Abstract:

This lecture series will first review the elementary processes and techniques on which particle detectors are based. These must always be kept in mind when discussing the limits of existing technologies and motivations for novel developments. Using the examples of LHC detectors, the limits of state of the art detectors will be outlined and the current detector R&D trends for the LHC upgrade and other future experiments will be discussed. This discussion will include micro-pattern gas detectors, novel solid state detector technologies and trends in microelectronics.
1) History of Instrumentation
Cloud Chambers/Bubble Chambers/Geiger Counters/Scintillators/Electronics/Wire Chambers

2) Electro-Magnetic Interaction of Charged Particles with Matter
Excitation/ Ionization/ Bethe Bloch Formula/ Range of Particles/ PAI model/ Ionization Fluctuation/ Bremsstrahlung/ Pair Production/ Showers/ Multiple Scattering

3) Signals/Gas Detectors
Detector Signals/ Signal Theorems/
Gaseous Detectors/ Wire Chambers/ Drift Chamber/ TPCs/ RPCs/ Limits of Gaseous Detectors/ Current Trends in Gaseous Detector Development

4) Solid State Detectors

5) Calorimetry & Selected Topics
EM showers/ Hadronic Showers/ Crystal Calorimeters/ Noble Liquid Calorimeters/ Current Trends in Calorimetry
History of Instrumentation

A look at the history of instrumentation in particle physics gives a complementary view on the history of particle physics, which is traditionally told from a theoretical point of view.

This history of instrumentation is in addition quite entertaining. The importance and recognition of inventions is the field of instrumentations is proven by the fact that several Nobel Prices in physics were awarded mainly or exclusively for the development of detection techniques.

1927: C.T.R. Wilson, Cloud Chamber
1939: E. O. Lawrence, Cyclotron & Discoveries
1948: P.M.S. Blacket, Cloud Chamber & Discoveries
1950: C. Powell, Photographic Method & Discoveries
1954: Walter Bothe, Coincidence Method & Discoveries
1960: Donald Glaser, Bubble Chamber
1968: Luis Alvarez, Bubble Chamber & Discoveries
1992: Georges Charpak, Multi Wire Proportional Chamber
History of Particle Physics

1895: X-rays, W.C. Röntgen
1896: Radioactivity, H. Becquerel
1899: Electron, J.J. Thomson
1911: Atomic Nucleus, E. Rutherford
1919: Atomic Transmutation, E. Rutherford
1920: Isotopes, E.W. Aston
1920-1930: Quantum Mechanics, Heisenberg, Schrödinger, Dirac
1932: Neutron, J. Chadwick
1932: Positron, C.D. Anderson
1937: Mesons, C.D. Anderson
1947: Muon, Pion, C. Powell
1947: Kaon, Rochester
1950: QED, Feynman, Schwinger, Tomonaga
1955: Antiproton, E. Segre
1956: Neutrino, Rheines
etc. etc. etc.
History of Instrumentation

1906: Geiger Counter, H. Geiger, E. Rutherford
1910: Cloud Chamber, C.T.R. Wilson
1912: Tip Counter, H. Geiger
1928: Geiger-Müller Counter, W. Müller
1929: Coincidence Method, W. Bothe
1930: Emulsion, M. Blau
1940-1950: Scintillator, Photomultiplier
1952: Bubble Chamber, D. Glaser
1962: Spark Chamber
1968: Multi Wire Proportional Chamber, C. Charpak
Etc. etc. etc.
History of Instrumentation

**History of ‘Particle Detection’**

**Image Tradition:** Cloud Chamber  
Emulsion  
Bubble Chamber

**Logic Tradition:** Scintillator  
Geiger Counter  
Tip Counter  
Spark Counter

**Electronics Image:** Wire Chambers  
Silicon Detectors  
…

Peter Galison, *Image and Logic: A Material Culture of Microphysics*
History of Instrumentation

Image Detectors

Bubble chamber photograph

‘Logic (electronics) Detectors’

Early coincidence counting experiment
History of Instrumentation

Both traditions combine into the ‘Electronics Image’ during the 1970ies

Z-Discovery at UA1 CERN in 1983
IMAGES
John Aitken, *1839, Scotland:

Aitken was working on the meteorological question of cloud formation. It became evident that cloud droplets only form around condensation nuclei.

Aitken built the ‘Dust Chamber’ to do controlled experiments on this topic. Saturated water vapor is mixed with dust. Expansion of the volume leads to super-saturation and condensation around the dust particles, producing clouds.

From steam nozzles it was known and speculated that also electricity has a connection to cloud formation.
Charles Thomson Rees Wilson, * 1869, Scotland:

Wilson was a meteorologist who was, among other things, interested in cloud formation initiated by electricity.

In 1895 he arrived at the Cavendish Laboratory where J.J. Thompson, one of the chief proponents of the corpuscular nature of electricity, had studied the discharge of electricity through gases since 1886.

Wilson used a ‘dust free’ chamber filled with saturated water vapor to study the cloud formation caused by ions present in the chamber.
Conrad Röntgen discovered X-Rays in 1895.

At the Cavendish Lab Thompson and Rutherford found that irradiating a gas with X-rays increased its conductivity suggesting that X-rays produced ions in the gas.

Wilson used an X-Ray tube to irradiate his Chamber and found ‘a very great increase in the number of the drops’, confirming the hypothesis that ions are cloud formation nuclei.

Radioactivity (‘Uranium Rays’) discovered by Becquerel in 1896. It produced the same effect in the cloud chamber.

1899 J.J. Thompson claimed that cathode rays are fundamental particles \( \rightarrow \) electron.

Soon afterwards it was found that rays from radioactivity consist of alpha, beta and gamma rays (Rutherford).
Using the cloud chamber Wilson also did rain experiments i.e. he studied the question on how the small droplets forming around the condensation nuclei are coalescing into rain drops.

In 1908 Worthington published a book on ‘A Study of Splashes’ where he shows high speed photographs that exploited the light of sparks enduring only a few microseconds.

This high-speed method offered Wilson the technical means to reveal the elementary processes of condensation and coalescence.

With a bright lamp he started to see tracks even by eye!

By Spring 1911 Wilson had track photographs from alpha rays, X-Rays and gamma rays.
Cloud Chamber

Wilson Cloud Chamber 1911
Cloud Chamber

X-rays, Wilson 1912

Alphas, Philipp 1926
Cloud Chamber

1931 Blackett and Occhialini began work on a counter controlled cloud chamber for cosmic ray physics to observe selected rare events.

The coincidence of two Geiger Müller tubes above and below the Cloud Chamber triggers the expansion of the volume and the subsequent illumination for photography.
Cloud Chamber

Magnetic field 15000 Gauss, chamber diameter 15cm. A 63 MeV positron passes through a 6mm lead plate, leaving the plate with energy 23MeV.

The ionization of the particle, and its behaviour in passing through the foil are the same as those of an electron.

Positron discovery,
Carl Andersen 1933
Cloud Chamber

The picture shows an electron with 16.9 MeV initial energy. It spirals about 36 times in the magnetic field.

At the end of the visible track the energy has decreased to 12.4 MeV. From the visible path length (1030 cm) the energy loss by ionization is calculated to be 2.8 MeV.

The observed energy loss (4.5 MeV) must therefore be caused in part by Bremsstrahlung. The curvature indeed shows sudden changes as can most clearly be seen at about the seventeenth circle.

Fast electron in a magnetic field at the Bevatron, 1940
Cloud Chamber

Nuclear disintegration, 1950

Taken at 3500m altitude in counter controlled cosmic ray Interactions.
Particle momenta are measured by the bending in the magnetic field.

‘... The V0 particle originates in a nuclear Interaction outside the chamber and decays after traversing about one third of the chamber. The momenta of the secondary particles are $1.6^{+0.3}_{-0.3}$ BeV/c and the angle between them is 12 degrees ... ‘

By looking at the specific ionization one can try to identify the particles and by assuming a two body decay on can find the mass of the V0.

‘... if the negative particle is a negative proton, the mass of the V0 particle is 2200 m, if it is a Pi or Mu Meson the V0 particle mass becomes about 1000m ...’
Nuclear Emulsion

Film played an important role in the discovery of radioactivity but was first seen as a means of studying radioactivity rather than photographing individual particles.

Between 1923 and 1938 Marietta Blau pioneered the nuclear emulsion technique.

E.g.
Emulsions were exposed to cosmic rays at high altitude for a long time (months) and then analyzed under the microscope. In 1937, nuclear disintegrations from cosmic rays were observed in emulsions.

The high density of film compared to the cloud chamber ‘gas’ made it easier to see energy loss and disintegrations.
In 1939 Cecil Powell called the emulsion ‘equivalent to a continuously sensitive high-pressure expansion chamber’.

A result analog to the cloud chamber can be obtained with a picture 1000x smaller (emulsion density is about 1000x larger than gas at 1 atm).

Due to the larger ‘stopping power’ of the emulsion, particle decays could be observed easier.

Stacks of emulsion were called ‘emulsion chamber’.
Discovery of the Pion:

The muon was discovered in the 1930ies and was first believed to be Yukawa’s meson that mediates the strong force.

The long range of the muon was however causing contradictions with this hypothesis.

In 1947, Powell et. al. discovered the Pion in Nuclear emulsions exposed to cosmic rays, and they showed that it decays to a muon and an unseen partner.

The constant range of the decay muon indicated a two body decay of the pion.
Nuclear Emulsion

Energy Loss is proportional to $Z^2$ of the particle

The cosmic ray composition was studied by putting detectors on balloons flying at high altitude.
Nuclear Emulsion

First evidence of the decay of the Kaon into 3 Pions was found in 1949.
# Particles in the mid 50ies

By 1959: 20 particles

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In the early 1950ies Donald Glaser tried to build on the cloud chamber analogy:

Instead of supersaturating a gas with a vapor one would superheat a liquid. A particle depositing energy along it’s path would then make the liquid boil and form bubbles along the track.

In 1952 Glaser photographed first Bubble chamber tracks. Luis Alvarez was one of the main proponents of the bubble chamber.

The size of the chambers grew quickly

- 1954: 2.5” (6.4cm)
- 1954: 4” (10cm)
- 1956: 10” (25cm)
- 1959: 72” (183cm)
- 1963: 80” (203cm)
- 1973: 370cm
Unlike the Cloud Chamber, the Bubble Chamber could not be triggered, i.e. the bubble chamber had to be already in the superheated state when the particle was entering. It was therefore not useful for Cosmic Ray Physics, but as in the 50ies particle physics moved to accelerators it was possible to synchronize the chamber compression with the arrival of the beam.

For data analysis one had to look through millions of pictures.
In the bubble chamber, with a density about 1000 times larger than the cloud chamber, the liquid acts as the target and the detecting medium.

**Figure:**
A propane chamber with a magnet discovered the $\Sigma^0$ in 1956.

A 1300 MeV negative pion hits a proton to produce a neutral kaon and a $\Sigma^0$, which decays into a $\Lambda^0$ and a photon.

The latter converts into an electron-positron pair.
Bubble Chamber

The 80-inch Bubble Chamber

BNL, First Pictures 1963, 0.03s cycle

Discovery of the $\Omega^-$ in 1964
Gargamelle, a very large heavy-liquid (freon) chamber constructed at Ecole Polytechnique in Paris, came to CERN in 1970. It was 2 m in diameter, 4 m long and filled with Freon at 20 atm.

With a conventional magnet producing a field of almost 2 T, Gargamelle in 1973 was the tool that permitted the discovery of neutral currents.
The detector began routine operations in 1974. The following year, the 7-foot chamber was used to discover the charmed baryon, a particle composed of three quarks, one of which was the "charmed" quark.

The photograph of the event in the Brookhaven 7-foot bubble chamber which led to the discovery of the charmed baryon (a three-quark particle) is shown at left.

A neutrino enters the picture from below (dashed line) and collides with a proton in the chamber’s liquid. The collision produces five charged particles: a negative muon, three positive pions, and a negative pion and a neutral lambda.

The lambda produces a characteristic 'V' when it decays into a proton and a pi-minus.

The momenta and angles of the tracks together imply that the lambda and the four pions produced with it have come from the decay of a charmed sigma particle, with a mass of about 2.4 GeV.
Bubble Chamber

3.7 meter hydrogen bubble chamber at CERN, equipped with the largest superconducting magnet in the world.

During its working life from 1973 to 1984, the "Big European Bubble Chamber" (BEBC) takes over 6 million photographs.

Can be seen outside the Microcosm Exhibition
Bubble Chambers

The excellent position (5μm) resolution and the fact that target and detecting volume are the same (H chambers) makes the Bubble chamber almost unbeatable for reconstruction of complex decay modes.

The drawback of the bubble chamber is the low rate capability (a few tens/second). E.g. LHC $10^9$ collisions/s.

The fact that it cannot be triggered selectively means that every interaction must be photographed.

Analyzing the millions of images by ‘operators’ was a quite laborious task.

That’s why electronics detectors took over in the 70ties.
Logic and Electronics
Early Days of ‘Logic Detectors’

Scintillating Screen:

Rutherford Experiment 1911, Zinc Sulfide screen was used as detector.

If an alpha particle hits the screen, a flash can be seen through the microscope.

Electroscope:

When the electroscope is given an electric charge the two ‘wings’ repel each other and stand apart.

Radiation can ionize some of the air in the electroscope and allow the charge to leak away, as shown by the wings slowly coming back together.

Victor Hess discovered the Cosmic Rays by taking an electroscope on a Balloon
In 1908, Rutherford and Geiger developed an electric device to measure alpha particles.

The alpha particles ionize the gas, the electrons drift to the wire in the electric field and they multiply there, causing a large discharge which can be measured by an electroscope.

The ‘random discharges’ in absence of alphas were interpreted as ‘instability’, so the device wasn’t used much.

As an alternative, Geiger developed the tip counter, that became standard for radioactive experiments for a number of years.
Detector + Electronics 1925

‘Über das Wesen des Compton Effekts’
W. Bothe, H. Geiger, April 1925

Bohr, Kramers, Slater Theorie:

Energy is only conserved statistically testing Compton effect

\[ h\nu \]  
\[ h\nu' \]
“Electronics”:

- Cylinders ‘P’ are on HV.
- The needles of the counters are insulated and connected to electrometers.

Coincidence Photographs:

- A light source is projecting both electrometers on a moving film role.
- Discharges in the counters move the electrometers, which are recorded on the film.
- The coincidences are observed by looking through many meters of film.
In 1928 Walther Müller started to study the spontaneous discharges systematically and found that they were actually caused by cosmic rays discovered by Victor Hess in 1911.

By realizing that the wild discharges were not a problem of the counter, but were caused by cosmic rays, the Geiger-Müller counter went, without altering a single screw from a device with ‘fundamental limits’ to the most sensitive instrument for cosmic rays physics.
1930 - 1934

Rossi 1930: Coincidence circuit for n tubes

Cosmic ray telescope 1934
Geiger Counters

By performing coincidences of Geiger Müller tubes e.g. the angular distribution of cosmic ray particles could be measured.

“... Robert Oppenheimer used to tell of the pioneer mysteries of building reliable Geiger counters that had low background noise. Among his friends, he said, there were two schools of thought.

One school held firmly that the final step before one sealed off the Geiger tube was to peel a banana and wave the skin three times sharply to the left.

The other school was equally confident that success would follow if one waved the banana peel twice to the left and then once smartly to the right ... “

(Alvarez, Adventures of a Physicist)
The procedure to make a fast counter is as follows:

1. Starting with a copper-in-glass counter with a tungsten wire, clean the copper thoroughly with about 6 normal nitric acid. (A water aspirator is indispensable for admitting and removing solutions.) Such a concentration of acid will leave the copper very bright.

2. After rinsing well, introduce a solution of 0.1 normal nitric acid. This will remove any copper compounds formed by the stronger acid.

3. Rinse thoroughly (at least 10 times) with distilled water and dry.

4. With dry air inside, heat the whole counter in a large flame until the copper turns a uniform brownish-black color.

5. Seal the counter off temporarily and then heat for several hours at about 400°C. Upon cooling, the copper cylinder will be coated with the bright red oxide, Cu₃O.

6. Evacuate and admit dry NO₂ gas to a pressure of 1 atmosphere. (This gas can be made by the action of 16 normal nitric acid on copper. It may be dried by passing through CaCl₂ and P₂O₅.)

7. Heat the counter with the NO₂ until the Cu₃O turns a dark velvety color. Pump out the NO₂.

8. Admit argon (commercial, 99 per cent pure is satisfactory), which has been bubbled through xylene, to a pressure of 6 to 10 cm of mercury pressure. The counter should be tried at this point. For a 1-inch counter the threshold should be 600 to 800 volts for 8 cm of mercury pressure. If the counter does not work properly, the gas should be pumped out and more argon, which has been bubbled through the xylene, admitted.

9. When the counter is found to work satisfactorily, it may be sealed off.

Although all the above steps may not be necessary in all cases, yet this procedure has been found to give very satisfactory counters having reaction times of $10^{-3}$ second or better. The characteristics of the counters also seem to be permanent. The photoelectric properties as well as the electrical resistance of the surface are probably radically changed by this treatment.
In the late 1940ies, scintillation counters and Cerenkov counters exploded into use.

Scintillation of materials on passage of particles was long known.

By mid 1930 the bluish glow that accompanied the passage of radioactive particles through liquids was analyzed and largely explained (Cerenkov Radiation).

Mainly the electronics revolution begun during the war initiated this development. High-gain photomultiplier tubes, amplifiers, scalers, pulse-height analyzers.
Antiproton

One was looking for a negative particle with the mass of the proton. With a bending magnet, a certain particle momentum was selected ($p=mv\gamma$).

Since Cerenkov radiation is only emitted if $v>c/n$, two Cerenkov counters (C1, C2) were set up to measure a velocity comparable with the proton mass.

In addition the time of flight between S1 and S2 was required to be between 40 and 51ns, selecting the same mass.
Reines and Cowan experiment principle consisted in using a target made of around 400 liters of a mixture of water and cadmium chloride.

The anti-neutrino coming from the nuclear reactor interacts with a proton of the target matter, giving a positron and a neutron.

The positron annihilates with an electron of the surrounding material, giving two simultaneous photons and the neutron slows down until it is eventually captured by a cadmium nucleus, implying the emission of photons some 15 microseconds after those of the positron annihilation.
Spark Counters

The Spark Chamber was developed in the early 60ies.

Schwartz, Steinberger and Lederman used it in discovery of the muon neutrino.

A charged particle traverses the detector and leaves an ionization trail.

The scintillators trigger an HV pulse between the metal plates and sparks form in the place where the ionization took place.
Multi Wire Proportional Chamber

Tube, Geiger- Müller, 1928

Multi Wire Geometry, in H. Friedmann 1949

G. Charpak 1968, Multi Wire Proportional Chamber, readout of individual wires and proportional mode working point.
Individual wire readout: A charged particle traversing the detector leaves a trail of electrons and ions. The wires are on positive HV. The electrons drift to the wires in the electric field and start to form an avalanche in the high electric field close to the wire. This induces a signal on the wire which can be read out by an amplifier.

Measuring this drift time, i.e. the time between passage of the particle and the arrival time of the electrons at the wires, made this detector a precision positioning device.
The Electronic Image

During the 1970ies, the Image and Logic devices merged into ‘Electronics Imaging Devices’
W, Z-Discovery at UA1/UA2 1983

UA1 used a very large wire chamber.

Can now be seen in the CERN Microcosm Exhibition

This computer reconstruction shows the tracks of charged particles from the proton-antiproton collision. The two white tracks reveal the Z's decay. They are the tracks of a high-energy electron and positron.
The ALEPH Detector

All Gas Detectors
ALEPH Higgs Candidate Event: $e^+ e^- \rightarrow HZ \rightarrow b\bar{b} + jj$
Tracks in the Star TPC Detector

Pb+Pb Collisions
Near Future: CMS Experiment at LHC

Large Hadron Collider at CERN.

The CMS detector will use more than 100 million Channels detector channels.
Summary

- Particle physics, ‘born’ with the discovery of radioactivity and the electron at the end of the 19th century, has become ‘Big Science’ during the last 100 years.

- A large variety of instruments and techniques were developed for studying the world of particles.

- Imaging devices like the cloud chamber, emulsion and the bubble chamber took photographs of the particle tracks.

- Logic devices like the Geiger Müller counter, the scintillator or the Čerenkov detector were (and are) widely used.

- Through the electronic revolution and the development of new detectors, both traditions merged into the ‘electronics image’ in the 1970ies.

- Particle detectors with over 100 million readout channels will operate in the near future.