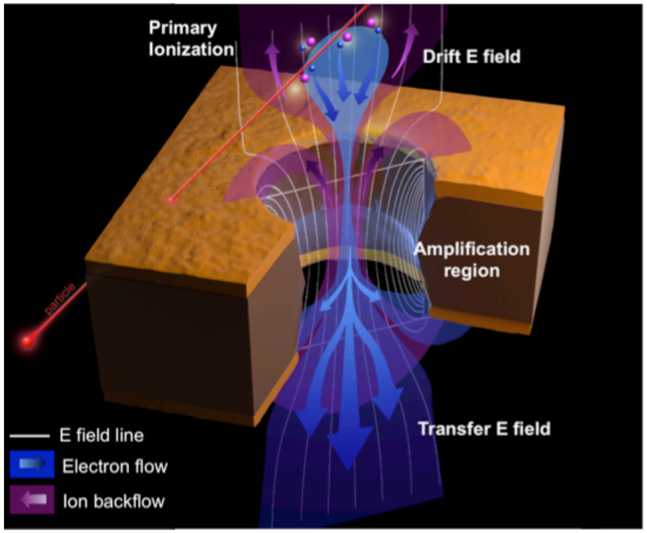
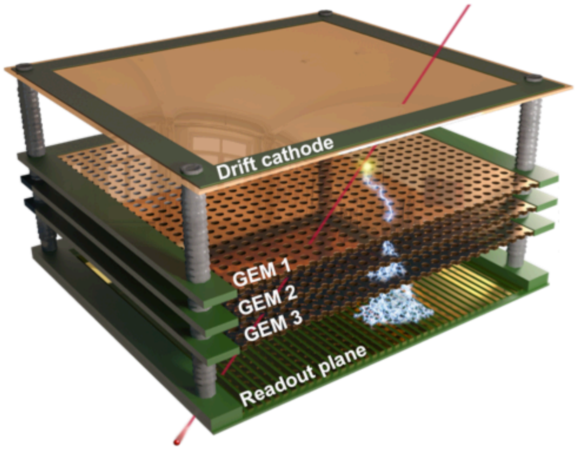
Upgrade of the CMS Forward Muon System with Gas Electron Multipliers

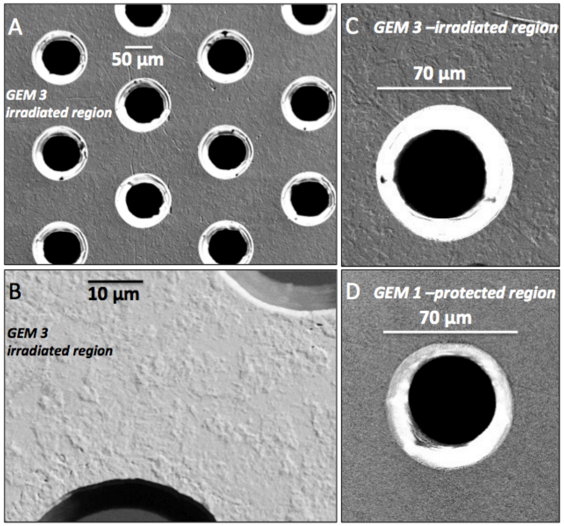
Jeremie A. MERLIN

Detector Physics Seminar

September 13, 2019







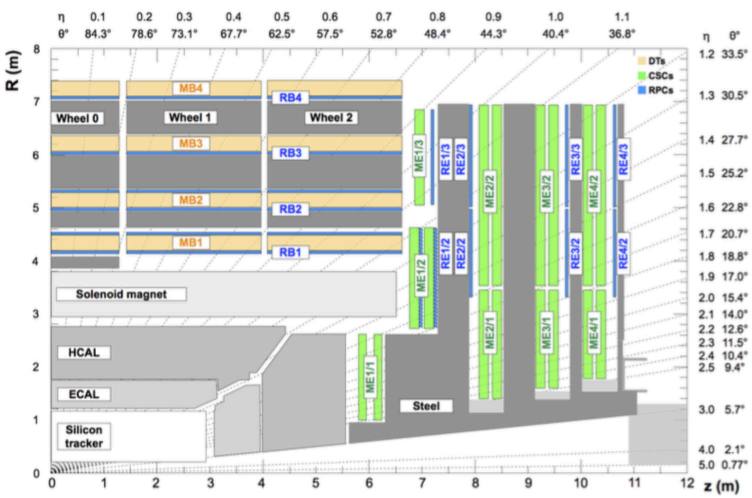
Outline

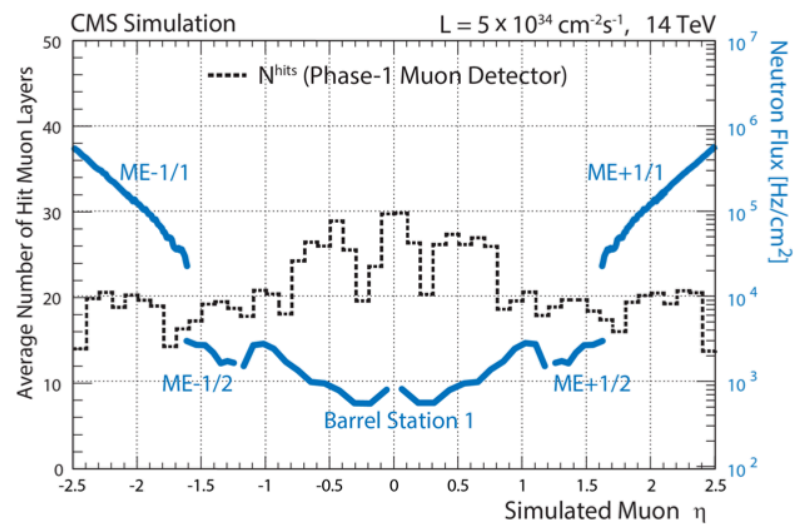
- Introduction
  - Upgrade of the CMS forward muon system
  - Overview of the GEM technology
- GE1/1 R&D Phase
  - GE1/1 prototyping
  - Performance tests
  - Longevity studies
  - Discharges studies
- GE1/1 Detector Mass-Production
  - Organization of the mass production
  - Detector assembly and quality control
  - Status summary
- Future Developments
- Summary

INTRODUCTION

Upgrade of the CMS Muon System

- **New challenges for the particle physics**
  - **Higgs precision measurement (properties and couplings)**
  - **Electroweak precision measurement**
  - **New physics: high mass resonance, dark matter, extended Higgs sectors etc…**
- **Limitations of the actual forward muon system**
  - **Low magnetic field (small bending angle)**
  - **High background and low hit multiplicity**
  - ➢ **Trigger rate dominated by soft muon mis-reconstructed as high p_T muons (will be even worst at HL-LHC)**



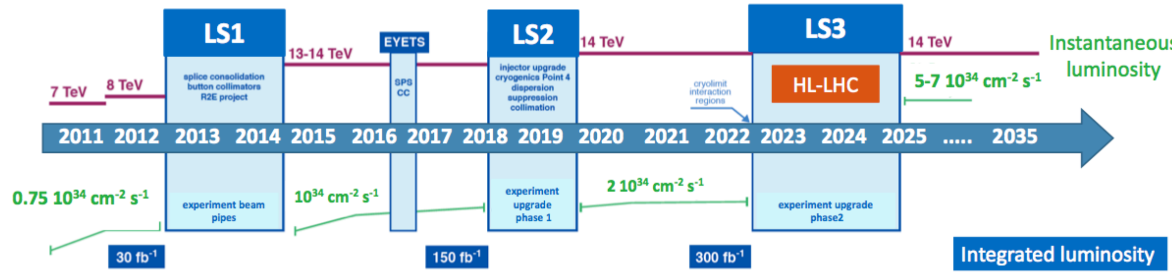


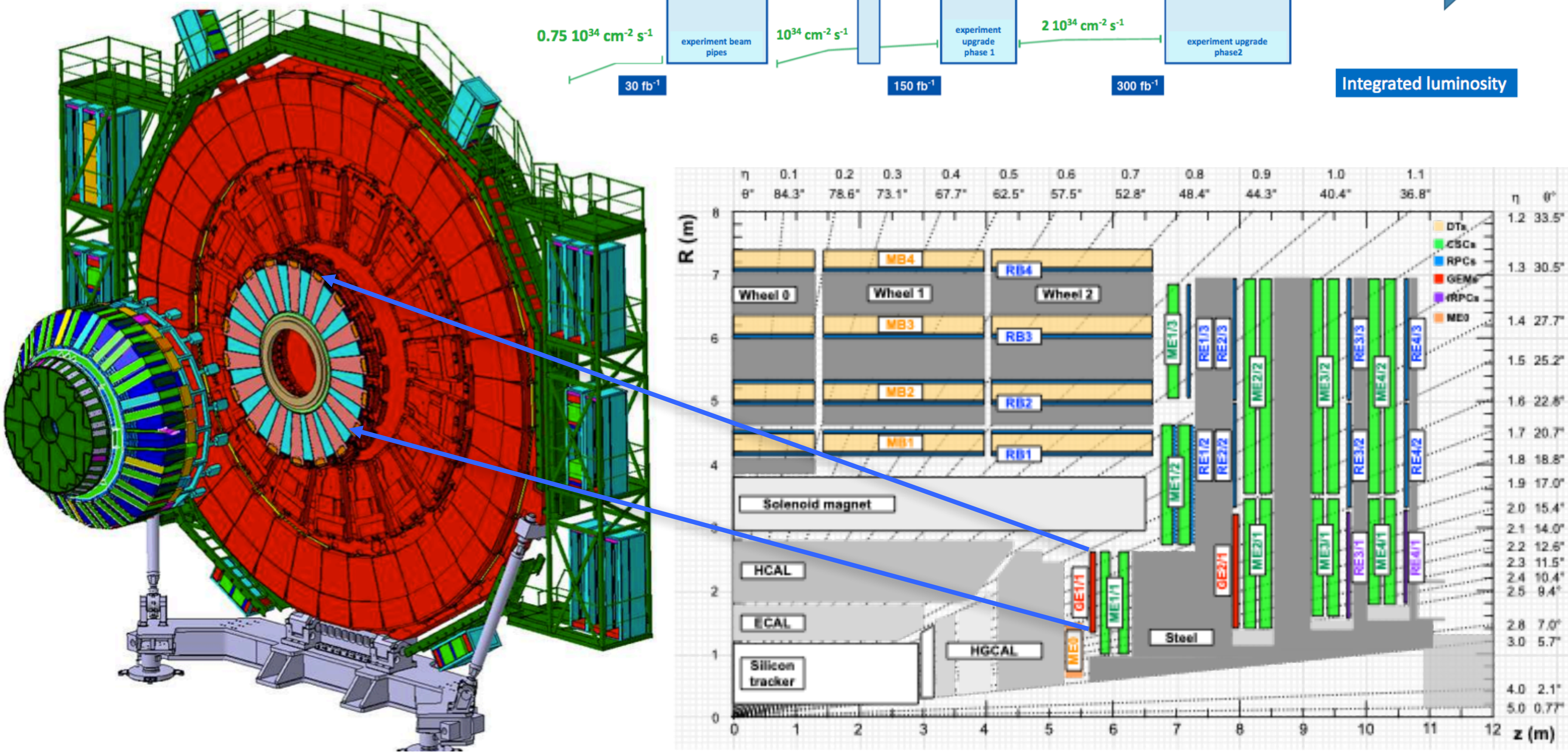
CMS TDR

Upgrade of the CMS Muon System

- Insertion of new muon stations in the existing high-η system

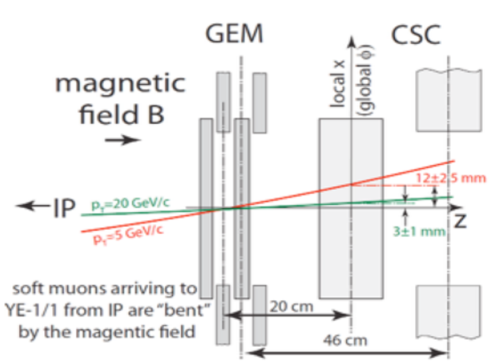
GE1/1

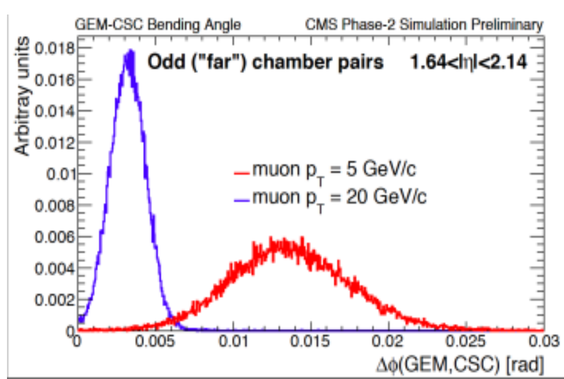


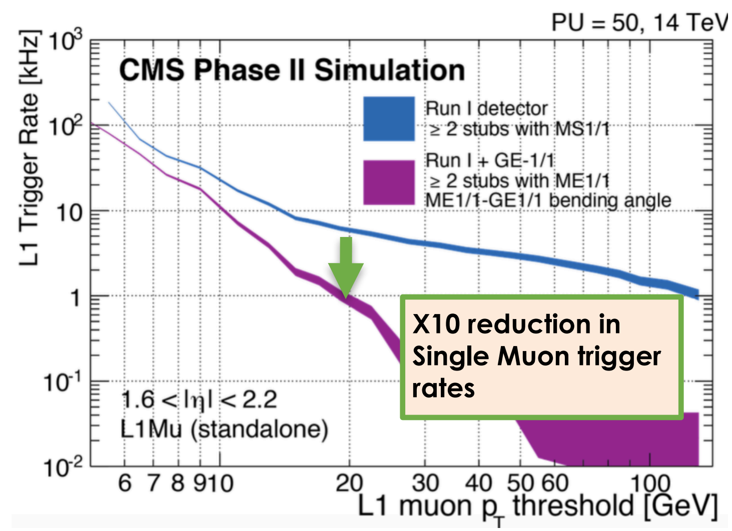


Upgrade of the CMS Muon System

- **New detection layers in front of the ME1/1 station**
  - Interesting region with higher magnetic field, lever arm and small scattering
  - Addition of redundancy to improve the p_T estimation
  - Compensate possible loss in the CSC system (aging)
- **GE1/1 based on the "GEM" technology**
  - 36 super-chambers (2 detection layers) per end-cap
  - Trapezoidal chambers (about 1 m long by 0.5 m)
  - Eta coverage: $1.55 < \eta < 2.18$



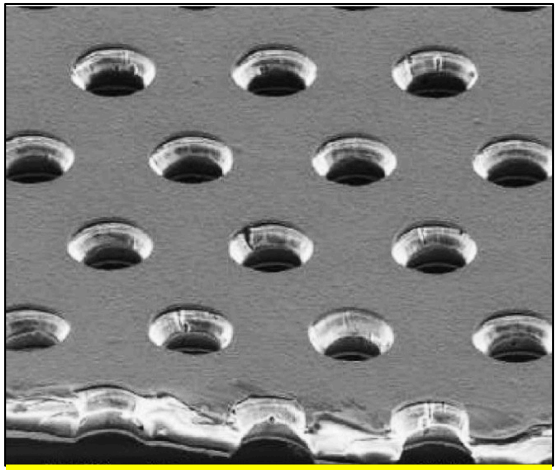




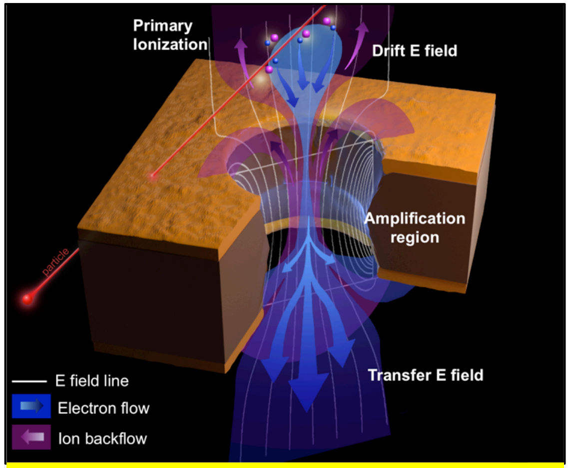
CMS TDR

Overview of the GEM Technology

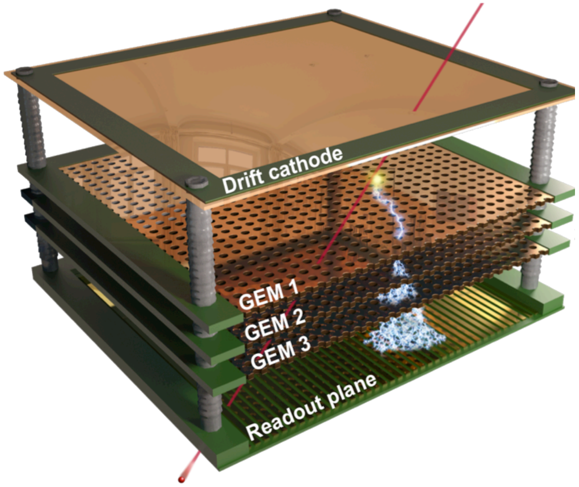
- Gas Electron Multiplier (GEM)
  - Introduced by F. Sauli in 1997 to pre-amplify signals in MSGCs
  - Polyimide foil copper coated on both sides and perforated with a high density of microscopic holes
  - Triple-GEM structures allow gas gains up to 10^5
  - High rate capability, high resistance to aging, good stability
  - High performance compatible with the CMS requirements



SEM picture of a GEM foil



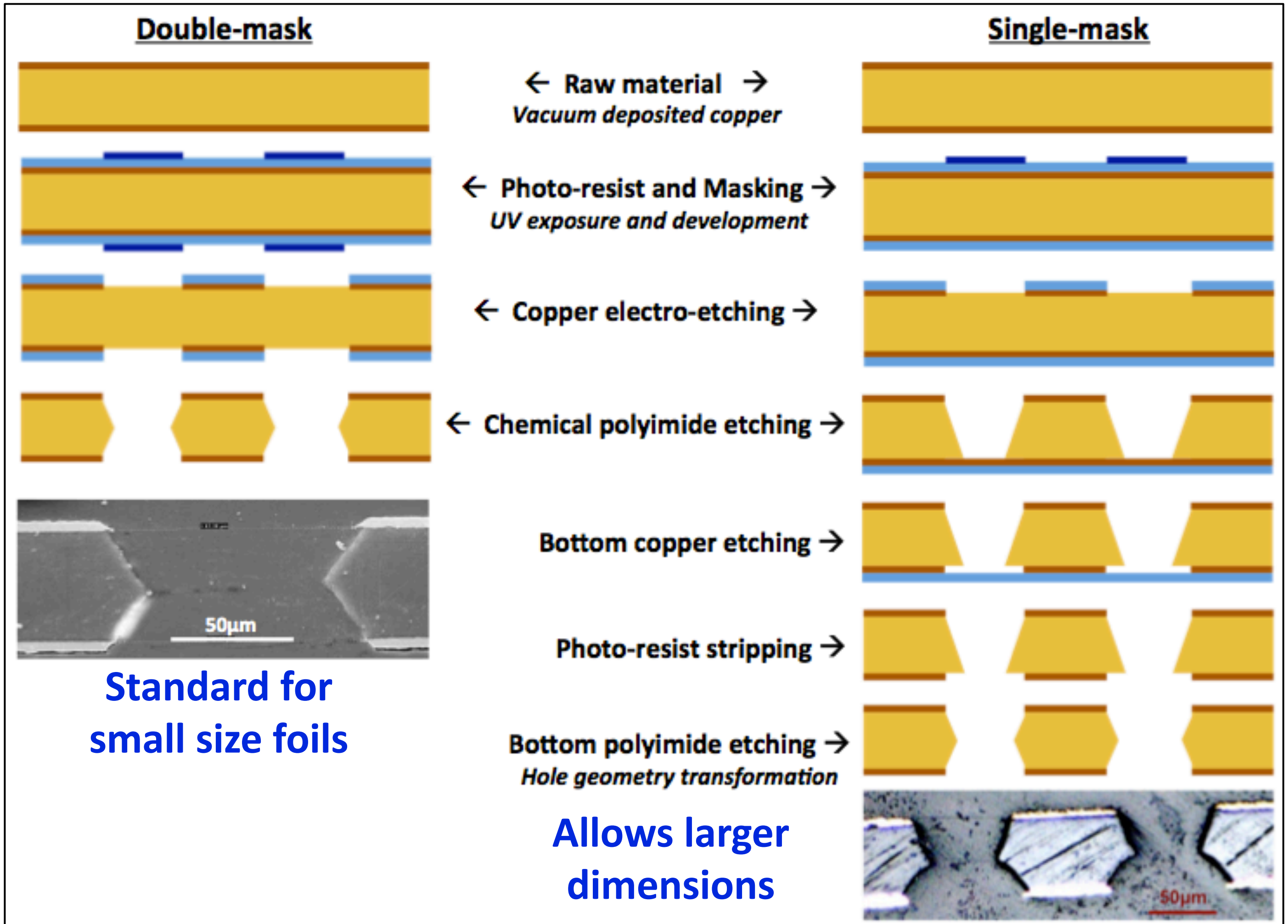
Electric field map in a GEM hole

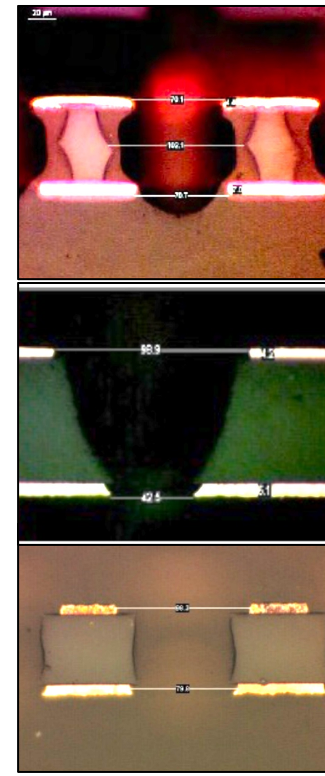


Triple-GEM detector

Overview of the GEM Technology

- GEM foil fabrication based on photolithography techniques





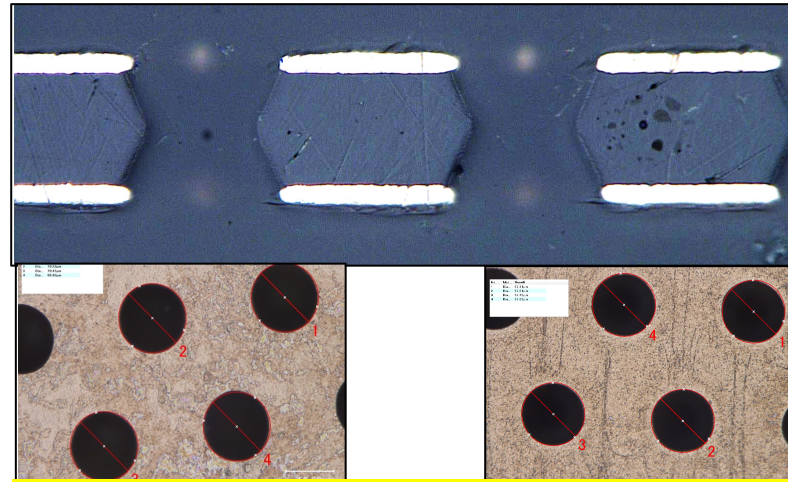
Cross-sections of different types of GEM geometries

Overview of the GEM Technology

Typical GEM geometries

- **Double-mask:**
- Standard for small GEMs
- Bi-conical shape

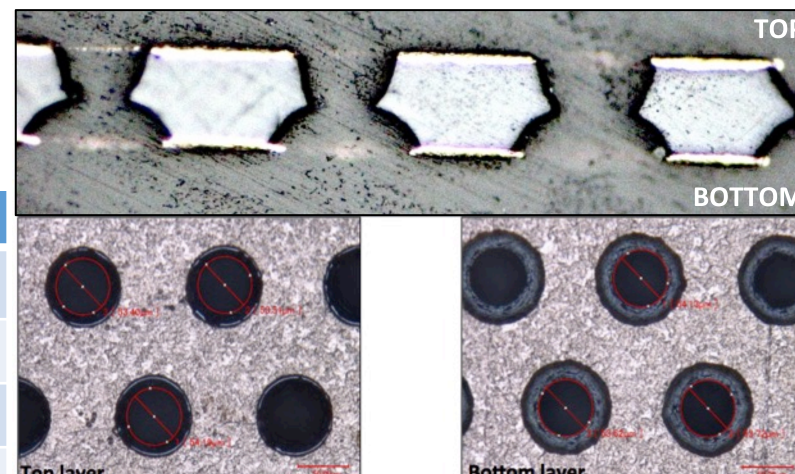
Diameters	cross section optical microscopy	
Hole location	Diam. [µm]	Err. [µm]
Top	70.1	± 0.2
Middle	49.1	± 1.2
Bottom	69.4	± 0.8



Double-mask geometry

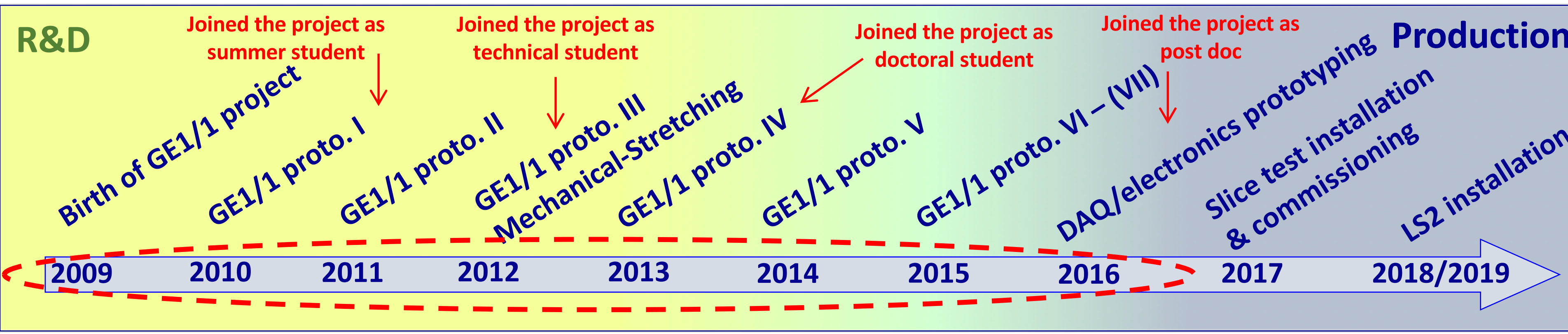
- **Single-mask:**
- Suitable for large size GEMs
- **Asymmetric** bi-conical shape

Diameters	digital microscopy		cross section optical microscopy	
Hole location	Diam. [µm]	Err. [µm]	Diam. [µm]	Err. [µm]
Top	73.8	± 3.3	71.0	± 2.1
Middle	51.3	± 2.7	52.8	± 5.4
Bottom	85.5	± 4.1	86.1	± 4.9



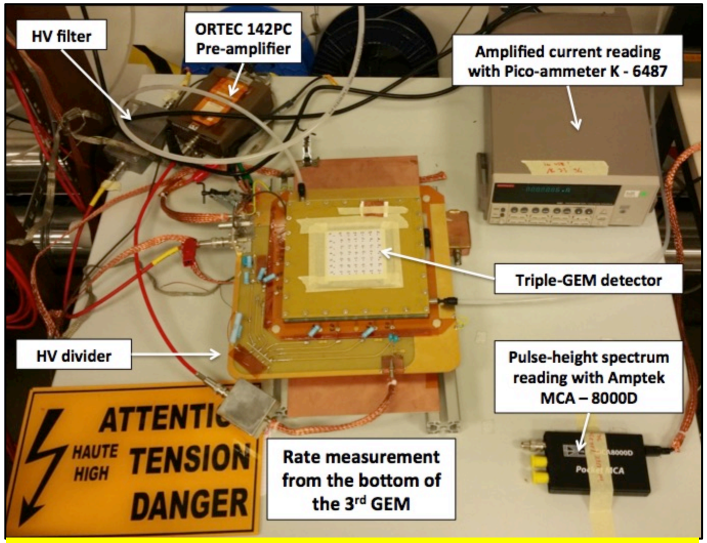
Single-mask geometry

GE1/1 R&D PHASE
Prototyping

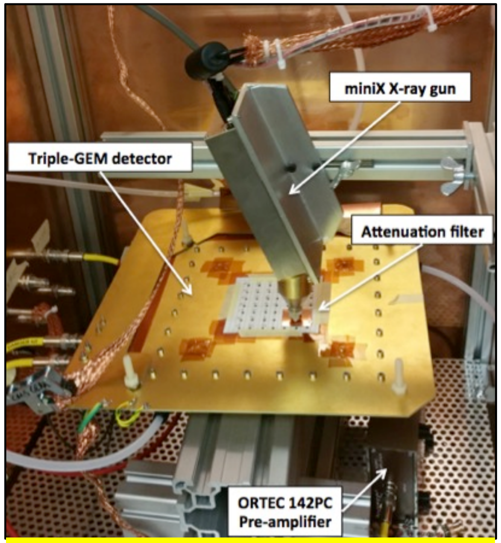


GE1/1 Prototyping

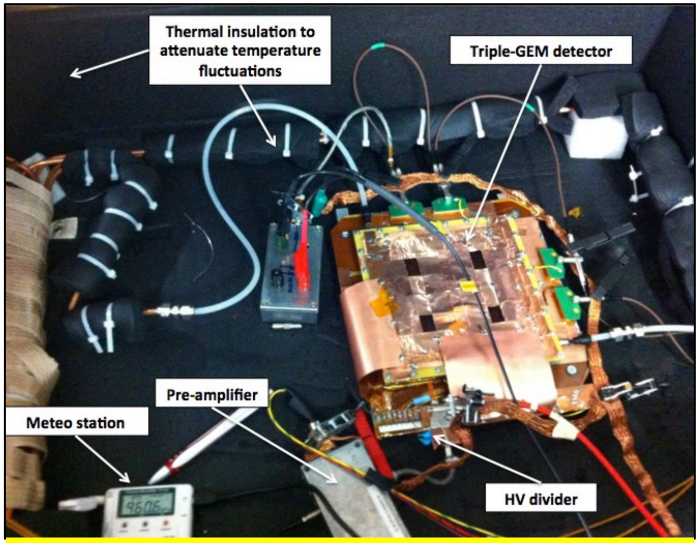
- Starting with small size detectors
  - Standard 10x10 cm^2 available at CERN MPT workshop
  - Easy to assemble, to manipulate and to operate
  - Low cost (can be used for destructive tests)
  - ➢ Suitable for almost all studies (local effects or phenomena not depending on the GEM size)



Double-sided 10x10 prototype



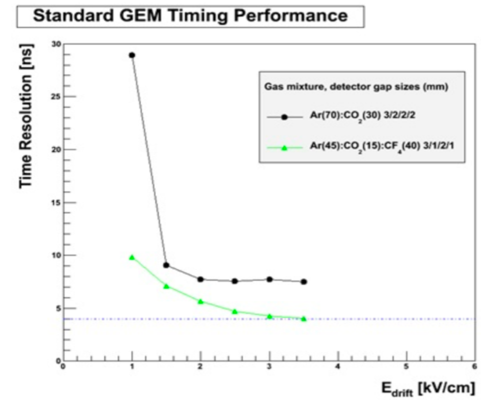
10x10 for rate capability test

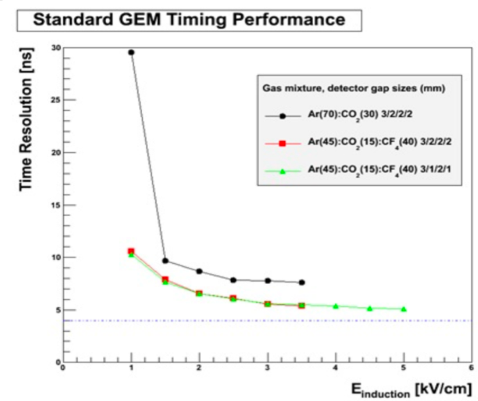


10x10 for temperature dependency test

GE1/1 Prototyping

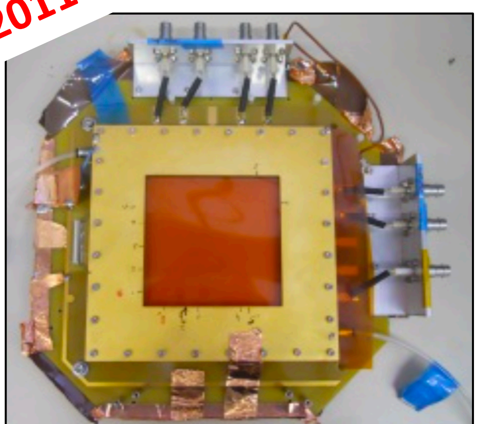
- First approach with the Timing GEM
  - 10x10 cm² triple-GEM (double-mask)
  - Variable internal geometry
  - Variable electric fields (multichannel PS)
  - ➤ Fully characterized in laboratory and with particle beams (H4 – H2 areas at CERN)
  - ➤ Used to define the final **gap** configuration and the **electric field** configuration for CMS



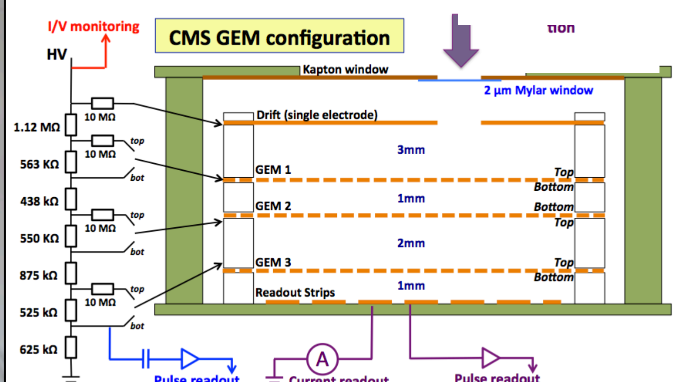


2009-2011

A. Marinov, PhD Thesis
Universiteit Gent, 2013



The Timing GEM



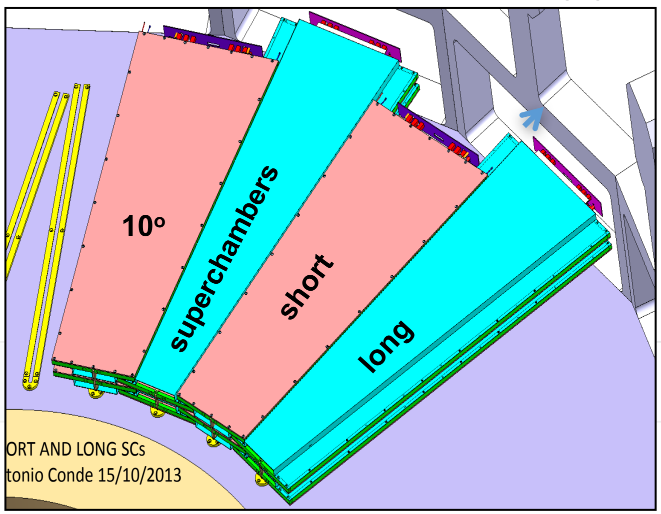
Region	Gap $[mm]$	Electric field $[kV/cm]$
Drift	3	3
Transfer 1	1	3.5
Transfer 2	2	3.5
Induction	1	5
Region	**Voltage $[V]$**	**Average Electric field $[kV/cm]$**
Δ_{GEM1}	450	89
Δ_{GEM2}	440	88
Δ_{GEM3}	420	84

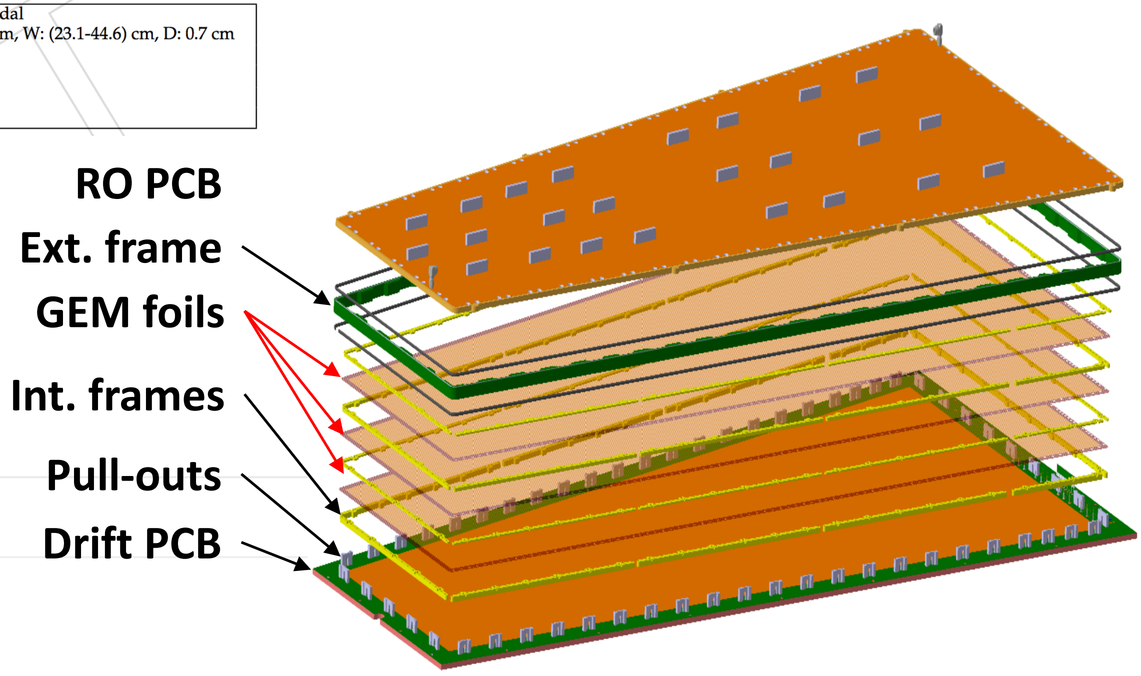
CMS GEM gap and electric field configuration

GE1/1 Prototyping

- Moving to large size detectors
  - Establish the final geometry required in the CMS end-caps
  - Define (and then validate) the GEM foil fabrication process and the detectors assembly process
  - Confirm the detection performance with large volumes

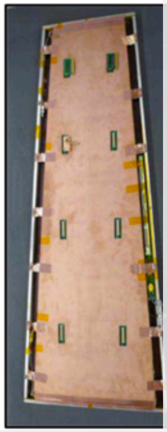
GE1/1 detector		
Specification	Short	Long
Chamber Shape	Trapezoidal	Trapezoidal
Chamber Dimensions	L:106.1 cm, W:(23.1-42.0) cm, D:0.7 cm	L:120.9 cm, W: (23.1-44.6) cm, D: 0.7 cm
Chamber Thickness	3.5 cm	3.5 cm
Active readout area	0.345 m^2	0.409 m^2
Active chamber volume	2.6 liters	3 liters
Geometric acceptance in η	1.61-2.18	1.55-2.18





GE1/1 Prototyping

- Large size prototyping: historical overview



GE1/1-I (2010)

First attempt with large size GEM (first largest GEM detector ever built):
- Size: short only
- Config.: 3/2/2/2 mm
- 1024 RO channels
- Fabrication with glue

GE1/1-II (2011)

Introduced final s
layout (granularit
pitch) as defined
simulation:
- Size: short onl
- Config.: 3/2/2/
mm
- 3072 RO channels
- Fabrication with glue

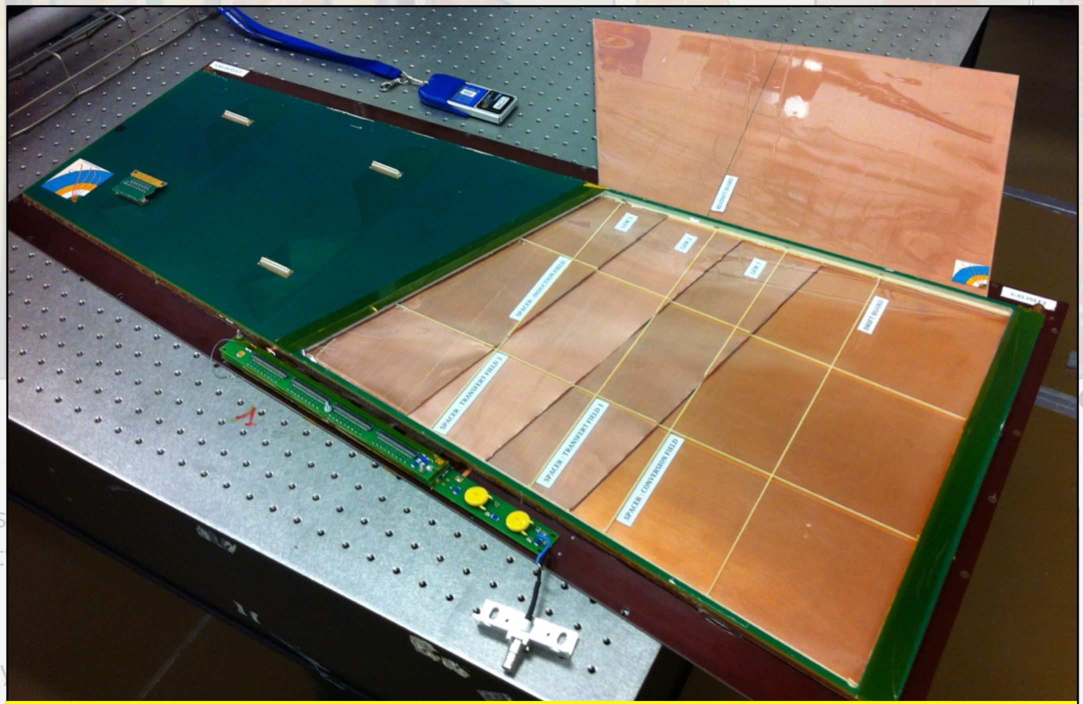
- Fabrication based on mechanical stretching

mechanical stretching

- 3072 RO channels
- Fabrication based on mechanical stretching

GE1/1-X (2017)

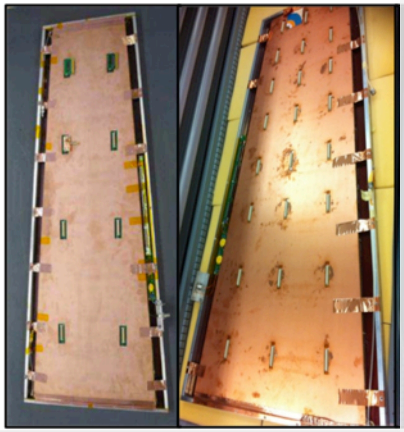
"very final" version:
- Size: short and long
- Config.: 3/1/2/1 mm
- 3072 RO channels
- Fabrication based on mechanical stretching



GE1/1 First generation displayed at the CERN Microcosm museum

GE1/1 Prototyping

Large size prototyping: historical overview



GE1/1-I (2010)	GE1/1-II (2011)	GE1/1-III (2012)	GE1/1-IV (2013)

First attempt with large size GEM (first largest GEM detector ever built):
- Size: short only
- Config.: 3/2/2/2 mm
- 1024 RO channels
- Fabrication with glue

Introduced final strip layout (granularity and pitch) as defined by simulation:
- Size: short only
- Config.: 3/2/2/2 mm
- 3072 RO channels
- Fabrication with glue

Introduced the final gap configuration an
new assembly technique:
- Size: short only
- Config.: 3/1/2/1 mm
- 3072 RO channels
- Fabrication based on mechanical stretching

- 3072 RO channels
- Fabrication based on mechanical stretching

- Config.: 3/1/2/1 mm
- 3072 RO channels
- Fabrication based on mechanical stretching

-X
7)

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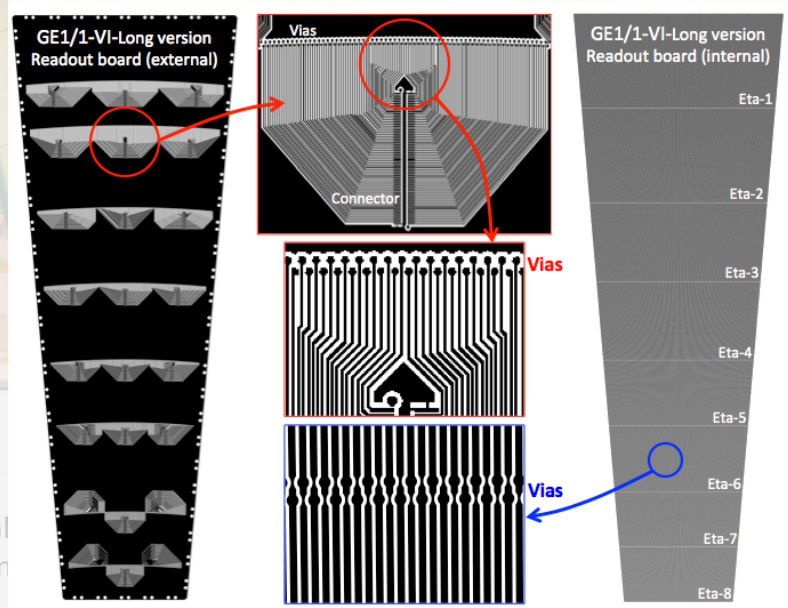
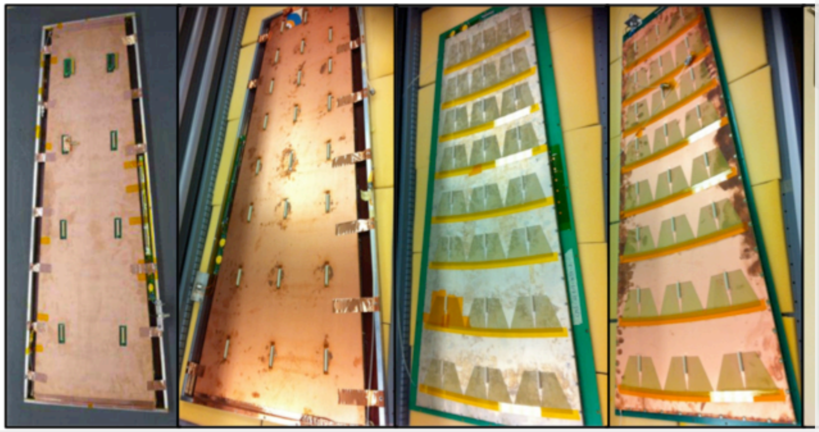


Full granularity readout board (3072 strips divided in 24 partitions)

GE1/1 Prototyping

Large size prototyping: historical overview



GE1/1-I (2010)	GE1/1-II (2011)	GE1/1-III (2012)	GE1/1-IV (2013)

First attempt with large size GEM (first largest GEM detector ever built):
- Size: short only
- Config.: 3/2/2/2 mm
- 1024 RO channels
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Introduced final strip layout (granularity and pitch) as defined by simulation:
- Size: short only
- Config.: 3/2/2/2 mm
- 3072 RO channels
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Introduced the final gap configuration and a new assembly technique:
- Size: short only
- Config.: 3/1/2/1 mm
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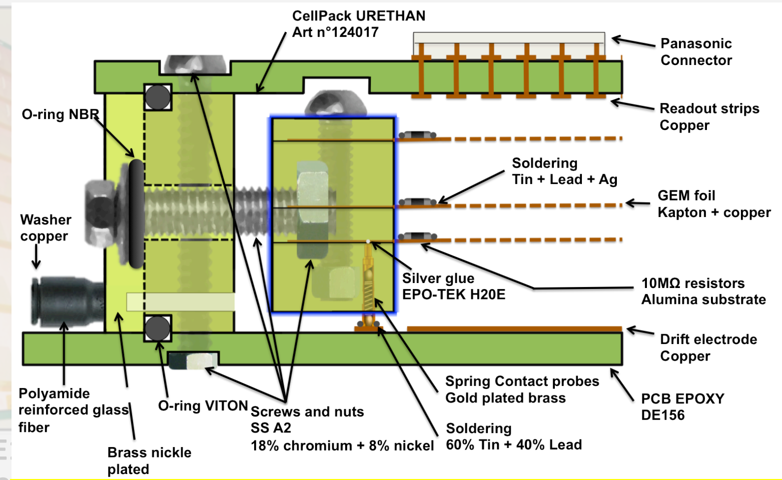
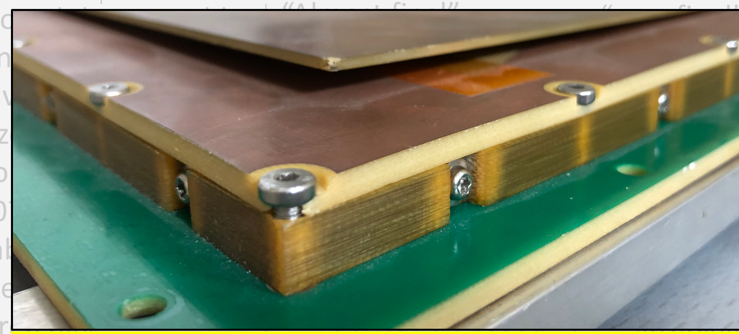


Schematic cross-section of the first mechanical stretching



Pictures of the GE1/1 generation IV external frame

GE1/1 Prototyping

Large size prototyping: historical overview

GE1/1-I (2010) | GE1/1-II (2011) | GE1/1-III (2012) | GE1/1-IV (2013) | GE1/1-V (2014) | GE1/1-VI (2015)

First attempt with large size GEM (first largest GEM detector ever built):
- Size: short only
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Introduced final strip layout (granularity and pitch) as defined by simulation:
- Size: short only
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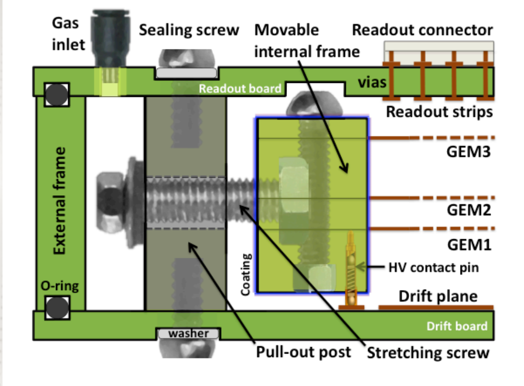
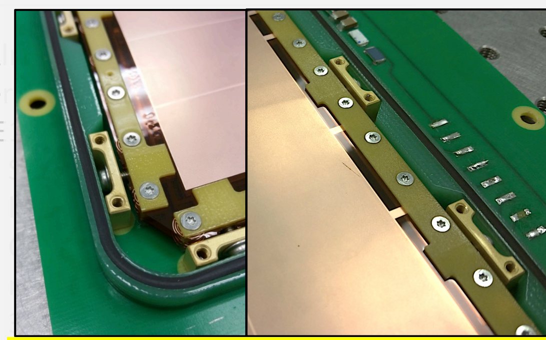
Introduced the final gap configuration and a new assembly technique:
- Size: short only
- Config.: 3/1/2/1 mm
- 3072 RO channels
- Fabrication based on mechanical stretching

Improved the assembly technique and try the long version of GE1/1:
- Size: short and long
- Config.: 3/1/2/1 mm
- 3072 RO channels
- Fabrication based on mechanical stretching



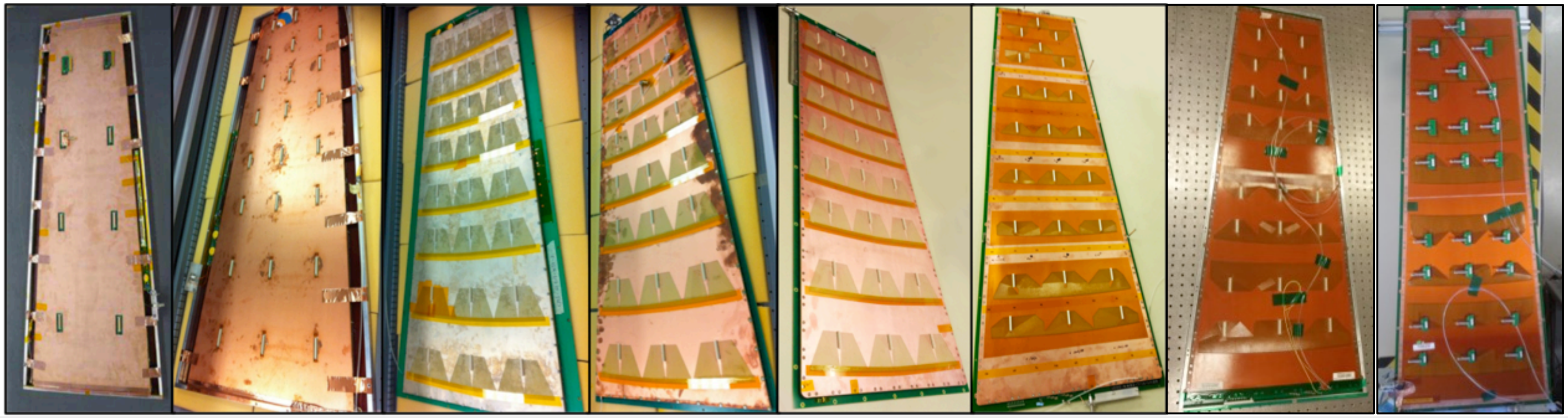
Schematic cross-section of the final mechanical stretching



Pictures of the final mechanical stretching

GE1/1 Prototyping

- Large size prototyping: historical overview



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

First attempt with large size GEM (first largest GEM detector ever built):
- Size: short only
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- 1024 RO channels
- Fabrication with glue

Introduced final strip layout (granularity and pitch) as defined by simulation:
- Size: short only
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- Size: short only
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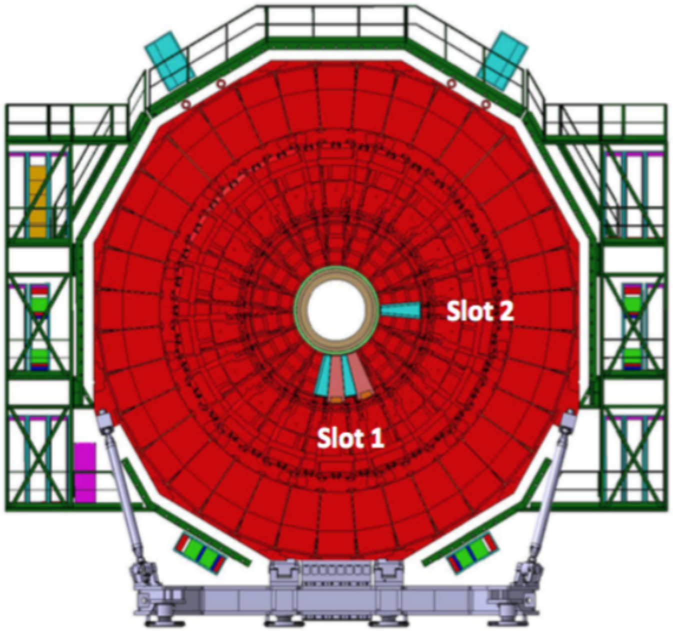
Improved the assembly technique and try the long version of GE1/1:
- Size: short and long
- Config.: 3/1/2/1 mm
- 3072 RO channels
- Fabrication based on mechanical stretching

“Almost final” version for the GE1/1 slice test:
- Size: short and long
- Config.: 3/1/2/1 mm
- 3072 RO channels
- Fabrication based on mechanical stretching

“very final” version:
- Size: short and long
- Config.: 3/1/2/1 mm
- 3072 RO channels
- Fabrication based on mechanical stretching

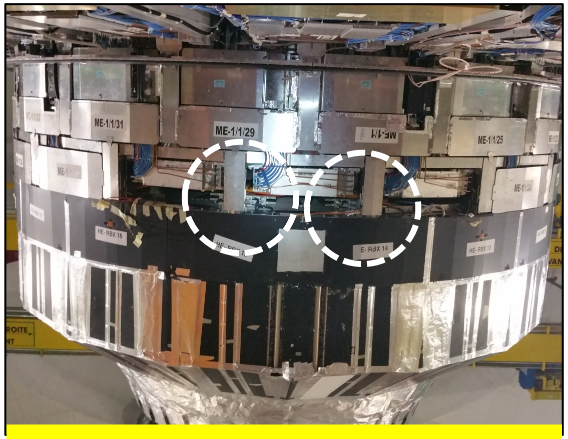
GE1/1 Prototyping

- GE1/1 Slice Test (2016-2018)
  - Production and installation of 5 super-chambers (almost final version)
  - Continuous operation within the CMS framework
  - ➢ First experience in the real CMS environment: services, installation, commissioning, DCS, DSS, DQM, DAQ etc …



Transport trolley with the slice test chambers

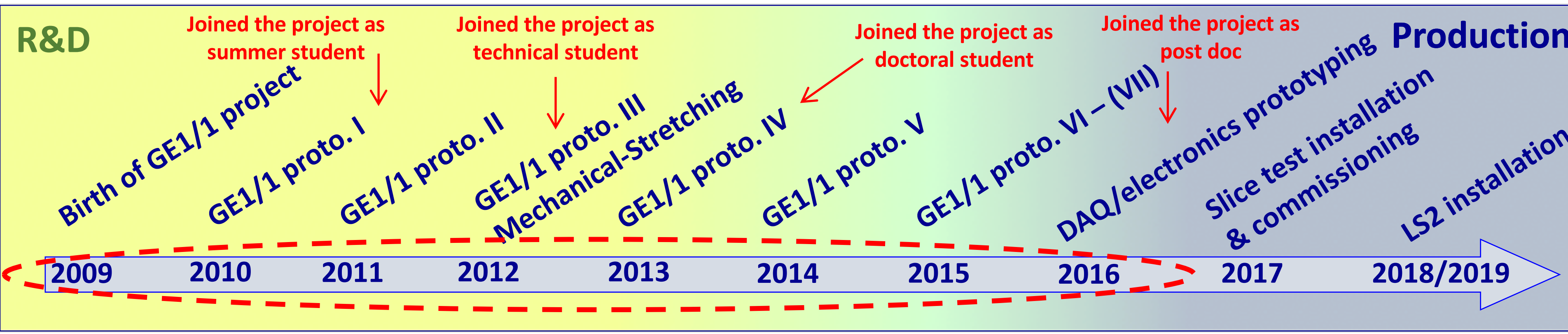
The installation team (Jan. 2017)



First GE1/1 detectors in CMS

GE1/1 R&D PHASE

Characterization and Performance tests



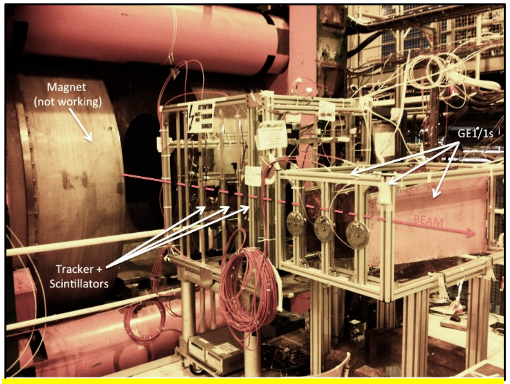
GE1/1 Characterization and Performance

Characterization

GE1/1 R&D and production laboratory at CERN (TIF)

- Understand the GEM properties
  - Precise measurement with the most appropriate electronics
  - Gain calibration
  - Spectrum analysis
  - Short term stability
  - Rate/flux capability

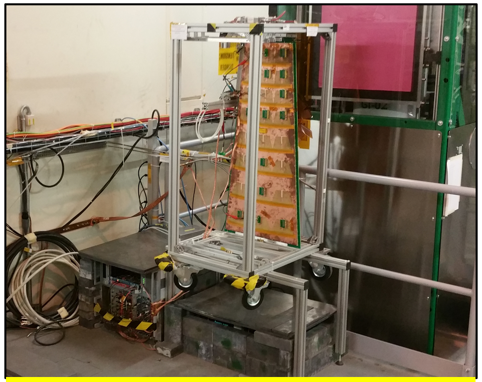
Performance



Test Beam (2012) at CERN H2 SPS

- Understand the GEM performance
  - Full system (with CMS electronics)
  - Real conditions (Muon/pion beams)
  - Detection efficiency
  - Spatial resolution
  - Time resolution

Longevity

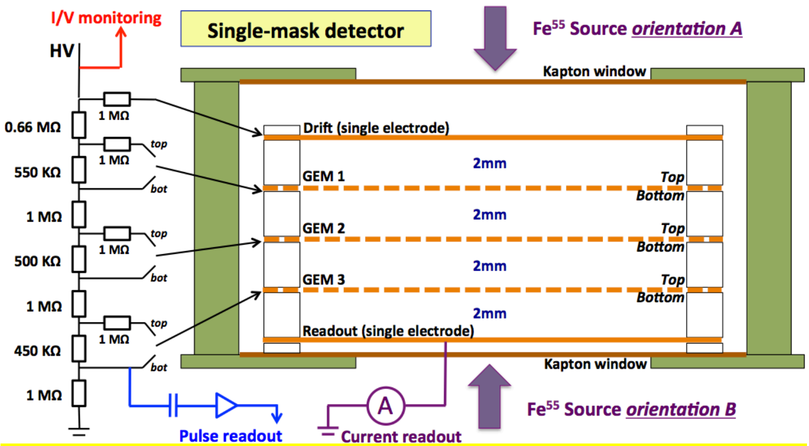


Aging Test at CERN GIF++

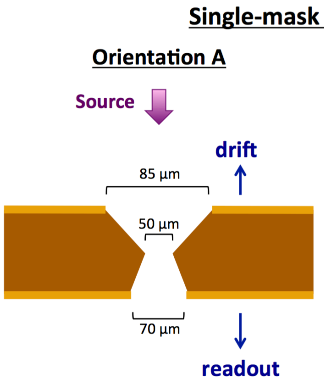
- Ensure the long-term stability
  - Reproduce the background radiations (gammas and/or neutrons)
  - Sustained operation at high rate
  - Gain stability
  - Outgassing effects
  - Discharge rate

GE1/1 Characterization and Performance

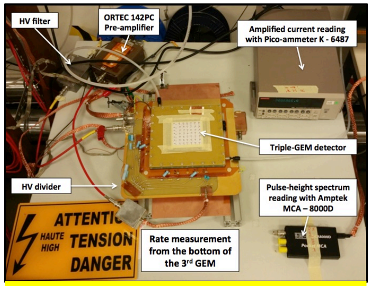
- Characteristics of the single-mask GEM foils
  - GEM (double-mask) is a mature technology: TOTEM, LHCb, COMPASS…
  - Single-mask foils have a different geometry compared to double-mask
  - How does the production technique affect the detector operation ?
  - ➢ Designed a special « symmetric » detector to qualify both GEM foils orientations in term of gain, stability and flux capability
  - ➢ Using the CMS GEM electric field configuration (for more realism)



Design of a special “symmetric” triple-GEM detector



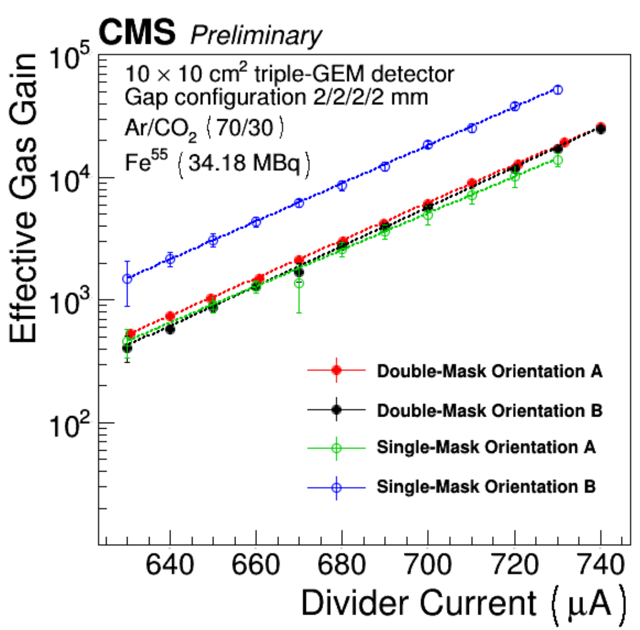
Schematic of the single-mask GEM foils orientations

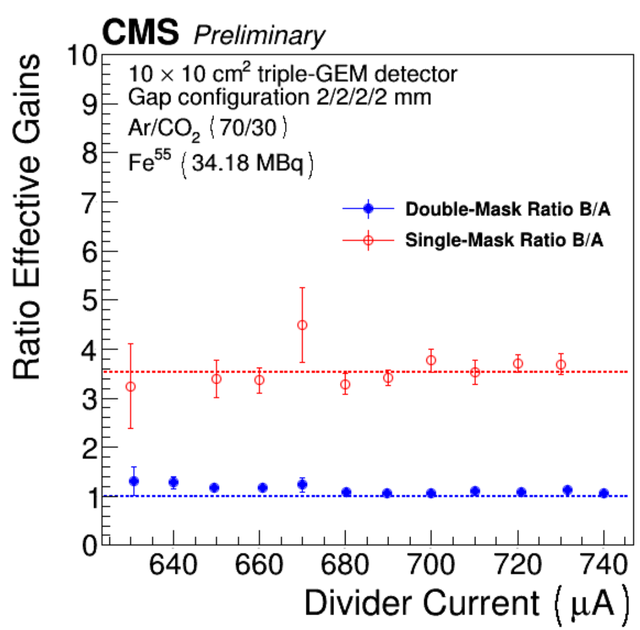


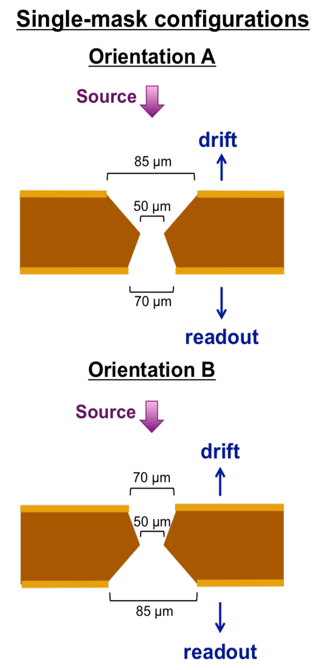
“symmetric” triple-GEM detector

Gain Calibration of the single-mask GEM foils

- Single-mask orientation A and double-mask have similar behavior
- Single-mask orientation B shows higher effective gain at same HV point
- ➢ Measurements indicate that having a larger hole diameter at the exit of the GEM holes increases the electron **extraction efficiency**

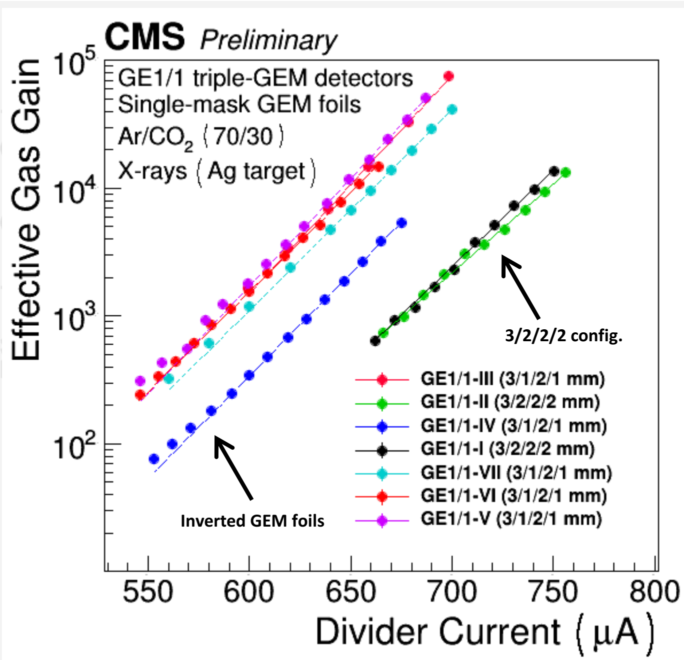


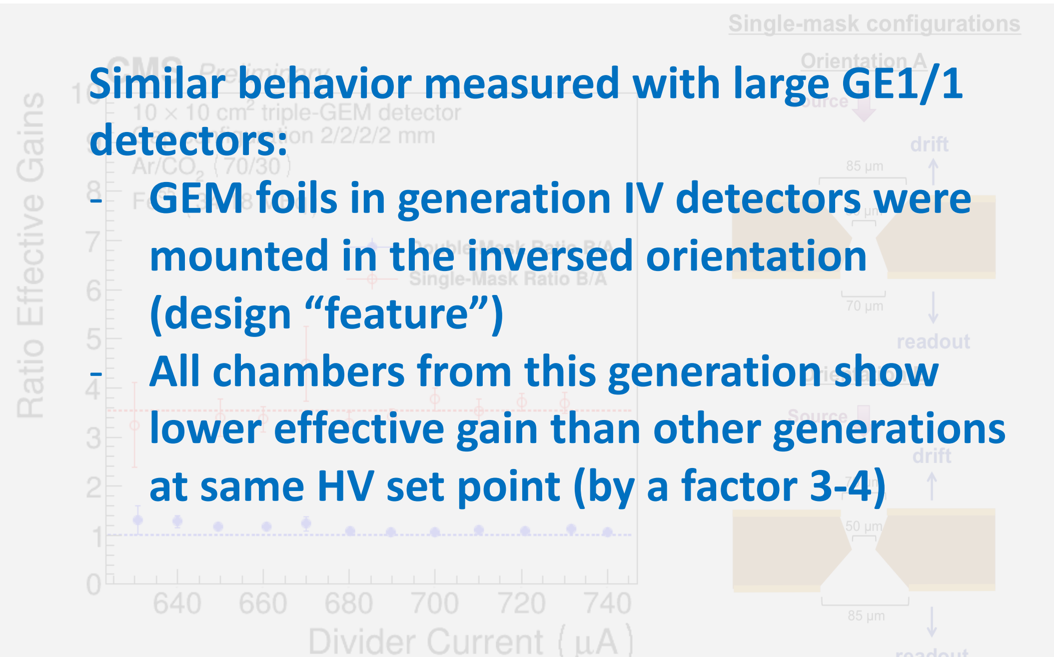




GE1/1 Characterization and Performance

- Gain Calibration of the single-mask GEM foils
  - Single-mask orientation A and double-mask have similar behavior
  - Single-mask orientation B shows higher effective gain at same HV point
  - ➢ Measurements indicate that having a larger hole diameter at the exit of the GEM holes increases the electron **extraction efficiency**



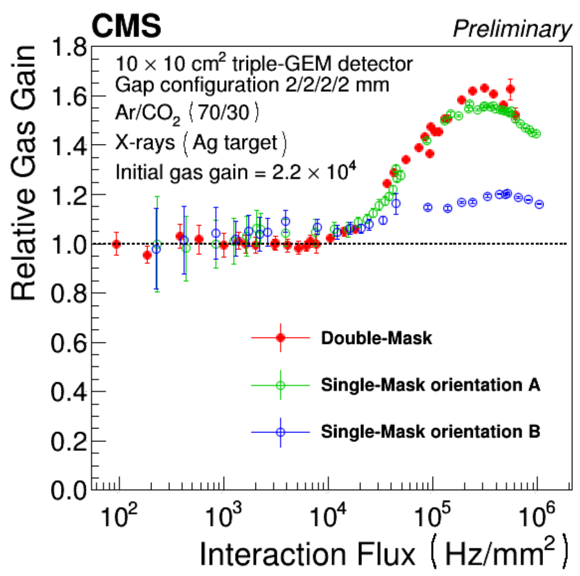


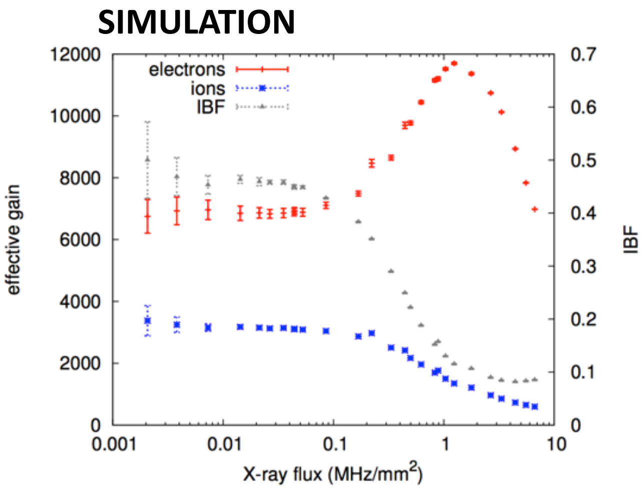
Similar behavior measured with large GE1/1 detectors:

- **GEM foils in generation IV detectors were mounted in the inversed orientation (design "feature")**
- **All chambers from this generation show lower effective gain than other generations at same HV set point (by a factor 3-4)**

GE1/1 Prototyping

- Flux capability of the GEM technology
  - GEM detector locally irradiated by an intense beam of X-rays
  - X-ray rate (interaction flux) is carefully monitored during the test
  - Single-mask orientation A and double-mask have similar behavior
  - Single-mask orientation B shows better stability at high fluxes
  - ➤ Similar behavior was reproduced by simulation in 2015 -> space charge effects
  - ➤ Confirmation that the single-mask orientation B has higher **electron transparency**

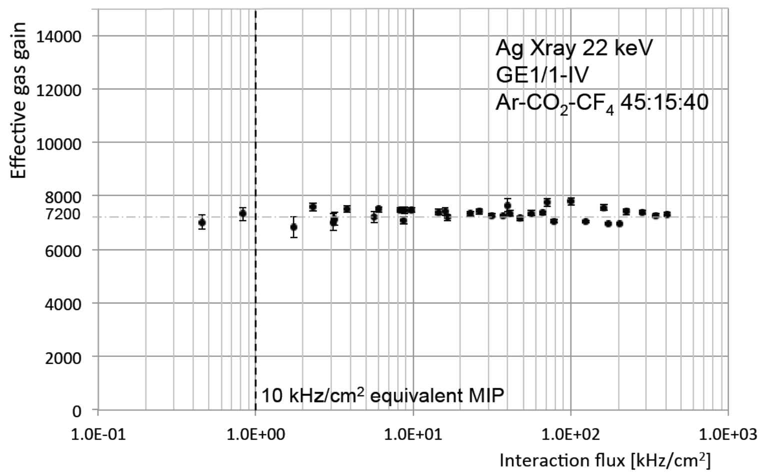


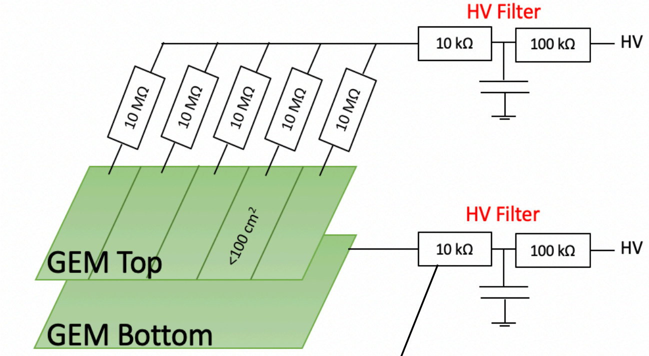


Effects of High Charge Densities in Multi-GEM detectors – P. Thuiner et al. – MPGD2015
https://agenda.infn.it/getFile.py/access?contribId=106&sessionId=2&resId=0&materialId=slides&confId=8839

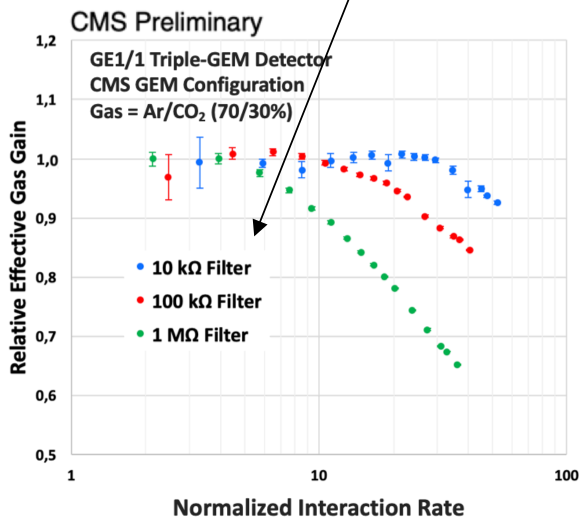
GE1/1 Performance

- Rate capability of GE1/1 chambers
  - Total rate capability of a complete detector (including HV filters) is different than the flux capability of the foils
  - Electrons/ions capture by the foils generate a current that flows out of the foils through the power supply lines
  - The rate capability is limited by the value of the resistances used in the powering system





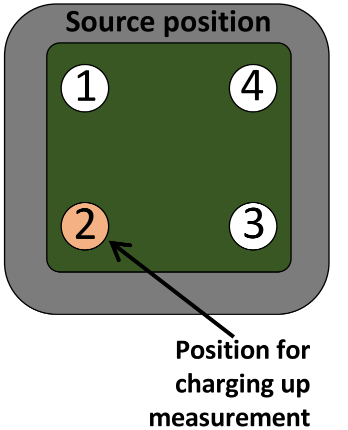
GEM foil powering scheme in GE1/1

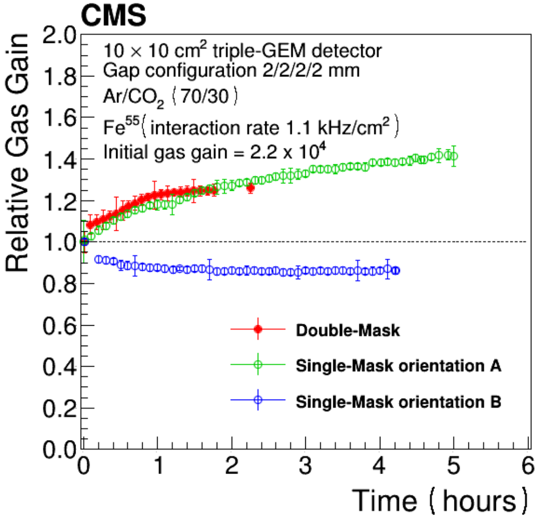


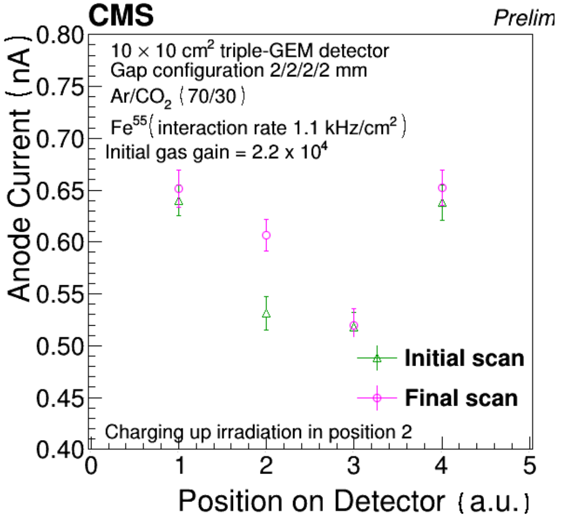
(normalized to the expected CMS total rate - simulation-)

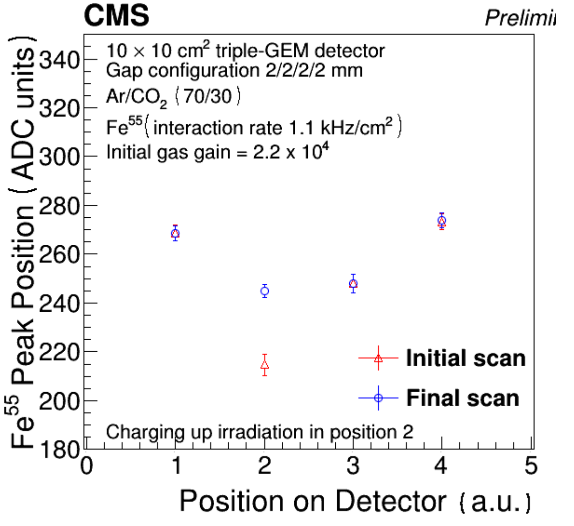
GE1/1 Prototyping

- Charging up effects
  - A fraction of the electrons and ions moving through the GEM holes can be attached to the polyimide walls and accumulate to form charged islands
  - Local distortion of the electric field causes short-term gain variations
  - Amplitude and timing of the charging up depends on the incoming article rate and energy
  - More stable behavior with single-mask orientation B





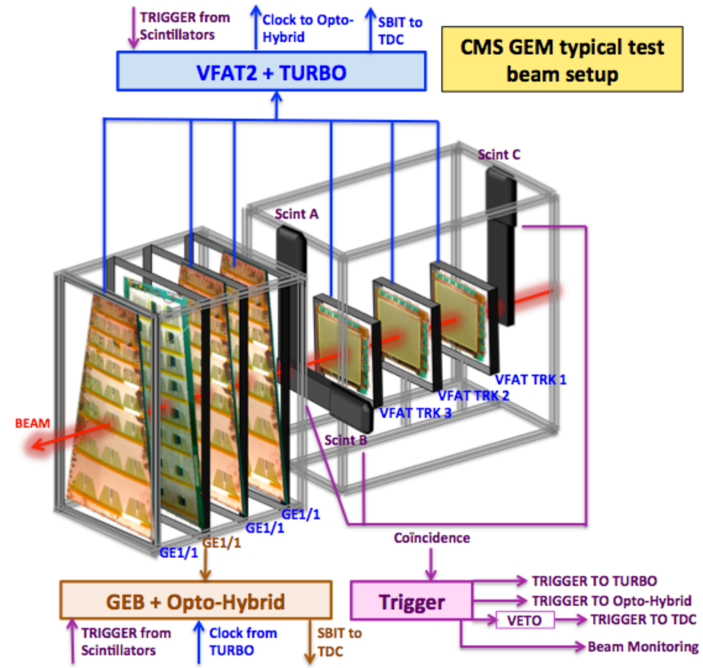


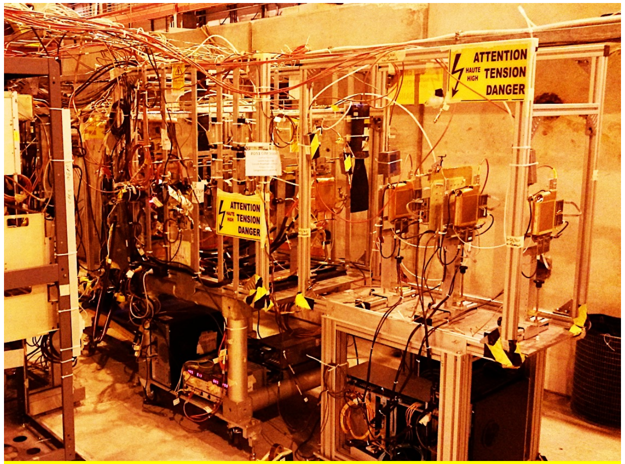


GE1/1 Performance

- Performance tests with muon beams
  - Charged particles that cross the GEM chambers can be "analyzed" by reference detectors to determine the detection performance of GE1/1
  - Trigger system made out of scintillator planes (>2) to identify the crossing of charged particles
  - Tracking chambers with good spatial resolution can reconstruct the muon trajectory and the expected hit position in the detector under test

➢ Gives the possibility to measure detection **efficiency**, **spatial resolution** and **time resolution**

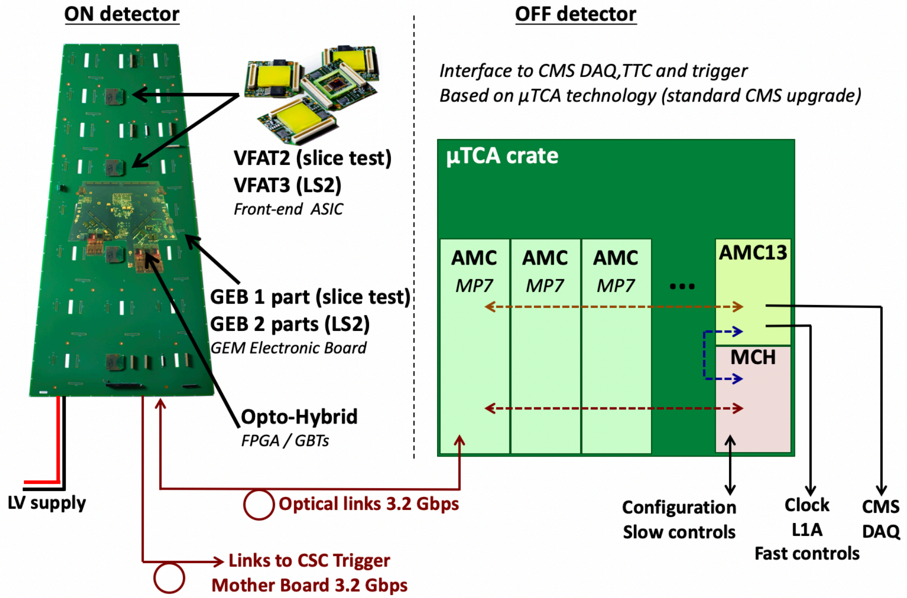




Test bean setup in H4 (CERN SPS 2014)

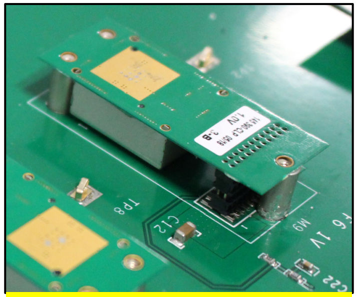
GE1/1 Prototyping

- GE1/1 electronics system
  - 3 main components: **VFAT**, GEM Electronics Board (**GEB**) and Opto-Hybrid (**OH**)
  - VFAT: front-end ASIC (digital) to provide fast trigger signals and register tracking information
  - GEB: multilayer PCB including power lines and communication channels (replacing space consuming cabling)
  - OH: on-detector FPGA responsible for fast data processing and communication with external systems



Schematic overview of the GE1/1 electronics system

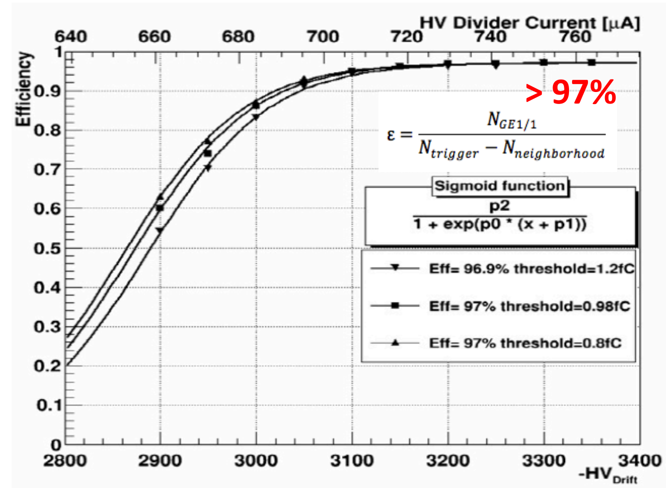
LV power is ensured thanks to FEASTs modules (on-detector DC-DC converters)



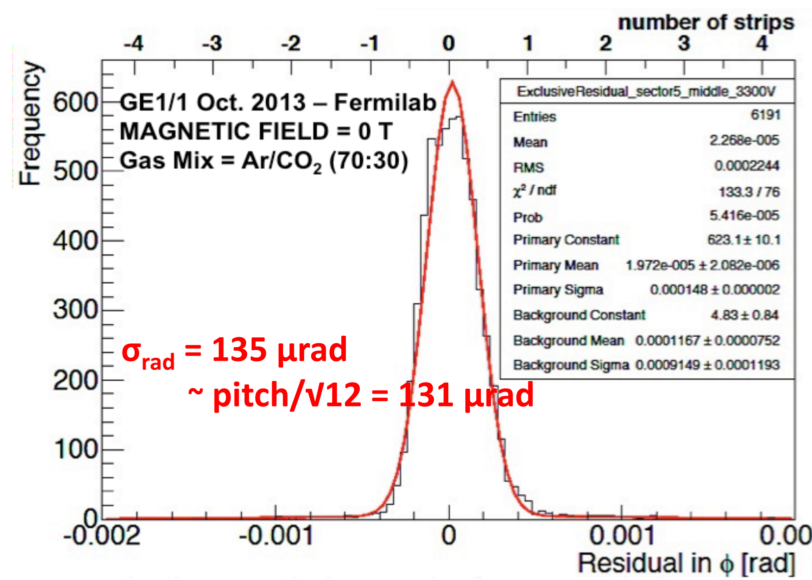
FEAST

GE1/1 Performance

- **Detection efficiency**
  - Comparing the extrapolated tracks with the detector hits
  - Defines the probability to detect a particle signal and process it with the electronics
  - Plateau above 97% reached above gains of 8000



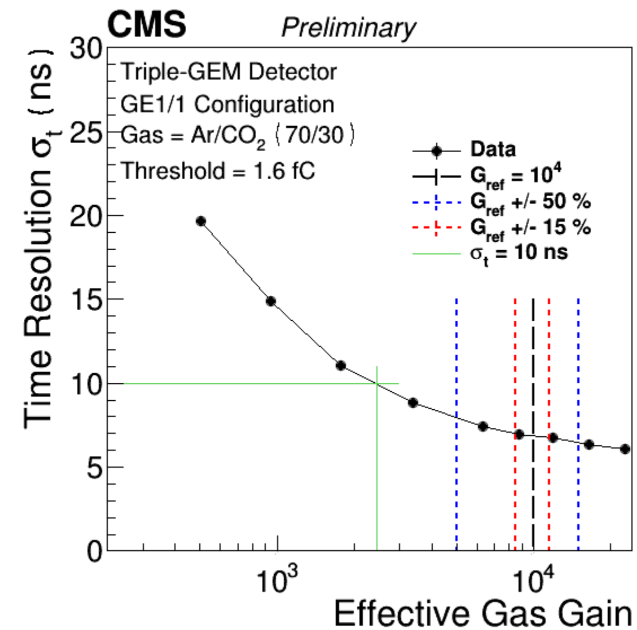
- **Spatial resolution**
  - Describes the accuracy of the hit reconstruction
  - Residual distribution built by comparing the expected hit position from the extrapolated tracks with the actual measurement
  - Spatial resolution = RMS of the residual distribution (combining exclusive and inclusive methods)
  - Measured resolution compatible with the strip pitch

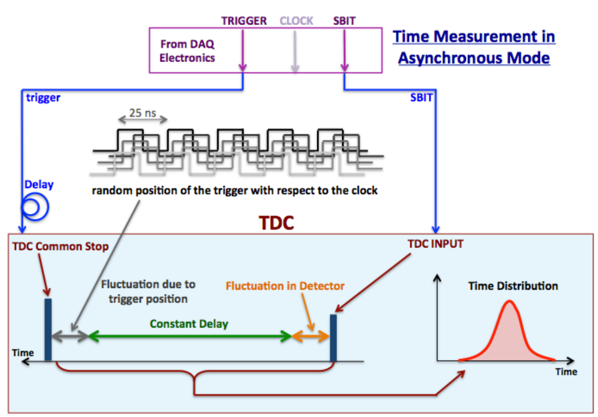


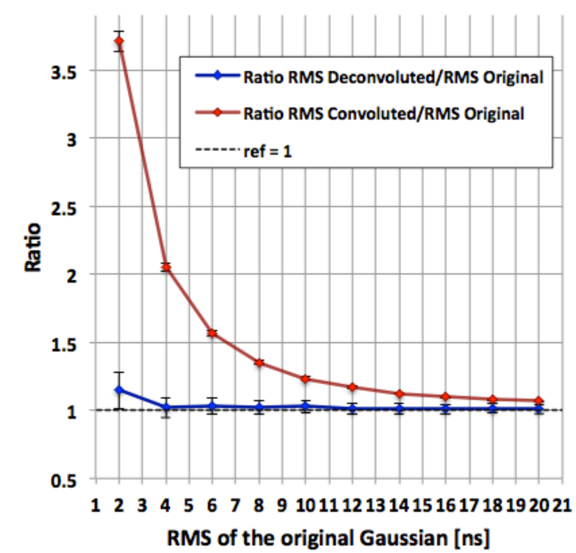
GE1/1 Performance

- Time resolution in Ar/CO_2
  - Describe the efficiency to assign the correct bunch crossing to a particle hit (trigger precision)
  - Measured by comparing the time between the scintillator trigger and the detector hit (time response distribution)
  - ➢ However, since the electronics only reacts on the rising edge of the clock, the measured time response distribution is in fact convoluted with a 25 ns square function

➢ Over-estimation of the time uncertainty



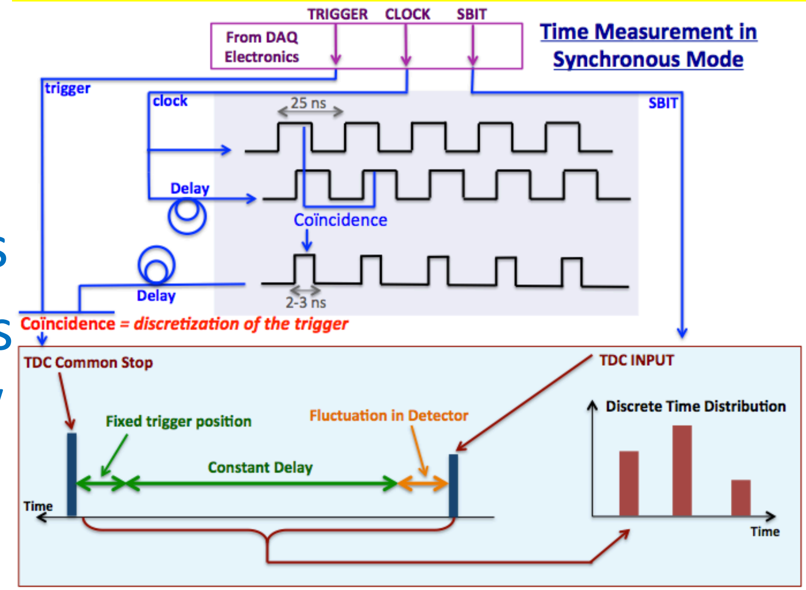


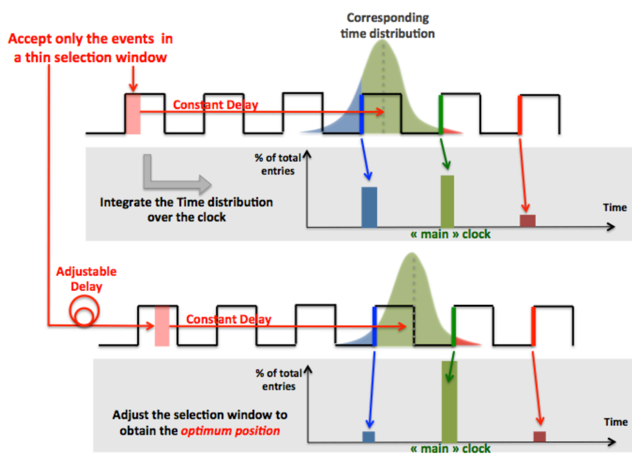


GE1/1 Performance

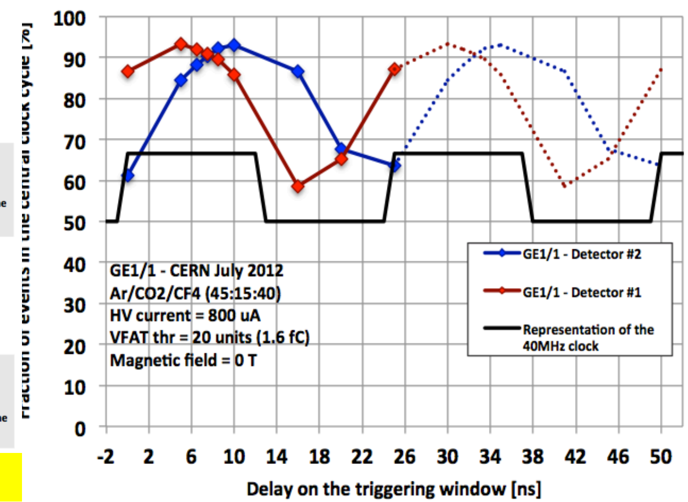
- Time resolution in Ar/CO_2
  - Proposed a new method to estimate the bunch crossing identification efficiency using synchronous triggers
  - Triggers coming from the scintillators are put in coincidence with a narrow time window made out of the clock
  - The delay of the DAQ system is then adjusted to match the mean of the time distribution with the center of two consecutive cock cycles

Schematic representation of the synchronous trigger method



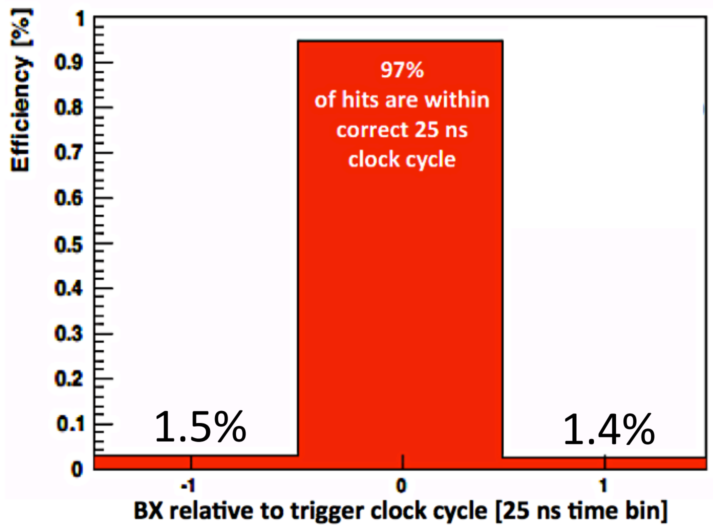


Schematic representation of the delay optimization

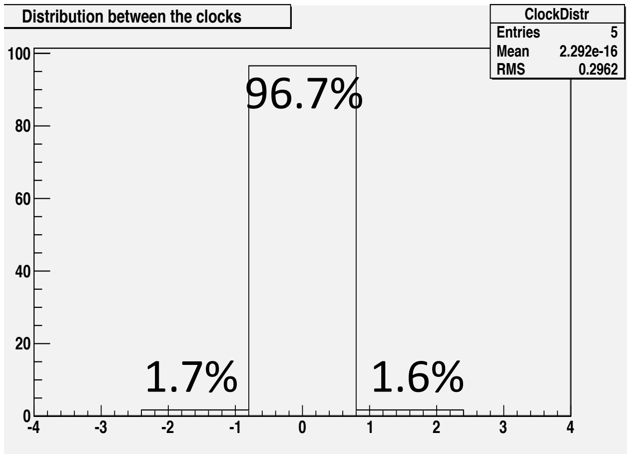


GE1/1 Performance

- Time resolution in Ar/CO_2
  - Synchronous method: 97% of proper bunch crossing identification at a gain of 10^4
  - The method was validated by comparing the measurements of the synchronous trigger with the de-convoluted version of the asynchronous data taken in the same conditions
  - ➢ DAQ design and procedure well understood for future timing studies



Result of a synchronous trigger run

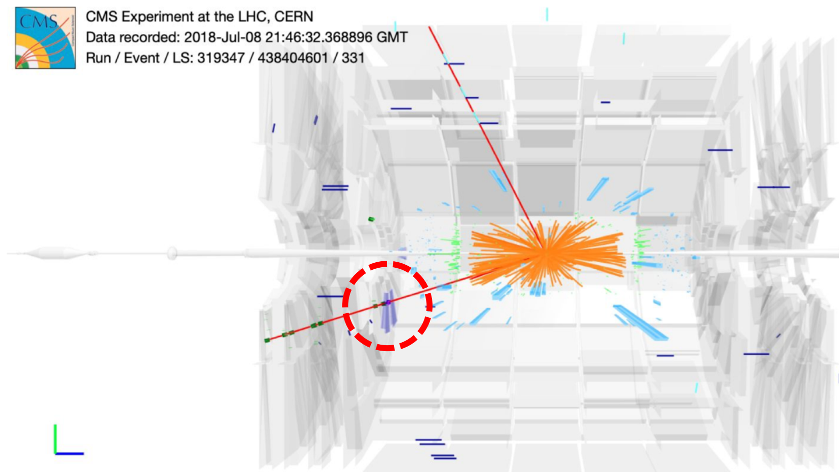


Result of a asynchronous trigger run deconvoluted with the clock and convoluted with the 2ns selection window

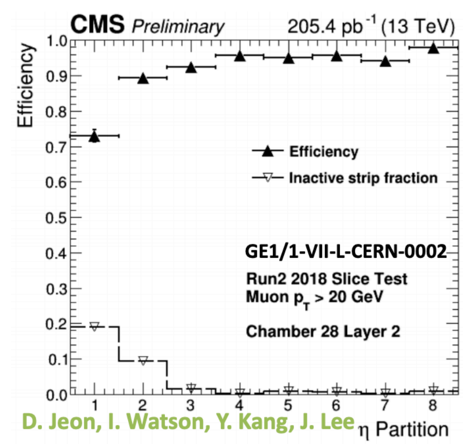
GE1/1 Performance

- Performance summary
  - All GE1/1 generations tested at beam facility at CERN and in USA
  - Use of different versions of electronics
    - APV25+SRS
    - VFAT2+TURBO
    - VFAT3+GEB+OH (CMS option)
  - Results fully compatible with the CMS requirements
  - ➢ Actual GE1/1 chambers installed for the slice test were also carefully analyzed after real operation in CMS

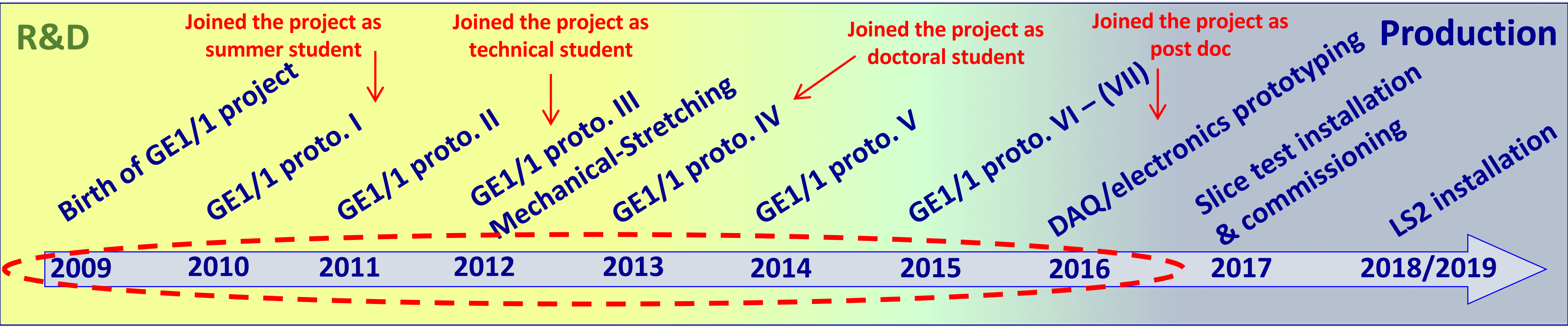
Properties	CMS requirements	GE1/1 performances
Rate capability	$> 10\ KHz/cm^2$	$100\ MHz/cm^2$
Single chamber efficiency (MIP)	$> 97\ \%$	$97-98\ \%$
Angular resolution	$< 300\ \mu rad$	$\sim 135\ \mu rad$
Single chamber time resolution	$< 10\ ns$	$4-5\ ns$ with $Ar/CO_2/CF_4$ $(45:15:40)$ $7-8\ ns$ with Ar/CO_2 $(70:30)$



Candidate Z→μμ event with muon hits recored in the slice test chambers



GE1/1 R&D PHASE
Longevity studies



GE1/1 Longevity

- Longevity studies : motivations
  - How to maintain the good performance over 10 years or more of continuous operation in a high rate environment ?
  - Detector lifetime can be represented by time but also the total accumulated charge : particle rate x ionization x gain x time x q_e
    - GE1/1: 6 mC/cm^2 → 18 mC/cm^2 including a safety factor x3
  - What can affect the long-term operation?
    - ~~Radiation damages (affect physical and chemical property of the materials)~~
    - ~~Mechanical deformation (foil stretching)~~
    - **Classical aging of gaseous detectors (polymerization)**

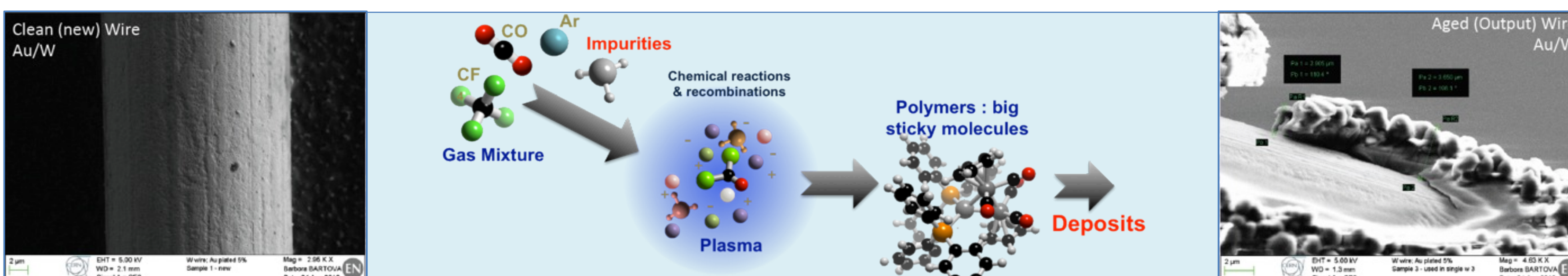
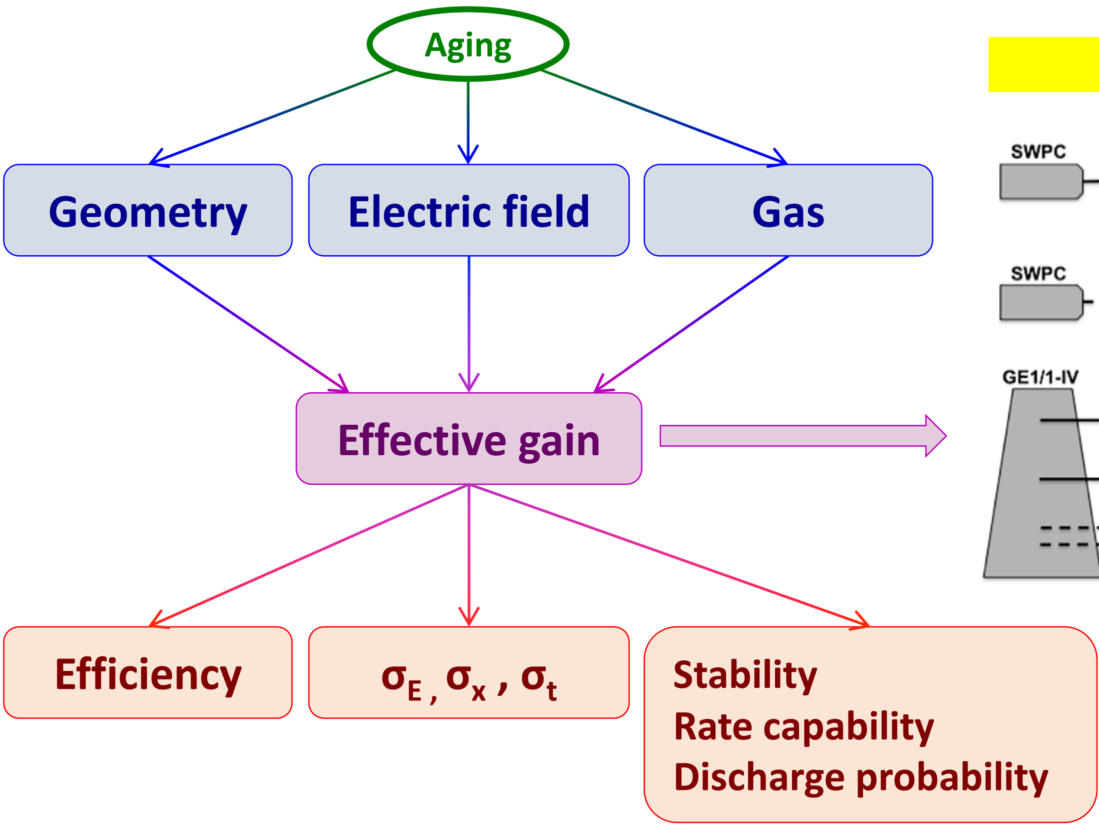


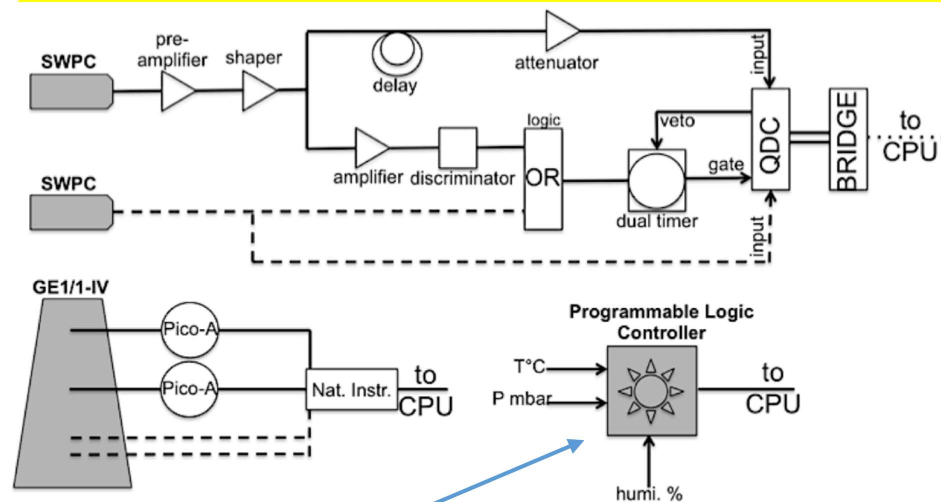
Illustration of the “classical aging” effect (gas polymerization) in a wire proportional chamber

GE1/1 Longevity

- Identification of the aging effects
  - Direct measurement of the detector performance vs. intense sustained irradiation → heavy setup and possibility to disturb the measurements
  - Monitor the effective gas gain vs. intense sustained irradiation



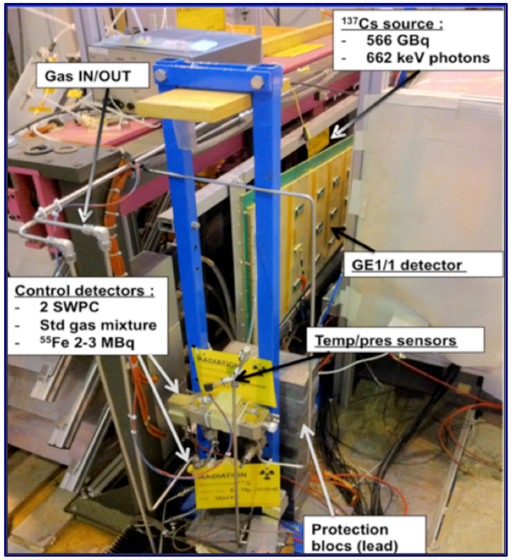
Overview of a typical aging test setup



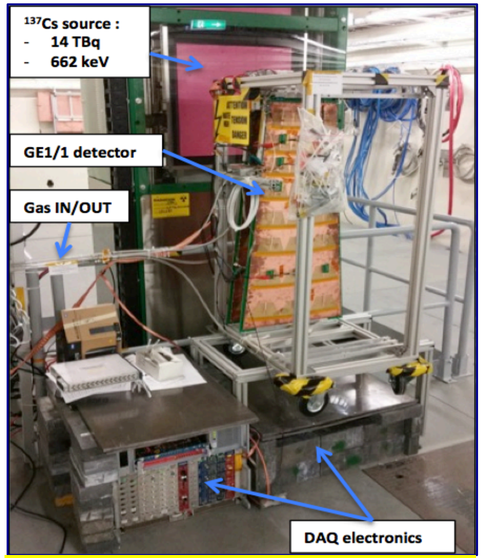
- However the effective gain can also fluctuate because of environmental variations → to be monitored continuously

GE1/1 Longevity

- Reproduce the aging in a controlled environment



Aging setup at the GIF facility



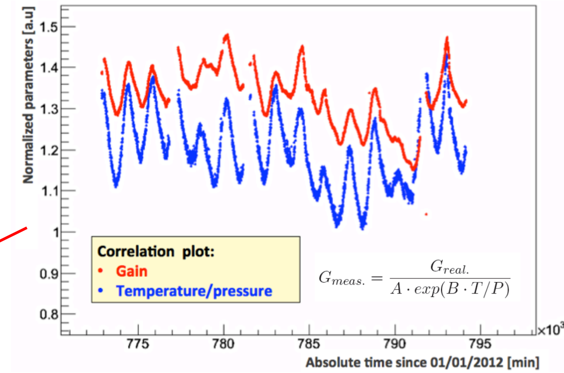
Aging setup at the GIF++ facility

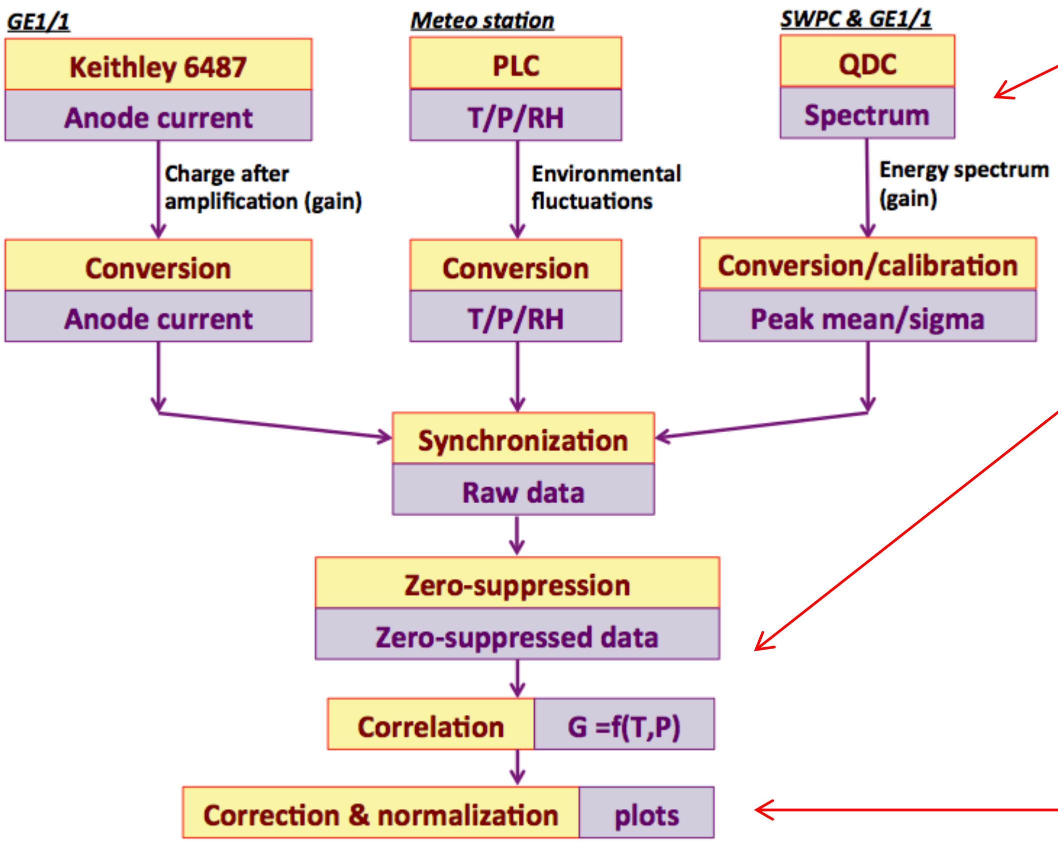
Aging setup in the GE1/1 production lab.

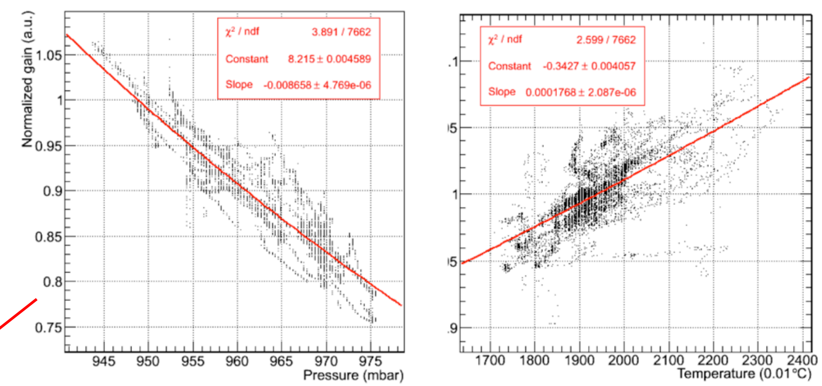
- GIF
  - ^{137}Cs @ 0.6 TBq
  - 662 keV photons
  - Aging rate about 10 times GE1/1 @ HL-LHC
- GIF ++
  - ^{137}Cs @ 14 TBq
  - 662 keV photons
  - Aging rate about 30 times GE1/1 @ HL-LHC
- GEM Production lab
  - ^{137}Cs @ 14 TBq
  - 662 keV photons
  - Aging rate about 400 times GE1/1 @ HL-LHC

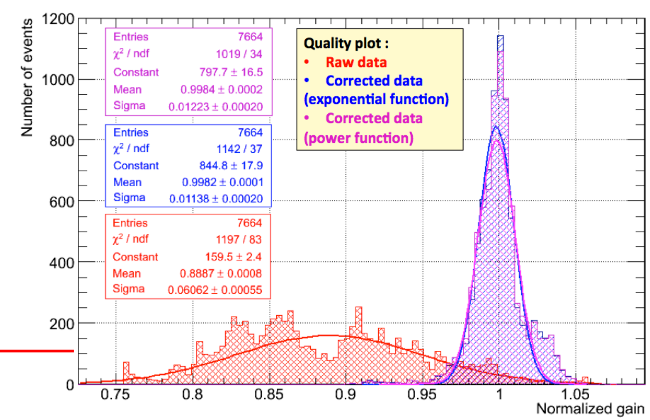
GE1/1 Longevity

- Data analysis and correlation with the environment
  - Measuring both anode current and energy spectra vs accumulated charge



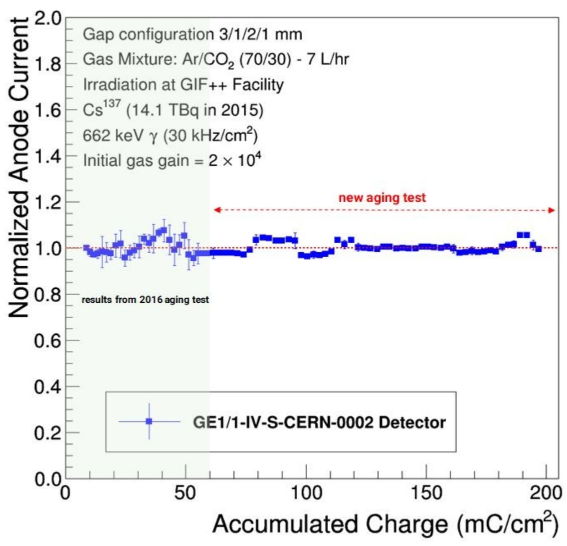


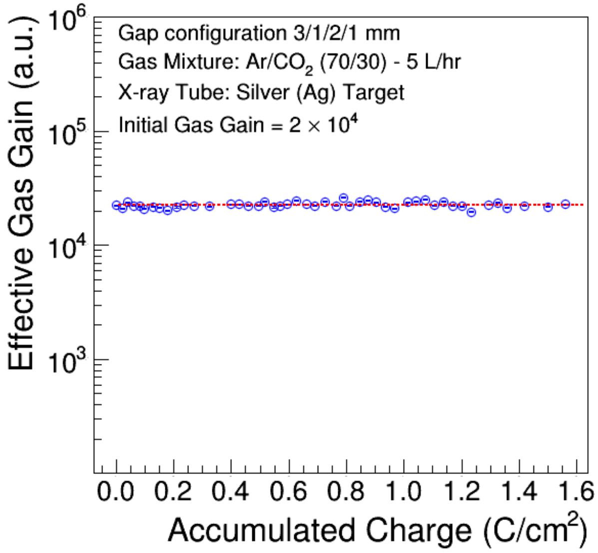


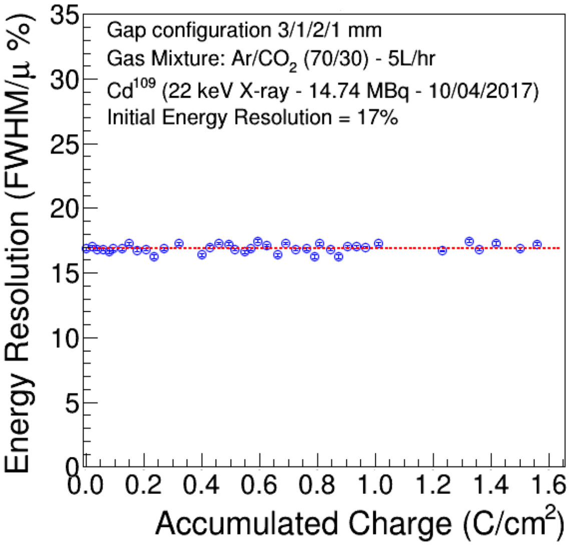


GE1/1 Longevity

- Classical aging tests
  - About 5 years of cumulative tests in GIF, GIF++ and production lab
  - Accumulated a charge up to 1.6 C/cm^2 in Ar/CO_2
  - No aging effect observed (gain loss, energy resolution degradation)
  - Confirmation of the resistance of the GEM technology to aging
  - ➢ Two main advantages: clear separation between amplification and readout ; sharing of the amplification among foils and holes

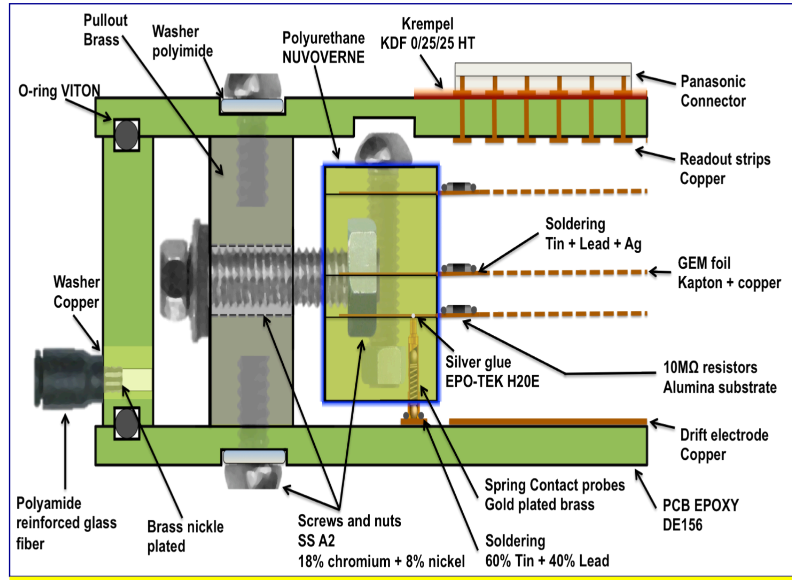




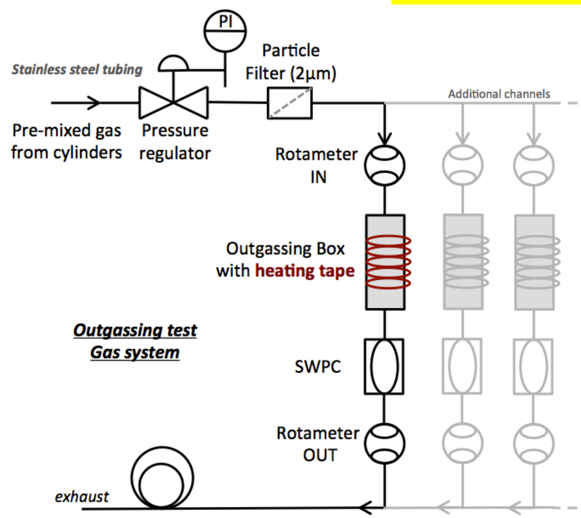


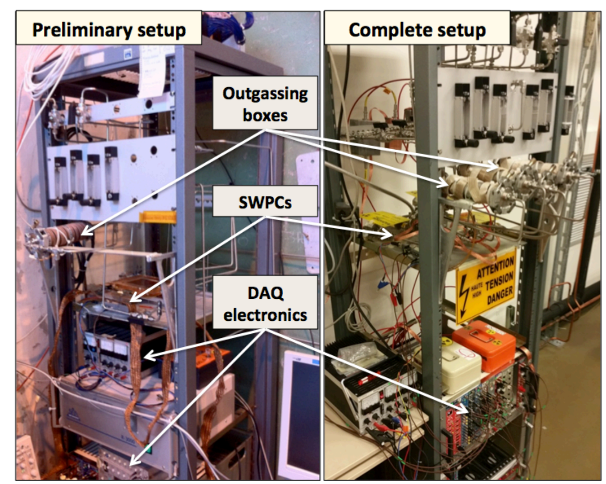
GE1/1 Longevity

- Material validation
  - Identification of possible sources of pollutants that could trigger polymerization after long-term exposure
  - Use of single wire proportional counters to detect small quantity of outgassed molecules
  - Perform systematic study for all new components or materials with new composition



Overview of the GE1/1 materials

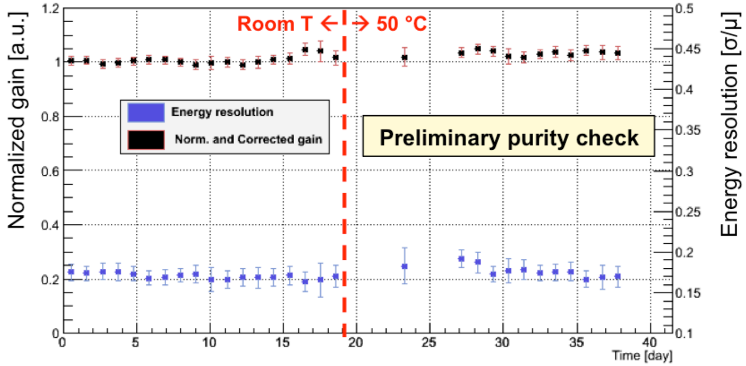


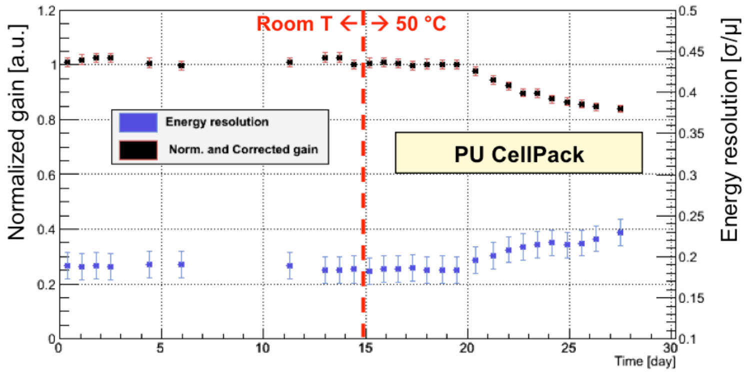


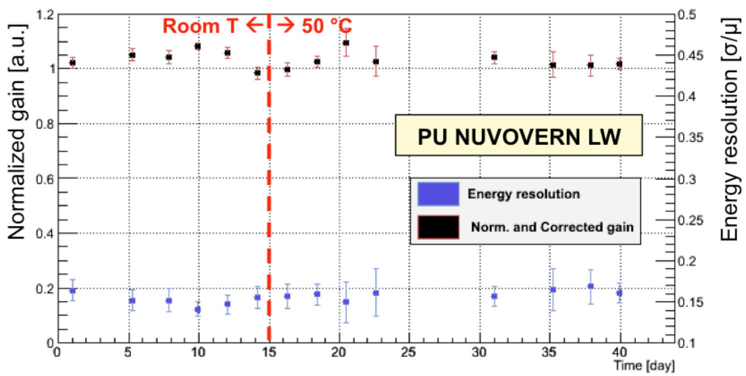
Outgassing test setup

GE1/1 Longevity

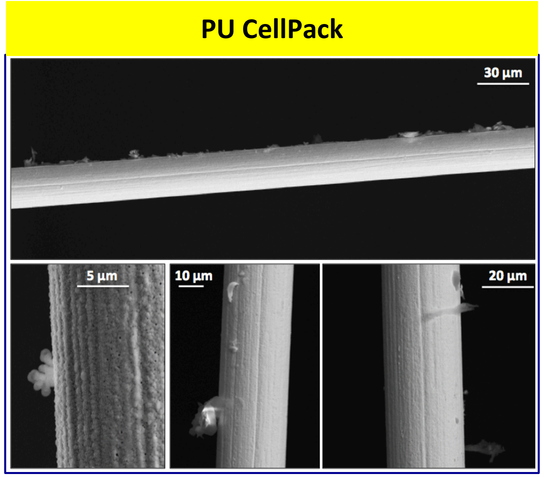
- Outgassing test results
  - All gas lines systematically verified with a purity check measurement (1 month)
  - All materials tested at room temperature (2 weeks) and at 50°C (2 weeks)
  - Systematic SEM analysis of the SWPC





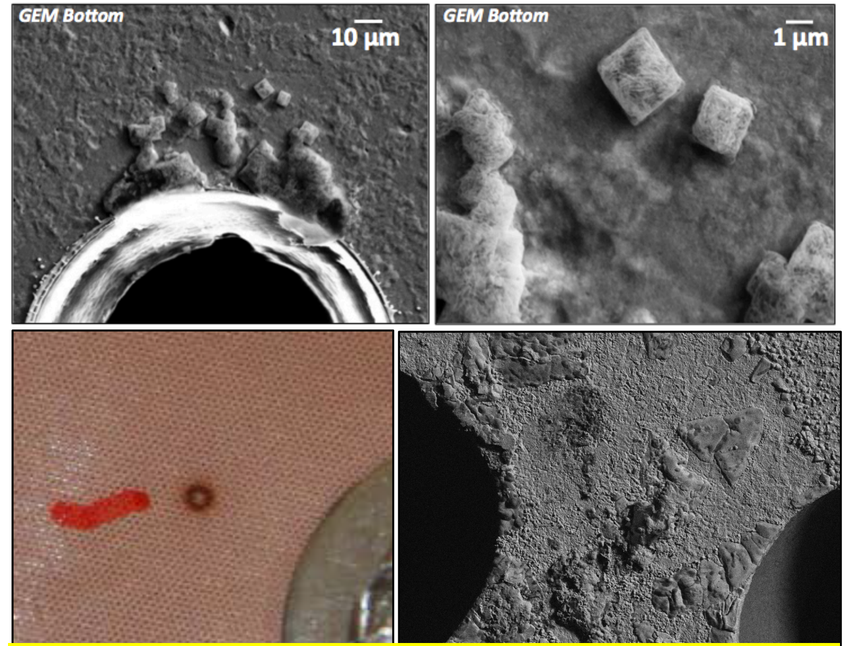


➢ The polyurethane CellPack was found to be outgassing silicon compounds that affected the wire chamber operation. It was therefore replace by the NUVOVERN, which has no effect on the detectors



GE1/1 Longevity

- Additional observations
  - While no aging effects were observed in GE1/1 chambers, local "light" polymer deposits can be found near discharge points when operating the chambers in dirty gas environments
  - Only few observations (rare events)



Example of polymer deposits after a discharge

Hypothesis → **Implications** → ***Applications***

Hypothesis
- **Polymerization rate depends on the energy transferred through the holes**

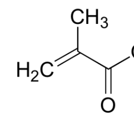
Implications
- **Primary charge plays an important role in the aging process**
- **Higher primary charge means higher aging rate ?**

Applications
- **Accelerated aging tests in laboratory should consider the whole particle spectrum encountered in the experiments (especially HIP)**

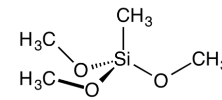
HIP can trigger aging that can't be visible with usual photon irradiation (?)

GE1/1 Longevity

- Special aging test setup
  - Operate a GEM chamber is a very contaminated gas to “force” polymerization and aging effects
  - Irradiate the same chamber with low energy X-rays and Alphas particles

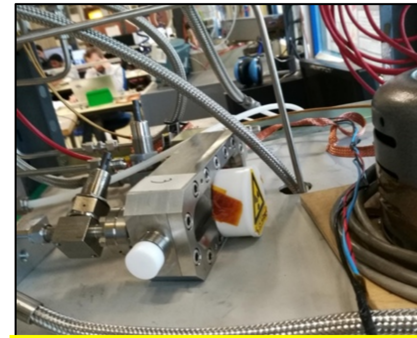


Methyl Methacrylate

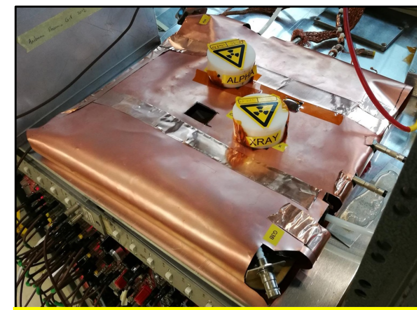


Methyltrimethoxysilane

Polluting sample



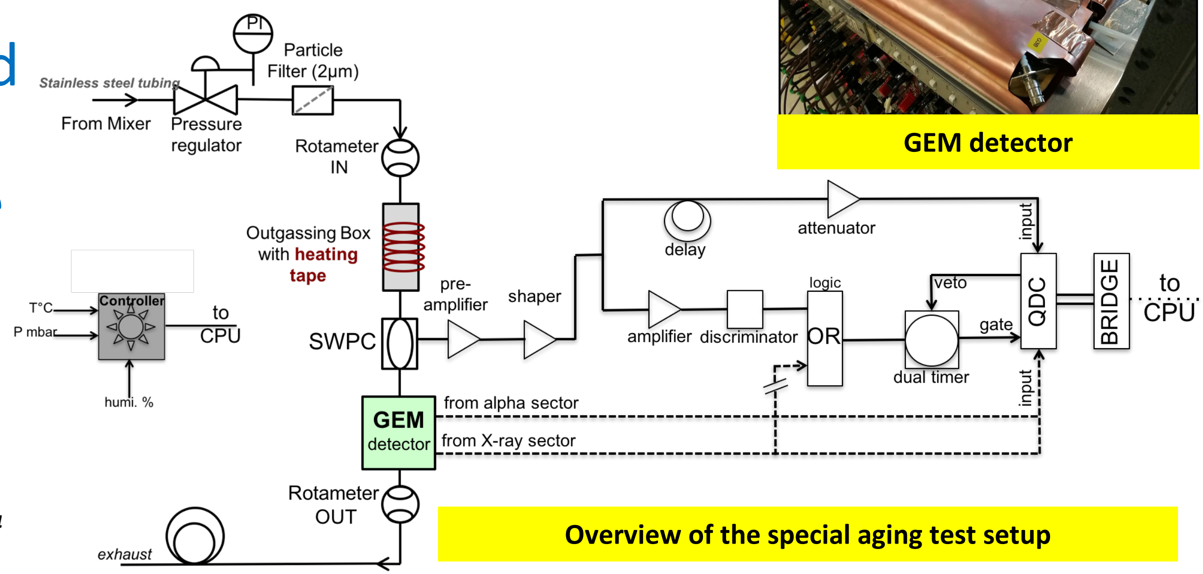
Wire chamber



GEM detector

  - An additional wire chamber was inserted in the gas line to indicate the presence of pollutants

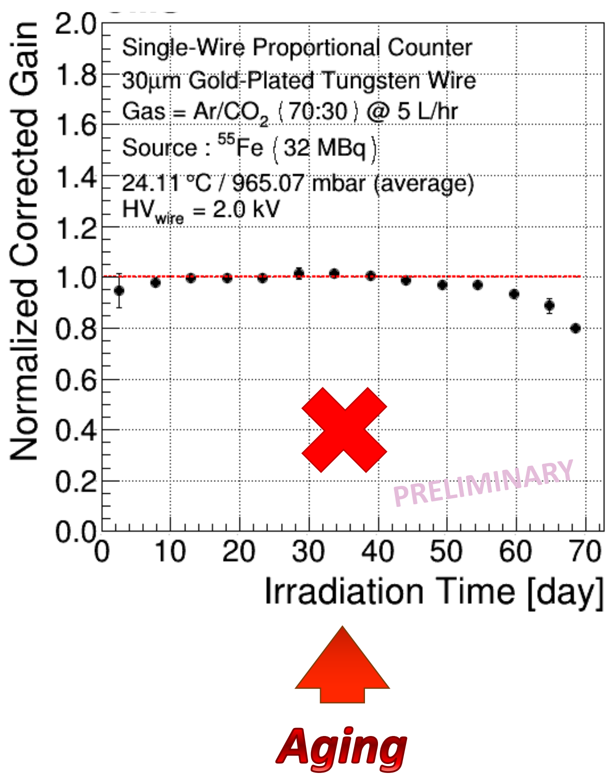
- Low energy X-rays (5.9 keV) $N_{primaries}$~2x10^2
- Alpha source (5.5 MeV) $N_{primaries}$~2x10^4

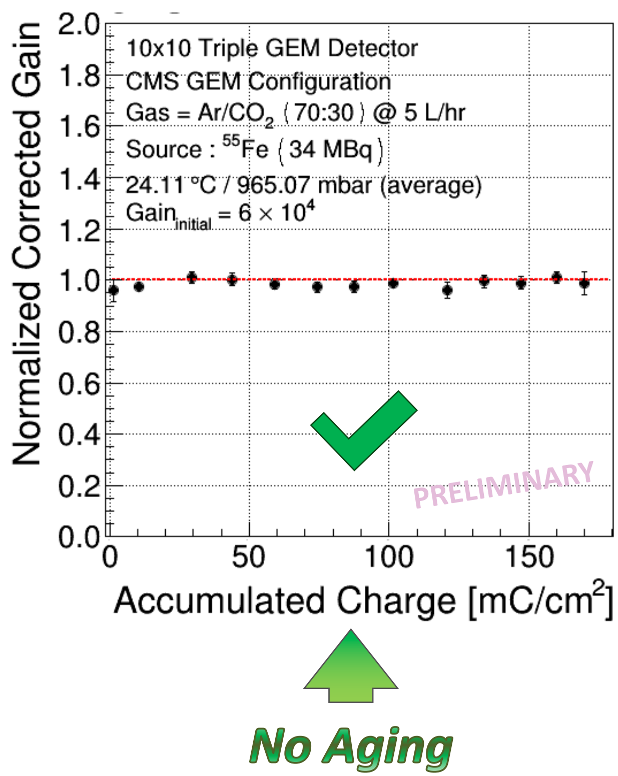


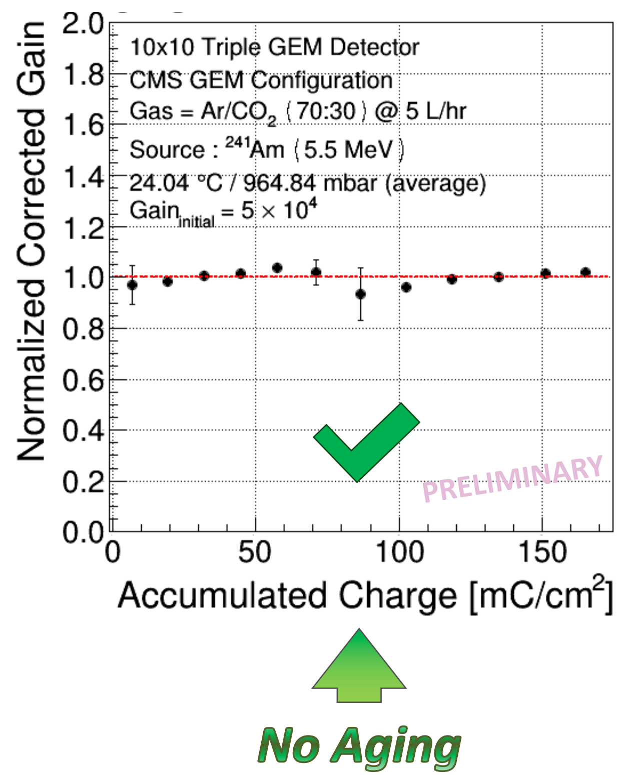
Overview of the special aging test setup

GE1/1 Longevity

- Special aging test results
  - All positions were irradiated for several months up to an accumulated charge of 170 mC/cm^2
  - Clear evidence of polymerization in the wire chamber
  - No effects in the GEM detectors

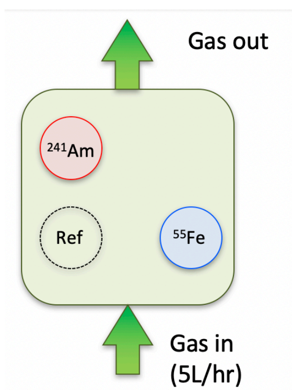


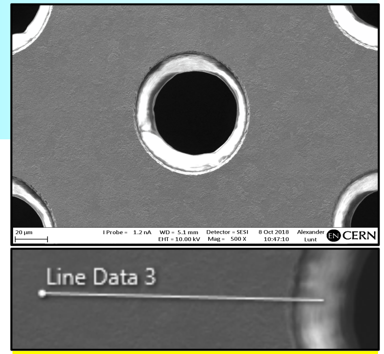




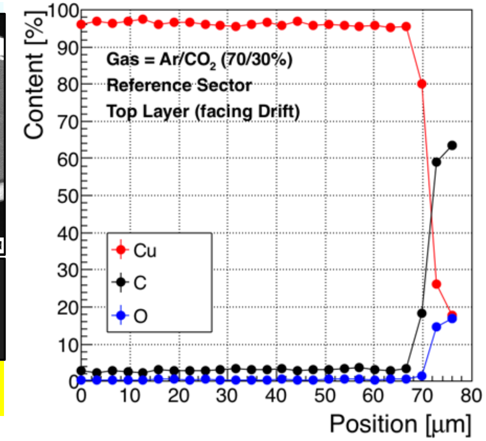
GE1/1 Longevity

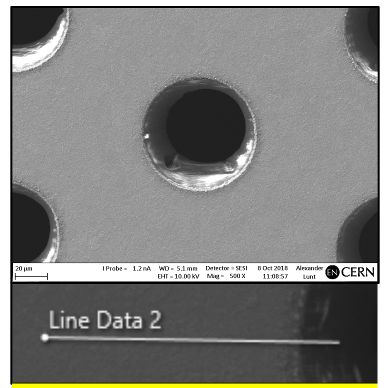
- EDS/SEM analysis
  - Reference sector (not irradiated) shows clean surfaces with no traces of pollutants nor polymer deposits
  - Light polymer deposition on the the X-ray sectors, mostly on the top electrode
  - Large presence of polymers on the Alpha sector



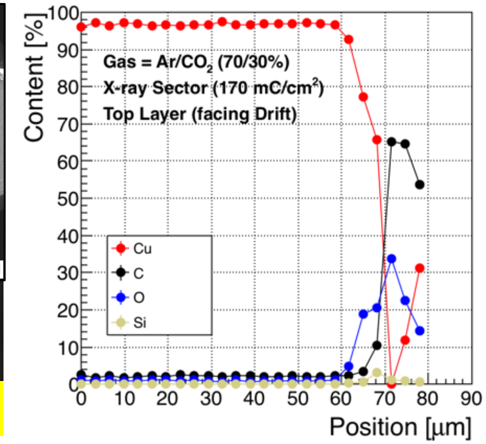


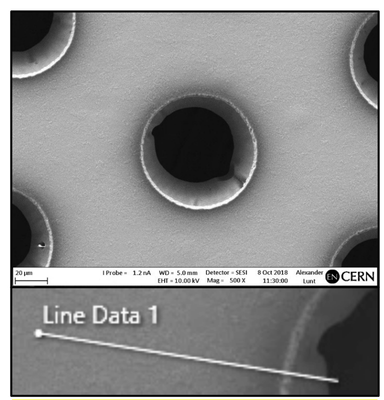
Reference sector



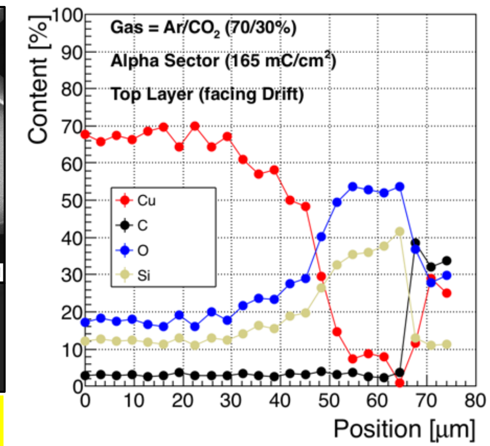


X-ray sector



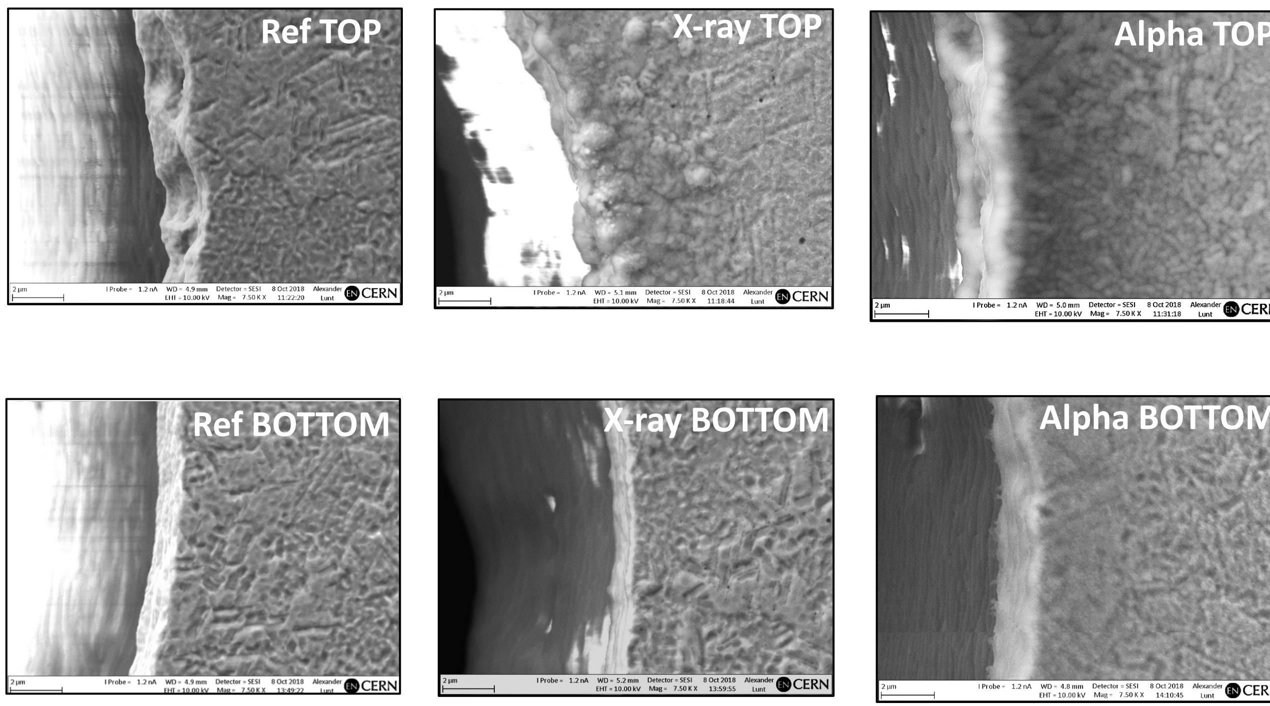


Alpha sector

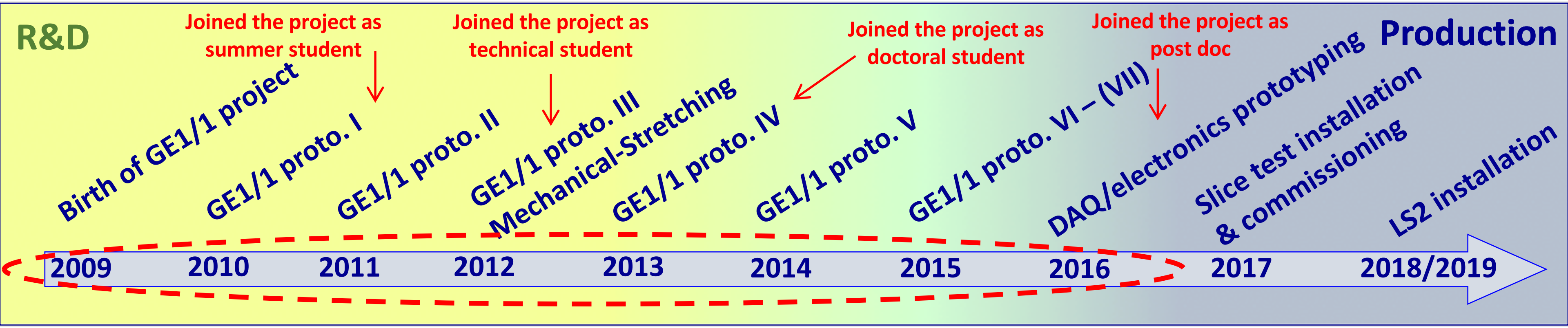


GE1/1 Longevity

- EDS/SEM analysis
  - Confirmation of the dependency between primary ionization power and polymerization rate
  - ➢ Further studies are on-going to better quantify this dependency
  - ➢ Need for improvement of aging test procedures for future high rate applications
  - Interesting note: despite of the polymer deposits, there was no visible degradation of the GEM operation (gain and energy resolution

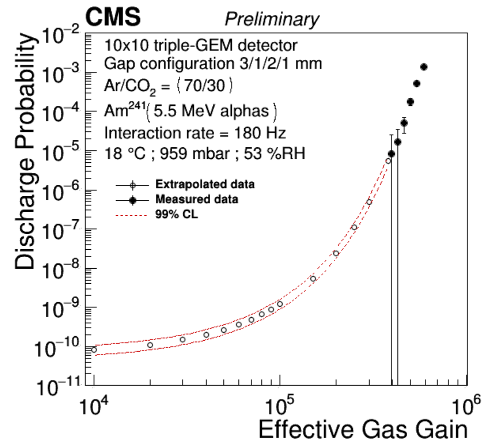


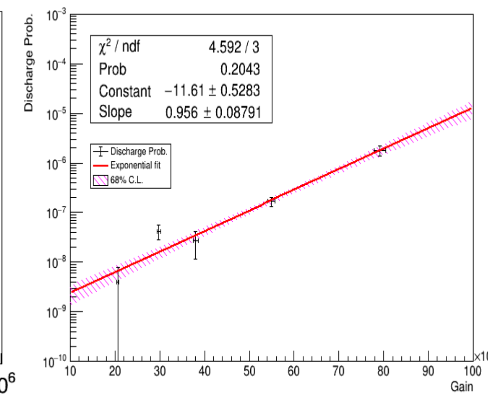
GE1/1 R&D PHASE
Discharge studies



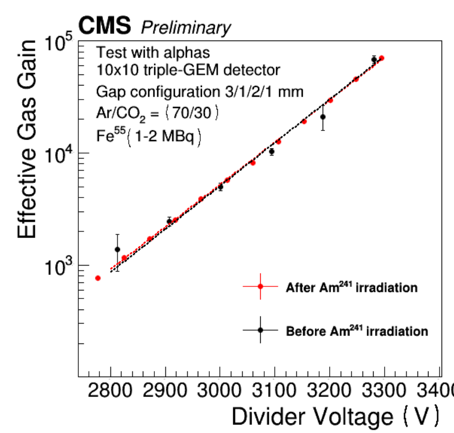
GE1/1 Discharges

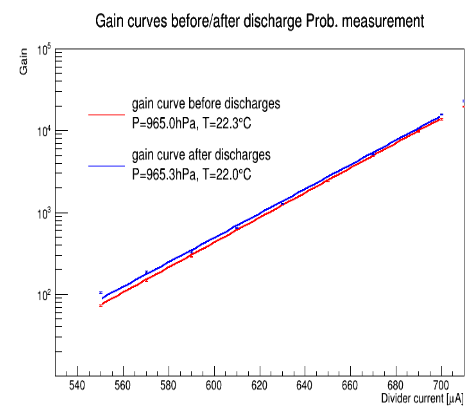
- **Measuring the discharge probability:**
  - Tests in laboratory (alpha particles) with both small and large detectors
  - Tests in neutron facilities with CMS-like particle background
- **Test results:**
  - Determined lower and upper limits for discharge probability
  - Estimate total number of discharges 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





I. Yoon, LHC KCMS Workshop, 09/01/2019

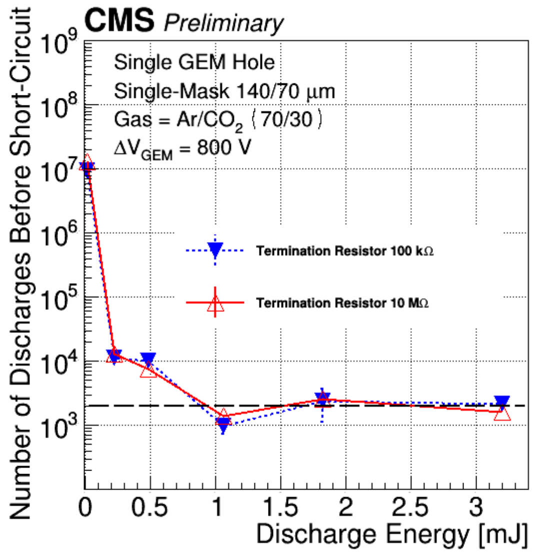


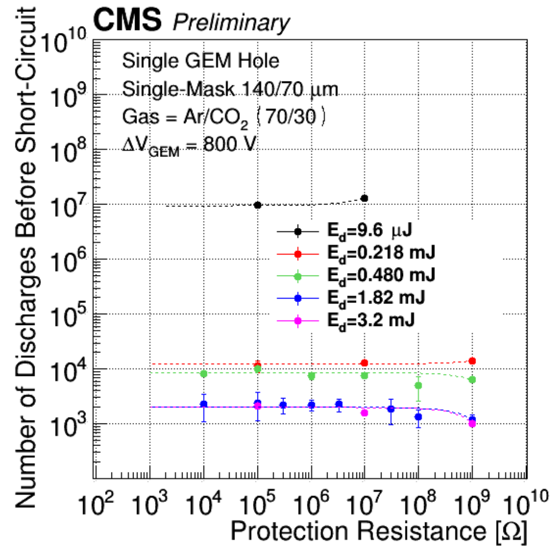


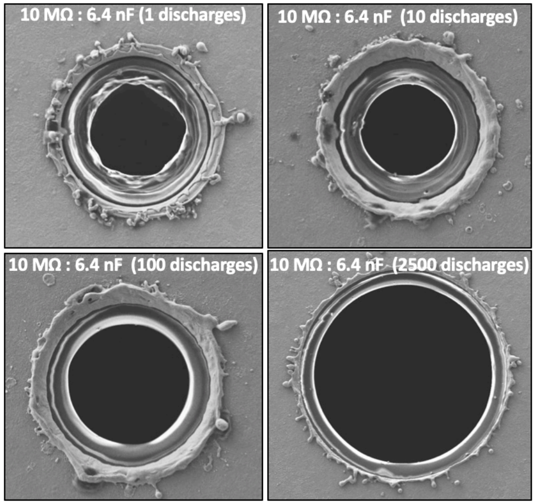
I. Yoon, LHC KCMS Workshop, 09/01/2019

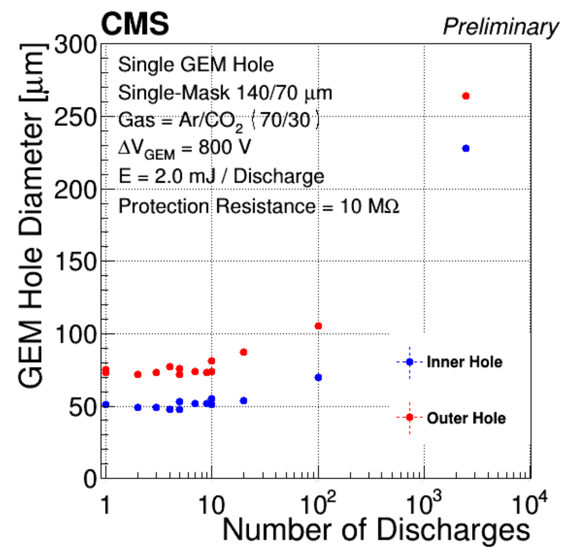
GE1/1 Discharges

- **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

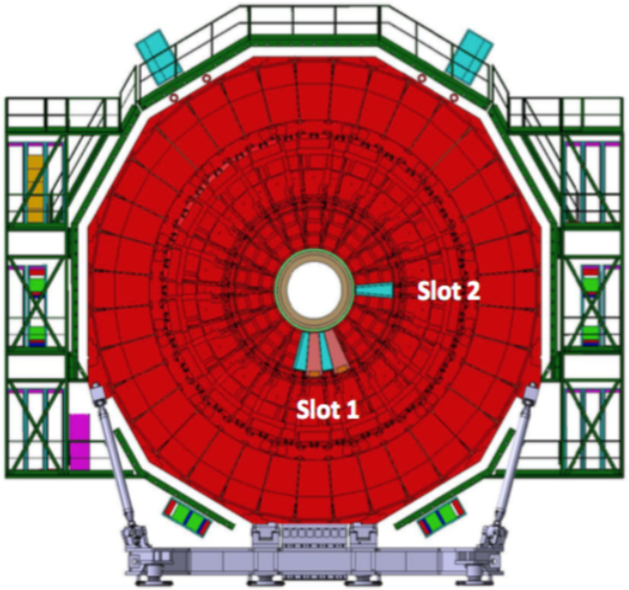


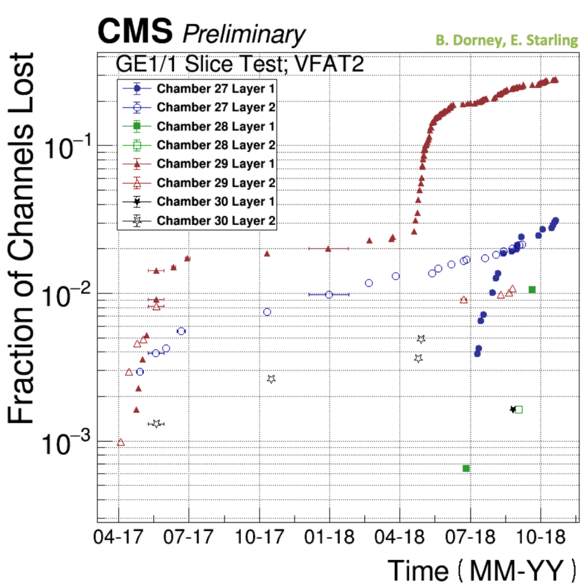






GE1/1 Discharges



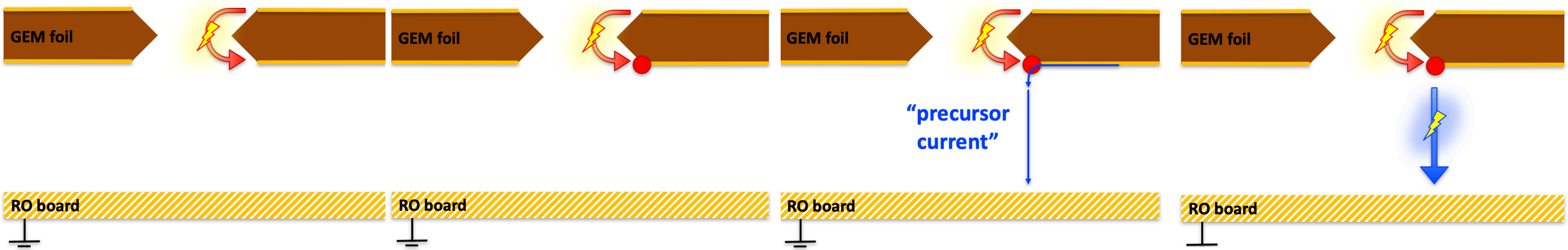


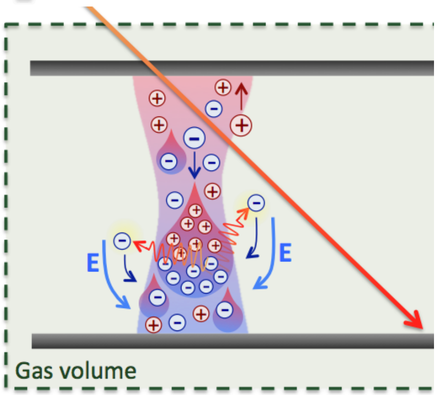
- **GE1/1 Slice Test:**
  - First opportunity to observe real-life discharges with the entire system (detector+HV+electronics+BKG particles)
  - Observation of gradual channel loss caused by a specific type of discharges propagating to the RO board

Note: in the same period, new tools and techniques recently developed to identify discharges (initiated by RD51 community, ALICE GEM and CMS GEM groups)

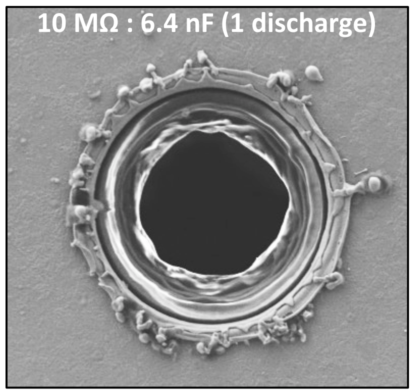
- Triggered a new R&D campaign to understand the discharge propagation process and determine mitigation techniques

GE1/1 Discharges



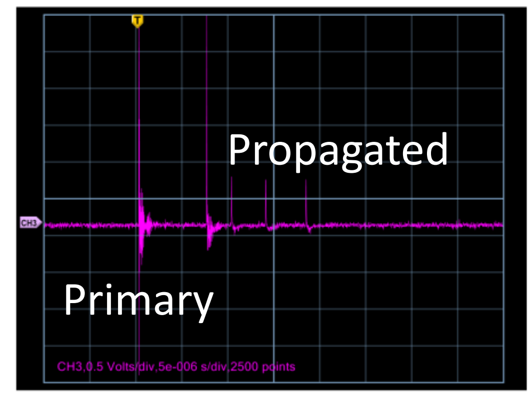


Typical development of avalanche into a streamer



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

Extensive study initiated by Alice and RD51 communities (Technical University of Munich, University of Zagreb et al.)

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GE1/1 Discharges

CMS

Channel loss rate = BKG rate * discharge prob. * propagation prob. * damage prob.

Discharge Probability → **Propagation Probability** → **Damage Probability**

Intrinsic to all gaseous technologies
Low probability with triple-GEM (~10^{-9}-10^{-10})

It is a "no pain no gain" parameter

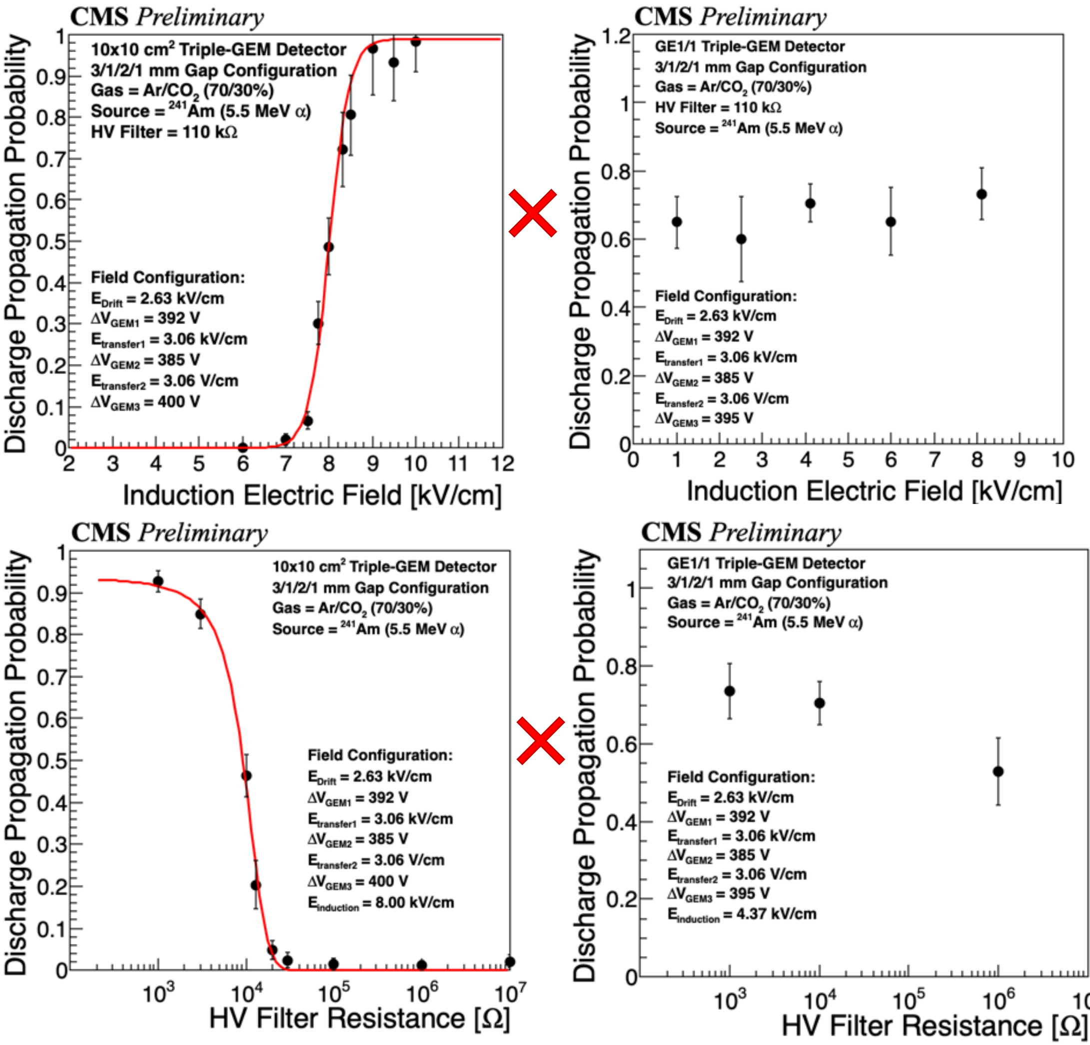
Complex process depending on:

- **Gap thickness**
- **Gap Capacitance**
- **Electrics Fields**

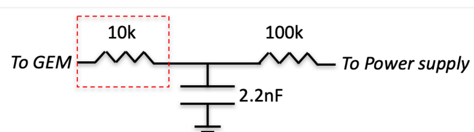
Theoretical Approach → Small Detector setup in CMS configuration → Long GE1/1 setup in CMS configuration

Base on past experience and recent studies from MPGD community

GE1/1 Discharges



HV Filter



Tests with small 10x10 detectors:

- Influence of the induction field and filter resistor

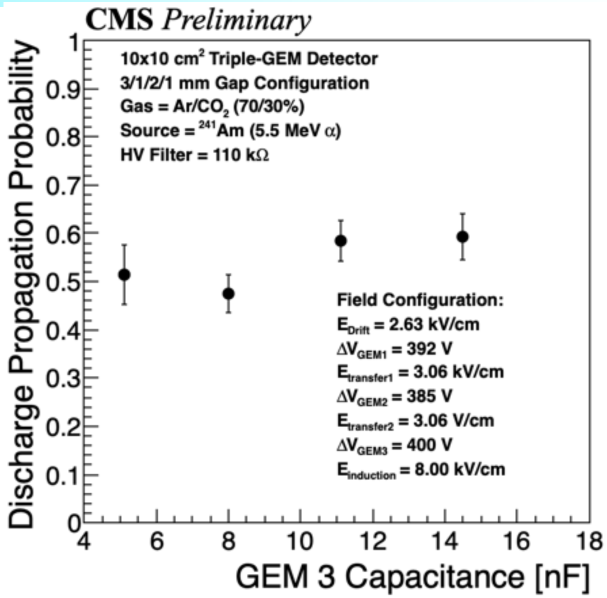
Tests with large detectors:

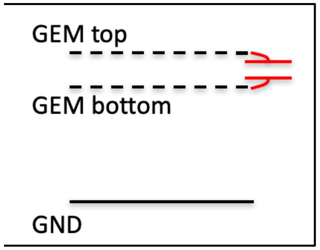
- No dependency on the induction field
- No effect from the filter resistor
- Clear inconsistency between small and large chambers
- Clear increase of the propagation probability with the induction capacitance → i.e. sufficient amount of energy on the foil to feed the precursor current and trigger discharge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

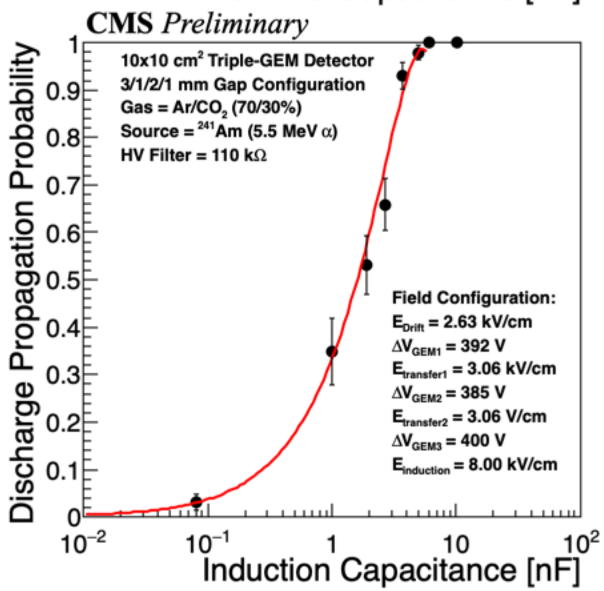
GE1/1 Discharges

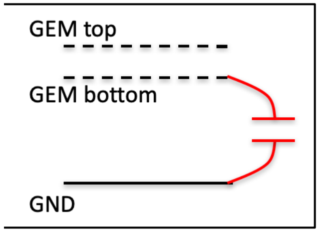
- **Further studies to understand the differences between small and large chambers:**
  - No dependency with the GEM foil capacitance → no influence of the primary discharge energy
  - Clear increase of the propagation probability with the induction capacitance → i.e. sufficient amount of energy on the 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



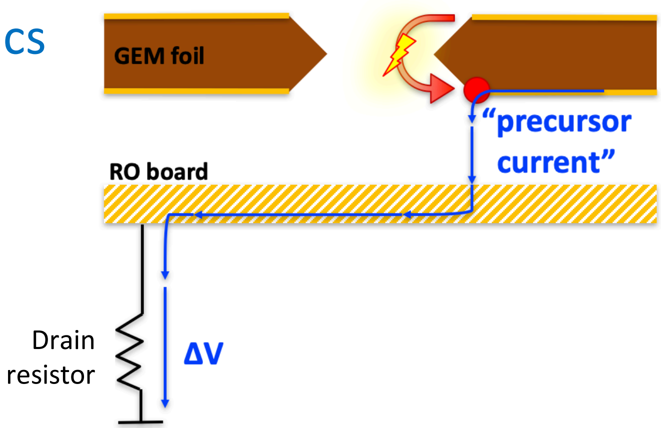


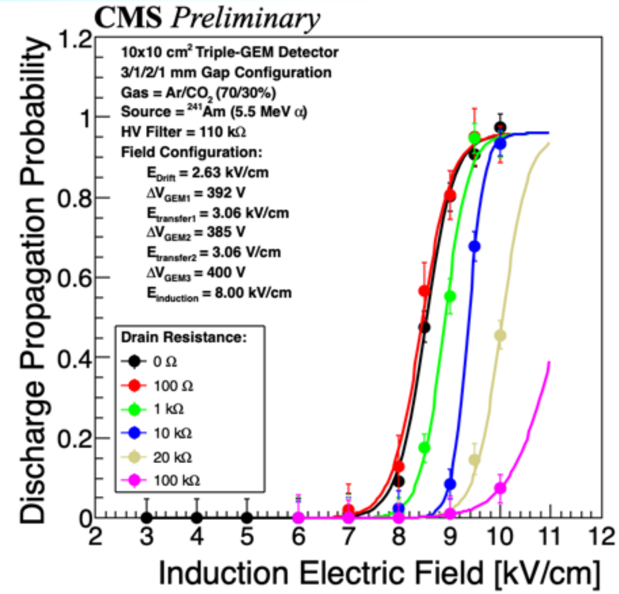


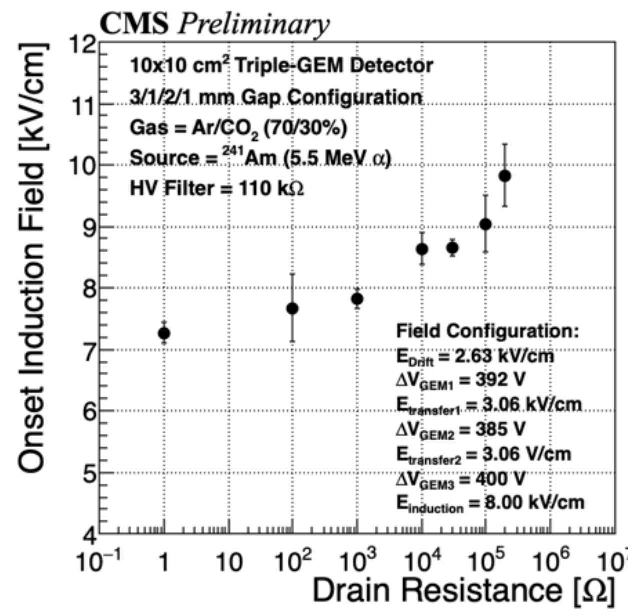


GE1/1 Discharges

- **Self-quenching of the precursor current:**
  - Drain resistor between readout strips and ground causes temporary reduction of the induction field after the primary discharge
  - The precursor current cannot grow and develop into a streamer regardless the energy available on the GEM foil
  - Efficient way to stop propagation before it even happens
  - Specific de-coupling circuit can be implemented between readout board and electronics







GE1/1 Discharges

Channel loss rate = BKG rate * discharge prob. * propagation prob. * damage prob.

Discharge Probability → **Propagation Probability** → **Damage Probability**

Discharge Probability

Intrinsic to all gaseous technologies
Low probability with triple-GEM (~10^{-9}-10^{-10})

It is a "no pain no gain" parameter

Propagation Probability

Understood the process od propagation in large detectors
→ Mainly driven by the large induction capacitance

<u>Found 3 ways to mitigate discharge propagation:</u>
→ Reduce foil capacitance
→ Increase filter resistance
→ Use drain resistors

Damage Probability

Depends mainly on:
- Energy of the propagating discharges
- Electronics input protection

Theoretical Approach → Small Detector setup in CMS configuration → Long GE1/1 setup in CMS configuration

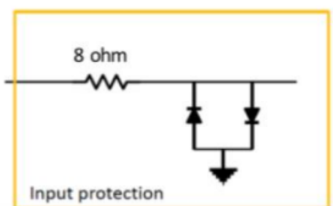
Base on past experience and recent studies from MPGD community

GE1/1 Discharges

HV3b_V2

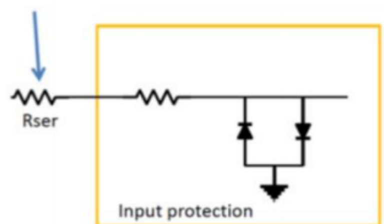
Initial baseline

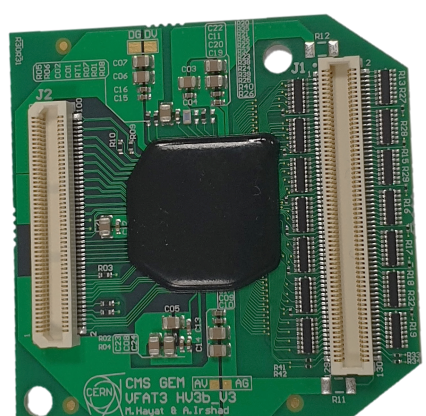
Internal input protection only (diode)



HV3b_V3

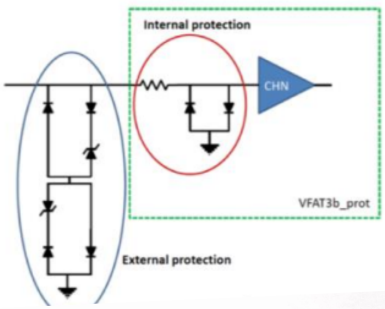
Ext. input protection (R=330 Ω)

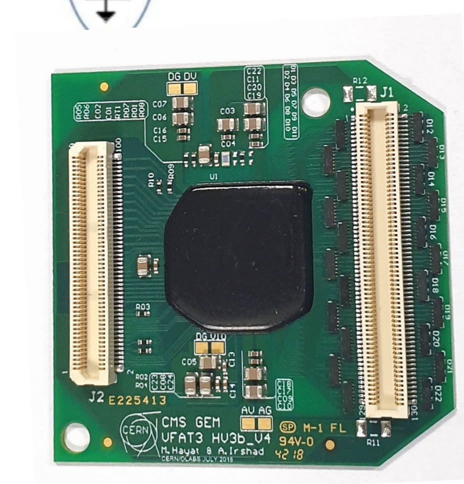




HV3b_V4

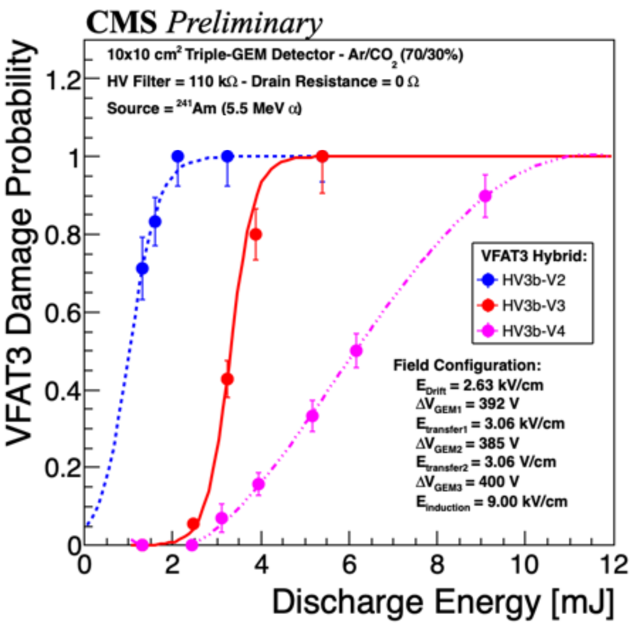
Ext. input protection (diodes)



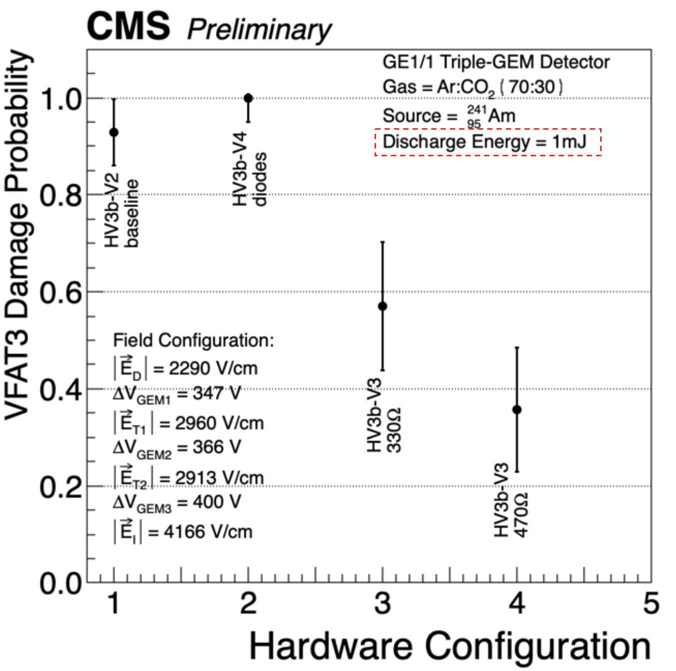


GE1/1 Discharges

Small Detector

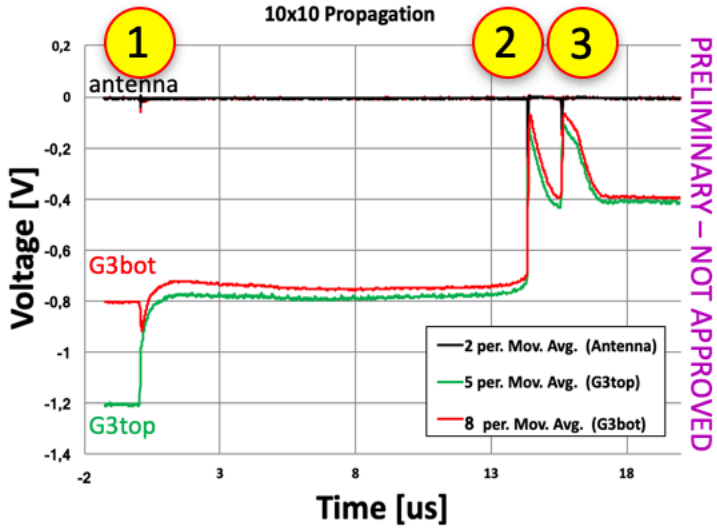


Large Detector



- **First validation on small 10x10 detectors:**
  - Observations meet the expectations
  - Energy required to cause VFAT damage is higher with Hybrid V3 and V4
  - Input protection circuits are efficient at nominal operating voltage and above
- **Comparison with large detectors:**
  - Damage probability of all hybrids is higher than expected due → because discharges accumulate more energy during their propagation
  - Hybrid V3 with 470 Ω gives the lowest damage probability, so far …

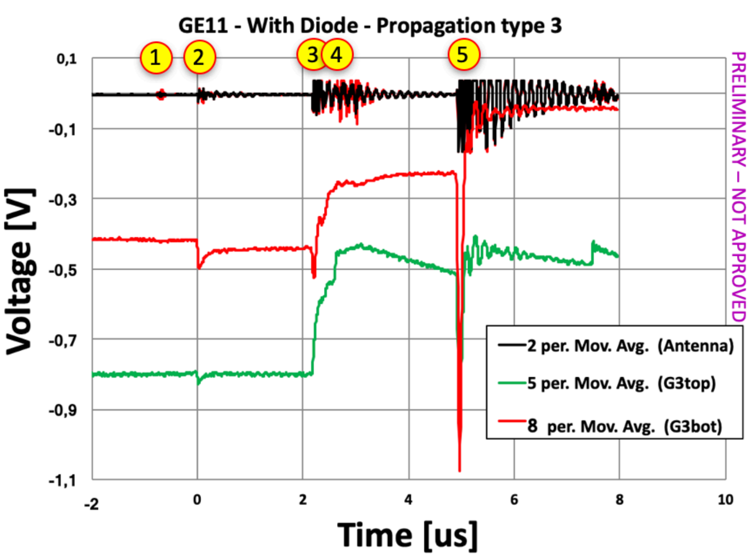
GE1/1 Discharges



Small Detector

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



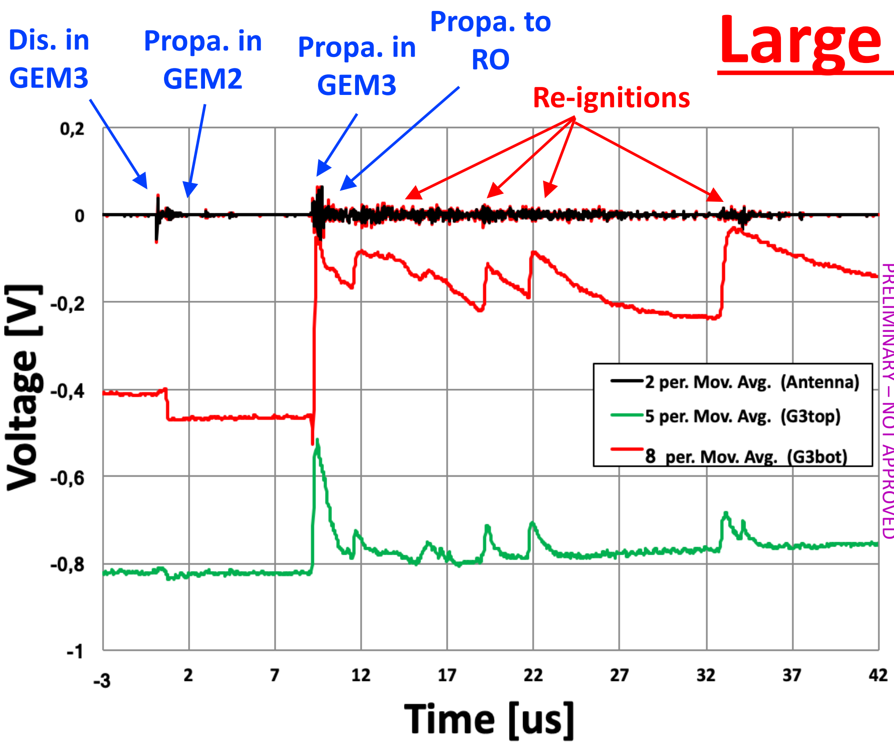
Large Detector

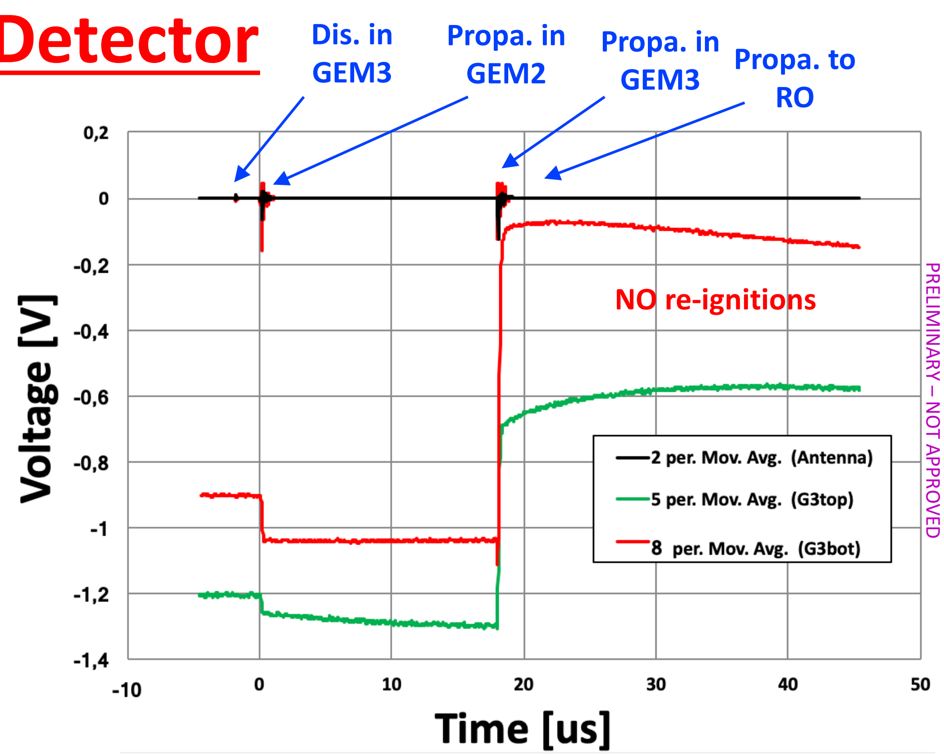
1. Primary discharge in GEM3
2. Propagation backward in GEM2
3. Propagation forward in GEM3
4. Propagation from GEM3 to Readout
5. Re-ignition of the propagation

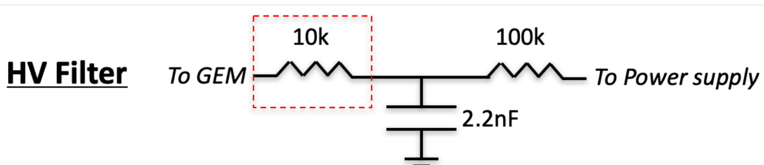
Propagation process in large detectors is more complex (discharges ”travel” backward and forward, accumulating more energy)

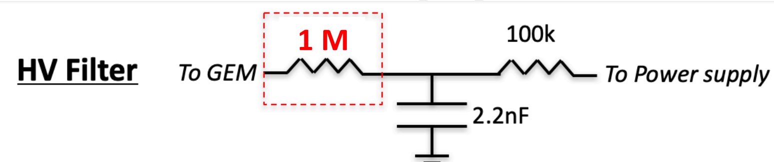
GE1/1 Discharges

Large Detector









- **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

GE1/1 Discharges

Channel loss rate = BKG rate * discharge prob. * propagation prob. * damage prob.

Discharge Probability → **Propagation Probability** → **Damage Probability**

"no pain no gain" parameter

- **Reduce induction gap capacitance**
- **AC-coupled RO with drain resistor**

- **Increase Filtering resistance**

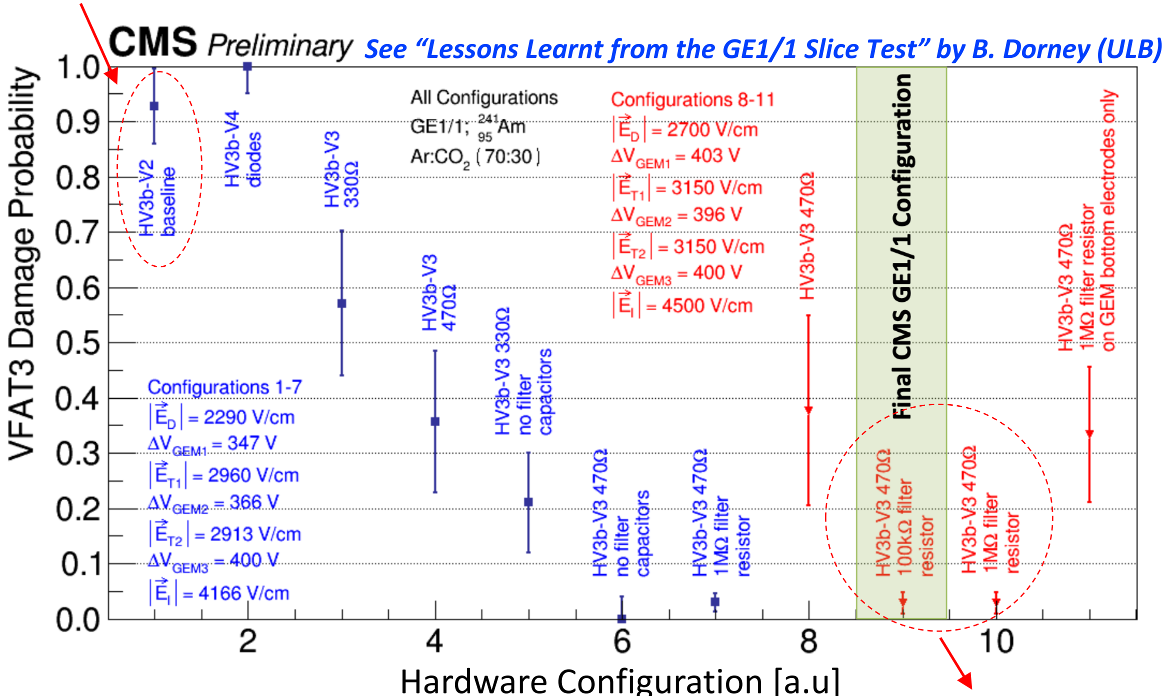
- **Improve VFAT input protection**
- **Suppress re-ignition propagation**

Feasible for GE2/1 and ME0

Feasible for GE1/1

GE1/1 Discharges

Baseline configuration used during Slice Test ~95-100% damage probability



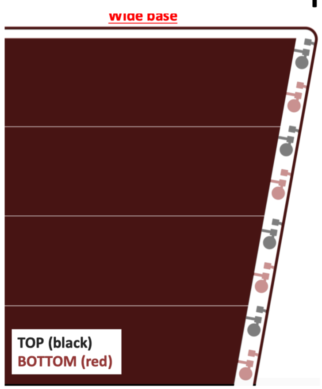
Optimum configurations <3% damage probability

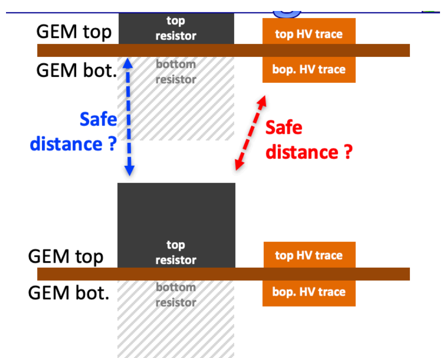
- **Optimum configuration for GE1/1:**
  - Optimum configuration allows the reduction of the damage probability by almost 2 orders of magnitude (**VFAT hybrid V3 - 470Ω** + **modified HV filter**)
  - Also works at operating voltage higher than standard range
  - No side effects on detector operation (in particular rate capability)

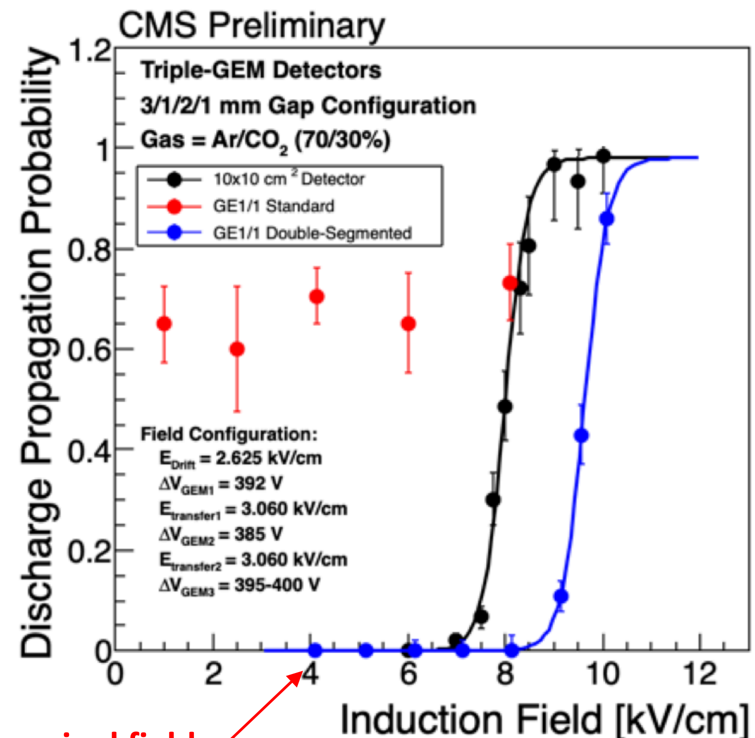
GE1/1 Mass Production

Double Segmented foils

- **First prototype produced and assembled:**
  - Reduce capacitance, improve foil protection and HV sectors de-coupling
  - First measurements are very promising (no propagation observed so far)
  - Full R&D program established



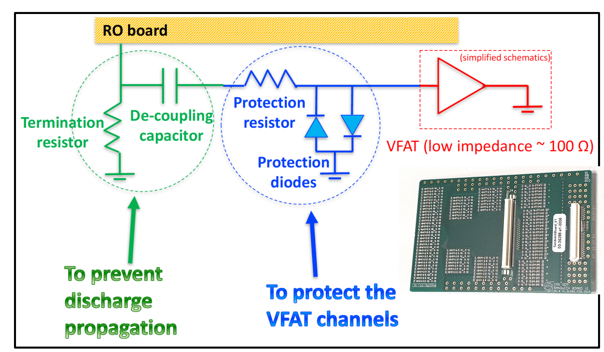




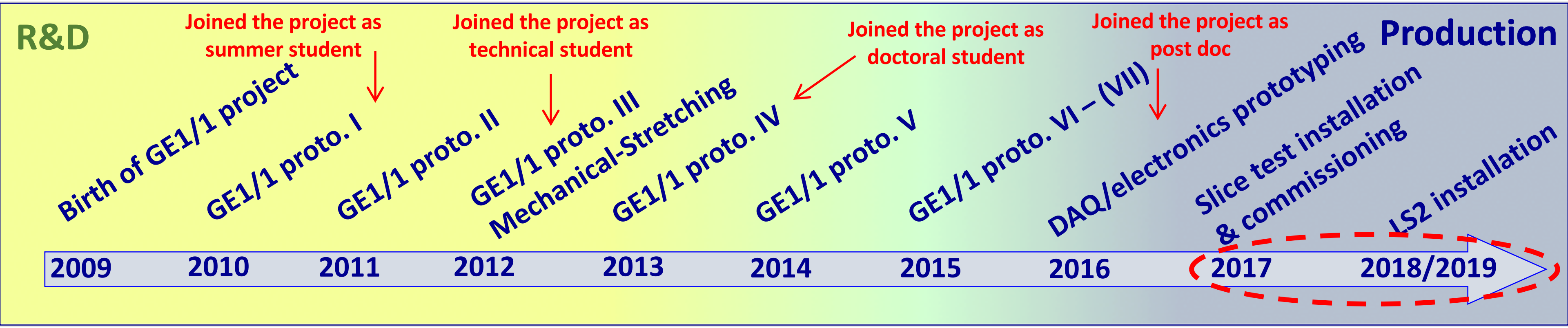
CMS nominal field

Sandwich boards

- **Prototypes boards designed and produced:**
  - De-coupling circuit and better VFAT protection
  - Test is on-going on large detector
  - Integration to final chambers is under investigation



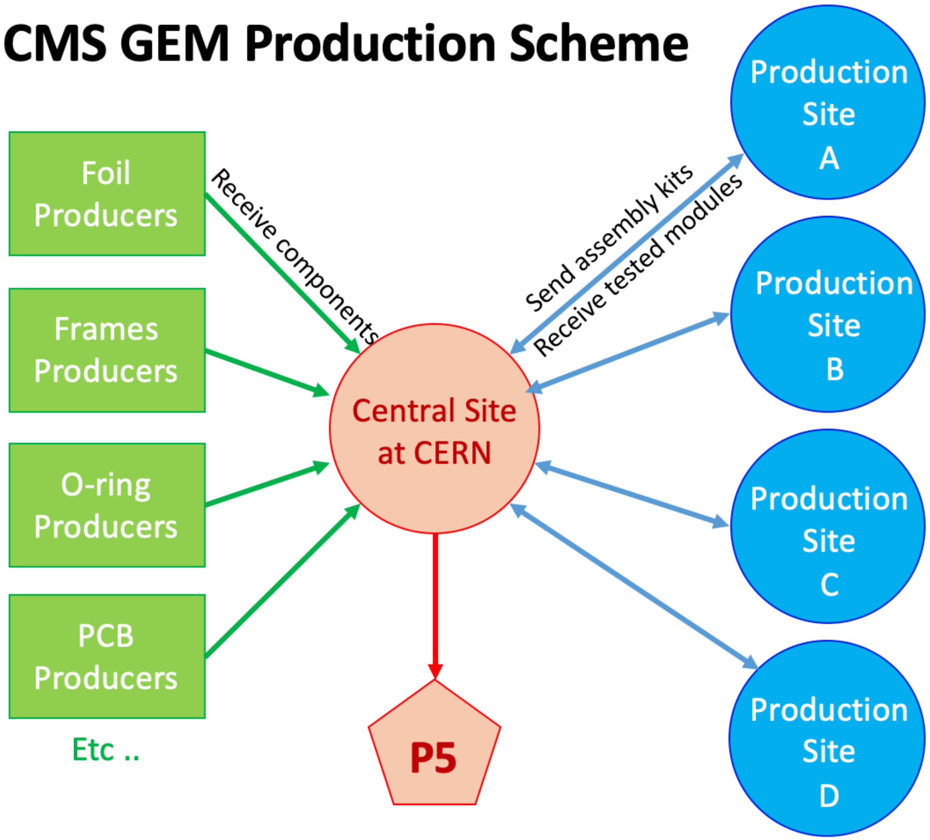
GE1/1 Mass Production



GE1/1 Mass Production

- 144 Detectors + spares

CMS GEM Production Scheme



- **Distribution of the production among several 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

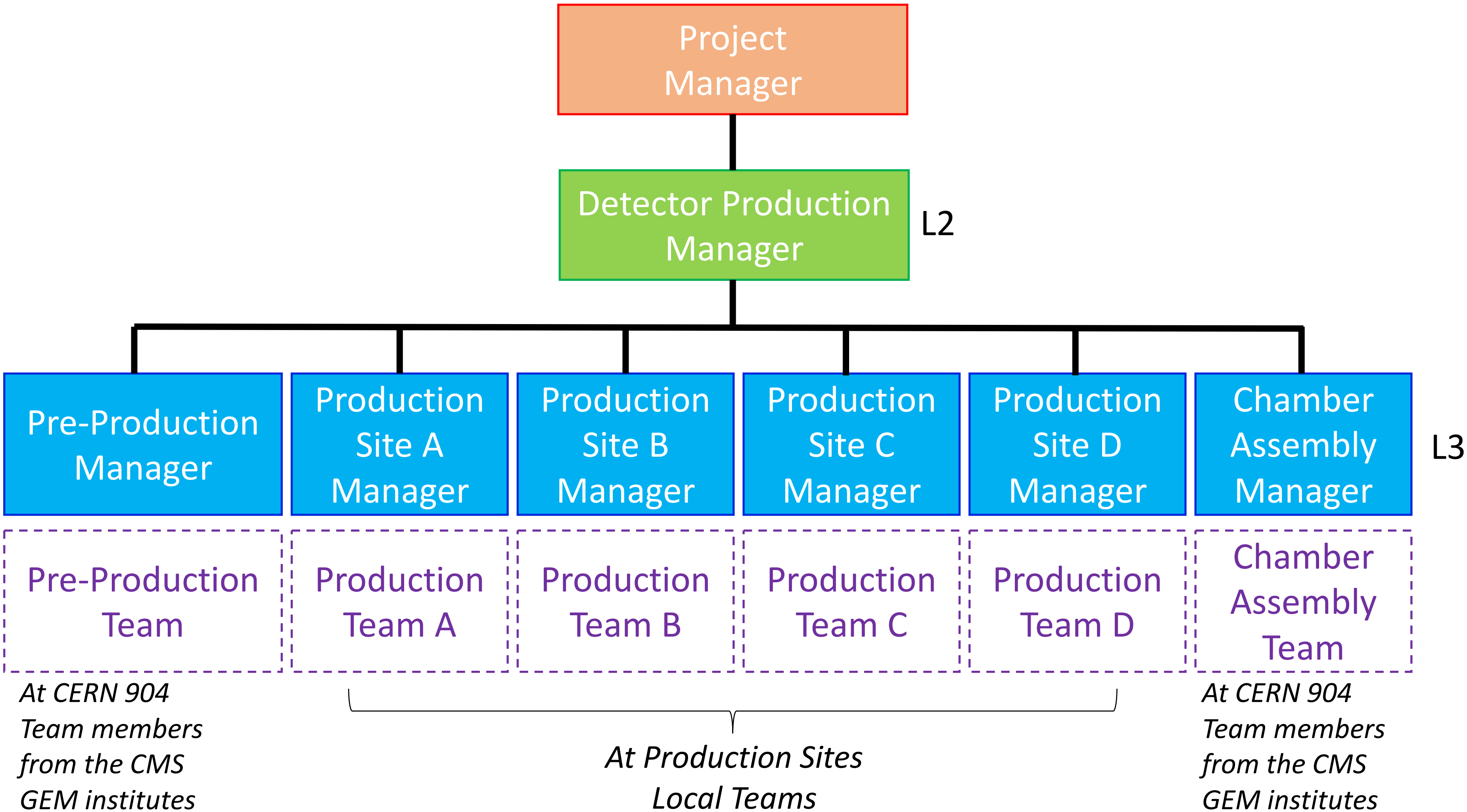
- **Improved Risk Mitigation**
  - Parallel production mitigates the impact of a single site failure on the overall production
  - All sites have the technical skills to produce a complete module
  - Any issues observed in a particular production site is immediately shared with the rest of the community

GE1/1 Mass Production

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

- **Production Community (all institutes involved in the GEM production)**
  - Certify of new production sites
  - Define the specifications and acceptance criteria for chambers and components
  - Review the QC data, validate/reject GEM modules
  - Participate to central site activities (provide manpower)

GE1/1 Mass Production



GE1/1 Mass Production

CERN
- QC1/QC2 — **Material inspection GEM Test**

Production Sites
- Assembly — **Chamber construction**
- QC2 — **GEM Test**
- QC3 — **Gas Leak Test**
- QC4 — **HV Test**
- QC5 — **Gain Calibration**

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

"Single-chamber" production:

- **161/161** triple-GEM detectors assembled at production sites
- All chambers tested against **gas** leaks, **HV** instability and **gain** issues
- All QC results are combined to select the **most similar** chambers to form super-chambers

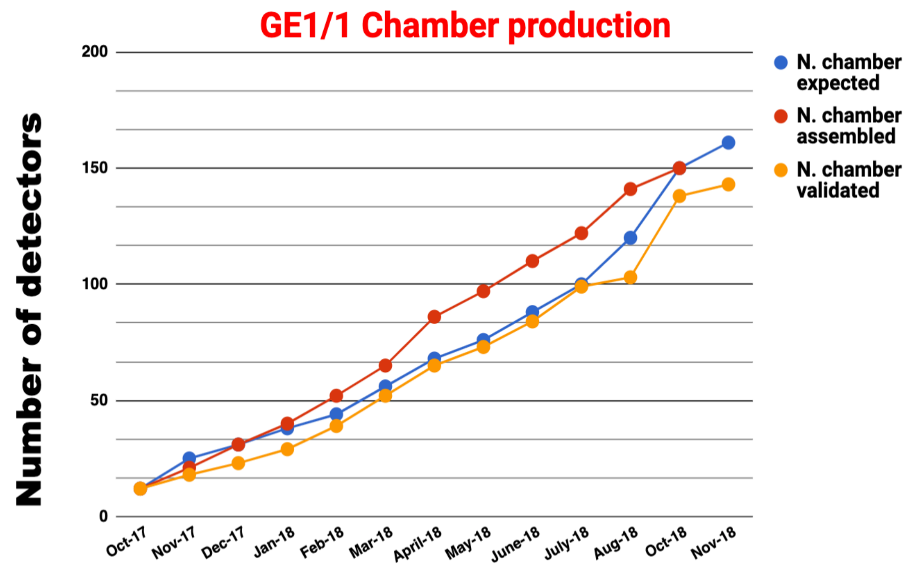
"Super-chamber" production:

- Installation of final **mechanics, electronics, HV** and **LV** on-chamber services
- Test and characterization of the SC with **cosmic rays**
- **Photogrammetry** and **storage**

GE1/1 Mass Production

- **GE1/1 Production Summary:**
  - Successful and on-time production of both endcaps from Sep 2017 to Dec 2018
  - 161 GE1/1 Detectors:
    - 3 QC on-going
    - 3 requires in-depth investigations
    - 155 Fully validated up to QC5

    (yield > 96%)

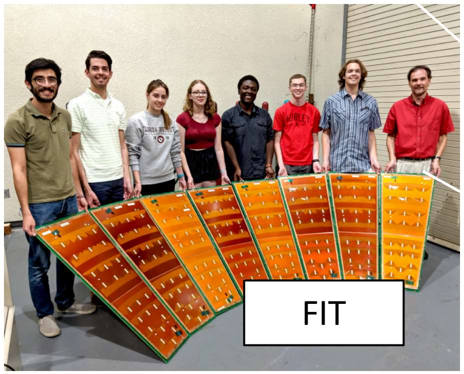


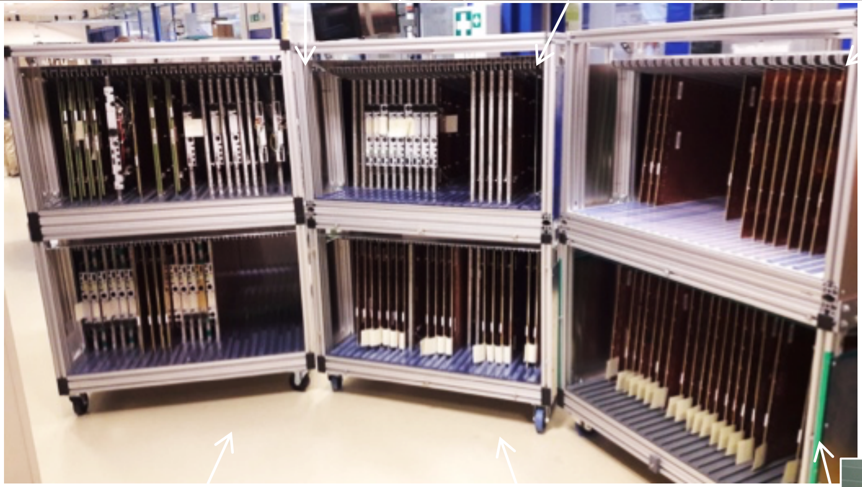
GE1/1 Slice Test Production (2015-2016)

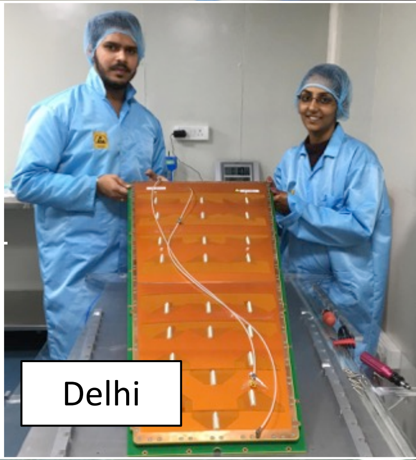
GE1/1 Mass Production (2017-2018)

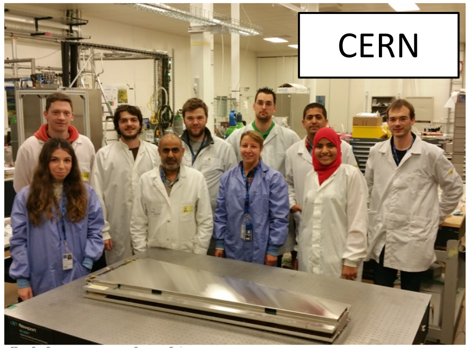
GE1/1 Mass Production

Wall of fame



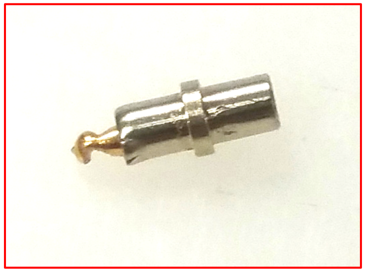




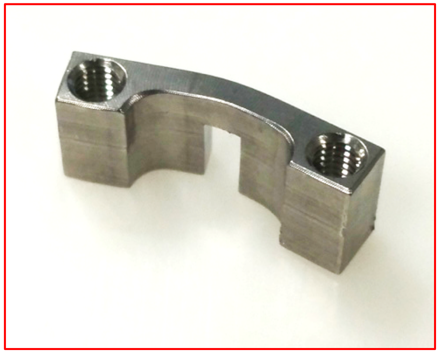


GE1/1 Mass Production

Wall of shame

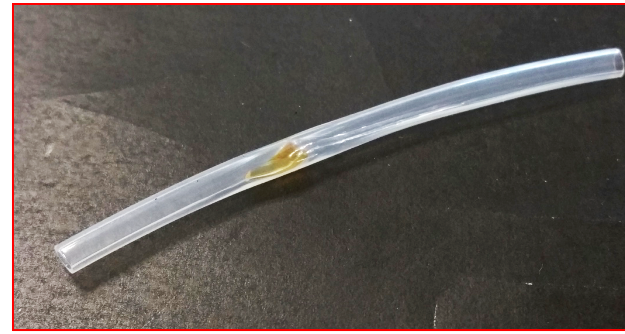


Broken HV pin

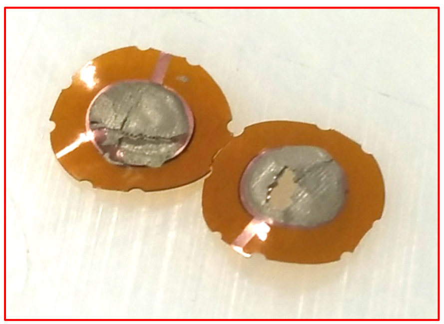


Bended pullouts

Faulty washers



Faulty gas pipes



Damaged HV pads

Clogged connectors

Faulty screws

Broken HV lines

GE1/1 Mass Production

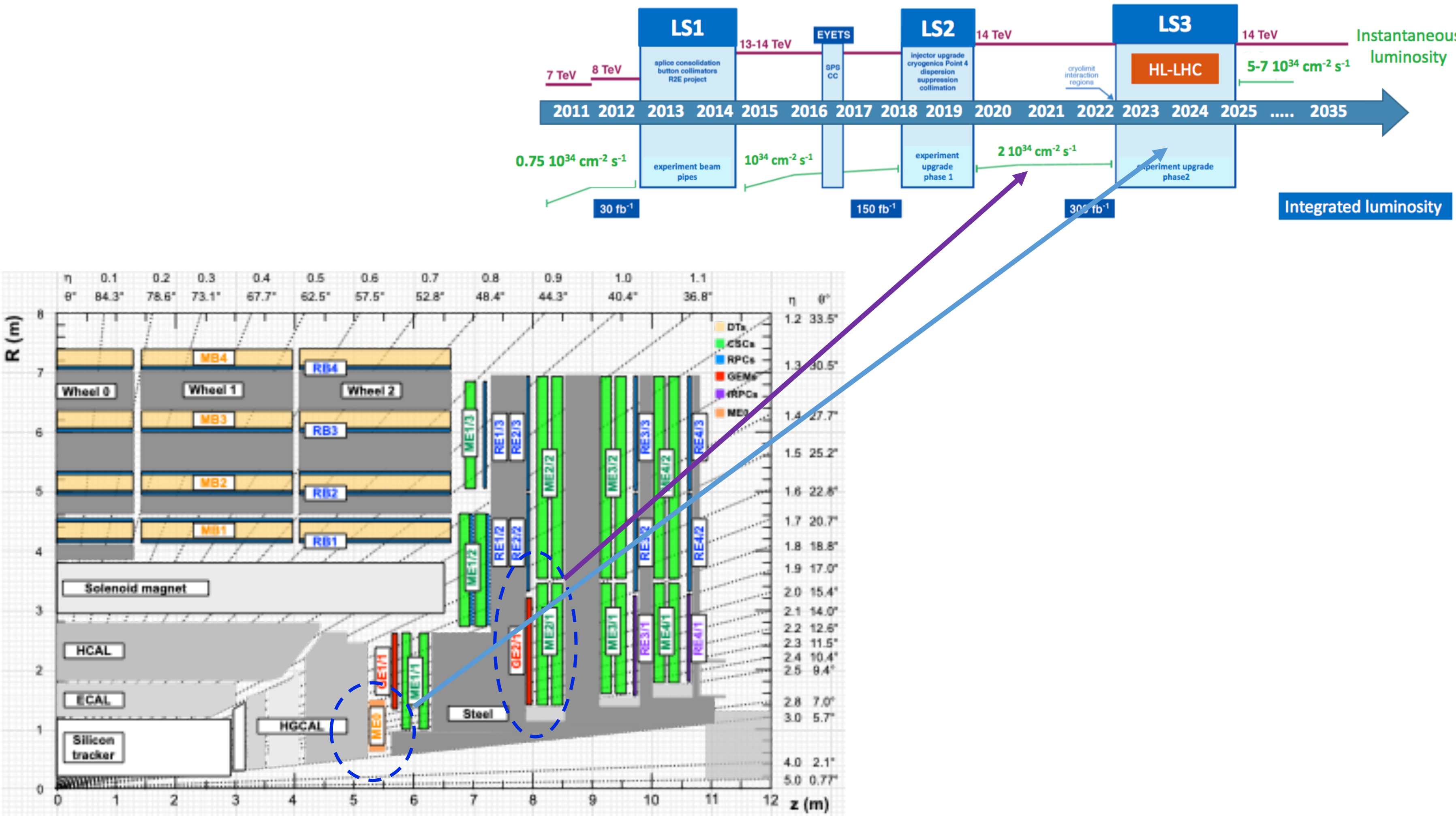
- Early installation and partial commissioning of 2 GE1/1 super-chambers on July 25th

Storage of GE1/1 chamber at CERN

Transporting the first GE1/1 SC to P5 in July 2019

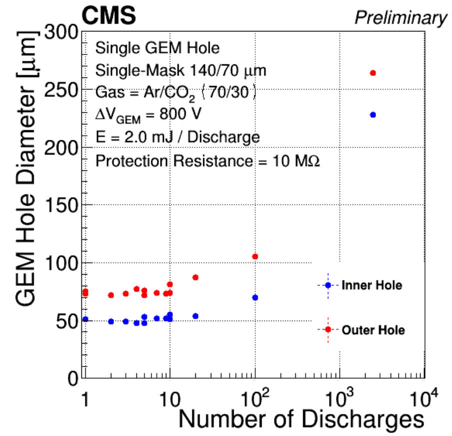
Installation in the negative end-cap on July 25th

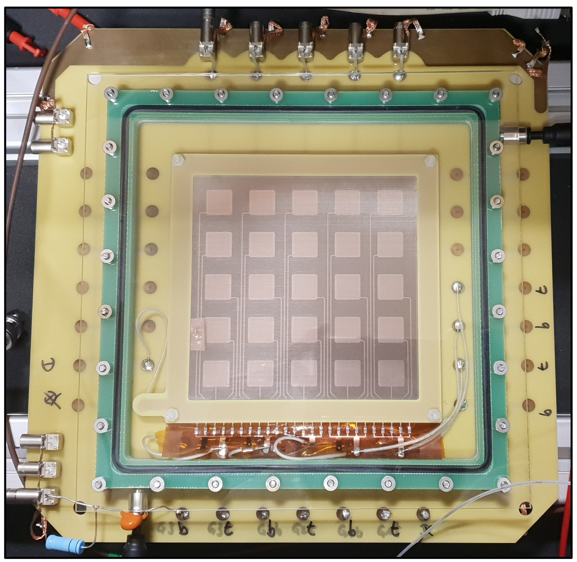
Future Developments



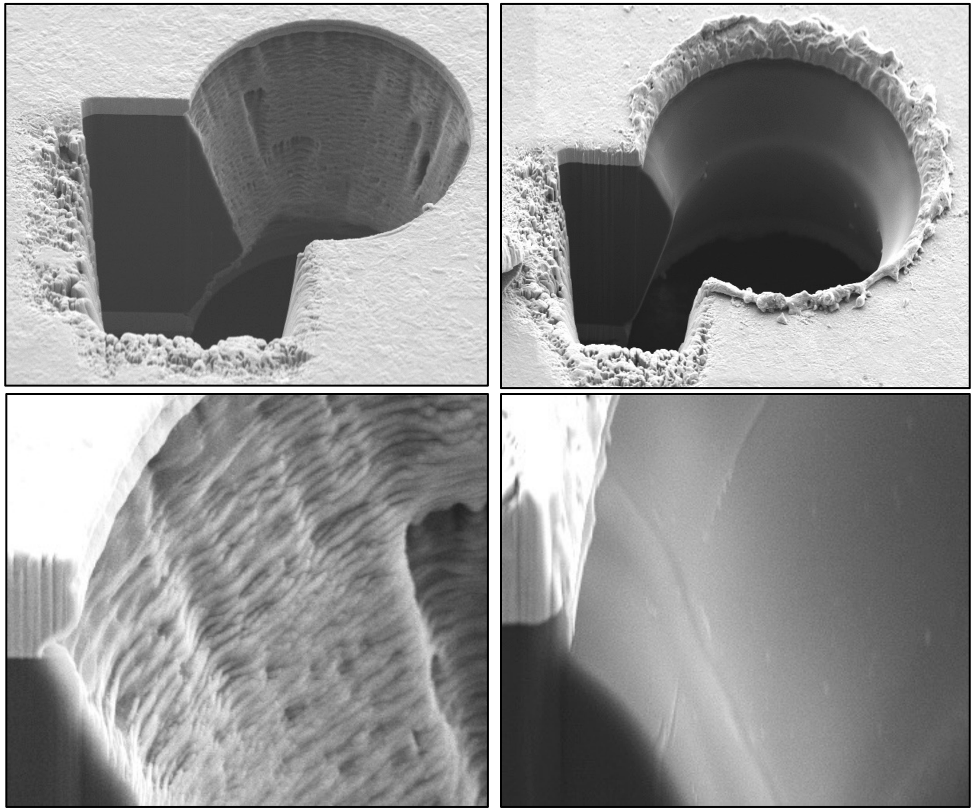
Future developments

- Additional studies on discharges
  - Initial studies showed a clear modification internal surface of the holes after discharges
  - Need to quantify the effect on the GEM foil operation and detector performance





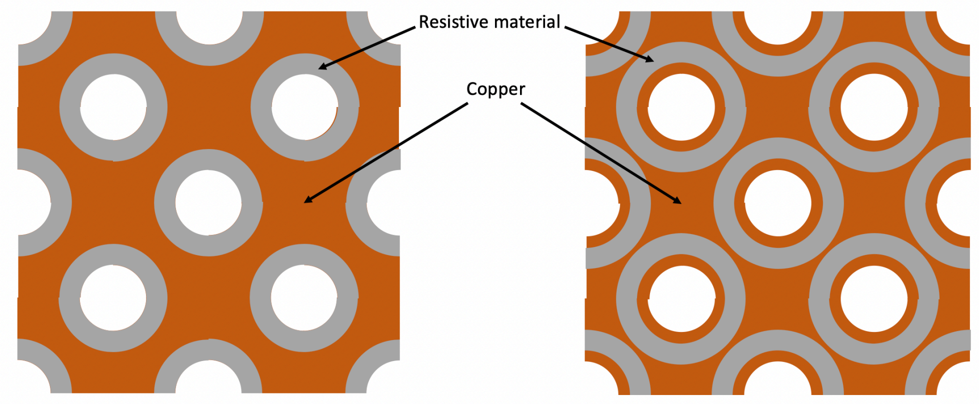
Special segmented 10x10 GEM setup



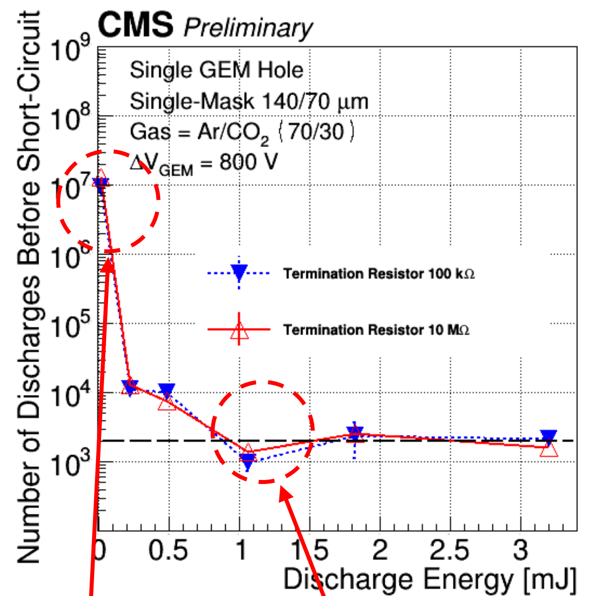
SEM of GEM holes before and after discharges

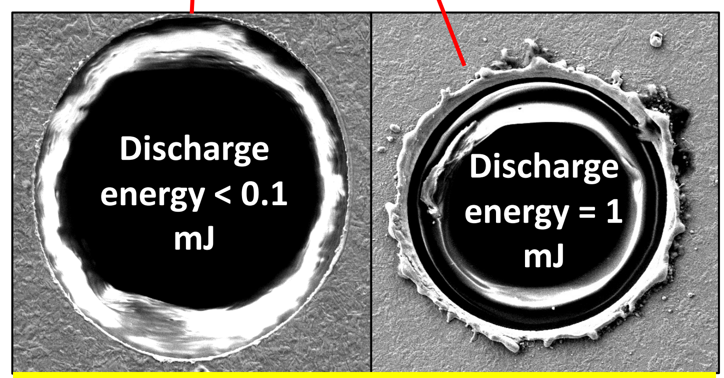
Future developments

- Additional studies on discharges
  - Initial studies with single GEM hole indicate a clear improvement of the GEM longevity when the maximum discharge energy it below 0.5 mJ
  - However such energy range is not reachable with the standard GEM technology



Proposals for new types of GEM is under investigations





SEM of GEM holes after discharges

Summary

- Introduction
  - Upgrade of the CMS forward muon system
  - Overview of the GEM technology
- GE1/1 R&D Phase
  - GE1/1 prototyping → **10 years of experience with the CMS GEM design – 10 generations of prototypes**
  - Performance tests → **All GE1/1 generations tested carefully characterized and tested with muon beams**
  - Longevity studies → **5 years of continuous testing confirmed the longevity of the GEM technology**
  - Discharges studies → **Deep understanding of the discharge process and its propagation**
- GE1/1 Detector Mass-Production
  - Organization of the mass production → **Succesful production of 161 chambers in 9 produciton sites**
  - Detector assembly and quality control → **Test setup and protocols fully understood and validated**
  - Status summary → **All chambers qualified up to QC5, half of the super-chambers (almost) validated for P5**
- Future Developments → **Proposals to continue the discharge study for future high rate GEM-based detectors**
- Summary

Grazie !