UNIVERSITY OF BIRMINGHAM

School of Physics and Astronomy
Technical Document

Laser TCT & Strontium-90 CTT Experimental Procedure at the BILPA Laboratory

April 19, 2022

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Abstract

This document details the experiment setup and procedures needed to perform laser TCT and timing measurements as needed by the Low Gain Avalanche Detector (LGAD) project in collaboration with Teledyne e2v. Reference will often be made to the measurements performed for this project as examples. The two experimental setups will be discussed independently. Discussion will begin with the theoretical need and justification for the measurements that each setup will provide. There will be a brief discussion on the theory of how detectors and amplifiers work, but this is meant to supplement ones understanding not define it. This will also include the analysis techniques required to extract important parameters. Following on will be a discussion of the physical setup, how to connect the components together ready for data-taking. Finally, there will be a discussion of the relevant procedures and python scripts needed to control and manage long data-taking sessions.

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1 Laser Transient Current Technique

1.1 Theory & Analysis

1.1.1 Theoretical Background

One of the most important properties of a detector is the way it responds to an injection of charge. In the particular case of an LGAD, this is even more important since they have a measurable intrinsic gain and their timing resolution improves with a higher gain.

Pulsed lasers are a good source of charge injection since they can be very well controlled. This means that the wavelength, intensity, pulse duty cycle, pulse frequency, etc. are well known and consistent. The pulsing of the laser provides short separate packets of photons which provide a consistent amount of charge injected into the sensor. This means that the charge injection is both consistent and repeatable and so comparisons between different devices can be made very easily.

When charge is injected into the sensor, electron-hole pairs are generated and begin to separate under the p-n junction's electric field (boosted by the reverse bias). The movement of electrons and holes is a current. This cannot be measured directly so it is preferred to work with a voltage which can be directly measured by an oscilloscope. This is done using a Charge Sensitive Pre-amplifer (CSP). This type of amplifier is an integrator circuit with a capacitor providing the feedback loop. The capacitor stores the current generated by the electron and holes and begins to charge. After the charge has injected, the capacitor can then completely discharge. During this entire process, the voltage across the capacitor can be measured. Figure **??** shows a CSP connected to the pad of an LGAD producing an ideal voltage pulse. The voltage pulse then triggers an oscilloscope which records and displays the waveform.

There are numerous properties of this waveform that can tell you about the device's response to the injected charge from the laser. For instance, one could measure the rise time or more simply the height of the recorded pulse. However, in terms of gain, the integrating (or summation) nature of the CSP means that the most important property is the integral of the pulse since this is proportional to the charge collected by the CSP.

Consider a laser which injects a charge q into the sensor with each pulse. The intrinsic gain of an LGAD, G_L, means that the total charge, Q_L can be described as,

$$Q_L = qG_L. \tag{1}$$

The same applies to a PiN which has a gain of G_P which is assumed to be one since there is no intrinsic gain layer. The CSP also amplifies the signal by some constant, A, which means that the integral, S_L, of the final waveform is given as,

$$S_L = \int_{t_0}^{t_0+t_w} V(t)\,dt = qAG_L, \tag{2}$$

where $V(t)$ is the waveform which is the voltage as a function of time, t. The limits of the integral are defined by t_0, the start time of the pulse, and t_w, the time width the integral is performed over. Again, the same can be applied for the PiN, where S_P is the integral of the PiN's waveform. Figure **??** shows an example pulse from an LGAD and a PiN with their integral windows.

Note that t_0 and t_w need to be carefully chosen such that the entire pulse, but no reflections (extra pulses arriving after a primary pulse) are included. Including some noise is prefered over exclusion of part of the signal. Ideally, integrating noise should give zero although in practice this is not always the case and so care should be taken to choose the best limits.

Assuming that q and A remain constant between a measurement of an LGAD and a PiN and ensuring that t_w is also consistent, then one can write the following,

$$\frac{S_L}{S_P} = \frac{G_L}{G_P}. \tag{3}$$

Note that if the laser power is changed, or any ND filters are used, then a correction will need to be applied to the integral. Some example data should be provided with the document although it is always best to repeat these calibrations to ensure they are correct and still apply. If the assumption that $G_P = 1$ is indeed correct, then this equation can be rewritten as,

$$G_L = \frac{S_L}{S_P}, \tag{4}$$

and thus the gain of the LGAD can be extracted through laser charge injection by comparing the integral of an LGAD pulse to the integral of a PiN pulse.

The gain of an LGAD will increase with the bias voltage and so calculating the gain for a range of voltages is desirable. Figure **??** is an example showing both an LGAD and a PiN. Note how the PiN's integral, once fully depleted, does not vary with bias voltage. When calculating the gain, an average of S_P, taken above $\sim 50V$, can be used as a baseline for gain calculations for all bias voltages which should result in a more accurate value of S_P.

Figure **??** is the gain plot using the integral sweep described earlier. Note how the shape of the curve is defined by the shape of the LGAD's integral and is exponential with respect to bias voltage.

1.1.2 Known Limitations

There are two major limitations with using a laser as a source of charge for gain measurements. The first is the assumption that the charge injected into the laser, q is a constant. Unfortunately it has been shown that is not the case and that the laser currently used in our setup is not a reliable source of charge. It appears that during a continue run of the laser than q does remain constant, but between sessions (shown for measurements over a day apart), q does indeed change. This problem, and its solution, is discussed in more detail in the next section.

The second major limitation is with the measurement of gain itself. As the bias voltage across an LGAD increases, so does the gain. When the gain is sufficiently high, an event called "gain suppression" can occur. Summarised very simply, gain suppression is caused by a localised electric field which works to counteract the electric field create by the bias voltage (which generates the gain in the first place). This means that the effective gain of the sensor is reduced from what it theoretically could be without this reactive E-field. The reason this is a problem is because of the way energy is deposited by the laser versus a charged particle.

A charged particle travels along an exact path and deposits energy along it. If the particle travels vertically (perpendicular to the gain layer), then all of the electron-hole (e-h) pairs that it generates will drift along the same vertical path. This will mean there is a very high density of e-h pairs especially once the electrons reach the gain layer and begin to multiply. The localised E-field caused by this will be extremely high causing a significant suppression of the gain.

When the laser illuminates the sensor, the inject charge is spread over the beam width ($\sim 50\ \mu m$). This can often be many times larger than the equivalent width of the charged particles path. With the charge spread out over a much larger area, the density of e-h pairs is much lower and therefore the effect of gain suppression is significantly lower.

This creates a disparity in the gain in a certain voltage range depending on how charge is injected. This is very important since the timing resolution strongly depends on the gain and so we may be artificially inflating our value of gain at a given voltage, especially when using it to make a plot of gain versus timing. This is the reason collaborations will tune their laser to inject a MIPs worth of charge to make it equivalent to a charged particle. However, if the beam width is not made sufficiently small, then even injecting a MIP equivalent will not provide the necessary charge density needed to replicate gain suppression. At the time of writing, there is no implemented solution to this problem, and more investigation is required to find a way around it.

1.1.3 Charge Calibration Method

As discussed in the previous section, the charge injected into the sensor by the laser, q, is not constant and can vary from session to session. Since q cannot be controlled, we need to be able to measure it. More specifically, we need to be able to measure a change in q.

For this task we can use a piece of equipment called a beam monitor. The beam monitor contains a beam splitter and a photodiode. The beam splitter means that the beam can be monitored whilst also illuminating a device. The photodiode is there to respond to the other part of the split beam and will be used for the monitoring. The current beam splitter has a 50 : 50 ratio which unfortunately means that the photodiode saturates too easily while measurements at low gain (with a PiN for example) become impossible. Instead, a new beam monitor with a 90 : 10 split ratio will be used (at the time of writing it is yet to be delivered) which should rectify these issues.

The photodiode and its associated amplification electronics, should follow the same logic discussed in Section 1.1.1. So, for a more generic sensor and readout electronics, the integrated signal, S, can be written in the form,

$$S = qB, \tag{5}$$

where B is an arbitrary constant due to amplification. Consider that on another day, the injected charge is different and given by q'. The integrated signal is now,

$$S' = q'B, \tag{6}$$

Using this prime convention, we can take the ratio from one day to another and find that B cancels to give us,

$$\frac{S'}{S} = \frac{q'}{q} \tag{7}$$

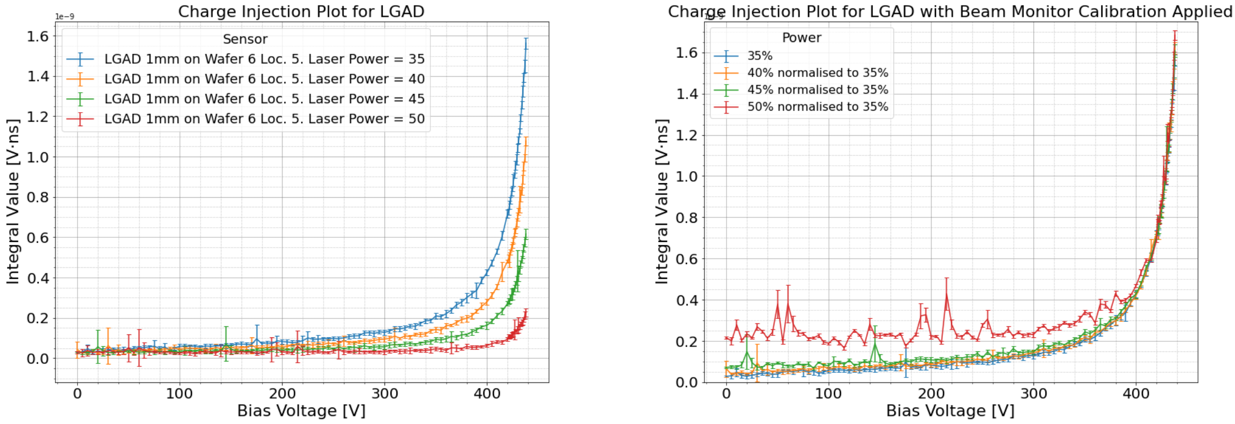
Replacing S with S_{bm}, which specifically refers to the beam monitor, we can use this as a conversion factor when measuring another sensor such as an LGAD. Recall Equation 2 which with q' becomes,

$$S'_L = q'AG_L. \tag{8}$$

We can use Equation 7 to convert q' to q resulting in,

$$S'_L = qAG_L\frac{S'_{bm}}{S_{bm}}. \tag{9}$$

Now when we take the ratio between two devices of different gain (an LGAD and a PiN for example), we can use the ratio of the beam monitor integrals to ensure that q is a constant and thus cancels out correctly. This premise is demonstrated clearly in Figure 1, where the power of the laser is changed thereby changing the injected charge, which is then corrected for by the beam monitor integral. Note that for low laser powers, the noise becomes quite significant and so the correction does not work for lower (gain) bias voltages. This data was also taken with the beam monitor with a 50 : 50 ratio beam splitter, which further explains the issue with noise.



(a) (b)

Figure 1: (a) Signal integral as a function of bias voltage at four different laser powers (b) The same bias voltage sweeps but with a correction applied using beam monitor integrals

1.2 Setup

The following section includes a series of images and diagrams detailing the Laser Transient Current Technique (TCT) setup.

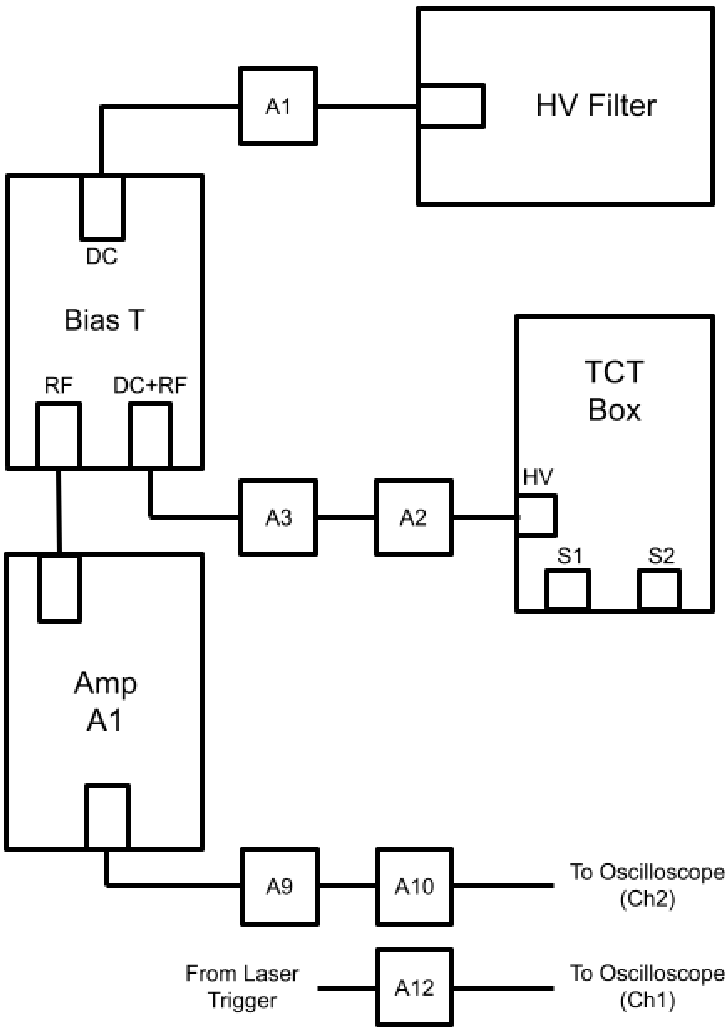


Figure 2: A simplified schematic diagram showing the components used in a gain measurement. Each box with a label, A3 etc., represents a different cable with the same code labelled on either end of the cable. The Bias T and Amp A1 are connected by a short SMA male-to-male adapter. There are other cables involved such as a source for the HV and the power supply for Amp A1. Most of these are not likely to change but will be referred to in photos later on.

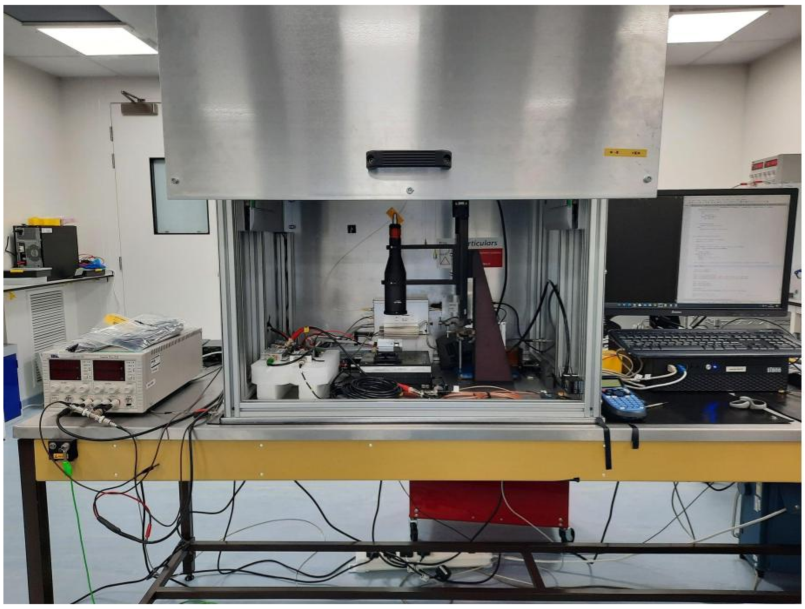


Figure 3: A wide photo showing the major components of the TCT setup (the Oscilloscope sits to the right of the PC). The majority of the cabling and equipment is placed inside of a metal box in the centre to shield the device from light and interference. Power supplies are placed on the left outside of the metal box. The PC to the right of the metal box controls the power supplies and oscilloscope allowing nearly full automation of testing.

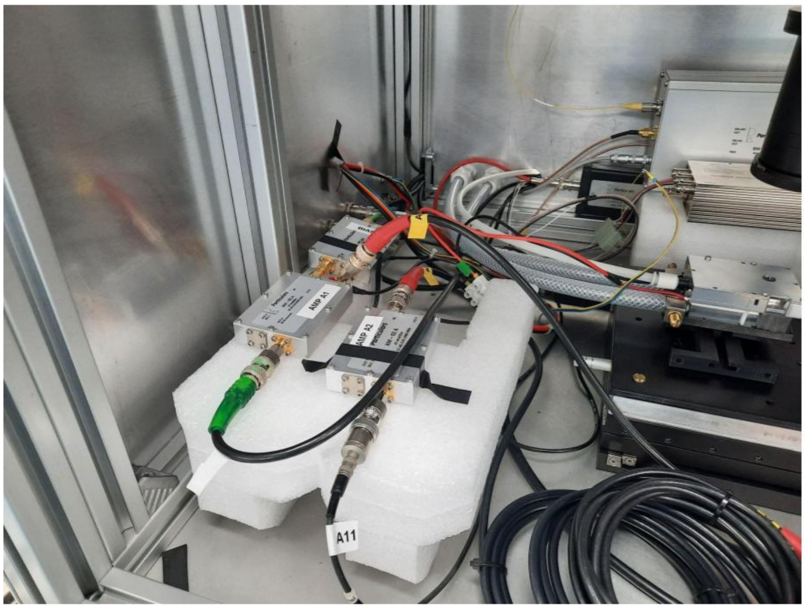


Figure 4: The key electronics raised by a piece of foam to protect in the event of coolant leakage. Two amplifiers are place with one currently connected to a Bias-T which separates the RF signal from the DC bias of the device under test (DUT).

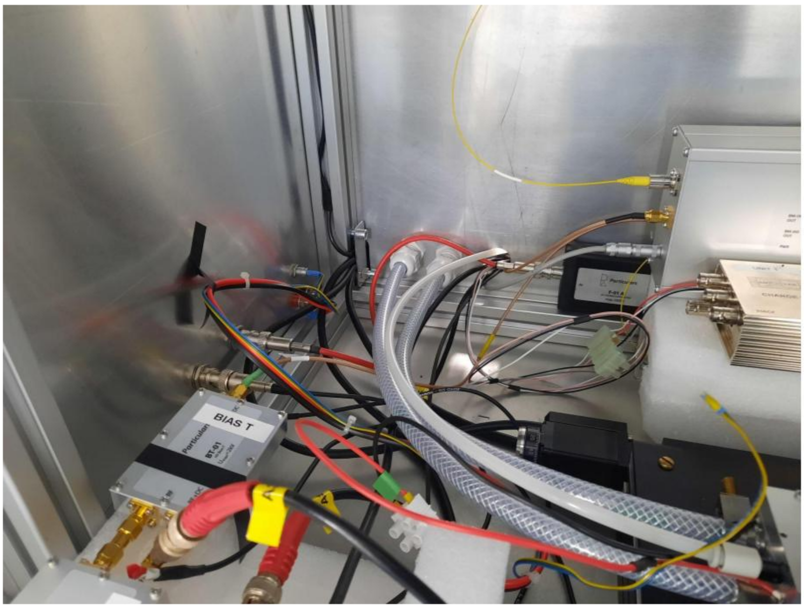


Figure 5: Just a little further back from the amplifiers and Bias-T is the main cabling bulkheads and feed-through. Power for the amplifiers and bias and cooling peltiers are fed through from the left. The cooling pipes come from the rear with a simple bend round to the sensor. They can be tightened into place such that they apply the least tension to the sensor's holder minimising unwanted movement. Just next to the coolant pipes is the feed-through for various cables. For example, the nitrogen flow, power for the beam monitor, and various output cables leading to the oscilloscope run through here. The black box to the right of this feed-through is the HV-filter which ensure that the HV bias is pure DC (no noise spikes from the power lines etc.). The cables to and from this box are standard and are unlikely to need to change.

Figure 6: At the very back of the metal box is the beam monitor with three cables coming out of the left hand side. In ascending order these are: the power, the output SMA, the optical fibre output. The other side has two inputs for optical fibre cables. Input "A" is normally used. This model of beam monitor has a 50:50 beam splitter between the output and the internal photodiode. Just in front of the beam monitor is a slow amplifier with a known calibration for the input charge. Behind both of these are the drivers for the laser with their various power and trigger cables and an output fibre optic cable. The majority of these need not be changed.

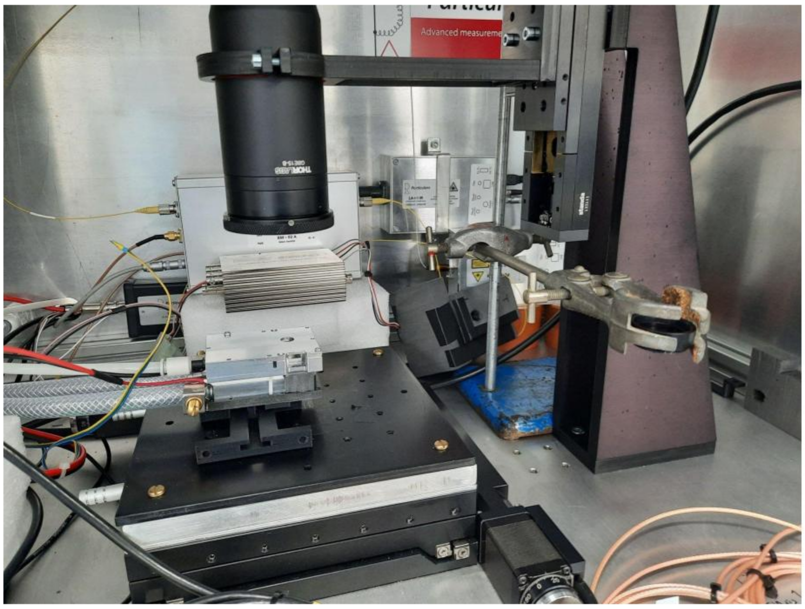


Figure 7: The centre of the TCT setup. An optical fibre is carefully screwed into the black optics at the top. The laser then focuses on the device held in the metal box (PCB holder) below. The PCB holder can be cooled and filled with nitrogen through cables out the back. Peltier cables also emerge from this side. The PCB holder is then attached to some plastic adapters and slides into a holder which is bolted to the stage. The stage is a small optical bench plate with two stepper motors which can precisely control and position the stage in the X and Y (lateral) directions. The Z direction is controlled by a motor towards the top of the optics (See the vertical stand). To the right is a clamp stand with an ND filter in the clamp. This is tightened such that it is free to swing about the pole and be placed between the optics and the sensor, in order to fine tune the intensity of the laser.

Figure 8: An artistic photo of the PCB holder surrounded in some simple foam. This foam is built from some small slabs and taped together into two pieces. The first contains has a humidity sensor (and crude temperature sensor) which sits just below one of the holes in the PCB holder. The second foam piece needs to be mounted separately since an SMA cable needs to run through it and into the PCB holder. The two foam pieces can be push-fit into place and together and will form a sufficient seal to stop more nitrogen leaking than is pumped in, keeping the humidity sufficiently low.

1.3 Procedure

This section will guide a user through all the steps needed to perform a simple voltage sweep on a target device.

1.3.1 Initial Setup

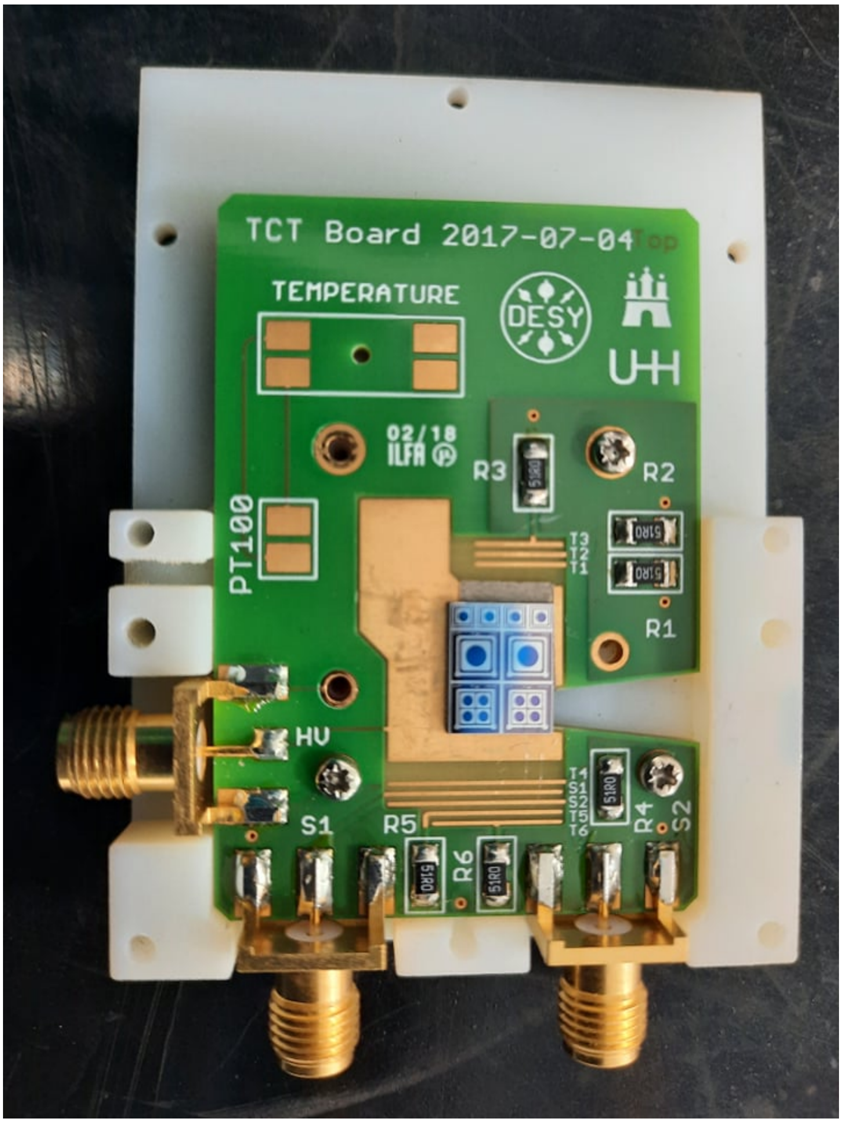


Figure 9: The TCT PCB placed in an older version of the PCB holder which is made from plastic and is therefore not designed for cooling. For simple gain measurements, the SMA on the left provides the HV bias and also returns the RF pulse. A single wire-bond is needed from the pad of interest to the large via just left of the main pad as annotated. This completes the circuit. The PCB can be screwed into the holder which then requires a lid before being placed on the stage.

Before beginning any measurements with the TCT system, the device under test DUT, needs to be attached and wire-bonded to a TCT board and placed in the PCB holder as per Figure 9. The PCB holder can then slide into place on the TCT stage as in Figure 7.

The next step is to refer to the diagram and photos in Section1.2 and ensure that all necessary connections are in place and working order. Even if everything looks in place already, it is recommended to re-tighten some of the SMA connections as a slightly loose connections can sometimes cause reflections or spikes in the RF signal.

With the setup and cabling complete, it is time to begin powering up all of the supporting equipment. This includes: the LV and HV power supplies to the left of the TCT box (for the amplifier and sensor biasing respectively; the PC to the right of the TCT box; the oscilloscope to the right of the PC; the laser power supply is a black box around the back of the TCT box (and should have two cables coming out as one connects to the beam monitor); and finally the plug labelled "Xilab" which powers the stage controllers.

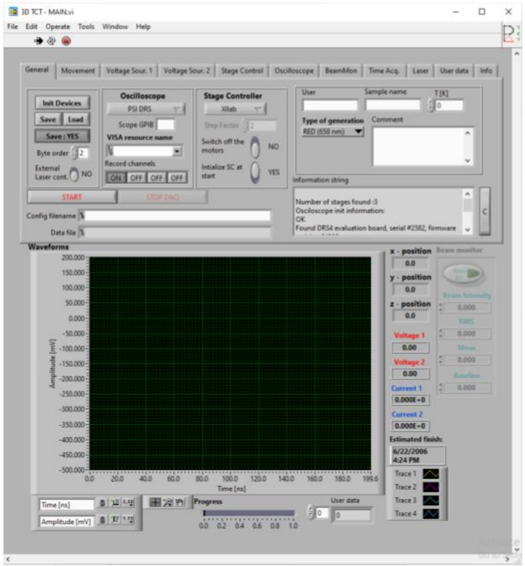


Figure 10: The LabView program which enables the user to manually control the stage controllers for manual alignments. It also contains other functionality such as the ability to perform scans and interface with a DRS4 scope.

Although you are likely reading this on the PC to the right of the TCT box, the password for that PC is "tct2020". Once logged in, there are a few programs that need to be opened.

The first is a LabView program called "3D TCT - Main" which should be on the task bar and look like Figure 10. This program has many different functions, but the primary use for now will be the ability to manually control the stage controllers for manual alignment. There are then 4 simple steps to initialise the program, all from the first screen in Figure 10:

1. Change the stage controller to "Xilab"
2. Increase the stage controller step factor to "2"
3. Click the arrow in the top left corner (means the program is actually in a running state)
4. Click the "Init Devices" button (allows the program to connect to Xilab etc.)
5. Ensure that the Xilab stage controllers (3 of them) are found in the output log

If there are any issues with the LabView program, ensure that the Xilab plug is definitely plugged in. If there are still issues you may need to restart the program, and sometimes even a full PC reboot is required to flush the system.

With the inital setup complete, the stage controller can be accessed on the "Stage Controller" tab with its small window shown in Figure 11. The step factor "2" in the previous stage means that the numbers in this tab are in micrometres. In the 'Positioning Control' section, a step size can be set (around 250 μm is a good start) and then the arrow buttons can be used to move by this amount in each direction. Alternatively, the exact desired position can be typed. If a good alignment is found, the “Reset” section allows you to set the current stage positions as the zero point (the stage does not move during this), so you can set an alternate home point.

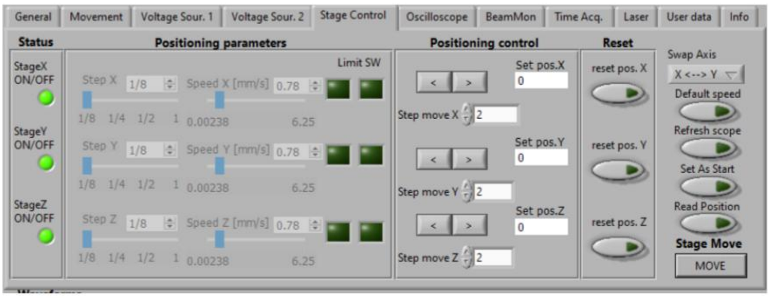


Figure 11: This is a snippet of the window which changes when the “Stage Control” tab is selected. From here, the stage controller can be moved step by step or to a desired position, all defined in micrometres.

It is advised that the “z” axis is rarely, if ever, used. This will effect the focus of the beam which is something that needs to stay constant between measurements if they are to remain comparable. Similarly, the aperture at the bottom of the optics in Figure 7 is very hard to quantify and control. Neither of these should be changed unless absolutely necessary.

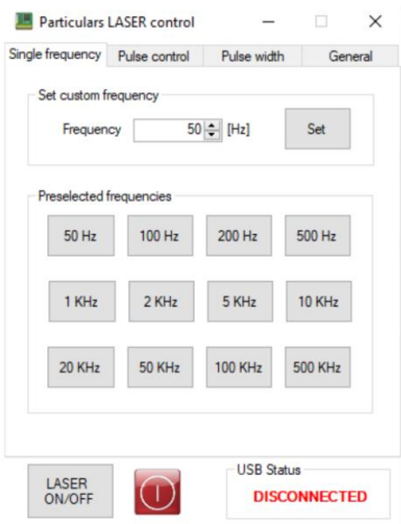


Figure 12: The laser control program. Specially the screen where the pulse frequency can be selected

With the LabView up and running, the next program to open is the "Particulars LASER control" which is also found on the taskbar and looks like Figure 12. In order for this program to have an effect, the front hatch of the TCT box needs to be closed so that the interlock is activated (for safety purposes). If the "USB Status" is not connected, then you may need to turn the laser power supply off and on again. At this stage, the small box in the middle of the window should be green which indicates that the laser is firing. The button to the left can stop this.

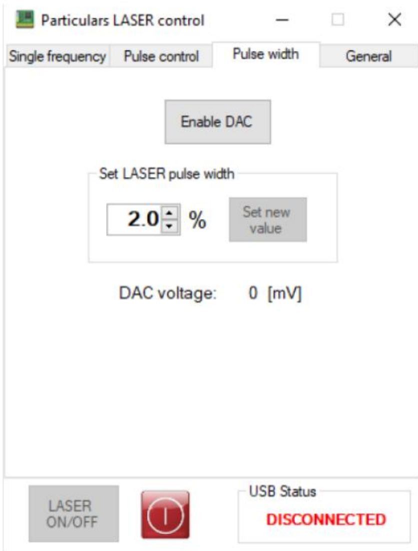


Figure 13: The pluse width tab where the power of the laser can be set

Clicking on the "Pulse width" tab allows you to control the laser power, as shown in Figure 13. Only if the USB is connected can you then click "Enable DAC", which is the way the laser power is modulated. The laser pulse width can then be set as a percentage and the button "Set new value" needs to be clicked to actually change the laser power. The exact DAC (Digital-Analogue-Converter) voltage is given on this tab. Note that when you switch to this tab, the laser automatically switches off. Bear in mind that a lower pulse width percentage results in a higher intensity. Typically you won't see a signal below 50% power and the highest you should go is 10%

Switching back to the "Single Frequency" tab, shown in Figure 12, a custom frequency (or preset one) can be easily chosen. Usually 50 Hz is sufficient. Note that this is a pulsed laser so the frequency is of the pulsing not the laser light (which for the IR laser is $1064nm$).

It's also very important to remember that every time the interlock is broken (when the TCT box is opened) the laser defaults back to the original frequency and intensity. You do not need to re-enable the DAC, just set the new value and then select the frequency.

The final thing to setup is the python scripts which will operate the various power supplies and oscilloscope. Running the scripts is done with a program called "git bash" which is basically a mini Linux environment. The easiest way to do this is to right click the folder containing the python scripts you wish to run, and selecting the option "Git Bash Here". Once in git bash you then run a command with an argument such as,

```
python test.py jmIV
```

"test.py" is the main file which contains all the test functions needed. "jmIV" is an example argument, which in this case will perform an IV sweep. The next sections provide more details on the commands you can run.

The path for the python scripts is the following:

```
C:\Users\bilpa_login\Desktop\LGAD_Project\Python_Scripting\jmProbeStationCode
```

At this point everything should be up and running and ready for a measurement.

1.3.2 Manual Laser Alignment

The next job is to align the laser with the device you want to test. There are two ways to approach this. The first is the manual method using the LabView described in the previous section. By unscrewing the fibre optic cable ontop of the optics in Figure 7, a red laser pen can be held in its place providing a red laser spot on the device below. Using the LabView program to move the stage, the device can be moved until the laser spot is over the opening in the sensor. With a bit of practice, this can become a very convenient and fast way to roughly align the laser to a point where you should be able to see a signal from the device.

1.3.3 Automatic Laser Alignment - Spiral Search

```
python test.py jmLaserAlignment
```

The second method involves calling the "test.py" script with the argument "jmLaserAlignment". The algorithm is split into two steps. Both steps make the assumption that the device is biased to a sufficient voltage such that a sufficiently strong signal can be detected. The first step is the spiral search. The stage moves in a spiral pattern defined by,

$$r = a\theta, \tag{10}$$

where r and θ are the 2D polar coordinates relative to the origin, and a is a constant to be defined. The stage moves in discrete steps with the minimum distance between steps defined by the user. For LGADs with a size of 1 mm and an opening even smaller, a minimum travel distance, d_{min}, is defined as 500 μm. This can be used to define the constant, a, where the distance between each full revolution needs to be d_{min}. In other words,

$$d_{min} = a \times 360. \tag{11}$$

where our coordinate system is using degrees rather than radians, although either works. The next step in the spiral is found by incrementally increasing θ by $0.1°$ until the distance between the new step and the last step is larger or equal to d_{min}.

Not that due to these two restraints, an intermediate step is required between the origin and the start of the spiral, which by definition must start d_{min} away from the origin. This step is a circle with a radius of half d_{min} in $30°$ steps. This should cover a device which is on the limit of detection.

During each step of the search, the oscilloscope is triggered and a waveform is saved to the PC. The algorithm then searches the waveform for the minimum voltage and compares it to a threshold, V_{th}. This is typically around -75 mV which is above the noise level, although it can be easily adjusted by the user. The threshold could be set lower, however for Te2v PiNs, there are openings in the metal outside of the gain layer region which can produce a noticeable signal which can trigger a smaller threshold.

Each time a waveform is taken, the maximum voltage is also checked to make sure it does not go above 40 mV. If it does then there was likely some reflections in the waveform which will effect the signal and so another waveform is taken. Once the threshold voltage has been met, the origin is set to the current position and the first step of the algorithm is complete. The second step then immediately starts.

This step can be skipped if the laser is manually aligned since a waveform is taken before the stage moves. It is the users choice which they prefer. The automatic spiral search can be useful in the case that the device is knocked out of alignment ever so slightly while the electronics (such as the SMA cables) are being changed.

1.3.4 Automatic Laser Alignment - 4x1D Scans

This second step of the automatic alignment is the most important since it ensures that the laser is aligned to the centre of the device. The algorithm performs four 1D scans (4x1D), two in each axis. For each scan, the stage starts at the origin and then moves forward in 25 μm steps. At each step a waveform is saved and the minimum voltage is recorded. The algorithm also checks for reflections and retakes the waveform if necessary, just like during the spiral search. Once the minimum voltage goes below V_{th}, five additional steps are completed to provide a baseline. The stage then returns to the origin and starts moving in the opposite direction.

From this 1D scan, the (negative) peak height can be plotted against the position of the stage. The algorithm then runs through the scan and finds when the peak heights cross 75% of the maximum peak height. Figure **??** shows one of these scans in the "X" direction. Finding the midpoint of the intersection gives us the centre of the device in this axis. The stage moves to this midpoint and sets it as the origin.

The algorithm then performs a scan in the other axis. Once both axes have been scanned once, the algorithm performs a second scan in each axis (resulting in a total of four 1D scans). This second scan is a sanity check to ensure the true centre is found. The midpoint shouldn't be more than a few microns from the current home position, as shown in Figure **??**. This mainly catches the case where the initial alignment was very close to the edge and therefore the initial scan does not have many steps to work with and thus is inaccurate in it's determination of the device's centre point in that axis.

Once all four scans have been completed, each scan is saved as plot in the folder:

```
C:\Users\bilpa_login\Desktop\LGAD_Project\Oscilloscope_Data\Alignment_Data
```

Some scripts will also copy this data to ensure that the latest alignment scan is kept with an associated test.

1.3.5 Beam Monitoring

Currently there are two main commands that can be used for TCT tests. The first command, "jmBeamMonitor_Fixed", is designed to be a long-time monitor of the system called in the usual way:

```
python test.py jmBeamMonitor_Fixed
```

The command runs for a fixed length of time, defined in code by the user. This can be anywhere from 15 minutes to 3 days. The command assumes that a laser is firing and either a biased sensor is connected, a beam monitor is in use, or both. Every 5 seconds the oscilloscope will be triggered and a waveform will be saved and analysed. The peak height and integral of both the device signal and the beam monitor signal are extracted and stored against the time relative to the start of the test. Once the desired overall time has elapsed, plots and data files for each metric (peak height and integral for the device (just called signal) and beam monitor) versus time are saved to the following path:

```
C:\Users\bilpa_login\Desktop\LGAD_Project\Oscilloscope_Data\Beam_Monitoring_Data
```

These tests are really good for checking that the charge injection from the laser remains constant over a long period of time. This is shown in Figure ?? where the beam monitor peak height is very consistent over an 84 hour period. Looking closer at the same plot in Figure ?? however, it is clear that there is some brief, 5 or 10 minute, turn on time needed for the laser to stabilise.

This is something that requires a little more investigation to understand fully and set a plan to deal with. For the time being. It is recommended that this command is run for brief period to check that the laser is stable before performing a proper measurement.

1.3.6 Bias Sweep

The ultimate goal of this setup is to measure the response of a device to an injection of charge by a laser. In the case of an LGAD this can lead to calculating its gain, which is important when comparing to the time resolution at the same voltage. The second of the two main commands for the TCT setup is "jmLCIsweep" again called like:

```
python test.py jmLCIsweep
```

The command performs a bias voltage sweep while recording waveforms. The precise steps of the sweep are easily adjustable by the user, but the user should first perform a manual sweep to check which voltage is suitable to test up until. As a rule of thumb, the signal on the oscilloscope should not exceed $\sim 1\ V$ (although it can often be pushed higher, but due care and attention should be paid in these cases). The most significant sign that too much current is being sent to the amplifier is that the signal becomes significantly deformed and erratic. In this case the bias should be immediately reduced and should not exceed the voltage in which this happens form this point forwards.

At each voltage step, the command triggers the oscilloscope and saves a waveform. It repeats this a pre-defined number of times so that an average can be taken. Each repeat at each voltage is saved with a file name in the format "xxxV-Ryyy.csv", where "xxx" is the bias voltage and "yyy" is the repeat number. Typically 10 repeats is sufficient. This particular command does not check for reflections in the signal, so this must be done in post analysis (although this feature could be easily implemented in the future). However, the command does copy the latest set of alignment data to the same folder found in:

```
C:\Users\bilpa_login\Desktop\LGAD_Project\Oscilloscope_Data\Gain_Sweep_Data
```

Afterwards the analysis discussed in Section 1.1.1 can be used on the data taken by this command.

1.4 Troubleshooting

This section is designed to be a collection of common issues and problems faced when using the TCT setup and how to approach solving them. This section will be continuously updated as these issues arise and are subsequently resolved.

Sometimes the signal out of the amplifier is experiencing constant and significant reflections well in excess of 40 mV in amplitude. One solution is to make sure that all SMA connections are tightened. Some of them, especially the "RF + DC" connector of the Bias-T can come loose under tension. Other times loosening a connector fully and then re-tightening it can help too. You will want to play around with the setup a little bit until these reflections settle. The cable lengths have been optimised as best as reasonably possible, but sometimes they need a little nudge.

The automatic spiral search algorithm is not perfect. It is a balance between choosing a d_{min} which covers every possible location and one which does not take a ridiculous 3 hours to complete. If it is struggling to find the device, or it is taking a long time to do so, it is often easier to perform a manual alignment with the LabView program and red laser pen. This can then be followed up with the same alignment command for the more detailed 4x1D alignment scan.

2 Strontium-90 Coincidence Timing Technique

2.1 Theory & Analysis

While a laser produces a very nice consistent and controlled injection of charge, this is not what a real detector will experience in an experiment such as ATLAS or CMS. These conditions can be well simulated with a Strontium-90 (Sr-90) source. Sr-90 beta decays with an energy of 0.55 MeV into Yttrium-90 which then further beta decays with an energy of 2.28 MeV. The latter decay is crucial, since electrons with an energy above $\sim$ 1 MeV are called Minimum Ionising Particles (MIPs).

MIPs are important because their mean energy loss rate through a medium is close to the minimum. Electrons also better simulate the conditions an LGAD will actually face in a beam line compared to a laser since the energy they deposit follows a landau distribution. A laser does not create these landau fluctuations which influence the timing resolution. Lasers also exhibit a rise time where the intensity takes some time to reach an equilibrium. This can add an additional jitter which is not present when using electrons.

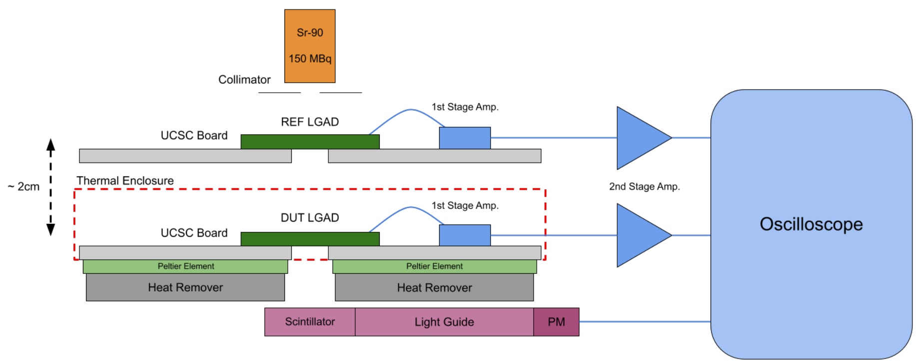


Figure 14: The arrangement used to extract the timing resolution of LGADs. Two SCTB are placed in line with a Sr-90 source such that two LGADs can detect the same electron. The setup includes a cooling mechanism which can be used for testing irradiated structures.

Using Sr-90 as the source of MIPs, the timing resolution of a detector can be measured using the setup shown in Figure 14. Two SCTBs are placed on-top of each other. A device is wire-bonded to each board and carefully aligned with a small hole in the PCB's pad which must align with the hole in the other board. The two LGADs are then biased alongside the on-board amplifiers and the signal is fed into two external second-stage amplifiers. The outputs are then connected to an oscilloscope which records the pulses once an electron strikes one of the sensors. The LGAD on-top will see many more events than the LGAD below, since the 0.55 MeV electrons will interact with the first LGAD but then be absorbed before reaching the second LGAD. Triggering is therefore performed with the second LGAD to reduce unnecessary data collection.

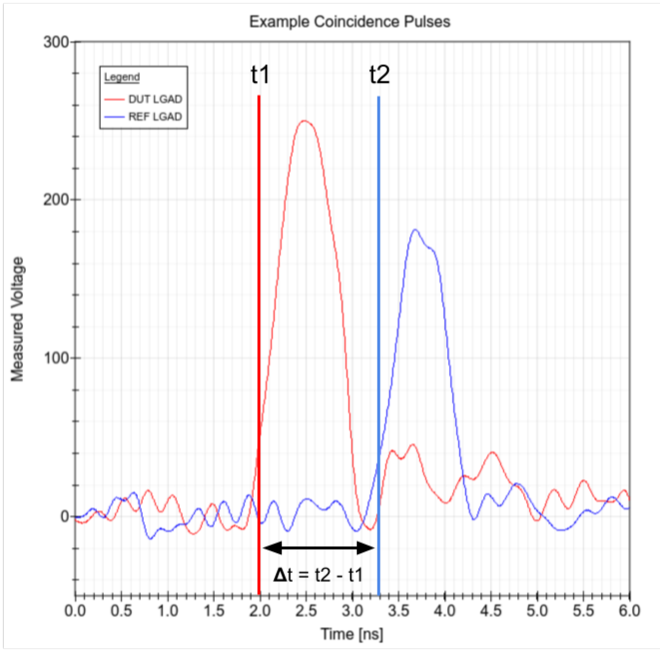


Figure 15: The signal response from two LGADs detecting the same electron. Using a constant fraction discriminator, a time can be assigned to each pulse and the time difference can be calculated.

Not all collected events, those which cause a trigger on the second LGAD, are of interest. The timing resolution comes from the jitter of the response pulse measured on the oscilloscope. To measure this, two pulses are required so that the timing difference between then, and then the standard deviation of that difference, can be calculated. Not all collected events exhibit this 'coincidence' since the electrons path must perfectly intersect both devices. Hence, offline discrimination is needed to check that pulses exist for both LGADs.

Once a coincidence has been found, the time difference between them can be measured. This is done using a Constant Fraction Discriminator (CFD), usually around 20 %. The time of each pulse is then defined as the point at which the signal reaches 20 % of the peak's height. Figure 15 shows the result of a coincidence event between two LGADs in the timing setup. Both LGADs are biased at 200 V and the two signals are separated by ~ 1.6 ns. The shape of each pulse is not particularly consistent and varies depending on the energy of the incoming electron. The raw time interval itself is not very useful since there are various factors which cause a large impact. For example, an extra half of a metre of BNC cable for one LGAD will cause ~ 6 ns delay. Even the travel time of the electron between the boards at nearly the speed of light will cause ~ 100 ps delay. This delay is not that important, but instead how accurately one can determine the time of arrival is actually what the timing resolution means. So instead a histogram can be plotted of the time intervals. A Gaussian can then be fitted to this histogram from which a standard deviation is extracted. Although in the right range, the standard deviation is a combination of the time resolution of the two LGADs under test such that,

$$\sigma^2_{MEAS} = \sigma^2_{DUT} + \sigma^2_{REF}, \tag{12}$$

where σ_{MEAS} is the standard deviation from the fitted Gaussian, σ_{REF} is the time resolution of the reference (REF) LGAD placed on-top and σ_{DUT} is the timing resolution of the device under test (DUT) placed below. If the two LGADs are to the same specification, then their timing resolution can be assumed to be the same and hence equation 12 simplifies to,

$$\sigma_{DUT} = \frac{\sigma_{MEAS}}{\sqrt{2}}. \tag{13}$$

However, this assumption of identical timing resolution is not necessarily reliable. Either way, this assumption can be removed by measuring three devices in three different pairings. Consider three different devices of different flavours, $FA2$, $FB1$ and $FC2$, with timing resolutions σ_A, σ_B and σ_C respectfully. Using Equation 12, we can define the total standard deviation of the three pairings as,

$$\sigma_1^2 = \sigma_A^2 + \sigma_B^2, \tag{14}$$

$$\sigma_2^2 = \sigma_C^2 + \sigma_B^2, \tag{15}$$

$$\sigma_3^2 = \sigma_A^2 + \sigma_C^2, \tag{16}$$

The linear combination of these pairing can then be used to extract the timing resolution of just one device. For example,

$$\sigma_1^2 + \sigma_2^2 - \sigma_3^2 = 2\sigma_B^2. \tag{17}$$

Cycling through which pairing is subtracted will then yield σ_A and σ_C. This process has been completed for the three flavours discussed earlier and $FB1$ was selected to be a reference device going forward. This means that to measure a new device, Equation 12 can be used directly where now,

$$\sigma_{REF} = \sigma_{FB1} = (45.92)\ ps, \tag{18}$$

which was measured at a 160 V bias.
(To be updated with an accurate error shortly)

2.2 Setup

The following section includes a series of images and diagrams detailing the Strontium-90 Coincidence Timing Technique (CTT) setup.

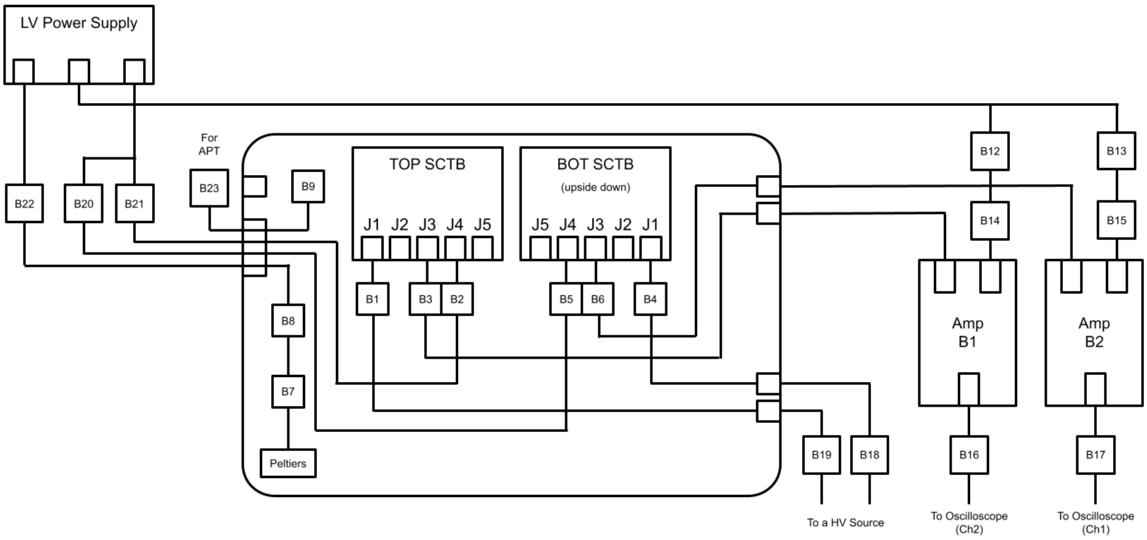


Figure 16: Schematic diagram showing all of the electrical connections. The labels for each cable matches their real life counterparts. In most cases there is a bulkhead feeding a cable from outside to inside of the box. The cables for an APD are present although the APD is not typically used. The high voltage (HV) source is usually a Keithley 2410 although any HV source is applicable. Usually a separate HV source is required for each Santa Cruz Timing Board (SCTB) since the bias voltage of the two devices will be different.

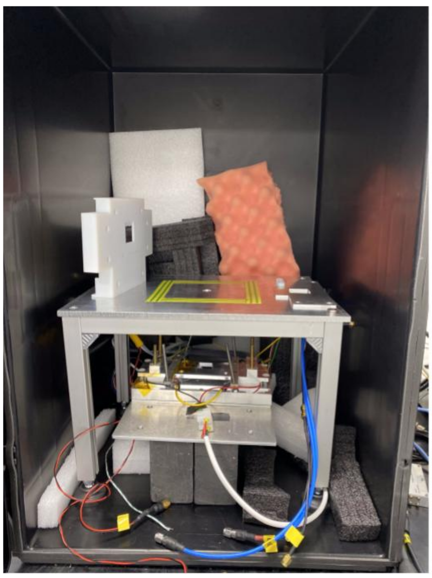


Figure 17: The inside of the CTT setup, fully disassembled. Two lead blocks support and shield the underside of the metal block which contains the peltiers and pipework used for cooling. The foam in the background is used to help reduce the volume of air that needs to be dried by the nitrogen. The entire setup is encapsulated in a black box which keeps the setup light-tight, somewhat air-tight and keeps the radioactive source secure when unattended.

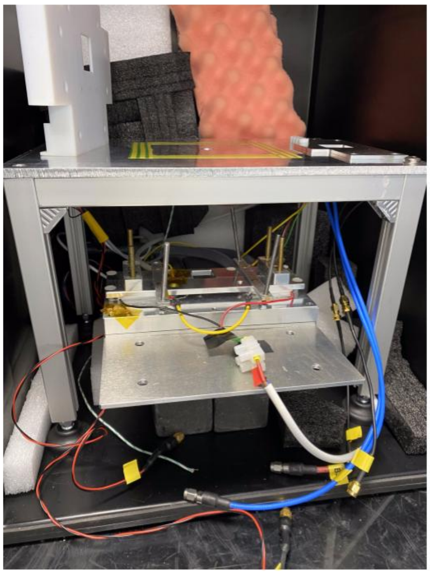


Figure 18: Assembly Stage 0: A closer look at the disassembled setup. Note the three steel threaded bars and the four brass threaded bars used for alignment and to hold the SCTBs together. The cables around the front are labelled and match the schematic diagram at the beginning of this section.

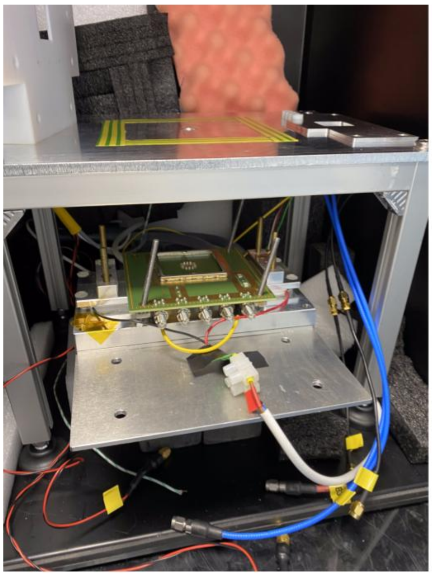


Figure 19: Assembly Stage 1: The bottom SCTB board is placed upside down through the three steel threaded bars. The board is upside down so that it fits flatter with the remaining pieces and also for alignment purposes due to the way a hole in the pad was drilled.

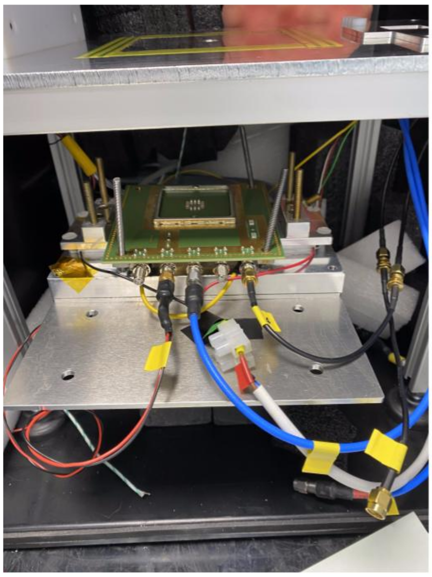


Figure 20: Assembly Stage 2: Connecting up the three cables as per the schematic diagram. The schematic diagram already takes into account the fact that the board is upside down, but the board has labels on the topside for each SMA, so one should convince oneself that the wiring is correct before biasing.

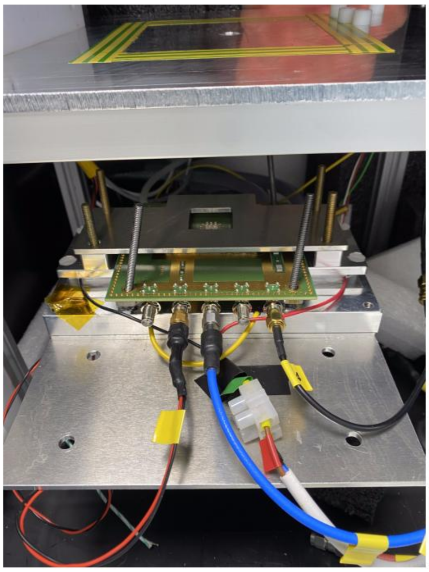


Figure 21: Assembly Stage 3: Placing a metal plate through the four brass threaded bars. This metal place sits on the metal of the SCTB and creates a good thermal contact between the SCTB and the thermal block below. The plate contains an opening for particles to travel between the two boards.

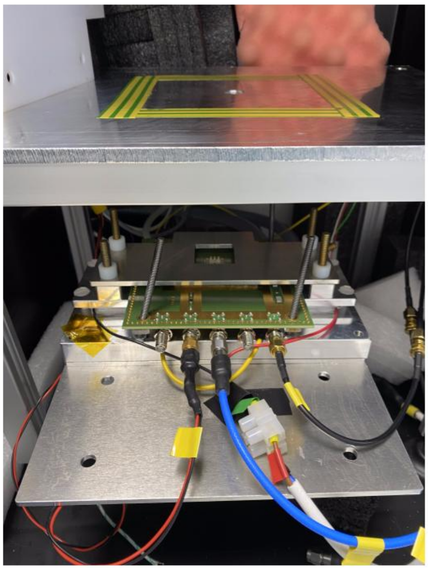


Figure 22: Assembly Stage 4: Four plastic spacers are placed on the four brass threaded bars ready to support the next stage of assembly whilst also creating an insulating barrier between the metal plate and the top SCTB

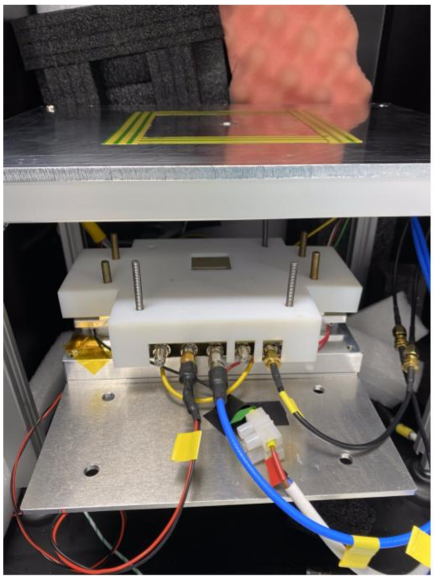


Figure 23: Assembly Stage 5: A large plastic piece is place over all seven threaded bars to create an insulating barrier between the top and bottom of the setup, while also creating a flat surface for the top SCTB

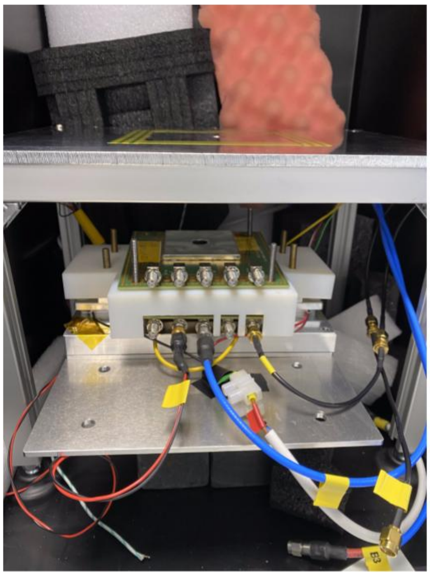


Figure 24: Assembly Stage 6: The final SCTB is placed on-top of the large plastic piece. Note the metal plate with a small opening that push-fits onto the top. This helps to protect the sensor somewhat. A piece of metal foil can also be placed over the hole to absorb low energy electrons which are undesirable. That has been omitted from all tests so far however.

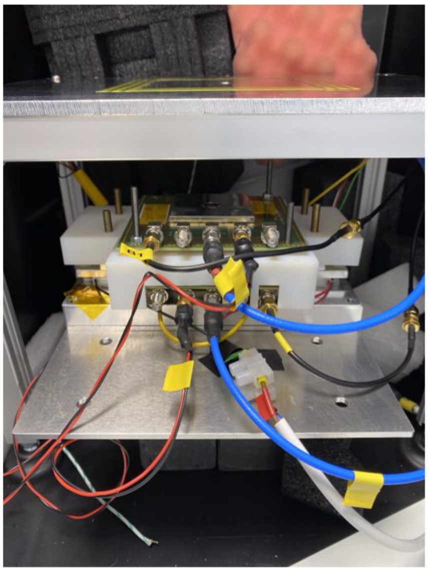


Figure 25: Assembly Stage 7: Two nuts are placed on the front left and rear right steel threaded bars to hold the top SCTB in place. Note that it is important to keep the SCTB flat and not to bend the board by over-tightening the nuts. The relevant cabling is also attached as per the schematic diagram.

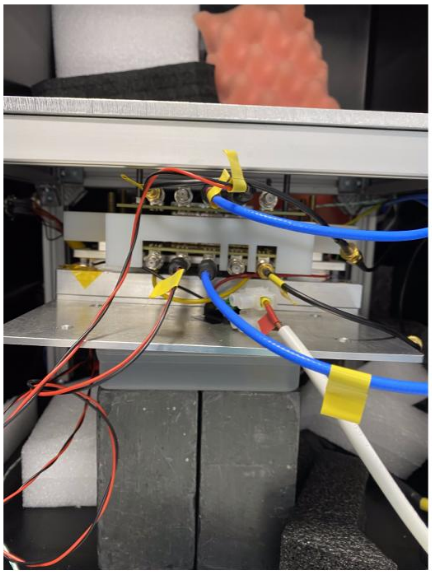


Figure 26: Assembly Stage 8: In order to reduce the distance to the source and therefore maximise the count rate, the entire setup is raised using a small plastic box. This has to be done last since access to the three steel threaded bars is limited once raised.

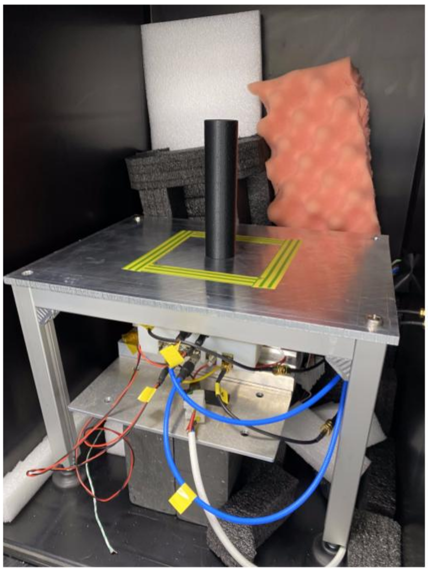


Figure 27: The setup now needs to be aligned with the hole in the support stand. This should firstly be done manually by looking over the hole and moving the setup until the sensor can be seen. A finer alignment can then be used with the alignment tool. This black piece of plastic slides into the hole in the support stand. It has a small hole running through its center which effectively acts as a visible light collimator. This allows the user to much more easily check that the device of interest is directly under the center of the hole in the support stand. You will probably need to use your phone's flash light to illuminate the sensor while using the alignment tool.

Figure 28: The Strontium-90 (Sr-90) source can now be placed onto the support stand. The yellow and green tape is there for alignment of the source. The source block's lip (surrounded in red tape) can then be pulled out slightly. The source block is now "live", emitting electrons below unhindered.

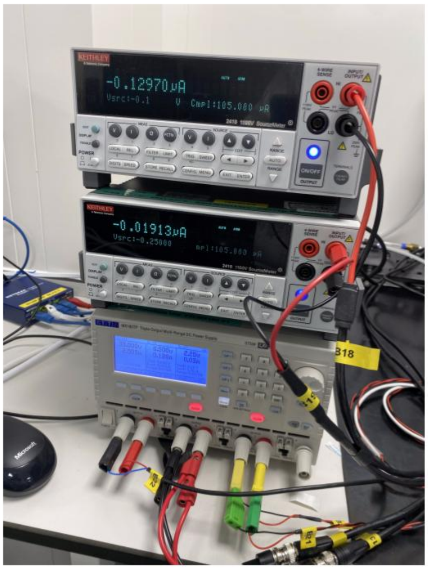


Figure 29: The power source stack which powers everything in the CTT setup. The two Keithley 2410s on the top can be used to separately bias each SCTB. They can also be connected from the back via an RS232 cable in order to control the bias voltage for a sweep.

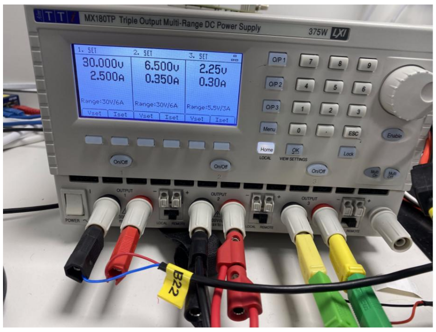


Figure 30: A close up of the low voltage (LV) power supply. There are three separate outputs. The far-left output is for the peltiers. A current of 2.5 A should sufficiently cool the bottom SCTB to $-20°C$. The middle output powers the second stage amplifiers. They require between 6.5 V and 10 V bias and draw between 100 mA and 200 mA depending on the bias voltage. The far-right output powers the first stage amplifiers which are found on the SCTB. They both require 2.25 V for bias.

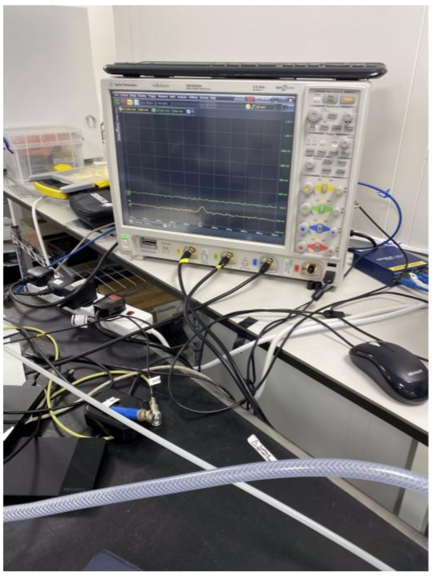


Figure 31: The oscilloscope which is used to measure the output from both SCTBs. It is shared with the TCT setup and so the BNC cables will need to be swapped between the two setups.

2.3 Procedure

This section will guide a user through all the steps needed to perform a simple voltage sweep on a target device. There is no assumption that you have read about the TCT operation in Section 1.3.1

2.3.1 Initial Setup

Just like the TCT setup, the first job when working with the CTT setup attach your device under test (DUT) to a SCTB and make three wire-bonds. As per Figure **??**, the first wire-bond needs to go from the pad of the DUT to the second golden trace. This trace has been soldered to the input pad of the first stage amplifier. This wire-bond is equivalent to the wire-bond needed for the TCT PCB. The second wire-bond connects the guard ring of the DUT to the first golden trace. The third wire-bond then connects the first golden trace to the outside ground ring on the SCTB. Additional grounding wire-bonds can be made to the first golden trace as necessary for your device.

Ensure that you refer to the diagram and photos in Section1.2 and ensure that all necessary connections are in place and working order. Even if everything looks in place already, it is recommended to re-tighten some of the SMA connections as a slightly loose connections can sometimes cause reflections or spikes in the RF signal.

Now, all of the external equipment can be switched on. This includes the HV & LV stack to the left of the CTT box; the oscilloscope further left; and the PC to the left of the oscilloscope.

Although you are likely reading this on the PC to the left of the CTT box, the password for that PC is "tct2020". Once logged in, the only thing that needs to be opened is "git bash" in order to run the Python scripts which will operate the various power supplies and oscilloscope. The easiest way to do this is to right click the folder containing the python scripts you wish to run, and selecting the option "Git Bash Here". Once in git bash you then run a command with an argument such as,

```
python test.py jmIV
```

"test.py" is the main file which contains all the test functions needed. "jmIV" is an example argument, which in this case will perform an IV sweep. The next sections provide more details on the commands you can run.

The path for the python scripts is the following:

```
C:\Users\bilpa_login\Desktop\LGAD_Project\Python_Scripting\jmProbeStationCode
```

At this point everything should be up and running and ready for a measurement.

2.3.2 Manual Measurements

With all the equipment setup, the first thing to do is to perform a manual check to see if there are any counts to be seen. The LV power supply should have the outputs turned on for both the first and second stage amplifiers. The oscilloscope should be set to trigger on Channel 2, which should be connected to the top SCTB which will receive a significantly higher fluence of electrons than the bottom SCTB. A trigger level of 50 mV should be sufficient initially, although this may need to be increased the closer to breakdown the device is biased. The bias from the HV supply can then slowly be increased. It is important to watch the oscilloscope for triggers and to check that the pulses are not too distorted. Remember to keep an eye on the leakage current and ensure that the device does not go into breakdown. Generally be very cautious when approaching breakdown in general. Hopefully as breakdown is approached, a significantly higher trigger rate is noticeable. Note that if the top device is the reference LGAD, "FB1" from Te2v, it should be biased upto 160 V for reference measurements (and so it should clearly be triggering at this voltage).

At this point, the trigger source can be changed to channel 1 (the bottom SCTB). The bias voltage for this device can now be slowly increased until counts can be seen. The device can then be biased towards breakdown. It is useful during these manual tests to see the maximum voltage the DUT can be biased too safely as this will inform you later when deciding on what voltages to sweep.

2.3.3 Efficiency & Rate Testing

With the setup built and both devices biased and detecting, a short efficiency test can be performed by running the standard python script with the following argument:

```
python test.py jmTimingEfficiency
```

This script runs for a short time, usually around 5 to 15 minutes, and runs a standard timing measurement collecting trigger events on channel 1, the bottom SCTB. The script sets the oscilloscope to trigger and then saves the waveform to the PC when a trigger has occurred. At this moment, the file is opened and analysed. All this brief analysis does is to check the peak height of both SCTB signals and check if they are above a threshold usually set to $40mV$. If both SCTB signals are above the threshold, then this is a coincidence event (or count). The number of counts and triggers are recorded until the measurement is complete. Once completed, a short file called "Summary.txt" is created which includes this data as well as some additional parameters. The file is stored at:

```
C:\Users\bilpa_login\Desktop\LGAD_Project\Oscilloscope_Data\Timing_Efficiency_Tests
```

In this files, the raw data presented includes the run time, the number of triggers and the number of counts (coincidence events), t, N_t and N_c respectively. From this, four additional values can be generated. The first is the trigger rate which is simply defined as,

$$\nu_t = \frac{N_t}{t}, \tag{19}$$

which is often expressed as triggers per minute. One would expect, from observation, that ν_t will slowly rise as the bias voltage is increased but sharply rise as breakdown is approached. Similarly, the count rate can be defined as,

$$\nu_c = \frac{N_c}{t}. \tag{20}$$

Any value between 4 and 10 counts per minute is usually observed. Anything lower than this can be problematic. It should be noted that a higher bias voltage does not always result in a higher ν_c. The trigger rate, ν_t, certainly increases and this can include additional lower energy electrons which would not normally be detected. This means that ν_c cannot necessarily increase in the same way. At the same time, a drop in ν_c is observed due to an increase in dead time from the additional trigger events. Each time the oscilloscope triggers, it must take time to record the waveform and save it onto disk. This takes time, and usually around 0.5 s to 1.5 s. With more trigger events, there is also more dead time which means more of the coincidence events can be missed and hence a drop in ν_c is seen at bias voltages extremely close to breakdown.

One solution to this problem is a change to the Python script. At the time of writing, the script will wait a set amount of time between each command. Any attempt to reduce this time will result in errors from the oscilloscope and the program will crash. An alternate method would be to try to ask the oscilloscope when it is ready for a new command. That way we can reduce the dead time in certain events but allow the program to run as long as it needs for others. This needs investigation to prove this is actually possible to implement of course. The second solution would be to use a more advance oscilloscope which can trigger on both channels. There would still be an inefficiency from dead time, but 100% of triggers would be counts in this case, and so ν_c would be reaching a near maximum.

The third property is the efficiency which is defined as,

$$\eta = \frac{N_c}{N_t} \times 100\%. \tag{21}$$

This tells you how many coincidence are found as a proportion of the total triggers which is useful in telling whether your setup is properly aligned or not. An efficiency between 10% and 15% is usually expected. Just as N_c drops as N_t rises close to breakdown, so therefore will η drop.

The fourth and final property is the time it would take to achieve 2000 counts. This is defined as,

$$t_{2000} = \frac{2000}{\nu_c}. \tag{22}$$

This is useful because these measurements require very good statistics to produce a suitable Gaussian. Somewhere between 1000 and 2000 counts are ideal without taking too much time. Typically the value of t_{2000} can vary between 4 hours to upwards of 10 hours for low gain and poor alignment.

2.3.4 Automated Measurements

With all the equipment setup and the efficiency now checked. Full measurements looking to acquire in the range of 2000 counts can begin. All that is needed to perform this is the following command:

```
python test.py Sr90HitCollection
```

This command performs very similarly to the “jmTimingEfficiency” command in the previous section. The oscilloscope will await a trigger. Once triggered, the waveform will be saved and afterwards the oscilloscope will be reset and await to be triggered once more. This process continues indefinitely until the user interrupts the bash terminal with a “ctrl+c” press.

This particular command is very useful when just one voltage needs to be tested with as many counts as reasonably possible, for example at the highest possible bias voltage where the efficiency is reduced anyway. The location in which the data is saved can be defined in code by the user. This is particularly important for this command since a large amount of data is saved, upwards of 20 GB on occasions. For this reason, it is advised to connect an external hard disk to the oscilloscope and tell the command to save to that disk. That way the disk and be removed for analysis whilst a second disk replaces it for another measurement to be immediately started.

For a more controlled operation, the following command can be used instead:

```
python test.py Sr90HitCollection_Fixed
```

This command is very similar to the previous command besides two key differences. The first is that the command will stop itself after a set amount of time, which is set in the code and available to change by a user. The amount of time should be informed by the previous efficiency tests to ensure that a sufficient number of counts are captured. The second new feature is the ability to ramp the bias voltage through an RS232 cable. Just like with the TCT setup and scripts, an array of bias voltages can be defined. Once the required time as elapsed, the sensor is biased to the next voltage in the array and a new measurement begins. It is again advised to save the data directly to an external hard drive. The script will handle the additional folders needed for each voltage.

2.4 Troubleshooting

This section is designed to be a collection of common issues and problems faced when using the CTT setup and how to approach solving them. This section will be continuously updated as these issues arise and are subsequently resolved.

Similarly to the TCT setup, the output from the amplifiers can sometimes be sporadic with intense reflections. This is observed more often in this setup with slightly different amplifiers. Usually the SMA connections just require a little bit of tightening. This is especially true for the blue SMA cables which make the crucial connection from the output of the first stage amplifier to the input of the second stage amplifier. Usually a bit of fiddling about can resolve the issue. In this case it can also be easier to switch the oscilloscope's trigger mode to "Auto" which doesn't require a pulse from an electron to trigger it.