Faculty of nuclear science and physical engineering

Czech technical university

# Semiconductor Detectors in Contemporary Particle Physics Experiments

Review work

Author: Jan Hýbl

Supervisor: Václav Vrba (FZU AV ČR)

## Content:

# 1. Standard model

The Standard model of elementary particles summaries our present knowledge and understanding of the structure of matter. The matter constitutes are quarks and leptons; the forces between them are mediated by bosons fields.

- **Quarks**

  There are six types of quarks. They are divided into three families. The first family contains quarks *u* and *d*. The Second contains *c* and *s* and the third *t* and *b*. These letters mean "up, down, charm, strange, top and bottom". For example, proton and neutron are made from up and down quarks. Quarks have fractional electrical charge 2/3 or -1/3.

- **Leptons**

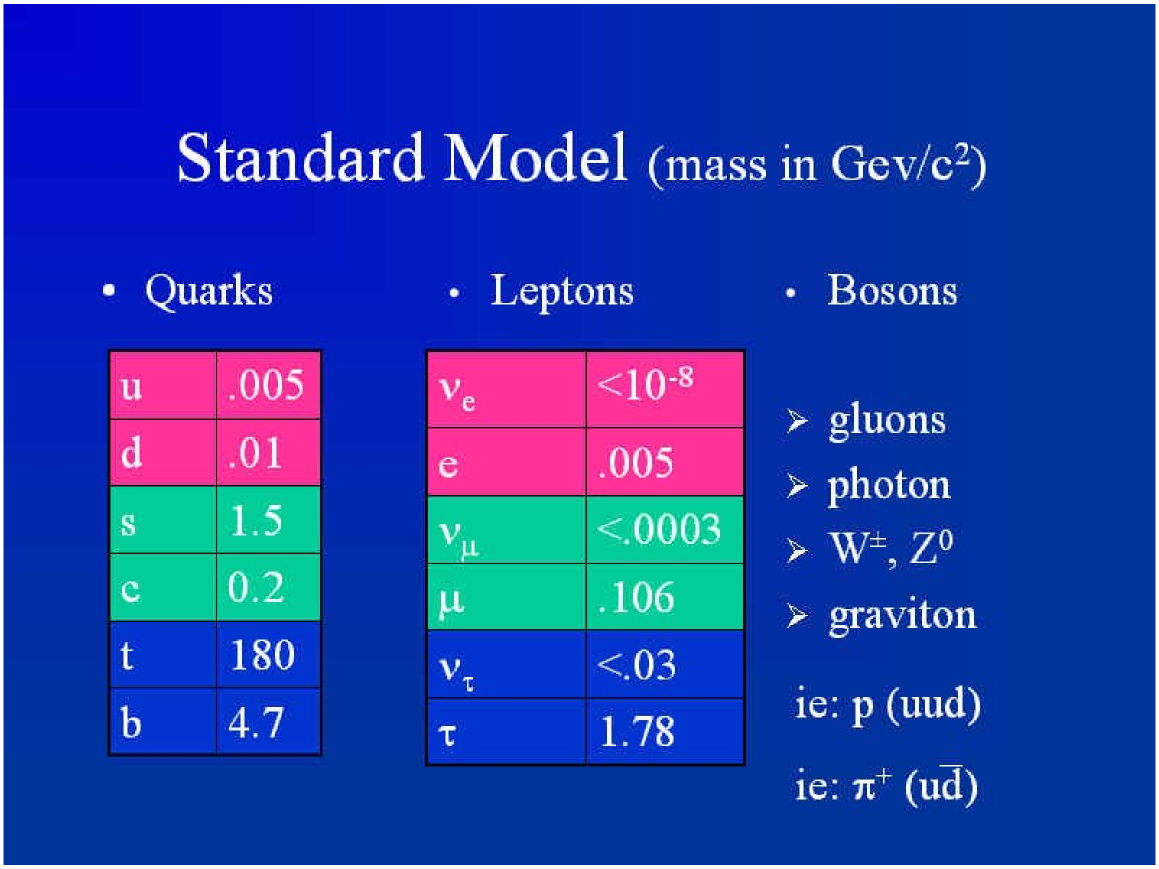
There are also six lepton: electron, muon, tau and three types of neutrino ($\nu_e$, $\nu_\mu$, $\nu_\tau$ ). The electron was discovered by Joseph Thomson in 1898 as a constituent of atoms. The muon is produced by the interaction of cosmic rays in the upper atmosphere. The electron – neutrino pair is produced in nuclear beta decay. The other three leptons: the tau, the muon and the tau neutrino, were discovered at particle at particle accelerators. The neutrinos have no electrical charge and little mass.

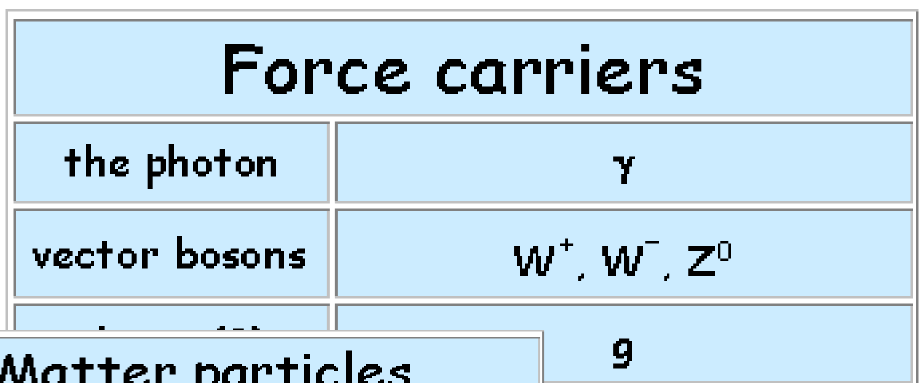
- **Force bosons**

The photon ( $\gamma$ ), eight gluons (g) and three vector bosons ($W^+$ , $W^-$ , Z) are responsible for the interaction between particles. The photon is responsible for the interaction between electrically charge particles, for example electrons, protons, antiproton etc. The W and Z bosons mediate the "weak nuclear" interaction. The gluons are responsible for the "strong" interaction.

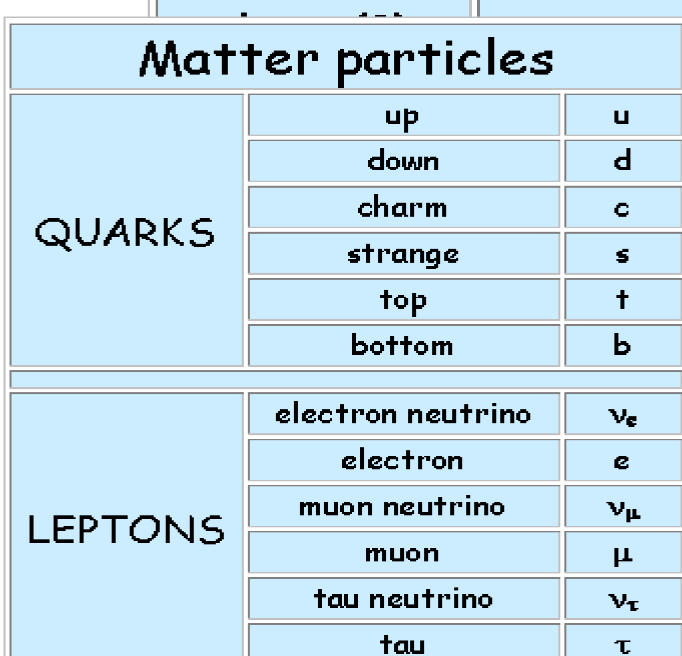
In the Figure **1.1** are shown 3 generation (families) of "elementary" constitutes of matter. It is interesting that everything in the world can be built just of the quarks and leptons of the first family. It is one of the mysteries, which is puzzling physicist why we observe 3 of such particle families.

As we can see in a ***Figure 1.1***, that there are three families of quarks as a three families of leptons .This fact come very good up to symmetry. But we don't know, why there are just three families.



| Force carriers | |
|---|---|
| the photon | $\gamma$ |
| vector bosons | $W^+, W^-, Z^0$ |
| [illegible] | g |



| Matter particles | | |
|---|---|---|
| QUARKS | up | u |
| | down | d |
| | charm | c |
| | strange | s |
| | top | t |
| | bottom | b |
| LEPTONS | electron neutrino | $\nu_e$ |
| | electron | e |
| | muon neutrino | $\nu_\mu$ |
| | muon | $\mu$ |
| | tau neutrino | $\nu_\tau$ |
| | tau | $\tau$ |

**ndard Model**

For each mass constituent particle (quarks and leptons) exist corresponding antiparticle. The most important different between the particle and its corresponding antiparticle is that their electrical charges have opposite signs.

The Higgs particle is neither a force carrier nor a matter particle. It appeared in the equations of the Standard Model when these where changed to allow particles with mass. The scientists hope to prove the existence of the Higgs particle at LHC accelerator at CERN after its launch in operation in 2007.

Standard model was established during the 1960`s a 1970`s. By the end of this period was discovered the most of quarks and leptons. Standard Model is for a present only one theory provides the most consistent picture of the world. It was shown that the predications of a Standard Model are consistence with results from the LEP at CERN, SLC at SLAC, California and Tevatron at Fermilab. The discovery of top quark was a triumph of the standard model.

Figure 1.1

| Force carriers | |
|---|---|
| the photon | $\gamma$ |
| vector bosons | $W^+, W^-, Z^0$ |
| gluons (8) | g |

Among the force carriers there are only the three vectors bosons of the weak interaction that have mass. The others, the photon and the eight gluons, all have zero mass. The quarks and the leptons all have different masses. The three neutral leptons, the neutrinos, have very small masses. Until recently it was not excluded that they had no mass.

As mentioned before, very high energies are used for study of structure of elementary particles. These energies are required, because from the Heisenberg uncertainty principle

$$\Delta P \Delta X \geq \frac{\hbar}{2\pi}$$

**Uncertainty principle**

follows that the smaller object (smaller distance) we would like to investigate, the higher momentum (or energy) of the projectile particle we need, here Δx is the uncertainty or imprecision (standard deviation) of the position measurement, Δp is the uncertainty of the momentum measurement in x direction at the same time as the x measurement.

## 2. Some Problems of Contemporary Particle Physics

Standard model, in its present form, has number of phenomenological parameters, which value is not given or explored by model itself. For example, masses of particles are not fixed by the model and the model would be consistent with the particles zero mass. The Higgs mechanism of the spontaneous symmetry breaking provides a mechanism by which particle acquire non zero mass. To prove such approach the discovery of the Higgs particle is essential.

There are several ways how to built unified model of electroweak, strong and gravitation interaction. One of relatively straightforward way suggests so called supersymetric models, which assumes an existence of supersymetric partners to “ordinary” particles.
The search for supersymetric particles is one of the tasks of the contemporary experimental particle physics. Another hot question is compositeness - question whether “elementary” fermions are really point like object or have further internal structure.

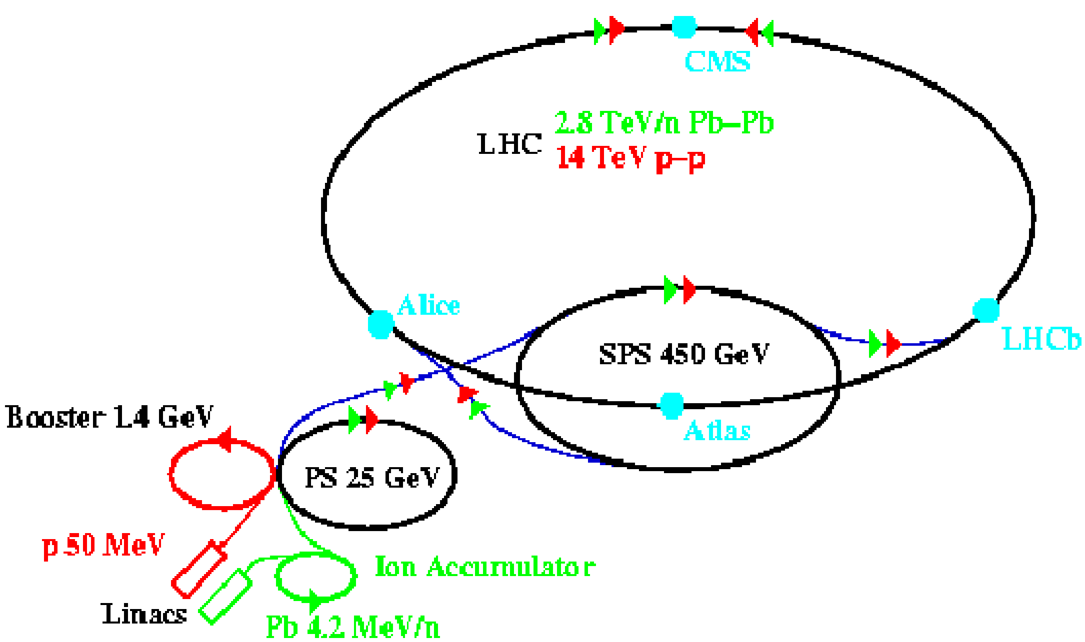


**Figure 1.2**
**The complex of accelerators of particles in CERN**

Many answers on our presents question can be given by experiments at biggest world accelerator. One of the places where the scientists try to solve these problems is CERN on the border of Switzerland and France. The accelerator system is shown on Figure 1.2. In CERN is under construction new accelerator LHC (Large Hadron Collider). Physicists expect interesting result and the answers to their questions, especially the question about existence of Higgs particle.

The LHC is going to be the biggest accelerator ever built. The Large Hadron Collider (LHC) is a circular particle accelerator. It will be placed in the already existing 27 km long tunnel of the former the LEP Collider. In LHC protons will be accelerated in both directions and will collide inside the detectors.

With the ATLAS detector it will be possible to look inside to the mechanism of how masses are 'created'. The most potent theory describes the mass through what is called the Higgs field. According to this theory, invented by the Scottish physicist P. Higgs, the vacuum not really empty, but it is filled with something called the Higgs field. When particles move in this Higgs field they accumulate mass. The stronger the interaction between the particles and the Higgs field is the more mass the particles get. The Higgs field should also manifest itself as a particle and it can be discovered by ATLAS, if it exists at all.

In the next chapter I will describe the layout of the Atlas detection system, its components functioning of individual components and their contribution to the physics research programe.

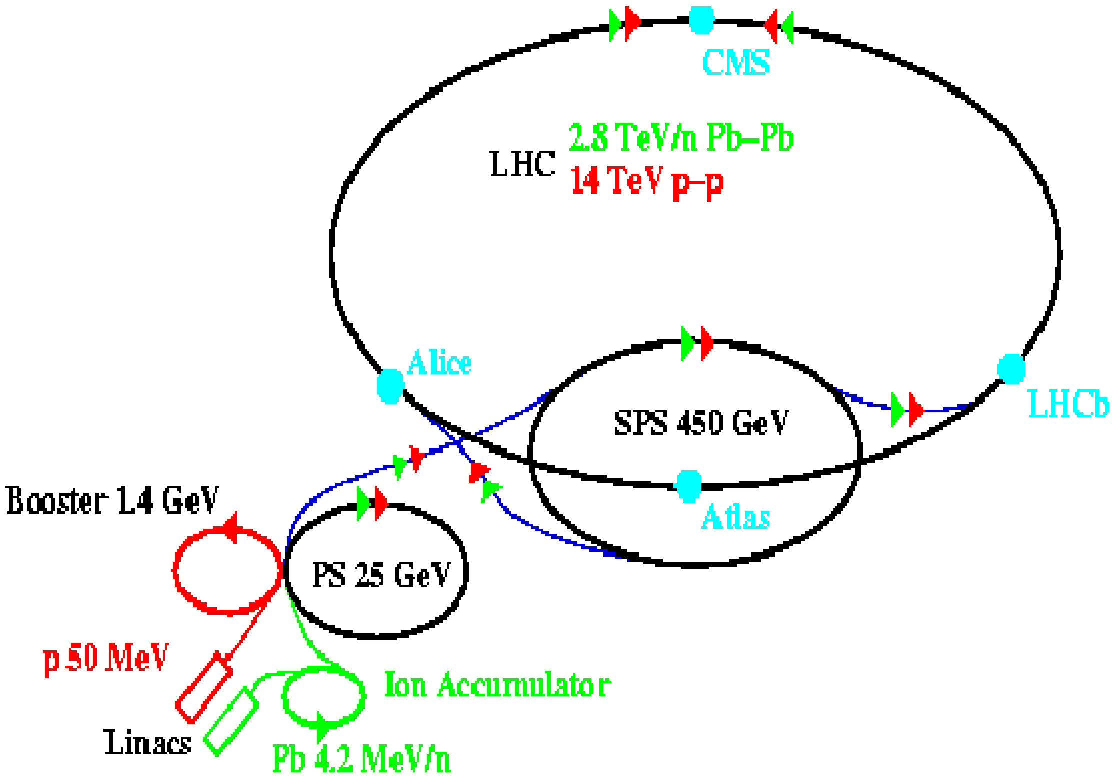
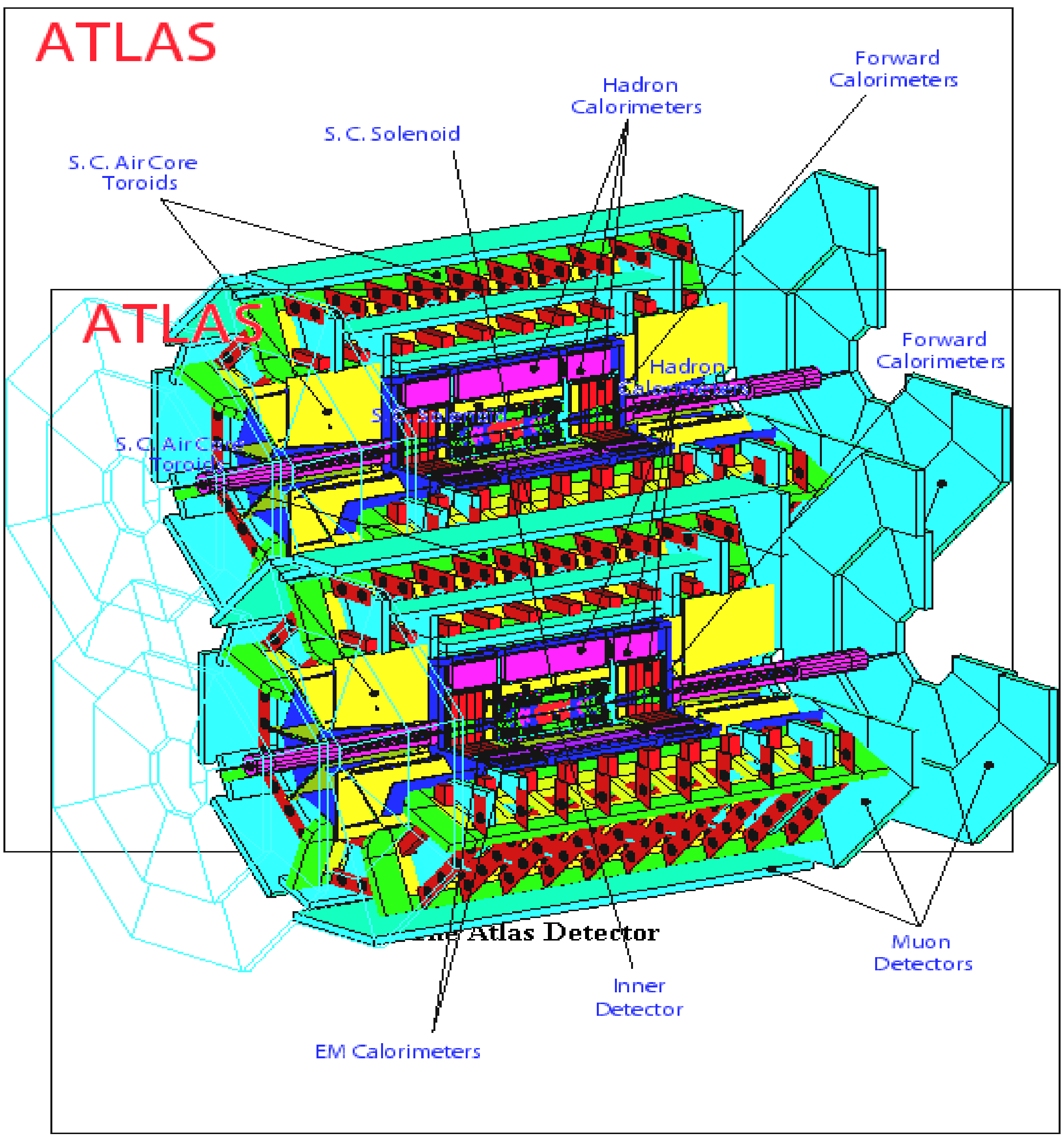



**Figure 1.2**
**The complex of accelerators of particles in CERN**

## Atlas Experiment

The Atlas (A **T**oroid **L**HC **A**pparat**us**) Experiment is one of the two experiments built for the 14 TeV p – p collision at LHC. LHC (Large Hadron Collider) accelerates protons in opposite direction in a vacuum pipes. The Atlas detector will be among the largest and most complex devices for experimental research ever undertaken, and obtained experimental data are expected to point to exciting, even revolutionary advances in the understanding of matter and forces.

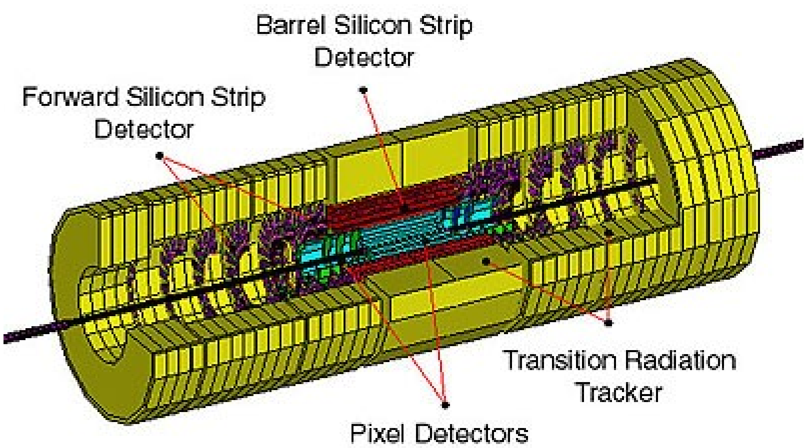
The ATLAS detector, see Figure **1.3** will be very large and complex: 42- meters long, 22-meters in diameter, and will weight 7,000 tons. It will be the first detector to use superconducting air-core toroid magnets of this size.



Atlas detector consists of the Inner Detector, providing high resolution momentum and vertex measurements, the Electromagnetic and Hadron Calorimeters, which measure the energy and position of electrons, photons and hadrons and play an important role in particle identification, the Muon Spectrometer which measures the deflection of muon tracks by Toroid Magnets.

### *Inner Detector*

The Inner Detector measures the directions, momenta, and sign of charge of electrically-charged particles produced in each proton-proton collision. It is located closest to the interaction point. Therefore to obtain an optimal resolution it consists of three different systems of sensors all immersed in a magnetic field parallel to the beam axis.




Inner Tracker

The Inner Detector combines the function of precious tracking with continuous tracking using high resolution semiconductor detectors (silicon pixels, strips) within a radius of 60 cm and Transition Radiation Tracker, built using straw tubes all in 2 Tesla solenoid field.

### 3.1.1 Pixel Detector

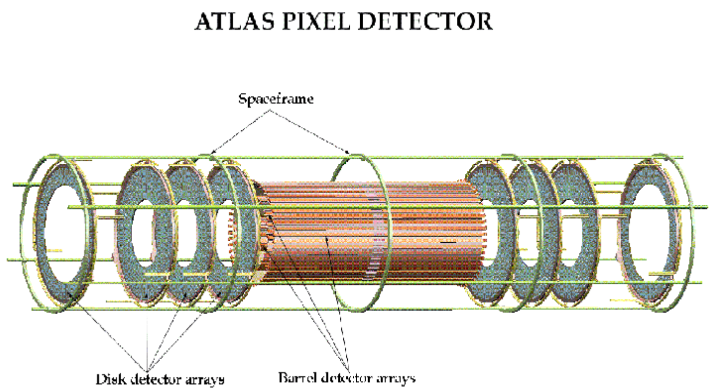



Figure 1.4

Inner Detector contains a lot of pixel detectors as much as 140M channels; it gives resolution of about 15µm in rϕ and 120 µm in z. It is made of 3 barrel and 8 disk layers providing at least three measured points on a track. Pixel Detector is closest to interaction point. Pixel Detector is a mosaic of 2600 tesseras, called modules; each module is made of one silicon detector. Each detecting element has dimension 50 x 400µ. Thanks to small detector capacitance (~ 0.1 pF per pixel) it is possible to design fast electronics (rise time < 50 ns).

### Barrel and Forward Silicon Strip Detector

The strip detectors are used for the best determination of full trajectory. They are just behind the pixel detector. Strips are about 80 microns wide and 6 centimeters long. Each layer actually has two sets of strips, running at an angle of 2.3 degrees relative to each other. On cylinders, the strips run parallel to the beam axis. On disks, the strips are radially oriented.

If a charged particle goes through the strip detector, signals identify which strip in which modules has been traversed. These penetrates of those two struck strips provides a very precise 3-dimensional position measurement around the cylinder or disk and much less so in the other direction of the sensors.

## Transition Radiation Tracker (TRT)

At larger radii, it becomes too expensive to cover large area with silicon strip detectors, and the different set of devices is necessary. These are collections of gas-wire drift detectors that consist of 4mm-diameter tubes (like straws) with thin wires running through the tube centers. The tubes are filled with an appropriate gas and high voltage is maintained between the wire and the metallized tube wall. When a particle traverses a tube, its wire produces a discharge that not only identifies which tube was traversed, but, through accurate timing of the discharge, determines how far from the wire the particle passed.

TRT has outer diameter 216 cm, length 700 cm, weight 1500 kg. It contains 52544 barrel straws and 319488 end-cap straws, which ever is 150 cm length (in barrel) and 39 or 55 cm length (in end-cap). It expends 15kW.

Transition radiation consists of X-rays generated when charged particles, moving at speeds extremely close to the speed of light, traverse interfaces between solid materials and gas. Whereas heavier particles do not at the relevant energies, they produce transition radiation. In the TRT, foam and foils are used to produce the interfaces, and the transition X-rays interact in the gas of the "straw" tubes, and produce much larger pulses than traversing charged particles. Detection of such large pulses helps identify the particle producing the transition X-rays as an electron.

## *3.1. Atlas Calorimetry System*

Calorimeter is a device that absorbs whole energy of particle and its output is equal to this energy. The particle goes through and loses a fraction and all energy. Function of Calorimeter is found on principle of creation of electromagnetic or hadronic shower. Electromagnetic Calorimeters measure the energy of leptons (such as electrons) and photons (light particles) as they interact with the electrically charged particles inside matter. Hadronic Calorimeters measure the energy of hadrons (particles contains quarks) by the help of their interaction with atomic nuclei. The Calorimeters are divided into two groups. The first group is: Homogenous – the whole dimension is sensitive. The second is: Compound – it is composite from convertor (the shower is evolving, it is made of lead or iron) and sensitive dimension (lead-glass, liquid argon, silica aerogel, etc.).

### 3.2.1 Electromagnetic Calorimeter

The Electromagnetic Calorimeter absorbs the energies of all electrons and photons traversing it and produces signals proportional to their energy. The electromagnetic calorimeter of Atlas consists of thin lead plates (about 1.5 mm thick) separated by sensing devices. The lead plates are immersed in a bath of liquid argon. When high energy photons or electrons traverse the lead (or any high-atomic-number material), they produce an electron shower. The liquid argon gaps (about 4 mm) between plates are subjected to a large electric field. When one of the shower electrons or positrons produced in the lead gets into the argon, it makes a trail of electron-ion pairs along its path; that is, it knocks out electrons from some of the atoms it encounters, leaving ions in their place. The electric field causes the ionization electrons to drift to the positive side (they move more quickly than the ions), and their motion produces an electric current in an external circuit connected to the calorimeter. The greater the incident energy, the more shower electrons there are, and the greater is the current. To determine the precise relation between this current and the corresponding electron or photon energy, one must calibrate the calorimeter.

To determine the measured direction of electromagnetic energy the electrical connections to the calorimeter (“electrodes”) are subdivided into small rectangular regions. Such regions at various depths are grouped and connected together to make towers pointing away from the interaction point. The current signals associated with each tower are read out, and provide a measure of the electromagnetic energy in the range of directions associated with the given tower. This is required for locate cluster of particles called jets.

### 3.2.2 Hadron Calorimeters

The Hadron Calorimeter surrounds the electromagnetic calorimeter. It absorbs and measures the energies of hadrons, including protons and neutrons, pions and kaons (electrons and photons have been stopped before reaching it). The ATLAS Hadron Calorimeters consist of steel absorbers separated by tiles of scintillating plastic. Interactions of high energy hadrons in the plates transform the incident energy into a "hadron shower" of many low energy protons and neutrons, and other hadrons. This shower, when traversing the scintillating tiles, causes them to emit light in an amount proportional to the incident energy.

***The Hadron Calorimeter parameters**:*

- *Dimensions* : Cylinder with $R_{int}$=2280mm, $R_{out}$=4230mm, subdivided into a 5640 long central barrel and two 2880mm long extended barrel.
- *Segmentation* : Three longitudinal samplings with 1.5, 4.2 and 1.9 $\lambda$ at $\eta = 0$.
- *Granularity* : $\Delta\eta \times \Delta\phi = 0.1 \times 0.1$ (0.2 x 0.1 in third sampling)
- *Readout channels* : 10000
- *Weight* : 2300 tons

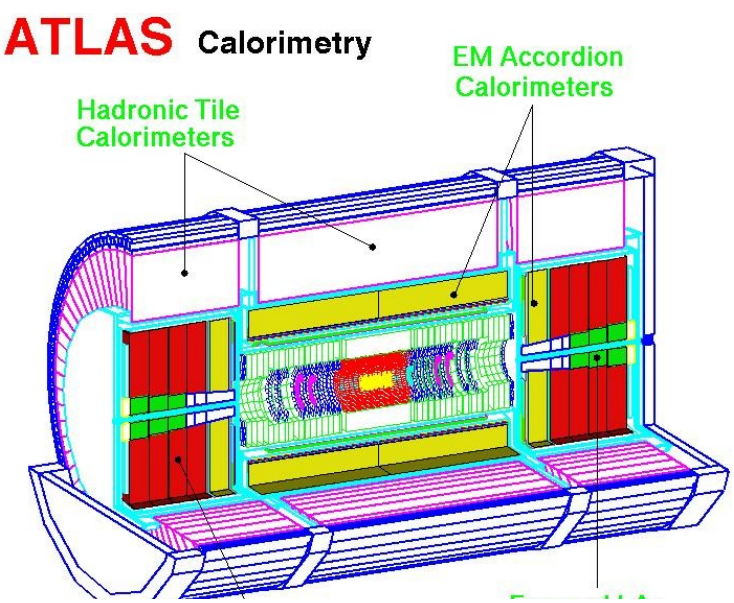



Figure 1.5
The division of Hadron Calorimeter

The Hadron Calorimeter has two major functions. The first is measurement of energy and direction of jets (clusters and particles). The measurements of jets energy and jets direction we can interpret as an energy and direction of quarks and gluon by the proton – proton collision. The second function is inference of particles which we didn't measure on the basic of principle of conservation of momentum. The total vector momentum of all collision products must be zero, since momentum is conserved in the collision and since the colliding protons have equal and oppositely directed momenta. Thus, if the transverse components of momentum are not equal to zero (within errors), the presence of one or more undetected neutral particles is inferred. This inference is reliable only if the calorimeter is "hermetic", that is, it has no holes, except a small one for the beam pipe, through which collision products that should be detected sneak through unseen. The division of Hadron Calorimeter is shown below and on a figure **1.5**.

### *A, The Tile Hadron Calorimeter*

The Tile Hadron Calorimeter consists of a steel plate structure interspersed with scintillator tiles of 3 mm thickness. The scintillator "senses" the hadronic shower particles, and produces signals proportional to their number, which itself is proportional to the energy. Hadrons emitted at angles greater than 25 degrees relative to the two proton beams are absorbed in the Tile Calorimeter. The subdivision of the scintillator into tiles provides the segmentation to allow measurement of the directional dependence of the energy.

### B, The Liquid Argon End Cap Hadronic Calorimeter

The total radiation emanating from the collision point is least intense at large angles (near 90 degrees), and most intense at the smaller angles to the beam. Because scintillating tiles are damaged by excessive exposure to radiation, hadron calorimetry at angles to the beams between 5 and 25 degrees is provided by a liquid argon device very similar to the electromagnetic calorimeter. The main differences are that the lead plates are replaced by copper plates (thickness 2.5 cm) more appropriate to the hadronic showering process and the argon gaps are 8 mm.

### *C, The Liquid Argon Forward Calorimeter*

To provide the needed full coverage, it is necessary to extend the calorimeter to detect jets at angles as small as 1 degree relative to the beams. Because of the extremely hostile radiation environment in the angular region between one and five degrees, the calorimetry must be designed with special care. It is of the liquid argon variety, but the metal plates are replaced by a metal matrix in which are embedded hollow tubes of 5 mm inner diameter. Metal rods of 4.5 mm diameter are centered in the tubes, and the argon fills the small gaps between rod and tube wall. A few hundred volts between rod and tube produce the electric field to make electrons drift in the argon-filled gap.

## *Muon detector*

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Muons are the only charged particle that can travel through all of the calorimeter material and reach the outer layer. The Muon Detector is placed the farthest from the beam, because only neutrinos and muons get this far. The Muon Detector determines the signs and momenta of muons with better precision than the inner tracking system does. Muons are about 200 times more massive than electrons, they are much less affected by the electric forces of the atomic nuclei. They lose energy almost solely by the formation of electron-ion pairs along their path, and for a substance like steel or copper, this amounts to an energy loss of about 1 MeV per millimeter of path. Thus muons with energy above, say, 5 GeV will penetrate about 5 meters of steel. The measurement starts at 5m distance from the interaction point and extends over a distance 5 – 10 m.

To achieve more precision measurement of muon momenta than do the inner detector we use toroid magnets. The additional set of magnets located in the regions downstream (outside) of the calorimeters produces a magnetic field whose field lines are circles centered on, and perpendicular to the beam line. The toroid field deflects the muons in the plane defined by the beam axis and the muon position.

The muon sensors consist principally of gas-filled metal tubes, 3 cm in diameter, with wires running down their axes. With high voltage between the wire and the tube wall, traversing muons can be detected by the electrical pulses they produce. With careful timing of the pulses, muon positions can be measured to an accuracy of 0.1 mm. The reconstructed muon path determines its momentum and sign of charge.

## *The Magnet System*

The Atlas superconducting Magnet System is an arrangement of a central solenoid, providing the Inner Detector with magnetic field, surrounded by a system of three large air-core toroids generating a magnetic field for the Muon Spectrometer. The overall dimensions of the Magnet System are 26 m in length and 20 m in diameter. The two and-caps toroids are inserted in the barrel toroid at each end and line up with the central solenoid. The have a length of 5 m, an outer diameter of 10.7 m and an inner diameter of 1.65 m. The central solenoid provides a central field of 2 T with a peak magnetic field of 2.6 T. The peak magnetic fields on the superconductors in the barrel toroid and end-cap toroids are 3.9 and 4.1 T.

Each of three toroids consist eight coils assembled radially and symmetrically around the beam axis. The end-cap toroids coil system is rotated by 22.5° with respect to the barrel toroid coil system order to provide radial overlap and to optimize the bending power in the interface regions of both coil systems. The barrel toroid coils are of a flat racetrack type with two double-pancake windings made of 20.5 kA aluminium-stabilized NbTi superconductors. The central solenoid coil is designed to be as thin as possible without sacrifice the operational safety and reliability. Minimum coil material and an adequate safety margin for operation are obtained by distributing the stress uniformly between the coil components.

The magnets are indirectly cooled by a forced flow of helium at 4.5 K through tubes welded on the casing of the windings. The central solenoid is cooled via a dewar coupled to the refrigerator, whereas the barrel toroid and end-cap toroids in addition have cold helium pumps to guarantee appropriate cooling by a forced helium flow.

# 3. Semiconductor Detector

The detection of Semiconductor Detectors is based on creation of pair of electron – hole with charge about 3eV. It gives high signal for low transferred energy. The output signal is adequate to energy of particle. Semiconductor Detectors have very good energy resolution. They are almost made of silicon or germanium. To achieve a small resistance, they are cooled by liquid nitrogen. They are very good for determine energy of low – energy quanta of gamma and electrons. At present they are almost used SSD – Silicon Strip Detector and SDD – Silicon Drift Detector.

Semiconductor detectors have been used in high-energy physics applications in the form of pixel detectors, microstrip detectors pads; they are popular due to their unmatched energy and spatial resolution, and have excellent response time. These detectors are manufactured mainly of silicon, traditionally on high-resistivity single crystal float-zone material.Further we will study only Silicon detector.

## *4.1 Silicon Detectors*

The functionality of semiconductor (silicon too) detectors is based on the formation of pn junction known as semiconductor diode. When a particle goes through silicon matter it exits the silicon atoms and kick out one of the four valence electrons. It is creating electron – hole pair. Separated by the electric field, the holes drift to the back-plane, the electrons to the readout strips. This provides the signals that are amplified and used to determine the track of the particle. All of this is shown in the figure **1.6**, see below, it shows function of particle track.

**Properties:**

- ***Size*** : 64 mm x 64 mm x 0.3 mm thick
- ***Bulk Material*** : Silicon semi-conductor wafer with negative charge carriers (n-type)
- ***Implants*** : Regions with positive charge carriers (p-type) and regions with a higher density of negative carriers (n+).
- ***Readout strips*** : The signals from the detector are collected on n+ strips implanted 0.08 mm apart. Intermediate p+ implants separate them

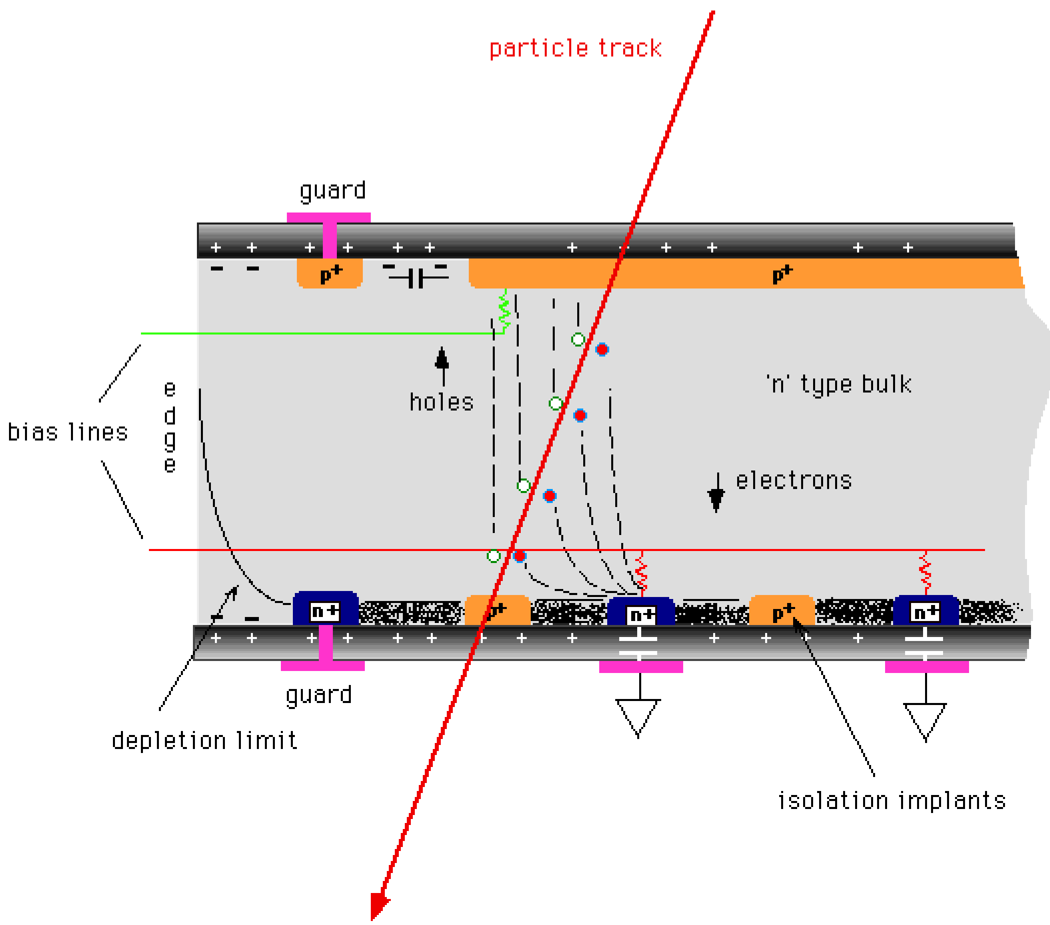


**Figure 1.6**
**Function of silicon detector**

## *4.2 Silicon properties*

Silicon is an element of the IV group of the group of elements and has 4 electrons on the valence shell. All the conductivity is realized by electrons excited from the valence band into the conducting one. Such an excitation leads to a generation of hole - empty state that left after the electron excitation and that behaves as a positively charged particle. In the silicon without impurities the densities of electrons and holes are the same. By replacing some of the silicon atoms by atoms from the III or V groups the p- or n-type materials are obtained. Elements from the III group (acceptors) have 3 valence electrons and easily attach an electron from silicon atoms. Elements from the V group (donors) have one very weakly bound electron that can be easily excited to the conduction band. The "binding" energy of electrons in n-type and of holes in p-type silicon semiconductor is approximately 45 meV. Very heavily doped semiconductors are marked n+ or p+ respectively. In both n- and p-type semiconductors there are the other type carriers as well, due to thermal excitations, called minority carriers.

Properties of silicon material are shown on a Figure **1.7**. Particle passing through the detector ionizes the Si atoms and so effectively creates the e-h pairs. For typical thickness of silicon detector 300 nm the number of generated e-h pairs by MIP passing perpendicular through the detector is $3.2\ 10^4$ which is 4 orders magnitude lower than the total number of free carriers in intrinsic silicon of a surface of 1 $cm^2$ and the thickness. In doped material the S/N ratio would be even smaller. One way to increase the ratio is to cool the semiconductor.

| | |
|---|---|
| Atomic number | 14 |
| Atomic weight | 28.08 |
| Atomic density | $4.99 \cdot 10^{22}$ cm$^{-3}$ |
| Density | 2.33 g/cm$^3$ |
| Dielectric constant | 11.6 |
| Gap energy | 1.11 eV |
| Effective states density in conduction band | $2.80 \cdot 10^{19}$ cm$^{-3}$ |
| Effective states density in valence band | $1.04 \cdot 10^{19}$ cm$^{-3}$ |
| Electron mobility | 1350 cm$^2$V$^{-1}$s$^{-1}$ |
| Hole mobility | 480 cm$^2$V$^{-1}$s$^{-1}$ |
| Electron Hall mobility | 1670 cm$^2$V$^{-1}$s$^{-1}$ |
| Hole Hall mobility | 370 cm$^2$V$^{-1}$s$^{-1}$ |
| Electron diffusion constant | 34.6 cm$^2$s$^{-1}$ |
| Hole diffusion constant | 12.3 cm$^2$s$^{-1}$ |
| Intrinsic carrier density | $1.45 \cdot 10^{10}$ cm$^{-3}$ |
| Breakdown field | 30 V/$\mu$m |
| Diamond type lattice spacing | 0.5431 nm |
| Mean energy for $e$-$h$ pair creation | 3.63 eV |
| Fano factor | 0.115 |

**Figure 1.7**

**The physical properties of silicon at room temperature**