

GEM Detectors: Operating Principles and Applications.



Deywis Moreno

Bogota

10/Junio/2026.

The poster features a background image of a modern university campus with several buildings and green spaces. In the top left corner, there is a white box containing the logo of Universidad de los Andes (a yellow shield with a black cross) and the text 'Universidad de los Andes' and 'Facultad de Ciencias Departamento de Física'. The main title 'Taller: Aplicaciones Interdisciplinarias de Detectores de Partículas.' is written in large, bold, white and green letters across the center. Below the title, the dates 'Junio 10 - 12.' are displayed in white, and the year '2026' is shown in large green digits on the right. At the bottom left, there is a white box with the text 'Idioma Oficial: Español / Ingles.' and 'Official Language: Spanish/English.'

Universidad de los Andes Facultad de Ciencias Departamento de Física

Taller: Aplicaciones Interdisciplinarias de Detectores de Partículas.

Junio 10 - 12. 2026

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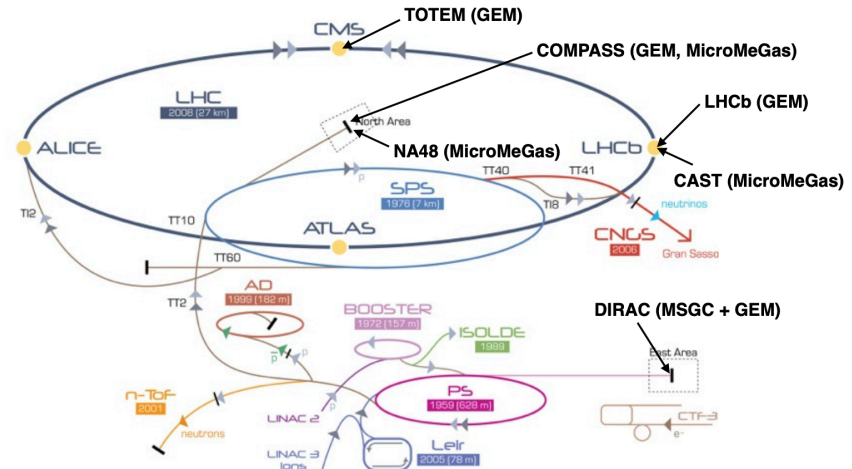
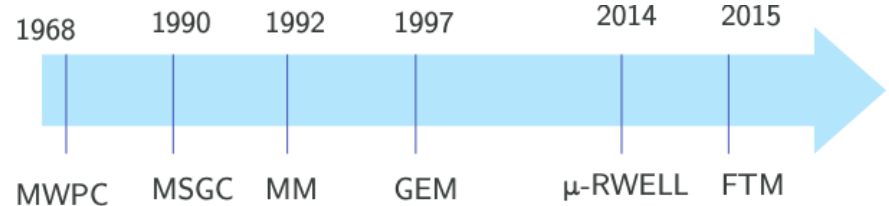
1. Gaseous Detectors
2. MPGs overview
3. GEMs
4. GEMs at LHC
5. UAN GEMs
6. Outlook



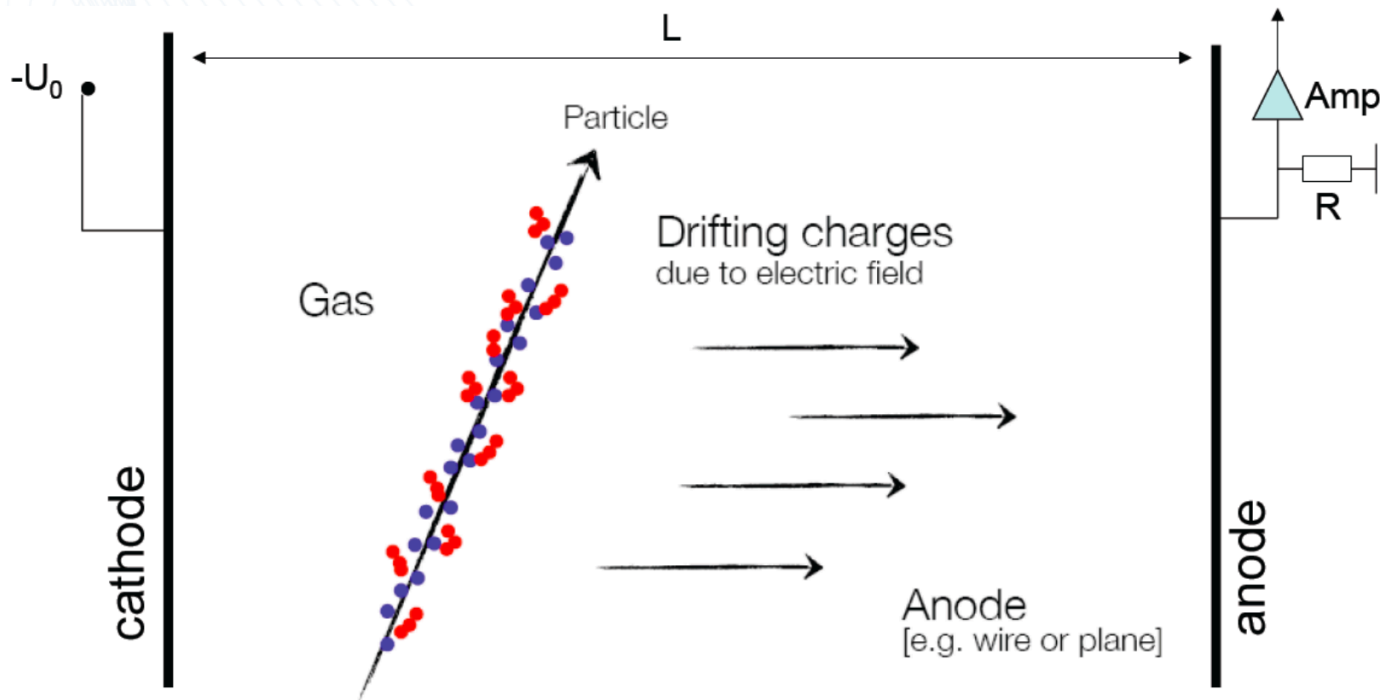
Micro-pattern Gaseous detectors

MPGDs are gaseous detectors with microscopic electronic structures to amplify ionization signals

- High rate capability $O(\text{MHz}/\text{cm}^2)$
- High spatial resolution (50-100 μm)
- Good time resolution (5-10 ns)



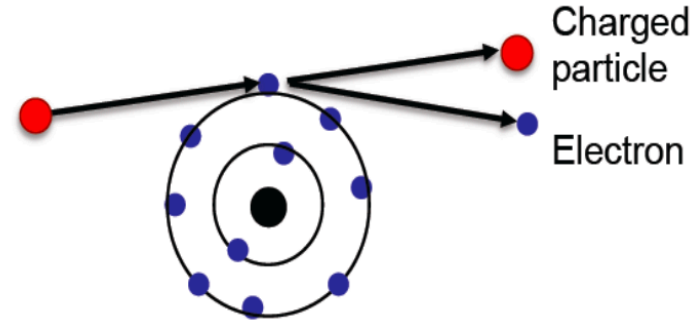
Gaseous detectors: Operating Principle



- Primary Ionization
- Secondary Ionization (due to δ -electrons)

1. For an ionization:

$$X + p \rightarrow X^* + p + e^-$$
2. Interaction dominated by elastic collisions with electrons
3. The trajectory of the charged particle is unchanged after scattering.
4. Ions and electrons produced by incident radiation are known as primary ionization
5. Primary electrons can further ionize the medium (delta rays) leaving long tracks



1. Number of Primary Electrons

$$\langle n_p \rangle = \frac{L}{\lambda}$$

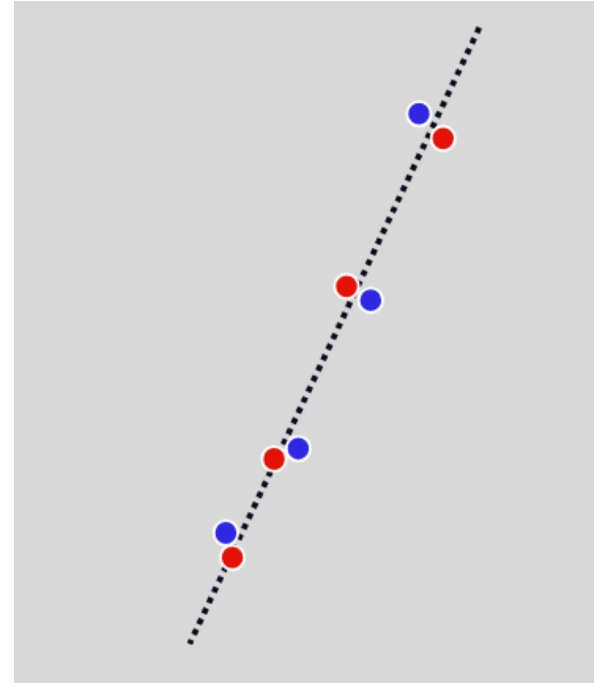
2. Total Number of pairs :

$$\langle n_T \rangle = \frac{\Delta E}{\omega_i}$$



Gaseous detectors: Recombination and Electron Attachment

1. Produced pairs need to remain free long enough to be collected.
2. No electric field: Ion-electrons recombine.
$$X^+ + e^- \rightarrow X + h\nu$$
3. Electron attachment: Capture of free electrons by electronegative atoms:
$$e^- + X \rightarrow X^- + h\nu$$
4. Electronegative gases:





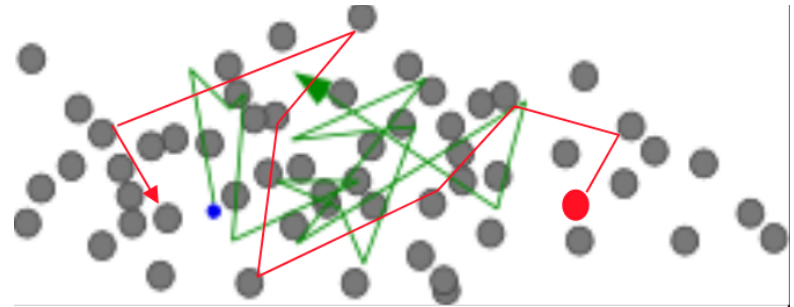
Gaseous detectors: Transport of Electrons and Ions in gases

1. Electrons and ions produced diffuse uniformly from the creation point for $E = 0$.
2. Thermal equilibrium is reached and finally they recombined.
3. Due to the stochastic process: Charge distribution after a distance is Gaussian

$$\frac{dN}{dx} = \frac{N_0}{\sqrt{4\pi Dt}} \exp\left(-\frac{x^2}{4Dt}\right)$$

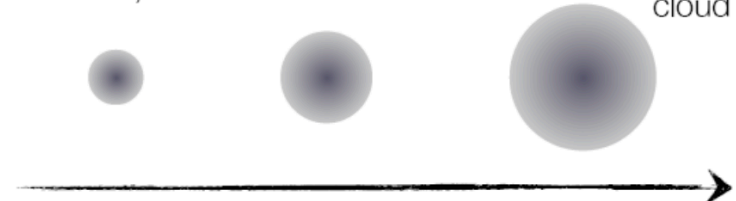
4. D is the Diffusion Coefficient:

$$D = \frac{2}{3\sqrt{\pi}} \frac{1}{P\sigma_0} \sqrt{\frac{(kT)^3}{m}}$$



Diffusion
without E,B field

Electron
cloud



time 7



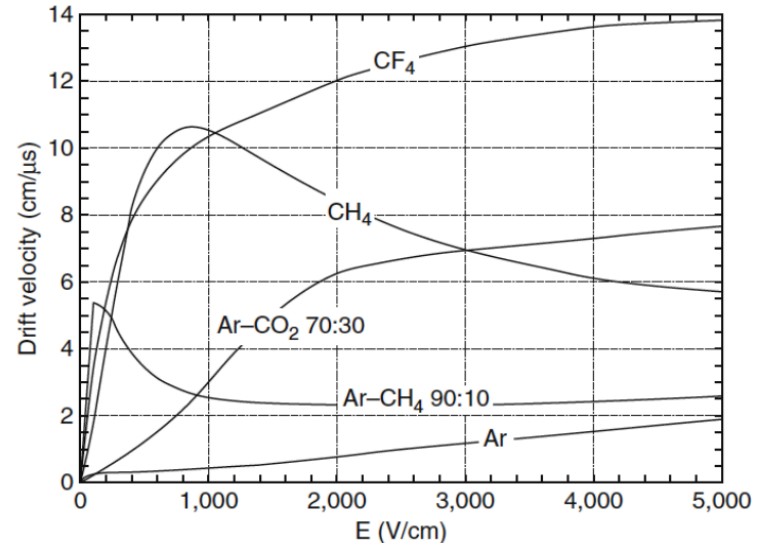
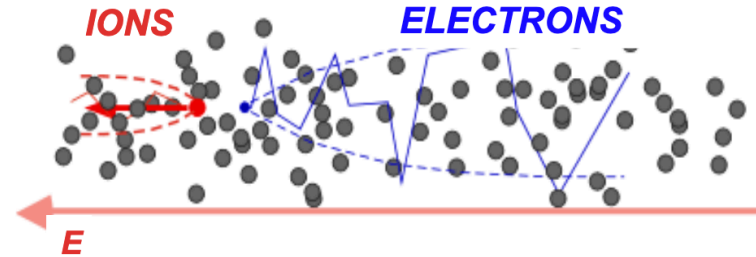
Gaseous detectors: Transport of Electrons and Ions in gases

1. Electrons and Ions obtain velocity (v_D) in addition to thermal motion if $E \neq 0$
2. The movement is along field lines
3. The Drift Velocity of a charge is:

$$\vec{v}_D = \mu \vec{E}$$

$$4. E \approx 1 \frac{kV}{cm} \rightarrow v_D(Ions) \approx \frac{cm}{ms}$$
$$\rightarrow v_D(e^-) \approx \frac{cm}{\mu s}$$

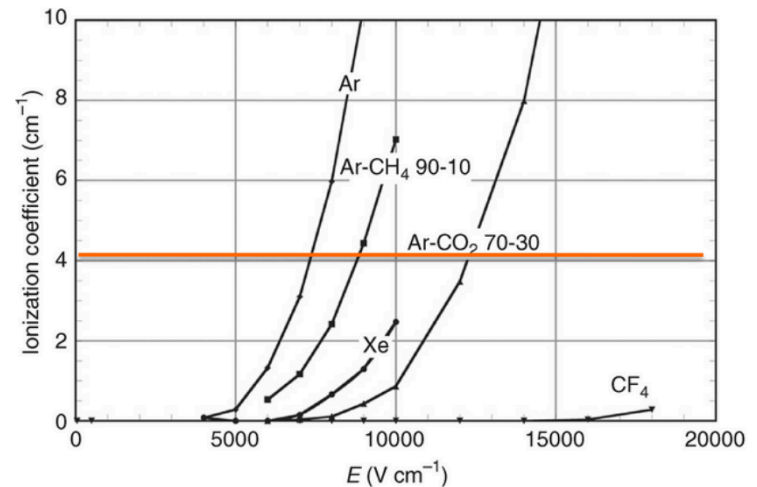
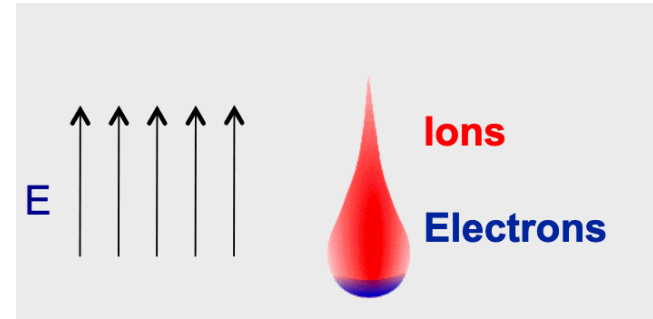
$$5. \tau(Collection) \approx \frac{1}{v_D}$$



1. Gas multiplication occurs when primary ionization electrons gain sufficient energy
2. The avalanche has the form of a liquid drop.
3. The total number (n) of electrons created in a path x is:

$$n(x) = n_0 \exp(\alpha x)$$
4. The coefficient α is known as first Townsend Coefficient
5. The multiplication factor or Gain is:

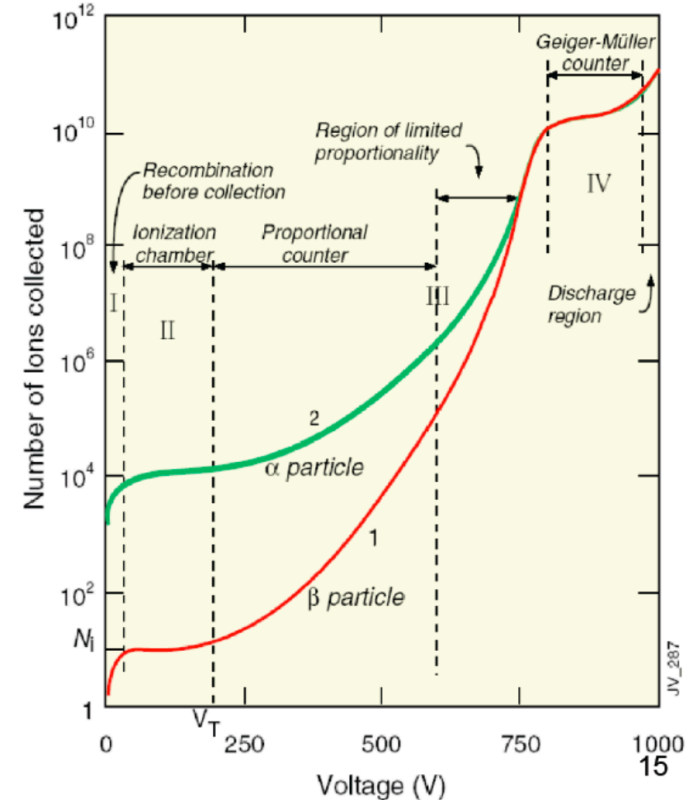
$$G = \frac{n}{n_0} = \exp(\alpha x)$$



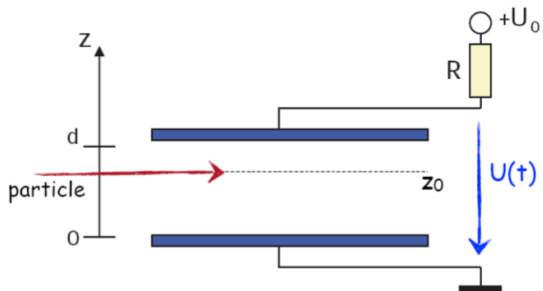


Gaseous detectors: Operating Principle

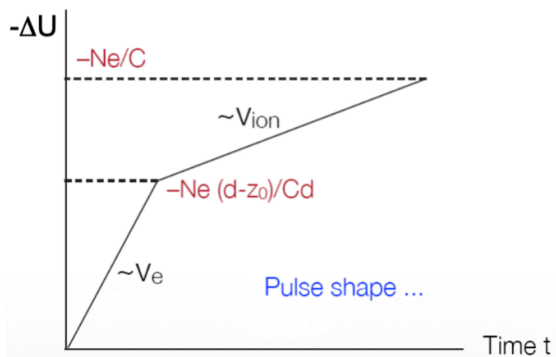
1. Region I: No E field, recombination before collection
2. Region II: Ionization chamber. No gain. Full Charge collected
3. Proportional Counter: Multiplication, signal proportional to original ionization. Quenching needed.
4. Limited Proportionality: Strong photoemission. Large signal
5. Geiger mode: Massive photo emission.



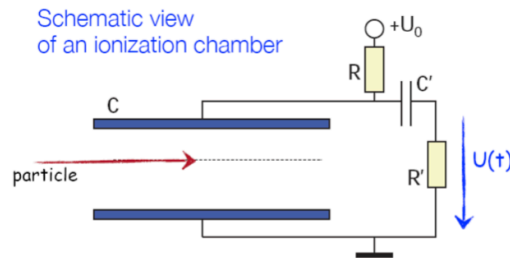
Gaseous detectors: Signal shaping



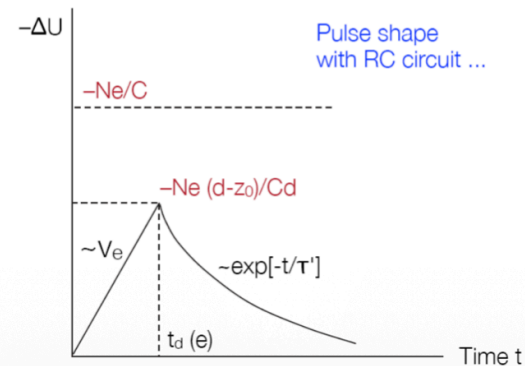
Schematic view of an ionization chamber



Pulse shape ...



Schematic view of an ionization chamber



Pulse shape with RC circuit ...

Gaseous detectors: Modeling

- **Detector = capacitance C_d**

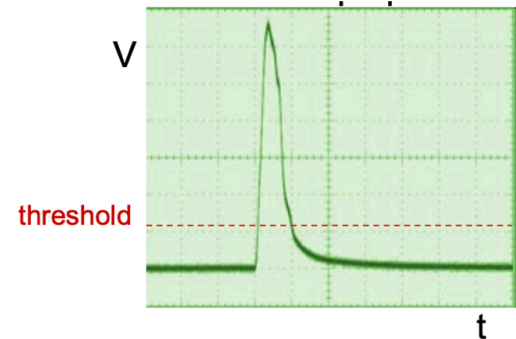
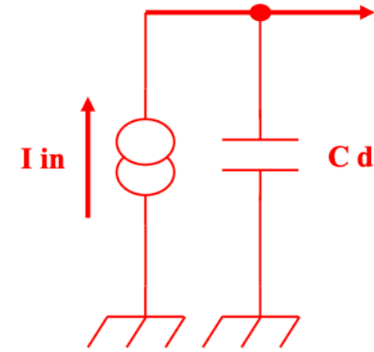
- Silicon : 0.1-10 pF
- PMTs : 3-30pF
- Ionization chambers 10-1000 pF

- **Signal : current source**

- Silicon : $\sim 100e^-/\mu\text{m}$ ($\sim 1\text{fC}/100\mu\text{m}$)
- PMTs : 1 photoelectron $\rightarrow 10^5\text{-}10^7 e^-$
- Wire chambers : a few $10^3 e^-$
- Modeled as an impulse (Dirac) : $i(t)=Q_0\delta(t)$

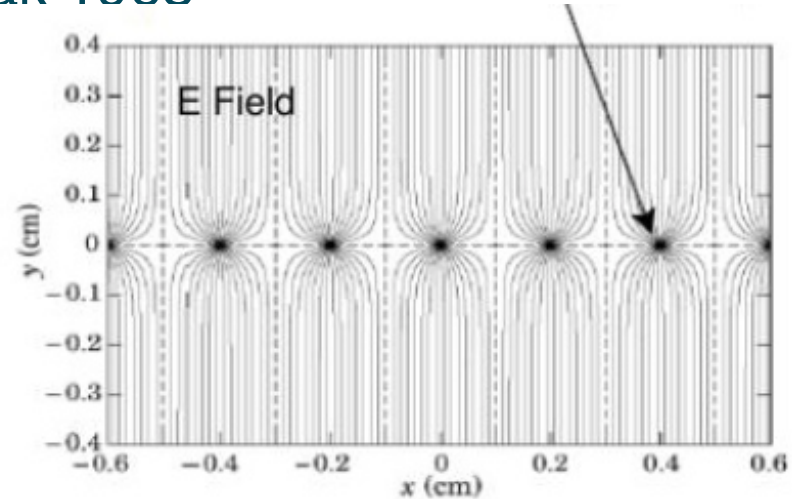
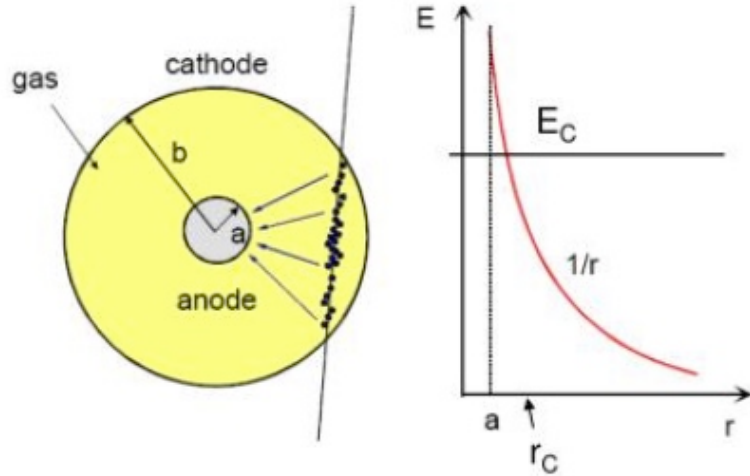
- **Missing :**

- High Voltage bias
- Connections, grounding
- Neighbours
- Calibration...



Proportional counter

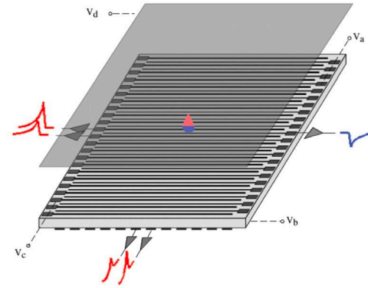
MultiWire Proportional Chamber, Charpak 1968



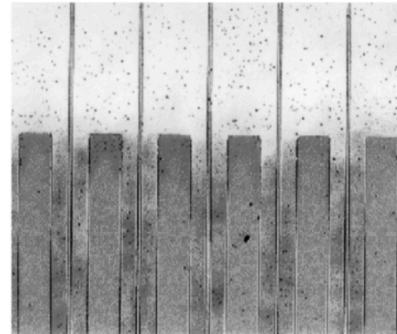
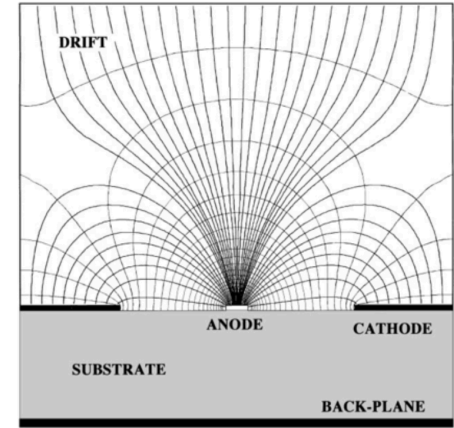
Chambers made of planes of independent electrodes.

MicroStrip Gas Counter, A. Oed 1988

- Electrodes on solid substrate
- Smaller pitch (200 μ m)
- Higher spatial resolution
- Fast evacuation of ions
- High flux capability



Scheme of a MSGS



Picture of first microstrip plates



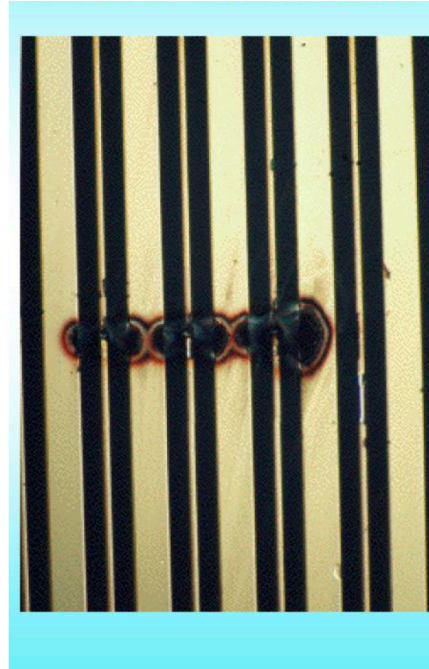
MicroPattern Gaseous Detectors

Problems

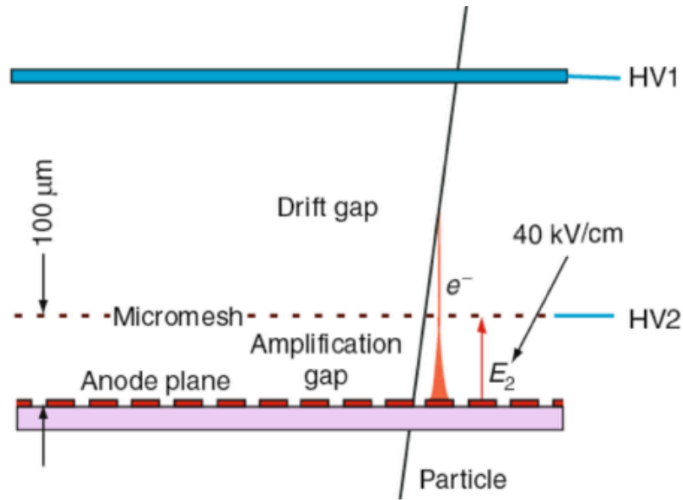
- Charging up effects
- Aging
- Limited gas gain
- Low spark resistance

Mitigation

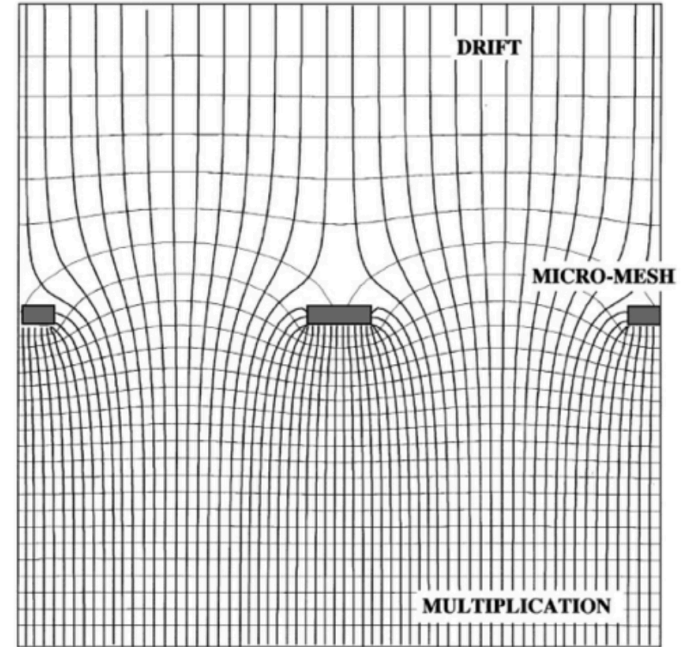
- Use of semiconductor coating
- Gas optimization
- Preamplification in the drift



Micro-Mesh Gaseous Structure, Charpak 1992

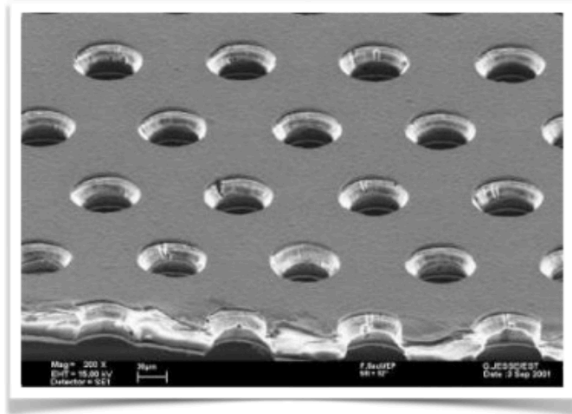


- Two regions with different electric fields
- Small gap

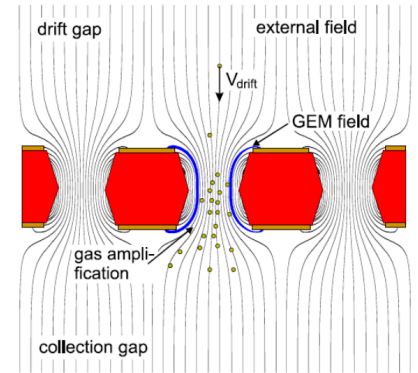
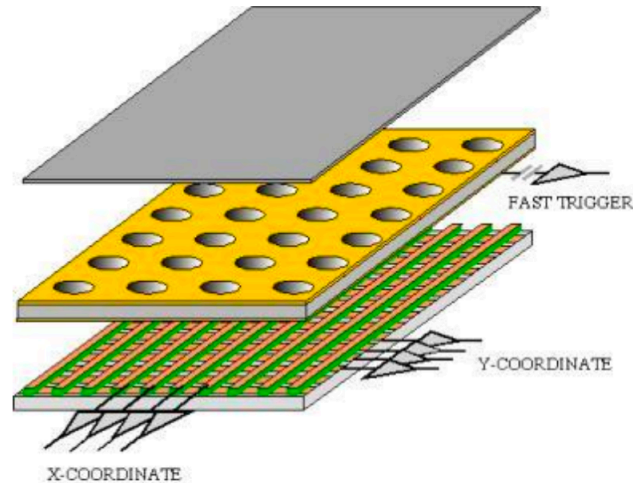


Electric field in the MicroMegas

Gas Electron Multiplier, Sauli 1995



- Hole diameter: 70 μm
- Foil thickness: 50 μm
- Hole spacing: 140 μm

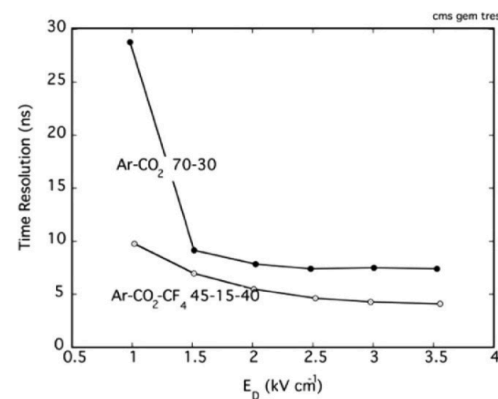
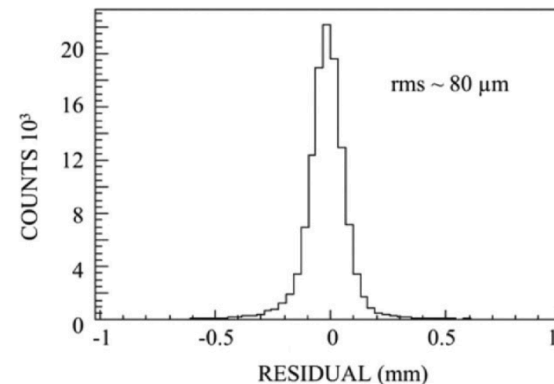
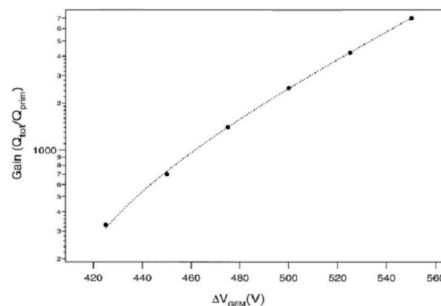
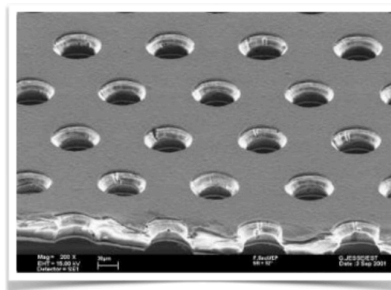


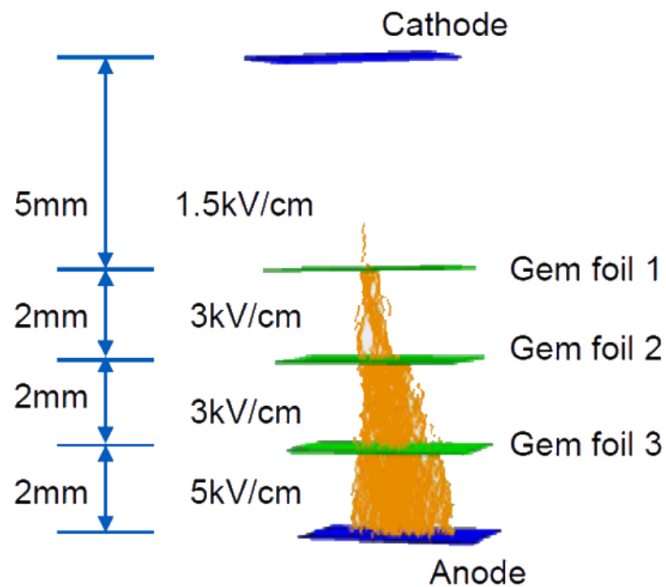
Scheme of a GEM Detector

Gas Electron Multiplier, Sauli 1995

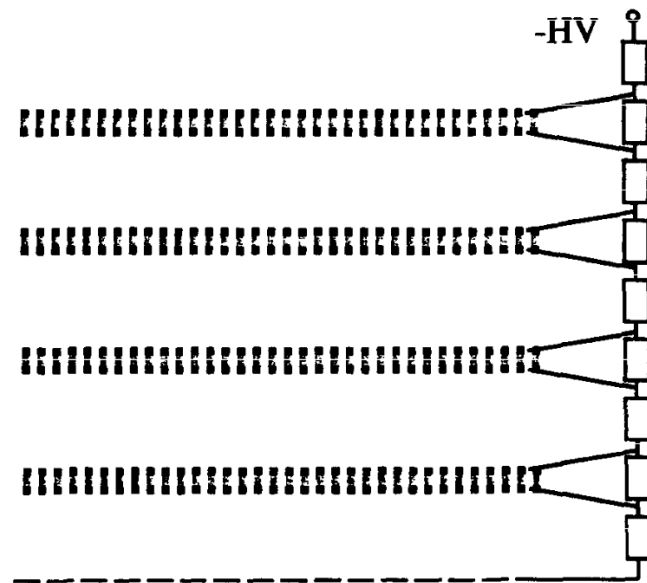
The main characteristics and performances of GEM detectors are:

- Operation in most gas fillings, including pure noble gases
- Proportional gains above 10^5
- Energy resolution 18% FWHM at 5.9 keV
- Space localization accuracy $60\mu\text{m}$ rms or better
- Rate capability above 10^5 counts/ mm^2sec
- Active areas up to 1000 cm^2
- Flexible detector shape and readout patterns
- Robust, Low cost

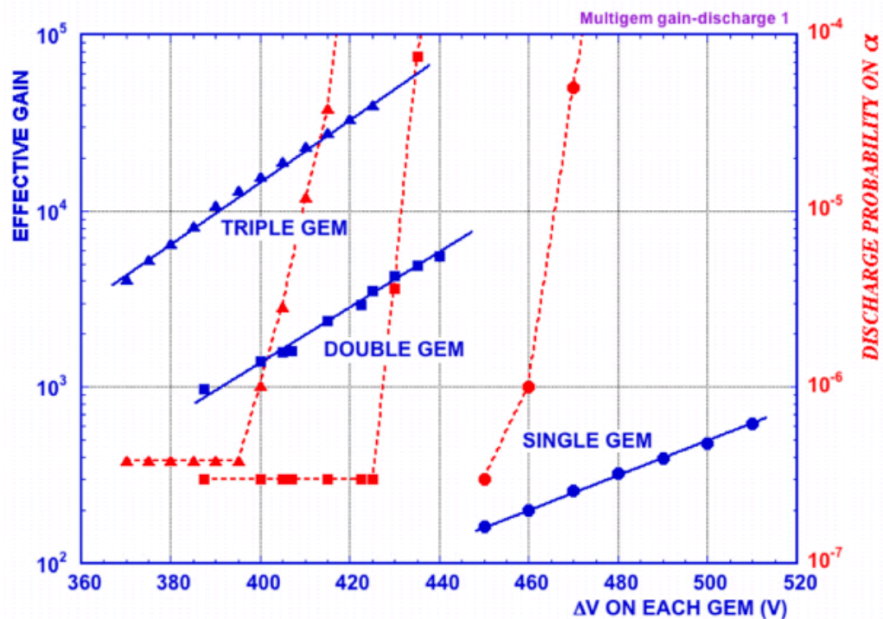




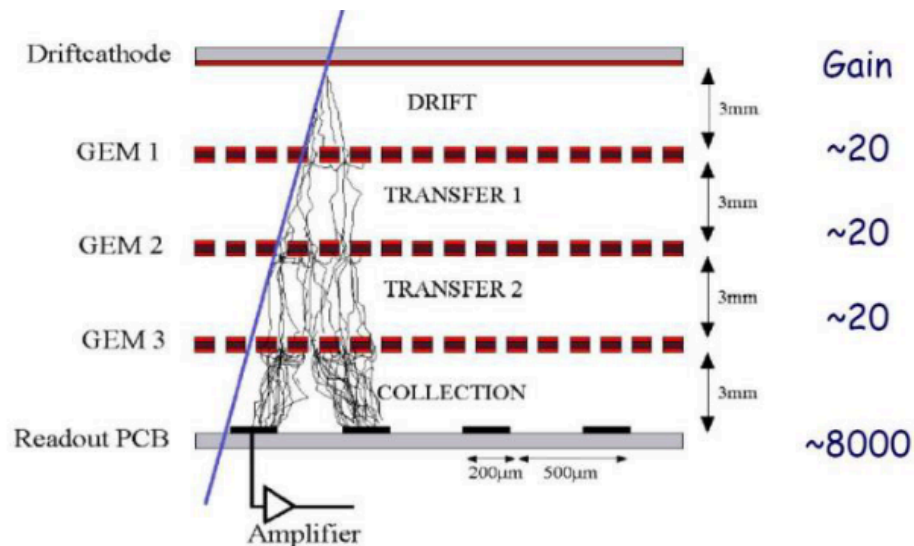
Scheme of a TGEM Detector



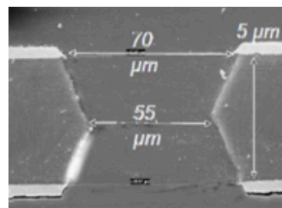
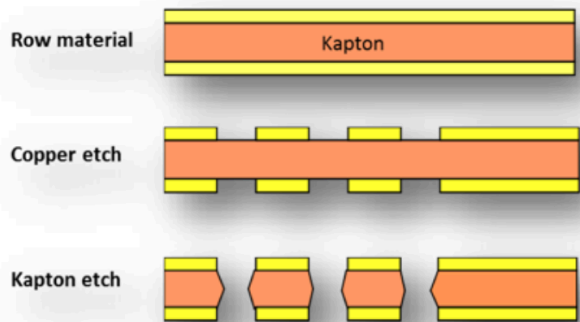
TGEM Detector connection



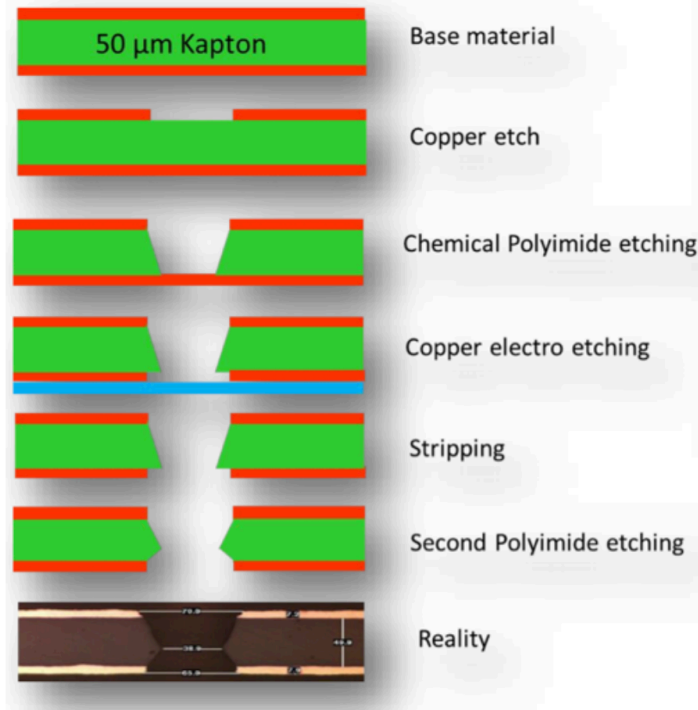
S. Bachmann et al, NIMA 479(2002)294



Scheme of a TGEM Detector

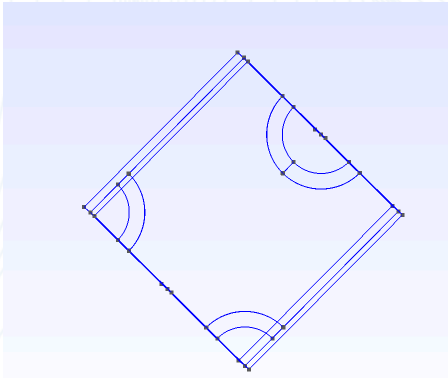


Original production

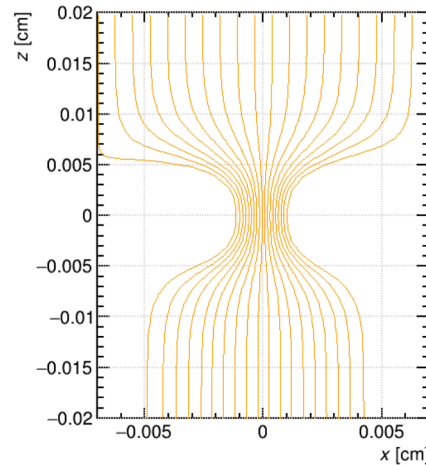


For larger areas

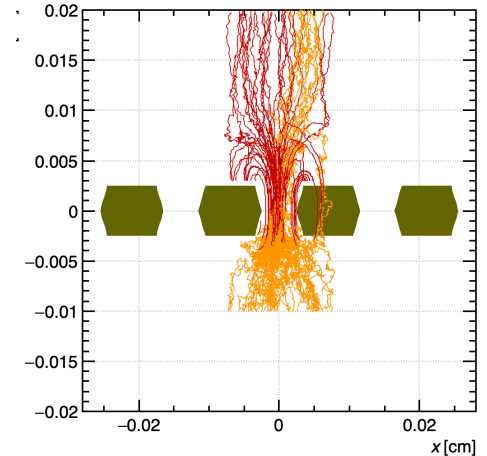
Geometry modelling



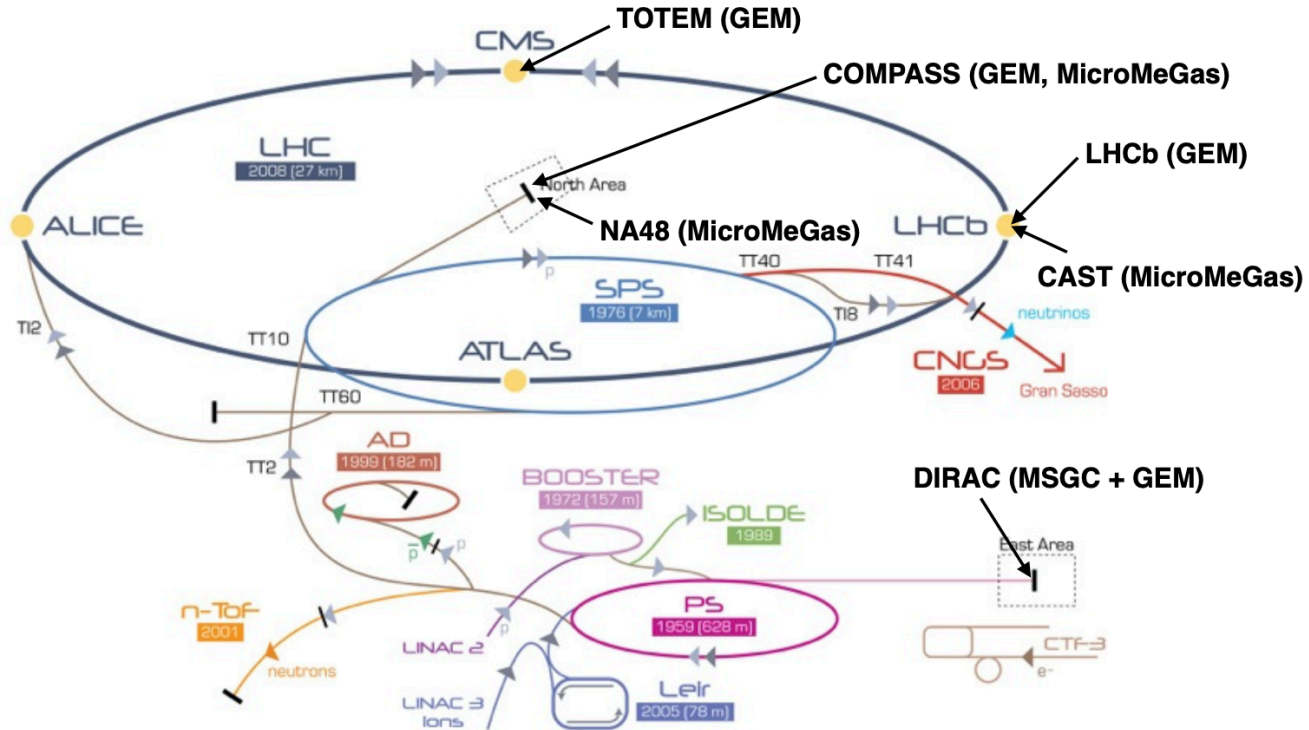
Field calculation



Particle generation



- G M S H : A three-dimensional finite element mesh generator
- Elmer: open source multiphysical simulation software
- Garfield++: toolkit for the detailed simulation of detectors





GEMs at CMS

CMS DETECTOR

Total weight : 14,000 tonnes
 Overall diameter : 15.0 m
 Overall length : 28.7 m
 Magnetic field : 3.8 T

STEEL RETURN YOKE
 12,500 tonnes

SILICON TRACKERS
 Pixel ($100 \times 150 \mu\text{m}^2$) $\sim 1 \text{ m}^2$ $\sim 66\text{M}$ channels
 Microstrips ($80\text{--}180 \mu\text{m}$) $\sim 200 \text{ m}^2$ $\sim 9.6\text{M}$ channels

SUPERCONDUCTING SOLENOID
 Niobium titanium coil carrying $\sim 18,000 \text{ A}$

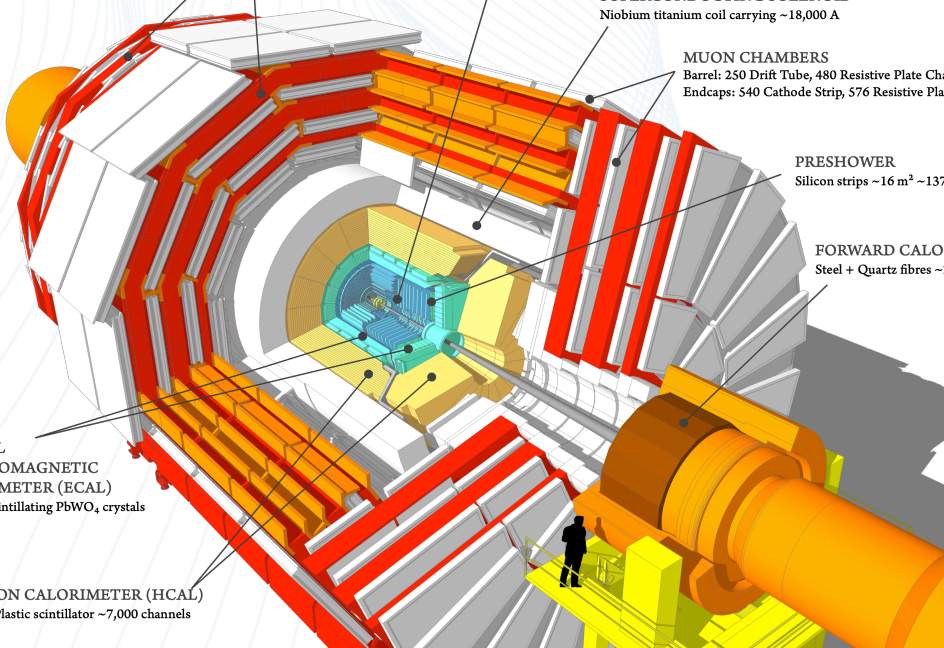
MUON CHAMBERS
 Barrel: 250 Drift Tube, 480 Resistive Plate Chambers
 Endcaps: 540 Cathode Strip, 576 Resistive Plate Chambers

PRESHOWER
 Silicon strips $\sim 16 \text{ m}^2$ $\sim 137,000$ channels

FORWARD CALORIMETER
 Steel + Quartz fibres $\sim 2,000$ Channels

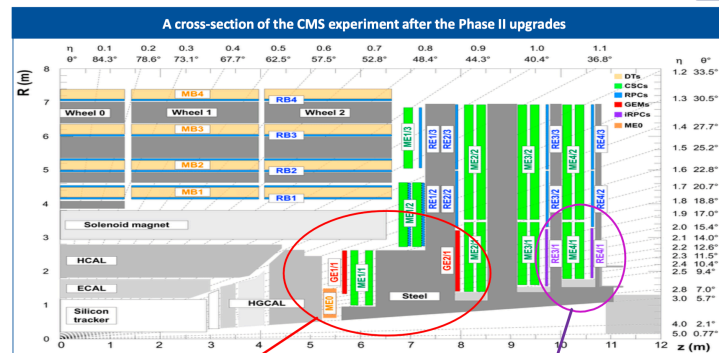
CRYSTAL ELECTROMAGNETIC CALORIMETER (ECAL)
 $\sim 76,000$ scintillating PbWO₄ crystals

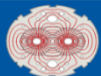
HADRON CALORIMETER (HCAL)
 Brass + Plastic scintillator $\sim 7,000$ channels



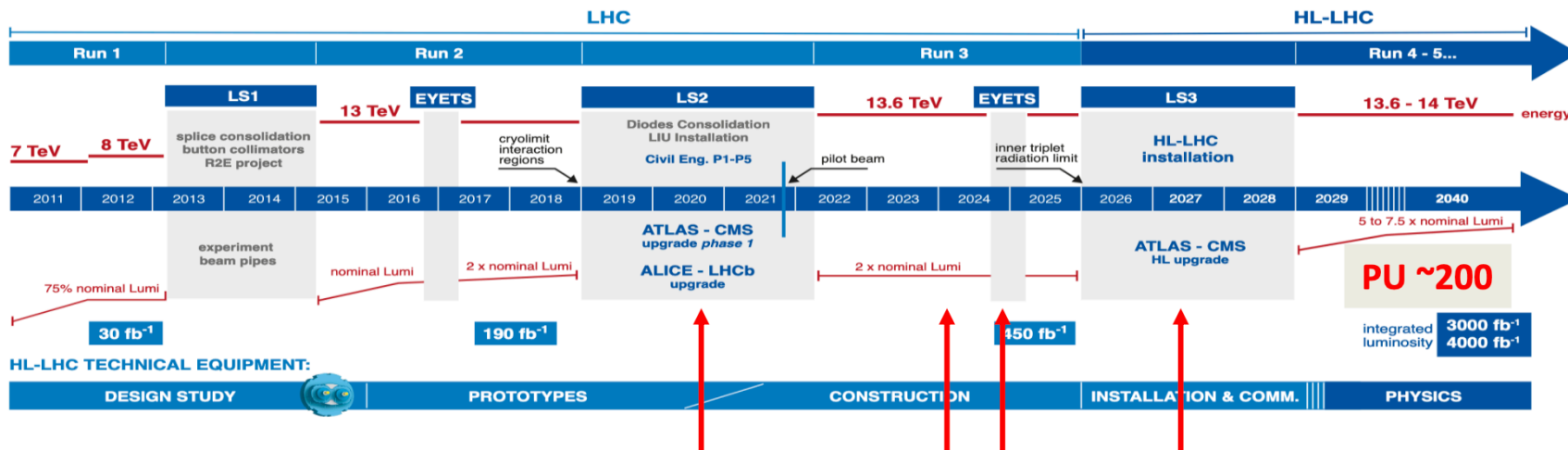
GEM detectors in front of the existing CSCs (Cathode Strip Chambers).

- Will increase the path length within the first muon station.
- Will improve muon momentum resolution,
- Reduce misidentified muons.





LHC / HL-LHC Plan

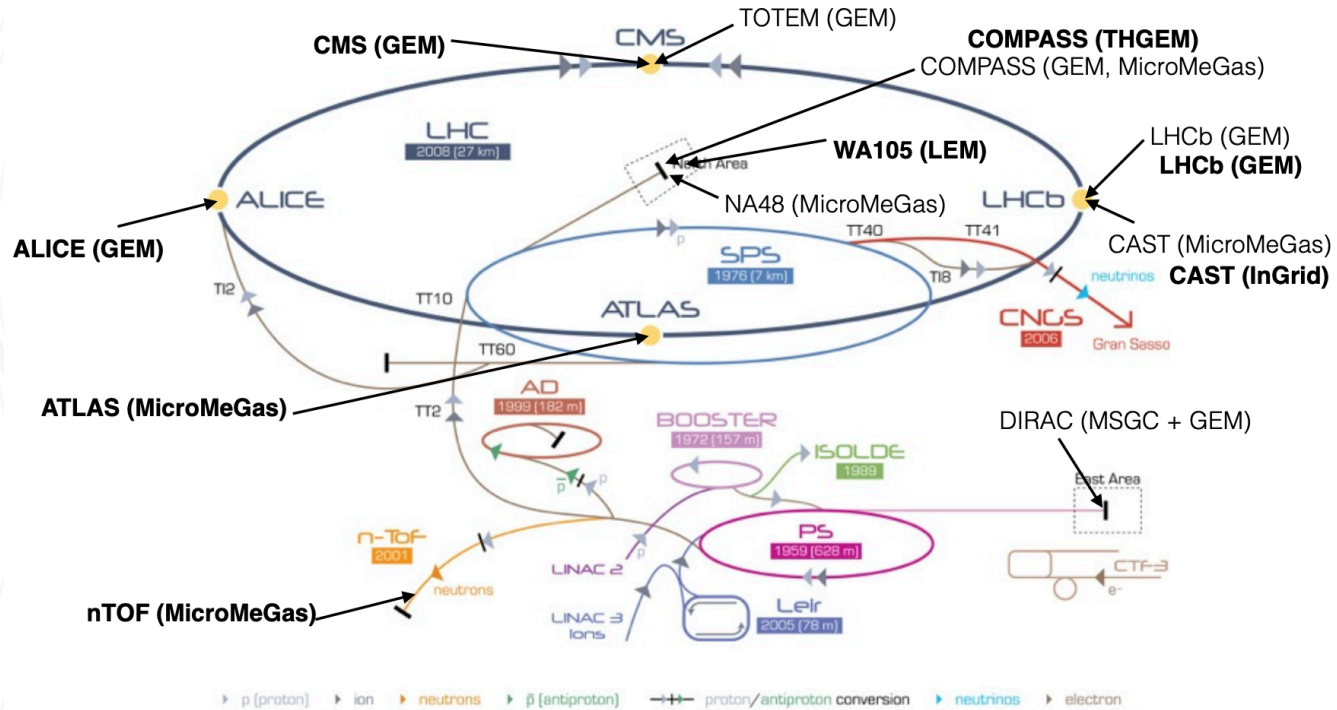


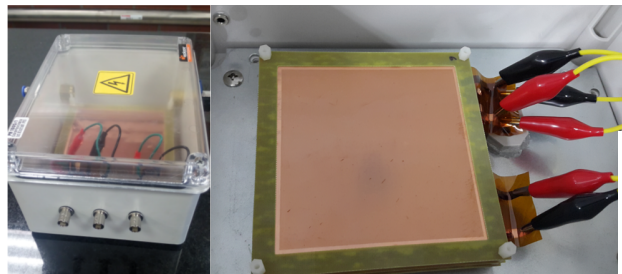
GE1/1

GE2/1

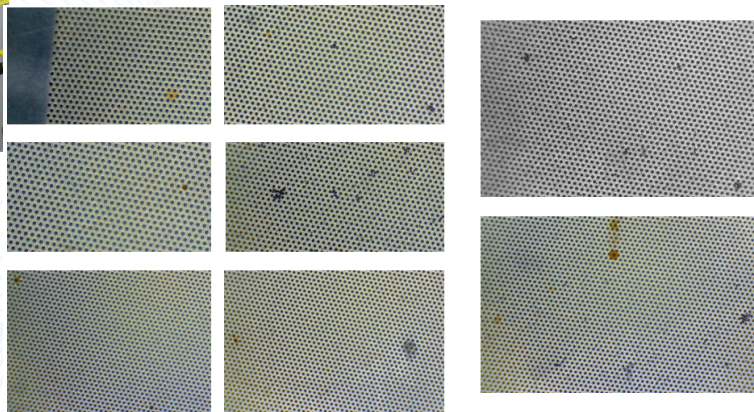
ME0

Future for GEMs at LHC

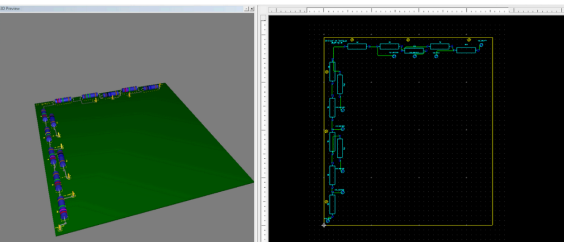




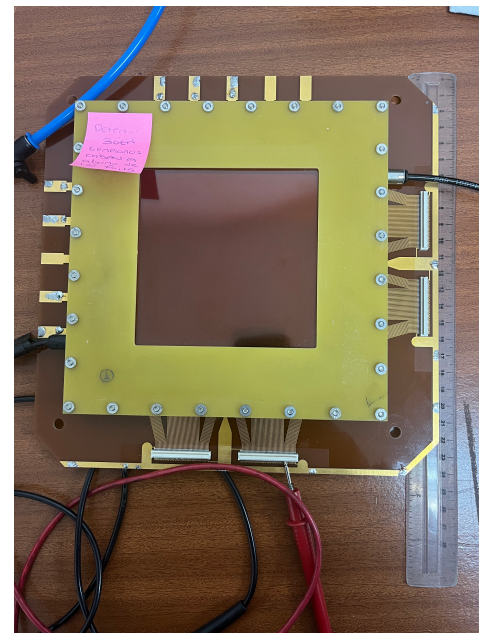
Testing box for electrical quality control test



Visual quality control performed using digital microscope

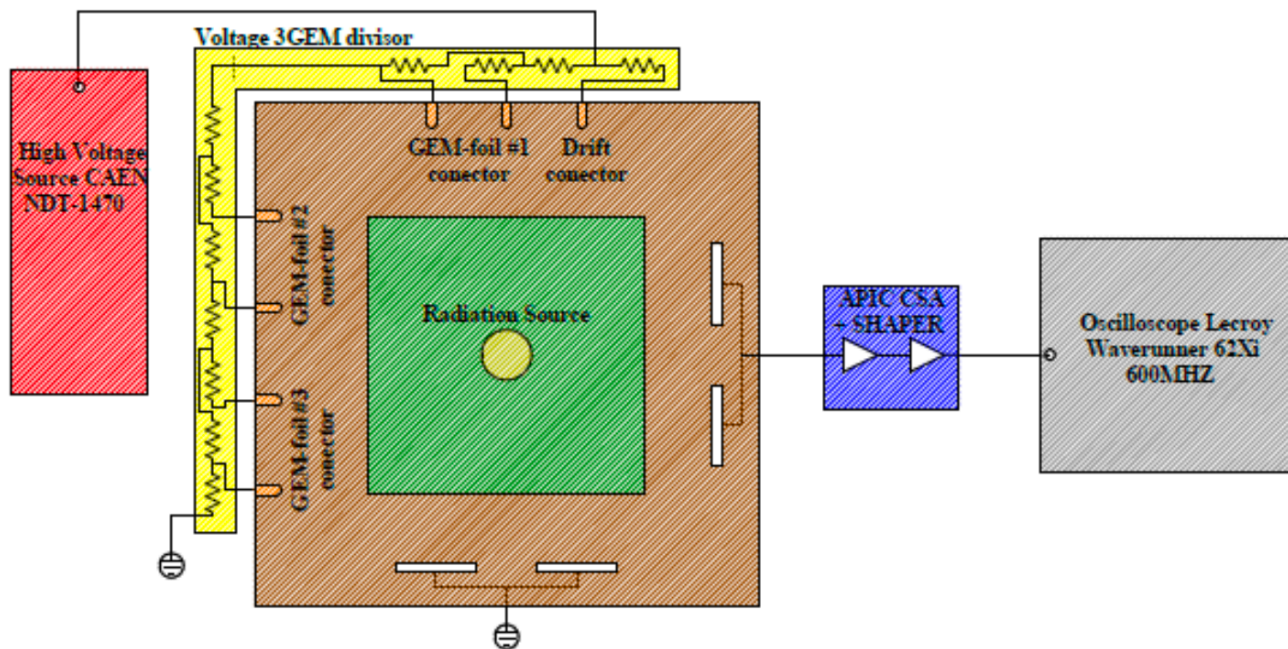


Voltage divider designed and assembled at UAN

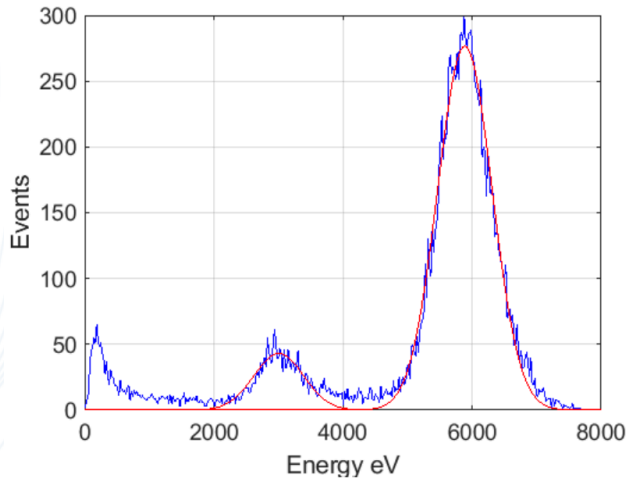


TGEM at UAN

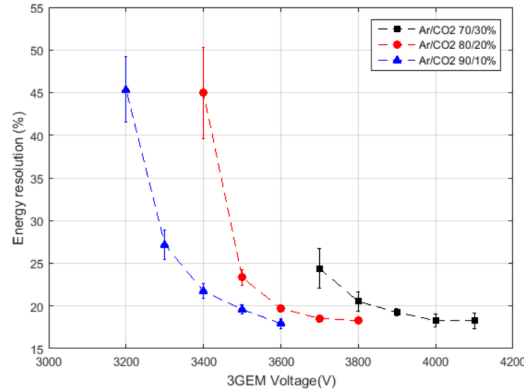
Testing GEMs with Fe55



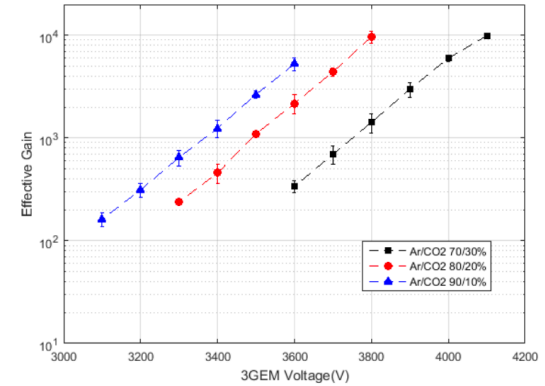
Testing GEMs with Fe55



Energy spectrum from ^{55}Fe
at 4100V and Ar/CO₂ 70/30

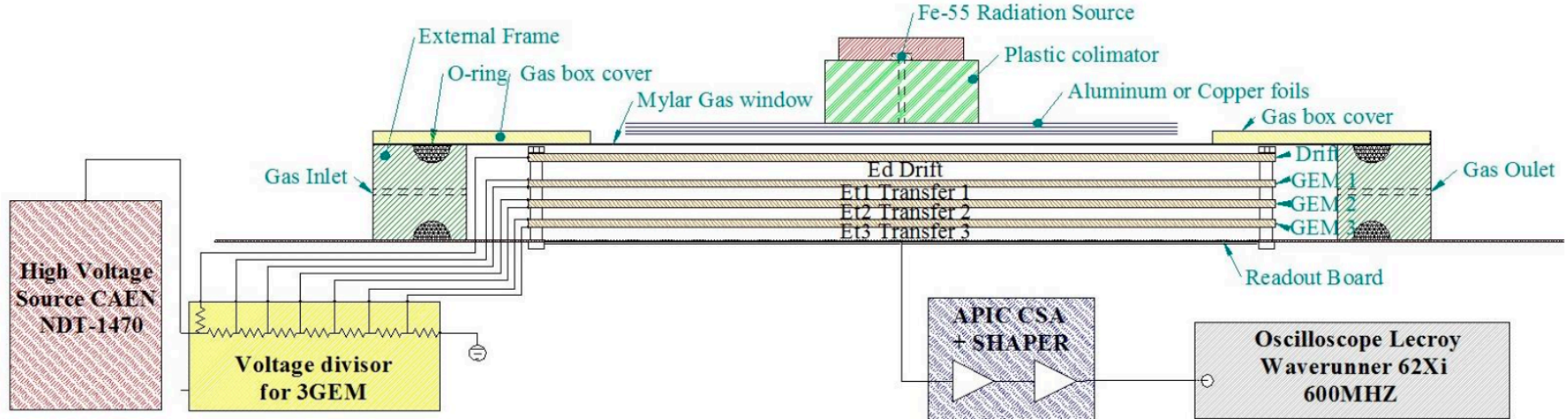


Energy resolution
from different voltages
and Ar/CO₂ mixtures

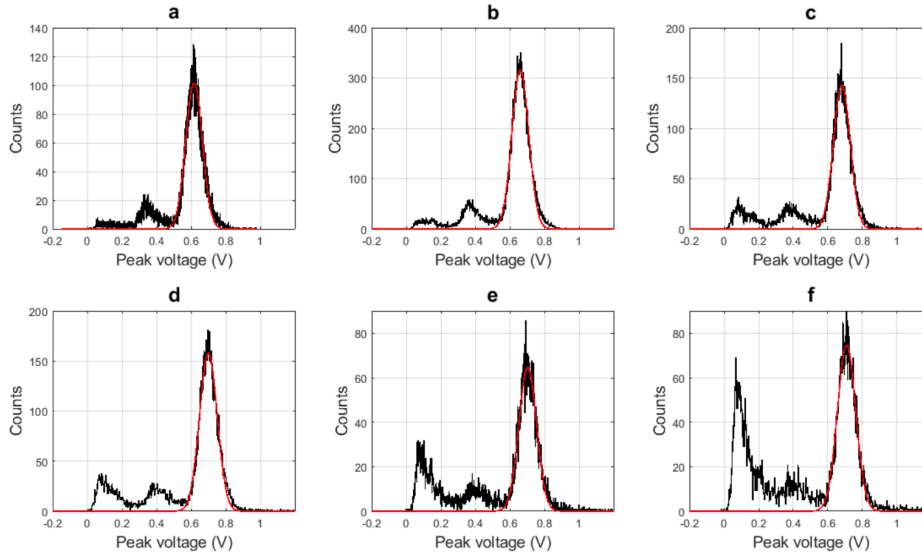


3GEM effective gain

Measuring thickness with GEMs



Measuring thickness with GEMS

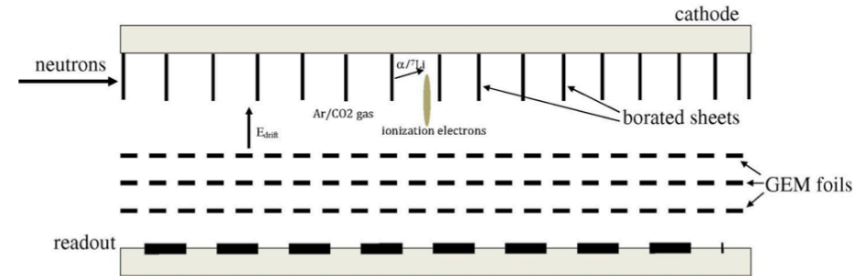
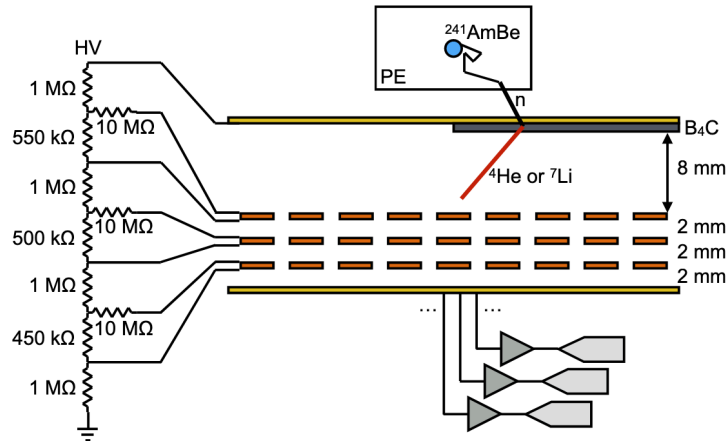


Patente de invención

“DISPOSITIVO Y MÉTODO PARA LA MEDICIÓN DEL ESPESOR DE LÁMINAS DELGADAS MEDIANTE DETECTOR MULTIPLICADOR GASEOSO DE ELECTRONES”

Energy spectrum from aluminum layers by the transmission of the Fe-55

Using GEMs for Neutron detection



- Neutron detectors based on MPGDs,” JINST 10 (2015) 04, P04004
- A solid layer of $^{10}\text{B}_4\text{C}$ of $1\ \mu\text{m}$ thickness sputtered onto a $25\ \mu\text{m}$ thick aluminium foil was used as neutron converter
- Reaction: $^{10}\text{B}(n, \alpha)^7\text{Li}$ and $^{10}\text{B}(n, \alpha\gamma)^7\text{Li}$

- Eur. Phys. J. Plus (2015) 130: 118 DOI 10.1140/epjp/i2015-15118-1. GEM-based detectors for thermal and fast neutrons.
- Neutrons impinge a lateral side epoxy glass window.
- $n + ^{10}\text{B} \rightarrow ^1\text{H} + ^7\text{Li}$ ($Q = 2.8\ \text{MeV}$, BR 7%)
- $n + ^{10}\text{B} \rightarrow ^1\text{H} + ^7\text{Li} + \gamma$ (478keV) ($Q = 2.3\ \text{MeV}$, BR = 93%)



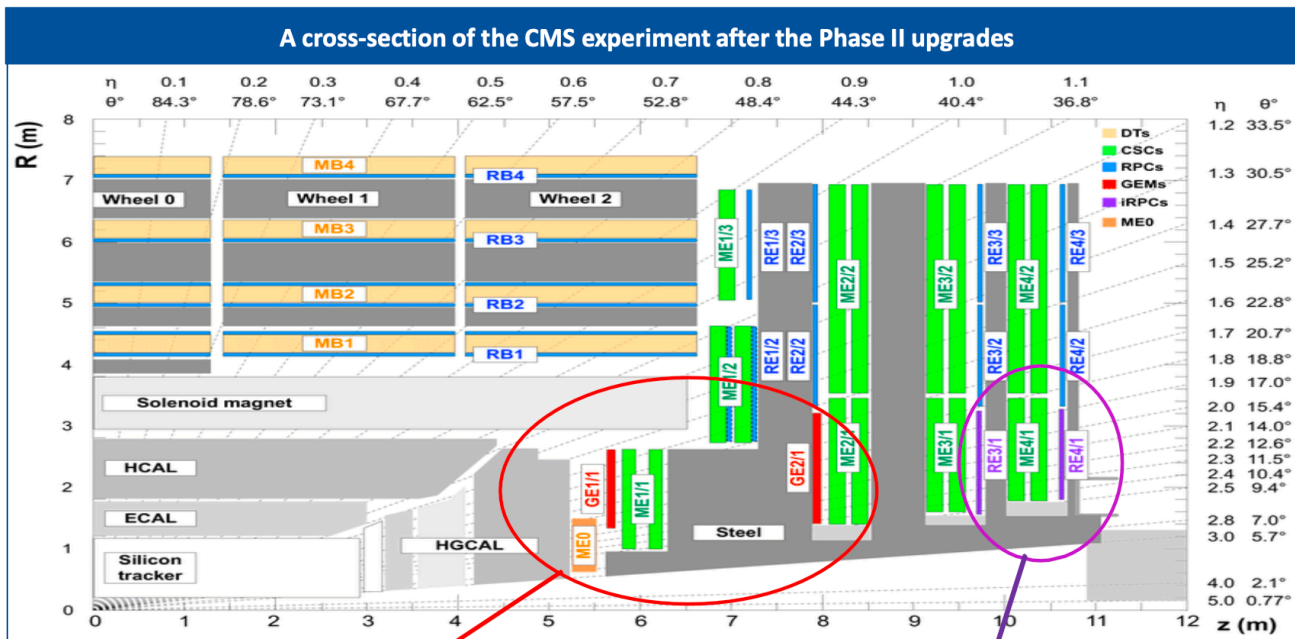
1. Very active community of developers and users of GEMs
2. Several applications and growing interest outside high energy physics
3. Thick GEMs are a new branch of development
4. New substrate materials (ceramic, teflon, FR4)
5. New methods for producing foils: laser bombardment, mechanical drilling
6. Adding more material: Scintillating glass, graphene



Gaseous detectors: Operating Principle

- Detection of Charged Particles → • Ionization, Bremsstrahlung, Cherenkov
- Detection of γ -Rays → • Photoelectric effect, Compton, Pair Prod.

Total charged produced and/or light emitted by the final Products is collected.



GEM upgrade: Three new stations
GE1/1, GE2/1 and MEO

RPC upgrade

Gaseous detectors: Frequently used gases

Gas	ρ (g/cm ³) (STP)	I_0 (eV)	W_i (eV)	dE/dx (MeVg ⁻¹ cm ²)	n_p (cm ⁻¹)	n_t (cm ⁻¹)
H ₂	$8.38 \cdot 10^{-5}$	15.4	37	4.03	5.2	9.2
He	$1.66 \cdot 10^{-4}$	24.6	41	1.94	5.9	7.8
N ₂	$1.17 \cdot 10^{-3}$	15.5	35	1.68	(10)	56
Ne	$8.39 \cdot 10^{-4}$	21.6	36	1.68	12	39
Ar	$1.66 \cdot 10^{-3}$	15.8	26	1.47	29.4	94
Kr	$3.49 \cdot 10^{-3}$	14.0	24	1.32	(22)	192
Xe	$5.49 \cdot 10^{-3}$	12.1	22	1.23	44	307
CO ₂	$1.86 \cdot 10^{-3}$	13.7	33	1.62	(34)	91
CH ₄	$6.70 \cdot 10^{-4}$	13.1	28	2.21	16	53
C ₄ H ₁₀	$2.42 \cdot 10^{-3}$	10.8	23	1.86	(46)	195



Gaseous detectors: Frequently used gases

Interaction of Charged Particles

Bethe-Bloch Equation (Quantum Calculation)

$$-\left\langle \frac{dE}{dx} \right\rangle = 2\pi N_a r_e^2 m_e c^2 \rho \frac{Z}{A} \frac{z^2}{\beta^2} \left[\ln\left(\frac{2m_e c^2 \beta^2 \gamma^2}{I^2} W_{\max}\right) - 2\beta^2 - \delta(\beta\gamma) - \frac{C}{Z} \right]$$

$$= 0.1535 \text{ MeV cm}^2/\text{g}$$

$$\frac{dE}{dx} \propto \frac{Z^2}{\beta^2} \ln(a\beta^2\gamma^2)$$

Fundamental constants

r_e = classical radius of electron
 m_e = mass of electron
 N_a = Avogadro's number
 c = speed of light

Absorber medium

I = mean ionization potential
 Z = atomic number of absorber
 A = atomic weight of absorber
 ρ = density of absorber
 δ = density correction
 C = shell correction

Incident particle

z = charge of incident particle
 β = v/c of incident particle
 γ = $(1-\beta^2)^{-1/2}$
 W_{\max} = max. energy transfer in one collision