How a Brilliant Idea Can Transform the Field of Particle Detectors

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Homage to Georges Charpak

By

Giacinto de Cataldo and Vladimir Peskov

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To my brotherly friend and university colleague, Piero Novielli and to my dearest Anna, Silvia, Gianluca and Francesco.

—***GDC***

To my wife, Tatiana Peskova, whose unwavering support has guided me throughout my scientific journey.

—*V. P.*

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PREFACE

Georges Charpak was awarded the Nobel Prize in Physics in October 1992 for his invention of the Multiwire Proportional Chamber (MWPC), a groundbreaking detector that has played a pivotal role in numerous major advances in physics. While several technical publications have thoroughly detailed the underlying physical principles of the MWPC, this book takes a different approach.

Here, we explore the innovative ways in which the MWPC has been employed in major physics discoveries, as well as its applications beyond the realm of particle physics enabled by its unique capabilities and versatility.

Over the course of our careers, both authors have acquired extensive experience in the design and use of gaseous detectors, working on collider experiments, spectrometers, and underground instruments for cosmic ray research, along with various interdisciplinary applications. One of us had the privilege of knowing and collaborating with Georges Charpak personally, a connection that inspired us to honour his many brilliant contributions to particle detector technology.

This book is aimed at a broad audience, from students to young researchers and engineers. It combines accessible sections introducing fundamental concepts with more advanced material requiring a solid grasp of instrumentation and particle physics. We hope it inspires young researchers to embrace creativity and curiosity in their work, contributing to the ongoing advancement of science and technology.

ABOUT THE AUTHORS

Giacinto De Cataldo

G. De Cataldo is an Italian physicist of the *Istituto Nazionale di Fisica Nucleare (INFN),* leading two international projects within the ALICE experiment at CERN. He also lectures in Particle Physics (PHY3232) at the University of Malta. From 1987 to 2000, he was involved in research on cosmic ray composition and participated in R&D activities for a large-area Transition Radiation Detector (TRD) designed for installation in underground laboratories for cosmic ray studies. Beginning in 1995, he participated in two missions in collaboration with the University of New Mexico (USA) and NASA, aimed at searching for primordial antimatter in primary cosmic rays using spectrometers flown on helium-filled stratospheric balloons. These spectrometers featured compact TRDs based on Multi-Wire Proportional Chambers and straw tubes. Within the same collaboration, he led the development of a position-sensitive Time-of-Flight system for a satellite-based spectrometer, employing neural network signal processing. In 1997, he worked on the design of a large-area calorimeter integrating a TRD for muon detection, targeting the study of neutrino oscillations over a 700 km baseline between CERN and the Gran Sasso Laboratory, Italy. Since 2000, he has been a member of the ALICE collaboration at CERN, focusing on the study of the Quark–Gluon Plasma (QGP) via ultra-relativistic heavy-ion collisions at the Large Hadron Collider (LHC). From 2002 to 2004, he served as a paid scientific associate at CERN. In 2010, he was appointed Project Leader of the ALICE–LHC Interface project, and from 2012 to 2023, he led the High Momentum Particle Identification detector project within ALICE. G. De Cataldo is the author or co-author of more than 500 scientific publications, spanning research on cosmic rays, neutrino oscillations, the QGP, and the development of gaseous detectors.

Vladimir Peskov

Vladimir Peskov is a professor and visiting scientist at CERN, currently affiliated with the University of Bari in Italy. From 1971 to 1985, he worked at the Physics Laboratory of the Russian Academy of Sciences in Moscow, led by Nobel laureate P.L. Kapitza, where he conducted research on ultrahigh-frequency plasma phenomena. During this period, he developed innovative plasma diagnostics methods based on MWPC, which led to the discovery of new phenomena in plasma physics.

From 1986 to 1992, Peskov was a scientific associate at CERN, working in the Charpak group. His primary achievement during this period was the development of gaseous detectors combined with CsI and other solid photocathodes. These advancements led to a new generation of Ring Imaging Detectors, later used in ALICE and other high-energy physics experiments.

Between 1992 and 2004, Peskov worked at various research centres, including Fermilab, NASA, and the Royal Institute of Technology in Stockholm. From 2004 to 2010, he closely collaborated with G. Charpak on the development of supersensitive detectors for sparks, flames, and dangerous gases, aimed at enhancing environmental safety. From 2004 to 2006, he was a member of the nTOF experiment at CERN, and since 2006, he has been involved with the ALICE experiment at the LHC.

Since 2008, he participated in the RD51 project, where he played a key role in developing spark-protective micropattern detectors. Peskov is also the author and co-author of more than 300 publications and four books on gaseous detectors of ionizing radiation.

INTRODUCTION

Why was that title chosen for the book?

We aim to illustrate to readers (particularly young ones aspiring to join the realm of physics science) how a brilliant and seemingly simple concept transformed significantly the area of particle physics detectors.

It is important to highlight that, generally, both science and technology do not progress steadily and uniformly over time; instead, they advance through abrupt breakthroughs made by the input of geniuses (exceptionally talented individuals). Numerous general examples exist; let’s highlight two randomly selected ones: Edison’s major inventions (the light bulb, movies, phonograph...) and the groundbreaking methods brought forth by W. Roentgen (radiology, medical research utilizing X-rays).

The examples can certainly be extended: Marconi, Bell, etc. However, what led us to select G. Charpak? What is his rank among other inventors? Are his contributions comparable to those of other renowned inventors?

Making a direct comparison is not an easy task since the inventions mentioned pertain to various disciplines. Edison and Röntgen's inventions significantly enhanced the quality of our everyday lives, while Marconi's radio, linking everyone globally, sparked the first instances of 'globalization.' In comparison, Charpak’s research focuses on experiments within fundamental physics, examining the essential components of matter and the interactions between them. In this intriguing discipline, a unique role is held by the so-called “imaging detectors,” which enable the visualization of particle trajectory in three-dimensional space. Through the study of particle kinematics, it is possible to explore the features of the fundamental interactions and to infer fundamental physical laws.

Physics is filled with innovative concepts that have become essential for advancing understanding in that area. In physics particle detectors, the Multiwire Proportional Chamber (MWPC) is among those concepts.

George Charpak invented it in 1968 for tracking, leading to a revolution in detection methods. It is a gas detector utilizing parallel elongated wires, several tens of microns in diameter, positioned at a spacing of several millimetres, with a length of nearly one meter. In this grid, situated between two cathodic planes, every wire functions as an individual proportional counter. This design allows for the construction of detectors with active areas ranging from tens of square centimetres to several square meters.

During the initial prototype phase, integrated circuits containing hundreds of transistors, significantly smaller than bulky electronic tubes, emerged following the USA's aerospace missions. Right away, researchers at the European Organization for Nuclear Research (CERN) began outfitting every wire with electronic circuits that incorporated all necessary components for signal processing and data storage on computers. Custom electronic read-out systems with thousands of channels were subsequently designed and built specifically for MWPCs.

The MWPC enabled, for the first time, the electronic capture of charged particles and energetic photon events at a high rate.

Shortly, two MWPCs configured with perpendicular wires, or a single detector with resistive wires and left-right signal sharing, were employed as trackers in fixed-target experiments. They offered two-dimensional (2-D) readouts with high positional accuracy, surpassing the wire pitch.

An additional clever concept emerged from G. Charpak. Indeed, he investigated the “drift time” of groups of electrons, and in 1971 this concept was utilized for the drift chamber and subsequently for the Time Projection Chamber.

The drift chamber, featuring a simpler design compared to two perpendicular MWPCs, could deliver the two coordinates of the event with great accuracy: the first from the affected wire (like the MWPC), and the second, at right angles, from the drift time of the electron cluster to reach the wire.

Subsequently, MWPCs, drift chambers, and magnetic dipoles were combined in spectrometers to conduct experiments at fixed target accelerators or colliders. Significant discoveries occurred, such as the charm quark at the AGS proton accelerator of Brookhaven in 1974 (J.J. Aubert, 1974, 1404-1406) and, around the same period, the affirmation at the SPEAR e+e- collider at Stanford Linear Accelerator Center [Augustin , 1974, 1406-1408].

The time projection chamber, employing MWPCs as readout detectors positioned at the endcaps of a cylindrical drift region filled with noble gas, successfully generates three-dimensional representations of charged particle tracks. By introducing a magnetic field into the gas volume and measuring the ionization density along the particle trajectory, this detector, alongside its strong tracking capabilities, was inherently equipped with efficient particle identification functionality.

In the 1980s, detectors like drift chambers and time projection chambers enabled physicists to achieve significant breakthroughs in high-energy physics experiments.

In 1983, C. Rubbia and his team in the UA1 and UA2 experiments at the CERN Super Proton Synchrotron collider identified the W and Z° bosons, which are the heavy mediators of the weak force.

In 1989, G. Charpak's next innovative concept was to investigate the capabilities of the MWPC utilizing CsI-activated photocathodes for detecting ultraviolet photons.

In the 1990s, the MWPC featuring a pad-segmented cathode for 2-D readout, activated by a thin CsI layer, was effectively employed for pattern recognition in Ring Imaging Cherenkov counters. Even now (2025), these detectors are used in various experiments; for instance, the High Momentum Particle Identification detector in the last twenty years is collecting data in ALICE experiment at CERN's Large Hadron Collider. By the 1990s, MWPCs were central to nearly all experiments in particle physics.

In 1992, Georges Charpak was awarded the Nobel Prize in Physics "for inventing and developing particle detectors, especially the multiwire proportional chamber."

In 1995, Charpak created his final invention – a micropattern gas detector called MICROMEGAS. Presently, its altered edition is implemented in the ATLAS experiment at CERN.

The MWPC was the first electronic imaging device. Following that, additional varieties of imaging detectors were introduced: Microchannel Plate photomultiplier, position-sensitive solid-state detectors, position-sensitive photomultipliers, and gaseous micropattern detectors. They rely on the identical 2-D or 3-D signal readout principles that employ segmented electrodes and drift time, as initially established by G. Charpak's team and their successors.

At present, conceptually novel particle detectors are proposed for the High-Luminosity Large Hadron Collider (2025 onwards) and/or the Future Circular Collider. They consist of entirely solid-state solutions, 25 microns thick, featuring expansive silicon sheet surfaces measured in square meters that can be curved into cylindrical forms. Their functioning ought to be easier than that of gas detectors, featuring outstanding timing capabilities; they come with readout systems containing billions of channels built directly into the silicon detector. This advancement in technology appears to be setting the stage for substituting the dependable, traditional MWPC with conceptually innovative detectors in particle physics.

This book primarily seeks to highlight the creative application of the MWPC in particle physics, nonetheless, a review of its different uses in fields such as astrophysics, medicine, biology, industry, homeland security and environmental protection illustrates the importance of this “brilliant concept” beyond particle physics alone. A remarkable spin-off effect!

The latest advancements in modern electronic components and state-of the art signal processing techniques used in particle detectors are also discussed. Currently, Graphics Processing Units and Artificial Intelligence technologies are consistently enhancing the MWPC's performance in complex experiments at colliders.

This book is designed to appeal to a broad audience, encompassing a diverse range of readers, from students who are just beginning their exploration of the subject, to young researchers and engineers seeking to deepen their understanding. In line with this approach, the material presented spans a wide spectrum of complexity. Some chapters and sections are crafted with an accessible style and straightforward explanations, making the concepts easy to grasp for those new to the field. However, the book also includes more advanced material that delves into the technical intricacies of instrumentation and the fundamental principles of particle physics. These more demanding sections are intended to challenge readers who already possess a foundational knowledge in these areas, offering them the opportunity to expand their expertise and engage with the subject at a deeper level

In the end, we aspire for this book to motivate students and researchers to engage in detector development, exercising their creativity to advance experimental physics and science in general, like G. Charpak!

CHAPTER 1

A BIT OF DETECTOR HISTORY

Abstract

In this chapter, a brief history of the development of position-sensitive detectors for elementary particles and X-ray photons is provided. To fully recognize Charpak's impact on science and technology, it is crucial to examine the condition of particle detectors before and after 1968, the year he invented the MWPC.

*Figure 1-1***.** *An image captured using a photographic plate wrapped in black paper and placed in contact with uranium salt ($K_2UO_2(SO_4)_2$). The shadow of a metal cross is visible, created by the mysterious radiation emitted by the uranium (from https://www.edpsciences.org/images/stories/archives/Becquerel.pdf).*

Historically, the earliest "visualizations" of photons and elementary particles were achieved using film plates. For example, Fig. 1-1 shows an image of invisible radiation, which Becquerel accidentally discovered while studying phosphorescence.

Photographic plates were widely used from the late 19th century to the early 20th century by many researchers, including Röntgen, who utilized them to study, and later apply, the X-rays he discovered. For instance, Fig. 1-2 shows the famous X-ray image of his wife's hand, which marked the beginning of groundbreaking advancements in X-ray applications.

Figure 1-2. The X-ray image of Mrs. Wilhelm Röntgen's hand, captured using X-ray technology (from https://www.google.ru/search?q=images+obtained+by+roentgen&newwindow=1&tbm=isch&tbo=u&source=univ&sa=X&ved=0ahUKEwijlo7-0Z7bAhXrF5oKHb9iDcQQsAQIKQ&biw=1181&bih=847#imgrc=p60OGK5UiAiO6M),

At that time, however, the low sensitivity of available photographic films made it impossible to detect a single photon or elementary particle. This capability emerged a few years later, in 1908, with the invention of the Rutherford-Geiger counter.

1.1. Ionization chambers

The ionization chamber, historically the first gas detector used in measurements at the beginning of the 20th century, could adopt various geometrical forms, such as flat, cylindrical, or spherical, depending on experimental requirements. Despite these variations in shape, its operating principle remains unaffected by its geometry.

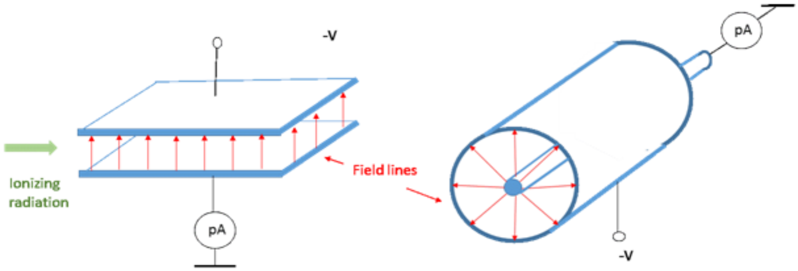

Figure 1-3. Schematic diagrams of planar and cylindrical ionization chambers

Fig. 1-3 provides a schematic representation of a planar and a cylindrical ionization chamber. These chambers consist of two metal electrodes, an anode and a cathode, with a voltage difference applied between them.

These detectors can operate in various gases, including air, typically at pressures around 1 atm. They remain widely used today, particularly in high-energy physics and medicine for dosimetry applications (see, for example, [https://en.wikipedia.org/wiki/Ionization_chamber#:~:text=Ion%20chambers%20are%20widely%20used,energies%20above%2050%2D100%20keV] and references therein).

When an intense flux of ionizing radiation (such as X-rays, gamma rays, or high-energy particles) enters the detector volume, it generates ion-electron pairs in the gas. The resulting current, measured as a function of the voltage applied between the electrodes, exhibits a characteristic behaviour:

- At low voltages, the current increases with voltage until it reaches a saturation region, often referred to as the 'plateau.'
- In this region, nearly all the ion-electron pairs produced by the ionizing radiation are collected on the electrodes before recombination can occur.

From the value of the saturation current, one can deduce the absolute intensity of the incident radiation.

1.2. Geiger-Muller counters

At the beginning of the 20th century, ionization chambers were widely used to study cosmic radiation. However, they lacked the ability to detect single events, a capability that became possible slightly later. In 1903, a ZnS scintillator was introduced into experimental techniques. This scintillator emitted a faint light pulse during ZnS de-excitation when ionizing particles passed through it. For the first time, this allowed the detection of individual particles.

This breakthrough was quickly adopted by Rutherford in his seminal experiments with alpha particles. At the time, the scintillation light produced by the ZnS screen could only be recorded visually, making the experiments labour-intensive and requiring significant preparation. Before measurements, researchers had to spend several hours in complete darkness to achieve the necessary visual sensitivity to detect the faint light pulses.

H. Geiger, a close collaborator of Rutherford, was an active participant in these experiments. Likely, the tedious nature of visually detecting particles inspired Geiger to seek a more efficient detection method. This led to the development of a groundbreaking idea: utilizing electron avalanche multiplication in gas to detect particles. This phenomenon had been discovered and studied a few years earlier by Townsend, as detailed in Chapter 1.

After conducting a series of experiments with Rutherford, Geiger successfully developed a reliable device in 1908 that could electronically detect single ionizing events (see Fig. 1-4).

The counter consisted of a coaxial cylinder filled with gas at a pressure of 0.1–1 atm. The outer cylinder acted as the cathode, while a thin wire at the center served as the anode. Due to this geometry, a strong electric field was generated near the wire. When a charged particle passed through the detector's gas volume, it produced primary ionization, creating electrons and positive ions.

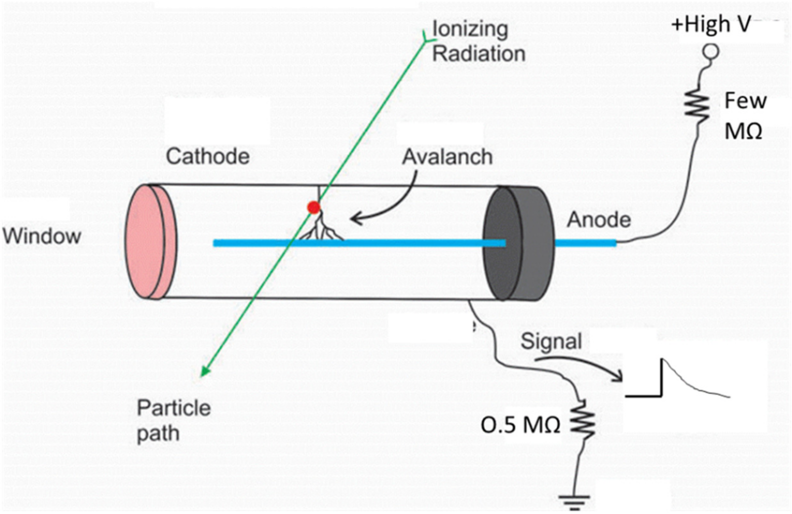

Figure 1-4. Schematics of Geiger counter (adapted from https://www.imagesco.com/geiger/geiger-counter-tube.html, with permission from John Iovine, Images Scientific Instruments Inc).

The primary electrons drifted toward the wire, triggering a corona discharge. This discharge generated a current, which produced a voltage pulse across a resistor load connected in series with the electrical circuit. The pulse amplitude was on the order of a few hundred volts, making it easy to detect. At the same time, the voltage drop caused by the pulse reduced the actual voltage across the detector electrodes, thereby interrupting the discharge.

After a short recovery time, typically on the order of milliseconds, the voltage was restored, and the detector was ready to record another event. This enabled the counter to detect up to 10^3 particles per second. This device was the first electronic detector of charged particles and can be regarded as a precursor to Charpak's later inventions.

1.3. Cloud chambers, bubble chambers and spark counters

At the beginning of the 20th century, photographic plates, scintillators, and Geiger counters were not imaging detectors of charged particles and lacked the ability to precisely determine the ionization tracks produced in the media. As a result, their contribution to particle physics was limited. The major advancements came with the next generation of detectors invented in the first half of the 20th century: cloud chambers, bubble chambers, and spark counters. These detectors enabled the visualization of particle tracks in three dimensions with high positional resolution, often much below 1 mm, providing physicists with powerful tools for their studies. For their groundbreaking contributions, the inventors of the first particle imaging detectors, Charles Wilson (cloud chamber, 1927) and Donald Glaser (bubble chamber, 1960), were awarded Nobel Prizes in Physics.

It is fascinating to explore how these brilliant individuals arrived at their inventions.

Charles Wilson originally focused on studying weather phenomena and sought to recreate cloud formation under laboratory conditions. To achieve this, he built a closed vessel filled with air saturated with water vapour (see Fig. 1-5). By rapidly expanding the volume of the vessel, he successfully created a supersaturated state of the vapour and observed that dust particles acted as condensation centers, playing a crucial role in the cloud formation process. To confirm this hypothesis, he meticulously cleaned the air used in his experiments to remove any dust particles.

To his great surprise, Wilson observed that even after removing all dust from the chamber, a small number of droplets still formed spontaneously. Moreover, these droplets often traced distinct paths, leading him to hypothesize that ions in the air could serve as condensation nuclei. To test this hypothesis, he exposed his device to the recently discovered X-rays and observed intense vapour condensation. Shortly thereafter, Wilson also reported observing alpha, beta, and gamma rays. This marked the development of the first imaging detector of ionizing radiation!

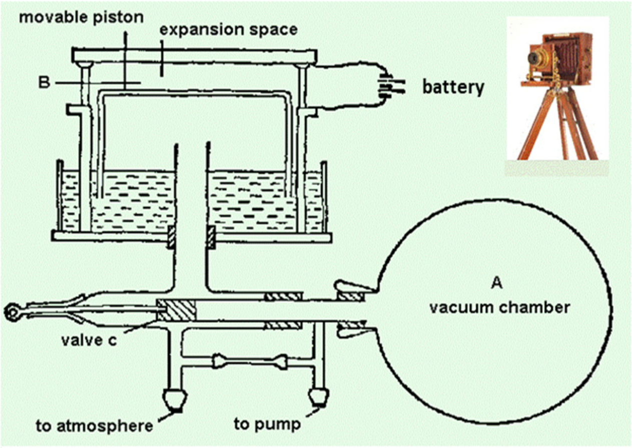

Figure 1-5. One of the original drawings of Wilson's chamber. The water-saturated air is contained in the volume marked B, while the vacuum vessel, labeled A, is kept evacuated with the valve C closed. To create supersaturated vapours, valve C is opened, allowing the air under the piston to be pumped into vessel A. As the piston falls, it causes the air in B to expand and cool, enabling the formation of droplets at centers of condensation (adapted from: https://www.uefap.com/reading/exercise/ess3/campbell.html).

A photographic technique was employed to record these tracks, producing their 2D images. Examples of such images are shown in Figs 1-6 and 1-7. The spatial resolution of this detector was approximately 0.5 mm. ([Brander, H “Bubble chambers”_ http://laplace.ucv.cl/Cursos/Fisica_Contemporanea_2/Old/annurev.ns.10.120160.000545.pdf) The expansion cycle frequency, in the best cases, ranged from 0.2 to 0.5 Hz, although, in principle, it could be even higher [Gaerther, 1949, 588-595], [Curtiss, 1933, 579-58].

Wilson imaging detectors made a remarkable contribution to high-energy physics experiments. For example, they played a crucial role in the discovery of several elementary particles, including the positron (1931), the muon (1936), and the kaon (1947).

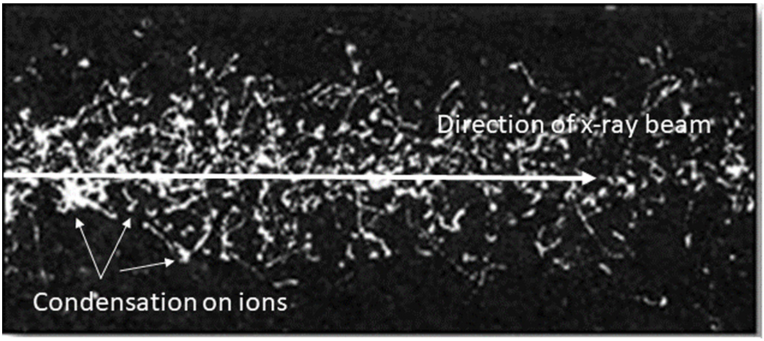

Figure 1-6. Images of ionization clusters produced in the Wilson chamber by X-ray radiation (adapted from: http://www.cambridgephysics.org/cloudchamber/cloudchamber13_1.html)

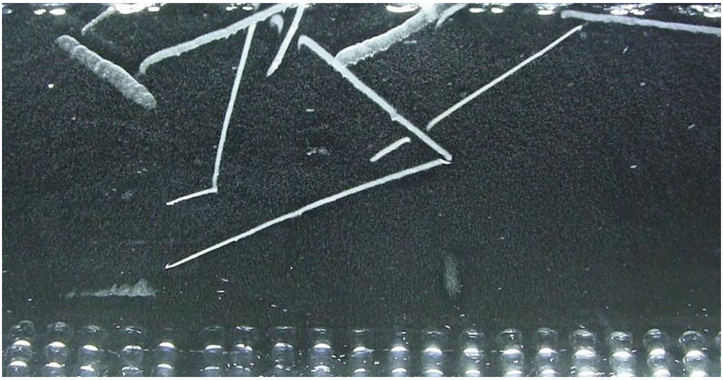

Figure 1-7. Images of ^{220}Rn decay events captured in a cloud chamber (source: https://commons.wikimedia.org/wiki/File:Radon220_decay_in_a_cloud_chamber.jpg, licensed under CC BY-SA 3.0.).

However, like any device, cloud chambers had their limitations. They were too small for use in large accelerators, and the air density was insufficient to effectively interact with highly energetic particles. Additionally, the piston cycle of the chambers was too slow to keep up with the rapidly increasing speed of accelerator cycles.

These drawbacks were partially addressed in 1952 with the development of another imaging detector by Donald Glaser. He successfully achieved bubble formation on ions in superheated fluids, paving the way for a new approach to particle detection.

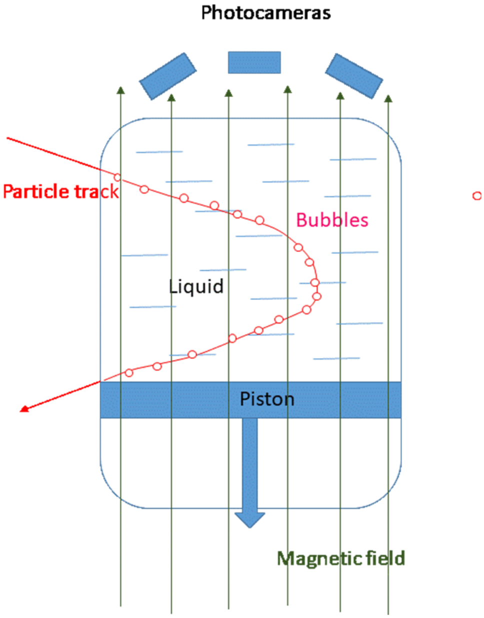

Figure 1-8. Schematic illustration of the Glaser bubble chamber.

The bubble chamber, in principle, was somewhat similar to the Wilson cloud chamber. It consisted of a large cylinder filled with a liquid heated just below its boiling point (Fig. 1-8). At the bottom of the chamber, a piston was installed. When a charged particle passed through the chamber, the piston rapidly reduced the internal pressure, causing the liquid to transition into a superheated phase. This process led to the formation of bubbles along the particle's path, making its trajectory visible.

To record stereoscopic images of these tracks, several cameras were mounted around the chamber. The typical position resolution of such a detector was approximately 50 µm, and the expansion cycle frequency was about 10 Hz (Brander, H., Bubble chambers_ http://laplace.ucv.cl/Cursos/Fisica_Contemporanea_2/Old/annurev.ns.10.120160.000545.pdf)

Typically, the bubble chamber is placed inside a solenoid, where a strong magnetic field causes charged particles to move in helical trajectories. By analyzing the radius of these trajectories, one can determine the charge-to-mass ratio and the velocities of the particles (see, for example, Fig. 1-9).

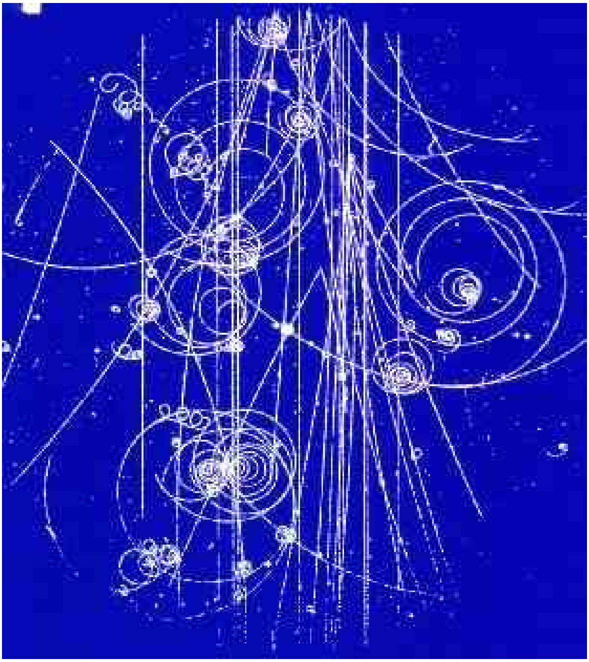

Figure 1-9. Example of particle track images obtained using a bubble chamber. Image credit: CERN.

With the help of bubble chambers, significant discoveries were made. For instance, in 1973, the Gargamelle experiment at CERN revealed *weak neutral currents*, confirming the possibility of unifying the electromagnetic and weak interactions within the electroweak theory. Remarkably, bubble