History of Particle Detectors

Artist's View of a Bubble Chamber by a CERN physicist
Early Image Detectors

Second half of 19th century

- growing interest in meteorological questions
  - climate, weather phenomenon, cloud formation
- people started to study condensation of water vapour in the lab
  - also motivated by raising use of steam engines

John Aitken built a “Dust Chamber” 1888

- water vapour mixed with dust in a controlled way
- result: droplets are formed around dust particles
- further speculations
  - electricity plays a role (from observations of steam nozzels)

Charles T. R. Wilson became interested

- first ideas to build a cloud chamber 1895
  to study influence of electricity/ions
  - also to solve question why air shows natural slight conductivity
Cloud chamber (1911 by Charles T. R. Wilson, Noble Prize 1927)

- chamber with saturated water vapour
- charged particles leave trails of ions
  - water is condensing around ions
- visible track as line of small water droplets

Also required

- high speed photographic methods
  - invented by Arthur M. Worthington 1908 to investigate the splash of a drop
  - ultra short flash light produced by sparks

First photographs of α-ray particles 1912
Arthur H. Compton used the cloud chamber in 1922 to discover scattering of photons on electrons (Compton effect) (Nobel Prize 1927 together with Charles T. R. Wilson)

- X-rays emitted into cloud chamber
  - photon scattered on electrons (recoiling electron seen in cloud chamber)
  - photon with reduced energy under certain angle visible by photo effect or Compton effect again

$$\gamma + e \rightarrow \gamma' + e'$$

Fig. 10. An electron recoiling at an angle $\theta$ should be associated with a photon deflected through an angle $\varphi$. 
Cloud Chamber III

Was also used for the discovery of the positron

- predicted by Paul Dirac 1928 (Nobel Prize 1933)
- found in cosmic rays by Carl D. Anderson 1932 (Nobel Prize 1936)

Anderson also found the muon in 1936, the first 2nd generation particle in the Standard Model

Positron is losing energy in lead, 23 MeV at exit

\[ \text{downward going positron, 63 MeV} \]

\[ \text{6 mm lead plate} \]

\[ \text{1.5 T magnetic field} \]

Isidor Isaac Rabi said: “Who ordered that?”
**Nuclear Emulsion I**

Pioneered by Marietta Blau between 1923 – 1938 (no Nobel Prize)

- photographic emulsion layer, 10 – 200 µm thick, uniform grains of 0.1 – 0.3 µm size
- very high resolution for particle tracks
  - analysis of developed emulsion by microscope

Since early 20th century

- important role of photography to study radioactivity
- but capability to make individual tracks visible not seen until nuclear emulsion technique was developed

nuclear disintegration from cosmic rays, observed 1937 for the first time
Nuclear Emulsion II

Discovery of the **pion** in cosmic rays by Cecil Powell 1947 (Nobel Prize 1950)

Discovery of the **kaon** 1949 (G. Rochester)

- Muon stops and decays
- Other pion decays, muon has always same length (energy)
- $\pi \rightarrow 2$-body decay $\pi \rightarrow \mu \nu_\mu$
Nuclear Emulsion III

Still used in actual experiments with highest precision requirements over a large volume

- $\nu_\mu$ beam sent from CERN to Gran Sasso Underground lab in Italy (732 km)
- OPERA experiment is searching for $\nu_\tau$ appearance after neutrino oscill. $\nu_\mu \rightarrow \nu_\tau$
  - need to reconstruct $\tau$ decays ($\nu_\tau + N \rightarrow \tau^- + X$) (few ~100 μm track length)
  - 235'000 “bricks” (1.7 ktons) of lead + emulsion sheets

OPERA at Gran Sasso

CNGS beam

automatic emulsion scanning

single brick

bricks

$\nu_\mu$ interaction

$\tau$ decay
**Bubble Chamber I**

**Intended 1952 by Donald Glaser (Noble Prize 1960)**

- similar to could chamber
- chamber with liquid (e.g. H₂) at boiling point ("superheated")
- charged particles leave trails of ions
- formation of small gas bubbles around ions

*was used at discovery of the “neutral current” (1973 by Gargamelle Collaboration, no Noble Prize yet)*

![Gargamelle bubble chamber](CERN)

[Diagram of neutrino decay]

![400 MeV electron](NOT this track...)
**Bubble Chamber II**

**BEBC (Big European Bubble Chamber) at CERN, 1973 – 1984**

- largest bubble chamber ever built (and the last big one...), $\varnothing$ 3.7 m
- 6.3 million photographs taken, 3000 km of developed film
- now displayed in permanent exhibition at CERN

- production of $D^*$ meson with long decay chain
Bubble Chamber III

Particle ID by eye...

- Photon conversion: $\gamma \rightarrow e^+ e^-$
- $K^-$-decay
- Individual ionization clusters
- Thick tracks, no individual clusters, high $dE/dx$, low $\beta\gamma$
- $\delta$-electrons

$K^-$
Advantages of bubble chambers

- liquid is BOTH detector medium AND target
- high precision

Disadvantages

- SLOW!!!
  - event pictures taken with cameras on film
  - film needs to be developed, shipped to institutes
  - and optically scanned for interesting events
- Need FASTER detectors (electronic!)

However:
Some important social side effects of bubble chamber era...

- scanning was often done by young “scanning girls” (students)...
- ...who later got married with the physicists...
1911: Ernest Rutherford + studied (elastic) scattering of $\alpha$ particles on gold atoms (famous Rutherford experiment)

- discovery of atomic nucleus:
  small (heavy) positively charged nucleus orbited by electrons

Zinc sulfide screen with microscope (spinthariscope by William Crookes 1903) was used to detect scattered $\alpha$ particles

- light flash was observed by eye
  - to increase light sensitivity, “bella donna” (from the deadly night shade plant = Tollkirsche) was often used to open eye's pupil
Early Electronic Detectors - Electroscope

- Gold-leaf electroscope already invented 1787 by Abraham Bennet

- End of 19th century raising interest on electricity in gases
  - cathode ray tubes, glow discharges
  - observation: charged electroscope is loosing its charge in dry air after some time
    - source of conductivity? ionisation by recently discovered radioactivity?

Victor Hess discovered cosmic rays 1912 (Nobel Prize 1936)

- used calibrated string electrometer by Theodor Wulf
- found increasing ionisation at higher altitudes at a series of balloon ascents
  - not related to sun radiation!
**Geiger-Müller Tube**

The Geiger-Müller tube (1928 by Hans Geiger and Walther Müller)

- Tube filled with inert gas (He, Ne, Ar) + organic vapour
- Central thin wire (20 – 50 µm Ø), high voltage (several 100 Volts) between wire and tube

- Strong increase of E-field close to the wire
  - electron gains more and more energy
  - above some threshold (>10 kV/cm)
  - electron energy high enough to ionize other gas molecules
  - newly created electrons also start ionizing

- **avalanche effect**: exponential increase of electrons (and ions)
- measurable signal on wire
  - organic substances responsible for “quenching” (stopping) the discharge

![Diagram of Geiger-Müller tube](image)
Coincidence Units


- single tube has no information on direction of incoming particle
  - two or more tubes giving signals within the same time window give direction
  - also information if two particles come from the same decay

**Walther Bothe**

**cosmic ray telescope 1934**

**coincidence unit with vacuum tubes for 2 Geiger-Müller tubes**
Photo Multiplier Tubes (PMT)

Invented 1934 by Harley Iams and Bernard Salzberg (RCA Cooperation)

- based on photo effect and secondary electron emission
- sensitive to single photons, replaced human eye + belladonna at scintillator screen

- first device had gain ~8 only but already operated at >10 kHz
  (human eye: up to 150 counts/minute for a limited time)

- nowadays still in use everywhere, gain up to $10^8$

- recent developments: multi-anode (segmented) PMTs, hybrid and pure silicon PMs
**Multi Wire Proportional Chambers I**

**Geiger-Müller tube just good for single tracks with limited precision (no position information inside tube)**

→ in case of more tracks more tubes are needed or...

**Multi Wire Proportional Chamber (MWPC)**
(1968 by Georges Charpak, Nobel Prize 1992)

→ put many wires with short distance between two parallel plates
Multi Wire Proportional Chambers II

Multi Wire Proportional Chamber (MWPC)
- was first electronic device allowing high statistics experiments
- with multiple channels and reasonable resolution

Typically several 100 – 1000 wires, ~ 1 mm spacing
- if charged particle is passing the MWPC → one wire gives signal
- resolution: \( \sigma_x \approx \frac{d}{\sqrt{1/2}} \) e.g. for \( d = 1 \text{ mm} \) → \(~300 \mu\text{m}\)

If many MPWCs are put one after each other
- each particle creates one point per MWPC (~300 \(\mu\text{m}\) resolution per point)
  
  can reconstruct track with e.g. 4 points

one coordinate only, use additional MWPCs tilted by 90° to get other coordinate

Probability

\( \sigma_x \)
\( \text{d/2} \)
**Drift Chamber**

Resolution of MWPCs limited by wire spacing

- better resolution $\rightarrow$ shorter wire spacing $\rightarrow$ more (and more) wires...
  - larger wire forces (heavy mechanical structures needed)
  - (too) strong electrostatic forces when wires too close to each other

**Solution by A. H. Walenta, J. Heintze, B. Schürlein 1971**

- obtain position information from drift time of electrons (fewer wires needed)
  - drift time = time between primary ionization and arrival on wire (signal formation)

\[
s = \int_{t_{\text{start}}}^{t_{\text{stop}}} v_D \, dt
\]

*start signal (track is passing drift volume) has to come from external source: scintillator or beam crossing signal*

Need to know drift velocity $v_D$

to calculate distance $s$ to wire

($=$ track position within the detector)
**Time Projection Chamber (TPC)**

- A 3D-imaging chamber with rather long drift length

- Homogeneous B- and E-fields
- Anode plane equipped with MWPC wire chambers

Problem: pads have to be large (otherwise not enough induced charge)

Limits number of points and double track resolution
Time Projection Chamber (TPC)

- Invented by David Nygren (Berkeley) in 1974
- Proposed as central tracking device for the PEP-4 detector at the PEP $e^+e^-$ collider at SLAC 1976
- More (and even larger) TPCs were built or are planned at other colliders:
  - TRISTAN (KEK, 2 x 32 GeV $e^+e^-$, 1986 – 1995)
  - TOPAZ
  - LEP (CERN, 2 x 104 GeV $e^+e^-$, 1989 – 2000)
    - ALEPH, DELPHI
  - RHIC (BNL, 2 x 100 GeV/nucleus, 2001 – )
    - STAR
  - LHC pp and Pb-Pb collider (CERN)
    - ALICE
  - ILC $e^+e^-$ collider
    - ILD
Recent Developments: Micro Pattern Gas Detectors (MPGD)

Replace wires at TPC with Micro Pattern Gas Detectors

- **MicroMegas** (metallic micromesh)
- **GEM** (Gas Electron Multiplier)

Concept

- 2D structures with holes + underlying pads
- Gas amplification inside holes, collect electrons on small pads, few mm²

![Image of MicroMegas structure with details on hole sizes and materials](image.png)
**Wire Chambers – Ageing**

Wire Chambers don't work/live forever

- gas avalanche region close to wire is region of plasma formation
  - ...and plasma chemistry not well understood in general

**Avalanche region**

- dissociation of detector gas and pullutants
- formation of highly active radicals
- polymerization of organic quenchers
- insulating deposits on anodes and cathodes

**Conclusions of an ageing workshop many years ago:**

CO\(_2\) helps with water, and alcohol admixtures...

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Malter effect”, first seen by L. Malter in 1936:
L. Malter, Phys. Rev. 50 (1936), 48
Gaseous Detectors in LHC Experiments

Mainly used in Muon Systems (ALICE, ATLAS, CMS, LHCb)
- precise muon tracking (drift tubes) and triggering (RPC plates)

Also in Inner Tracking system (ALICE, ATLAS, LHCb, TOTEM)
- mainly straw tubes = small, light weighted tubes
- but not the innermost detector layer
  - domain of semi conductor (silicon) detectors

Specific LHC challenges (for gaseous detector systems)
- high track rate (25 ns) and density (~1000 tracks per bunch crossing)
  - need short drift times (avoid integrating over too many bunch crossings)
    + high granularity = fast gases, small sized detectors
  - need “ageing-free” gases/detectors
    - lots of effort spent over years in this field
    - extensive irradiations with Gamma irradiation source, lab studies with X-ray sources etc.
Solid State Detectors

First transistor was invented 1947 by William B. Shockley, John Bardeen and Walter Brattain (Nobel Prize 1956)

- Transistors and diodes became common soon after
- Germanium diodes were used for particle detection
- P-type and n-type doped silicon material is put together and operated with reversed voltage

- Around junction of p- and n-type material depletion zone is created
- Zone free of charge carriers
  - No holes, no electrons
  - Thickness of depletion zone depends on voltage, doping concentration

Charged particle typically creates 20'000 – 30'000 electron/hole pairs in 300 µm thick material -> sufficient signal size
**Silicon Strip Detectors**

Now take a large Si crystal, e.g. 10 x 10 cm$^2$, 300 µm thick

- make bottom layer p-type
- and subdivide the top n-type layer into many strips with small spacing

**Advantage compared to wire/gas detectors**

- strip density (pitch) can be rather high (e.g. ~20 µm)
  - high position accuracy
  - but also many electronics channels needed

Many diodes next to each other (like MWPC at wire chambers) with position information
The first Silicon Strip Detector

First operational silicon strip detector used in an experiment (NA11 at CERN) by J. Kemmer, R. Klanner, B. Lutz et al. 1983

- B. Lutz was founder of MPI Halbleiterlabor in Munich
- NA11 aimed to search for new short lived particles

- first observation of $D_s$
- many branching ratio and lifetime measurements

8 silicon strip planes
(4 groups of 2 planes each with tilted strips to measure $xy$ coordinate)

24 x 36 mm$^2$ size per chip
1200 strips, 20 µm pitch
240 read-out strips
4.5 µm single hit resolution

D$^-$ decay
Si-Detector Electronics and Si-Pixels

Silicon strip detectors have a large number of electronics channels, \( \sim 10^7 \) each for ATLAS and CMS Si trackers

- requires highly integrated chips for amplification, shaping, zero suppression (only information of strips with signals is read-out) and multiplexing (put all strip signals on a few cables only)

- electronics is directly connected to the sensor (the “multi-diode”) via wire bonds

Si-stripe detectors provide only 1 coordinate, Pixel detectors are 2D detectors

Pixel detector need “bump” bonding and have even more channels, \( \sim 10^8 - 10^9 \)
Recent Developments: Hybrid Technologies

Combine MPGD gaseous detector with silicon pixel detector

Use MediPix2/TimePix chip as active TPC “padplane” for ILC detector

- MediPix2 = 256x256 pixels with 55x55 $\mu$m$^2$ size for medical applications (X-ray film replacement)

- MicroMegas mesh (provides gas amplification) integrated on top of pixel chip

Individual ionization visible: the digital Bubble Chamber is in reach
Detector History

Cloud Chambers, Nuclear Emulsions + Geiger-Müller tubes dominated until the early 1950s
- Cloud Chambers now very popular in public exhibitions related to particle physics

Bubble Chambers had their peak time between 1960 and 1985
- Last big bubble chamber was BEBC at CERN

Wire Chambers (MWPCs and drift chambers) started to dominate since 1970s

Since late 1980s solid state detectors are in common use
- Started as small sized vertex detectors (at LEP and SLC)
  - Now ~200 m² silicon surface in CMS tracker

Most recent trend: hybrid detectors
- Combining both gaseous and solid state technologies
A typical Today's Particle Detector

Cut-away view of CMS

Tracker  Calorimeter  Coil  Muon Detector and iron return yoke