Characterization of solid state detectors using TCT and ALiBaVa readout system

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Semiconductor theory

A semiconductor is a solid whose electrical conductivity can be controlled by doping; adding impurities. It has an electrical resistivity between that of a conductor and insulator. The material is characterised by an energy band diagram with an energy gap between the conduction and valance bands of a few electron volts (more than 4 eV the material is said to be an insulator). The current in a semiconductor is carried by a flow of electrons and or by positively charged particles called 'holes' in the electron structure of the material. The electrons are free to conduct (known as free electrons) when they inhabit the conduction band. This takes place due to thermal excitation or doping. When an electron is excited from the valance band to the conduction band it leaves behind a hole in the valance band; which can be treated as a charge carrier with positive charge.

The conductivity of the material is controlled by the impurity concentration. Silicon is a group IV element with four valance electrons. Doping with a group V material (with 5 valence electrons) introduces an extra electron into the crystal structure which inhabits the conduction band. This is known as n-type doped material. Similarly doping with a group III element (three valence electrons) introduces a lack of an electron, or a hole, into the material. This is known as p-type material. A simple diode structure, called a p-n junction, is formed when a piece of p-type and a piece of n-type doped material are brought together. In the p-n junction electrons diffuse, due to the carrier concentration difference, from the n-type material to the p-material leaving a net positive fixed charge in the n-type region. The electrons recombine with the holes in the p-type material. Likewise, free holes diffuse from the p-type material to the n-type, recombining with electrons, leaving a region of negative fixed charge in the p-type material. The fixed positive charge causes a force on the charge carriers and creates a drift current that is opposite in direction to the diffusion current. Eventually a steady state is reached. The region of fixed space charge is known as the depletion region as it is depleted (free of) mobile charge carriers. Due to the fixed

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charge a potential is present over the depletion region, and therefore an electric field exists. The application of a reverse bias over the p-n junction causes the depletion region to grow and eventually the material will become fully depleted, i.e. leading to a region free from mobile charge carriers.

For a silicon detector a p^+-i-n^+ structure is typically used. The intrinsic material (denoted by an i) is in fact either very slightly n or p type (denoted as n^- and p^-). The positive superscript signifies that the doping concentration is high. The doping concentrations are typically 10^{18} atoms cm^{-3} for the n^+ and p^+ type doped sections and 10^{11} atoms cm^{-3} for the near intrinsic region; while intrinsic silicon has a doping level of 1.5×10^{10} atoms cm^{-3} at room temperature. The detector's doped areas can be segmented into strips or pixels to enable position sensitivity. The heavily doped regions are only a few microns in thickness while the near intrinsic region is typically hundreds of microns in thickness. For operation as a detector the diode is reverse biased, where biasing refers to the application of an external voltage across the p-n junction of the detector, to set up a depletion region across the full thickness of the intrinsic material and therefore an electric field across the entire device. When a charged particle or photon enters the material the silicon is ionized and free electron hole pairs (charge carriers) are produced. The electric field causes the charge carriers to separate, before they can recombine, and to drift towards the heavily doped regions which form the external electrodes of the diode. The introduction of the charge carriers and their subsequent drifting induces a signal on the external electrodes which is measured by external electronics.

The p-n junction is illustrated in Figure 1. The first two sub-figures show the material with the fixed space charge illustrated as a sign inside a circle and the free charge carries as "-"and "+" signs. The other sub-figures illustrate physical attributes of the junction.

The electric field and the electrostatic potential inside an abrupt p^+-n junction can be calculated with the use of Poisson's equation, given in Equation 1, where Neff is the effective doping density of the semiconductor.

$$\frac{dE}{dx} = \frac{d^2V}{dx^2} = -\frac{\rho}{\varepsilon} = \frac{q}{\varepsilon_{Si}\varepsilon_0} N_{eff}$$

Equation 1 : Poisson's equation

The boundary conditions are that the electric field and the potential are both equal to zero at the edge of the space charge region, that is:

$$\frac{dV(x=w)}{dx} = 0$$
$$and$$
$$V(x=w) = 0$$

Equation 2 : boundary conditions for the abrupt p^+-n junction

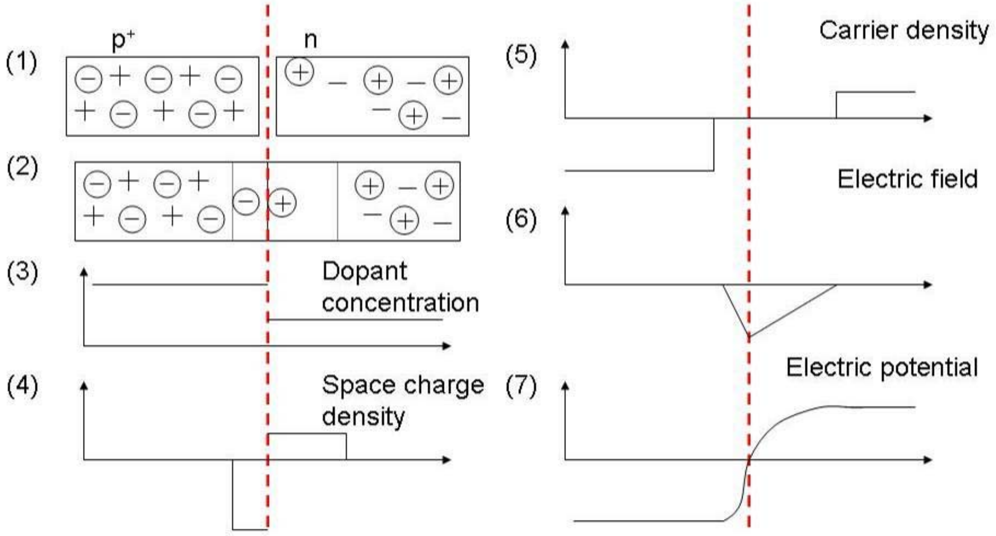


Figure 1 : The p-n junction. 1) p and n-type material 2) p and n junction in thermal equilibrium 3) absolute doping concentration 4) space charge density 5) free carrier density 6) electric field 7) electric potential

Solving Poisson's equation gives the potential as a function of distance inside the junction as given by Equation 3. Inserting the device thickness gives the full depletion voltage of the diode. The depletion width can also be expressed as a function of the applied potential, as given in Equation 4.

$$V(x) = \frac{q}{2\varepsilon_{Si}\varepsilon_0}\left|N_{eff}\right|x^2$$

Equation 3 : Potential inside the p$^+$-n abrupt junction as a function of distance

$$w(V) = \sqrt{\frac{2\varepsilon_{Si}\varepsilon_0}{q\left|N_{eff}\right|}V}$$

Equation 4 : The width of the depletion region as a function of the applied bias

Using the fact that the capacitance is given as the rate of change of the charge with potential, the capacitance of the junction can be expressed as a function of the doping density of depletion width as shown in Equation 5 and 6.

$$C = \frac{dQ}{dV} = \frac{dQ}{dw}\cdot\frac{dw}{dV}$$

Equation 5 : The definition of capacitance as a function of depth inside the junction

$$C(V) = A\cdot\sqrt{\frac{\varepsilon_0\varepsilon_{Si}q\left|N_{eff}\right|}{2V}}$$

Equation 6 : The junction capacitance as a function of applied voltage

Device Types

Pad detector

The pad detector (see Figure 5) is a very basic silicon detector. It consists of a p^+-i-n^+ junction with one large heavily doped pad on either face of the intrinsic bulk material. One face is p^+ doped and the other n^+ doped. This means there is no way of deducing a particles interaction point except to say that is occurred within the detector. The signal induced will depend on the type of ionizing particle interacting in the detector and the depletion width (controlled by the applied bias voltage).

Strip and Pixel Detectors

The detector's highly doped regions (electrodes) can be segmented into strips or pixels (see Figure 2). When an ionising particle enters the detector ionising the material free electron-hole pairs are created. These drift under the influence of the electric field in the depletion region and a signal is induced on the electrodes in the vicinity of the original ionisation. This enables the original position of the ionising particle to be reconstructed from the signal collected on the segmented electrodes. Both types of detectors work in this way, the difference between them being that the pixel detector has individual contacts that are arranged in a 2D array while the strip device has only a 1D array of contacts. Therefore, the pixel detector allows the 2D determination of the original ionisation point rather than just the 1D. This laboratory will only use strip devices.

Energy deposition from a high energy particle

When a silicon detector is traversed by a high energy particle and only a small amount of energy is lost by that particle per unit thickness of the detector, such a particle is known as a Minimum Ionising Particle (a MIP). When the ionising particle passes a silicon atom in the lattice it will tend to liberate a loosely bound valance electron. The electron will be ionised at an excited energy state and via collision will enter thermal equilibrium with the lattice as a free electron in the conduction band. Occasionally the ionising particle will interact with a more tightly bound electron than the silicon valence electrons and as a result create an electron with a significant amount of kinetic energy. This liberated electron can cause secondary ionisation of the silicon. The energy deposited for this interaction is therefore higher than that for the interaction with the valence electrons. As a result of these rare high energy events the energy spectrum of the deposited energy in the silicon detector is a non-symmetric distribution as shown in Figure 2. The distribution was first described by Landau and therefore takes his name.

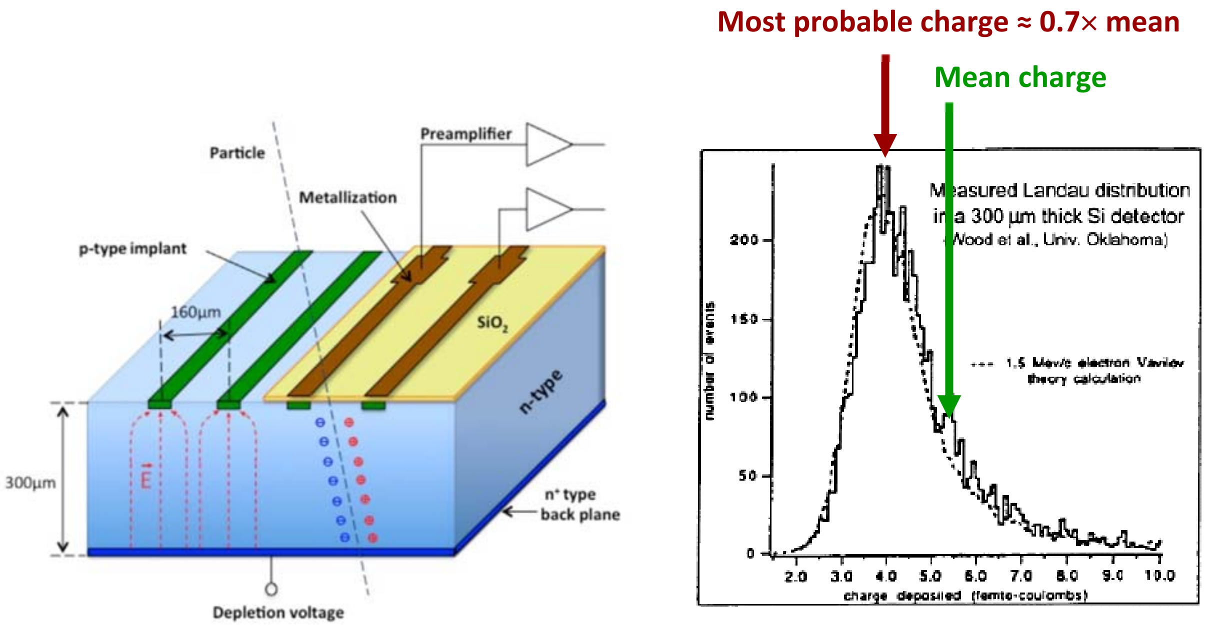


Figure 2: Particle incidence/energy deposition inside a silicon strip detector and the Landau distribution.

Due to the non-symmetric nature of the distribution the mean value is higher than the most probable value. For a MIP the mean energy loss per unit length is 3.88 MeV cm-1 or 116 keV for 300 µm of silicon; while the most probable energy loss is approximately 0.7 times this or 81 keV for a 300 µm thick detector. In silicon it takes 3.6 eV to create an electron hole pair under ionisation by a MIP. Therefore, the mean number of charge carriers created is 108 per µm and the most probable is 72 per µm. This results in a mean signal from a 300 µm thick detector of 32000 electrons or a most probable value of 22500 electrons; which is equal to 3.6 fC. It is the most probably energy that is used for calculations of collected charge from a silicon detector.

Signal Generation and Ramo's Theorem

The signal is induced on the external electrodes by moving charges and is observed as pulses on an oscilloscope. Ramo's theorem provides a way of calculating signals induced on the electrodes of a detector by the movement of charge carriers. The drift field determines the trajectory and velocity of the charge carriers. The induced signal on the electrode was first formulated by Ramo (Published in Proc.IRE.27:584-585, 1939) for a vacuum tube system, and is valid for a semiconductor detector, using the Gauss identity. The theorem states that the induced current is given by the dot product of the velocity vector $\underline{v_q}$ and the weighting field E_W, as given in Equation 7. The weighting field is calculated for the condition that all the electrodes in the system are held at zero potential except the collecting electrode which is held at 1V.

$$i = q\vec{E}_W \cdot \vec{v}_q$$

Equation 7 : Ramo's theorem for the induced current

The induced charge is simply given as the integral of the induced current for the movement of the charge carrier from point r_0 to point r_1, as given in Equation .

$$Q_a = \int i_a dt = -q\int_{r_0}^{r_1} \vec{E}_w \cdot dr$$

Equation 8 : Ramo's theorem for the collected charge from the movement of a charge q from point r_0 to r_1.

The velocity of the charge carriers is given by Equation 7, where μ is the carrier mobility and E the electric field.

$$v = \mu E$$

Equation 7 : Carrier drift velocity

The mobility is carrier type dependent and given below for silicon (subscript n for electrons, p for holes).

$$\mu_n = 1350 \mathrm{cm}^2\mathrm{V}^{-1}\mathrm{s}^{-1}$$
$$\mu_p = 480 \mathrm{cm}^2\mathrm{V}^{-1}\mathrm{s}^{-1}$$

For a simple pad detector, the electric field is given as V/d and the weighting field is given as 1/d where d is the separation of the electrodes (equal to the thickness of the device). As a consequence, the signal is generated equally for a given increment of travel for a charge carrier throughout the thickness of the detector.

In a strip or pixel detector the drift electric field is close to that of a pad device. However, the weighting field is more complex as the 1V potential is applied only to the sense strip or pixel. This gives a very non-uniform weighting field, as shown in Figure 3. As a consequence, the signal on the collecting electrode is dominated by the movement of the charge carriers close to the collection electrode rather than equally throughout the bulk of the detector.

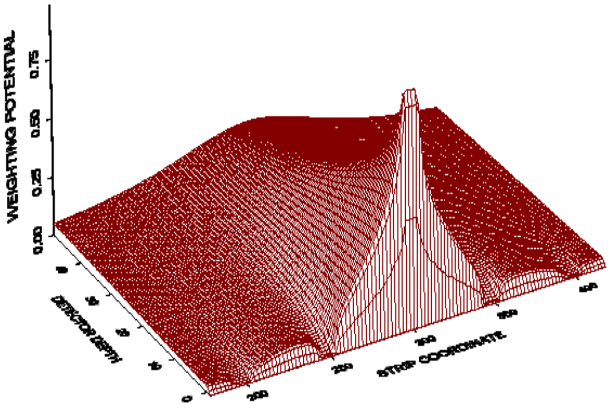


Figure 3 : Weighting potential for a strip (pixel) detector.

Exercise part 1: TCT -Transient Current Technique

As the sensor is traversed by a charged particle, it creates/ionizes free charge carriers, electron-hole (e-h) pairs, which separate under the influence of an externally applied electric field and travel towards their respective electrodes (see Figure 4). Each charge carrier induces current in the pad electrodes (pad size >> thickness):

$$I = e_0 v/D = e_0 \mu E/D, \tag{Eq.10}$$

where e_0 –elementary charge, v – velocity of electrons or holes, μ - mobility of charge carriers, E – electric field, D – sensor thickness. This equation shows that it is possible to determine different sensor properties from the shape of the induced current: e.g. the mobility of charge carriers and the electric field profile. Minimum ionizing particles are ionizing free charge carriers along its whole path and therefore it is difficult to separate the contributions of electrons and holes to the induced current. Since silicon has a very narrow energy gap of merely 1.12 eV, it is possible to generate free charge carriers also using light. The penetration depth is wavelength dependent and it's only a few µm for red light (660 nm, 1.9 eV). If the detector surface is illuminated, charge is generated near the electrode. Therefore, charge carriers of one type end their drift at the nearby electrode, while the other travel through the whole detector thickness and induce current (Figure 4).

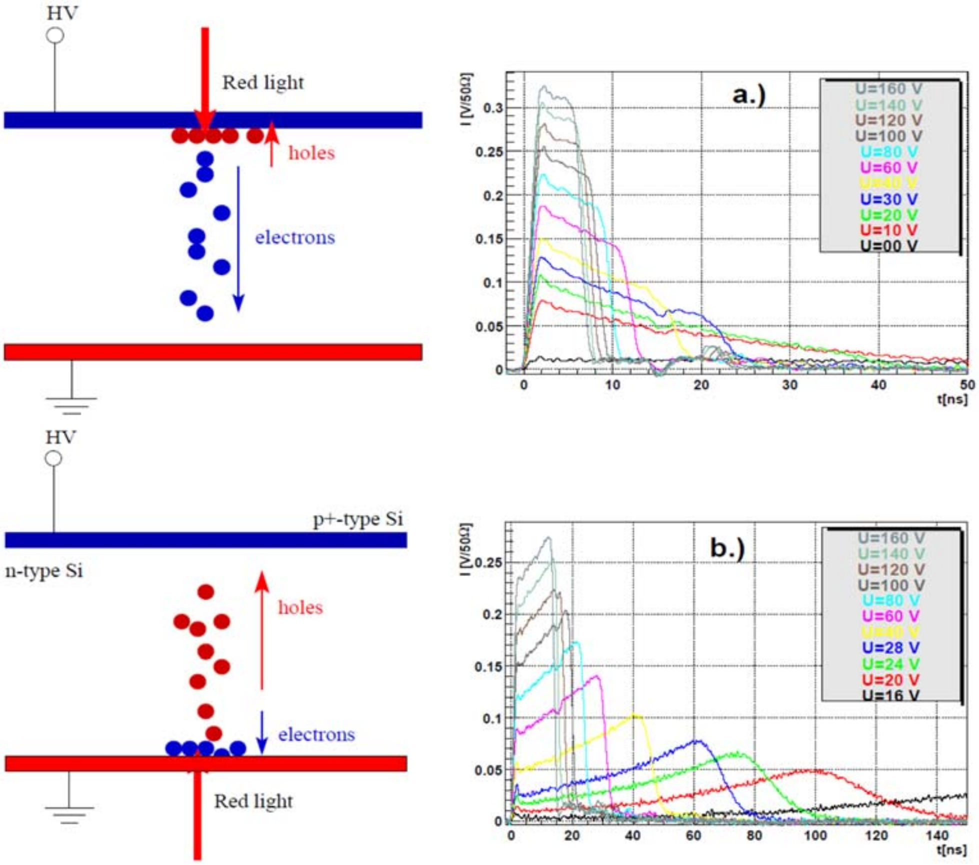


Figure 4: **Schematic representation of e-h pair generation when observing induced signals from electrons (a) and holes (b). Electrons are travelling from the high field region towards the small field region, while for holes it is the other way around.**

By observing the induced current, it is possible to determine the main detector properties such as effective space charge (hence electric field), full depletion voltage and also material properties such as e.g. mobility of charge carriers, saturation velocity or minority carrier lifetime in un-depleted bulk.

As follows from eq.10, the current is proportional to the velocity of the charge carriers and thereby the electric field. Hence, the increase in current with time signifies that the charge is moving in the increasing electric field and vice-versa. The steepness of the rise/decrease depends on the field magnitude. In very high fields, the velocity saturates and there is virtually no change in the induced current (signal). At bias voltages higher than the full depletion voltage, the signals get narrower. The passage of generated carriers from one electrode to the other depends on the illumination side and the difference can be clearly observed. If the full depletion voltage of the detector is small (very low Neff, highly resistive silicon), an almost homogenous electric field can be obtained already at moderate voltages. With the detector thickness known, as well as the travel time of generated charge carriers, it is possible to calculate the velocity of these charge carriers and by that also their mobility as a function of the electric field strength.

Tasks:

1) Observing the induced current signals in the detector
    a. Explain the influence/contribution of both electrons and holes to the collected charge (current integral in time). Explain its dependence on the bias voltage.
2) Determine the dependence of electrons and holes mobility on the electric field
    a. Which diode is appropriate for determining the mobility?
    b. What is approximate saturation velocity of charge carriers in silicon?
3) Determine the dependence of the saturation velocity of electrons and holes on the temperature (if time permits).

Apparatus:

Pad detectors will be used shown in Figure 5. These detectors are appropriate for studying silicon properties, as they are small and only have two electrodes. On the top side they have an opening in the metallization layer which allows laser illumination. The whole bottom side is for this purpose metalized in form of a net. The active part of the detector is 5x5 mm^2 in size.
In this exercise, the sample is mounted in a way so that it is possible to be cooled down using the Peltier element.

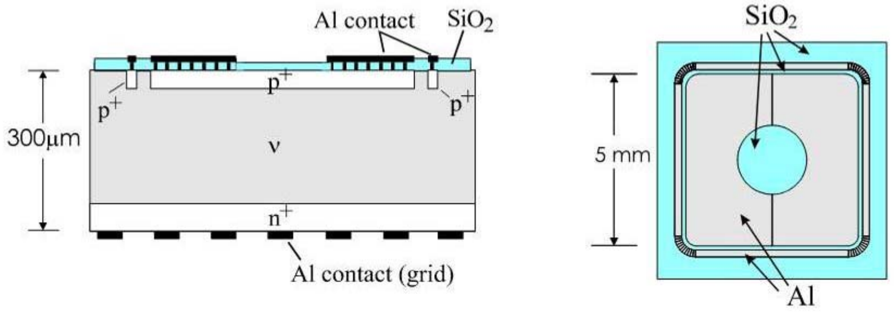


Figure 5: Schematic view of a diode used in the study. The guard ring (Al) surrounds the electrode at the top side. Inside the electrode there is an opening that allows for charge generation using light.

The measurement system for determining the induced current signals:

The schematic view of the setup/measurement system is shown in Figure 6, while the photo of the whole setup is shown in Figure 7. The measurement system is composed of: a laser, amplifier, Bias-T (decoupling circuit) and HV filter. The photo also shows how these components are connected between each other. Laser positioning, its frequency and pulse width is performed manually.

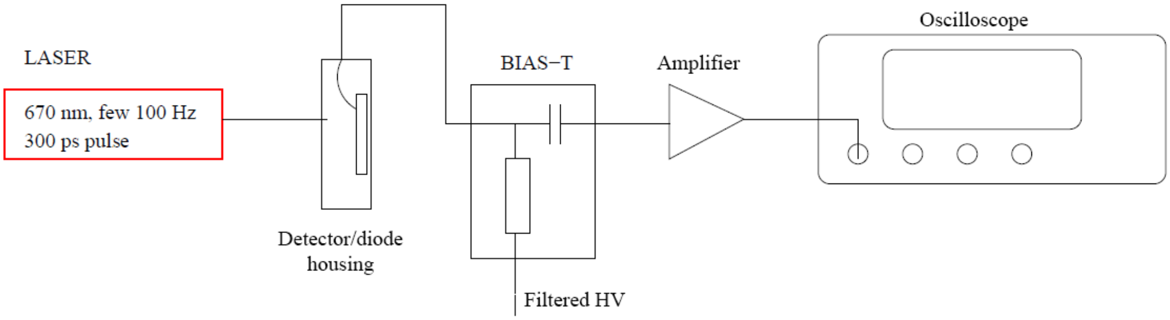


Figure 6: Schematic view of the Transition Current Technique (TCT) measuring system. The laser pulse generates charge carriers at the detector surface, which then travel under the influence of the electric field inside the detector and induce current in the readout electrodes. This current signal is amplified and shown on the oscilloscope. The Bias-T circuit is used for decoupling high voltage from the amplifier input.

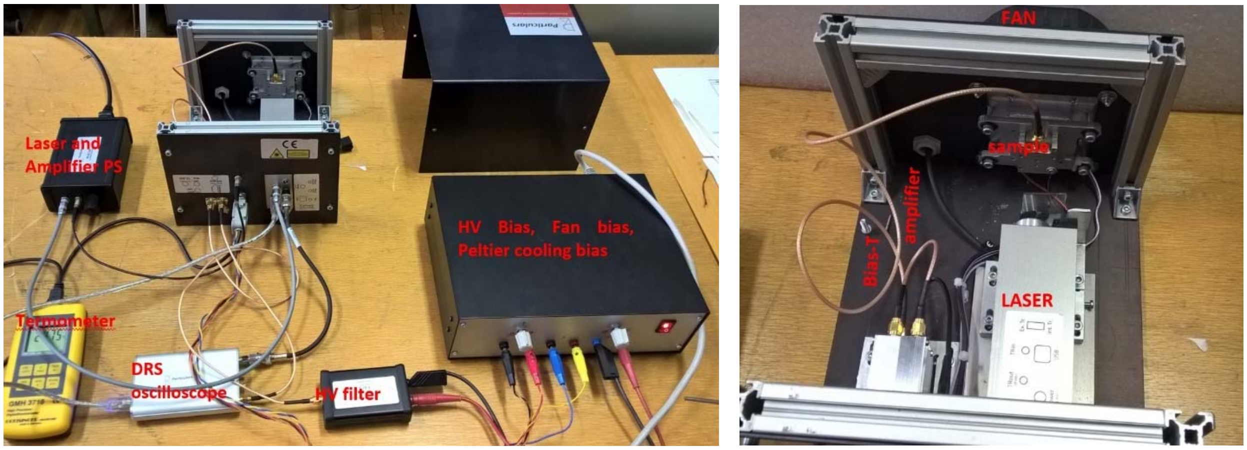
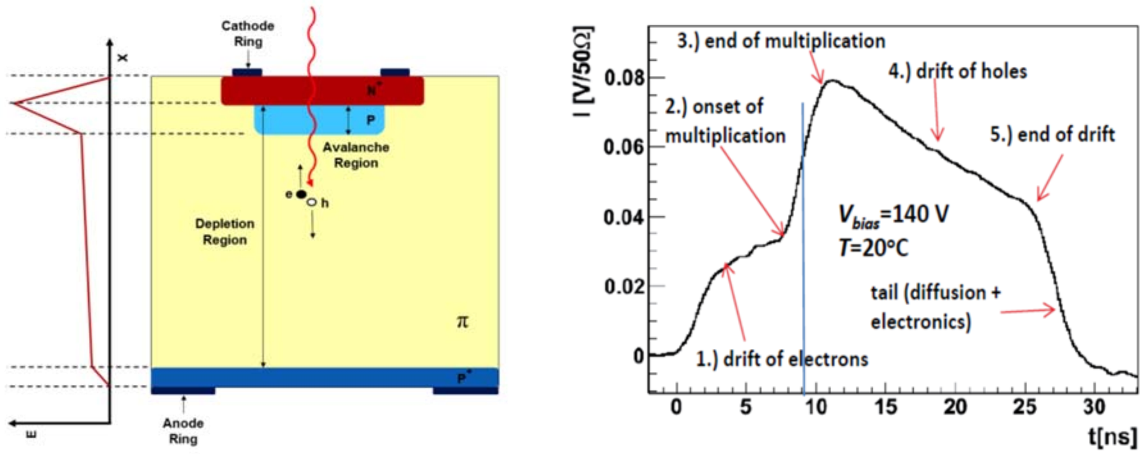


Figure 7: Photos of a TCT measuring system with appropriate components labelled.

Measurements with LGAD ("Low Gain Avalanche Detectors"):

If a thin layer of highly doped p-type semiconductor is inserted between n and p layers of the n^{+}-p detector, an n^{++}-p^{+}-p ($^{+}$ indicates high doping in the order of 10^{16} cm^{-3}, while $^{++}$ stands for extremely high doping in the order of 10^{19} cm^{-3}) structure is obtained. Figure 8 gives a schematic representation (not to scale) of such processed detector, with its expected electric field profile shown on the left.



(a) (b)

Figure 8: a) Schematic representation of an LGAD detector (not to scale; the n^{++}-p^{+} layers are typically ca. 1-3 µm thick); established electric field profile shown on the left; b) a typical pulse from an n^{+}-p detector, resulting from back side illumination.

Inside this thin layer, the electric field may reach very high magnitudes, causing electrons to gain sufficient energy ($E_g = 1.12$ eV) within their free path and multiply (charge multiplication), inducing secondary ionization/e-h pair generation. The process is similar to the one encountered in gas proportional detectors (GPDs). The required electric fields for the onset of this multiplication process are of the order of 15-20 V/µm. These detectors are able to achieve better Signal-to-noise ratio and hence detection efficiency, spatial resolution and time resolution as well, because the signal is big and fast enough for application even in very thin detectors (ca. 50 µm). The induced signal shape in such a detector is different from standard detectors, because at high enough multiplication most of the signal comes from the long drift of holes created in the multiplication layer, traveling towards the back plane of the detector. A typical pulse resulting from back side illumination of a fully depleted detector (this is how the drift of electrons towards the upper electrode is observed in n^{+}-p detectors) is shown in Figure 8b.

Five different stages of signal development can be observed: 1) drift of electrons, traveling from the backplane of the detector (where they were created by laser illumination) towards the front, 2) multiplication of electrons, 3) end of multiplication, 4) drift of holes towards the back plane of the detector, 5) end of drift. The magnitude of multiplication can be easily estimated from the shape of the pulse, if the integral of induced current is divided into two parts: a part coming from the drift of electrons Q_e (current integral between 0 and 9 ns in Figure 8b) and a part which comes from the drift of holes Q_h (9 – 32 ns). Charge multiplication factor is then simply calculated as:

$$G = \frac{Q_e + Q_h}{Q_e} = 1 + \frac{Q_h}{Q_e}$$

Tasks:

1) Determine the multiplication factor for the device under test (DUT) depending on the applied bias voltage.
2) What is the full depletion voltage of the DUT?

Exercise part 2: ALiBaVa readout system

Aim:

The aim of this system and the exercise part is to illustrate the structure and operation of silicon strip detectors, in particular:

- To introduce the silicon detector module: consisting of the silicon detector, readout chip and thermal and mechanical aspects.
- To observe the noise of a silicon strip detector as a function of bias voltage.
- To observe the signal spectra due to a minimum ionising particle in a silicon detector and demonstrate the Landau distribution shape of collected charge.
- To observe the physical size of a charge cluster from a minimum ionising particle and relate this to the position resolution of the detector.

Apparatus:

The apparatus for this experiment consists of two silicon strip detectors, readout amplifier chips, the readout system to control the readout chip, a Sr-90 beta electron source and a Scintillator coupled to PMT for the trigger. The whole system is driven over the USB by a laptop. There is a dedicated data acquisition code with a graphical user interface (GUI), and a root/python based data analysis code. Each item is described below and shown in pictures at the end of the lab script.

The source and trigger:

The experiment will attempt to characterise the silicon detector under the illumination of minimum ionising particles, as found in a particle physics experiment. The experiment uses a Strontium-90 source as the source of ionisation.

Strontium-90 source

Strontium-90 beta decays to Yttrium-90 which beta decays to Zirconium-90 which is stable.
End point energy of Sr-90 decay is 0.546MeV. End point energy of Y-90 decay is 2.28MeV.
Sr-90 can be considered to be a pure electron emitter.

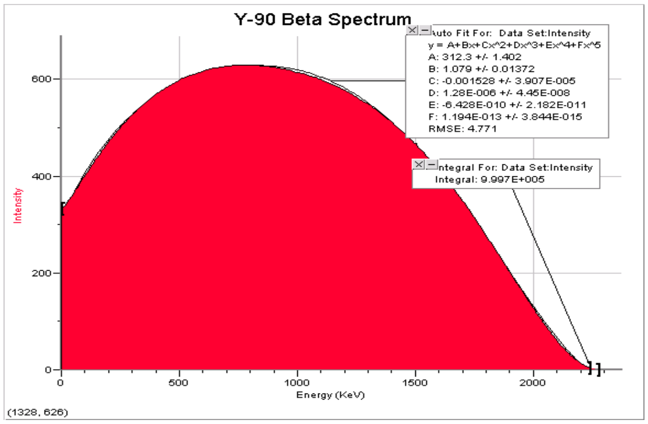


Figure 9: Y-90 beta spectrum

The setup

The ALiBaVa (***A**nalogue **Li**verpool **Ba**rcelona **Va**lencia*) system is a next generation readout system for semiconductor particle detectors, in particular silicon strip sensors. It is based on the radiation hard Beetle chip, which was developed for the LHCb experiment VELO detector. It is designed to be particularly compact, portable and easy to run. The system is controlled from a software application in communication with an FPGA which interprets and executes the orders. The system's hardware part acquires and processes the data in order to be stored in a PC. The software part mainly controls the whole system and processes data acquired, storing it in an adequate format file for further data analysis.

The Alibava system has a hardware block based on a dual board system. It consists of a **Motherboard** (MB), which processes the analogue data coming from the readout chips, the trigger input signal in case of a radioactive source setup or to generate a one if a laser setup is used, to control the whole system and to communicate with a PC via USB. The **Daughterboard** (DB) is a small board containing two Beetle readout chips (2x128 analogue readout channels, 25 ns shaping time) and has fan-ins with a detector support to interface the sensors. A schematic view of the system is shown in Figure 10.

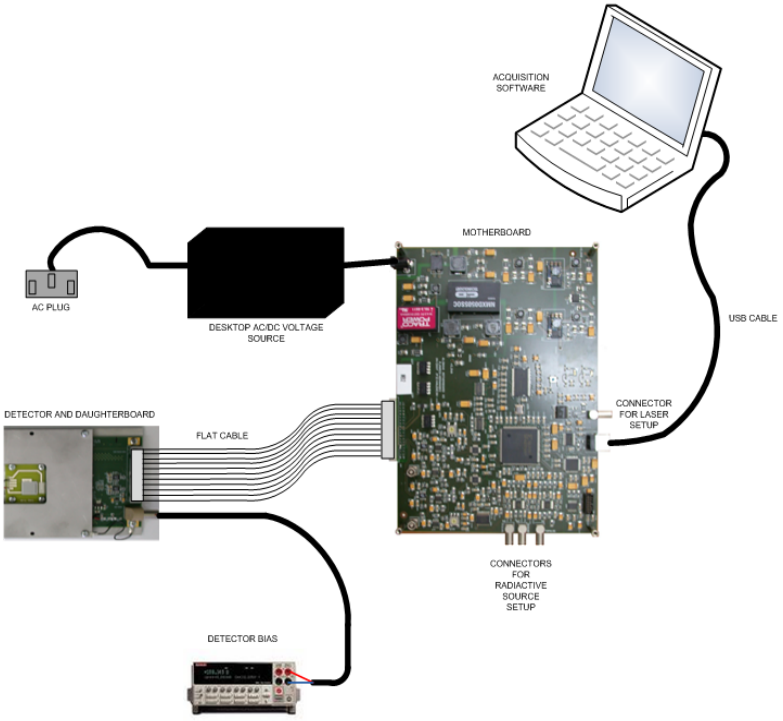


Figure 10: Schematic view of the ALiBaVa readout system

The hardware part is divided into two boards to allow separate cooling of detectors only. Both boards communicate via flat ribbon cable for the analogue data signals coming from the Beetle chips, slow and fast control digital signals to the Beetle chips, a temperature signal, as well as the voltage supply level for the Beetle chips. The high voltage detector power supply is provided directly to the daughterboard or the sensor board.

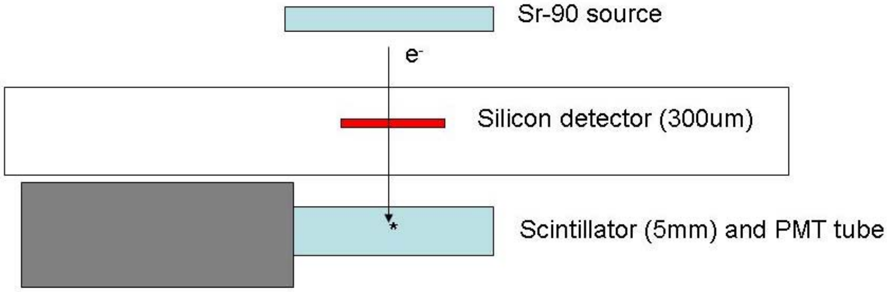


Figure 11: Schematic view of the DB module setup

The electrons pass through the silicon and deposit all of their remaining energy in the scintillator. The size of the signal from the scintillator/PMT is proportional to the electron energy. The signal from the PMT will trigger the readout of the silicon detector if the signal is over a user set threshold value.

Look on the scope at the trigger signal from the PMT (see Figure 12).

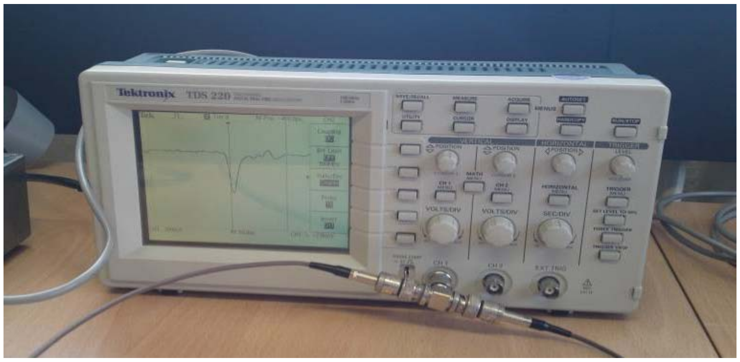


Figure 12: Example of the trigger signal on the oscilloscope.

Adjust the threshold of the scope to decide on a good value for the threshold

- What happens if the threshold is too low?
- What happens if the threshold is too high?
- If the trigger threshold is set to trigger on low energy electrons, what problem in the collected charge would happen?

The strip detector module

We have a 1x1 cm ATLAS12 prototype (mini) silicon strip detector with 100 strips. We have two readout chips in our module with 128 channels each. Each channel is an independent preamplifier with shaping to get full charge collection within 25 ns. Below are photos (Figure 13) of the setup/module that will be used in the experiment.

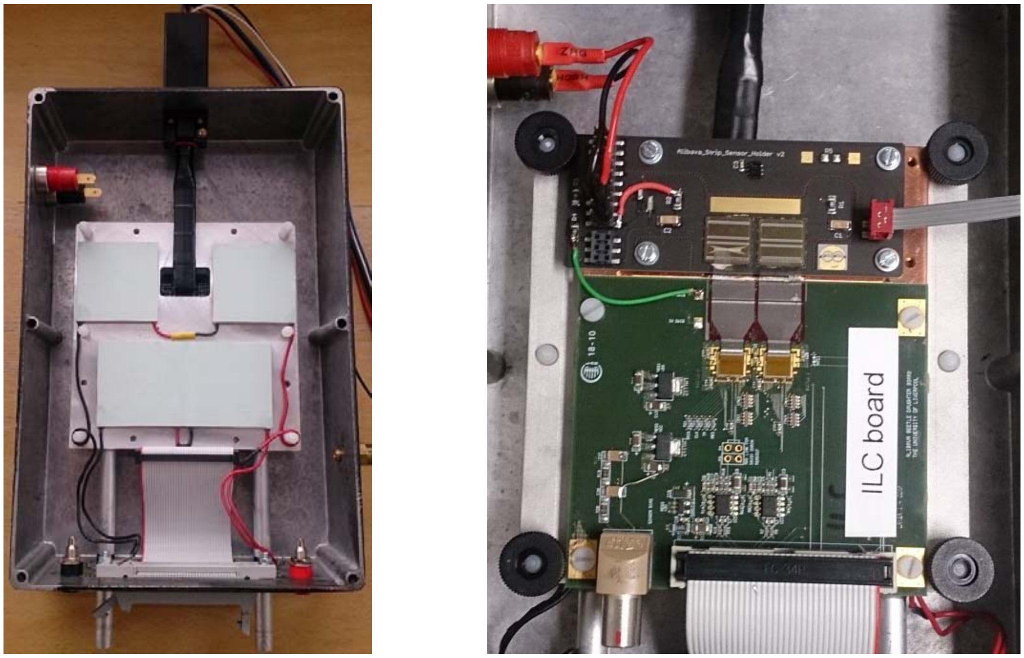


Figure 13: Example photos of the setup/module

- Identify different parts of the experimental setup
- Identify the different parts of the module (silicon strips, amplifier chip, etc)
- Why are the chips and silicon detectors not next to each other?
- What is between the chip and detector?

A strip detector is semiconductor device with an arrangement of strip like shaped narrow implants, usually few tens to few hundreds of micro meters apart, acting as charge collecting electrodes. Placed on top of a low doped silicon bulk, these implants form a one-dimensional array of p-n diodes. The strips can be either n^+ or p^+, defining the detector type (see Figure 14).

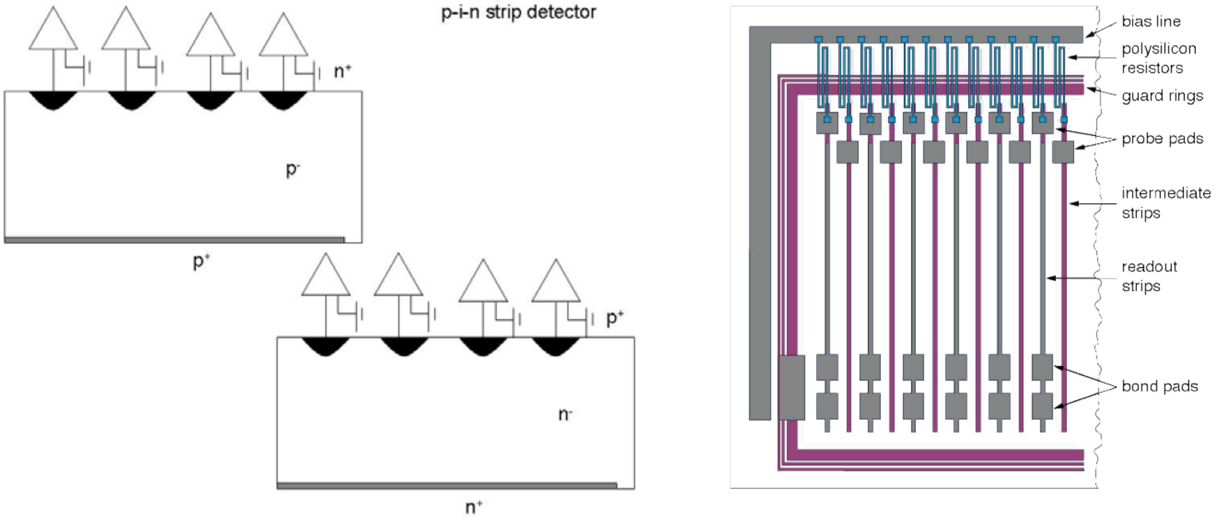


Figure 14: Diagrams of different types of silicon strip detectors (left) and top view (right) of an AC coupled strip detector with integrated polysilicon resistors

Typical values of doping concentrations are:

- n & p ~ 10^{-12} cm^{-3}
- n^+ & p^+ ~ 10^{-15} to 10^{-18} cm^{-3}

The strips are connected to a single implanted *bias ring*, providing common bias rail for depleting the detector. However, to prevent the flow of signals generated in the strips through the bias ring instead of readout electronics, polysilicon resistors (from a few 10 kΩ to a few 100 MΩ) are put in between the strip implant and the bias ring. Strip detectors also usually have a guard ring (or a more complex structure of guard rings) at the edges, acting as a sink for the surface currents from the detector edges.

- For the two diagrams what is the sign of the bias voltage applied to the back side of the detector required to reverse bias the detector?
- What happens to the silicon material after heavy irradiation?
- What effect does this have on the position of the p-n junction and how it grows with bias voltage?

Noise

The total noise of the system measured as an equivalent noise charge at the input of the amplifier, ENC, is given by:

$$ENC_{tot}{}^2 = ENC_{pa}{}^2 + ENC_i{}^2 + ENC_{RP}{}^2 + ENC_{RS}{}^2$$

The individual noise sources are:

$$ENC_{pa} = A + B \times C_{load}$$

Equation 8: ENC for the preamplifier, where A and B are pre-amplifier constants and C_{load} is the capacitive load at the input of the pre-amplifier

$$ENC_i = \frac{e}{q}\sqrt{\frac{qI\tau}{4}}$$

Equation 9: ENC due to the detector leakage current for CR-RC shaping. τ is the shaping time of the shaper.

$$ENC_{RP} = \frac{e}{q}\sqrt{\frac{\tau kT}{2R_b}}$$

Equation 10: ENC for the thermal noise from the parallel resistors. R_b is the bias resistor of the detector.

$$ENC_{RS} = 0.395 \times C_{load}\sqrt{\frac{R_s}{\tau}}$$

Equation 11: ENC for the series resistance in the circuit. Rs is the resistance of the readout strip

The two main noise sources, which contribute in silicon detectors, are the **detector capacitances** and the **leakage current**.

The reverse (leakage) current of a p-n junction is temperature dependent and is given by:

$$I \propto T^{\frac{3}{2}} \times \exp\left(-\frac{E_g}{2kT}\right) \qquad \text{(Eq.15)}$$

Run the DAQ software and run a pedestal run. Look at the pedestal and noise histograms.

- What is the pedestal? Noise?
- Can you identify the two chips from the pedestal plot?
- Comment on the high and low points on the noise histogram
- Estimate what the average noise of the detector is?

Increase the bias voltage slowly from 0 to 200V

- What happens to the noise?
- What is changing with increasing bias and how does this change the noise?
- What could happen if the detector current was higher and increasing with bias voltage.
- Try now doing the same with the second (irradiated) sensor. Explain what happens.

Signal

The signal is induced on the external electrodes by moving charges (electrons and holes). To find the signal in a given event, the signal collected on each given amplifier channel is compared in turn to a cut, known as the seed cut. If the value is higher than the cut the channel is considered to have signal.

If the signal is higher than the seed cut, the output the neighbouring channel is looked at. A second cut, the neighbour inclusion cut, is applied to this channel to include the signal on the neighbour into the event (cluster). If the neighbouring channel is included the neighbour inclusion cut is applied to its neighbouring channel. This process is repeated until the signal on the neighbouring strip is below the inclusion cut.

The signal size is the sum of the signals on all the strips in the cluster. The cut applied must reduce the likelihood of including noise, but should keep the signal. Look at the following table of likelihood of an event being under a Gaussian function as a function of the cut applied.

Number of standard deviations	Probability of being under the curve
1	0.682689492137
2	0.954499736104
3	0.997300203937
4	0.999936657516
5	0.999999426697
6	0.999999998027

Table 1 : Probabbility of being inside a Gaussian distribution

- What is a good value of the seed cut in units of standard deviations of the noise Gaussian?
- What do you think is a reasonable value for the neighbour inclusion cut?

Data collection

1. Bias the non-irradiated sensor to 200 V. Take a pedestal run and Log the Data file as ‘pedestal.h5’. Take 1000 events.

2. Now take the Sr-90 source and align it with the non-irradiated sensor and the scintillator below.

Check that the trigger is set as you require (OR and Trigger in) and the threshold value as you determined from the oscilloscope.
Log the Data to a file ‘rsrun.h5’ and take 10 000 events.
Click on RS (radioactive source).
Click on Run.

You should see some data rate depending on the strength of the source (1 - 400 Hz).

For the on-line analysis a seed cut of 5 noise sigmas is used.

Look at the different pull-down menus
- What is being plotted in each window?

In the signal page look at the two chips individually
- What can you say about the signal in the two chips?
- Is the S/N cut good enough?
- What addition feature adds to the noise that you can remove in an off-line analysis?

In the signal page look at the time projection
- What is this showing you?
- Would this detector be any good for the LHC? (bunch crossing 25ns)

If the Strontium source is too weak and the time is short to collect this many events, then there is an example data file for the off-line analysis.

Data Analysis

Run the **Noise analysis** code (Noise_Analysis.py). Several windows (known as canvases) will appear. Look at the analysis canvases.

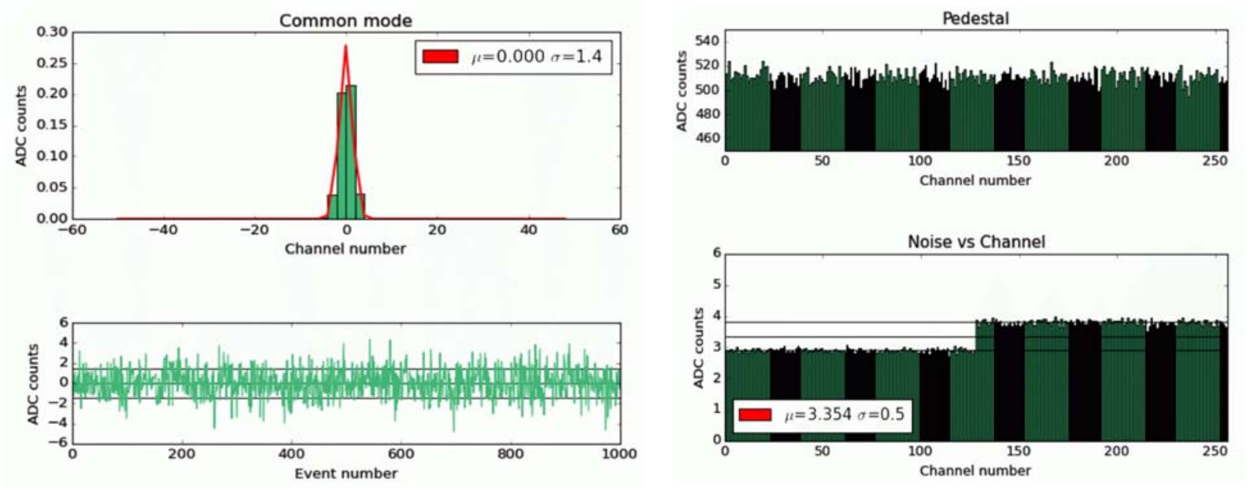
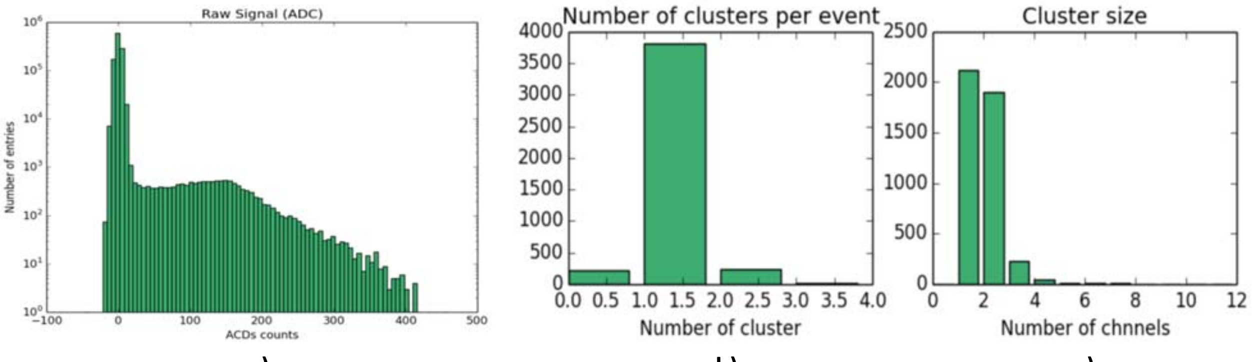


Figure 15: Pedestal, noise and common mode analysis.

- What is plotted in each canvas? Comment on the shape of the plots.
- Why are chip 1 and chip 2 different? What does this say about hit occupancy?
- If you were designing a detector system would you read out all the channels, if not, why?

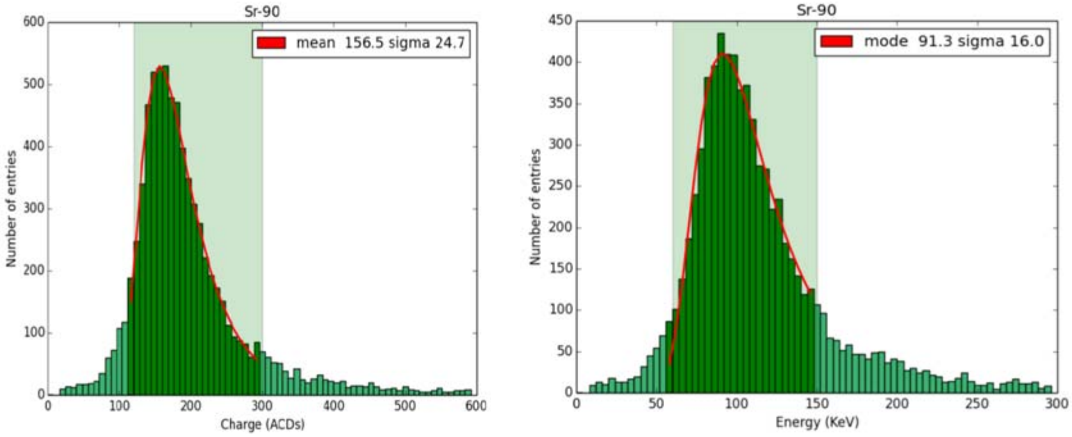
Run the **Charge analysis** code (Charge_Analysis.py). Look at the analysis canvases.

- What is plotted in each canvas? Comment on the shape of the plots.
- Why are the cluster widths 1 and 2 the highest? Do you think this is reasonable?
- Why are there clusters more than 2 strips wide?
- Comment on the charge spectrum and energy deposition plots.



a) b) c)

Figure 16: a) Raw data signal distribution in ADC counts after pedestal and common mode subtraction, b) number of clusters per event and c) number of strips in a cluster



a) **b)**

Figure 17: a) Charge spectrum and b) energy deposition of a MIP particle (electron) crossing 300 µm of silicon

Conclusions

Look at both sets of results from each part of the experiment. Consider the different attributes from each detector and the different ways in which they could be used.

Appendix

Strip detector

The strip detector is a more complex detector than the pad device. The strip layout means the signal can be picked up on several electrodes and depending on the relative strength of the signals the interaction position of the particle can to be determined. The silicon sensor in this experiment is 1 cm x 1 cm and 300 µm thick. There are 100 strips at a pitch of 80 µm. The strip detector has a silicon oxide layer between the implant and the aluminium readout electrode. This oxide layer acts as a capacitor between the diode and the amplifier. Why do you think this might be? To enable a D.C. connection across the diode a set of bias resistors are used to connect each strip implant to a common implant (known as the bias rail or bias ring). This common connection is connected to the H.V. return 9 at the ground potential of the daughter board). The H.V. bias is supplied via a back-side contact to the strip detector.

The detector is mounted on the daughter board and connects to a Beetle amplifier chips. The two experiments use different types of strip detector. One has a p^+-n-n^+ diode and the other an n^+-p-p^+ diode, where the first implant is the segmented strip structure.

Beetle Chip

The Beetle chip is an analogue readout chip. The daughter board contains two Beetle readout chips. They each have 128 independent input channels of analogue amplifier and shaper with a 25ns peaking time. The analogue signal from each channel is readout from each chip as a multiplexed analogue signal. The input dynamic range of the amplifier is around ±110000 electrons, that is to say about 5 MIPs of either positive or negative polarity.

Trigger, Pipeline

Triggered systems are used to identify what events should be stored for later analysis. As only a limited number of events can be stored the trigger is used to rapidly decide which ones are interesting enough to keep. In the case of this lab the trigger will select events where a particle passed through the sensor and deposits enough energy in the scintillator for the output of the PMT to exceed a predefined value. Therefore, in this set-up a scintillator trigger is used.

The pipeline stores the events on the Beetle chip waiting for the trigger to decide whether or not they are ‘interesting’.

Readout System

The readout system consists of the daughter board which supports the Beetle chips and the mother board. The daughter board has an additional amplifier to amplify the signal for transmission to the mother board. The mother board digitizes the data and transfers it via the USB to the PC. The system contains two front-end readout chips. There are two analogue outputs on the motherboard in order to probe the analogue output signal of each Beetle chip before they are digitised. The mother board accepts an analogue signal from a PMT to use as a trigger for data acquisition.

The Software

There are two software codes; the data acquisition code to collect the data and perform on-line data analysis and the data analysis code to perform detailed off-line data analysis.

The graphs produced by the on-line data analysis program are:

- **Signal** – used for the calibration and radioactive source runs. Only of interest for the radioactive source run.
- **Pedestals and noise** – used for the pedestal and radioactive source runs. The chip output is about 500 with no input signal. This varies from channel to channel and event to event. The zero value is known as the pedestal. The noise on each channel is calculated by calculating the standard deviation of the signal (pedestal value) on that channel. The value is constantly updated. You will see on the graph the distinction between the two chips on the daughterboard as only one is connected to the detector so we will get a larger noise on one of them. Which one is it? A large spike indicates a noisy channel and a low spike indicates an unbonded channel. Both need to be masked out later. Also need to mask off 28 channels on the chip connected to the detector as there is no signal on them as the detector only has 100 strips. The noise will change with bias voltage – which way will it change and why?
- **Hitmap** – shows you the signal on the channel that is hit.
- **Temperature** – of the daughterboard
- **Time structure** – shows the time a trigger occurs, this should be uniform
- **Event display** – this doesn't give the average, it displays the data on each channel for just 1 event updated every 100 events.
- **Noise/Common mode** – the noise graph gives the average noise for each chip as a function of event number, the common noise is how the chip channels change in a common fashion (for example they all jump up together). This is displayed as a function of the event number, not channel number.

The Calibration run

The charge in ADC counts can be converted into energy deposition using the calibration curve. The system injects pulses using a capacitor of known charge into the readout ASIC (Beetle chip) for calibration. Figure 18 shows a calibration curve to convert ADC counts to charge (number of electrons).

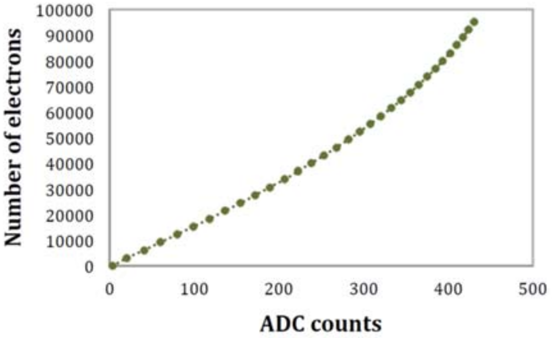
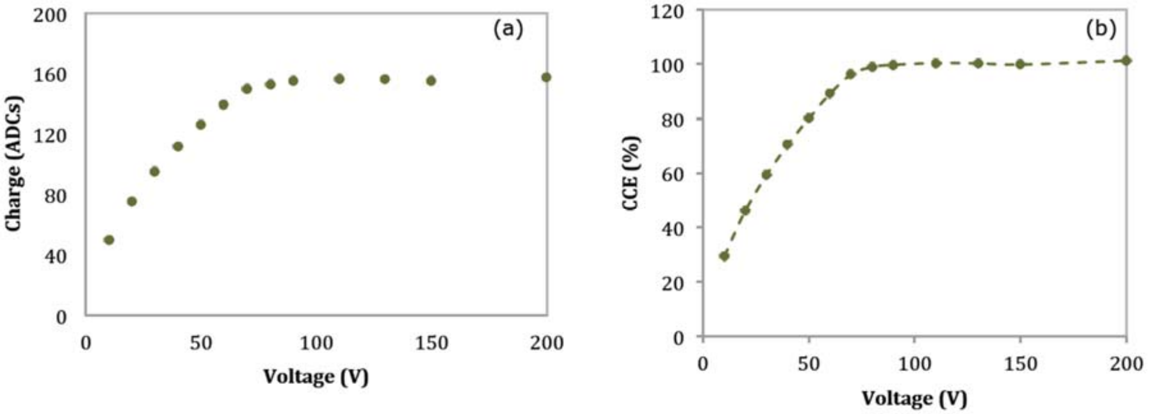


Figure 18: Calibration curve (amplifier gain calculation)

Charge collection (MPV) and Charge Collection Efficiency (CCE)

The Charge Collection Efficiency is defined as the ratio of the collected charge, over the collected charge when the sensor is fully depleted. Figure 19a shows the most probable charge obtained for different bias voltages. The collected charge increases with voltage until it reaches a plateau when the detector is fully depleted. The distribution can be normalized to the mean charge of this plateau to obtain the CCE (Figure 19b).

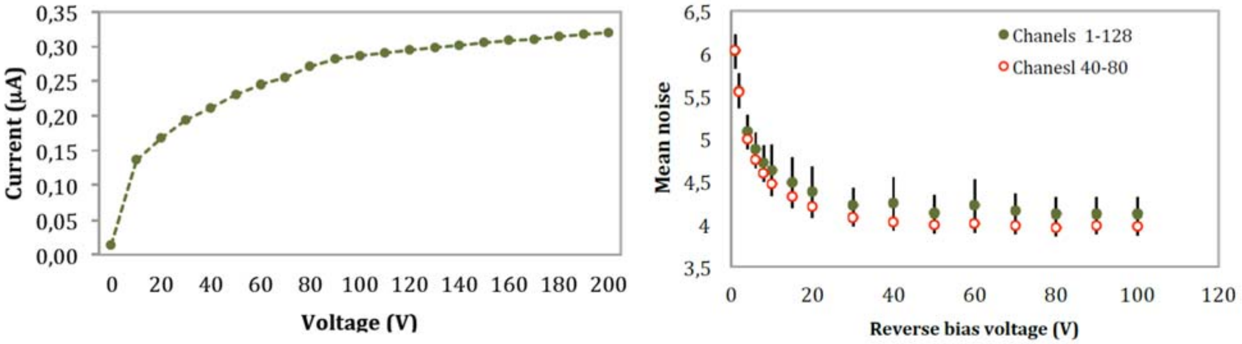


a) b)

Figure 19: a) Most probable charge as a function of bias voltage b) Charge Collection Efficiency (CCE) as a function of bias voltage.

Leakage current and noise

As described earlier, the electronic noise depends on the capacitance at the entry of the preamplifier, the shaping time, the resistances of the detector and the readout chip, the temperature and the leakage current. The shaping time and the resistances are constants for a given device. Assuming temperature remains constant, noise can be studied as a function of the reverse bias voltage and the relation with the detector capacitance and the leakage current (see Figure 20).



a) b)

Figure 20: a) Leakage current and b) Mean noise and as a function of (reverse) bias voltage

EASY_Charge _Analysis.py

Program to calculate charge deposition in ADCs and Energy, after calibration. The program also plots the common mode noise, hit map, pedestal, noise, number of clusters, and number of strips in cluster.

To run the program:

```
>> python EASY_Charge_Analysys.py  Data-file.h5 [options]
```

```
Options:
  -h, --help          show this help message and exit
  --gauss             It will try a gauss fit to the data
  --landau            It will try a Landau-like fit to the data (default)
  --tmin=TMIN         Minimum TDC to be considered in the analysis (default=0.)
  --tmax=TMAX         Maximum TDC to be considered in the analysis (default=100.)
  --fmin=FMIN         Minimum ADC for the fit  (default=100)
  --fmax=FMAX         Maximum ADC for the fit  (default=250
  --ADCmin=ADCMIN     Minimum ADC for the plot  (default=0)
  --ADCmax=ADCMAX     Maximum ADC for the plot  (default=600)
  --ADCbin=ADCBIN     Binning for ADC plot  (default=6)
  --Emin=EMIN         Minimum energy for the fit  (default=70)
  --Emax=EMAX         Maximum energy for the fit  (default=200)
  --Eplotmin=EPLOTMIN  Minimum Energy for the plot  (default=0)
  --Eplotmax=EPLOTMAX  Maximum Energy for the plot  (default=300)
  --Eplotbin=EPLOTBIN  Binning for Energy plot  (default=3)
  --label=LABEL       Label for the plots  (default=Sr-90)
  --s/n=SNCUT         Signal/Noise cut  (default=5)
  --PE0=PE0           Parameter 0 to convert ADCs to Energy (default=-270.13)
  --PE1=PE1           Parameter 1 to convert ADCs to Energy (default=160.904)
  --PE2=PE2           Parameter 2 to convert ADCs to Energy (default=0.174026)
  --PE3=PE3           Parameter 3 to convert ADCs to Energy (default=-0.000734166)
  --PE4=PE4           Parameter 4 to convert ADCs to Energy
                      (default=.00000187504)
```

EASY_Noise_Analysis.py

Program to calculate pedestal, common noise and electrical noise. The program also plots the pedestal and noise calculates by the data acquisition program (Alivaba-gui). The input data file should be taking with the Pedestal run.

To run the program:

```
>> python EASY_Noise_Analysys.py  Data-file.h5 [options]
```

Options:

```
  -h, --help        show this help message and exit
  --nevents=NEVENTS  Number of events to analyse (DEFAULY ALL)
  --maxch=MAXCH      Maximum channel for noise analyse (DEFAULY=128)
  --minch=MINCH      Minimum channel for noise analyse (DEFAULY=1)
```