DETECTOR TECHNOLOGIES

Lecture 1: Generalities

Gaseous detectors

Principle of operation

Proportional counters and beyond
Goal:
Observation and identification of final states (whatever the processus)

A particle is defined by its:
- Mass
- Electrical Charge
- Momentum
- Energy
- Lifetime
  (spin, flavour, color, ...)

A Detector: does not give any measurement.
Gives an information coming after an interaction between the particle and a medium, through energy deposition
Energy deposition
- **Limited** (the particle goes almost undisturbed)
  - Momentum
  - Electrical charge (if magnet)
    → Trajectography
- **Total** (the particle stops)
  - Energy

Various processes:
- **Ionization** (Bethe-Bloch)
- **Radiation** (Bremstrhalung or Transition Radiation)
- **Scattering** (Coulomb or direct)
- **Particle production** (photon)
- **Cerenkov** emission
Types of detectors:

Trackers (position and momentum measurement)
Calorimeters (energy measurement)
Identifiers (identification of various types of particles)
Trigger counters (decision)
Gaseous detectors : Principle of operation

E. Rutherford and H. Geiger (1908) "An electrical method of counting the number of α particles from radioactive substances," Proceedings of the Royal Society (London)

1. A charged particle is passing through a gaseous medium: loss of energy

\[
\frac{dE}{dx} = KZ^2 \frac{1}{A} \beta^2 \left[ \frac{1}{2} \ln \frac{2m c^2 \beta^2 \gamma^2 T_{\max}}{I^2} - \beta^2 - \frac{\delta(\beta \gamma)}{2} \right]
\]

\[
T_{\max} = \frac{2m \beta^2}{1 - \beta^2} \quad \text{Ex: proton 1 GeV/c^2}
\]

\[
T_{\max} = 1.2 \text{ MeV}
\]

K = 4 π N_A \text{ } \text{r_e}^2 \text{ } m_e = 0.3071

A, Z : atomic mass and number relative to the medium

N_A : Avogadro’s number

T_{\max} : maximum possible energy transferred to an electron in the medium

z : charge of the incoming particle

β, γ : relatives to the particle

Usually, we have to deal with MIPs

Minimum Ionizing Particles (βγ≈ 3-4)
2. **$E_i$**: Ionization Energy corresponds to the energy required to remove a single electron from a single atom (or molecule). Approximation: $E_i \approx 16Z^{0.9}$

3. If $T_{\text{max}} > E_i$ One or more pairs electron – ion is created

<table>
<thead>
<tr>
<th>Gas</th>
<th>$E_i$ (eV)</th>
<th>$\frac{dE}{dx}$ (MeV)</th>
<th>N pairs /cm</th>
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<tbody>
<tr>
<td>H2</td>
<td>15.4</td>
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<td>DME</td>
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4. If exists an **electrical field**: Electrons (and ions) are drifting ...

Signal...
Gaseous detectors: Principle of operation

First example: Geiger-Muller counter

Idea from Hans Geiger in 1913 – Development with Walther Muller in 1928

Radial Electrical field: \( E(r) = \frac{V_o}{r \ln \frac{r_a}{r}} \)

- \( r_a \) = anode radius
- \( r \) = counter radius

Signal collected \( V = \frac{N_e}{C} \)

Example: \( r = 1 \) cm
- Gas: Argon
- Particle = MIP \( \rightarrow 120 \) pairs
- \( C = 10 \) pF
- Signal: 2 \( \mu \)V

Extremely weak signal... (One electron = \( 10^{-9} \) Coulomb...)

But: what can append to the electrons (and ions) during the drift before collection?

It depends on the Electrical Field (applied voltage)
Gaseous detectors: Principle of operation

Collection - Ionization chamber:
All $e^-$ are drifting towards the anode.
Weak signal (typically $1 e^-$ for 30 eV)

Multiplication - proportionnal regime:
$E$ big enough for accelerating $e^-$ above $E_i$
Production of secondary $e^-$... Avalanche
Multiplication factor (Gain) can reach $10^5 - 10^6$
Saturation and Streamer mode - Geiger-Muller regime:

Electronic avalanche amplified by desexcitaion of ions through $\gamma$ (pair creation)
Saturation of the signal.
Loss of proportionnality

Breakdown: Continuous discharges between anode and cathode... Ultimate destruction...
Gaseous detectors: Principle of operation

Transport of electrons and ions in the gas:

With an electric field, electrons and ions are accelerated along the field lines. Their movement is interrupted by collisions (mean free path...) which limit the maximum average velocity.

This drift velocity is low compared to the thermal velocity.

The ion collection time is determinant!
Gaseous detectors: Principle of operation

**Choice of gas**: Of course, ionization exists in any possible gas.
- Maximum gain (primary electrons)
- Applied voltage as low as possible
- Avalanche with a good proportionality
- Drift velocity as high as possible

A good compromise: Noble gas (Ar, Xe, Ne...):

Example: Argon: 30 primary electrons
   Possible gain $10^3 - 10^4$
   e – drift velocity: 100 μm/nsec. at $E = 1kV/cm$

**Limitation**: Noble gas have an high excitation energy (typically 10-12 eV). Excited atoms formed in the avalanche desexcite giving photons which can ionize, causing further avalanche... ... Possible discharges.

**Solution**: the quencher

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Gaseous detectors: Principle of operation

Quencher: one has to add a polyatomic gas in order to absorb the photons created either by multiple collisions or molecule dissociation. Usually CH4, CO2, CF3, C2H4 ....

With a mixture of Noble gas – Quencher, one can achieve gains up to $10^6 - 10^7$

Magic Gas: 70% Ar, isobutane 29.6%, Fréon 0.4%.

Problem: after dissociation, the organic molecules will polymerize on the anode.
→ Loss of efficiency
→ Need gas circulation

One has to add another agent.... (alcohol...)

One of the BEST possible choice:
DME: Dymethylether $\text{CH}_3\text{OCH}_3$
   - No polymerization
   - Good gain ($10^6$)
   - But it is a solvant!
Gazeous detectors: Principle of operation

Recipe for a Gas detector

- **Thin** (minimization of $dE/dx$, does not perturb the particle trajectory)
- **Maximum gain** (choice of gas)
- **Stability** (High Voltage, choice of quencher)
- **Choice of material** (to avoid polymerization)
- **Precision** (by construction, placement...)

Evolution from **GM counter** to **Multiwire Proportional Chamber (MWPC)**

G. Charpak and all., 1968

Basic requirement for a gas detector: determination of particle trajectories
Gaseous detectors: MWPC

An array of closely spaced anode wires in the same volume

Is equivalent to

An array of proportional counters tubes
Gazeous detectors: MWPC

Classical figure of electrical field disturbed by a misplaced anode wire
Gaseous detectors: MWPC

Signal: as seen for the GM proportional counter:

\[ V = \frac{N_e}{C} \quad C = \frac{2\pi \varepsilon}{\ln \frac{r_a}{r}} \]

For an MWPC chamber (\( L \gg s \gg d \))

\[ C = \frac{2\pi \varepsilon}{\pi \frac{L}{s} - \ln \frac{\pi d}{s}} \]

Spatial resolution:

The charges due to the particle passing in the gas are distributed over more than one anode. The spatial resolution of a MWPC is the variance of this distribution.

\[ \sigma = \frac{a}{\sqrt{12}} \]

Typically \( \approx 200 \) µm

Signal formation time: depends on the drift time for electrons (typically 50 nsec)

Dead time: depends on the drift time for the ions (typically 200 nsec)
Gazeous detectors: MWPC limitations

**Limitation 1**: Typically: anode spacing of the order of 1-1.5 mm
(Résolution ≈ 200 – 500 µm)
In order to improve the spatial résolution: closer anodes?
Does not work. Instabilities due to electrostatic forces anode-anode.

**Limitation 2**: MWPC can measure only one coordinate.
A second MWPC?
X-Y coordinate with a second anode row

Precision: \( \Delta \alpha \approx \frac{1}{L} \sigma \)
One can reduce the wire spacing...
Or increase L (dimensions...)
Gazeous detectors: MWPC evolution

Cathode read-out chamber: One anode plan
Segmented cathode plan
Analog read-out

The features of one chamber module of the final stack were the following:
- half gap: $5 \pm 0.02$ mm
- anode pitch: 4 mm
- anode wire diameter: 20 $\mu$m
- cathode strip pitch: 10 mm
- cathode strip width: 9 mm
- sensitive area: $1100 \times 970 \text{ mm}^2$
- gas composition: Ar 80% + CO$_2$ 20% (vol).

The total stack thickness was 1 radiation length.

Spatial localization was investigated by comparing the analog chamber results with the information given by the set of digital MWPCs. A value of $\sigma = 2.4$ mm (98% of events inside 10 mm) was obtained for 4 GeV shower electrons after 4 radiation lengths (fig. 8). The resolution deteriorated quickly for lower energies ($\sigma = 5.9$ mm, 91% of events inside 10 mm at 2 GeV) and for wider strips ($\sigma = 5.3$ mm, 86% of events inside 10 mm for 4 GeV electrons, when going from 8 mm to 16 mm strip width).

Experiment R704 (CERN) 1981 - 1985
Gaseous detectors: Pad chambers

Direct 2-D detector: Pad chambers

cathode segmented in pads

Needs a lot of electronics

Pads regrouped in cells

PHENIX experiment
Gaseous detectors: Pad chambers

PHENIX at RHIC
Gazeous detectors : Pad chambers

<table>
<thead>
<tr>
<th>chamber</th>
<th>Wire dist (mm)</th>
<th>Z-resol. (mm)</th>
<th>Perp res (mm)</th>
<th>Rad. Thickn.</th>
</tr>
</thead>
<tbody>
<tr>
<td>PC1</td>
<td>8.4</td>
<td>1.7</td>
<td>2.5</td>
<td>1.2%</td>
</tr>
<tr>
<td>PC2</td>
<td>13.6</td>
<td>3.1</td>
<td>3.9</td>
<td>2.4%</td>
</tr>
<tr>
<td>PC3</td>
<td>16.0</td>
<td>3.6</td>
<td>4.6</td>
<td>2.4%</td>
</tr>
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**Gazeous detectors: Drift Chambers**

A drift chamber is a particle tracking detector that measures the drift time of ionization electrons in a gas to calculate the spatial position of ionizing (charged) particles. Similar to MWPC, but with better accuracy.

Measure of the position of the particle by measuring the drift time of the electrons

Need:
- Precise knowledge of drift velocities
- Precise timing (trigger)

![Diagram](image)

\[ X = V_d \Delta t \]

Possible resolution down to 50 µm
Gazeous detectors: Drift Chambers

Main limitation: non-uniformity of the field (non-uniformity of the drift time)

Solution: defining a cell (basic unit of field)
Gaseous detectors: Drift Chambers

MarkII (1985 – 1990) big Drift Chamber

12 layers
Length: 2.3 m
Radius: 1.6 m
5732 sense wires (anodes)
31104 potential wires
Gas mixture: 89% Ar, 10% CO2, 1% methane
Gain: $2 \times 10^4$
Drift filed: 900 V/m
Spatial resolution: $\approx 150 \mu$m
Gaseous detectors: Drift Chambers

ATLAS DRIFTS TUBES (MUON SPECTROMETER)

370,000 tubes
Surface: 5,500 m²

Max counting rate: 20 Hz/m
Gas leak < 10⁻⁸ Bar.l/sec.
Wire tension tolerance: 17g
Wire position tolerance: 25 µm
Gazeous detectors: Drift Chambers
Gazeous detectors: Time Projection Chambers

TPC: « The best of the best evolution »
Combination of a Drift Chamber and a MWPC (Pad chamber)

- Position (X and Y measurements)
- Drift time (Z measurement)
- Huge (and empty) drift volume
- Multi channels (read out pads)
- Drift volume full of ions
  → séparation for the avalanche region
Gaseous detectors: Time Projection Chambers – The ALICE TPC at LHC

Length: 5 meter
Radius: 2.5 meter
Gas volume: 83 m³
Total drift time: 92 µs
High voltage: 100 kV
End-cap detectors: 32 m²
Readout pads: 557568
159 samples radially
1000 samples in time
Gas: Ne/CO₂/N₂ (90-10-5)
Low diffusion (cold gas)
Gain: > 10⁴
Diffusion: σ₁ = 250 µm
Resolution: σ ≈ 0.2 mm
σₚ/ρ ≈ 1%; ε ≈ 97%
σₑ/ₑdx/(dE/dx) ≈ 6%
Magnetic field: 0.5 T
Pad size: 5x7.5 mm² (inner)
6x15 mm² (outer)
Temperature control: 0.1 K
Gaseous detectors: Time Projection Chambers – The ALICE TPC at LHC

Fig. 6. Space point resolution in pad direction (momentum plane) as a function of drift length. Solid line shows the fit and dashed line the extrapolation.

Fig. 7. Space point resolution in drift direction as a function of drift length. Solid line shows the fit and dashed line the extrapolation.

<table>
<thead>
<tr>
<th></th>
<th>Experiment</th>
<th>Monte Carlo</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sigma_{\phi}$ (µm)</td>
<td>800 ± 80</td>
<td>900</td>
</tr>
<tr>
<td>$\sigma_z$ (µm)</td>
<td>900 ± 100</td>
<td>900</td>
</tr>
</tbody>
</table>
Gaseous detectors: Resistive Plate Chamber

RPC: Thin (2 mm) drift volume sandwiched between Two highly resistive ($2.5 \times 10^{10} \, \Omega \cdot \text{cm}$) plates
Simple – inexpensive – fast (used as trigger)

Thin drift volume and High field
Works usually in streamer mode
Large signal, but slow (100 nsec)

At LHC: in avalanche mode
Lower signal, but fast (1-10 nsec)
Resistive plates: $1 \times 10^{12} \, \Omega \cdot \text{cm}$
Gas mixture:
$\text{C}_2\text{H}_2\text{F}_4$ (92.5 %)–$\text{C}_4\text{H}_{10}$ (4.5%) – $\text{SF}_6$ (0.3%)
HV: 8.5 – 9.7 kV
RPC efficiency > 97%
Rate capability > 1 kHz/cm²
Operation efficiency plateau > 400 V
Time resolution < 3 ns
Cluster size < 3
Dead time should be few nano seconds
Gaseous detectors: Straw Chambers

**SWPC**: Single Wire Proportional Chamber
Single proportional counter in an array
- Cheap and simple to build
- Capable of withstanding very high fluxes

![SWPC Diagram](image-url)

*OT double layer cross section*
Gaseous detectors: Straw Chambers

**Straw Chambers**: the ATLAS read-out system for the Transition Radiation Tracker

- 372000 straw proportional tubes
- $|\eta|<2.5$
- Xe-CO$_2$ -O$_2$, 70%, 27%, 3%
- Gain $\sim$2.5-4 $10^4$
- 4ns e- collection time in B=2T

**Beam test result:**

Hit efficiency: 96.7 ± 0.8%

Drift-time accuracy: 133 ± 4 cm
Gazeous detectors: MicroStrips Gas Detector

MSGC: following an idea of Oed (1989):
A MWPC where the wires are replaced by strips deposited on an insulating substrate (glass)

High field: gain $\approx 10^4$
Spatial resolution: $\sigma \approx 20 \mu m$
Dead time $\approx 10^{-5}$ sec.
(Short distance for the ions)
Gas: Ar – DME / Ne - DME
Gazeous detectors: MicroStrips Gas Detector

MWPC
anode spacing: 1-3 mm

MSGC
anode spacing 200 µm

Rate capability comparison
MSGC seems to be well adapted to high fluxes of particles (LHC)
Gaseous detectors: MicroStrips Gas Detector

Energy resolution ~11% for 5.9 keV

Spatial resolution = 34.5 ± 0.4 μm
2-track resolution ~400 μm
Gaseous detectors: MicroStrips Gas Detector

Surface charging: Bulk or surface resistivity of the support material is modified by irradiation (flux)
Choice of support (special glass or doping)

Ageing: Polymerization due to construction material (DME is a solvent)
Choice of non-solvable material in DME

Discharges: Possible with higher flux or low energetic particles
Certain with dust (short between anode and cathode (50 µm))
Gazeous detectors: MicroStrips Gas Detector

**Cathode edge passivation**

![Diagram of Cathode edge passivation]

- advanced passivation: polyimide (2μm)
- metal: gold (0.5-0.8μm)
- undercoating: Pespov or S8900 glass (0.5-1μm)
- substrate: Desag glass (300 μm)

**Advanced passivation**

**Standard passivation**
Gazeous detectors: Gas Electron Multiplier

GEM (on a MSCG): préamplification at ≈ 100 µm above the substrate kapton foil (copper coated) with amplification holes
Gaseous detectors: MSGC + GEMs

**MicroStrip Gas Chamber**

CMS (rejected)
Advanced passivated MSGC
Telescope of 32 MSGCs tested at
PSI in Nov99 (CMS Milestone)

**Compass**

**HERA-B Inner Tracker**
MSGC-GEM detectors
$R_{min} \sim 6 \text{ cm}$
$10^8 \text{ particles/cm}^2\text{s}$
$300 \mu \text{m pitch}$
184 chambers: max 25x25 cm$^2$
$\sim 10 \text{ m}^2$; 140,000 channels

**D20 diffractometer at ILL**
for neutron detection
1D localisation
48 MSGC plates (8 cm x 15 cm)
Substrate: Schott 58900
Angular coverage: $160^\circ \times 5.8^\circ$
Position resolution: $2.57 \text{ mm (0.1}\arcmin)$
5 cm gap; 1.2 bar CF4 + 2.8 bars 3He
Efficiency 60% @ 0.8 Å

**DIRAC**
MSGC-GEM detectors
Hadron beam
$3 \times 10^8 \text{ particles/cm}^2\text{s}$
4 planes; 10x10 cm$^2$
Gazeous detectors: Micromegas

Micromegas: (G. Charpak and Y. Giomataris – 1992) is similar to a MSGC+GEM and a drift chamber. The cathode is a mesh at 100mm from the anodes (strip deposited on a substrate).

Y. Giomataris et al, NIM A 376 (1996) 29
Gazeous detectors: Micromegas

Limitation: Mesh spacers (loss of acceptance)

Prototype (1997)
Gazeous detectors: Micromegas

Compass
Set of 12 plates 40x40 cm$^2$

T2K / TPC
Set of 12 plates 40x40 cm$^2$
Example: The GE1/1 project for CMS:

Adding CF$_4$ to the « classic Ar/CO$_2$ mixture to increase the time response (5 nsec)

Effect: dissociation of CF$_4$ leads to HF (hydrofluoric acid) which etch the copper...

Example:
Etching of the GEM Holes (GE1/1 project)
Gaseous detectors: « New » Aging problems

In future machine (HL-LHC, FCC...) at very high Luminosity, the particle flux will degrade the performances of the detectors.

One has to test the irradiation effects!
But simulation is « impossible »....

Example:
Gain versus irradiation (corresponds to 10 years of Operation at CMS)
Gaseous detectors : Conclusions

Conclusion :
- Evolution of gaseous detectors : MGD (Micro Gap Detectors)
  - GEM
  - Micromégas
- Main problem for these detectors :
  - Cleaningness
  - Long term operation

EASY TO DESIGN

COMPLICATED TO BUILD

DIFFICULT TO OPERATE ON A LONG TERM BASIS
R&D on Big GEM Chambers: a nice nightmare!
R&D on Big GEM Chambers: 1. DEFINING THE PARAMETERS

Extensive study on GEM detectors:
- Basic operation with X-ray sources
- Calibration tests with different:
  - gas mixtures
  - GEM geometries
  - HV power systems
  - sizes of detectors
- Defining the best configuration

![Graph showing gas gain vs. current in divider (μA)]

Ar/CO2/CF4 (45/15/40)

![Graph showing energy spectrum (keV) with different isotopes: Am241, Cd109, Fe55)]
R&D on Big GEM Chambers: 2. VERIFYING THE PARAMETERS

Advanced measurements and characterization:
- General understanding on GEM technology
- Comparison with past measurements
- Charging up effects (short-term stability)
  - 5-10% after 1 hour
- Discharge probability
  - < $10^{-12}$ at a gain of $10^4$
- Rate capability
  - No gain loss up to 1 MHz/mm²
R&D on Big GEM Chambers : 3. BEAM TESTS

Detectors performances:
- Intense beam of charged particles
- All generations tested in different config. And B field.
- Characterization of the beam and comparison with the detector response
- Information about:
  - Efficiency
  - Space resolution
  - Time resolution
- Characterization of new electronics and DAQ systems

\[ \sigma_x < 300 \text{ \mu m (digital readout)} \]

Detector efficiencies above 98%
R&D on Big GEM Chambers: 4. LONG TERM TESTS...

Aging Test at CERN GIF
- $^{137}$Cs source 566 GBq
- Gamma emission 662 keV
R&D on Big GEM Chambers: 5. AGING TESTS

Outgassing Study:
- select “clean” materials to prevent self-contamination and increase longevity
- 9 materials already tested / 8 approved