Status of the ME0 detector production for the phase-II upgrade of the CMS muon system

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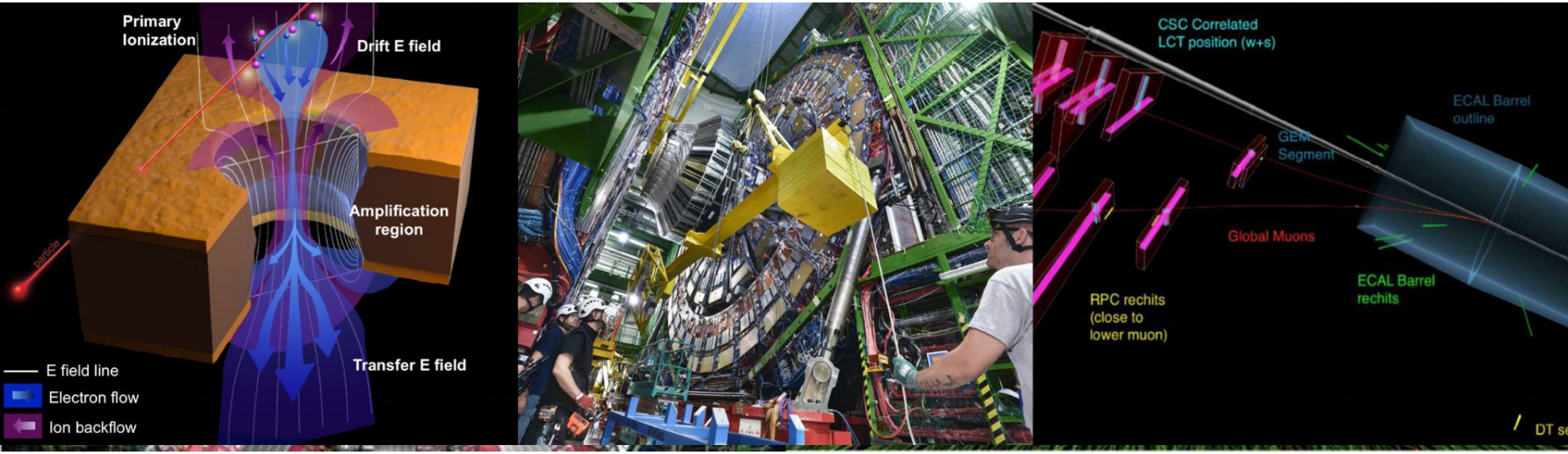
On Behalf of the CMS Muon Group

DRD1 Collaboration Meeting

December 2024, CERN



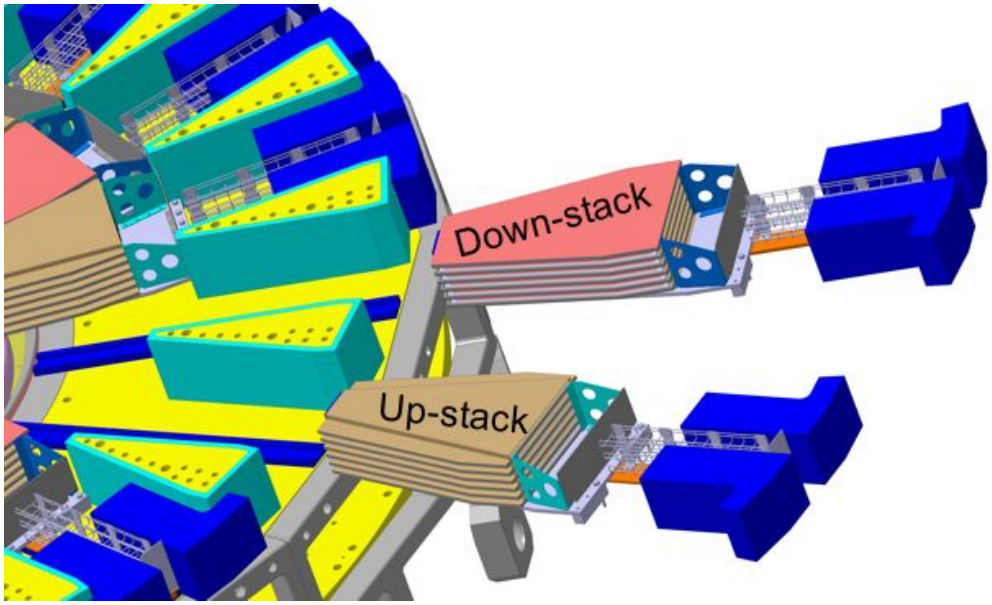
ME0 System Overview

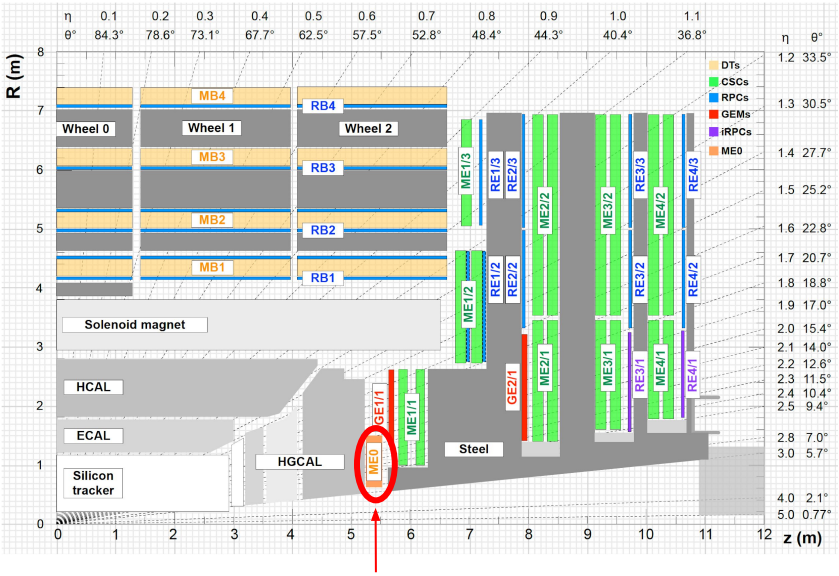
ME0 is one of the three new GEM stations to be used in the CMS forward region

ME0 Detector:

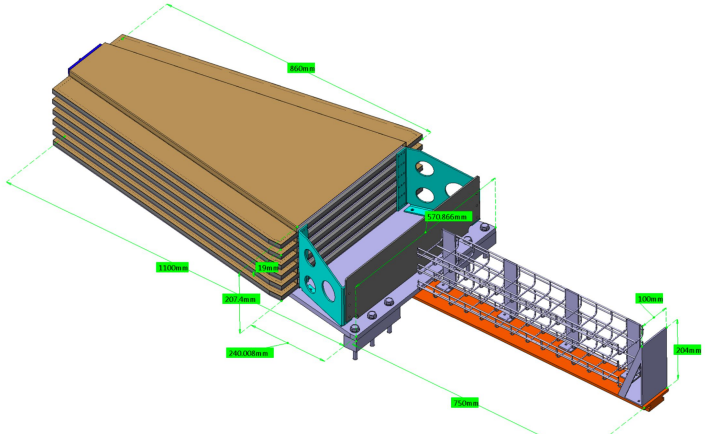
- Triple GEM detector (~ 1m x 0.5m)
- Coverage: $2.00<|\eta|<2.80$
- 36 ME0 stacks (18 per end-cap)
- 6 modules per stack

→ 216 ME0 modules needed (231 including spares)





ME0 ($2.00 < |\eta| < 2.80$)

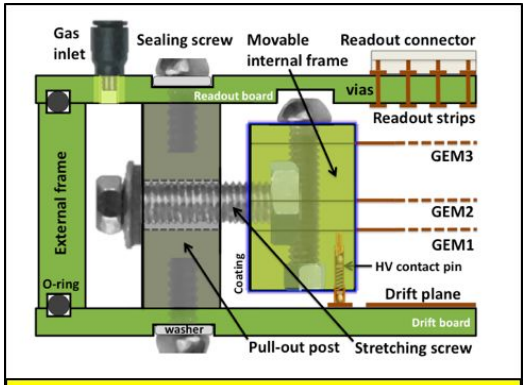


CMS GEM Design

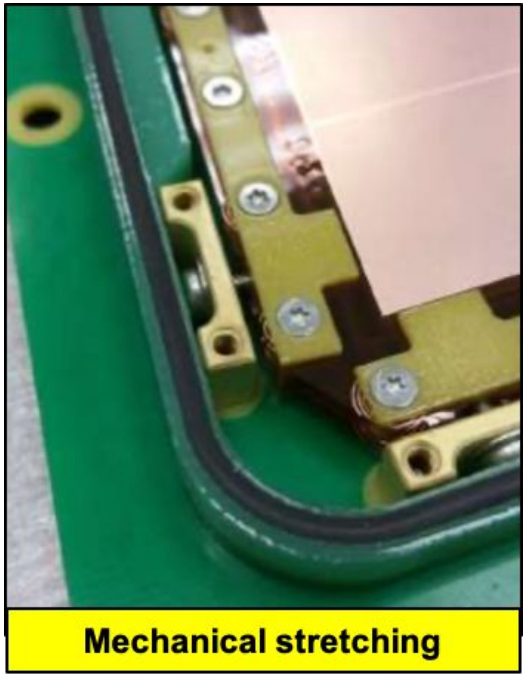
CMS triple-GEM common design:

- 3 detector projects in the forward muon endcap
- All based on same triple-GEM technology and same material
- GEM configuration 3(drift)/1/2/1 mm
- Gas: Ar/CO2 (70/30%)
- Max. background rates from a few kHz/cm2 (GE2/1) to 150 kHz/cm2 (ME0)
- **Nearly 700 detectors: 600 m2 of GEM foils for 1.5 M of RO channels**

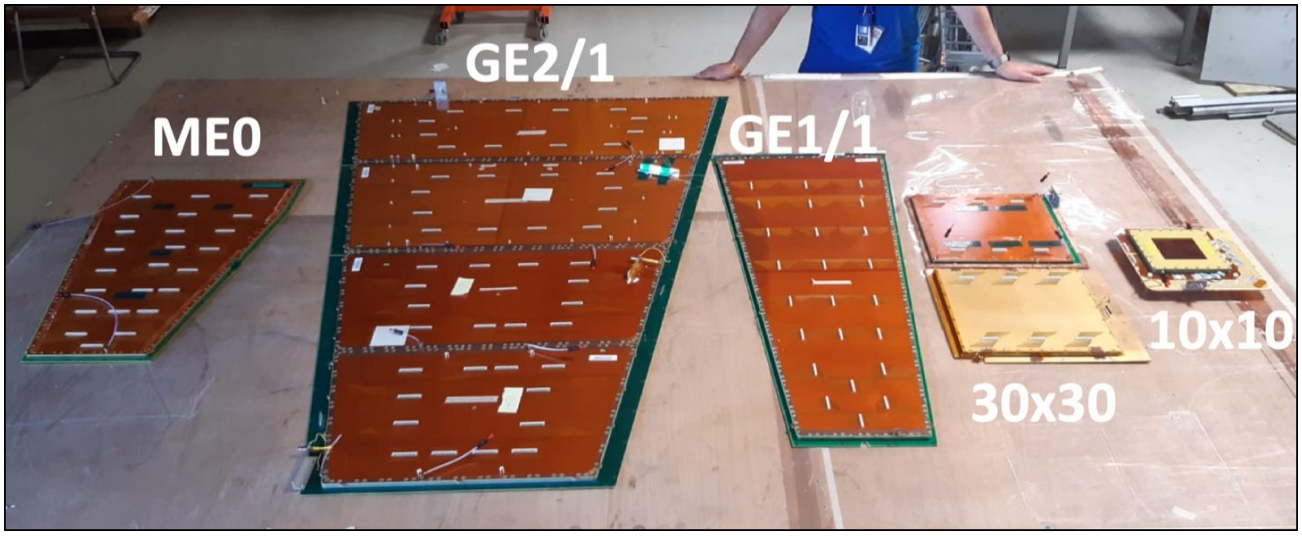
  → about 360 detectors already produced



Self-stretching mechanism



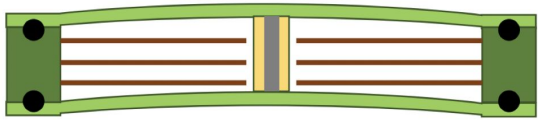
Mechanical stretching



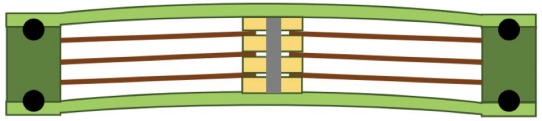
ME0 Design Features

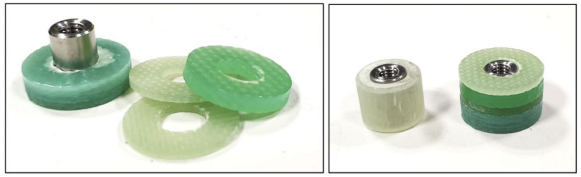
Use of **central pillars** with **inner rings** to maintain the gaps in case of PCB bending:
→ small loss of active area to ensure uniform performance (gain variations: 30% → <10%) and to prevent HV issues due to thin gaps

Initial Design



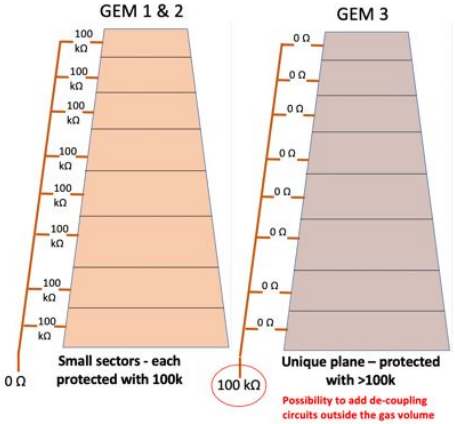
ME0 Final Design

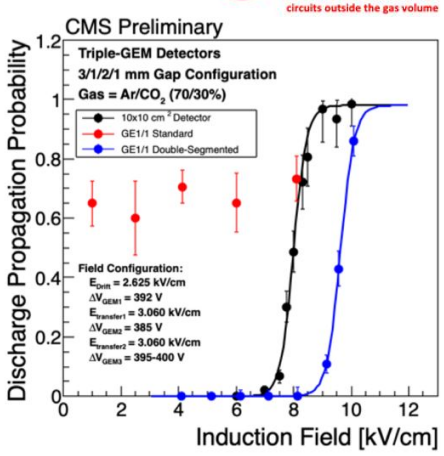




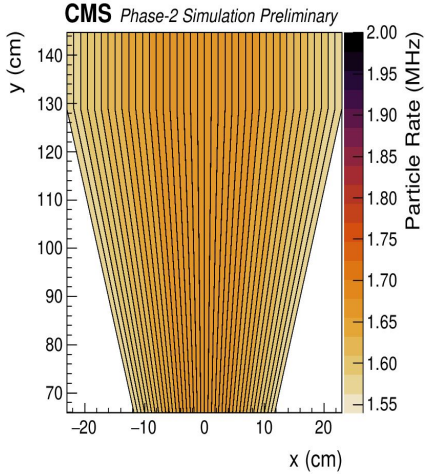
Central pillars with inner rings

Mixed configuration of double-segmented (G1;G2) and single-segmented (G3) GEM foils to mitigate discharge propagation

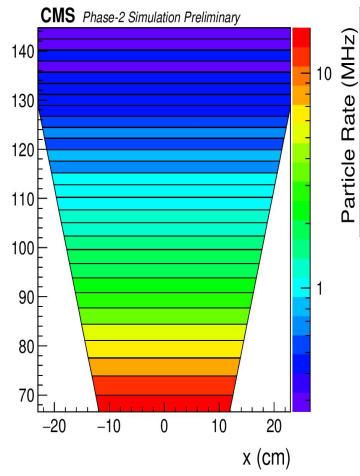




Use of **radial HV segmentation** instead of horizontal segmentation to mitigate the gain drop issue in high rate and non-uniform environment:
→ Each HV segment sees the same gradient of particle rate
→ Similar flux on all segments allows for the uniform voltage compensation of the entire detector
⊕ Improved HV supply scheme to minimize voltage drop



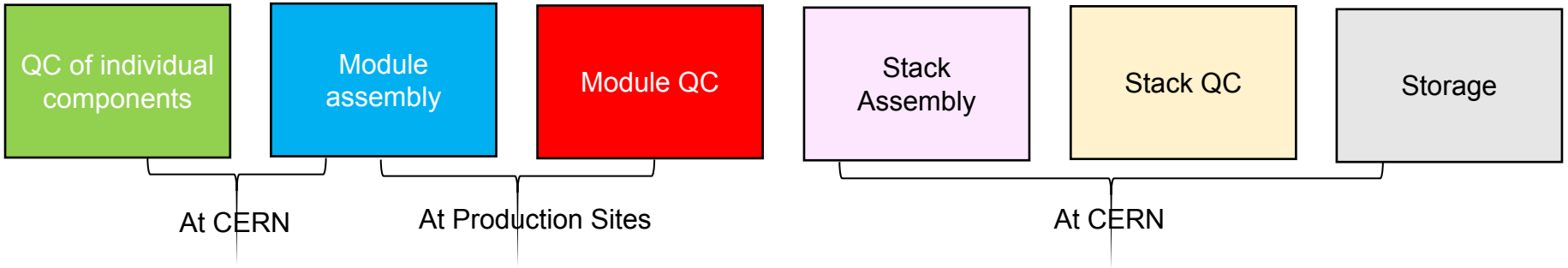
Radial Segmentation



Horizontal Segmentation

Production Strategy

Production Sequence: same as GE1/1 and GE2/1



- **Distribution of the production among several sites: production in parallel**
  - Not all sites necessarily running at the same time (depending on material available and team planning) → usually **4 sites active at the same time**
  - CERN 904 acts as **central site**: component inspection; shipment box preparation; post-production validation; storage; logistics towards installation in CMS

- **Improved risk mitigation**
  - Parallel production mitigates the impact of a single site failure on the overall production
  - All sites have the technical skills to produce a complete module

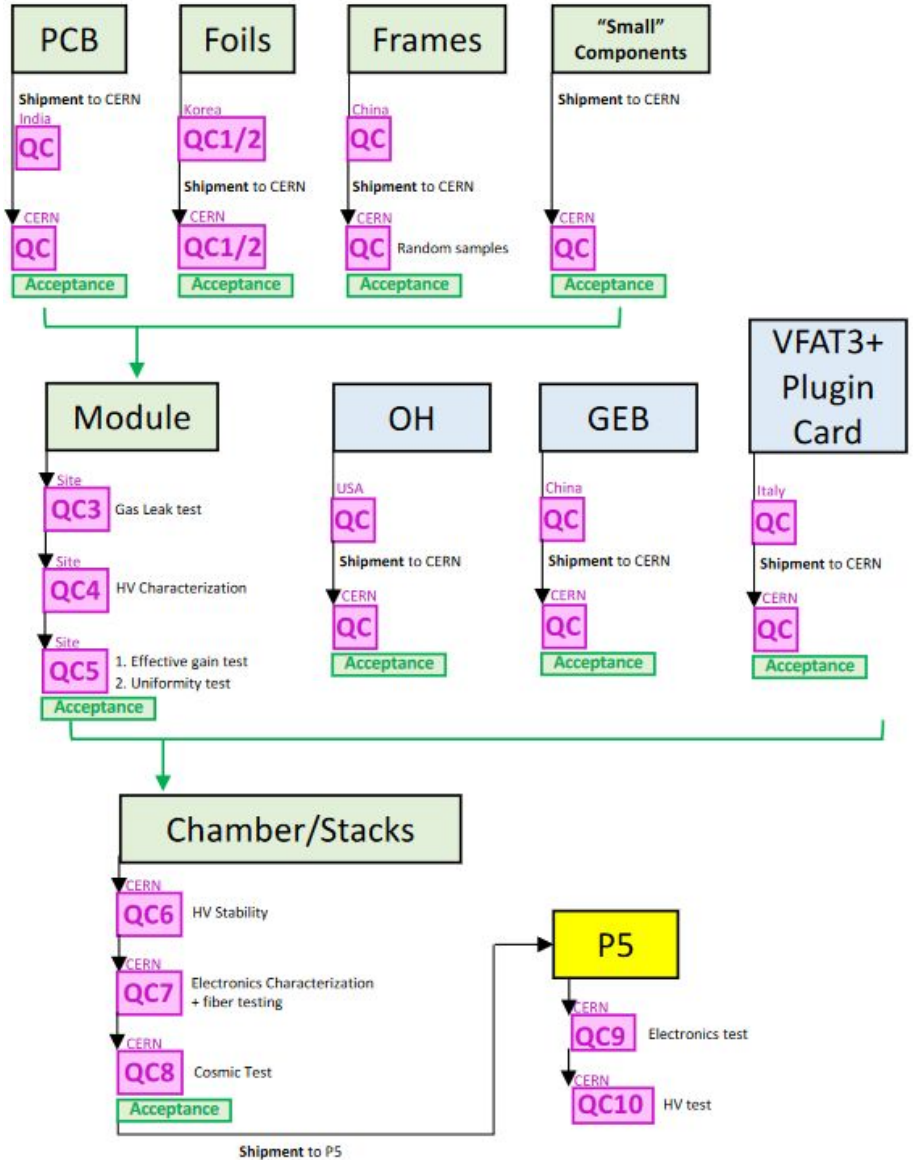
✔ **1 production site at CERN (with double capacity)**
✔ **3 production + 1 QC sites in EU (Ghent, Bari, Frascati and Aachen)**
✔ **1 production site in China (PKU)**
✔ **2 production sites in India (Panjab & Delhi Universities)**

Production Workflow

QC Flow – Same as GE1/1 & GE2/1

QC Step	Procedure
1	Initial inspection of the module components
2	(part 1) Electrical cleaning of the GEM foils and resistance check
	(part 2) Long-term monitoring of the GEM foil leakage current
Assembly	Module assembly with the approved components
3	Leak test of closed detector volume
4	High voltage linearity test
5	(part 1) Effective gas gain measurement
	(part 2) Response uniformity measurement
6	HV stability test
7	(part 1) Test of the on-detector electronics (module only)
Assembly	Stack assembly with validated modules
7	(part 2) Test of the on-detector electronics (stack)
8	Cosmic test

→ Continuous update of the QC/assembly procedures based on production feedback
→ All activities and results are documented and stored on DB and Elogs

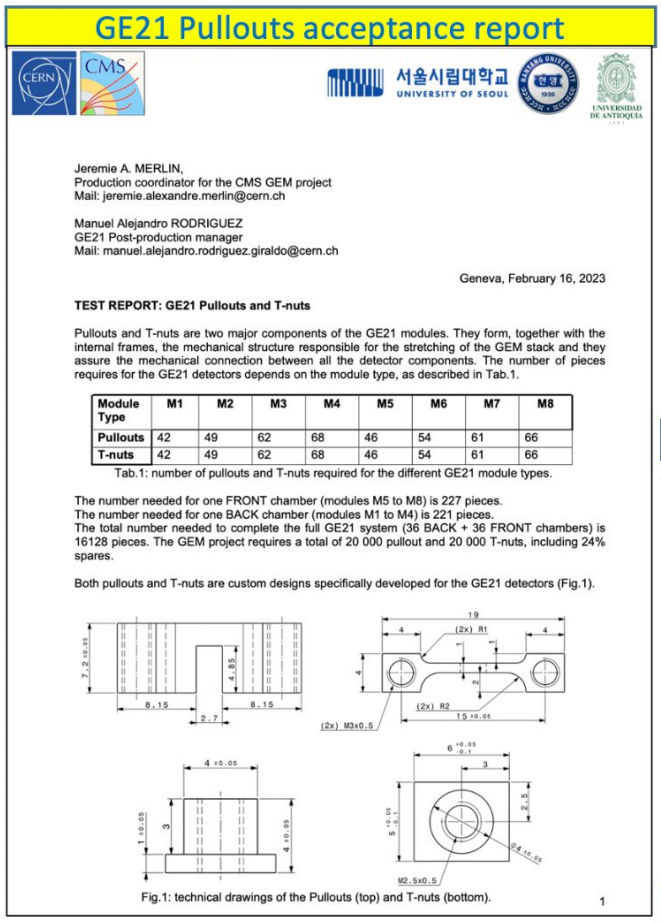


Production Workflow

Documentation

- All QC reports are **verified** and **approved** by relevant experts and coordinators
- All QC activities/results are **stored** on DB, Dashboards and Elogs
- **Acceptance documents** are reviewed and uploaded to CERN EDMS

GE21 Pullouts acceptance report



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Geneva, February 16, 2023

TEST REPORT: GE21 Pullouts and T-nuts

Pullouts and T-nuts are two major components of the GE21 modules. They form, together with the internal frames, the mechanical structure responsible for the stretching of the GEM stack and they assure the mechanical connection between all the detector components. The number of pieces requires for the GE21 detectors depends on the module type, as described in Tab.1.

Module Type	M1	M2	M3	M4	M5	M6	M7	M8
Pullouts	42	49	62	68	46	54	61	66
T-nuts	42	49	62	68	46	54	61	66

Tab.1: number of pullouts and T-nuts required for the different GE21 module types.

The number needed for one FRONT chamber (modules M5 to M8) is 227 pieces.
The number needed for one BACK chamber (modules M1 to M4) is 221 pieces.
The total number needed to complete the full GE21 system (36 BACK + 36 FRONT chambers) is 16128 pieces. The GEM project requires a total of 20 000 pullout and 20 000 T-nuts, including 24% spares.

Both pullouts and T-nuts are custom designs specifically developed for the GE21 detectors (Fig.1).

Fig.1: technical drawings of the Pullouts (top) and T-nuts (bottom).

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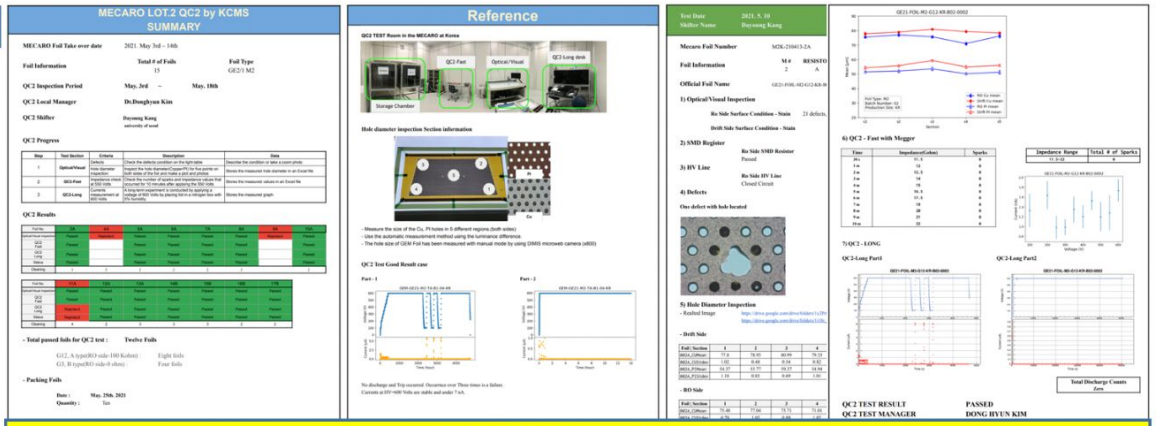
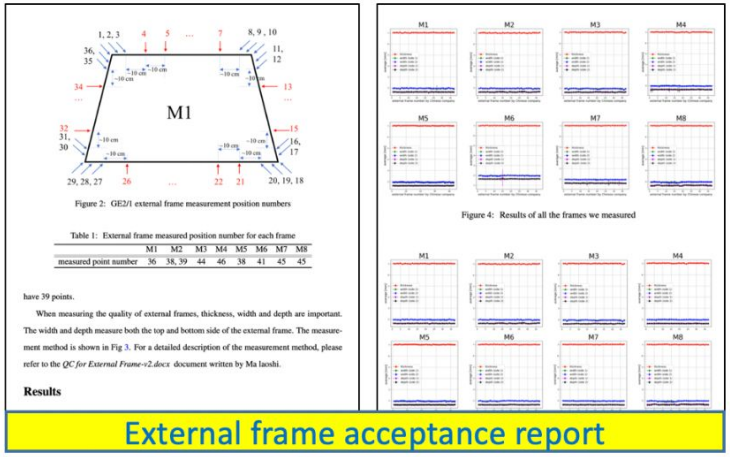
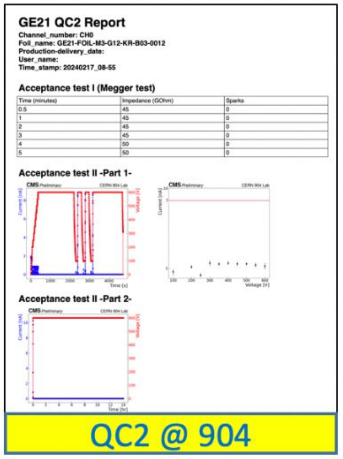
GEM foil QC report



External frame acceptance report



QC2 @ 904



Component Procurement

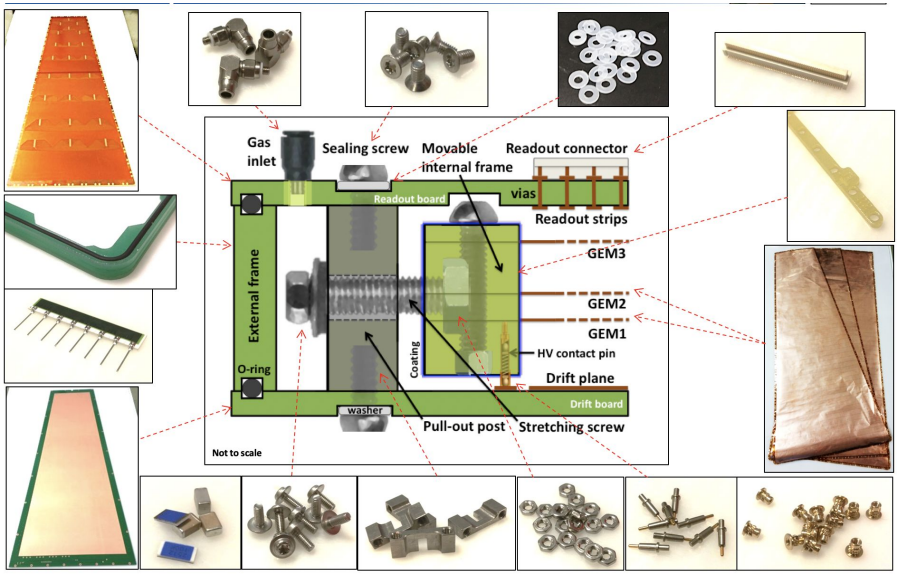
Each ME0 detector has nearly 1000 components in it …

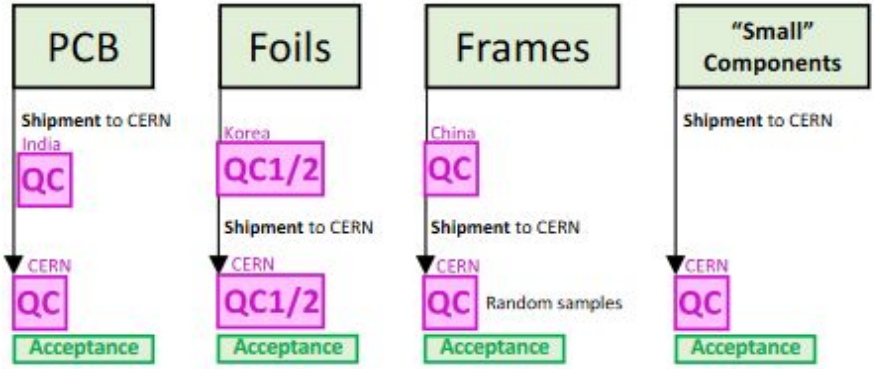
« Major Components »

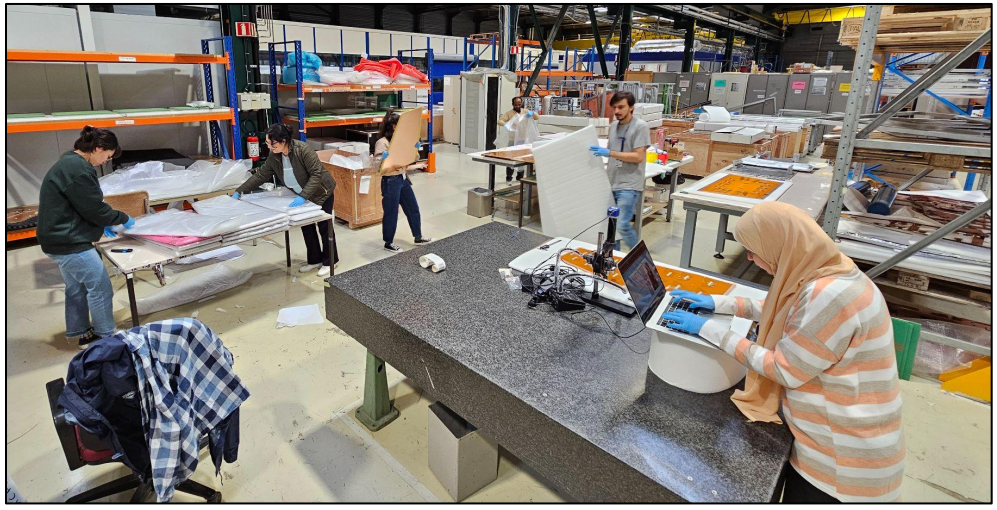
- Specific designs
- GEM foils, External and Internal frames, DRIFT and RO PCBs

« Minor Components » (not less important!)

- Commercial or simple design
- O-ring, T-nuts and pullouts, internal screws, stretching screws, PA washers, closing screws, HV pins, SMD resistors, gas plugs, HV divider







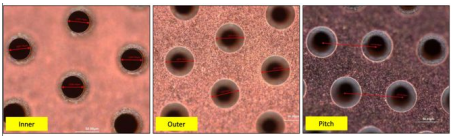
Component Procurement

GEM Foil Production:

- Main producer is **Korea CMS** (Korea)
  → same producer as GE21 (300 foils)
  → **New facility** established in KR in 2023 (in less than 1y!)
  → Production rate of 30 good foils per month (demonstrated)
  → Double-mask technique
- 20% (125 foils) produced at **CERN MPT**, in parallel to KCMS, to increase margin on schedule

Preparation for mass production:

→ First batch delivered in October 2023 for **in-depth inspection in collaboration with MPT and MME**
→ Internal review before mass-production held in December 2023

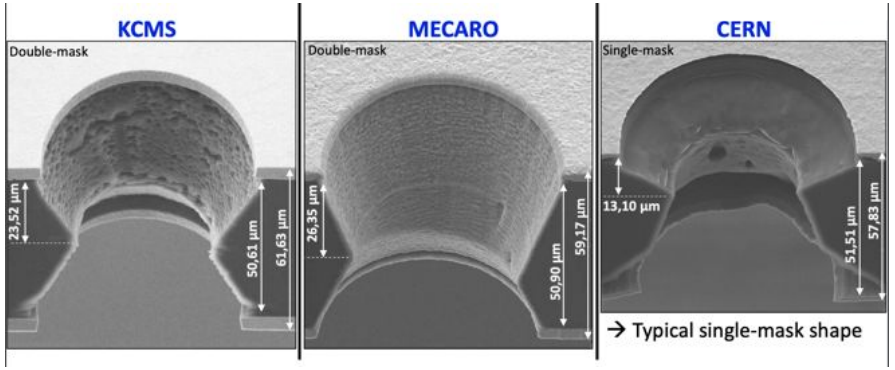


KCMS	KCMS (diameter)			
	Outer		Inner	Pitch
Double-mask	DRIFT	RO		
AVG	74,1	74,5	45,9	139,8
STD	1,6	1,4	1,9	0,5
Statistic	79	77	97	32

MECARO	MECARO (diameter)			
	Outer		Inner	Pitch
Double-mask	DRIFT	RO		
AVG	76,6	80,1	52,4	139,5
STD	2,5	5,3	5,3	0,4
Statistic	27	23	16	4

CERN	CERN (diameter)			
	Outer		Inner	Pitch
Single-mask	DRIFT	RO		
AVG	76,3	86,6	51,5	140,7
STD	0,9	4,5	4,6	1,2
Statistic	31	33	24	5

→ Exceptional performance of the KCMS teams and facilities
→ **Korean GEMs fully approved for ME0**

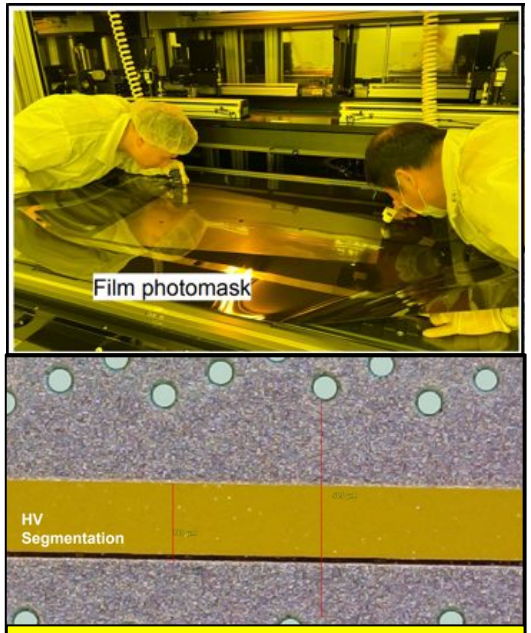


Component Procurement

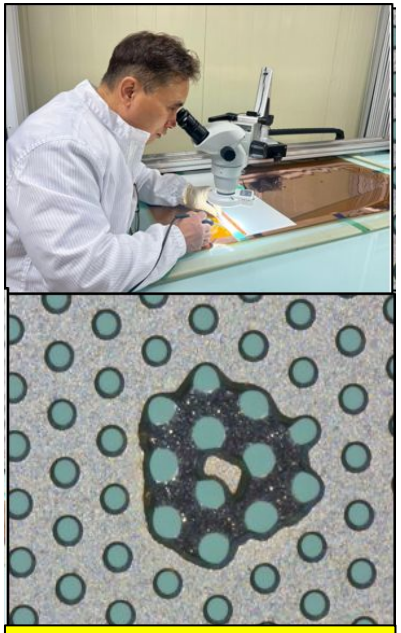
GEM Foil QC flow at the Korean factory:

- All GEM foils undergo in-depth inspection during and after the manufacturing process
  - **Microscopic inspection** (geometry, defects, contaminants)
  - Evaluation of the **GEM uniformity** (alignment, diameter)
  - **Electrical testing** (leakage current, discharge rate)
- Foils are packed following a specific procedure to ensure **safe transport to CERN**
- All tests are documented

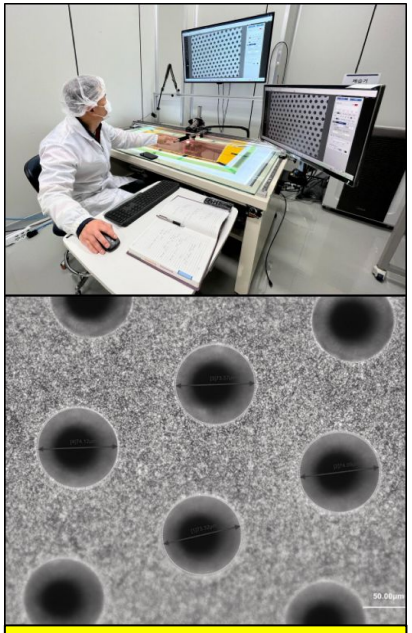
Safe Packaging and shipment to CERN



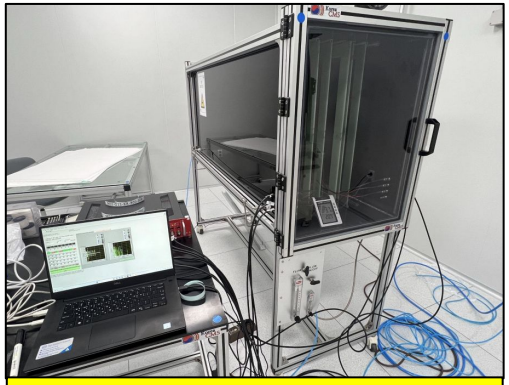
Mask alignment check



Defect identification



Hole diameter meas.



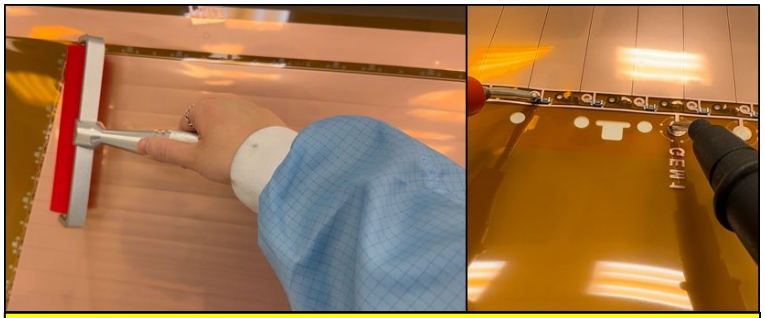
HV characterization and stability test

→ Same procedure as in GE11 and GE21

Component Procurement

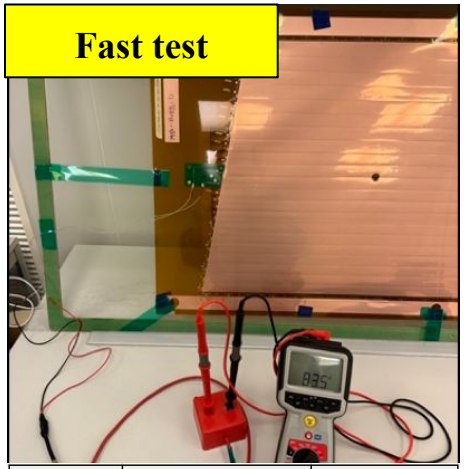
GEM Foil QC flow at CERN:

- **Foil preparation**: cleaning with dust roller; verification of the protection resistors (new)
- **Fast test (5min)**: impedance check + discharge rate
- **Long test (15 hours)**: ramp-up; cycling test; stability test with discharge monitoring
- Foils are then packed again and prepared for **shipment to production sites**



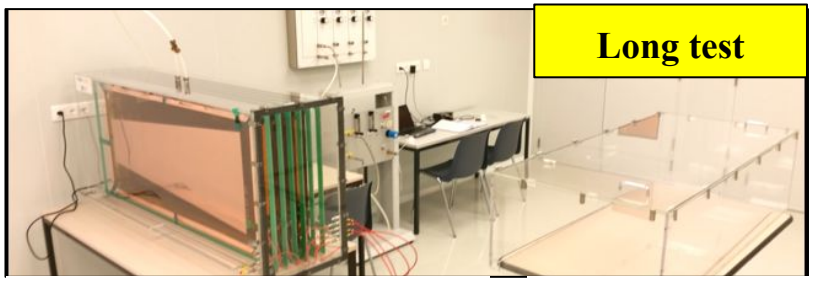
Cleaning and resistance check

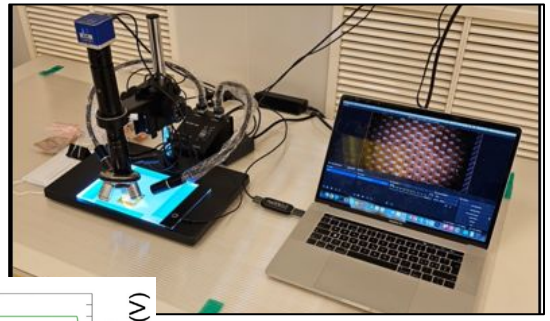
Fast test

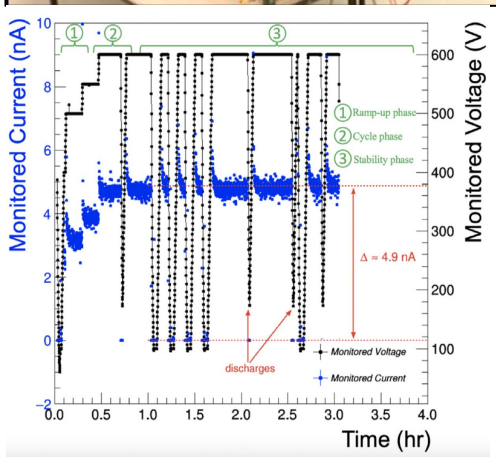


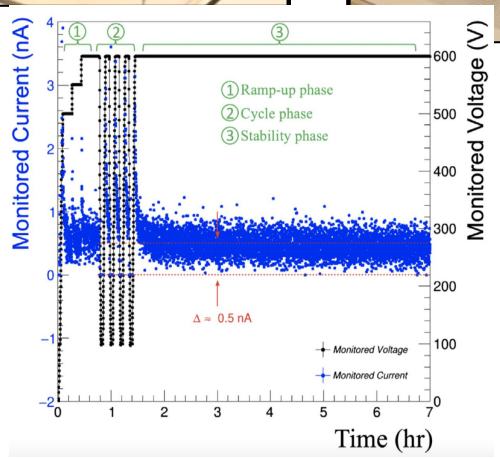
Time (min)	Impedance (Gohm)	Sparks
0,5	19	3
1	25	1
2	35	0
3	40	0
4	40	0
5	45	0

Long test







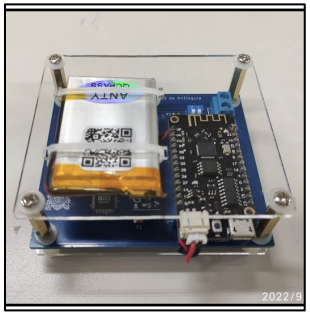


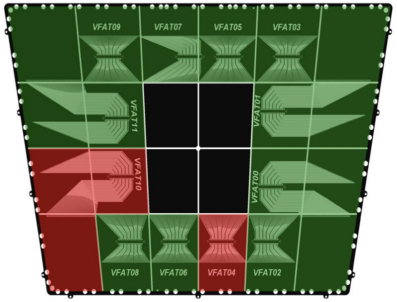
→ Additional inspection with microscope is foreseen in case a foil is behaving unexpectedly

Component Procurement

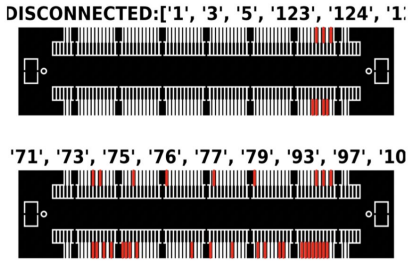
PCB Production:

- Main producer is **Micropack** (India)
  → same producer as GE11 and GE21 (about 500 PCBs)
- Critical component that hosts the Drift electrode, the RO strips and that forms the main body of the modules





→ Bluetooth device to measure short circuit between strips and continuity issues

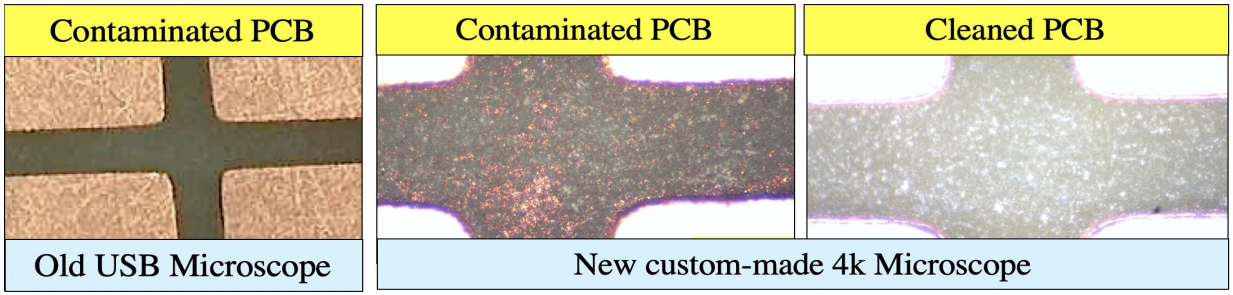


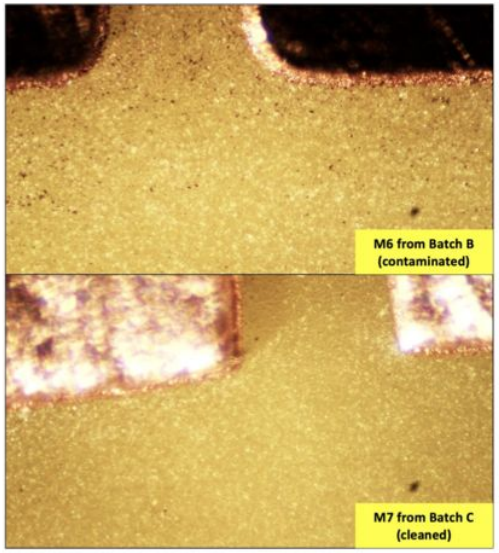
Initial QC procedure:

- **Visual inspection** (stains, scratches, contaminants)
- **Bending measurement** (max 1 mm corner to corner)
- **Connectivity test** of the RO strips

Updated QC procedure: (additional steps)

- **Thickness measurement** (tight requirement for ME0 stacks)
- **Microscopic inspection** of the RO board (reaction to copper dust contamination observed in GE21 boards)



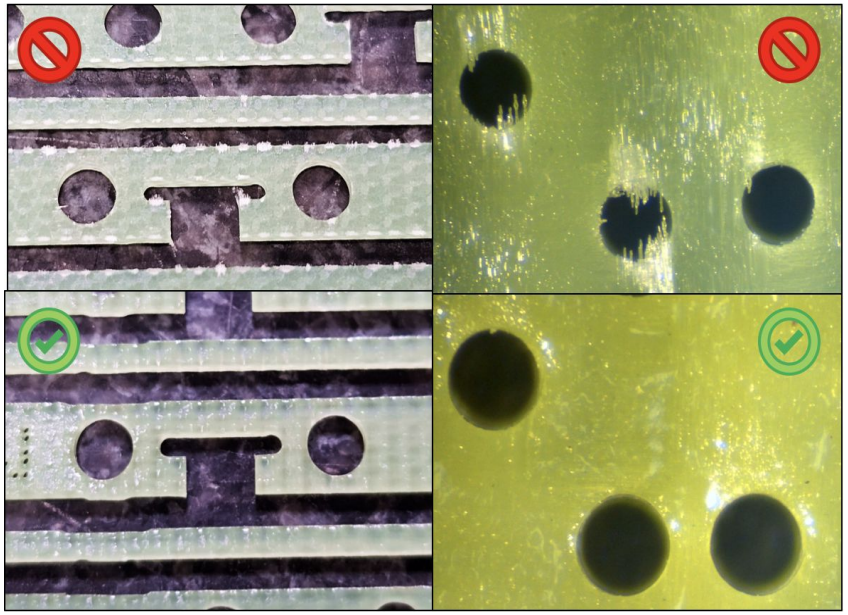


→ The QC procedure is now conducted first at the factory by the India institutes and then performed again at CERN before shipment to production sites

Component Procurement

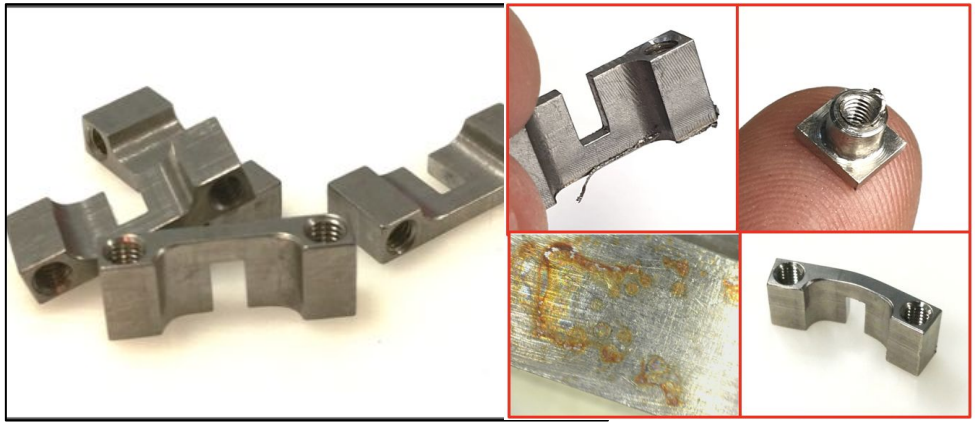
Internal FR4 Frame Production:

- Main producer is **MPT** (CERN)
- Critical component in contact with the GEM foils
  → structure that holds the foils together with the proper gap configuration
- Initial production had issues (loose fibers, coating irregularities, defects)
  → possible source of contaminants in the gas volume
  → Improved manufacturing technique with more in-depth inspection at the workshop and by the GEM group



Pullouts and T-nuts Production:

- Main producer is **Hardcoats** (India)
- Central component of the self-stretching mechanism
  → requires specific tolerance on several dimensions (often underestimated by companies)
- Improved QC procedure with detailed inspection:
  → Dimension checks
  → Hole threading checks
  → Material checks (with CERN MME)

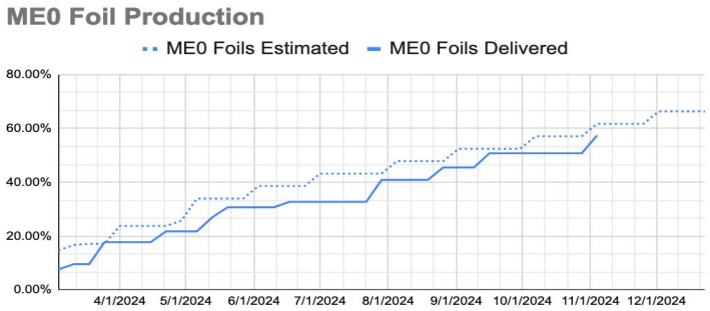


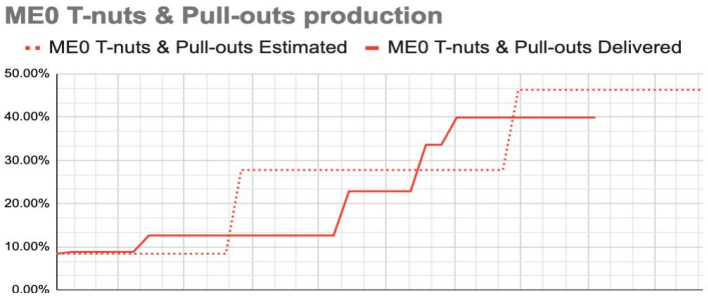
Component Status

GEM foils:

- ❑ 648 foils needed (+ 45 spares)
- ❑ 412 produced in total (60%)

ME0 Foils (CERN)	125	ME0 Foils (KCMS)	287
Tested foils	125	Tested foils	197
Validated foils	115	Validated foils	187
Problematic foils	7	Problematic foils	8
Rejected foils	3	**Rejected foils**	2
Untested foils	0	Untested foils	90

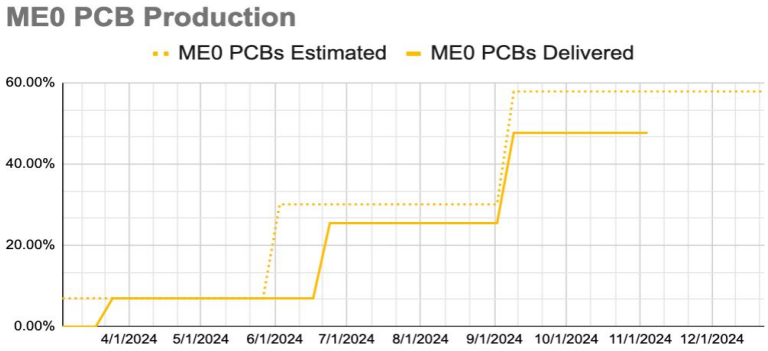


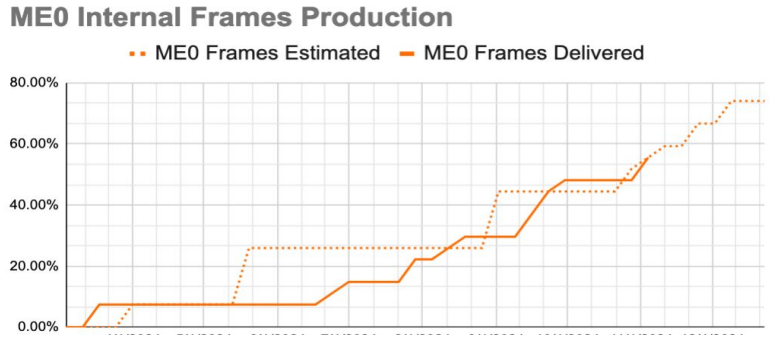


PCBs:

- ❑ 216 kits needed (+ 15 spares)
- ❑ 180 produced in total (78%)

ME0 PCBs	180
Under test at the factory	77
Under test at CERN	8
Validated kits	95

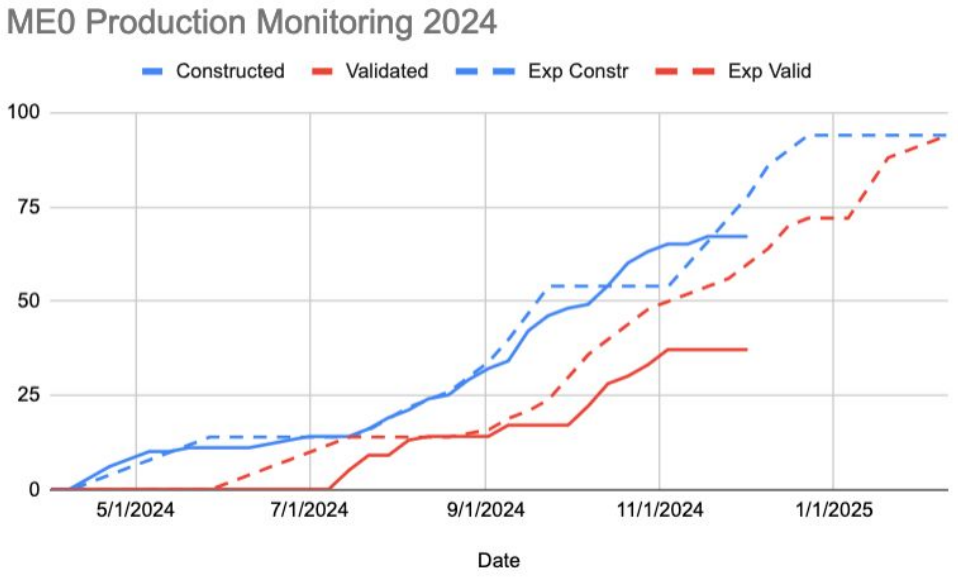




Module Production

Module Production and QC status:

- 216 needed (+15 spares)
  → 66 modules (30%) **assembled**
  → 38 modules (17%) **fully validated**
  → QC procedure ongoing for the rest



Project milestones:

→ 80 assembled (50 validated) be the end of the year

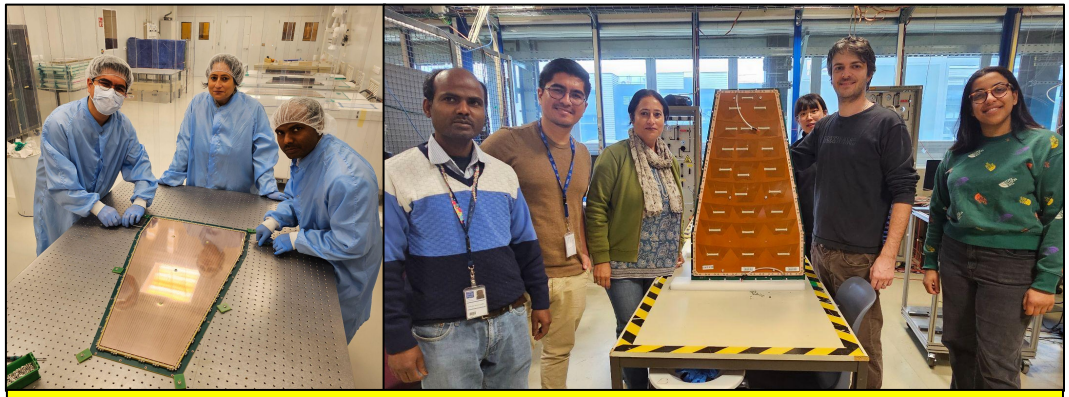
→ 108 modules for the first end-cap ready by Q2 2025

→ 216 modules (full production) assembled and tested by Q2 2026

Production Plan:

- 1st round July – Sep 2024 (done)
- 2nd round Oct – Dec 2024 (on-going)
- 3rd round Feb – Apr 2025 (in prep.)
- 4th & 5th rounds in 2025
- 6th round in 2026

→ Each assembly round involves 4 sites to produced 40 modules (18.5% of full production)

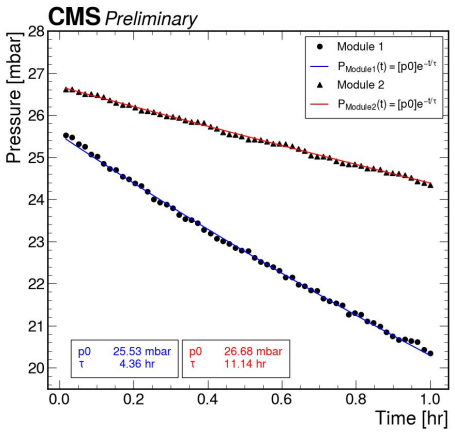


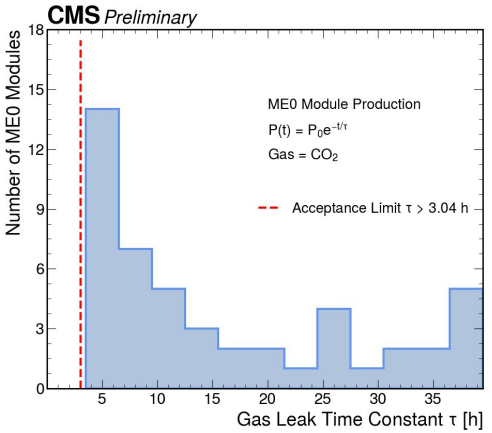
Assembly of the first production-grade ME0 modules at CERN

Module Production

Module gas leak test:

→ All detectors pressurized to 25 mbar (max. nominal pressure in CMS)
→ Internal pressure is monitored for 1h
→ Time constant of the pressure curve should be greater than 3h (i.e. **max 1% leak of the nominal input flow**)
Summary: 50 detectors passed the test

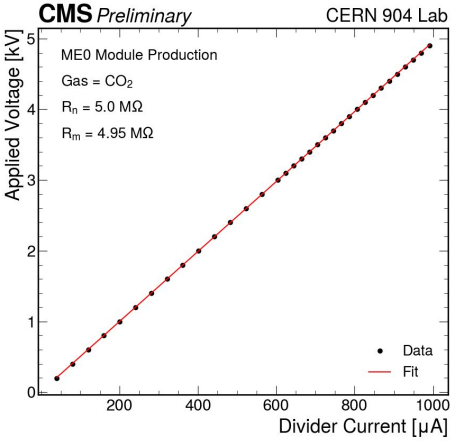


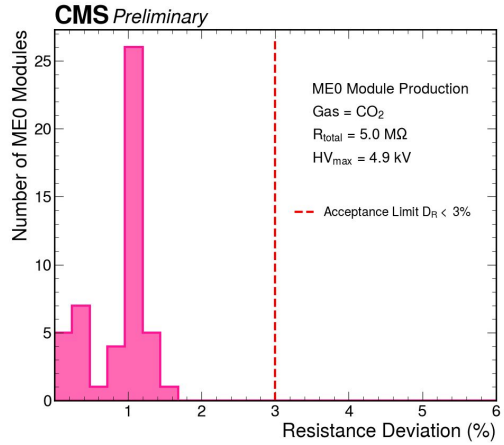


Typical issues with previous detectors: bad compatibility between O-ring diameter and External Frames groove
→ fixed with ME0 by improving the O-ring QC and defining the best coupling prior assembly
→ Gas leak is not the most complex issue, but the most time consuming (because re-opening of the module…)

Module HV linearity test:

→ All detectors equipped with temporary HV divider to power all electrodes with single HV
→ Ramp-up in pure CO2 up to 150% of the nominal operating point in CMS
→ HV linearity is expected in case of healthy detector (not necessarily of with a different slope in case of HV issues)
Summary: 50 detectors passed the test





Typical issues with previous detectors: reduced induction gap due to stretching issues of PCB bending
→ fixed with ME0 thanks to the improved design and revised stretching procedure during assembly
→ HV issues are rare but also time consuming (because re-opening of the module…)

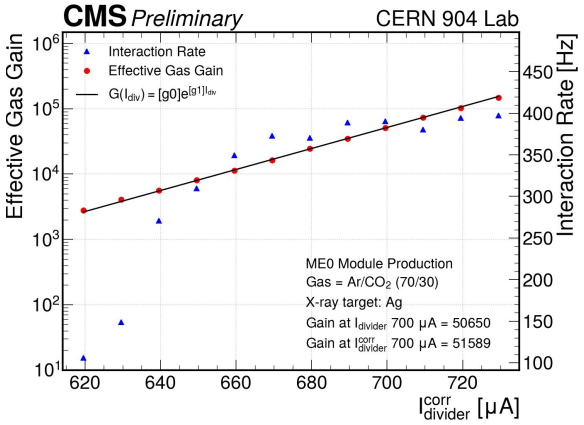
Module Production

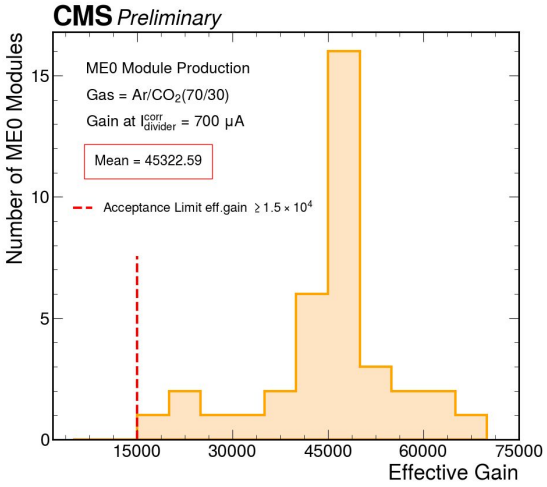
Effective gain test:

→ All detectors tested in Ar/CO2 with a 22 keV X-ray source in the central region

→ Effective gain compensated for different T and P environments

→ Effective gain at nominal HV point should be greater than 15k.





Response uniformity test:

→ All detectors tested with a large beam of 22 keV X-rays covering the entire surface

→ Analog readout with APV25+SRS

→ Detector divided into 768 slices for analysis

→ Photo-peak ADC value for compared with all slices

Summary: 37 detectors passed the test

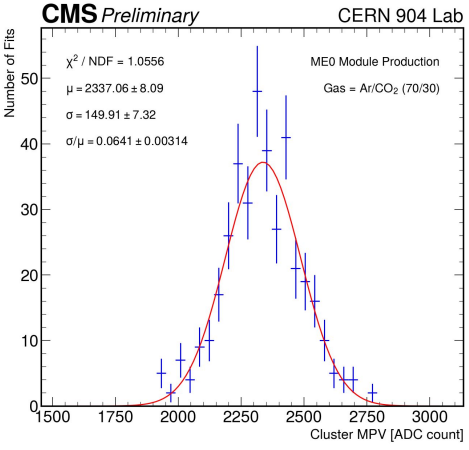
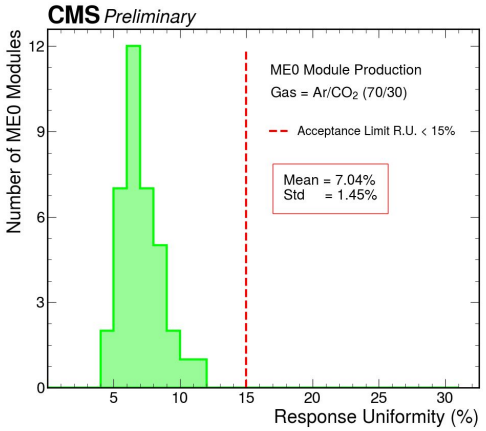
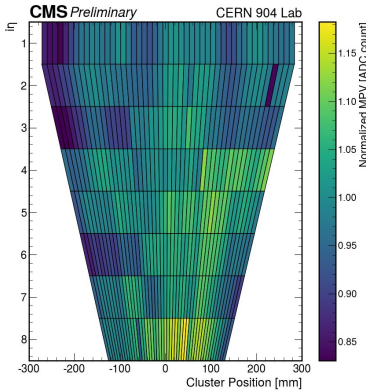


Photo-peak distribution



Distribution spread



Detector Slicing

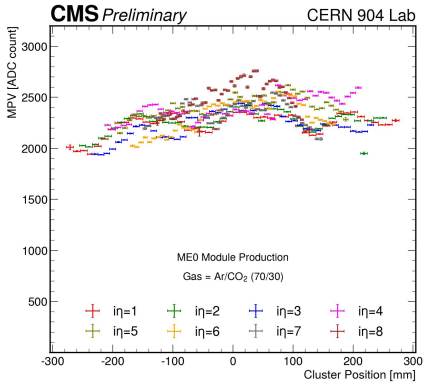


Photo-peak ADC value

Module Production

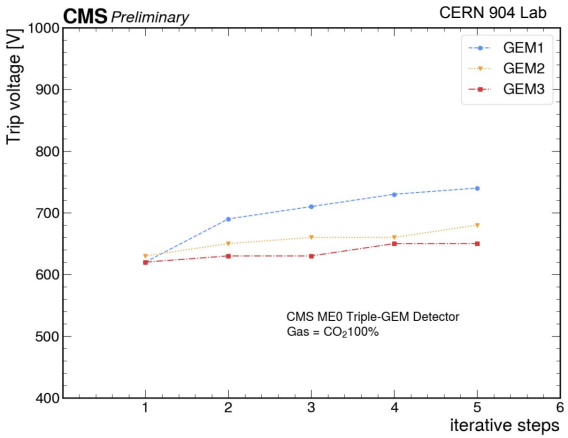
HV Stability test:

→ All detectors tested in pure CO2 final HV distribution filter

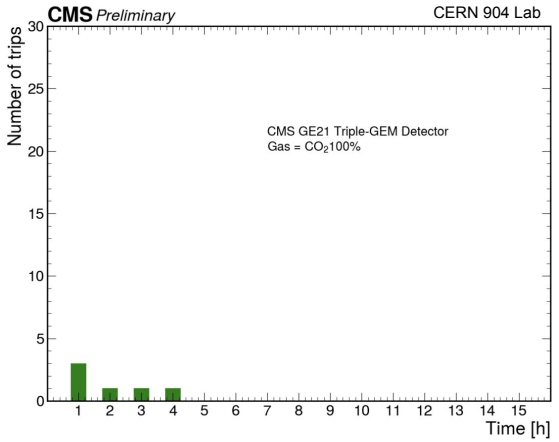
→ Each foil is stressed by ramping up to 1kV with thigh trip limit (several iterations, HV limit should be higher than 550V and increases with iterations)

→ Discharge monitoring at max, HV for 15h

Summary: 30 detectors passed the test



HV stress test



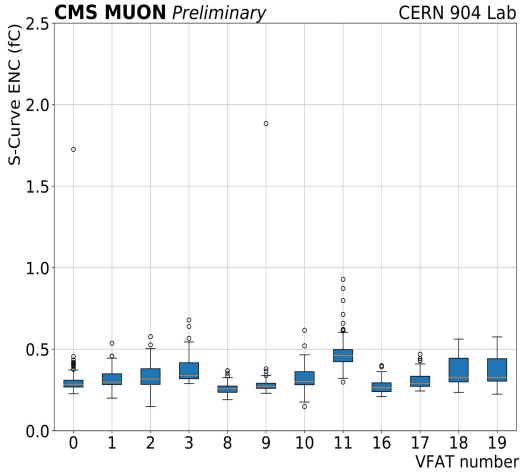
Discharge rate monitoring

Electronics connectivity test:

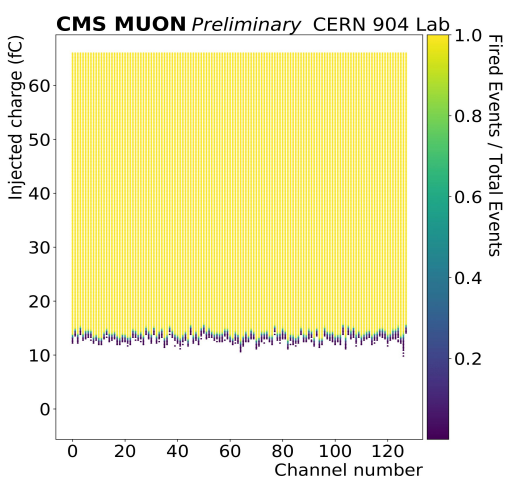
→ All detector+electronics subject to electronics sanity check (fas test without cooling)

→ Communication test, Noise measurement, dead channel identification

→ Same test performed on the stacks after cooling assembly



Noise characterization

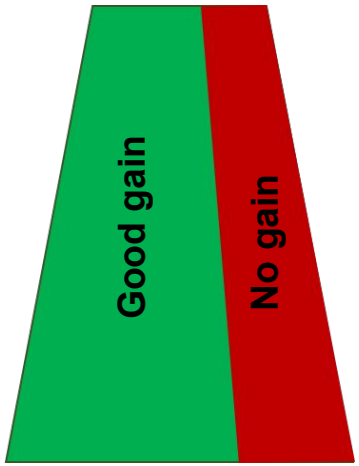


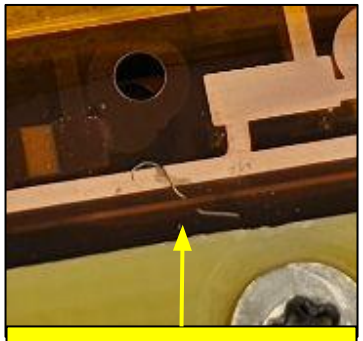
Dead channel identification

Module Production

Example of outstanding issues found thanks to the gain tests and other QC:

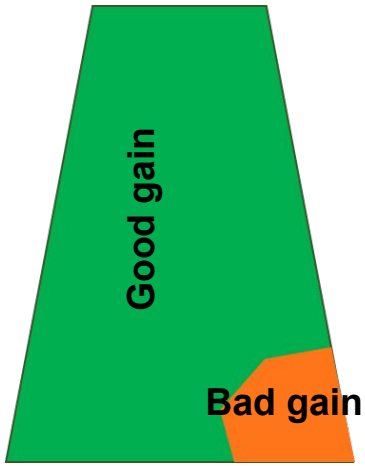
Inactive region

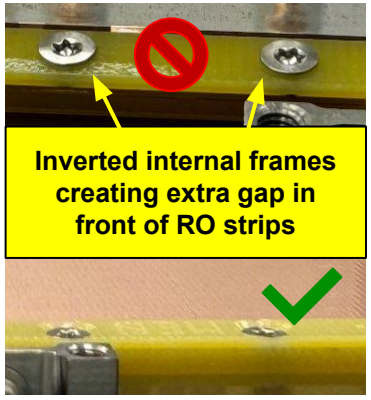




Broken HV line due to contaminant during GEM manufacturing

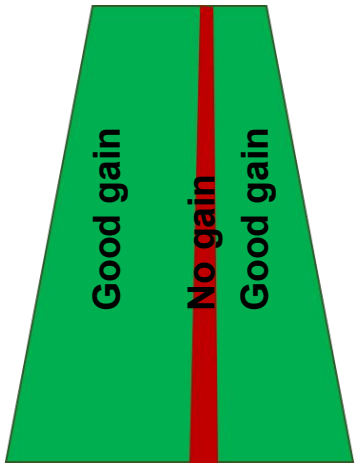
Bad gain region

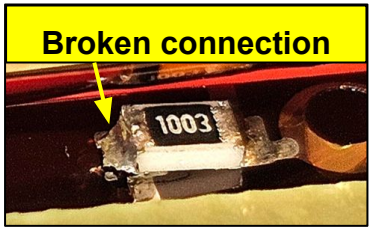




Inverted internal frames creating extra gap in front of RO strips

Inactive sector





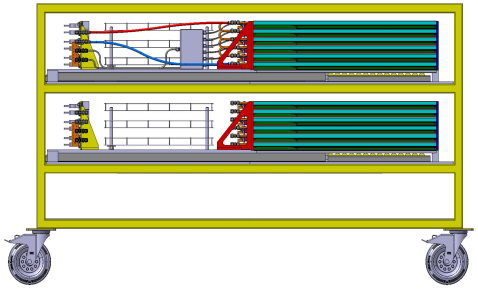
Burnt sector

Under investigations (hopefully very rare)

Stack Production

Stack Production and QC status:

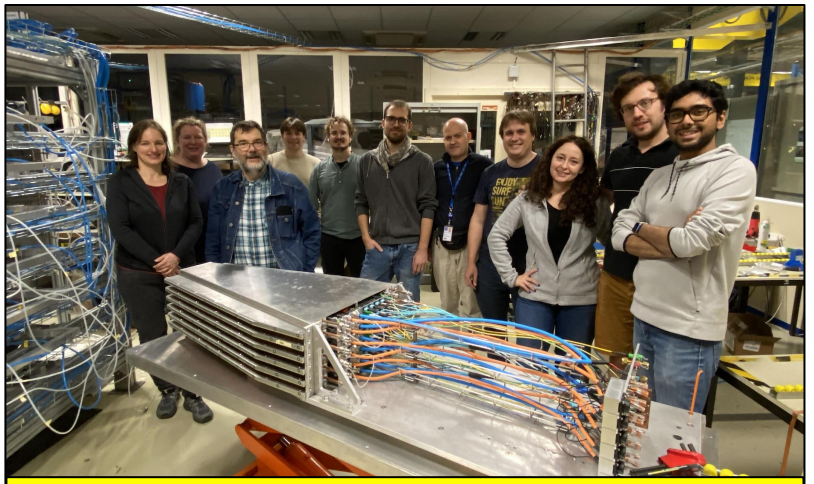
- 36 needed (+2 spares)
  → 1st pre-series stack (2%) **assembled**
  → 2nd pre-series stack soon to be produced
  → Mass production will start in March 2025 with 3 stacks per months until project completion



Cosmic Stand:

- Efficiency, time res.
- 2 stacks (12 layers)

Status:
→ Mechanics/services are ready
→ DAQ system + analysis SW are ready
→ Trigger system with scintillators is being finalized
→ 1st stack being used to commission the stand



Assembly of the first production-grade ME0 stack at CERN

ME0 Cosmic stand

Project milestones:

→ 18 stacks (first endcap) assembled and tested by Q4 2025
→ 36 stacks (full production) assembled and tested by November 2026

Summary

CMS GEM group has a long experience in building triple-GEM detectors for high-rate application

- Clear strategy for producing and testing detectors
- Parallel production scheme with the contribution of many experts from various institutes

Detector construction Status

- About 360 modules produced so far (all projects)
- Now focusing on the **ME0 project (216 modules)** - most challenging in term of requirements and operating conditions
- **Production is on schedule** so far: critical path driven by the availability of the components → careful monitoring and risk evaluation
- First end-cap ready by Q4 2025, second end-cap ready by Q4 2026
- **Installation planned in 2027** during LS3

Construction and QC strategy:

- Detector assembly and testing is well under control
- Component validation and good training is the key to successful mass production
- Continuously reviewing ourselves → regular updates of our activities based on actual experience and new observations

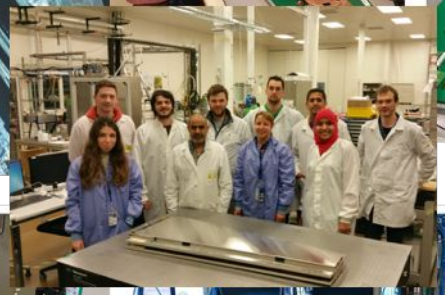
Thank you














Production Strategy

Training and knowledge transfer

- All Production sites and collaborators have access to a set of in-depth documents with technical description of the activities

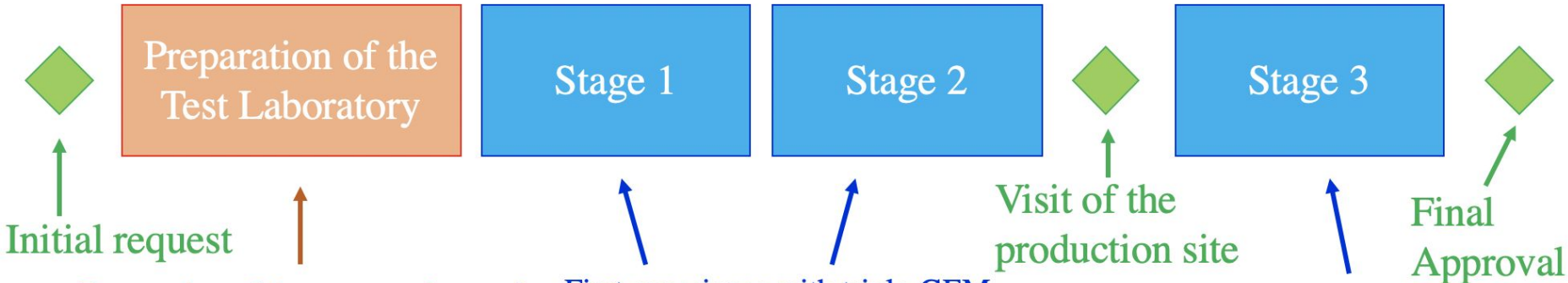
- The Site Checkout Document is a set of requirements, recommendations, comments and procedures to support the last stages of the approval of GE1/1 production sites: *list of managerial practices, items/facilities, recommendations, suggestions*
  https://cernbox.cern.ch/index.php/s/2DC6HluDx8bFYy7
  10+ pages
- The Quality Control Instructions Manual describes the test stands, procedures and deliverables: step-by-step procedure of all QCs, operation of the setup, usage of HW/SW
  https://cernbox.cern.ch/index.php/s/Hao4qAUIlqYrLTg
  50+ pages
- The Technical Assembly Manual describes the preparation and assembly: step-by-step procedures of all assembly steps, instructions to ensure the safety of the sensible components and recommendations
  https://cernbox.cern.ch/index.php/s/lmG9axlHQtRjQ88
  60+ pages
- The Assembly video tutorial illustrates the preparation and assembly: step-by-step procedures
  https://cernbox.cern.ch/index.php/s/ffeyrlftqWjJnne
  1h+ video
- Assembly Training at CERN : multiple sessions organized regularly (since 2015)

GEM training School (March 2024)

- 1 week of lectures and hands-on activities on detector construction and P5 operation
- https://indico.cern.ch/event/1379236/

Production Strategy

- **A 2-years Training Program to ensure Successful Production**
  - All sites are required to use the **same infrastructures/tooling**, the **same assembly/test procedures,** the **same data/deliverable formats**
  - Progressive training (small to large detectors & simple to complex tasks)
  - Every steps are reviewed and approved by the production community



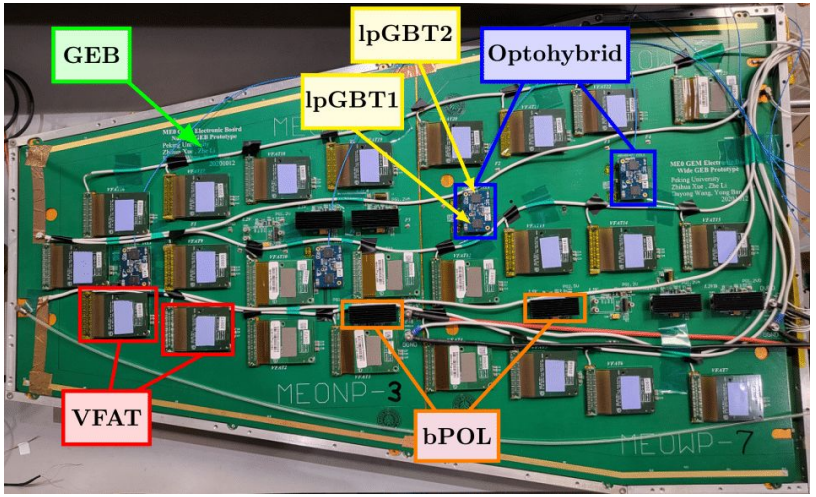
- Preparation of the test stand
- Procurement of the readout electronics for QC
- Procurement of the specific tools for assembly
- Update of the existing infrastructure (clean room, gas system, services)

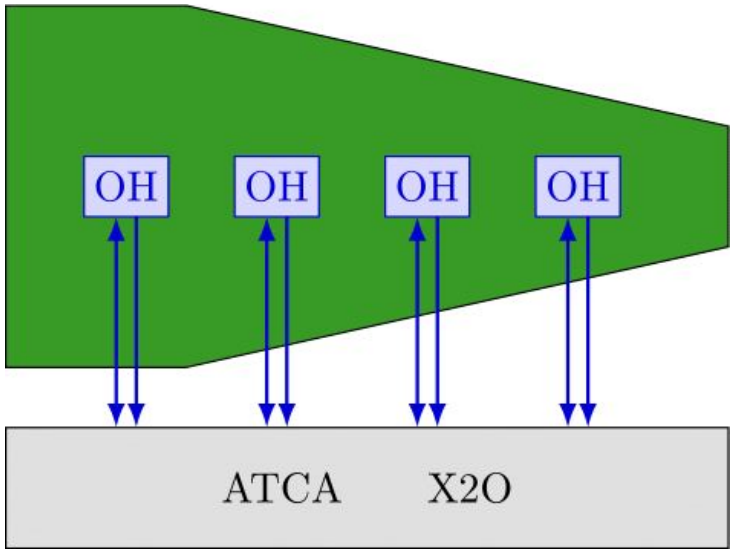
- First experience with triple-GEM technology (small 100 cm^2 detectors)
- QC3 to QC5
- Test of large detectors (no assembly)
- Provide deliverables define by the community
- Meet the time requirements for each step

- Production in real conditions
- Use of final detector kits
- Assembly and QCs following restrictions of the mass-production (timing, certification criteria)

ME0 Electronics Overview

- VFAT3 plugin cards: digitizes and reads out ionization signals
- OH: Optohybrid sends data from the VFATs to the back-end
  - lpGBT : low power Gigabit Transceiver chips used for data processing on the OHs
- GEB: GEM Electronics Board to route connections between the VFATs and OHs
- bPOL: DC-DC converters to supply voltage to the front-end electronics
- Two ME0 stacks connect to an X2O back-end board hosted in ATCA crates
- ME0 passed EDR/ESR in 2023 and is currently in production

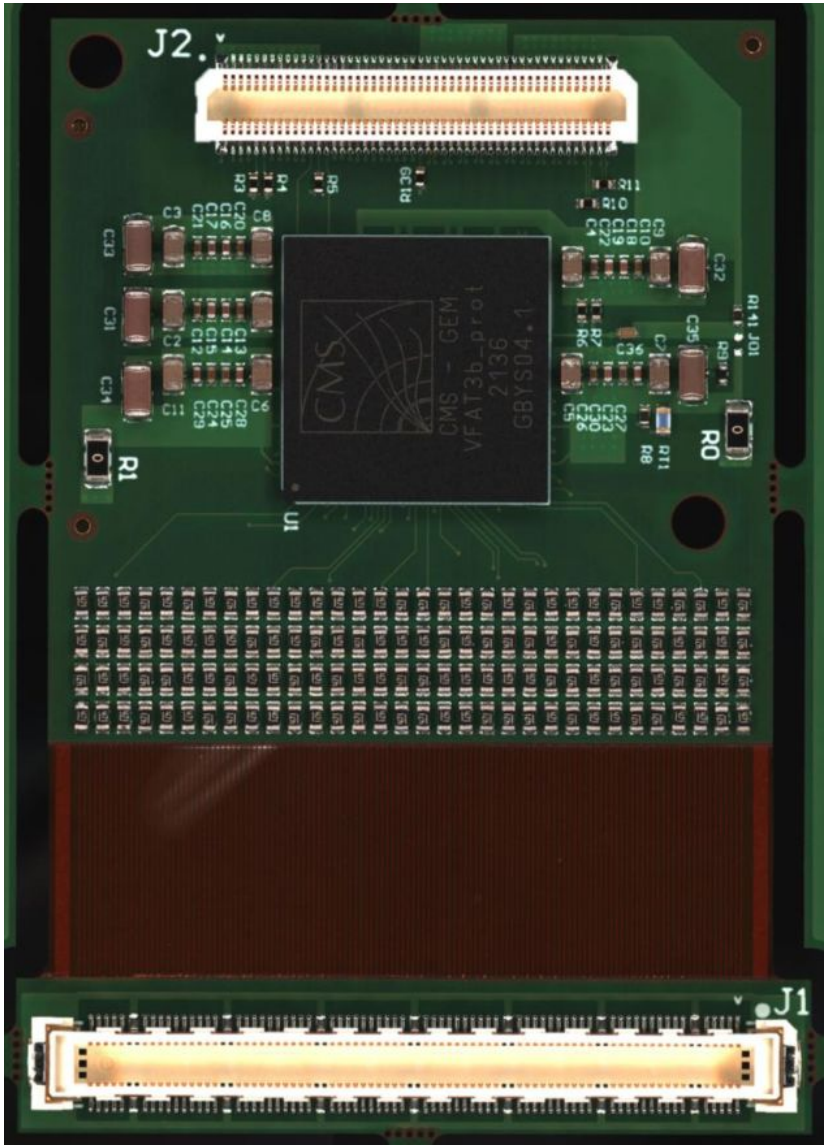




ME0 Packaged VFATs

- VFAT packaging **completed** (10250 ASICs, 8000 for ME0)
  - 96.3% packaging yield
  - Delivered to Bari at the end of August
- Testing of packaged VFATs at Bari started at the beginning of September:
  - Currently 2000 VFATs passed the testing (5472 total needed on-detector)
  - Testing for the rest is ongoing
  - Some problems with the BGA socket on the tester board, will be replaced
- 1680 tested VFATs sent for first batch of plug-in card production

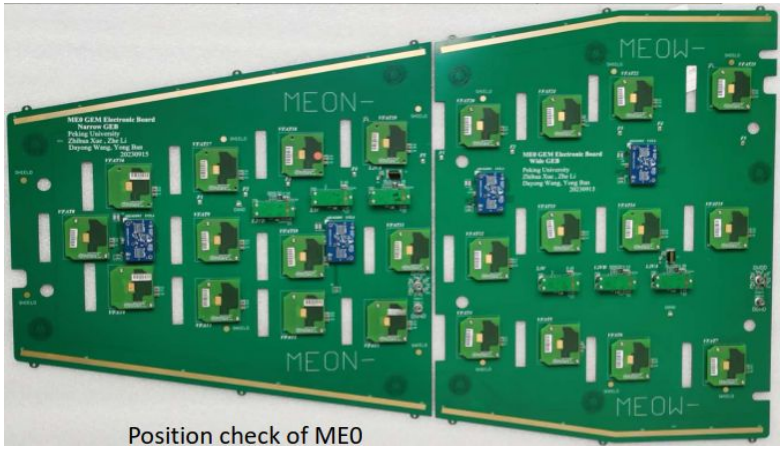
ME0 VFAT3 Plugin Cards



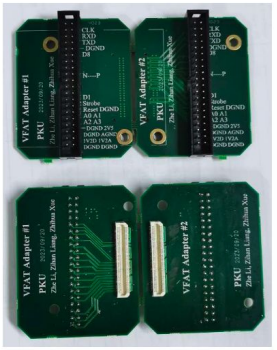
- Modified design with respect to GE2/1, strip to VFAT trigger bit mapping
- Design **validated** with 150 prototypes produced earlier this year with GE2/1 company (NES)
- New company (OSHINO) for final ME0 plugin card production
  - 150 pre-series cards produced and **validated**
- Expecting first batch of 1500 production cards by mid Nov – **on schedule**
- Testing rate of packaged VFATs in Bari will determine production rate

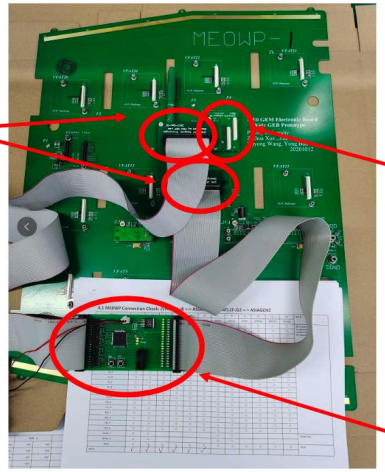
GEB Production Status

- **Passed** GEM Manufacturing Readiness Review in Jan 2024
- 14 pre-series boards produced and tested by PKU and **validated** at CERN
- First batch of production GEBs (40%) arrived at CERN
  - Validation at CERN ongoing
- Production of second batch of GEBs (60%) **completed**
  - Testing ongoing at PKU
  - Expected to arrive at CERN by early 2025



Position check of ME0





OH Production Status

- **Passed** GEM Manufacturing Readiness Review in Aug 2023
- 1018 boards produced in total
  - 24 pre-series + 994 series
- Testing **completed** at UCLA:
  - **70%** boards passed all tests and selected to use on the detector
  - Almost all of them arrived at CERN
    - Re-testing ongoing
- **30%** boards rejected:
  - Most of them during visual inspection, due to a PCB manufacturing defect by the vendor
    - They still pass all tests but rejected as a safety precaution
  - New boards being produced to replace them
    - Additional validation steps in place to catch similar issues before assembly
  - Expected to be completed and tested by Feb/March 2025 – still **on schedule**