Silicon Strips and Pixel Technologies

Hands-on: Silicon Strip Detectors

Aim

This section of the laboratory has several aims which are:
- 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.

Introduction

This part of the laboratory illustrates the operation of a silicon strip detector with LHC readout electronics. The first measurement demonstrates the change in the noise of the system with detector bias voltage. The second measurement shows the response of the detector to high energy electrons from a Strontium-90 source. Three sets of apparatus will be available. Two equipped with non-irradiated silicon strip sensors; one with p-type strip implants and a near intrinsic n-type bulk, the other with n-type strip implants and a near intrinsic p-type bulk. The third has an irradiated sensor with n-type strip implants and a p-type bulk. The irradiated sensor must be operated cold to reduce the reverse current of the device to a manageable level, while the others are operated at room temperature.

Apparatus

The apparatus for this experiment consists of a silicon strip detector, a readout amplifier chip, the readout system to control the readout chip, a Sr-90 beta electron source and a Scintillator coupled to PMT for the trigger, plus a cryostat for the irradiated device. The whole system is driven over the USB by a laptop running Linux. There is a dedicated data acquisition code with a graphical user interface, gui, and a root 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. The beta spectrum from the source is given in Figure 1.
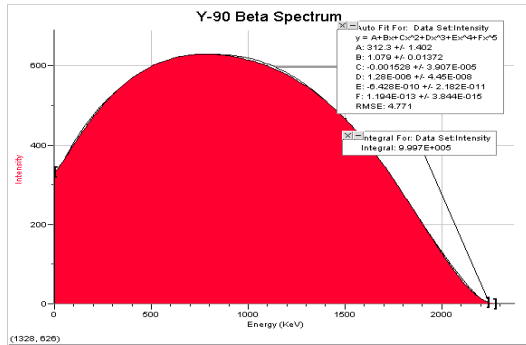
Figure 1: Y-90 beta spectrum

The absorption of the beta electron is described by via the Bethe-Bloch process:
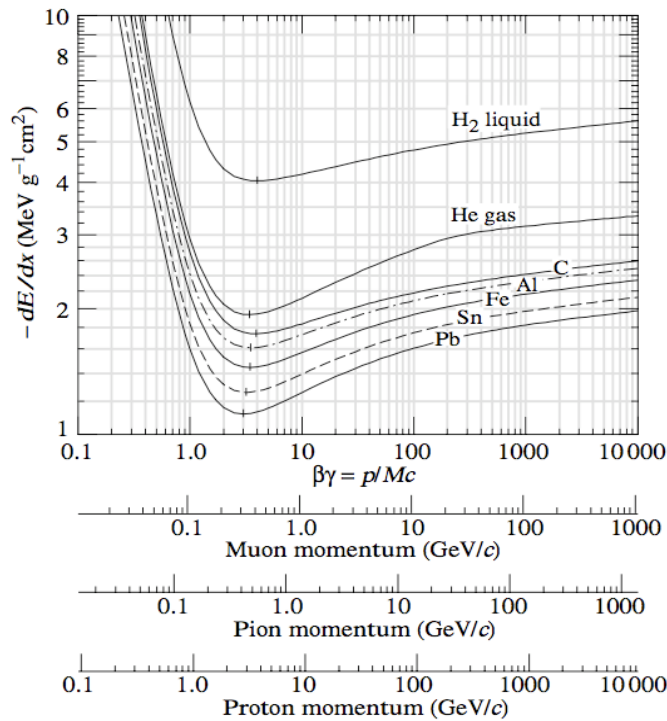

Figure 2: Bethe-Bloch graph

The set-up: The electrons pass through the silicon, depositing some energy according to Figure 2, 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.
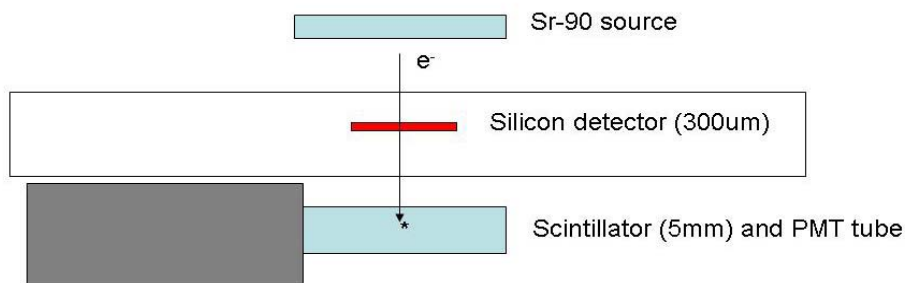
**Figure 3: Diagram of source/detector/Scintillator trigger**

- Bias up the PMT (11V)
- Look on the scope at the trigger signal from the PMT.

Question: What happens if the threshold is too low?
Question: What happens if the threshold is too high?

The strip detector module: We have a 1cm long prototype silicon strip detector with 100 (or 128) 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 25ns.
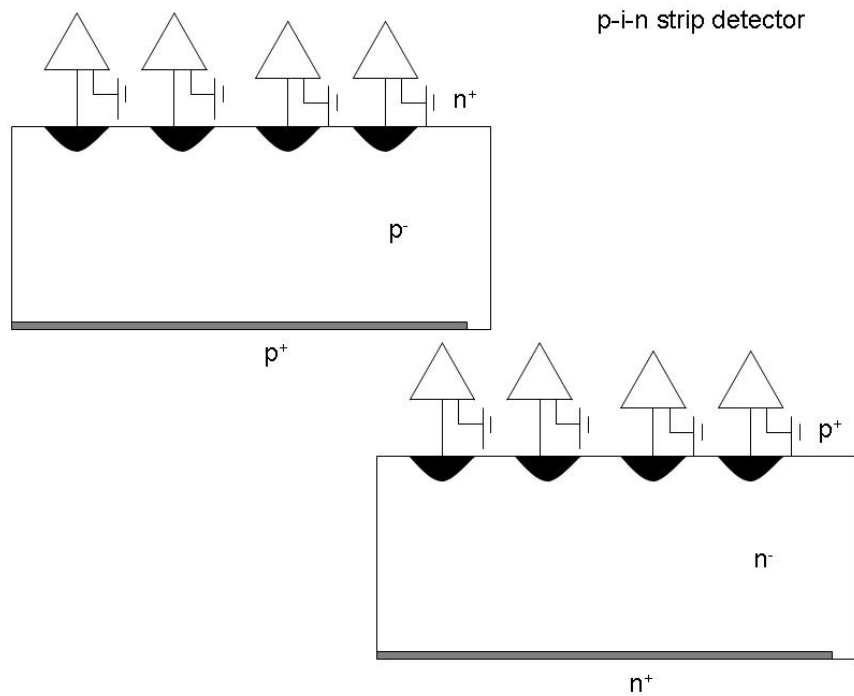
The module has delicate wire bonds between the amplifier chip and the detector and therefore the box containing the module will not be opened. Below is a picture of the module that will be used in the experiment.
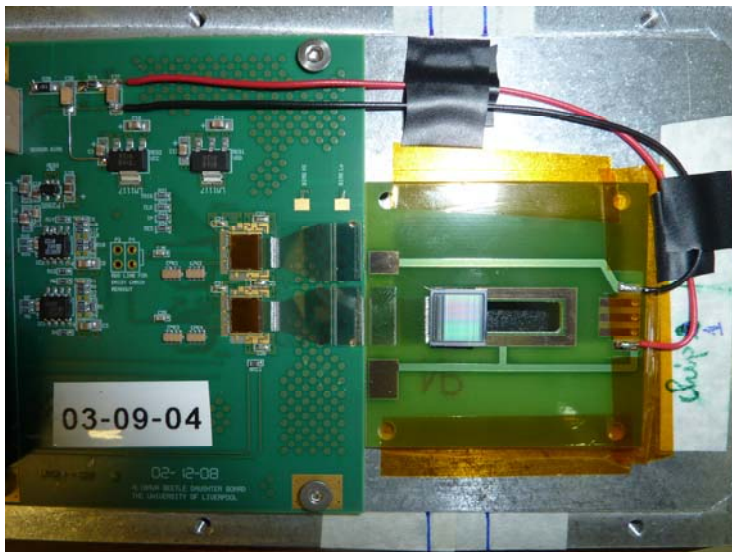
Figure 4: Photograph of the Alibava "module"

The strip detector is a p-i-n diode.
The strips can be either n^+ or p^+, see the diagram

Figure 5 : A diagram of the silicon strip detector

Typical values of doping concentrations are:
n^- & $p^- \sim 10^{-12}$ cm^{-3}
n^+ & $p^+ \sim 10^{-15}$ to 10^{-18} cm^{-3}

Question: 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?
Question: What happens to the silicon material after heavy irradiation?
Question: What effect does this have on the position of the p-n junction and how it grows with bias voltage?

Measurement 1: 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 given in Equation 1 to Equation 4.

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

Equation 1 : 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 2 : 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 3 : 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 4 : ENC for the series resistance in the circuit. Rs is the resistance of the readout strip

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

$$I \propto T^{\frac{3}{2}} \times \exp\left(-\frac{E_{g}}{2kT}\right)$$

Equation 5 : The leakage current dependence on the temperature of the p-n junction

- Run the DAQ software
- Run a pedestal run (Click on Pedestal, Click on Start).

Look at the pedestal and noise histograms. Discuss what is being shown, considering the questions below will aid discussion.

> **Question:** What is being plotted in each?
> **Question:** What is the pedestal?
> **Question:** Is the value constant
>> - across the two amplifiers?
>> - with time?
> **Question:** Can you identify the two chips from the pedestal plot?
> **Question:** What is plotted in the noise histogram?

Question: Can you identify where the detector is (100 strips)?
Question: Comment on the high and low points on the noise histogram
Question: Estimate what the average noise of the detector is?

- Increase the bias voltage slowly from 0 to 20V

Question: What happens to the noise in the detector?
Question: What is changing with increasing bias and how does this change the noise, look at equations above?
Question: Think about what could happen if the detector current was higher and increasing with bias voltage, for example in a heavily irradiated silicon detector. Also think about the effect of the temperature on the noise at the output of the amplifier.

Measurement 2: Signal from a Sr-90 source

Analysis background: 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, know 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 on 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 cluster 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.

Table 1 : Probabbility of being inside a Gaussian distribution

Cut in 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

Question: What do you think is a good value of the seed cut in units of standard deviations of the noise Gaussian for our detector?

Question: Explain why you have chosen this value

Question: What do you think is a reasonable value for the neighbour inclusion cut?

Data collection:

- The Sr-90 source, Detector module and Scintillator are aligned
- The aim will be to collect several data sets at different bias voltages. Bias the detector according to the table below.
- Log the Data to a file for the data from the detector (you need to decide upon a name which preferably includes the voltage)
- Click on RS (radioactive source)
- Click on Start

Table 2: Bias voltages for data collection

Set-up 1 / n-type	Set-up 2 / p-type	Set-up 3 / p-type irradiated
100V	100V	300V
200V	200V	1000V
300V	300V	

You should have a data rate of between 30 (irradiated detector set-up) and 300 Hz.

For the on-line analysis a seed cut of 5 times the noise sigma is used.
- Look at the different pull down menus

Question: What is being plotted in each window?

- In the signal page look at the two chips individually

Question: What can you say about the signal in the two chips?
Question: Discuss the implications of the choice of the S/N cut.
Question: 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 of the signal from the chip connected to the detector.

Data is added to this histogram on an event by event basis for the largest signal in the data stream. The histogram shows the signal as a function of the time between the random trigger and the periodic readout signal that takes place every 25ns.
Question: Comment on the shape of the plot
Question: Would this detector be any good for the LHC? (bunch crossing 25ns)

You should collect data for about 30 minutes.
If time is short, don't worry there is an example data file for the off-line analysis.

- Collect data sets for the other bias voltages in the same fashion as above.

Data Analysis:

- Run the analysis code
  - cd to DataAnalysis directory
  - Run root
  - In root run analysis macro "run_single.C" that performs the analysis.
- Values used in the root macro define the input data files, and the cuts applied to the data for the analysis :
  - fnameData = your data file
  - fnameCalib = Calibration file recorded before (if used)
  - fnamePedestal = Pedestal file recorded before (if used)
  - polarity = -1 or +1 depending on your detector type
  - doFit = 1 (to perform fit)
  - timeCutLow and timeCutHigh = time cuts used to select in-time data
  - fitLow and fitHigh is the range used for fitting the Landau function

There is a mask file (masked.txt) that is already created which lists strips that the analysis code will mask out, including noisy strips and un-used readout channels. This should not need to be changed. The seed and neighbour inclusion cuts have been set appropriately for the analysis (seed = 5, neighbour = 3).

Several windows (know as canvases) will appear. Some of these will be familiar from the on-line analysis.

- Look at the analysis canvas

A timing cut is applied to the data to only include the data that is in the peak section (+/- 10ns around the peak). For this analysis this data is called the peak data. Data is also plotted for a timing cut of 80-100ns and called the baseline.
Question: What do you expect to be in the base line data plots?

- Loot at the top right hand plot

Question: Do you see any noise events?
Question: How does the noise affect the signal?
Question: What can you say about the shape of the signal plot?
Question: Can you explain the physics behind the shape?
Question: Is the reported peak at the same place as the apparent peak of the fit?
Question: If not, do you think the fit is correct?

- Look at the Henrycanvas (not Henrycanvas2)

Question: What is plotted?
Question: Comment on the shape?
Question: Why is the cluster width 2 highest and do you think that this is reasonable?
Question: Why are there clusters more than 2 strips wide?

- Look at Peak Distribution canvas

Question: What are you looking at?

Question: What can you say about the difference in the plots on the top left and bottom left?

Question: Do you think that this has a physical reason?

- Thinking about the plots in the Henrycanvas and Peak distribution canvas

Question: Do you think the position resolution will be affected by larger clusters? If so is the affect always good? Explain why.

If time permits

Question: Read the slides – "delta electrons and resolution in a silicon detector"

For the last 15-10minutes all the groups will come together.

- For the data sets record the most probable value for the signal pulse height spectra and the associated noise value.
- Add the data to the spreadsheet of the data collected in the laboratory session.
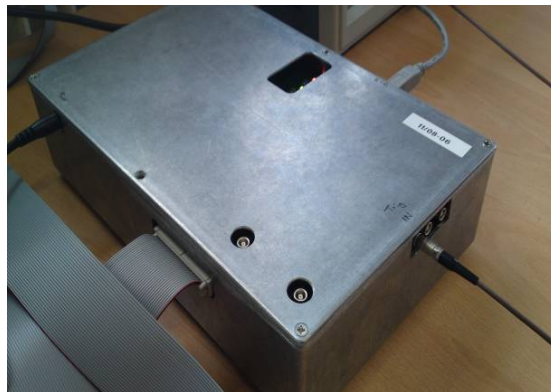
Question: Comment on the differences, if any, between the two sets of data for different bias voltages

Question: Comment on the signal from the three different sensors.

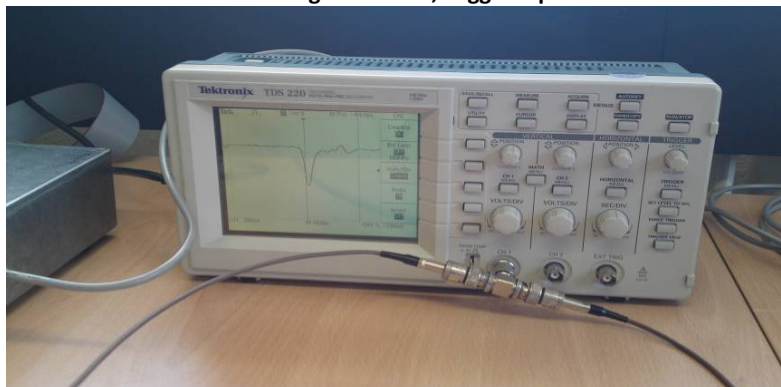## Pictures of the Strip laboratory set-up

Figure 6 : A sr-90 source aligned above the silicon detector with an aligned Scintillator trigger below.

Figure 7 : Motherboard with flat cable to daughter board, trigger input from PMT and USB cable connected.

Figure 8 : Example of the trigger signal on the oscilloscope.

Appendix on strip detector apparatus and code

The appendix has details on the hardware and the software for the strip detector laboratory. These details are not required to perform the laboratory but should be of interest to the student.

The hardware

More details for the hardware are given here.

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 (know 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 amount 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.

To start the DAQ system.
1. Start by opening a terminal window then type '**ls**'. This brings up the list of directories. Make sure you see the directory Analysis_Compiled then type '**cd Analysis_Compiled**' to take you into that directory.
2. Plug the USB cable into the laptop and the motherboard, and plug in the motherboard's power supply. A green and red LED on the motherboard should illuminate to show you it's switched on.
3. In the terminal type '**dmesg | grep tty**'. The *dmesg* code checks amongst other things the connections to the USB hub, and *grep* looks for the structure *tty* in the codes output. The pipe (i.e. "|") can be found by holding the "Alt Gr" button and the button above tab. The last line of the code that appears should read "FTDI USB Serial device convertor now attached to ttyUSB0". The 0 could be replaced by any other number and this is the number you use in the next line of code. We'll just assume it's 0 but make sure to change it if it's any different.
4. Type '**change_priv 0**' and press the blue reset button on the motherboard.
5. Type '**alibava-gui – dev=/dev/ttyUSB0 lars.ini**'. This will open the Alibava program gui window. The input file lars.ini contains the set-up details for the Beetle chips.

- On-line data analysis:

The graphs produced by this 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 boas voltage – which way will it change and why?

- o **Hitmap** – shows you the signal on the channel that is hit.
- o **Temperature** – of the daughterboard
- o **Time structure** – shows the time a trigger occurs, this should be uniform
- o **Event display** – this doesn't give the average, it displays the data on each channel for just 1 event updated every 100 events.
- o **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.

Beta electron data analysis

The data analysis code allows you to reproduce the analysis performed by the acquisition code and also apply your own cuts.

- Edit the analysis code to upload your data files:
    1. In the terminal window type '**ls**' and check you can see the files you have just created.
    2. **cd** to "/DataAnalysis" directory
    3. Run root which will run the rootlogon.C file and load the correct code.
    4. You will need to use your data file as the input of the analysis code sin_preguntas. It takes the form of:

sin_preguntas("RS file", "Calibration file, "Pedestal file", polarity, fit, timecutlow, timecuthigh, baselinetimelow, baselinetimehigh).

Suggested values are noted below.

    5. Edit the line so that RS file, Calibration file, and Pedestal file correspond to the files that you wish to analyse.
    6. *Where the polarity is the sign of the signal collected. This should be -1 if you are collecting electrons and +1 if you are collecting holes. If you have a device with +ve biased strips with respect to the back side what will be collected, holes or electrons, what should the polarity be set to?*
    7. *The fit value should be 1 to ask the code to perform the fits required.*
    8. *Timecutlow (5) and timecuthigh (15) are cuts applied to the data to select only events that are on the peak of the signal in the data analysis. This is described further down in more detail.*
    9. *baselinetimelow (80), baselinetimehigh (100) are cuts applied to the data to select events that are not on the peak so that we can check that things look fine where there is no signal. The default values for these should not need to be changed.*
    10. .q to quite root and close the canvases.

- Editing of cuts used in the analysis:

As described above we will want to apply a cut to the data to include it as a signal so we don't include noise in the data. The signal seed cut is normally run at 6 times the noise distribution standard deviation as described above. The signal to noise cut is to allow neighbour inclusion and is set at a value of around 3 standard deviations of the noise. This can be changed in sin_preguntis.cpp.

To change the cuts:
1. in the terminal type "**nano sin_preguntas.C**"
2. type "**ctrl W**" for search
3. search for the string **Seedcut**

This finds the line:

    A->set_cuts(6., 3.); //First: Seedcut, Second Neighcut FOR RS data

The first number is the seedcut, second is neighbour inclusion cut.
4. Change these to see the effect on the data.
5. click **ctrl** and **X** to exit. It will ask if you'd like to modify buffer. Type **yes**.

- Changing the range of the fit to the Landau spectrum:

You may also need to change fit range used on the final spectrum.

This should not normally be required. However, it might be of interest to see how the returned value of the peak is affected by the choice of the fit range.

To change the fit range
1. in the terminal type "**nano analysis.cpp**"
2. ctrl **W** for search
3. search for the string **// fit that we use**

This finds :

hx->Fit("fFitLandSimple", "wr", "", 20, 250); // fit that we use and
// the range over which it is performed.

4. Change 20 and 250 for lower and upper limits respectively to the number that you desire.
5. click **ctrl** and **X** to exit. It will ask if you'd like to modify buffer. Type **yes**.

- Running the analysis code:

When ever you make any changes to the code you will need to re-run root.
Several new windows (canvas) will appear and text will be output to the terminal screen.

The first canvas is the analysis canvas which should have 6 plots on it. Plots 1 and 2 show the hits on chips 1 and 2 respectively. The time graph shows the signal size as a function of

the time between the trigger and the sampling time of the signal. This is in effect a reconstruction of the shape of the signal out of the Beetle chips.

1. Note the peak of the plot. You will need to re-run sin_preguntas with the timecutlow and timecuthigh cuts so that the values for the time cuts are +/- 5 around this peak (This will make sure that the data used in the analysis is data that is in time)
2. Before re-running examine the noise and common mode noise plots. The noise and the common noise plots are the same as on the on-line analysis. You need to generate a masked file to mask out bad strips (noisy or not connected) and the whole chip that isn't connected to the detector. From the noise plot note the strips that are not-bonded and that are noisy. The strip numbers can be read off from the noise histogram whose scale can be edited by clicking on the histogram.
3. Check masked_example.txt for an example of the mask file.
4. Edit the mask file using the nano code to include a list of all the channels to mask. Save as masked.txt. The first chip has channels that run from 0 to 127 and the second from 128 to 255.
5. Re-run sin_preguntas with the correct time cuts and the new mask file.

- Average detector noise:

The terminal window outputs some information on the analysis. At the end of this it states the average recorded noise for chip 1 and 2.

- The output canvases:

The screens are the root code canvases for different plots from the results that were recorded. Look at these in turn. The Peak clusters are those found for the in-time events and the baseline are those found for the out of-time events. The baseline plots should be more or less empty.

1. **Analysis canvas** is divided into 4 main sections. The top left shows on a log plot all the data collected for each chip individually. The bottom left shows the average signal size as a function of the time between the PMT trigger and the sample signal. This is a reproduction of the signal time waveform. The top right plot is the pulse height spectra after the signal to noise cuts and timing cuts have been applied. A Landau convoluted with a Gaussian is fitted to the data. The final plot (bottom right) is the noise plot showing the average noise per channel and a histogram of the common mode noise contribution.
2. The **distribution canvas** has a graph which shows the size of the signal as a function of the number of strips in the cluster. A black dot is draw for each event in the analysis. *Comment on the shape of the distribution.*
3. The **peak distribution canvas** has four graphs. These are histograms of the signal recorded on the detector for clusters that are only 1 strip wide, 2 strips and 3 or more strips wide. The 4th graph of the total signal looks like the signal expected, the total of all the strips put together. The distributions increase in value and have higher energy tails as you get clusters which are more strips wide. *Consider why this happens.*

4. The **baseline distribution canvas** is similar to the peak cluster but is for the out-of-time events and should look pretty empty.
5. The **Imax canvas** has a histograms which shows the number of events recorded for each channel number; a nice collimated source should be visible.
6. *The* **neighbour canvas** has a histogram is like the peak distribution. It shows the number of events as a function of deposited energy for the signals recorded on the neighbouring strips (left and right and second strip left and right). *Comment on the histograms.*
7. The **temperature canvas** gives the temperature of the daughter board as a function of time.
8. There are **two Henry canvases** one for the peak and one for the baseline. It is a histogram of the cluster width. You can get rid of the bigger clusters by playing with the noise inclusion cut.

To exit the program, type .q.