Invention and development of the multiwire proportional chamber

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Seminar on Nobel Prizes in Particle Physics

November 27, 2015

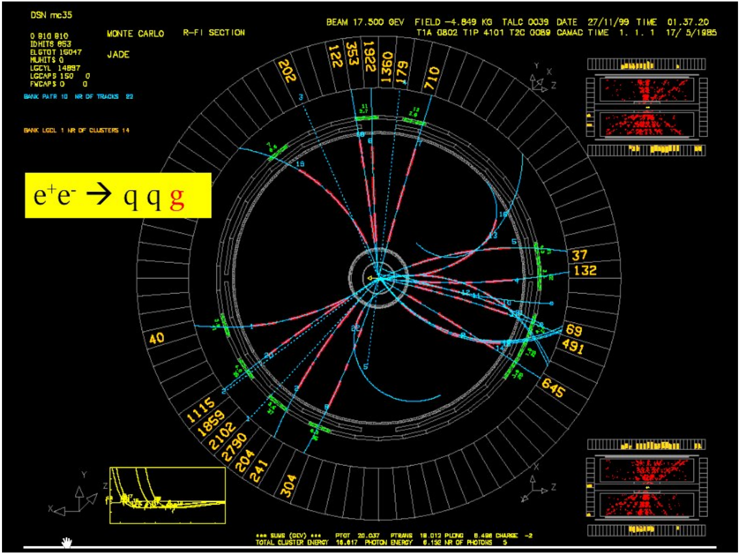

Figure 1: Event display recorded by the JADE experiment of a 3-jet event

Outline

1. Introduction
2. Georges Charpak
3. The multiwire proportional chamber
    - Principle of operation
    - Properties
    - Applications
4. Further developments
5. Summary

Particle detection before the multiwire proportional chamber

Particle detectors in the first half of the 20th century:

- cloud chambers, scintillation counters, photo multiplier tubes, flash tubes, proportional counters, Geiger-Müller tubes, ...
- optical and (later) electronic read-out of detectors
- in the 1950s and '60s: mainly **bubble** and **spark chambers**

Bubble chambers

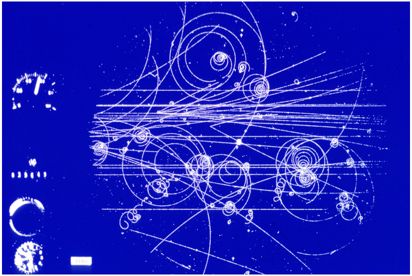

Figure 2: Event display in a bubble chamber

- charged particle leaves trail of bubbles in boiling liquid
- "bubble track" is illuminated and photographed
- operation in magnetic field allows for momentum measurement

→ together with dE/dx measurement: particle identification

More on this subject in Thomas' talk in January!

Spark chambers

- charged particle ionises gas
- high-voltage pulse (triggered by scintillation counters) applied to electrodes
  → spark discharge marks track of particle

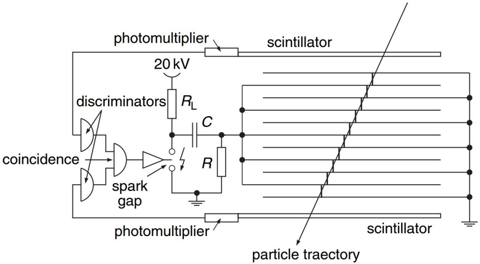

Figure 3: Sketch of a spark chamber

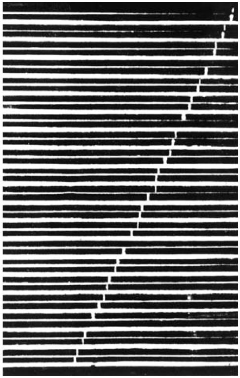

Figure 4: Track of a muon in a spark chamber

Problems and limitations

some examples for problems and limitations:

- bubble chamber:
  - development and analysis of photographs is very time-consuming
  - cannot be triggered
  - rate-limitated
- spark chamber:
  - dead time of several ms to clear positive ions from detector volume
    → cannot be triggered more than about a hundred times per second

Georges Charpak

- born 1924 in Poland, died 2010 in France
- PhD in Nuclear Physics at the Collège de France in 1954
- research position from 1948 to 1959 at the National Centre for Scientific Research (CNRS), then from 1959 to 1991 at CERN

  → became involved in high-energy particle physics
- published paper in 1968:
  "The use of multiwire proportional counters to select and localize charged particles"
- in the following years, > 200 papers, many on multiwire proportional chambers and their developments

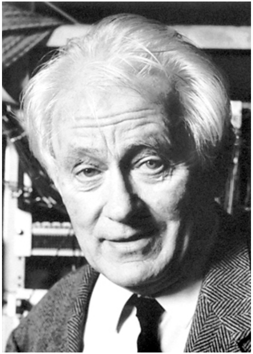

Figure 5: Georges Charpak

Nobel prize in 1992 "for his invention and development of particle detectors, in particular the multiwire proportional chamber"

The multiwire proportional chamber (MWPC)

> "A breakthrough in the technique for exploring the innermost parts of matter."
>
> Press release of the Nobel Prize in Physics 1992

Purpose of a MWPC

General purpose of a multiwire proportional chamber:

- tracking of charged particle → momentum measurement in magnetic field via position of passage
  - → MWPC in B-field (collider experiments)
  - → forward spectrometer:

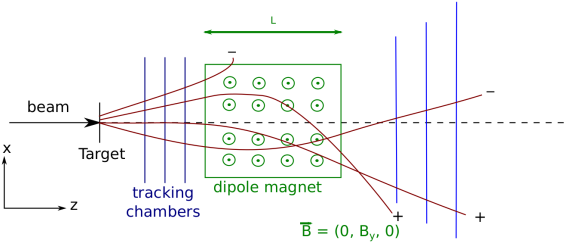

Figure 6: Sketch of a forward spectrometer

- particle identification via measurement of energy loss (dE/dx)

What is a MWPC?

For a start, we take a look at the name:

Multiwire proportional chamber

What is a MWPC?

For a start, we take a look at the name:

Multiwire $\boxed{\text{proportional}}$ chamber

↓

let’s have a look at this

Proportional counters

- setup: thin wire at high potential in gas-filled tube
- charged particle ionises gas

  → electrons drift to wire
- avalanche formation close to wire due to high electric field ($\propto 1/R$)
- electrons continue to drift to wire, positive ions drift to walls

  → drift induces electric signal
- signal is proportional to the number of electrons collected

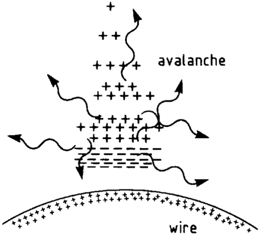

Figure 7: Avalanche formation in a proportional counter

Gas properties

- suitable counting gas: noble gases (e.g. Ar or Xe)
  (can be operated at much lower fields than complex molecules)
- excited atoms (from avalanche formation) de-excite by emitting photons
  → can cause new avalanche shortly after first one
  → need a "quencher" to absorb photons before new avalanche can form
- suitable quenching gas: CO_2, CH_4, hydrocarbons, ...
- problem with quenchers: can deposit on anodes and cathodes
  → functionality is impaired
  → amount of quenching gas is kept low

Construction of a MWPC

planar structure of proportional counters:

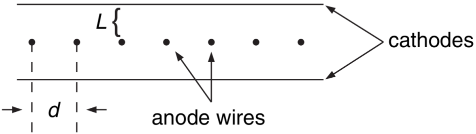

Figure 8: Sketch of a MWPC

- parallel anode wires (usually gold-plated tungsten) stretched between two cathode planes
- cathodes can either be made of wire planes or conducting foil

typical values:

- $d \sim 2$ - 5 mm
- $L \sim 5$ - 10 mm
- $r_i \sim 20$ - 25 μm
- $U_0 \sim 1$ - 5 kV

Signal formation in a MWPC

The signal formation on a **single wire** of a MWPC is essentially the same as in a proportional counter:

- electrons from gas ionisation drift to anode wires
- gas amplification close to wire → avalanche formation

  only ends when electrons reach wire, or when space charge from positive ions “counters” electric field
- drift of electrons and mainly ions induces signal on both anode and cathodes → position measurement possible

Characteristic of the MWPC: Every wire acts as an **independent** proportional counter!

Electric field in a MWPC

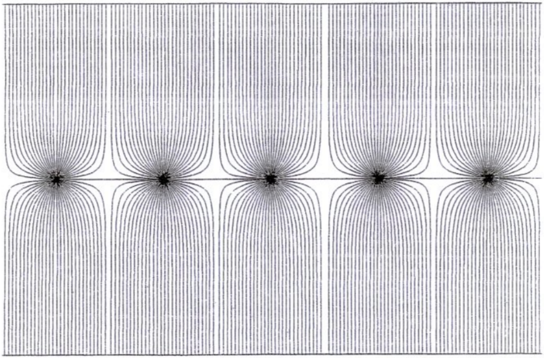

Figure 9: Field configuration in a MWPC

electric field close to wire is not influenced by other wires
→ every wire is an independent detector

Resolution of a MWPC

- signal on wire closest to avalanche is negative, signals on neighbouring wires are positive

  → electronics read out only anode wire with negative signal

- but: only information about closest wire

  → resolution is limited to $\delta_x = \frac{d}{\sqrt{12}}$

  e.g. for $d = 2$ mm: $\delta_x = 577$ μm

- only 1-dimensional and rather imprecise

  → also use cathode read-out

Resolution improvement

- read-out not only on anode wires, but also on cathodes
- segementation of cathodes

  → charge sharing allows for more precise measurement of centre of gravity
- resolution of y coordinate (along the wire) of $\geq$ 50 µm possible

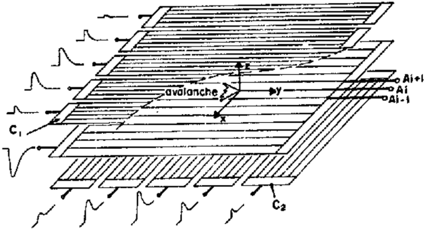

Figure 10: Localisation of avalanches in a MWPC

Limitations due to wire instability

electrostatic repulsion:

- if two wires are put too close together, they will repel each other
  → puts limit on d and wire length l
- to achieve stability, tension on wires must be larger than

$$T \geq \left(\frac{U_0 \cdot l}{d}\right)^2 \cdot 4\pi\epsilon_0 \left[\frac{1}{2\left(\frac{\pi L}{d} - \frac{2\pi r_i}{d}\right)}\right]^2$$

- example: $l = 1$ m, $d = 2$ mm, $r_i = 15$ µm, $L = 10$ mm and $U_0 = 5$ kV
  → $T \approx 0.5$ N

  → need a stable framework!

  → tension on wires cannot be too much

gravitational sagging:

- horizontal wires will show a sag f under their weight
- for wire with mass m, length l, tension T: $f = \frac{mlg}{8T}$
- same example as before: $f \approx 34$ μm → difference in gain

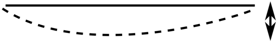

Figure 11: Gravitational sagging

some of these problems can be solved by "straw chambers":

- cylindrical cathode (∅ 5 - 10 mm) for every anode wire
- spatial resolution ≥ 30 μm possible
- problem of broken wires is minimised
- short drift lengths → high-rate capability

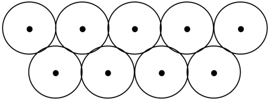

Figure 12: Sketch of a straw tube chamber

Wire stability is very important!

Even small displacement will cause distortion of field lines:

→ resolution worsens

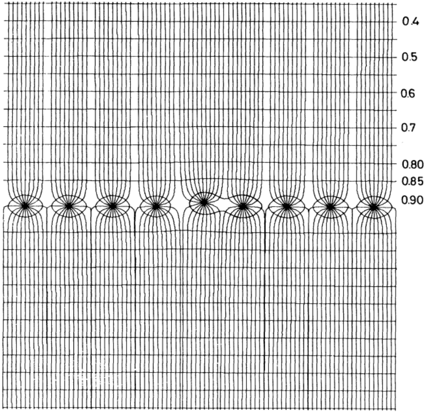

Figure 13: Field lines in a MWPC with a displaced wire

Applications of MWPCs

→ widely used in particle physics experiments as track detectors
→ contribution to some important discoveries in particle physics
(charm quark, W and Z bosons, gluon,...)

a few examples of different applications:

- “normal” planar MWPCs
- drift chambers
  - → planar drift chambers
  - → cylindrical drift chambers
- time projection chambers
- applications outside of particle physics

Drift chambers

- invented by A. Walenta, J. Heintze at the Physikalisches Institut in Heidelberg
- general idea: measure drift time of primary ionisation to anode wire
  → improve spatial resolution perpendicular to wire

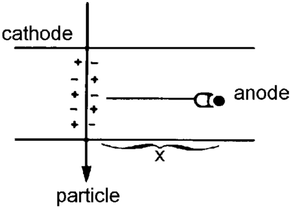

Figure 14: Principle of operation of a planar drift chamber

- electric field between wires very low in a MWPC
  → introduce so-called "field wires" at negative potential to achieve suitable electric field

Planar drift chambers

- problem: time measurement makes no statement about whether particle came from right or left side

  → use staggered double layer of drift chambers

- achievable resolution: 200 µm for large chambers, 20 µm for small chambers

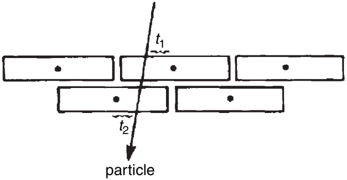

Figure 15: Resolving the left-right ambiguity

Cylindrical drift chambers

operation in magnetic field → transverse momentum from track curvature:

$p[GeV/c] = 0.3B[T] \cdot \rho[m]$

(ρ: bending radius)

- wires stretched parallel to beam axis (z direction) between two end plates
- alternating cylindrical layers of field and anode wires

  → coordinate in $r\varphi$
- determination of z coordinate via "stereo angle":

  layer of anode wires tilted by small angle $\gamma \rightarrow \sigma_z = \sigma_{r\varphi}/sin\gamma$

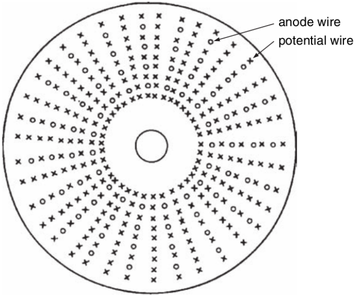

Figure 16: View of a cylindrical drift chamber along the wires ($r\varphi$ plane)

example: the JADE experiment

- length: 2.4 m, diameter: 1.6 m, solid angle coverage: 90%
- gas mixture: 88.7% argon, 8.5% methane, 2.8% isobutane
- spatial resolution: $\sigma_{r\varphi} = 180\ \mu\text{m}$, $\sigma_z = 16\ \text{mm}$
- anode wire: $\varnothing\ 20\ \mu\text{m}$, field wires: $\varnothing\ 100\ \mu\text{m}$
- in total 1536 anode wires (plus field wires)
  → pull at end plates with total force of 1.2 t!
- built at the Physikalisches Institut in Heidelberg by Heintze, Heuer, ...
  → exhibited in front of the Joachim-Heintze lecture hall, INF 308

Figure 17: The JADE drift chamber

Time Projection Chambers (TPCs)

Figure 18: The ALICE Time Projection Chamber

TPC operation

- gas-filled cylinder with central electrode

  → electron drift to endcaps in homogeneous electric field
- MWPCs at endcaps for read-out
- 3-dimensional measurement of track:
  - → z coordinate from drift time
  - → x and y coordinates from MWPC
- particle identification via dE/dx from charge measurement

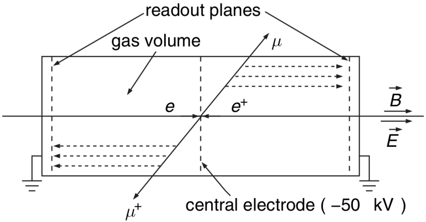

Figure 19: Working principle of a TPC

problem: ions from MWPCs have long drift path back to electrode

→ deterioration of electric field due to space charge effects

→ use "gating grid":

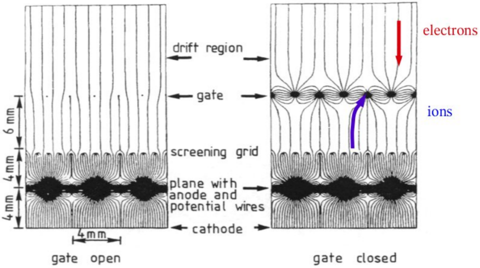

Figure 20: Gating grid in the ALEPH TPC

- gate is open for electron drift, closes after maximum drift time
  → ions from amplification region are collected on grid
- but: limitation in rate (no new event can be detected when grid is closed)

Applications outside of Particle Physics

MWPC offered new opportunities for imaging ionizing radiation

→ main applications in X-ray and γ-ray imaging:

- X-ray crystallography using MWPC as detector
  → replaced X-ray film
  → allowed for example study of protein structures
- low energy neutron imaging
  → structures in molecular biology
- positron cameras for γ-ray detection
- X-ray of human body with decreased doses

Replacements for MWPCs

- construction of MWPCs not easy (high geometric precision, stability,...)
- wires age, can be destroyed by discharges

  → go away from wire detectors
- possible replacements: microstrip detectors
  - wires are replaced by strips
  - all MWPC dimensions reduced by a factor 10

    → only short ion drift, high rate capability, good resolution
  - but: discharges destroy anode structure

    → did not work out
- different design: Gas Electron Multipliers (GEMs)

GEMs

- thin, metal-coated foil with holes placed before anode read-out structure
- potential on metal films

  → gas amplification in holes
- electrons drift to anode (read-out), ions are (mostly) collected on GEM foils
- several layers of GEMs on top of each other
  - → achieve substantial gain
  - → prevent backflow of ions more effectively

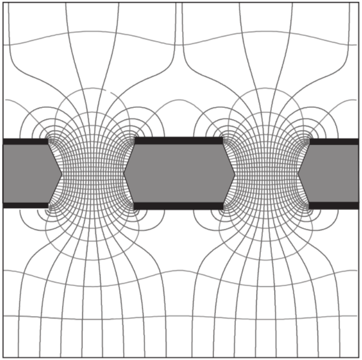

Figure 21: Electric field lines in a GEM detector

replacement of MWPCs by GEMs for the ALICE TPC in progress

Summary

- MWPC was a great advancement in particle detector physics
- successful applications in different forms
  - → some particle discoveries possible due to MWPCs (charm quark, W/Z bosons,...)
  - → some applications, like TPCs, are still used today
- however, wires are prone to aging, construction is difficult
  - → movement to replace MWPC with "wireless" detectors
  - → maybe GEMs are the next step? We'll probably see in a few years...

Thank you for your attention!

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