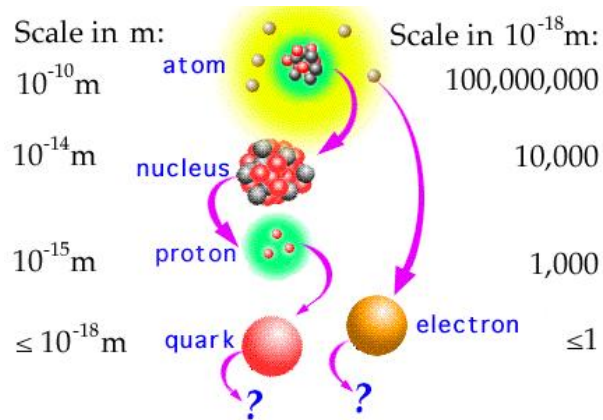
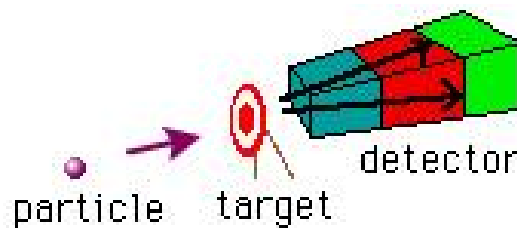


1 Worksheet 1: Introduction to the Project

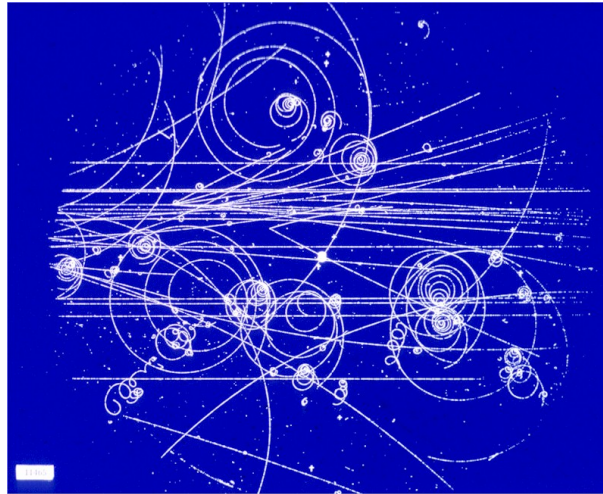


The main aim of this project is to give you some experience of carrying out modern particle physics experiments, and to introduce you to some of the difficulties faced with these experiments. Particle physics is an area of physics which is interested in the universe on a tiny scale. We ultimately want to be able to answer the question “*What are we made up of?*” We know that all organic life is made up of molecules, and that these in turn are made up of complex arrangements of atoms. We can break these up further since we have our picture of the atom as a nucleus being orbited by electrons, and that the nucleus contains a number of protons and neutrons. The number of protons in a nucleus determines which element the atom is, and hence how it behaves chemically. But the important point for particle physicists is that the atom is made up of protons, neutrons and electrons. But can we split these up any further? Well, it turns out that for the electron the answer is no! The electron cannot be broken down into any smaller constituent particles. As far as we know, the electron is not made up of any other particle. In the particle physics jargon we say that it is a *fundamental* or *elementary* particle. However, the story for the proton or neutron is very different indeed. Experiments in particle physics starting in the 1960s have proved beyond any doubt that protons and neutrons are not fundamental, but are made of fundamental particles called *quarks*.



The proton was first discovered in 1919 but quarks were not even proposed until 1964, and not discovered until around 1968. So you might ask “Why did it take 50 years to find out what a proton is made of?” and that is a sensible question. The main difficulty we have when it comes to performing particle physics experiments is the fact that particles are so incredibly small. The proton has a diameter of around 10^{-15} m. That’s one million billionth of a metre! The most powerful optical microscope in the world can view objects which are no smaller than 10^{-9} m, which is incredibly impressive, but the proton is 1 million times smaller than this. Since we have no chance of directly seeing a proton, we require some very clever and very sophisticated techniques in order to show that it is there and to perform experiments on it. In fact, the most common experiment carried out is to fire a beam of particles, for example electrons, at a target made purely of protons, and to investigate the angles at which the electrons are deflected. The distribution of particles after they have been through the target can tell you many things, including the size of the target

particle. This type of experiment, where a beam of particles is fired at a target, is usually called a fixed target experiment.



Particles colliding in a Bubble Chamber

Performing experiments on the quarks inside the proton is much more difficult. In order to observe quarks, the particles in the beams have to be at extremely high energies. If the particles have a high enough energy, then they can break apart the proton and interact with the quarks inside. However, the quarks will never remain separated, and will very quickly form new particles. Particles are created from the energy of the collision. You may have come across Einstein's famous equation: $E = mc^2$. This equation tells us that any particle which has a mass, m , also has an energy associated with that mass which can be calculated from Einstein's equation. This works in the opposite direction as well: if we have some energy (i.e. from our collision between particles) we can create particles which have mass. If the energy of the collision is increased, then we can make particles of higher mass. This is the main goal of particle physics experiments, to collide particles at the highest energies possible in order to create new particles which have never been seen before, but could provide us with the clues we need to answer the big questions in particle physics. However, it gets increasingly difficult to make beams at the highest energies, and so we are constantly looking for new ways to produce high energy collisions.



Many current particle physics experiments, rather than having a beam of particles colliding with a fixed target, collide two beams of particles travelling in opposite directions. This means that the energy of the collision will be much higher. The highest energy collisions are currently being

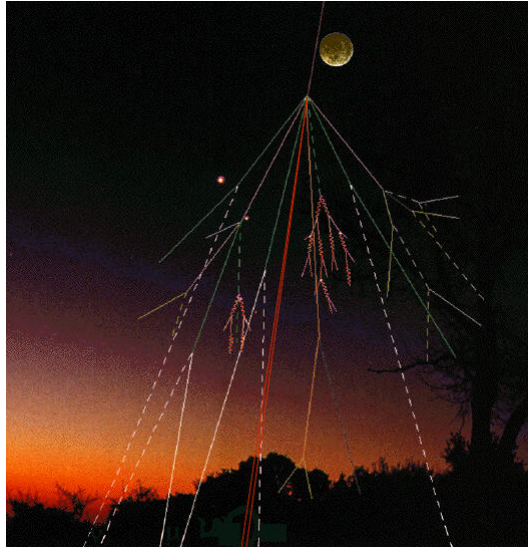
produced at the Large Hadron Collider (LHC). This has two beams of protons travelling in opposite directions around a 27km tunnel 100m underground. The protons collide at an energy of 14 TeV (TeV stands for tera electron-volt; $1 \text{ TeV} = 10^{12} \text{ eV}$). Measuring which particles are produced in these collisions requires sophisticated detectors and extremely fast electronics in order to keep up with the number of particles produced and the rate at which collisions take place. The detectors required are the size of a building and contain millions of electronic readout channels.



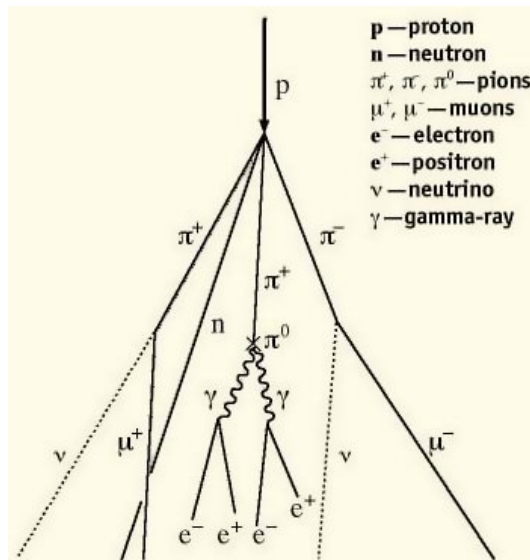
Clearly, it is not feasible for a single group to pay for and manage an experiment of this scale. For this reason, particle physics experiments tend to be international collaborations. People from different groups (e.g universities, national laboratories etc.) all contribute to the experiment, designing the detectors and the electronics and then analysing the data which is recorded once the machine is up and running. Experiments record a huge amount of data, which needs to be sent all around the world so that everybody on the experiment can access it from their office in order to run their analysis. Particle physicists have therefore had to develop sophisticated, large scale computing systems which are capable of coping with the enormous flow of data.

Throughout this project, you will experience some of the difficulties we face in detecting particles, collecting and interpreting data and in collaborating with groups from all around the country.

1.1 What are cosmic rays?



Cosmic rays are particles which originate in outer space. They are principally protons, with a small fraction of alpha particles and some heavier nuclei. There are many different sources of cosmic rays in the universe: for example, supernovae. When a large star comes to the end of its life, it collapses in on itself, which causes a huge explosion, and a shockwave which accelerates nearby particles to high energies and flings them off in all directions. Cosmic rays which originate from astrophysical sources like this are usually called *primary* cosmic rays. Since the universe is mostly empty, a lot of these particles will just travel through space without ever encountering another particle. Some will actually hit the Earth. Luckily, we are protected by our atmosphere. When the primary cosmic rays approach the Earth, they collide with nuclei in the atmosphere. The energy of these collisions will then make new particles, called *secondary* cosmic rays. These particles will then also interact with the upper atmosphere to produce yet more particles, and so for each primary cosmic ray, a shower of secondary cosmic rays will be produced. Some of these secondary cosmic rays will then travel down to ground level where we can detect them.

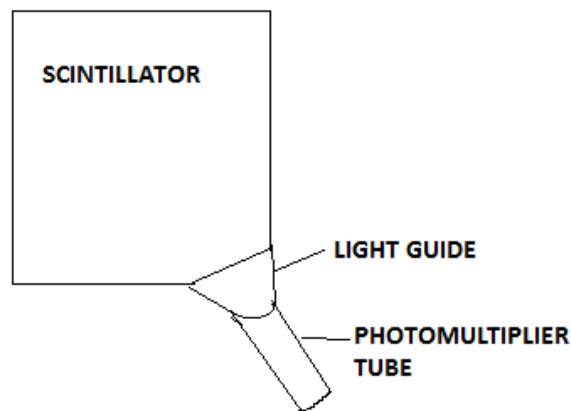


But why are we interested in cosmic rays? Some high energy primary cosmic rays produce collisions in the atmosphere with an energy of 140TeV, 10 times higher than the LHC can produce. Studying

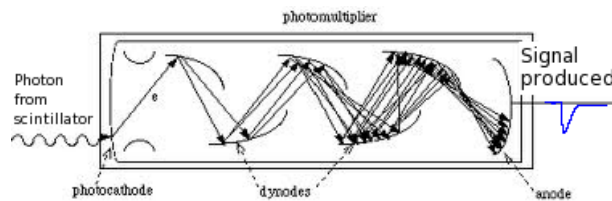
the collisions of these ultra high energy cosmic rays is therefore extremely useful for particle physics. The only problem is that it is impossible to control the collisions, and difficult to put detectors in the atmosphere where the collisions take place. Also, most cosmic rays have a much lower energy than this, and so it is quite rare to see these ultra high energy cosmic rays. However, studying the secondary cosmic rays which reach sea level can give us valuable information about the sources of the primary cosmic rays.

1.2 How can we “see” cosmic rays?

Within the shower of secondary cosmic rays there will be a lot of muons. These are leptons, like electrons, but much heavier, and we can detect muons using scintillation counters.



They consist of large squares of a plastic material called scintillator. When a charged particle, like a muon, passes through the plastic, it uses some of its energy to remove electrons from the atoms, or ionises it. The electrons then try to join back up with the atoms, but they can only do this if they give off some of their energy by emitting photons, or a flash of light. The light then bounces around the scintillator until it reaches one corner, where we have placed a photomultiplier tube, or PMT. This can take the tiny flash of light, and convert it into an electrical signal which tells us that a charged particle has passed through.

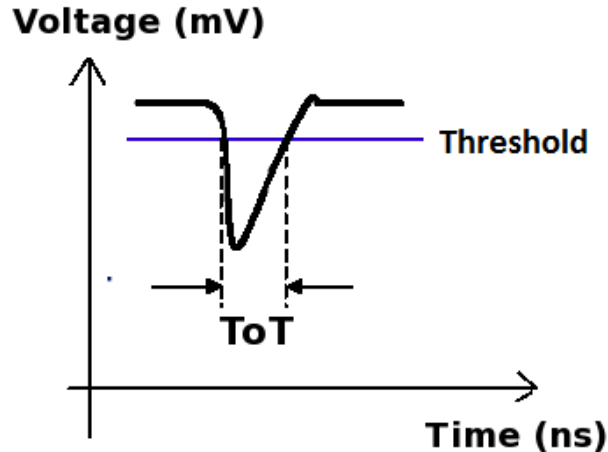


A diagram of the PMT is shown above. When a photon strikes the photocathode surface, it releases an electron. This electron is then attracted to a series of dynodes. A negative high voltage is applied across the dynodes so that the electron is accelerated as it approaches them. This means that when it strikes the dynode, 3 or 4 electrons are then emitted, so that at each stage the signal is amplified. The electrons eventually strike the anode at the end which is held at 0V and produces a negative pulse for a signal. The size of the signal is determined by the high voltage across the dynodes. The PMTs we use do not require a high voltage. We apply a small control voltage using the power distribution unit (PDU), and the base of the PMT converts this into a high voltage to apply across the dynodes.

Four scintillation counters are then placed one on top of the other. Since muons produced by collisions of cosmic rays are travelling at nearly the speed of light, they will pass through all detectors at essentially the same time. So we can look at the electrical signals from all of the

PMTs and use a data acquisition board (DAQ board) to analyse the signals and decide if they arrived at the same time. If all the counters produce a signal at the same time then we call this a coincidence, and that is our evidence that a cosmic ray muon has passed through. We can then use the DAQ board to work out how many muons are passing through the counter each second, or the flux of muons, and move our detectors to investigate what factors affect the flux.

1.3 The Signal

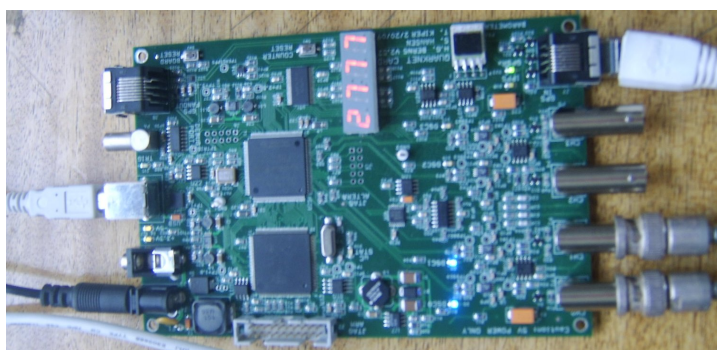
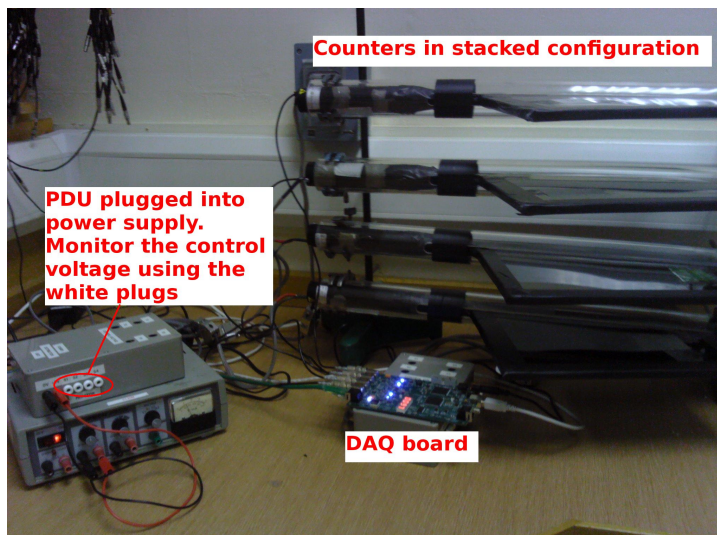


The picture above shows a typical signal which comes from the PMT when it detects a cosmic ray muon. The size of the signal depends on both the control voltage, which sets the operating voltage of the PMT and the amount of energy deposited by the muon as it passes through the scintillator. Since every muon deposits approximately the same amount of energy, we expect the signal from cosmic rays to be constant.

In reality, the PMT will not only produce signals which come from cosmic rays. There are some which come from other ionising particles passing through, from light leaking into the counter or from random signals being produced in the PMT itself. These signals, which do not come from cosmic rays, are called noise since we are not interested in them, and they make detecting the cosmic rays harder. The reason we look for a coincidence between more than one counter is that it is unlikely for noise signals to be produced in all the counters at the same time.

But there is another method we use to remove the noise, and that is to set a threshold. Noise signals are usually much smaller than cosmic ray signals, and so we only accept signals which are above a certain level, called the threshold. The higher the threshold, the fewer noise signals get through, but at the same time the possibility of not detecting a genuine cosmic ray is increased. The threshold can be set using a program called Hyperterm, which will be discussed later, and can be found in the appendix.

The figures below show the 4 counters stacked above each other, and the DAQ board which the signals are fed into.



1.4 What is recorded?

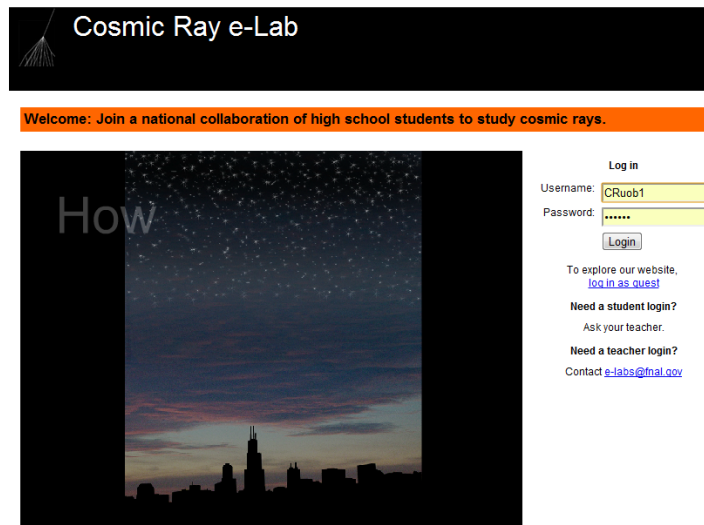
A program called Hyperterm is used to record the signals from the PMTs, but what is actually measured?

The signals from all four PMTs are fed into the DAQ board. The DAQ board is also connected to a GPS arial, which sends signals to the board about both time and position. Using this method, the board can apply an accurate time stamp, correct to within 10ns, to every signal which comes in from the PMTs. For each signal, you can record the time it goes above the threshold, and the time it goes back below the threshold, so you can calculate the total time the signal spends above the threshold. The board can also check whether or not the signals arrive at the same time and so can be considered a coincidence, and so only record those signals. You are free to choose whichever coincidence level you want. If you set a 4-fold coincidence level, signals are only recorded if there are 4 signals within 100ns of each other. If you set a 1-fold coincidence then all signals are recorded.

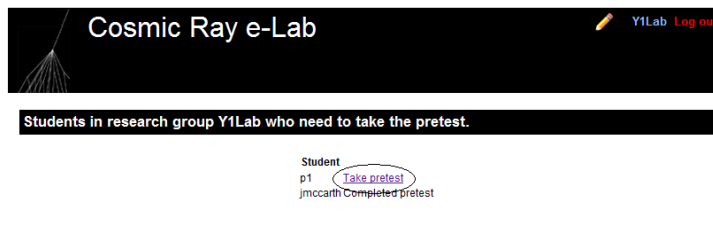
1.5 Getting started with the project

1.5.1 The Cosmic Ray e-lab

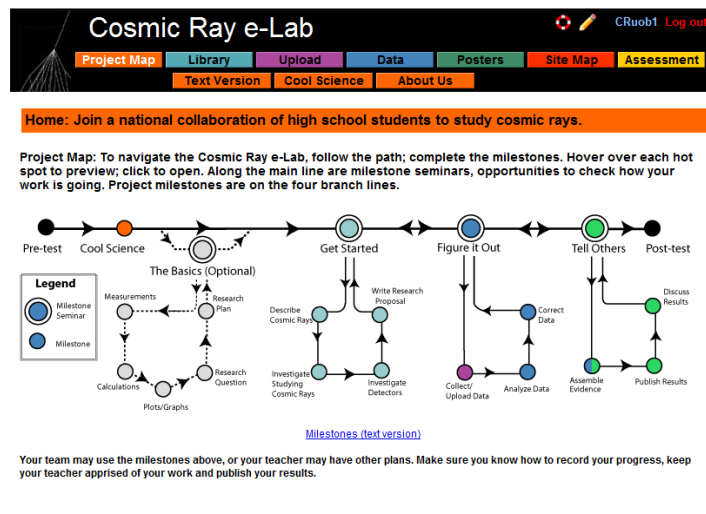
Your most valuable tool for this project is going to be the cosmic ray e-lab website. This contains all the resources you need to understand cosmic rays, and contains the tools to analyse the data you collect. The website is <http://www18.i2u2.org/elab/cosmic/home/>



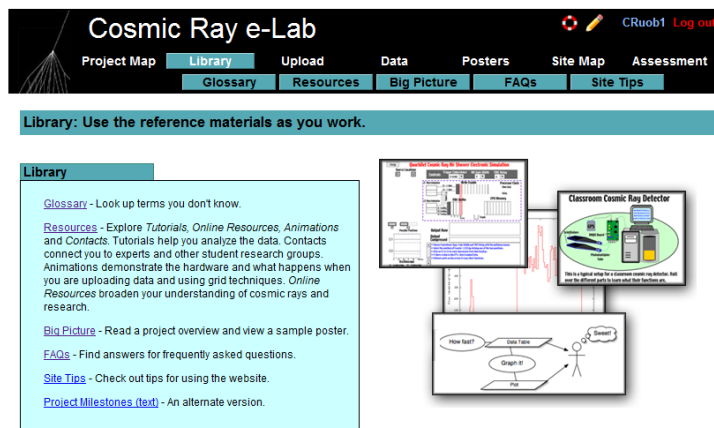
Your teacher will be able to provide you with the details you need to log into the website.



If it is your first time logging on then you will need to complete a short pre-test, just to establish what you already know before you start the project. Everybody in your group will need to complete the test before you can start.



The first page you are presented with is then the project map. This shows you the various milestones you are expected to complete through the project. Clicking on each of the circles will give you more information about that milestone.



By clicking on the “library” tab at the top of the page, you can access all of the learning resources available on the site. The glossary contains a list of technical terms along with what they mean, and the resources page contains useful information about cosmic rays, and step-by-step tutorials about how to use the website. Refer to this section if you ever need help navigating through the site or using the analysis tools, and you cannot find the information in this Student Pack. It would be a good idea to spend some time getting yourself familiar with the website and the tools available to you.

1.5.2 Setting up the detectors

The first thing you need to do is set up the detectors so you can measure the flux of cosmic rays. Refer to the sheet entitled “Connecting the muon detector” in the appendix to find out how to connect up the detector.

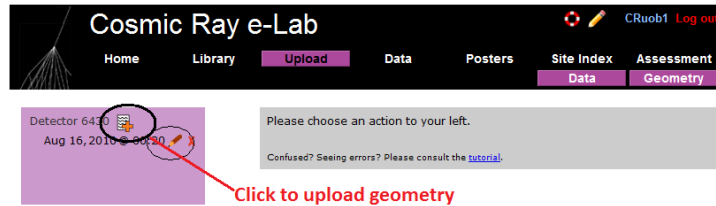
1.5.3 Using Hyperterm

Hyperterm is the program which you will be using to collect and record the data being provided by the DAQ board. The sheet entitled “Using hyperterm” in the appendix will give you all the information you need to get started using hyperterm. To check that the counters are working, type the command V1 into Hyperterm. This should bring up information on the counters, including the various settings you are using. You should not need to change these settings from the default, but they can be changed using Hyperterm. Next check that the GPS module is working by typing the command DG. The GPS status should be VALID.

1.5.4 Uploading the geometry of the detectors

Once you have the detector set up and working, you need to enter the geometry of the detector into the e-lab website. It is essential that this is correct, since the information is used to calculate the flux of muons from the data you collect.

- To upload the geomtery of the detector click on the upload tab on the e-lab website and then click on the geometry tab.
- Click on “add entry”. You should see the following pages.



Cosmic Ray e-Lab

Home Library **Upload** Data Posters Site Index Assessment

Detector 6430 Aug 16, 2010 @ 00:20

Edit Detector 6430 Entry Aug/16/10 @ 00:20 UTC:

Detector Configuration

Confused? Seeing errors? Please consult the [tutorial](#).

Select channels used

Active Channels: 1 ☒ 2 ☒ 3 ☐ 4 ☐

	Cable Length (m)	Area (cm ²)	E-W (m)	N-S (m)	Up-Dn (m)
1	0.83	780.0	0.9	0.65	1.5
2	0.93	780.0	0.9	0.65	1.64
3					
4					

Enter the details of each channel

Stacked Orientation Unstacked

Select stacked or unstacked

GPS Location

Latitude: 52.27.0222 N Longitude: 01.55.7221 W

e.g., 47:39.2347 N e.g., 122:18.68 W

Altitude (m): 134 GPS Cable Length (m): 25.0

Enter info from GPS

Commit Geometry

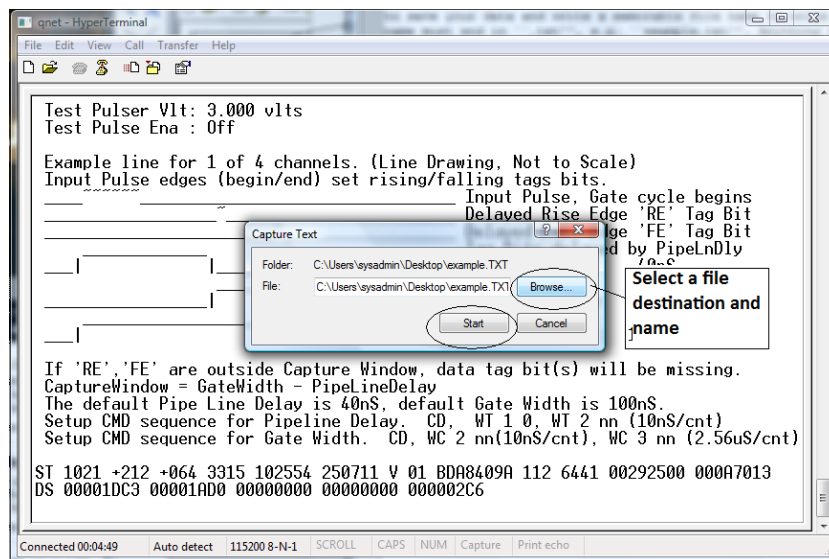
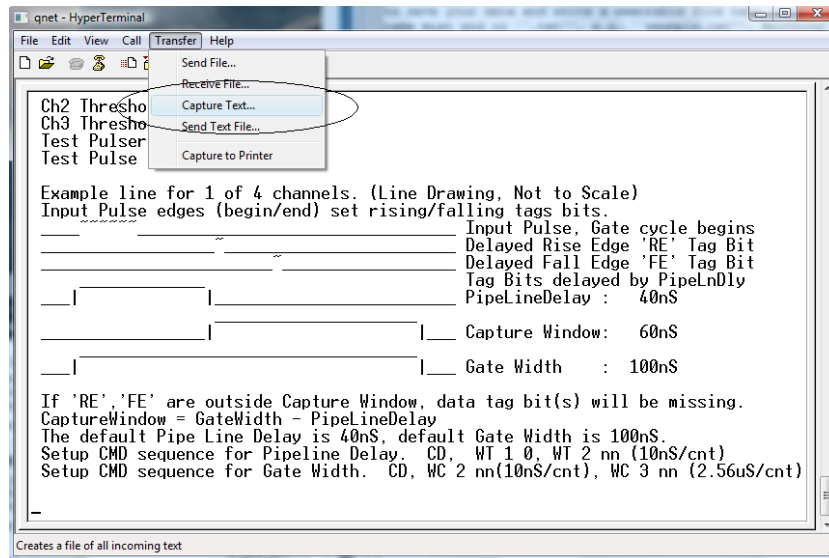
- Fill in the details of the detector setup.
 - First, tick the boxes corresponding to the channels which you are using.
 - Next, enter the required details for each counter.
 - The cable length is the length of cable from the PMT to the DAQ board.
 - The area is the surface area of the counter in units of cm².
 - The E-W (East-West), N-S (North-South) and Up-Down measurements are the distances of the counters from the GPS antenna. Make sure the difference between the Up-Down measurements of the counters is accurate, as this is vital in calculating the flux.
 - Next you need to select the orientation of the detector. Select stacked if the counters are on top of each other or unstacked if they are all on the same level. To start with, your detector should be stacked.
 - Finally, you need to enter details of the GPS antenna. The longitude, latitude and altitude measurements can be found by typing the DG command into Hyperterm.
 - The GPS cable length is the length of cable connecting the GPS module to the DAQ board.

Make sure you always upload the geometry before you start taking data. The website links the data with the current geometry at the time the data was recorded, not when it was uploaded. To upload a geometry for data already recorded, change the time and date from the upload page to just before you started taking data.

1.5.5 Collecting data

Now that the detectors are set up and the geometry has been uploaded to the website, you are ready to start taking data.

- Open up Hyperterm.
- From the “Transfer” menu, select “Capture Text”. Choose where you want to save your data and write a memorable file name to write the data to. The file name must end in “.txt”, e.g. “example.txt”. Anything that now appears on the Hyperterm screen will also be saved to the file you selected.



```

qnet - HyperTerminal
File Edit View Call Transfer Help

DG
DG
Date+Time: 25/07/11 10:30:20.031
Status: V (invalid)
PosFix#: 0
Latitude: 52:27.016426 N
Longitude: 001:55.716881 W
Altitude: 161.872m
Sats used: 2
PPS delay: +0064 msec (CE=1 updates PPS,FPGA data)
FPGA time: 49C56CAB
FPGA freq: 25000000 Hz (Cmd V3, freq history)
ChkSumErr: 0
ST 2 5
ST Enabled, with scalar data.
CE
53FC3102 AC 00 2B 00 00 00 00 00 52F8049A 103027.007 250711 V 02 0 +0040
53FC3102 00 00 3D 38 00 00 00 00 52F8049A 103027.007 250711 V 02 0 +0040
53FC3103 00 22 00 21 00 00 00 00 52F8049A 103027.007 250711 V 02 0 +0040
54332914 BA 00 38 00 00 00 00 00 52F8049A 103027.007 250711 V 02 0 +0040
54332915 00 00 00 24 00 00 00 00 52F8049A 103027.007 250711 V 02 0 +0040
54332915 00 2B 00 00 00 00 00 00 52F8049A 103027.007 250711 V 02 0 +0040

Connected 00:08:35 Auto detect 115200 8-N-1 SCROLL CAPS NUM Capture Print echo

```

- Before you start taking any data, you need to enter the following commands:
 - V1
 - V2
 - DG
 - TL
 - ST 2 5
- The first 4 commands display information about the status of the detector, which is needed by the website to analyse your data. The last command writes out a status line every 5 minutes, which is also required during analysis of the data you collect.
- You can now start reading out the data from the counters by typing the command CE. Now, everytime the counters detect a cosmic ray muon, data about the signal received will be shown on the screen and recorded in the text file.
- You can then leave the detector running and collecting data for as long as you wish. Just remember that the more data you take, the more accurate your results will be, so there is an advantage to leaving the detector running for as long as you can.
- Once you have collected enough data, tpe the command CD to stop reading the data to the screen.
- Now select “Stop” from the Transfer menu in order to stop recording the data.

1.5.6 Analysing data

Now that you have your data recorded on a file, you can upload it to the e-lab website for analysis.

- Click on the upload tab, and then click on data.
- Now select the file that you recorded the data and on click on “upload”.

The screenshot shows the Cosmic Ray e-Lab website's 'Upload' page. The header includes the site name, navigation tabs (Project Map, Library, Upload, Data, Posters, Site Map, Assessment), and user information (CRuob1, Log out). The 'Upload' tab is active, and sub-tabs for 'Data' and 'Geometry' are visible. A purple banner at the top of the main content area reads 'Upload raw data collected by your cosmic ray detector.' Below this, three bullet points provide instructions: select a detector, click 'Choose File' to locate the data file, and click 'Upload' to upload the file. The main form area contains a warning box about file size (2 GB), a 'Choose detector' dropdown menu with '6430' selected, a 'Raw Data File:' section with a 'Choose File' button and 'No file chosen' text, and a text area for 'Optional comments on raw data:'. At the bottom is an 'Upload' button. Red annotations with arrows point to the 'Choose detector' dropdown, the 'Choose File' button, and the 'Upload' button, with accompanying text: 'Select your detector and click to find your data file' and 'Once you have selected your file click on "Upload"'.

Cosmic Ray e-Lab

Project Map Library Upload Data Posters Site Map Assessment

CRuob1 Log out

Upload raw data collected by your cosmic ray detector.

- Select the detector associated with the data you are uploading.
- Click Choose File/Browse to locate the data file on your computer.
- Click Upload to upload the file.

Please *do not* upload files larger than 2 GB in size. You'll have to split them up into smaller pieces. Questions? See the [FAQ](#)

Choose detector

6430

Raw Data File: Choose File No file chosen

Optional comments on raw data:

Upload

Select your detector and click to find your data file

Once you have selected your file click on "Upload"

Now that the data are uploaded to the website, you can analyse it using the “Data” tab. We will explore each analysis option in the coming weeks, but first you need to make sure your counters are set up and working correctly. Go to worksheet 2 to find out how to Plateau your counters.