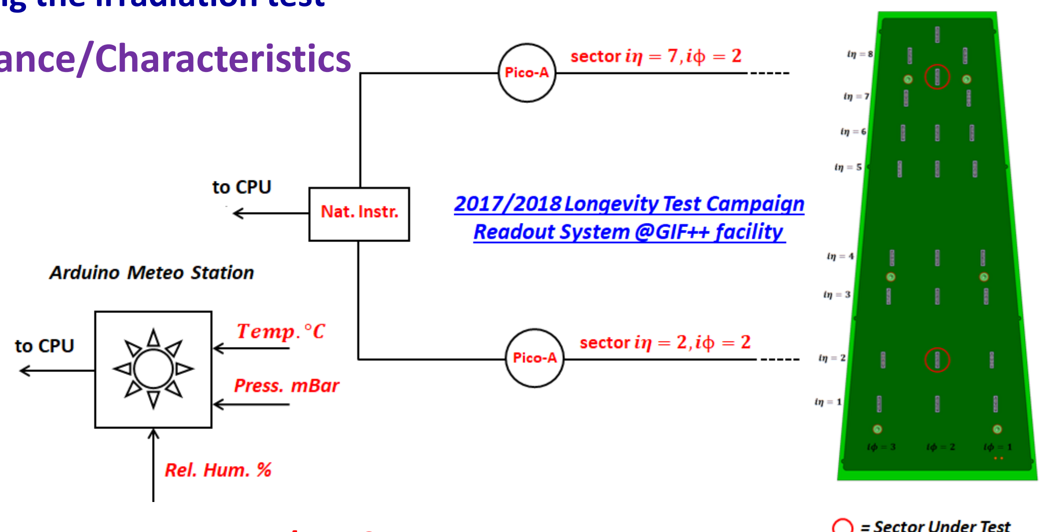
- upper half of the detector is operating under a particle flux just below $10^8\ Hz/cm^2$
- lower half receive a flux lower by four orders of magnitude ($10^4\ Hz/cm^2$)

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



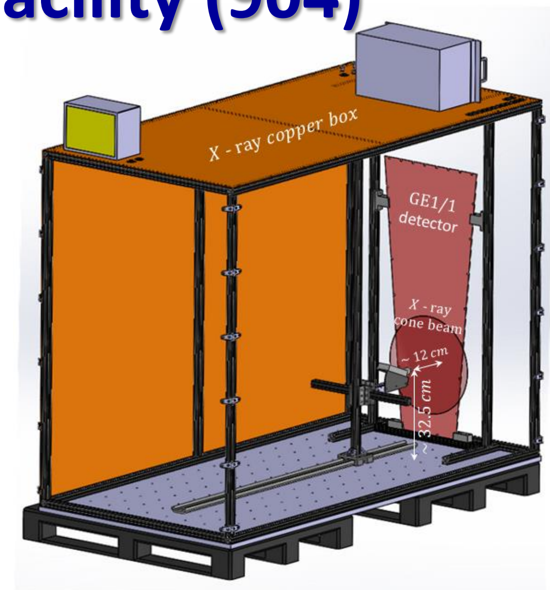


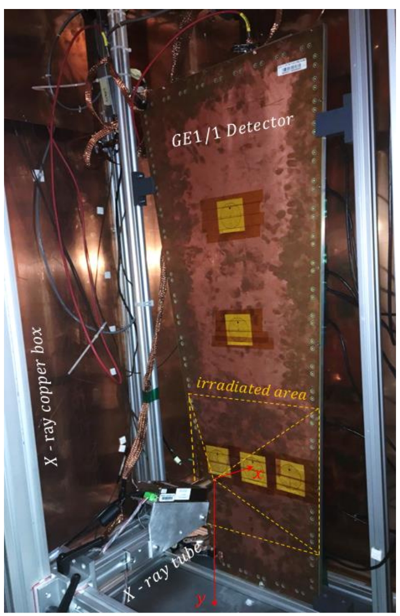
Readout System:
2 pico-ammeters to monitor the anode current during the irradiation test.

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

Experimental Setup at CMS-GEM facility (904)

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





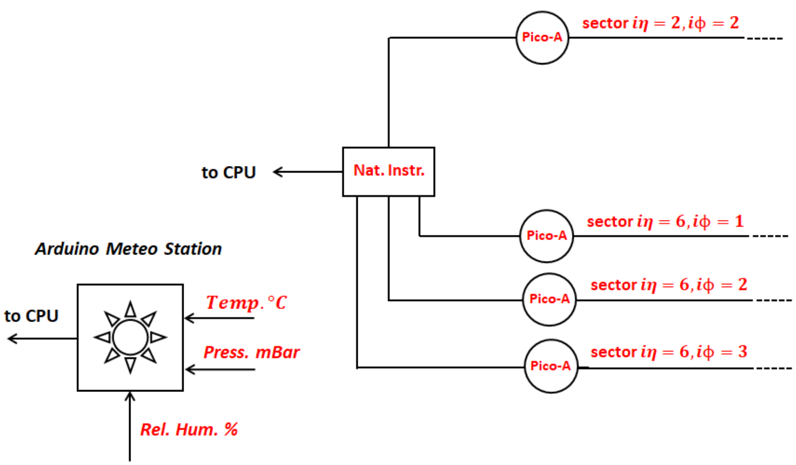
X-ray configuration:

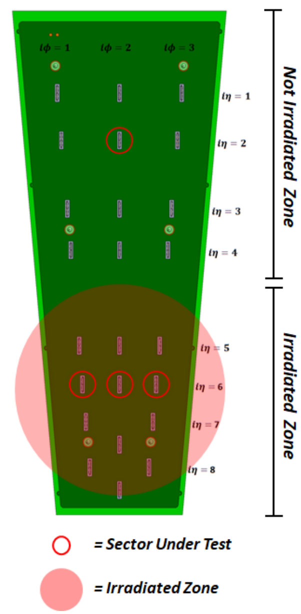
The X-Ray gun has been placed at $12cm$ from the detector in order to:

- **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.**

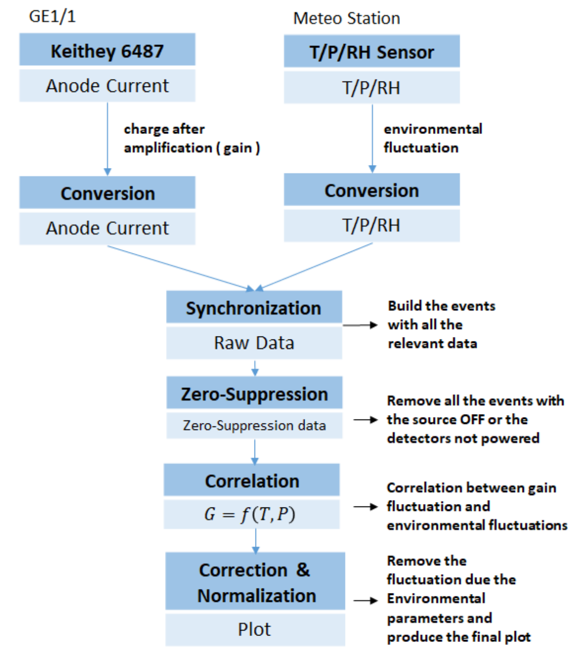
Data Acquisition and Analysis Procedure

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:

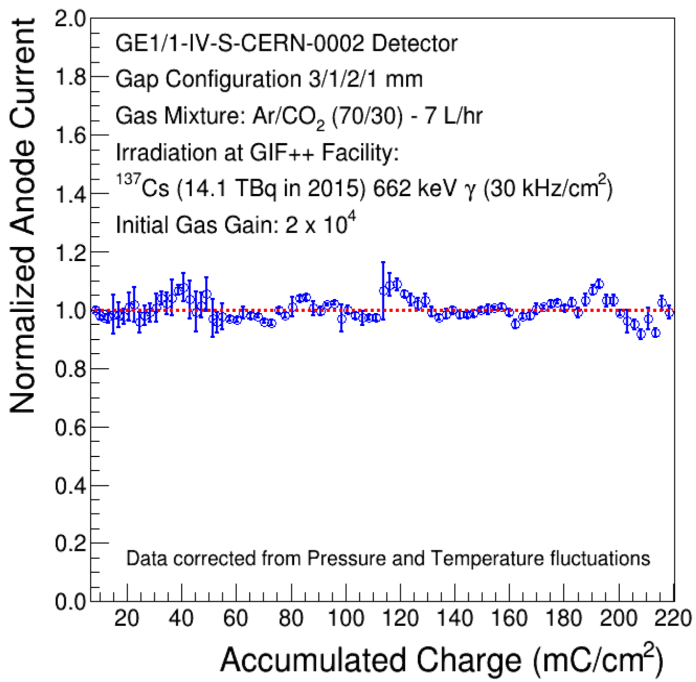
Arduino Meteo Station inside the X-ray copper box to monitor environmental parameters.

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

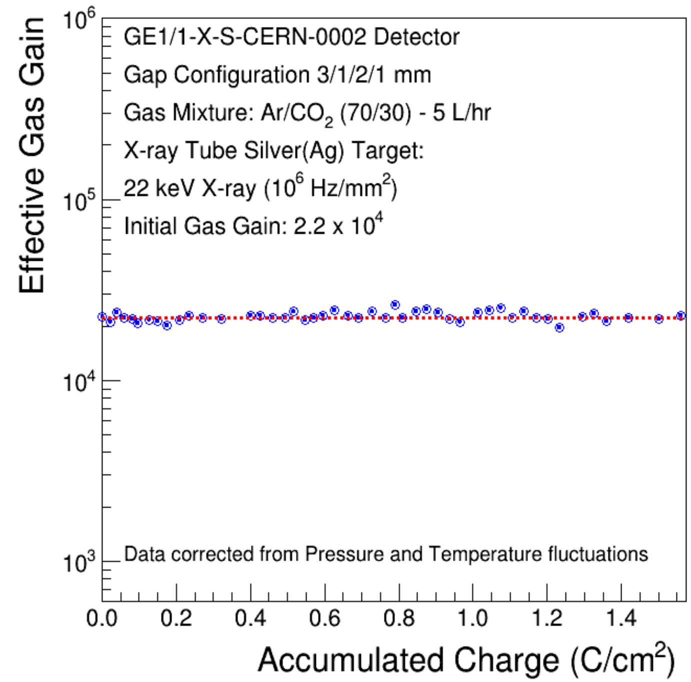
- **The *effective gas gain* and the *energy resolution* have been continuously measured every week on the readout sectors under test.**
- **The *gas gain map uniformity* measurements have been performed every month to check for the gas gain variation between the irradiated and non irradiated detector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

Annex E (Triple GEM Longevity Studies)

Accumulated Charge and Anode Current Measurement @ GIF and 904



GIF++ Triple-GEM aging test. Normalized anode current as a function of the accumulated charge. Chamber operating in Ar/CO2 (70/30) at an initial gas gain of 2x10^4 equipped with CERN GEM-foils based on single-mask photolithography technique developed by CERN PCB Workshop; The chamber accumulated a total charge of 218mC/cm2 after 28 months of continuous irradiation

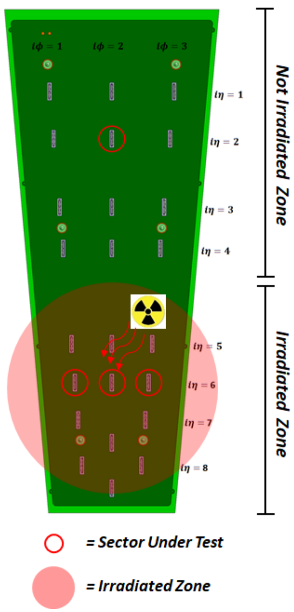


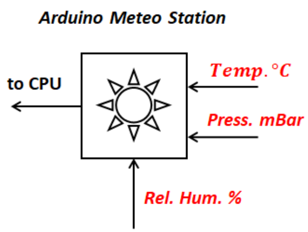
X-ray Triple-GEM aging test in 904; Normalized gas gain as a function of the accumulated charge Chamber operating in Ar/CO2 (70/30) at an initial gas gain of 2x10^4 equipped with CERN GEM-foils based on single-mask photolithography technique developed by CERN PCB Workshop; The chamber accumulated a total charge of 1.56 C/cm2 after 18 months of continuous irradiation

Annex E (Triple GEM Longevity Studies)

Weekly Energy Resolution Measurement in 904 setup

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

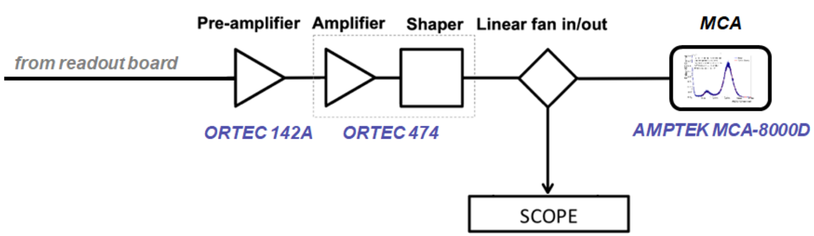


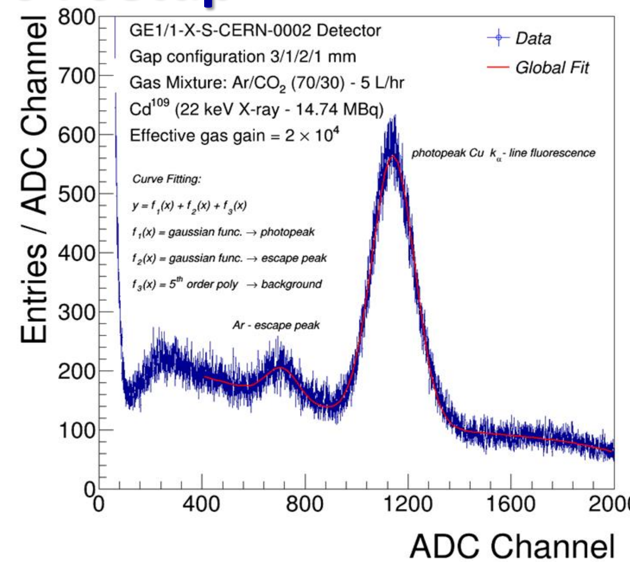


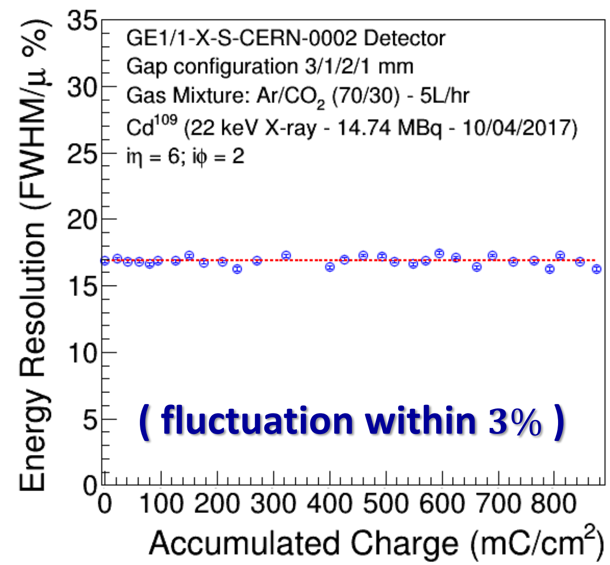
^{109}Cd *source*

22 keV X − ray photons

Activity: 14.74 MBq







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

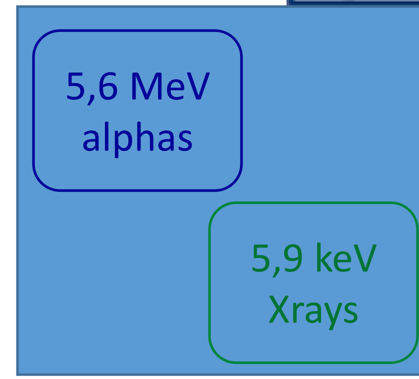
$$\frac{FWHM}{\mu}\% = \frac{2\sqrt{2ln(2)}\,\sigma}{\mu}\%$$

Annex E (Triple GEM 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:

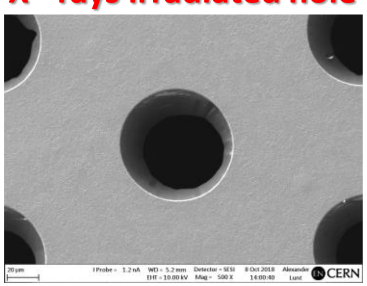
- GEM $10 \times 10\ cm^2$ prototype irradiated in two different sectors

Method to accelerate the aging:

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

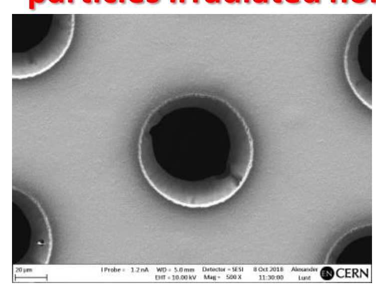
SEM and EDS analysis to study polymer density around GEM holes

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 $10 - 15\ \mu m$ around the holes

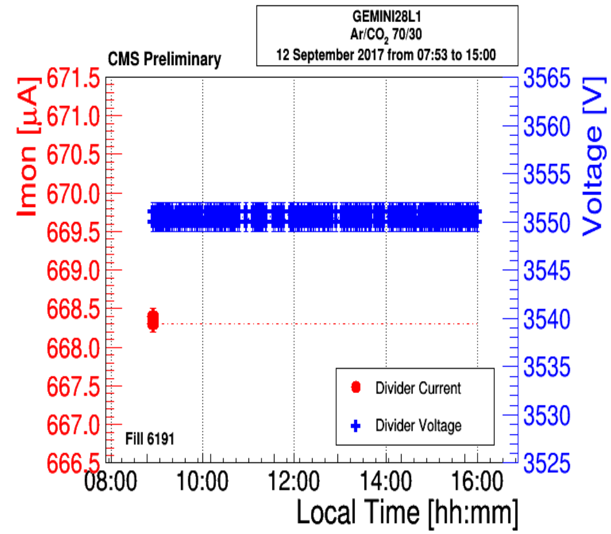
Backup

The GE1/1 Slice Test

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

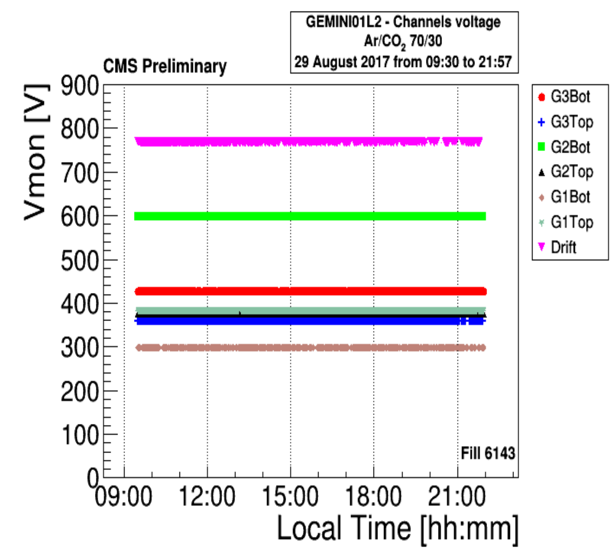
- **Single HV channel**

  → **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**

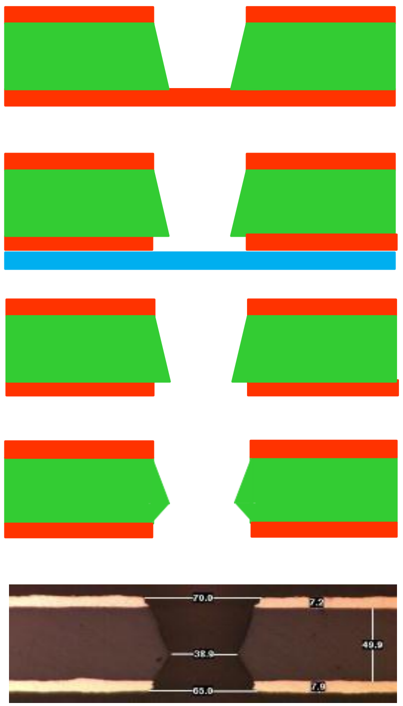
  → **high voltage fluctuations $< 1\%$** observed for all 7 HV channels in a period of **12** hours during LHC collisions ($L_{max} \approx 9.3 \times 10^{33} cm^{-2} s^{-1}$)

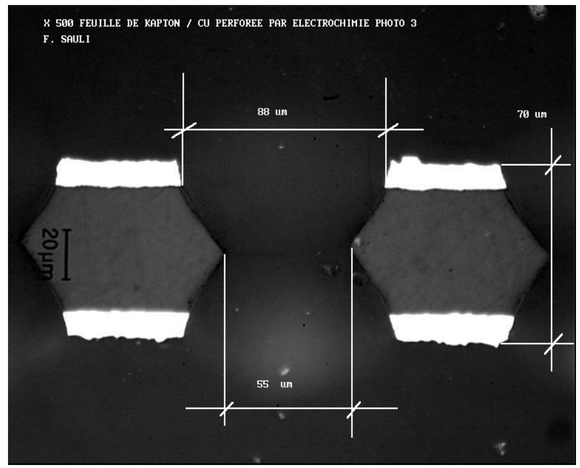


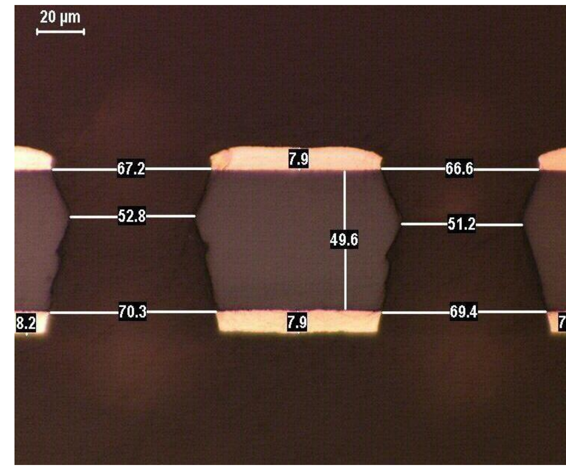
- **LV channels**

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

Mastering GEM





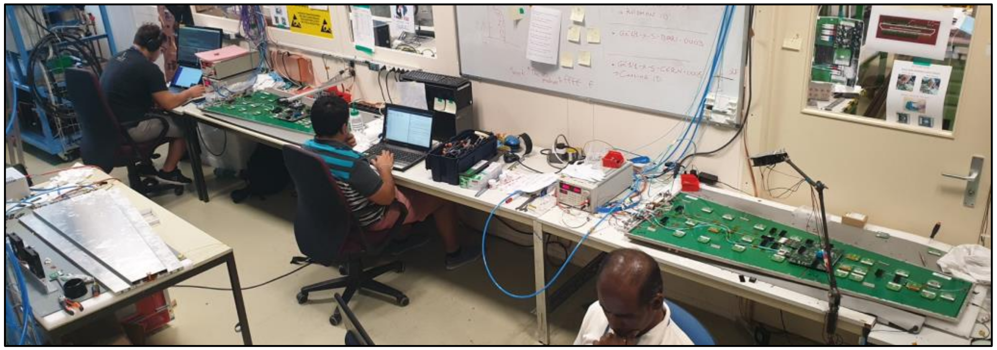


- Similar patterns , similar behavior, same material.
- Angles can be adjusted in both structure (Typ. value : 70um copper hole , 50um polyimide hole)

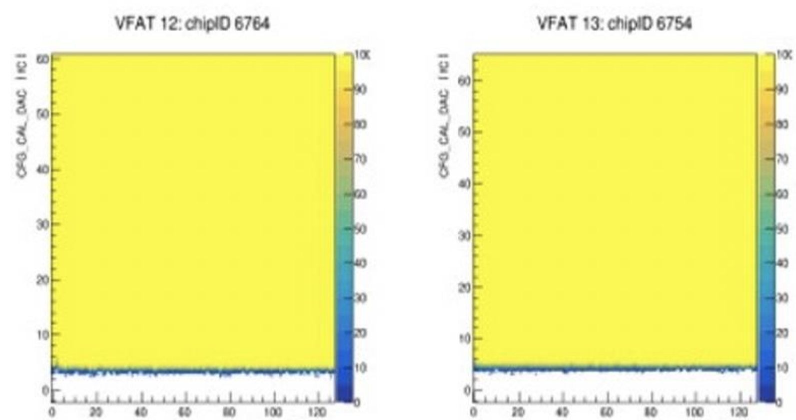
    Steeper angles give lower gain but also reduced charging up

GE1/1 electronics integration tests

Goals: Test the connectivity of the electronics components, monitor the communication stability, check noise level and output signals



- Connectivity
- Calibration
- Identification of dead/hot channels
- Global threshold scans (SBIT line) per VFAT
- ENC measurement (S-curves)
- Local threshold scans (SBIT line) per channel (to identify disconnected channels)



The entire procedure is repeated after mounting the cooling plate and the chimney

The GE2/1 Project

Production schema, material flow and validation/certification as for GE1/1

- Mass-production organized in parallel in several production sites, at CERN and outside (same as GE1/1)
- 8 production sites:
  - 6 already participated to GE1/1
  - 2 new sites already validated
- Dedicated pre/post-production teams
- Chambers assembly & validation at CERN, as for GE1/1, with the contribution of the whole GEM community

Note: Additional training sessions and refreshing courses are continuously organized in 904

- **Vendors**
  - Manufacturing of the detector components
  - Shipment to CERN
- **Central Site (at CERN)**
  - Material inspection (QC1/QC2)
  - Pre-assembly work
  - Preparation of assembly kits
  - Shipment to/back from production sites
- **Production Sites**
  - Module assembly
  - QC2-QC5 tests
  - Data Base updates