# Contents

# Chapter 1

# Introduction

Curiosity is the driving force behind the development of human civilisation. Over centuries, scientists have discovered new methods for understanding Nature and the fundamental mechanisms governing the Universe, using continually improving research methods and technology to peer ever deeper into the heart of matter.

After the initial discovery of atoms, their underlying structure was soon revealed to be that of a positively charged core surrounded by a cloud of orbiting electrons. The atomic nucleus was subsequently decomposed into protons and neutrons, which themselves were found to consist of three tiny quarks. Studying these minuscule building blocks of visible matter has made it possible to understand more about the intricate complexities of the Universe, and the mechanisms that guide its behaviour and evolution.

Discoveries of this magnitude would not have been possible without the technologies developed to carry out such experiments. On one hand, the energy of the experimental devices has been increasing continually, allowing smaller and smaller distance scales to be probed. On the other hand, the devices used to observe and measure the phenomena created in these experiments have had to be designed with improved precision, speed and durability.

Keeping these factors in mind, the goal of this work was to find "the perfect material". Diamond proved to be a worthy contender, offering both outstanding electrical and mechanical properties which make it the material of choice for a number of applications in experimental physics. However, much remains to be learned about its behaviour, and this thesis adds a small piece to the shimmering mosaic of diamond research efforts.

The first chapter introduces some of the leading particle physics research institutes, and describes how their research is carried out. The second chapter discusses the properties of diamond detectors used in high energy particle physics experiments. A diamond sensor irradiation study is presented in chapter 3. The conclusions of this study, which define the constraints for the two diamond detector applications, are presented in the final two chapters.

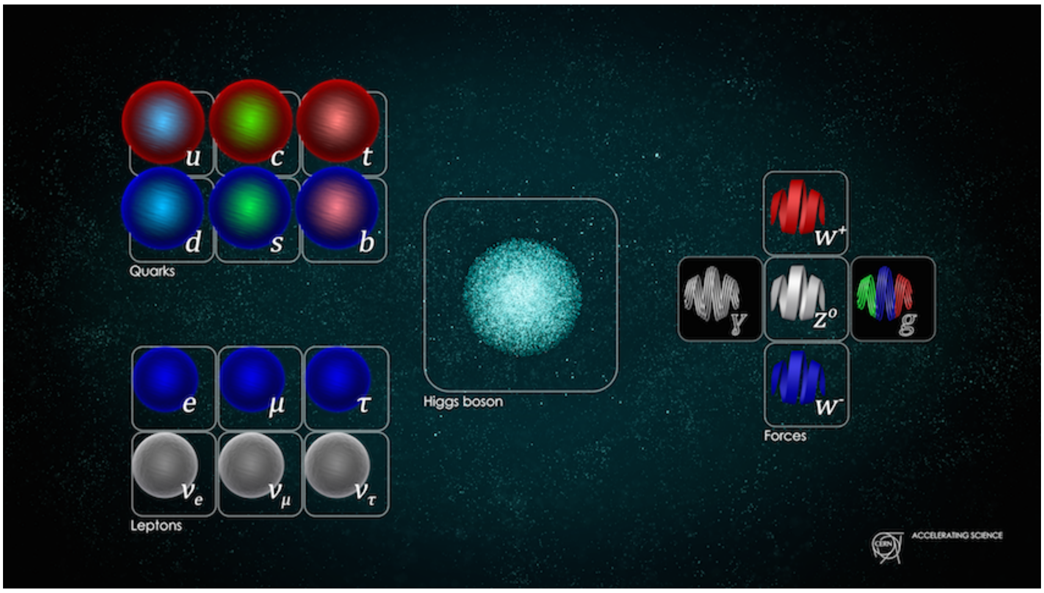


Figure 1.1: The Standard model [8].

## 1.1 Fundamental research

The aim of fundamental research is to define scientific theories and verify them to improve our understanding of the universe. It does not in itself focus on applying this research by developing products and is not meant to create a direct return on investment. Instead, it expands the overall knowledge of the human kind - by making the results freely available to the general public.

Particle physics research peers into the smallest constituents of the universe, dissecting the atoms into quarks and electrons, catching cosmic rays and figuring out what dark matter is made up of. Particle physicists want to explain the phenomena surrounding us by studying the fundamental particles and the mechanisms governing their interactions. By understanding this, we would be able to answer difficult questions; How did the universe begin? What is the invisible force (dark matter, dark energy) pushing the galaxies apart from each other? Where does mass come from? Why is there almost no antimatter in the universe? In this effort, scientists have formed several theories. One of them, the Standard Model of particles, is currently the best theory to describe the constituents of matter and their interactions.

**The Standard Model** (SM) is a physics theory developed in the 1970's [12]. It was designed to explain the current experimental results. As such, it was also able to predict new discoveries and was a driving force for the scientists to invest time and money in developing new experiments. To date, it is by far the most established and verified physics theory. It explains how the basic building blocks of matter – *fermions* – interact with each other via mediators of interactions called *bosons*. There are two main families of fermions - *quarks* and *leptons*, as shown in figure 1.1. Each group consists of six members divided into three *generations*, the first being the lightest and most stable and the last the heaviest – unstable. The nature around us is made up of the stable particles – those from the second or third generations can only be found in cosmic rays or produced artificially using particle accelerators.

Quarks have a spin of 1/2 and a charge of either +2/3 (up, charm, top) or -1/3 (down, strange, bottom) while the leptons have a spin of 1/2 and a charge of either 1 (electron, muon, tau) or 0 (electron neutrino, muon neutrino, tau neutrino). Leptons only exist individually – they do not cluster. Quarks, however, immediately form a cluster of either two (unstable), three (more stable) or five (unstable). Two up and one down quark make up a proton whereas two down and one up quark make up a neutron.

In addition to fermions, each particle has its corresponding antiparticle – a particle with the same mass but the opposite charge. If an antiparticle hits a particle, they annihilate each other, producing energy in form of photons.

Bosons are the carriers of force, mediating weak ($W^+$, $W^-$ and Z bosons), strong (gluons) and electromagnetic (photons) interactions. The weak interaction is responsible for the radioactive decay of subatomic particles, thus playing an essential role in nuclear fission – a process taking place in the stars. The electromagnetic interaction works at a macroscopic level – it allows particles to interact via electric and magnetic fields. The strong interaction is effective at distances of a femtometer and it governs how quarks interact and bind with each other. An additional boson is the Higgs boson and was discovered at CERN in 2012 []. It is a representation of the Higgs mechanism, which gives rise to the mass (or lack thereof) of all the particles in the Standard Model.

## 1.2 Research institutes

This section gives a short overview of some of the institutes and collaborations carrying out fundamental physics research. These facilities were used for the research carried out for this thesis.

**CERN** (European Centre for Nuclear Research) [2] is the largest particle physics laboratory in the world, straddling the Swiss-French border just outside Geneva. It was established in 1954 to bring the war-torn Europe together by means of fundamental scientific research. Today, its 22 member state countries and several observer states contribute approximately 1 billion CHF annually to fund the research and development. More than 10000 scientists, engineers, technicians, students and others from all around the globe work at CERN on many projects in research fields ranging from particle to nuclear physics. The scope is to probe the fundamental structure of the universe and to understand the mechanisms governing it. Therefore CERN's main function is to provide the infrastructure for high-energy physics experiments. These are carried out using large machines called particle accelerators. These instruments boost beams of particles to high energies before making them collide with each other

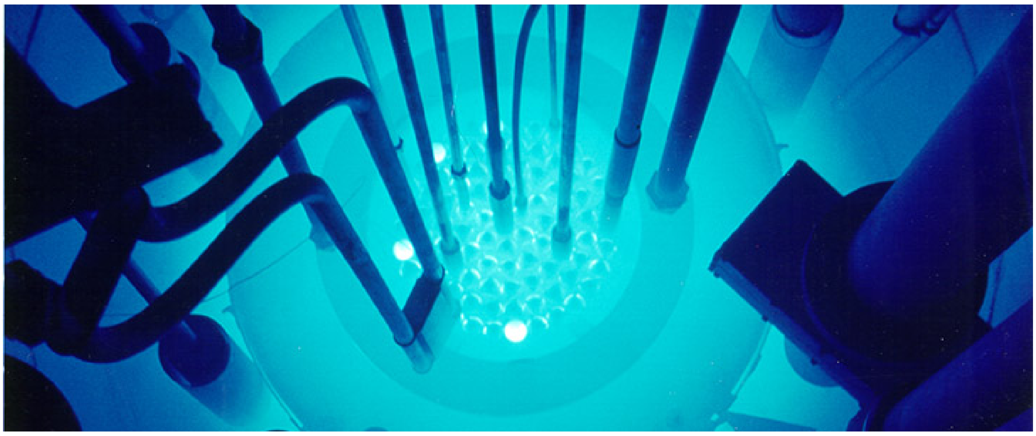

Figure 1.2: The TRIGA MARK II neutron reactor [5].

or with stationary targets. The resulting collisions are recorded by particle detectors and later analysed by physicists. To carry out research on the smallest constituents of matter, their dynamics and structure, very high energies are needed. This is why the most powerful accelerators are used for fundamental research. The largest accelerators at CERN are the Proton Synchrotron [], the Super Proton Synchrotron [11] and the Large Hadron Collider, described in 1.3.

**Atominstitut, Vienna** (ATI) [1], an institute for atomic and subatomic physics, was established in 1958 in Vienna as an inter-university institute. It currently houses around 200 people involved in a broad range of research fields: quantum, particle, neutron, nuclear, radiation and reactor physics, quantum optics etc. As of 2002 the ATI is part of the University of Technology in Vienna.

Its central facility is a *TRIGA MARK II* [4], a neutron reactor of a swimming-pool type used for training, research and isotope production. It is one of 40 such reactors worldwide, produced by the Californian company General Atomic in the early 60's. It is capable of continuous operation at a maximum output power of 250 kW. The reactor core consists of 3 kg of 20 % enriched uranium ($^{235}$U). The fuel moderator rods are mostly made up of zirconium with low percentage of hydrogen and uranium. Both the core and the rods are immersed in a pool of water as shown in figure 1.2 for the purpose of cooling and radiation protection. The surrounding concrete walls are 2 m wide with an added graphite layer for improved shielding. Four main experimental beam holes are placed radially through the walls. All exits are heavily shielded to prevent radiation damage to people, but still leaving enough space to set up experiments. Apart from the beam holes, there are several other exits and components, e.g. a thermal column for generation of thermal (low energetic) neutrons.

**n-ToF** (neutron Time-of-Flight) [3] is a scientific collaboration with the aim of studying neutron-nucleus interactions. Over 30 institutes and universities are currently active members of this collaboration, among them Atominstitut in Vienna. n-ToF is also a facility at CERN where the experiments are carried out in a 200 m long experimental area. The knowledge stemming from the experimental results can then be applied in various fields ranging from nuclear technology and cancer therapy to astrophysics.

A pulsed beam of highly energetic protons (20 GeV/c) is produced by the Proton Synchrotron (PS) and aimed at a fixed lead spallation target. Each proton hitting the target produces around 300 neutrons of various energies. Initially highly energetic neutrons are slowed down by the target and by a slab of water placed behind it. This broadens their energy spectrum, which then ranges from meV (thermal neutrons) to GeV (fast neutrons). The neutrons are then collimated and sent through a 185 m long evacuated pipe to the experimental area, where they are made to collide with another target or a sample. The radiation resulting from the collisions is detected by a set of dedicated detectors around the interaction point, as shown in figure 1.3. Having different energies, neutrons travel with different speeds, highly energetic ones reaching the target faster than those with low energies. The analysis of collisions with a precise timing allows for a determination of the interaction probability with the sample material as a function of incident neutron energy.

## 1.3 The Large Hadron Collider

A particle accelerator is a machine that accelerates beams of charged particles like protons, electrons, ions etc. It generates electric fields that add kinetic energy to the particles, speeding them up. It then uses magnets to retain them within a defined trajectory and inside the evacuated beam pipe. The trajectory can be either linear (linear accelerators) or circular (circular or cyclic accelerators). The advantage of the latter ones is that they can accelerate particles many times while keeping them in orbit.

Particle accelerators are used in numerous fields ranging from fundamental and material research, cancer treatment to industrial applications, such as biomedicine and material processing. Several types of accelerators exist: electrostatic accelerators, linear accelerators (LINACs), cyclotrons, synchrocyclotrons, synchrotrons, synchrotron radiation sources and fixed-field alternating gradient accelerators (FFAGs).

The Large Hadron Collider (LHC, figure 1.4) at CERN is the largest particle collider in the world. It was build between 1998 and 2008 and was first successfully started in 2010 and operated stably until 2013 when it underwent a two years long upgrade. Its second operational cycle started at the beginning of 2015.

The LHC is a 27 km long circular machine set up in a tunnel deep under the surface, ranging from 50 to 175 m below ground. It accelerates two proton beams to the energy of 6.5 TeV per beam before it makes them to collide with each other with the energy of 13 TeV at four different points around its circumference. The hair-thin particle beams travel inside two evacuated pipes with a $\sim$5 cm radius. Coils made up of a superconductive material are wound up around the pipes in special patterns.

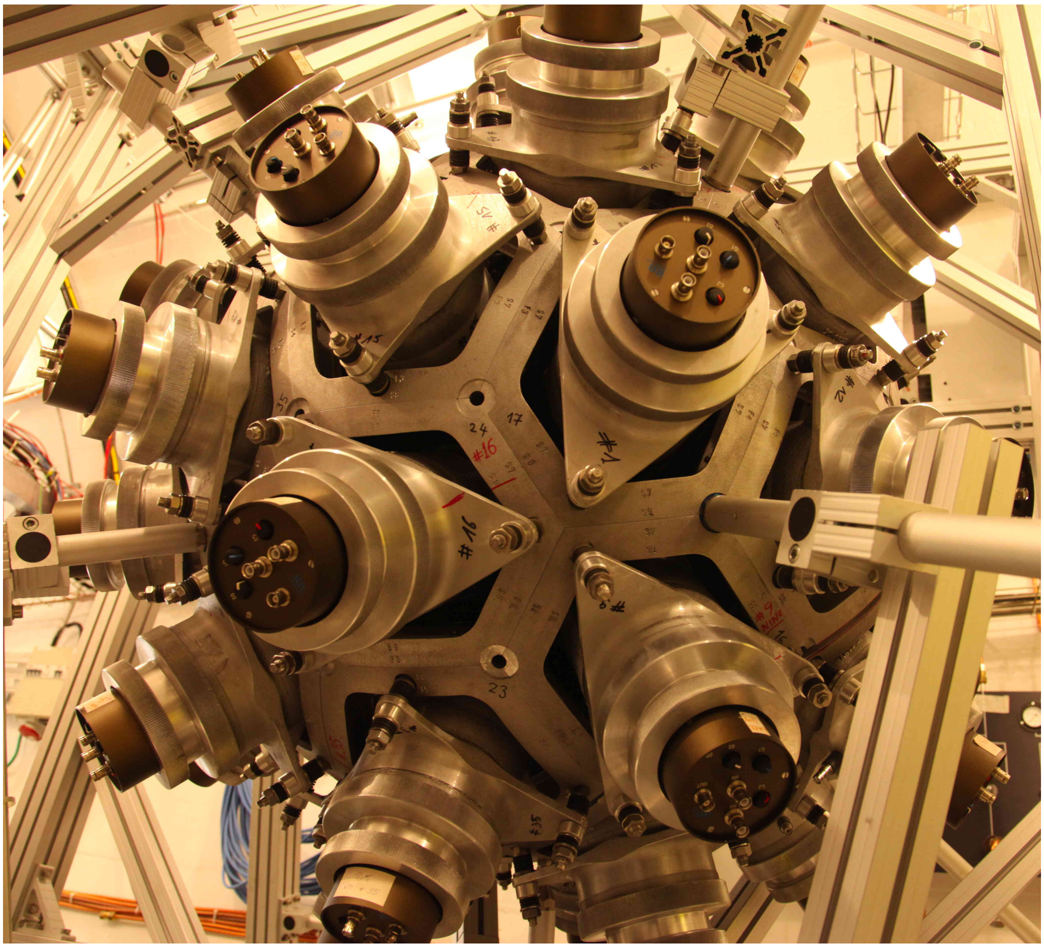


Figure 1.3: The calorimeter in the n-ToF area [6].

When cooled down to -271 °C using liquid helium, they become superconductive; the resistivity of the material drops significantly, minimising the heat dissipation despite high electric currents. These produce strong magnetic fields which bend the particles and keep them in a circular trajectory. The particles are accelerated when traversing the radio-frequency (RF) cavities with the RF frequency of 400 MHz. This oscillating frequency creates buckets – compartments for bunches of highly energetic particles – which are 2.5 ns long. Only one out of ten buckets is filled, so the bunches are spaced at 25 ns. This defines the machine's clock (40 MHz) as well as the maximum rate of collisions - the bunches travelling in the opposite direction cross at the intersections up to 40 million times per second. Currently around 20 collisions occur during every bunch crossing, yielding the maximum collision rate of the order of $10^9$ s$^{-1}$. The number of collisions will further increase in the following years; the number of particles in every bunch will be increased and the transverse spread of the bunches will be decreased, squeezing the bunches further. The density will therefore be increased, which will in turn increase the collision probability – the cross-section. The original design number of collisions accumulated over the years of operation is presented in the form of integrated luminosity [] and is of the order of 300 fb$^{-1}$ (inverse femtobarn).

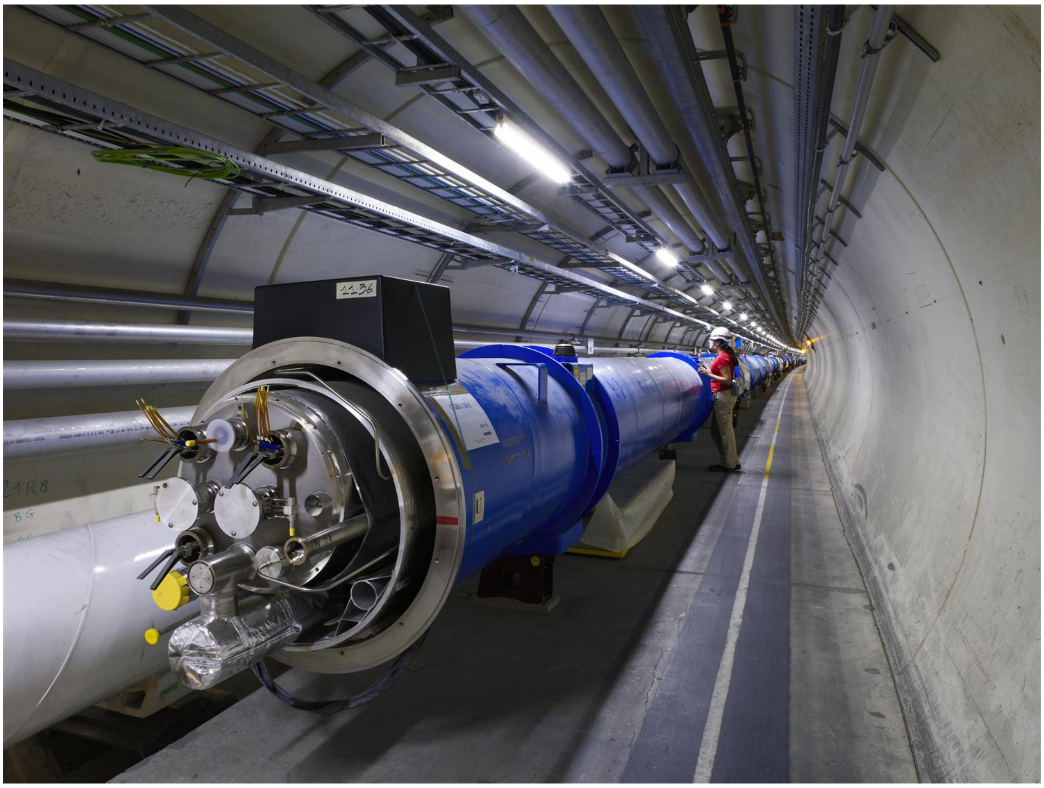

Figure 1.4: The Large Hadron Collider [7].

After the planned upgrades in 2020, the High-Luminosity LHC [] will achieve up to 3000 $\mathrm{fb}^{-1}$.

## 1.4 The ATLAS experiment

ATLAS (short for A Toroidal Lhc ApparatuS, figure 1.5) [] is a particle physics experiment at CERN. Its purpose is to verify current theories and to search for new discoveries by observing and analysing high energy proton-proton collisions produced by the LHC. It is the biggest experiment at CERN by dimensions (45 m in length and 26 m in height) and the number of people involved (more than 3000 physicists and engineers). The ATLAS experiment consists of a number of detectors, each designed to measure a specific property of the particles and photons produced during the collision. The closest to the collision point is the Inner Detector (ID), which consists of several layers of highly spatially segmented semiconductor sensors recording single points of the incident particles. These points are later reconstructed into particle tracks. In addition, a strong magnetic field of 2 T curves the paths of the charged particles, which in turn allows the ID to identify an individual particle's charge and momentum. The next two parts are the electromagnetic and tile calorimeter. These detectors weigh a few thousand tonnes and measure the energy of the particles that are stopped in the material. The only particles that make it through the calorimeters are muons.

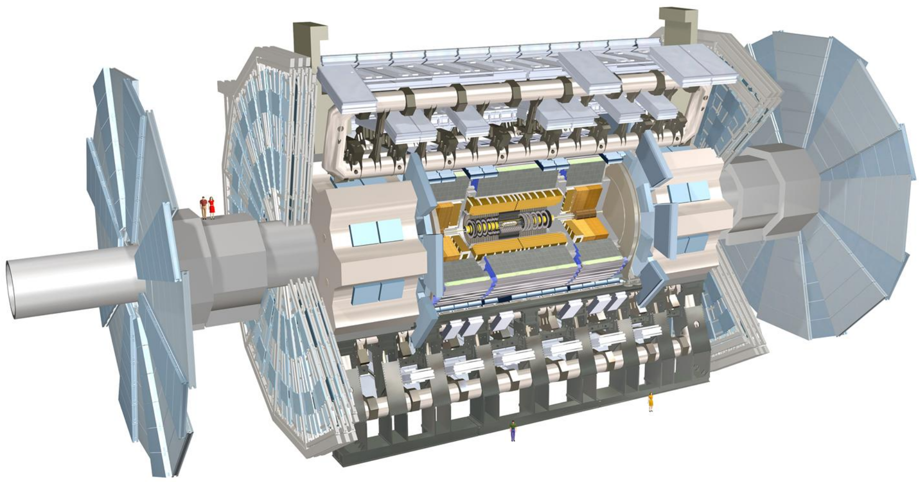

Figure 1.5: The ATLAS Experiment [13].

These are detected by the Muon Spectrometer, a set of large detector plates placed all around the calorimeters. Last is the superconductive magnet, which provides the magnetic field through the entire ATLAS except the ID, which already has its own magnets. To sum up, the Inner Detector measures the charge and momenta of the particles, the calorimeters measure their energies, the Muon Spectrometer measures muons and the magnets provide magnetic fields, which curve the trajectories of the charged particles, allowing for identification of particle momentum.

A complex Trigger and Data Acquisition system (TDAQ) is in place to distribute the clock signal, configure the detectors, trigger them and handle the output data. They are then stored at the CERN computer centre and distributed across the globe by means of the GRID – a distributed data analysis and data storage system.

The ATLAS detector has been designed to measure every collision taking place in its core. With 25 ns between collisions, this makes up 40 million collisions per second. In reality, the maximum achievable rate is about 300 kHz. The recorded collision is called an event. Every event holds information from all the detector channels within ATLAS. With $\sim 10^6$ channels, an event size is approximately 10 MB. At the maximum achievable rate this means a data rate of up to 3 TB/s. To reduce the amount of data stored a special classification system with a complex trigger logic is in place to decide which events should be stored and analysed further. It is programmed to decide in the order of tens of microseconds after an event whether it is potentially interesting or not. If so, the system triggers the readout of the entire detector. This way the recorded event rate is reduced from 300 kHz to $\sim$500 Hz.

## 1.5 Particle detectors

Particle detectors, or radiation detectors, have first come into use at the end of the 19th century. At that time Wilhelm Röntgen used a photographic plate onto which he shone X-rays. Soon after, in 1912, Victor F. Hess discovered cosmic rays during a balloon flight. This paved the way for development of particle detectors. A cloud chamber was designed – a chamber filled with a supersaturated vapour of water or alcohol. If a highly energetic particle traversed the chamber, the mixture ionised, creating condensation nuclei. These traces were visible and were photographed. All the subsequent particle detectors relied on the same principle of interaction between the particles – ionisation. The bubble chamber invented in 1952 used a superheated transparent liquid – a liquid heated just below its boiling point. A particle ionised the liquid, forming microscopic bubbles along its trajectory. Then followed the spark chamber and the wire chamber where the particle ionised the gas, causing a spark between two parallel plates at a high potential difference. These are nowadays used in museums as showcases. Next were ionisation chambers, which measured the induced current of the free ionised charges moving in an externally applied electric field. Finally in the 1960s, semiconductor detectors were introduced. Their principle of operation is similar to that of an ionisation chamber, with the difference that a semiconductive material is used as an ionisation medium instead of gas. Nowadays an ensemble of several types of detectors is used as a single detector system. Many considerations need to be taken into account when designing such a system: detector geometry, segmentation, event rate, efficiency, readout, support structures, cabling, cooling, cost etc.

Particle detectors can be divided in two groups: tracking detectors and calorimeters. The former are designed to measure trajectories (momentum) of particles and photons with a minimal impact on their flight path or energy with the aim to optimise the spatial resolution. Typically they are semiconductor detectors. The calorimeters, on the other hand, measure the energy of the particles/photons by stopping them. This means they need to be heavy and dense. A typical physics experiment nowadays would consist of a tracking detector enclosed by a calorimeter. This way both the momentum and energy are derived, measuring energy, charge and trajectory of every particle/photon.

### 1.5.1 Semiconductor detectors

Semiconductor particle detectors are devices that use a semiconductor for detecting radiation. They work on the principle of an ionisation chamber. An incident particle or a photon ionises the atoms in the crystal lattice. The charges are freed if the deposited energy is higher than the energy band gap. The freed charge carriers start drifting in an externally applied electric field, inducing current on the electrodes.

A number of semiconductor materials exist, each with a different band gap. Germanium (Ge) for instance has a band gap of 0.67 eV, which means that most of the electrons at the room temperature are already in an excited state due to thermal

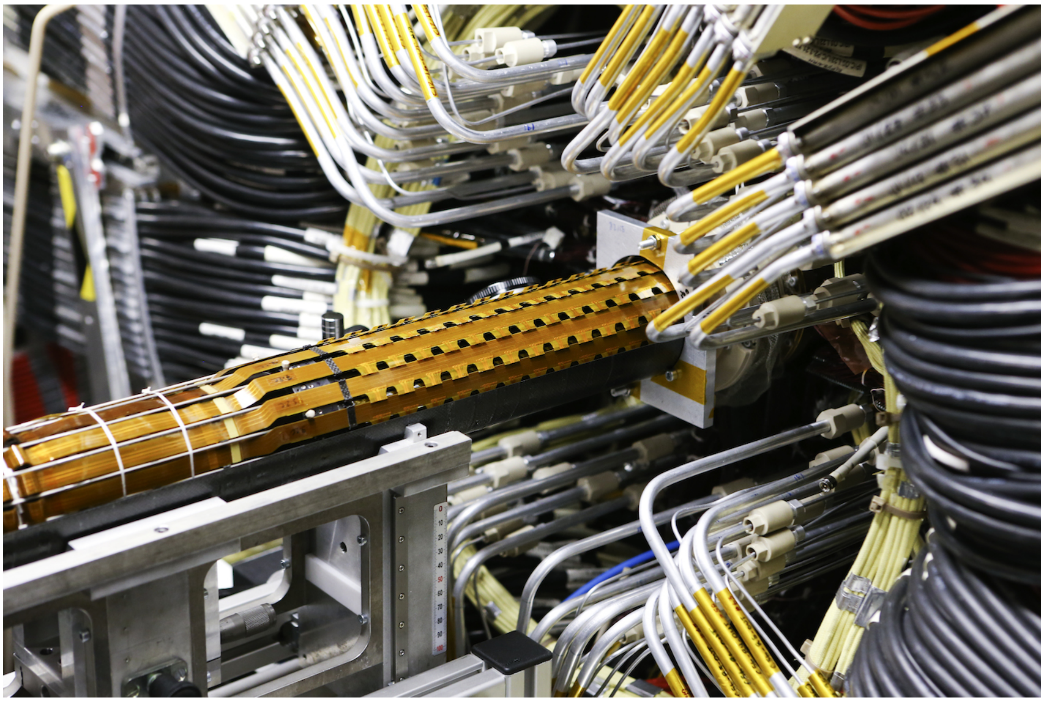

Figure 1.6: The Insertable B-Layer – a silicon particle tracker installed in the ATLAS experiment in 2014 [10].

excitation. The 5.5 eV band gap in the diamond, on the other hand, prevents the thermally excited electrons to jump to the conduction band. In addition, the gap is too wide for the visible light to excite the electrons. Silicon with an energy gap of 1.12 eV fulfils most of the needs for particle physics requirements and is therefore the most widely used material for particle detection.

Semiconductor detectors are most widely used for tracking applications, like the Insertable B-Layer shown in figure 1.6 [14], which was installed in ATLAS Experiment in 2014. First, they can be produced in thin layers to minimise the impact on the path of the incident particles. Second, their low sensor capacitance allows for a fast signal response. Third, they are highly efficient and highly resistant to radiation damage. Finally, the industrial processes allow for a fine spatial segmentation, which in turn improves the track resolution of a detector system.

Semiconductor sensors come in several configurations. The simplest type is a pad – a single plate with two electrodes. Pads are used for particle counting and radiation monitoring. Next is a strip detector, a more finely segmented detector made out of long parallel sensing areas or strips. Normally each strip has its own signal line for readout. Usually the strip detectors are used in pairs – one detector is placed on top of the other at an angle to increase spatial resolution in both axes. The third and the most finely segmented is a pixel detector, consisting of a 2D array of independent sensing areas. In tracking applications, pixel detectors are used where the need for a high detection resolution and granularity is the highest. Due to their high production cost and a high number of signal channels, they can only cover limited areas. Strip

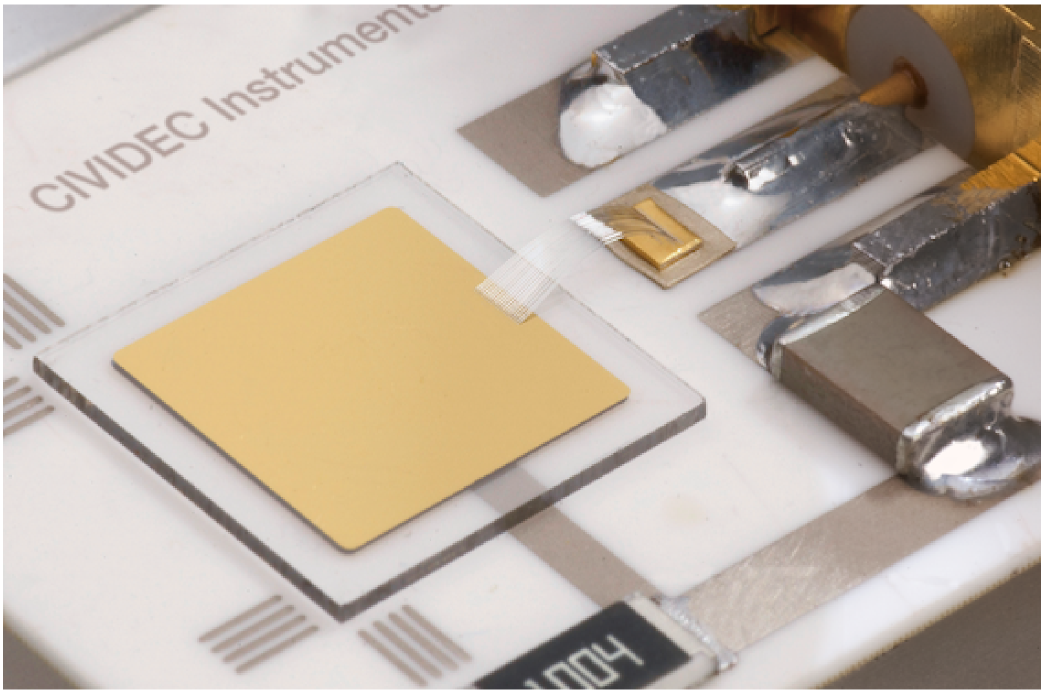


Figure 1.7: A pCVD diamond pad detector [9].

detectors are cheaper to produce and can be used to cover larger areas in several consecutive layers.

### 1.5.2 Diamond sensors

Diamond has been known for over two millennia, valued for its mechanical properties and its appearance. When the procedures for its synthesis were discovered, diamond made its way to a broad range of industries which exploit its optical and electrical properties. The discovery of the Chemical Vapour Deposition (described below) as a new synthesis process gave rise to a range of new applications. Purer specimens are used in electronics, high-power switching devices, electrochemical systems, radiation sensors, quantum computing etc. Recently it was found that it also exhibits superconductivity. This thesis focuses on the use of diamond for radiation detection.

Compared to a natural diamond, a detector-grade CVD diamond has almost no impurities (foreign atoms like nitrogen or boron). If proper procedures are followed, the diamond lattice can be grown very uniformly. This in turn improves electrical properties of the grown sample. Diamond is an almost perfect thermal and electrical insulator. Compared to silicon, the most widely used semiconductor material for radiation detection, it has many advantages, which are described in detail in chapter **??**. Figure 1.7 shows a diamond pad sensor produced by CIVIDEC Instrumentation GmbH.

**Chemical vapour deposition** (CVD) [] is a process where a material is deposited from a gas onto a substrate, involving chemical reactions. It is often carried out under high pressure and high temperatures. It takes place in enclosed chambers called furnaces with careful regulation of the temperature, pressure and gas mixture. Synthetic diamond is grown at 700–900 °C with a mixture of hydrogen and methane gas. At this temperature the molecules dissociate into carbon and hydrogen atoms. The carbon atoms are the building blocks and are deposited on the surface of the substrate.

Under a carefully controlled pressure and temperature conditions with an added abrasive atomic hydrogen the graphitic bonds break and form into diamond bonds. The speed of the growth can be anywhere between 0.1 and 10 μm per hour. The detector grade samples are grown at a rate of the order of 1 μm per hour. They can grow up to several millimetres in thickness. The width of the samples, however, depends entirely on the substrate used. Diamond can be deposited on various materials: diamond, silicon, tungsten, quartz glass etc. The substrate material must be able to withstand the high temperatures during the CVD process. The diamond substrate does not need any surface pre-treatment. Carbon atoms form bonds with atoms in the existing crystal structure. This is the homo-epitaxial growth where the newly deposited atoms retain the orientation of the structure in the substrate. Other non-diamond substrates, however, need to be pre-treated, usually by being polished using diamond powder. Some powder particles remain on the surface, acting as seeds for the growth of small crystals or grains. These grains grow and at some point merge with the adjacent ones, making up a compact material. The lower side is later polished away. These diamonds are called *polycrystalline* (pCVD) whereas those grown on a diamond substrate are *single crystal* (sCVD) diamonds. The area of the former can be large - up to 0.5 m$^2$ or more compact 15 cm$^2$ in the case of detector grade diamonds. The sCVD diamonds, on the other hand, can currently only measure up to 1.5 cm$^2$.

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