Fast Spectroscopic Measurement of Electric Breakdown in a High Pressure Hydrogen Gas Filled RF Test Cell for a Muon Collider

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Abstract

We developed a fast spectrometer system to study the gas plasma dynamics created by RF electric breakdown in a high pressure hydrogen gas filled RF test cell. The plasma temperature and density can be estimated by measuring the spectrum of breakdown light. It took four hours to complete one spectroscopic measurement in the old system. By using a fast pulse counter controlled by a LabView VI, the acquisition time becomes six times shorter, e.g. 40 minutes swept 250 - 750 nm with 1 nm resolution. We found that the spectrometer system was not sensitive in the longer wavelength region from 500 - 800 nm. This can be improved by using a new photomultiplier tube that is more sensitive to longer wavelengths of light.

1 Introduction

1.1 HPRF Background

The idea behind an HPRF (high pressure hydrogen gas filled RF) cavity is to cool the phase space of a muon beam via energy loss from beam-induced hydrogen ionization in the cavity. When the muon beam is created it has a high transverse momentum (perpendicular to the direction of the beamline of an accelerator). This transverse momentum must be reduced to match the acceptance of an accelerator. This can be done by filling the RF cavity with high-pressure hydrogen gas. However, beam-induced ionization of the hydrogen in the cavity reduces the longitudinal momentum (in the direction of the beam-lines) as well as the transverse momentum of the beam. This is a factor working against the efficiency of the HPRF as the purpose of a particle accelerator is to increase the longitudinal momentum of the particles. Hydrogen gas also serves to prevent electric breakdown in the RF cavity. The cavity operates under a strong

magnetic field that is needed to keep a muon beam in the beam line. Electric breakdown occurs when the potential across the RF test cell is too high and electrons arc across the test cell. This electron streamer is confined by the magnetic field. This results in higher breakdown probability at stronger magnetic field. The hydrogen gas serves as a buffer gas to the electron streamer which increases the breakdown potential of the cavity.

We tested the concept of an HPRF cavity using an HPRF test cell, Figure 2. Unlike a true copper RF cavity, our test cell consists of two copper electrodes across which electric breakdown occurs at local volume. We tested the test cell by varying the RF power, varying the pressure of the hydrogen gas (1-100 atm), adding a dopant gas, and adding a strong magnetic field. The light from electric breakdown contains information useful in understanding the plasma dynamics in the test cell. In past measurements the plasma temperature and density were determined from spectroscopic measurements of the breakdown light. Since the spectroscopic light is so dim, accumulation of the spectroscopic light signal takes a long time. It typically took four hours for an entire measurement in the old system. In order to speed up the spectrometer system, we used a fast pulse counter to record the number of single spectroscopic photons. LabView was coded to control the system. Consequently, the duration of data acquisition becomes six times shorter, around 40 minutes. We found that the spectrometer system was not sensitive in the wavelength region from 500 - 800 nm. We are considering ways to upgrade the system to improve the amount of breakdown light it receives and increase its sensitivity to this higher wavelength light.

1.2 RF Spectroscopy

Two optical pickups in our test cell allow us to collect the breakdown trigger and spectroscopic light signals from electric breakdown. There are two different spectroscopic light signals from the hydrogen gas in our RF test cell. Molecular hydrogen in the gas has many vibrational and rotational modes and emits a continuum spectrum. This emission from hydrogen molecules results in a blackbody radiation spectrum from the breakdown plasma. This allows us to calculate the plasma temperature by fitting a continuum spectrum using Plancks equation (Equation 1). Atomic hydrogen in the gas emits specific excitation lines during its de-excitation process known as Balmer lines. The discrete Balmer excitation lines are broadened via the Stark effect due to the high electric field in the dense breakdown plasma. Therefore, we can estimate the plasma density by measuring the change in the width of the Balmer resonance lines (Equation 2). We also expect to measure excitation lines from copper ionization, since the electrodes in the test cell across which breakdown occurs are made of copper.

In order to measure the intensity spectrum from 200 800 nm we use a Horiba Micro-HR spectrometer to select light from the breakdown. This allows us to measure light intensity at a particular wavelength due to breakdown.

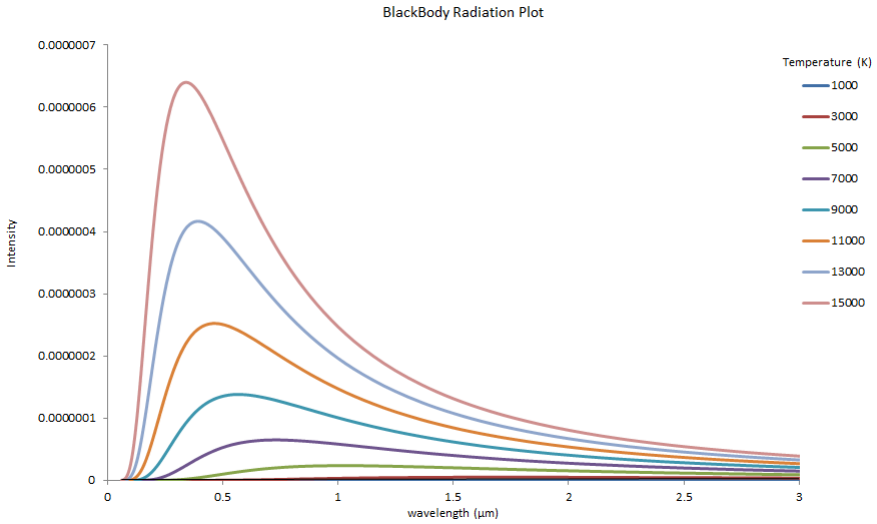


Figure 1: BlackBody Radiation Spectrum

$$B_\lambda(T) = \frac{2hc^2}{\lambda^5} \frac{1}{e^{\frac{he}{\lambda \kappa_B T}} - 1} \tag{1}$$

$$\Delta\lambda = 0.549(\frac{N_e}{10^{23}})^{0.68} \tag{2}$$

2 Experimental Setup

2.1 Data Acquisition Apparatus

The electric breakdown was induced in an HPRF test cell by applying higher RF voltage than the stable RF operation voltage. Once the breadown occured, the test cell was completely shorted. A great amount of RF power was released in a short amount of time. A single breakdown process took place in an RF cycle. An intense breakdown light was always observed at the breakdown event. Therefore, breakdown light is a good signal to distinguish whether RF breakdown occurs or not in an RF cycle. To collect light from electric breakdowns inside our HPRF test cell, we use two optical feedthroughs into the cavity. These feedthroughs are pressure sealed and allow optical fibers to extend approximately 1 mm into the cavity. One potential issue with these fibers is that they are off center from the area where electric breakdown occurs in the cavity, which is in the center of the test cell between the two copper electrodes, Figure 2. This could potentially reduce the amount of breakdown light received through the optical fibers.

Figure 3 shows a block diagram of two optical signals leaving our RF cavity. The signals travel a distance from the test area holding our RF test cell to our

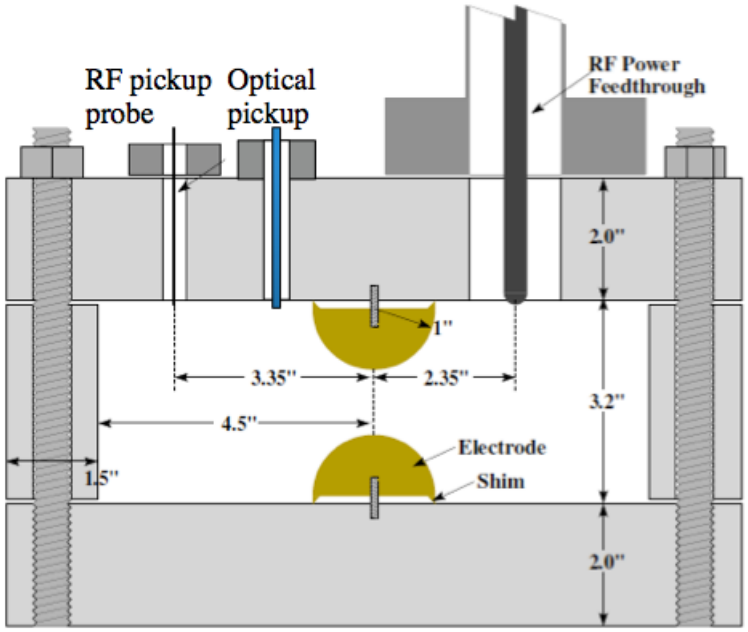


Figure 2: Cross-section of HPRF test cell [1]

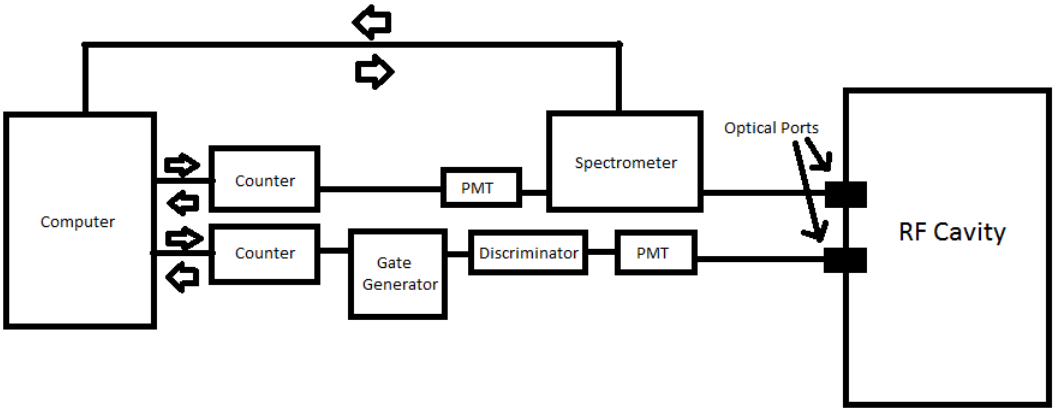


Figure 3: Experimental setup for spectroscopic measurement

data acquisition area. We refer to one of these signals as our "spectroscopic" light signal and the other signal as our "white" light signal. We measured the number of single spectroscopic photons by using a fast pulse counter. For the spectroscopic light signal, light from the optical fiber in the RF cavity travels to a spectrometer where it is wavelength selected, that is light of a certain wavelength is allowed to pass. This light then travels to a photomultiplier tube (PMT). The PMT amplifies light signals using the photoelectric effect and a cascade of electrons. It then transforms an incident photon into a detectable electric signal. The PMT is important to our setup because the spectroscopic light signal we get from the RF cavity is so weak. This light signal is made even weaker after it passes through the spectrometer because only a small wavelength band of the white light signal is selected by the spectrometer. This electrical signal then travels to an Agilent 53220A Universal Frequency Counter which counts the number of electrical pulses from photons hitting the PMT. The counter has a high counting rate and a threshold voltage level to avoid noise.

On the other hand, the white light was measured to count the number of breakdowns by using an NI-DAQ (Nation Instument Data Acquisition) evaluation board. The"white" light signal also travels to a PMT where it is amplified and transformed into an electrical signal. In contrast to the spectroscopic light, the white light is intense. The PMT output is an integrated photon signal in a breakdown process. In order to avoid double counting breakdown events, we used a logic circuit. First, The electrical signal from the PMT is sent to a discriminator. The purpose of this discriminator is to only pass signals that meet a certain voltage threshold. This is to avoid counting noise or signals that do not represent electric breakdown with our counter. Using a discriminator is necessary because the NI-DAQ counter does not have a voltage threshold. The electric signal is then sent to a gate generator. The purpose of the gate generator is to stretch the logic signal to the RF pulse length to avoid double counting of breakdown events. This is necessary because an electric breakdown produces a number of photons that reach the PMT at different times. Since we only wish to count the breakdown itself, the first photon that reaches the gate generator triggers an electric pulse that is a little longer than the time duration of the electric breakdown. This insures that the counter will only count the breakdown itself, because no photons will arrive to retrigger the gate after the breakdown is over.

The computer in our setup uses LabView to control the counters and spectrometer. The LabView program works by telling the spectrometer to select a certain wavelength. The counters are then triggered for a length of time during which they count the number of electric breakdowns that occur and the intensity of the light from the breakdowns. LabView then tells the spectrometer to move to the next wavelength and the spectrometer takes data there too. In this way the LabView VI steps over a range of wavelengths and takes light intensity data over the spectrum. The total number of spectroscopic photons is normalized by the number of breakdowns.

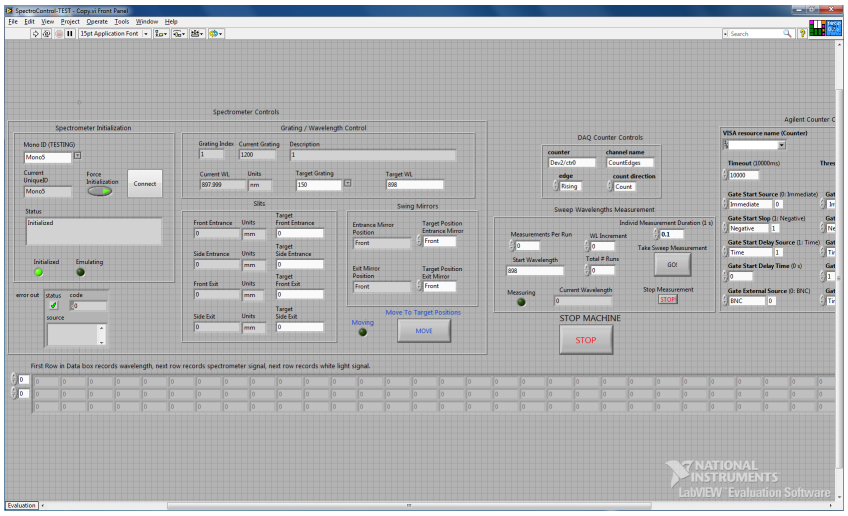


Figure 4: Picture of Labview VI for spectrometer and counters

2.2 LabView VIs for Counter and Spectrometers

A LabView VI existed from the manufacturer for the Agilent Counter, NI-DAQ counter and the Horiba spectrometer that we are use to take data. These VIs were then taken and incorporated into one interface shown in Figure 4. Refer to the LabView manual in Appendix D for instructions on running these VIs.

2.3 Calibration of Spectrometer

We used a reference light source to calibrate our spectrometer. We wanted to make sure that the intensity peaks observed by our spectrometer matched the peaks in intensity output by the reference light. Figure 5 shows that the intensity of the light source matches up to some degree up to 450 nm. It suggests that the present spectrometer system seems to have less sensitivity at longer wavelength than 500 nm. Closer views of all the peaks show in the calibration are included in Appendix A.

3 Result of Spectroscopic Measurements

Figures 6-8 show results of spectroscopic measurments in different gas conditions. First, we looked at the breakdown spectrum taken at a low gas pressure, 27 atm as shown in Figure 6. This data was taken with a 1 nm step size and 10 second measurment duration per point. We did not see the structure from the hydrogen or copper spetral lines that we expected. We believe this is because the data was obtained at a low RF power. Thus, the number of photons we got at each wavelength was quite small.

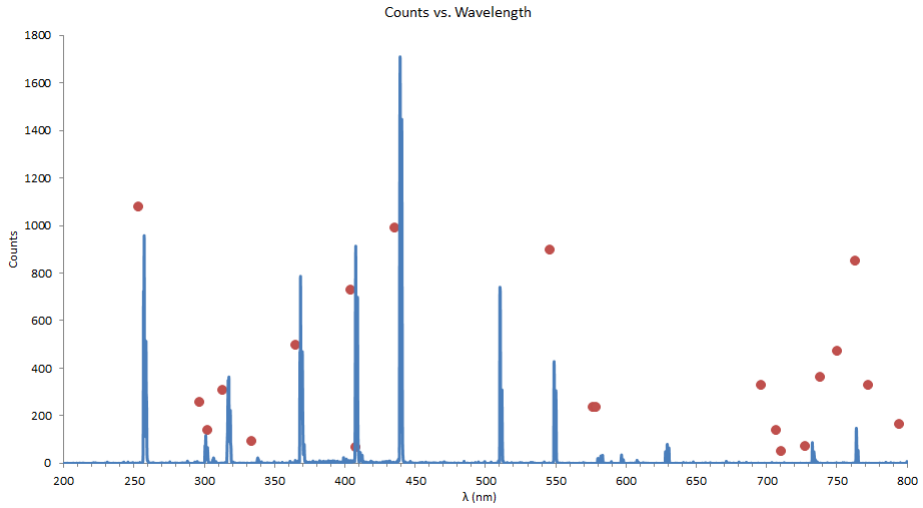


Figure 5: Counts vs. wavelength for light source spectrum

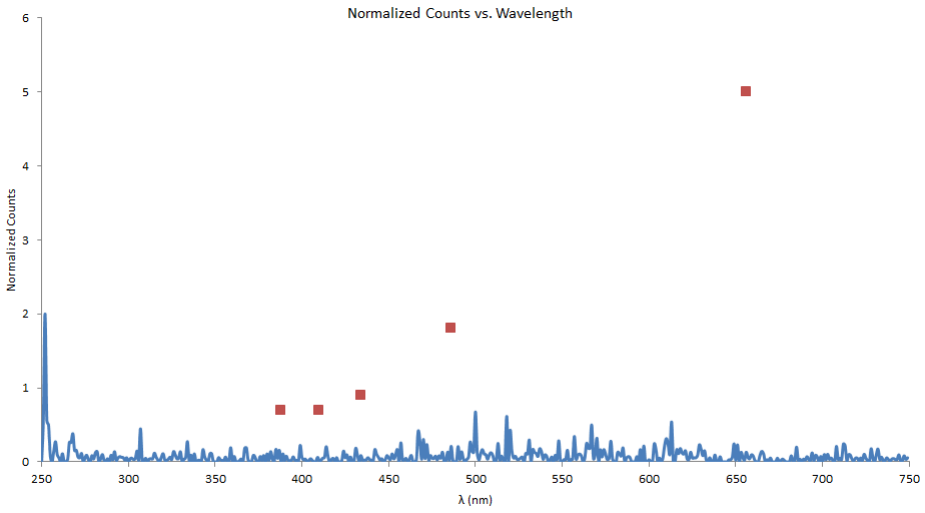


Figure 6: Normalized counts vs. wavelength for low pressure hydrogen gas (27 atm) in test cell with expected Balmer lines superimposed from 200 - 800nm

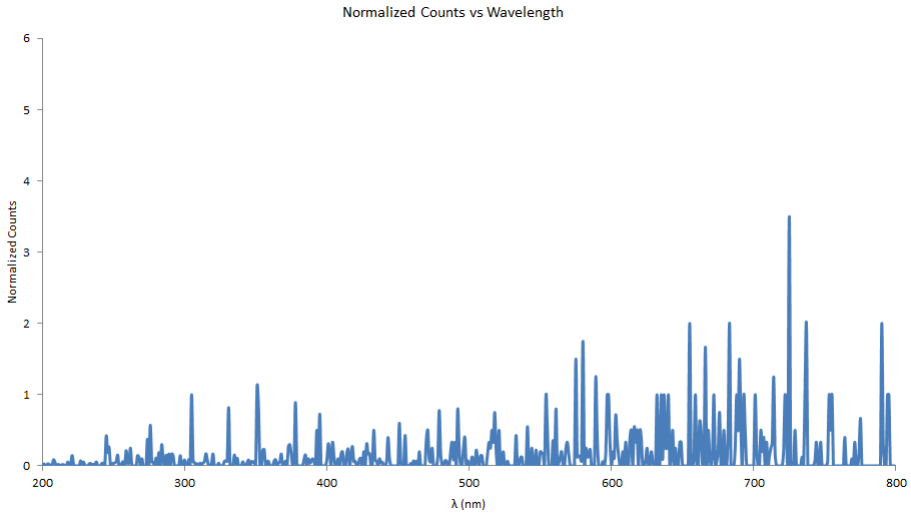


Figure 7: Normalized counts vs. wavelength for high pressure hydrogen gas (95 atm) in cavity from 200 - 800nm

We performed another measurment at higher hydrogen gas pressure (95 atm) as shown in Figure 7. We expected to see a higher light signal with higher pressure gas. This data was taken with a 1 nm step size and 5 second duration per point.

For the measurment at a hydrogen pressure of 95 atm in Figure 8, we took a narrow sweep from 500nm - 700nm in an effort to see the most intense Balmer excitation line at 656.3nm. This data was taken with a 1nm step size and a 10 second measurement duration per point. We did not observed peaks corresponding to the Balmer lines for hydrogen or the excitation lines for copper.

4 Timing Calibration

When electric breakdown occurs light is emitted and RF power decays. We want to know where the light is emitted relative to the decay in RF power. This requires taking timing calibrations of our system and taking the time delay into account with our LabView VI. Figure 9 shows an image of the RF bucket, or phase space of the RF signal before and after electric breakdown. The top signal in Figure 9 is the RF phase space. The bottom signal is from the PMT and shows a signal when electric breakdown occurs.

In order to calibrate the timing of our magnetic probe signal, which picks up the RF signal, and the PMT and SiPM that provide our light signal, we used a fast triggering laser system. We shone the trigger signal of the laser through the magnetic probe and then the other signal to the PMT or SiPM. This allowed us to measure the difference in time it took the two signals to reach our data

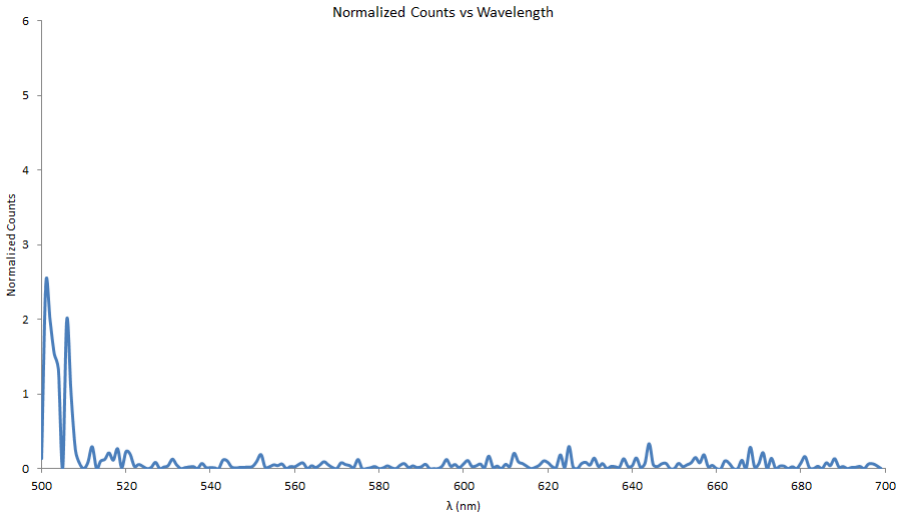


Figure 8: Normalized counts vs. wavelength for high pressure hydrogen gas (95 atm) in cavity from 500 - 700nmm

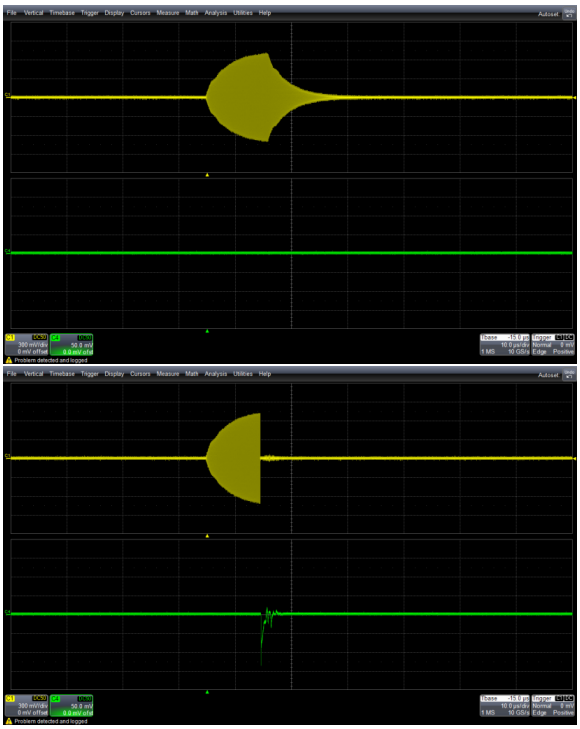


Figure 9: RF phase space bucket and breakdown light PMT signal before and after electric breakdown

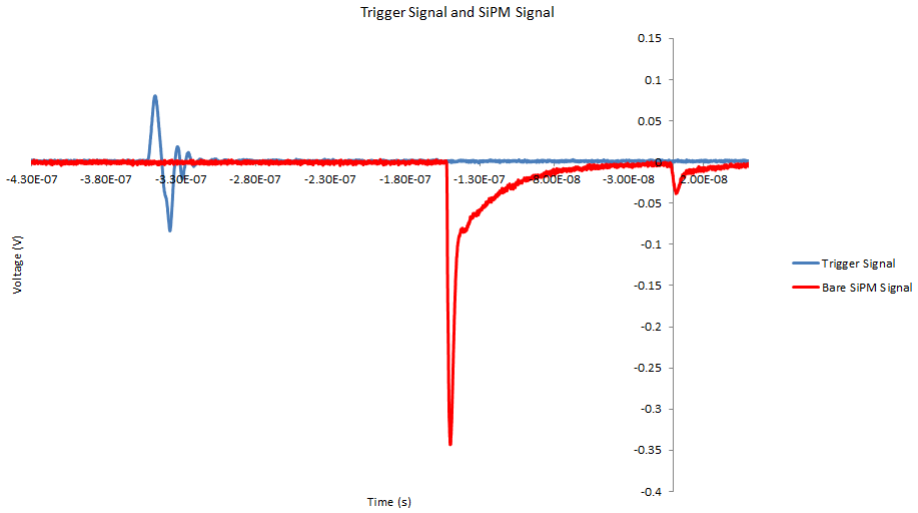


Figure 10: Trigger signal through magnetic probe channel and optical signal through bare SiPM channel

collection apparatus. Figure 10 shows an example of a trigger signal through the magnetic probe channel and an optical signal going to the SiPM channel. Taking time difference measurements and using the fact that there is an intrinsic delay of 70.8 ns between the laser trigger signal and the laser head signal, we found the delay between the PMT and RF signal to be 135.9 ns and the delay between the SiPM and RF signal to be 147.6 ns. A Mathematica script was used to find these differences. A signal registered at 6 sigma above or below the mean noise signal. This Mathematica script is included in Appendix E.

5 Timing between RF signal and Breakdown Light

The timing difference between the RF signal and breakdown lightl seemed highly variable with the first data set we worked with. The electric breakdown did not appear to follow any fixed pattern with regard to decay of the RF power. It was observed occurring far after RF power decay and far before as well. This was puzzling initially but we believe the reason for this variability is that the data we were working with came from a test run with a very high breakdown probability. We believe this led to sequential breakdowns which interfered with our ability to pick up the breakdown signal accurately relative to the decay of RF power. Because of this we analyzed data from another test run in which the breakdown probability was lower. The timing calibration figures for this first, problematic timing correction are included in Appendix B.

In this second timing analysis we found a more consistent relationship between the decay of RF power and the electric breakdown light signal. The light

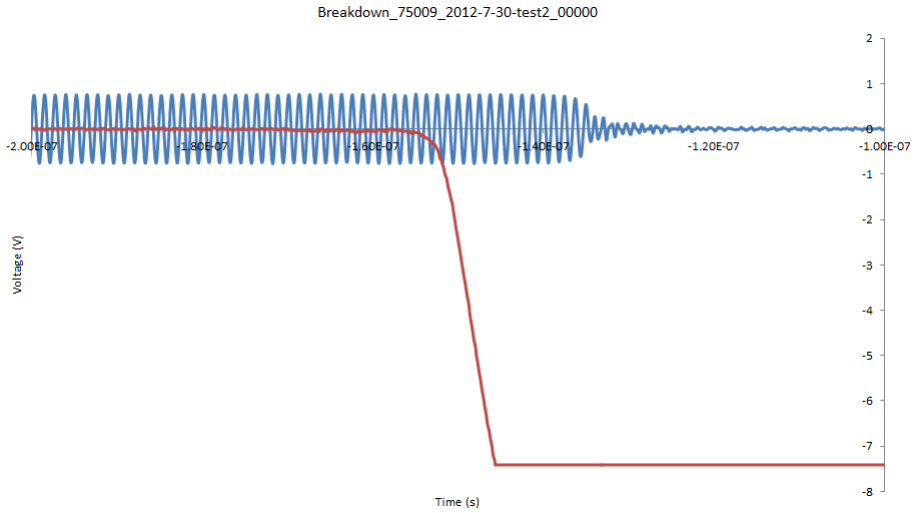


Figure 11: Plot of PMT signal vs. decay in RF power corrected for timing calibration

was emitted before the decay in RF power occurred with a couple of exceptions. Figure 11 illustrates our finding for one breakdown. Additional breakdown timing corrections are included in Appendix C.

6 Conclusion

We built a fast spectroscopic light measurement system using a spectrometer and two frequency counters controlled by a Labview code. We successfully calibrated the wavelength of the spectrometer with a reference light source. The timing between the PMT signal and the RF signal was calibrated successfully using a fast triggering laser system. We attempted to take spectroscopic measurements at 27 atm hydrogen gas pressure in the test cell and saw no spectroscopic signal from excitation of molecular and atomic hydrogen. We tried again at a hydrogen pressure of 95 atm, expecting the higher electric power in the cavity to result in more intense breakdown light. So far we have failed to see spectroscopic light.

In the future we will use a PMT that is sensitive at a higher wavelength range, one that is more likely to detect the H/alpha excitation line. We may also increase the light intensity received through the optical feedthrough by increasing the size of the feedthrough or adding more feedthroughs.

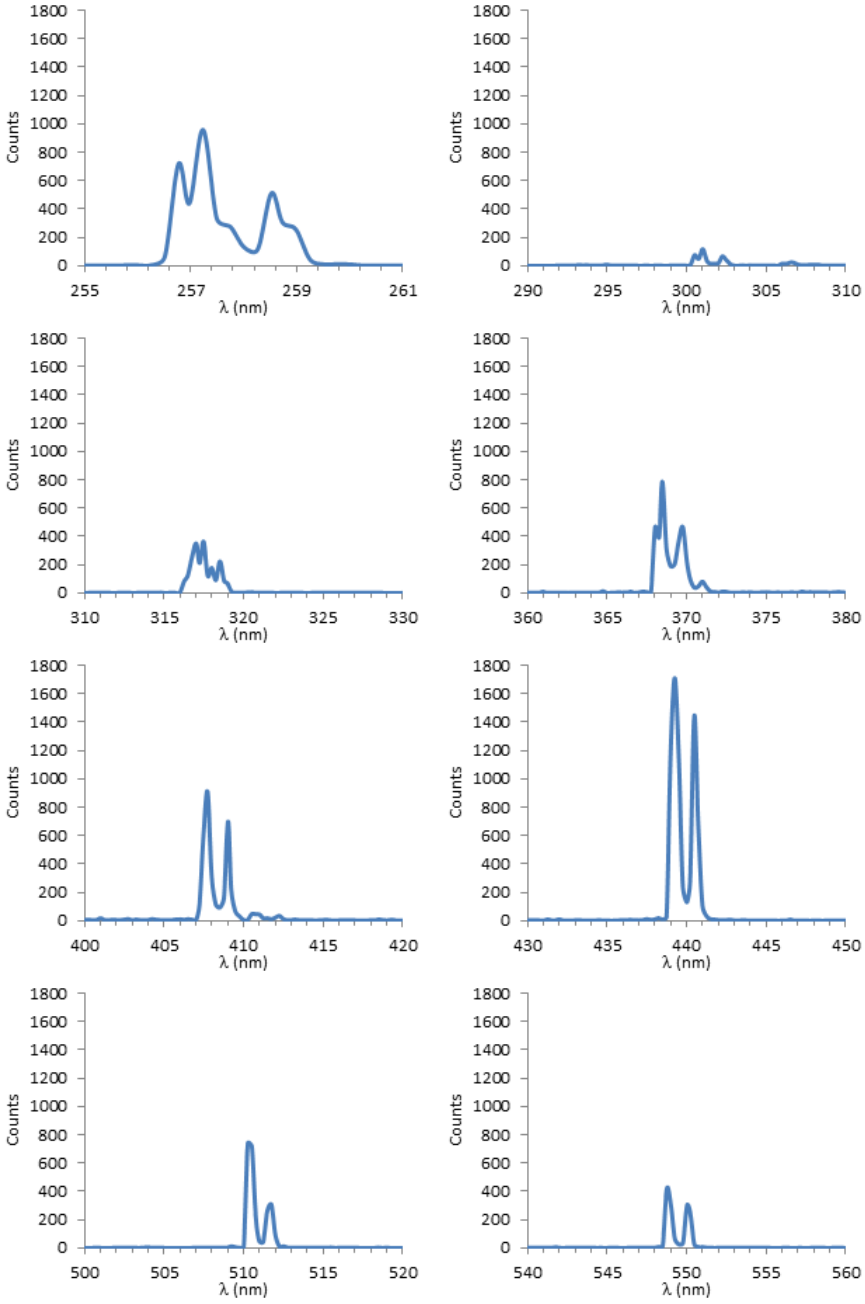
References

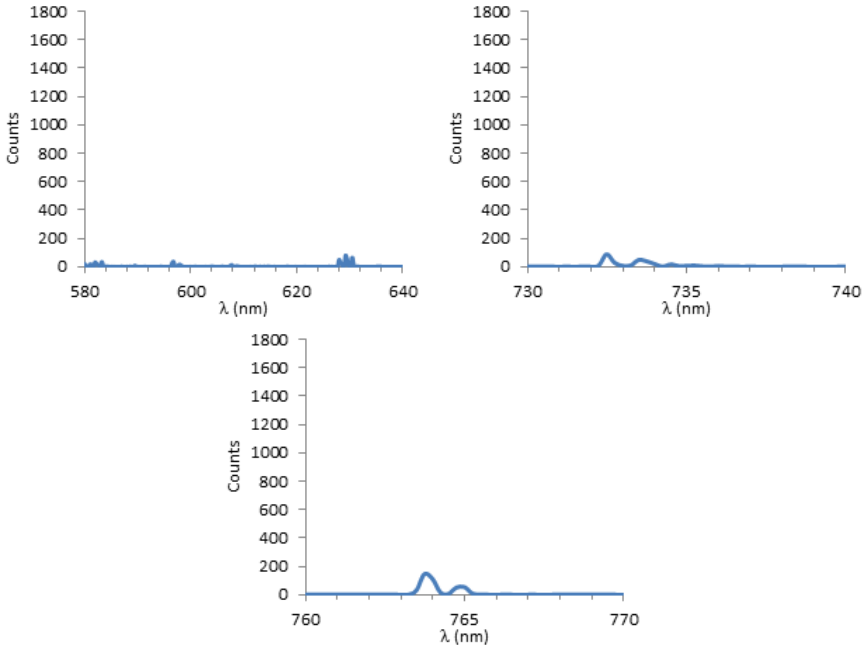
[1] K. Yonehara et al., Proceedings of IPAC 2010, WEPE069

Appendix

Appendix A

Closer views of peaks in spectrometer calibration plot using light source




Counts
λ (nm)
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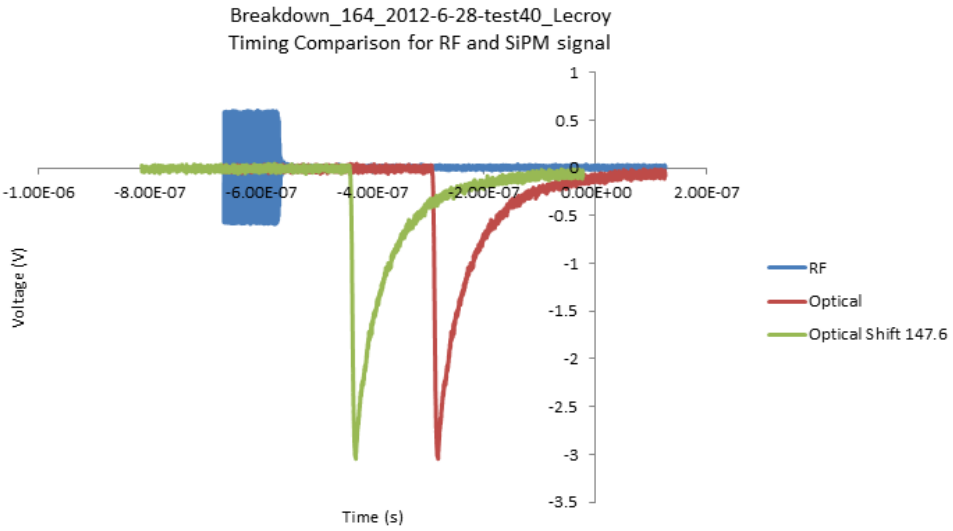
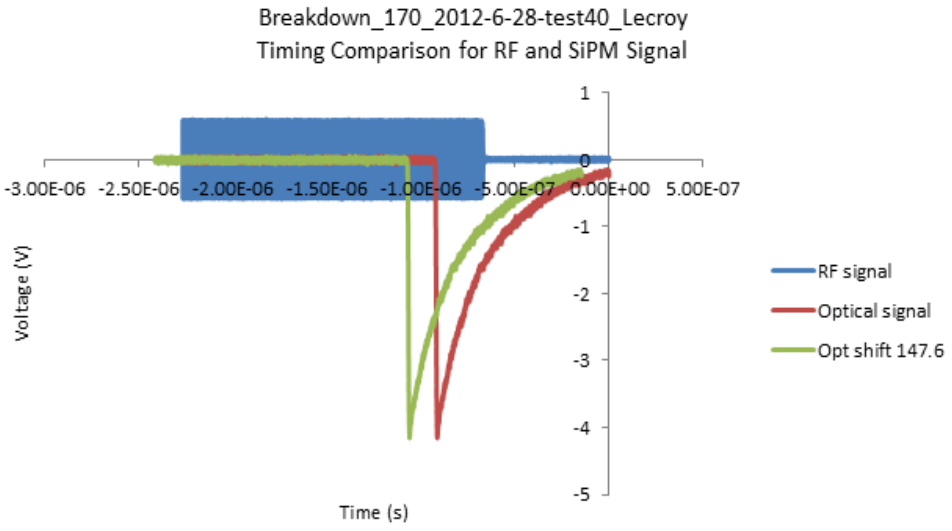
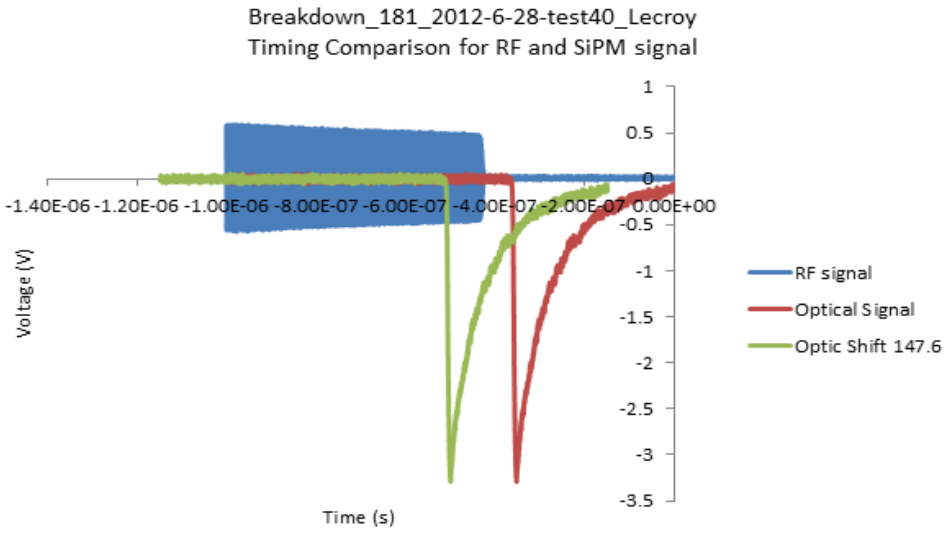
1600
1400
1200
1000
800
600
400
200
0
580
600
620
640
730
735
740
760
765
770

Appendix B

The plots show the original arrival time for the optical signal from the SiPM. It also shows the corrected time for the arrival of the signal from the SiPM. This corrected arrival time is found by subtracting the time difference between the RF magnetic probe signal and the SiPM found with our laser timing measurement. These data were taken on 6/28/2012 using the Lecroy oscilloscope in the MuCool test area.



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Timing Comparison for RF and SiPM signal
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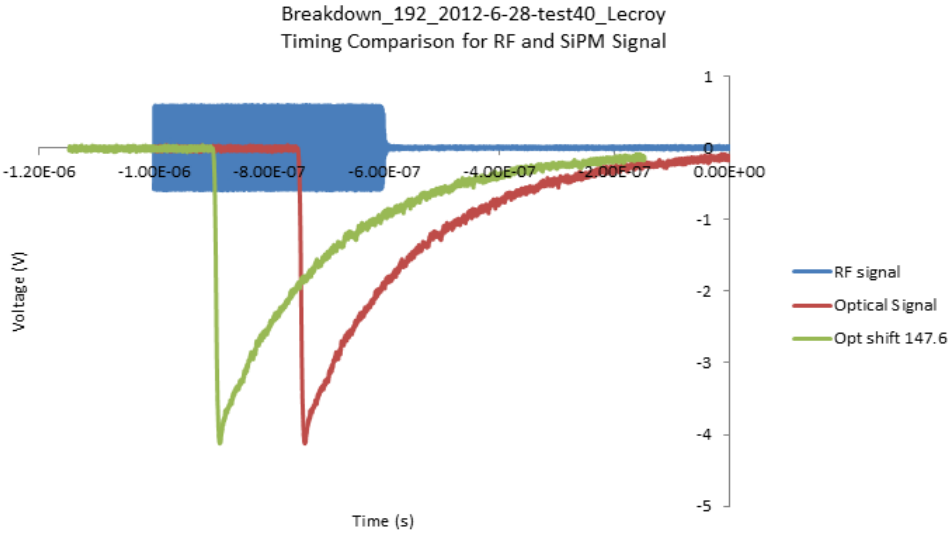
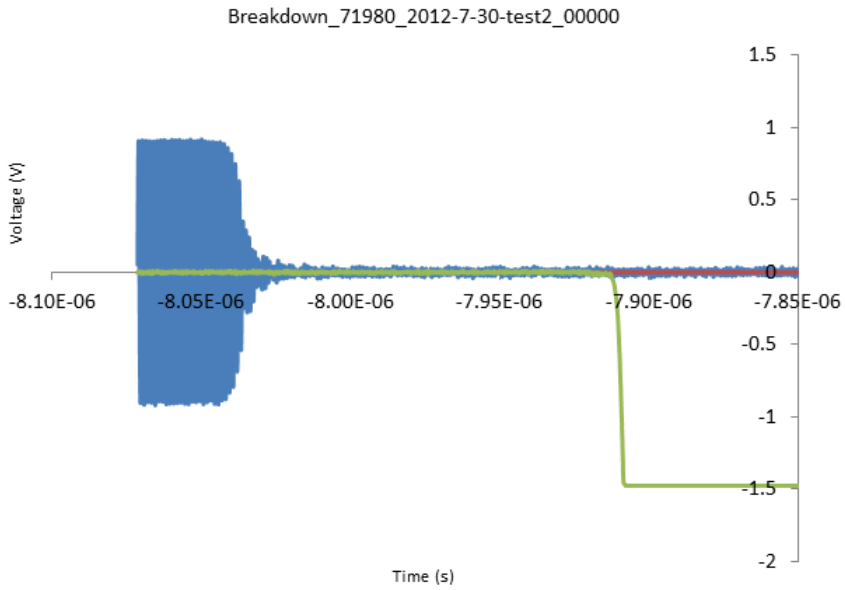
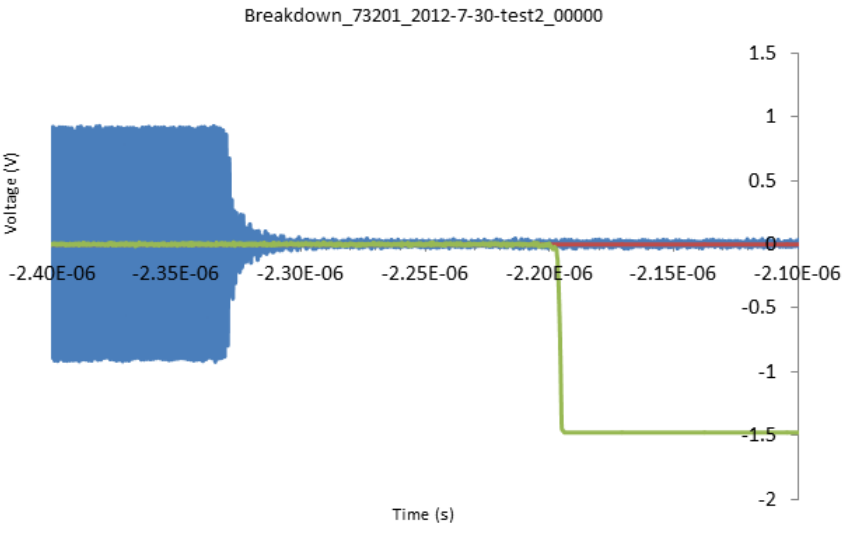
0
-0.5
-1
-1.5
-2
-2.5
-3
-3.5
-1.40E-06 -1.20E-06 -1.00E-06 -8.00E-07 -6.00E-07 -4.00E-07 -2.00E-07 0.00E+00
Voltage (V)
Time (s)
RF signal
Optical Signal
Optic Shift 147.6

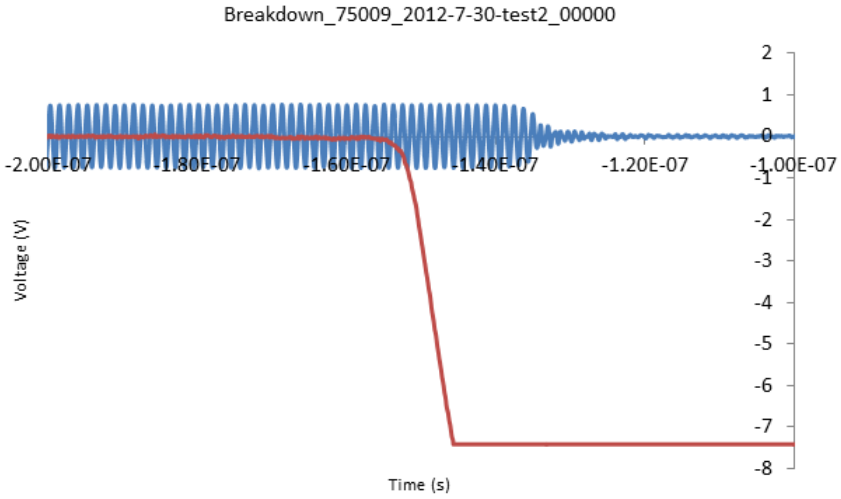

Breakdown_192_2012-6-28-test40_Lecroy
Timing Comparison for RF and SiPM Signal
1
0
-1
-2
-3
-4
-5
-1.20E-06 -1.00E-06 -8.00E-07 -6.00E-07 -4.00E-07 -2.00E-07 0.00E+00
Voltage (V)
Time (s)
RF signal
Optical Signal
Opt shift 147.6

Appendix C

Note that for some of the timing plots either the RF pulse or the PMT signal is cut off. This is due to the range we took the snapshot in on the oscilloscope. The scale of these snapshots of data was then changed so they would be as comparable as possible.



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0
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-3
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-5
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-7
-8
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-1.60E-07
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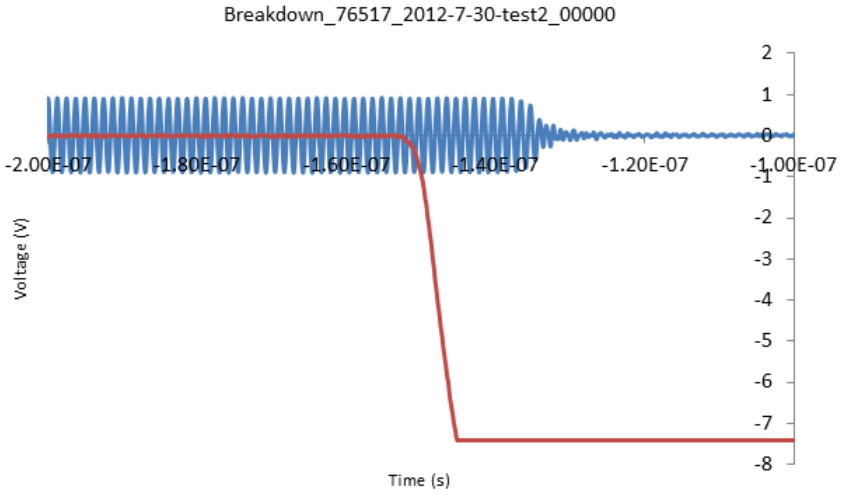
-1.20E-07
-1.00E-07
Voltage (V)
Time (s)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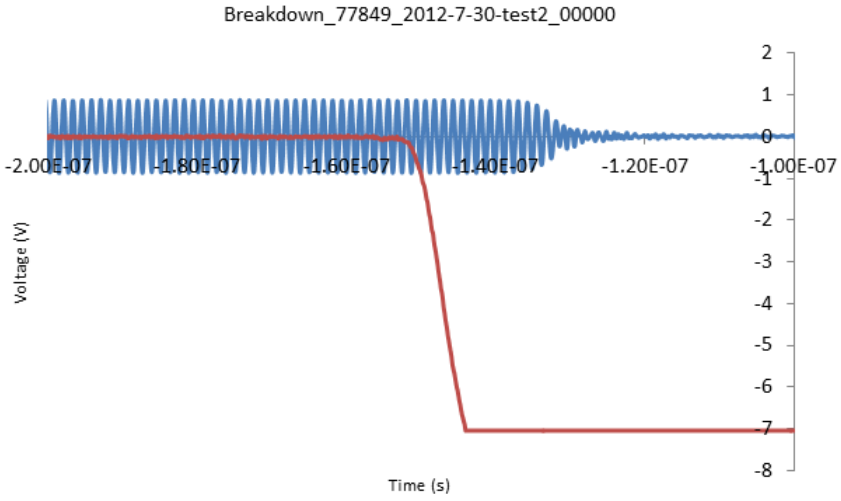
Voltage (V)
Time (s)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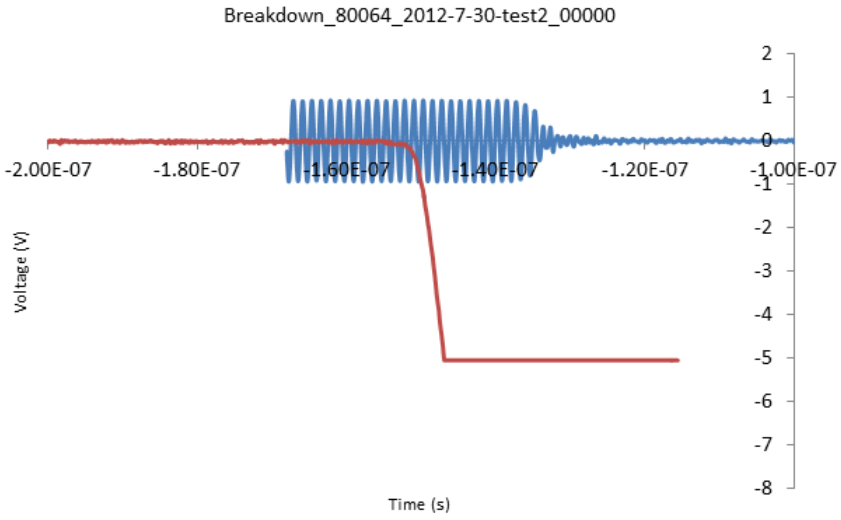
Voltage (V)
Time (s)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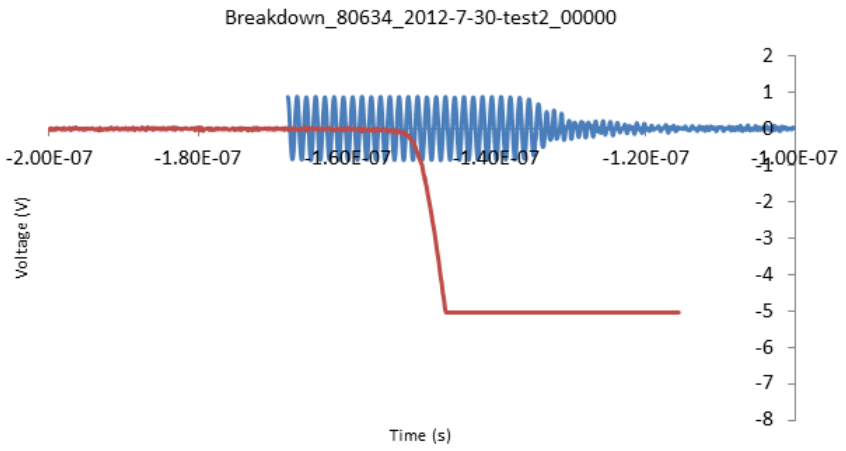
Voltage (V)
Time (s)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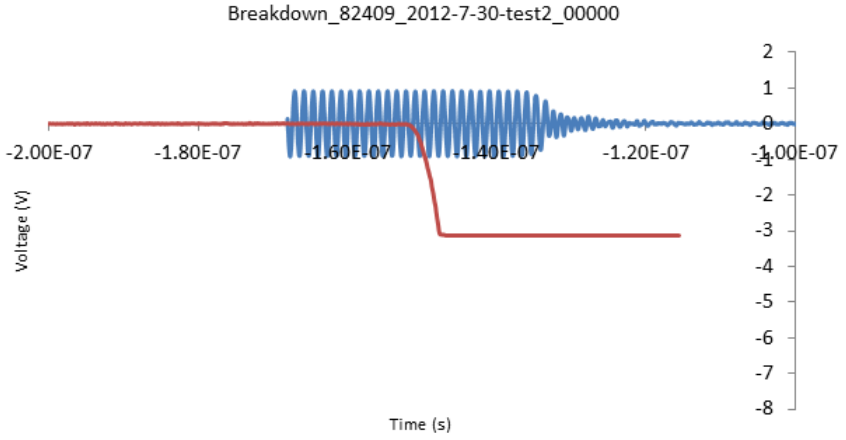
Voltage (V)
Time (s)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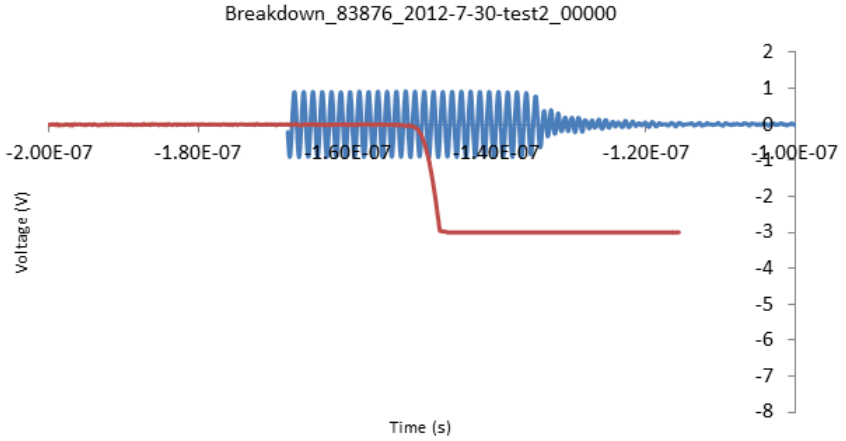
Voltage (V)
Time (s)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-1
-2
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-5
-6
-7
-8
-2.00E-07
-1.80E-07
-1.60E-07
-1.40E-07
-1.20E-07
-1.00E-07
Voltage (V)
Time (s)

Appendix D

Labview VI manual for running measurement apparatus VIs

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Installation, Configuration and Operation Instructions

Labview Spectroscopy Measurements with

Horiba Micro-HR Automated Spectrometer

Agilent 53220A Universal Frequency Counter

& NI-USB 6211 DAQ Counter

Important Notes for Installation of the spectrometer and counter are included in this file as well as instructions on how to use them. You must use Labview 2011 in order for the Vis to work. The Labview 2011 license is a trial license is a trial license on mtarflv2. It is a 30 day license. I was able to avoid it expiring by turning back the date on the Desktop of the computer. Don't despair if you can't get the VIs working. There are lots of little things you have to adjust and deal with. Don't forget to refer to the documents from the manufacturer in the file "IMPORT-DOCS" on mtarflv2 in the MuCool test area. This work was done on the local admin account with username: "mtarflv2\localadmin" with password "fermilab@0703". Most of the instructions, drivers, etc. for these devices can be found on the internet or requested from the manufacturer. Getting it all to work together with the right editions of Windows, Labview, etc. can be irritating and time consuming. I can be reached at asibley@trinity.edu or janisper116@gmail.com .

Spectro-Counter Labview VI Notes

Spectrometer Initialization

To start using the Labview VI that controls the Horiba Automated Micro-HR spectrometer, the NI-DAQ counter, and Agilent 52330A Counter you must click the run button in the upper left hand corner of the Lab-view window. This will start the VI. You must then initialize the spectrometer if you have not initialized it recently. After being initialized the spectrometer will remain in its initialization state for some time. This is done by setting the "Mono ID" in the "Spectrometer Initialization" control box to "TESTING". The different IDs you see in the box are for different configurations of spectrometers. This is the correct one to use. You should then click the "Connect" button. The initialization and connection to the spectrometer is not instantaneous and may take up to a minute.

If the light indicates that the spectrometer is initialized it is probably right. This may not always be the case however. If you cannot get the spectrometer to work you should try to reinitialize it. If the light seems to not be working the indicator you should look for is the "Current WL" indicator in the "Grating/Wavelength and Control" box which should turn to some negative number, or simply change. This is your hint that the spectrometer is initialized and connected. Hitting "STOP MACHINE" will stop the machine all together. It will not work when the machine is moving to a new wavelength or changing grating. It will also not work when a "Sweep Wavelengths Measurement is being taken.

Changing Gratings and Wavelength

In order to switch gratings you must change "Target Grating" to your desired grating. You can also change the wavelength by changing "Target WL". To order the machine to change to your desired grating and move to your desired wavelength you must hit the "Move to Target Positions" button. The movement should take a moment, indicated by the light. The values of “Current Grating” and “Current WL” will change to the values you requested.

NI-DAQ Counter Controls

The NI-DAQ counter controls should not need to be changed. The NI-DAQ control is set to use the counter number zero. “channel name” is an unimportant setting. “edge” specifies whether the NI-DAQ will use the rising or falling edge of the signal. “count direction” specifies whether the number the NI-DAQ counts will be incremented or decremented by one. You will not need to change it.

Agilent Counter Controls

For our application we only use first four controls for the counter “VISA resource name”, “Reset Counter”, “Timeout” and “Threshold Voltage”. “VISA resource name” should be set to “Counter”. The main importance of "Reset Counter" is that if you turn it on it will set the defaults of the counter (things like threshold voltage and measurement length) when you run the VI. This will obliterate whatever settings you had set on the counter manually. If you wish to preserve the settings you manually put into the counter, turn it off. If you want to set new defaults for the counter (other than the ones already set by the current Labview VI) you will have to alter the functionality of the Labview VI for the counter, to add new buttons to allow for control of those parameters. The “timeout” control indicates how long you wish the VI controlling the Agilent counter to wait for measurements from the Agilent counter before it returns an error. This parameter should be larger than “Measurements per Run” multiplied by “Individ Measurement Duration”. This is the amount of time you would expect it to take the counter to return measurements to the VI. If your measurements for one run take longer than this timeout the VI definitely will not work. We generally set “threshold voltage” to 0.1. “Threshold voltage” is the minimum signal for the counter to register an event. Threshold voltage will dictate the sensitivity of your counter. We set “threshold voltage” because our PMT signal has fine structure that we do not wish to be counted as well. We wish to count only the single event. It is not clear if this is where “threshold voltage” should actually be, but it seems to work ok. I’m not convinced of our reasons for settings “threshold voltage” at the level we do (it seems too arbitrary) but that is what we have used up to this point.

Sweep Wavelengths Measurement

In order to take data over a range of wavelengths you must use the controls inside the "Sweep Wavelengths Measurement" box. This measurement will start at the wavelength you indicate in “Start Wavelength”. It will take the number of “Measurements per Run” that you indicate at that wavelength. It will then increment the starting wavelength by the value you put in “WL Increment”. It will increment and take new runs the number of times you indicate in “Total # Runs”. The “Individ Measurement Duration” parameter sets the time per measurement. Pressing the "Take Sweep Measurement" button will start measurements. If you wish to stop measurements you can just hit the "Stop Measurement" button. If a

measurement is taking place and you hit the "STOP MACHINE" button, it will not work, because the sweep wavelengths operation must be complete first.

Data output from the sweep measurement appears in a table near the bottom of the VI. The first row records the wavelength at which the measurements were taken. The second row records the counts registered from the spectrometer signal. The third row records the number of breakdowns recorded at the DAQ board. You can extend the table if you want to see more data, you can also right click on the corner of the table and select export to copy the data to clipboard or export to excel. Data output from the sweep measurement is also plotted in the graph near the bottom of the VI. There are several buttons for manipulating both the graph and data table on the VI. In addition you can indicate whether you wish the data written to an excel file upon completion of the measurement.

Horiba Micro-HR Automated Spectrometer Notes

Installation

In order to get the Horiba spectrometer working with Labview you will need to get the Labview VIs for the device. These are available online but are very sensitive to the version of Windows you are using and the version of Labview as well. It is important to note that Labview must be run in XP compatibility mode (XP service pack 3 worked fine for me) in order for the Labview VIs to work. You can do this by right clicking on the Labview desktop icon and selecting properties and then compatibility. It is best to contact the manufacturer via a request on their website to get the appropriate drivers. You will need to give them the version of windows and Labview that you are using as well as the info for the spectrometer, particularly the serial number. Also, the Horiba drivers for the spectrometer must be installed before the Labview VIs will work. You will need the white disk that says ”spectrometer utilities”. After installing the driver and utilities you may also need to configure the spectrometer. The configuration process is lengthy and is detailed in a PDF in the “IMPORT-DOCS” folder on the desktop of mtarflv2’s local admin account, as mentioned in the introduction to this document. Lastly, you may need to disable DEP to get Labview working on your computer. The details on how to do this are also in a PDF in the “IMPORT-DOCS” folder.

This should be all you need to get it working. Just don't forget that it is very sensitive to Labview and Windows version and you need to run in XP compatibility mode. The Horiba customer service seems to be very good in general, so they should work with you to get the appropriate drivers.

Operation

The spectrometer Vis work well in general but do have a few issues. The main issue is that if you disconnect the USB connection to the computer you may have trouble reconnecting again. I think this may also be related to using the Horiba control software for the spectrometer. If you are having trouble reconnecting to the spectrometer using the Labview Vis, where it was working previously, it is best to exit out of Labview, maybe unplug the spectrometer and maybe restart your computer. That issue gave me a lot of headaches.

Agilent 52330A Universal Frequency Counter Notes

Installation

In order to get the Agilent counter to work with Labview you will need to download the Labview VI which can be found on Agilent's website. The latest version available when I last checked was Labview 2010 but that will work fine. You will also need to install Agilent's IO Library Suite. This will install Agilent's version of VISA which is the most important thing, it communicates with the Counter better than the version of VI that comes with Labview. This can be found in the same place you find the Labview drivers for the counter on the website. Detailed instructions for installation from manufacturer are found in the "IMPORT-DOCS" folder.

Operation

The Agilent counter has some issues with freezing up. If you do not install Agilent's IO Library Suite it will be almost impossible to communicate with the counter at all. Some pieces may work, but in general National Instruments VISA isn't capable of interfacing with the Agilent counter effectively. You need Agilent's version of VISA, which is included in Agilent's IO Library. Agilent's IO Library also has a tendency to crash. If the IO Library crashes you will not be able to communicate with the Agilent counter any longer. The counter will freeze up as well. The solution to this problem is to restart the computer. You will also have to restart the counter. The only way I have found to do this is to turn off the power button, this could be harmful to the machine but nothing else has worked for me. An issue you may encounter is timeout problems. This will happen when you do not change the default timeout of Labview Vis when you are running measurements on the counter that take longer than the default timeout for the VI.

NI-USB 6211 DAQ Counter Notes

Installation

To install the NI-USB 6211 DAQ counter you must download the drivers from the National Instruments website. To generate a Labview VI to control the DAQ as a counter you must use the DAQ assistant. This will allow you to configure a channel on one of the DAQs two counters. The counter I used is located on the very first input on the DAQ. This is port #1 on the "Digital I/O and Analog Output" side of the DAQ. It is the first of the two channels you have an option to select when you configure the counter measurement, "ctr 0".

Operation

The DAQ counter requires few adjustments. The controls can generally be left as they are. A problem with the DAQ counter for which we could not find a resolution was the lack of a voltage threshold setting for the counter measurements. With the DAQ counter we would have liked to set a voltage threshold for the same reason we set one for the Agilent counter, to avoid counting the fine structure of a voltage pulse generated by an incident photon on the PMT. Because of our inability to do this on the DAQ counter we used a discriminator and gate generator both external to the DAQ counter. The discriminator served to only pass events above a certain voltage threshold. This allowed us to avoid counting the fine structure of events. The gate generator served to record breakdown events rather than single photon events. We wanted to record breakdown events instead of single photon events because the dielectric breakdown generates many photons. Since we are using the white light signal going to the DAQ counter to normalize the signal from the spectrometer, we do not wish to measure every single photon with the DAQ counter. We only wish to measure the number of breakdowns that occur. Since the breakdown event lasts

for approximately 50 μs, we configured the gate generator to give a pulse with a width of 50 μs upon the detection of a photon. This ensured that we would get only one signal from a breakdown event, as the breakdown event would be over in the length of the pulse output by the gate generator.

Appendix E

Mathematica code for timing calibration

The timing data that are loaded in the Mathematica file were taken with the Lecroy oscilloscope in the MuCool test area on 2012-7-13. Ch1 shows the trigger signal from the laser system sent through the magnetic probe channel. Ch4 shows the optical signal from the fast triggering laser system sent through the bare SiPM, PMT and the SiPM "T" juction. Three snapshots were taken for each case.

Clear all variables

```
ClearAll["Global`*"]
```

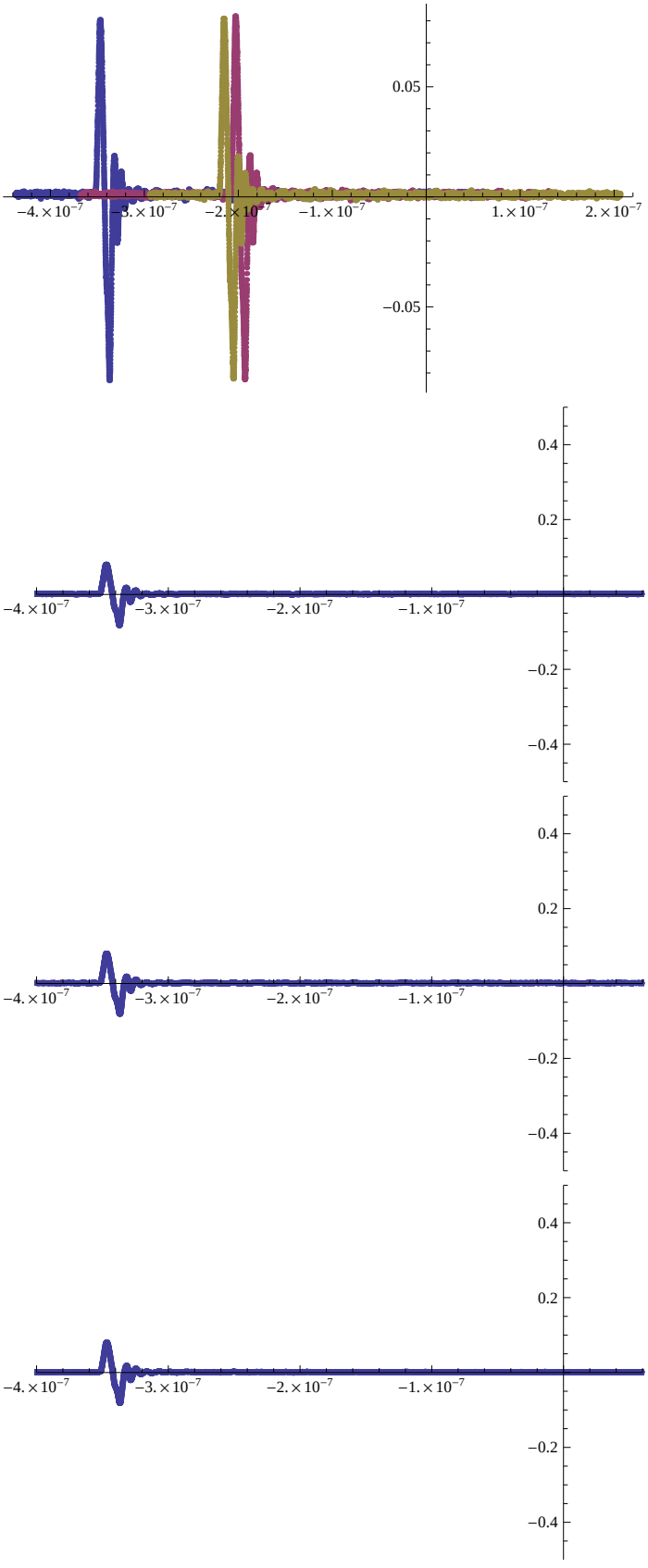
Set data directory

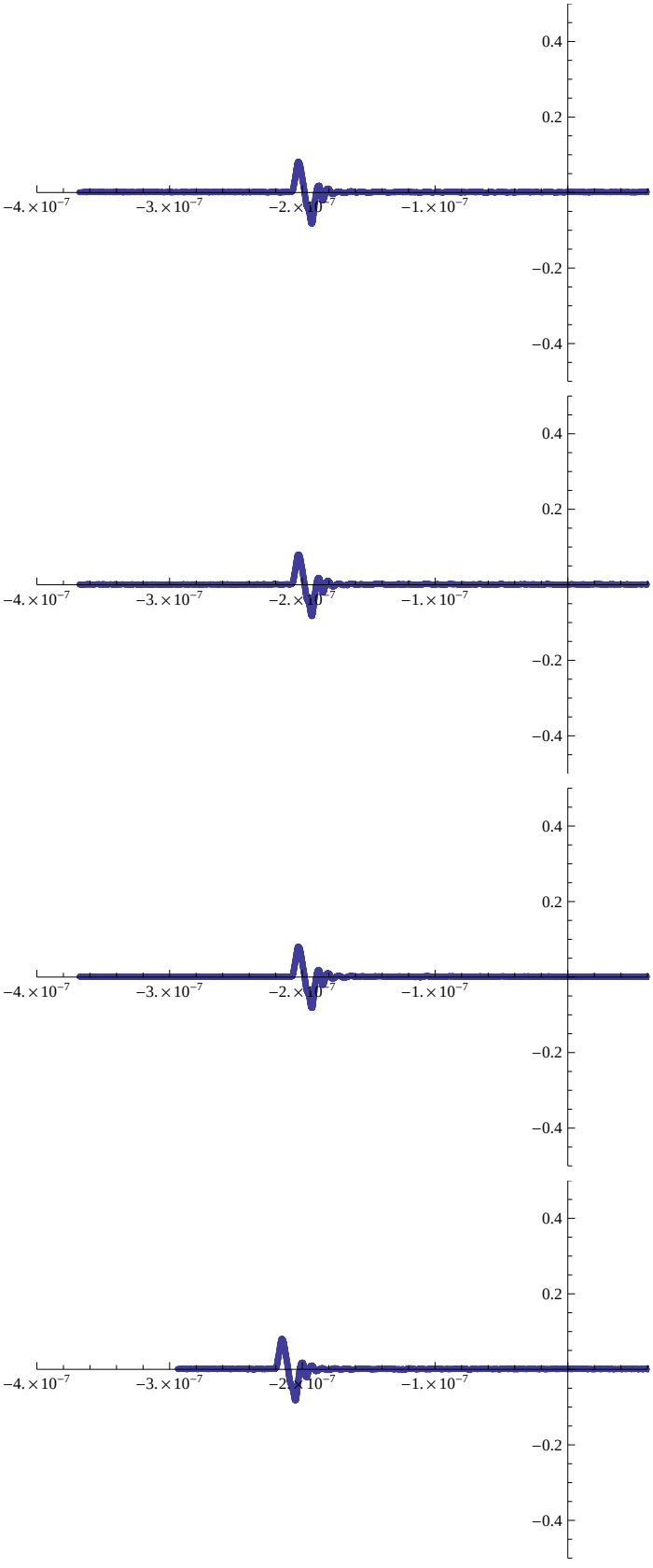
```
(*SetDirectory["/Users/sibley/Desktop/csv"];*)
```

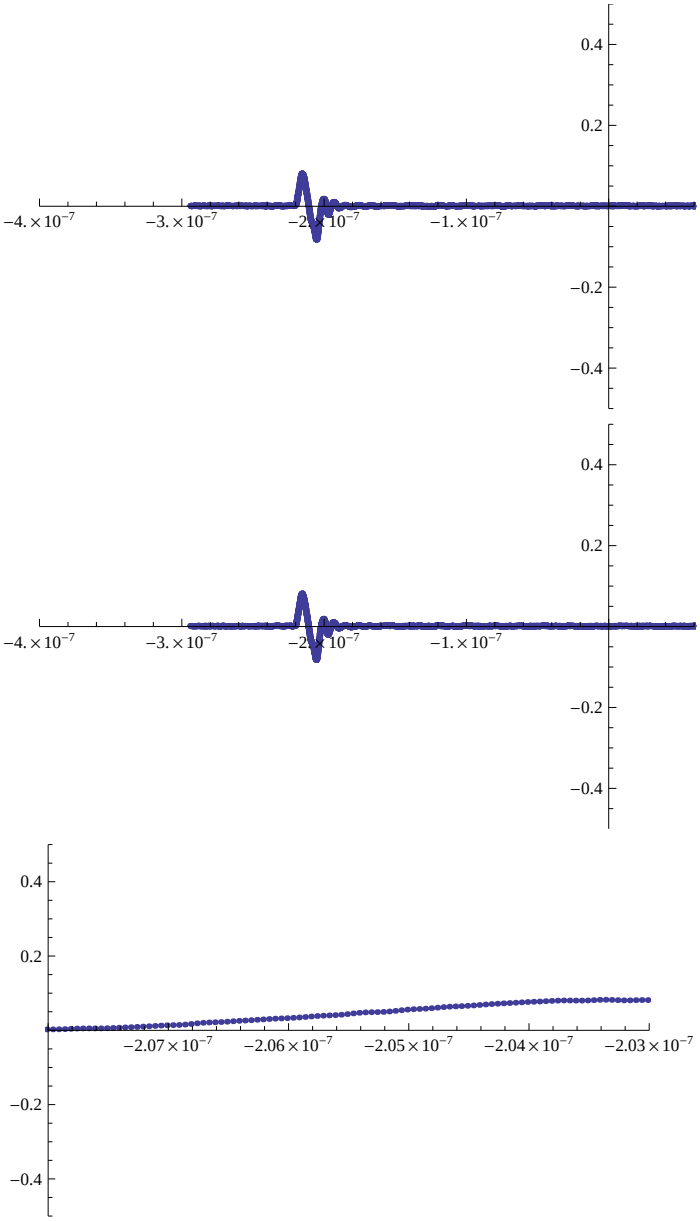
Read raw data
You need to change the file name
I will convert a csv file into a binary

```
rawdat = BinaryReadList["C1mp-bare-sipm-0100000.bin", "Real64"];
C1Bsipm1 = Partition[rawdat, 2];
rawdat = BinaryReadList["C1mp-bare-sipm-0200000.bin", "Real64"];
C1Bsipm2 = Partition[rawdat, 2];
rawdat = BinaryReadList["C1mp-bare-sipm-0300000.bin", "Real64"];
C1Bsipm3 = Partition[rawdat, 2];
```

```
rawdat = BinaryReadList["C1mp-pmt-0100000.bin", "Real64"];
C1pmt1 = Partition[rawdat, 2];
rawdat = BinaryReadList["C1mp-pmt-0200000.bin", "Real64"];
C1pmt2 = Partition[rawdat, 2];
rawdat = BinaryReadList["C1mp-pmt-0300000.bin", "Real64"];
C1pmt3 = Partition[rawdat, 2];

rawdat = BinaryReadList["C1mp-T-sipm-0100000.bin", "Real64"];
C1Tsipm1 = Partition[rawdat, 2];
rawdat = BinaryReadList["C1mp-T-sipm-0200000.bin", "Real64"];
C1Tsipm2 = Partition[rawdat, 2];
rawdat = BinaryReadList["C1mp-T-sipm-0300000.bin", "Real64"];
C1Tsipm3 = Partition[rawdat, 2];


ListPlot[{C1Bsipm1, C1pmt1, C1Tsipm1}, PlotRange → {All, All, All}]

ListPlot[{C1Bsipm1}, PlotRange → {{-4 * 10^-7, 0.6 * 10^-7}, {0.5, -0.5}}]
ListPlot[{C1Bsipm2}, PlotRange → {{-4 * 10^-7, 0.6 * 10^-7}, {0.5, -0.5}}]
ListPlot[{C1Bsipm3}, PlotRange → {{-4 * 10^-7, 0.6 * 10^-7}, {0.5, -0.5}}]

ListPlot[{C1pmt1}, PlotRange → {{-4 * 10^-7, 0.6 * 10^-7}, {0.5, -0.5}}]
ListPlot[{C1pmt2}, PlotRange → {{-4 * 10^-7, 0.6 * 10^-7}, {0.5, -0.5}}]
ListPlot[{C1pmt3}, PlotRange → {{-4 * 10^-7, 0.6 * 10^-7}, {0.5, -0.5}}]

ListPlot[{C1Tsipm1}, PlotRange → {{-4 * 10^-7, 0.6 * 10^-7}, {0.5, -0.5}}]
ListPlot[{C1Tsipm2}, PlotRange → {{-4 * 10^-7, 0.6 * 10^-7}, {0.5, -0.5}}]
ListPlot[{C1Tsipm3}, PlotRange → {{-4 * 10^-7, 0.6 * 10^-7}, {0.5, -0.5}}]

ListPlot[{C1pmt1}, PlotRange → {{-2.08 * 10^-7, -2.03 * 10^-7}, {0.5, -0.5}}]
```

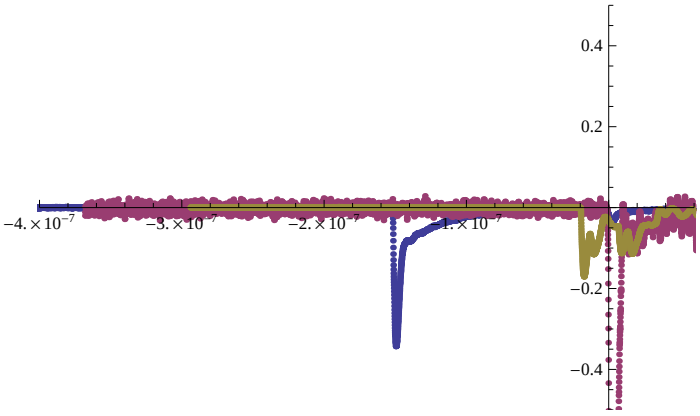

0.05
−0.05
−4.×10^−7
−3.×10^−7
−2.×10^−7
−1.×10^−7
1.×10^−7
2.×10^−7
0.4
0.2
−0.2
−0.4

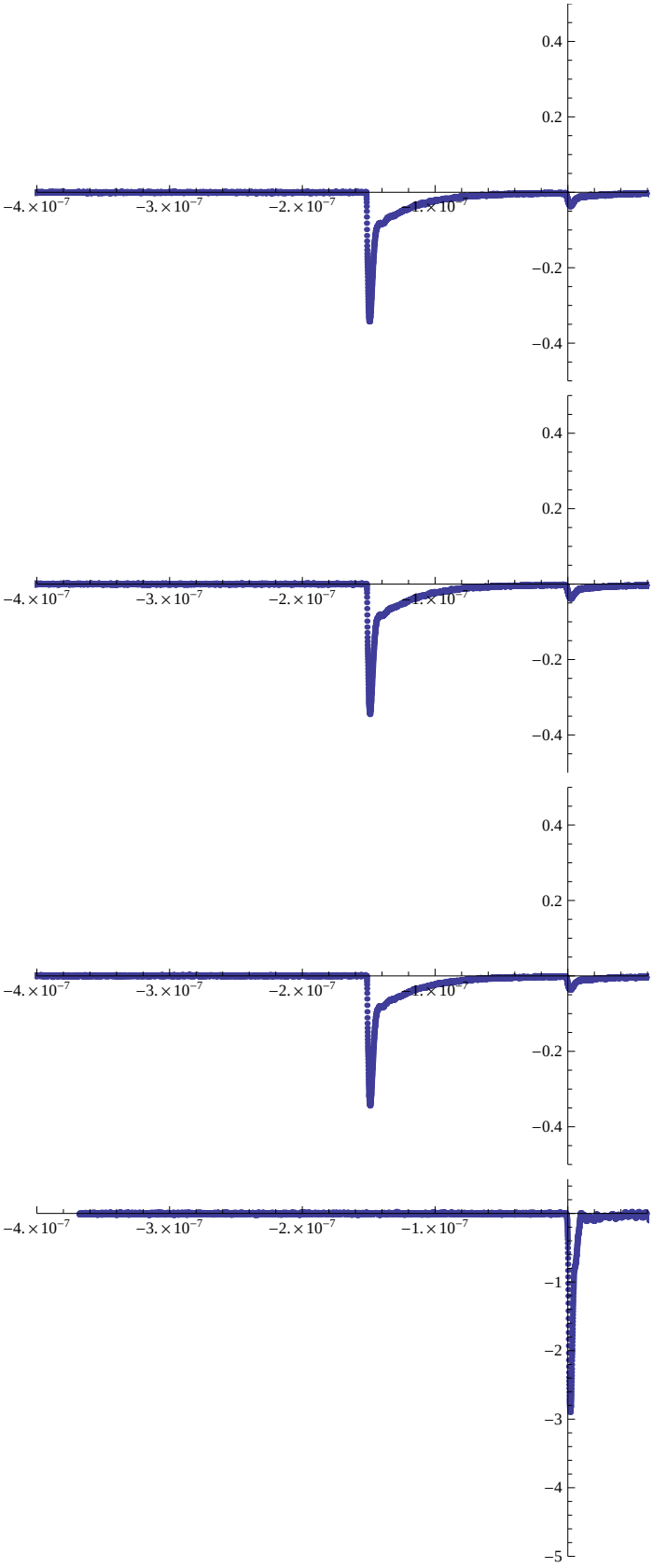

0.4
0.2
−0.2
−0.4
−4.×10^−7
−3.×10^−7
−2.×10^−7
−1.×10^−7

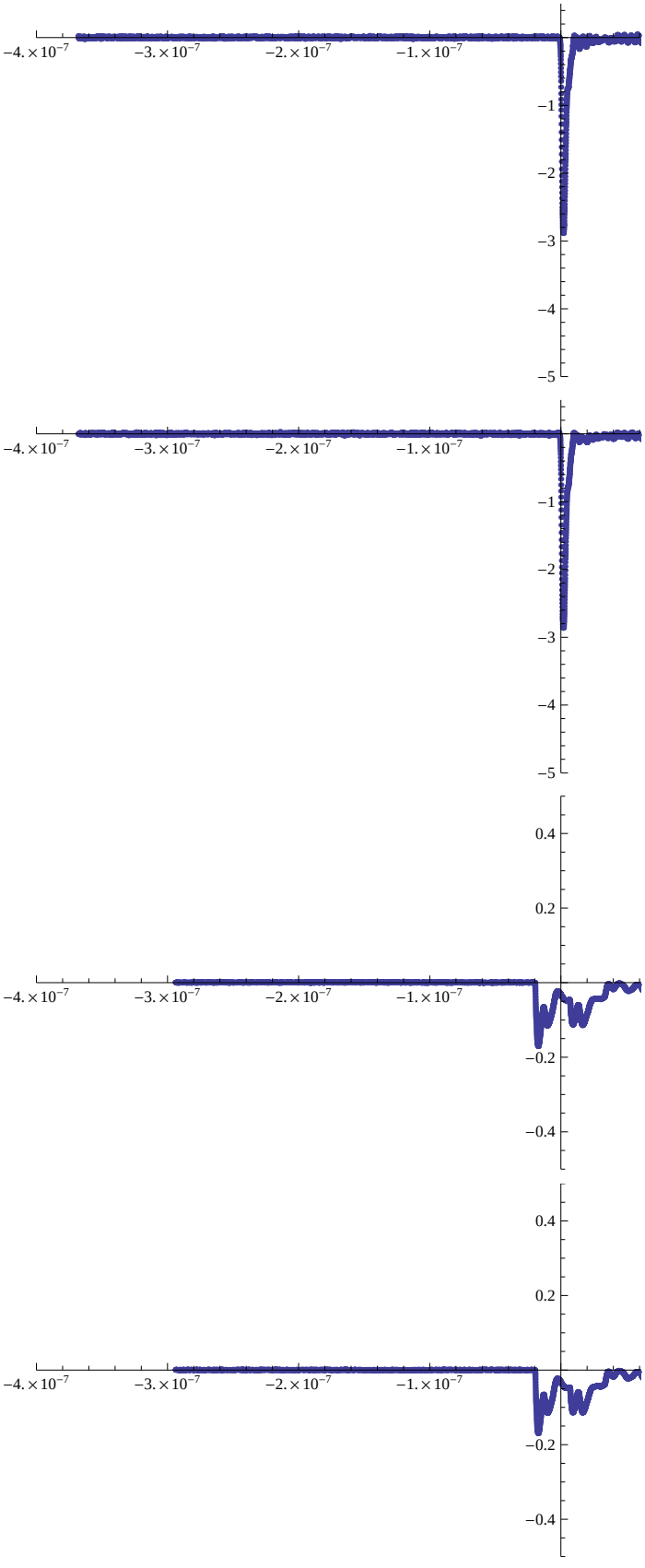

0.4
0.2
−0.2
−0.4
−4.×10^−7
−3.×10^−7
−1.×10^−7
0.4
0.2
−0.2
−0.4
−4.×10^−7
−3.×10^−7
−1.×10^−7

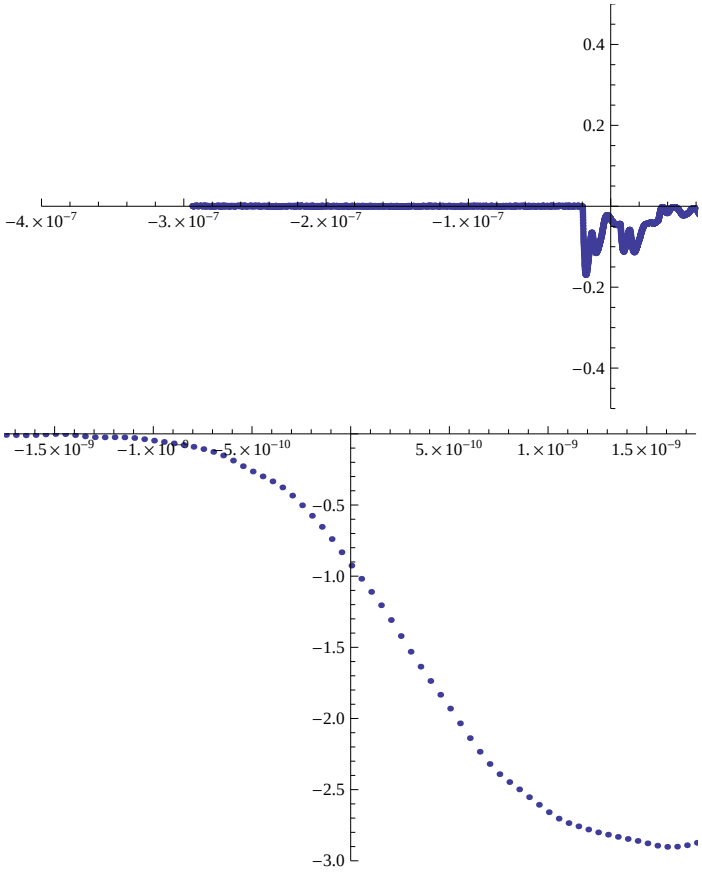
0.4
0.2
−0.2
−0.4
−2.07×10^−7
−2.06×10^−7
−2.05×10^−7
−2.04×10^−7
−2.03×10^−7

```
rawdat = BinaryReadList["C4mp-bare-sipm-0100000.bin", "Real64"];
C4Bsipm1 = Partition[rawdat, 2];
rawdat = BinaryReadList["C4mp-bare-sipm-0200000.bin", "Real64"];
C4Bsipm2 = Partition[rawdat, 2];
rawdat = BinaryReadList["C4mp-bare-sipm-0300000.bin", "Real64"];
C4Bsipm3 = Partition[rawdat, 2];

rawdat = BinaryReadList["C4mp-pmt-0100000.bin", "Real64"];
C4pmt1 = Partition[rawdat, 2];
rawdat = BinaryReadList["C4mp-pmt-0200000.bin", "Real64"];
C4pmt2 = Partition[rawdat, 2];
rawdat = BinaryReadList["C4mp-pmt-0300000.bin", "Real64"];
C4pmt3 = Partition[rawdat, 2];

rawdat = BinaryReadList["C4mp-T-sipm-0100000.bin", "Real64"];
C4Tsipm1 = Partition[rawdat, 2];
rawdat = BinaryReadList["C4mp-T-sipm-0200000.bin", "Real64"];
C4Tsipm2 = Partition[rawdat, 2];
rawdat = BinaryReadList["C4mp-T-sipm-0300000.bin", "Real64"];
C4Tsipm3 = Partition[rawdat, 2];



ListPlot[{C4Bsipm1, C4pmt1, C4Tsipm1},
 PlotRange → {{-4 * 10^-7, 0.6 * 10^-7}, {0.5, -0.5}}]

ListPlot[{C4Bsipm1}, PlotRange → {{-4 * 10^-7, 0.6 * 10^-7}, {0.5, -0.5}}]
ListPlot[{C4Bsipm2}, PlotRange → {{-4 * 10^-7, 0.6 * 10^-7}, {0.5, -0.5}}]
ListPlot[{C4Bsipm3}, PlotRange → {{-4 * 10^-7, 0.6 * 10^-7}, {0.5, -0.5}}]

ListPlot[{C4pmt1}, PlotRange → {{-4 * 10^-7, 0.6 * 10^-7}, {0.5, -5}}]
ListPlot[{C4pmt2}, PlotRange → {{-4 * 10^-7, 0.6 * 10^-7}, {0.5, -5}}]
ListPlot[{C4pmt3}, PlotRange → {{-4 * 10^-7, 0.6 * 10^-7}, {0.5, -5}}]

ListPlot[{C4Tsipm1}, PlotRange → {{-4 * 10^-7, 0.6 * 10^-7}, {0.5, -0.5}}]
ListPlot[{C4Tsipm2}, PlotRange → {{-4 * 10^-7, 0.6 * 10^-7}, {0.5, -0.5}}]
ListPlot[{C4Tsipm3}, PlotRange → {{-4 * 10^-7, 0.6 * 10^-7}, {0.5, -0.5}}]

ListPlot[{C4pmt1}, PlotRange → {{-.0175 * 10^-7, 0.0175 * 10^-7}, {0, -3}}]
```




0.4
0.2
−0.2
−0.4
−4.×10^−7
−3.×10^−7
−2.×10^−7
−1.×10^−7
0.4
0.2
−0.2
−0.4
−4.×10^−7
−3.×10^−7
−2.×10^−7
−1.×10^−7
0.4
0.2
−0.2
−0.4
−4.×10^−7
−3.×10^−7
−2.×10^−7
−1.×10^−7
−1
−2
−3
−4
−5
−4.×10^−7
−3.×10^−7
−2.×10^−7
−1.×10^−7


−4.×10^−7
−3.×10^−7
−2.×10^−7
−1.×10^−7
−1
−2
−3
−4
−5
−4.×10^−7
−3.×10^−7
−2.×10^−7
−1.×10^−7
−1
−2
−3
−4
−5
0.4
0.2
−4.×10^−7
−3.×10^−7
−2.×10^−7
−1.×10^−7
−0.2
−0.4
0.4
0.2
−4.×10^−7
−3.×10^−7
−2.×10^−7
−1.×10^−7
−0.2
−0.4



ra3out is needed to find the baseline
ra3out should be the time before the real signal appears

```
# Data for Ch1 T Sipm;

rainC1Tsipm1 = -1 * 10^-7;
raoutC1Tsipm1 = 1 * 10^-7;
rainC1Tsipm2 = -1 * 10^-7;
raoutC1Tsipm2 = 1 * 10^-7;
rainC1Tsipm3 = -1 * 10^-7;
raoutC1Tsipm4 = 1 * 10^-7;

meanC1Tsipm1 =
  Mean[Select[C1Tsipm1, #[[1]] ≥ rainC1Tsipm1 && #[[1]] < raoutC1Tsipm1 &]][[2]];
meanC1Tsipm2 = Mean[Select[C1Tsipm2,
     #[[1]] ≥ rainC1Tsipm2 && #[[1]] < raoutC1Tsipm2 &]][[2]];
meanC1Tsipm3 = Mean[Select[C1Tsipm3,
     #[[1]] ≥ rainC1Tsipm3 && #[[1]] < raoutC1Tsipm3 &]][[2]];

rmsC1Tsipm1 = StandardDeviation[
   Select[C1Tsipm1, #[[1]] ≥ rainC1Tsipm1 && #[[1]] < raoutC1Tsipm1 &]];
rmsC1Tsipm2 = StandardDeviation[Select[C1Tsipm2,
    #[[1]] ≥ rainC1Tsipm2 && #[[1]] < raoutC1Tsipm2 &]];
rmsC1Tsipm3 = StandardDeviation[Select[C1Tsipm3,
```

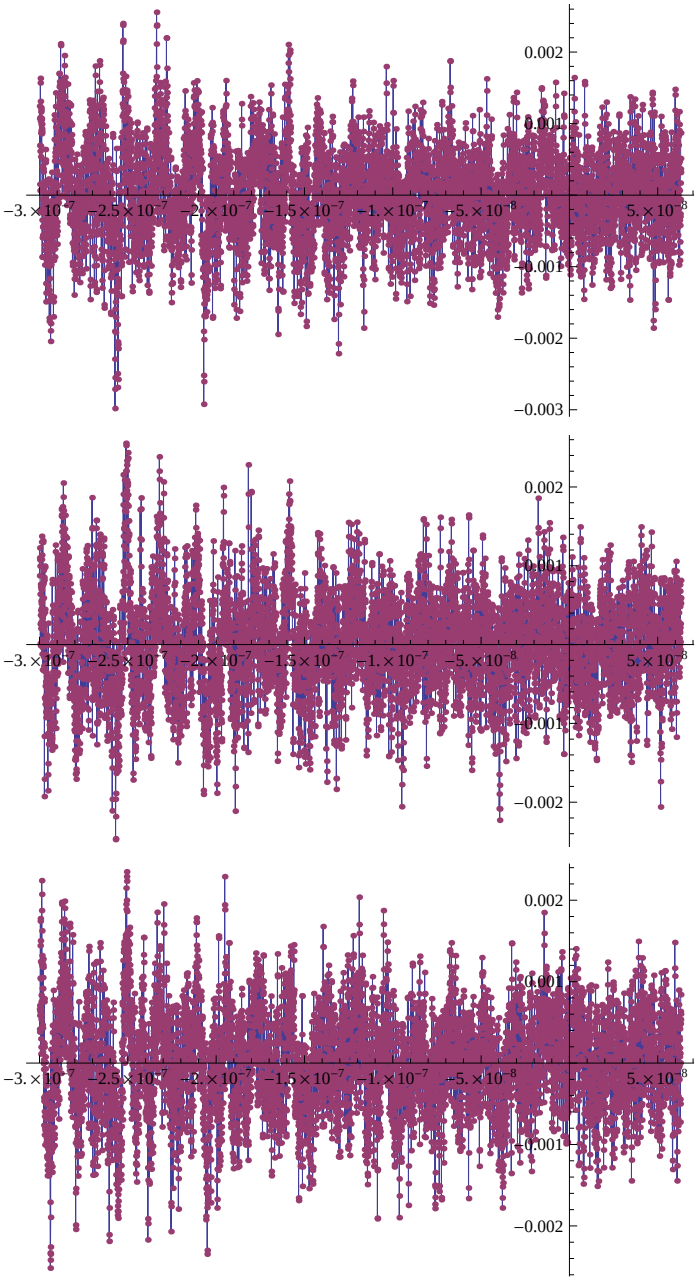
```
    #[[1]] ≥ rainC1Tsipm3 && #[[1]] < raoutC1Tsipm3 &]];

# Data for Ch4 T Sipm;

rainC4Tsipm1 = -2.8 * 10^-7;
raoutC4Tsipm1 = -.5 * 10^-7;
rainC4Tsipm2 = -2.8 * 10^-7;
raoutC4Tsipm2 = -.5 * 10^-7;
rainC4Tsipm3 = -2.8 * 10^-7;
raoutC4Tsipm3 = -.5 * 10^-7;

meanC4Tsipm1 =
  Mean[Select[C4Tsipm1, #[[1]] ≥ rainC4Tsipm1 && #[[1]] < raoutC4Tsipm1 &]][[2]];
meanC4Tsipm2 = Mean[Select[C4Tsipm2,
     #[[1]] ≥ rainC4Tsipm2 && #[[1]] < raoutC4Tsipm2 &]][[2]];
meanC4Tsipm3 = Mean[Select[C4Tsipm3,
     #[[1]] ≥ rainC4Tsipm3 && #[[1]] < raoutC4Tsipm3 &]][[2]];

rmsC4Tsipm1 = StandardDeviation[
   Select[C4Tsipm1, #[[1]] ≥ rainC4Tsipm1 && #[[1]] < raoutC4Tsipm1 &]];
rmsC4Tsipm2 = StandardDeviation[Select[C4Tsipm2,
    #[[1]] ≥ rainC4Tsipm2 && #[[1]] < raoutC4Tsipm2 &]];
rmsC4Tsipm3 = StandardDeviation[Select[C4Tsipm3,
    #[[1]] ≥ rainC4Tsipm3 && #[[1]] < raoutC4Tsipm3 &]];

# Data for Ch1 Bare Sipm;

rainC1Bsipm1 = -3 * 10^-7;
raoutC1Bsipm1 = 1 * 10^-7;
rainC1Bsipm2 = -3 * 10^-7;
raoutC1Bsipm2 = 1 * 10^-7;
rainC1Bsipm3 = -3 * 10^-7;
raoutC1Bsipm3 = 1 * 10^-7;

meanC1Bsipm1 =
  Mean[Select[C1Bsipm1, #[[1]] ≥ rainC1Bsipm1 && #[[1]] < raoutC1Bsipm1 &]][[2]];
meanC1Bsipm2 = Mean[Select[C1Bsipm2,
     #[[1]] ≥ rainC1Bsipm2 && #[[1]] < raoutC1Bsipm2 &]][[2]];
meanC1Bsipm3 = Mean[Select[C1Bsipm3,
     #[[1]] ≥ rainC1Bsipm3 && #[[1]] < raoutC1Bsipm3 &]][[2]];

rmsC1Bsipm1 = StandardDeviation[
   Select[C1Bsipm1, #[[1]] ≥ rainC1Bsipm1 && #[[1]] < raoutC1Bsipm1 &]];
rmsC1Bsipm2 = StandardDeviation[Select[C1Bsipm2,
    #[[1]] ≥ rainC1Bsipm2 && #[[1]] < raoutC1Bsipm2 &]];
rmsC1Bsipm3 = StandardDeviation[Select[C1Bsipm3,
    #[[1]] ≥ rainC1Bsipm3 && #[[1]] < raoutC1Bsipm3 &]];

# Data for Ch4 Bare Sipm ;

rainC4Bsipm1 = -4.5 * 10^-7;
raoutC4Bsipm1 = -2.0 10^-7;
rainC4Bsipm2 = -4.5 * 10^-7;
raoutC4Bsipm2 = -2.0 10^-7;
rainC4Bsipm3 = -4.5 * 10^-7;
raoutC4Bsipm3 = -2.0 10^-7;
```

```
meanC4Bsipm1 =
  Mean[Select[C4Bsipm1, #[[1]] ≥ rainC4Bsipm1 && #[[1]] < raoutC4Bsipm1 &]][[2]];
meanC4Bsipm2 = Mean[Select[C4Bsipm2,
     #[[1]] ≥ rainC4Bsipm2 && #[[1]] < raoutC4Bsipm2 &]][[2]];
meanC4Bsipm3 = Mean[Select[C4Bsipm3,
     #[[1]] ≥ rainC4Bsipm3 && #[[1]] < raoutC4Bsipm3 &]][[2]];

rmsC4Bsipm1 = StandardDeviation[
   Select[C4Bsipm1, #[[1]] ≥ rainC4Bsipm1 && #[[1]] < raoutC4Bsipm1 &]];
rmsC4Bsipm2 = StandardDeviation[Select[C4Bsipm2,
    #[[1]] ≥ rainC4Bsipm2 && #[[1]] < raoutC4Bsipm2 &]];
rmsC4Bsipm3 = StandardDeviation[Select[C4Bsipm3,
    #[[1]] ≥ rainC4Bsipm3 && #[[1]] < raoutC4Bsipm3 &]];

# Data for CH1 PMT;

rainC1pmt1 = -1 * 10^-7;
raoutC1pmt1 = 1 * 10^-7;
rainC1pmt2 = -1 * 10^-7;
raoutC1pmt2 = 1 * 10^-7;
rainC1pmt3 = -1 * 10^-7;
raoutC1pmt3 = 1 * 10^-7;

meanC1pmt1 = Mean[Select[C1pmt1, #[[1]] ≥ rainC1pmt1 && #[[1]] < raoutC1pmt1 &]][[2]];
meanC1pmt2 = Mean[Select[C1pmt2, #[[1]] ≥ rainC1pmt2 && #[[1]] < raoutC1pmt2 &]][[2]];
meanC1pmt3 = Mean[Select[C1pmt3, #[[1]] ≥ rainC1pmt3 && #[[1]] < raoutC1pmt3 &]][[2]];

rmsC1pmt1 =
  StandardDeviation[Select[C1pmt1, #[[1]] ≥ rainC1pmt1 && #[[1]] < raoutC1pmt1 &]];
rmsC1pmt2 = StandardDeviation[
   Select[C1pmt2, #[[1]] ≥ rainC1pmt2 && #[[1]] < raoutC1pmt2 &]];
rmsC1pmt3 = StandardDeviation[Select[C1pmt3,
    #[[1]] ≥ rainC1pmt3 && #[[1]] < raoutC1pmt3 &]];

# Data for CH4 PMT;

rainC4pmt1 = -3.6 * 10^-7;
raoutC4pmt1 = -0.2 * 10^-7;
rainC4pmt2 = -3.6 * 10^-7;
raoutC4pmt2 = -0.2 * 10^-7;
rainC4pmt3 = -3.6 * 10^-7;
raoutC4pmt3 = -0.2 * 10^-7;

meanC4pmt1 = Mean[Select[C4pmt1, #[[1]] ≥ rainC4pmt1 && #[[1]] < raoutC4pmt1 &]][[2]];
meanC4pmt2 = Mean[Select[C4pmt2, #[[1]] ≥ rainC4pmt2 && #[[1]] < raoutC4pmt2 &]][[2]];
meanC4pmt3 = Mean[Select[C4pmt3, #[[1]] ≥ rainC4pmt3 && #[[1]] < raoutC4pmt3 &]][[2]];

rmsC4pmt1 =
  StandardDeviation[Select[C4pmt1, #[[1]] ≥ rainC4pmt1 && #[[1]] < raoutC4pmt1 &]];
rmsC4pmt2 = StandardDeviation[
   Select[C4pmt2, #[[1]] ≥ rainC4pmt2 && #[[1]] < raoutC4pmt2 &]];
rmsC4pmt3 = StandardDeviation[Select[C4pmt3,
    #[[1]] ≥ rainC4pmt3 && #[[1]] < raoutC4pmt3 &]];

# Def p funct

Def funct p #1
```

```
pfunction[min_, max_, list_, mean_] := Show[
  ListPlot[{Map[{#[[1]], #[[2]] - mean} &, Select[list, #[[1]] > min && #[[1]] < max &]],
    Map[{#[[1]], #[[2]] - mean} &, Select[list, #[[1]] > min && #[[1]] < max &]]},
   Joined → {True, False}]]
```

```
# Statistics for CH1 bare Sipm Trigg Signal all three cases;
```

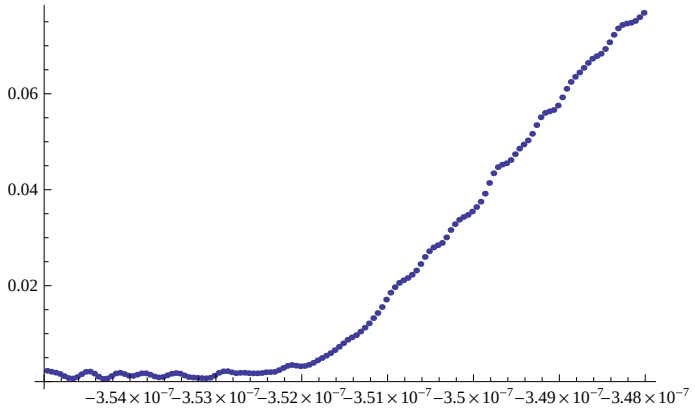
```
pfunction[rainC1Bsipm1, raoutC1Bsipm1, C1Bsipm1, meanC1Bsipm1]
pfunction[rainC1Bsipm2, raoutC1Bsipm2, C1Bsipm2, meanC1Bsipm2]
pfunction[rainC1Bsipm3, raoutC1Bsipm3, C1Bsipm3, meanC1Bsipm3]
```

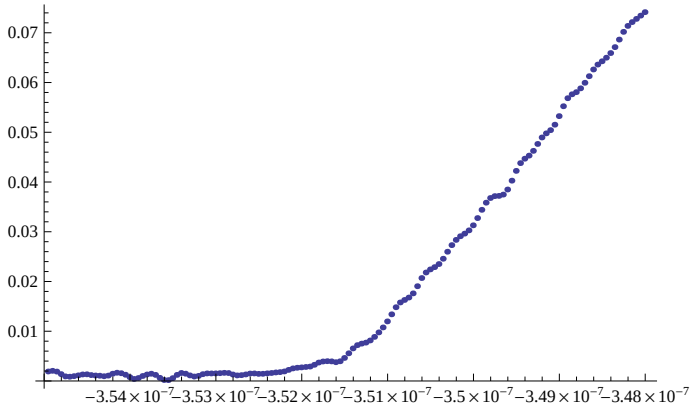


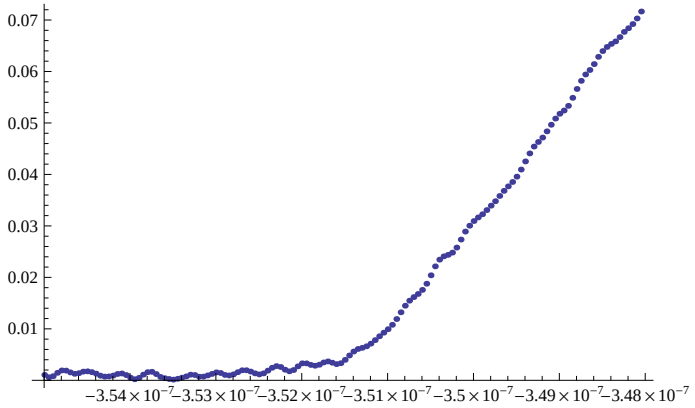
You have to find when we see the signal
bg2in is the timing just before the real signal appear
d2 is a duration time of data

```
beginC1Bsipm = -3.55 * 10^-7;
durationC1Bsipm = 0.07 * 10^-7;
```

```
lC1Bsipm1 = Map[{#[[1]], #[[2]]} &,
   Select[C1Bsipm1, #[[1]] > beginC1Bsipm && #[[1]] < beginC1Bsipm + durationC1Bsipm &]];
lC1Bsipm2 = Map[{#[[1]], #[[2]]} &, Select[C1Bsipm2,
    #[[1]] > beginC1Bsipm && #[[1]] < beginC1Bsipm + durationC1Bsipm &]];
lC1Bsipm3 = Map[{#[[1]], #[[2]]} &, Select[C1Bsipm3,
    #[[1]] > beginC1Bsipm && #[[1]] < beginC1Bsipm + durationC1Bsipm &]];

ListPlot[lC1Bsipm1]
ListPlot[lC1Bsipm2]
ListPlot[lC1Bsipm3]
```

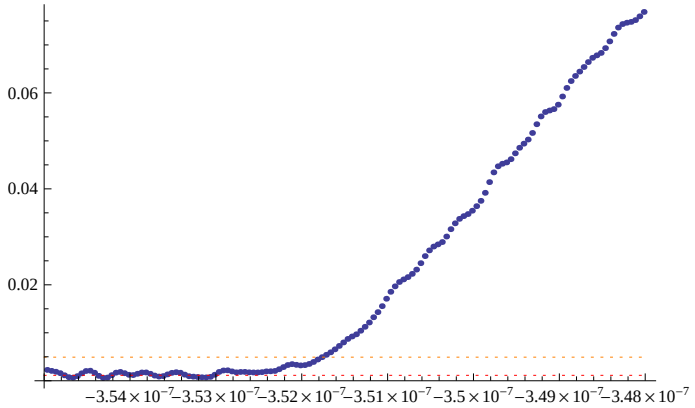


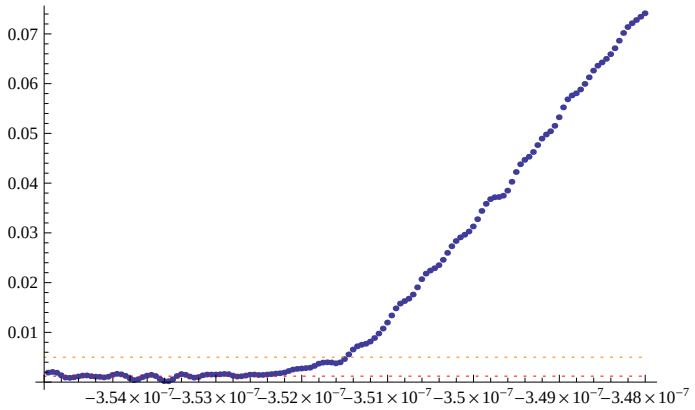


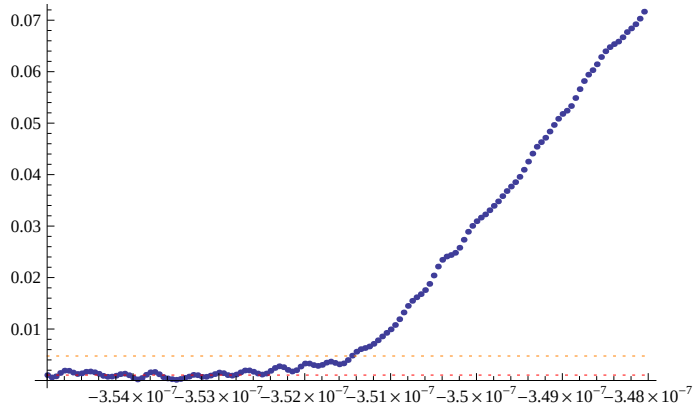


Plot shows the raw data with three lines
A middle line is an average of bg data
Two other lines are 2 sigma (RMS) away from the average value

```
Show[ListPlot[Map[{#[[1]], #[[2]]} &,
   Select[C1Bsipm1, #[[1]] > beginC1Bsipm && #[[1]] < beginC1Bsipm + durationC1Bsipm &]]],
 Graphics[{Red, Dotted, Line[{{beginC1Bsipm, meanC1Bsipm1},
     {beginC1Bsipm + durationC1Bsipm, meanC1Bsipm1}}]}],
 Graphics[{Orange, Dotted, Line[{{beginC1Bsipm, meanC1Bsipm1 + 6. rmsC1Bsipm1[[2]]},
     {beginC1Bsipm + durationC1Bsipm, meanC1Bsipm1 + 6. rmsC1Bsipm1[[2]]}}]}],
 Graphics[{Orange, Dotted, Line[{{beginC1Bsipm, meanC1Bsipm1 - 6. rmsC1Bsipm1[[2]]},
     {beginC1Bsipm + durationC1Bsipm, meanC1Bsipm1 - 6. rmsC1Bsipm1[[2]]}}]}]]

Show[ListPlot[Map[{#[[1]], #[[2]]} &,
   Select[C1Bsipm2, #[[1]] > beginC1Bsipm && #[[1]] < beginC1Bsipm + durationC1Bsipm &]]],
 Graphics[{Red, Dotted, Line[{{beginC1Bsipm, meanC1Bsipm2},
     {beginC1Bsipm + durationC1Bsipm, meanC1Bsipm2}}]}],
 Graphics[{Orange, Dotted, Line[{{beginC1Bsipm, meanC1Bsipm2 + 6. rmsC1Bsipm2[[2]]},
     {beginC1Bsipm + durationC1Bsipm, meanC1Bsipm2 + 6. rmsC1Bsipm2[[2]]}}]}],
 Graphics[{Orange, Dotted, Line[{{beginC1Bsipm, meanC1Bsipm2 - 6. rmsC1Bsipm2[[2]]},
     {beginC1Bsipm + durationC1Bsipm, meanC1Bsipm2 - 6. rmsC1Bsipm2[[2]]}}]}]]

Show[ListPlot[Map[{#[[1]], #[[2]]} &,
   Select[C1Bsipm3, #[[1]] > beginC1Bsipm && #[[1]] < beginC1Bsipm + durationC1Bsipm &]]],
 Graphics[{Red, Dotted, Line[{{beginC1Bsipm, meanC1Bsipm3},
     {beginC1Bsipm + durationC1Bsipm, meanC1Bsipm3}}]}],
 Graphics[{Orange, Dotted, Line[{{beginC1Bsipm, meanC1Bsipm3 + 6. rmsC1Bsipm3[[2]]},
     {beginC1Bsipm + durationC1Bsipm, meanC1Bsipm3 + 6. rmsC1Bsipm3[[2]]}}]}],
 Graphics[{Orange, Dotted, Line[{{beginC1Bsipm, meanC1Bsipm3 - 6. rmsC1Bsipm3[[2]]},
     {beginC1Bsipm + durationC1Bsipm, meanC1Bsipm3 - 6. rmsC1Bsipm3[[2]]}}]}]]
```



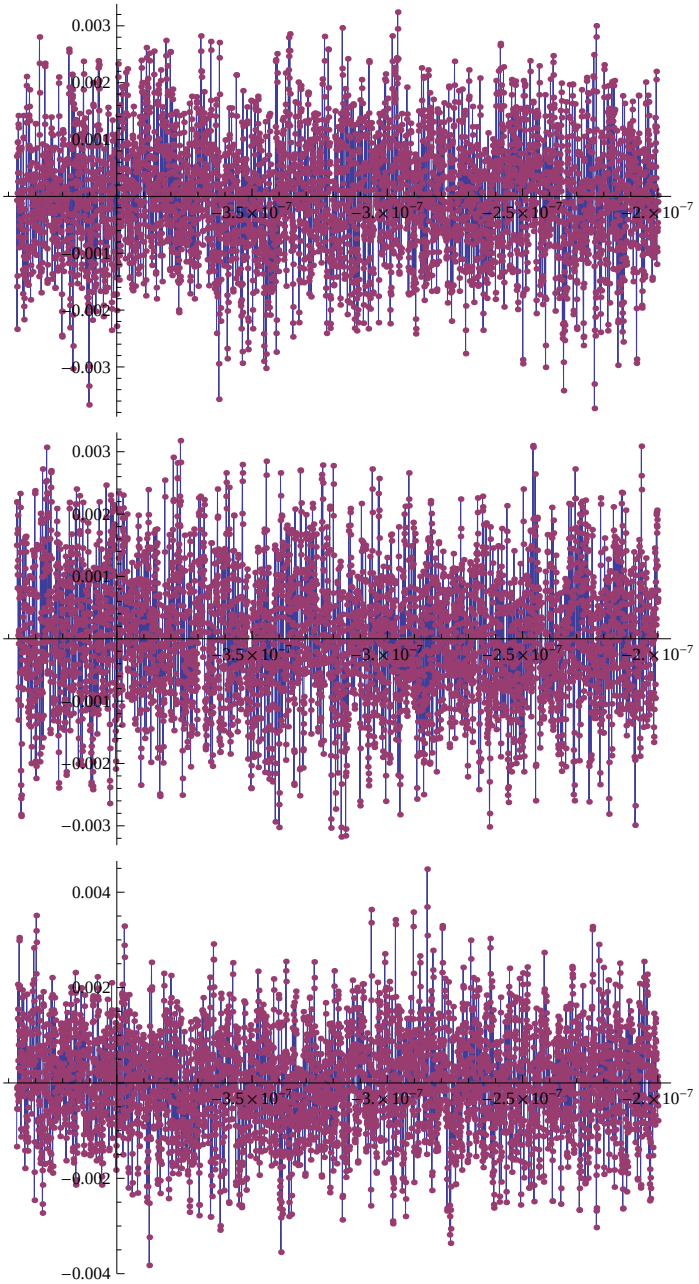





```
minC1Bsipm1 = Select[lC1Bsipm1,
   #[[2]] > Abs[ meanC1Bsipm1 + 6 rmsC1Bsipm1[[2]]]  && #[[1]] > beginC1Bsipm &];
minC1Bsipm2 = Select[lC1Bsipm2,
   #[[2]] > Abs[ meanC1Bsipm2 + 6 rmsC1Bsipm2[[2]]]  && #[[1]] > beginC1Bsipm &];
minC1Bsipm3 = Select[lC1Bsipm3,
   #[[2]] > Abs[ meanC1Bsipm3 + 6 rmsC1Bsipm3[[2]]]  && #[[1]] > beginC1Bsipm &];
```

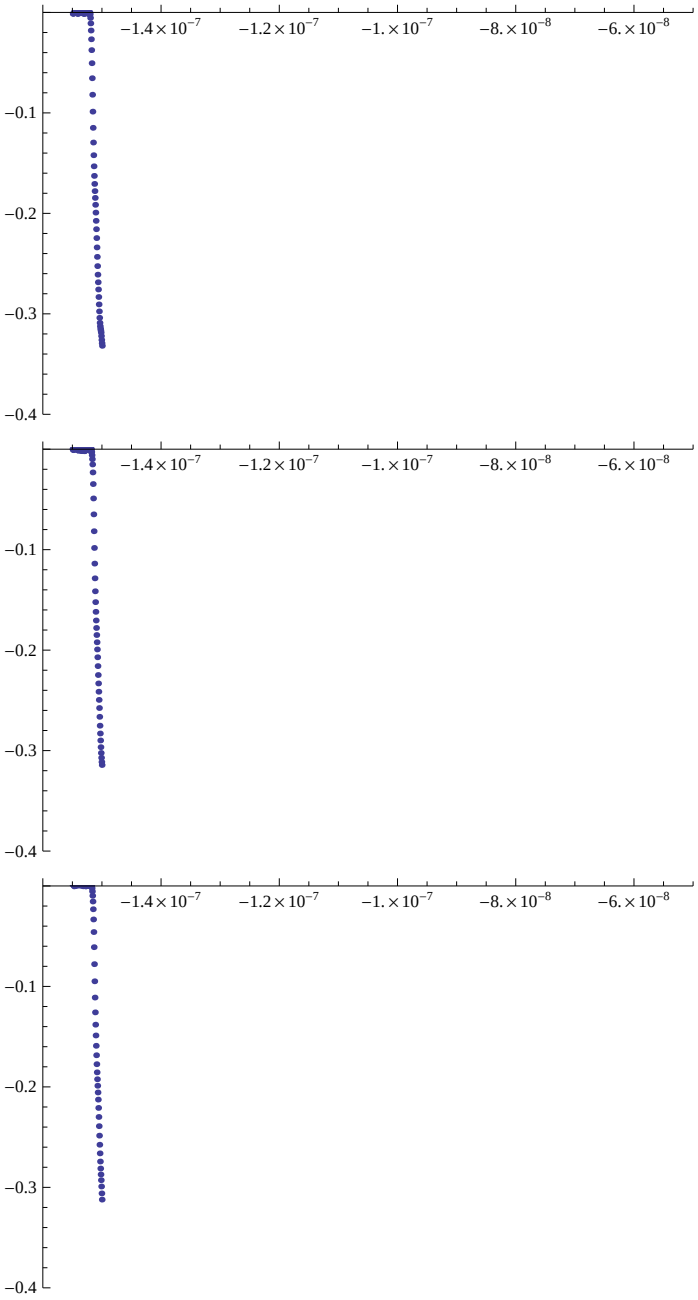
```
# Statistics for CH4 Bare Sipm Optical Signal three cases;
```

```
pfunction[rainC4Bsipm1, raoutC4Bsipm1, C4Bsipm1, meanC4Bsipm1]
pfunction[rainC4Bsipm2, raoutC4Bsipm2, C4Bsipm2, meanC4Bsipm2]
pfunction[rainC4Bsipm3, raoutC4Bsipm3, C4Bsipm3, meanC4Bsipm3]
```

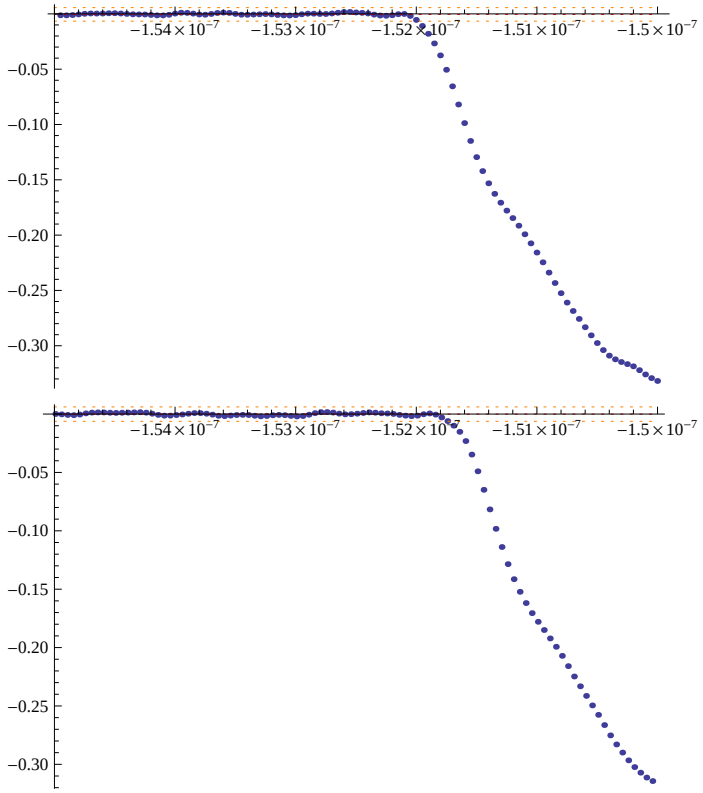


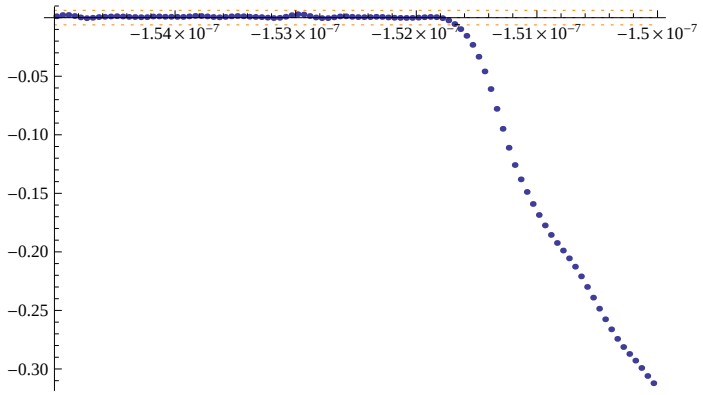

```
beginC4Bsipm = -1.55 * 10^-7;
durationC4Bsipm = 0.05 * 10^-7;

lC4Bsipm1 = Map[{#[[1]], #[[2]]} &,
   Select[C4Bsipm1, #[[1]] > beginC4Bsipm && #[[1]] < beginC4Bsipm + durationC4Bsipm &]];
lC4Bsipm2 = Map[{#[[1]], #[[2]]} &, Select[C4Bsipm2,
    #[[1]] > beginC4Bsipm && #[[1]] < beginC4Bsipm + durationC4Bsipm &]];
lC4Bsipm3 = Map[{#[[1]], #[[2]]} &, Select[C4Bsipm3,
    #[[1]] > beginC4Bsipm && #[[1]]  < beginC4Bsipm + durationC4Bsipm &]];
```

```
ListPlot[{lC4Bsipm1}, PlotRange → {{-1.6 * 10^-7, -0.5 * 10^-7}, {0, -0.4}}]
ListPlot[{lC4Bsipm2}, PlotRange → {{-1.6 * 10^-7, -0.5 * 10^-7}, {0, -0.4}}]
ListPlot[{lC4Bsipm3}, PlotRange → {{-1.6 * 10^-7, -0.5 * 10^-7}, {0, -0.4}}]
```



```
Show[ListPlot[Map[{#[[1]], #[[2]]} &,
   Select[C4Bsipm1, #[[1]] > beginC4Bsipm && #[[1]] < beginC4Bsipm + durationC4Bsipm &]]],
 Graphics[{Red, Dotted, Line[{{beginC4Bsipm, meanC4Bsipm1},
     {beginC4Bsipm + durationC4Bsipm, meanC4Bsipm1}}]}],
 Graphics[{Orange, Dotted, Line[{{beginC4Bsipm, meanC4Bsipm1 + 6. rmsC4Bsipm1[[2]]},
     {beginC4Bsipm + durationC4Bsipm, meanC4Bsipm1 + 6. rmsC4Bsipm1[[2]]}}]}],
 Graphics[{Orange, Dotted, Line[{{beginC4Bsipm, meanC4Bsipm1 - 6. rmsC4Bsipm1[[2]]},
     {beginC4Bsipm + durationC4Bsipm, meanC4Bsipm1 - 6. rmsC4Bsipm1[[2]]}}]}]]

Show[ListPlot[Map[{#[[1]], #[[2]]} &,
   Select[C4Bsipm2, #[[1]] > beginC4Bsipm && #[[1]] < beginC4Bsipm + durationC4Bsipm &]]],
 Graphics[{Red, Dotted, Line[{{beginC4Bsipm, meanC4Bsipm2},
     {beginC4Bsipm + durationC4Bsipm, meanC4Bsipm2}}]}],
 Graphics[{Orange, Dotted, Line[{{beginC4Bsipm, meanC4Bsipm2 + 6. rmsC4Bsipm2[[2]]},
     {beginC4Bsipm + durationC4Bsipm, meanC4Bsipm2 + 6. rmsC4Bsipm2[[2]]}}]}],
 Graphics[{Orange, Dotted, Line[{{beginC4Bsipm, meanC4Bsipm2 - 6. rmsC4Bsipm2[[2]]},
     {beginC4Bsipm + durationC4Bsipm, meanC4Bsipm2 - 6. rmsC4Bsipm2[[2]]}}]}]]

Show[ListPlot[Map[{#[[1]], #[[2]]} &,
   Select[C4Bsipm3, #[[1]] > beginC4Bsipm && #[[1]] < beginC4Bsipm + durationC4Bsipm &]]],
 Graphics[{Red, Dotted, Line[{{beginC4Bsipm, meanC4Bsipm3},
     {beginC4Bsipm + durationC4Bsipm, meanC4Bsipm3}}]}],
 Graphics[{Orange, Dotted, Line[{{beginC4Bsipm, meanC4Bsipm3 + 6. rmsC4Bsipm3[[2]]},
     {beginC4Bsipm + durationC4Bsipm, meanC4Bsipm3 + 6. rmsC4Bsipm3[[2]]}}]}],
 Graphics[{Orange, Dotted, Line[{{beginC4Bsipm, meanC4Bsipm3 - 6. rmsC4Bsipm3[[2]]},
     {beginC4Bsipm + durationC4Bsipm, meanC4Bsipm3 - 6. rmsC4Bsipm3[[2]]}}]}]]
```






```
minC4Bsipm1 = Select[lC4Bsipm1,
    Abs[#[[2]]] > Abs[ meanC4Bsipm1 + 6 rmsC4Bsipm1[[2]]]  && #[[1]] > beginC4Bsipm &];
minC4Bsipm2 = Select[lC4Bsipm2,
    Abs[#[[2]]] > Abs[ meanC4Bsipm2 + 6 rmsC4Bsipm2[[2]]]  && #[[1]] > beginC4Bsipm &];
minC4Bsipm3 = Select[lC4Bsipm3,
    Abs[#[[2]]] > Abs[ meanC4Bsipm3 + 6 rmsC4Bsipm3[[2]]]  && #[[1]] > beginC4Bsipm &];
```

```
diff1 = Abs[minC1Bsipm1[[1, 1]] - minC4Bsipm1[[1, 1]]]
diff2 = Abs[minC1Bsipm2[[1, 1]] - minC4Bsipm2[[1, 1]]]
diff3 = Abs[minC1Bsipm3[[1, 1]] - minC4Bsipm3[[1, 1]]]
```

1.99764×10^{-7}

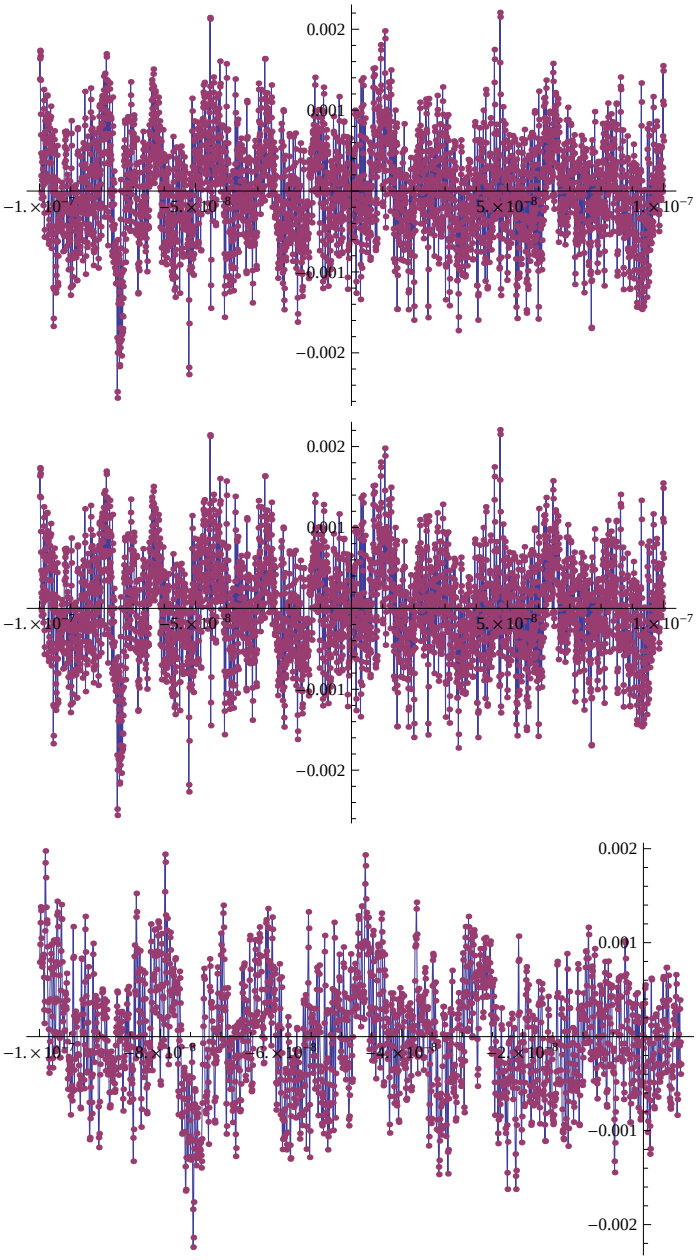
1.99764×10^{-7}

1.99814×10^{-7}

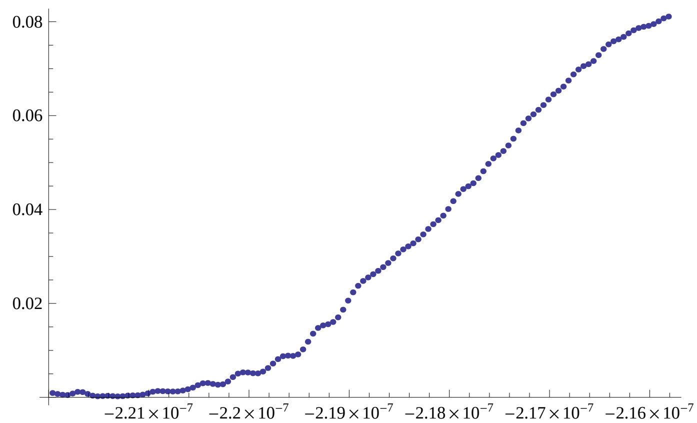
```
(diff1 + diff2 + diff3) / 3
```

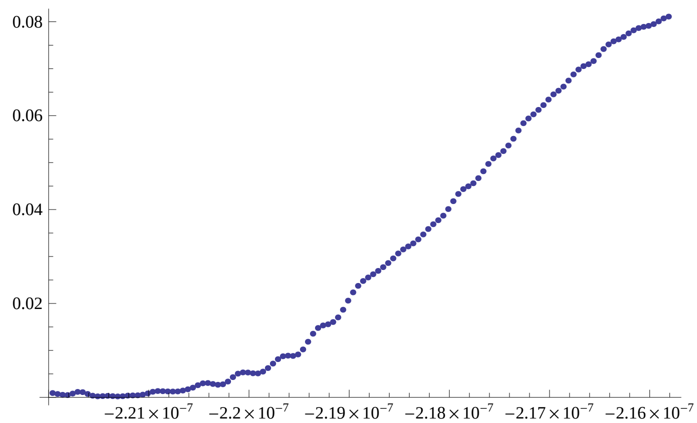
1.99781×10^{-7}

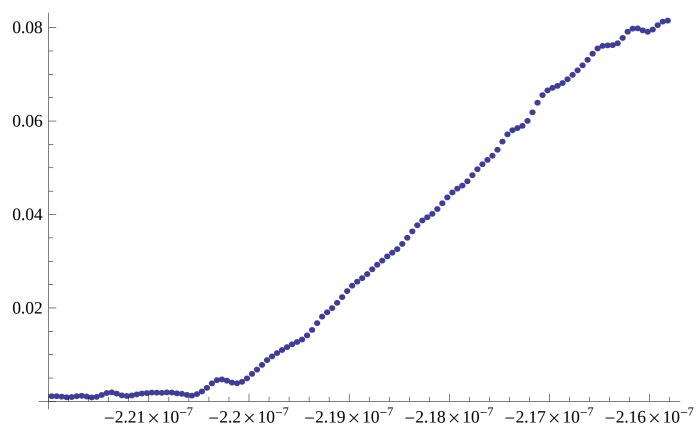
```
# Statistics for CH1TSiPM three trig cases;

pfunction[rainC1Tsipm1, raoutC1Tsipm1, C1Tsipm1, meanC1Tsipm1]
pfunction[rainC1Tsipm2, raoutC1Tsipm2, C1Tsipm2, meanC1Tsipm2]
pfunction[rainC1Tsipm3, raoutC1Tsipm3, C1Tsipm3, meanC1Tsipm3]
```



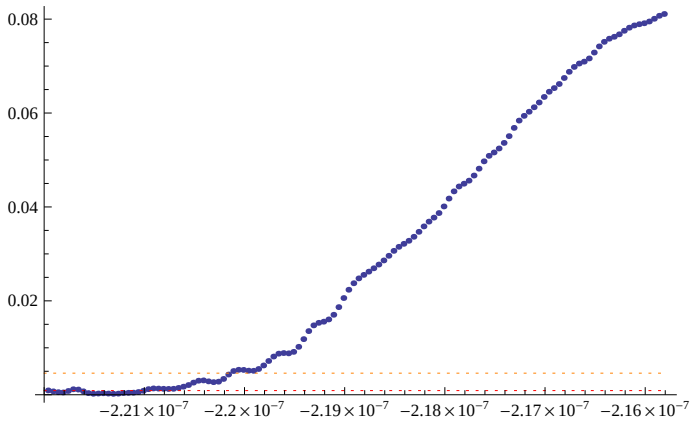
```
beginC1Tsipm = -2.22 * 10^-7;
durationC1Tsipm = 0.062 * 10^-7;

lC1Tsipm1 = Map[{#[[1]], #[[2]]} &,
   Select[C1Tsipm1, #[[1]] > beginC1Tsipm && #[[1]] < beginC1Tsipm + durationC1Tsipm &]];
lC1Tsipm2 = Map[{#[[1]], #[[2]]} &, Select[C1Tsipm2,
    #[[1]] > beginC1Tsipm && #[[1]] < beginC1Tsipm + durationC1Tsipm &]];
lC1Tsipm3 = Map[{#[[1]], #[[2]]} &, Select[C1Tsipm3,
    #[[1]] > beginC1Tsipm && #[[1]] < beginC1Tsipm + durationC1Tsipm &]];

ListPlot[lC1Tsipm1]
ListPlot[lC1Tsipm2]
ListPlot[lC1Tsipm3]
```

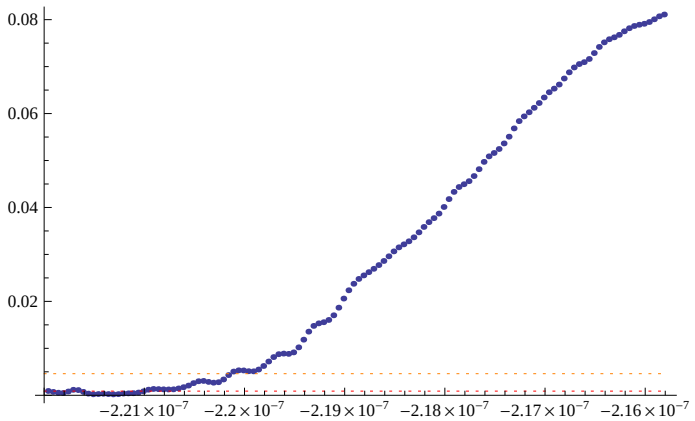


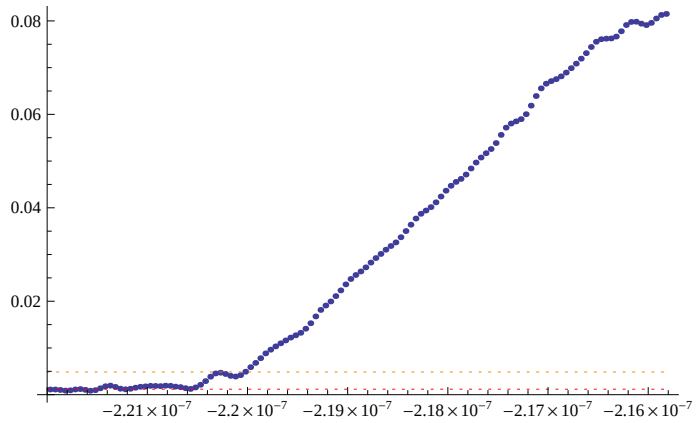




```
Show[ListPlot[Map[{#[[1]], #[[2]]} &,
   Select[C1Tsipm1, #[[1]] > beginC1Tsipm && #[[1]] < beginC1Tsipm + durationC1Tsipm &]]],
 Graphics[{Red, Dotted, Line[{{beginC1Tsipm, meanC1Tsipm1},
     {beginC1Tsipm + durationC1Tsipm, meanC1Tsipm1}}]}],
 Graphics[{Orange, Dotted, Line[{{beginC1Tsipm, meanC1Tsipm1 + 6. rmsC1Tsipm1[[2]]},
     {beginC1Tsipm + durationC1Tsipm, meanC1Tsipm1 + 6. rmsC1Tsipm1[[2]]}}]}],
 Graphics[{Orange, Dotted, Line[{{beginC1Tsipm, meanC1Tsipm1 - 6. rmsC1Tsipm1[[2]]},
     {beginC1Tsipm + durationC1Tsipm, meanC1Tsipm1 - 6. rmsC1Tsipm1[[2]]}}]}]]

Show[ListPlot[Map[{#[[1]], #[[2]]} &,
   Select[C1Tsipm2, #[[1]] > beginC1Tsipm && #[[1]] < beginC1Tsipm + durationC1Tsipm &]]],
 Graphics[{Red, Dotted, Line[{{beginC1Tsipm, meanC1Tsipm2},
     {beginC1Tsipm + durationC1Tsipm, meanC1Tsipm2}}]}],
 Graphics[{Orange, Dotted, Line[{{beginC1Tsipm, meanC1Tsipm2 + 6. rmsC1Tsipm2[[2]]},
     {beginC1Tsipm + durationC1Tsipm, meanC1Tsipm2 + 6. rmsC1Tsipm2[[2]]}}]}],
 Graphics[{Orange, Dotted, Line[{{beginC1Tsipm, meanC1Tsipm2 - 6. rmsC1Tsipm2[[2]]},
     {beginC1Tsipm + durationC1Tsipm, meanC1Tsipm2 - 6. rmsC1Tsipm2[[2]]}}]}]]

Show[ListPlot[Map[{#[[1]], #[[2]]} &,
   Select[C1Tsipm3, #[[1]] > beginC1Tsipm && #[[1]] < beginC1Tsipm + durationC1Tsipm &]]],
 Graphics[{Red, Dotted, Line[{{beginC1Tsipm, meanC1Tsipm3},
     {beginC1Tsipm + durationC1Tsipm, meanC1Tsipm3}}]}],
 Graphics[{Orange, Dotted, Line[{{beginC1Tsipm, meanC1Tsipm3 + 6. rmsC1Tsipm3[[2]]},
     {beginC1Tsipm + durationC1Tsipm, meanC1Tsipm3 + 6. rmsC1Tsipm3[[2]]}}]}],
 Graphics[{Orange, Dotted, Line[{{beginC1Tsipm, meanC1Tsipm3 - 6. rmsC1Tsipm3[[2]]},
     {beginC1Tsipm + durationC1Tsipm, meanC1Tsipm3 - 6. rmsC1Tsipm3[[2]]}}]}]]
```

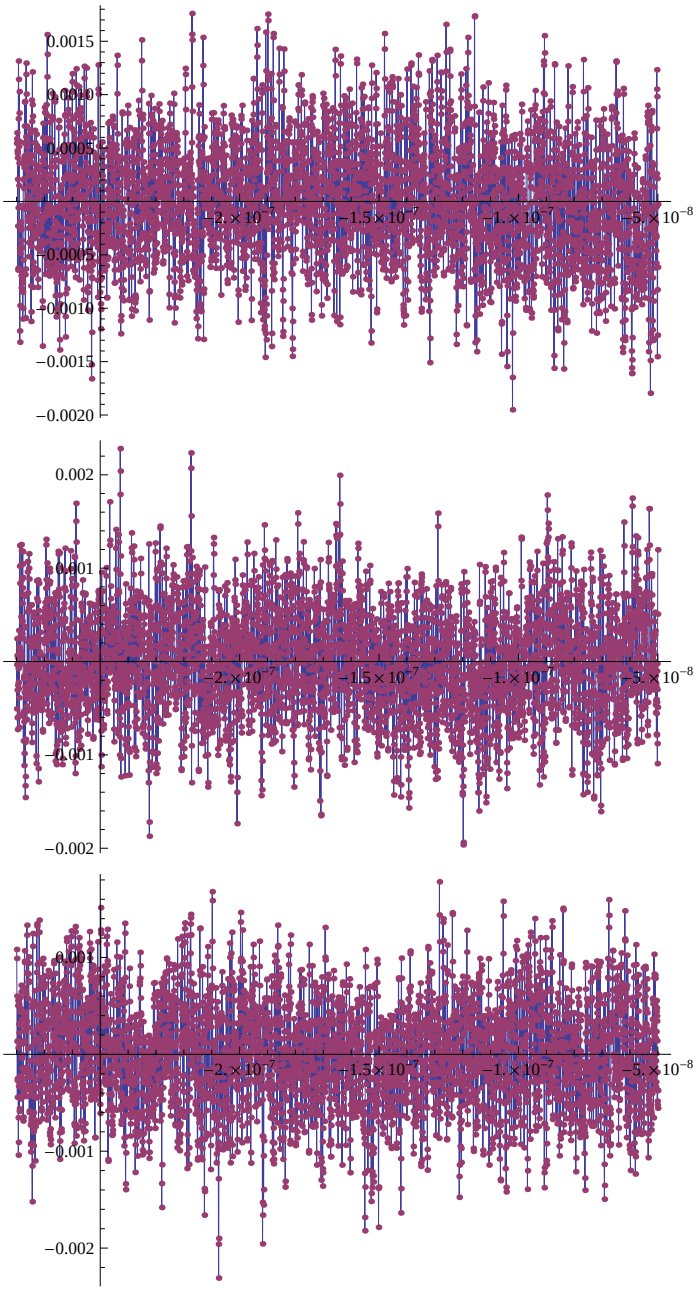




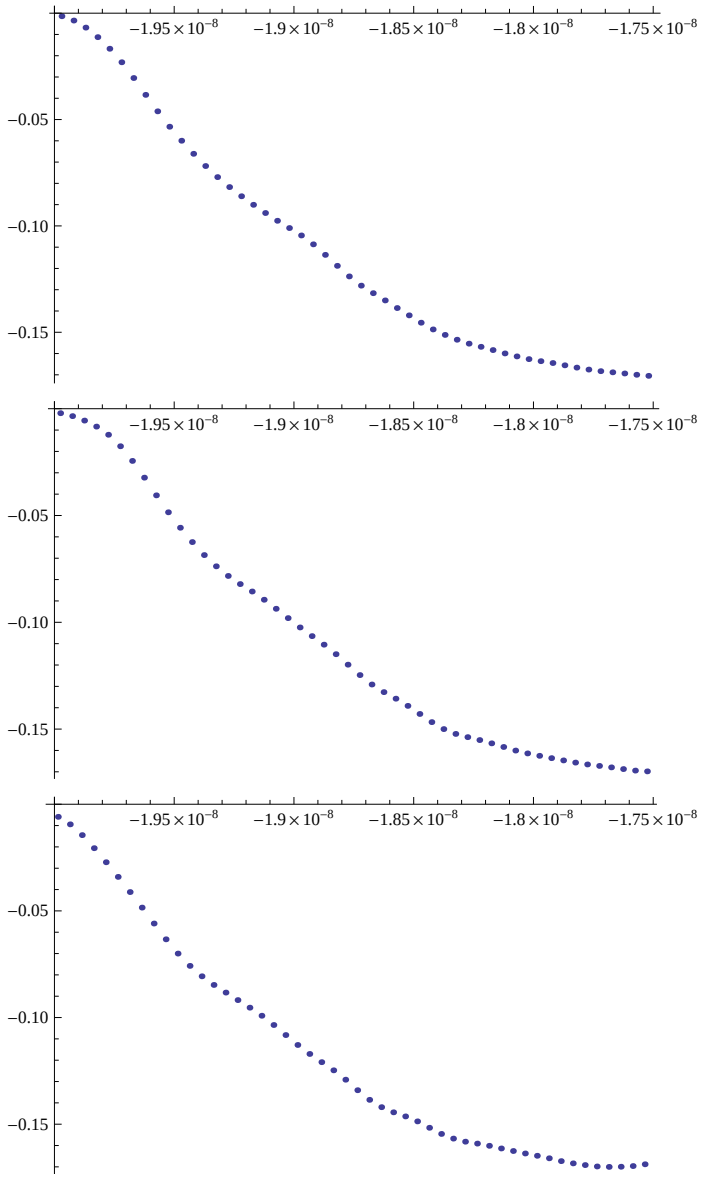



```
minC1Tsipm1 = Select[lC1Tsipm1,
   #[[2]] > Abs[ meanC1Tsipm1 + 6 rmsC1Tsipm1[[2]]]  && #[[1]] > beginC1Tsipm &];
minC1Tsipm2 = Select[lC1Tsipm2,
   #[[2]] > Abs[ meanC1Tsipm2 + 6 rmsC1Tsipm2[[2]]]  && #[[1]] > beginC1Tsipm &];
minC1Tsipm3 = Select[lC1Tsipm3,
   #[[2]] > Abs[ meanC1Tsipm3 + 6 rmsC1Tsipm3[[2]]]  && #[[1]] > beginC1Tsipm &];
```

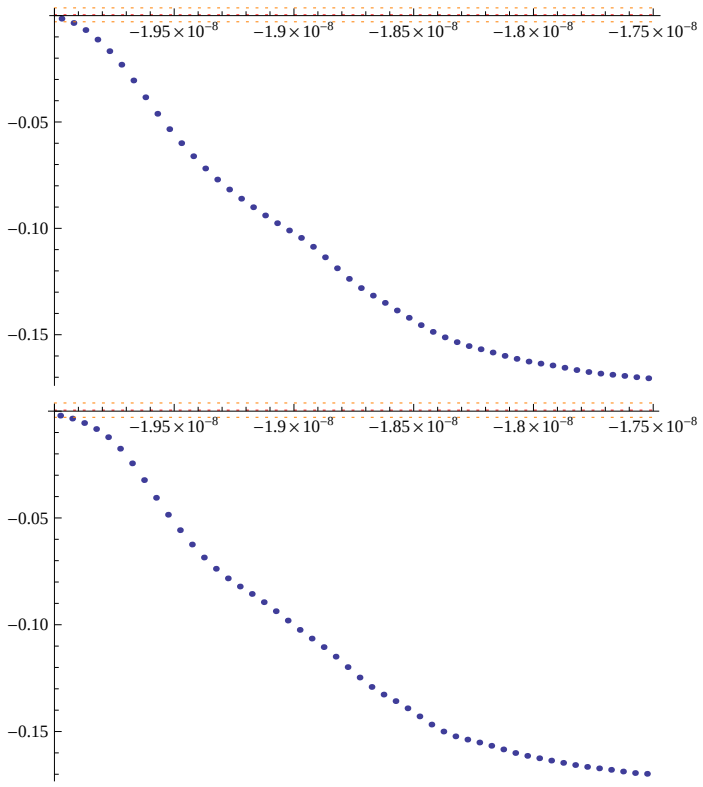
```
# Statistics for Tsipm CH4 optical signal three cases;

pfunction[rainC4Tsipm1, raoutC4Tsipm1, C4Tsipm1, meanC4Tsipm1]
pfunction[rainC4Tsipm2, raoutC4Tsipm2, C4Tsipm2, meanC4Tsipm2]
pfunction[rainC4Tsipm3, raoutC4Tsipm3, C4Tsipm3, meanC4Tsipm3]
```

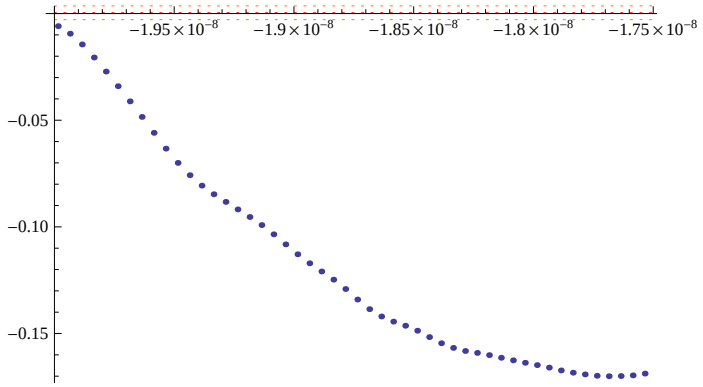


```
beginC4Tsipm = -0.2 * 10^-7;
durationC4Tsipm = 0.025 * 10^-7;

lC4Tsipm1 = Map[{#[[1]], #[[2]]} &,
   Select[C4Tsipm1, #[[1]] > beginC4Tsipm && #[[1]] < beginC4Tsipm + durationC4Tsipm &]];
lC4Tsipm2 = Map[{#[[1]], #[[2]]} &, Select[C4Tsipm2,
    #[[1]] > beginC4Tsipm && #[[1]] < beginC4Tsipm + durationC4Tsipm &]];
lC4Tsipm3 = Map[{#[[1]], #[[2]]} &, Select[C4Tsipm3,
    #[[1]] > beginC4Tsipm && #[[1]]  < beginC4Tsipm + durationC4Tsipm &]];

ListPlot[{lC4Tsipm1}]
ListPlot[{lC4Tsipm2}]
ListPlot[{lC4Tsipm3}]
```



```
Show[ListPlot[Map[{#[[1]], #[[2]]} &,
   Select[C4Tsipm1, #[[1]] > beginC4Tsipm && #[[1]] < beginC4Tsipm + durationC4Tsipm &]]],
 Graphics[{Red, Dotted, Line[{{beginC4Tsipm, meanC4Tsipm1},
     {beginC4Tsipm + durationC4Tsipm, meanC4Tsipm1}}]}],
 Graphics[{Orange, Dotted, Line[{{beginC4Tsipm, meanC4Tsipm1 + 6. rmsC4Tsipm1[[2]]},
     {beginC4Tsipm + durationC4Tsipm, meanC4Tsipm1 + 6. rmsC4Tsipm1[[2]]}}]}],
 Graphics[{Orange, Dotted, Line[{{beginC4Tsipm, meanC4Tsipm1 - 6. rmsC4Tsipm1[[2]]},
     {beginC4Tsipm + durationC4Tsipm, meanC4Tsipm1 - 6. rmsC4Tsipm1[[2]]}}]}]]

Show[ListPlot[Map[{#[[1]], #[[2]]} &,
   Select[C4Tsipm2, #[[1]] > beginC4Tsipm && #[[1]] < beginC4Tsipm + durationC4Tsipm &]]],
 Graphics[{Red, Dotted, Line[{{beginC4Tsipm, meanC4Tsipm2},
     {beginC4Tsipm + durationC4Tsipm, meanC4Tsipm2}}]}],
 Graphics[{Orange, Dotted, Line[{{beginC4Tsipm, meanC4Tsipm2 + 6. rmsC4Tsipm2[[2]]},
     {beginC4Tsipm + durationC4Tsipm, meanC4Tsipm2 + 6. rmsC4Tsipm2[[2]]}}]}],
 Graphics[{Orange, Dotted, Line[{{beginC4Tsipm, meanC4Tsipm2 - 6. rmsC4Tsipm2[[2]]},
     {beginC4Tsipm + durationC4Tsipm, meanC4Tsipm2 - 6. rmsC4Tsipm2[[2]]}}]}]]

Show[ListPlot[Map[{#[[1]], #[[2]]} &,
   Select[C4Tsipm3, #[[1]] > beginC4Tsipm && #[[1]] < beginC4Tsipm + durationC4Tsipm &]]],
 Graphics[{Red, Dotted, Line[{{beginC4Tsipm, meanC4Tsipm3},
     {beginC4Tsipm + durationC4Tsipm, meanC4Tsipm3}}]}],
 Graphics[{Orange, Dotted, Line[{{beginC4Tsipm, meanC4Tsipm3 + 6. rmsC4Tsipm3[[2]]},
     {beginC4Tsipm + durationC4Tsipm, meanC4Tsipm3 + 6. rmsC4Tsipm3[[2]]}}]}],
 Graphics[{Orange, Dotted, Line[{{beginC4Tsipm, meanC4Tsipm3 - 6. rmsC4Tsipm3[[2]]},
     {beginC4Tsipm + durationC4Tsipm, meanC4Tsipm3 - 6. rmsC4Tsipm3[[2]]}}]}]]
```






```
minC4Tsipm1 = Select[lC4Tsipm1,
    Abs[#[[2]]] > Abs[ meanC4Tsipm1 + 6 rmsC4Tsipm1[[2]]]  && #[[1]] > beginC4Tsipm &];
minC4Tsipm2 = Select[lC4Tsipm2,
    Abs[#[[2]]] > Abs[ meanC4Tsipm2 + 6 rmsC4Tsipm2[[2]]]  && #[[1]] > beginC4Tsipm &];
minC4Tsipm3 = Select[lC4Tsipm3,
    Abs[#[[2]]] > Abs[ meanC4Tsipm3  + 6 rmsC4Tsipm3[[2]]]  && #[[1]] > beginC4Tsipm &];

diff1  =  Abs[minC1Tsipm1[[1, 1]] - minC4Tsipm1[[1, 1]]]
diff2  =  Abs[minC1Tsipm2[[1, 1]] - minC4Tsipm2[[1, 1]]]
diff3  =  Abs[minC1Tsipm3[[1, 1]] - minC4Tsipm3[[1, 1]]]

(diff1 + diff2 + diff3) / 3
```

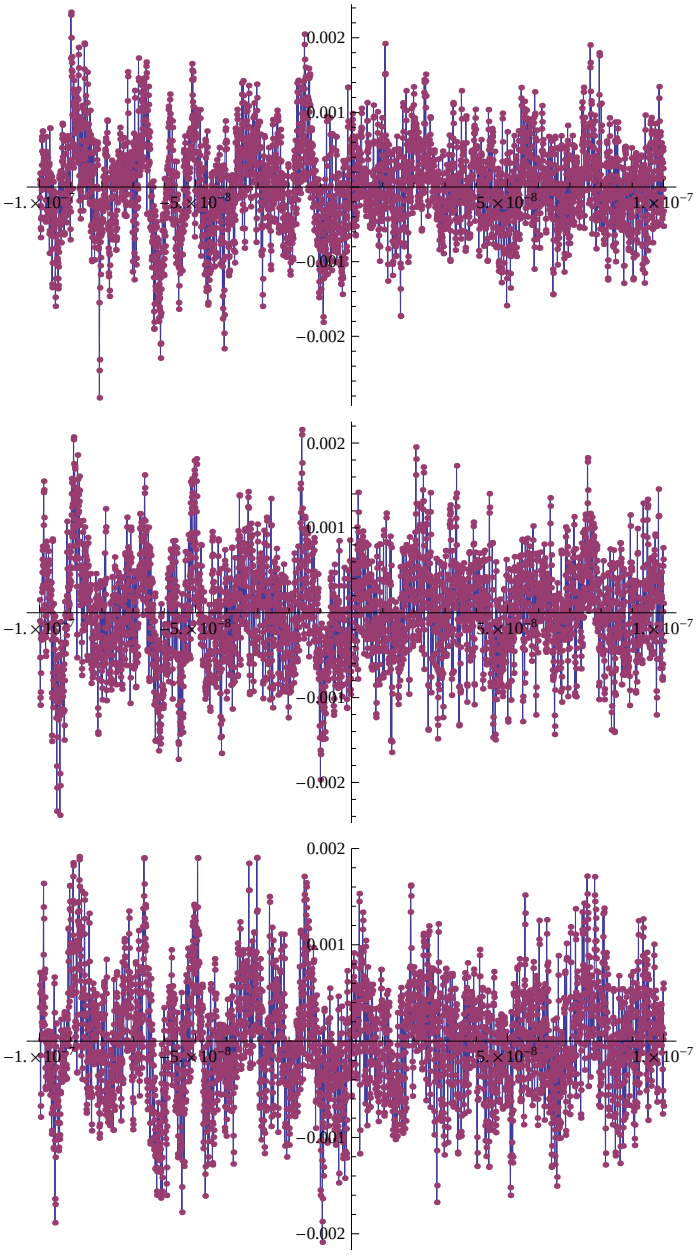
2.18392×10^{-7}

2.18387×10^{-7}

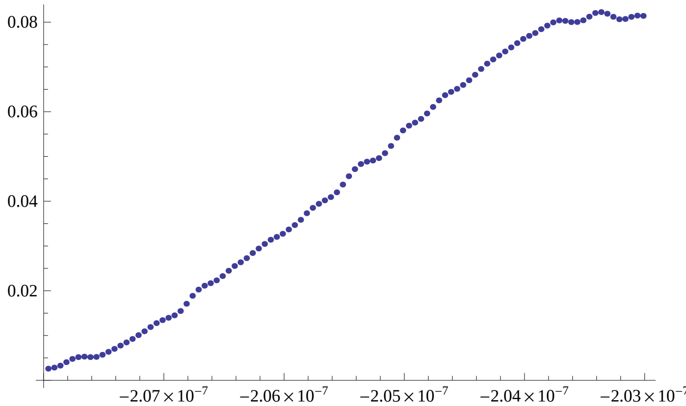
2.18287×10^{-7}

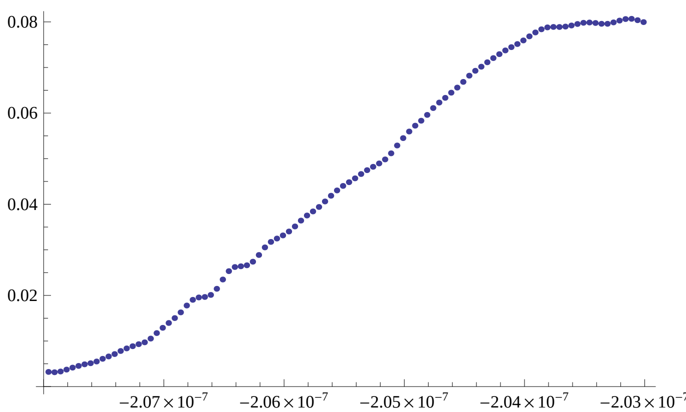
2.18355×10^{-7}

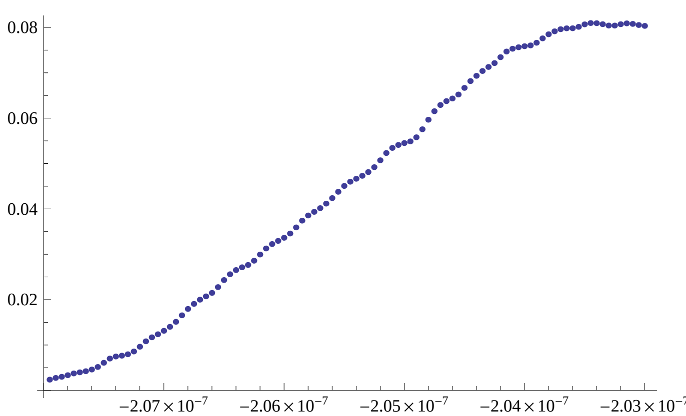
```
# Statistics for PMT CH1 trigger signal with three measurements;

pfunction[rainC1pmt1, raoutC1pmt1, C1pmt1, meanC1pmt1]
pfunction[rainC1pmt2, raoutC1pmt2, C1pmt2, meanC1pmt2]
pfunction[rainC1pmt3, raoutC1pmt3, C1pmt3, meanC1pmt3]
```



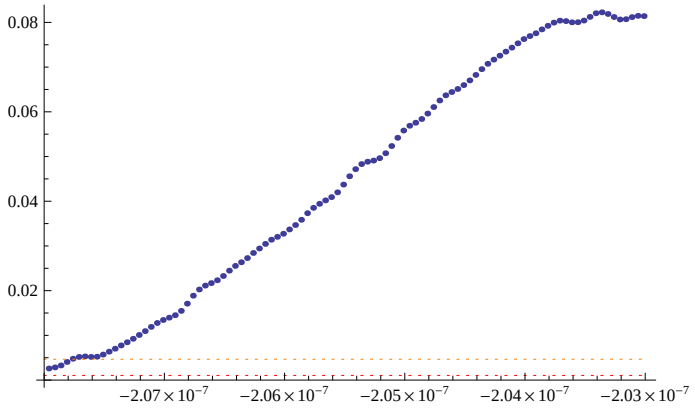
```
beginC1pmt = -2.08 * 10^-7;
durationC1pmt = 0.05 * 10^-7;

lC1pmt1 = Map[{#[[1]], #[[2]]} &,
   Select[C1pmt1, #[[1]] > beginC1pmt && #[[1]] < beginC1pmt + durationC1pmt &]];
lC1pmt2 = Map[{#[[1]], #[[2]]} &, Select[C1pmt2,
    #[[1]] > beginC1pmt && #[[1]] < beginC1pmt + durationC1pmt &]];
lC1pmt3 = Map[{#[[1]], #[[2]]} &, Select[C1pmt3,
    #[[1]] > beginC1pmt && #[[1]] < beginC1pmt + durationC1pmt &]];

ListPlot[lC1pmt1]
ListPlot[lC1pmt2]
ListPlot[lC1pmt3]
```

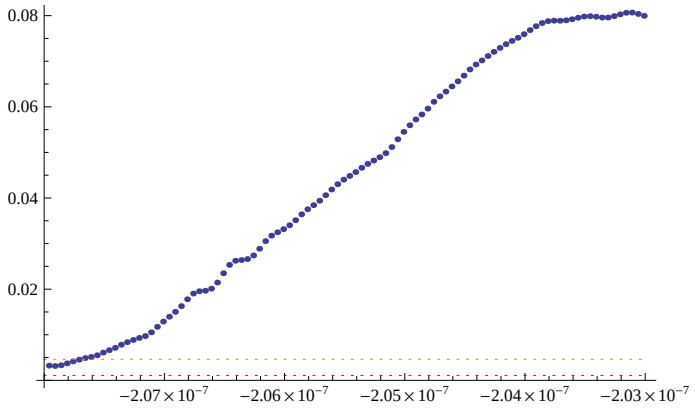


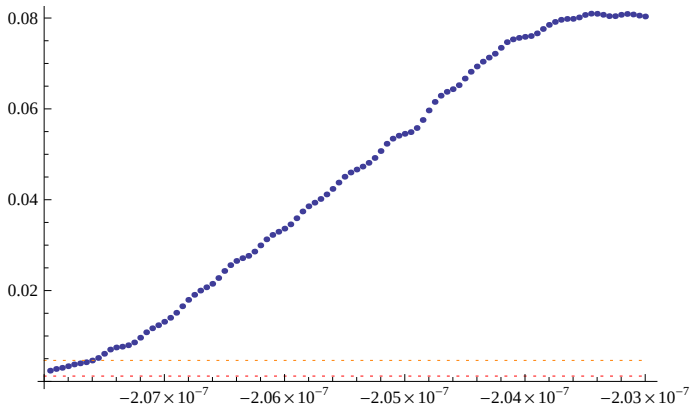




```
Show[ListPlot[Map[{#[[1]], #[[2]]} &, Select[C1pmt1,
    #[[1]] > beginC1pmt && #[[1]] < beginC1pmt + durationC1pmt &]]], Graphics[{Red,
   Dotted, Line[{{beginC1pmt, meanC1pmt1}, {beginC1pmt + durationC1pmt, meanC1pmt1}}]}],
 Graphics[{Orange, Dotted, Line[{{beginC1pmt, meanC1pmt1 + 6. rmsC1pmt1[[2]]},
     {beginC1pmt + durationC1pmt, meanC1pmt1 + 6. rmsC1pmt1[[2]]}}]}],
 Graphics[{Orange, Dotted, Line[{{beginC1pmt, meanC1pmt1 - 6. rmsC1pmt1[[2]]},
     {beginC1pmt + durationC1pmt, meanC1pmt1 - 6. rmsC1pmt1[[2]]}}]}]]

Show[ListPlot[Map[{#[[1]], #[[2]]} &, Select[C1pmt2,
    #[[1]] > beginC1pmt && #[[1]] < beginC1pmt + durationC1pmt &]]], Graphics[{Red,
   Dotted, Line[{{beginC1pmt, meanC1pmt2}, {beginC1pmt + durationC1pmt, meanC1pmt2}}]}],
 Graphics[{Orange, Dotted, Line[{{beginC1pmt, meanC1pmt2 + 6. rmsC1pmt2[[2]]},
     {beginC1pmt + durationC1pmt, meanC1pmt2 + 6. rmsC1pmt2[[2]]}}]}],
 Graphics[{Orange, Dotted, Line[{{beginC1pmt, meanC1pmt2 - 6. rmsC1pmt2[[2]]},
     {beginC1pmt + durationC1pmt, meanC1pmt2 - 6. rmsC1pmt2[[2]]}}]}]]

Show[ListPlot[Map[{#[[1]], #[[2]]} &, Select[C1pmt3,
    #[[1]] > beginC1pmt && #[[1]] < beginC1pmt + durationC1pmt &]]], Graphics[{Red,
   Dotted, Line[{{beginC1pmt, meanC1pmt3}, {beginC1pmt + durationC1pmt, meanC1pmt3}}]}],
 Graphics[{Orange, Dotted, Line[{{beginC1pmt, meanC1pmt3 + 6. rmsC1pmt3[[2]]},
     {beginC1pmt + durationC1pmt, meanC1pmt3 + 6. rmsC1pmt3[[2]]}}]}],
 Graphics[{Orange, Dotted, Line[{{beginC1pmt, meanC1pmt3 - 6. rmsC1pmt3[[2]]},
     {beginC1pmt + durationC1pmt, meanC1pmt3 - 6. rmsC1pmt3[[2]]}}]}]]
```

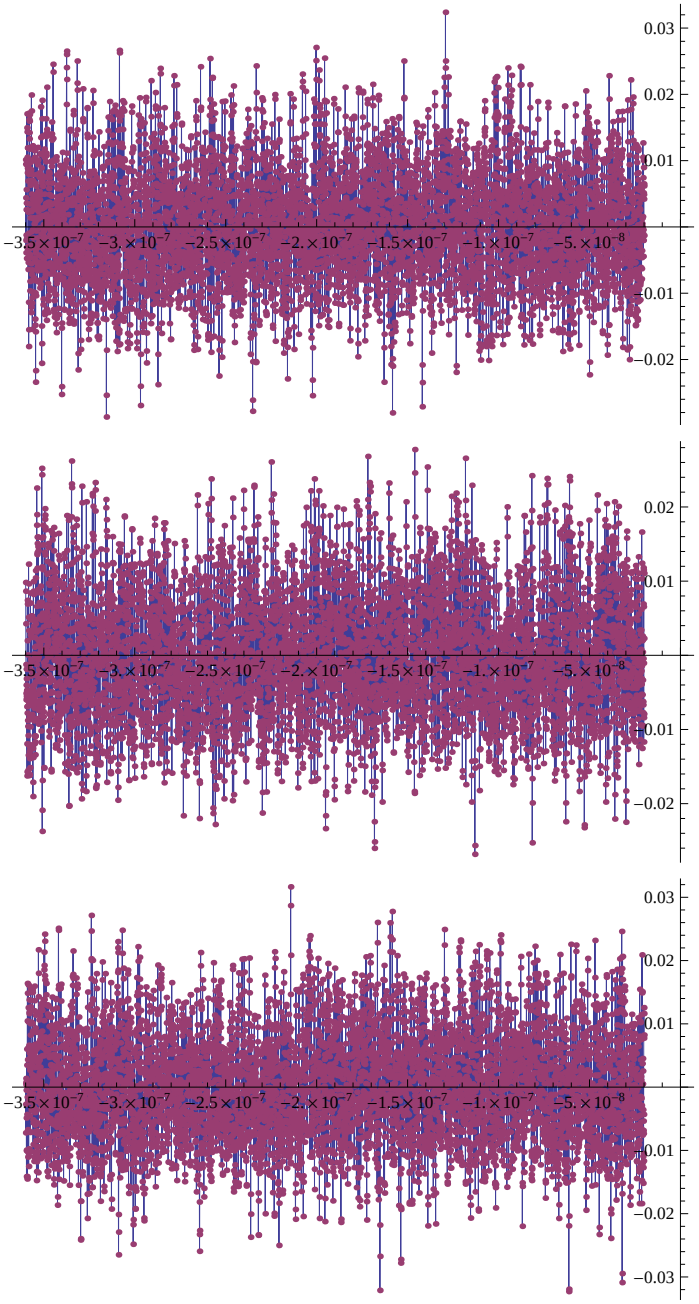




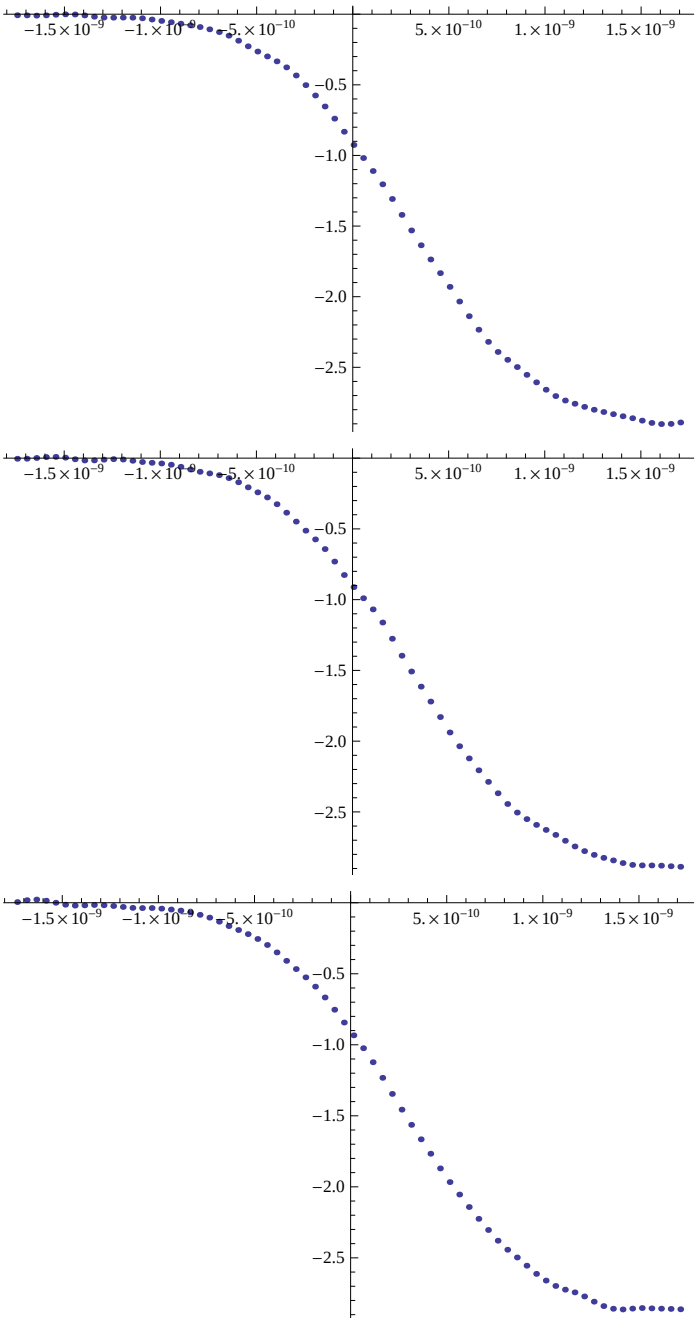



```
minC1pmt1 =
  Select[lC1pmt1, #[[2]] > Abs[ meanC1pmt1 + 6 rmsC1pmt1[[2]]]  && #[[1]] > beginC1pmt &];
minC1pmt2 = Select[lC1pmt2,
   #[[2]] > Abs[ meanC1pmt2 + 6 rmsC1pmt2[[2]]]  && #[[1]] > beginC1pmt &];
minC1pmt3 = Select[lC1pmt3,
   #[[2]] > Abs[ meanC1pmt3 + 6 rmsC1pmt3[[2]]]  && #[[1]] > beginC1pmt &];

# Statistics for PMT CH1 optical signal with three measurements;
```

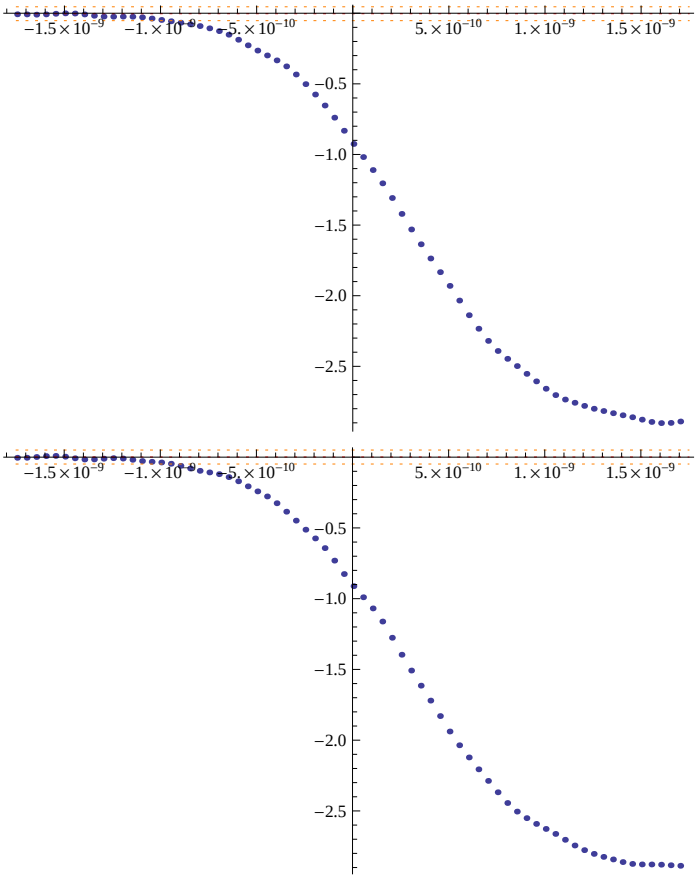
```
pfunction[rainC4pmt1, raoutC4pmt1, C4pmt1, meanC4pmt1]
pfunction[rainC4pmt2, raoutC4pmt2, C4pmt2, meanC4pmt2]
pfunction[rainC4pmt3, raoutC4pmt3, C4pmt3, meanC4pmt3]
```

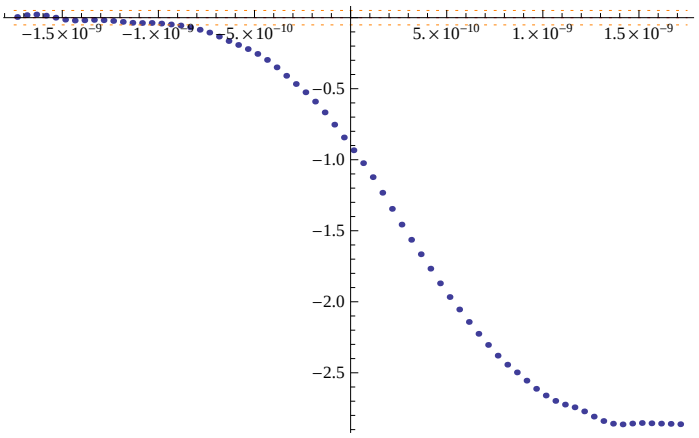


```
beginC4pmt = -0.0175 * 10^-7;
durationC4pmt = .035 * 10^-7;

lC4pmt1 = Map[{#[[1]], #[[2]]} &,
   Select[C4pmt1, #[[1]] > beginC4pmt && #[[1]] < beginC4pmt + durationC4pmt &]];
lC4pmt2 = Map[{#[[1]], #[[2]]} &, Select[C4pmt2,
    #[[1]] > beginC4pmt && #[[1]] < beginC4pmt + durationC4pmt &]];
lC4pmt3 = Map[{#[[1]], #[[2]]} &, Select[C4pmt3,
    #[[1]] > beginC4pmt && #[[1]]  < beginC4pmt + durationC4pmt &]];

ListPlot[{lC4pmt1}]
ListPlot[{lC4pmt2}]
ListPlot[{lC4pmt3}]
```



```
Show[ListPlot[Map[{#[[1]], #[[2]]} &, Select[C4pmt1,
    #[[1]] > beginC4pmt && #[[1]] < beginC4pmt + durationC4pmt &]]], Graphics[{Red,
   Dotted, Line[{{beginC4pmt, meanC4pmt1}, {beginC4pmt + durationC4pmt, meanC4pmt1}}]}],
 Graphics[{Orange, Dotted, Line[{{beginC4pmt, meanC4pmt1 + 6. rmsC4pmt1[[2]]},
     {beginC4pmt + durationC4pmt, meanC4pmt1 + 6. rmsC4pmt1[[2]]}}]}],
 Graphics[{Orange, Dotted, Line[{{beginC4pmt, meanC4pmt1 - 6. rmsC4pmt1[[2]]},
     {beginC4pmt + durationC4pmt, meanC4pmt1 - 6. rmsC4pmt1[[2]]}}]}]]

Show[ListPlot[Map[{#[[1]], #[[2]]} &, Select[C4pmt2,
    #[[1]] > beginC4pmt && #[[1]] < beginC4pmt + durationC4pmt &]]], Graphics[{Red,
   Dotted, Line[{{beginC4pmt, meanC4pmt2}, {beginC4pmt + durationC4pmt, meanC4pmt2}}]}],
 Graphics[{Orange, Dotted, Line[{{beginC4pmt, meanC4pmt2 + 6. rmsC4pmt2[[2]]},
     {beginC4pmt + durationC4pmt, meanC4pmt2 + 6. rmsC4pmt2[[2]]}}]}],
 Graphics[{Orange, Dotted, Line[{{beginC4pmt, meanC4pmt2 - 6. rmsC4pmt2[[2]]},
     {beginC4pmt + durationC4pmt, meanC4pmt2 - 6. rmsC4pmt2[[2]]}}]}]]

Show[ListPlot[Map[{#[[1]], #[[2]]} &, Select[C4pmt3,
    #[[1]] > beginC4pmt && #[[1]] < beginC4pmt + durationC4pmt &]]], Graphics[{Red,
   Dotted, Line[{{beginC4pmt, meanC4pmt3}, {beginC4pmt + durationC4pmt, meanC4pmt3}}]}],
 Graphics[{Orange, Dotted, Line[{{beginC4pmt, meanC4pmt3 + 6. rmsC4pmt3[[2]]},
     {beginC4pmt + durationC4pmt, meanC4pmt3 + 6. rmsC4pmt3[[2]]}}]}],
 Graphics[{Orange, Dotted, Line[{{beginC4pmt, meanC4pmt3 - 6. rmsC4pmt3[[2]]},
     {beginC4pmt + durationC4pmt, meanC4pmt3 - 6. rmsC4pmt3[[2]]}}]}]]
```






```
minC4pmt1 = Select[lC4pmt1,
    Abs[#[[2]]] > Abs[ meanC4pmt1 + 6 rmsC4pmt1[[2]]]  && #[[1]] > beginC4pmt &];
minC4pmt2 = Select[lC4pmt2,
    Abs[#[[2]]] > Abs[ meanC4pmt2 + 6 rmsC4pmt2[[2]]]  && #[[1]] > beginC4pmt &];
minC4pmt3 = Select[lC4pmt3,
    Abs[#[[2]]] > Abs[ meanC4pmt3  + 6 rmsC4pmt3[[2]]]  && #[[1]] > beginC4pmt &];

# Average time delays;

pmtdiff1 = Abs[minC1pmt1[[1, 1]] - minC4pmt1[[1, 1]]];
pmtdiff2 = Abs[minC1pmt2[[1, 1]] - minC4pmt2[[1, 1]]];
pmtdiff3 = Abs[minC1pmt3[[1, 1]] - minC4pmt3[[1, 1]]];

pmtavgtdiff = (pmtdiff1 + pmtdiff2 + pmtdiff3) / 3;

Bsipmdiff1 = Abs[minC1Bsipm1[[1, 1]] - minC4Bsipm1[[1, 1]]];
Bsipmdiff2 = Abs[minC1Bsipm2[[1, 1]] - minC4Bsipm2[[1, 1]]];
Bsipmdiff3 = Abs[minC1Bsipm3[[1, 1]] - minC4Bsipm3[[1, 1]]];

Bsipmavgtdiff = (Bsipmdiff1 + Bsipmdiff2 + Bsipmdiff3) / 3;

minC4Tsipm1 = Select[lC4Tsipm1,
    Abs[#[[2]]] > Abs[ meanC4Tsipm1 + 6 rmsC4Tsipm1[[2]]]  && #[[1]] > beginC4Tsipm &];
minC4Tsipm2 = Select[lC4Tsipm2,
    Abs[#[[2]]] > Abs[ meanC4Tsipm2 + 6 rmsC4Tsipm2[[2]]]  && #[[1]] > beginC4Tsipm &];
minC4Tsipm3 = Select[lC4Tsipm3,
    Abs[#[[2]]] > Abs[ meanC4Tsipm3 +  6 rmsC4Tsipm3[[2]]]  && #[[1]] > beginC4Tsipm &];

Tsipmdiff1 = Abs[minC1Tsipm1[[1, 1]] - minC4Tsipm1[[1, 1]]];
Tsipmdiff2 = Abs[minC1Tsipm2[[1, 1]] - minC4Tsipm2[[1, 1]]];
Tsipmdiff3 = Abs[minC1Tsipm3[[1, 1]] - minC4Tsipm3[[1, 1]]];

Tsipmavgtdiff = (Tsipmdiff1 + Tsipmdiff2 + Tsipmdiff3) / 3;

pmtavgtdiff
```

2.06733×10^{-7}

```
Bsipmavgtdiff
```

1.99781×10^{-7}

```
Tsipmavgtdiff
```

2.18355×10^{-7}