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Laboratory course on silicon strip detectors

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Abstract. In this laboratory course we present an elementary introduction to the characteristics and applications of silicon detectors in High-Energy Physics, through performing some measurements which give an overview of the properties of these detectors as position resolution. The principles of operation are described in the activities the students have to develop together with some exercises to reinforce their knowledge on these devices.

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1. Introduction

Radiation is invisible for us, it cannot be smelled, touched, seen and nevertheless it can be harmful. It was necessary to characterize the radiation to have control in it and indeed apply it for our own benefit. The way radiation can be identified is through devices which can response when passing or stopping in them. Some process can take place when radiation interacts with matter: photoelectric effect, pair production, compton scattering, bremsstrahlung, as others.

The development of radiation detectors has passed for several periods, from identifying a single sound (geiger-muller) as radiation passed over, to the hability of localizing the position incidence (wire chambers, silicon detectors). Before 1950 Geiger counters, photographic emulsions and Wilson's cloud chamber were the major detection instruments used; after that the bubble chamber took over much of the task. In the early sixties the spark chamber entered and evolved to the proportional wire chamber. Nowadays there exist several kinds of detectors whose development depended on the application. There are ionizing chambers, proportional counters, scintillation material coupled with photomultiplier tubes, cerenkov detectors, semiconductor detectors among others.

The principle of many detectors is the detection of a track left by the passage of a charged particle. When it passes through matter, it knocks out electrons from the atoms, thereby disturbing the structure of the material and also creating loose electrons. Thus a charged particle passed through matter leaves a trace of disturbed matter and move electrons from their positions that can be collected.

We will refer in this lab to two kind of these detectors. Scintillation and semiconductor detectors are widely used in many research areas. They have some advantages over other detectors, mainly they are fast in the sense that their response to the interacting radiation is of the order of nanoseconds. Between them also there are advantages and disadvantages.

It is known that plastic scintillators have relatively poor energy resolution. The path in converting the incident radiation energy to light and the generation of the electric signal through a photomultiplier involves many inefficient steps. It is necessary an energy of about 1000 eV to produce a photoelectron as an information carrier, so there would be around thousands of these carriers where the statistical fluctuations have an important role.

To avoid this statistical limit for the energy resolution it is necessary to increase the number of information carriers. This is achieved by semiconductor detectors. Instead of light, the information carriers in these devices are electron-hole pairs.

More than two decades ago silicon detectors have been used in high energy physics experiments mainly in the identification of charged particles and tracking position[1]. Thanks to their versatility they also have been applied in other fields as Astrophysics, Medical Physics and others.

The great amount of applications of silicon detectors is due to parallel development in electronics of low noise and very large system integration (VLSI). When radiation crosses this detector a relative small production of charge is created. This small charge, which is the signal of this radiation, is hidden by the electronic noise. So it is necessary to have an electronic system with very low levels of noise. In fact, to a good application of these devices it is needed to get at least a signal-to-noise ratio of one order of magnitude. The amount of charge deposited in the typical 300 μm of thickness of a silicon detector is very small (25,000 electrons is the average value for a relativistic, singly-charged particle traversing the detector orthogonally to its surface).

In this laboratory there are exercises where the students will learn the properties of silicon detectors, a little of scintillation detectors and some valutation of position resolution. This lab is based in a previous one[2] and it is mentioned in the acknowledges.

2. Silicon Detectors

When an electric field is created in the semiconductor, the electron-hole pairs present in the material undergo a net migration. This effect is called the drift velocity of the carriers. If the electric field is increased this velocity saturates and the time required to collect the charge could be of nanoseconds. Semiconductor detectors can be included among the fastest-responding of all radiation detector types.

In a semiconductor, a charged particle passes through creating many electron-hole pairs along the track of the particle. It is said that the incident charge particle ionizes the material, see fig.1. The quantity of practical interest for detector applications is the average energy when creating these pairs. This quantity, often called ionization energy is experimentally observed to be independent of both the energy and type of radiation.

The dominant advantage of semiconductor detectors lies in the smallness of the ionization energy. The main elements to produce semiconductors are silicon and germanium. For them it is required only an energy of 3.6 eV to create an electron-hole pair while for a gas-filled detectors a 30 eV is needed. As we can see there is a difference of one order of magnitude. As it was pointed before this increment has two beneficial effect on the energy resolution; the statistical fluctuations diminishes and the signal to noise ratio improves considerable.

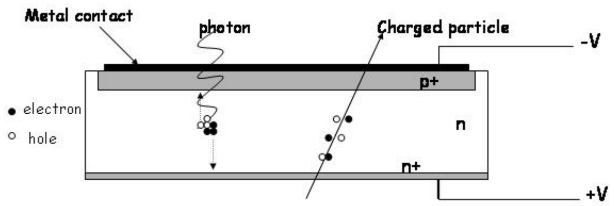

Figure 1. X-ray hitting a silicon detector.

The main characteristics of the silicon detectors that make them useful devices are:

- Speed of reaction when radiation cross the surface of 10 ns.
- Spatial resolution $\sim 10\mu$m.
- Flexibility of design.
- Small amount of material (0.003 X_0 for 300 μm thick detector).
- Linearity of the response vs. the deposited energy.
- Good resolution in the deposited energy.
- Tolerance to high radiation doses.

A silicon detector can be visualized as a diode with a junction of p^+ and n material where a depletion zone is created. Applying an inverse voltage this depletion region expands, decreasing the production of charges (leakage current), letting the region prepared for detecting radiation that will originate charges when crossing the wafer surface. These parameters, leakage current and depletion voltage are very important because they can influence the performance of the readout electronics. The electric field created guides the generated charge to the cathodes. These cathodes are the p^+ material which collect the charge that will be transmitted to the electronics. For our detector these cathodes are the microstrips. Above each cathode there is a metallic cover to permit the connection between the detector and readout electronics via a microbounding. Once passed to the electronic chain, these signals are amplified, recorded and at the end with some programing techniques it can be determine the position that the particle hits (see next section). All this requires very fast electronics.

In a silicon crystal each silicon atom is bound to its neighbors by the four covalent bounds formed by its four valence electrons. If dopant atoms with five valence electrons are introduced, it also forms the same number of bonds with its neighboring Si atoms. Therefore, the fifth electron is loosely bound, and even at room temperature it is essentially free of moving around the lattice, leaving the atom as a positively charged ion. Such a crystal will be called n-type because of the presence of the free negative charges, available for conduction, and the dopant is called a donor. In case of a trivalent dopant atom, one electron is missing to form the four covalent bonds, and this 'hole' can be filled by another electron of the lattice, which in turn will leave its position vacant. The hole can be treated as a free positive charge, and the trivalent atom, now with four covalent bonds, will remain as a negatively charged ion. In this case the dopant atom is called an acceptor, and the doped crystal will be called p-type because of the presence of free positive charge carriers. If we put in contact p-type and n-type silicon we obtain a p-n junction.

The size of the detector can be very large, in fact up to the largest size of silicon wafers industry can handle. At the moment detectors are produced mostly out of wafers of four, five or six inches of diameter. Since the fabrication technology of silicon detectors is analogous to the one of integrated electronics circuits, one can include in the detector additional features: very frequently resistors, capacitors and even transistors are integrated on the detector substrate.

The detector used in this laboratory is known as micro-strip silicon detector. We will refer to it as silicon strip detector during this report. Our detector has 256 strips, 50 microns pitch, 300 microns wide and an area of $2 \times 1.25cm^2$. However in our case the viking chip is connected only to 128 strips so it covers an active area of $2 \times 0.625cm^2$.

Microstrip detectors provide therefore the measurement of one coordinate of the particle's crossing point with high precision. Using very low noise readout electronics, the measurement of the centroid of the signal over more than one strip further improves the precision. Clearly the precision of this procedure depends on the noise of the readout chain (including the quantization error introduced by the analog-to-digital converter, which is important when using small signals). If digital readout is used (strip hit or not hit), the resolution is simply $\sigma = \frac{pitch}{\sqrt{12}}$[3].

2.1. Viking chip

For the application of silicon detectors in identifying β radiation and X-ray a low noise electronic system is required. VIKING, a low noise silicon strip readout VLSI chip has been designed for this purpose. It was constructed in $1.5\mu m$ CMOS technology[4].

The chip contains 128 low power (1.5 mW/channel) charge sensitive preamplifiers followed by CR-RC shapers and sample and hold circuit, input and output multiplexing and one output buffer. Use of time continuous shaping facilitates triggered applications and enables optimum signal to noise ratios.

Two signals activate the start/stop unit in the chip, which creates an internal clock, a "start" signal for the shift registers and an activate signal for the output buffer. This signal is necessary to allow daisy chaining of chips and hence only one output buffer at any time should be swhitched on. The "start" goes into the output multiplexer and the internal clock shifts it through the 128 channels. For one clock cycle each channel is connected to the output buffer to read the channels out. After 128 clock cycles the outcoming signal from channel 128 stops the internal clock, disables the output buffer and creates a shift-out which can be used as a shift-in for the next readout chip. The peaking time is $1.5\,\mu s$ and the noise is typically $70\,e^- + 12\,e^- C$.

For low energy X-ray applications the noise has to be as low as possible. A 10 keV X-ray will only produce 2800 electron-hole pairs in silicon. So, if a signal to noise ratio of one order of magnitude, as mentioned before, has to be reached it is necessary to reduce all the sources of unwanted electric signals inside the electronic chain. The contributions of the silicon detector to the total noise of the assembly come from:

- The load capacitance of the silicon detector.
- The leakage current in the silicon detector.
- Possible resistance between the active element of the detector and ground, or the bias supply.

Therefore it is important for these kind of detectors to have a very low noise electronics. Generally the development of these detectors implies a similar development of their electronics.

2.2. Scintillator detectors

Charged particles through certain organic materials may produce visible photons. This was originally discovered for naphthalene. In these kind of materials electrons may be kicked into higher orbit. Next these electrons fall back to their original orbit and the energy released is emitted in the form of photons. This light can be seen as a very short, blue tinted flash. Scintillation detectors are based on this effect. Obviously this works only if the material is transparent to the light produced, so that this light can be detected outside the material.

Scintillation detectors are the most useful devices for the detection and spectroscopy of radiation. Any good scintillation detector has to achieve:

- High efficiency in converting the energy of the hitting particle to light.
- The light yield should be proportional to deposited energy.
- The medium has to be transparent to its own emitted light.
- A fast ($\sim ns$) decay time of the induced light.
- The material should be subjet to be manufactured.
- Index of refraction of the order of glass (1.5) for coupling with PMT.

For a scintillator detector it is very important to convert a fraction as large as possible of the incident radiation energy to fluorescence, while it has to avoid phosphorescence. It is worth to remember that fluorescence is the prompt emission of visible radiation. Phosphorescence is the emission of longer wavelength light than fluorescence and the characteristic time is much slower.

Among many kind of scintillators, plastic ones have become extremely useful for radiation detection. Because the material of which they are fabricated is relatively inexpensive, plastics are often the only practical choice when a large volume of solid scintillators is needed.

Plastic scintillator is one part of this detector. The other part is a device that converts the light produced by the plastic to electric signals. This device, called a Photomultiplier (PMT), works through the photoelectric process. When the charge is creates the PMT also accelerates this charge (electrons) via a set of dinodes. They react producing more electrons (charge), multiplying the quantity of the charged carriers, that is the reasons of its name (photoMULTIPLIER). Finally there is an important quantity of charge that is possible to be registed by some instrument, an oscilloscope for example. This charge can also go to a discriminator module which produce a digital signal when the charge exceedes a threshold level ($\sim 30mV$ minimum).

There is generally a light guide between the plastic scintillator and the PMT. This is used to match properly the geometry of the plastic to the entrance of the PMT. The transmition of

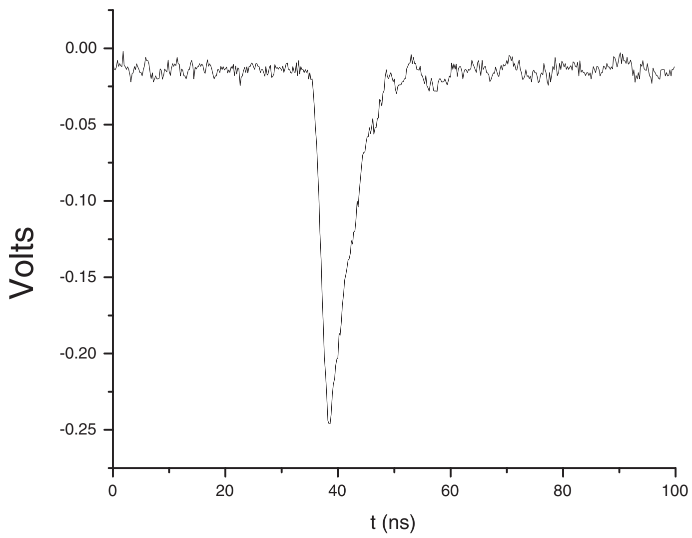

Figure 2. Common pulse of a cosmic ray detected by a scintillator detector coupled to a PMT.

light to the PMT can be done also through clear optic fibers. In our case, because the geometry permits so, the plastic is coupled directly to the PMT.

3. Laboratory Course on Silicon Detectors

This laboratory course consists of two different mini sessions, in order to give the student some hands-on experience on various aspects of silicon detectors and related integrated electronics. The experiments to carry out are:

- Trigger system of the microstrip detector using a plastic scintillator coupled to a PMT.
- Measurement of the position resolution of a microstrip detector with a laser.

In this lab session the students require some knowledge on diodes, scintillator material and some skills in managing electronic devices as an oscilloscope, multimeter, voltages supplies, NIM technology, etc.

3.1. Trigger system

The development of this system includes a start for detecting an event (trigger) in one of the 128 channels. Triggering is a common tool in particle detectors to be able to synchronize them with others and the whole system.

The trigger sends a signal in order to let the channels transmit their information or voltages to the electronic system. When a particle is detected and impinges in the active zone one or some strips show a voltage peak of different values going from 50 to 200 mV, see fig. 2.

As it was mentioned before we will use a platic scintillator with a PMT to produce, via cosmic rays, the trigger signal. The plastic scintillator and the PMT used in this laboratory are

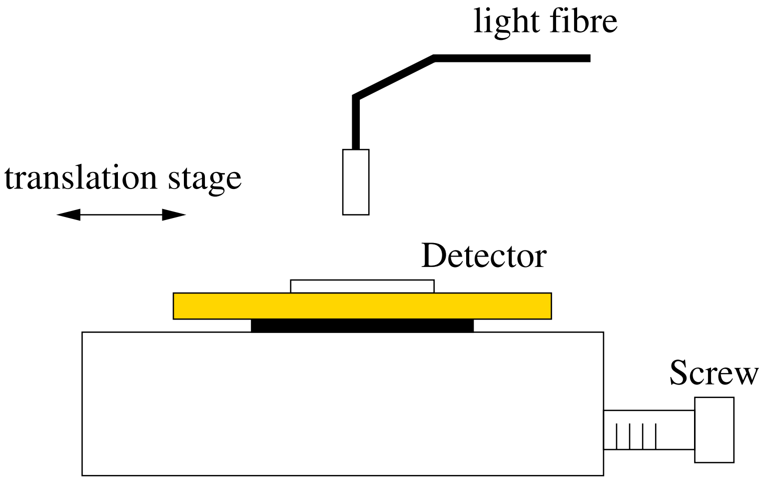

Figure 3. Device to move the laser perpendicular too the strips.

an organic poliviniltoluen material (BC-408) and a hamamatsu H5783, respectively. We use a $5 \times 5 \times 2cm^3$ plastic volume, so we have an active area of $25cm^2$ if the radiation is normal to this surface. The signal produced by a cosmic ray is sent to a discriminator module. This creates a NIM signal necessary to activate the "trigger in" placed on the viking timing module.

If the scintillator detector is placed above the silicon detector one can create a coincidence between these two devices and one can see the cosmic ray in the oscilloscope as a peak in any of the 128 channels. Therefore it is possible to develop the exercise consisting in counting how many cosmic rays arrive by time and by square meter. We know that this frequency depends on many factors, latitude, sea level and more. We expect to have a rate of $1/cm^2/minute$.

3.2. Study of the position resolution of a silicon microstrip detector

As we have seen during this report, silicon microstrip detectors are the most commonly used device for high resolution tracking in particle physics. The strip design allows a large sensitive area with relatively few readout channels. The basic strip detector is read out on one side giving information of the track position only in one dimension. Various solutions to measure track position in two dimensions exist. The simplest solution is to glue two single-sided sensors back-to-back, but a more demanding design is to process strips on both sides of the detector.

To trigger the viking timing module and at the same time to send a laser light pulse to the detector, we will use a laser diode. In order to enable the laser as a light pulse mode, we used a wave generator instrument. The circuit of the laser diode gives also an electric pulse which will be used as trigger. So a cable with this electric signal goes to the module and the laser light goes to shine the detector transmitted by an optic fiber. This fiber is placed in a micro manipulator which can be moved with good precision (although it presented backlash (see fig.3). The transfer direction is orthogonal to the strips so we can see in the oscilloscope the strips hit by the light and how their gain is changing.

4. The laboratory setup

In this experiment we use the following equipment:

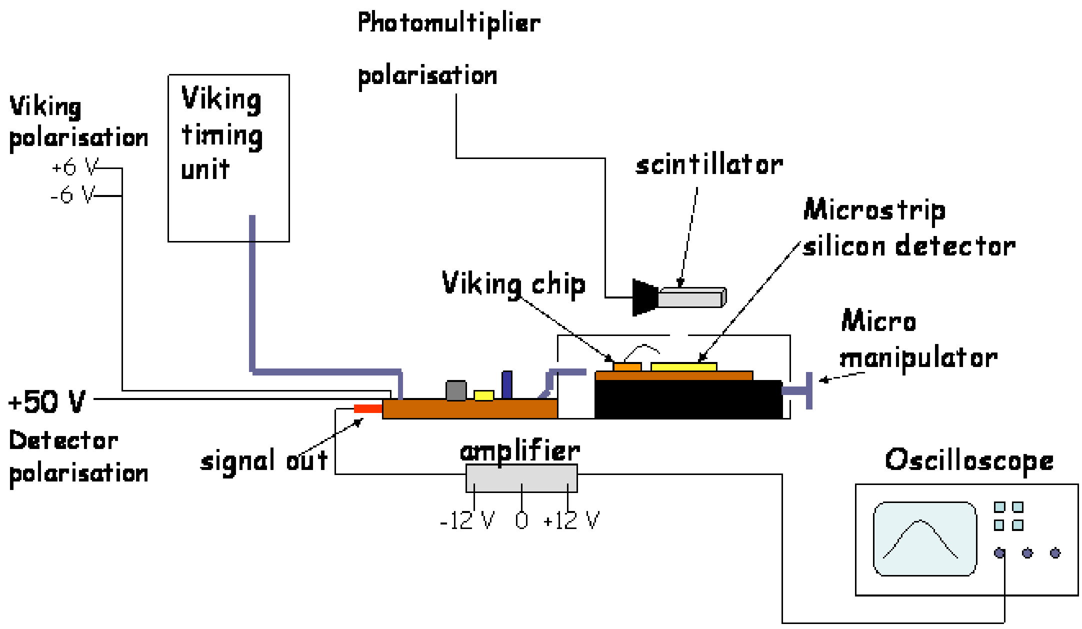

Figure 4. Set-up to obtain a trigger with scintillator and silicon.

1. Timing unit for readout circuit, VIKING TIMING;
2. Function generator for trigger and laser;
3. Current limited power supply for readout circuit;
4. NIM crate;
5. Discriminator NIM module; Scaler NIM module
6. Oscilloscope;
7. Laser diode;

The silicon microstrip detector is wire bonded to the Viking readout circuit, which has been placed on a readout PCB (Printed Circuit Board). Fig. 4 shows a scheme of the first set-up.

The first exercise consists in verifying the trigger system with the scintillation detector. Once achieved this, we can proceed to count the number of those triggers which will be the number of cosmic ray we are able to identify. In counting this events we can compare to the expected rate. Then the scintillator detector must be put over the metallic box keeping the microstrip to obtain coincidences.

The second exercise consists in using a laser to make some studies of the spatial resolution. In this case it is required to modify a little the set-up. A special assembly, a micro manipulator has been mounted on the metallic box containing the silicon detector, which can be precisely moved such that the translation direction is orthogonal to the strips. An optical fiber has been mounted there to move the light shining the strips and register it in the oscilloscope. There is about 100 μm distance from the laser to the silicon surface. See Fig. 5

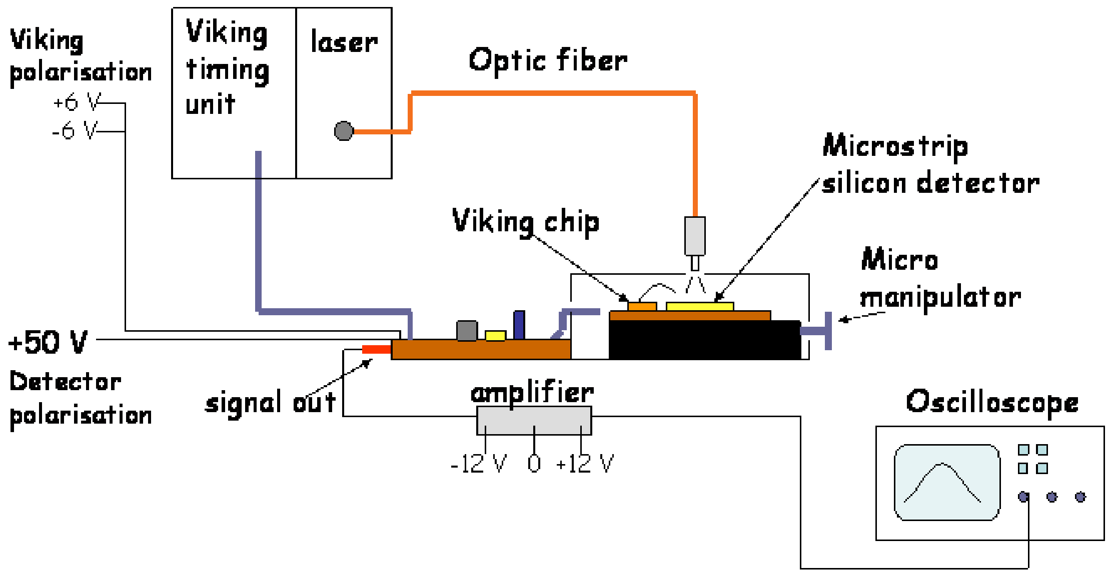

Figure 5. Set-up with laser and silicon.

4.1. Measurements

First, we will obtain coincidences between the scintillator and the silicon detector. The plastic has to be put over the metallic box containing the microstrip. This box is necessary to avoid the increment of noise in the silicon detector produced by visible light and it will permit us to have a signal as clean as posssible. Every time the plastic is hit by a cosmic ray there is in the oscilloscope a signal (fig.6) without a peak. Only in the case the cosmic ray passes through the plastic AND the microstrip we will see a peak as the figure mentioned before. We will get few coincidences because the active area of the silicon detector is small compared to the plastic one (Active area of microstrips $\sim 1cm^2$ while for scintillator is $25cm^2$). We will count both, cosmic rays hitting the plastic and coincidences.

After the first exercise is done, next we will try to determine the position resolution of the silicon microstrip detector. A little lense was placed in the output of the optic fiber in order to focalize the light. In this way we were able to obtain the laser spot a few strips wide. We require the information from a number of strips in order to accurately determine the peak position. This is done by determining the center of mass of the pulse. Moving the laser some known distance, we can calculate the spatial resolution comparing this distance vs. the interval between two center of mass of each pulse. It is important to say that we need seven complete turns to move the laser 1 mm. So we can proceed as follows:

1. Move the micro manipulator by turning the micrometer placed on the box. Using an oscilloscope you will now see the signal from the light moving from one strip to another.
2. Place the laser in a region with a nicely distributed signal.
3. Determine and write down the amplitudes of the channels in the peak by moving the cursor on the oscilloscope.
4. Turn the screw one seventh of a complete turn and repeat step 3.

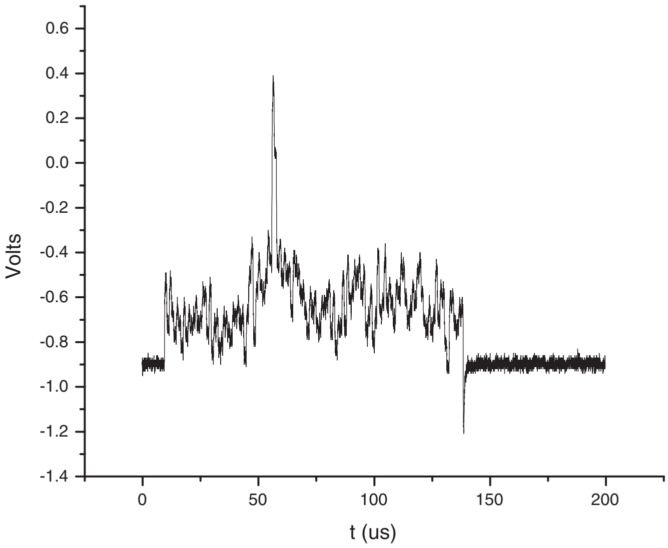

Figure 6. Trigger with cosmic ray using silicon and scintilllator.

4.2. Results

We verified the coincidence between the scintillator and silicon detector looking at the oscilloscope the spectrum of the 128 channels and the one hit. We did some counting of the events where there was a coincidence and there was only signal in the scintillation detector. In table 1 we show the results. We have a mean coincidence around 1 per minute. This is close to what we expected, taking into account the active area of the silicon detector.

On the other hand, for the frequency of events in the scintillator we have a mean value of 30 per minute. We have an active area of $25cm^2$, so it is of the order of magnitude that we expected.

Table 1. Raw data from the first setup.

minute	scintillator	coincidences	scintillator	coincidences
1	30	0	32	1
1	28	1	29	0
1	28	0	27	0
1	28	1	26	2
1	15	3	18	1
1	32	0	28	0
1	24	1	32	1
1	23	2	34	0
1	33	1	30	0
1	32	0	24	0

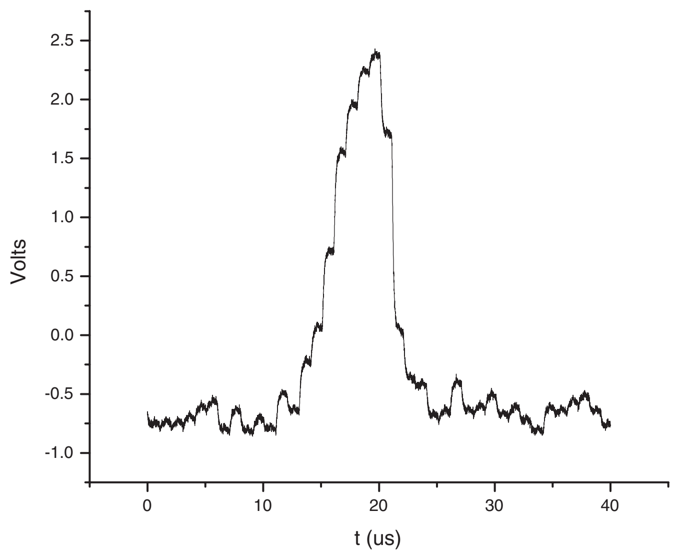

Figure 7. Laser signal of the microstrip in the oscilloscope.

Table 1 shows two similar sets of data taken by the students in two of the four days this lab was given. In each of them we show the events detected only by the scintillator and both detectors (coincidences).

Now, for the second experiment we will use the laser. First we tried to get a very small spot of light. So after making some exercises of focalization, the light should hit some strips. There were zones where we hit more channels or strips as it is shown in Fig.7. However there were zones in which we only have signal for less than six strips.

Moving the laser along the detector and being its light spot perpendicular to the strips we register the amplitudes. Table 2 shows the measured amplitudes (in mV) of the signal for different strips in some positions of the laser.

Table 2. Raw data from the second setup.

Strip n	0 μm	20 μm	40 μm	60 μm
1	820	610	480	460
2	1040	800	630	490
3	1310	1020	840	750
4	1130	1290	1220	1140
5	980	1050	1330	1280
6	720	910	1150	750
7	490	710	980	460

As it is shown in fig. 7 we write down the amplitude of each strip. These strips are manifested as little steps in the distribution. Each step corresponds to $1\mu s$. Table 3 shows the results for this measurement.

Table 3. Results from the position resolution measurement (in μm).

	$0\ \mu m$	$20\ \mu m$	$40\ \mu m$	$60\ \mu m$
Calculated peak	135	154	172	159
Difference		19	18	-13

The peak position can be determined by calculating the centroid :

$$C = \frac{\sum A_i \cdot x_i}{\sum A_i} \tag{1}$$

A_i represents the amplitude and x_i the strip number multiplied by the pitch (50 μm). The results from the measurement are shown in table 3. Except for the last measurement, which was probably affected by a backlash of the micro manipulator when moving the screw, it can be seen that the measured difference between the peak positions is very close to the expected one of 20 μm.

Since we are averaging the signals from the Viking in order to minimize the electronics noise, and taking 7 points to calculate the centroid, it can be seen that position accuracy down to a few μm can be achieved. To determine in a more precise way the resolution of the detector one should take several measurements for "single events" (i.e. not averaging the signal, but taking only one signal for each mesurement) and fill an histogram with the distribution of the errors on the measured peak differences. The r.m.s of this distribution would represent the detector resolution.

4.3. Acknowledgments

I want to thank Alan Rudge for letting me to use for this lab the Viking system he had given me in the past. Also to Elisabetta Crescio for clarifying some details of the system and to M. Fontaine for his technical support. Thanks to the organizers for having invited me to give this lab and for their warm hospitality.

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