The Basics of Particle Detection

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Outline

Lecture 1 – Interaction of charged particles

Lecture 2 – Gaseous and solid state tracking detectors
  • Concept of momentum measurement
  • Gas detectors
  • Solid state (Silicon) detectors
  • More interactions of charged particles and photons

Lecture 3 – Calorimetry, scintillation and photodetection
Momentum measurement

Momentum $p$

Measure the radius of curvature $\rho$ in a magnetic field
Momentum measurement (in solenoidal field)

\[ p_T = p \sin \theta \]

\[ L^2 - 4 \]
Momentum measurement

We measure only $p$-component transverse to B field!

$$p_T = qB\rho \quad \rightarrow \quad p_T \text{ (GeV/c)} = 0.3B\rho \quad (T \cdot m)$$

$$\frac{L}{2\rho} = \sin \alpha/2 \approx \alpha/2 \quad \rightarrow \quad \alpha \approx \frac{0.3L \cdot B}{p_T}$$

$$s = \rho(1 - \cos \alpha/2) \approx \rho \frac{\alpha^2}{8} \approx \frac{0.3L^2B}{8p_T}$$

the sagitta $s$ is determined by 3 measurements with error $\sigma(x)$:

$$s = x_2 - \frac{x_1 + x_3}{2} \quad \frac{\sigma(p_T)}{p_T} \bigg|_{\text{meas.}} = \frac{\sigma(s)}{s} = \sqrt{\frac{3}{2}} \frac{\sigma(x)}{s} = \sqrt{\frac{3}{2}} \frac{\sigma(x)}{0.3BL^2} \quad \frac{\sigma(p_T)}{p_T} \bigg|_{\text{meas.}} \propto \frac{\sigma(x) \cdot p_T}{BL^2}$$

for $N$ equidistant measurements, one obtains  
(R.L. Gluckstern, NIM 24 (1963) 381)

$$\frac{\sigma(p_T)}{p_T} \bigg|_{\text{meas.}} = \frac{\sigma(x) \cdot p_T}{0.3BL^2} \sqrt{\frac{720}{N + 4}} \quad \text{ (for } N \geq \sim 10)$$
Momentum measurement

What is the contribution of multiple scattering to \( \frac{\sigma(p)}{p_T} \)?

remember
\[
\frac{\sigma(p)}{p_T} \propto \sigma(x) \cdot p_T
\]
\[
\sigma(x) \propto \theta_0 \propto \frac{1}{p}
\]

More precisely:
\[
\left| \frac{\sigma(p)}{p_T} \right| = 0.045 \frac{1}{B \sqrt{LX_0}}
\]

Example:
\[p_t = 1 \text{ GeV/c}, \ L = 1 \text{m}, \ B = 1 \text{ T}, \ N = 10\]
\[\sigma(x) = 200 \mu\text{m}: \quad \left| \frac{\sigma(p_T)}{p_T} \right|^{\text{meas.}} \approx 0.5\%
\]

Assume detector (L = 1m) to be filled with 1 atm. Argon gas (\(X_0 = 110\)m),
\[
\frac{\sigma(p)}{p_T}^{\text{MS}} \approx 0.5\%
\]

Optimistic, since a gas detector consists of more than just gas!
A more realistic example: CMS Silicon Tracker

- B = 3.8 T, L = 1.25 m, average N \approx 10 layers,
- Average resolution per layer \approx 25 \mu m,

\[ \sigma(p_T)_{\text{meas.}} = \frac{\sigma(x) \cdot p_T}{0.3 \cdot B L^2} \sqrt{\frac{720}{(N + 4)}} \]

\[ \Rightarrow \sigma_p/p = 0.1 \% \text{ momentum resolution (at 1 GeV)} \]
\[ \Rightarrow \sigma_p/p = 10 \% \text{ momentum resolution (at 1 TeV)} \]

Material budget (Si, cables, cooling pipes, support structure...)

- B = 3.8 T, L = 1.25 m, \( t/X_0 \approx 0.4-0.5 \) @ \( \eta < 1 \)

\[ \sigma(p)_{\text{MS}} = 0.045 \frac{1}{B \sqrt{LX_0}} = 0.045 \frac{1}{B \cdot L} \sqrt{\frac{t}{X_0}} \]

\[ \Rightarrow \sigma_p/p = 0.7\% \text{ from multiple scattering} \]

(\( \eta = \text{pseudo rapidity: } \eta = -\ln(\tan \frac{\theta}{2}) \))
Ionisation of Gases

Fast charged particles ionise atoms of gas. Often, the resulting primary electrons will have enough kinetic energy to ionize other atoms.

\[
n_{\text{total}} = \frac{\Delta E}{W_i} = \frac{dE}{dx} \frac{\Delta x}{W_i}
\]

\[
n_{\text{total}} \approx 3 \ldots 4 \cdot n_{\text{primary}}
\]

- \(n_{\text{total}}\) - number of created electron-ion pairs
- \(\Delta E\) = total energy loss
- \(W_i\) = effective \(<\text{energy loss}>\)/pair

Number of primary electron/ion pairs in frequently used gases.
Visualization of charge clusters and $\delta$ electrons

Cluster counting with a hybrid gas detector: pixel readout chip + micromegas

He / isobutane 80/20

Micromegas foil

Medipix chip
256 x 256 pixels,
55 x 55 $\mu m^2$, each

~ 14 x 14 mm$^2$

15 mm

50 $\mu m$

track by cosmic particle (mip): 0.52 clusters / mm, ~3 e$^-$/cluster

M. Campbell et al., NIM A 540 (2005) 295
The actual number of primary electron/ion pairs is Poisson distributed.

\[ P(m) = \frac{\mu^m e^{-\mu}}{m!} \]

The detection efficiency is therefore limited to:

\[ \varepsilon_{\text{det}} = 1 - P(0) = 1 - e^{-\mu} \]

For thin layers \( \varepsilon_{\text{det}} \) can be significantly lower than 1.

For example for 1 mm layer of Ar \( n_{\text{primary}} = 2.5 \rightarrow \varepsilon_{\text{det}} = 0.92 \).

Consider a 10 mm thick Ar layer

\[ n_{\text{primary}} = 25 \rightarrow \varepsilon_{\text{det}} = 1 \]
\[ n_{\text{total}} = 80-100 \]
100 electrons/ion pairs created during ionization process are not easy to detect. Typical (equivalent) noise of an electronic amplifier ≈ 1000 e⁻

→ we will increase the number of charge carriers by gas amplification.
Single Wire Proportional Chamber

Electrons liberated by ionization drift towards the anode wire.

Electrical field close to the wire (typical wire Ø~few tens of µm) is sufficiently high for electrons (above 10 kV/cm) to gain enough energy to ionize further

→ avalanche → exponential increase of number of electron ion pairs → several thousands.

→ the signal becomes detectable.

\[ E(r) = \frac{CV_0}{2\pi \varepsilon_0} \cdot \frac{1}{r} \]

\[ V(r) = \frac{CV_0}{2\pi \varepsilon_0} \cdot \ln \frac{r}{a} \]

where:

- \( E(r) \) is the electrical field
- \( V(r) \) is the voltage
- \( C \) is the capacitance/unit length
- \( r \) is the radial distance
- \( a \) is the anode size

\( CV_0 \) is the total capacitance

\( 2\pi \varepsilon_0 \) is the permittivity of free space

\( E_{\text{threshold}} \) is the threshold electrical field

\( \ln \) is the natural logarithm
Multiplication of ionization is described by the first Townsend coefficient $\alpha(E)$

$$dn = n \cdot \alpha \, dx \quad \alpha = \frac{1}{\lambda} \quad \lambda \text{ – mean free path}$$

$$n = n_0 e^{\alpha(E) x} \quad \text{or} \quad n = n_0 e^{\alpha(r)x}$$

$\alpha(E)$ is determined by the excitation and ionization cross sections of the electrons in the gas.

It depends also on various and complex energy transfer mechanisms between gas molecules. There is no fundamental expression for $\alpha(E) \rightarrow$ it has to be measured for every gas mixture.

$$M = \frac{n}{n_0} = \exp \left[ \int_{a}^{r_c} \alpha(r) \, dr \right] \quad \text{Amplification factor or Gain}$$

$(E/p = \text{reduced electric field})$
In noble gases, ionization is the dominant process, but there are also excited states.

De-excitation of noble gases only via emission of photons; e.g. 11.6 eV for Ar.
This is above ionization threshold of metals, e.g. Cu 7.7 eV.
→ new avalanches → permanent discharges!

Solution: addition of polyatomic gas as a quencher
Absorption of photons in a large energy range (many vibrational and rotational energy levels).

Energy dissipation by collisions with gas molecules or dissociation into smaller molecules.
### SWPC – Operation Modes

- **ionization mode** – full charge collection, but no charge multiplication; gain ~ 1
- **proportional mode** – multiplication of ionization starts; detected signal proportional to original ionization → possible energy measurement (dE/dx); secondary avalanches have to be quenched; gain ~ $10^4 – 10^5$
- **limited proportional mode** (saturated, streamer) – strong photoemission; secondary avalanches merging with original avalanche; requires strong quenchers or pulsed HV; large signals → simple electronics; gain ~ $10^{10}$
- **Geiger mode** – massive photoemission; full length of the anode wire affected; discharge stopped by HV cut; strong quenchers needed as well
Avalanche formation within a few wire radii and within $t < 1 \text{ ns}$. Signal induction both on anode and cathode due to moving charges (both electrons and ions).

\[
dv = \frac{Q}{lCV_0} \frac{dV}{dr} dr
\]

Electrons collected by the anode wire i.e. $dr$ is very small (few $\mu$m). Electrons contribute only very little to detected signal (few %).

Ions have to drift back to cathode i.e. $dr$ is large (few mm). Signal duration limited by total ion drift time.

Need electronic signal differentiation to limit dead time.
Multiwire Proportional Chamber

Simple idea to multiply SWPC cell: Nobel Prize 1992

First electronic device allowing high statistics experiments!!

Typical geometry
5mm, 1mm, 20 μm

Normally digital readout:
spatial resolution limited to

\[ \sigma_x \approx \frac{d}{\sqrt{12}} \]

for \( d = 1 \text{ mm} \) \( \sigma_x = 300 \text{ μm} \)

G. Charpak, F. Sauli and J.C. Santiard
Cylindrical geometry is not the only one able to generate strong electric field:

- Parallel plate
- Strip
- Hole
- Groove

MicroMegas

GEM

Ø 50-70 µm

Kapton

Copper
From 1D to 2D detectors

Crossed wire plane → 2N channels
However: ghost hits (≥2 particles)

Stereo geometry (e.g. ±5°) → 2N channels.
One coordinate has worse resolution than other.
Ghost hits only local.

True 2D readout. Signals from wires are induced on readout plane just behind wires. → N² channels!
Drift Chambers

Spatial information obtained by measuring time of drift of electrons

- Measure arrival time of electrons at sense wire relative to a time $t_0$.
- Need a trigger (bunch crossing or scintillator).
- Drift velocity independent from E.

Advantages: smaller number of wires → less electronics channels.

Resolution determined by diffusion, primary ionization statistics, path fluctuations and electronics.

$v_{\text{drift}} \sim 5 \text{ cm/\mu s}$
The Basics of Particle Detection

TPC – Time Projection Chamber

Time Projection Chamber
full 3D track reconstruction:

- \( x-y \) from wires and segmented cathode of MWPC (or GEM)
- \( z \) from drift time
- momentum measurement:
  space resolution + B field (multiple scattering)
- \( \text{dE/dx} \) measurement:
  measurement of primary ionization \( \rightarrow \sim \beta \)
- Particle ID

\[ m_0 = \frac{p}{\beta \gamma c} \]
Alice TPC

HV central electrode at −100 kV
Drift length 250 cm at \( E = 400 \text{ V/cm} \)
Gas Ne-CO\(_2\) 90-10
Space point resolution \( \sim 500 \text{ \mu m} \)
\( dp/p = 2\% @ 1 \text{GeV/c}; 10\% @ 10 \text{ GeV/c} \)

Events from STAR TPC at RHIC
Au-Au collisions at CM energy of 130 GeV/n
Typically \( \sim 2000 \) tracks/event
Gas Detectors in LHC Experiments

ALICE: TPC (tracker), TRD (transition rad.), TOF (MRPC), HMPID (RICH-pad chamber),
Muon tracking (pad chamber), Muon trigger (RPC)

ATLAS: TRD (straw tubes), MDT (muon drift tubes), Muon trigger (RPC, thin gap chambers)

CMS: Muon detector (drift tubes, CSC), RPC (muon trigger)

LHCb: Tracker (straw tubes), Muon detector (MWPC, GEM)

TOTEM: Tracker & trigger (CSC, GEM)
Solid state detectors = mostly Silicon detectors

We are looking for a detector to overcome some of the limitations of the gaseous detectors
• Small primary signal $\rightarrow$ need of gas amplification (not discussed: aging, rate limitations)
• Moderate spatial resolution (100 μm)
• Massive frames, high voltage, gas circulation

Silicon (also GaAs, diamond) is a very promising material

- ultra pure crystalline material
- $\rho_{\text{Si}} = 2.33 \text{ g/cm}^3$
- Energy loss of particles in Si = 3.8 MeV/cm
- E(e-h pair) = 3.6 eV (≈ 20-30 eV for gas detectors)
- A particle traversing 300 μm of Si creates $\sim 30'000$ e/h pairs

BUT: Si is a semiconductor. It contains already free charge carriers.

At room temperature, in $1 \times 1 \times 0.03 \text{ cm}^3$, there are $4.5 \cdot 10^8$ free charge carriers. We have to eliminate the free charges (= deplete the detector), such that our signal can be seen.

→ Use the principle of the pn junction
1. Dope Silicon with acceptor and donor atoms

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Boron: extra free holes → p-Si

Phosphor: extra free electrons → n-Si

2. Bring the two doped regions in contact

3. In the interface region holes and electrons will neutralise each other and create a depleted zone without any free charge carriers.

4. The resulting electric field separates newly created free charges → signal current

5. An external (reverse bias) voltage depletes the whole volume and makes it sensitive.
In the real world, Si-sensors are not produced by joining p and n doped material, but by implanting acceptors in a n-doped bulk (or donors in a p-doped bulk).

Simplest example: **(PIN) photodiode**

More complex: **Si microstrip detector**
Highly segmented silicon detectors have been used in Particle Physics experiments for 30 years. They are the favourite choice for Tracker and Vertex detectors (high resolution, speed, low mass, relatively low cost).

A real detector with 2 sensors, pitch adapter, readout electronics and flex cable

- **Pitch ~ 50μm**
- **Resolution ~ 5μm**
• HAPS – Hybrid Active Pixel Sensor
  • segment silicon to diode matrix with high granularity readout (⇒ true 2D, no reconstruction ambiguity)
  • electronic with same geometry (every cell connected to its own processing electronics)
  • connection by “bump bonding”
  • requires sophisticated readout architecture
  • Hybrid pixel detectors are/will be used in LHC experiments: ATLAS, ALICE, CMS and LHCb
Particle Identification via their lifetime

High resolution silicon detectors allow to observe secondary and tertiary vertices.

\[
\begin{align*}
\text{PV} & : \quad \mu \rightarrow x + B_s \\
\bar{B}_s & \rightarrow D_s^+ + \mu^- \\
D_s^+ & \rightarrow \pi + K^+ + K^- \\
\end{align*}
\]

\[\tau_0(B_s) \approx 1.5 \text{ ps}\]
\[\tau_0(D_s^+) \approx 0.4 \text{ ps}\]
Silicon tracking detectors are used in all LHC experiments: Different sensor technologies, designs, operating conditions, ….
Interaction of charged particles

**Energy loss by Bremsstrahlung**

Radiation of real photons in the Coulomb field of the nuclei of the absorber medium

\[-\frac{dE}{dx} = 4\alpha N_A \frac{Z^2}{A} Z^2 \left( \frac{1}{4\pi \varepsilon_0} \frac{e^2}{mc^2} \right)^2 E \ln \frac{183}{Z^{1/3}} \propto \frac{E}{m^2}\]

Effect is only relevant for $e^\pm$ and ultra-relativistic $\mu$ (>1000 GeV)

For electrons:

\[-\frac{dE}{dx} = 4\alpha N_A \frac{Z^2}{A} r_e^2 E \ln \frac{183}{Z^{1/3}}\]

\[-\frac{dE}{dx} = \frac{E}{X_0}\]

energy loss is proportional to actual energy

\[E = E_0 e^{-x/X_0}\]

$X_0 = \frac{A}{4\alpha N_A Z^2 r_e^2 \ln \frac{183}{Z^{1/3}}}$

radiation length [g/cm²]

(divide by specific density to get $X_0$ in cm)
Interaction of charged particles

**Critical energy \( E_c \)**

\[
\frac{dE}{dx}(E_c) \bigg|_{Brems} = \frac{dE}{dx}(E_c) \bigg|_{ion}
\]

For electrons one finds approximately:

\[
E_c^{solid+liq} = \frac{610 \text{ MeV}}{Z + 1.24} \quad E_c^{gas} = \frac{710 \text{ MeV}}{Z + 1.24}
\]

\( E_c(e^-) \) in Cu \((Z=29) = \approx 20 \text{ MeV} \)

For muons \( E_c \approx E_c^{elec} \left( \frac{m_\mu}{m_e} \right)^2 \)

\( E_c(\mu) \) in Cu \( \approx 1 \text{ TeV} \)

Unlike electrons, muons in multi-GeV range can traverse thick layers of dense matter.

Find charged particles traversing the calorimeter? → most likely a muon → Particle ID
Interaction of photons

In order to be detected, a photon has to create charged particles and / or transfer energy to charged particles

**Photo-electric effect:**

\[ \gamma + \text{atom} \rightarrow \text{atom}^+ + e^- \]

Only possible in the close neighborhood of a third collision partner → photo effect releases mainly electrons from the K-shell.

Cross section shows strong modulation if \( E_\gamma \approx E_{\text{shell}} \)

\[
\sigma_{\text{photo}}^K = \left( \frac{32}{\varepsilon^7} \right)^{\frac{1}{2}} \alpha^4 Z^5 \sigma_{Th}^e \quad \varepsilon = \frac{E_\gamma}{m_e c^2} \quad \sigma_{Th}^e = \frac{8}{3} \pi r_e^2 \quad (\text{Thomson})
\]

At high energies (\( \varepsilon \gg 1 \))

\[
\sigma_{\text{photo}}^K = 4 \pi r_e^2 \alpha^4 Z^5 \frac{1}{\varepsilon} \quad \sigma_{\text{photo}} \propto Z^5
\]
Interaction of photons

Compton scattering:

\[ \gamma + e \rightarrow \gamma' + e' \]

\[ E_\gamma' = E_\gamma \left( \frac{1}{1 + \epsilon (1 - \cos \theta_\gamma)} \right) \]

\[ \epsilon = \frac{E_\gamma}{m_e c^2} \]

\[ E_e = E_\gamma - E_\gamma' \]

Assume electron as quasi-free.

Klein-Nishina

\[ \frac{d\sigma}{d\Omega}(\theta, \epsilon) \]

At high energies approximately

\[ \sigma_c^e \propto \frac{\ln \epsilon}{\epsilon} \]

Atomic Compton cross-section:

\[ \sigma_c^{\text{atomic}} = Z \cdot \sigma_c^e \]
Detection of 511 keV (annihilation) photons in a LYSO crystal scintillator (Lu\(_{2-x}\)Y\(_x\)SiO\(_5\) (with x~0.1-0.2))

Compton:

\[ E'_\gamma = E_\gamma \frac{1}{1 + \varepsilon (1 - \cos \theta_\gamma)} \]
\[ \varepsilon = \frac{E_\gamma}{m_e c^2} \]
\[ E_\gamma = 511 \text{ keV} \rightarrow \varepsilon = 1 \]

\[ E_{\gamma}^{\text{min}} = E'_\gamma (\theta = 180^\circ) = E_\gamma \frac{1}{1 + 2\varepsilon} = E_\gamma / 3 \approx 170 \text{ keV} \]
\[ E_e^{\text{max}} = E_\gamma - E_{\gamma}^{\text{min}} = 511 - 170 = 340 \text{ keV} \]
Interaction of photons

- **Pair production**

\[ \gamma + \text{nucleus} \rightarrow e^+ e^- + \text{nucleus} \]

Only possible in the Coulomb field of a nucleus (or an electron) if \( E_\gamma \geq 2m_e c^2 \)

Cross-section (high energy approximation)

\[ \sigma_{pair} \approx 4\alpha e^2 Z^2 \left( \frac{7}{9} \ln \frac{183}{Z^3} \right) \]

\[ \approx \frac{7}{9} \frac{A}{N_A} \frac{1}{X_0} \]

\[ \approx \frac{A}{N_A} \frac{1}{\lambda_{pair}} \]

\[ \lambda_{pair} = \frac{9}{7} X_0 \]

Energy sharing between e\(^+\) and e\(^-\) becomes asymmetric at high energies.

\[ \gamma + e^- \rightarrow e^+ e^- + e^- \]

\[ \gamma + \text{nucleus} \rightarrow e^+ e^- + \text{nucleus} \]
Interaction of photons

In summary: \( I_\gamma = I_0 e^{-\mu x} \)

\( \mu \): mass attenuation coefficient
\[ \mu_i = \frac{N \sigma_i}{A} \left[ \text{cm}^2 / \text{g} \right] \]
\( \mu = \mu_{\text{photo}} + \mu_{\text{Compton}} + \mu_{\text{pair}} + \ldots \)

- Rayleigh scattering (no energy loss !)
- Compton scattering
- Photo effect
- Pair production
Summary: basic electromagnetic interactions

- **e⁺ / e⁻**
  - Ionisation

- **γ**
  - Photoelectric effect
  - Compton effect
  - Pair production

- Bremsstrahlung

\[ \frac{dE}{dx} \]

\[ E \rightarrow \beta \gamma \]

\[ \sigma \rightarrow E \]
Backup slides
Diffusion of Free Charges

Free ionization charges lose energy in collisions with gas atoms and molecules (thermalization). They tend towards a Maxwell-Boltzmann energy distribution:

\[ F(\varepsilon) \propto \sqrt{\varepsilon} \cdot e^{-\frac{\varepsilon}{kT}} \]

Average (thermal) energy:

\[ \varepsilon_t = \frac{3}{2} kT \approx 0.040 \text{eV} \]

Diffusion equation:

Fraction of free charges at distance \( x \) after time \( t \).

\[ \frac{dN}{N} = \frac{1}{\sqrt{4\pi D t}} e^{-\frac{x^2}{4Dt}} dt \quad D: \text{diffusion coefficient} \]

RMS of linear diffusion:

\[ \sigma_x = \sqrt{2Dt} \]
Drift and Diffusion in Presence of E field

E=0  thermal diffusion

\[ \langle v \rangle_t = 0 \]

E>0  charge transport and diffusion

\[ \langle v \rangle_t = v_D \]

\[ v_D = \frac{\Delta s}{\Delta t} \quad \text{Drift velocity} \]

\[ \sigma_x = \sqrt{2D t} = \sqrt{2D \frac{s}{v_D}} \quad \text{Diffusion} \]

Electric Field

Electron swarm drift

\[ \Delta s, \Delta t \]
Simplified Electron Transport Theory

Townsend expression: \[ v_D = a \tau = \frac{eE}{m} \tau = \mu E \]  (1) \[ \tau = \text{time between collisions} \]

\[ \tau = \frac{1}{N \sigma(\epsilon) v} \]  (2)

Energy balance: \[ \frac{x}{v_D \tau} \lambda(\epsilon) \epsilon_E = eE x \]  (3) \[ \text{collision losses} = \text{energy gained in E-field} \]

\[ \frac{x}{v_D \tau} \text{ number of collisions; } \lambda(\epsilon) \text{ fractional energy loss per collision} \]

\[ \epsilon_E \text{ equilibrium energy (excl. thermal motion)} \]

\[ \epsilon_E = \frac{1}{2} m v^2 \]  (4) \[ v \text{ instantaneous velocity} \]

Insert (2) in (1) and then use (3) and (4) \[ v_D^2 = \frac{eE}{mN \sigma(\epsilon)} \sqrt{\frac{\lambda(\epsilon)}{2}} \]

Drift is only possible if \( \lambda(\epsilon) > 0 \)!

\( \sigma(\epsilon) \) large \( \rightarrow \) slow gas
\( \sigma(\epsilon) \) small \( \rightarrow \) fast gas

\( \sigma \) and \( \lambda \) are both functions of energy!

\( \rightarrow \) Parameters must be measured

CSC – Cathode Strip Chamber

Precise measurement of the second coordinate by interpolation of the signal induced on pads. Closely spaced wires makes CSC fast detector.

Space resolution

CMS

Center of gravity of induced signal method.
**RPC – Resistive Plate Chamber**

Multigap RPC - exceptional time resolution suited for TOF and trigger applications

Operation at high E-field $\rightarrow$ streamer mode.
Rate capability strong function of the resistivity of electrodes.

$\sigma = 77 \text{ ps}$

**A. Akindinov et al., NIM A456(2000)16**

**Typical time spectrum from 5 gap MRPC**

Time resolution
Large range of drift velocity and diffusion:

Rule of thumb: $v_D$ (electrons) ~ 5 cm/µs = 50 µm / ns. Ions drift ~1000 times slower.
Diffusion Electric Anisotropy

Longitudinal diffusion (µm for 1 cm drift)

Transverse diffusion (µm for 1 cm drift)

S. Biagi http://consult.cern.ch/writeup/magboltz/
Drift Chambers

Spatial information obtained by measuring time of drift of electrons

Measure arrival time of electrons at sense wire relative to a time $t_0$.

Need a trigger (bunch crossing or scintillator).

Drift velocity independent from $E$.

Advantages: smaller number of wires $\rightarrow$ less electronics channels.

Resolution determined by diffusion, primary ionization statistics, path fluctuations and electronics.
Drift Chambers

Planar drift chamber designs

Essential: linear space-time relation; constant E-field; little dependence of $v_D$ on $E$. 

U. Becker in Instrumentation in High Energy Physics, World Scientific
Equation of motion of free charge carriers in presence of E and B fields:

\[ m \frac{d\vec{v}}{dt} = e\vec{E} + e(\vec{v} \times \vec{B}) + \vec{Q}(t) \]

where \( \vec{Q}(t) \) stochastic force resulting from collisions

Time averaged solutions with assumptions: \( \vec{v}_D = \langle \vec{v} \rangle = \text{const.} \); \( \langle \vec{Q}(t) \rangle = \frac{m}{\tau} \vec{v}_D \) friction force

\[ \langle \frac{d\vec{v}}{dt} \rangle = 0 = e\vec{E} + e(\vec{v}_D \times \vec{B}) - \frac{m}{\tau} \vec{v}_D \]

\[ \tau \text{ mean time between collisions} \]

\[ \vec{v}_D = \frac{\mu |\vec{E}|}{1 + \omega^2 \tau^2} \left[ \hat{E} + \omega \tau (\hat{E} \times \hat{B}) + \omega^2 \tau^2 (\hat{E} \cdot \hat{B})\hat{B} \right] \]

In general drift velocity has 3 components: \( \| \vec{E}; \| \vec{B}; \| \vec{E} \times \vec{B} \)

- \( B=0 \) \( \rightarrow \) \( \vec{v}_D^B = \vec{v}_D^0 = \mu \vec{E} \)
- \( \vec{E} \parallel \vec{B} \) \( \rightarrow \) \( \vec{v}_D^B = \vec{v}_D^0 \)
- \( \vec{E} \perp \vec{B} \) \( \rightarrow \) \( \vec{v}_D^B = \frac{E}{B} \frac{\omega \tau}{\sqrt{1 + \omega^2 \tau^2}} \)

particles follow E-field

particles follow B-field
Diffusion Magnetic Anisotropy

\[ \vec{E} \parallel \vec{B} \]

\[ \sigma_L = \sigma_0 \]

\[ \sigma_T = \frac{\sigma_0}{\sqrt{1 + \omega^2 \tau^2}} \]

F. Sauli, IEEE Short Course on Radiation Detection and Measurement, Norfolk (Virginia) November 10-11, 2002
The Basics of Particle Detection

Induced charge on the plane

\[ \text{Induced charge on the plane} \]

\[ \text{Time Projection Chamber} \]

Full 3D track reconstruction:

\[ x-y \text{ from wires and segmented cathode of MWPC (or GEM)} \]

\[ z \text{ from drift time} \]

- **momentum resolution**
  - space resolution + B field
  - (multiple scattering)

- **energy resolution**
  - measure of primary ionization
TPC – Time Projection Chamber

Alice TPC
HV central electrode at –100 kV
Drift length 250 cm at $E = 400 \text{ V/cm}$
Gas Ne-CO$_2$ 90-10
Space point resolution ~500 $\mu$m
dp/p = 2%@1 GeV/c; 10%@10 GeV/c

Events from STAR TPC at RHIC
Au-Au collisions at CM energy of 130 GeV/n
Typically ~2000 tracks/event
Micropattern Gas Detectors (MPGD)

General advantages of gas detectors:
- low mass (in terms of radiation length)
- large areas at low price
- flexible geometry
- spatial, energy resolution …

Main limitation:
- rate capability limited by space charge defined by the time of evacuation of positive ions

Solution:
- reduction of the size of the detecting cell (limitation of the length of the ion path) using chemical etching techniques developed for microelectronics and keeping at same time similar field shape.
Micromegas – Micromesh Gaseous Structure

Metal micromesh mounted above readout structure (typically strips).
E field similar to parallel plate detector. 
\( E_a/E_i \sim 50 \) to ensure electron transparency and positive ion flowback suppression.

Space resolution

\( \sigma = 70 \, \mu m \)
Thin, metal coated polyimide foil perforated with high density holes.

Electrons are collected on patterned readout board. A fast signal can be detected on the lower GEM electrode for triggering or energy discrimination. All readout electrodes are at ground potential. Positive ions partially collected on the GEM electrodes.
Full decoupling of the charge amplification structure from the charge collection and readout structure. Both structures can be optimized independently!


Both detectors use three GEM foils in cascade for amplification to reduce discharge probability by reducing field strength.
TPC – Time Projection Chamber

Positive ion backflow modifies electric field resulting in track distortion.

**Solution:** gating

Prevents electrons to enter amplification region in case of uninteresting event;
Prevents ions created in avalanches to flow back to drift region.

ALEPH coll., NIM A294(1990)121
GEM – Gas Electron Multiplier

**Rate capability**

- DOUBLE GEM + PCB
- Effective Gain
- DO-GEN Gain-Rate
- \( \Delta V_{\text{gain}} = 500 \text{ V} \)
- \( E_1 = 600 \text{ V} \), \( E_2 = 1200 \text{ V} \), \( 6 \text{ keV X-rays} \)
- \( \Delta V_{\text{GB}} = 250 \text{ V} \)
- 2x10^5 Hz/mm^2

**Time resolution**

- Ar/CO\(_2\) 70/30
- rms = 9.7 ns
- Ar/CO\(_2\)/CF\(_4\) 60/20/20
- rms = 5.3 ns
- Ar/CO\(_2\)/C\(_2\)H\(_5\) 65/28/7
- rms = 4.5 ns
- Ar/CO\(_2\)/CF\(_4\) 45/15/40
- rms = 4.8 ns

**Space resolution**

- \( \sigma = 69.6 \text{ µm} \)

**Charge correlation (cartesian readout)**
Limitations of Gas Detectors

**Classical ageing**
Avalanche region → plasma formation
(complicated plasma chemistry)

- Dissociation of detector gas and pollutants
- Highly active radicals formation
- Polymerization (organic quenchers)
- Insulating deposits on anodes and cathodes

**Anode:** increase of the wire diameter, reduced and variable field, variable gain and energy resolution.

**Cathode:** formation of strong dipoles, field emission and microdischarges (Malter effect).
Limitations of Gas Detectors

Solutions: careful material selection for the detector construction and gas system, detector type (GEM is resistant to classical ageing), working point, non-polymerizing gases, additives suppressing polymerization (alcohols, methylal), additives increasing surface conductivity ($H_2O$ vapour), cleaning additives ($CF_4$).

Discharges
Field and charge density dependent effect.
Solution: multistep amplification

Space charge limiting rate capability
Solution: reduction of the length of the positive ion path
Insulator charging up resulting in gain variable with time and rate
Solution: slightly conductive materials